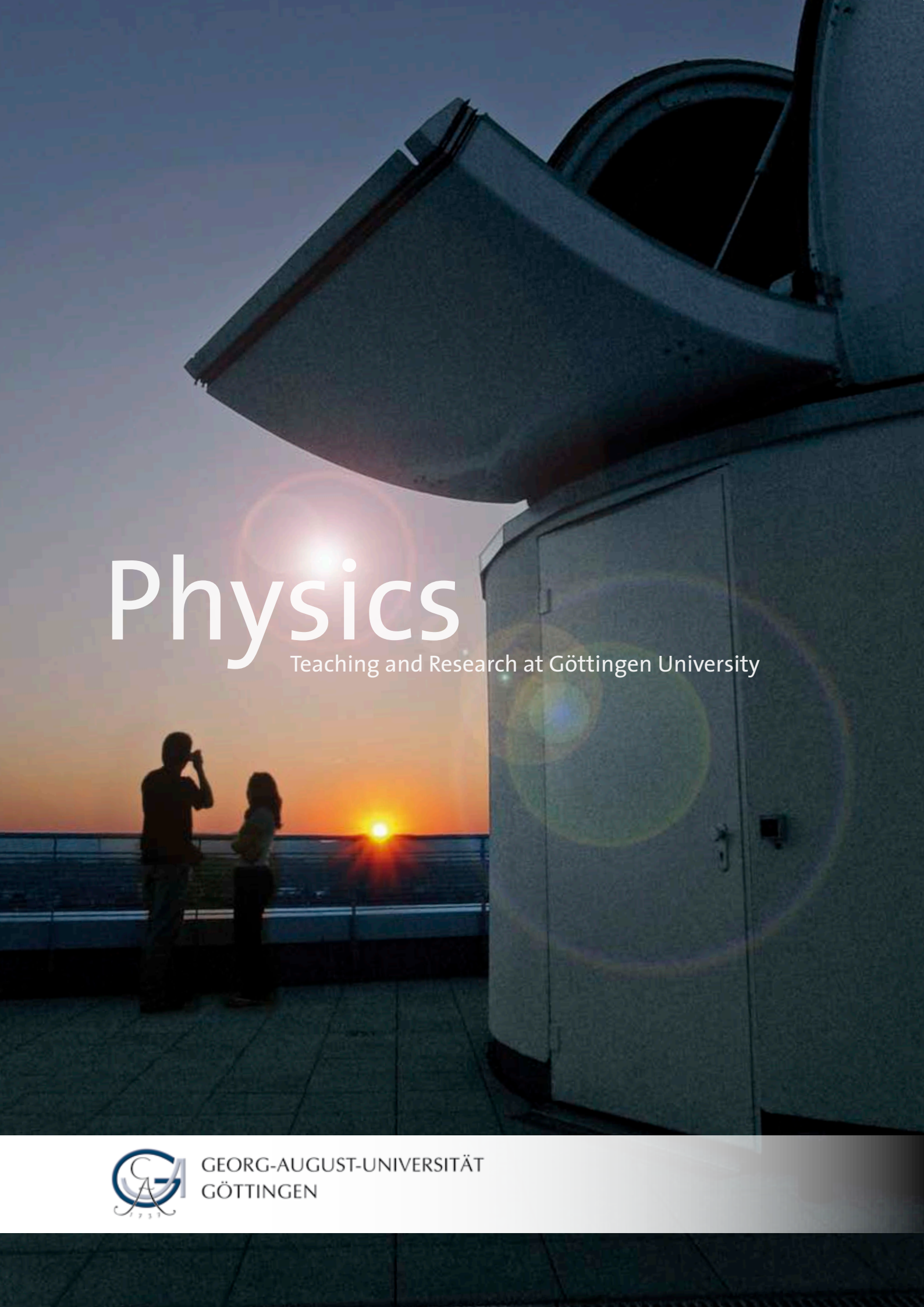


Physics

Teaching and Research at Göttingen University

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Greeting from the President

Physics has always been of particular importance for the Georg-August Universität Göttingen. As early as 1770, Georg Christoph Lichtenberg became the first professor of Physics, Mathematics and Astronomy. Since then, Göttingen has hosted numerous well-known scientists working and teaching in the fields of physics and astronomy. Some of them have greatly influenced the world view of physics. As an example, I would like to mention the foundation of quantum mechanics by Max Born and Werner Heisenberg in the 1920s. Göttingen physicists such as Georg Christoph Lichtenberg and in particular Robert Pohl have set the course in teaching as well. It is also worth mentioning that Göttingen physicists have accepted social and political responsibility, for example Wilhelm Weber, who was one of the Göttingen Seven who protested in 1837 against the abrogation of the constitutional law by King Ernst August. By signing the Göttingen declaration of 1957, eighteen nuclear scientists fought against the nuclear armament of the Federal Republic of Germany.

Physics in Göttingen experienced its heyday from about 1900 onwards, when famous scientists such as Werner Heisenberg, Max Born, Emil Wiechert and Karl Schwarzschild taught and did research here. When the National Socialists came to power in 1933, this golden age came to an abrupt end. Not until the end of the Second World War could Physics in Göttingen start to develop again. Further institutes were affiliated with the Faculty of Physics, amongst them the Institute of Geophysics, which was founded in 1898, and the Institute of Astrophysics, which originated from the University Observatory. This observatory was founded in 1816 and has always been in close contact with physics since the time when Carl Friedrich Gauß was its first director. In addition to low temperature physics, nuclear physics and theoretical physics, several other modern areas of research have been established. The Institute for Semiconductor Physics was founded in 1965. Later, the Institute for Materials Physics and, with the availability of synchrotrons as intensive X-ray sources, the Institute of X-ray physics were added. Today the Faculty of Physics comprises ten institutes thus enabling a broad spectrum of research and manifold options within degree courses.

Current research focuses on solid state and materials physics, astrophysics and particle physics, biophysics and complex systems, as well as multi-faceted theoretical physics. Since 2003 the Physics institutes have been housed in a new physics building on the north campus with the natural science faculties, in close proximity to chemistry, geosciences and biology as well as to the Max Planck Institute (MPI) for Biophysical Chemistry, the MPI for Dynamics and Self Organization and soon the MPI for Solar Systems and Beyond. This is also associated with intense interdisciplinary scientific cooperation, exemplified by two collaborative research centers, the Bernstein Center for Computational Neuroscience (BCCN) and the Center for Molecular Physiology of the Brain (CMBP). Participation in new interdisciplinary degree programs in materials science and medical natural sciences is in the planning stage. With this booklet, the Faculty of Physics presents itself as a highly productive and modern faculty, with the institutes united in one new building, embedded in an attractive and powerful scientific environment and thus perfectly prepared for future scientific challenges.

Prof. Dr. Kurt von Figura
President of Georg-August-Universität Göttingen

Greeting from the Dean

Since Georg Christoph Lichtenberg became the first professor of Physics in Göttingen in 1770 and since the appointment of Carl Friedrich Gauß as director of the University Observatory in 1807, physics and astronomy in Göttingen have had a remarkable development that is respected worldwide. The period of prosperity of Göttingen physics in the first three decades of the 20th century was marked by the foundation of quantum mechanics by Max Born and Werner Heisenberg, the development of seismic methods by Emil Wiechert and the work of Karl Schwarzschild on the theory of relativity. At the end of the 20th century, the Faculty of Physics comprised 10 institutes: the 1st and 2nd Institutes being devoted to experimental physics going back to Robert Pohl and Nobel laureate James Franck, the Institute for Theoretical Physics with Nobel laureate Max Born as its first director, the Institute of Astrophysics originating from the University Observatory, the Institute of Geophysics and the younger Institutes of Semiconductor Physics, Materials Physics, X-ray Physics, Nonlinear Dynamics and Biophysics.

With the advent of the 21st century, there were three significant developments at the Faculty of Physics in Göttingen.

Firstly, a change of generation gave rise to several new appointments. This opened up new directions in research and teaching such as biophysics, astrophysics and cosmology, particle physics, solid state physics, materials physics and theoretical physics. In connection with this development, there is an intensifying cooperation with other science faculties and extra-faculty research institutes located in Göttingen, such as the Max Planck Institutes. This is reflected in two current collaborative research programs and the research centers Bernstein Center for Computational Neuroscience (BCCN) and Center for Molecular Physiology of the Brain (CMBP). Furthermore, the Faculty of Physics participates in national research networks in particle physics and condensed matter physics as well as international collaborations in the field of particle physics and astrophysics.

Secondly, the different institutes of the faculty were able to share a new physics building for the first time. This building promotes scientific exchange and gives the faculty a new visible corporate identity. State-of-the-art research labs, lecture halls, lab course and seminar rooms are now available and offer attractive teaching and learning conditions for students and an ideal research environment for meeting the scientific challenges of the 21st century.

The third new development concerns the introduction of bachelor and master study programs as well as structured graduate programs leading to the degrees of Dr. rer.nat. or Ph.D. For the Faculty of Physics, it was of utmost importance to transfer the recognized high quality of the previous diploma study program to the bachelor and master programs. Moreover, novel teaching concepts were implemented in the new study programs and a variety of choices for specialization are currently offered. With the new study programs, the faculty is also striving to open up internationally. By the year 2010, the three mentioned developments will be essentially completed. With this booklet, the Faculty of Physics presents itself as a new, modern and forward looking faculty and gives an overview of its broad research spectrum, comprehensive teaching and the modern infrastructure of the new physics building. I am convinced that the Faculty of Physics will be an inspiring place for scientific exchange more than ever. Scientists and students from all over the world are cordially welcome to this new domain of physics in Göttingen.

Prof. Hans Hofsäss
Dean of the Faculty of Physics

Content

Research Groups from A to Z

Solid State Physics and Materials Physics

Biophysics and Physics of Complex Systems

Astrophysics and Elementary Particle Physics

Adjunct Professors:

Faculty of Physics

Central facilities	Dean's office	
	Dean of Students' office	
	Service Centre (for financial accounting)	
	Central mechanical workshop	
	Collection of lecture hall experiments	
	Collection of historic instruments	
Institutes	I. Institute of Physics	Prof. Samwer
		Prof. Gegenwart
	II. Institute of Physics	Prof. Quadt
		Prof. Frey
		Prof. Hofsäss
		N.N.
	III. Institute of Physics	Prof. Enderlein
		Prof. Schmidt
		Prof. Wörgötter
	IV. Institute of Physics	Prof. Ulbrich
		Prof. Rizzi
	Institute for Nonlinear Dynamics	Prof. Geisel
		Prof. Bodenschatz
	Institute for Theoretical Physics	Prof. Zippelius
		Prof. Schönhammer
		Prof. Pruschke
		Prof. Müller
		Prof. Kree
		N.N.
	Institute for Materials Physics	Prof. Volkert
		Prof. Kirchheim
		Prof. Jooß
	Institute of Geophysics	Prof. Bahr
		Prof. Tilgner
	Institute for X-ray Physics	Prof. Salditt
		N.N.
	Institute for Astrophysics	Prof. Dreizler
		Prof. Niemeyer

Dean's office, Dean of Students' office and Service Centre (for financial accounting)

Faculty of Physics: research and structure

The Göttingen Faculty of Physics is organized into several central facilities and ten institutes, most of them comprising several groups working in three main fields of research: (i) *Solid State Physics and Materials Physics,* (ii) *Biophysics and Physics of Complex Systems,* and (iii) *Astrophysics and Elementary Particle Physics.*

Two junior research groups of a **Courant Research Centre** *Nanospectroscopy and X-ray-Imaging* (established with the Excellence Initiative) are integrated in the faculty.

Additionally, via shared professorships, the faculty is linked to interdisciplinary research centres of the university: **DFG – Research Centre** *Molecular Physiology of the Brain,* and **BMBF** – *Bernstein Center for Computational Neuroscience.*

There are further shared professorships at renowned external research facilities in Göttingen, supporting the excellent multidisciplinary research of the faculty: **Max Planck Institute for Solar System Research, Max Planck Institute for Dynamics and Self-Organization,** and **Institute for Aerodynamics and Flow Technology (German Aerospace Center).**

In collaborative research projects, the faculty cooperates closely with the **Faculties of Chemistry, of Mathematics, of Medicine,** and with the **Max Planck Institute for Biophysical Chemistry,** and the **Laser-Laboratorium Göttingen.** Therefore the faculty is involved in numerous interdisciplinary and cross-departmental collaborative research projects, like **DFG-Collaborative Research Centres:**

- **No. 602** *Complex Structures in Condensed Matter from Atomic to Mesoscopic Scales*
- **No. 755** *Nanoscale Photonic Imaging*
- **No. 803** *Functionality Controlled by Organisation in and between Membranes*

and **BMBF-Research Foci:**

- Research Focus No. **101 (ATLAS):** closely connected to CERN
- Promotional Focus *Astrophysics with Earthbound Telescopes;* involved in the international very large telescope projects of ESO.

The Study Paths in Physics

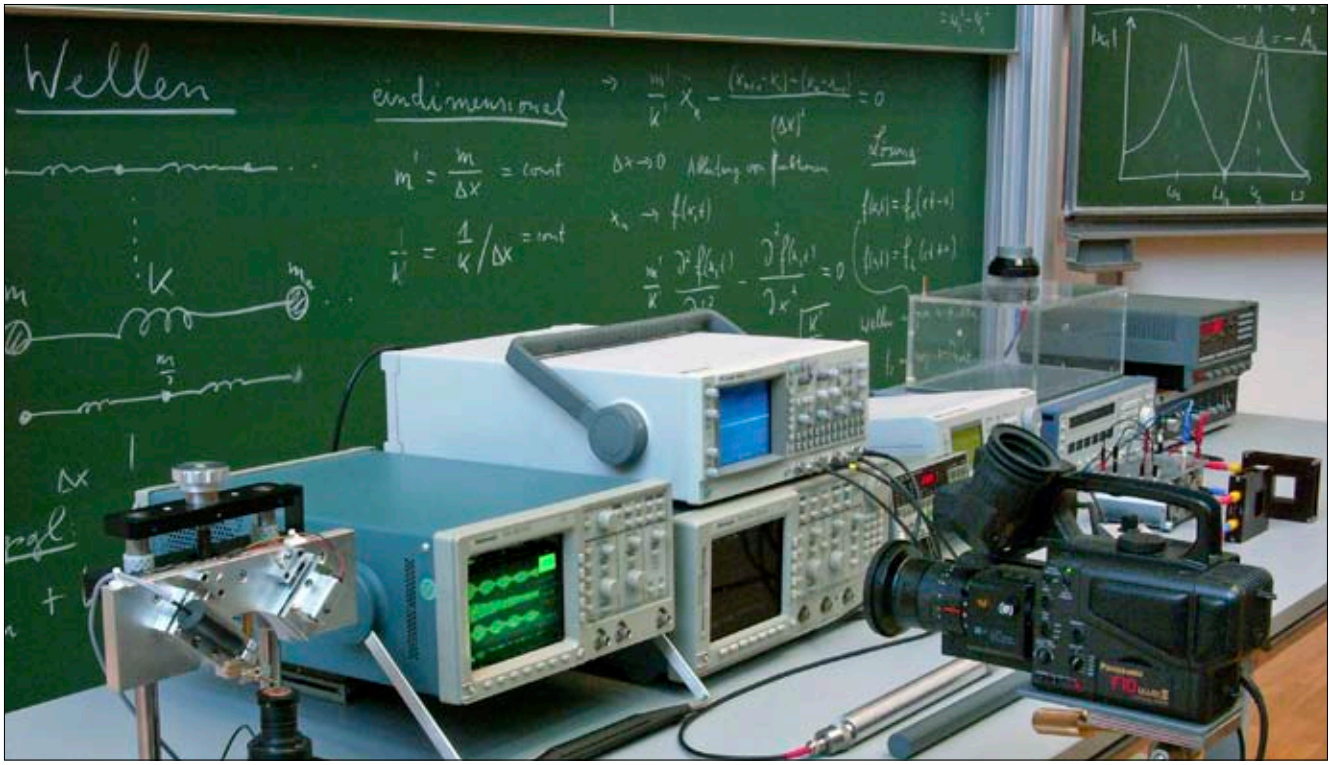
The faculty of physics offers bachelor, master and Ph.D programmes in physics. In addition the programmes bachelor of art and master of education are dedicated to the education of qualified teachers. Together with the faculties of chemistry and geosciences a bachelor programme in materials science was recently initiated. Furthermore, an interdisciplinary four year bachelor programme on medical natural sciences is in preparation. The new physics building in Göttingen offers several modern lecture halls with an extensive collection of demonstration experiments, computer rooms with more than 100 computers for student access and computer-aided lectures, w-lan internet access, an in-house library with modern text books and scientific journals, numerous lab course rooms with modern equipment and a variety of seminar rooms.

The three year modular bachelor programme in physics (B.Sc.) imparts basic knowledge in physics as well as specialized knowlege in physics and other areas of natural sciences. The lectures are held in German language. The bachelor degree qualifies for a professional career in selected fields such as technology, economy and finances and is the prerequisite for enrolling to a master degree programme. Within the bachelor programme the students may chose modules and courses according to scientific profiles like astro- and geophysics, biophysics and complex systems, nuclear and particle physics, solid state and materials physics. Career oriented specialization profiles are nanostructure physics and physical informatics. Unique featurers of the Göttingen bachelor programme in physics are integrated courses, a variety of practical training and lab courses and a 3 month bachelor thesis. The basic physics courses are tought by a team of two lecturers as so-called intergrated courses as a combination of theoretical physics and experimental physics. Lab courses prepare for the thesis work and range from basic lab courses, experimental project course, electronics lab course, advanced lab course and scientific methods lab course.

The two year modular master programme has a restricted admission and the students have to select one of the specialization topics: astrophysics and geophysics, biophysics and the physics of complex systems, solid state and material physics, nuclear physics and particle physics. During the first year, the students participate in a research-oriented curriculum. The second year of the master course is dedicated to

Fig. 1: The physics of rockets: the mass changes during the flight

Fig. 2: A lecture theatre



the compilation of the master thesis, including preceeding methodical courses.

The three year modular bachelor programme with degree bachelor of art (B.A., the so-called 2-Fach bachelor (two disciplines bachelor), comparts funadamental and methodical knowledge in two disciplines (e.g. physics and mathematics or physics and a language) as well as technical didactics and related-to-practice education relevant for high school teachers. Currently physics can be combined with mathematics, chemistry biology or the language programmes German, English, French, Latin and Spanish. Starting with basic introductory physics courses together with the above B.Sc programme, the B.A. programme offers specific courses in optics, quantum physics, theoretical physics and technical didactics adjusted to the needs of future high school teachers.

The consecutive two year programme with degree master of education (M.Ed.) comparts deepend knowlege in physics, technical didactics, pedagogics and education related topics and prepares the students for the required period as trainee teacher at high schools.

The Ph.D programmes in physics and related fields are embedded within the Georg-August University School of Science (GAUSS) graduate programme, offering the grades Dr. rerum naturalium (Dr. rer. Nat.) and philosophiae doctor (Ph.D). There exist a basic Ph.D programme called PROPHYS as well as several specialized programmes ensuring a high quality graduate programme and defining mandatory requirements regarding research, curriculum, supervision and participation in teaching. The duration of the research-oriented thesis work is typically three years and can be carried out at one of the ten institutes of the faculty of physics, the related Max-Planck Institutes, the Laser laboratory and the DLR. Together, they provide a large variety of possible thesis projects in fundamental and applied research.

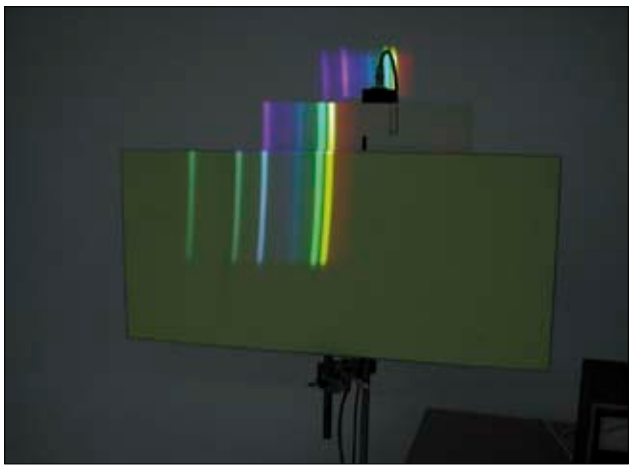


Fig. 3: A demonstration experiment

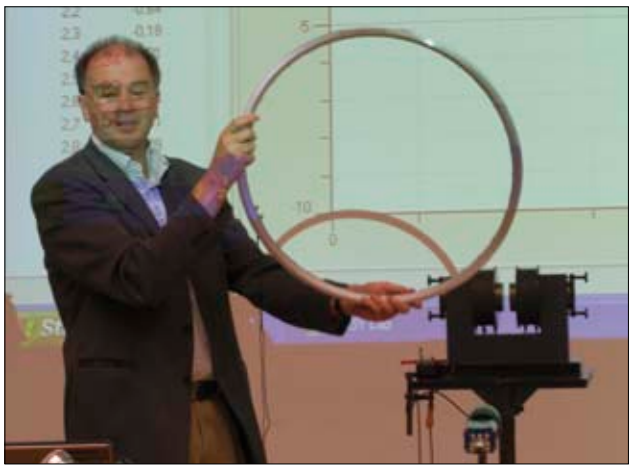


Fig. 4: A better demonstration experiment

Activities of the Student Body

The faculty of physics also has a very committed student body. Students are very involved in outreach activities. For example Saturday Morning Physics, a lecture series given by professors of the faculty for pupils and citizens interested in physics, is regularly organized. In addition, the physics show took place in Göttingen for the first time this year. In this show, which was initiated and organized by Prof. Dr. Arnulf Quadt, students of all years demonstrated spectacular experiments like fire tornados and superconducting monorails. In three performances, the show was attended by over 300 viewers. Further activities are the committee work of the student council and the pupil information days, where pupils get the opportunity to gain insight into the faculty of physics and are informed about studying physics in Göttingen.

The student body also takes care of the freshman students. Their first week starts with an "orientation week", during which they get information about the most important things, like the course of studies, as well as a guided tour through the faculty and the opportunity to meet their future professors. They also get integrated in a student-mentor program, including a short trip organized for them to get to know each other.

Moreover, since the introduction of tuition fees, students are also responsible for new ideas of how to use them sensibly. For instance, these fees are used to reduce the group size of tutorials, to buy new books and to give extra courses. But there are also some new and innovative projects, like the aforementioned physics show or the "Lehrportal", an e-learning platform, made by students for students.

In order to honor good teaching, the student body is awarding the Pohl-Medal, named after the famous physicist Robert Wichard Pohl from Göttingen, given annually to the best lecturer during the last term. Last but not least, there are of course some social events organized by students as well, like the tabletop soccer tournament and the annual summer festival, which makes studying physics in Göttingen even more enjoyable.

Studies of Physics Education

The education program at the Georg-August-Universität Göttingen is focused on teacher training at the Gymnasium level (academic-track secondary school). In total, the program spans eight departments comprising 19 subjects and their respective subject didactics, as well as general educational sciences (school pedagogy and educational psychology). As a classic comprehensive and research university, Göttingen offers an extremely broad range of subjects, with over 200 subject combinations recognized by the state government of Lower Saxony. Approximately 2,300 students are enrolled in double-major Bachelor and Master of Education degree programs preparing them to teach at the Gymnasium level and approximately 30 % of future Gymnasium teachers in Lower Saxony are trained in Göttingen up to their final teaching internship (Referendariat). Of the "MINT" subjects, the program in Göttingen offers mathematics, information science, biology, chemistry, and physics. These subjects are accredited towards the double-major Bachelor in teaching and the Master of Education. All MINT subjects benefit from the strength of the various disciplines at Göttingen, which has been named a "University of Excellence", and from the network among the MINT subjects and the educational sciences at the Centre for Empirical Teaching Research (Zentrum für Empirische Unterrichtsforschung, ZeUS).

The degree program

The degree in teaching encompasses a six-semester double-major Bachelor in teaching and the four-semester Master of Education. The subject of physics can be combined with all 18 subjects; approximately 60 % of the students choose the combination physics and mathematics, which provides the greatest synergy. In order to make it easier for students to begin studying, preparatory courses in physics and mathematics are held every September. Experienced tutors are also available for help with subject-specific problems.

The double-major Bachelor program provides students with conceptual knowledge and methodological skills in two subjects in the area of professionalization relating to their professional field (subject didactics, school pedagogy, school internships, and key competencies) and is completed with a Bachelor thesis. In the subject of physics, the program first provides a foundation of basic scientific and methodological knowledge in the branches of classical, modern and theoretical physics that are relevant at the school level. Students gain insight into current research in various aspects of physics and physics education. The practical training takes place in the framework of training events in school pedagogy, school internships and extra-curricular events held outside the school context, for example, at the Experimental Laboratory for Young People (Experimentallabor für junge Leute, XLAB) and the DLR_School_Lab.

The Master of Education qualifies graduates to begin their teaching internship or continue on to obtain further qua-

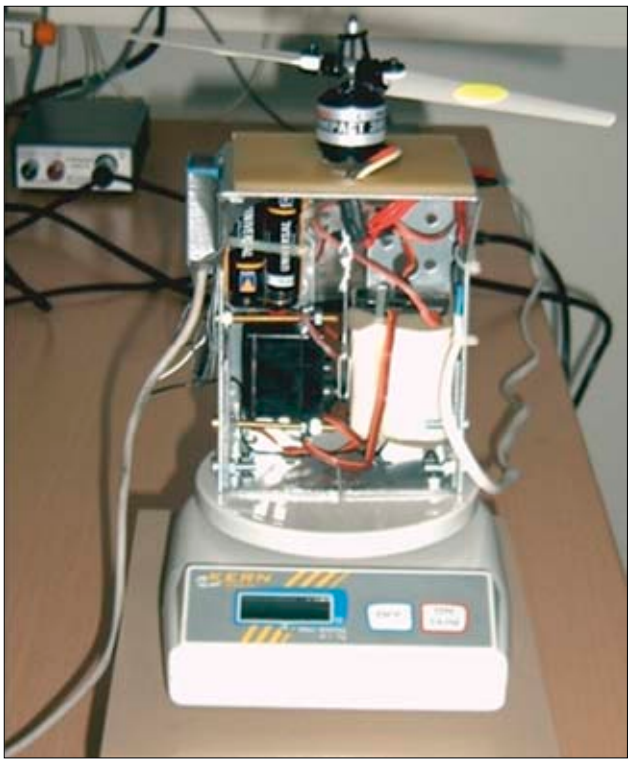


Fig. 1: Model of a helicopter rotor built by students. By setting the model on a scale, the lift of the rotating horizontal rotors can be measured as a reduction in the helicopter's weight force.

lifications in a doctoral program. The master's program encompasses competence in the specific subject matter and in subject didactics, in school pedagogy and educational psychology as branches of educational science, and also includes the Master module in which students write their final thesis. Students gain further practical experience through two internships in their subject, where one of these internships may also be a research internship. During the master's program, students complete an indepth module in one of several fields of physics. A module on "Building a deeper understanding of experimental techniques and enhancing practical skills" is held at a partner Gymnasium in Göttingen. Further projects on classroom and school research take place in cooperation with the MINT Gymnasien in the Göttingen area.

Master's thesis

Students may complete their master's thesis in the various subjects, in subject didactics, or as an empirical study in educational science. Within the field of subject didactics, one focus of study and research in which students are often eager to write their master's thesis deals with the interest and motivation of students in introductory classes in the natural sciences. Master's theses can also be completed in cooperation with the two extracurricular learning sites XLAB and DLR_School_Lab, where new experimental learning units are always under development.

Fig. 2: Fully functional model of a modular wind tunnel. The tunnel's properties can be changed by exchanging modules. It was built as part of a master's project and is now used in the DLR_School_Lab.

Doctoral degree

Holders of a master's degree who are interested in obtaining further educational qualifications in the field of subject didactics may enter a doctoral program. They will benefit from the interdisciplinary network among the disciplines and the educational sciences at Göttingen university's Center for Empirical Teaching Research (ZeUS), which is situated at the interface between research in subject didactics and research on learning and instruction carried out in close cooperation with schools and oriented towards teaching the fundamentals.

Recent Master's theses

Steffen Ravekes: Einsatz von LEGO-Robotern und Eigenbausensoren in der Schulphysik – Konzepte zu Unterrichtseinheiten zur Thematik "Marsroboter", Göttingen 2009

Matthias Block: Kernzerfälle beobachten im Schülerexperiment – Entwicklung einer Lerneinheit am XLAB, Göttingen 2008

Desiree Dauber: Modellversuche zum Golfstrom – Eine Unterrichtseinheit für den Physikunterricht der 5. Klasse, Göttingen 2007

Jürgen Schwedhelm: Überschallströmung und deren Visualisierung: Entwicklung von Experimenten am außerschulischen Lernort DLR_ School_Lab, Göttingen 2007

Yvonne Lembeck: Interessendifferenzen zwischen Jungen und Mädchen im Physikunterricht – ein Vergleich von vier internationalen Studien, Göttingen 2006

Susanne Schneider

After completing her undergraduate diploma in physics, physics education, and German language education in 1988, Susanne Schneider went on to receive her PhD in physics in 1992 from the University of Göttingen. In 1993 she became a Dorothea von Erxleben fellow of the state of Lower Saxony and spent two years as research fellow at the California Institute of Technology in Pasadena (USA). She earned her Habilita-tion in 2001. In 2005 she was awarded an extraordinary professorship at the University of Göttingen. She is head of the section Physics Education.


Garderobe
Schliessfächer
Hörsaal 5
Ausgang
Institute
Praktika, Seminar-
und Übungsräume

On the Shoulders of Giants: a brief History of Physics in Göttingen

18th and 19th centuries

Georg Ch. Lichtenberg (1742-1799) may be considered the forefather of experimental physics in Göttingen. His lectures were accompanied by many experiments with equipment which he had bought privately. To the general public, he is better known for his thoughtful and witty aphorisms. Following Lichtenberg, the next physicist of world renown would be *Wilhelm Weber* (1804-1891), a student, coworker and colleague of the „prince of mathematics" C. F. Gauss, who not only excelled in electrodynamics but fought for his constitutional rights against the king of Hannover (1830). After his re-installment as a professor in 1849, the two Göttingen physics chairs , W. Weber and B. Listing, approximately corresponded to chairs of experimental and mathematical physics. After Listing, *Woldemar Voigt* (1850-1919), working in optics, took over the theoretical physics department. He discovered what Poincaré named „Lorentz transformations". During this time *Eduard Riecke* (1845-1915) held the experimental chair and *Johannes Stark* (1874-1957) did his experiments on the Doppler effect of canal rays (1905) in Göttingen. This brought him a Nobel prize (Stark Effect). In experimental physics, a division for applied electricity under H. Th. Simon was created in 1907.

Since C. F. Gauss, the astronomical observatory has been in contact with physics. Its director from 1901-1909 was *Karl Schwarzschild* (1873-1916), who derived a famous solution of Einstein's gravitational theory which led to the concept of the black hole. Also, a geophysical institute was founded in 1898 under *Emil Wiechert* (1861-1928), where seismic methods for the study of the Earth's interior were developed. An institute for applied mathematics and mechanics under the joint directorship of the mathematician *Carl Runge* (1856-1927) (Runge-Kutta method) and the pioneer of aerodynamics, or boundary layers, *Ludwig Prandtl* (1875-1953) complemented the range of institutions related to physics proper. In 1925, Prandtl became the director of a newly established Kaiser-Wilhelm-Institute for Fluid Dynamics.

A new and well-equipped physics building opened at the end of 1905. After the turn to the 20th century, *Walter Kaufmann* (1871-1947) did precision measurements on the velocity dependence of electron mass; they played an important role for the discussion of Einstein's special relativity and a rival theory of the Göttingen lecturer Max Abraham. In 1914, a professorship for the Dutch theoretician and later Nobel prize winner *Peter Debye* (1884-1966) was established (Debye-Scherrer method). Debye left Göttingen in 1920. When the three chairs in physics had to be refilled around 1920, a fortunate choice brought the theoretician *Max Born* (1882-1970) as well as the experimental physicists *James Franck* (1982-1964) and *Robert Pohl* (1884-1976) to the university. Early in the 1920's, physics was reorganized into four institutes: two experimental, a theoretical, and an upgraded „Institute for Applied Electricity" under *Max Reich* (1874-1941). The „faculty for mathematics and natural sciences"separated from the philosophical faculty only in 1922.

Fig. 1: Wolfgang Pauli and Paul Ehrenfest (1929)

Fig. 2: Viktor Weisskopf, Maria Goeppert, Max Born

Fig. 3: I. Institute of Physics and II. Institute of Physics

Weimar Republic

With the coming to Göttingen of the three friends Born, Franck and Pohl, an exceptional decade for physics began. Franck received a Nobel Prize in 1925 (Franck-Hertz experiment). Among his students, the names *Patrick M. S. Blackett* (Nobel prize 1948) and *Edward Condon* (Franck-Condon effect) appear as well as those of numerous subsequent physics professors (e.g., W. Hanle, H. Kopfermann, H. Maier-Leibnitz, Herta Sponer). Born and his coworkers *Werner Heisenberg* (1901-1976, in Göttingen 1923/26 and 1948/57) and *Pascual Jordan* (1902-1980) were responsible for the completion of quantum theory (1925-1927). The concept „quantum mechanics" was coined by Born in 1924. From the observed atomic spectra Heisenberg distilled a mathematical formalism permitting the calculation of observables like transition frequencies, intensity and polarization of atomic radiation (Nobel Prize 1932). Born recognized the hidden mathematical structure (matrices, linear operators) and showed that Schrödinger's wave function must be connected with a probability interpretation (Nobel Prize 1954). P. Jordan, at the same time as P. A. M. Dirac, published a formalism combining both Schrödinger's wave- and Heisenberg's matrix theory. He also found what now is called Fermi-Dirac statistics. Born's probability interpretation and Heisenberg's uncertainty relations have immensely furthered our understanding of nature. Among Born's PhD students, assistants and scientific guests were five later Nobel prize winners: Max Delbrück, Maria Goeppert-Mayer, Wolfgang Pauli, Enrico Fermi and Gerhard Herzberg. Many other outstanding physicists also worked under Born, among them George Gamov, Walter Heitler, Erich Hückel, Friedrich Hund, Lothar Nordheim, Robert Oppenheimer, G. Uhlenbeck and Viktor Weisskopf. The long-time tradition of a strong interaction with mathematics continued, as is exemplified by the 1926 lecture on quantum mechanics by David Hilbert, and the subsequent mathematical foundation of quantum theory by John v. Neumann in Göttingen.

1933-1945 and thereafter

With the seizure of power by the National Socialists and the expulsion of both Jewish and democratically minded physicists from the university and from Germany, this golden era of physics came to an abrupt end. During the Nazi period and the 2nd world war, Robert Pohl pursued his research in the foundations of solid state physics (inner photo effect in crystals, thin layers) and transformed the lecture hall into a show room. He and the nuclear physicist *Hans Kopfermann* (1895-1963) (hyperfine structure, nuclear moments, betatron for medical use) and the theoretical physicist Richard Becker (1887-1953) working on magnetic properties of materials, succeeded to keep a high standard both in teaching and research. All four institutes continued uninterrupted through 1945. One of the people who took over courses from M. Born was Gustav Heckmann from the observatory. In the early 30's, he had made an important contribution to cosmology. During the war, the observatory's director *Paul ten Bruggencate* (1901-1961) even built a special station for studies of the sun's activity.

The end of the second world war had some advantageous consequences for the university. The town had remained in good order such that many well-known physicists, among them the three Nobel prize recipients (Max Planck, Max v. Laue, and the chemist Otto Hahn) moved here from a ruined Berlin. Others coming from the areas lost to Poland and the USSR followed suit. In 1946, the Kaiser-Wilhelm- (later Max Planck) Institute for Physics in Berlin with its director, Heisenberg, re-opened in Göttingen and stayed here until 1958. This included a department headed by C. F. v. Weizsäcker. In Kopfermann's Institute, *Wolfgang Paul* (1913-1993) worked as a professor on nuclear quadrupole moments while *Hans Georg Dehmelt* (1922-) wrote his PhD thesis. Together, they received the Nobel Prize in 1989 (atom traps). In 1952, at the Institute for Theoretical Physics, *Herbert Kroemer* received his doctoral degree under Fritz Sauter (1906-1983), who would

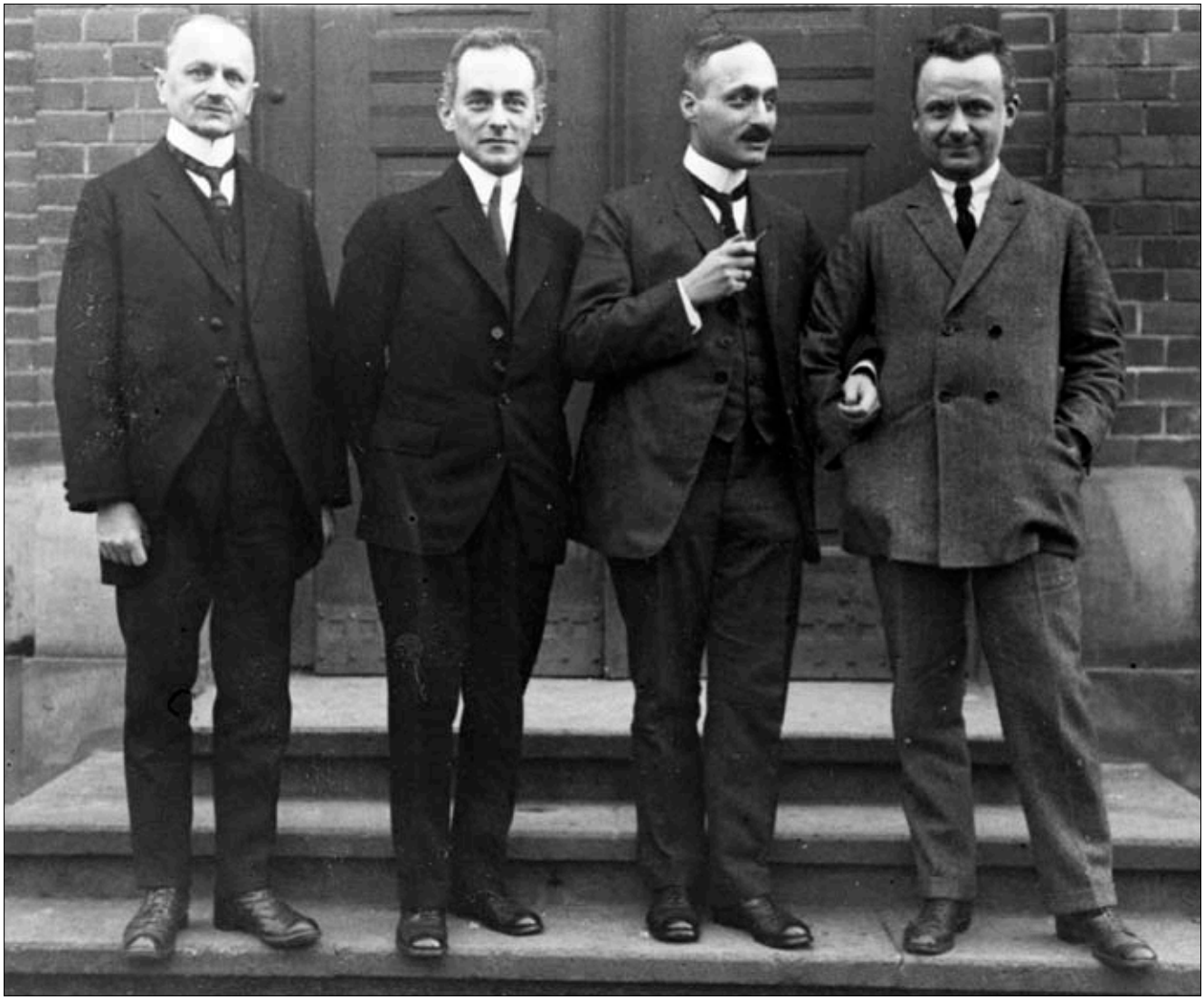


Fig. 4: Max Reich, Max Born, James Franck, Robert Pohl

later be full professor in Cologne. Kroemer became a Nobel prize winner in the year 2000 (opto-electronics). In place of the discontinued institutes for applied mechanics and applied electricity, a third experimental institute for the physics of vibrations and acoustics was opened in 1947. The Institute for Metal Physics was added to physics, having transfered from the chemistry department. It would later be expanded into an institute of Materials Science. Prandtl's successors as directors at the Max Planck Institute for Fluid Dynamic were also given the position of full professor of physics at the university. Likewise, a link of director's positions between geophysics and the Max Planck Institute for Aeronomy in Katlenburg/Lindau near Göttingen came about. In 1957, prominent physicists like M. v. Laue, M. Born (who had returned to Bad Pyrmont near Göttingen), W. Heisenberg, W. Paul, H. Kopfermann, and C. F. v. Weizsäcker formulated a protest against the nuclear arming of the German Armed Forces and worldwide nuclear arms build-up.

The late 1960's and early 1970's brought a big influx of students and a sizable increase in both positions and institutions in physics. A fourth experimental Institute for semiconductor physics had opened in 1965, and an institute for X-ray physics in the 70s (X-ray microscopy). A third Max Planck Institute, for Biophysical Chemistry, had been established in 1949. Under its subsequent directors, *Manfred Eigen* (Nobel prize in 1967) and *Erwin Neher* (Nobel prize in 1991), a closer relationship with physics ensued. The cooperation with the Max Planck Institutes complemented the research opportunities for physics students and post-docs. By 1994, the mere two professors of physics with a dozen of helpers in the 19th century had been replaced by 111 positions for research and teaching. The same number of technical and administrating personnel were added. The present size of physics in Göttingen reflects the changes in research: the increasing topical and instrumental differentiation of the field, and the trend away from the single researcher toward research groups and interdisciplinary interactions. At present, two Collaborative Research Centres on "Complex structures in condensed matter from atomic to mesoscopic scales" and "Nanoscale Photonic imaging" in the faculty of physics are funded by German Research Foundation. Nevertheless, as this summary focusing on the personalities behind some highlights of physics in Göttingen shows, creative ideas spring from individual minds.

Hubert Goenner,
Institute of Theoretical Physics, 2009.

Museum „Physicalisches Cabinet“

The collection of historic instruments is located at the entrance to the new lecture halls. It echoes, from the beginnings of systematic research in the 18th century to its most famous period as the world-leading center for physics and mathematics in the first half of the 20th century, the history of physics in Göttingen.

Physics in the early years of the university

The witnesses of more than 250 years the physics tradition gives us a unique insight in the university teaching and research in the 18th and 19th century. The first physics lectures were given by the philosopher Samuel Christian Hollmann (1696-1787) in 1734, predecessing the official founding of the university in 1737. He came as a well known critical mind from the university of Wittenberg to teach ethics, psychology, logic and metaphysics and established the tradition of well-visited lectures on natural sciences. Due to the politics of the newly funded university to appoint researchers with fresh thoughts, Göttingen became a well-known German university for advanced education of students and researchers in the spirit of the period of enlightenment were gathered in Göttingen. One of them was Tobias Mayer (1723-1762) who joined in 1751. His field was applied mathematics and astronomy and he developed an outstanding reputation for his first precise moon observations, fixed star map using and lunar table, later earning him the title “Mayer Immortalis”, nicknamed by Gauß. His quadrant holding the telescope made by Bird (London 1756) was at the first observatory in the city, which can still be seen in the new physics building.

18th century: Lichtenberg

When *George Christoph Lichtenberg* (1742-1799) came from Darmstadt as a student in 1763 for three years, the lectures he listened to were mainly devoted to mathematics, but he was introduced into astronomy. In 1778 Lichtenberg took the lectures on physics of his colleague, the natural scientist Johann Polycarp Erxleben (1744–1777), and gave his famous experimental physics lectures from 1778 to 1799. A novelty at that time, he put the experiments in focus, giving the first experimental physics lectures. He had more than hundred students listening in his private rooms at that time, out of the university’s a few hundred in total, which stands as a testament to his popularity and for the popularity of over 600 demonstration experiments investments at that time purchased from private. They ranged from small demonstration experiments in mechanics and energy conservation, density of liquids and thermal expansion, spectrum of light and optics to the demonstration of magnetic forces (a selection shown in Fig. 1).

His most expensive instrument was a vacuum pump crafted by Naire and Blunt (London 1782) which was an investment of one year of his salary (Fig. 2). It allowed the demonstration of the effect of evacuation, which inhibits the propagation of sound of a metal bell in the evacuated glass jar. This experi-

Fig. 1: Historic instruments from Lichtenberg’s collection “Physicalische Apparate”, built up in between 1771-1779.

Fig. 2: Vacuum pump (manufactured by Naire and Blunt, London 1782). It was the most expensive piece of equipment in Lichtenberg's collection, reaching a vacuum of 0.5 mbar.

ment prompted a maidservant to repeat the experiment with a captured nightingale, a situation depicted on a contemporary copperplate print. In 1777 he had started to work in the field of electricity. He bought his first apparatus, an electrostatic generator, and experimented with large isolating dielectrics (electrophorus) to produce electrostatic charge via electrostatic induction. The flat 'cake' of resinous material like pitch on a metal plate (Fig. 3) is rubbed by a cat's fur which builds charge in the dielectric. He could study electric discharges 70 cm in length. By accident, he recognized that the plates decorated by the resin dust showed two well defined shapes: one fine structured and symmetric looked positive and the other rather unstructured viewed as negative. With this important discovery he could show that there two types of e+ and e-, which are not connected to the material but reveal a general character. In 1789, Lichtenberg sold his impressive collection of instruments to the university, which formed the basis for demonstration experiments in the following years and the foundation of our current collection today.

19th century: Gauss and Weber

It was *Carl Friedrich Gauß* (1777-1855) who set new measures in astronomy, mathematics and physics. Born in Brunswick, his school tuition was financed by his duke, who recognized his mathematical talent. At the age of twenty, he was in the first league of mathematicians already. His mathematical knowledge allowed him to calculate the orbit of a small planet Ceres with data of only 41 days of observation. He predicted the position for its rediscovery, which founded his worldwide fame as an astronomer. Since the electorate of Hannover wanted to fund a novel observatory, his appointment as a professor in 1807 was accelerated and he moved into the newly built observatory outside of Göttingen a few years later. Besides mathematic and astronomy the third field of his strong contributions was in physics. Inspired by the observation that sun light reflected by the St. Michaelis church in Hamburg could be observed as a bright spot while he visited Lüneburg about 50 km away, he developed a new method to measure distances for a land survey campaign in the kingdom of Hanover. The instrument developed by him, the so called Vize-Heliotrop, can be seen in its original in our collection (Fig. 4). With this sensitive instrument, he could measure the spherical excess of the curved surface on 100 km distance. In fact, this inspired his work on conformal maps in the field of mathematics, later addressed by Riemann in detail. Following a discussion with Alexander von Humboldt, exploration of the Earth's magnetic field became another topic of interest. Through the coordination of the exploration of the earth's field components at hundred places around the word, it was possible by Gauß's mathematical knowledge to calculate a map of the full magnetic field of the earth in its components (Fig. 5, from a publication of the magnetic society "atlas of the earth magnetism" 1840).

This was at a time when *Wilhelm Eduard Weber* (1804-1891) had been appointed as a professor for physics in Göttingen, the former chair of Lichtenberg. As a candidate strongly supported by Gauß, they developed a fruitful collaboration. The physics institute became a research institute. Weber's novel research field at Göttingen electromagnetism was stimulated by Oersted's finding of a force in between wires which are flown by a current. With Weber's experiments (Fig. 6) precise measurements of the strength of the magnetic field in absolute units became possible and his definition of the current is still valid. It allowed Weber and Gauß to realize a unit system connecting electric and magnetic quantities to the basic units of length, time and

Fig. 3: Electrophorus and cat fur on the left at around 1780. With the tin foil coated wooden plate the charge could be separated and impressive electric sparks up could be generated. Lichtenberg figure for a positive charge on the right.

Fig. 4: Gauß's Vize-Heliotrop (manufactured by Troughton, London, 1810) in the hands of Prof. Gustav Beuermann. It was on the back of the 10 DM note. It was developed for a measurement campaign in the kingdom of Hanover, and its sensitivity allowed the study of the spherical access of the curved earth's surface.

mass. Weber's theory contained only one parameter connecting the force between static and dynamic electrons, which he could complete in experiments together with Rudolf Hermann Kohlrausch (1809-1858). This was the first electric determination of the propagation speed of light, later verified by Maxwell's theory. To satisfy Gauß and Weber's need for highest quality optical and electric apparatus, local fine mechanics workshops developed. One most famous instrument maker was Moritz Meyerstein (1808–1882) who made the transportable magnetometer developed by Gauß to ensure the highest possible sensitivity (Fig. 5). This laid the foundation for many companies of Göttingen's measurement valley as Lambrecht, Sartorius and Zeiss (in Grone) and other companies founded later in the periphery of the university. However, Ernst Abbe, founder of the world renowned Zeiss in Jena, was a student of Weber and Riemann at that time. Another example of their excellent engineering skills is the first telegraph, built in 1833. Weber and Gauß put up a one kilometer long wire in-between the observatory outside the town walls and Weber's institute, transmitting messages by using an induction transducer and detection of the binary coded current pulses by a mirror galvanometer. It was shown at the world exhibition in Vienna 1873, during a dispute on patent rights, and can be visited in the museum (Fig. 7).

20th century: birth of quantum mechanics

At the turn of the century, the aim of experimental research was to understand the nature of electric conductivity ("electron gas" in metals), on cathode ray to determine the nature of the electron (e/m) and spectroscopy to access the nature of the atom. A collection of various spectrometers and X-ray tubes of the first generation remain from that time, exhibited in the museum. The mathematics institute with Felix Klein (1849-1925), David Hilbert (1862-1943) and Hermann Minkow-

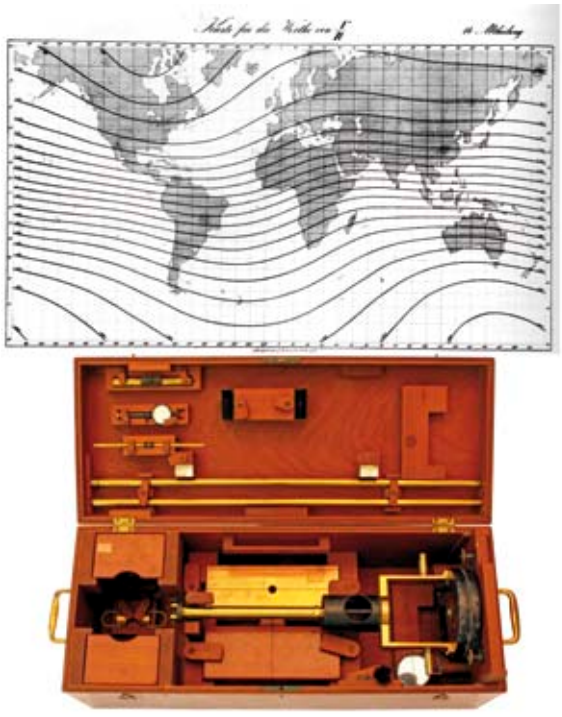


Fig. 5: Transportable magnetometer from Weber (manufactured by Meyerstein Göttingen, 1839). It was motivated by Alexander von Humboldt to map the earth's magnetic field component, which was deduced from 100 experimental stations all over the world and printed in Gauß' and Weber's atlas of the earth's magnetism.

Fig. 7: Gauß-Weber telegraph (here the sender) as shown at the word exhibition in Vienna 1873. The image shows the experiment in 1833 with the double wiring through Göttingen and Gauß at the observatory receiving station.

ski (1864-1909) was a well-known international Centre of mathematics. Belonging now to Prussia, the ministry at Berlin wanted to develop Göttingen as a Centre for mathematics and physics. These sciences were on the verge to become an important motor for industrial developments. Klein and Hilbert wanted to get Max Born (1882-1970) for the position of theoretical physics as successor to *Peter Debye* (1884-1966). With Born, *James Franck* (1882-1964) came to Göttingen. Together with *Robert Pohl* (1884-1976) head of the first institute, they headed the three physics institutes (I., II. and theory) in the 1920's. Göttingen became one of the famous Centres of quantum mechanics and attracted important people from outside. The interaction between Hilbert, Born, Franck and Pohl created a unique atmosphere. Their seminar on the "structure of matter" brought all physics and mathematicians together. The famous years of quantum mechanics were abruptly ended by the devastating rise of national socialism in Germany in the 1930's. The beginnings of atomic physics and solid state physics are the latest exhibits found in the collection. However some of the most important work on quantum mechanics of that time is displayed in the foyer of the museum.

Fig. 6: Weber's instruments to measure the magnetic field generated by the circular current loop from 1837. With the Tangtenbussole (Bussole=compass), sensitive deviations of the needle were be determined thus it was the first practical instrument to measure the magnetic field generated by the current through the wire loop. The wiring can be seen at the bottom.

The Museum

The history of the museum begins when the exhibits were moved from Michaelishaus to the new physics building on Bunsenstrasse, which luckily survived mostly undisturbed in a naturally acclimatized cellar for almost 250 years. In the last century, when the university had its 250th jubilee and the "Sammlung Physicalischer Apparate" of the I. Physics Institute was described and newly catalogued by Prof. von Minnigerode and Prof. G. Beuermann. By Prof. G. Beuermann, the collection of historic instruments of the early days of physics in Göttingen was built up and found a new home in the museum „Physicalisches Cabinet and Lichtenberg collection" in the new physics building. In addition, the museum hosts exhibits of the collection of historical instruments of the astrophysics observatory "Historische Instumente der Sternwarte", from geophysics, "Geophysicalische Historische Sammlung", and on the birth of quantum mechanics. It is opened to public on a regular basis. The unique contemporary witnesses of more than 250 years the physics tradition of the University of Göttingen are found there. One can imagine Lichtenberg sitting at his desk taking notes, an electrophorus nearby, surrounded by dull leather, misty glass and fragile brass. It is the hands on experience that makes a tour through 250 years of physics in Göttingen an impressive experience. Guided tours with the current curator, Prof. M. Münzenberg, I. Physics Institute, can be arranged. (Tel: 0551 39-7604, http://www.uni-goettingen.de/de/47114.html).

[1] Friedrich Hund, *Die Geschichte der Göttinger Physik*, Göttingen 1987, in Göttinger Universitätsreden, Vandenhoeck Ruprecht.

[2] Ausstellungskatalog: *Die Göttinger Sieben. Eine Ausstellung der Georg-August-Universität Göttingen*, Hrsg. von H. Wellenreuther, Göttingen 1987.

Faculty Building

Lichtenberg lecture hall with 350 seats

Practical training laboratory

Cafeteria

Since spring 2005 the Faculty of Physics has had a building on Göttingen North Campus where various science faculties and non-university research centres are located. Chemistry, informatics, geoscience, forestry, microbiology and genetics, molecular bioscience, the Laser Laboratory Göttingen, the German Primate Center, the European Neuroscience Institute, and the Experimental Laboratory for Young People are within spitting distance of physics. Also nearby are the medical school as well as the Max Planck Institutes for Biophysical Chemistry, Dynamics and Self-Organization, and Experimental Medicine.

Providing an overall ground-plan area of 45 600 m² the faculty building contains all facilities for teaching and research under one roof. Five lecture halls with extra space for the preparation of experiments, eighteen seminar rooms, laboratories for the practical training of students, space for computer pools as well as for doing assignments and tutorials form the core area for teaching. It is complemented by the physics division of the Goettingen State and University Library which provides 65 000 volumes and offers about 200 topical scientific journals. A light cafeteria gives a pleasant atmosphere to work on assignments.

The cafeteria is also a place of communication and of lively scientific debate among the staff.

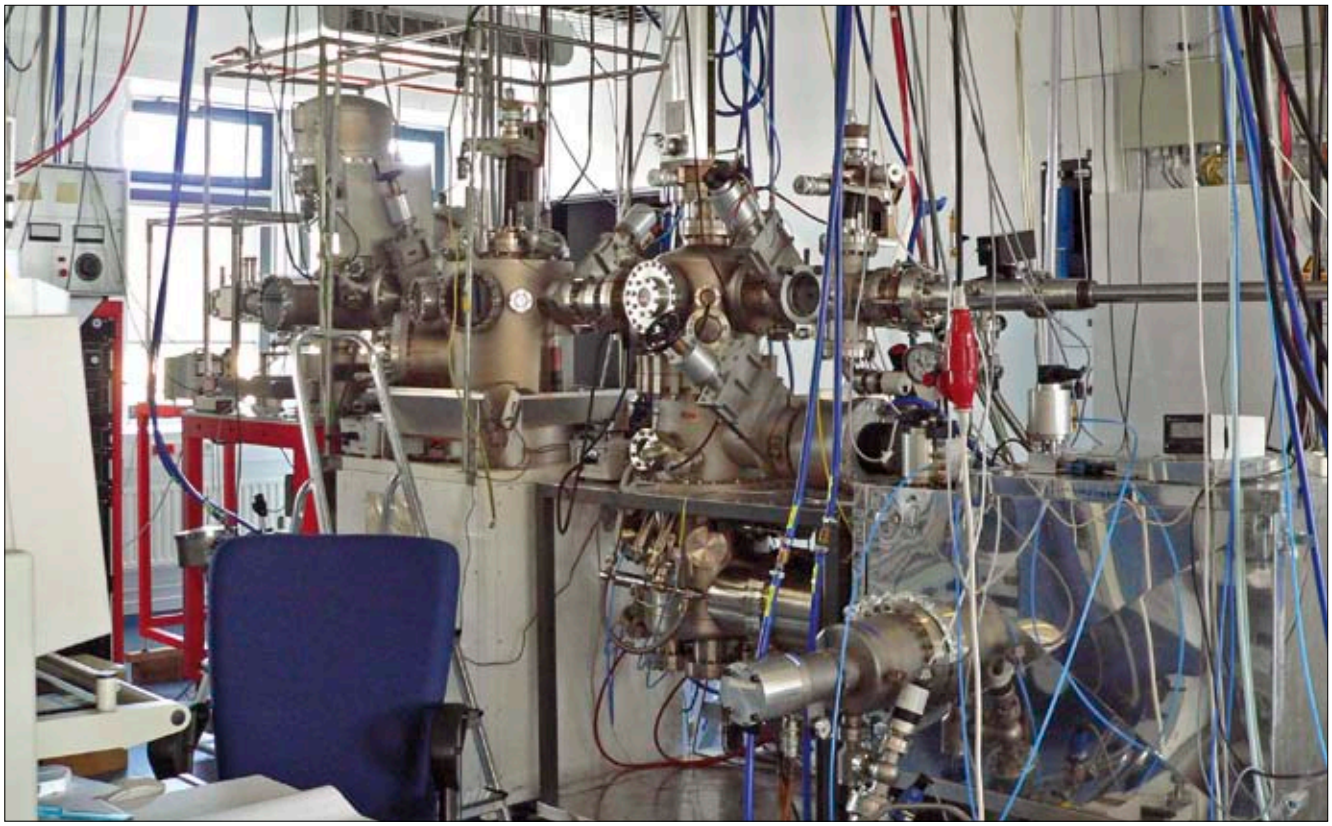
The varied research groups occupy more than 170 laboratories and measuring rooms as well as 340 workrooms. The conceptual design of the building guarantees extremely little vibration from structure-born noise. Special measuring

rooms are provided with separate base-plates keeping vibration amplitudes to below 150 nm. Constant temperature is maintained by the treatment of 200 000 m^3 air per hour in centralised air-conditioning plants. For some laboratories temperature variations are smaller than 0.1K per 10 minutes. Care is taken to avoid interfering electromagnetic fields in general. For particular applications laboratories are shielded to keep amplitudes of disturbing magnetic fields to less than 100 nT. Special facilities such as a hall for a particle accelerator, cleanrooms, chemistry, and cell culture laboratories are also available.

The research groups benefit greatly from the expertise of the technical staff in precision mechanics, electronics, and information technology. The faculty building houses almost 40 workshops with a total area of 2500 m^2 for the development and construction of complex devices which are not commercially available.

Precision-mechanics workshop

Air-conditioning plant



Ultra-high vacuum installation

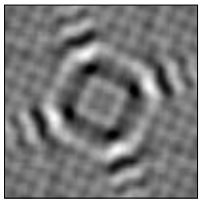
Mechanical Machine Shop

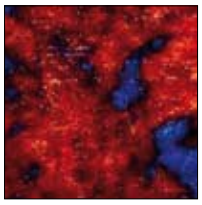
The mechanical machine shop of the faculty of physics is a state-of-the-art workshop equipped with computerized numerical control (CNC) lathes and milling machines, CNC electrical discharge machining, anodization techniques, computer aided design (CAD) as well as various welding techniques and varnishing facility. Currently 8 members of staff and 3 trainees are constructing and manufacturing complex workpieces, complete instruments, ultra-high vacuum systems and mechanical components as on-of-a-kind or small batch series. The mechanical machine shop manufactures custom-built research equipment for the different institutes as well as equipment for lab courses and lecture demonstration experiments. The mechanical machine shop is able to process a variety of different materials and manufactures high precision workpieces meeting industrial standards.

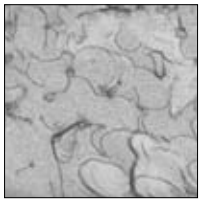
Collection of Lecture Hall Experiments

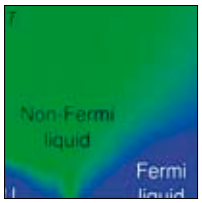
The faculty of physics houses an extensive collection of lecture hall experiments which support the introductory lectures in experimental physics but also more specialized lectures on quantum and atomic physics, nuclear physics, biophysics solid state physics and low temperature physics. Supported by four technicians, the lecturers regularly present selected physics experiments in the 5 lecture halls of the faculty. The tradition of presenting lecture hall experiments was initiated by Robert Wichard Pohl in the 1920s, who invented numerous outstandingly designed and in the meantime widespread demonstration experiments until his retirement in 1952. In honor of his achievements the German Physical Society annually awards the „Robert-Wichard-Pohl-Award“ for outstanding achievements in Physics, in particular for the proliferation of scientific knowledge in education and didactics of physics. The Göttingen collection of lecture hall experiments is continuously supplemented and modernized to meet the requirements of modern experimental physics lectures.

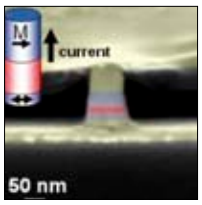
SFB 602: Complex Structures in Condensed Matter from Atomic to Mesoscopic Scales

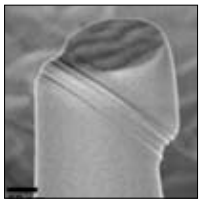


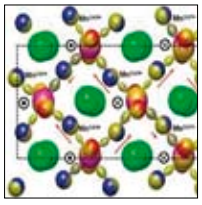


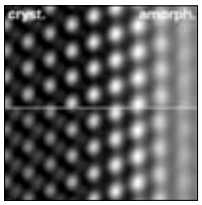








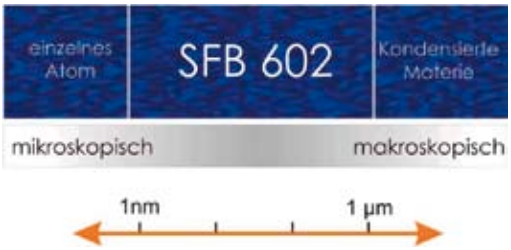




The SFB 602 is organized into two topical areas on collective electron behavior and cooperative atom processes. The 15 projects, involving 22 project leaders and 29 doctoral students from the Faculty of Physics, Faculty of Chemistry, and the Max Planck Insitute for Biophysical-Chemistry, work on addressing common questions:

- How do electrons/spins/atoms/defects interact with each other to create cooperative phenomena?
- How do boundaries and length scales influence the phenomena?
- Are there general, common principles underlying the phenomena?

In the final phase of funding (2009-2012), we will continue to address these issues using a variety of experimental techniques and analytical and numerical theory.



Section A: Collective Electron Behavior

To investigate interactions between individual spins, electrons and the lattice and how they lead to collective phenomena:

- *Metal-Insulator Transition in External Magnetic Fields* – Samwer, Mosneaga, Damaschke, Jooß
- *Kondo effect in dense systems* – Pruschke, Schönhammer, Wenderoth, Ulbrich
- *Atomic structure and electronic properties of metal-semiconductor-contacts* – Wenderoth, Ulbrich
- *Structure and transport in magnetic tunnel junctions with ultrathin barriers* – Münzenberg, Seibt
- *Molecular bimetallic complexes as building units for complex 1D-ferrimagnetic and gridtype spin structures* – Meyer
- *Spin order in dilute magnetic semiconductors* – Malindretos, Rizzi
- *Quantum fluctuations and strong correlations from mesoscopic to macroscopic length scales* – Honecker, Pruschke
- *Novel electronic states near discontinuous quantum phase transitions* – Gegenwart
- *Photoinduced cooperative behaviour in magnetic perovskites* – Techert, Jooß

Section B. Cooperative Atom Processes

To investigate the response of a system to an applied load, from individual defects to global plasticity:

- *Viscoleastic properties of isotropic and liquid crystalline gels* – Zippelius, Müller
- *Dynamical heterogenities in undercooled melts* – Krebs, Samwer
- *Mechanical behaviour of metal-polymer-nanocomposites* – Krebs, Volkert
- *The effect of size on elastic to plastic transition in amorphous and crystalline metals* – Volkert, Samwer
- *Plastic deformation mechanisms in metals at the nano- to micro-scale* – Pundt, Volkert
- *Preparation and Plasticity of Nanostructured Iron-Carbon Alloys* – Kirchheim

Low-Temperature Physics of Strongly Correlated Electrons

The study of electronic correlations in condensed matter has led to the discovery of various fascinating phenomena which also have strong technological impact. Functional materials often display different states like magnetic – nonmagnetic or metallic – insulating, which compete with each other. This competition is strongest near quantum critical points, where condensed matter undergoes smooth transformations from one quantum phase to another. The driving fluctuations are both collective and quantum mechanical, leading to emergent low-temperature phases with fascinating properties such as diverging charge carrier masses or high-temperature superconductivity. In order to study quantum criticality, clean, high-quality samples are required. The group synthesises single- and polycrystals as well as thin films of rare-earths based heavy-fermion metals, ruthenates, and iron-pnictides using various techniques. Thermodynamic, magnetic and transport experiments are performed down to temperatures as low as 10 mK and in magnetic fields up to 18 Tesla.

Quantum criticality

Recently, a strategy for the discovery of novel quantum phases in condensed matter has been found, which is based on the continuous suppression of magnetic order by suitable variation of a non-thermal parameter, as indicated in Figure 1. Heavy-fermion metals are prototype systems to investigate quantum critical points. They contain a dense lattice of instable f-moments embedded in the sea of conduction electrons. Dependent on the strength of their mutual interaction they are either magnetically ordered or paramagnetic at low temperatures. A tiny change in composition, pressure or applied magnetic field could then tip the balance from one to the other side and the strong quantum fluctuations associated with this competition leads to drastic deviations from the standard model of metals, Landau's Fermi liquid theory. This is demonstrated in Figure 2 for quantum critical $YbRh_2Si_2$, which displays a linear, as opposed to quadratic, behavior in the electrical resistivity, accompanied by a divergence of the effective charge carrier masses.

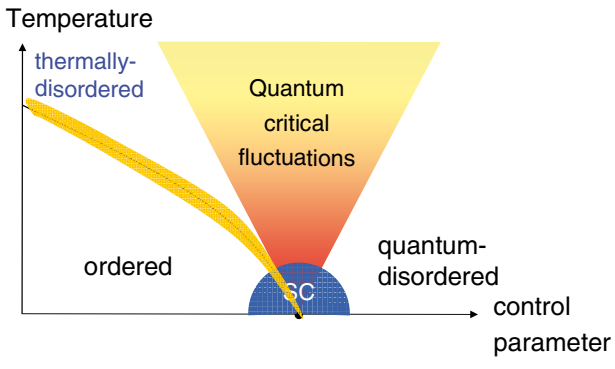


Fig. 1: Quantum criticality, arising from the continuous suppression of an ordered state by tuning a non-thermal control parameter such as pressure, doping or magnetic field. The quantum critical state is distinct from the phases at both sides because it contains highly collective low-energy excitations. This type of quantum criticality is often accompanied by a window of superconductivity (SC).

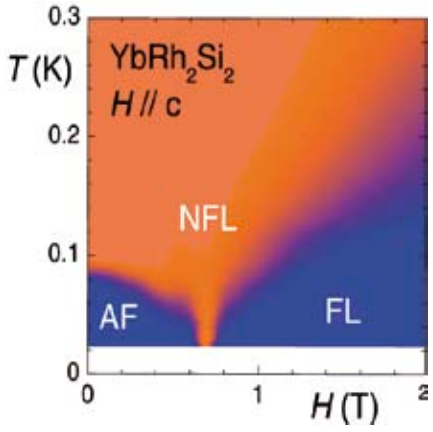


Fig. 2: Violation of the Fermi liquid (FL) theory near a quantum critical point. The heavy-fermion system $YbRh_2Si_2$ orders antiferromagnetically (AF) at very low temperatures. The suppression of this order by a magnetic field drives the system through a quantum critical point, above which non-Fermi liquid behavior (NFL) is observed. In this regime, the resistivity varies linearly with temperature as indicated by the orange colour (blue: quadratic behavior), indicating a divergence of the scattering rate of mutual collisions between the charge carriers.

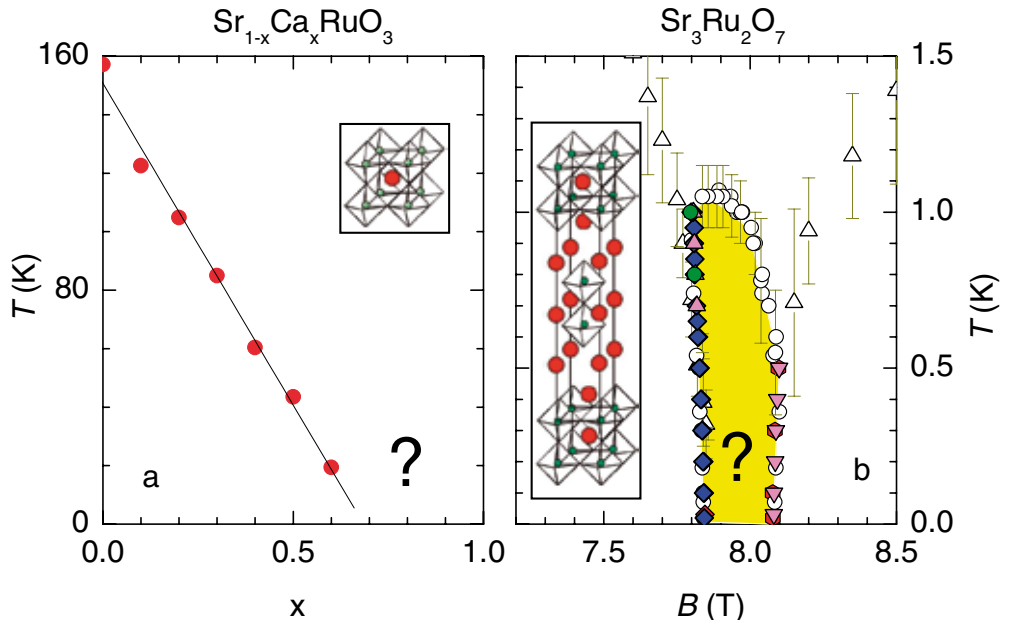


Fig. 3: Novel metallic states in cubic (a) and layered ruthenates (b). The red dots in the left panel indicate the ferromagnetic Curie temperature, which is suppressed by Ca-doping x. The low-temperature regime for $0.7 \leq x \leq 1$ displays signatures of a "non-Fermi liquid" phase. The yellow region in (b) highlights the "electronic nematic phase" of $Sr_3Ru_2O_7$, which occurs in close vicinity to a putative metamagnetic quantum critical end point.

To study the electronic properties near the quantum critical point, high-quality samples are required. The group prepares single crystals of heavy-fermion systems by flux, Bridgeman, and crucible-free floating-zone techniques. For the latter, a four-mirror optical furnace is utilized (see Figure 5) in which large high-quality single crystals can be obtained. After structural, chemical and physical characterization, selected crystals are studied in detail by low-temperature thermodynamic, transport and magnetic techniques using ^{3}He/^{4}He dilution refrigerators down to 10 mK.

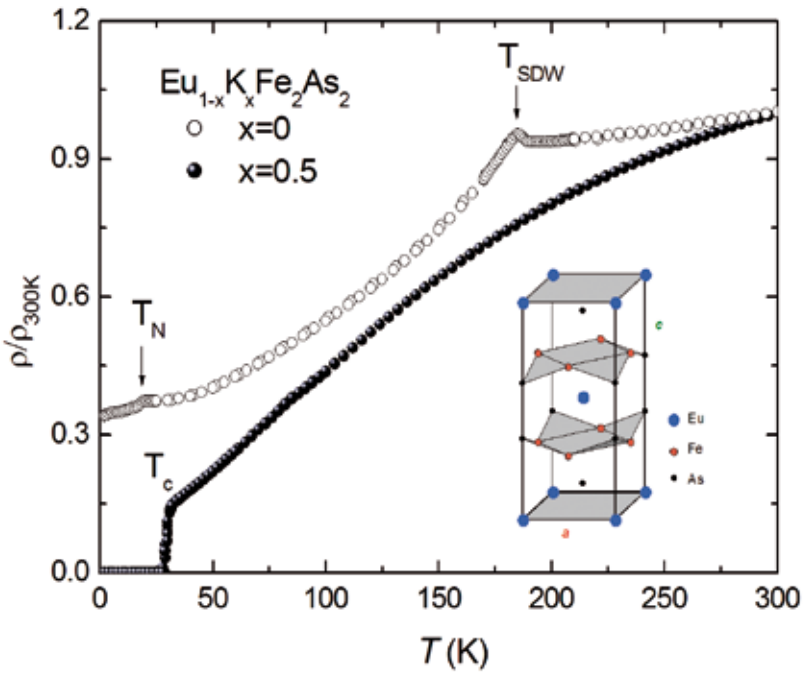


Fig. 4: Superconductivity the iron-pnictide $Eu_{1-x}K_xFe_2As_2$. The undoped system (x=0) displays a spin-density-wave (SDW) due to iron 3d-states, as well as a local-moment antiferromagnetic ordering (T_N) due to europium 4f-moments. Once the SDW is suppressed by K-doping, superconductivity at 32 K emerges out of a highly unusual normal state with linear resistivity.

Unconventional superconductivity

Superconductivity (SC), discovered by Heike Kamerlingh Onnes in 1911, is characterized by exactly zero electrical resistance and the exclusion of the interior magnetic field. Until 1979 when heavy-fermion SC was discovered, all superconductors where conventional, i.e. SC is mediated by lattice vibrations and restricted to very low temperatures. By contrast, SC in heavy-fermion systems could be related to the strong magnetic fluctuations near the quantum critical point, as sketched in Figure 1. Further classes of "unconventional" superconductors have been found close to the disappearance of long-range magnetic order, among which the high-Tc cuprate superconductors with transition temperatures up to 160 K are most prominent. SC can even appear in weak itinerant ferromagnets close to the ferromagnetic quantum critical point. Very recently, the observation of transition temperatures up to 56 K in iron-based compounds has attracted much interest. In these systems, layers of iron-pnictides form an antiferromagnetic (spin-density-wave) state. When this magnetic ordering is suppressed by the application of pressure or by suitable doping, unconventional superconductivity emerges as shown in Fig. 4 for the system $Eu_{1-x}K_xFe_2As_2$.

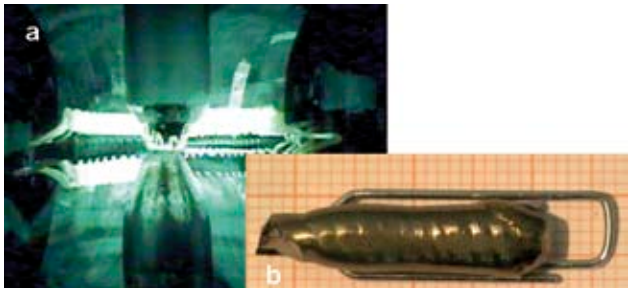


Fig. 5: Photographs of the stretched melt at the beginning of the single crystal growth in the image furnace (a) and resulting single crystal of the quantum critical heavy-fermion system $CeNi_2Ge_2$ (b).

Discontinuous ferromagnetic quantum phase transitions

In contrast to their antiferromagnetic counterparts, ferromagnetic quantum phase transitions are often discontinuous at low temperatures, leading to first-order transitions and electronic phase separation. In some cases, evidence for extended regions in the phase diagram has been found, where Landau's Fermi liquid theory breaks down and novel metallic behavior emerges. The group investigates such states in the ruthenates $Sr_{1-x}Ca_xRuO_3$ and $Sr_3Ru_2O_7$, which crystallize in the cubic and layered perovskite structure, respectively, cf. Figure 3.

[1] Tokiwa, Y.; Radu, T.; Geibel, C.; Steglich, F.; Gegenwart, P.: *Divergence of the Magnetic Gruneisen Ratio at the Field-Induced Quantum Critical Point in $YbRh_2Si_2$. Phys. Rev. Lett.* 102, 066401 (2009).

[2] Jeevan, H. S.; Hossain, Z.; Kasinathan, D.; Rosner, H.; Geibel, C.; Gegenwart, P.: *High-temperature superconductivity in $Eu_{0.5}K_{0.5}Fe_2As_2$. Phys. Rev.* B 78, 092406 (2008).

[3] Gegenwart, P.; Si, Q.; Steglich, F.: *Quantum criticality in heavy-fermion metals. Nature Phys.* 4, 186 (2008).

[4] Gegenwart, P.; Westerkamp, T.; Krellner, C.; Tokiwa, Y.; Paschen, S.; Geibel, C.; Steglich, F.; Abrahams, E.; Si, Q.: *Multiple energy scales at a quantum critical point. Science* 315, 5814 (2007).

[5] Gegenwart, P.; Weickert, F.; Garst, M.; Perry, R. S.; Maeno, Y.: *Metamagnetic quantum criticality in $Sr_3Ru_2O_7$ studied by thermal expansion, Phys. Rev. Lett.* 96, 136402 (2006).

[6] Grigera, S. A.; Gegenwart, P.; Borzi, R. A.; Weickert, F.; Schofield, A. J.; Perry, R. S.; Tayama, T.; Sakakibara, T.; Maeno, Y.; Green, A. G. and Mackenzie; A. P.: *Disorder-Sensitive Phase Formation Linked to Metamagnetic Quantum Criticality. Science* 306, 1154 (2004).

Philipp Gegenwart

Philipp Gegenwart, born in 1967 in Frankfurt/Main, studied Physics at the Darmstadt University of Technology. From 1994 until 1998 he worked on his PhD in the group of Frank Steglich on superconductivity and magnetism in heavy-fermion systems. In 1998, he moved to the Max-Planck Institute for Chemical Physics of Solids (MPI CPFS) in Dresden, where, in 2000, he was appointed head of the competence group "Low Temperatures". The research in his group focused on the rapidly developing field of quantum phase transitions. From 2004-2005 he worked as a visiting scientist at the School of Physics and Astronomy in St. Andrews (Scotland) in the group of Andy Mackenzie on metamagnetic quantum criticality in the bilayer ruthenate $Sr_3Ru_2O_7$. After return to the MPI CPFS in Dresden, he moved to his current position at the Georg-August University in October 2006.

Femtosecond Spin Dynamics and Spin Transport

What are the limits of ultrafast magnetic manipulation? What are the ultimate timescales for manipulating spin? These are the underlying fundamental questions in spin dynamics. On the other side, spin transport has been one of the most innovative fields in magnetism over the last decade due to groundbreaking discoveries such as magnetic-quantum size effects, giant tunnel magnetoresistance (giant TMR) and the interaction of spin-currents within a magnetic nanometer sized pillar, the so called ‚spin-transfer torque'. Our aim is to bring the understanding of femtosecond spectroscopy and transport through magnetic nanostructures together.

Femtosecond spectroscopy and magnetization dynamics

Dynamics on an ultrafast timescale determine the read-write access time in future memory's. Our research explores the physics of ultrafast spin dynamics and spin manipulation with the help of femtosecond laser pump-probe experiments (Fig. 1). The fundamental understanding of light-matter interaction on the femtosecond timescale allows an insight into the elementary spin relaxation in spin-electronic materials, such as half metals. We developed novel tools to characterize their spin polarization (Fig. 2). Within shorter time scales it is possible to have access to spin waves at terahertz (THz) frequency. Their exploration is a key to ultrafast switching and spin-wave condensation in periodic confinements (magnonic crystals) and sets the foundation for novel magnonic logic devices and spin-wave based computing.

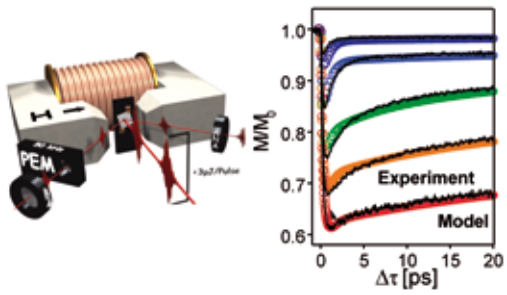


Fig. 1: Femtosecond laser experiment probing ultrafast spin dynamics. The spin system is demagnetized to 60% of its original value within about 150 fs, here shown for a 15 nm thick nickel film at laser fluencies varied from 10-50 mJ/ cm².

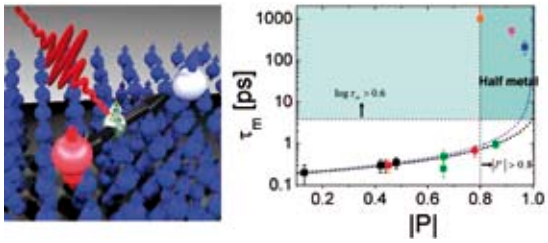


Fig. 2: Schematic of the photo-excited electron probing its neighboring electronic surrounding. We developed a model (dotted lines) for the characterization of half metals, an important material class with 100 % spin polarization P: Because of a high spin-polarization their demagnetization time τ_m is very slow.

Spin transport in magnetic nanostructures

Which elementary processes determine the output signal and functionality of a magnetic transport device? Within the collaborative research center SFB 602 we study the optimization of giant tunneling magnetoresistance (giant TMR) devices which have shown resistance changes of more than 500 %. They are the building blocks for magnetic random access memory (MRAM) based processors, owning non volatile information at system restart, and, via the spin-transfer torque effect, they are nanometer sized sources of tunable GHz waves for inter-chip communication. Together with the University of Bielefeld and Prof. M. Seibt's electron microscopy group, we connect the fundamental spin-transport properties through nanometer thick highly-ordered oxide layers, serving as an "electron spin filter", with structural order of the ferromagnet evolving at the interfaces on an atomic scale.

[1] Müller, G.; Walowski, J.; Djordjevic, M.; Miao G.-X.; Gupta A.; Ramos, A. V.; Gehrke, K.; Moshnyaga, V.; Samwer K.; Schmalhorst, J.; Thomas A.; Hütten, A.; Reiss, G.; Moodera, J. S.; Münzenberg, M.: *Spin polarization in half metals probed by femtosecond spin excitation,* Nature Materials 8, 56 (2009).

[2] Walowski, J.; Müller, G.; Djordjevic, M.; Münzenberg, M.; Kläui, M.; Vaz, C. A. F. and Bland, J. A. C.: *Energy equilibration processes of electrons, magnons, and phonons at the femtosecond time scale,* Phys. Rev. Lett. 100, 246803 (2008).

[3] Miao, G. X.; Park, Y. J.; Moodera, J. S.; Seibt, M.; Eilers, G.; Münzenberg, M.: *Effect of oxygen vacancy on the coherent Tunneling in Epitaxial Fe/MgO/Fe Magnetic Tunnel Junctions,* Phys. Rev. Lett. 100, 246803 (2008).

[4] Djordjevic, M.; Münzenberg, M.: *Connecting the timescales in picosecond remagnetization experiments,* Phys. Rev. B 75, 012404 (2007).

[5] Münzenberg, M.; Moodera, J. S.: *Superconductor-ferromagnet tunneling measurements indicate sp-spin and d-spin currents,* Phys. Rev. B 70, 060402 (2004).

Markus Münzenberg

Markus Münzenberg was 1971 born in Giessen. After studies of physics at Göttingen University 1992, he received his PhD in the end of 2000. His main research field was magnetism and X-ray magnetic circular dichroism at European's synchrotron facilities. In the time as a postdoc at Jagadeesh S. Moodera's group at the Massachusetts Institute of Technology (MIT) Cambridge USA from 2001-2002, he switched his research to spin transport in ferromagnetic tunneling magnetoresistance (TMR) structures. Having the idea in mind to combine spin-transport processes with femtosecond laser spectroscopy and spin dynamics, he started his optics group at the Institute for Semiconductor Physics as a Junior faculty at Göttingen University from 2002 to 2008, which finally moved in late 2008 to the Institute for Low Temperature Physics. There he is a currently appointed as an Apl. Professor.

Oxide Magnetic Thin Films

Mixed-valence perovskite manganites, like $La_{1-x}Ca_xMnO_3$ (LCMO), are f erromagnetic with Curie temperatures, T_C=100-360 K, and exhibit an insulator to metal (MI) transition at T_{MI}~T_C (Fig. 1). Manganites show a complex phase diagram with a number of competing crystallographic, electronic and magnetic phases, thus yielding interesting and useful effects. The "Colossal magnetoresistance" (CMR) effect was discovered in thin manganite films by R. von Helmolt, K. Samwer et al. CMR, quantified as a relative change of electrical resistivity in applied magnetic field, CMR=100%*[r(0)-r(B)]/r(B), can be very large ~10^5 % for magnetic fields of several Tesla.

Recently it was argued theoretically and observed experimentally that the electronic properties of manganites may be spatially inhomogeneous. Namely, metallic and insulating electronic phases can coexist within the same sample of a definite chemical composition over different length scales from sub-micrometer down to few nanometers. In our group we focus on experimental study of the magnetotransport properties in manganite thin films. The films have been prepared by a metalorganic aerosol deposition (MAD) technique (Fig. 2) as well as by d.c. magnetron sputtering. The structure of the films is characterized by X-ray diffraction (Siemens D5000, D8). The morphology of the films is viewed by room temperature AFM and STM microscopy (Nanoscope II/IV). To perform global electric and magnetic measurements for T=1.5-450 K & B=0-7 T we use a MAGLAB cryostat (Oxford Inst.) and a SQUID (Quantum Design) magnetometer. Moreover, a vibrating sample magnetometer for high-T measurements is available.

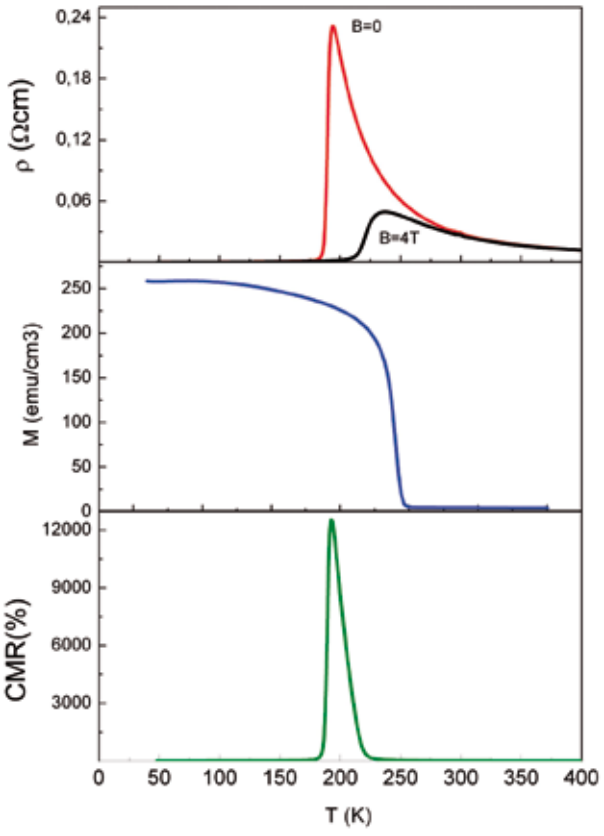


Fig. 1: Typical transport behavior of doped manganites: MI-transition, magnetic transition and CMR-effect of manganite thin films.

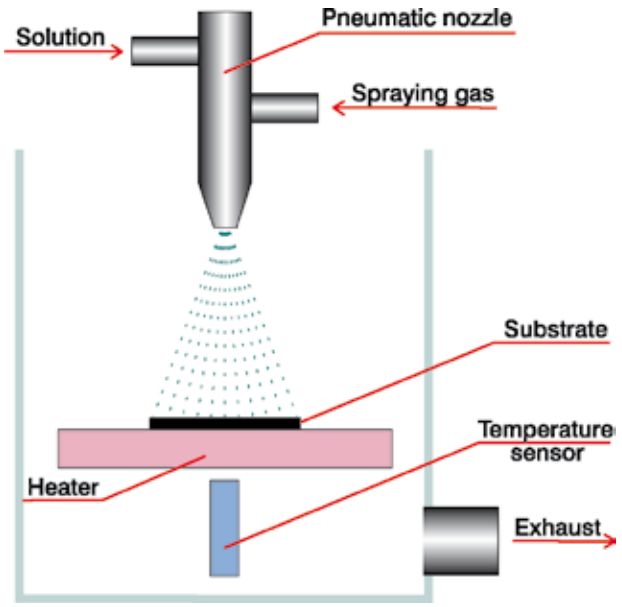


Fig. 2: Preparation of manganite thin films by Metallorganic Aerosol Deposition (MAD) technique.

We have also an unique possibility to study local magneto-transport properties in thin films by using scanning tunneling microscopy (STM) combined with scanning tunneling spectroscopy (STS). Three systems are available: a variable temperature (T=20-300 K) UHV STM; a variable temperature (T=20-300 K) UHV STM/AFM system and a low-T bath cryostat STM/MFM system in UHV (T=6-300 K, B=0-7 T). By using the local probe techniques we observed an inhomogeneous distribution of the tunneling conductivity with a percolative MI-transition at TC.

Another branch of our activity is the study of nanocomposite films like $LCMO_{1-x}$:MgO_x (Fig. 4), in which the structure and the transport of the primary manganite phase can be tuned by an elastically coupled second phase (MgO). A new structural phase transition (P_{nma} to R3c) was found at the percolation threshold, x_c~0.3. Additionally the MgO phase builds efficient vertical tunneling barriers in polycrystalline $LSMO_{1-x}$:MgO_x nanocomposite films grown on Al_2O_3 substrates. Closely related is the problem of preparation of multiferroic (ferromagnetic and ferroelectric) composites, which seem to be very promising for device applications.

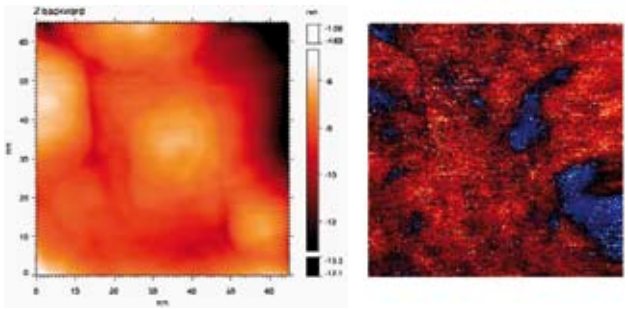


Fig. 3: STM topography (a), 65x65nm², and STS (b) on a Ca-doped manganite thin film showing the distribution of metallic (red) and insulating (blue) regions within the same area at 78 K.

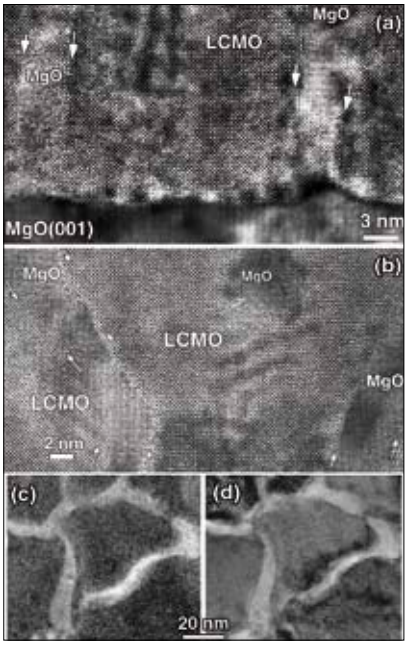


Fig. 4: (a), (b): Scanning electron microscopy (SEM) study of the microstructure of a composite $LCMO_{1-x}$:MgO_x film with x=0.5 in cross section and plan view modes, respectively. (c), (d): Transmission electron microscopy (TEM) images: (c) Mg-map by energy filtered TEM; (d) corresponding TEM plan view.

[1] Sudheendra, L.; Moshnyaga, V.; Samwer, K.: *Metal-insulator transition and colossal magnetoresistance: relevance of electron-lattice coupling and electronic phase separation,* Contemporary Physics 48 (2007) 349

[2] Ferromagnetic Manganite Films, Moshnyaga, V.; Samwer, K.; Handbook of Magnetism and Advanced Magnetic Materials, Vol. 5: *Spintronics and Magnetoelectronics,* 2007, John Wiley & Sons Ltd. ISBN 978-0-470-02217-7

[3] Moshnyaga, V.; Sudheendra, L.; Lebedev, O. I.; Köster, S. A.; Gehrke, K.; Shapoval, O.; Belenchuk, A.; Damaschke, B.; van Tendeloo, G. and Samwer, K.: *A-Site Ordering versus Electronic Inhomogeneity in Colossally Magnetoresistive Manganite Films,* Phys. Rev. Lett. 97 (2006) 107205

Konrad Samwer

Konrad Samwer was born 1952 in Göttingen. He studied physics at the Universities of Göttingen and Bonn and got his Doctoral degree 1981 in the group of G. von Minnigerode, Göttingen. After Postdoc positions in Göttingen and at the California Institute of Technology, he obtained his habilitation in Göttingen. In 1989, he became a C4 professor at the University of Augsburg and later he switched back to Göttingen in 1999.

Konrad Samwer has received a number of respected awards, including having been awarded the DFG's prestigious Leibniz Prize. He is a member of the Academy of Sciences at Göttingen and the National Academy (Leopoldina). He has held a lot of official positions in the science community and, since 2007, he has served as vice president of the DFG.

Physics of Amorphous Materials, Dynamical Heterogeneities in Undercooled Melts and Relaxation Phenomena

A material is referred to a "glass", if it has an amorphous structure in the solid state and undergoes a glass transition when heating into an undercooled melt. Bulk metallic glasses are often composed of many components. Appearance and some properties of such glasses are similar to that of crystalline metals, but their mechanical (rheological) behavior is completely different.

Sample preparation

The samples can be prepared by rapid quenching from the melt using various techniques:

- Splat-Quenching: The liquid sample is quenched between two copper pistons.
- Melt-spinning: This method, which is commonly used commercially, produces narrow ribbons by quenching the melt on a rotating copper wheel.
- Mold-Casting: Solidification in a cooled copper mold yields bulk samples.
- Vapor deposition of glass forming alloys onto a cold substrate under UHV-conditions yields amorphous thin films.

Mechanical Spectroscopy

Mechanical spectroscopy on different time scales offers a way to measure elastic constants, viscosity of liquids, polymers, biological systems and glasses as well as to investigate loss mechanisms in those complex fluids.

For low frequencies (0.1-50 Hz) and a temperature range of -100 °C to 1000 °C, we use a dynamic mechanical analyzer (DMA) to apply static and dynamic forces on the sample. For the kHz range (about 5.4 kHz), the double paddle oscillator (DPO) is a very sensitive tool. Operated at its resonance frequency, it allows for the analysis of mechanical properties of thin films. For low temperatures (Room temperature to -2 K) a pulse echo ultrasound measurement unit (USO) is used, which can detect very small changes in the elastic moduli for a given frequency in the MHz range. Most recently an Acoustic Atomic Force Microscope (AFAM) was built with the help of W. Arnold, which allows also local spectroscopy at surfaces.

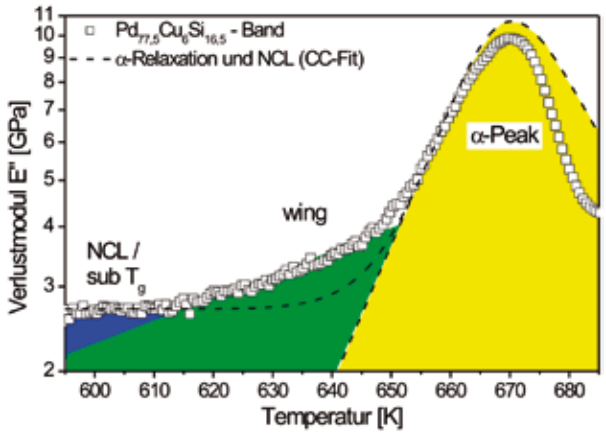


Fig. 5: Loss spectroscopy as a function of temperature: Identification of the β-process (wing) in the loss spectra of PdCuSi.

For a deeper understanding of the connection of microscopic and macroscopic behavior of glasses, the correlation between α- and β-relaxation as seen in loss spectra needs further explanation. At the moment, we discuss the α-process in the context of shear transformation zones (STZ) and the β-process with chain like excitations (Strings).

To examine microscopic processes which are not accessible experimentally, molecular dynamics simulations are employed for comparisons, which are done in collaboration with several colleagues. Also quasielastic neutron scattering has been used to study diffusion mechanisms in the melt.

The great progress achieved in the description of the primary (α-)relaxation is supported by the results of computer simulations.

The thermophysical properties of semiconductor melts are investigated in an international project with experiments in microgravity environment (parabola flights, International Space Station). The samples are processed in an electromagnetic levitator in UHV and can be analysed with contactless techniques to measure thermal expansion, surface tension and viscosity.

[1] Chathoth, S. M.; Damaschke, B.; Koza, M. M.; Samwer K.: *Dynamic Singularity in Multicomponent Glass-Forming Metallic Liquids,* Phys. Rev. Lett. 101 (2008) 037801

[2] Harmon, J. S.; Demetriou, M. D.; Johnson, W. L.; Samwer, K.: *Anelastic to Plastic Transition in Metallic Glass-Forming Liquids,* Phys. Rev. Lett. 99 (2007) 135502

[3] Johnson, W. L.; Samwer, K.: *A universal criterion for plastic yielding of metallic glasses with a* $(T/T_g)^{2/3}$ *temperature dependence,* Phys. Rev. Lett. 95 (2005) 195501

Ion Beams and Materials

Ion beams are essential for fabricating electronic devices, thin film coatings, for surface processing and for elemental thin film analysis. Our group operates several ion beam facilities providing ion beams from eV to GeV energies for materials modification, synthesis of thin films, ion implantation of impurities, dopant atoms and probe atoms as well as ion beam analysis of materials. Material modifications include surface pattern formation by keV ion irradiation and ion track formation by irradiation with swift heavy ions with GeV energies. Low energy ion beam deposition is ideal to synthesize diamond-like materials like DLC and cubic boron nitride. Rare earth doped semiconductors exhibiting unique luminescent behavior are prepared by ion implantation. Also semiconductors and metallic compounds are implanted with radioactive probe atoms for nuclear spectroscopy. Our ion beam analysis techniques are RBS, high resolution RBS (nm resolution), PIXE and nuclear reaction analysis.

Ion beam facilities

Our group operates several low energy ion beam systems for thin film growth and surface modification. A dedicated mass selected UHV ion beam system provides low energy mass selected ions in the energy range 10 eV to 60 keV for the synthesis of high quality diamond-like materials like tetrahedral amorphous carbon (ta-C) and cubic boron nitride (c-BN) and for shallow implantation of various dopants.

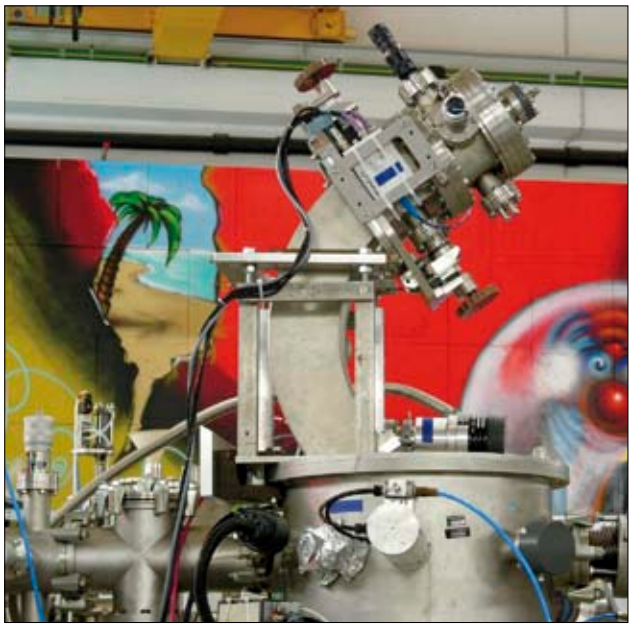


Fig. 1: High resolution RBS setup showing the scattering chamber and the cylindrical electrostatic analyzer providing a depth resolution of < 2 nm (Wallpainting by Helge Steinmann).

Three low energy ion beam systems are optimized for ion beam erosion of surfaces to investigate pattern formation processes at surfaces in particular under the influence of surfactant atoms.

A 500 keV multi purpose heavy ion implanter is available for ion implantation of nearly all elements, including some radioactive isotopes (^{111}In). The implanter also provides up to 1 MeV He^{2+} for RBS analyses as well as protons for nuclear reaction analysis. A high resolution RBS setup provides a depth resolution of 1-2 nm for thin film analyses (Fig.1).

A 3 MeV Pelletron tandem accelerator is equipped with beam lines for RBS, external beam PIXE, microbeam PIXE and nuclear reaction analysis. A dedicated setup for hydrogen profiling using the resonant $^{1}H(^{15}N,\alpha\gamma)^{12}C$ reaction is available.

Materials modification

Formation of nanoscale periodic ripple and dot patterns at surfaces by ion beam erosion with keV ions is a well known phenomenon. We have extended this process by introducing surfactant atoms by co-deposition during sputter erosion. These surfactant atoms strongly modify the erosion process and lead to a variety of novel surface patterns, to surface smoothing and to the formation of nanostructured ultrathin films. The evolution of an initial flat ta-C surface under Xe ion irradiation with increasing surface coverage of tungsten is shown in Fig. 2.

Swift heavy ions (SHI) with energies up to GeV cause a tremendous local electronic energy loss up to 40 keV/nm in

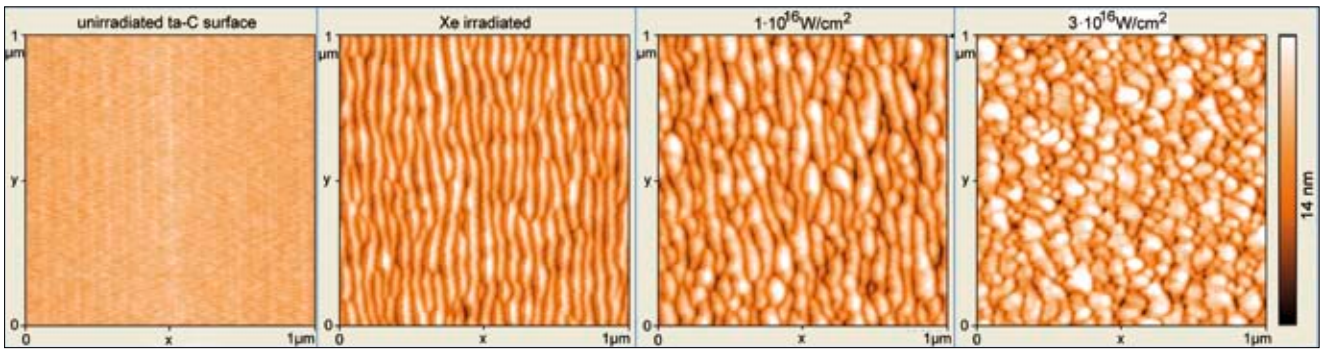


Fig. 2: AFM images of ta-C surfaces after ion beam erosion with $3 \cdot 10^{16}$ Xe/cm² at 5 keV and 70° incidence angle with increasing simultaneous coverage of tungsten surfactants.

materials leading to the formation of ion tracks. Latent ion tracks in polymers can be used to create nanopores after wet etching. SHI irradiation of high resistivity diamond-like ta-C creates highly conducting filaments with few nm diameter. These filaments are identified using atomic force microscopy by measuring the topography and the corresponding current mapping of a SHI irradiated ta-C film. Both conducting ion tracks and self-aligned ion track lithography are investigated regarding the electronic transport in reduced dimensions and regarding fabrication of ion track based electronic devices.

Ion implanted rare earth doped semiconductors

Wide band gap semiconductors like ZnO, c-BN, diamond and in particular 2H–AlN, with its high thermal conductivity and stability, chemical inertness, and band gap above 6 eV, are very promising candidates for the implementation of ultraviolet (UV) light emitters. Due to the wide band gap the possible optical applications of rare-earth-based light emitters are extended, exploiting parts of the energy level diagram of the rare earths hidden to prominent hosts such as GaN or Si. Typical examples are the upper energy levels of Tm^{3+} and Gd^{3+} but also Ce^{3+} and Pr^{3+}, at the beginning of the lanthanide series, whose energy-level structures predict the lowest 5d levels at positions still within the band gap of the widest band-gap semiconductors. This makes such systems interesting candidates for, e.g., phosphor illuminators playing an important role in the design of white light emitters.

We investigate the luminescence behavior as well as the structural properties of ion-implanted rare earth impurities in wide band gap materials. Luminescence is measured after electron and UV excitation at high spectral resolution. For structural characterization we apply the emission channeling technique and Mössbauer spectroscopy. An example of intense UV light emission at room temperature is ion implanted Gd into AlN. After annealing the implantation de-

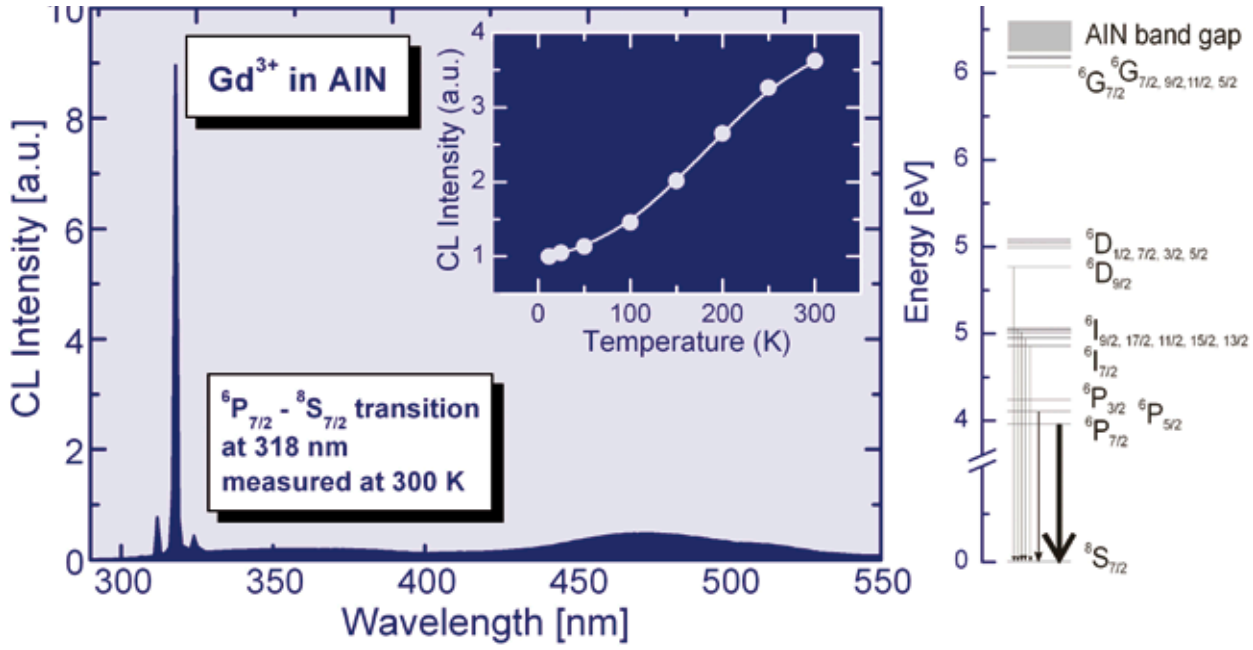
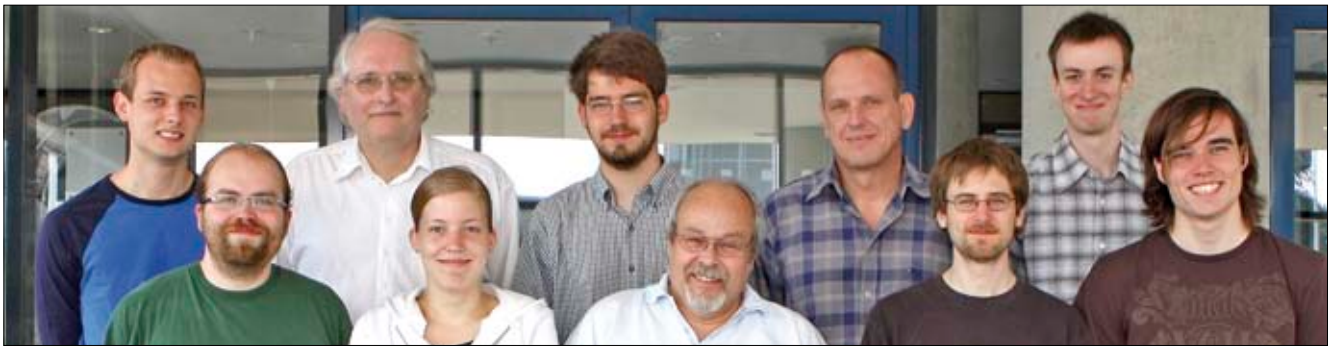


Fig. 3: Intense UV luminescence at 318 nm from Gd implanted AlN after electron beam excitation (cathodoluminescence, CL). The luminescence originates from the excited state $^6P_{7/2} \rightarrow {}^8S_{7/2}$ ground state transition in Gd^{3+}. The intensity increases strongly with temperature.



fects at 1473 K, Gd^{3+} shows an intense and sharp UV emission at 318 nm (Fig.4), corresponding to the excited state $^6P_{7/2} \rightarrow {}^8S_{7/2}$ ground state transition. Other examples investigated are Pr and Sm in AlN, Eu in c-BN and Tm in AlN.

Characterization of MAX phases

MAX phases are ternary carbides and nitrides of IIIa and IVa transition metals (e.g. Ti_3SiC_2 or Ti_2AlC). Their extraordinary physical properties combine those of metals and ceramics. The behavior of MAX phases with their complex nano-laminated structure (Fig.5) under external influence like temperature or pressure is poorly understood. Such investigations require microscopic methods with high local sensitivity. We apply perturbed angular correlation using the nuclear probes $^{111}In/^{111}Cd$ und $^{181}Ta/^{181}Hf$ for a precise measurement of electrical field gradients at the probe sites, allowing us to detect smallest variations of the local structure of MAX phases as function of temperature and pressure. Complemented by X-ray diffraction and electron microscopy we study the thermally stability, phase transformations and limits of reversible plastic deformation of various MAX phase materials.

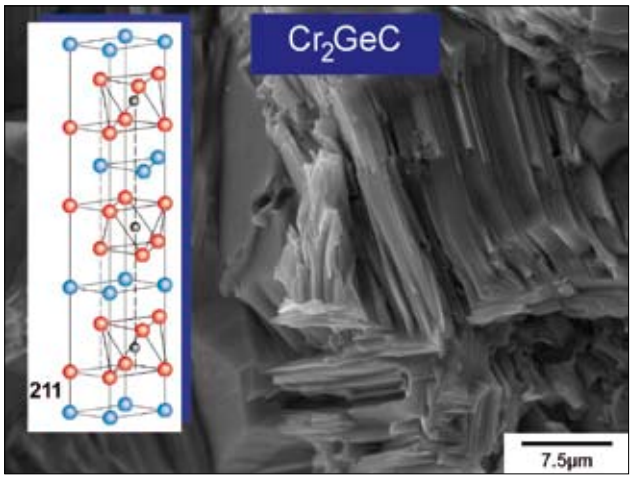


Fig. 4: SEM image of a polycrystalline Cr_2GeC MAX phase showing the nano-laminted layered structure. The insert shows the 211 unit cell. Black: Carbon atoms, red: Cr atoms, blue: Ge atoms.

[1] Hofsäss H.; Zhang K.: *Surfactant Sputtering,* Appl. Phys. A: Materials Science and Processing 92 (2008) 517

[2] Zhang K.; Rotter F.; Uhrmacher M.; Ronning C.; Hofsäss H.; KrauserJ.: *Ion induced nanoscale surface ripples on ferromagnetic thin films with correlated magnetic texture,* New J. Phys. 9 (2007) 29

[3] Krauser, J.; Nix, A.-K.; Gehrke, H.-TG.; Hofsäss, H.; Trautmann, C.; Weidinger, A.; Wünsch, F.; Bruns, J.: *Ion track lithography and graphitic nanowires in diamond-like carbon,* J. Vac. Sci Technol 26 (2008) 2468

[4] Vetter, U.; Zenneck, J.; Hofsäss, H.: *Intense ultra violet cathodoluminescence at 318 nm from Gd^{3+} - doped AlN,* Appl. Phys. Lett. 83 (2003) 2145

[5] Jürgens, D.; Uhrmacher, M.; Hofsäss, H.; Röder, J.; Wodniecki, P.; Kulinska, A.; Barsoum, *M.: First PAC Experiments in MAX-Phases,* Hyp. Int. 178 (2007) 23

Hans Hofsäss

Hans Hofsäss was born in 1956. After studying physics at Konstanz University he received his Dr. rer. nat. in 1986. For his doctoral thesis on electron emission channelling he received the Dornier research award in 1988. Following a post doc stay in the group of Wei-Kan Chu at the University of North Carolina, Chapel Hill, he was a research assistant in Ekkehard Recknagel's group at Konstanz University working on nuclear solid state physics, semiconductor physics and synthesis of diamond-like films. He directed a research group at the ISOLDE facility at CERN. In 1994 he obtained his habilitation from Konstanz University. Since 1998 he is a professor at the 2nd Institute of Physics of Georg-August University. His research interests are ion beam synthesis and modification of materials, nuclear solid state physics, semiconductor physics and physics of nanostructures.

Group III-N based Functional Hetero- and Nanostructures

In the last two decades GaN, InN, AlN and related alloys have played a major role among the compound semiconductor materials. Impressive is the successful application in GaN-based solid-state lighting and lasers, with excellent performances in emitted luminous intensity and short wavelength read/write processing, respectively. Our aim is to explore new functionalities of the group III-N material class through dopant incorporation, interfacial phenomena, and low dimensional nanostructures, as well as to obtain a fundamental understanding of the microscopic processes, towards a truly revolutionary technology of the future. The know-how in our group and the facilities at our disposal allow for the preparation and characterization of state-of-the-art GaN-based material, heterostructures and nanostructures by molecular beam epitaxy (MBE) through both top-down and bottom-up approaches. At present our research activities focus on magnetic epitaxial layers, quantum well structures also for energy conversion and sensor applications, and nanowires.

Molecular Beam Epitaxy

The technique of molecular beam epitaxy (MBE, from the gree*k epi* : above *taxis* : in ordered manner) allows the reproducible preparation of multilayer structures with atomically abrupt material changes at the interfaces as well as with controlled profiles of composition and doping on a nanometer scale, d~10^{-9} m. The MBE process runs under ultra high vacuum conditions, p~10^{-8} Pa.

Magnetic epitaxial layers

The doping of GaN with magnetic ions bears the potential of making semiconductors magnetic and providing transport of spin-polarized currents. Semiconductor spintronics aims at integrating the spin degree of freedom into semiconductor information technology, thus combining the non-volatility of magnetic storage devices with the overwhelming computing power of charged-based semiconductor switching logic.

The doping of either Mn or Gd magnetic atoms in epitaxial GaN layers gives rise to ferromagnetic coupling at room temperature, as shown by the measured magnetization loops. However, the microscopic mechanism is still unclear and induced defects might play a central role. The electronic properties, especially current transport, are investigated to answer questions both about the magnetism and about the transport of spin-polarized currents.

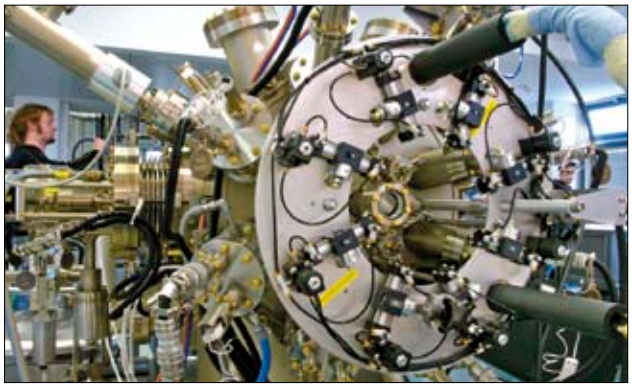


Fig. 1: MBE growth chamber. Close-up view of the material source flange.

Heterostructures and Interfaces

GaN/AlGaN quantum well (QW) structures grown along the polar axis induce an accumulation of electronic charge at the interface, forming a quasi two-dimensional electron gas (2DEG) whose motion along the growth direction is confined by the QW potential. The modulation of the 2DEG conductance by an external potential is a key process, which finds applications in high-frequency, high-power transistors as well as in biosensors, e.g. pH sensors. Furthermore Ga/AlGaN QW structures offer the possibility to create conditions where chemical energy released at a surface might be directly converted to light, allowing optical detection and analysis of chemical reactions at surfaces. 2DEG heterostructure is a versatile and powerful system for interdisciplinary studies and applications.

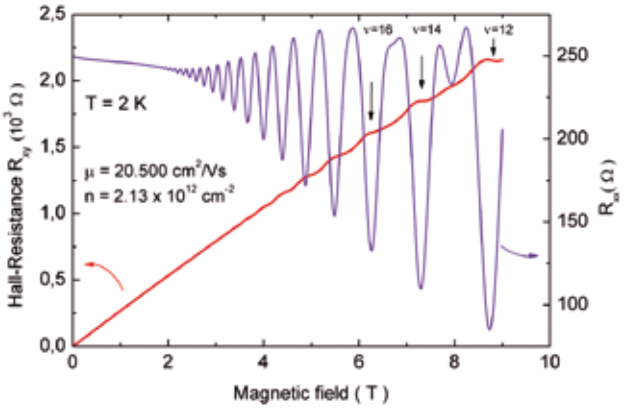


Fig. 2: Magnetic field dependence of the transverse (red) and longitudinal (violet) resistance of a high mobility AlGaN/GaN(0001) 2DEG heterostructure at low temperature. The plateaus in the Hall resistance (red) arise from the Quantum-Hall Effect.

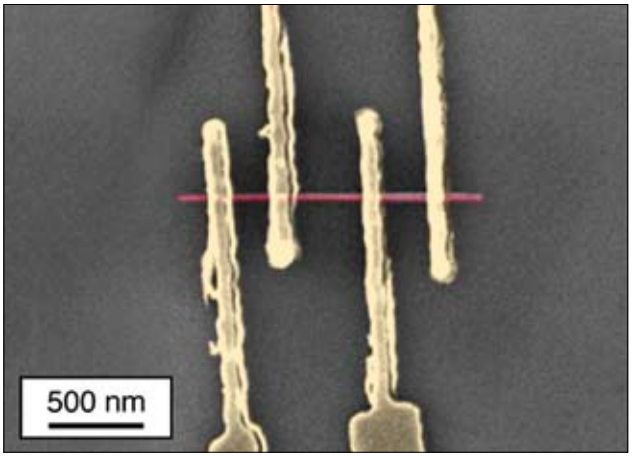


Fig. 3: Scanning electron microscope image of a single InN nanowire contacted by electron beam lithography in a four-point probe geometry [4].

Nanowires

Nanowires (NWs) are intensively studied, since quantization in spatially confined quasi one-dimensional structures (quantum wires) has the potential to revolutionize nanotechnology. In the framework of our present work on InN and GaN, NWs quantum confinement is not expected and nanowires were chosen mainly for their high surface-to-volume ratio together with their integration potential in nanoscale electronics. The small band gap and good electron transport characteristics make InN a promising material for high efficiency IR emitters, detectors, and solar cells as well as high frequency electronic devices. InN NWs embedded either in an InxGa1-xN shell or functionalized with light absorbing organic molecules are investigated in view of solar energy conversion.

Principal investigators

Angela Rizzi, Jörg Malindretos

[1] Bedoya-Pinto, A.; Malindretos, J.; Roever, M.; Mai, D.-D.; Rizzi, A.: *Variable range hopping transport in ferromagnetic GaGdN epitaxial layers,* Phys. Rev. B, 80 (2009) 195208-5

[2] Martinez-Criado, G.; Sancho-Juan, O.; Garro, N.; Sans, J. A.; Cantarero, A.; Susini, J.; Roever, M.; Mai, D.-D.; Bedoya-Pinto, A.; Malindretos, J.; Rizzi, A.: *X-ray absorption in GaGdN: A study of local structure,* Appl. Phys. Lett., 93 (2008) 021916-3

[3] Rizzi, A.: *Surface and Interface Electronic Properties of Group III-Nitride Heterostructures,* Appl. Surf. Science 190 (2002) 311

[4] Werner, F.; Limbach, F.; Carsten, M.; Denker, C.; Malindretos, J.; Rizzi, A.; *Electrical Conductivity of InN Nanowires and the Influence of the Native Indium Oxide Formed at Their Surface,* Nano Letters 9 (2009) 1567

[5] Segura-Ruiz, J.; Garro, N.; Cantarero, A.; Denker, C.; Malindretos, J.; Rizzi, A.: *Optical studies of MBE-grown InN nanocolumns: Evidence of surface electron accumulation,* Phys. Rev. B. 79, (2009) 115305

Angela Rizzi

Angela Rizzi was born in 1958 in Vignola, Italy. After studying Physics at the University of Modena, she received her PhD from the Technical University in Milano in 1987. From the study of the electronic properties of semiconductor surfaces and interfaces by electron spectroscopies her research interests turned to the experimental investigations of novel semiconductor epitaxial layers and heterostructures, such as iron disilicide and group III-N materials. After a post-doc stay at the Forschungszentrum Jülich as a Humboldt-fellow she held a Researcher position with teaching duties at the University of Modena, Italy still maintaining her main research activity at the Forschungszentrum Jülich. In 2002 she was appointed a professorship in Experimental Physics at the Georg-August University of Göttingen.

Electronic and Atomic Structure of Defects and Interfaces

Electronic and optical properties of semiconducting materials, devices and nanostructures are governed by defects and interfaces that introduce electronic states into the bandgap. In order to address the relation of their atomic and electronic structure, atomically resolved transmission electron microscopy (HRTEM) is combined with spectroscopic techniques. Currently, our research is mainly focused on semiconductors for photovoltaic applications aiming at understanding and quantitatively modeling defect reactions at the atomic level as a basis for successful defect engineering in such materials.

Quantitative high-resolution and analytical electron microscopy

At interfaces between crystalline and amorphous solids atomic arrangements qualitatively change from long-range to short-range ordering. Using quantitative matching of simulated and experimental HRTEM images the atomic distribution function at such images is determined showing that long-range atomic correlations decay from the crystalline to the amorphous material on a length scale of a few atomic layers [1]. In collaboration with Bielefeld University and the group of Prof. Markus Münzenberg we currently study the effect of such ordering on spin-polarized tunneling within the SFB602.

Object wave functions reconstructed by maximum-likelihood techniques from defocus series are used to study dislocation arrangements in Mn-doped GaN in collaboration with Prof. Rizzi's group. Mn dopants are preferentially incorporated on Ga-sites as has been determined from ALCHEMI studies [2] where Bloch functions are adjusted to achieve a site-selective X-ray emission.

Defect interaction in semiconductors for photovoltaics

Metal impurities in various forms reduce the efficiency of crystalline silicon solar cells. A plethora of reactions with intrinsic and extrinsic point defects as well as with dislocations and grain boundaries makes their control a formidable task which needs fundamental understanding of the underlying physics [3]. Spectroscopic investigations combined with physics-based simulations are used to study their electronic structure and thermodynamic properties necessary to successfully adjust metal impurity distribution to minimize their deteriorating effects, i.e. impurity gettering [4]. A recent development in our group facilitates structural and chemical analysis on the atomic scale of single recombination-active extended defects (see Figure).

[1] Borgardt, N. I.; Plikat, B.; Schröter, W.; Seibt, M.; Wagner, T.: *Atomic structure of the interface between silicon (111) and amorphous germanium,* Phys. Rev. B 70, 195307 (2004)

[2] Niermann, T.; Mai, D. D.; Roever, M.; Kocan, M.; Zenneck, J.; Malindretos, J.; Rizzi, A.; Seibt, M.: *Substiutional-to-interstial ratio of manganese in nanostructured GaN by electron channeling enhanced microanalysis,* J. Appl. Phys. 103, p.073520 (2007)

[3] Seibt, M.; Khalil, R.; Kveder, V. V. and Schröter, W.: *Electronic states at dislocations and metal silicide precipitates in crystalline silicon and their role in solar cell materials,* Appl. Phys. A 96, p.235-253 (2009)

[4] Abdelbarey, D.; Kveder, V.; Schröter, W.; Seibt, M.: *Aluminum gettering of iron in silicon as a problem of the ternary phase diagram,* Appl. Phys. Lett. 94, p.061912 (2009)

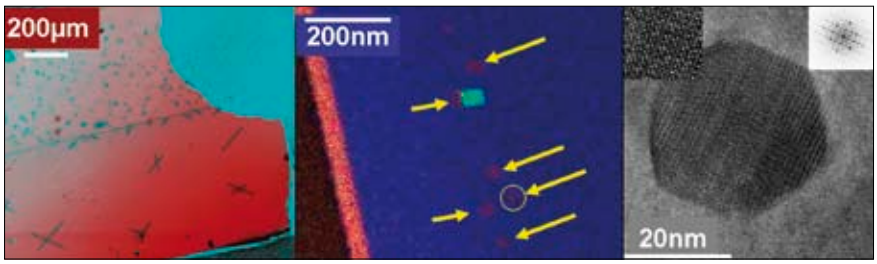


Fig. 1: Left: EBIC map of recombination-active defects. Centre: Chemical map obtained by X-ray analysis in the TEM; arrows indicate copper-rich nanoscale precipitates. Right: structure analysis of a nano-precipitate using direct lattice imaging. Please note that the magnification increases by about a factor or 10000 from left to right.

Michael Seibt

Michael Seibt was born in Bremen in 1958. After studying physics at the Georg-August-University in Göttingen he received his PhD with work on electron microscopy of nickel silicide precipitates in silicon in 1986. During his time as a post-doc in Göttingen he worked on solid-state reactions and the atomic and electronic structure of defects and interfaces in semiconductors. In the early 90's he joined Bell Laboratories in Holmdel, New Jersey, as a Humboldt scholar (Feodor-Lynen scholarship) and worked on quantitative high-resolution electron microscopy which has since become a branch of his research. His work in semiconductor defect physics is now mainly focused on semiconductors for photovoltaic applications aiming at understanding and quantitatively modeling defect reactions at the atomic level. Michael Seibt is currently appointed as an apl. Professor at the Institute of Semiconductor Physics.

Solid-State Spectroscopy on the Atomic Scale

Studying matter on the atomic scale and modifying its constituents to obtain new functionalities is the core of todays solid state physics and technology. Physics and chemistry came along very different paths – top down versus bottom up – and have merged into the interdisciplinary field of "nanoscience", forging tools for useful applications. Semiconductor science pioneered the miniaturization process over five decades: the size of basic building blocks has since been reduced steadily. Continuous scaling has brought geometric dimensions down to the nanometer scale, such that the classification of materials in metals, semi- conductors and insulators looses its meaning, and further reductions in size will soon meet the ultimate limit of every solid state device, the atom. Our group is developing and applying experimental tools for this challenging era: scanning probe microscopies and optical spectroscopies to investigate complex structural and electronic properties of solids on the atomic scale [Refs. 1-5].

Charge Switching of Single Atoms

The tip of an STM is used to control electronic charges on individual impurity atoms buried under the surface of a semiconductor. We position the tip and tune the region under it to measure the ionization threshold of e.g. donor bound states with high precision. The screened electrostatic binding potential of the donor core is then extracted. Dopant *ensembles* show electronic switching characteristics of a confined many-electron system [Ref. 1].

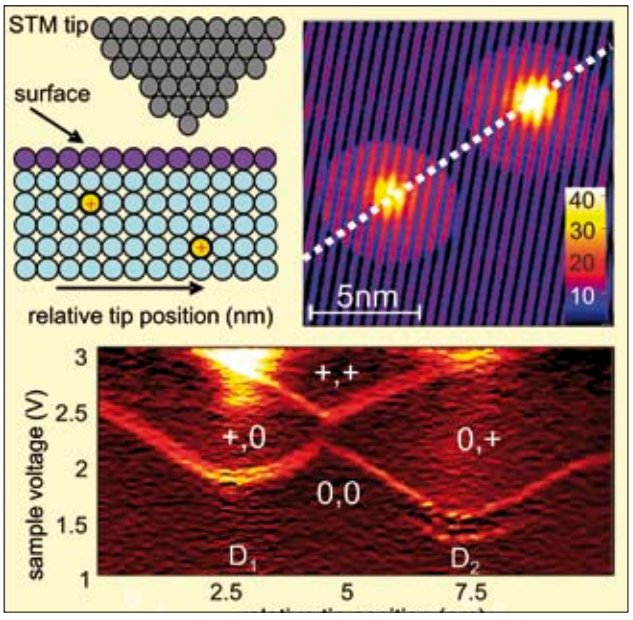


Fig. 1: Switching single atoms buried under the surface (side view, top view, and spectra).

Wave Function Mapping

We aim at a better understanding of microscopic charge and spin transport through semiconductor-metal interfaces and the manipulation of electron spins with external electric and magnetic fields. Recent theoretical work predicted that spin-orbit coupling may have a significant larger influence on evanescent states as compared with transport involving states from the real part of the band structure. Here we have mapped signatures of individual acceptor atoms in real space to investigate SO-coupling effects (Dressel-haus/Rashba) on the atomic scale [Ref. 2].

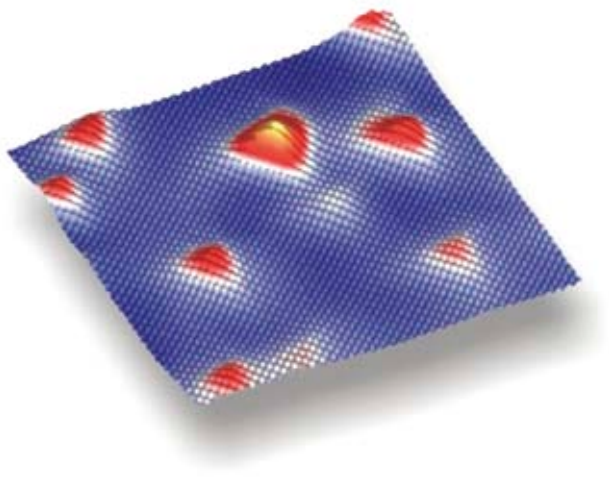


Fig. 2: Topography of individual carbon atoms in GaAs (110).

Electron Focussing in Solids

The Fermi-surface of a bulk solid can be imaged with high-resolution STM when isolated subsurface point scatterers are present. Their scattered wave pattern modulates the local density of states (LDOS) at the nearby surface which is accessible with the STM. The shapes of Fermi-surfaces of crystalline solids are, in general, non-spherical. This causes anisotropic electron propagation on the nanoscale, similar to "caustics" in optics. The scattered waves are confined in beam-like paths, and carry explicit phase information on details of the scattering process. We are currently studying phase shifts connected with the Abrikosov-Suhl resonance, i.e. the Kondo-effect, of magnetic impurities (single Co and Fe atoms and ensembles) buried under single crystal surfaces [Ref. 3].

Ohm's Law at the Nanoscale

A constant electron current through a normal conductor is affected by local elastic scattering at defects as well as non-local inelastic phonon scattering. Both effects contribute to the global potential drop which is usually observed: they constitute Ohm's law. Although this concept is well established for macroscopic solids, it has not yet been tested on the atomic scale, e.g. around an individual scattering center. To tackle this question, we have studied the gradient of the electrochemical potential μec in a current-carrying 2-d electron gas confined in a layer of silver atoms on terraces of atomically smooth. At mono-atomic steps the drop in μ_{ec} extends over less than 1 nm. It has been modeled with known macroscopic conductivity parameters of the 2DEG and a step transmission coefficient T=0.2 according to Landauer's ballistic conductance concept [Ref. 4].

Interferometric Nanoparticle Tracking

This biophysics-oriented project explores the potential of phase- and amplitude-resolved spectroscopy to study dynamical properties of nanoscale objects in the visible range with sub-wavelength resolution. Heterodyne techniques allow to visualize trajectories of single nano-particles (Au spheres, semiconductor quantum dots) and tagged macromolecules in aqueous solution with low-level light intensities. We work towards a multi-color extension of this minimal invasive linear optical method, with 3-d spatial (< λ/10) and temporal (< 100 μs) resolution.

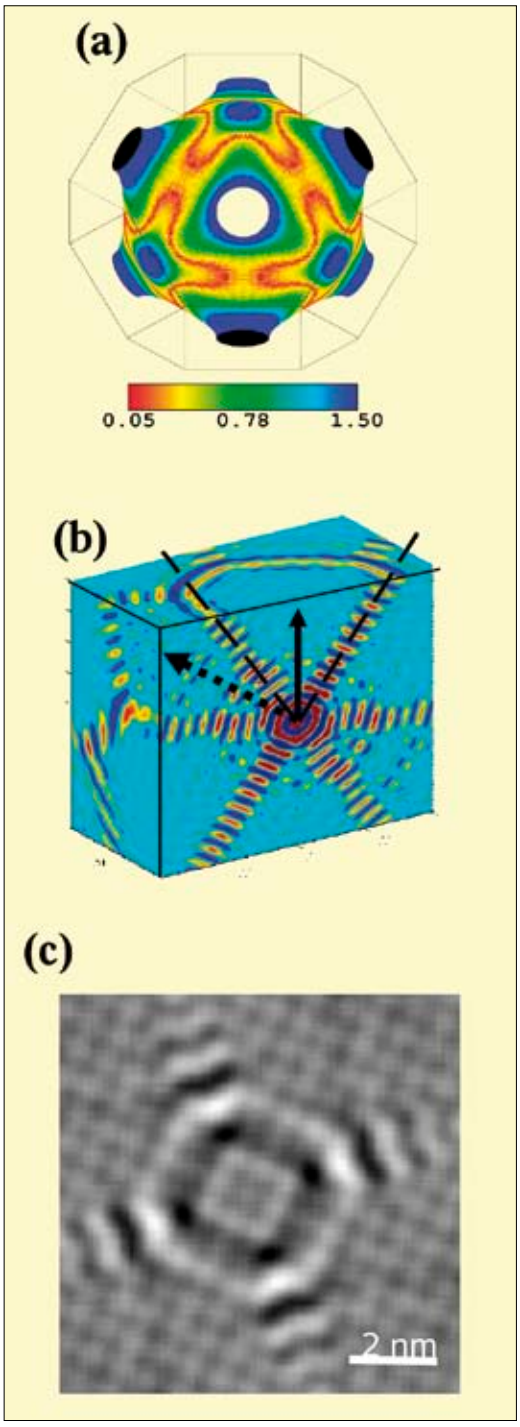


Fig. 3: The warped Fermi surface of Cu (a) causes electron focussing in real space (b) which is detected with an STM (top view, c).

Principal investigators

R. G. Ulbrich, M. Wenderoth

[1] Teichmann, K.; Wenderoth, M.; Loth, S.; Ulbrich, R. G.; Garleff, J. K.; Wijnheijmer, A. P. and Koenraad, P. M.: *Controlled Charge Switching on a Single Donor with a Scanning Tunneling Microscope* Phys.Rev.Lett.101, p.076103 (2008). See also Wijnheijmer, A. P.; Garleff, J. K.; Teichmann, K.; Wenderoth, M.; Loth, S.; Ulbrich, R. G.; Maksym, P. A.; Roy, M.; Koenraad, P. M.: *Enhanced Donor Binding Energy Close to a Semiconductor Surface,* Phys. Rev. Lett. 102, p.166101 (2009).

[2] Loth, S.; Wenderoth, M.; Winking, L.; Ulbrich, R. G.; Malzer S.; Döhler, G.H.: *Probing semiconductor gap states with resonant tunnelling,* Phys.Rev. Lett. 96, p.066403 (2006), see also Reusch, T.C.G.; Wenderoth M.; Winking L.; Quaas, N.; Ulbrich, R. G.: *Origin of Schottky Barriers in Gold Contacts on GaAs (110),* Phys. Rev.Lett.93, 206801 (2004).

[3] Weismann, A.; Wenderoth, M.; Lounis, S.; Zahn, P.; Quaas, N.; Ulbrich, R. G.; Dederichs, P. H.; Blügel, S.: *Seeing the Fermi Surface in Real Space by Nanoscale Electron Focusing,* Science 323, p.1190 (2009).

[4] Homoth, J.; Wenderoth, M.; Druga, T.; Winking, L.; Ulbrich, R. G.; Bobisch, C. A.; Weyers, B.; Bannani, A.; Zubkov, E.; Bernhart, A. M.; Kaspers, M.R. and Möller, R.: *Electronic Transport on the Nanoscale: Ballistic Transmission and Ohm's Law,* NanoLetters 9, p.1588 (2009).

[5] Ropers, C.; Wenderoth, M.; Winking, L.; Reusch, T. C. G.; Erdmann, M.; Ulbrich, R. G.; Grochol, M.; Grosse, F.; Zimmerman, R.; Malzer, S.; Döhler, G. H.: *Atomic scale structure and optical emission of AlxGa1-xAs/GaAs quantum wells,* Phys. Rev. B 75, p.115317 (2007).

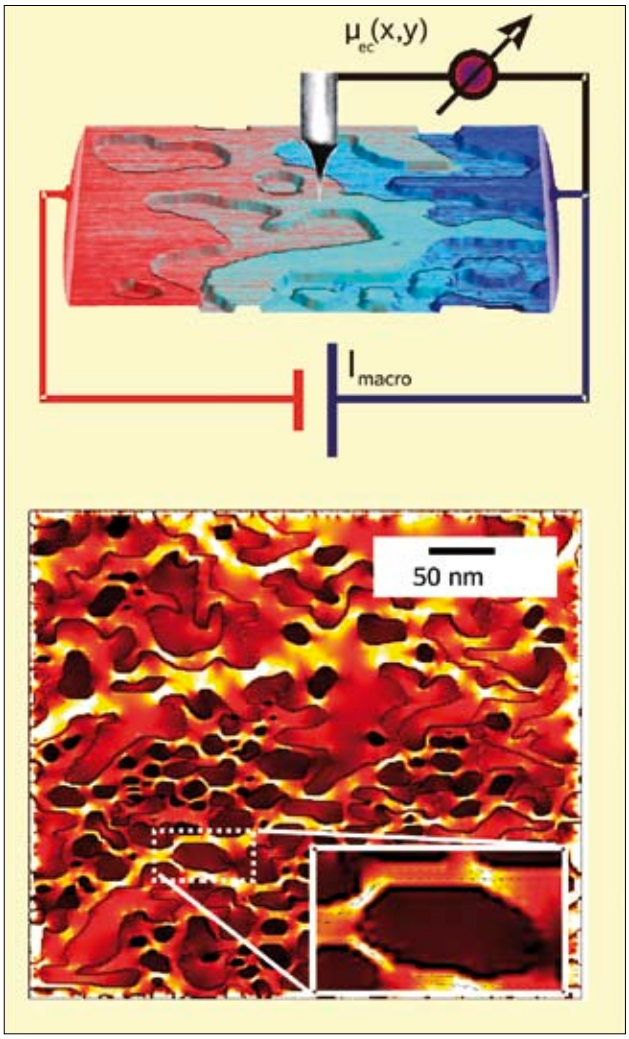


Fig. 4: Electro-chemical potential μ_{ec} of a current-carrying 2-d electron gas (left). The insert shows current density vectors around a 50 nm-sized terrace on the underlying Si (111) substrate.

Rainer G. Ulbrich

Born Nov. 1944 in Dornreichenbach, Sachsen. After studying physics (1965-1969, PhD 1972) at J.W.Goethe-University,Frankfurt/M., postdoctoral fellow at IBM Research Center in Yorktown Heights. In 1976 appointed a professorship at Dortmund University. Spectroscopies with ultrashort laserpulses, inelastic light scattering, and phonon transport in semiconductors. From 1988 full professor at physics faculty in Göttingen. Work focussed on (i) dynamics of elementary excitations in solids, (ii) scanning probe microscopies on solid surfaces (RTM and SNOM) and (iii) optical spectroscpy of semiconductor nanostructures. Visiting professor at Ecole Polytechnique (Palaiseau, 1976, 1977), Bell Labs (1979, 1983), IBM Yorktown (1987), Lawrence Berkeley Lab (1992). From 1993-1996 spokesperson of the SFB 345, from 1991-2003 head of faculty team that established the new physics building. Served the faculty as dean (2005-2007) and in many other functions. Member of Akademie der Wissenschaften in Göttingen.

Nano-Optics and Ultrafast Dynamics

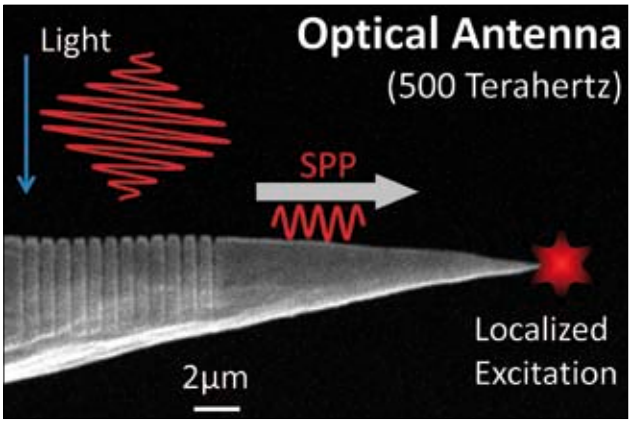
Understanding light propagation and localization is among the leading themes in modern optics. Metallic structures offer unique possibilities to guide, control and confine light on the nanoscale. Such handles are required for a future integration of optics and electronics on microchips. The research group Nano-Optics and Ultrafast Dynamics investigates the spatiotemporal properties of optical fields in nanostructures, and implements localized, ultrafast sources of light and electrons.

Plasmonic Nanostructures

Surface Plasmon Polaritons (SPPs) are surface-bound waves at an interface between a metal and a dielectric. They represent a combined excitation of the collective oscillation of conduction electrons (plasmon) and an electromagnetic mode near the metal's surface. SPPs can be used to collect and guide optical energy on a metal. We use tailored nanostructures that display surface plasmon resonances for efficient excitation. In these structures, SPPs can be concentrated in very small volumes (few nanometers diameter), for example, to create a confined light source for near-field optical microscopy. By scanning such a "nanolight" close to a material, we can obtain microscopic optical resolutions of only 10 nm. In contrast to conventional near-field light sources based on optical fiber, these metallic systems possess very little chromatic dispersion, so that pulses as short as a few femtoseconds can be induced at the tip apex. This allows for near-field microscopy with femtosecond temporal resolution.

Localized femtosecond electron pulses

The strong confinement of light at sharps tips is assisted by field enhancement, an optical effect analogous to lightning rod action. Our research group employs optical field enhancements to strengthen nonlinear optical processes occurring at extremely high light intensities. One such example is the *multiphoton photoelectric effect*. Differing from the regular photoelectric effect, in multiphoton electron emission, several photons of energy below the work function cooperatively lead to an emission of one electron from a metal. In conjunction with few optical cycle laser pulses, a localized beam of femtosecond electron pulses can be created, which we utilize to develop nanometric imaging techniques (see Fig.2). Such sources will also be integrated in complex electron optics, such as a transmission electron microscope, to facilitate so-called "ultrafast transmission electron microscopy". In the future, such methods will give access to the study of the most rapid atomic processes in materials.



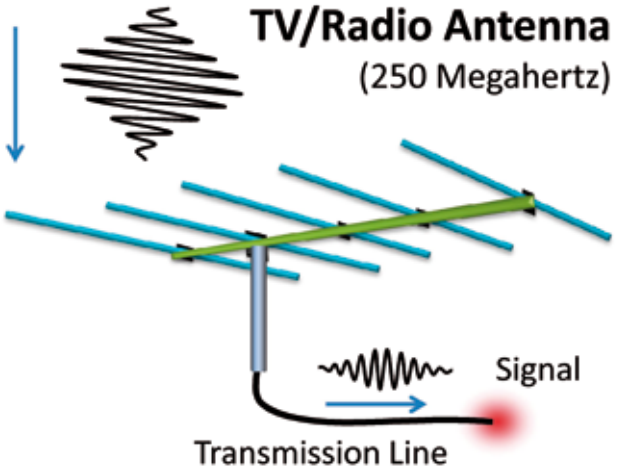
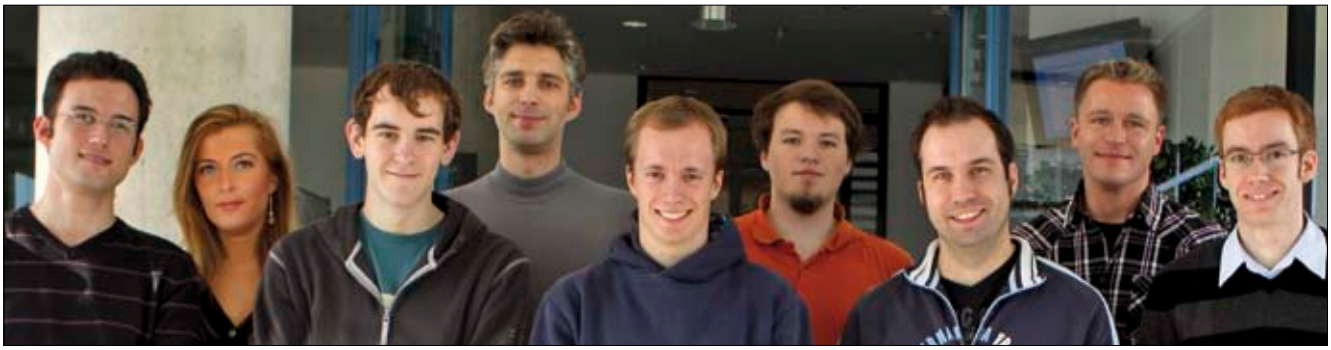


Fig. 1: Microscopic optical antenna made of a nanostructured gold needle (picture on the left). Light is collected in an antenna structure, here a grating, and transformed into surface plasmons, which converge at the needle apex in a spot size of about 10 nanometers. The operating principle is very similar to that of a macroscopic radio or TV antenna (picture on the right), albeit at about two million times higher frequency.



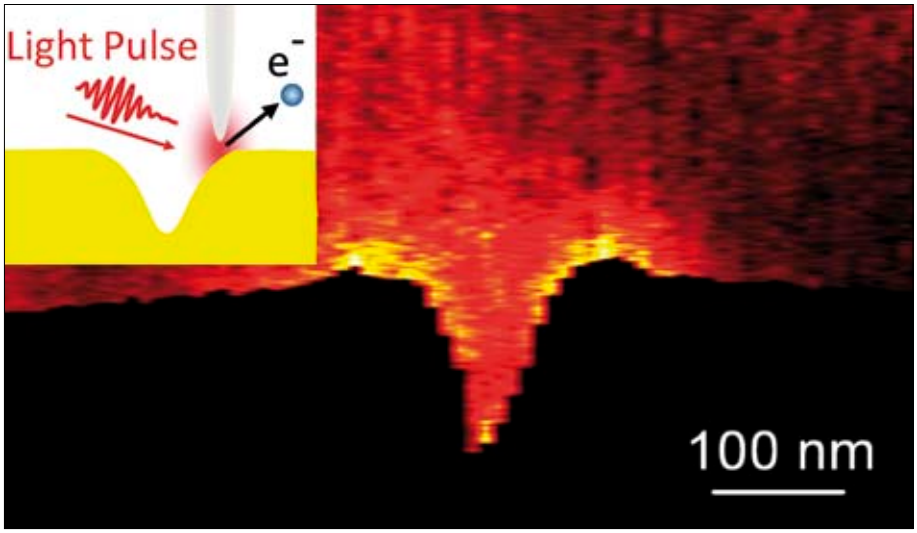


Fig. 2: Imaging nanostructures with a localized beam of femtosecond electrons. A metal tip (gray) is brought near a sample (V-shaped groove in a surface), and the generated electron current is recorded during illumination of the tip-sample gap with a femtosecond laser pulse.

[1] Ropers, C.; Park, D.J.; Stibenz, G.; Steinmeyer, G.; Kim, J.; Park, D. S. and Lienau, C.: *Femtosecond light transmission and subradiant damping in plasmonic crystals,* Phys. Rev. Lett. 94, 113901 (2005)

[2] Ropers, C.; Solli, D. R.; Schulz, C.-P.; Lienau, C. and Elsässer, T.: *Localized multiphoton emission of femtosecond electron pulses from metal nanotips,* Phys. Rev. Lett. 98, 043907 (2007)

[3] Ropers, C.; Neacsu, C. C.; Elsässer, T.; Albrecht, M.; Raschke, M. B. and Lienau, C.: *Grating-coupling of surface plasmons onto metallic tips: A nano-confined light source,* Nano Lett. 7, 2784 (2007)

[4] Solli, D. R.; Ropers, C.; Koonath, P. and Jalali, B.: *Optical Rogue Waves,* Nature 450, 1054 (2007)

[5] Breusing, M.; Ropers, C. and Elsässer T.: *Ultrafast Carrier Dynamics in Graphite,* Phys. Rev. Lett. 102, 086809 (2009)

Claus Ropers

Claus Ropers, born in 1977 in Stade, studied Physics at the University of Göttingen and the University of California at Berkeley until 2003. At the Max Born Institute in Berlin, he worked on ultrafast optical excitations in metallic nanostructures (advisor Prof. T. Elsässer). He received a Ph.D. from the Humboldt University in Berlin in 2007 and was awarded the Carl Ramsauer Prize 2008 for his dissertation. He is currently leading the research group 'Nano-Optics and Ultrafast Dynamics' (CRC Nano-Spectroscopy and X-ray Imaging) at the University of Göttingen as a tenure track junior professor. He also holds a strong connection with the University of California at Los Angeles as an affiliated scientist (Photonics Laboratory, Department of Electrical Engineering). In 2009, he received the German 'Nanowissenschaftspreis 2008'.

Low-Temperature Dynamics of Interacting Quantum Systems

Condensed matter theory deals with the calculation and interpretation of properties of liquids and solids. Of particular interest are transport and ordering phenomena like magnetism or superconductivity, as they are the key for developing novel devices relevant to, for example, information technology. As these properties are determined by a number of nuclei and electrons on the order of 10^{23} which are strongly interacting via the Coulomb interaction, one needs the toolbox of quantum many-particle physics for a reliable description. Fortunately, the nuclei are much heavier than the electrons, which allows to treat them as being at rest in a first approximation and concentrate on the electrons only.

The low temperature thermodynamic properties of simple metals, like the alkalis, can then be qualitatively very well understood in terms of the *Sommerfeld model* which treats the conduction electrons as non-interacting fermions. It took almost thirty years to understand why the low temperature properties of *interacting fermions* are in some cases qualitatively the same. Landau's phenomenological *Fermi liquid* theory (1957) introduces the notion of *quasi-particles* which behave in many respects like non-interacting fermions but involve renormalized quantities like an effective mass, typically larger than the mass of a free electron, and quasi-particle interaction parameters, which are difficult to calculate microscopically.

The consistency of the approach was shown using perturbation theory to infinite order and more recently by renormalization group techniques. Landau's work marks the beginning of the general theory of (normal) *quantum liquids*, which are many body systems in which the indistinguishability of the elementary constituents is important. The description of interacting bosons (liquid Helium 4, or the Bose alkali gases) is another theoretical challenge. These systems can undergo the phenomenon of Bose condensation. The related effect of Cooper pairing can occur in interacting fermion systems (liquid Helium 3, electrons in the superconducting state).

One-Dimensional Quantum Liquids

The problem of interacting fermions (and bosons) simplifies in one dimension. In a pioneering paper Tomonaga (1950) treated the case of fermions with a long-ranged two-body interaction. He showed that the low energy excitations of the non-interacting as well as the interacting system can be described in terms of *noninteracting bosons*. Luttinger (1963) later studied a more idealized model, which turned out to be exactly solvable. Various correlation functions exhibit a power law or *algebraic* behavior with exponents determined by a single number, the so-called *anomalous dimension*, which can be calculated explicitly for the Tomonaga-Luttinger model. It was an important observation of Haldane (1981) that the low-energy physics of the exactly solvable *Tomonaga-*

Fig. 1: Sketch of a typical experimental setup used to study the conductance of quantum wires. The wire is attached to higher dimensional leads, which further extend outside the image.

Luttinger-model provides the generic scenario for one-dimensional fermions with repulsive interactions, which are now called *Luttinger liquids*.

Strictly one-dimensional systems are of course a theoretical idealization. Apart from this even the coupling to an experimental probe like the leads in a resistivity measurement presents a nontrivial disturbance of a Luttinger liquid. Also, the coupling between the chains in a very anisotropic 3d compound generally, at low enough temperatures, leads to *true long range order.* The order develops in the phase for which the algebraic decay of the corresponding correlation function of the single chain Luttinger liquids is slowest. This can lead e.g. to charge density wave, spin density wave order or superconductivity.

Photoemission and transport measurements are important experiments in the attempt to verify the Luttinger liquid concept put forward by theoreticians [1]. For the theoretical description of angular resolved photoemission the momentum and frequency dependent spectral function of the one-particle Green's function is needed. It shows clearly the phenomenon of "spin-charge-separation". The charge excitations propagate with velocity v_c independently of the spin excitations having the velocity v_s. This manifests itself in the spectral function by two power law singularities which disperse linearly with the deviation from the Fermi momentum with the two different velocities [2].

The unusual transport properties of Luttinger liquids were pointed out by Kane and Fisher (1992) using a field theoretical description. Weak impurities in the 1d system which in the noninteracting case lead to backscattering with a small probability behave very differently when a repulsive interaction between the fermions is introduced. Then the impurity presents a relevant perturbation which for an infinitely long chain leads to a conductance which vanishes with temperature T like $T^{2\alpha_B}$, where α_B is the boundary anomalous dimension. At zero temperature an arbitrarily weak impurity "cuts the chain".

Since the pioneering work of K. G. Wilson, renormalization group methods have become a widely and very successfully used approach in the field of condensed matter physics. With collaborators we have devised a functional renormalization group approach for the description of zero- and one-dimensional systems (quantum dots and wires). The method can directly be applied to microscopic models, offering advantages over effective field theoretical approaches. The starting point is an infinite system of coupled flow equations for the vertex functions. A simple truncation scheme for this hierarchy allows for the description of the behavior of Luttinger liquids in inhomogeneous one dimensional wires and Kondo physics in quantum dots. Extended truncation schemes to include dynamic and non-equilibrium situations are being developed.

In particular, we have used this functional renormalization group technique to describe the transport properties for microscopic models at arbitrary strength of the impurities and more general geometries [3-5]. In many experiments on quantum wires, realized e. g. by single wall carbon nanotubes, the temperature dependence of the linear conductance was measured and indications of Luttinger liquid behaviour were identified. A typical experimental setup is shown in Fig. 1. A wire of finite length is coupled via tunnel barriers to two quasi two-dimensional (Fermi liquid) leads. We recently extended our FRG approach to include such geometries. The length scales set by the overhanging parts of the leads and the wire introduce new energy scales, which strongly affect the temperature dependence of the conductance [5].

Higher dimensional systems

The physical phenomena in two or three dimensional interacting quantum systems typically are of a quite different type. Here one often has to deal with a competition between the formation of a "normal" Landau Fermi liquid and the tendency to exhibit long-range order, like magnetism or superconductivity, and the precise values of the Landau parameters like effective mass and quasi-particle interactions are of vital importance to correctly predict the phases of the system. But even the precise nature of a Fermi liquid state can be of interest. For example, in compounds involving transition metal or rare-earth elements the interactions or correlations in the d- respectively f-shells lead to Landau parameters which can be orders of magnitude larger ("Heavy Fermions") than in conventional metals, strongly influencing the physical properties: One finds a variety of phases showing different types of magnetic, orbital and sometimes superconducting order, metal-insulator transitions accompanied by phenomena like "colossal magneto resistance" and the like.

The elaborate tools developed for one-dimensional systems cannot, however, be readily applied for $D \geq 2$. While for $D=2$ one can in principle use modern high performance computers to simulate quantum many-particle systems, such an approach becomes quickly intractable for $D=3$, and the restriction to relatively small systems makes the identification of strongly enhanced Landau parameters at least difficult.

Nevertheless, we use such tools to study one- and two-dimensional systems numerically. The focus here is on the influence of competing interactions – either due to geometric properties of the system or intrinsic effects – on thermodynamics and dynamics. Interesting effects can be expected, when such competitions lead to phase transitions at T=0, so-called *quantum phase transitions*, which are at the heart of a large number of presently investigated phenomena in low-dimensional materials. Other approaches use the idea of a generalized mean-field theory. One divides the lattice into small treatable clusters and calculates the properties of a given cluster under the averaged influence of all others [6]. The simplest version is to define the cluster as one single site, which then leads to the *dynamical mean-field theory* (DMFT) extensively used in our group.

The actual task to perform in such a mean-field theory is to calculate properties of a single atom or small cluster of atoms in the presence of the averaged rest of the system or "bath". This problem is also called *quantum impurity problem* and has applications beyond the DMFT, for example in nano structures like quantum dots and transport through biological molecules. It is an old problem dating back to the early 1960s, but still poses a severe challenge. To solve it, we employ different kinds of modern numerical tools, including numerical renormalization techniques and quantum Monte-Carlo. Using these kinds of mean-field theories, one is actually in a position to not only calculate electronic properties beyond Landau's phenomenological model but possibly also extract the Landau parameters. As example, Fig. 2 shows a calculated photoemission spectrum for a typical metal [7]. The white dots represent the predictions by Fermi liquid theory. The real system obviously has much more structure, but in particular around zero energy more or less follows Landau's model. Using such results, one can then ask further questions about transport properties like resistivity or thermo-electric effects [6,8] or investigate magnetism [9] and superconductivity [10].

Even more exotic states of matter can arise in the presence of quantum fluctuations. Such exotic states are favored e.g. if more conventional ordered states are suppressed by competing interactions. Competing interactions can come up from "geometric frustration". The kagome lattice, shown in Fig. 3, is an example of a highly frustrated lattice. If one considers classical spins on such a lattice, it is no longer possible to align each spin antiparallel to its neighbour. In fact, the antiferromagnetic classical Heisenberg model has a huge number of ground states and classical order is clearly absent (the arrows in Fig. 3 show an example). A quantum magnet can then be either disordered down to zero temperature or exhibit novel types of *quantum order* [11]. Note that the same type of phys-

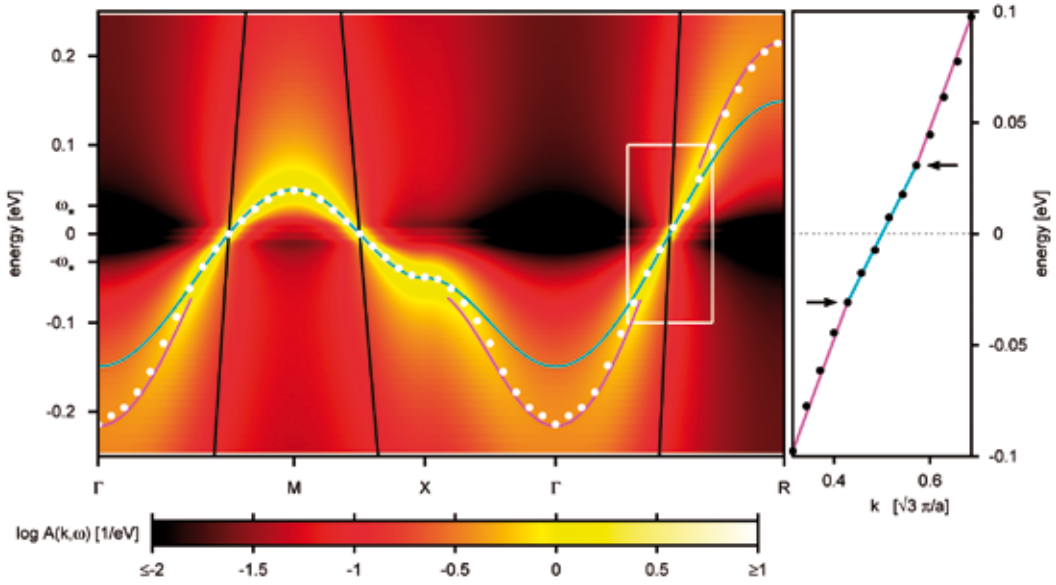


Fig. 2: Electron photoemission spectrum of a solid. The magenta line shows the results for noninteracting electrons, the cyan one for the low-energy Landau quasi-particles (from [7]).

ics can also be realized by ultracold atoms in optical lattices [12], promising further experimental possibilities. In an antiferromagnetic compound with competing interactions, the degeneracy can be tuned with an external magnetic field. This opens new perspectives for efficient low-temperature refrigeration using adiabatic demagnetization [13].

An experimental realization is given by the natural mineral azurite (the left panel of Fig. 4 shows a single crystal). Azurite has been used for its color since ancient times, but has attracted renewed attention from solid-state physicists after Kikuchi and co-workers (2005) exhibited a 1/3 magnetization plateau in high-field experiments. This quantum effect is understood to be related to diamond-chain structures formed by the copper atoms in the crystal, but a precise determination of the model parameters turns out to be a major effort. In this context we have recently performed a computation of the magnetic excitations using the dynamical "Density Matrix Renormalization Group". The result is shown in the right panel of Fig. 4 and compares favourably with inelastic neutron scattering experiments (Rule et al., 2008).

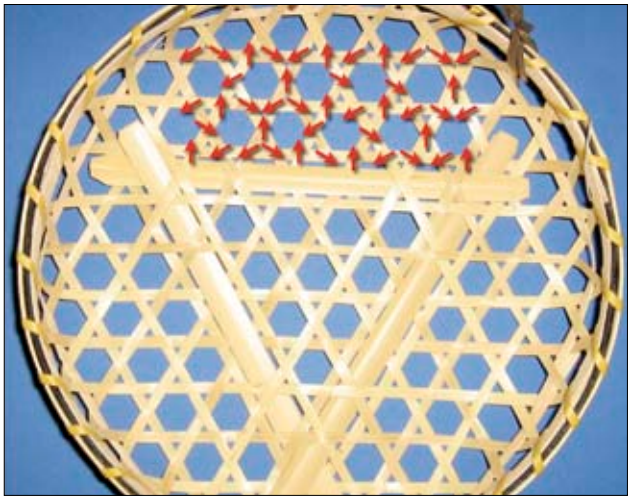


Fig. 3: Japanese kagome basket. Classical magnets (antiferromagnetic "spins") which are placed at the intersection points of the laths give rise to a highly degenerate ground state, see upper half of the picture for an example.

[1] Schönhammer, K.; *Luttinger Liquids: the basic concepts,* in *Strong interactions in low dimensional systems*, Editors: D. Baeriswyl and L. Degiorgi, Kluwer Academic Publishers (2005)

[2] Meden, V. and Schönhammer, K.: *Spectral functions for the Tomonaga-Luttinger model,* Phys. Rev. B 46, 15753 (1992)

[3] Enss, T.; Meden, V.; Andergassen, S.; Barnabé-Thériault, X.; Metzner, W. and Schönhammer, K.: *Impurity and correlation effects on transport in one-dimensional quantum wires,* Phys. Rev. B 71, 155401 (2005)

[4] Barnabé-Thériault, X.; Sedeki, A.; Meden, V. and Schönhammer, K.: *Junction of Three Quantum Wires: Restoring Time-Reversal Symmetry by Interaction,* Phys. Rev. Lett. 94, 136405 (2005)

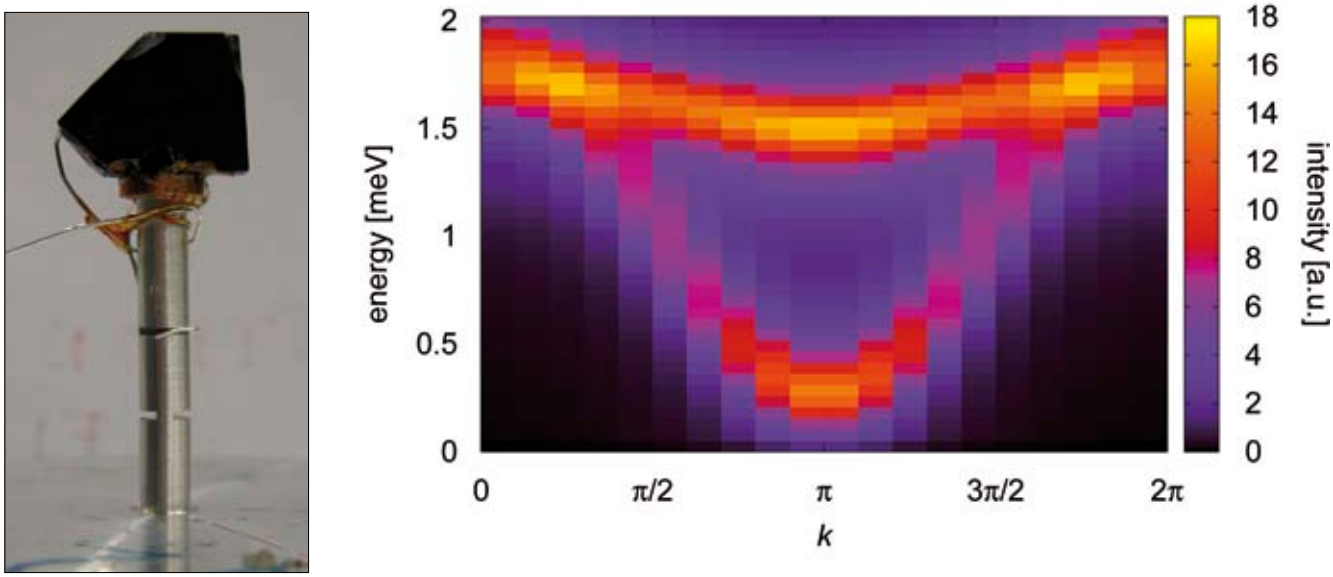


Fig. 4: A single crystal of the mineral azurite mounted and aligned for neutron scattering (left panel). This mineral contains quantum spin chains with a diamond-like structure. The right panel shows the result of a model computation for the longitudinal dynamic structure factor in an external magnetic field. The color scale encodes the scattering intensity of polarized neutrons in arbitrary units.

[5] Wächter, P.; Meden, V. and Schönhammer, K.: *Coupling-geometry-induced temperature scales in the conductance of Luttinger liquid wire,* J. Phys. Condens. Matter 21, 215608 (2009)

[6] Maier, Th.; Jarrell, M.; Pruschke, Th. and Hettler, M. H.: *Quantum cluster theories,* Rev. Mod. Phys. 77, 1027 (2005)

[7] Byczuk, K.; Kollar, M.; Held, K.; Yang, Y.-F.; Nekrasov, I. A.; Pruschke, Th. and Vollhardt, D.: *Kinks in the dispersion of strongly correlated electrons,* Nature Physics 3, 168 (2007)

[8] Pruschke, Th.; Jarrell, M. and Freericks, J. K.: *Anomalous normal-state properties of high-Tc superconductors: intrinsic properties of strongly correlated electron systems,* Adv. in Physics 44, 187 (1995)

[9] Pruschke, Th.: *Antiferromagnetism and Metal Insulator Transition in the Frustrated Hubbard Model,* Prog. Theo. Phys. Suppl. 160, 274 (2005)

[10] Maier, T.; Jarrell, M.; Pruschke, T. and Keller J.: *d-Wave Superconductivity in the Hubbard Model,* Phys. Rev. Lett. 85, 1524 (2000)

[11] Richter, J.; Schulenburg, J. and Honecker, A.: *Quantum Magnetism in Two Dimensions: From Semi-Classical Néel Order to Magnetic Disorder,* Springer Lecture Notes in Physics 645, 85 (2004)

[12] Kalz, A.; Honecker, A.; Fuchs, S. and Pruschke, T.: *Phase Diagram of the Ising Square Lattice with Competing Interactions,* Eur. Phys. J. B 65, 533 (2008)

[13] Zhitomirsky, M. E. and Honecker, A.: *Magnetocaloric Effect in One-Dimensional Antiferromagnets,* J. Stat. Mech.: Theor. Exp., P07012 (2004)

Kurt Schönhammer

Kurt Schönhammer, born in Munich 1946, studied physics at the TU Munich and received his Ph.D. there in 1972 under the supervision of Wilhelm Brenig. After postdoctoral periods at UC San Diego (1975-76) with H. Suhl and at the University of Pennsylvania (1976-77) with J.R. Schrieffer he finished his Habilitation 1978 at the TU Munich. A period as a staff member at the IBM research lab in Rüschlikon (Switzerland) followed. In 1979 he was appointed Associate professor at the University of Hamburg. In 1984 he accepted the offer of a full professorship at the University of Göttingen. His work is in theoretical solid-state physics. The main topic is "electronic many body effects" which were studied in fields like surface physics, mixed valent compounds and more recently in low-dimensional systems. He is presently spokesperson of the Review Board "Condensed Matter Physics" of the German Research Foundation (DFG).

Thomas Pruschke

Thomas Pruschke was born in 1959 in Berlin. He studied physics at the Technical University Darmstadt, where he received his Dr. rer. nat. in 1989. From spring 1990 until December 1991 he stayed as post-doctoral fellow of the Alexander-von-Humboldt foundation at the Tokyo Institute of Technology, followed by a second Post-Doc period from April until September 1992 at the Ohio State University in Columbus, Ohio. From fall 1992 until summer 2001 he worked as Wissenschaftlicher Assistent and Oberassistent at the University of Regensburg, where he obtained his Habilitation in 1996. In summer 2001 he became Akademischer Rat at the University of Augsburg and in September 2003 Professor for Computational Physics at the University of Göttingen. The research area is dynamics and ordering phenomena in transition metal and rare-earth compounds.

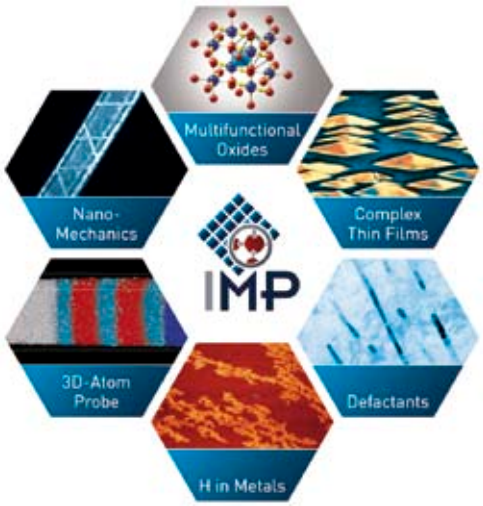
Andreas Honecker

Andreas Honecker was born in 1967 in Tübingen. He studied physics at Bonn University where he received his PhD in 1995. Post-doc stays followed at the Free University of Berlin, S.I.S.S.A. (Trieste, Italy) and the ETH Zürich. During this period his interests shifted from mathematical physics over statistical physics to theoretical condensed matter physics. He then spent several years as Wissenschaftlicher Assistent at the TU Braunschweig where he obtained his Habilitation in 2003. After short detours across invited professor positions in Hannover and in France, he has been working at the Georg-August University since January 2006. In 2007, the DFG awarded him a Heisenberg fellowship in order to support his research on correlated electronic systems and competing interactions.

Institute for Materials Physics

Understanding atomic level mechanisms in nano-scale materials

The goal of research at IMP is to understand how collective behavior emerges from the interactions of individual atoms or entities and to apply this understanding to develop new and better materials for applications such as renewable energy and information technologies. Over the years, IMP has moved from studying bulk metals, in the time of Peter Haasen, to investigating properties of nano-scale materials. Some of the actual fundamental topics involve designing properties by changing length scale, composition, and correlations, studying phase and mechanical stability at the nanoscale and controlling energy conversion and dissipation.



Teaching fundamental concepts of materials physics

IMP contributes to teaching of the general physics curricula, of specialized courses in the area of Condensed Matter and Materials Physics, and in the inter-Faculty Bachelors program in Materials Science. We supervise ca. 55 Bachelors, Diploma, and Doctoral students in cutting-edge research projects. IMP also has active trainee programs with eight lab and electronics technician apprentices. Public outreach contributes to informing the general community of important materials science issues, including developing materials and processes for a sustainable future.

Equipment and Resources

The research and teaching at IMP is made possible by modern, cutting-edge equipment and high quality technical support. Using in-situ transmission and scanning electron microscopy, the scientists at IMP are able to observe real-time processes in materials during mechanical, electrical, and optical stimulation. Atomic level chemical structure is determined using field ion microscopy and 3d atom probe. Nanoscale mechanical characterization is performed using atomic force microscopy and nanoindentation. Synthesis and nanostructuring are available through a variety of controlled thin film preparation techniques, a focused ion beam microscope and lithography. In addition, IMP houses a joint electronics and a precision machine shop.

Nanoscale Multifunctional Oxides

Metal oxide compounds reveal a broad richness of physical phenomena spanning from high-temperature superconductivity and resistance changes in external fields to new mechanisms for energy conversion in thermoelectric, photovoltaic or photocatalytic processes. The strong correlation of electronic, magnetic and atomic degrees of freedom gives rise to a novel complexity, where e.g. an electrical current can change the crystal structure or a mechanical stimulation can alter the electric resistivity. The fundamental understanding of mechanisms in multifunctional materials offers new opportunities in the development of high-efficiency devices for electronic or energy-conversion applications.

Phase transitions in external fields: Resistive switching

Several oxide materials, sandwiched by two metallic electrodes, reveal a pronounced remanent resistance change due to a short voltage pulse (Fig. 1). The electric pulse induced resistance switching effect is a typical example of a device, where atomic structure is changed by applying an external stimulation [1,2]. Such a device is a promising candidate for a new generation of non-volatile data storage systems.

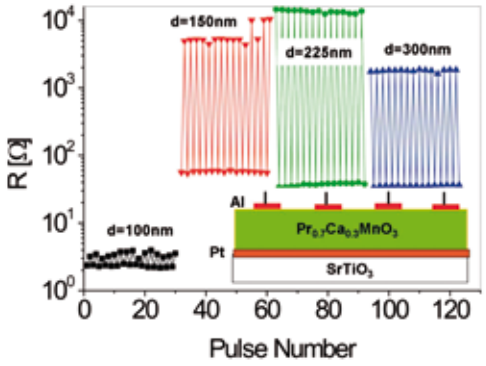


Fig. 1: Complex oxide based non-volatile memory device consisting of a $Pr_{0.7}Ca_{0.3}MnO_3$ oxide layer sandwiched by two metal electrodes. The high resistance state is present after applying a "write" pulse, the low resistance state after applying the "erase" pulse [1].

Energy conversion by correlation effects: Light harvesting in solar cells

Light harvesting using new solar cell materials has the goal to maximize the conversion of solar energy into electrical power. Some complex oxides exhibit strong light absorption with long living electron-lattice excitations. Choosing appropriate interfaces this energy can be converted into electrical energy (Fig. 2). In order to improve fundamental understanding of light matter interaction in correlated materials, light induced structural phase transitions are investigated in the framework of the SFB 602.

From atomic structure to collective behaviour: Mechanisms of atomic and electronic correlations at the nanoscale

The strong correlation between lattice and electronic degrees of freedom in complex oxides gives rise to extreme sensitivity of multifunctional properties to chemical composition, defect structure, length scale and external fields. In high-T_c superconductors, grain boundaries and dislocations segregate oxygen vacancies leading to a local superconductor-insulator phase transition [3,4,5]. Multilayer structures allow for reduction of thermal conductivity by phonon

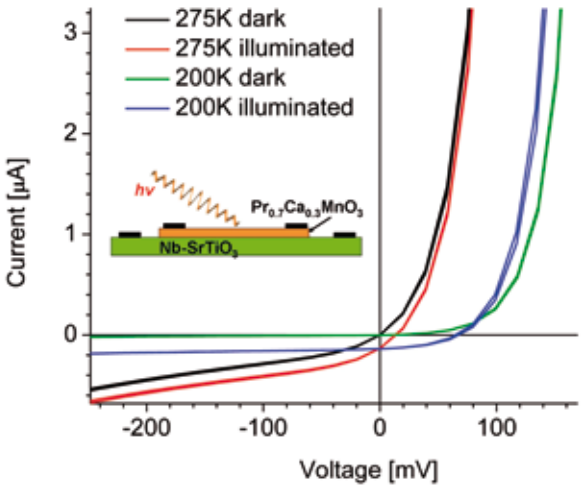


Fig. 2: Current-voltage characteristic of a Nb-$SrTiO_3$ / $Pr_{0.7}Ca_{0.3}MnO_3$ solar cell with and without illumination, converting light into electric energy (Diploma Thesis G. Saucke).

blocking; the mechanisms are investigated within the DFG SPP 1386 "Nanostructured Thermoelectrics". Study of fundamental mechanisms of energy conversion, dissipation and transport as a function of length scale and correlation has goal eliminating thermal and entropic losses and designing new nanostructured materials to control thermoelectric, photovoltaic and photocatalytic effects.

Nanoscale materials design and in-situ microscopy

Materials design of nanostructured complex oxides and interfaces is performed by artificial and self-organized patterning processes on various length scales (Fig. 3), including multilayers, nanodots, microbridges and nanocomposites. In order to determine structure property relations, we use various high-resolution analytical techniques for structure, chemical composition, magnetic properties, thermal and electric transport. A focus is in-situ microscopy (fig. 4) allowing for atomic resolution electrical, optical and photovoltaic measurements in a transmission electron microscope.

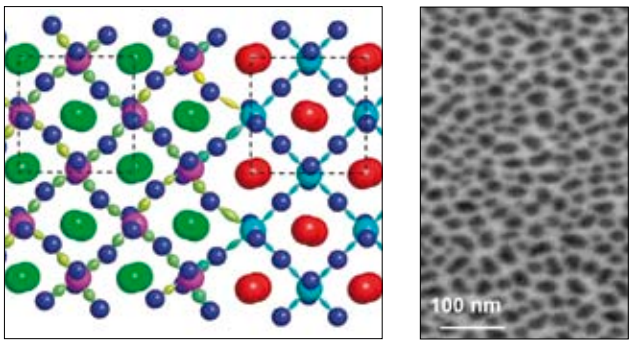


Fig. 3: Understanding phase stability at the nanoscale is important for designing nanocomposites. Left: Calculated interfacial structure of a Manganite-Titanite solar cell. Right: Self-organized multifunctional nanocomposite film composed of ferroelectric $BaTiO_3$ and ferromagnetic $CoFe_2O_4$ (Bachelor Thesis B. Jasper).

[1] *Electric pulse induced resistance change effect in manganites due to polaron localization at the metal-oxide interfacial region*, Jooss, Ch. et al. Phys. Rev. B 77 (2008) 132409.

[2] *Polaron melting and ordering as key mechanisms for colossal resistance effects in manganites,* Jooss, Ch. et al. PNAS 104 (2007) 13597.

[3] *Enhanced current transport at grain boundaries in high-T_c superconductors,* Klie, R. F. et al. Nature, 435 (2005) 475.

[4] *Direct evidence for negative grain boundary potential in Ca-doped and undoped YBaCuO,* Schofield, M. A. et al. Phys. Rev. Lett. 92 (2004) 19550.

[5] *Magneto-optical studies of current distributions in high T_c superconductors,* Jooss, Ch. et al. Rep. Prog. Phys. 65, 651, (2002)..

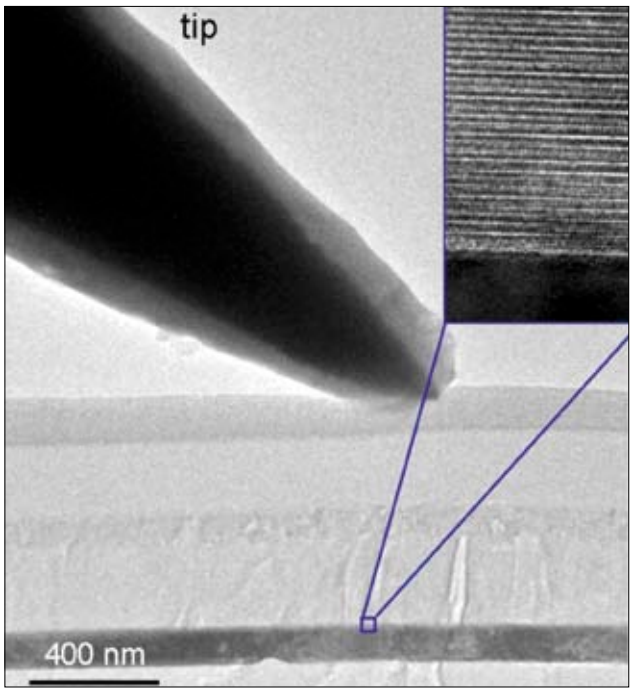


Fig. 4: Observation of a metal-oxide multilayer with a transmission electron microscope during electric stimulation by a nanotip (Ch. Jooss, J. Norpoth, Y. Zhu, unpublished).

Christian Jooß

Christian Jooß was born 1967 in Stuttgart. He performed his PhD at the Max-Planck-Institute of Metal Research, Stuttgart in the field of High-Temperature Superconductors. In 1998, he started a research group on superconducting and magnetic thin films at the Institute of Materials Physics, University of Göttingen, where he received his habilitation 2002. In 2006, he moved to Brookhaven National Laboratory to the group of Y. Zhu, where he turned his attention to in-situ Transmission Electron Microscopy. He obtained a professor position at University of Göttingen in 2008.

Defactant/Defect-Interaction

Besides total composition and average crystalline and/or amorphous structure, properties of materials are controlled by inhomogeneities of solute atoms and crystalline defects on the micro- and nanometer scale and their interaction. Namely mechanical properties are affected by the solute/defect-interaction in both a positive and negative way [1,2]. Knowing these interactions is also indispensible for the development of novel materials.

Atom probe tomography [3]

For Atom Probe Tomography (APT) tips with a radius of curvature of less than 100 nm (1 nm = 10^{-9} m) are eroded out of a sample with a focused ion beam (a few nm in diameter). With a kHz frequency high voltage pulses ionize atoms which fly to a position sensitive detector. Thus by stripping of atom by atom allows determining position and chemical nature of the atoms throughout the sample (Fig. 1). The APT activities will be continued in a newly formed group lead by Dr. Carsten Nowak.

Solute/defect interaction [4,5]

Crystalline materials are not perfect infinite lattices. Common defects are empty lattice sites (vacancies), ending lattice planes (dislocation), planes across which lattice orientation changes (grain boundaries) and the border of a finite lattice (surface). Different elements will interact differently with defects leading to an inhomogeneous distribution of solute atoms and/or changing properties. This is exemplified for hydrogen interacting with defects in steel which causes hydrogen embrittlement (Fig. 2). Miniaturization of devices leads to a high density of interfaces and defects which might interact with various available atoms (Fig. 3).

The novel defactant concept [2,4]

In liquids so-called surfactant molecules (surface acting agent) are enriched on the surface and reduce surface tension. Therefore, surface or interface areas can be enlarged with ease in the presence of surfactants. Then expanding lungs, forming foams and emulsions as well as removing dirt by washing can be achieved with less energy. The relation between surface tension, excess surfactants and their thermodynamic activity were derived by Willard Gibbs a long time ago. But only recently [2,4,5] this relation was generalized to include all kinds of crystalline defects of solid. Thus the enrichment of so-called defactants (defect acting agent) at defects including the surface reduces the defect formation energy. Many phenomena of solute/defect-interaction will be understood in a novel way by the defactant concept [2,4,5].

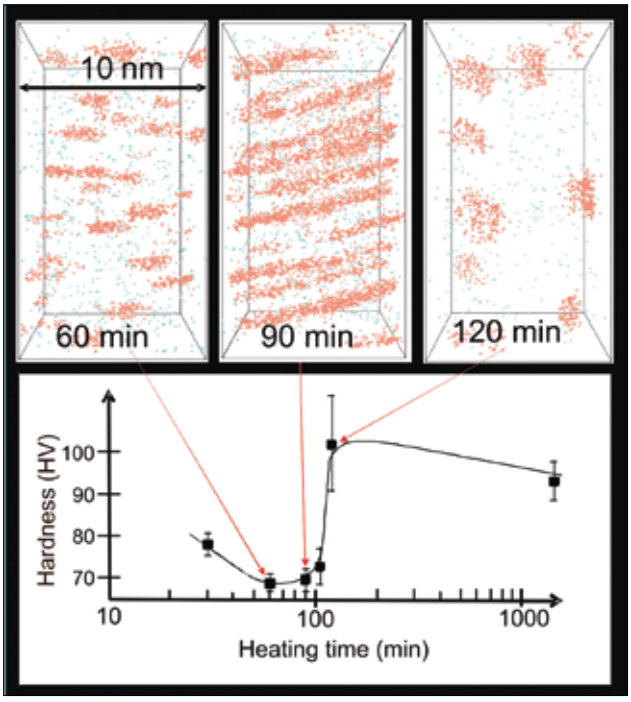


Fig. 1: Positions of cobalt-atoms (red and blue dots) in a copper alloy after heating at 490 °C for the times given. Initially the Co-atoms were distributed homogeneously. After 60 min some of the Co-atoms marked in red agglomerate or precipitate, respectively. At 90 min the Co-precipitates have a rod like shape shrinking to more spherical agglomerates at later annealing times. The precipitates are obstacles for the motion of dislocations, which are defects of the crystalline lattice being responsible for the pronounced ductility of metals. The more the movement of dislocations is hindered the harder a material becomes. The measured hardness of the copper alloy at various annealing times reveals that rod-shaped precipitates are less effective than spherical ones.

[1] Pundt, A.; Kirchheim, R.: *Annual Review of Materials Research,* 36, 2006, 555-608

[2] Kirchheim, R.: *Int. J. of Materials Research,* 100, 2009, 483-488

[3] Ene, C. B.; Schmitz, G.; Kirchheim, R.; Hütten, A.: *Acta Materialia,* 53, 2005, 3383-3393

[4] Kirchheim, R.: *Acta Materialia,* 55, 2007, 5129-5138 and 5139-5148

[5] Kirchheim, R.: *Solid solutions of hydrogen in complex materials,* In Solid State Physics, eds. H. Ehrenreich and F. Spaepen, Elsevier, Amsterdam Vol. 59, 2004, 203-305

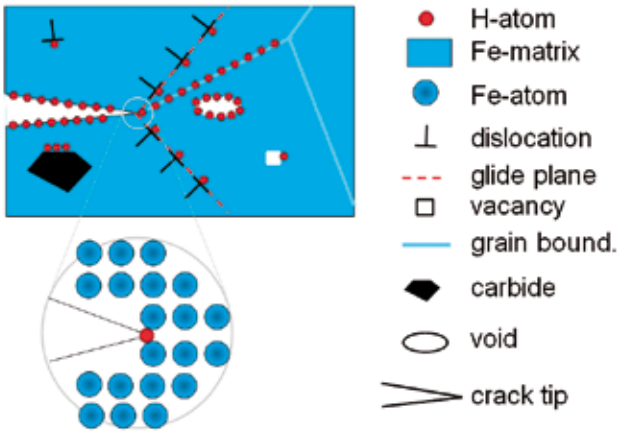


Fig. 2: Hydrogen embrittlement of steels is a severe unsolved problem for a coming hydrogen technology. The vicious phenomenon is interpreted in a variety of different ways: Fracture and plastic deformation of steels (iron carbon alloy) are all affected by hydrogen atoms. Crack propagation during fracture may be enhanced by H-atoms loosening Fe-bonds (magnified version of the crack tip) which also cause cracks to run along grain boundaries covered with hydrogen. H-atoms at carbide/iron-interfaces may initiate crack formation. In addition, the defactant concept (described in the text and in [2,4]) states that formation of all defects becomes easier in the presence of excess hydrogen. Thus excess hydrogen (i) at the newly formed surfaces of a crack decreases its formation energy, (ii) at dislocations decreases their formation and migration energy and allows crack propagation by dislocation emmission, (iii) at vacancies decreases their formation energy and leads to a concomitant increase of their concentration which enhances void formation in front of the crack tip. Dislocation emission at the crack tip and along the glide planes moves extra half planes of the crystal lattice away and thus leads to crack propagation. This is also achieved by the connection of the crack tip with a void.

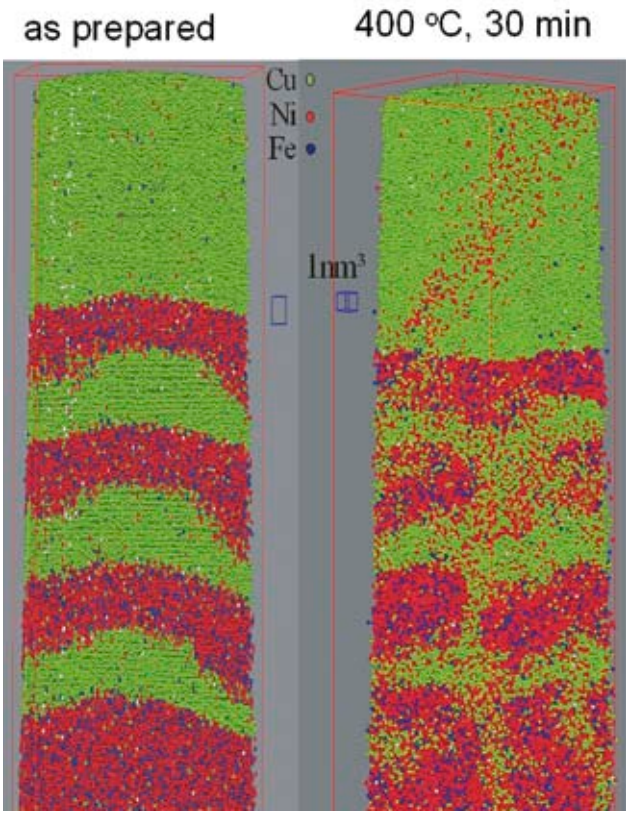


Fig. 3: Atom Probe Tomography revealing the position of copper- (green), nickel- (red) and iron-atoms (blue) in a stack of copper and permalloy layers [3]. After preparation (left picture) the layers are bend because they were deposited on a curved tungsten tip. Permalloy consists of 75% nickel and 25% iron and the magnetic interaction between the ferromagnetic permalloy layers and the non-magnetic copper changes the electrical resistivity of the stack. This effect called Giant Magnetic Resistance (GMR) is applied for sensing magnetic fields and its discovery lead to the Nobel Prize in Physics for Peter Grünberg and Albert Fert. At higher temperature the GMR-effect vanishes because the atoms start to intermix in an inhomogeneous way along grain boundaries (right picture).

Reiner Kirchheim

Reiner Kirchheim was born in 1943 in Halle/Saale. He studied physics at the University of Stuttgart and conducted his diploma, thesis and habilitation work devoted to the physicochemical behavior of solutes in metals, transport phenomena and passivity of metals at the MPI for Metals Research in Stuttgart. This period was interrupted by extended stays at Rice-University, University of Illinois and Ohio State University. In 1993 Reiner Kirchheim accepted an offer from the Georg-August-University becoming the director of the Institute for Metal Physics. He extended his studies including the behavior of hydrogen in metals with reduced dimensions and the interaction of solute atoms with defects. He also set-up an Atom Probe Tomography Lab studying solute segregation, precipitation and interdiffusion on the atomic scale. Since 2009 he is continuing his work as a Professor of Lower Saxony focusing on the defactant concept.

Complex Laser Deposited Thin Films

New complex thin films consisting of different materials or even different material classes are of high interest for today´s technical applications and offer new properties due to the combination of the specific properties of the constituents. For the preparation of complex films, we use the versatile pulsed laser deposition (PLD) technique allowing us to deposit almost all kinds of materials. This is very helpful for the development of novel materials and complex material combinations with properties adjusted by the micro¬structure. Our research is supported by the DFG in SFB602, SFB755, and GK782.

Pulsed laser deposition (PLD)

Pulsed laser deposition (PLD) is a powerful and flexible thin film technique to grow complex perovskite structures, all kinds of oxides, carbides, nitrides, metals, and even polymers [1-3]. During the PLD process, a stoichiometry transfer between target and substrate exists, high deposition rates are obtained, and the particles ablated from the targets can possess kinetic energies of up to 100 eV.

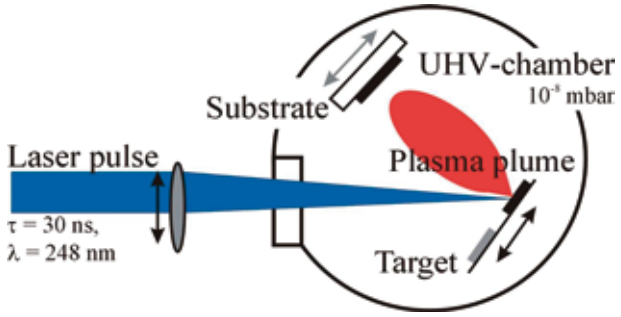


Fig. 1: Pulsed laser deposition (schematically).

Better understanding of the PLD processes

In order to control the film microstructure and properties, it is important to understand the atomic processes occurring during ablation from the target and deposition on the substrate surface. They depend on the used material class and are still very much under discussion. But also the film properties, which often are far from equilibrium, are strongly influenced by the laser parameters (for instance wavelength and fluence). In addition, also a background pressure within the vacuum chamber can be used to systematically reduce and tune the kinetic energy of the deposited particles due to collision of the ablated particles with the gas atoms.

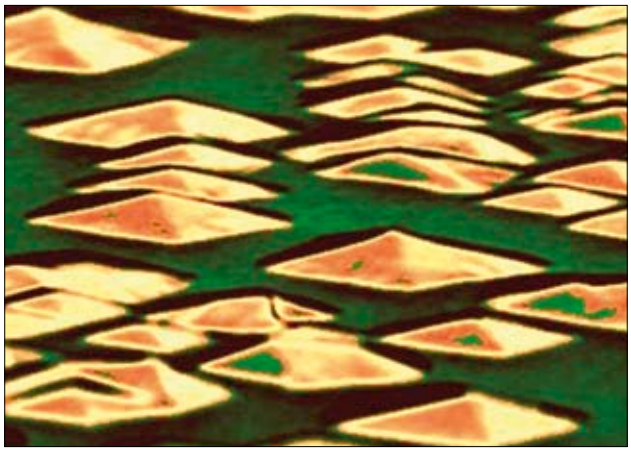


Fig. 2: Epitaxial growth of µm-sized triangular pyramides on Si(111).

Characterization of the thin films

For characterization of the film properties, a broad variety of methods is used, as electron microscopy (SEM, TEM), X-ray diffraction (XRD, XRR), scanning force microscopy (AFM), infrared spectroscopy (FTIR), mechanical spectroscopy and indentation, ... One goal is to understand the growth processes at the substrate surface, the kinetics on an atomic scale, and the dependence of the properties on the preparation conditions. This is especially important, because films can be formed with different structures and morphologies, amorphous or nanocrystalline with statistic grain orientation, textured or epitaxially, depending on the growth parameters.

Actual systems

A variety of more or less complex systems are of interest: pure metals, supersaturated alloys, oxides, polymers, polymer-metal composites, and metal-metal as well as ceramics-metal multilayers. An example for an epitaxial growth of a pure metal is shown in Fig. 2, where µm-sized triangular

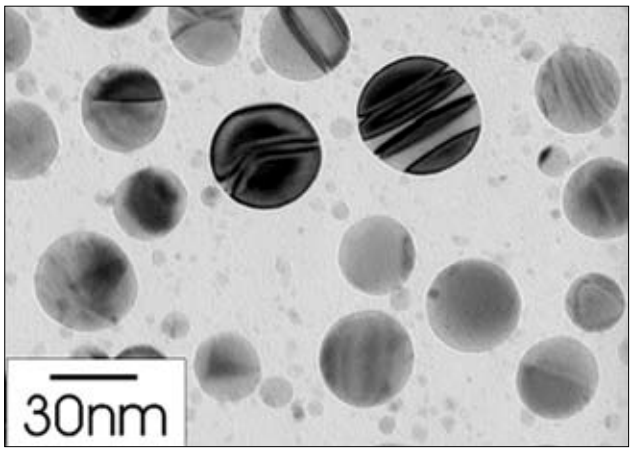


Fig. 3: Electron micrograph of Ag clusters embedded in poly (methyl methacrylate).

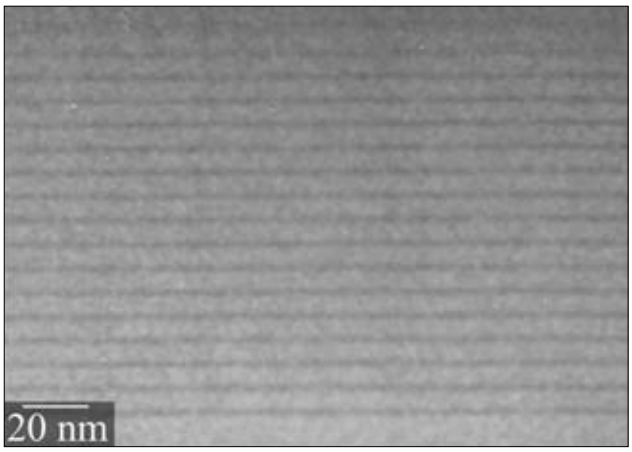


Fig. 4: Cross-section electron microscopy (TEM) of anoxide-metal multilayer.

Cu-pyramides are formed on a Si(111)-substrate. In the case of polymers, thin poly(methyl methacrylate) or polycarbonate films are investigated. Especially the frequency dependent atomic processes within the polymer are of interest, but also relaxation processes, the changes of the mechanical hardness with temperature or ultraviolet-radiation. Composites of polymers with embedded metals (see fig. 3) are studied, because in such a nanocomposite the elastic properties of the polymer are combined with special optical and mechanical properties of the metal clusters, which are strongly size dependent. Using PLD, the size of the metal clusters can be tuned by the number of laser pulses.

Another aim is to develop specially designed multilayer structures for applications. For instance, new ceramics-metal multilayers for X-ray mirrors in the so-called „water window" (wavelenghts between 2.3 nm and 4.4 nm) are grown by PLD (see Fig. 4). Soft X-ray microscopy using such mirrors is of large interest in biological science or polymer and colloid research.

[1] Fähler, S. and Krebs, H.-U.: *Calculations and experiments of material removal and kinetic energy during pulsed laser ablation of metals,* Appl. Surf. Sci. 96-98 (1996) 61.

[2] Krebs, H.-U. et al.: *Pulsed laser deposition (PLD) – a versatile thin film technique,* Adv. in Solid State Phys. 43 (2003) 505.

[3] Krebs, H.-U.: *Pulsed laser deposition of metals", chapter 16 in „Pulsed laser deposition,* R. Eason, ed., (Wiley 2007), 363-382.

Hans-Ulrich Krebs

Hans-Ulrich Krebs was born 1955 in Wertheim. After study of physics at the Universities of Würzburg and Göttingen, he performed his PhD at the Institute of Metal Physics, Göttingen, in the field of amorphous metallic glasses in 1984. During 1986 he was post-doc at the Stanford University in California, USA. After that he studied high temperature superconductors and metallic systems. In 1993 he got his habilitation in metal physics at Göttingen University on "Characteristic properties of laser deposited metallic systems". In 1998, he became Apl.-Professor at the University of Göttingen. His research topics are now the design of the microstructures and properties of complex films by controlling and tuning the growth processes.

Thermodynamics and Kinetics of Nanoscale Systems – H in Metals

Hydrogen as the smallest atom can be easily and fast absorbed in many metals, enabling storage and transport of electrical energy in the metal-hydrogen (M-H) systems. By changing length scale, geometry and chemistry, the systems' properties can be tuned and optimized for storage applications. Thermodynamic and kinetic properties of M-H thin films, multi layers and clusters are one research focus of the group. These M-H systems can also be used as model systems to study general material properties like phase stabilities or defect generation evolving on the nanoscale. Further, hydrogen influences the host metal by creating defects, changing the defect mobility and generating mechanical stress. The stability of such systems is a second research focus of the group.

Thermodynamics of M-H thin films and clusters

With regard to lattice structure, defect types and the mechanical stiffness of the stabilizer, chemical potentials and other thermodynamic properties of model M-H systems are studied. We have demonstrated the strong impact of the stabilizer/substrate on thin films and clusters properties, resulting from mechanical stress of several GPa.[1] Mechanical stress affects solubility limits as well as chemical potentials. [2,3] Nano-systems stabilized with low mechanical stress, behave more bulk-like.

Below a critical size, M-H clusters possess different lattice structures compared to bulk, affecting the H solubility. Vice versa, H solution affects the stability of these nano-scale structures. [4] The knowledge of property changes with size reduction is essential for the nano-design of materials.

System morphologies

Hydrogen absorption results in lattice expansion, depending on H concentration, local chemistry, substrate bonding and the nano-systems morphology. The expansion effect can be used to interconnect separated clusters at desired threshold pressures. At the percolation limit strong effects on the electrical conductance are expected, making such systems interesting for sensor applications. [5]

Monitoring the systems surface with scanning probe microscopy shows the development and lateral distribution of phases during hydrogen absorption and phase transformation on the local scale.[6]

Below a critical system size, the interplay of defect and strain energy results in coherent phase transformations, affecting the energy conversion in the system.

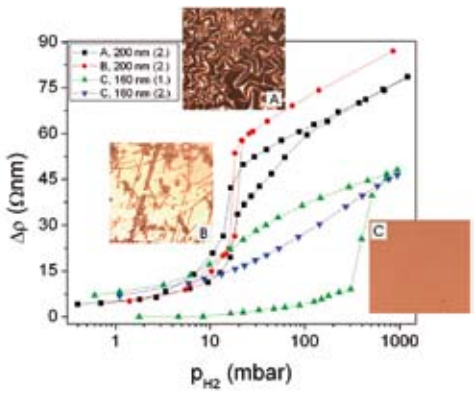


Fig. 1: Isotherms of Pd-Fe thin films of similar micro structure are strongly affected by the substrate: quasi-free films behave more bulk-like. (S. Wagner,[3])

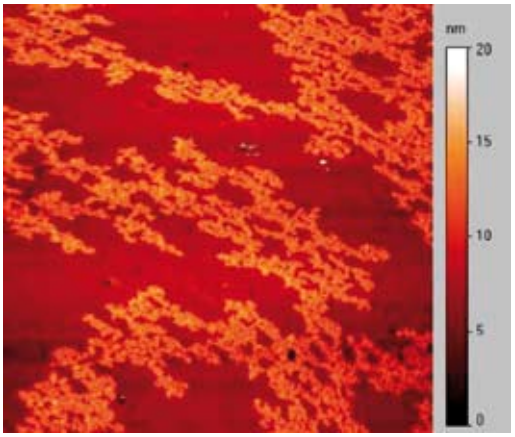
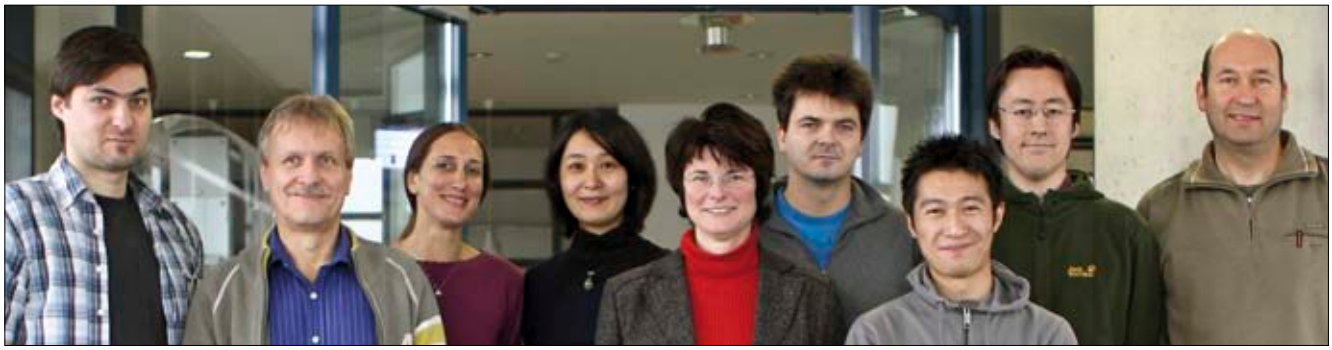


Fig. 2: Scanning tunnelling microscopy surface topography of a 70 nm Nb-H thin film at $5 \cdot 10^{-4}$ Pa (10 µm x 10 µm). Hydride phase volumes in the film (bright) elevate the surface topography by about 5 nm above the original base level (dark).(K. Nörthemann,[6])



Microstructural effects: surfaces, interfaces and defects

The matrix' chemistry strongly affects the H solubility. As one of the first groups worldwide we successfully study the local H distribution and matrix chemistry with the 3D Atom Probe on the atomic scale. This is of special interest at material interfaces, where effects of intermixing suppress or enhance hydrogen solubility. [7]

The impact of hydrogen on vacancy formation as well as dislocation generation and mobility is a further point of interest of the group. It is linked to hydrogen embrittlement of materials.

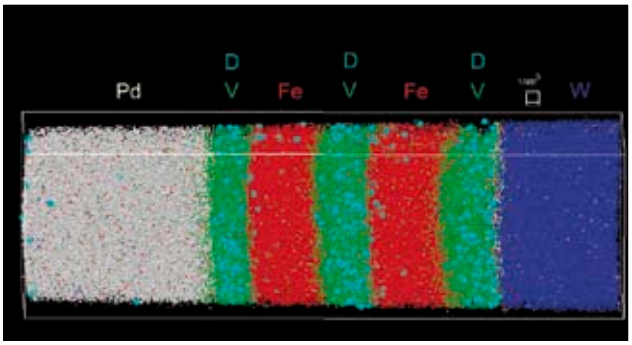


Fig. 3: 3-d Atom Probe measurement of the local deuterium, Fe and V distribution in a thin film package. Reconstructed volume of 14nm x 14nm x 51nm. (R. Gemma,[7])

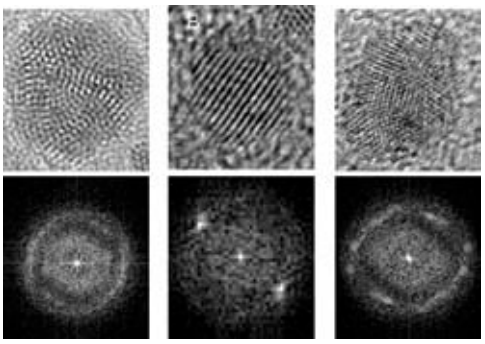


Fig. 4: HREM of 3.6 nm Pd clusters, showing different structures. (A) icosahedral, (B) cubic, (C) multi-twinned. The bottom line shows FFT images of the clusters after removing the background. (M. Shtaya, [4])

[1] *Hydrogen in nano-sized metals* (Review), Pundt, A.; Adv. Engin. Mat. 6 (2004) 11.

[2] *Hydrogen in metals: microstructural aspects,* Pundt, A.; Kirchheim, R., Annual Review Materials Research 36 (2006) 555.

[3] *Mechanical stress impact on thin Pd1-xFex -films thermodynamic properties,* Wagner, S.; Pundt, A., Appl. Phys. Lett. 92 (2008) 051914.

[4] *Evidence for cuboctahedral-to icosahedral transition of quasi-free Pd-H clusters controlled by the hydrogen content,* Pundt, A. et al., Eur. Phys. J D 19 (2002) 333.

[5] *Conduction mechanisms during the growth of Pd thin films: Experiment and model,* Wagner, S.; Pundt, A., Phys. Rev. B 78 (2008) 155131.

[6] *Coherent-to-semi-coherent transition of precipitates in niobium hydrogen thin films,* Nörthemann, K.; Pundt, A., Phys. Rev. B 78 (2008) 014105.

[7] *APT analyses of deuterium-loaded Fe/V multi-layered films,* Gemma, R. et al., Ultramiocroscopy 109 (2009) 631.

Astrid Pundt

Astrid Pundt was born in 1966 in Braunschweig. She studied physics at the Technical University of Braunschweig and graduated 1991 in the group of Prof. J. Hesse at the institute of metal physics and nuclear solid state physics with Mössbauerspectroscopy of thin amorphous films. She continued her doctoral studies at the institute of metal physics in Göttingen with Prof. Haasen, especially by performing Field ion microscopical studies and thermodynamical calculations on thin magnetic films. In strong collaboration with Prof. Kirchheim she started focussing on hydrogen in metals. 1996 she build up a research group that studies the properties of nano-sized M-H systems, thin films, multi-layers and clusters. In this field she obtained her habilitation in 2001. In 2008 she achieved the apl-professorship at the University of Göttingen. Starting in March 2010, she will be supported by a Heisenberg-Fellowship of the Deutsche Forschungsgemeinschaft. Astrid Pundt is married and has two young children.

Nano-mechanics

The mechanical response of nanoscale materials is dramatically different from that of bulk materials due to length scale constraints on the evolution of the defect structures responsible for deformation. A variety of different nanoscale model systems are being investigated using in-situ electron microscopy and micro-mechanical testing methods, with the goal of revealing the underlying principles controlling the emergence of collective behaviour of defects in mechanically driven systems. Size effects in mechanical behaviour can be used to great advantage in designing materials with optimal reliability or mechanical integrity, and are the basis for the high performance of many technological and natural materials.

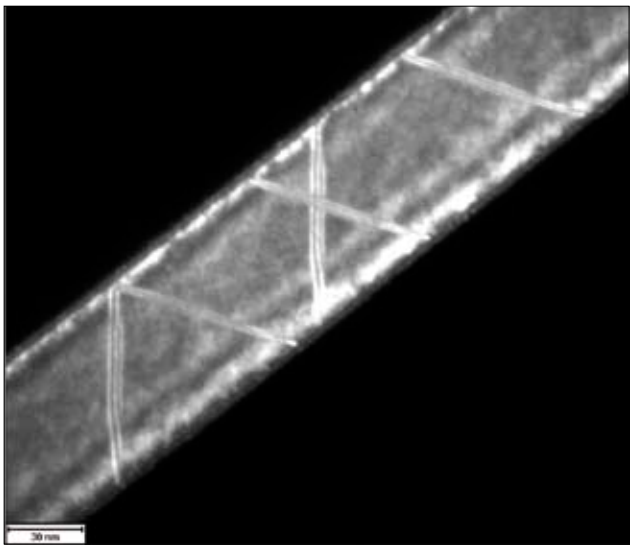


Fig. 1: Transmission electron microscope image of stacking faults in a 70 nm diameter Au nanowire during in-situ tensile testing. [B. Roos, C.A. Volkert, G. Richter, unpublished].

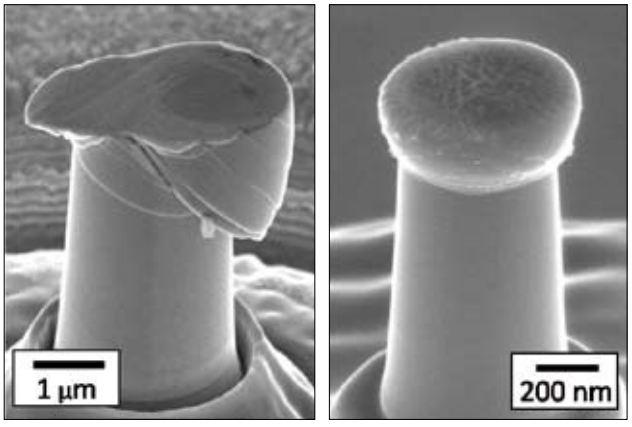


Fig. 2: Morphologies of compressed amorphous PdSi columns showing a size-dependent difference in deformation mechanism between a 2 µm diameter (left) and a 500 nm diameter column (right) [3]

Evolution from local to global excitations

Deformation in solids proceeds by the collective activation of defect structures. Since defects interact strongly with interfaces and surfaces, the deformation mechanisms depend on sample size, even at length scales much larger than the interaction distances of individual defects. Using specially designed testing methods [1], the evolution of defect structures can be investigated. For example, in-situ TEM testing of nanowires [2] allows a rare glimpse into the behaviour of dislocations in highly loaded systems (Fig. 1). Similarly, SEM studies reveal the effect of sample size on deformation mechanisms in amorphous metals (Fig. 2). Model systems including nanowires, nanoparticles, sub-micrometer columns, and thin films of polymers, oxides, and metals are currently being investigated.

Stability at the nanoscale

The effect of length scale and interfaces on stability and mechanical integrity is being investigated in cyclically loaded systems. Examples include the formation of dislocation structures in fatigued metal films and multilayers. In addition, atomic-level chemical changes due to cyclic chemical, mechanical, and electrical loading of nanoporous battery and fuel cell electrodes are being investigated in collaboration with the 3d atom probe group (Dr. Carsten Nowak).

Designing properties by changing length scale

Mechanical properties such as ductility and strength depend on the sample size (Fig. 4). This allows length scale to be used as a means of tailoring properties in composite materials – in addition to the usual approach of varying composition and composite geometry. Thus, the film thickness in metal-polymer and amorphous-crystalline metal multilayer samples or the ligament diameter in foams such as nanoporous Au (with and without infiltrated polymer) or the particle size in granular materials can be used to optimize stability and strength.

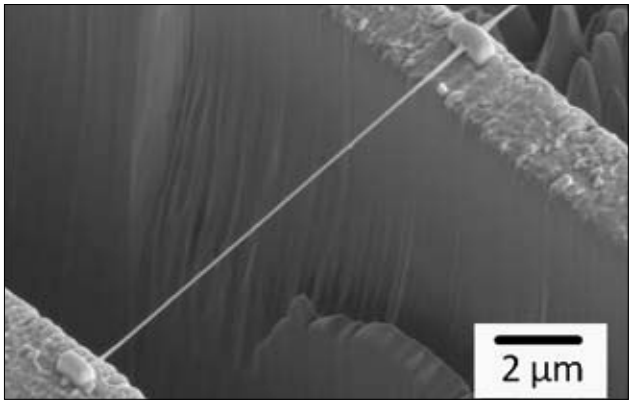


Fig. 3: 100 nm diameter Au nanowire mounted in place for tensile testing in the scanning electron microscope.

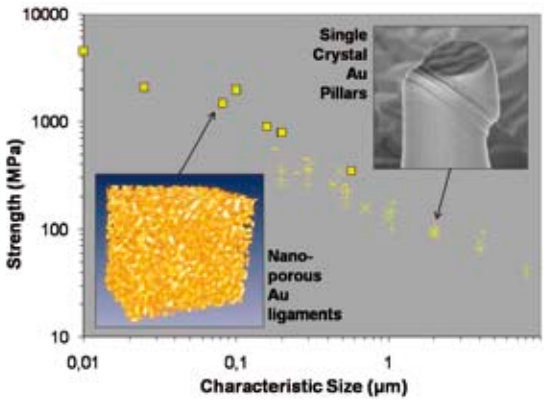


Fig. 4: Strength vs size for Au [4,5]. The strengths approach theoretical values at small sizes, due to the inhibition of dislocation activity as size is decreased.

Understanding atomic mechanisms for energy dissipation

The elastic energy stored in materials during mechanical loading is eventually dissipated in irreversible deformation. Just how and when the energy is converted into the collective activation of defects depends on many material properties including the phonon spectra, thermal diffusivity, and detailed chemical structure. These correlations are being studied using AFM and nanoindenter investigations of local energy dissipation in nanostructured metals and oxides, as well as in thermoelectric materials. Such studies should eventually help us to understand energy dissipation at the atomic level and to design better materials for sustainable energy technologies and the environment.

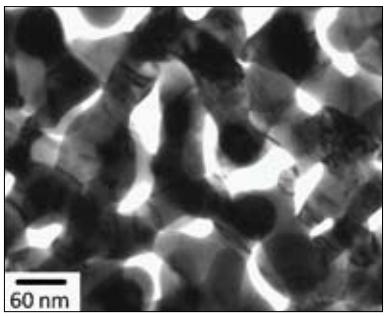


Fig. 5: Stacking faults in deformed nanoporous Au.

1. Volkert, C. A.; Minor, A. M.: *Focused Ion Beam Microscopy and Micromachining,* MRS Bulletin 32 (2007) 389.
2. Richter, G.; Hillerich, K.; Gianola, D. S.; Mönig, R.; Kraft, O.; Volkert, C. A.: *Ultrahigh Strength Single Crystalline Nanowhiskers Grown by Physical Vapor Deposition,* Nano Letters 9 (2009) 3048.
3. Volkert, C. A.; Donohue, A.; Spaepen, F.: *Effect of sample size on deformation in amorphous metals,* J. Appl. Phys. 103 (2008) 083539.
4. Volkert, C. A.; Lilleodden, E. T.: *Size effects in the deformation of sub-micron Au columns,* Phil. Mag. 86 (2006) 5567.
5. Volkert, C. A., Lilleodden, E. T.; Kramer, D.; Weissmüller, J.: *Approaching the theoretical strength in nanoporous Au,* Appl. Phys. Lett. 89 (2006) 061920.

Cynthia A. Volkert

Cynthia A. Volkert was born in the USA in 1960. She studied physics at McGill University in Montreal, Canada and at Harvard University in Cambridge, Massachusetts. She then spent 10 years working at Bell Labs in New Jersey on problems of ion-solid interactions, mechanical behavior of thin films, electromigration, and thermal diffusion before moving to Germany. Cynthia went first to the Max-Planck-Institute for Metal Research in Stuttgart and then to the Institute for Materials Research-II in Karlsruhe where she studied grain growth, mechanical behaviour, and atomic transport in metal films and small structures, primarily using in-situ methods. She joined the University of Göttingen as a professor in 2007, where she continues her research in nanoscale materials and in-situ electron microscopy.


METALLICA

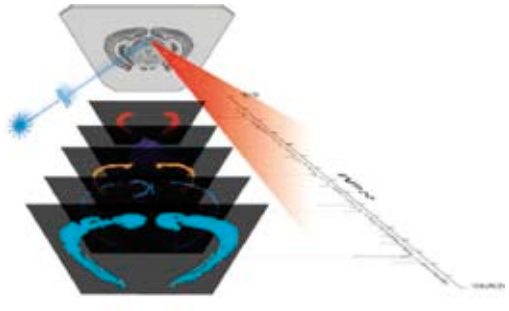
SFB 755: Nanoscale Photonic Imaging

The central research goal of the SFB 755 is the visualization of macromolecular assemblies and their kinetics at the nanoscale under the relevant environmental conditions. The collaborative research centre comprises projects using visible light, EUV/XUV, soft x-ray and hard x-ray photons. The combination of spectroscopy and microscopy leads to spectromicroscopy, which can be used to unravel the structure, composition, and dynamics of complex matter such as building blocks of life. Nanoscale Photonic Imaging has the goal to push the limits of imaging and spectroscopy significantly beyond the current capabilities, resolving structures and dynamics in space and time on the nanometer scale and on timescales ranging over many orders of magnitude. Apart from the university institutes the following institutes are also members of the SFB 755: the Max Planck Institute for Dynamics and Self-Organization and the Laser-Laboratorium GmbH Göttingen.

Area A: Visible light beyond limits

Area A is devoted to the development of high-resolution methods using visible light and their application to complex fluids and cells:

- *Fluorescence microscopy with <50nm 3D resolution (Dr. Alexander Egner, Prof. Dr. Stefan W. Hell)*
- *Nanoparticle tracking with heterodyne spectroscopy (Prof. Dr. Rainer G. Ulbrich, Dr. Martin Wenderoth)*
- *High-resolution stress-field mapping in complex fluids and biological cells (Prof. Dr. Christoph F. Schmidt)*
- *Data driven image selection for photonic count data (Prof. Dr. Axel Munk)*
- *Nanoscale dynamics of individual protein and peptides (Prof Dr. Jörg Enderlein)*



Area B: Spectromicroscopy of complex fluids

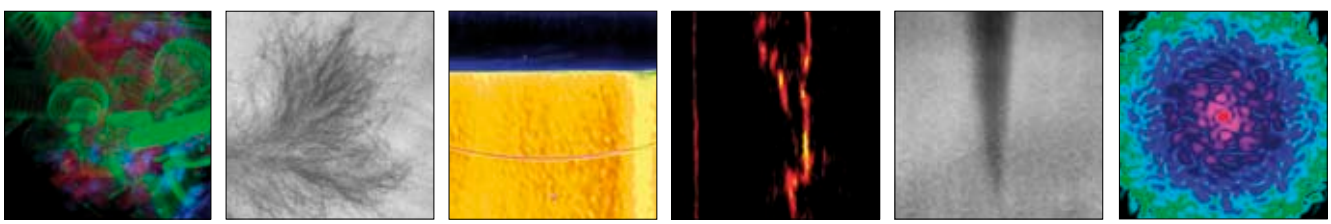
Area B is devoted to the application of spectro-microscopic and time-resolved studies of complex fluid systems which are highly relevant for contemporary scientific problems.

- *Imaging the self assembly of matrix proteins by scanning x-ray micro-and nanodiffraction (Dr. Thomas Pfohl, Prof. Dr. Stephan Herminghaus)*
- *Kinetics, intermediates, and mechanisms of the aggregation of amyloid protein systems (Prof. Dr. Bernd Abel)*
- *Time-resolved spectroscopy and x-ray diffraction of self-organising systems (PD Dr. Simone A. Techert)*
- *Interaction of short X-ray pulses with biomolecules (Prof. Dr. Helmut Grubmüller)*
- *X-ray spectromicroscopy of biomolecular matter in the environment (Dr. Jürgen Thieme)*
- *Dynamics of intermediate filament self-assembly (Prof. Dr. Sarah Köster)*

Area C: X-ray optics and imaging

Area C is devoted to x-ray optics and imaging and the corresponding proof-of-principle experiments.

- *Holographic microscopy based on x-ray waveguides (Prof. Dr. Tim Salditt)*
- *Inverse scattering problems without phase (Prof. Dr. Rainer Kress)*
- *X-ray optics using foams in microsystems (Dr. Ralf Seemann, Dr. Christian Bahr, Prof. Dr. Stephan Herminghaus)*
- *Waveguides and multilayer mirrors for laboratory-scale soft x-ray sources (Prof. Dr. Hans-Ulrich Krebs, Dr. Klaus Mann)*
- *Optimized focussing of hard X-ray beams by nanostructures (Prof. Dr. Thorsten Hohage, Prof. Dr. Tim Salditt)*
- *Nanoscale mass-spectrometric imaging (Prof. Dr. Bernd Abel, Dr. Klaus Mann)*



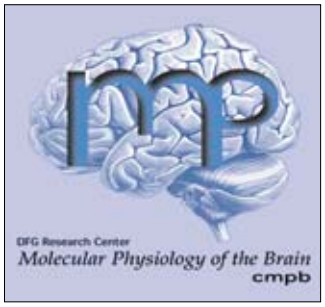
Molecular Physiology of the Brain and Microscopy at the Nanometer Range (CMPB)

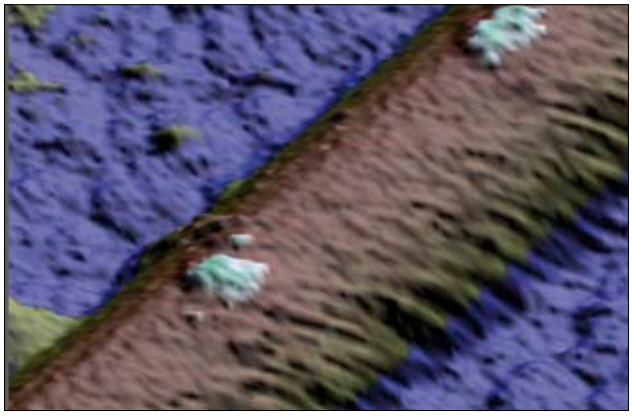
The human brain is probably the most complex structure that nature has ever produced. One hundred billion neurons and ten times as many glia cells make up a complex network that accomplishes extraordinary tasks, such as sensation, learning and memory. These functions are ultimately performed by interacting biomolecules. The Center for Molecular Physiology of the Brain (CMPB) is a multidisciplinary and multi-institutional DFG Research Center in Göttingen, extended to a Cluster of Excellence by the program "Microscopy at the Nanometer Range". It pursues a broad research program striving to link molecular mechanisms to system function, with the ultimate goal of applying the findings to the diagnosis and therapy of neuronal diseases.

The observation of molecular processes within cells is only possible when conventional resolution limits are broken. The Cluster of Excellence is build arround innovative technological developments such as super-resolution STED microscopy, atomic-force microscopy, X-ray microscopy and new methods of nuclear magnetic resonance spectroscopy and applications of these techniques to neurophysiological problems.

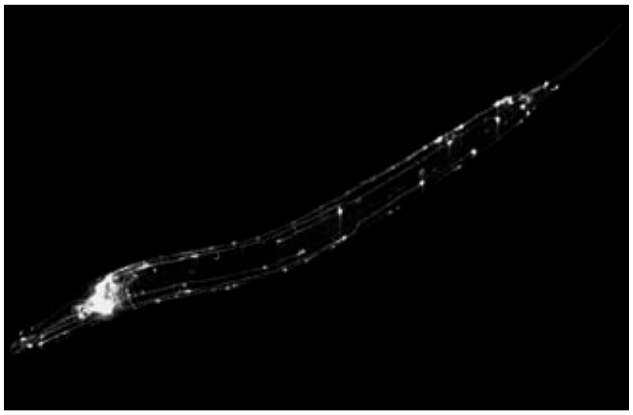
Participating institutions are the Medical School and the Faculties of Physics and Biology of the Georg August University, the German Primate Center, and the Max Planck Institutes for Biophysical Chemistry and for Experimental Medicine.

Participating groups in the Faculty of Physics are: C. Schmidt, D. Klopfenstein, I. Schaap (Biophysics), T. Salditt (X-ray physics).

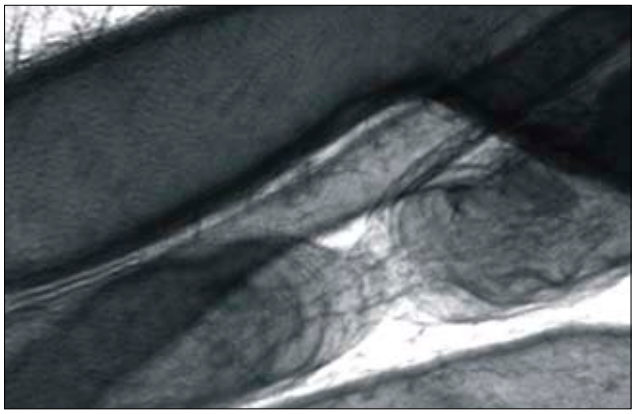




Molecular resolution in physiological conditions can be achieved by atomic force microscopy. The image is a still frame from a movie of two kinesin motors of about 8 nm size moving along a microtubule.



Molecular motors lighting up the nervous system of the worm C. elegans. The Kinesin-3 motor is responsible for presynaptic vesicle transport in neurons. The motor has been labelled with the "green fluorescent protein" appearing as bright spots in axons and synapses.



Transmission X-ray micrograph showing a myelinated axon (nerve fiber) fiber prepared. The interior structure of the node of Ranvier is visualized in x-ray absorption contrast. From a set of projection images The full 3D structure is retrieved by tomographic reconstruction.

Bernstein Center for Computational Neuroscience (BCCN) Göttingen

Coordinator

Prof. Dr. Theo Geisel
Max Planck Institute for Dynamics and Self-Organization,
Institute of Nonlinear Dynamics, Georg-August-Universität Göttingen

The Bernstein Center for Computational Neuroscience (BCCN) Göttingen founded to advance Theoretical Neurophysics focuses on the adaptivity of the nervous system ranging from the level of single synapses to the level of cognitive processes. The brain's capability of allocating resources adaptively, i.e. flexibly and adequately, is one of the reasons why neuronal information processing is extremely swift and accurate.

What are the mechanisms underlying this adaptivity? What role do synaptic dynamics play in the flexible encoding of sensory stimuli? What are the mechanisms which assign neuronal resources to specific cognitive tasks through selective attention? These are examples of problems whose solutions require mathematical modelling and computer simulations in combination with sophisticated experimental methods.

In the BCCN Göttingen, research groups from three faculties of the University of Göttingen (Physics, Biology, and Medicine), the Max Planck Institute for Dynamics and Self-Organization, the Max Planck Institute for Biophysical Chemistry, the Max Planck Institute for Experimental Medicine, the German Primate Center, and the research lab of Otto Bock HealthCare GmbH collaborate in joint projects applying a wide range of modern experimental and theoretical methods. The work achieved at the BCCN will also contribute to the scientific foundations of future applications in neuroprosthetics.

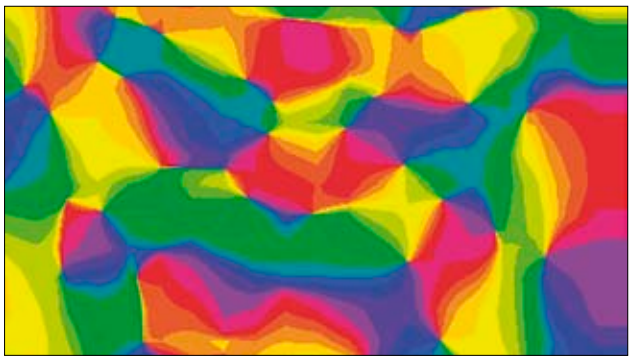


Fig. 1: Pattern of contour-detecting neurons in the cerebral cortex (live imaged in an intact brain). Colours encode the angle of visual contours that is most strongly activating neurons at a given position. The brain circuits underlying this pattern are formed by elementary learning mechanisms as the animal learns to see. It encompasses several million nerve cells in an area of 20 mm². This system is a paradigmatic model of a cooperative and adaptive neuronal processing architecture accessible to precision measurements in living brains as well as to quantitative mathematical modelling.

Participating Institutions and Members

J. Enderlein, T. Geisel, R. Kree, U. Parlitz, C. Schmidt, F. Wörgötter, A. Zippelius, Faculty of Physics, University of Göttingen

A. Fiala, H. Gibbons, M. Göpfert, M. Hasselhorn, T. Rammsayer, S. Treue, Faculty of Biology, University of Göttingen

M. Dutschmann, B. Keller, T. Moser, M. Müller, W. Paulus, D. Schild, Medical School, University of Göttingen

E. Bodenschatz, T. Geisel, M. Herrmann, S. Luther, M. Timme, F. Wolf, Max Planck Institute for Dynamics and Self-Organization, Göttingen

J. Frahm, E. Neher, Max Planck Institute for Biophysical Chemistry, Göttingen

W. Stühmer, Max Planck Institute for Experimental Medicine, Göttingen

A. Gail, H. Scherberger, S. Treue, German Primate Center

L. Mosler, Otto Bock HealthCare GmbH

Contact

Bernstein Center for Computational Neuroscience
Bunsenstrasse 10
D-37073 Göttingen
Tel.: + 49 (0) 551 5176-401
Fax: + 49 (0) 551 5176-402
geisel@ds.mpg.de
contact@bccn-goettingen.de

Bernstein Focus Neurotechnology (BFNT) Göttingen

Coordinator

Prof. Dr. Florentin Wörgötter
Georg-August-Universität Göttingen

The Bernstein Focus Neurotechnology (BFNT) in Göttingen focuses on the investigation and design of Neuro-Bionic Closed-Loop Systems. In a Neuro-Bionic Closed-Loop System biological and technical components are functionally tightly linked to form a control loop where a neuronal system influences a technical device, which in turn provides feedback to the neuronal system. Such systems require the extraction and analysis of neuronal activity, by which the device is adaptively controlled, and the generation of appropriate stimulation signals for neural control.

In the Bernstein Focus Neurotechnology (BFNT) Göttingen, engineers and theoreticians with a long-standing involvement in neuroscience collaborate with advanced experimental groups in order to investigate and design complete Neuro-Bionic Closed-Loop Systems, neuro-sensing and neuro-stimulation strategies. The research focus includes theoretical research groups based in the faculty of Physics of the Georg-August-University Göttingen, and the Max Planck Institute for Dynamics and Self-Organization, as well as experimental groups from the faculties of Medicine and Biology of the Georg-August-University Göttingen, the Max Planck Institute for Biophysical Chemistry, the Max Planck Institute for Experimental Medicine, the German Primate Center, the Hannover Medical School, and the Max Planck Institute for Biophysics in Frankfurt. Moreover, active collaboration with industrial partners further defines the scientific and technological core of the BFNT Göttingen: Otto Bock HealthCare GmbH, MED-EL GmbH, and Thomas Recording GmbH.

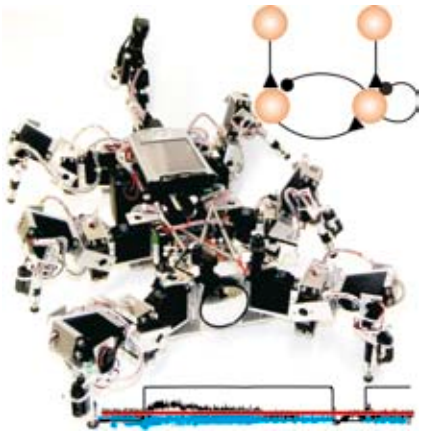


Fig. 1: Neuronal methods allows efficient robot control. Parts of the BFNT work is concerned with transferring such methods to the control of human prostheses.

bfnt göttingen

Participating Institutions and Members

T. Geisel, F. Wörgötter, Faculty of Physics, University of Göttingen

S. Treue, Faculty of Biology, University of Göttingen

T. Moser, W. Paulus, D. Schild, Medical School, University of Göttingen

A. Biess, T. Geisel, M. Herrmann, A. Neef, F. Wolf, Max Planck Institute for Dynamics and Self-Organization, Göttingen

A. Egner, J. Frahm, Max Planck Institute for Biophysical Chemistry, Göttingen

W. Stühmer, Max Planck Institute for Experimental Medicine, Göttingen

A. Gail, S. Treue, German Primate Center

E. Bamberg, Max Planck Institute for Biophysics, Frankfurt

T. Lenarz, Hannover Medical School

B. Graimann, Otto Bock HealthCare GmbH

I. Hochmair, MED-EL GmbH

U. Thomas, Thomas Recording GmbH

Contact

Bernstein Focus Neurotechnology
Georg-August-Universität Göttingen
Third Institute of Physics
Friedrich-Hund-Platz 1
D-37077 Göttingen
Tel.: + 49 (0) 551 39-10760
contact@bccn-goettingen.de
f.woergoetter@DPI.physik.uni-goettingen.de

Christian Doppler Laboratory for Cavitation and Micro-Erosion (CDLCME)

The CDLCME was established in 2009 in the Faculty of Physics and is projected to be active for up to seven years. It is located in the Third Institute of Physics (Biophysics). The CDLCME is jointly funded by the Austrian Christian Doppler Research Association (CDG) and an industrial partner, LAM Research AG. According to the CDG goals, the work is dedicated to applied fundamental research and thus explores basic physical phenomena needed for advanced industrial applications.

The CDLCME investigates the effect of acoustic streaming, cavitation and bubble collapse in liquids on solid surfaces on a microscopic scale. The envisaged major application of the results of this research is in wet processing and cleaning of nanostructured silicon wafers (computer chips), which is the expertise of the industrial partner. Settled in a multidisciplinary environment of acoustics, fluid dynamics and optics, the project builds on the traditional strengths of the Third Institute.

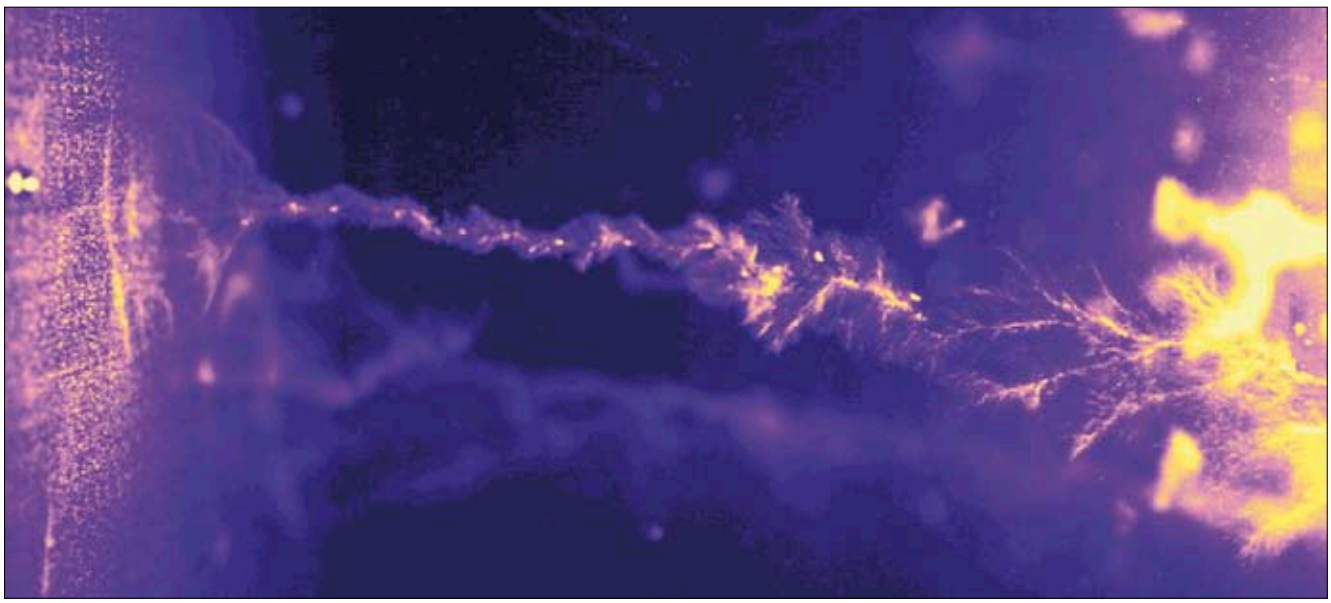
Participating researchers are: C. F. Schmidt, R. Mettin (Laboratory Head), T. Kurz.

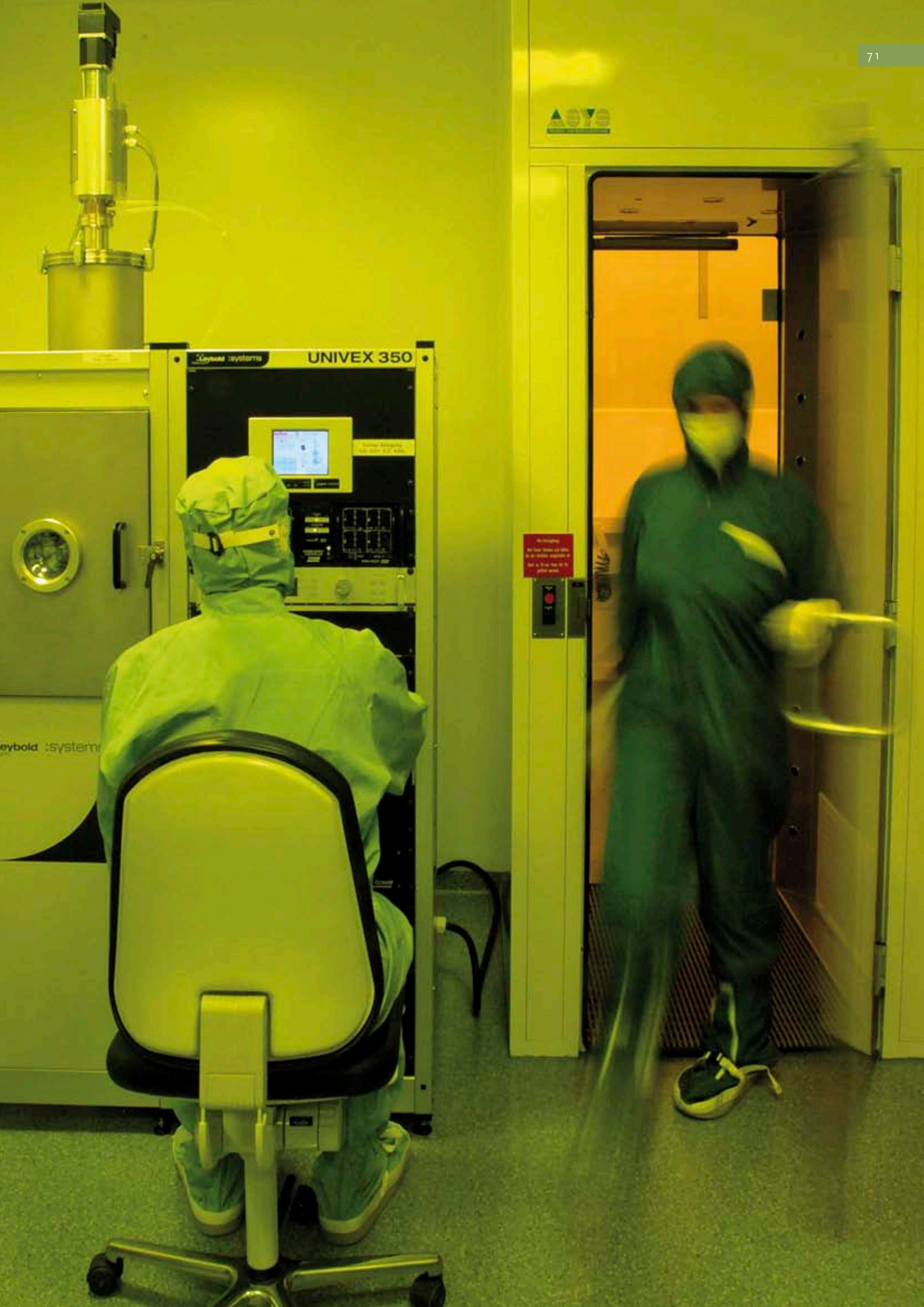
CDL ME Christian Doppler Laboratory for Cavitation and Micro-Erosion

Christian Doppler Forschungsgesellschaft

Lam® RESEARCH

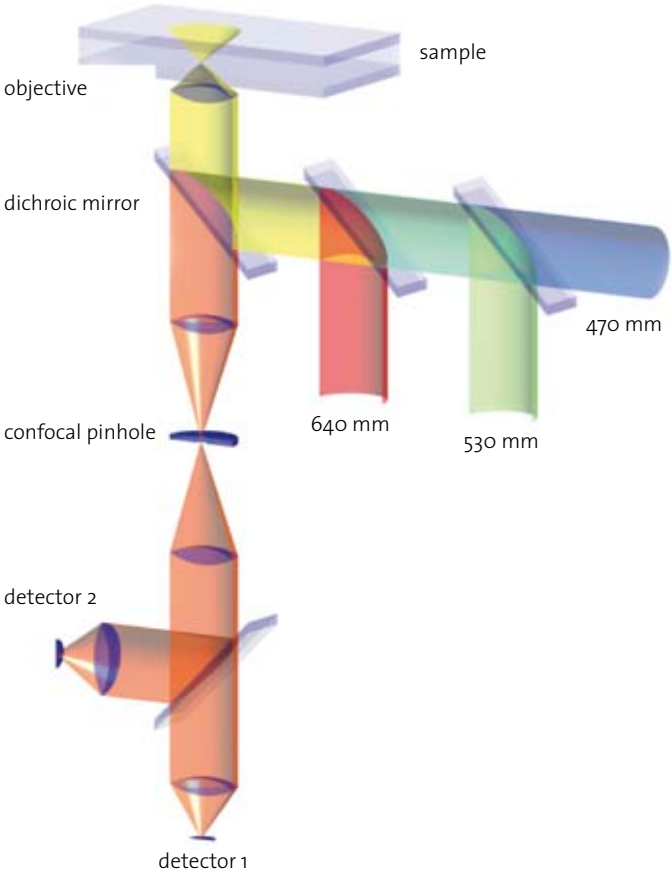
Changing the Value Equation™




UNIVEX 350

Single-Molecule Fluorescence Spectroscopy and Microscopy

Fluorescence spectroscopy and microscopy is one of the most advanced and important techniques in biophysical research. The enormous sensitivity of fluorescence allows for the direct detection, spectroscopy and imaging of individual molecules. During the last 20 years, this has led to completely new insights into the functioning, dynamics and interaction of individual bio-molecules such as proteins, DNA or RNA. Moreover, single molecule spectroscopy offers a unique way to directly observe the stochastic nature of molecular processes and thus connects advanced biophysics with fundamental statistical physics. Furthermore, due to the non-invasive character of fluorescence detection it is possible to track and watch individual molecules inside living cells. Last but not least, fluorescence microscopy itself has seen a dramatic development over the last decade, improving its resolving power by more than one order of magnitude, allowing for resolving cellular structures of only a few dozen nanometers wide.



Single-molecule fluorescence spectroscopy

Fluorescence correlation spectroscopy is a powerful technique to study molecular dynamics and interaction. In fluorescence correlation spectroscopy, fast fluctuations of fluorescence intensity generated by single molecules within a very small volume of only one picoliter (10^{-15} liter) are recorded and analyzed by correlation. One of the most important applications of this technique is to study protein folding. Proteins are the most important molecular building blocks of life, consisting of highly ordered structures made of long chains of amino acids. The mechanisms how a disordered long chain of amino acids (unfolded protein) finds the highly ordered final structure of the folded protein within a short time has remained one of the big questions of biophysics since the emergence of this problem some 50 years ago. The ability to watch the folding (and unfolding) of individual proteins offers an unprecedented view on this process and yields invaluable information for a better theoretical understanding of the protein folding mechanism.

Fig. 1: Schematic of a single-molecule fluorescence spectrometer: Three excitation lasers with different wavelengths are combined and that light is reflected by a dichroic mirror (reflective for laser excitation, transparent for fluorescence emission) into the objective, which focuses it into a tiny spot. Excited fluorescence light is collected by the same objective, focused through a confocal pinhole for background suppression, and finally detected by single-photon sensitive detectors.

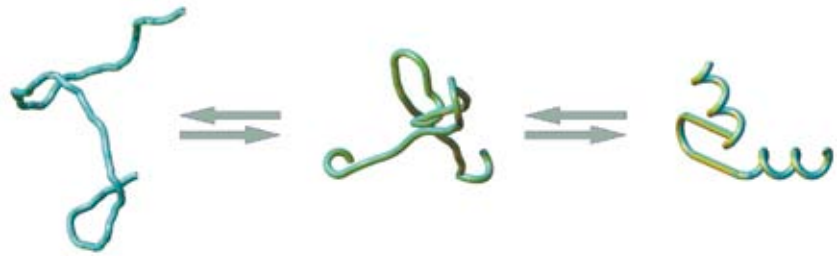


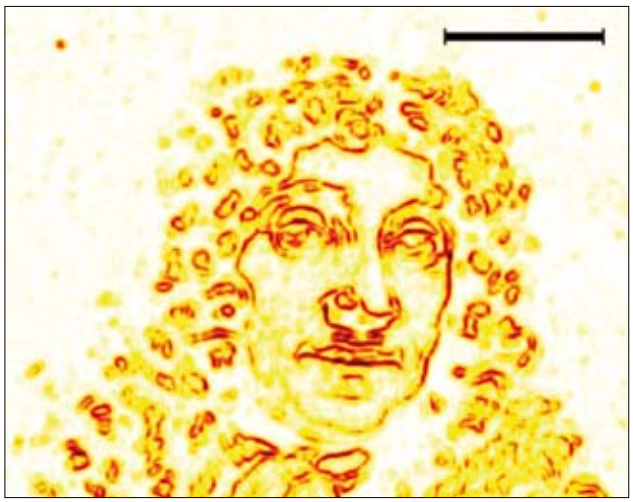
Fig. 2: Transition between unfolded (left) and folded (right) state of a mini-protein: A core application of single-molecule fluorescence spectroscopy is to study the temporal dynamics and pathways of the fast transitions between these states.

Single-molecule fluorescence imaging

Besides watching the fluorescence fluctuations of a single molecule, one can nowadays directly image single molecules using specialized high-sensitive CCD cameras. This is the core technique when using single molecule fluorescence for following molecular processes in living cells. The ability to 'see' a single molecule allows for localizing its position in space with nanometer accuracy, far below the conventional resolution-limit of light microscopy. This has been used in the past to resolve cellular structures with nanometer accuracy, or to watch the motion of individual proteins with similar resolution. We have developed a particular version of single-molecule imaging which enables us not only to see its position in space but also its three-dimensional orientation. In combination with the positional information, we are thus able to watch the complete motion and rotation of individual molecules and to elucidate how a protein turns and moves when functioning and interacting with other molecules. The same method is also used to study the local structure and dynamics of polymers and complex liquids.

Super-resolution fluorescence microscopy

Fluorescence microscopy is one of the most important tools when studying the architecture and structure of cells and tissues. The main reasons for this are its exceptional sensitivity (even individual molecules can be 'seen'), its non-invasiveness (using moderate light intensities does not harm a cell, in contrast to electron microscopy, that can only be performed on dead samples), and its specificity (the possibility to label different molecules of interest with different and well distinguishable fluorescent dyes). Unfortunately, for many years



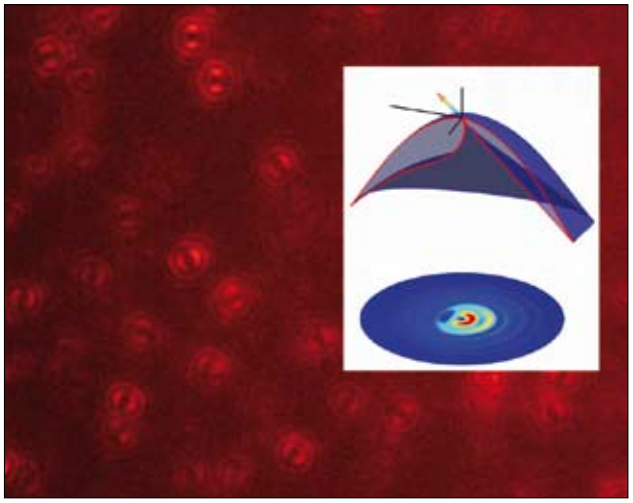


Fig. 3: Angular distribution of emission of a single molecule (inset) together with observed defocused images of single molecules: Each observed "double-banana" shaped pattern stems from a single molecule and contains information about its three-dimensional orientation in space.

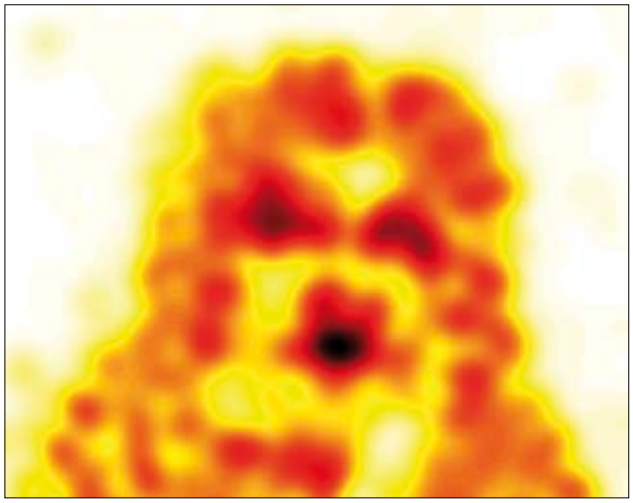


Fig. 4: Fluorescent microstructure (shaped after microscopy pioneer Antoni van Leeuwenhoek) as seen in super-resolution (top, bar = 1 micrometer) and with a conventional fluorescence microscope (bottom).

the spatial resolution of fluorescence microscopy was limited to ca. 250 nm which is due to the wave nature of light. Electron microscopy achieves a spatial resolution of up to three orders of magnitude better, using the short quantum wavelength of energetic electrons, but can be used only for treated dead samples. In recent years, the classical resolution limit of fluorescence microscopy has been overcome by exploiting various non-linear properties of fluorescence excitation and detection. Our group is involved in the further development and extension of these so called super-resolution microscopy techniques, which improve the spatial resolution of fluorescence microscopy by one order of magnitude. This opens a fascinating new window into living cells, visualizing cellular structure and dynamics with nanometer resolution.

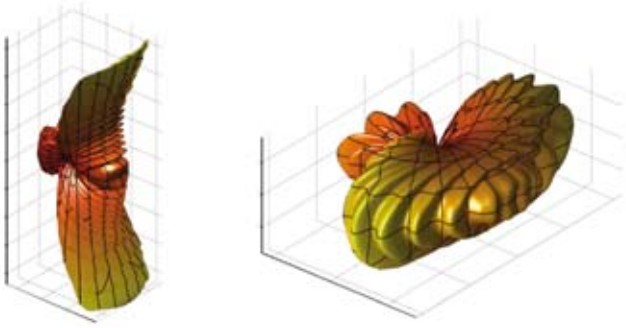


Fig. 5: Angular distribution of emission of a single molecule placed within a micro-cylinder. Shown are the distributions for two different molecule orientations.

Fluorescence nano-optics

From an electrodynamic point of view, fluorescent molecules can be understood as nanoscopic antennas that absorb and emit electromagnetic radiation. These nano-antennas probe the local density of states of the electromagnetic field. By placing them in nanometric metallic and/or dielectric structures, one can study how these structures alter the local density of states by measuring the changes in absorption and emission of the molecular fluorescence. This is of enormous importance for our fundamental understanding of the interaction between light and matter, but offers also the fascinating way to tune and tailor the fluorescence properties of molecules. Our group studies fluorescence nano-optics with sophisticated numerical modeling, and by performing advanced single-molecule spectroscopy measurements.

[1] Chizhik, A.; Schleifenbaum, F.; Gutbrod, R.; Chizhik, A.; Khoptyar, D.; Meixner, A. J.; Enderlein, J.: *Tuning the Fluorescence Emission Spectra of a Single Molecule with a Variable Optical Sub-wavelength Metal Microcavity,* Phys. Rev. Lett. 102, 2009, 073002-6.

[2] Sykora, J.; Kaiser, K.; Gregor, I.; Bönigk, W.; Schmalzing, G.; Enderlein, J.: *Exploring fluorescence antibunching in solution for determining the stoichiometry of molecular complexes,* Anal. Chem. 79, 2007, 4040-4049.

[3] Dertinger, T.; Pacheco, V.; von der Hocht, I.; Hartmann, R.; Gregor, I.; Enderlein, J.: *Two-Focus Fluorescence Correlation Spectroscopy: A New Tool for Accurate and Absolute Diffusion Measurements,* ChemPhysChem 8, 2007, 433-443.

[4] Toprak, E.; Enderlein, J.; Syed, S.; McKinney, S. A.; Petschek, R. G.; Ha, T.; Goldman, Y. E.; Selvin, P. R.: *Defocused orientation and position imaging (DOPI) of myosin, V* PNAS 103, 2006, 6495-6499.

[5] Enderlein, J.: *Breaking the diffraction limit with dynamic saturation optical microscopy,* Appl. Phys. Lett. 87, 2005, 095105.

Jörg Enderlein

Jörg Enderlein was born in 1963 in Berlin. After studying physics at the Ilya-Mechnikov-University in Odessa, he received his PhD from Humboldt-University in Berlin in 1991. While during his PhD time he was mainly concerned with the physics and chemistry of non-linear reaction-diffusion systems, he turned his attention afterwards to the then newly developing field of single molecule fluorescence spectroscopy and imaging. After a post-doc stay in Dick Keller's group at the Los Alamos National Laboratory in New Mexico, he obtained his habilitation from Regensburg University in 2000. Becoming a Heisenberg-Fellow of the DFG, he established his own research group at the Forschungszentrum Jülich, and with a short detour as a Professor for Biophysical Chemistry at Eberhard-Karls University in Tübingen, he switched to his current position at the 3rd Institute of Physics of the Georg-August University in late 2008.

Mechanics of Small Systems

The behavior of small systems (<100 nm) has attracted great interest in biology, chemistry and physics since nanoscopic entities such as molecular motors and machines manifest striking properties as a direct result of their small size. The physics of small systems is strongly governed by thermal fluctuations that produce significant deviations from the behavior of large ensembles. The ultimate small device is a single molecule, where fluctuations can be considered to be large and stochasticity dominates its thermal behavior. We are interested in the mechanics of small systems ranging from single molecules to living cells. Force mapping allows quantifying the viscoelastic behavior of soft matter on a local scale.

Nanotechnology is not a novel conception as it has been used by nature for a long time giving rise to complex and highly efficient machines on the nanometer scale, e.g. ATPase or flagella. Hence, artificial replications of biological concepts are envisioned in many scientific branches. For example, in materials science, the development of self-cleaning surfaces was inspired by the lotus plant that is in Buddhism a symbol for purity. Although the "lotus effect" is a famous mimic of nature's nanotech toolbox, it is merely one out of many examples from biomimetic engineering.

Mimicking detailed features of complex natural systems, like living cells, remains a challenge in actual research that is engaged in different strategies. Quantitative, systematic and reliable studies of individual biological phenomena are often only feasible by usage of simplified systems that focus exclusively on the subject of investigation, but with limited degree of complexity that still permits an authentic representation of biological activity. Hence, in actual research there is an ongoing demand for new and innovative biomimetic model systems enabling the investigation and understanding of fundamental processes in biology.

Mechanics of single molecules

Chemical reactions and structural transitions of supramolecular systems require a comprehensive understanding of the stochasticity of transformations on small length scales. Particularly, mechanically driven transformations as carried out by single molecule stretching experiments offer a unique way to study fundamental theorems of statistical mechanics as recently shown for the unzipping of RNA hairpins. In our research group, we design single-molecule experiments that allow to address fundamental statistical mechanics in an unprecedented way employing a molecular design based on oligo calix[4]arene catenanes (Fig. 1). These catenanes permit the control of the boundaries for separation and recombination of hydrogen bridges by mechanically locking the unbound state with intramolecularly entangled loops. This mechanically locked structure tunes the energy landscape of calixarene dimers, thus permitting the reversible rupture and rejoining of individual nanocapsules (Fig. 1). Stochastic modeling of hydrogen bonds under external load allows reconstruction of the energy landscape.

Local Mechanics of Biomembranes

Eukaryotic cells are supramolecular assemblies of vastly different composition and topology. A structural model for the adherent cell has been developed by drawing analogy to the so-called "tensegrity" (from tension integrity) structures found in modern architecture. A key feature of tensegrity structures is that they require tension in some of their elements to resist shape distortion due to an external load. Elasticity of cells largely determines fundamental cell behavior such as migration, differentiation, and interaction with each other. On the single cell level force can initiate cell protrusion, alters cell motility and affect biochemical pathways that regulate cell function division and death. Resolving cell mechanics on various length scales is therefore pivotal to understand how cells respond to mechanical stress and how the entity of plasma membrane and cytoskeleton framework interact with each other on a supramolecular level.

Atomic force microscopy allows not only visualizing the topography of submicrometer structures, it also permits to study material properties using phase imaging, pulsed force mode microscopy or force volume measurements. Crucial information about the cell membrane's bending resistance, however, remains inaccessible due to the complex elastic response of whole cells originating from interplay of cytoskeleton, cytoplasm, osmotic pressure and cell membrane. Our approach towards elasticity mapping of free standing cellular membranes relies on the combination of AFM as a scanning device

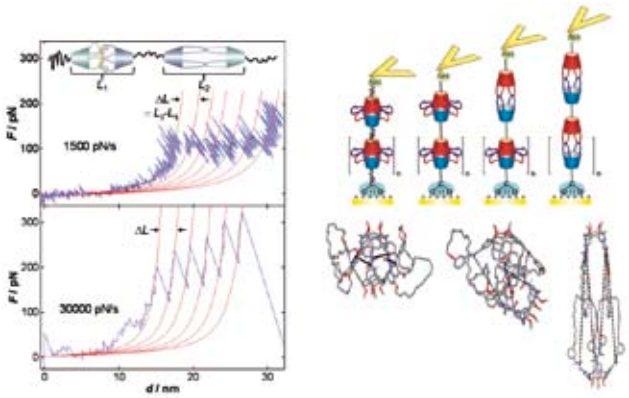


Fig. 1: Subsequent rupture of individual bis-loop calixarene dimers that are connected to form a dimer. A/B. Force extension curves at two different loading rates. C. Scheme illustrating the single-molecule experiment. D. MD-simulation of the rupture process.

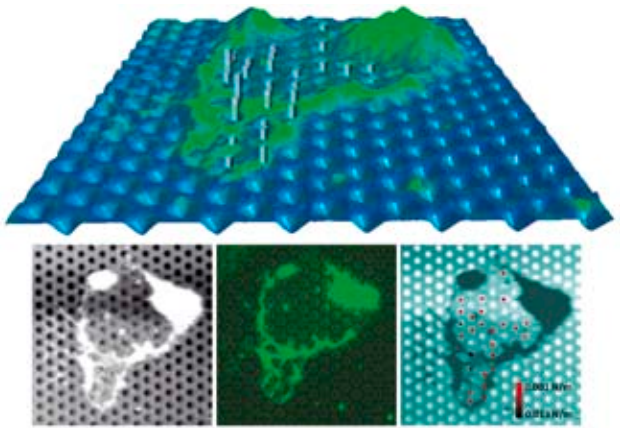


Fig. 2: 3D-overlay image showing topography from contact mode AFM (shown in B), FITC-phalloidin stained F-actin (shown in C) and an elasticity map (k_{app}) of a basolateral membrane fragment from confluent MDCK II cells on 1.2 µm sized pores. D 2-D overlay of the AFM image (A), fluorescence image (B), and the corresponding elasticity map (red dots).

with a substrate topology that allows bending membranes at locally defined positions (Figure 2). Highly ordered porous substrates with holes in the nano- to micrometer regime were employed to create a spatial mesh for elasticity mapping of basolateral cellular membranes prepared from epithelial cells.

[1] Janshoff, A.; Neitzert, M.; Oberdörfer, Y.; Fuchs, H. (2000): *Kraftspektroskopie an molekularen Systemen,* Angew. Chem. 112, 3346-3374.

[2] Janke, M.; Rudzevich, Y.; Molokanova, O.; Metzroth, T.; Mey, I.; Diezemann, G.; Marszalek, P. E.; Gauss, J.; Böhmer, V.; Janshoff, A. (2009): *Mechanically locked nanocapsules under force allow reversible hydrogen bond breakage,* Nat. Nanotechnol. 4, 225-229.

[3] Diezemann, G.; Janshoff, A. (2009): *Force-clamp spectroscopy of reversibly bonded systems,* J. Chem. Phys. 130, 041101.

[4] Diezemann, G.; Janshoff, A. (2008): *Dynamic force spectroscopy: Analysis of reversible bond-breaking dynamics,* J. Chem. Phys. 129, 084904.

[5] Mey, I.; Stephan, M. Schmitt, E. K.; Müller, M. M.; Ben-Amar, M.; Steinem, C.; Janshoff, A. (2009): *Local membrane mechanics of pore-spanning bilayers,* J. Am. Chem. Soc. 131, 7031–7039.

[6] Lorenz, B.; Mey, I.; Steltenkamp, S.; Fine, T.; Rommel, C.; Müller, M. M.; Maiwald, A.; Wegener, J.; Steinem, C. Janshoff, A. (2009): *Elasticity mapping of pore suspending native cell membranes,* Small 5, 832-838.

Andreas Janshoff

Andreas Janshoff, born in 1966, obtained a B.Sc. in Biology and a M.Sc. in Chemistry from the Westfälische Wilhelms-University Münster. Under the guidance of Hans-Joachim Galla, he received his PhD in 1997. After a postdoctoral stay at the Scripps Research Institute in La Jolla, CA (USA) in the group of Prof. M. Reza Ghadiri, he returned to the Institute of Physics at the University of Münster in 1999 as a DFG-fellow. Andreas Janshoff became associate professor for scanning probe techniques at the Institute of Physical Chemistry at the Johannes Gutenberg University in Mainz in 2001. In 2006, he was appointed a full professorship for Biophysical Chemistry. He received an offer from the University of Göttingen for a full professorship in 2008. Since August 2008, he is full professor at the Institute of Physical Chemistry at the Georg August University of Göttingen with his main research focus on soft matter physics and biophysical chemistry.

Complex Dynamical Systems

How do complex patterns and strange oscillations arise? Why is it so difficult to forecast the temporal evolution of many systems? What are the conditions for cooperative behavior, synchronization or other phenomena of self-organization? These are major topics in Nonlinear Dynamics and Complex Systems research providing a unifying framework for emergent structure formation processes in natural and man-made systems.

Nonlinear Dynamics and Complex Systems

Nonlinearity is a prerequisite for interesting and often surprising behavior of natural systems. In a nonlinear system, cause and action are not proportional to each other. Nonlinear systems are in general difficult to solve mathematically, but exhibit many interesting features like chaotic dynamics or structure formation. Chaotic systems are characterized by oscillations that appear irregular, but are purely deterministic and very sensitively depend on changes of initial values or external perturbations. This *sensitive dependence on initial conditions* makes it so difficult to forecast chaotic systems. Chaos may occur in all kinds of systems including lasers, neurons, electronic circuits, physiological rhythms etc., and special methods have been devised for signal analysis and control of chaotic dynamics.

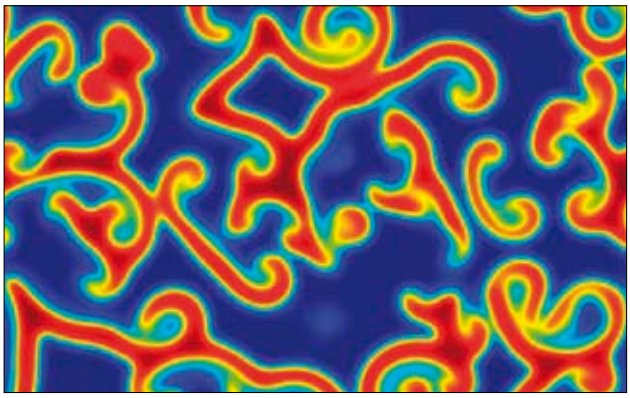


Fig. 1: Snapshot of a complex wave pattern occurring in a computer simulation of an excitable medium.

If many systems or elements are combined, larger networks of components result which may give rise to collective and adaptive behavior. Such complex systems exhibit emergent self-organization phenomena relevant for information processing, learning or evolution, in general *without* being governed by some central control units. Typical examples of complex systems are neural, ecological, or economic networks (e.g., brain, ant colonies, stock market,...), and Complex Systems research aims at characterizing and understanding their fundamental features.

Excitable Media and Cardiac Dynamics

An important class of (extended) dynamical systems are excitable media. If an excitable system at rest is stimulated by an (external) perturbation that exceeds some specific threshold, the system responds with a strong pulse where some system variables attain large values before the system converges to the equilibrium state again. Immediately after the pulse the system is in a refractory period, during which it cannot be excited, again. Spatially extended excitable systems are also called excitable media and may exhibit different types of wave patterns and chaotic dynamics (Fig.1).

Many biological systems are excitable. For example, excitation waves in cardiac tissue govern the contraction pattern of the pumping heart and there, turbulent wave patterns may lead to arrhythmias and other malfunctions.

[1] Ahlborn, A.; Parlitz, U.: *Laser stabilization with multiple delay feedback control,* Opt. Lett. 31(4), 2006, 465-467.

[2] Parlitz, U.; Pikovsky, A.; Rosenblum, M.; Kurths, J.: *Schwingungen im Gleichtakt,* Physik Journal 5 (10), 2006, 33-40.

[3] Ahlborn, A.; Parlitz, U.: *Chaos control using notch filter feedback,* Physical Review Letters 96, 2006, 034102.

[4] Ahlborn, A.; Parlitz, U.: *Control and synchronization of spatio-temporal chaos,* Phys. Rev. E 77, 2008, 016201.

[5] Yu, D.; Parlitz, U.: *Driving a network to steady states reveals its cooperative architecture,* Europhys. Lett. 81, 2008, 48007.

[6] Bittihn, P.; Luther, G.; Bodenschatz, E.; Krinsky, V.; Parlitz, U.; Luther, S.: *Far field pacing supersedes anti-tachycardia pacing in a generic model of excitable media*, New Journal of Physics 10, 2008, 103012.

Ulrich Parlitz

Ulrich Parlitz was born in 1959 in Hameln and studied physics at the Georg-August-Universität Göttingen, where he also received his PhD in 1987. After five years at the Institute for Applied Physics of the TU Darmstadt he returned to Göttingen in 1994 where he obtained his habilitation in 1997 and was appointed apl. Prof. of Physics in 2001.

He was a visiting scientist at the Santa Fe Institute (1992), the UC Berkeley (1992), and the UC San Diego (2002, 2003). Research interests of Ulrich Parlitz include nonlinear dynamics, data analysis, complex systems, and cardiac dynamics.

Atomic Force Microscopy on Biological Molecules

Since its invention in 1985, atomic force microscopy, which offers atomic resolution on solid inorganic samples, has been used with increasing success to study much softer biological objects. In principle, it allows us to directly visualize the structure and activity of individual biomolecules in a liquid environment at a sub-nanometer resolution. The challenge is now to obtain as high as possible resolution without disturbing the relatively fragile protein or DNA samples with the sharp scanning probe.

Nanometer resolution

To generate a topographical image, an atomic force microscope employs a very sharp probe that scans the sample. A great advantage over optical techniques is that no staining or labeling is required. We use the ability of the instrument to image samples immersed in water to study the structure and activity of biomolecules, ranging from single proteins (Fig. 1), viruses, to complete cells, all under physiological conditions.

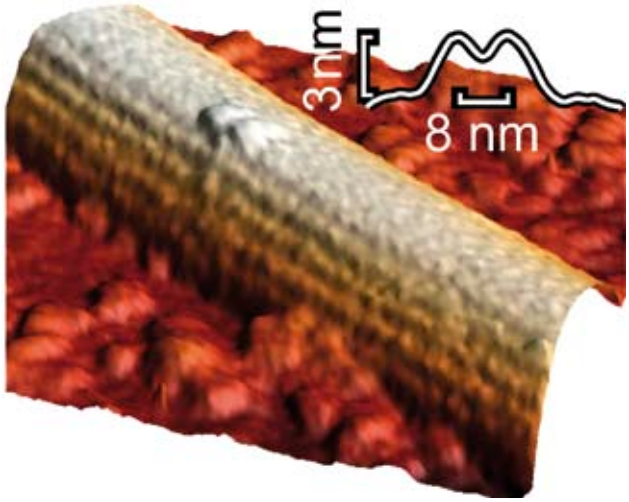


Fig. 1: Imaging of single kinesin motor proteins that are involved in intracellular transport. The 150 x 150 nm scan shows a dimeric kinesin motor protein bound on top of its substrate, a microtubule. The two motor domains, spaced 8 nm apart and the 1 nm diameter coiled coil are visible.

Mechanics of bio-materials

Atomic force microscopy has proven to be a valuable tool to measure material properties of nanometer sized objects. The scanning probe is brought in contact with the sample and then used to deform it, by indenting it for a few nanometers. From the measured deformation and forces, we are able to calculate the elasticity and fracture limits of biological objects, for example single virus particles (Fig. 2).

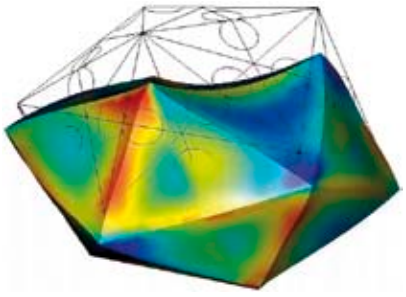


Fig. 2: Based on atomic force microscopy indentation measurements, finite element methods are used to compute the deformation of a 28 nm small virus.

[1] Schaap, I. A. T.; Hoffmann, B.; Carrasco, C.; Merkel, R.; Schmidt, C. F. (2007): *Tau protein binding forms a 1 nm thick layer along protofilaments without affecting the radial stability of microtubules,* J. Struct. Biol.158, 282-292.

[2] Schaap, I. A. T.; Carrasco, C.; de Pablo, P. J.; MacKintosh, F. C.; Schmidt C. F. (2006): *Elastic response, buckling and instability of microtubules under radial indentation,* Biophys. J. 91, 1521-1531.

[3] Goodman, R. P.; Schaap, I. A. T.; Tardin, C. F.; Erben, C. M.; Berry, R. M.; Schmidt, C. F.; Turberfield, A.J. (2005): *Rapid Chiral Assembly of Rigid DNA Building Blocks for Molecular Nanofabrication,* Science 310, 1661-1665.

Iwan Schaap

Iwan Schaap, born in 1973 in Delft, the Netherlands, studied molecular biology and virology in Utrecht, NL and in Glasgow, UK. He entered the field of biophysics by doing his PhD studies in the group of C. F. Schmidt in Amsterdam, NL. Afterwards he moved to the National Institute for Medical Research in London, UK where he worked with optical tweezers on motor proteins and studied the influenza virus with atomic force microscopy.

In November 2008, he got the opportunity to start a new research group at the Third Institute of Physics as part of the 'Cluster of Excellence for Microscopy at the Nanometer Range'.

Molecular and Cellular Biophysics

The interface between physics and biology offers a multitude of unsolved, fascinating and immediately relevant problems. Little is yet known about the physics of living cells and their components. The challenge and the richness of the field lie in the enormous complexity of biological systems. Experimental methods that can access the larger-scale dynamic properties of biomolecules and of macromolecular aggregates up to those of a whole cell or tissues are currently being developed. For example, techniques exist now which allow the direct observation of interacting single biomolecules, either in reconstituted model systems or in their native context in the cell. With such direct access to a microscopic level, the stage is set to explore the physics of cells and to eventually venture beyond single cells to tackle the quantitative understanding of tissues and system-level functions. At the same time there is the need to develop new physical models to approach conceptual challenges, presented, for example, by complexity and thermodynamic non-equilibrium of biological systems.

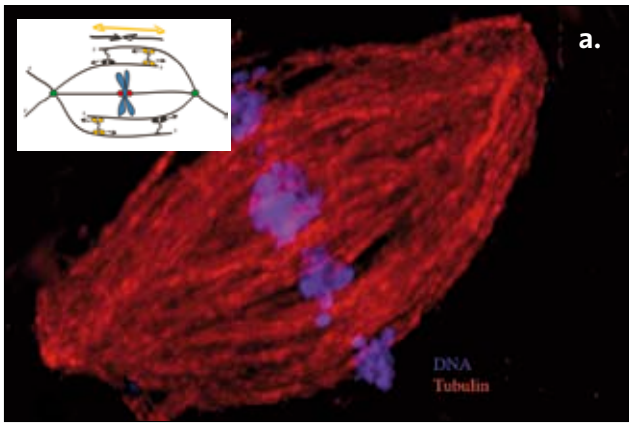
Motor protein dynamics

We study biological motor proteins in single-molecule experiments with the goal of understanding the physical principles of biological force generation in a multitude of active transport processes. Motor proteins are the ubiquitous nanometer-scale mechanical engines at the basis of many crucial processes of life. They present a case where the non-equilibrium dynamics of these biological macromolecules, usually embedded in a complex regulatory and functional environment, are the essence of their function. We work primarily with kinesin motors, particularly those involved in cell division (Fig. 1). We measure forces exerted by single motor molecules with focused laser beams, so-called optical traps, observe single molecules on the move directly with single-molecule fluorescence (Fig. 1b), and explore the dynamics of the motors' building blocks with atomic force microscopy (AFM) (Fig. 2).

DNA nanostructures

We use the unique structure and programmability of DNA to assemble nanometer-sized constructs, for example tetrahedra, from oligomeric DNA (Fig. 3). This type of design of self-assembling submicroscopic building blocks for specific functions holds great promise, both for biomaterials design and for possible medical applications, e.g. for drug delivery. We can image the structures, but also test their mechanical properties with AFM.

Fig. 1: a) The mitotic spindle is the machine built of microtubules (red) that separates chromosomes (blue) during cell division. This is done by motor proteins of the kinesin family, producing a delicate balance of forces. The sketch (insert) shows a four-headed Kinesin 5 (yellow) balancing a two-headed Kinesin 14 (black), between two microtubules (black lines). b) The single-molecule fluorescence kymograph shows how a Kinesin 5 (green line) slides one microtubule (slanted red lines) over a stationary microtubule (horizontal lines). The fact that the motor moves at half the speed of the microtubule (green line is half as steep as red line) shows that both ends are active.



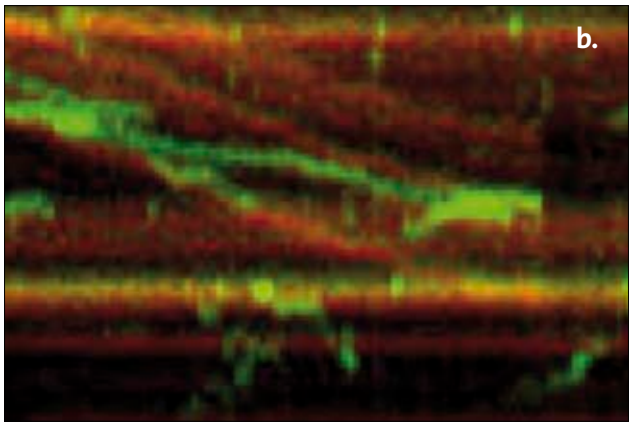


Fig. 4: Vertical cross section through an adhering PC3 epithelial cell, obtained with a confocal microscope imaging fluorescent actin. Protrusions on the cell surface suspend the pericellular matrix surrounding the cell.

Soft matter and biomaterials

We explore the mechanical properties and collective dynamics of systems ranging from synthetic colloids and polymers, single protein polymers, protein tubes and shells, to whole cells (Fig. 4) and cells in culture or in tissue, for example in blood vessels. We probe these systems both with single-molecule micromechanical and with so-called microrheology techniques. An approach that our group has pioneered is nanoshell mechanics with AFM, i.e. the study of elastic properties of virus shells and protein tubes such as microtubules (Fig. 5). Microrheology (Fig. 6) is a technique we developed about ten years ago. In particular, we study networks of semiflexible proteins, in reconstituted model systems and also in living cells, with the goal of understanding the functional principles of the cell cytoskeleton. The cytoskeleton is a protein network that plays a crucial role in processes such as cell division, cell locomotion, or cell growth, and also plays a part in mechanosensing and signaling. Semiflexible polymers are a new class of polymers also with potential use as technical materials. We use microscopy, and manipulation with optical traps, in conjunction with numerical and theoretical modeling to monitor the dynamics and measure the mechanical response of these systems. Samples we study include colloidal rods such as carbon nanotubes, surfactant systems, virus solutions, actin and tubulin (single filaments and networks), and intermediate filaments. An exciting new line of research addresses internally driven non-equilibrium systems which form a stepping stone towards real living cells (Fig. 6). We also study various physical aspects of cell behavior: mechanosensing with osteocytes and vascular endothelial cells, cell growth and intracellular transport with neurons and the mechanical control of the differentiation of stem cells. Fig. 7 shows a fibroblast, a common connective tissue cell, suspended between two optically trapped beads. With these "handles", we can measure forces generated by the cells and we can test how the cells react to forces exerted on them.

Fig. 2: Atomic force microscopy provides images with nm resolution, in watery samples an order of magnitude better than even ultra-resolution light microscopy. Here individual kinesin motor heads, 4 nm in size, can be seen bound to a microtubule along individual protofilaments.

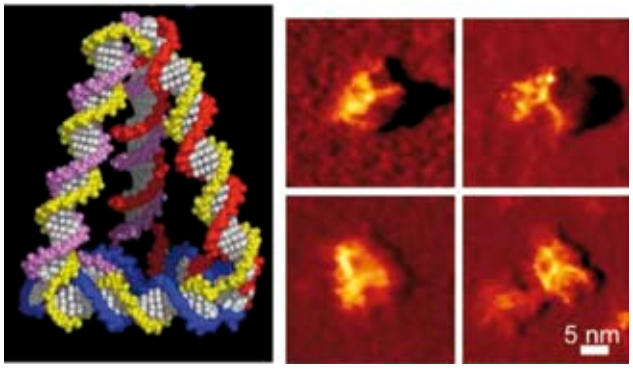


Fig. 3: Left: Model of a self-assembled DNA tetrahedron with edges of 20 and 30 base pairs, corresponding to ~7 and ~10 nm lengths. Right: AFM images of the same tetrahedra in buffer.

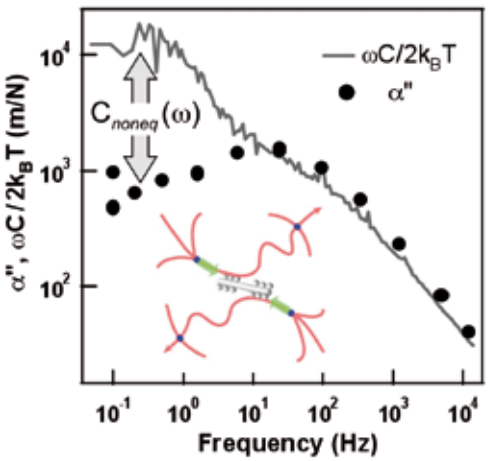


Fig. 5: Mechanical response of a model network of cross-linked actin filaments (red lines) driven out of equilibrium by myosin motors (grey bundles), measured by microrheology. Black dots show the frequency dependence of the elastic response function. The fluctuation spectrum (grey line) deviates at low frequencies from the response function, demonstrating the violation of the fluctuation-dissipation theorem in this non-equilibrium material.

[1] Svoboda, K.; Schmidt, C. F.; Schnapp, B. J.; Block, S.M.: *Direct observation of kinesin stepping by optical trapping interferometry,* Nature 365, 721-727, 1993.

[2] Gittes, F.; Schnurr, B.; Olmstedt, P. D.; Mackintosh, F. C.; Schmidt, C. F.: *Microscopic viscoelasticity: Shear moduli of soft materials determined from thermal fluctuations,* Phys. Rev. Lett. 79, 3286-3289, 1997.

[3] Kapitein, L. C.; Peterman, E. J. G.; Kwok, B. H.; Kim, J. H.; Kapoor, T. M.; Schmidt, C. F.: *The bipolar mitotic kinesin Eg5 moves on both microtubules that it crosslinks,* Nature 435, 114-118, 2005.

[4] Goodman, R. P.; Schaap, I. A. T.; Tardin, C. F.; Erben, C. M.; Berry, R. M.; Schmidt, C. F.; Turberfield, A.J.: *Rapid chiral assembly of rigid DNA building blocks for molecular nanofabrication,* Science 310, 1661-1665, 2005.

[5] Michel, J.P.; Ivanovska, I.L.; Gibbons, M.M.; Klug, W.S.; Knobler, C.M.; Wuite, G.J.L.; Schmidt, C.F.: *Nanoindentation studies of full and empty viral capsids and the effects of capsid protein mutations on elasticity and strength,* PNAS, 103, 6184-6189, 2006.

[6] Klug, W.S.; Bruinsma, R. F.; Michel, J.-P. , and Knobler, C. M.; Ivanovska, I.L.; Schmidt, C. F.; and Wuite, G. J. L.: *Failure of Viral Shells,* Phys. Rev. Lett. 97, 2006.

[7] Koenderink, G. H.; Atakhorrami, M.; MacKintosh, F. C.; and Schmidt, C. F.: *High-frequency stress relaxation in semiflexible polymer solutions and networks,* Phys. Rev. Lett. 96: 138307, 2006.

[8] Klug, W.S.; Bruinsma, R.F.; Michel, J.-P.; and Knobler, C.M.; Ivanovska, I.L.; Schmidt, C.F.; and Wuite, G.J.L.: *Failure of Viral Shells,* Phys. Rev. Lett. 97, 2006.

[9] Koenderink, G.H.; Atakhorrami, M.; MacKintosh, F.C.; and Schmidt, C.F.: *High-frequency stress relaxation in semiflexible polymer solutions and networks,* Phys. Rev. Lett. 96, 138307, 2006.

[10] Mizuno, D.; Tardin, C.; Schmidt, C.F.; MacKintosh, F.C.: *Nonequilibrium mechanics of active cytoskeletal networks,* Science, 315, 370-373, 2007.

[11] Atakhorrami, M.; Mizuno, D.; Koenderink, G. H.; Liverpool, T. B.; MacKintosh, F. C.; Schmidt, C.F.: *Short-time inertial response of viscoelastic Fluids measured with Brownian motion and with active probes,* Phys. Rev. E, 77: 061508, 2008.

[12] Atakhorrami, M.; Mizuno, D.; Koenderink, G. H.; Liverpool, T. B.; MacKintosh, F. C.; Schmidt, C. F. (2008): *Short-time inertial response of viscoelastic Fluids measured with Brownian motion and with active probes,* Phys. Rev. E, 77, 061508, 2008.

[13] Nijenhuis, N.; Mizuno, D.; Spaan, J.A.E.; and Schmidt, C. F.: *Viscoelastic response of a model endothelial glycocalyx,* Phys. Biol. 6: 025014, 2009.

[14] Mizuno, D.; Bacabac, R.; Tardin, C.; Head, D.; Schmidt, C.F.: *High-resolution probing of cellular force transmission,* Phys. Rev. Lett. 102, 168102, 2009.

[15] Nijenhuis N.; Mizuno D.; Spaan, J.A.E. and Schmidt, C.F. : *Viscoelastic response of a model endothelial glycocalyx,* Phys. Biol. 6, 025014, 2009.

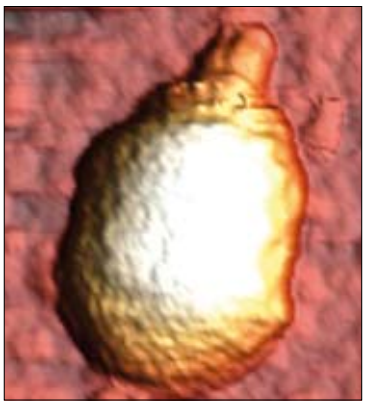


Fig. 6: AFM image of a Φ29 bacteriophage virus particle (42x54 nm ellipsoid). Indentation of the protein shell with an AFM tip provides data on the elastic response of the shells and helps to characterize the material properties of virus shells.

Fig. 7: Fibroblast cell suspended between two optically trapped beads of 4 micrometer diameter.

Christoph Schmidt

Christoph Schmidt was born 1956 in Frankfurt/M. He received a PhD in physics in 1988 from the Technical University Munich, developing light scattering and other optical methods for the analysis of biomolecular dynamics. For his postdoctoral work at Harvard and the Rowland Institute for Science in Cambridge, Massachusetts he worked with David Nelson, Dan Kiehart, Dan Branton and Steven Block, on topics ranging from 2D polymers in physics to motor proteins in biology. Here he pioneered single-molecule experiments with optical traps. After rising to the rank of tenured professor of physics at the University of Michigan in Ann Arbor, MI, he established a biophysics group at the Free University of Amsterdam before eventually moving to Göttingen in 2006 to head the 3rd Institute of Physics, which was then fundamentally re-oriented towards biophysics.

Computational Neuroscience and Neuro-Robotics

We are interested in understanding the dynamics and the self-organization (learning) in neuronal systems embedded in their environment. Over decades, neurons and brains have mainly been investigated as stimulus-response systems, where the output of the system does not affect its own inputs. Animals (and humans), however, operate differently in quite a fundamental way: Whatever action we perform, it will almost always immediately affect our sensory inputs. *In writing* these lines I *see* my fingers moving over the keyboard, *feel* their touch, *hear* the clicking of the keys, *notice* letters appeazring *bksp bksp bksp bksp* del appearing, where every typo (feedback error-signal) will *enact* a correction closing the perception-action loop. Hence, such perception-action loops are the normal mode of operation of all animals. It is our goal to understand the dynamics and the adaptivity of such systems in term of modern physics.

It is known that within such a loop some signals that come back to the animal's sensors are of direct relevance (like the seeing of a typo in writing), while others do not immediately drive the loop (like the clicking of the keys). Fundamentally, it is only the animal/human/agent who can decide which of the arriving sensor signals are relevant for the momentarily existing task and which are not. The behavior of any creature is therefore controlled by measuring its own inputs (input-control) and normally not by reinforcement from an external observer. Improved fitness will arise if an animal can do this in a predictive way, hence if it can use predictive mechanisms to anticipate the outcome of its own actions and, to some degree, also the "behavior of the world".

The goal of our studies is to understand how autonomous behavior arises in animals and agents through the development of complex perception-action loops and the learning of adaptive, anticipatory behavior through input-control with minimal external interference.

To this end we investigate (using neuro-physiological data as well as robots):

Input: Information processing in the visual system and its use in machine vision.

Dynamics and Adaptation: The biophysics of synaptic plasticity and correlation based learning mechanisms in animals and robots.

Reasoning: Decision making, planning and the discovery of the structure of the agent's environment.

Output: The sequencing of actions towards goal-directed behavior and the dynamics of such systems.

Naturally, this creates a rather wide research spectrum as we have to address all these aspects together without which we could neither design artificial closed loop systems (robots) nor could we try to understand real ones (animals/humans).

Vision and Machine Vision

Vision is the most important sensory modality for many vertebrates and especially for us humans. We can perform remarkable recognition tasks using our eyes and brain. For most robots, vision is equally important. In recent years, scientists working in this field have developed real-time vision algorithms with which moving scenes can be analyzed, objects found, and actions interpreted. For example the figure above shows how one can extract depth information from two stereoscopic images in scenes with little structure and large perspective shift ("disparity"). Our brain can easily perform such a task, which is difficult due to occlusions and perspective distortions. Recent research by our group has now made it possible to implement a brain-inspired and very efficient stereo analysis algorithm also in our machines.

Adaptation and Learning

In a robot, any pre-processed input (e.g. from vision) is used to trigger actions and this is usually done not in a stereotypical but rather in an adaptive way. Adaptation and learning are vital for the survival of any autonomous agent as these processes allow dealing with non-stationary environments, hence with situations that change albeit within a restricted range. Animals and some robots can do the same and we use neural network mechanisms to emulate (fast) adaptation and (slow) learning processes. During the last years we have developed a mathema-

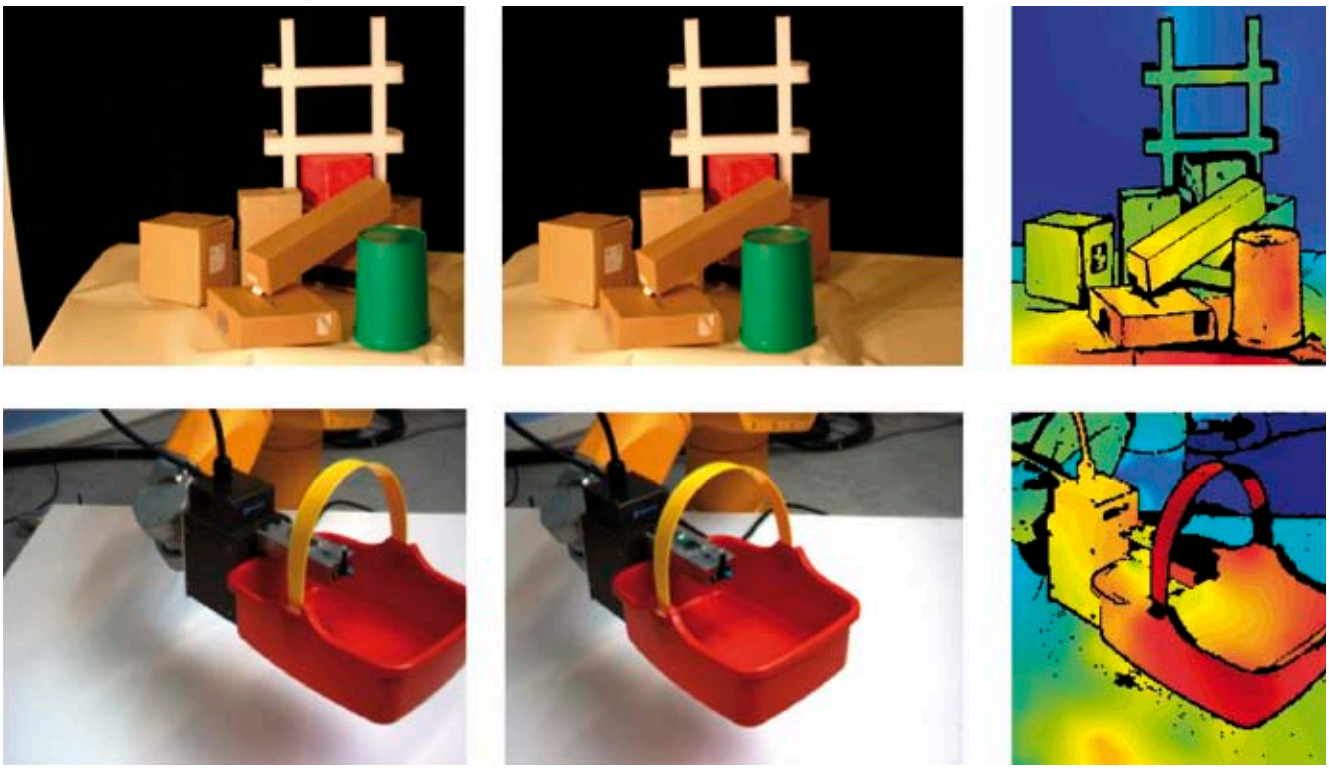


Fig. 1: Stereo image pair (left) and visual distance analysis (right, red encodes close objects and blue distant ones).

tical theory of a certain type of neural learning (differential hebbian synaptic plasticity) and implemented it in several robots to optimize their behavior. The walking robot RunBot, which for some time has been the fasted dynamic biped walking machine existing (given its size) can this way learn to walk up a slope, like a little child would do. It uses the experience from falling backwards to learn changing its gait and to lean its upper body component forward as soon as it needs to climb.

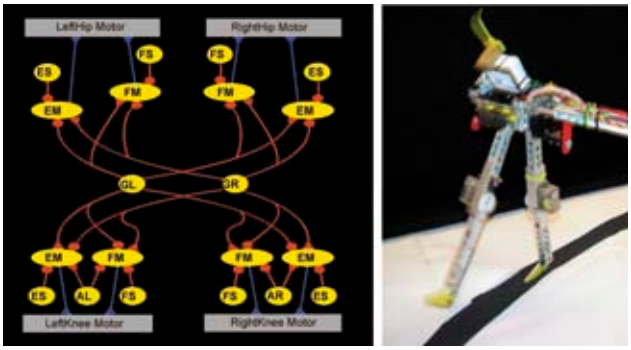


Fig. 2: A humanoid robot (ARMAR III, Univ. Karlsruhe) learns the action sequence required to sort cups on a sideboard.

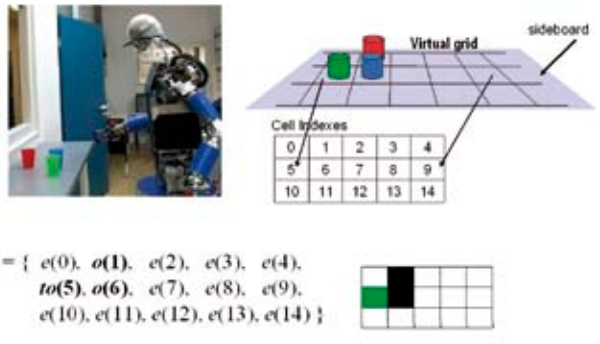


Fig. 3: The control network (left) of the biped RunBot, which allows it to learn walking up a slope (right).

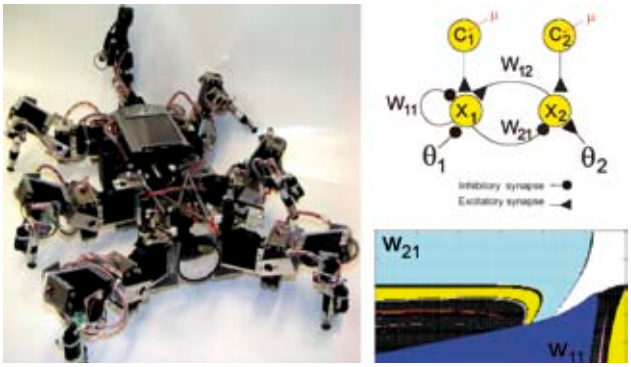


Fig. 4: The walking gait of the six-legged robot AMOS-WD6 (left) is determined by two neurons x (top right), which can be controlled by inputs c to operate in periodic or chaotic domains (bottom right, black denotes chaos, colors stand for different oscillation periods) depending on their mutual connection strengths w.

Decision Making, Reasoning and Planning

Adaptation and learning will still only deal with resolving situations from moment to moment. However, more advanced agents – those with cognitive properties – are able to learn from time-delayed events. For example, each of us can learn the correlation between opening the fridge, getting a drink, drinking it and its outcome, which is the quenching of your thirst. Cause and effect are in these cases temporally far removed from each other and the execution of such an action sequence requires decision making and planning. In a cooperation with the University of Karlsruhe (Prof. Dr. R. Dillmann, Dr. T. Asfour) and the Consejo Superior de Investigaciones Científicas (Barcelona, Prof. C. Torras), we have developed a set of algorithms which allow a robot to learn the rules of an action plan by interacting with a human. The machine can, for example, be taught to sort cups on a sideboard starting with no initial planning knowledge. Here, too, our methods are inspired by the neurosciences and by psychology asking how children would learn such a task.

Actions and Dynamics

Sensing, learning, and planning do not suffice to close the perception-action loop. For this the agent must finally execute its plan. It must move and act. Given the high number of sensors and the multitude of muscles which we have, it is quite amazing that animals and humans have reached such a high degree of proficiency in sensor-motor coupling. Skillful dancing, difficult manipulation using complex tools, and advanced skiing are examples how terrific our sensor-motor coordination indeed is. We address this problem, for example, by a small adaptive 2-neuron network which initial-ly operates in a chaotic way. By ways of sensor driven input the network can be controlled into expressing periodic oscillations and these can then – in turn – lead to periodic walking patterns (gaits) similar to those observed in real insects. Together with some neuronal post-processing one can this way achieve a very versatile and realistic behavioral repertoire: An autonomous, artificial insect that can sense, learn and act.

This shows how we address the problem of perception-action loops by ways of studying neural systems and building artificial agents which emulate certain neuronal operations. The long-term future challenge behind all this is the attempt to understand brain function to the degree that it will ultimately be possible to build advanced artificial cognitive systems that can interact and communicate with humans. There is still a long way to go, but the examples shown above demonstrate how autonomous systems can be built which express certain animal-like sub-functions with increasing degrees of complexity and realism and how we can understand those in terms of mathematical modeling.

[1] Ning, K. and Wörgötter, F. (2009): *A Novel Concept for Building a Hyper-Redundant Chain Robot*, IEEE Transactions on Robotics, DOI: 10.1109/TRO.2009.2032968 (in press).

[2] Ainge, J.; Tamosiunaite, M.; Wörgötter, F. and Dudchenko, P. (2007): *Hippocampal CA1 place cells encode intended destination on a maze with multiple choice points,* J. Neurosci., 27(36):9769-9779; doi:10.1523/JNEUROSCI.2011-07.2007.

[3] Manoonpong, P.; Geng, T.; Porr, B.; Kulvicius, T. and Wörgötter, F. (2007): *Adaptive, fast walking in a biped robot under neuronal control and learning,* PLoS Comp. Biol., e134 doi:10.1371/journal.pcbi.0030134.

[4] Kulvicius, T.; Tamosiunaite, M.; Ainge, J.; Dudchenko, P. and Wörgötter, F. (2008): *Odour supported place cell model and goal navigation in rodents,* J. Comp. Nsci., 25(3):481-500doi 10.1007/s10827-008-0090-x.

[5] Steingrube, S.; Timme, M.; Wörgötter, F. and Manoonpong, M. (2010): *Self-organized adaptation of simple neural circuits enables complex behavior,* Nature Physics, in press.

[6] Tamosiunaite, M.; Ainge, J.; Kulvicius, T.; Porr, B.; Dudchenko, P. and Wörgötter, F. (2008): *Path-finding in real and simulated rats: assessing the influence of path characteristics on navigation learning*, J.Comp. Nsci., 25(3): 562-582, doi 10.1007/s10827-008-0094-6.

[7] Wörgötter, F. and Porr, B. (2005): *Temporal sequence learning, prediction and control - A review of different models and their relation to biological mechanisms,* Neural Comp. 17, 245-319.

Florentin Wörgötter

Florentin Wörgötter studied Biology and Mathematics in Düsseldorf. He did a PhD in experimental neuroscience in Essen finishing in 1988. As a postdoc he worked at CALTECH in the field of modeling the visual system. Between 1990 and 2000 he was leader of the group of computational neuroscience and for 5 years Heisenberg Fellow at the Ruhr-University Bochum. During this time he continued his neuroscience research but also started to develop "neuronal" computer vision algorithms. This has led to several scientific and commercial applications in the field of image segmentation, data-fusion and stereo-depth analysis. Between March 2000 and June 2005 he held a Chair in the psychology department of the University of Stirling in Scotland. Since June 2005 he is professor for Computational Neuroscience at the Bernstein Center for Computational Neuroscience at the University of Göttingen, Germany, where he joined the Inst. of Physics III in August 2009.

Structure of Biomolecular Assemblies and X-ray Optics

My group and I study soft condensed matter and biomolecular assemblies. We want to understand the non-crystalline aggregation and self-assembly of biomolecular systems as well as the relevant interaction forces in quantitative physical terms. We want to know how functional properties of biomolecular assemblies depend on their nanoscale structure.

We adapt and develop X-ray methods for non-crystallographic structure analysis of multi-component systems in hydrated and functional environments. Since diffraction methods are mostly restricted to large ensembles and/or to relatively well-ordered and homogeneous structures, we increasingly use X-ray imaging in our work for example by using coherently X-ray nanofoccused beams.

Biological macromolecules exhibit astonishing abilities to self assemble into supra-molecular structures, which are held together by a variety of inter-molecular forces acting on different length scales. The self-assembly of biological membranes and of the simpler lipid model systems are fantastic examples for this property to self-assemble and to form higher order structures. The structure of these nanoscale ‚biomolecular interfaces' in turn determines mechanical, electrical properties and transport properties of biomolecules in the cell and the macroscopic properties of many soft composite materials. Apart from molecular interactions, entropic effects and thermal fluctuations in these structures are significant, and have an important influence on the phase state and on structural properties.

We have shown that single and multi-component lipid membranes can be deposited in form of highly ordered stacks on solid support and that the structure can be studied by modern interface-sensitive scattering techniques [1,2]. We have used both elastic X-ray scattering and inelastic neutron scattering to elucidate not only the average structure, but also fluctuations [3], collective dynamics [4], and interactions forces acting in charged and in charge neutral membranes. Liquid-like correlations, conformation and interaction forces of proteins and peptides in the aligned membranes could be inferred from the measured scattering distribution [5]. The self-assembly of lipids and polypeptides are not only interesting from a fundamental biophysical perspective, but

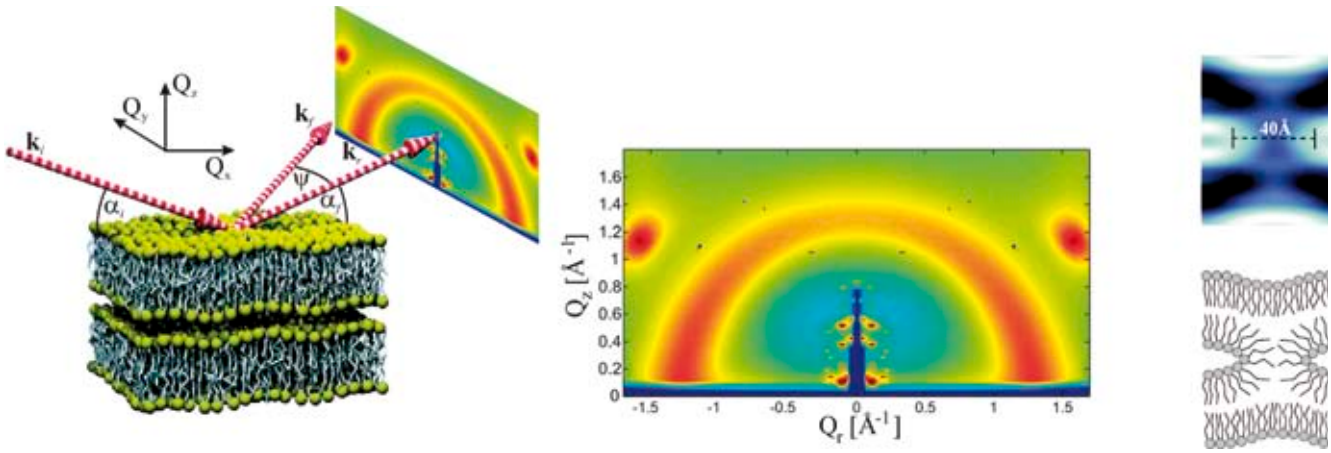
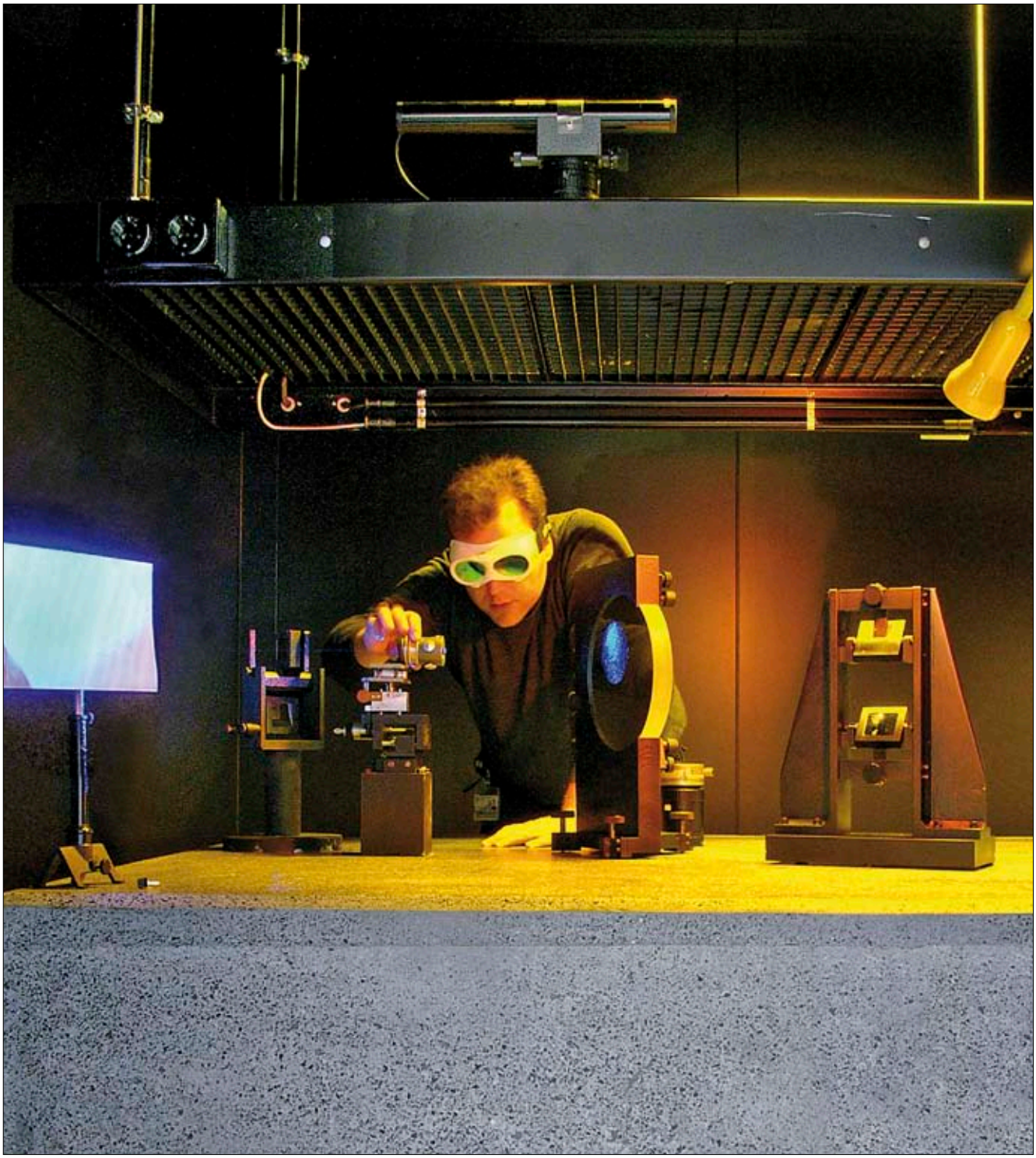


Fig. 1: Left: Schematic diagram of two planar lipid bilayers with incident, reflected and scattered beams. Middle: Diffraction pattern of a model lipid bilayer stack in the rhombohedral phase, where connections (‚stalks') are formed between neighboring bilayers. Right: Reconstructed electron density of a stalk, which can be considered as an intermediate structure occurring in membrane fusion (top). Schematic of lipids in a stalk (bottom) [9].



are also relevant for many biomedical applications. We have used aligned membrane model systems to study viral ion channels such as the membrane E protein of the SARS virus [6], and antibiotic peptides [5] in the past. Currently we use aligned membranes to study the physical mechanisms involved in membrane fusion.

Other examples of biomolecular assemblies and macromolecular materials which we have worked on include spider silk fibers, DNA/lipid complexes and polyelectrolyte films. In all examples the relationship between macromolecular self-assembly and structure, as well as between structure and functional properties pose tremendous challenges, and require high resolution structural characterization.

Currently, we want to bridge experiments in model systems to biomolecular structures studied in biological cells. The structural organization of membranes in the myelin sheath in nerve cells of higher organisms and the lipid-peptide assembly in synaptic vesicles are two examples which we work on in collaboration with colleagues from neurobiology in Göttingen. More generally, we want to adapt and to develop novel lens-less imaging methods to cellular and biomolecular imaging with high resolution in three dimensions, compatible with functional hydrated specimen. Complementing high resolution in space, high resolution in time, based on short X-ray pulses, will be the next step.

A particular imaging approach which we develop is holographic imaging based on nanoscale x-ray beams shaped and delivered by X-ray waveguides [7.,8], see Fig. 2. We couple synchrotron X-ray beams into nanoscale channels. By propagation in the channel and by exploiting of the optical mode properties, filtered and highly concentrated beams can be extracted and used to illuminate the sample coherently with well defined wave fronts. The hologram measured by a detector positioned in the far-field is then used for object reconstruction. The scope is to get a maximum of information from a minimum of delivered photons. Apart from resolution, quantitative contrast (phase measurements) is one of the assets of X-ray imaging which we want to exploit. The vision of molecular movies based on novel ultrafast X-ray sources such as the free electron laser is a goal which we share with our worldwide collegues in X-ray physics and X-ray optics. Before reaching these rather long-term goals, we hope to shed new (X-ray) light on biomolecular assemblies both in model systems and in biological cells using the novel lens-less X-ray microscope which we build for the new storage ring PETRA III at DESY, Hamburg. A brilliant future with new light and new sight!

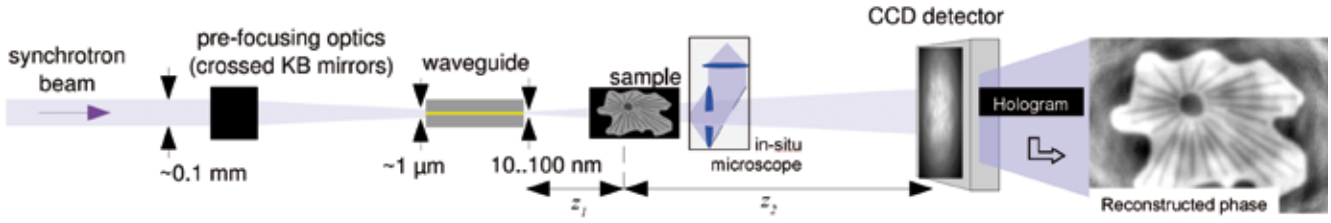


Fig. 2: Experimental setup for waveguide-based holographic microscopy of biological cells. The monochromatic synchrotron beam is focused into a 2-dimensional guiding-core of less than 100 nm diameter. The exiting divergent wavefield corresponds to a coherent single mode of the waveguide, generating a magnified inline-hologram of the sample on a CCD detector, after interacting with the sample

[1] Salditt, T.: *Thermal fluctuations and stability of solid-supported lipid membranes,* Journal of Physics, Cond. Matter, 2005, 17, R287 – R314, and references therein.

[2] Salditt, T.; Rheinstädter, M.: *Structure and Dynamics of Model Membrane Systems Probed by Elastic and Inelastic Neutron Scattering*, Neutron Scattering in Biology, Techniques and Applications, p 503-530, Fitter, J.; Gutberlet, T.; Kat-saras, J. (Eds.) Springer, 2006, XXIV, 558 p. ISBN: 3-540-29108-3, and references therein

[3] Salditt, T.; Vogel, M.; Fenzl, W.: *Thermal Fluctuations and Positional Correlations in Oriented Lipid Membranes,* Physical Review Letters, 2003, 90, 178101

[4] Rheinstädter, M.C.; Häußler, W.; Salditt, T.: *Dispersion Relation of Lipid Membrane Shape fluctuations by Neutron Spin-Echo Spectrometry,* Physical Review Letters, 2006, 97, 048103

[5] Salditt, T.: *Lipid-peptide interaction in oriented bilayers probed by interface-sensitive scattering methods,* Current Opinion in Structural Biology, 2003, 13, 467-478, and references therein.

[6] Arbely, E.; Khattari, Z.; Brotons, G.; Akkawi, M.; Salditt, T.; Arkin, I.: *A Highly Unusual Palindromic Transmembrane Helical Hairpin Formed by SARS Coronavirus E Protein,* Journal of Molecular Biolology, 2004, 341, 769-779

[7] Fuhse, C.; Ollinger, C.; Salditt, T.: *Waveguide-based off-axis holography with hard x-rays,* Physical Review Letters, 2006, 97, 254801

[8] Salditt, T.; Krüger, S. P.; Fuhse, C.; Bahtz, C.: *High-transmission planar x-ray waveguides,* Phys. Rev. Lett. 100, 2008, 184801

[9] Aeffner, S.; Reusch, T.; Weinhausen, B.; Salditt, T.: *Membrane fusion intermediates and the effect of cholesterol: An in-house x-ray scattering study,* Eur. Phys. J. E, 2009, 30, 205-214.

Tim Salditt

Tim Salditt was born in 1965 and studied physics in Munich and in Grenoble, France. He received his Ph.D. under the supervision of J. Peisl at the University of Munich, and was awarded the Ernst-Eckhard-Koch prize for an outstanding research work in his thesis using synchrotron radiation. He started to study the structure of biomolecular assemblies at the University of California at Santa Barbara (1996) with C. R. Safinya, funded by a NATO/DAAD postdoctoral fellowship (1997). Returning to Munich he joined the Centre for Nanoscience, where he finished his habilitation. In 2000, he was appointed Associate Professor at the University of the Saarland. In 2002 he became Full Professor for Experimental Physics at Göttingen University. Tim Salditt is an active user of several national and international synchrotron radiation facilities, and spokesperson of the collaborative research center Nanoscale Photonic Imaging in Göttingen.

Nanoscale Imaging of Cellular Dynamics

The cell as a whole, as well as cellular components, are governed by processes that take place on the nanometer to micrometer scale. The combination of microfluidics and micromechanics with high-resolution imaging and scattering techniques provides excellent tools to improve our understanding of the structural and dynamic principles in biological systems.

The physical properties, and in particular the mechanics of biological cells are mainly governed by three types of fibrous proteins (actin, microtubules and intermediate filaments) as well as associated binding proteins. Intermediate filaments form versatile cytoplasmic structures and are believed to play an important role in the ability of the cell to resist mechanical stress. Many processes, ranging from hierarchical self-assembly over single filament mechanics to dynamics of networks in live cells, can be studied in vitro provided that the experimental conditions are tailored to the specific biophysical question. Continuous and segmented microflow provides well-suited tools for this purpose such as controlled biochemical micro-gradients, forces controlled by defined flow fields, or geometric confinement and micro-compartments. Thus, these flow devices allow for an in situ control and manipulation of the experimental conditions and concomitant observation of the system.

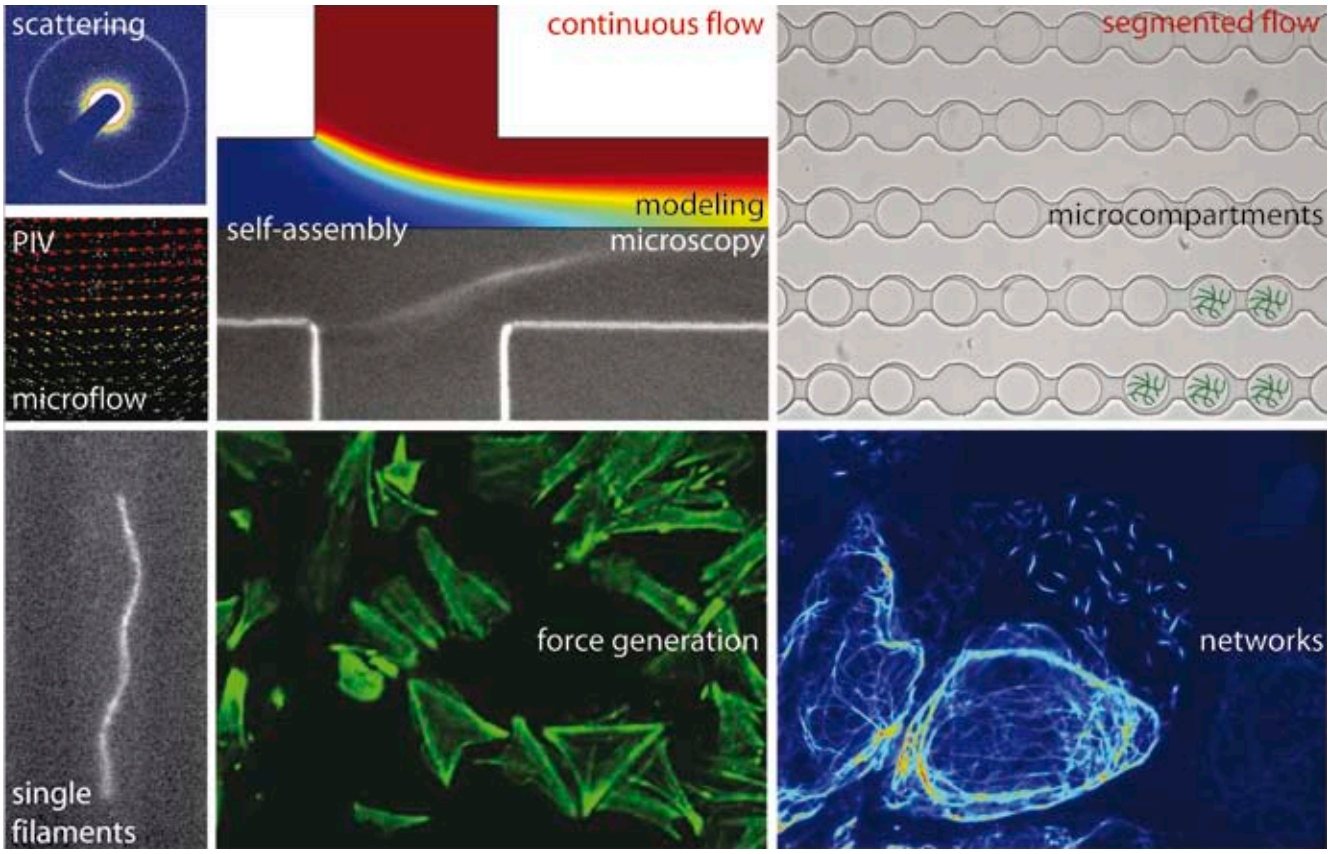
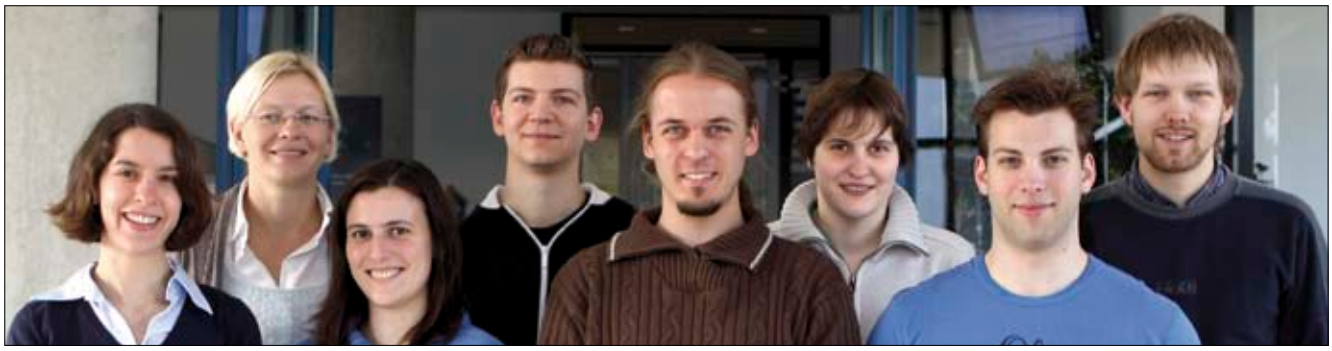


Fig. 1: Microfluidics in combination with imaging techniques allows for the in situ investigation of cells and cellular components. Clockwise, starting from top left corner: X-ray scattering signal of assembled collagen; continuous flow device (top: finite element method (FEM) simulation, bottom: polarized light microscopy); segmented flow device, water-in-oil emulsion; keratin network in a live cell; activated thrombocytes stained for actin cytoskeleton; single actin filament; particle image velocimetry (PIV) in microchannel.



Investigation of self-assembly processes and mechanical properties of individual filaments are necessary prerequisites for a better understanding of the mechanics of biopolymer networks and eventually whole cells. Besides their considerable importance in biological systems, fibrous proteins also provide excellent model systems for semiflexible polymer physics in general. The ability of reorganizing cytoskeletal structures, in turn, enables cells to interact with their environment and generate forces which they exert on other cells and connective tissues. We study the dynamic processes in cells and biological matter by combining state-of-the-art imaging, scattering and micromanipulation techniques to accomplish high spatio-temporal resolution.

[1] Köster, S. and Pfohl, T.: *An in vitro Model for Cytoskeletal Confinement,* Cell Motil. Cytoskel. (2009) 66,771-776.

[2] Köster, S. et al.: *Drop-based microfluidic devices for encapsulation of single cells,* Lab Chip (2008) 8, 1110–1115.

[3] Köster, S.; Kierfeld, J. and Pfohl, T.: *Characterization of single semiflexible filaments under geometric constraints,* Euro. Phys. J. E (2008) 25, 439-349.

[4] Köster, S.; Evans, H. M.; Wong, J. Y. and Pfohl, T.: *An in-situ study of collagen self-assembly processes,* Biomacromolecules (2008) 199-207.

[5] Köster, S.; Leach, J. B.; Struth, B.; Pfohl, T. and Wong, J.Y.: *Visualization of flow-aligned type I collagen self-assembly in tunable pH-gradients,* Langmuir, (2007) 23, 357-359.

[6] Köster, S.; Steinhauser, D. and Pfohl, T.: *Brownian motion of actin filaments in confining microchannels,* J. Phys.: Cond. Mat. (2005) 17, S4091-S4104.

Sarah Köster

Sarah Köster, born in 1979 in Reutlingen, Germany, studied physics at the University of Ulm and received her PhD from the University of Göttingen in 2006 under the supervision of Thomas Pfohl and Stefan Hermingshaus. Her thesis was awarded the Berliner-Ungewitter-Preis of the Göttingen physics faculty as well as the Otto-Hahn-Medaille of the Max-Planck-Society. In 2008, after postdoctoral studies at Harvard University with David Weitz, she returned to Göttingen as a junior professor. She leads the research group Nanoscale Imaging of Cellular Dynamics in the Courant Research Centre Nano-Spectroscopy and X-ray Imaging.

Pattern Formation in Complex Systems

Complex systems are composed of a large number of much simpler parts, which interact via simple, mechanical forces. They are called complex if they display properties which cannot be derived from studies of their isolated simple parts. Understanding the general mechanisms, which lead to such cooperative properties, is one of the deep and fundamental questions of contemporary physics. Two outstanding challenges in this field are the characteristic properties of living biological cells and the higher cognitive properties of the human brain. Can we understand these properties from interacting molecules, and electrophysiologically interacting neurons, respectively? Many insights and tools can be obtained from studies of simpler model systems, like equilibrium transitions to ordered phases, the glass transition, non-equilibrium pattern formation in driven systems, and others. They need levels of description from Boltzmann's equation to non-linear, stochastic continuum theories and use both analytical and simulation techniques.

Patterns in network models

Networks form a quite universal paradigm for modelling complex real world systems, which can be analysed from a similar theoretical point of view. This is illustrated by two examples, from completely different contexts: models of networks of neurons, interconnected via axons, which transport electrophysiological signals from one neuron to the synaptic contacts of other neurons are schematically shown in Fig. 1. A building is mapped to a network to model the transport of air, heat and moisture within its parts and zones as scetched in Fig.2. Although these systems seem to have nearly nothing in common, the theoretical tools and questions are quite similar for many practical purposes. On the one hand, we like to know the spatio-temporal activity patterns, if the system is driven by external stimuli (sensorical inputs for neurons, weather data for buildings) and on the other hand we like to study efficient ways to optimize the network structure. This corresponds to learning in the context of neural networks. On overview of contributions is given in Ref. 6. An analogous self-learning design for buildings is our technological vision. In some systems, the map to a network model is far less obvious. Glasses have an extremely complicated energy landscape, and the glassy dynamics is largely determined by the network of minima and saddle-points of this landscape in the high dimensional configuration space. This network can be explored by molecular dynamics computer simulations, as shown in Ref. 4.

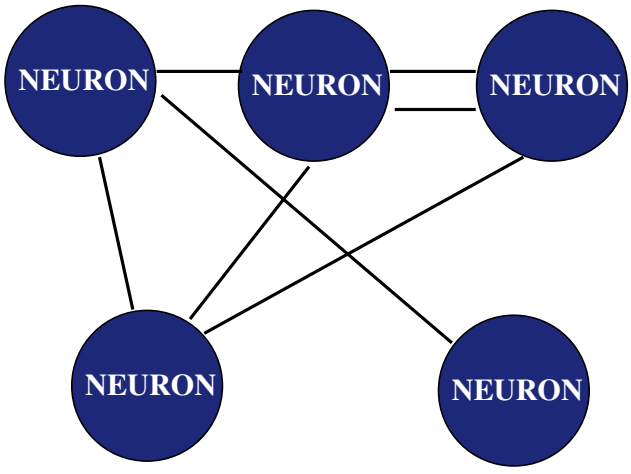


Fig. 1: A schemtic network of interconnected neurons. The state of each neuron is updated, depending upon the input of electrophysiological signals it receives from other neurons or from sensory cells.

Nano-patterns at driven surfaces

Nearly everybody has admired ripples in the sand at the beach or underwater. How do these regular structures appear – seemingly out of nothing – on the surface of sand driven by wind or water? They are good examples of pattern formation at driven surfaces, but we are more interested in the anaologous patterns on a completely different scale, the nanometer scale. Reproducible, self-organized nano-patterns at solid surfaces would render more expensive and complicated fabrication processes for nanotechnologies unneccessary. Besides, it is an amusing intellectual challenge to find out, whether gigantic desert sand dunes, little ripples on

the beach and 1 000 000 000 times smaller ripples on solid surfaces driven, for example, by ion beams or by added material from vapor are created by the same laws of physical pattern formation. Understandng the physical laws helps to diversify the patterns, which may form via self-organization and at the same time improve their quality. If the surfaces are driven by ions impinging with energies around 1000 eV (electron Volt), theoretical analysis has to bridge all physical processes from 1000 eV down to fractions of an eV, the typcial room temperature scale governing diffusional motion of atoms at a surface. This is achieved by two approaches: either using coarse-grained continuum descriptions or setting up Monte Carlo models and running computer simulations. Some results, which have been obtained by these techniques and a more detailed exposition can be found in Ref. 1 and 2.

Patterns from biochemical reactions coupled to transport

Modern molecular biology has provided a gigantic list of molecular parts of a biological cell and complicated circuit diagrams of chemical reactions between these parts. But still, this approach misses essential aspects of life, which does not only unfold in time but also in space, creating most beautiful and useful structures for its purposes. Leaving the further

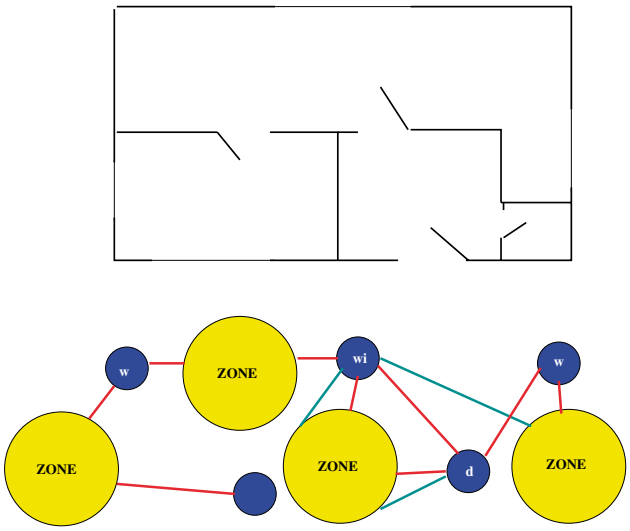


Fig. 2: Mapping a building to a network (only schematic). Zones roughly correspond to rooms. The other nodes of the network correspond to parts, like walls (w), windows (wi), doors and openings (d). Red arrows indicate heat transport, blue arrows indicate air transport. There is also transport of humidity (not shown).

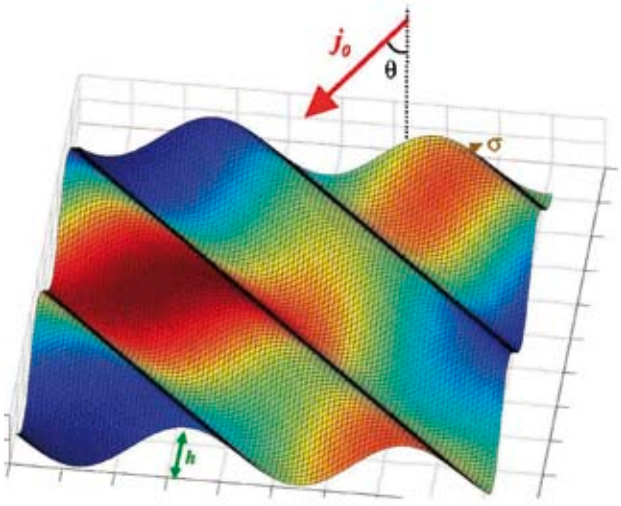


Fig. 3: Continuum picture of a driven surface. The arrow indicates the direction of the driving force, the colors indicate the state of the atoms (or grains) at the surface: red: high mobility, blue: low mobility. Differences in mobility arise from extra energy, transported to the surface by the driving force.

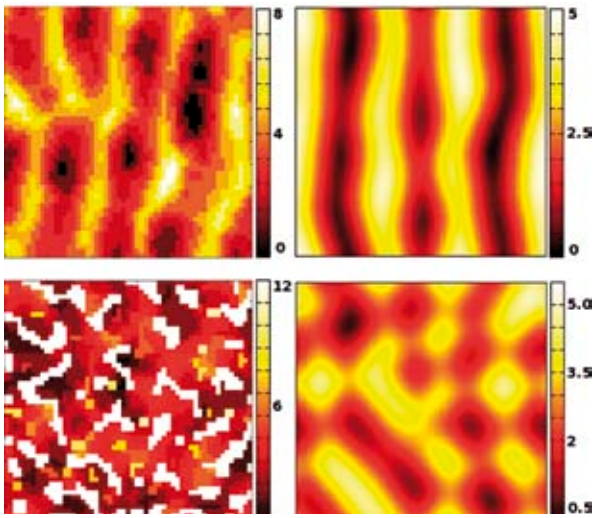


Fig. 4: Results of Monte Carlo simulations (left column) and continuum theory (right column) for pattern formation on a surface irradiated by ions, while at the same time, atoms of a different material are added by cosputtering a nearby target. Nano-ripples and ordered nano-dots may appear.

completion of molecular parts lists and biochemical interaction circuitry aside, we focus on the the formation of spatio-temporal patterns in biological matter from a physicist's point of view, emphasizing the important differences to more usual types of physical matter, i.e. active elements, cooperation by interaction between many, but also diverse parts and a high degree of spatial hetereogeneity down to nanometer scales. All these aspects are usually present in most important biological functions like cell signalling, cell motility and cell-cell interaction, which we study as examples. Pattern formation of ion channel proteins in biological membranes is possible due to a feedback of electro-diffusion of the charged proteins and the creation of electric fields along the membrane due to intermembrane currents through the channels. Such processes are studied using analytical techniques from bifurcation theory in Ref. 4. Another, physical rather than chemical regulation mechanism for patterns is based on the mechanical forces, which cells in growing tissue exert on each other, as explored by using a Monte Carlo model and computer simulations in Ref. 5.

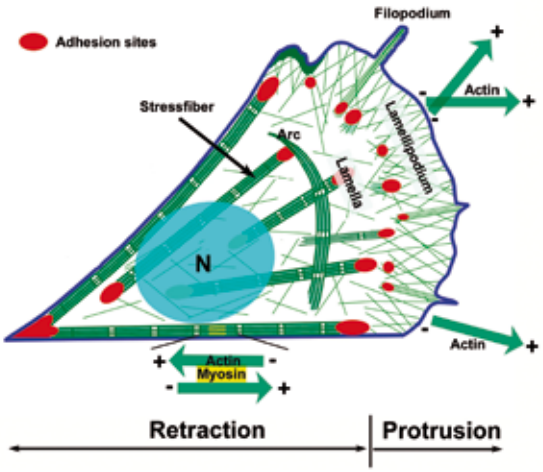


Fig. 5: A schematic picture of the apparatus of cell motility on a substrate: Behind a flattened membrane structure (lamellipodium), a network of polar macromolecules (actin) is growing, which exerts a driving force on th edge of the lamellipodum, leading to protrusion. A different, but closely apparatus of adhesion sites, which may bind or unbind to the substrate and of stress fiber bundles leads to retraction.

[1] Kree, R.; Yasseri, T.; Hartmann, A. K.: *Surfactant Sputtering: Theory of a new method of surface nanostructuring by ion beams,* Nucl. Instr. Meth. Phys. Res. B DOI: 10.1016/j.nimb.2009.01.150 (2009)

[2] Yewande, E. O.; Hartmann, A. K.; Kree, R.: *Morphological regions and oblique-incidence dot formation in a model of surface sputtering,* Physical Review B 73, 115434 (2006)

[3] Kramer, S. C.; Kree, R.: *Pattern formation of on channels with state-dependent charges and diffusion constants,* Phys. Rev. E 65, 051920 (2002)

[4] Bhattacharya, K.; Broderix, K.; Kree, R.; Zippelius, A.: *Energy Landscape and overlap distribution of binary Lennard-Jones glasses,* Europhys. Lett. 47, 449 (1999)

[5] Drasdo, D.; Kree, R. and McCaskill, J. S.: *A Monte-Carlo Approach to Tissue Cell Populations,* Phys. Rev E 52, 6635 (1995)

[6] Kree, R.: *Neural Networks: Architectures, Learning and Performance,* in Information Systems and Data Analysis, Springer-Verlag (1993)

Reiner Kree

Reiner Kree was born 1954 in Hamm in Westphalia. He studied physics at the universities of Dortmund, Cambridge (UK) and Karlsruhe, where he received his PhD in 1984 for work on disordered electronic systems. After a stay at Cornell University, he joined the theoretical physics group of Prof. Richard Bausch at the university of Düsseldorf, where he worked on a variety of topics in disordered systems, using methods from field theory applied to statistical physics. In 1990, he became a professor at the Institute for theoretical physics at the Georgia-Augusta. His main research interest has been and still is the understanding of complex physical systems, like neural networks, glasses and spin-glasses and biological matter. From 1999 to 2002 he was dean of the faculty of physics and from 2002-2006 he became vice-president of the Georgia-Augusta. Since then, he is back to science.

Computational Soft Matter and Biophysics

Soft and biological matter is characterized by a fascinating interplay between behavior on vastly different time, length and energy scales. Understanding how characteristics of individual molecules dictate macroscopic properties and collective phenomena, in which many molecules participate, is a great challenge. Using computer simulations of coarse-grained models and numerical SCF theory, we investigate collective phenomena in lipid membranes, structure formation in multi-component polymer systems, kinetics of phase transformation, wettability, flow and slippage at surfaces. A microscopic understanding of material properties and biological systems is important for practical applications, including e.g. fabricating device-oriented nanostructures, and simultaneously involves fundamental theoretical problems. Statistical physics has found fruitful application at this frontier between physics, chemistry, biology and material science and offers a unifying concept for investigating universal aspects of structure, dynamics, and collective phenomena.

Collective phenomena in lipid membranes

Phase transitions, pore formation, and fusion of lipid membranes entail large ranges of length and time – 10-1000 nm and µs-ms – and similar collective phenomena are observed in amphiphilic systems with very different microscopic interactions, e.g. biological lipids in water and copolymer melts. The qualitative behavior is dictated by only a few key properties, e.g., the molecular connectivity and repulsion between the amphiphilic units. This imparts a large degree of universality onto collective phenomena – a term borrowed from the theory of critical phenomena – and motivates the use of coarse-grained models (Fig. 1). These only retain the relevant interactions but sacrifice atomistic details in order to access the large, relevant, length and time scales in computer simulations. Such an approach assumes a clear scale separation, which is often justified for polymeric amphiphiles but less applicable to lipids. Our simulations aim at identifying relevant, molecular interactions and systematically investigating their role in collective phenomena of lipid membranes [1].

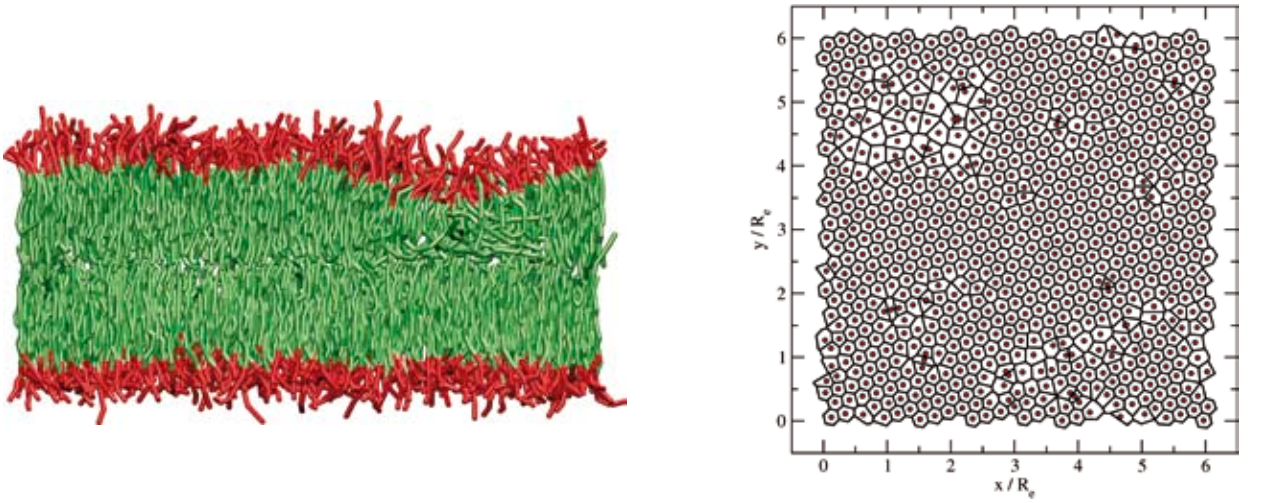


Fig. 1: Snapshot (left) of a fluid domain in the gel phase of a soft, solvent-free, coarse-grained model of a lipid bilayer. The non-bonded interactions take a form that is similar to a weighted density functional and allow us to parameterize thermodynamic properties and packing effects independently. The right panel depicts a Voronoi-tessellation of the lipid positions in the upper leaflet.

Fig. 2: Two morphologies – registered, stretched lamellae (lower, left panel) and surface reconstructed bulk lamellae (lower, right panel) – observed in the directed assembly of copolymers on a stripe surface pattern with 19 % larger periodicity than the bulk morphology. The figure illustrates how these structures are reversibly connected via an external, ordering field to calculate their free energy difference.

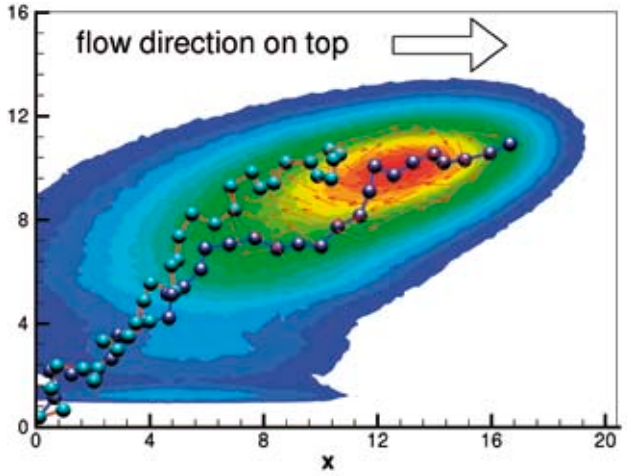


Fig. 3: Density and velocity distribution (arrows) of the terminal segment of a polymer brush. The snapshots illustrate two stages of the cyclic molecular motion, which results in a reversal of the flow direction inside the brush.

Structure formation in multi-component polymer systems

Self-assembly of amphiphilic copolymers is a strategy for fabricating nanostructures (e.g., as templates in microelectronic applications), whose dimensions can be controlled by the molecular architecture. Directing the structure formation by chemically patterned surfaces allows us to generate defect-free morphologies on macroscopic scales if symmetry and length scale of the surface pattern matches that of the bulk copolymer morphology [2]. Otherwise, the soft material exhibits an intricate surface reconstruction (Fig. 2), which persists tens of nanometers away from the surface [3, 4]. Our simulations contribute to identifying copolymer materials for replicating non-periodic patterns, e.g., by adding homopolymers or supramolecular units that reversibly form bonds.

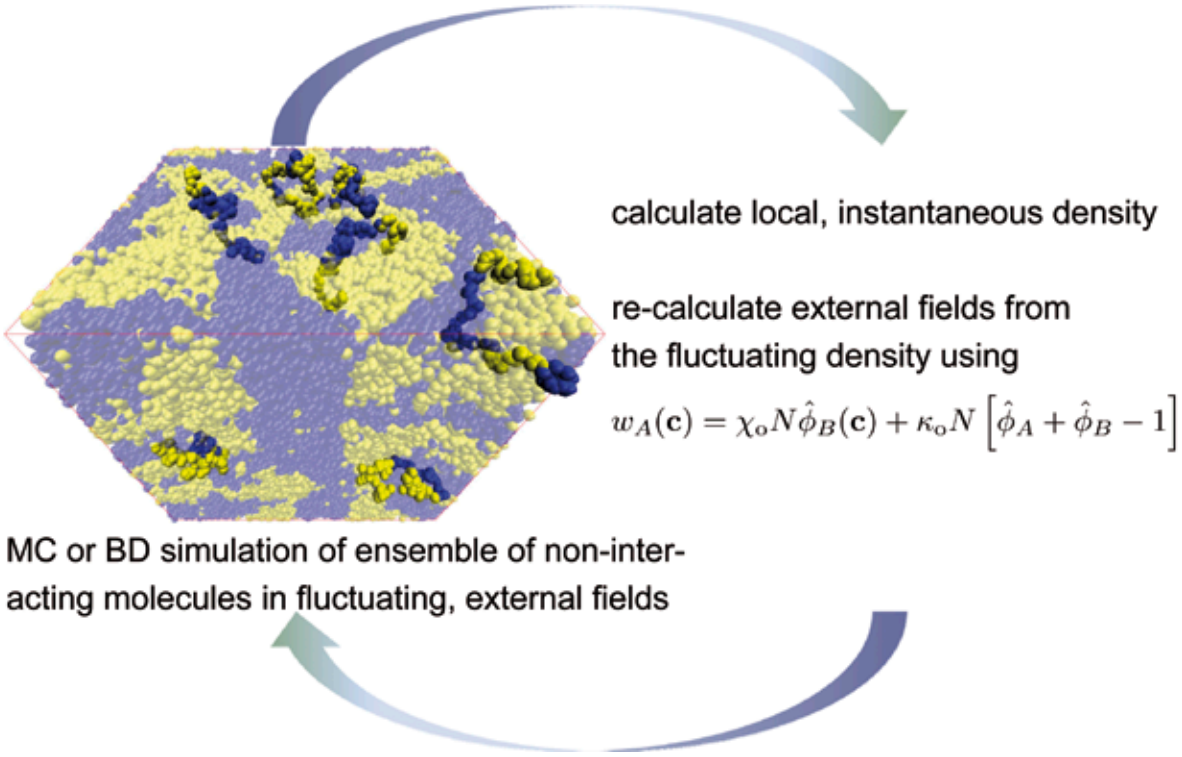


Fig. 4: Random copolymer melts studied by Single-Chain-in-Mean-Field simulations – a particle-based simulation scheme, where the interactions of a molecule with its surrounding are replaced by quasi-instantaneous external fields that are frequently recalculated from the fluctuating density distribution.

Related classes of structure-forming polymer systems include random block copolymers and multi-component polymer brushes. The former are comprised of a large number of components (sequences) and exhibit pronounced fractionation effects in the bulk and at surfaces [5]. The latter systems find practical applications as smart materials, which reversibly change their surface properties (e.g., adhesion and wettability) in response to environmental stimuli (e.g., solvent pH) [6]. The random, quenched positions of the brush's grafting points gives rise to microphase separation but the structures lack long-range order and the switching of the morphology exhibits strong memory effects.

Flow and slip at surfaces

The disparate scales in soft matter often cannot be addressed by a single computational model. In serial multi-scale modeling, thermodynamic properties, e.g., contact angle, viscosity, and hydrodynamic boundary conditions are extracted from a particle-based model. Through these quantities, the molecular structure in the bulk and at surfaces enters the continuum description, e.g., the Navier-Stokes equation, which, in turn, can address larger scales. Molecular simulations contribute to identifying microscopic dissipation mechanisms (friction) of flow past hard or deformable surfaces or in droplets. Qualitatively new phenomena can arise at complex surfaces, e.g., the failure of the Navier-slip boundary condition for glass-forming polymers at attractive surfaces [7] or the inversion of the flow direction inside a polymer brush via the collective but unsynchronized, cyclic motion of the tethered macromolecules (Fig 3)[8].

Modeling and algorithmic developments

A wide spectrum of numerical tools, including polymer-DFT, self-consistent field theory, Monte-Carlo and molecular dynamics simulation, as well as dissipative particle dynamics, is employed to study the structure and dynamics of coarse-grained models of soft and biological matter. A major thrust of our research is to combine and quantitatively map particle-based models onto field-theoretic or continuum descriptions. Both, parameter-passing schemes as well as concurrent coupling techniques, are investigated [9]. Another crucial component of our research is the development of efficient models (e.g., soft, solvent-free model for lipid membranes in Fig. 1) and accurate computational techniques (e.g., methods for measuring free energies in self-assembling systems in Fig. 2 or Single-Chain-in-Mean-Field simulations in Fig. 4).

[1] Müller, M.; Katsov, K.; Schick, M.: *Biological and synthetic membranes: What can be learned from a coarse-grained description?,* Phys. Rep. 434, 2006, 113

[2] Stoykovich, M. P.; Müller, M.; Kim, S. O.; Solak, H. H.; Edwards, E. W.; de Pablo, J. J.; Nealey, P. F.: *Directed assembly of block copolymer blends into non-regular device oriented structures,* Science 308, 2005, 1442

[3] Daoulas, K. Ch.; Müller, M.; Stoykovich, M. P.; Papakonstantopoulos, Y. J.; de Pablo, J. J.; Nealey, P. F.; Solak, H. H.: *Fabrication of complex three-dimensional nanostructures from self-assembling block copolymer materials on two-dimensional chemically patterned templates with mismatched symmetry,* Phys. Rev. Lett. 96, 2006, 036104

[4] Müller, M.; Daoulas, K. Ch.; Norizoe, Y.: *Computing free energies of interfaces in self-assembling systems,* Phys. Chem. Chem. Phys 11, 2009, 2087

[5] Houdayer, J.; Müller, M.: *Phase diagram of random copolymer melts: A Monte Carlo study,* Macromolecules 37, 2004, 4283

[6] Wang, J.; Müller, M.: *Microphase separation of mixed polymer brushes: Dependence of the morphology on grafting density, composition, chain-length asymmetry, solvent quality and selectivity,* J. Phys. Chem. B 113, 2009, 113842

[7] Servantie, J.; Müller, M.: *Temperature dependence of the slip length in polymer melts at attractive surfaces,* Phys. Rev. Lett. 101, 2008, 026101

[8] Müller, M.; Pastorino, C.: *Cyclic motion and inversion of surface flow direction in a dense polymer brush under shear,* Europhys. Lett. 81, 2008, 28002

[9] Müller, M.: *Concurrent coupling between a particle simulation and a continuum description,* Eur. Phys. J. Special Topics 177, 2009, 149

Marcus Müller

Marcus Müller received his Ph.D. in 1995 from the Johannes-Gutenberg-Universität in Mainz working with Kurt Binder on structure and thermodynamics of polymer blends. After a visit at the EPCC Edinburgh, studying ring polymers with Mike Cates, he went as a Feodor Lynen fellow to the University of Washington, where he worked with Michael Schick on homopolymer/copolymer mixtures and, later, fusion of model bilayer membranes. He returned to Mainz and obtained his Habilitation in theoretical physics in 1999. Before joining the ITP in 2005, he was an associate professor in the department of physics at the University of Wisconsin-Madison, USA, and a Heisenberg fellow of the DFG. He worked at the IFF, Jülich, and the INIFTA and CNEA, Argentina. The APS awarded him the 2004 John H. Dillon Medal. In the same year he received a Lichtenberg professorship from the Volkswagen foundation. Since 2008, he is a full professor at the ITP.

Complex Fluids

Complex fluids and soft matter are materials intermediate between conventional liquids and solids, displaying fluid-like as well as solid-like behavior. Examples are polymeric melts or solutions, glasses, gels, foams and granular matter. Many of these systems are inherently disordered and strongly heterogeneous with large fluctuations on a wide range of length- and time-scales. Furthermore many complex fluids, such as glasses or gels, never relax to equilibrium, which makes a theoretical analysis difficult. In our group we aim to understand the cooperative behavior of complex fluids and soft matter on the basis of the underlying constituents and their mutual interactions. For example we want to know: What structures can be formed in and out of equilibrium? What are the underlying principles of self-organization and what are other emergent phenomena as observed in complex fluids?

Gels and glasses

If the molecules in a polymeric melt or dense solution are sufficiently crosslinked, a gel transition is observed, when a macroscopic cluster of connected molecules forms for the first time (Fig. 1). Whereas in the fluid or sol phase at low cross-linking the molecules explore all the available volume, in the gel or amorphous solid phase the particles are localized at random positions and perform finite thermal excursions. Furthermore the fluid is characterized by a viscous response to a shear flow with a shear viscosity that diverges as the gel point is approached, indicating structural arrest. The amorphous solid has a finite stiffness to static shear deformations, which is lost at the gel point as indicated by a vanishing of the shear modulus. The experimental findings are sketched schematically in Fig. 2 where c denotes the concentration of crosslinks. In the past we have computed the viscoelastic response near the gel transition and in the highly crosslinked limit, using the methods of statistical mechanics.

Another interesting question is how to characterize the structure of an amorphous solid. What is the right order-parameter for the transition from the fluid to the amorphous solid or glassy state? On the basis of a snapshot of the glass, one cannot distinguish a fluid from a glassy state because both are disordered. On the other hand taking a second snapshot at a much later time and asking for the correlation between the two snapshots will reveal drastic differences between fluid and glassy phases. Whereas in the fluid the two disordered arrangements of the particles are completely uncorrelated, - in the amorphous solid or glass, the arrangements will be highly correlated, in fact perfectly correlated if thermal motion were suppressed. Hence an adequate order parameter is the long time limit of the incoherent scattering function

$$\Omega(\vec{q}) = \lim_{t\to\infty} \left[\langle e^{i\vec{q}\,(\vec{r}_i(t)-\vec{r}_i(0))}\rangle\right]_i$$

$$= \begin{cases} e^{-Dq^2 t} \to 0; & \text{fluid} \\ [e^{-q^2\xi^2}] \neq 0; & \text{glass} \end{cases}$$

where the localization length ξ is a measure for the extent of thermal motion. In a disordered system this quantity fluctuates from site to site, so that the main structural characteristic of an amorphous solid is the distribution of localization length: $P(\xi^2)$. It can be computed analytically within mean field theory and some results are shown in Fig. 3. Close to the transition ($c = 1.1$) $P(\xi^2)$ is a universal function. In the highly crosslinked limit ($c = 5.0$) the distribution consists of a set of peaks, each associated with a given coordination number.

We are presently generalizing these theories to anisotropic gels, displaying long range orientational order as well as glassy states. These systems show a variety of interesting new phenomena due to the coupling of stress and strain to orientational degrees of freedom which are easy to manipulate. For example, shape changes can be induced by temperature or external fields opening the route to a variety of applications

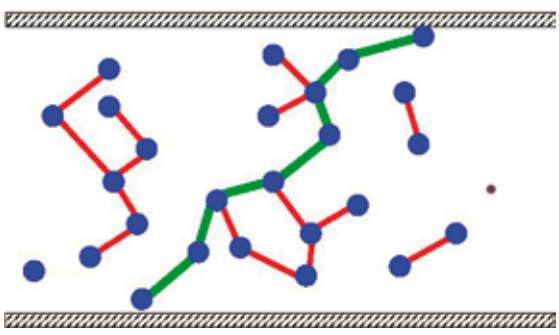


Fig. 1: Spanning cluster (green) of crosslinked molecules

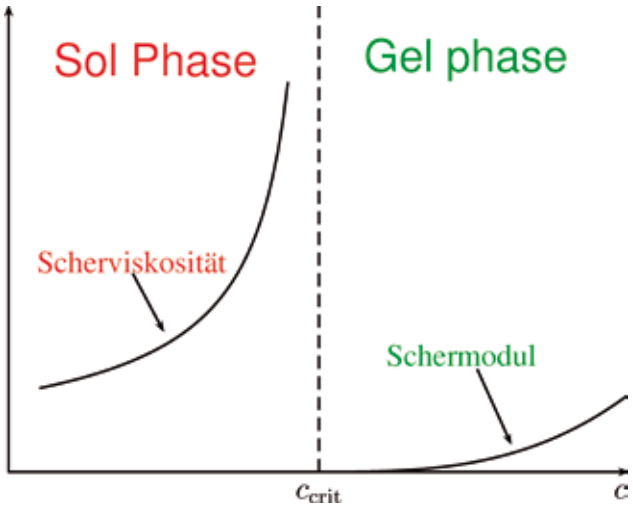


Fig. 2: Shear viscosity and shear modulus as a function of crosslink concentration c; geltransition at $c = c_{crit}$.

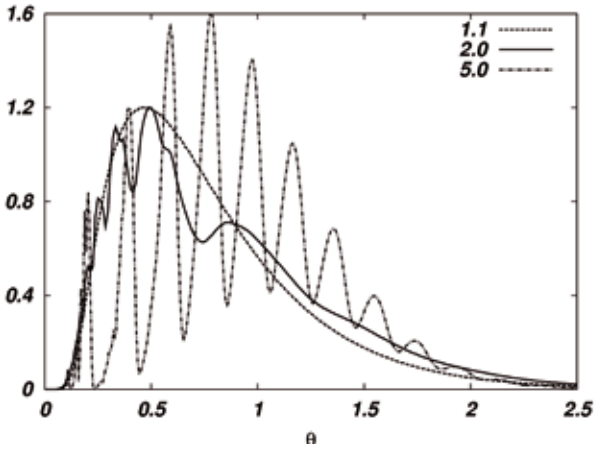


Fig. 3: Distribution of inverse localization length $w(\theta=(\bar{\xi} / \xi)^2)$; near the gel point (c = 1.1) and in the highly crosslinked limit c = 5.

such as artificial muscles. Anisotropic gels are also prominent in biological systems such as cells (Fig. 4), yet their viscoleastic properties are only poorly understood.

Collective dynamics of granular fluids

Granular media are an important and popular subject of current research which is owed partly to the striking phenomena which they reveal and partly to their ubiquity in nature and industry which makes a good understanding of their properties indispensable. Examples are sand, snow, gravel, and seeds to mention but a few. In fact the majority of industrial products are processed and handled in the form of granular media, such as powders. The materials are composed of macroscopic particles, which are big enough to render thermal agitation negligible. The interactions are in general dissipative, so that granular systems continuously loose energy unless they are externally driven to a stationary state.

We are doing basic research in our group and hence focus on simple model systems, such as hard, spherical particles which collide inelastically. The simplest problem is to understand, how a gas of such inelastically colliding particles cools down as a function of time. This problem has been investigated intensively for smooth granular particles ignoring frictional forces in collisions. Our focus is on particles with rotational degrees of freedom and friction, such that in collisions translational energy is transferred to rotational motion and vice versa. In the past we have shown that free cooling proceeds such that the ratio of translational to rotational energy relaxes quickly to a constant value which is not only different from equipartition, but depends on the details of the collision rules and the particles' properties (Fig. 5). We have also shown that the direction of the linear velocity is in general correlated with the axis of rotation such that the granular particles move in some systems predominantly like sliced tennis balls in other systems like cannon balls.

At present we are investigating the question, whether a driven granular gas undergoes a glass transition and if so, how the transition as well as the glassy state differ from an undriven, elastic glass-forming fluid. We perform event driven simulations and try to derive a mode-coupling theory, generalizing the results of molecular fluids to granular ones far from equilibrium. In the simulations we observe strong precursors of structural arrest: cage effects in the mean square displacement (Fig. 6), backscattering effects in the velocity autocorrelation and a strong decrease of the diffusion constant.

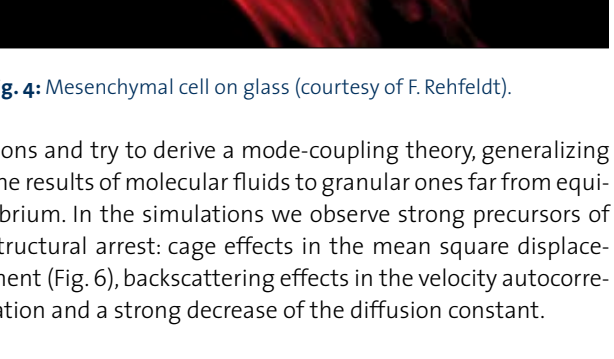


Fig. 4: Mesenchymal cell on glass (courtesy of F. Rehfeldt).

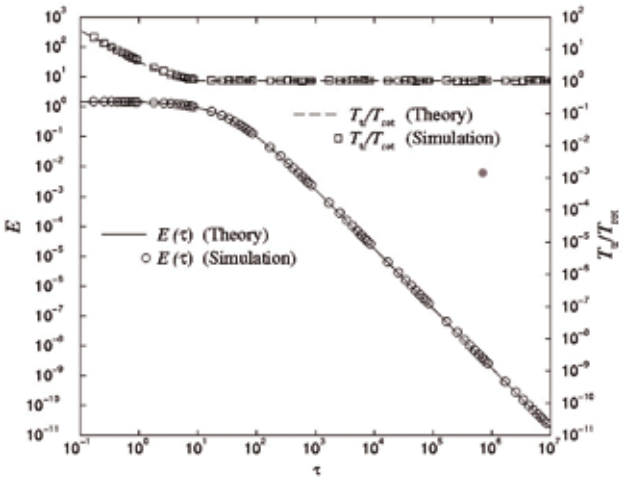
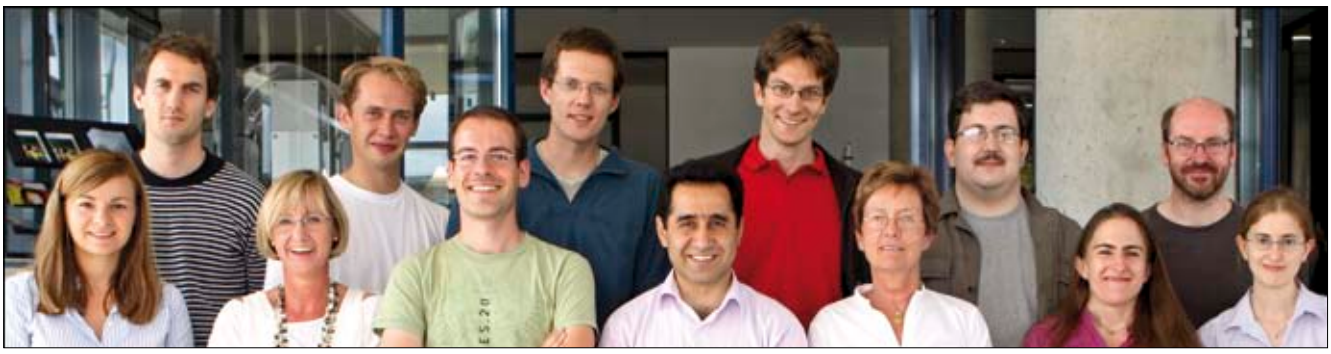


Fig. 5: Decay of the translational (T_{tr}) and rotational (T_{rot}) energy for a freely cooling gas of frictional particles.



Adding a small amount of liquid to a granular medium changes its properties dramatically, as is well known to everyone who has built sand castles. The difference in macroscopic behavior is reflected in the microscopic interactions. Wetted grains are covered by thin liquid films which merge, when the particles touch forming a liquid bridge. As the particles move apart the bridge is stretched and ultimately ruptures, provided the particles have enough kinetic energy. Rupture of a bridge gives rise to dissipation of a fixed amount of energy. In collaboration with the group of Prof. Herminghaus at the MPI for Dynamics and Self-organization, we study the dynamics and structure formation in wet granular gases. We have formulated an event driven algorithm which allows simulating large assemblies for a long time. A particularly important aspect of cooling in cohesive gases is aggregation, which sets in when the kinetic energy falls below the bond-breaking energy. The resulting clusters, an example is shown in Fig. 7 , are very loosely packed but stable structures with interesting fractal properties.

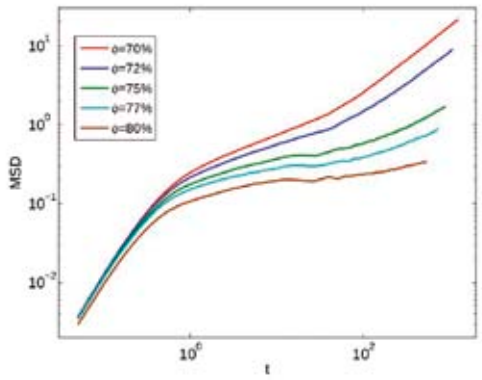


Fig. 6: Mean square displacement of a driven granular fluid in two dimensions; volume fraction Φ is increasing from Φ=70 % up to Φ=80 %.

[1] Ulrich, S.; Aspelmeier, T.; Röller, K.; Fingerle, A.; Herminghaus, S. and Zippelius, A.: *Cooling and Aggregation in Wet Granulates,* Phys. Rev. Lett. 102, 148002 (2009)

[2] Fiege, A.; Aspelmeier, T. and Zippelius, A.: *Long-time tails and cage effects in driven granular fluids,* Phys. Rev. Lett. 102, 098001 (2009)

[3] Trommershäuser, J.; Schneggenburger, R.; Zippelius, A. and Neher, E.: *Heterogeneous presynaptic release probabilities: Functional relevance for short-term plasticity,* Biophys. J. 84, 1563 (2003)

[4] Broderix, K.; Aspelmeier, T.; Hartmann, A. and Zippelius, A.: *Stress Relaxation of Near-Critical Gels,* Phys. Rev. E64, 021404 (2001)

[5] Broderix, K.; Bhattacharya, K.; Cavagna, A.; Zippelius, A. and Giardina, I.: *Energy Landscape of a Lennard Jones Liquid: Statistics of Stationary Points,* Phys. Rev. Lett. 85, 5360 (2000)

[6] Goldbart, P. M.; Castillo, H. E. and Zippelius, A.: *Randomly crosslinked macromolecular networks: Vulcanization transition to and properties of the amorphous solid state,* Adv. in Phys. 45, 393 (1996)

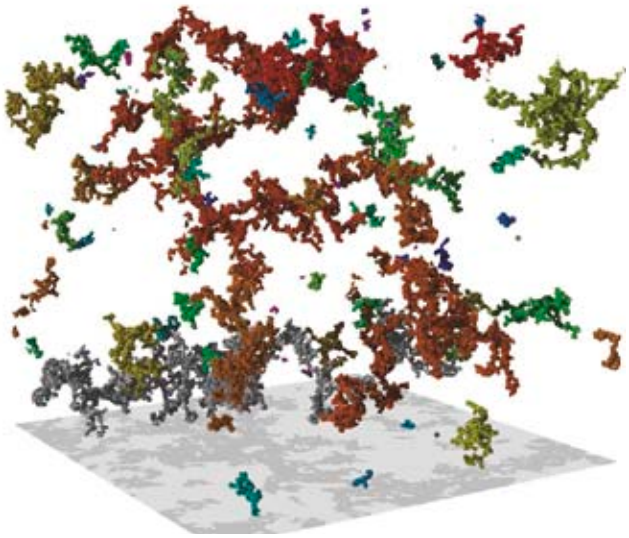


Fig. 7: Aggregated clusters in a freely cooling cohesive granular gas.

Annette Zippelius

Annette Zippelius studied physics at the Technical University of Munich and the University of Colorado in Boulder, USA, where she received a Masters degree. After finishing her PhD in Munich in 1977, she spent two years as a postdoc in Harvard and a third year in Cornell. Back in Munich she got her habilitation in 1982, joined the staff at the Forschungszentrum in Jülich in 1983 and became a full professor in Göttingen in 1988. Since 1993 she is a member of the Akademie der Wissenschaften in Göttingen. She was awarded the Gottfried-Wilhelm-Leibniz prize in 1998 and became a member of the Wissenschaftsrat in 2005. She is currently a Max Planck fellow at the MPI for Dynamics and Self-Organization

Liquid Crystals on Disordered Surfaces

Phase transitions are all around us. Think, for instance, of the melting of ice or the boiling of water. An important topic in physics is how phase transitions are altered when the substance undergoing the transition is confined in some way. As examples of confinement, one could think of water inside a narrow tube or of particles diffusing on a cell membrane. In the research group *Liquid Crystals on Disordered Surfaces* we focus on a rather special kind of confinement known as *quenched random disorder*. By this we mean a network of randomly distributed obstacles, for example disks, that do not move over time. A schematic representation of the sort of system that we are interested is shown in Fig. 1. Here the red disks form the random network, and hence do not move, while the green and purple disks are mobile particles moving around inside the random network.

Phase transitions of fluids or mixtures inside such random networks are of practical and fundamental importance. One obvious question is: how sensitive are phase transitions to the particular way in which the quenched disorder is realized? To answer questions such as these, we use computer simulations, mostly the Monte Carlo method. In simple terms, we prepare a random network in computer memory, let the mobile particles diffuse through these networks and "see what happens". The advantage of this approach is that computers are nowadays so fast that one can easily repeat this procedure for many different realizations of the random network, and hence get a good idea of what would happen in real life.

Note that Fig. 1 is still a relatively simple situation, with the particles being modeled as disks. We are also interested in the more complicated problem of liquid crystal phase transitions with quenched disorder. In this case, the particles are not simply spherical but shaped more like rods. Hence, not only the position of the particle matters, but also its orientation.

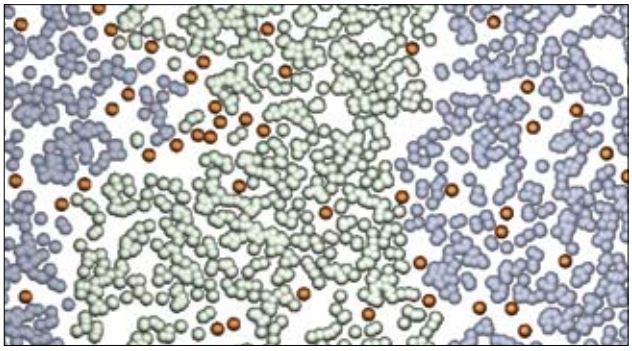


Fig. 1: Computer simulation snapshot of a fluid mixture inside a quenched random network. The red disks are randomly distributed obstacles that do not move over time, while the green and purple disks represent the mobile fluid particles (picture courtesy of Timo Fischer).

[1] Vink, R.L.C.: *Critical behavior of soft matter fluids in bulk and in random porous media: from Ising to random-field Ising universality,* Soft Matter (invited review) 5, 4388-4400 (2009).

[2] Fischer, T. and Vink, R. L. C.: *Restricted orientation liquid crystal in two dimensions: isotropic-nematic transition or liquid-gas (?),* EPL 85, 56003 (2009).

[3] Fish J. M. and Vink, R. L. C.: *Finite-size effects at first-order isotropic-to-nematic transitions,* Phys. Rev. B 80, 014107 (2009).

[4] Fischer, T. and Vink, R.L.C.: *The Widom-Rowlinson mixture on a sphere: Elimination of exponential slowing down at first-order phase transitions,* to appear in J. Phys.: Condens. Matter (2009), http://arxiv.org/abs/0910.5669.

Richard Vink

Richard Vink obtained his Ph.D. in 2002 at the University of Utrecht, the Netherlands, where he worked on the construction of amorphous silicon networks using computer simulation. In 2003, he accepted a postdoc position in the group of Kurt Binder at the University of Mainz. During this time, he specialized on colloid-polymer demixing, both in bulk and confinement, using high-resolution Monte Carlo methods and finite-size scaling. In 2005, he moved to the group of Hartmut Löwen in Düsseldorf, where the interplay between colloid-polymer demixing and quenched disorder was investigated. Since 2007, Richard is leading a junior research group financed by the Emmy Noether program of the Deutsche Forschungsgemeinschaft at the University of Göttingen.

Nonlinear Dynamics, Chaos, and Theoretical Neurophysics

Research at the Institute of Nonlinear Dynamics is concerned with complex systems and their behavior ranging from theoretical investigations in quantum chaos to nonlinear phenomena occuring in the brain. On one hand, we aim at a deeper understanding of the characteristic dynamics of mesoscopic systems, transport in electronic nanostructures and optical microstructures and the influence of disorder on such systems. On the other hand, relying on methods from nonlinear dynamics, we focus on complex neural behavior observed in biological and artificial neural networks. Finally, an important focus of our research is the theory and analysis of super- and subdiffusive transport phenomena in biological and epidemiological systems. In all areas, research ranges from projects combining mathematical modelling with experimental and empirical studies to the development of new mathematical and computational approaches.

Theoretical Challenges: From Quantum Chaos to Neural Networks

The Institute of Nonlinear Dynamics is closely connected with the Max Planck Institute for Dynamics and Self-Organization. Its research is motivated by such questions as: How do the neurons in our brain cooperate when we perceive an object or perform a task? How does the dynamics of such networks depend on their topology? What are the general principles governing the formation of patterns and neuronal representations in the cortex? What are the dynamical properties of mesoscopic quantum systems and how can they be described semiclassically? Are there statistical principles underlying human travel and can they be used to forecast the geographical spread of epidemics?

These questions typically address the complex dynamics of spatially extended or multicomponent nonlinear systems which still hold many surprises. As an example, we found unstable attractors in networks of spiking neurons, a phenomenon which would neither have been guessed nor understood without mathematical modelling and which many physicists consider an oxymoron. Such attractors have a full basin of attraction, but due to their unstable character they allow the network to switch easily and rapidly between different attractors under external stimulation. A dynamics shaped by unstable attractors may play an important functional role in the central nervous system by providing it with a high degree of flexibility in order to respond to frequently changing tasks.

This example illustrates the need and the role of mathematical analysis for the understanding of complex systems in nature. The concepts and methods developed previously in nonlinear dynamics and chaotic systems can now help us clarify the dynamics and function of spatially extended and multicomponent natural systems. On the other hand, rigorous mathematical analysis of the dynamics of such systems often cannot rely on mainstream recipes but po-

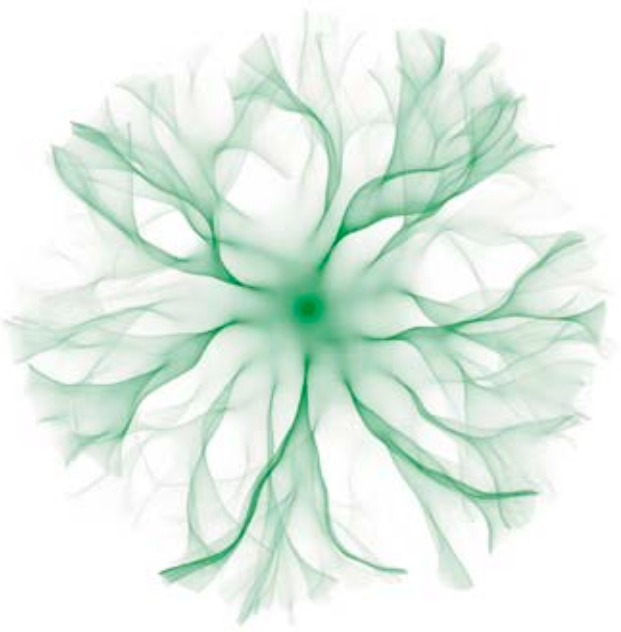


Fig. 1: Particles, as well as waves, moving through a weak-disorder potential show surprising branching effects. This has most notably been observed in two-dimensional electron gases, but is a phenomenon of much wider applicability. The picture shows the density of particles spreading balistically from a source in the center under the influence of a weak random potential.

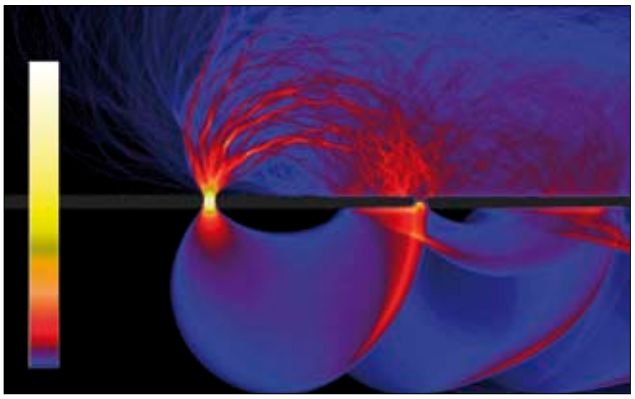


Fig. 2: Branching flow of electrons moving in a constant magnetic field. Upper half: density of electrons propagating in a weak disorder potential. Lower half: flow from an identical electron source without disorder. The electron source is the yellow birth spot on the left.

ses new and substantial challenges. In particular, neural systems exhibit several features that make them elude standard mathematical treatment: The units of the network e. g. communicate or interact at discrete times only and not continuously as in many-body theory in physics. There are significant interaction delays, which make the systems formally infinite dimensional. Complex connectivities give rise to novel multi-operator problems, for which we are devising new methods based on graph theory so as to obtain rigorous analytic results.

We are also applying graph theory in our work on quantum chaos. Similarly we use random matrix theory not only in quantum mechanical systems, but also to characterize the stability matrices of synchronized firing patterns in disordered neural networks. Neuronal spike trains can be modelled as stochastic point processes which is also a very versatile approach to characterize energy levels of quantum chaotic systems. This list of examples illustrates the extent to which cross-fertilization among the various research areas of the Institute of Nonlinear Dynamics is possible and often proves essential for achieving substantial progress in understanding complex systems. The accompanying figures provide further examples of such phenomena studied at the Institute.

Theoretical studies of complex systems are scientifically most fruitful when analytical approaches to mathematically tractable and often abstract models are pursued in close conjunction with comprehensive computational modeling and advanced quantitative analyses of experimental data. The Institute of Nonlinear Dynamics thus naturally

Fig 3: The Institute of Nonlinear Dynamics disposes of a set of dedicated high performance computing platforms, including the cluster of blade servers with 640 CPU cores shown above. They are used e.g. for simulation studies of the dynamics of neuronal activity in brain models, calculations of quantum mechanical wave propagation in complex semiconductor geometries, or studies of the dispersal of pathogens in human populations. The panels on the left show snapshots from a simulation of self-organizing neuronal circuits in the visual cortex of the brain. Colors encode the angle of preferred visual stimuli. In this simulation, the network was prepared by external stimulation in an initial state of approximate square symmetry. The state dynamically decays into a complex pattern, retaining signatures of the square symmetry. The simulated region represents roughly 100 million neurons.

has a strong background in computational physics and operates considerable computer resources. Research for which this is essential besides the network dynamics mentioned above includes e.g. studies of pattern formation in the developing brain, the dynamics of spreading epidemics, and transport in mesoscopic systems.

Cooperation with the Max Planck Society

The Institute of Nonlinear Dynamics, headed by Theo Geisel, was created by a joined initiative of the Max Planck Society and the University of Göttingen. It is connected with the Department of Nonlinear Dynamics of the Max Planck Institute for Dynamics and Self-Organization, which is headed also by Theo Geisel, and interacts closely with two new experimental departments at the Max Planck Institute established in 2003. It has also initiated and hosts the federally (BMBF) funded Bernstein Center for Computational Neuroscience Göttingen, in which it cooperates with advanced experimental neuroscience labs in Göttingen. The Department of Nonlinear Dynamics includes the Research Group Theoretical Neurophysics which was established in 2004 by the appointment of Fred Wolf as Research Group Leader (W2) by the President of the Max Planck Society. The Research Group Theoretical Neurophysics studies theoretical neuroscience problems from the dynamics of neuronal encoding in single neurons to the self-organization of large-scale networks in the brain.

[1] Hufnagel, L.; Brockmann, D.; Geisel, T.: *Forecast and control of epidemics in a globalized world,* PNAS 101, 15124-15129 (2004).

[2] Timme, M.; Wolf, F.; Geisel, T.: *Topological speed limits to network synchronization,* Physical Review Letters 92, 074101-04 (2004).

[3] Brockmann, D.; Hufnagel, L.; Geisel, T.: *The scaling laws of human travel.* Nature, 439, 462-465 (2006).

[4] Levina, A.; Herrmann, J. M.; Geisel, T.: *Dynamical synapses causing self-organized criticality in neural networks,* Nature Physics 3, 857-860 (2007).

[5] Hennig, H.; Fleischmann, R.; Kottos, T.; Geisel, T.: *Avalanches of Bose-Einstein condensates in leaking optical lattices,* New Journal of Physics 11, 073045-59 (2009). Ng G.S.

[6] Levina, A.; Herrmann, J. M.; Geisel, T.: *Phase transitions towards criticality in a neural system with adaptive interactions,* Physical Review Letters 102, 118110-13 (2009).

Theo Geisel

Theo Geisel studied physics and mathematics at the Universities of Frankfurt/M. and Regensburg, receiving his doctorate in 1975. After postdoctoral research at the Max Planck Institute for Solid State Research (1976-1977) and the Xerox Palo Alto Research Center (1978-1979) he completed his Habilitation in 1982. 1983-1987 he was Heisenberg Fellow at the University of Regensburg, 1988-1989 Professor at the University of Würzburg and 1989-1996 at the University of Frankfurt. Since 1996 he is Professor of Theoretical Physics at the University of Göttingen and Director at the Max Planck Institute for Dynamics and Self-Organization. Since 2008 he is Fellow of the American Physical Society and serves as Divisional Associate Editor of Physical Review Letters. He founded and heads the Bernstein Center for Computational Neuroscience Göttingen. Theo Geisel received the Gottfried Wilhelm Leibniz Prize (DFG) in 1994 and the Gentner-Kastler Prize (DPG and SFP) in 2009.

Fluid Dynamics, Pattern Formation and Nanobiocomplexity

Nonlinear systems which are out of equilibrium impact our everyday lives on many levels. They often show self-organization and complex, sometimes unpredictable spatio-temporal dynamics. Although they differ in detail, often the temporal and spatial structure of many different systems can be described by unifying principles. Searching for and understanding those principles is at the center of our research. To achieve this goal, we are focusing on well-defined problems in the physics of fluid dynamics and of cellular biology. Currently, we are investigating pattern formation, spatiotemporal chaos and turbulence in thermal convection. We study particle transport in fully developed turbulence of simple and complex fluids and their implications on fundamental theories, as well as practical issues like turbulent mixing, particle aggregation, and cloud micro-physics. Further research concerns the spatio-temporal dynamics of the electric signals in the heart (with Prof. S. Luther) and the intra-cellular processes leading to eukaryotic cell motility and chemotaxis.

Turbulence

In turbulent flows, mixing and transport are dominated by the huge fluctuations ranging from the scale where energy is injected (which could be hundreds of meters) to the scale where energy is dissipated by viscosity (which could be microns). Turbulence plays a central role, for example, in the reduction of emissions in aeronautics, in the efficient energy production, for the understanding of climate change, and in astrophysical galaxy formation. Considering its importance, our understanding of the physics of turbulence remains rudimentary. Investigations require flows with high Reynolds numbers under well-controlled conditions. In the foreseeable future, computational fluid dynamics will be able to substitute experiments, but only for flows with moderate Reynolds numbers and idealized flows. High Reynolds-numbers at manageable temporal and spatial scales can be realized with compressed and heavy gases. Thus, we have installed two unique facilities that use pressurized SF6 gas at up to 20 bar. The first is a wind tunnel with an extra long measurements section, allowing particle tracking of decaying turbulence. The second, called the "Uboot", is used for the investigations in turbulent mixers and of turbulent thermal convection (see Fig. 1). We are developing and applying advanced measurement technology for our studies. For example, we developed ultra-high-speed particle tracking systems that follow thousands of micron size particles in 3D. For the experiments in the wind tunnel and on the Zugspitze, a mountain in Germany, a high precision sled system has been built that drives the 3D particle tracking system with winds at speeds up to 7.5 m/s.

Fig. 1: Göttingen Turbulence Facility. The red tunnel is 18 m long and 6 m high. The blue 'Uboot' has a 2.5 m diameter and is 5 m long, the turret is 4 m high. The vessels can be filled up to 20 bar with SF6 gas.

Cloud Dynamics

Convection and turbulence play an essential role in cloud-micro-physical processes. They drive entrainment and mixing of temperature, moisture, aerosols, and droplets. They also impact droplet coalescence and collisions. Rain initiation in clouds and the associated dynamics of cloud droplets remains one of the open questions of meteorology. The lack in understanding of cloud-micro-physics leads to the largest uncertainty in climate predictions. In a combination of experiments in the wind tunnel, the “Uboot” and in the field we are addressing droplet dynamics in forced turbulence, entrainment and mixing, moist convection, and droplet dynamics in real clouds (see Fig. 2).

Fig. 2: 3D droplet imaging system being installed at Environmental Research Station Schneefernerhaus at 2700 m.

Pattern Formation

Naturally driven, non-equilibrium pattern-forming systems can simultaneously exhibit more than one symmetry breaking mechanism. Examples include frost heave rock-soil separation patterns in sloped alpine and polar regions, atmospheric flows over topography, and fingerprint formation in the presence of normal epidermic displacements. We use forced inclined layer convection of a shallow fluid layer as a paradigm for the quantitative investigation of such symmetry breaking mechanisms. Special interests are in localized, solitary states and the control of spatio-temporal chaos.

Cell Motility and Chemotaxis

Cell motility and chemotaxis are considered a paradigm for complex dynamics in biological matter. In higher organisms, pathways that link the membrane receptor input to rearrangements of the cytoskeleton are complex and only partly known. Eukaryotic cells like neutrophils or the amoeba Dictyostelium D. can detect chemoattractant gradients as small as

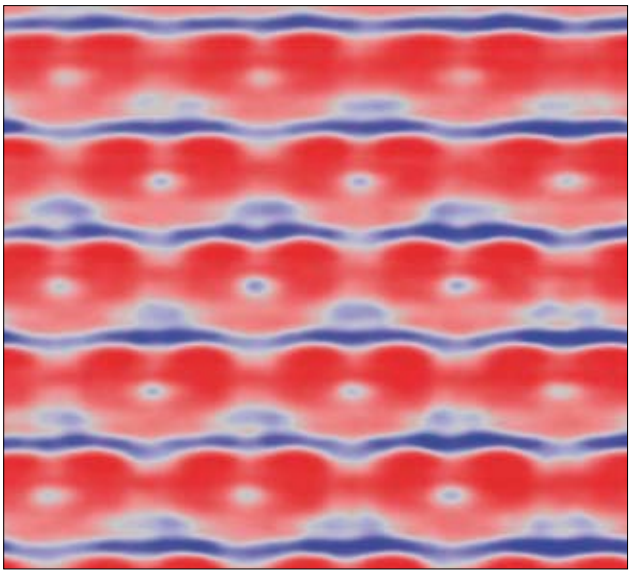
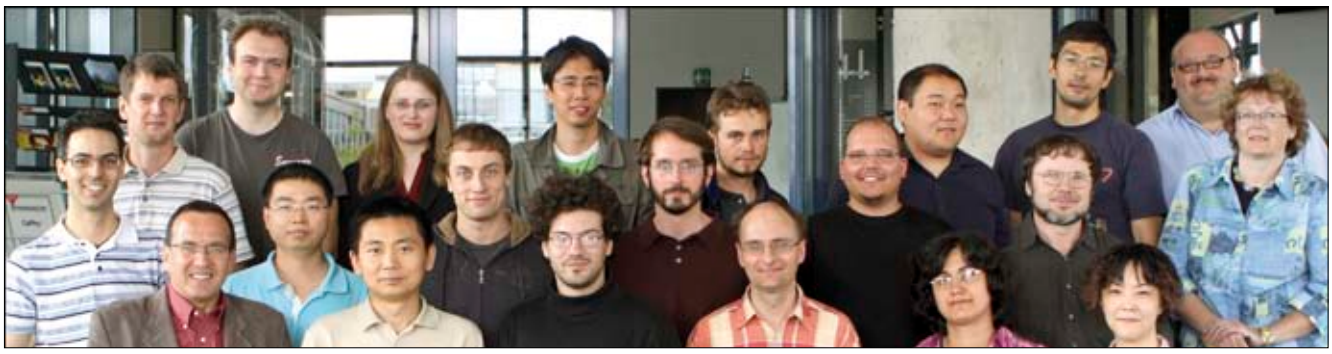


Fig. 3: False color shadowgraph image of the planar flow patterns (warm upflow red and cold downflow blue). The spacing between the blue lines is approx. 1mm.



a 1% difference in concentration between the front and the back of the cell and exhibit high sensitivity to gradients ranging over several orders of magnitude. This can be only achieved if highly nonlinear interactions govern the early stages of chemotactic signaling. Typically, during the first few seconds after exposure to a chemoattractant gradient, an intracellular symmetry breaking occurs, which is reflected in asymmetric spatial distributions of numerous proteins across the cell. These subcellular reorganizations can be experimentally observed by fluorescence microscopy imaging. We perform experiments on a Dictyostelium strains that carry fluorescently tagged proteins and investigate the intracellular response to well controlled stimulation. To do this, we use tailored microfluidic devices and state of the art imaging techniques. We compare our results quantitatively with theoretical predictions and, if necessary, develop and refine theoretical models. The aim is to better our understanding of the intracellular self-organization during chemotaxis and cell migration. LFPN has a microscopy facility, a class 1000 clean room for microfabrication and a cell biology laboratory.

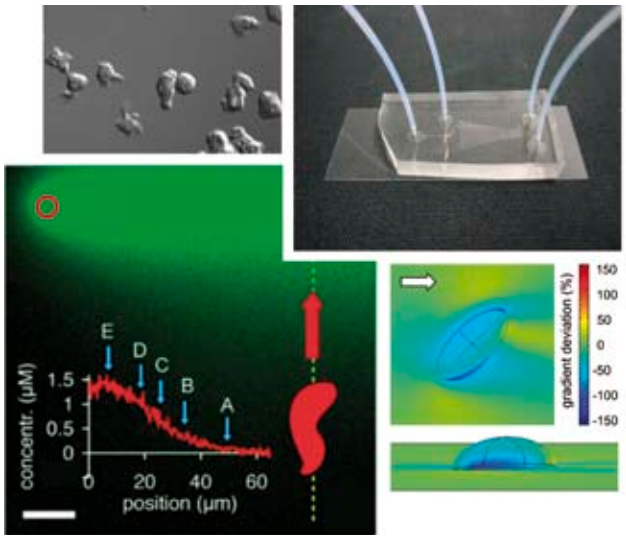


Fig. 4: (a) Dictyostelium cells in a microfluid device (cell size 10 micron); (b) microfluidic gradient mixer on a cover slip; (c) uncaged fluorescent dye in a microfluidc device. The red ring marks the uncaging region. A plot of the concentration as a function of position along the dashed line is schematically drawn with the cell in red; (d) simulation results of the deviation from the nominal gradient due to a virtual cell.

[1] Bourgoin, M.; Ouellette, N. T.; Xu, H.; Berg, J.; Bodenschatz, E.: *The role of Pair Dispersion in Turbulent Flow,* Science 311 (2006) 835-838.

[2] Xu, H.; Ouellette, N. T.; Bodenschatz, E.; *Evolution of geometric structures in intense turbulence,* New J. Phys. 10 (2008) 013012.

[3] Funfschilling, D.; Bodenschatz, E.; Ahlers, G.; *Search for the Ultimate State" in Turbulent Rayleigh-Bénard Convection,* Phys. Rev. Lett. 103 (2009) 014503.

[4] Seiden, G.; Weiss, S.; McCoy, J. H.; Pesch, W.; Bodenschatz, E.: *Pattern Forming System in the Presence of Different Symmetry-Breaking Mechanisms,* Phys. Rev. Lett. 101 (2008) 214503.

[5] Song, L. et al.: *Dictyostelium discoideum chemotaxis: Threshold for directed motion,* Eur. J. Cell Biol., 85 (2006) 981–989.

[6] Bae, A. J.; Beta, C.; Bodenschatz, E: *Rapid switching of chemical signals in microfluidic devices,* Lab Chip, 9 (2009) 3059-3065.

Eberhard Bodenschatz

After graduating in theoretical physics from University of Bayreuth in 1989, he went to UCSB with a DFG research fellowship. From 1992 to 2005 he was Professor of experimental Physics at Cornell University. In 2003, he became Director of the MPIDS, in 2005 Adjunct Professor of Physics and of Mechanical and Aerospace Engineering at Cornell University, and in 2007 Full Professor of Physics at the University of Göttingen. He is an Alfred P. Sloan Research Fellow (1993), a Cottrell Scholar (1995), and a Fellow of the APS (2003). He serves as Editor in Chief of New Journal of Physics, on the Editorial Board of Annual Review of Condensed Matter Physics, is on the Advisory Board of the KITP (UCSB), and on the Advisory Board of arXiv. He is a director of the Materials Research Society. He is a supporter of the first public international school of Lower Saxony, the Felix Klein Gymnasium, and a promoter of OA-Publishing.

Fluid Mechanics

DLR (German Aerospace Center) is Germany's national research centre for aeronautics and space. DLR's research portfolio ranges from fundamental research to innovative development of the applications and products of tomorrow in aeronautics, space, transportation and energy. Approximately 6,000 people work for DLR; the center has 29 institutes and facilities at 13 locations in Germany.

The Institute of Aerodynamics and Flow Technology at DLR's site Göttingen is engaged in numerical and experimental investigations on air, space and ground vehicles. Experiments are performed in wind tunnels and in real flight.

The department of Experimental Methods develops optical and acoustical field measurement techniques for the acquisition of fluid mechanical (velocity, pressure, density, deformation) and aero-acoustical quantities (sound pressure). Application is mainly performed with mobile measurement systems in large industrial wind tunnels and at in-flight testing in the scope of national and European projects, providing high quality data sets which constitute a reliable basis for the validation of numerical codes.

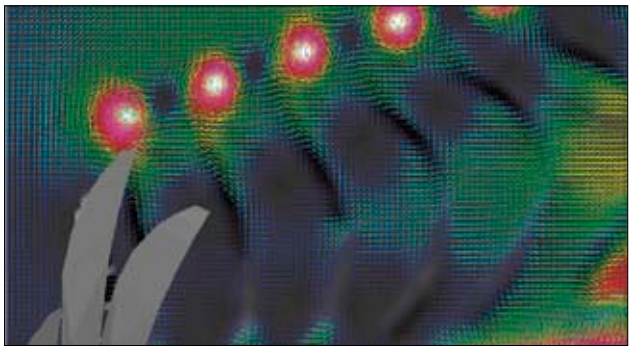


Fig. 1: Propeller slipstream development with wing interaction (Particle Image Velocimetry method - PIV).

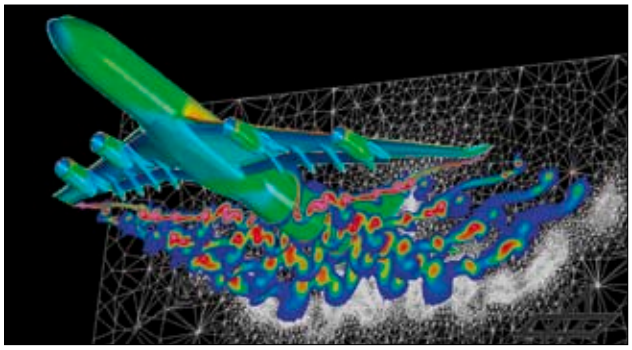


Fig. 2: Flow simulation about Airbus-like model in landing configuration with pressure distribution on the surface and vorticity in different cuts of the aircraft wake (grid adapted to the wake).

The department $C^2A^2S^2E$ (Center for Computer Applications in AeroSpace Science and Engineering) develops methods for the numerical simulation of flows about complex configurations based on hybrid, unstructured grids, which it provides to users in research and industry. These methods are the DLR-TAU Code, which e.g. is employed Europe-wide by Airbus as their tool for flow simulation of complete aircraft, as well as the THETA Code, which is mainly directed to the simulation for incompressible flows with varying density, e.g. in combustions or cabin simulations. The department works furthermore on improvement and development of physical models for turbulence and transition.

The major objective of the Spacecraft department is the virtual design of hypersonic vehicles and spacecrafts and their qualification in ground based facilities and flight. The core research topic is aerothermodynamics – a field with an extremely wide spectrum of applications in aerospace engineering. The major focus of the department is on space transportation, rocket propulsion, hypersonic technology and orbital technology. Numerical prediction methods and major ground based test capabilities are developed applied and validated. The department was involved in all major German and European Space Technology programs during the last two decades.

In the department Fluid Systems the aim of the research is to combine modelling with methods used for experimental and analytic-numerical studies of turbulent and multiphase flows. Problems of technical applications are thus solved through measurements, computation and the improvement of fluid dynamical systems. The latter are fluid systems in airplanes and the aircraft cabin as well as the flows which are of interest for the transportation, aerospace and energy industry.

The department Technical Flows develops solutions for the fluid mechanical optimization of helicopters, cars, trucks and trains. For this purpose conventional force, pressure and velocity measurements are applied as well as modern laser-

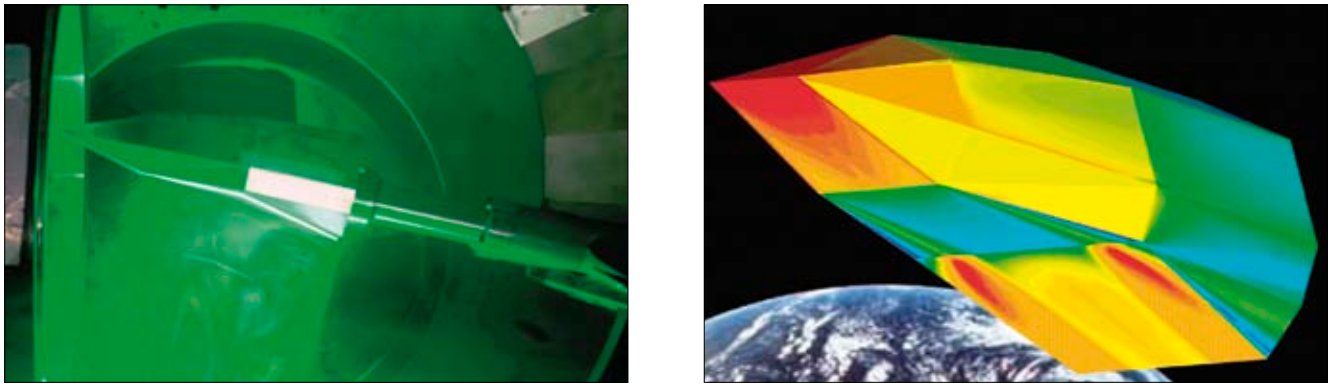


Fig. 3: Aerothermodynamical investigation of the DLR SHEFEX (SHarp Edge Flight EXperiment) configuration in the High Enthalpy Shock Tunnel Göttingen, HEG (left) and with the DLR TAU code (right).

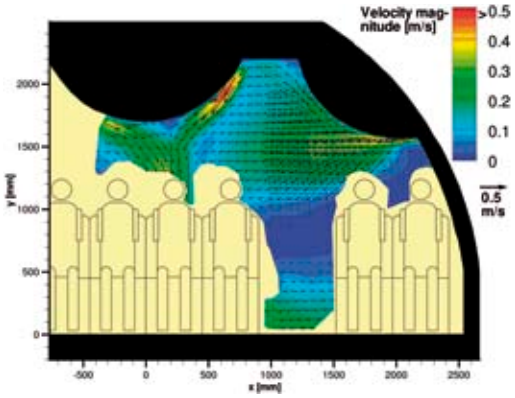


Fig. 4: Air flow in a generic 1:1 aircraft cabin model measured with large scale Particle Image Velocimetry.

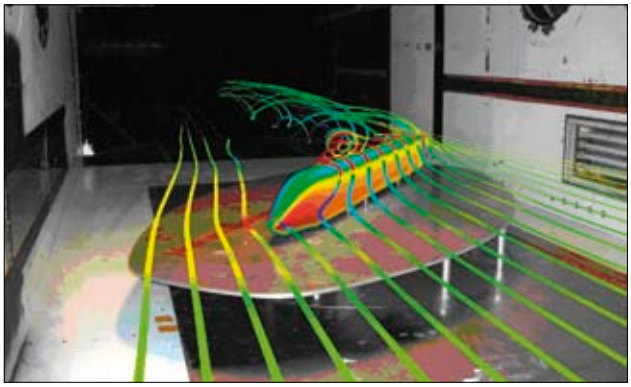


Fig. 5: Numerical simulation: streamlines and surface pressures on a high speed train model in the DNW-KKK wind tunnel under cross-wind conditions.

optical tools (e. g. Particle Image Velocimetry). They are used in modern simulation rigs, wind and water tunnels. Furthermore, noise prediction methods are developed in order to reduce traffic noise.

Special phenomena on flight vehicles at transonic and hypersonic speeds are the research topics of the High Speed Configurations department. Flow control methods for the enhancement of aerodynamic performance and unsteady effects on maneuvering flight vehicles and in separating flows are investigated. Advanced numerical tools as well as complex test and measurement techniques for wind tunnel experiments are being used to enhance aerodynamic performance such as lift, drag, maneuverability and heat loads.

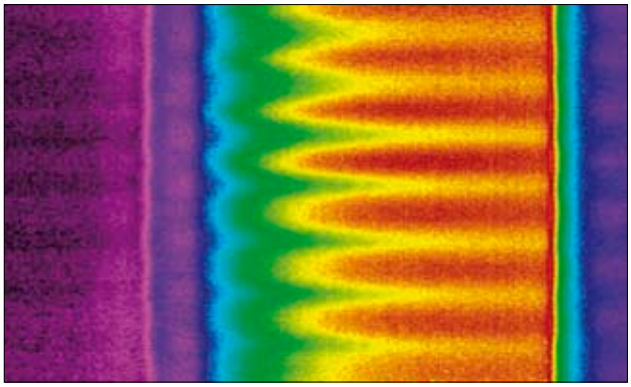
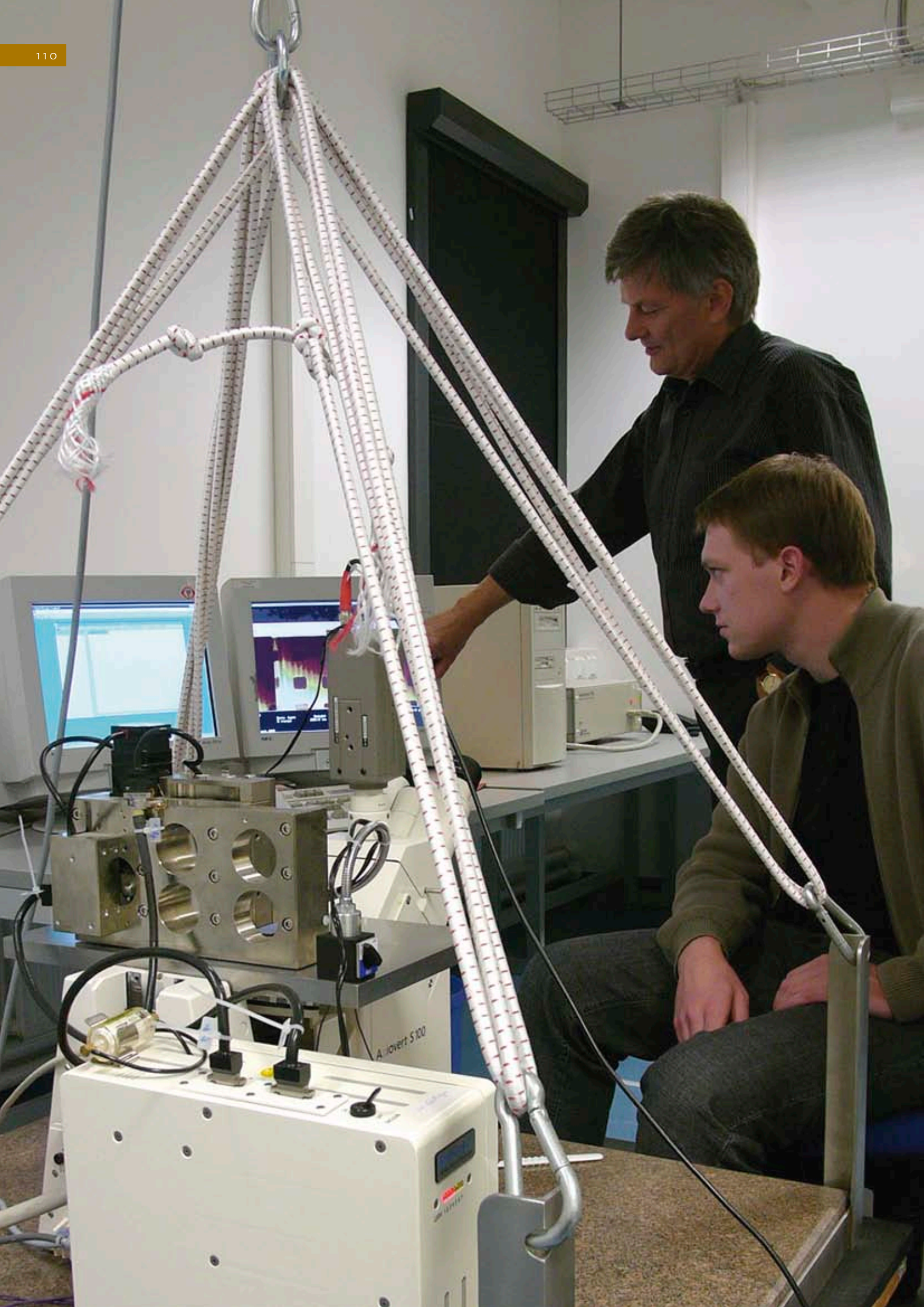


Fig. 6: Heat flux pattern underneath boundary layer structures at Mach 3.8.

Andreas Dillmann

Born 1961 in Karlsruhe, Andreas Dillmann got his diploma in mechanical engineering from the University of Karlsruhe in 1986. He completed his dissertation on homogeneous nucleation of supersaturated vapors at the Max Planck Institute for Fluid Dynamics and received his PhD from Georg-August-University, Göttingen in 1989. After changing to DLR, Institute of Fluid Mechanics in Göttingen he got his habilitation in fluid mechanics from the University of Hannover in 1995. From 1996 to 1998 he held a Heisenberg-Scholarship from the German Research Foundation (DFG). In 1998 he was appointed full professor of Theoretical Fluid Mechanics at the Technical University (TU) of Berlin. Since 2003 he is a full professor of fluid mechanics at Georg-August-University Göttingen and director of the Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen. His main scientific interests are in the fields of analytical fluid mechanics and aerodynamics.

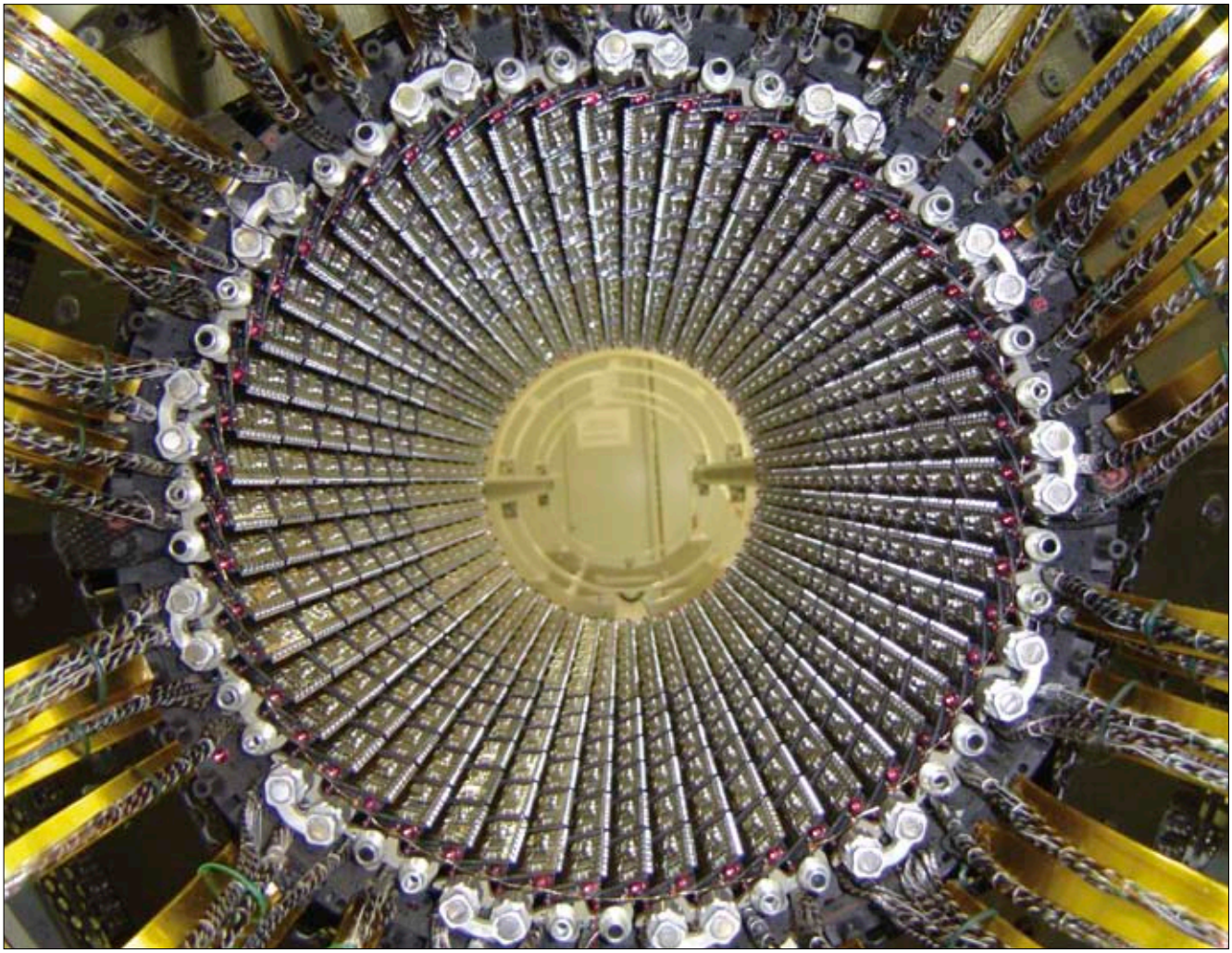


Collaborative Research Center by the Federal Ministry of Science and Education (BMBF-Forschungsschwerpunkt) FSP 101-ATLAS „Physics at the TeV-Scale at the Large Hadron Collider“

The BMBF-FSP 101-ATLAS consists of 14 university institutes together with one Max-Planck-Institute and DESY as associated partners at the international ATLAS experiment at the Large Hadron Collider LHC of the European laboratory for particle physics, CERN, in Geneva, Switzerland. It has been established by the BMBF in 2006 in order to enable the best German research groups to participate and compete in demanding scientific challenges on an international level and has recently been renewed until 2012.

The Large Hadron Collider, the worlds highest energy collider, will shed light on the microcosm at unprecedented detail. Starting data taking in the fall 2009, the LHC will provide new insights into elementary particles, the question of how particles acquire their mass and will allow for searches for heavy new particles. Some of the findings might explain mysteries such as the cold dark matter and hence change our scientific view of the world significantly.

The main physics activities of the German groups are the search for the Higgs boson, the search for supersymmetric particles, studies of exotics scenarios of physics beyond the standard model, physics of the standard model, physics of the top quark, B-meson physics as well as luminosity measurements and forwards physics. Furthermore, the German groups are involved in the development, operation and maintenance of several detector components of ATLAS as well as development of a World-Wide LHC Computing Grid.



Pixel Detector Development for Future Electron-Positron-Colliders

Experiments at particle colliders have been pivotal in advancing our knowledge about the fundamental building blocks of matter and the interactions between them. While the LHC will operate during the next years at the highest energy frontier, a complementary approach is taken in collisions of electrons with their anti-particles, positrons. The advantage of colliding these fundamental particles is the far superior achievable precision. To match this precision, the requirements on the detectors that record the interactions are very stringent. The area closest to the particle interactions are equipped with pixel detectors to measure the trajectory of charged particles. Novel silicon pixel detectors based on DEPFET technology are under development, which combine several favorable aspects: an integrated first amplification stage and thus low noise, large signal allowing for very thin sensors and sufficient radiation hardness. DEPFET pixel sensors are developed for two different projects, the International Linear Collider and the upgrade of the B-Meson factory in Japan.

The International Linear Collider

The ILC is planned to be the next large particle physics accelerator. It will provide e^+e^- collisions at center-of-mass energies between 500 and 1000 GeV, accelerated by superconducting cavities. The linear structure is chosen in order to minimize the energy loss due to synchrotron radiation. A site has yet to be chosen. The results from the ILC together with LHC will certainly elucidate our understanding of the microcosm. Precise determination of all properties of the elusive Higgs Boson will be possible, and possibly measurements of the hypothetical supersymmetric particles that include a good candidate to explain the dark matter in the universe. For accurate measurement of Higgs properties as well as precise studies of physics processes beyond the Standard Model, efficient distinction of heavy quark flavors, most notably, of bottom and charm quarks, is a must. This requires precise secondary vertex detection and results in a targeted single hit resolution better than 5 micrometers. DEPFET pixel detectors are one of the advanced semiconductor devices considered for the ILC vertex detector.

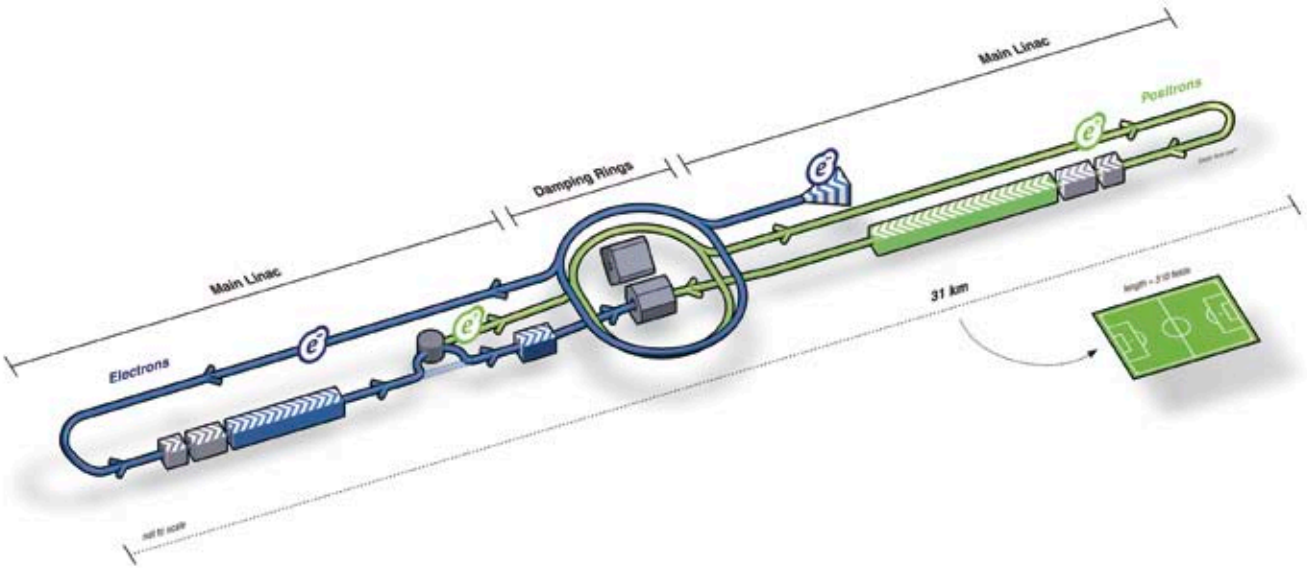


Fig. 1: The layout of the projected International Linear Collider with a length of 31 km. Particle collisions happen in the central region, where two detectors will record the data alternately. The positron beam is derived from the electron beam by directing the latter onto a suitable target.

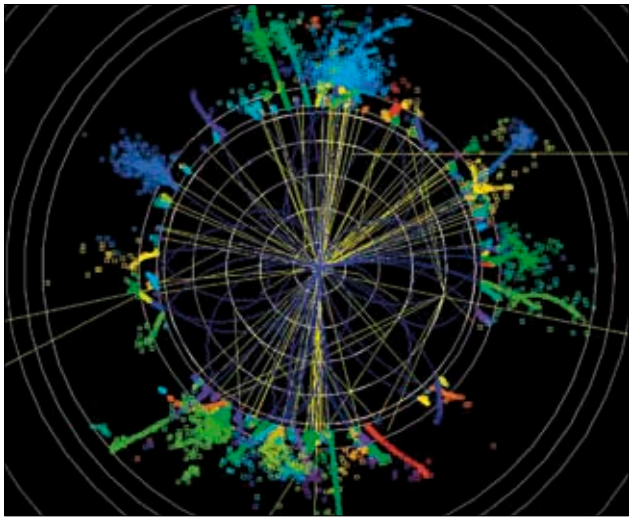


Fig. 2: Display of a simulated reaction at the ILC involving a Higgs Boson, viewed from the point of view of the incoming beam. The tracks of reconstructed charged particles are shown, as well as the energy deposits in the calorimeter.

Fig. 3: Areal view of the KEK site located about 70 km from Tokyo with Mount Tsukuba in the background. The 400 m long electron/positron linear accelerator and the buildings above the collider ring whose circumference is about 3 km can be seen.

Belle II – Upgrade of the B-Meson factory at KEK

The study of neutral B mesons, particles containing a beauty quark, holds very special interest: the Standard Model of particle physics predicts the occurrence of CP violation, the symmetry breaking that is responsible for the observed matter-antimatter asymmetry in our universe. Two experiments (BaBar at SLAC, USA and Belle at KEK, Japan) at accelerators optimized to produce copious amounts of B mesons have indeed confirmed CP violation in the B system, results which led to the award of the Nobel prize 2008 to Kobayashi and Maskawa for their theory of quark mixing and CP violation. At KEK, the Japanese particle physics center, an upgrade of the accelerator is scheduled for 2013 in order to increase the beam intensity by more than an order of magnitude. This will allow even more precise determinations of the Kobayashi-Maskawa quark mixing parameters as well as studies of rare decays and possibly hints of new physics phenomena. In order to deal with the increased rate, the inner subdetector parts of Belle have to be completely replaced, notably a novel DEPFET pixel detector will be installed by 2013. The group is also involved in the analysis of the data collected so far.

DEPFET Pixel Sensors

The DEPleted Field Effect Transistor (DEPFET) is a device with built-in amplification: The electrostatic field in a fully sideways oriented depleted silicon structure is shaped such that all electrons generated by ionizing particles, Xrays or photons are collected in a small volume which is located under the channel of an integrated p-channel field effect transistor. The negative charge in this internal gate leads to a modulation of the channel current. After readout, the signal charges are cleared out of the internal gate. Charge collection is also fully efficient while the device is switched off, such that a low power operation is possible.

Low noise is obtained due to the small capacitance of the internal gate (several 10 fF).

Thanks to the large signal, very thin sensors can be operated with still comfortably large signal-to-noise ratio. A special procedure has been developed allowing the production of pixel matrices thinned down to 50 µm in the active area and with a support frame entirely made from silicon for stability. Small DEPFET devices have undergone several successful beam tests and the Göttingen group is heavily involved in the analysis of the collected data. Moreover, the group is responsible for the electronics development of a fast link, including optical conversion, between the custom readout ICs and the data acquisition system. The DEPFET Collaboration consists of 11 groups from 4 countries (Germany, Spain, Czech Republic, Poland).

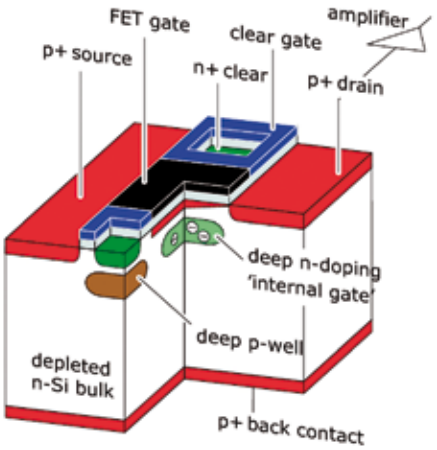


Fig. 4: Schematic of a DEPFET pixel cell, corresponding to a field effect transistor on top of a fully depleted Silicon bulk.

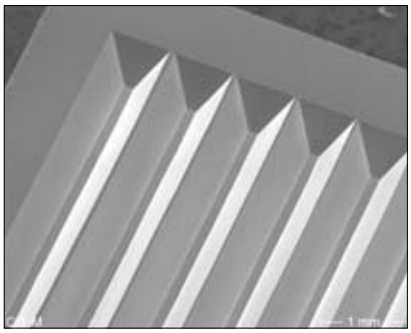


Fig. 6: Enlarged view of the backside Silicon support frame. In order to minimize the material of the module (which reduces the multiple scattering of particles) as much as possible is etched away from the support frame which stabilizes the thinned (50 µm) sensitive area.

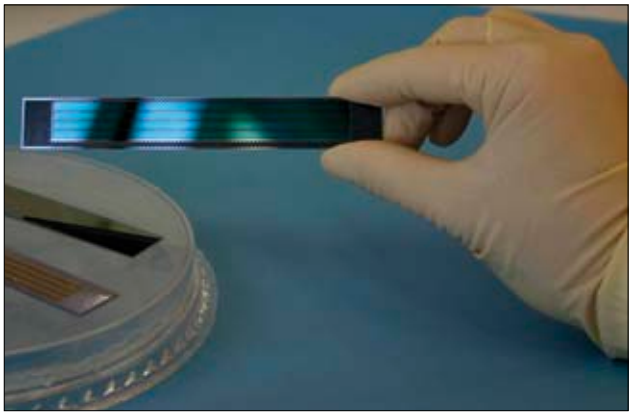


Fig. 5: A sample of a first layer ILC module with support bars along the sides.

[1] *K^0_s production in tau decays;* The ALEPH Collaboration; Eur. Phys. Jour. C 4:29-45, 1998

[2] *Measurement of the proton structure function F2 at low x and low Q^2 at HERA;* The ZEUS Collaboration; Z. Phys. C 69:607-620, 1996

[3] *The BaBar Detector;* The BaBar Collaboration; Nucl. Instr. Meth. A 479:1-116, 2002

[4] *Investigation of design parameters for radiation hard silicon microstrip detectors;* Braibant, S. et al.; Nucl. Instr. Meth. A 485:343-361, 2002

[5] *DEPFET, a monolithic active pixel sensor for the ILC;* Velthuis, J. J. et al ; Nucl. Instr. Meth. A 579:685-689, 2007

[6] *A DEPFET based beam telescope with submicron precision capability;* Velthuis, J. J. et al ; IEEE Trans. Nucl. Sci. 55:662-666, 2008

Ariane Frey

Ariane Frey studied physics at the University of Heidelberg and received her PhD in 1996 from the University of Bonn for a measurement of the internal structure of the proton performed with the ZEUS experiment at DESY/Hamburg. As a Feodor-Lynen fellow at the University of California Santa Cruz she developed the read out electronics for the innermost tracking detector of the BaBar experiment at the Stanford Linear Accelerator Center. From 1998 until 2005 she was research staff at the European particle physics Center CERN in Geneva. Her work focused on R&D for the Silicon tracking device of the CMS experiment at the LHC. Moving to the Max Planck Institute for Physics in Munich in the framework of the MPG excellence initiative, she became project leader of the International Linear Collider group. Since 2008 she holds a Lichtenberg professorship at the Georg-August University Göttingen.

Search for Dark Matter at the LHC

One of the most fascinating findings of astrophysics concerns the composition of the universe. Only 4 % of the total energy density can be accounted for by "ordinary" matter. Many observations indicate that a much larger fraction is made up by Dark Matter. We know today that the universe's current energy density is comprised by about 22 % of Dark Matter and 74 % of Dark Energy. So far we are not able to explain the nature of Dark Matter. However, it has been pointed out for some time that supersymmetric extensions to the Standard Model of particle physics could offer a very elegant answer to the question of the nature and origin of Dark Matter. It is therefore of significant importance to experimentally search for Supersymmetry. Not only would we be able to extend the Standard Model towards a more fundamental theory and thus help to improve our understanding of our world on the smallest scales, the discovery and study of Supersymmetry would be of major interest for astro-particle physics and cosmology. Experiments like ATLAS at the Large Hadron Collider at CERN offer a unique opportunity to carry out a wide variety of thorough searches for Supersymmetry and Dark Matter.

The University of Göttingen is involved in several aspects of these efforts:

- Preparation of Data Analysis

  It is expected that the LHC will provide data by the end of 2009. The amount and complexity of the data requires a thorough preparation. With simulated data analysis techniques, algorithms and methods are heavily tested, evaluated, and compared. Knowing that a good fraction of the early data is needed to understand the detector behavior these tests help also to assess what is needed to calibrate the detector and commission the data acquisition system.

- Trigger Studies

  Before the data can be analyzed it has to be selected and recorded. Only a tiny fraction of the proton-proton collisions will provide interesting information. Filtering (triggering) those events is a non-trivial task. In Göttingen we are investigating how trigger efficiencies can be derived from data without the need to rely on Monte Carlo simulations, how the trigger performance can be monitored while the actual data taking is in progress, and how the trigger information can be provided to the actual data analyzers.

- Data Interpretation

  The discovery of Supersymmetry would be a huge success for particle physics. However, the question for the relevance of Supersymmetry for Dark Matter requires some more work. The University of Göttingen is conducting a set of studies to investigate how well this question can be answered and how this answer can be improved. Although the results of this project will find their applications only in a few years from now, these studies are an important investment. Furthermore, a very interesting aspect of this work is that it brings together experimental and theoretical particle physicists as well as physicists from the fields of cosmology and astro-particle physics.

[1] Höpfner, K. (DESY); Skiba, A. (Hamburg U.); Hensel, C. (Münster U., ITP): *Analysis of light-yield spectra observed with multi-anode PMT and HPD,* 2002. Published in Nucl.Instrum.Meth.A483:747-757,2002.

[2] Hensel, C.: *Beam induced background at a TESLA detector,* LC-DET-2000-001, Jan 2000. In ‚2nd ECFA/DESY Study 1998-2001' 396-430.

[3] *Search for nearly mass degenerate charginos and neutralinos at LEP,* By OPAL Collaboration (G. Abbiendi et al.). CERN-EP-2002-063, Oct 2002. 26pp. Published in Eur.Phys.J.C29:479-489,2003. e-Print: hep-ex/0210043

[4] *First results from the central tracking trigger of the DØ experiment,* Maravin, Y. et al. 2004. 4pp. Prepared for 13th IEEE - NPSS Real Time Conference (RT 2003), Montreal, Canada, 18-23 May 2003. Published in IEEE Trans.Nucl. Sci.51:1848-1851,2004.

[5] *Measurement of the cross section for Z/gamma -> e^+e^- production at DØ,* The DØ Collaboration. DØ Note 5627

[6] *Measurement of pp->mumu yield in the Z mass region for DØ Run IIa data,* The DØ Collaboration. DØ Note 5269

Carsten Hensel

Carsten Hensel studied physics at the University of Münster and at the University of Hamburg where he received his PhD in 2003. Working for the University of Kansas in 2003 he moved to the Fermi National Accelerator Laboratory near Chicago to join the DØ collaboration. Beginning in 2008, holding an Emmy-Noether Fellowship, he established his Young Investigators group in Göttingen.

Hadron Collider Physics at the ATLAS Experiment at the LHC

The hadron collider physics experiments ATLAS at the LHC and DØ at the Tevatron provide today's deepest insight into the microcosm and the physics at the tera scale. The hadron collider physics working group was established in the fall 2006. It is involved in the ATLAS experiment at the proton-proton collider LHC at CERN and in the DØ experiment at the proton-antiproton collider Tevatron at Fermilab. The group is a member of the collaborative research center BMBF-FSP 101-ATLAS and of the Helmholtz-Alliance „Physics at the Terascale". The main research focus is the investigation of the physics of the top quark, the search for the Higgs boson, the search for supersymmetric particles as candidates for dark matter as well as contributions to the development of the ATLAS pixel detector, studies of the ATLAS high level trigger, the operation of a regional (Tier-2) and local (Tier-3) Grid computing center as part of the World-Wide LHC Computing Grid and the development of superconducting cavities using the second sound phenomenon.

Physics of the top quark:

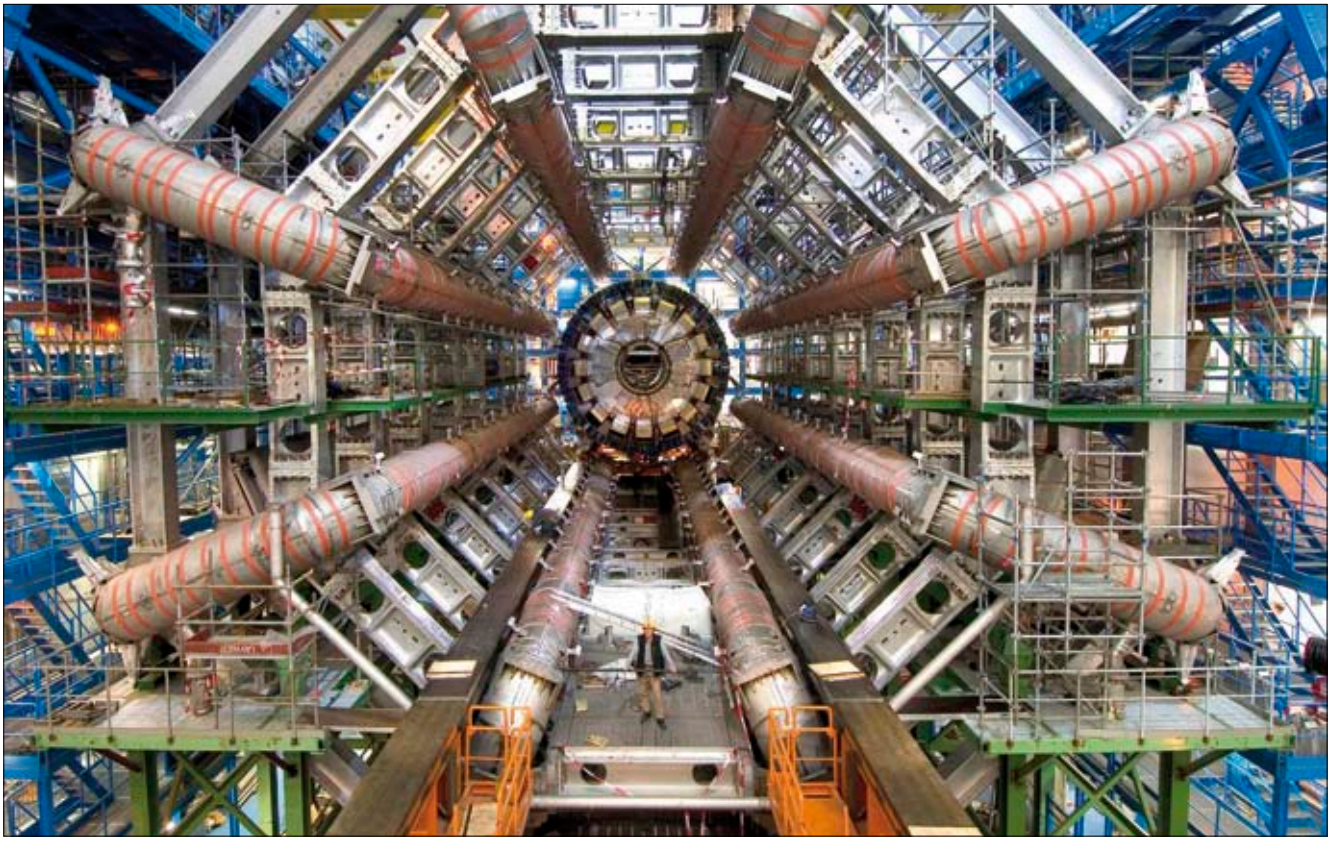
The top quark is by far the heaviest known elementary particle, allowing studies of this quark without chromomagnetic effects of bound states. It was discovered recently, in 1995, at the CDF and DØ experiments at the Tevatron. Hence, still only relevatively little is know about the top quark. Due to its large mass – comparable to that of a single gold atom – the top quark is speculated to play a special role in the mechanism of electroweak symmetry breaking. The properties of the top quark such as its mass, electric charge, its spin and its gauge couplings will be measured. Initially, top quarks produced via the strong interactions will be used to calibrate the detector and to study instrumental and physics background process. Later on, precision measurements will allow to search for physics beyond the standard model in the top sector and to test the validity and consistency of the standard model. For that purpose, a statistical analysis software toolkit is being developed and distributed to the international community.

Search for the Higgs boson:

The standard model successfully describes the interactions of fermions and bosons. The concept of particle masses is introduced via electroweak symmetry breaking, in particular via the Higgs mechanism. The LHC offers a discovery potential for the elusive Higgs boson, covering entirely the allowed kinematic range. One of the most promising channels is the Higgs boson production via weak boson fusion with subsequent decay to tau leptons. This channel would allow the discovery of the Higgs boson, the measurement of its mass and the determination of its couplings to fermions and bosons. Hence, first consistency tests of the Higgs mechanism could be performed. In the minimal supersymmetric extension of the standard model, the existence of five Higgs bosons is predicted with the lightest one having a mass below 135 GeV/c^2. Searches for those Higgs bosons will be carried out, in particular with b-quarks or with tau-leptons in the final state, providing high sensitivity in a large kinematic range.

Search for supersymmetric particles as candidates for dark matter:

In supersymmetry, new partner particles to the known fermions and bosons are introduced. Despite the increased particle content, this new symmetry has appealing consequences such as possible explanations for the stability of the Higgs boson mass and a solution to the hierarchy problem, a possible unification of the gauge couplings as predicted by Grand Unified Theories (GUTs), and the prediction of new particles which could serve as candidates for cold dark matter, observed in astrophysics. In close collaboration with the Emmy-Noether group of Dr. Carsten Hensel, searches for associate chargino-neutralino production, resulting in signatures of high-p_T leptons, missing transverse energy and jets in the detector are prepared and will be carried out at the Tevatron and at the LHC. Furthermore, studies towards the extraction of the underlying parameters of the new theory in case of the observation of a signal for new physics are in preparation.



Development of a Pixel Detector for ATLAS:

The ATLAS pixel detector allows the measurement of the trajectory and the momentum of charged particles resulting from the high-energy proton-proton collisions at a rate of 40 MHz. It is a hybrid silicon detector and comprises about 80 million readout channels of 50 by 400 μm^2 pixels. The group is involved in the operation of the existing pixel detector as well as in the development of the readout electronics and sensors for the upcoming upgrade of ATLAS in the near future.

High Level Trigger:

At the LHC, proton bunches collide at a rate of 40 MHz, resulting in several thousand particles in the final state. This huge rate as well as the resulting data volume cannot be readout online. Hence, a selection of interesting events is performed online in a three stage trigger system. The first level consists of custom-designed electronics while the higher levels consist of dedicated computer farms, running reconstruction and selection algorithms. In collaboration with the Emmy-

Workgroups of Ariane Frey, Carsten Hensel, and Arnulf Quadt

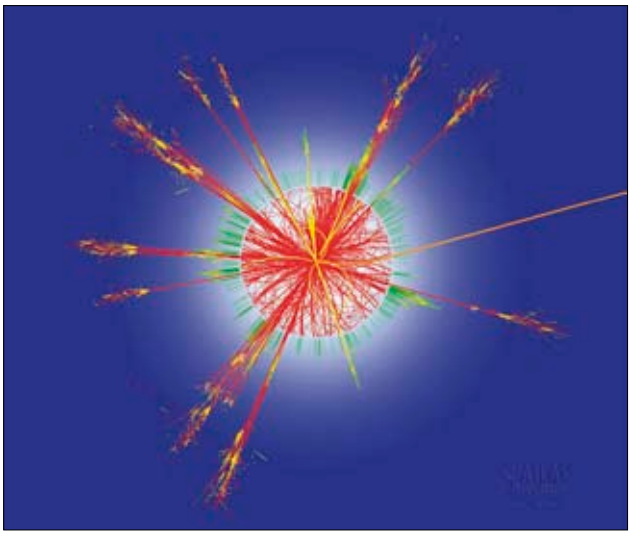
Noether group of Dr. Carsten Hensel, the group is involved in the development of software for monitoring and rate studies of the high level trigger as well as trigger efficiency studies.

Grid Computing:

The data volume recorded at the CMS and ATLAS experiment per year corresponds to stalk of DVDs 22 km tall. Conventional data storage and processing methods can no longer be used to analyse the data. Rather distributed computing and data distribution management need to be developed, called the Grid. The group has setup and operates a regional and a local Grid computer center (Tier-2/3) for the World-Wide LHC Computing Grid (WLCG) in federation with DESY. The cluster is part of the grid resource center GoeGrid, setup and operated jointly with groups in MediGrid, TextGrid, theoretical physics and the GWDG Göttingen.

Accelerator development:

Modern and future particle accelerators consist of powerful superconducting cavities. Today, the reproducibility of accelerator gradients represents a limitation for their application. Diagnosis procedures, in particular based on the phenomenon of second sound, are developed to study the quench behaviour of superconducting cavities and hence to improve their production quality.



[1] Measurement of the F_2 structure function in deep inelastic e^+p scattering using 1994 data from the ZEUS detector at HERA, Z.Phys.C72:399-424, 1996.

[2] Search for the standard model Higgs boson at LEP. By LEP Working Group for Higgs boson searches and ALEPH Collaboration and DELPHI Collaboration and L3 Collaboration and OPAL Collaboration (R. Barate et al.), Phys.Lett. B565:61-75, 2003.

[3] Search for neutral MSSM Higgs bosons at LEP. By ALEPH Collaboration and DELPHI Collaboration and L3 Collaboration and OPAL Collaborations and LEP Working Group for Higgs Boson Searches (S. Schael et al.), Eur. Phys. J.C47:547-587, 2006.

[4] Measurement of the top quark mass in the lepton+jets final state with the matrix element method. By DØ Collaboration (V. M. Abazov et al.), Phys.Rev. D74:092005, 2006.

[5] Top quark physics at hadron colliders, A. Quadt, Eur.Phys.J.C48:835-1000, 2006.

[6] Review of Particle Physics. By Particle Data Group (C. Amsler et al.). Phys. Lett.B 667:1, 2008.

Arnulf Quadt

Arnulf Quadt (*1969 in Troisdorf) studied physics and mathematics at the University of Bonn and the University of Oxford, where he received his PhD in 1996. His research focus was the structure of the proton, studies of the strong interaction and the development of the track trigger of the ZEUS experiment. For this work, he received the EPS prize 2001. In 1999, he moved on to the search for the Higgs boson at the OPAL experiment and the LEP-Higgs-Working Group at CERN. In 2001, at the University of Bonn, he worked on the search for Higgs bosons at the OPAL and ATLAS experiments. In Bonn and later as Feodor-Lynen fellow at the University of Rochester and Fermilab, he focused on physics of the top quark at the DØ experiment. After an interim professorship at the University of Göttingen in 2005 and a DFG Heisenberg fellowship to work on the ATLAS experiment at the MPI für Physik in Munich in 2006, he established particle physics at the University of Göttingen in the fall 2006.

Magnetotellurics and Experimental Geodynamics

Magnetotellurics is a passive exploration technique that utilises a broad spectrum of naturally occurring geomagnetic variations as a power source for electromagnetic induction in the Earth. It is related to geomagnetic depth sounding, which was developed in the late 19th century after the existence of magnetovariational fields owing to induction was demonstrated by Schuster and Lamb. They applied a mathematical technique invented by Gauss for separating magnetovariational fields originating internal in the Earth from those of external origin to geomagnetic observatory data and detected a significant internal component. In the 1950s, Tikhonov and Cagniard realised that if electric and magnetic field variations are measured simultaneously then complex ratios (impedances) can be derived that describe the penetration of electromagnetic fields into the Earth. The penetration depths of electromagnetic fields within the Earth depend on the electromagnetic sounding period, and on the Earth's conductivity structure. This is the basis of the magnetotelluric technique.

If combined with some knowledge of conduction mechanisms, mangetotellurics (MT) can provide insights into the evolution of the lithosphere. The electrical conductivity within the Earth is affected by small quantities of fluids (brines and partial melts) and graphite. The amount of fluid present at different depths within the Earth has important rheological consequences, given the effects of hydrolytic weakening. Graphitisation is promoted by shear stress, and its presence may therefore be indicative of shear deformation. Hence, electromagnetic studies can provide constraints on deformation mechanisms, locate plate boundaries and shear zones, and can detect mantle plumes.

Galvanic distortion

The electrical conductivity of Earth materials affects two physical processes: electromagnetic induction – which is utilised by magnetotellurics – and electrical conduction. If electromagnetic induction in media which are heterogeneous with respect to their electrical conductivity is considered, then both processes take place simultaneously: due to Faraday's law, a variational electric field is induced in the earth, and due to the conductivity of the subsoil an electric current flows as a consequence of the electric field. The current component normal to boundaries within the heterogeneous structure passes these boundaries continuously. Therefore the amplitude and the direction of the electric field are changed in the vicinity of the boundaries (Fig. 1). In electromagnetic induction studies, the totality of these changes in comparison with the electric field distribution in homogeneous media is referred to as galvanic distortion.

The electrical conductivity of Earth materials spans 13 orders of magnitude (e.g. dry crystalline rocks can have conductivities of less than 10^{-6} S/m, whilst ores can have conductivities exceeding 10^{6} S/m). Therefore MT has a potential for producing well constrained models of the Earth's electrical conductivity structure, but almost all field studies are affected by the phenomenon of galvanic distortion, and sophisticated techniques have been developed for dealing with it. The statistical evaluation of galvanic distortion data provides evidence for a fractal structure with an upper bond of the size of Fennoscandia. Such structures are modelled with random resisitor networks (Bahr et al., 2002).

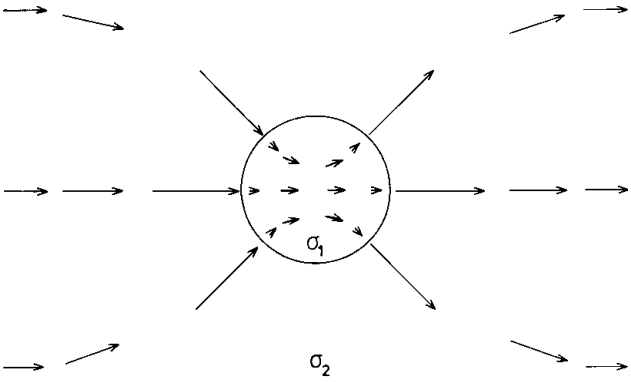


Fig. 1: Amplitude and direction of the electric field outside and inside a conductivity anomaly with a conductivity contrast between the anomaly and the host medium.

Fig. 2: Maintaining a magnetotelluric field roboter in the Black Forest.

Electrical anisotropy at the base of the lithosphere

In the geosciences the term 'electrical anisotropy' describes the direction dependence of the electrical conductivity of Earth materials. In the case of intrinsic anisotropy this direction dependence occurs on all scales, while in the case of macroscopic anisotropy composite media are formed from isotropic components in such a way that the bulk conductivity is anisotropic.

Studies aimed at investigating electrical anisotropy at the base of the lithosphere or in the sub-lithospheric upper mantle have been conducted in Australia (Simpson, 2001), Scandanavia (Bahr and Simpson, 2002) and Europe. Under Australia the direction of highest conductance is rotated 30° relative to the direction of the present day absolute plate motion (APM) that is determinated relative to the hotspot reference frame (Simpson, 2001). But the APM direction that is determined relative to a reference frame defined by requiring no-net rotation of the lithosphere matches the electrical anisotropy direction better (Simpson and Tommasi, 2005). Mantle flow models suggest that shear of the mantle imparted by the drag of an overriding plate favours alignment of olivine [100] axes parallel to the direction of plate motion. Hydrogen diffusivities enhance the conductivity of olivine crystals anisotropically, providing a possible explanation for magnetotelluric anisotropy if hotspots are not stationary relative to the deep mantle (Simpson and Tommasi, 2005).

Fig. 3: Field survey in the Pyrenees.

The conductance of 20,000 S found at the base of the lithosphere below the Rhenish Massif (Gatzemeier and Moorkamp, 2004) cannot be explained in terms of a partial melt model, but could be explained with a model of aligned 'wet' olivine. However, neither partial melt nor aligned 'wet' olivine appear to explain the degree of anisotropy detected in some magnetotelluric field studies, implying that the current model is incomplete.

[1] Bahr, K.; Smirnov, M.; Steveling, E. (2002): *A gelation analogy of crustal formation derived from fractal conductive structures,* J. Geophys. Res., 107, 2314, doi: 10.1029/2001JB000506.

[2] Bahr, K. and Simpson, F. (2002): *Electrical anisotropy below slow and fast-moving plates: paleoflow in the upper mantle,* Science, 295, 1270-1272

[3] Gatzemeier, A. and Moorkamp, M. (2004): *§D modeling of electrical anisotropy from electromagnetic array data: hypothesis testing for different upper mantle conduction mechanisms.* Phys. Earth Plant. Interior, 149, 225-242.

[4] Simpson, F. (2001): *Resistance to mantle flow inferred from the electromagnetic strike of the Australian upper mantle,* Nature, 412, 632-635.

[5] Simpson, F. and A. Tommasi (2005): *Hydrogen diffusivity and electrical anisotropy of a peridotite mantle,* Geophys. J. Int., 160, 1092-1102.

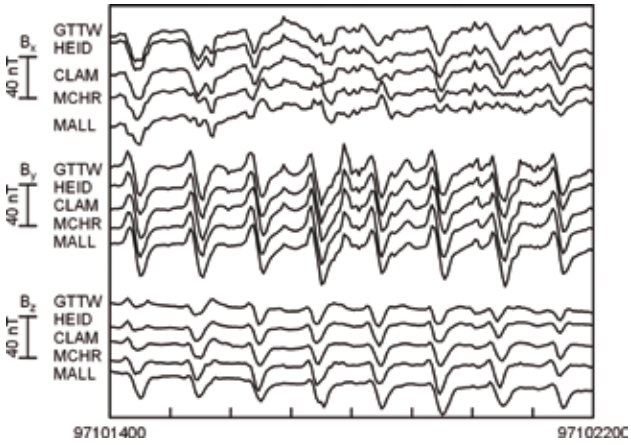


Fig. 4: Eight days of magnetovariational time series recorded simultaneously at five stations in western Europe: GTTW (Göttingen), HEID (Heidenheim, S. Germany), CLAM (Clamecy, central France), MCHR (Montecristo island), MALL (Mallorca).

Karsten Bahr

Karsten Bahr was born in 1956 in Göttingen and received his PhD in 1985. After performing the first commercial geophysical electromagnetic measurements in Germany, he joined the seafloor magnetotelluric group at the University of California at San Diego. He has had research posts in Frankfurt and at GeoForschungszentrum Potsdam and was a visiting scholar at Ecole Polytechnique in Montreal. He has been a Professor of Geophysics at Göttingen University since 1996.

In addition to magnetotellurics his research interests include percolation theory, conduction mechanisms, and the application of electromagnetic depth sounding techniques to geodynamic and tectonic questions. Between 1997 and 2006, he was a co-editor of Geophysical Journal International. In 2005, Fiona Simpson and Karsten Bahr published ‚Practical Magnetotellurics'.

Geophysical Fluid Dynamics

Navigation has relied on compass needles for centuries. Nowadays, we mostly use more sophisticated tools for navigation, but the magnetic field of the Earth is still considered essential for human life because it protects the Earth from particles arriving from space. The origin of the geomagnetic field remains mysterious in many ways. The only plausible mechanism for its creation is a dynamo effect which converts the kinetic energy of motion in the electrically conducting outer core into magnetic energy. The Earth's outer core being liquid, its dynamics share many characteristics with the dynamics of the atmosphere and the oceans. Geophysical fluid dynamics is a field of research exploring those common features, in particular the turbulence at small length scales and the organization into persistent large scale structures.

Planetary Magnetic Fields

All planets except Venus and Mars presently have their magnetic fields. Of course, we know Earth best, and thanks to observations made since Gauss, we can deduce the magnetic field at the core mantle boundary at a depth of 2900 km. The field is rather more complex than a simple dipole and it has been observed to have a time-dependence. The motion inside the core is likely to consist of numerous small eddies. It is impossible to numerically compute this complex flow, in the same way as it is impossible to predict the weather and atmospheric flow because of its small scale features. Nonetheless, some numerical approximations have been successful in predicting several properties of the geomagnetic field, such as the contribution of the dipole field to the total field.

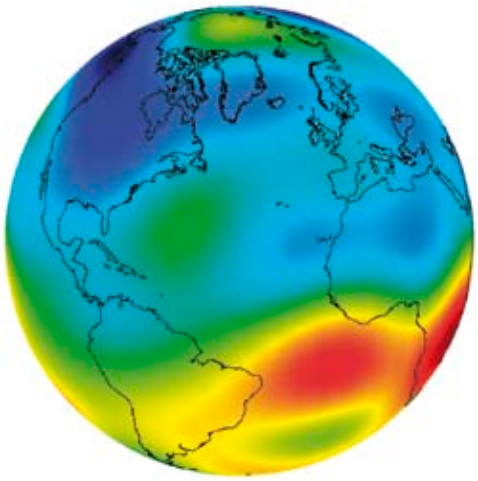


Fig. 1: The radial component of the magnetic field at the core mantle boundary at a depth of 2900 km in the year 1995.

Precession

There needs to be an energy source to maintain the motion in the liquid core. The precession of the Earth's rotation axis about the normal to the ecliptic with a period of 26,000 years is too slow to have any noticeable effect on everyday life, but it possibly contributes significantly to the energy budget of the core. Columnar vortices appeared in computer simulations of precessing fluid bodies performed in this group. These simulations also showed that a magnetic field can be generated by precession, but it is not known whether this actually happens in the Earth because of the uncertainty on the precise value of the viscosity of the core material.

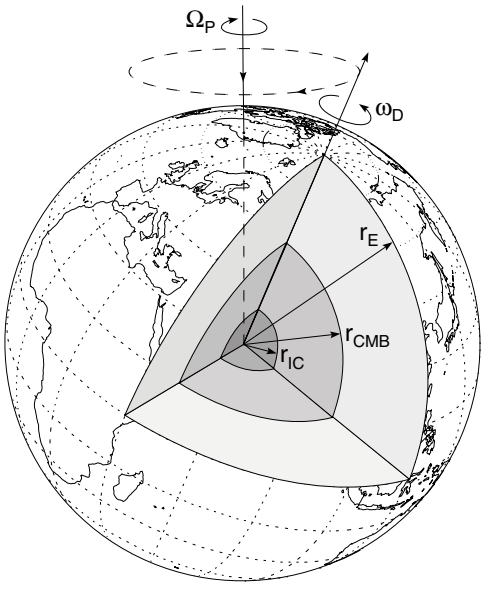


Fig. 2: Sketch of the precesseing Earth. Shown are the axis of rotation, the geographic axis, and the radii of the Earth, the core mantle boundary, and the inner core.

Convection

Thermal convection has many applications. It appears in the climate problem because the heat transported through the atmosphere needs to be calculated accurately in climate models. The whole planet Earth is cooling down as it ages, setting up a thermal gradient between the hot center and the cold surface, which allows convection. Buoyancy in the Earth's core is probably the strongest driving force for the geodynamo. Thermal convection is also a common problem in engineering. Fundamental properties of thermal convection have fascinated physicists since Rayleigh. In more recent times, the organization of convection at large scales has received much attention. It is remarkable that convection cells, rolls and plumes survive in a turbulent environment. Current research focuses on mechanisms responsible for the existence of these structures in turbulent flows and on the heat transported by them.

Dynamo experiments

Neither numerical simulations nor laboratory experiments are able to exactly reproduce the dynamics of the Earth's interior. A combination of both approaches is necessary in order to obtain a complete picture of the geodynamo. Dynamo experiments require considerable technical effort and volumes of several cubic meters of liquid sodium moving at velocities of several meters per second. There is no experiment of this type in Göttingen, but the group has been involved in both the design and the interpretation of such experiments. One result from this line of research is an estimate of the power dissipated by the geodynamo in the Earth's core. All previous experiments used non-rotating containers filled with liquid sodium. Future experiments will include rotation, so that the Coriolis force will influence the dynamics, and possibly show polarity reversals as observed in the Earth's magnetic field.

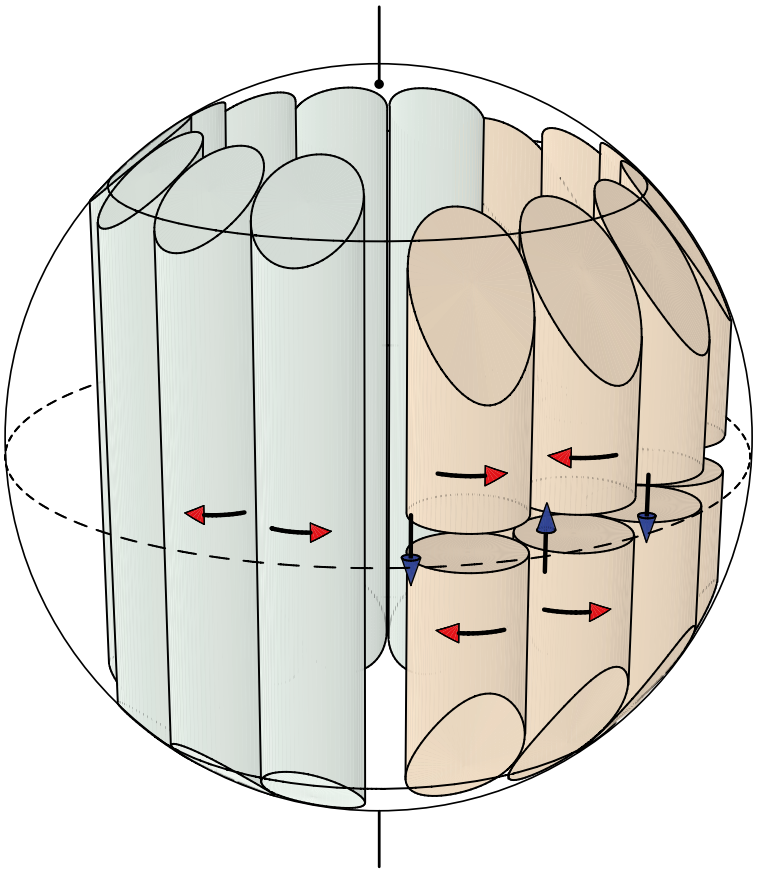


Fig. 3: Sketch of a flow driven by precession. Two belts of columnar vortices with opposite parity with respect to the equator appear. Only half of the vortices are drawn for clarity.

[1] Hartlep, T.; Tilgner, A.; Busse, F. H.: *Large scale structures in Rayleigh-Bénard convection at high Rayleigh numbers,* Phys. Rev. Lett. 91, 2003, 064501.

[2] Christensen, U. R. C.; Tilgner, A: *Power requirement of the geodynamo from ohmic losses in numerical and laboratory dynamos,* Nature 429, 2004, 169-171.

[3] Haramina, T.; Tilgner, A.: *Coherent structures in boundary layers of Rayleigh-Bénard convection,* Phys. Rev. E 69, 2004, 056306.

[4] Tilgner, A.: *Precession driven dynamos,* Phys. Fluids 17, 2005, 034104.

[5] Tilgner, A.: *Rotational Dynamics of the Core,* Treatise on Geophysics Vol. 8, Schubert G. editor, Elsevier 2007.

[6] Tilgner, A.: *Dynamo action with wave motion,* Phys. Rev. Lett. 100, 2008, 128501.

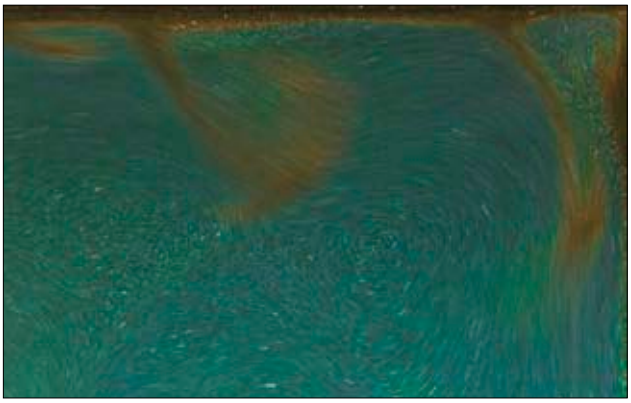


Fig. 4: Picture of eddies and plumes detaching from a cold plate at the top of the picture in convecting water. Particles filled with thermochromic liquid crystals have been suspended in the water. The liquid crystals change color with temperature, and the velocity field is visible as streaklines in this photograph with a 1 s exposure time.

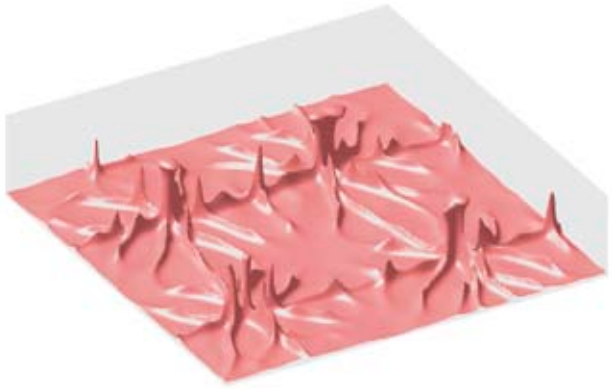


Fig. 5: Isosurface of temperature in a numerical simulation of thermal convection showing plumes emanating from the bottom boundary layer.

Andreas Tilgner

Andreas Tilgner was born in 1965 in Braunschweig. He studied physics at the Technische Hochschule Darmstadt until the Vordiplom and continued his studies at the Université Joseph Fourier in Grenoble until his PhD. The topic of his PhD thesis was laser spectroscopy on polymers at low temperatures, an example of a disordered system. During his Postdoc with Albert Libchaber at Princeton University, his attention shifted towards an even more disordered system: turbulent convection. In the period leading to his habilitation at the University of Bayreuth in the group of F. Busse in 2000, he worked mostly on the dynamo effect and in particular on the design of the Karlsruhe experiment, which was one of the two experiments demonstrating the dynamo effect in 1999. Work on precession and inertial modes also started during that time. He arrived in Göttingen in 2001.

Stellar Astrophysics

All chemical elements except hydrogen, helium, and lithium are the most tangible results of stellar evolution. Nuclear reactions in stellar interiors provide the first step in a cosmic recycling process. Mixing and mass loss as well as supernova explosions then set the enriched material free into the interstellar medium. Subsequently, new stars are formed out of interstellar gas clouds whose gas temperatures are sufficiently low to allow gravitational contraction. The next generation of stars continues this process. As a by-product of star formation, planets may form out of the dusty gas disks left over from the contraction of interstellar clouds during star formation. While the general scenario of star formation and evolution is clear, many important details remain to be investigated. The continuous improvement of astronomical instrumentation, observing programs at large international observatories, as well as sophisticated numerical simulations for the analysis and interpretation of the data are all required.

Instrumentation Projects

Progress in astronomy and astrophysics is tied intimately to the capability of the instruments. While larger and larger telescopes permit observations of fainter objects and space based observatories open new observing capabilities, the instrumentation for these telescopes has to keep up with the new possibilities and adapt to scientific requirements defined by the astronomical community. An active participation in this process has a long tradition in our group, namely with instruments for the Very Large Telescope of the European Southern Observatory at Paranal in Chile (Fig. 1). The current instrumentation project (MUSE) is being developed and built as part of an international collaboration partly funded by the BMBF: a spectrograph that will provide optical spectra not only for single point sources but rather for a complete field of view of one square arcminute with a spatial resolution of 0.3 arcseconds (Fig. 2). While application for this instrument range from cosmologic to planetary science cases, the Stellar Astrophysics group in Göttingen is especially interested in using this instrument for stellar objects in the Milky Way and in nearby galaxies. The project passed the design phase successfully in 2009 and should start operation in 2012.

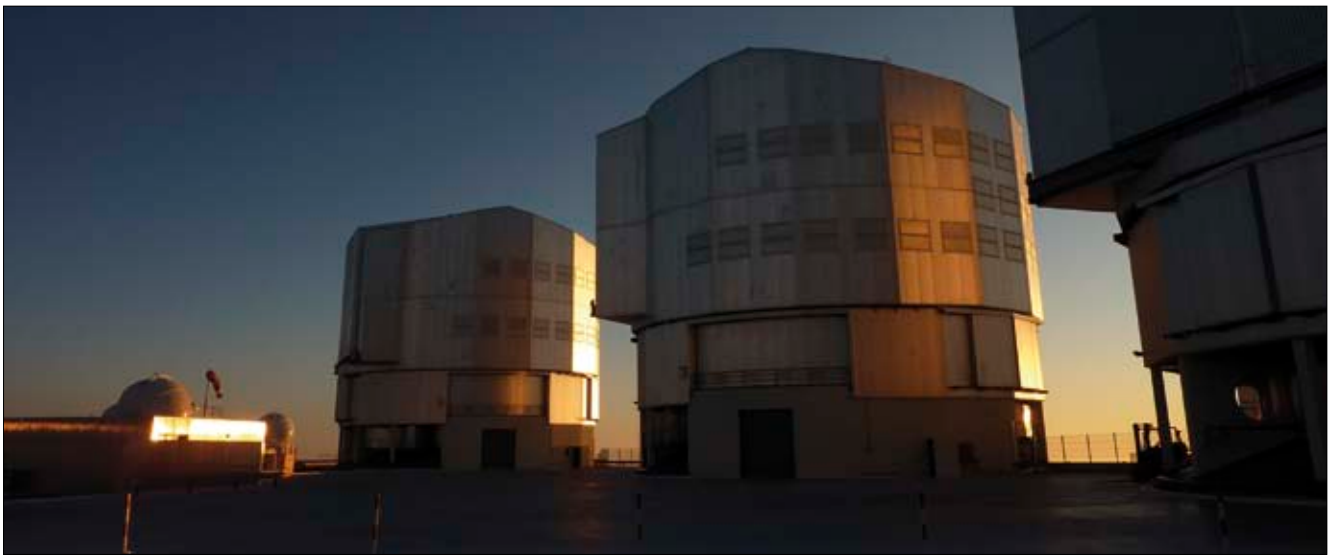


Fig. 1 The Very Large Telescope at the European Southern Observatory, Paranal, Chile.

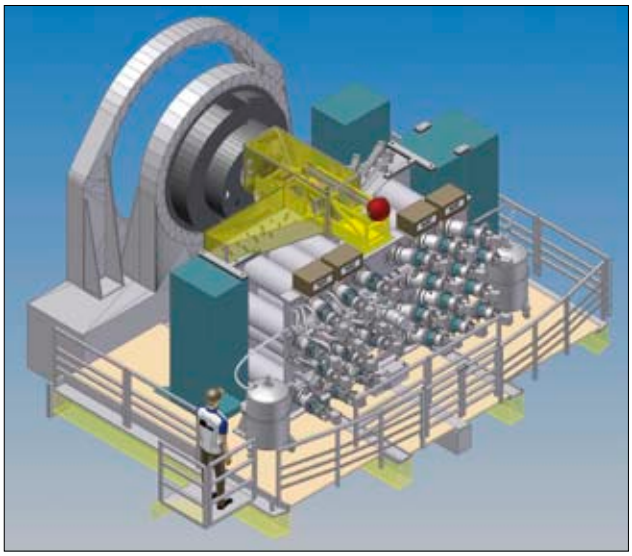


Fig. 2: Computer model of the Multi Unit Spectroscopic Explorer (MUSE) on the Nasmyth platform of the Unit 4 Telescope of the European Southern Observatory, Paranal, Chile.

Fig. 3: MONET South, a 1.2m robotic telescope operated by the Stellar Astrophysics group in Göttingen along with the South African Astronomical Observatory with the Milky Way in the background. (Photo: S. Potter/SAAO)

While observing time at large international observatories is very limited, long term projects are ideally conducted at dedicated telescopes. With funds from the Alfried Krupp von Bohlen und Halbach Foundation, two robotic telescopes (MONET) have been built, one at McDonald Observatory in Texas, one at the South African Astronomical Observatory (Fig. 3). These telescopes can be operated remotely from Göttingen and allow long term monitoring projects, e.g. the search for extrasolar planets (see below). The remote observations make the MONET telescopes also ideal for educational purpose, half of the observing time is devoted for school use, providing access to professional astronomical equipment for school classes all over the world.

Research topics

The Stellar Astrophysics group concentrates on extrasolar planets, low mass and solar-type stars as well as on late stages of stellar evolution. With the discovery of the first planet orbiting a star other than the sun in 1995 and the subsequent detection of more than 300 extrasolar planets, aspects of planet formation, evolution, and interaction with the host star have become key scientific topics. Our group participates in the direct search of extrasolar planets with various techniques. These techniques include gravitational lensing, a technique providing an unbiased search over a large range in our Milky Way, detection of radial velocity variations where we concentrate on very low mass planet host stars, and detection of transits, i.e. a partial eclipse of the planet host star by its planet. The latter method is especially interesting since a detailed photometric (Fig. 4) and spectroscopic analysis of the transit allows one to derive important information about the planet, e.g. its radius, mass, mean density, alignment of the stellar rotation axis with the planet´s orbital axis, or the proprties of the planetary atmosphere. These activities are closely linked to the Emmy Noether Research group of Ansgar Reiners and are partially embedded in a DFG-funded Graduate Research Centre, "Extrasolar Planets and their Host Stars", a collaborative project together with Hamburg Observatory and the Max Planck Institute for Solar System Research.

While stellar evolution is quite well understood in general, specific questions are still open. An important aspect is the evolution of close binaries. In their late stage of evolution, the primary star turns into a compact object: a white dwarf, neutron star or stellar black hole. In very close binary systems, mass transfer from the secondary to the primary leads to accretion of the material on the compact object, resulting in intensive high energy radiation. In our group, the X-ray emission from accretion processes are used to probe these accretion processes. A special class of stars, the subluminous O and B stars are likely the product of close binary evolution. Their interior is explored through the analysis of their oscillations (Fig. 5). Recently, variations of these stellar oscillations led to the discovery of a planet orbiting such a star, casting light on the fate of planetary systems at the end of a star's life.

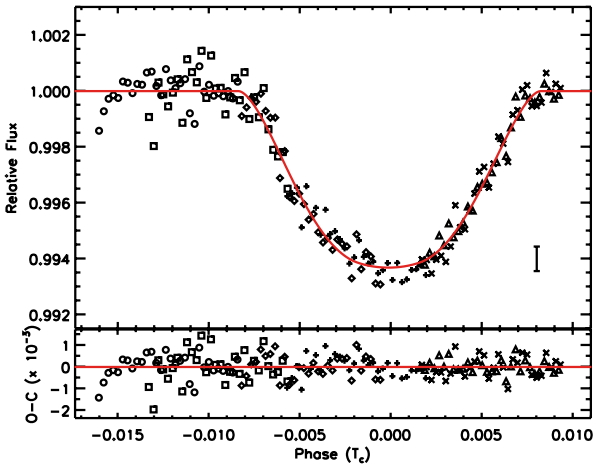


Fig. 4: observed transit light curve for GJ 436b (points) with best fit from our analysis (line) phased to the central transit time. The bar on the right indicates the average error size. Bottom: residuals from the fit (points). The different point styles in both panels indicate data from the different visits. (Bean et al. 2008, A&A 486, 1039)

Numerical Simulations

Most of the information of the physical condition of astronomical objects is obtained from the analysis of the emitted light. The derivation of temperature and density stratifications, chemical composition, velocity or magnetic fields require a comparison of simulated and observed spectra. These numerical simulations have to keep up with the advances in observing techniques. The steady development of sophisticated radiative transfer simulations is therefore an important tool in stellar astrophysics. A recent development of our group is the possibility to simulate spectra of the proto-planetary disks (Fig 6). Planets may be forming in such environments, so the derivation of the conditions in such disks is an important way of probing planet formation processes.

[1] Hügelmeyer, S. D.; Dreizler, S.; Hauschildt, P. H. et al., 2009: *Radiative transfer in circumstellar disks. I. 1D models for GQ Lupi,* Astronomy and Astrophysics, 498, 793

[2] Schuh, S.; Huber, J.; Dreizler, S. et al., 2006: *HS 0702+6043: a star showing both short-period p-mode and long-period g-mode oscillations,* Astronomy and Astrophysics, 445, L31

[3] Dreizler, S.; Rauch, T.; Hauschildt, P. H. et al., 2002: *Spectral types of planetary host star candidates: Two new transiting planets,* Astronomy and Astrophysics, 391, L17

[4] Werner, K.; Dreizler, S. 1999: *The classical stellar atmosphere problem,* Journal of Computational and Applied Mathematics, 109, 65

[5] Dreizler, S., Heber, U. 1998: *Spectral analyses of PG 1159 star: constraints on the GW Virginis pulsations from HST observations,* Astronomy and Astrophysics, 334, 618

[6] Dreizler, S.; Werner, K. 1996: *Spectral analysis of hot helium-rich white dwarfs,* Astronomy and Astrophysics, 314, 217

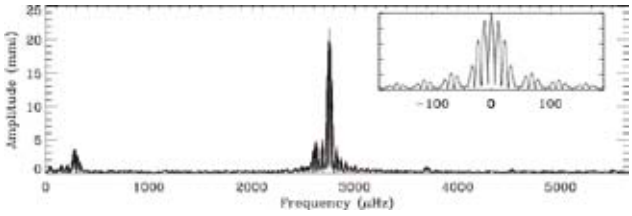


Fig 5: Discrete Fourier transform of the light curve of HS0702+6043 showing short period p-mode pulsations slightly below 3,000 μHertz and long period g-mode pulsations at about 300 μHertz. (Schuh et al. A&A 445, L31)

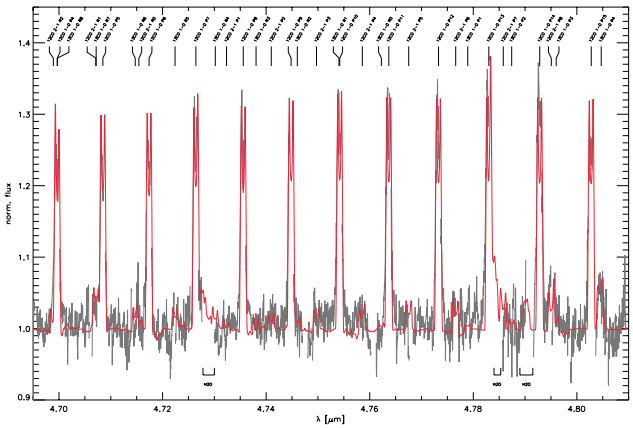


Fig. 6: Infrared Spectrum of the proto-planetary disk of GQ Lupi compared to a synthetic spectrum. (Hügelmeyer et al, A&A 498, 793)

Stefan Dreizler

Stefan Dreizler, born 1963 in Freiburg, studied physics at the Christian Albrechts University Kiel, where he received his PhD in 1992 under the supervision of Prof. Dr. K. Hunger. After postdoctoral studies at Erlangen University with Prof. Dr. U. Heber (1992) and at University Kiel with Prof. Dr. D. Koester (1996), he obtained a position as a research assistant at Tübingen University where he finished his habilitation in 2000. In 2003 he was appointed as full professor at the Georg August University Göttingen. From 2007 to 2009 he served as Dean of the physics faculty.

Magnetic Activity from Stars to Planets

Fig. 1: The Very Large Telescope of the European Southern Observatory in the Atacama desert on Paranal, Chile. We use the world's largest telescopes to obtain observations of stars, brown dwarfs, and planets (© Ulf Seemann).

Stars, Brown Dwarfs and Planets

Our Galaxy is made of stars, one of them being the Sun, that comfortably heats our planet Earth, on which we live. Billions of other stars are known, most of them less massive than our Sun. A few hundred planets and planetary systems around other stars are known today. The majority of stars in our Galaxy are less than half as massive and half as large as the Sun. Planets are at least 100 times less massive than the Sun, and they were formed around their host stars. From them, we can often only see the light coming from the nearby star that is reflected from the planet. Between stars and planets, another group exists – objects not hot enough to burn hydrogen into helium, but formed like stars. These objects, called brown dwarfs, do not reach a stable state. They become cooler during their entire lifetime, which exceeds by far the age of the Universe.

The physics of stars, brown dwarfs and planets, and the question of their formation are the topics that we investigate in our group.

Magnetic Activity

The Sun exhibits an 11-year cycle of activity during which dark spots, flares, faculae, and other transient events occur. These events are of magnetic nature, the magnetic field being induced by the vast amount of moving plasma that act as a gigantic dynamo. Magnetic activity also occurs on other stars, often much stronger, manifested as huge spots, massive energy release, and very strong magnetic fields. The physical mechanisms behind magnetic activity in stars and brown dwarfs, and the influence of planets are not well understood, not even in the Sun.

Solar, stellar and substellar magnetic activity are manifestations of the same processes occurring in physically related objects that possess very different atmospheres and surface structure. We investigate the physical principles of magnetic activity carrying out high precision spectroscopic experiments in stars and brown dwarfs; we investigate their atmospheres, magnetic fields, surface properties, and search for immediate drivers of magnetic activity. The main tools for our observations are large ground-based telescopes like the Very Large Telescope (VLT), Keck observatory, the Hobby Eberly Telescope, and others. We are also analyzing high precision photometric data from satellite missions, for example data for some 100,000 sun-like stars from the *Kepler* mission.

[1] Reiners, A.; Schmitt, J. H. M. M: *Rotation and differential rotation in field F- and G-type stars,* Astronomy and Astrophysics 398, 2003, 647-661

[2] Reiners, A.; Basri, G.: *The First Direct Measurements of Surface Magnetic Fields on Very Low Mass Stars,* The Astrophysical Journal 656, 2007, 1121-1135

[3] Christensen, U. R.; Holzwarth, V.; Reiners, A.: *Energy flux determines magnetic field strength of planets and stars,* Nature 457, 2009, 167-169

Ansgar Reiners

Born in 1973, Ansgar Reiners studied physics in Heidelberg and Uppsala, Sweden. In 2000, he finished his Diploma on magnetic hot star stars before he went to Hamburg for his PhD. In 2003, he finished his PhD thesis on differential rotation in sun-like stars and then remained in Hamburg as a postdoc for one more year. As a Marie Curie International Outgoing Fellow he spent two years, from 2004 to 2006, at the University of California at Berkeley, where he started working on magnetic fields of low mass stars and brown dwarfs. In 2006, he returned to Germany and came to Göttingen in 2007, where he established his own research group as an Emmy Noether Fellow.

Astrophysical Cosmology

Cosmology seeks to understand the structure and evolution of our universe as a whole in physical terms. In the past decades, it has advanced into a quantitative science driven by a wealth of data from satellites and ground based telescopes. Numerical simulations on the world's most powerful computers are necessary to extract the underlying physics from observations of complex, nonlinear phenomena involving gravity, gas dynamics, radiation transport, and magnetic fields. Presently, the main parameters describing the contents and geometry of our universe are known at the level of a few percent. Two of the major challenges that remain are to understand the nature of the dark matter and dark energy that make up roughly 95 percent of the matter content, and to confirm or falsify the occurrence of a phase of inflation prior to the hot big bang.

Physics of the Very Early Universe

A number of serious problems with the causal structure and the nearly flat spatial geometry of our universe can be solved by postulating a phase of accelerated expansion called "inflation" in the very early universe. In addition to creating the homogeneous spatial geometry that we observe, inflation predicts the generation of small curvature perturbations from quantum fluctuations which later gave rise to the formation of cosmological structures. Hence, an accurate reconstruction of the statistical distribution of primordial density fluctuations allows a rare glimpse at physics at otherwise inaccessibly high energy scales, perhaps as high as the Planck scale where quantum gravity becomes relevant.

This goal presents two very distinct challenges. First, we must look for unique signatures in the predictions of candidate theories for inflation – constructed, for instance, in the framework of superstring cosmology – in order to identify the underlying

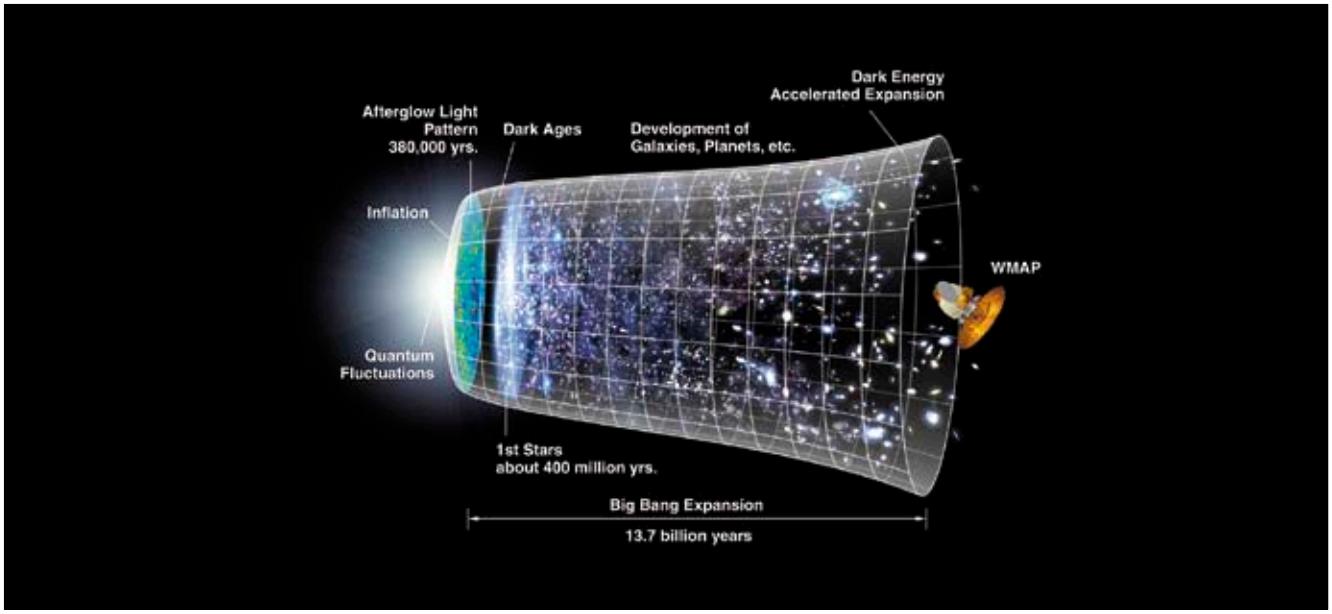


Fig. 1: Timeline of the Universe. The far left depicts the earliest moment we can now probe, when a period of "inflation" produced a burst of exponential growth in the universe. For the next several billion years, the expansion of the universe gradually slowed down as the matter in the universe pulled on itself via gravity. More recently, the expansion has begun to speed up again as the repulsive effects of dark energy have come to dominate the expansion of the universe. (NASA / WMAP Science Team)

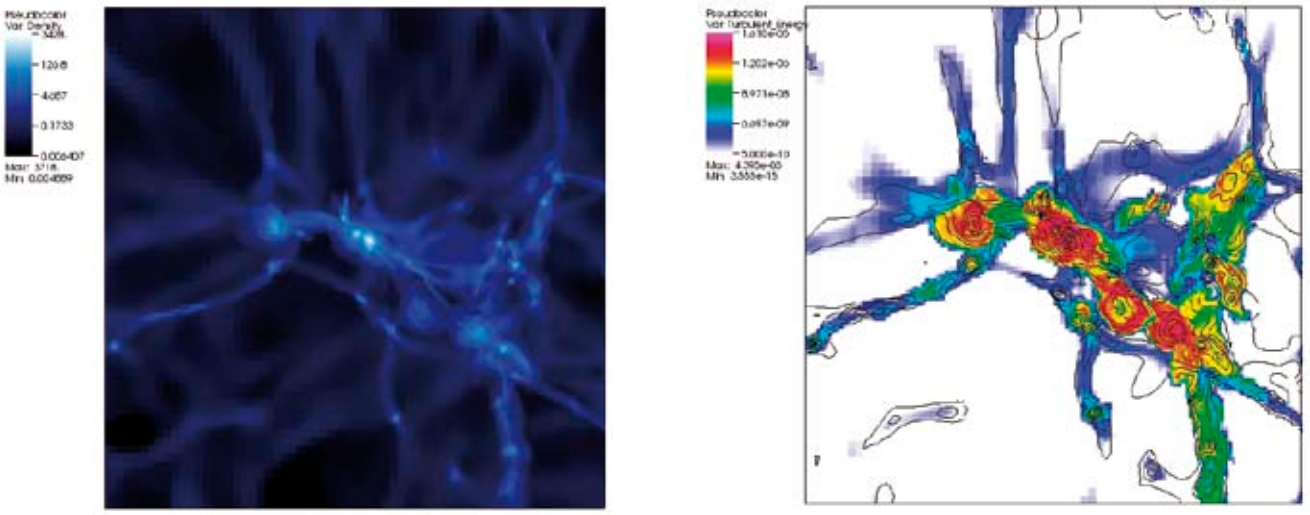


Fig. 2: Simulations of the formation of cosmological structures numerically solve the coupled equations of gas dynamics and pressureless dark matter under the influence of their own gravity on an expanding background. The figures show two-dimensional slices through the three-dimensional density (left) and turbulent kinetic energy (right) fields of a collapsed halo with a linear dimension of approximately 300 million lightyears.

physics. Above all, this part of the work involves expertise in high-energy and gravitational physics. Second, the primordial fluctuation spectrum must be extracted from observations of the cosmic microwave background (CMB) and the distribution of astrophysical objects – stars, galaxies, and intergalactic gas – governed by a variety of complex, nonlinear phenomena which must be well understood in order to be modeled accurately. Here, numerical simulations and statistical analysis of huge data sets require the use of supercomputers.

Looking even further into the past, we are interested in potential observables of a false-vacuum phase transition which might have preceded inflation. In this picture, our universe is one of infinitely many bubbles, some of which may have collided with ours in the distant past. Only if inflation has lasted the minimum amount of time allowed by the observations would these events still be visible. Their detection would thus yield information not only about the extent of inflation itself, but also about its very beginning.

From Intergalactic Gas to Stars and Galaxies

To our current knowledge, cosmological structures have evolved from the gravitational collapse of dark matter, followed by infalling baryonic gas from which, in turn, stars and galaxies were formed. Observations of quasar absorption lines and, using radio telescopes currently under development, the 21 cm emission of neutral hydrogen, allow us to measure the density and temperature distribution of the gas at different epochs. By accurately modeling the dominant physical processes, we can indirectly learn more about the properties of the dark matter – for instance, whether it contains a warm or decaying component – and a possible time dependence of the dark energy proposed to explain the accelerated expansion of the universe.

This combination of nonlinear, non-equilibrium phenomena can only be treated numerically with the help of large-scale simulations. However, even the largest computers are unable to capture the entire range of length and time scales relevant for this problem. We therefore work on developing and improving so-called subgrid models in order to mimic the influence of unresolved, small-scale physics such as turbulence and star formation on the resolved large scales.

Galaxy clusters take a special place in the family of cosmological structures. Not only are they the largest gravitationally bound objects, the intracluster gas also contains most of the baryons in the universe. They can be observed in X-ray and radio wavelengths. Again, numerical simulations can be used to study their formation and evolution in order to use them as probes of the density distribution and expansion history of the universe.

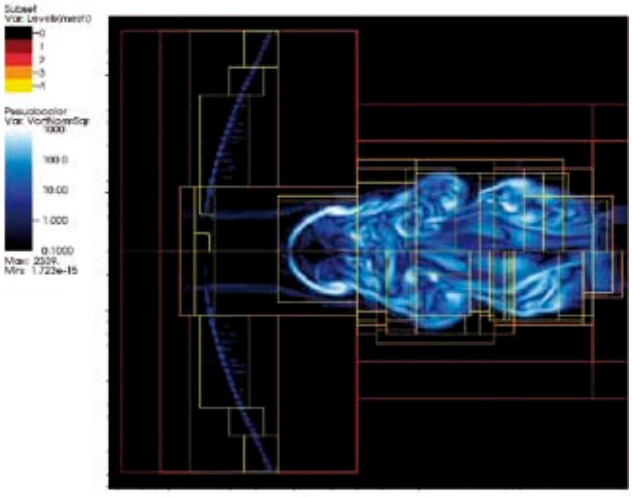


Fig. 3: Adaptive Mesh Refinement (AMR) is a powerful strategy to dynamically adapt the numerical resolution of the computational grid in order to follow the evolution of localized structures. In this example, a simplified galaxy subcluster falls into the gas halo of a larger cluster, creating a bow shock in front and a region of turbulence behind itself. The figure shows a snapshot of the vorticity with the superimposed grid structure.

Cosmic Turbulence

Turbulence plays many different roles on the different scales of cosmological evolution. On scales of molecular clouds embedded in the spiral arms of star forming galaxies, it has a major impact on the rate of gas transformed into stars. One of its key roles on scales of galaxies is its efficiency to mix metal enriched gas into the ambient intergalactic medium. In the cores of galaxy clusters, it contributes to thermal transport and might even make important corrections to mass reconstructions from hydrostatic equilibrium. Finally, on the largest scales of the intergalactic medium, turbulence is the prime candidate for amplifying magnetic seed fields and mixing gas from galactic winds.

One of the goals of our group is to improve our understanding of turbulence in all of these contexts, and to translate the results into effective models for numerically unresolved fluctuations in cosmological simulations.

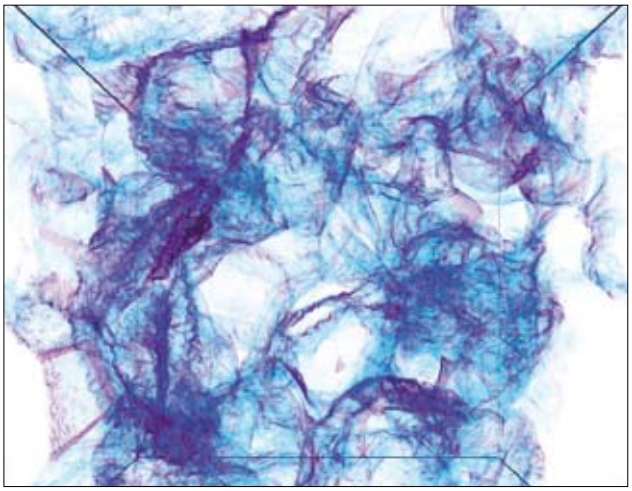


Fig. 4: Vorticity field in a simulation of supersonic isothermal turbulence under conditions typical for star forming regions in molecular clouds. The statistical information from these results can be used to build models for the star formation efficiency in cosmological simulations.

[1] Simon, D.; Adamek, J.; Rakic, A.; Niemeyer, J. C.: *Tunneling and propagation of vacuum bubbles on dynamical backgrounds,* eprint arXiv:0908.2757 (2009)

[2] Maier, A.; Iapichino, L.; Schmidt, W. and Niemeyer, J. C.: *Adaptively refined Large Eddy Simulations of a galaxy cluster: turbulence modeling and the physics of the intra-cluster medium,* submitted to ApJ (2009)

[3] Adamek, J.; Campo, D.; Niemeyer, J. C. and Parentani, R.: *Inflationary Spectra from Lorentz Violating Dissipative Models,* Phys. Rev. D, 78, 103507 (2008)

[4] Lapichino, L. and Niemeyer, J. C.: *Hydrodynamical adaptive mesh refinement simulations of turbulent flows – II. Cosmological simulations of galaxy clusters,* MNRAS, 388, 1089-1100 (2008)

[5] Schmidt, W.; Niemeyer, J. C.; Hillebrandt, W. and Röpke, F. K.: *A localised subgrid scale model for fluid dynamical simulations in astrophysics I: Theory and numerical tests,* Astron. Astrophys., 450, 265 (2006)

Jens Niemeyer

Born near Munich in 1968, Jens Niemeyer received his Diploma and PhD from the Technical University of Munich. For his PhD thesis, he developed models for thermonuclear supernovae with Wolfgang Hillebrandt at the Max-Planck-Institute for Astrophysics in Garching and with Stan Woosley at the Unversity of California in Santa Cruz, USA. He went to the University of Chicago as an Enrico-Fermi Fellow in 1997, working on early universe cosmology and supernovae, before returning to Garching in 2000. Following a faculty position at the University of Würzburg from 2002 - 2009, he started his position at the University of Göttingen, where he is currently building up a cosmology group.

Computational Radiation Hydrodynamics

Flows in the presence of strong radiation fields are typical for astrophysical situations. Their theoretical description and numerical treatment is the subject of 'Computational Radiation Hydrodynamics'. An example for research in this field is described here.

Radiation hydrodynamics of stellar envelopes

The envelopes of many luminous stars are characterized by a large contribution of the radiation pressure to the total pressure. Massive primordial stars, massive stars in the Galaxy like the spectacular object η Carinae, and some central stars of planetary nebulae and their progenitors are examples which exhibit this situation. The large fraction of radiation pressure gives rise to violent instabilities, whose mechanism and final result is investigated using a theoretical approach.

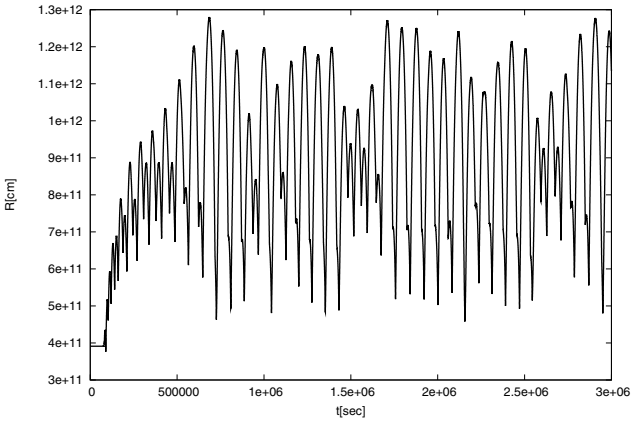


Fig. 1: Stellar radius as a function of time for a massive Wolf-Rayet star (from [2]). A radiation driven instability in the stellar envelope leads to finite amplitude pulsations.

Stellar evolution calculations and the linear stability analysis of the generated stellar models form the basis of the studies. For unstable stellar models the time evolution of the instability is then followed numerically into the nonlinear regime using a radiation hydro code [1] to determine the fate of the corresponding star. Depending on the particular stellar parameters, the instabilties can lead to finite amplitude periodic pulsations (Fig.1) or may show indications of chaotic behaviour. The mechanical energy flux associated with the pulsations turns out to be high enough to drive a stellar wind with significant mass loss rates [2].

Stellar mass loss is fundamental not only for stellar evolution but also for the environment of galaxies, yet it is still a poorly understood phenomenon. Accordingly, the aim of the current studies consists of proving strictly a connection between stellar pulsations and mass loss for the luminous stars considered. Numerically determined mass loss rates will considerably improve not only the understanding of their evolution but will also provide more reliable input for galactic matter circulation.

[1] Grott, M.; Chernigovski, S.; Glatzel, W.: *The simulation of non-linear stellar pulsations,* Mon. Not. R. Astron. Soc. 360, 2005, 1532 - 1544.

[2] Glatzel, W.: *Nonlinear strange-mode pulsations,* Comm. in Asteroseismology 158, 2009, 252 - 258.

Wolfgang Glatzel

Wolfgang Glatzel received his PhD in physics from the University of Göttingen in 1983. After postdoc positions at the Institute of Astronomy in Cambridge, England, and the Max Planck Institute for Astrophysics, Garching, he returned to Göttingen and completed his habilitation in 1992. He holds a position as Akademischer Rat at the Institute for Astrophysics Göttingen and was appointed außerplanmäßiger professor in 1998. His research interests are theoretical and numerical astrophysics, in particular astrophysical fluid mechanics, stellar structure, stability and evolution, and the physics of accretion discs.

Active and Normal Galaxies

Normal galaxies consist of about 100 billion stars, as well as gas and dust. Galaxies evolve on cosmological timescales with respect to their morphology, stellar composition and age, gaseous content and chemical composition. Massive black holes, a billion times more massive than our sun, are presumed to reside in the center of every galaxy in the Universe. Active Galactic Nuclei (AGN) around these black holes enable us to study the physics of their close environment and to measure their mass. The activity is connected with feeding of fresh gas from the outskirts of the galaxy into the central black hole. This feeding might be caused by tidal interactions of moving galaxies. Active Galactic Nuclei are the most powerful light sources in the Universe.

We are investigating with 1dim. and 2dim. spectroscopy, multi-frequency observations (optical, UV, radio, X-ray), as well as by comparison with model calculations the following topics:

- Physical processes in Active Galactic Nuclei: structures, accretion disks, velocities in the innermost AGN regions surrounding the central supermassive black holes.
- (AGN) Host galaxies: morphology, internal kinematics, starburst activity, stellar population/evolutionay synthesis.
- Environment of active galaxies: merging of galaxies, interacting galaxies, groups/ clusters of galaxies, large scale structures.

[1] Frieman, J.; ...; Kollatschny, W.: *The Sloan Digital Sky Survey-II Supernova Survey: Technical Summary,* 2008, AJ 135, 338

[2] Kollatschny, W.: *Spin orientation of supermassive black holes in active galaxies,* 2003, A&A 412, L61

[3] Kollatschny, W.: *Accretion disk wind in the AGN broad-line region: Spectroscopically resolved line profile variations in Mrk 110,* 2003, A&A 407, 461

[4] Kollatschny, W.; Bischoff, K.; Robinson, E. L.; Welsh, W. F.; Hill, G. J.: *Short-term emission line and continuum variations in Mrk 110,* 2001, A&A 379, 125

[5] Kollatschny, W.; Kowatsch, P.: *The X-ray jet in the merging galaxy system Markarian 266,* 1998, A&A 336, L21

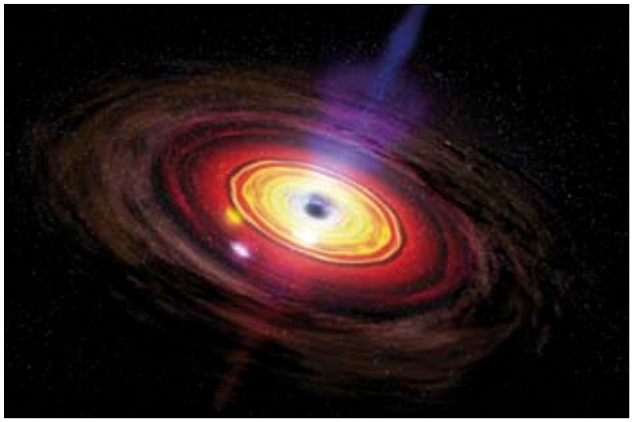


Fig.1: Artist's impression of the innermost region in AGN. A disk of hot gas is surrounding the central black hole. Two jets of high energy particles are propelled away from the vicinity of the black hole (NASA).

Fig. 2: The interacting galaxies NGC5426-5427 (Gemini observatory).

Wolfram Kollatschny

Wolfram Kollatschny was born in 1950 in Minden. He obtained his PhD in 1983 and his habilitation in 1991 at the University of Göttingen. He worked as a visiting professor at the University of Erlangen (1991) and at the University of Texas, Austin (1999-2000). He has done observations worldwide, at nearly every major optical observatory (ESO,Chile, LaPalma, Spain, MacDonald Observatory, USA, Calar Alto, Spain, Sutherland, SouthAfrica), radio observatories (VLA,NewMexico) and satellites (IUE, ROSAT, HST). He was the German representative to the ESO Users Committee, a member of the program committee of Calar Alto Observatory and he is a board member of many international large scale telescope projects (HET, Texas; SALT, Südafrika; NUVA).

Quantum Field Theory

Quantum field theory (QFT) is the „language“ describing the fundamental physics in the relativistic microcosmos, notably the elementary particles. In a continuous endeavor, the quantum field theory group in Göttingen (previously led by Max Planck medalists Gerhart Lüders, Hans-Jürgen Borchers, and Detlev Buchholz) pursues a mathematical approach in which the strong internal constraints imposed by the interplay between the principles of relativity, Einstein causality, and the stability of quantum systems are explored. It turns out that notions like „particle“, „charge“, and their fundamental interactions are far more subtle in QFT than in the more familiar setting of quantum mechanics. A careful analysis of these structures leads to insights that bear fruit in many applications.

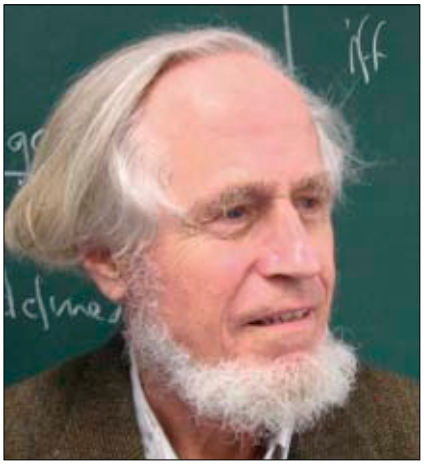
Charges and symmetries

Apart from the electric charge, particle physicists have become familiar with many different charges, including „flavor“ and „color“ of leptons and quarks. The traditional understanding of charge quantum numbers as characteristic eigenvalues in representations of internal symmetry groups involves unobservable entities. An intrinsic characterization in terms of observable data has confirmed this picture, but it has also revealed its limitations, e.g. in the presence of long-range forces. Especially in model theories in less than three space dimensions, the association of charges with symmetry groups cannot be maintained, and a world of new types of „quantum charges“ has been discovered, including the fascinating theory of generalized symmetries, which occur in real physics in the guise of critical behavior of statistical systems confined to surfaces.

Particles

The fundamental observables in relativistic quantum physics are neutral fields. Particles arise as excitations in certain states in which these fields can be measured. As such they may possess properties depending on the state. For instance, their mass can be temperature dependent, if it can be sharply defined at all. Defining the mass of a particle in interaction is not an easy task. In scattering theory, one can wait until the particle is far away from all other particles, and hence its mass can be defined as for non-interacting particles. This is clearly not possible if the particle is confined, as for quarks, or if it cannot be separated from a surrounding „photon cloud“ due to its electric charge and the long-range nature of the electromagnetic interaction, or if it moves in a thermal environment. The conceptual problems with the notion of „particle“ were attacked in Göttingen, and led to several new analytic tools allowing to compute their properties.

Gerhart Lüders



Hans-Jürgen Borchers

Detlev Buchholz

Hot matter

The interaction with a thermal background leads to a drastic change of particle behavior. They no longer arise as asymptotically stable entities, but rather as excitations of the background that dissipate less rapidly than all other perturbations. In large scale systems, thermal equilibrium can only exist locally. The question arises, then, how a local temperature can be defined in a relativistic quantum theory. These and related questions were addressed in our group, and new methods were developed to define and compute local temperatures within the microscopic theory and to derive transport equations for macroscopic observables such as particle densities.

Conformal symmetry

At very high energies, nature seems to exhibit a symmetry which goes beyond relativistic invariance: conformal symmetry. It is a very restrictive property that can be exploited both for the classification and for the construction of quantum field theory models. In two dimensions of spacetime, we have initiated a general theory how a given model can be extended, and how the presence of boundaries change the admissible states of a conformal quantum field theory. A program of constructing such theories in four dimensions of spacetime is presently pursued.

Construction

The rigorous construction of realistic models of interacting quantum field theory is a difficult task due to the highly singular nature of the fields and the strong quantum fluctuations of the vacuum state. In two dimensions of spacetime the situation is better, and large classes of models have been constructed. A variety of new schemes for construction, that build on the genuine quantum features rather than classical field equations, were developped in our group.

The challenge of Gravity

The consistent incorporation of the principles underlying the classical theory of Gravity and the principles of Quantum Theory into a future Theory of Quantum Gravity is one of the great challenges in fundamental physics. Our group pursues a systematic first step towards this goal: the study of the interaction between quantum fields of matter and classical gravitational fields. Recent progress in the understanding of the principle of General Relativity allows promising new applications, such as the systematic investigation of quantum matter in the neighborhood of black holes.

[1] Borchers, H.-J.: *On revolutionizing quantum field theory with Tomita's modular theory,* J. Math. Phys. 41 (2000) 3604-3673.

[2] Bros, J.; Buchholz, D.: *Asymptotic dynamics of thermal quantum fields,* Nucl. Phys. B 627 (2002), 289-310.

[3] Longo, R.; Rehren, K.-H.: *Local fields in boundary conformal QFT,* Rev. Math. Phys. 16 (2004) 909-960.

[4] Fredenhagen, K.; Rehren, K.-H.; Seiler, E.: *Quantum field theory: where we are,* Lect. Notes Phys. 627 (2007) 61-87.

[5] Buchholz, D.; Summers, S. J.: *Warped convolutions: a novel tool in the construction of quantum field theories,* in: Quantum Field Theory and Beyond, Proceedings Ringberg 2008, E. Seiler and K. Sibold, eds., World Scientific (2008), pp. 107-121.

[6] Nikolov, N. M.; Rehren, K.-H.; Todorov, I.: *Harmonic bilocal fields generated by globally conformal invariant scalar fields,* Commun. Math. Phys. 279 (2008) 225-250.

Karl-Henning Rehren

Karl-Henning Rehren, was born in 1956 in Celle. He studied physics and astronomy in Göttingen, Heidelberg and Freiburg im Breisgau, where he received his PhD 1984 under the supervision of Klaus Pohlmeyer. He had a scholarship semester at the École Normale Supérieure Paris, PostDoc positions at the Freie Universität Berlin and in Utrecht (Netherlands), and was an assistent at Hamburg University. He is Hochschuldozent (since 1997) and Professor (since 2002) at the Institute for Theoretical Physics, Göttingen University. Presently, he is Chairman of the Fachverband „Theoretische und Mathematische Grundlagen der Physik" in the Deutsche Physikalische Gesellschaft, member of the Graduiertenkolleg 1493 „Mathematical Methods in Modern Quantum Physics", and Principal Investigator in the Courant Research Centre „Higher Order Structures in Mathematics".

Fluid Mechanics

Current research relates to compressible flows, multiphase flows and aerodynamics using experimental approaches with analytical and numerical methods as support. Related studies are partly fundamental in nature with an emphasis on obtaining insight into the physical mechanisms that govern various flow phenomena. Other studies happen against the background of applications such as cold spray coating, erosion testing and the performance of aircraft.

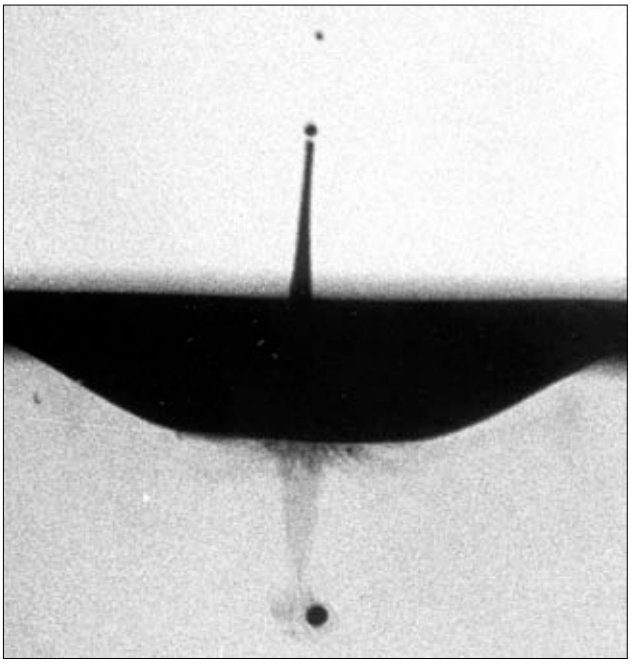


Fig. 1: Droplet impingement on a deep liquid: formation of a bubble and ejection of a high-rising thin jet.

Drop-surface interactions provide a fascinating variety of phenomena. For example, both the transition from spreading to splashing for drops impinging on solid surfaces and the formation of vortex rings after drop impact into liquids have been traced to capillary effects. Another effect seen during drop impact on liquid surfaces is the formation of a bubble and the ejection of a high-rising thin jet (Fig. 1). High-speed drop impacts result in the formation of shock waves and high pressures in the liquid which may cause serious erosion. Well-defined erosion tests have been developed that are based on thermal loads and particle impacts. Above a limiting impact velocity, instead of eroding the surface metal particles may adhere to the impacted surface, a phenomenon that is exploited in cold spray coating. In this coating method particles are accelerated in a supersonic jet that is directed against a substrate. The dynamics of the dispersed flow of particles in the shock layer formed ahead of the substrate is governed by self-excited flow oscillations. Different mechanisms for these oscillations have been analyzed both for one- and two-phase jets. Similarly, jet impacts are also present during vertical take off and landing of aircraft with vectored jets. Other current aerodynamic research topics concern the reduction of wave drag and the control of vortical flows over wings. Wave drag limits the maximum economic cruise speed of airplanes and is caused by nearly normal shock waves terminating supersonic regions formed locally above wings at transonic speeds. The effectiveness of reducing wave losses by changing a normal shock into a system of oblique shocks generated by cones placed above the wing has been evaluated in wind tunnel tests (Fig. 2). Another topic is the control of vortices and vortical flow fields. Research is progressing into shifting the position of both vortex cores and the vortex breakdown. These strategies may be used to change the lift of aircraft and reduce the strength of wake vortices.

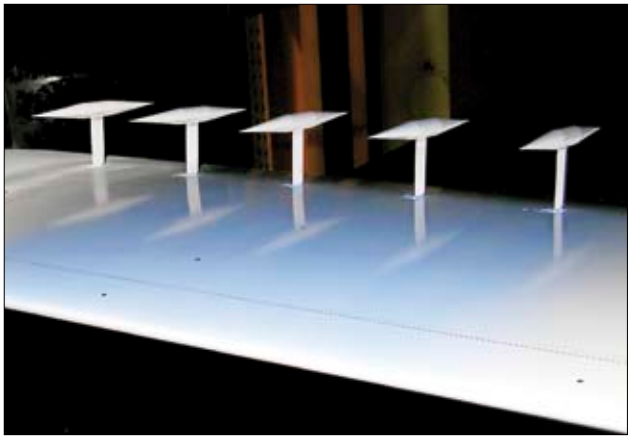


Fig. 2: Transonic wing with cones used for generating oblique shocks in the transonic wind tunnel DNW-TWG, Göttingen.

Martin Rein

Martin Rein received his diploma (1984) and doctoral (1987) degrees in Physics from the University of Göttingen working at the Max-Planck-Institut für Strömungsforschung. After a postdoctoral stay (1988-1989) at GALCIT, Caltech, he returned to Göttingen where he held positions at the Max-Planck-Institut für Strömungsforschung (1990-1993) and the University of Göttingen (1994). During a habilitation stipend (1994-1997) he also stayed at the Institute of Fluid Mechanics and Heat Transfer, Technical University of Vienna (1995), where he received a venia docendi in fluid mechanics in 1998. In 1998 he joined the Institute of Aerodynamics and Flow Technology of the German Aerospace Center (DLR). He obtained a venia legendi at the University of Göttingen in 2004, spent a sabbatical leave at UCSB in 2007, and was appointed senior scientist of DLR in 2006 and apl. Professor at the University of Göttingen in 2008.

Neurophysiology and Cellular Biophysics

The research in our group focuses on the biophysics and the physiology of how molecules or mixtures of molecules are detected by biological and artificial sensors and how the resulting signals are processed to allow the identification or perception of odorants and odors. The experimental or computational projects carried out in our lab are concerned with single molecule interactions using fluorescence correlation spectroscopy, optical as well as metal oxid semiconductor sensors as the hardware input stage for electronic nose algorithms, high-resolution microscopy, electrophysiology and imaging of olfactory receptor neurons in the nose of tadpoles, single molecule processes and modulation (e.g., by endocannabinoids),electrophysiology (patch clamp) and imaging of the olfactory bulb as the secondary computational neuronal network of the olfactory system.

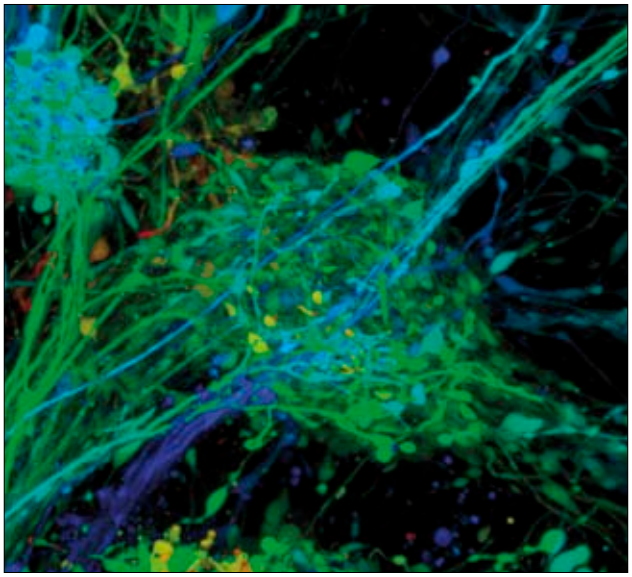


Fig. 1: Synaptical network of sensory fibers. The image was taken by Eugen Kludt using a two-photon absorption laser scanning microscope. The individual nerve fibers that can clearly be seen have a diameter of less than 1µm.

Motivation

The five classical senses are vision, audition, touch, taste and smell. For the former three we have reasonably good intruments for recording the underlying physical parameters, e.g., frequencies of sound or light, etc. For the sense of smell everyday instrumentation is still in its kindershoes. There are virtually no simple devices for the online and realtime detection of pollutants in water, hazardous substances in food, or for differentiating various species of coffee, olive oil, or wine. This is the motovation of our research on the olfactory system on the one hand and the development of artificial chemosensory systems on the other.

Olfactory System

This sensory modality mainly consists of three stages: (i) the olfactory receptor neurons, (ii) the olfactory bulb, and (iii) higher olfactory brain centers. We analyse (i) single molecule processes in signal cascades in sensory cells using the patch clamp technique as well as confocal imaging metods and FCS, (ii) the functional map from the sensor cells onto the olfactory bulb in order to understand the selforganization of this map, and (iii) the synaptic interactions within the olfactory bulb in order to understand the filtering and transfer function of this neuronal network.

Electronic nose

Currently we are interested in measuring chemical components of grain in order to differentiate polluted from wildtype grain. We are setting up artificial sensor array systems that yield chemotypical signals from which the relevant features are extracted.

Detlev Schild

Detlev Schild, born 1951 in Detmold, studied Physics and Medicine in Göttingen, where he obtained the PhD in 1985 and the Dr.med. In 1987. After an initial interest in biorhythmicity, frequency entrainment and nonlinear oscillations he turned to the study of membrane biophysics, in particular in excitable cells in the brain. After stays in Siena and Brighton he started to study the properties of olfactory sensory neuron as well as the neuronal network involved in the combinatorial coding of odors. Since 1997 he is chair of the department of neurophysiology and cellular biophyics.Cozzarelli Prize of the National Academy of Sciences USA (2008) Various administrative activities. Member of the academic senate (2007-09) and since then of the foundation counsil of the university.

Theoretical and Computational Biophysics

The aim of the group is to reveal the physics, the function, and the underlying mechanisms of biomolecules – particularly proteins – at the atomic level. These true "molecular nanomachines" are essential for all life forms; their structure and their atomic motions determine their function. Fig. 1 shows F-ATP synthase, which produces up to 60 kg of ATP per day in our bodies. In contrast to conventional chemical synthesis, which rests on random thermal motion, F-ATP synthase literally 'puts together' the product molecule by 'nanomechanics'. Nearly all biomolecular functions are carried out by proteins, and their malfunction is the origin of most diseases.

Can we reveal the tricks which nature has developed during the past billion years?

We address this question using large-scale atomistic simulations, which implies highly interdisciplinary research at the interface between statistical mechanics, quantum mechanics, biochemistry, structural biology, mathematics, and computer science. We further seek for new physical concepts that properly describe biomolecular dynamics. In this endeavor, close collaboration with experimental groups is essential (Fig. 2).

Our field is young and rapidly expanding. Up to now there is no unifying 'protein theory'; rather, there is an evolving 'patchwork' of new methods and concepts, each capable of describing a different facet of these quite complex many-particle systems. Accordingly, success depends on the ability to develop, to apply, to combine, and to implement many of these 'patches'. Our group thus offers projects with many different 'flavors' to students, ranging from new methods developments to projects that put the focus on a particular 'molecular nanomachine'.

Our simulations often involve several million atoms and are computationally quite demanding; currently accessible time scales range up to microseconds, which renders an increasing number of biomolecular processes directly accessible. Many others occur at slower time scales, however. We therefore strive for methodological, algorithmic, and computational advancements, each of which opens up access to new systems. One particularly challenging example is protein folding, which typically requires milliseconds to seconds to be completed and is one of the `holy grails' of molecular biophysics.

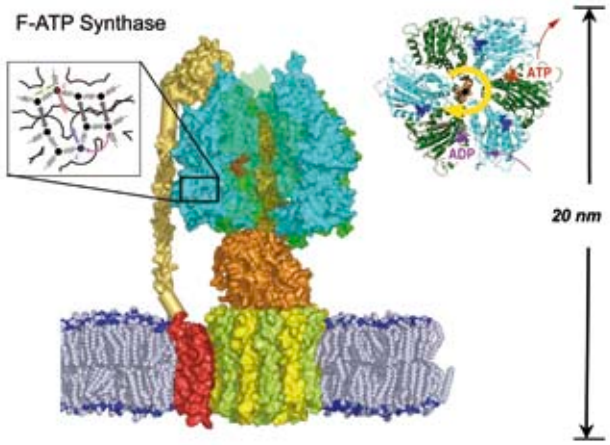


Fig. 1: F-ATP synthase embedded in a lipid membrane. The membrane part drives rotation of the orange axis which transmits the energy for ATP synthesis to the ATP binding sites via fine-tuned atomic motions. This electroosmotic-mechano-chemical energy conversion proceeds at close to 100% thermodynamically possible efficiency.

New ways to separate relevant from irrelevant degrees of freedom, non-equilibrium statistical mechanics and sampling techniques, advanced quantum chemistry, as well as algorithms for massively parallel computer clusters are our methodological focus.

Much of the molecular territory is still uncharted. Exploring an increasing number of biomolecular systems, we seek to push the limits by sharpening our computational tools, to check newly developed concepts and methods against experiment, to suggest new experiments, and thus to expand our knowledge on how life works at the atomic level.

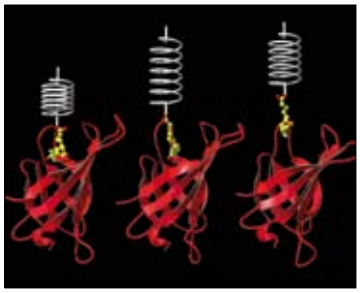


Fig. 2: Atomistic simulation of a single molecule atomic force microscopy experiment in which the binding force between the vitamin biotin and its receptor streptavidin is measured. This complex forms one of the strongest non-covalent biological interactions known.

Helmut Grubmüller

Professor Dr. Helmut Grubmüller received his PhD in theoretical physics at the Technical University of Munich in 1994. From 1994 to 1998, he worked as a research assistant at the Ludwig Maximilians University in Munich. In 1998, he moved to the Max Planck Institute for Biophysical Chemistry as research group head. Research visits brought him to the University of Illinois, U.S.A., Grenoble, and the ETH Zurich, Switzerland. He has led the Department of Theoretical and Computational Biophysics at the Max Planck Institute for Biophysical Chemistry as a director since 2003. Helmut Grubmüller is also honorary professor of physics at the University of Göttingen and is contributing numerous lectures and classes within the physics curriculum of the University of Göttingen.

NanoBiophotonics

Since the discovery of the diffraction barrier by Ernst Abbe in 1873, it has been commonly accepted that the resolution of a light microscope is essentially limited to about half the wavelength of light (>200 nm). The diffraction barrier also affected fluorescence microscopy which is the most popular microscopy modality in the life sciences, because it allows the specific observation of labeled proteins, lipids and nucleic acids. We have demonstrated in the recent past that in fluorescence microscopy, the resolution limiting role of diffraction can be fundamentally overcome by exploiting specific transitions between fluorophore molecular states. Concretely, switching the ability of markers to fluoresce enables imaging without diffraction limit, if the switching is implemented in such a way that neighboring molecules emit successively in time. Switching is realized by toggling the fluorophores between an emitting and a dark molecular state.

Stimulated Emission Depletion (STED) Microscopy is the first focused light microscopy method that is no longer fundamentally limited by diffraction. Here, the focal spot of a molecular excitation beam is accompanied by a red-shifted (usually) doughnut-shaped 'STED' beam that transiently switches off the fluorophores at the spot periphery using stimulated emission. Whereas the molecules subject to the STED beam are essentially confined to the ground ('off') state, those at the doughnut center remain in the fluorescence 'on' state and fluoresce freely. Typically, the resolution is improved by 10-fold compared to conventional microscopes, thus allowing discerning labeled protein assemblies that are only 20-30 nm apart. However, increasing the brightness of the STED beam reduces the spot further in size, in principle, down to the size of a molecule. In other words, the diffraction barrier is truly broken. Undergoing development under fast pace, STED microscopy has been applied to areas as diverse as biology and the material sciences. Examples include the imaging of the diffusion of synaptic vesicles inside a neuron at video rate, lipid molecules in the plasma membrane of a cell, the nanoself-assembled structures in polymer films, or crystal defects in diamond.

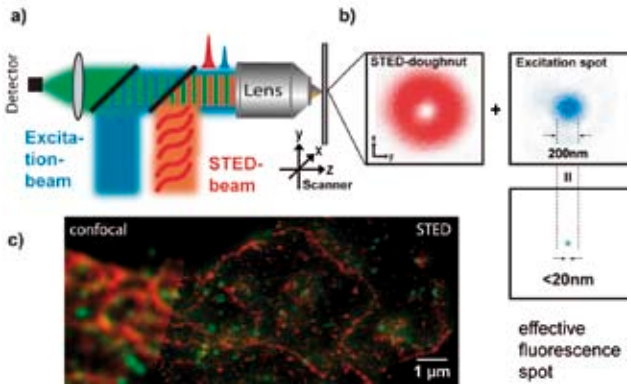


Fig.: (a) Schematic drawing of a STED microscope. The excitation beam (blue) is followed by a beam with a central zero (STED-beam, red). (b) The STED-beam switches off the fluorescence ability of the dye by stimulated emission at the excitation spot periphery. This results in a remaining fluorescent spot with nanoscale extensions, providing nanoscale resolution. (c) STED image of a glioblastoma cell from the most frequent malignant brain tumor. Clathrin protein is green; β-tubulin protein is stained red. In contrast to the blurred standard (confocal) image (left), the STED image (right) shows details far below half the wavelength of light.

A fascinating alternative to switching off with stimulated emission is to switch the molecule between metastable (long-lived) states; it allows one to break the diffraction barrier at low light levels. In a method called RESOLFT, fluorophores are switched between such metastable conformational states or binding states of organic molecules or fluorescent proteins with a light intensity distribution featuring a zero, similarly to STED. Switching individual fluorophores randomly in space is also very effective for producing images with resolution on the nanometer scale, as pursued in the methods STORM, PALM, and GSDIM.

Our interdisciplinary workgroup, which has initiated this research area of 'far-field optical nanoscopy' comprises physicists, chemists, and biologists working together to conceive, develop, and apply radically new optical microscopes with resolution at the nanometer scale. In physics, our daily research topics encompass 1) theoretical /computational aspects of physics such as imaging theory, molecular statistics, 2) experimental (bio) physics such as the study of biomolecules in the cell, and 3) applied aspects such as single molecule spectroscopy, ultrafast lasers, and modern optical instrument development.

Stefan W. Hell

Prof. Dr. Dr. h.c. Stefan W. Hell received his PhD in physics at the University of Heidelberg in 1990 and worked from 1991 to 1993 at the European Laboratory for Molecular Biology in Heidelberg. From 1993 to 1996, he worked at the Universities of Turku (Finland) and Oxford (UK). Subsequently, he obtained his habilitation in physics from Heidelberg. In 1997, he moved to the Max Planck Institute for Biophysical Chemistry in Göttingen, where he was appointed director and head of the Department of NanoBiophotonics in 2002. Stefan Hell has received many awards for his research, among them the Prize of the International Commission for Optics (2000), the Helmholtz Prize (2001), the 10th German Future Prize of the Federal President (2006) and the Julius Springer Prize (2007). In 2008, he received the Leibniz Prize and in 2009 he was awarded the Otto Hahn Prize in physics.

Computational Biomolecular Dynamics

Proteins are biological nanomachines. They enable, control or support nearly all the processes occurring in our bodies. Accordingly, the consequences are frequently severe when proteins do not function properly. Many diseases are caused by such dysfunctions.

Which interactions give rise to aggregation of proteins and thus cause disorders such as Alzheimer's or Parkinson's disease? How do cells regulate the influx and efflux of molecules such as water, ions and nutrients? How does molecular recognition function? These are some of the questions we investigate in the computational biomolecular dynamics group.

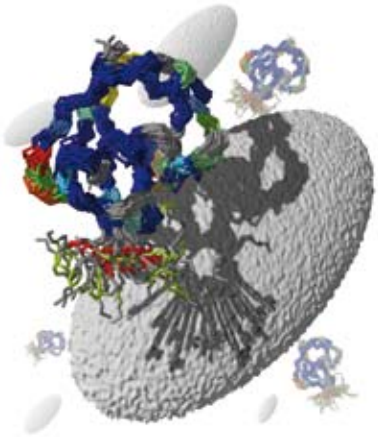


Fig. 1: Molecular recognition by ubiquitin. Since ubiquitin can rapidly assume other shapes, it recognizes many different binding partners. One can imagine it to be like a key ring with which different locks can be opened.

In order to understand the function and dysfunction of proteins, it is usually insufficient to know their structure. Many proteins fulfill their respective task only by means of well-orchestrated movements. Our objective is to understand protein dynamics at the molecular level and to unravel the mechanisms underlying such dynamics.

One class of proteins investigated in the group are aquaporins. They form pores in the cell membrane, which function as perfect, highly selective water filters. Only water molecules can pass through; ions and larger molecules are blocked. By means of molecular dynamics simulations we were able to resolve the mechanism which allows aquaporins to selectively filter in such a way.

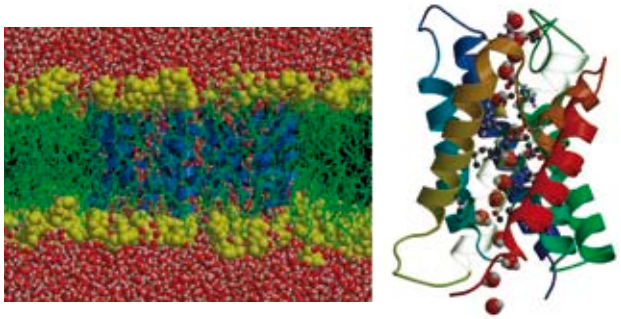


Fig. 2: Water flow through an aquaporin channel Left: Water (red/white) does not pass through the lipid membrane (green/yellow), but rather through special pores, which aquaporin forms in the membrane (blue). Right: Path of the water molecules through the aquaporin channel. Specific interactions allow the passage of water, but prevent larger molecules or ions from passing through in an uncontrolled manner. Even tiny protons (hydrogen ions) are excluded.

In addition, we have a true multitalent among the proteins under investigation: ubiquitin. It is part of a sophisticated recycling system in the cell, which marks certain proteins as cellular "trash". But how does ubiquitin manage to recognize and bind so many different partner molecules? With the aid of molecular dynamics calculations and NMR experiments in we were able to demonstrate that ubiquitin is surprisingly mobile. Like a swiss army knife it continuously changes its shape, extremely rapidly – within a millionth of a second – until it accidentally fits its partner.

[1] Lange, O. F.; Lakomek, N. A; Fares, C.; Schröder, G. F.; Walter, K. F. A.; Becker, S.; Meiler, J.; Grubmüller, H.; Griesinger, C.; de Groot, B. L.: *Recognition dynamics up to microseconds revealed from RDC derived ubiquitin ensemble in solution,* Science 320, 1471-1475 (2008).

[2] Hub, J. S.; de Groot, B. L.: *Mechanism of selectivity in aquaporins and aquaglyceroporins,* Proc. Nat. Acad. Sci. 105, 1198-1203 (2008).

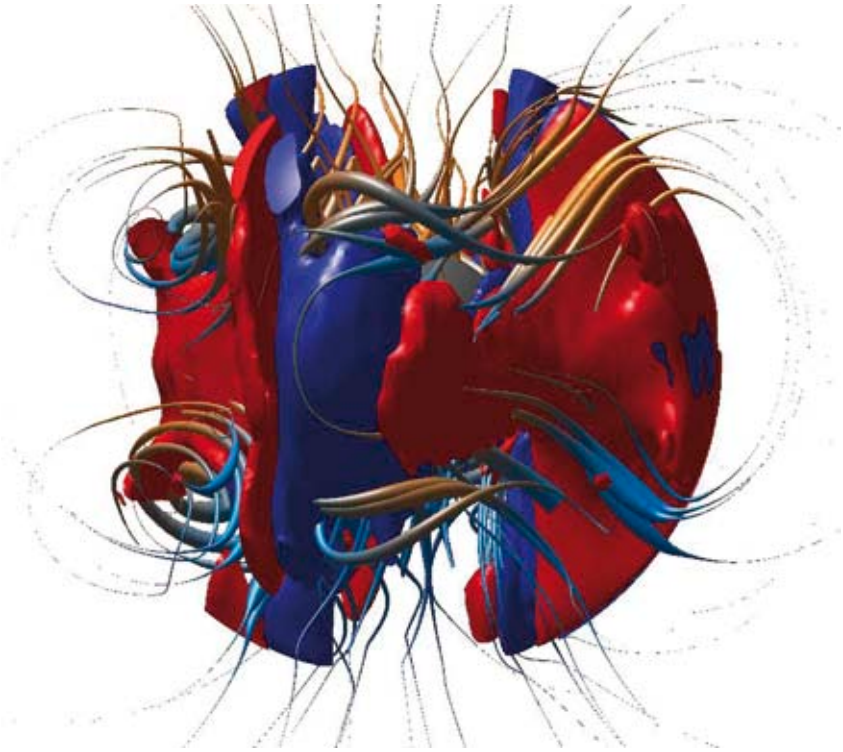
[3] Seeliger, D.; Haas, J. and de Groot, B. L.: *Geometry-based sampling of conformational transitions in proteins,* Structure 15, 1482-1492 (2007).

Bert de Groot

Bert de Groot received his PhD in biophysical chemistry at the University of Groningen (The Netherlands) in 1999. From 1999 to 2003 he worked as a postdoctoral fellow in Helmut Grubmüller's research group at the Max Planck Institute for Biophysical Chemistry in Göttingen. He heads the „Computer-Aided Biomolecular Dynamics" Research Group there since 2004. Bert de Groot is an associate professor of physics at the University of Göttingen since 2009.

Dynamics of Planetary Interiors

The planetary theory group at the Max Planck Institute for Solar System Research concentrates on studying the internal structure and dynamics of planetary bodies. We simulate the generation of magnetic field in the core of the Earth and other planets in numerical models. Flow of liquid iron or other electrically conducting fluids is driven by convection and is strongly influenced by the Coriolis force of planetary rotation. Electromagnetic induction generates electric currents and magnetic field in a self-sustained dynamo process. We aim at (1) understanding fundamental aspects of the dynamo process, (2) explaining in detail the characteristic properties of the geomagnetic field and (3) understanding the differences in the magnetic fields of the various solar system planets and of stars. The illustration shows magnetic field lines and regions of strong positive (red) and negative (blue) flow vorticity for a simple dynamo model that reveals how a magnetic field is generated. We also model the internal circulation in gas planets such as Jupiter, which gives rise to jet streams that cause the banded appearance of their surfaces. We are preparing for analyzing forthcoming data from space missions that will provide information on the basic internal structure of various planets. These are the tidal deformation of Mercury, to be measured by laser altimetry, the shape information together with gravity data that will be obtained at the dwarf planets Vesta and Ceres, and future seismological data for Mars and the Moon.



Ulrich Christensen

Ulrich Christensen obtained his doctoral degree in geophysics from the Technical University in Braunschweig in 1980. He worked as a staff scientist at the Max Planck Institute for Chemistry in Mainz and at the Arizona State University in Tempe on problems of convection in the Earth's silicate mantle. From 1992 to 2003 he was full professor at the Institute of Geophysics at the University in Göttingen, where he extended his research interests to processes in the Earth's core and in the interior of other planets. Since 2003 he is director of the Department for Planetary Sciences at the Max Planck Institute for Solar System Research in Katlenburg-Lindau. Among various awards are the Gottfried Wilhelm Leibniz prize (1994), Fellowship of the American Geophysical Union (2000), Honorary Fellowship of the European Union of Geosciences (2003) and the Augustus Love Medal of the European Geoscience Union (2009).

Solar Magnetohydrodynamics

Magnetic fields are responsible for the restless activity of the Sun and other astrophysical objects. Magnetohydrodynamics (MHD) describes the interaction of a magnetic field with an electrically conducting dense plasma. The research areas of the MHD group at the Max Planck Institute for Solar System Research include

- interaction of magnetic fields with radiative convection in the surface layers of the Sun and other stars
- generation of magnetic flux in a self-excited dynamo process
- structure and dynamics of sunspots and starspots
- emergence, transport and decay of magnetic flux at the solar surface
- development of methods and codes for the numerical simulation of (radiative) MHD processes

Using large-scale numerical simulations of the relevant physical processes on massively parallel computers, we aim at understanding the origin of solar and stellar magnetism as well as its rich variety of manifestations in the form of magnetic activity. Our work is closely connected to solar and stellar observations: we calculate observable quantities from the simulation results and compare them with actual observations. More detailed information can be found in http://www.mps.mpg.de/projects/solar-mhd.

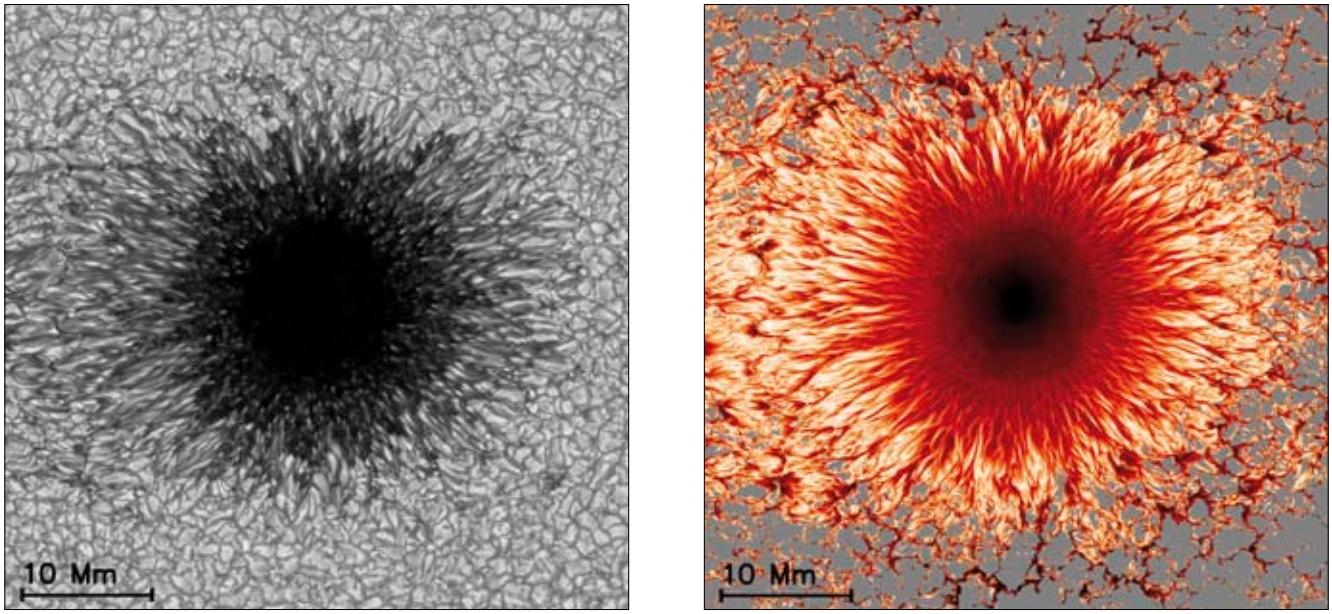


Fig. 1: Snapshot from a numerical simulation of a sunspot. The radiative MHD equations have been simulated in a three-dimensional domain with a numerical grid of 1536 x 3072 x 384 cells. The left panel gives a brightness map, showing the sunspot and its environment of convective plumes. The right panel shows the inclination of the magnetic field with respect to the vertical direction (black: vertical field, white: horizontal field). It illustrates the highly intricate fine structure of the penumbra, the region surrounding the dark core of the sunspot (the umbra).

Manfred Schüssler

Manfred Schüssler received his PhD in 1977 from the University of Goettingen, where he worked as a Research Associate until 1983. From 1983-1999 he was a staff scientist at the Kiepenheuer Institute for Solar Physics, Freiburg, and then joined the Max Planck Institute for Solar System Research. He teaches astrophysics at the University of Goettingen since his habilitation in 1991 and became an Apl. Professor at the Faculty of Physics in 1999. He received the Heinz Maier Leibnitz Prize in 1982 and held the Gauss professorship of the Goettingen Academy of Sciences in 1996. He is author or co-author of more than 230 scientific publications (including 120 papers in refereed journals and 35 review papers) dealing with solar and stellar activity, photospheric magnetic structure and dynamics, magnetic fields in convection zones and dynamo theory, as well as numerical methods for magnetohydrodynamic simulations and radiative transfer.

Dynamics of Complex Fluids

A fluid is called 'complex' if its constituents are complex systems on their own: the macro-molecules in the polymer melt, the lamellae within the foam, the (dissipative) grains in the granulate, or the bio-molecules in the cytoplasm. Can one predict, on the basis of the properties of these constituents, the dynamic behavior of the complex fluid, i.e. the polymer, the foam, the granulate, or the biomaterial? It has become clear that these materials are governed by self-organization and self-assembly processes. Macroscopic properties emerge from these processes on larger scales. Are there general principles of such ‚emergence'? We tackle these questions by means of experimental as well as theoretical methods. We are led not only by fundamental interest, but also by the wealth of potential applications. Once one has achieved a detailed understanding of these systems, the design of self-organized ‚soft' micro- or nano-machines may come within reach, pointing to fascinating novel technologies for the future.

Packing problems and wet granular matter

Processes of self-organization and emergence require the system under study to be far from thermal equilibrium. Since most textbook physics is limited to equilibrium systems, there is still a need for model systems which allow to study the principles of dynamics far from thermal equilibrium. One such system, which belongs to the class of complex fluids, is wet granular matter. Fluid interfaces, which span between the grains by virtue of surface forces and rearrange in response to displacements of the latter, determine the 'free energy landscape' of the whole system, and thereby its macroscopic static and dynamic properties. There are two main avenues of study. One concerns the collective properties of dissipative gases, such as wet granulates. The other focuses on dense wet granular systems and their physical properties. Here we have to investigate the possible geometries of packing, the effects of grain shape upon this geometry, and the dynamics of liquid interfaces forming within such packings when these are wetted. Aside from a wide range of other applications, these studies are of great importance for geophysical problems, such as oil recovery or the storage of carbon dioxide in depleted oil reservoirs.

Gel emulsions in microfluidic systems

An emulsion is called a gel emulsion if its continuous phase has a very low volume fraction (Foam may be considered as a gel emulsion of air in water). When the droplets of such emulsions are equal in size, the system will look like a perfect crystal of droplets. As opposed to the wet granulates discussed above, the liquid interfaces are then not spanning between grains, but between each other, thus generating a scaffold of thin membranes. If the droplets consist of an aqueous phase, and the continuous phase is an oil, the oil lamellae separating two adjacent droplets may collapse by expelling the remaining oil into the closest Plateau border, thus generating a double layer out of the surfactant we used for generating the emulsion. These double layers can be used for modeling biological membranes (e.g., by incorporating membrane proteins), or for accommodating other nano-objects with an appropriate hydrophilic-hydrophobic structure. We are presently incorporating molecular electronics components into these membranes, aiming at the construction of self-assembled molecular electronic circuitry.

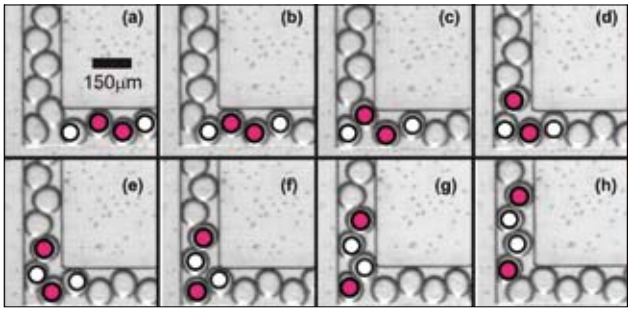


Fig. 1: An emulsion of equally sized water droplets in oil. As the droplets are pumped past the corner, well-defined changes in their relative arrangement occur. This may be used for ‚chemical micro-processors', or other sophisticated micro-fluidic devices.

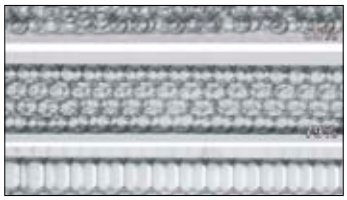


Fig. 2: An emulsion of equally sized water droplets in oil. Depending on volume fraction, the arrangement of droplets may be either ‚amorphous' or ‚crystalline', and resemble a dry foam.

Stephan Herminghaus

Stephan Herminghaus was born in 1959 in Wiesbaden. He studied physics at the University of Mainz, where he received his PhD in 1989 with a thesis on laser ablation. After a postdoctoral stay at the IBM research labs in San Jose (CA), where he studied optically non-linear polymer films, he moved to the University of Konstanz, where he obtained his Habilitation in 1994 with investigations on wetting and thin film optics. In 1996, he started an independent research group at the MPI for Colloid and Interface Science (Berlin), where he initiated and coordinated the DFG Priority Program 'Wetting and Structure Formation at Interfaces'. In 1999, he became full professor and head of the applied physics department at the University of Ulm. Since 2003, he is a director at the MPI for Dynamics and Self-Organization in Göttingen.

Biomedical Physics

How do life-threatening cardiac arrhythmias occur? Why are they so difficult to control? The Biomedical Physics Group seeks to unravel the mechanisms and genetics of cardiac arrhythmias and develops novel approaches for their control.

Mechanisms and Genetics of Cardiac Arrhythmias

Self-organized complex spatial-temporal dynamics underly health and disease states in excitable biological systems such as the heart. During cardiac fibrillation, synchronous contraction is disrupted by vortex-like rotating waves of electrical activity, resulting in complex – and often chaotic – spatial-temporal excitation patterns [1-3]. This electro-mechanical malfunction of the heart can rapidly evolve into Sudden Cardiac Death (SCD). SCD is a leading cause of mortality worldwide, with an estimated 738.000 deaths per year in the European Community alone. Yet the physical mechanisms underlying the dynamics and control of electrical turbulence pose a scientific riddle that remains unanswered even today: how do arrhythmias arise, and how can they be terminated efficiently? In answering these questions, the theory of dynamical systems plays a central role in integrating biological experiments with physical and mathematical developments. An important example are instabilities based on molecular defects in Na^+ and Ca^{2+} transport, which mediate arrhythmia initiation and perpetuation and likely manifest themselves at all levels, from the sub-cellular, cellular, tissue, and organ levels to the entire organism. Our international, interdisciplinary team collaborates to develop and apply hierarchical models, advanced data analysis algorithms and high-resolution fluorescence imaging techniques.

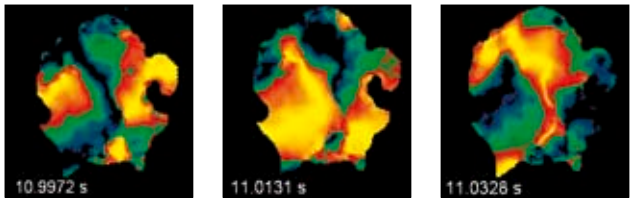


Fig. 1: Spatial-temporal excitation pattern during cardiac fibrillation on the surface of the heart (field of view 6 x 6 cm^2). Colour code: black = resting, yellow = excited.

Controlling Spatial-temporal Chaos in the Heart

Today, the only effective method of terminating fibrillation is a high-energy electric shock (1 kV, 30 A, 12 ms). This empirical approach has intolerable side effects, including traumatic pain and tissue damage. Our research suggests an entirely new approach to the control of spiral-defect chaos in the heart. While the prevailing high-energy control paradigm aims at indiscriminately eliminating all waves, we are developing methods that selectively target the system where it is most susceptible to perturbations, i.e. at the vortex or spiral cores. This approach permits low-energy control of cardiac fibrillation [1], removing the drawbacks of conventional techniques.

By combining theoretical and experimental methods from physics, biology and computer science, the Biomedical Physics Group aims at elucidating physical mechanisms that may – over the long-term – open new paths for translating fundamental research into practical applications aimed at improving human health.

[1] Fenton, F.H. et al.: Circulation 120, 467-476 (2009).
[2] Bittihn, P. et al.: New J. Phys. 10, 103012 (2008).
[3] Otani, N. F. et al.: Phys. Rev. E. 78, 021913 (2008).
[4] Toegel, R.; Luther, S. and Lohse, D.: Phys. Rev. Lett. 96, 114301 (2006).
[5] Luther, S.; Rensen, J. and Guet, S.: Exp. Fluids 36, 326 (2004).
[6] van den Berg, T. H. et al.: Phys. Rev. Lett. 94, 044501 (2005).
[7] Luther, S. et al.: Exp. Thermal and Fluid Science 29, 821-812 (2005).

Stefan Luther

Stefan Luther was born in 1969 in Springe (Deister) and studied Physics at the University of Hannover and at the Georg August University Göttingen, where he received his PhD in 2000. He obtained his postdoctoral training at the University of Enschede (NL) and at the Laboratory of Atomic and Solid State Physics (LASSP), Cornell University, Ithaca NY. Since 2006 he is head of the Max Planck Research Group Biomedical Physics at the MPI for Dynamics and Self-Organization. In 2008 he was appointed Honorary Professor at the Georg August University and in 2009 adjunct Associate Professor at the Department of Biomedical Sciences, Cornell University. In 2008 his group received the Medical Innovation Award from the German Federal Ministry of Education and Research. His research interests include nonlinear dynamics [4], data analysis [5], and complex systems [6, 7].

Mathematical Physics

Nonlinear integrable systems and soliton-like structures

The mathematical description of physical systems typically involves nonlinear partial differential or difference equations (PDEs). These often possess solutions that exhibit quite unexpected organizational or chaotic behavior. In most cases there is hardly a chance to find exact solutions, but examples of relevance for physics exist (in the non-chaotic realm) which are in a certain sense solvable. The latter are usually called "completely integrable", and some may be regarded as generalizations of finite-dimensional Liouville-integrable Hamiltonian systems of mechanics. Such integrable PDEs appear as special cases or approximations of equations governing physical systems in areas ranging from fluid dynamics and optics to general relativity and string theory. Some of them exhibit soliton solutions, which are superpositions of "particle-like" localized waves. Because of their peculiar properties it may not come as a surprise that integrable PDEs also play an important role in various branches of mathematics. Our present work mostly contributes to this interface between mathematics and physics.

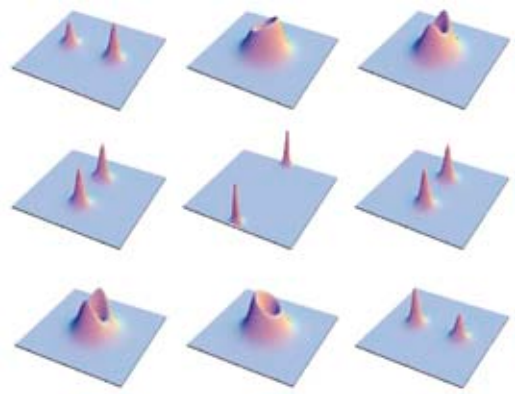


Fig. 1: An anomalous scattering process. Two soliton-like objects („lumps") approach each other, merge, then separate in the orthogonal direction until they reach a certain maximal separation. Then they approach each other again and finally continue moving in the original direction. This displays an exact solution of Ward's modified chiral model. The same process exists for soliton-like solutions of the famous Kadomtsev-Petviashvili I equation, which models fluid surface waves in the case where surface tension plays an essential role. So far these structures are outside the reach of experiments, however.

Geometry and Physics

Differential geometric structures are essential ingredients of fundamental physical theories, most notably general relativity. They also play a crucial role in many applications. Algebraic generalizations of geometric concepts have been developed extensively during the last three decades, especially under the heading of "noncommutative geometry". Corresponding generalizations or deformations of differential geometric structures appeared e.g. in the context of (Moyal) deformation quantization, in quantum integrable models (exhibiting quantum groups), string theory, and in Connes' approach to the standard model of elementary particle physics. We demonstrated that they are also useful in areas like lattice gauge theory, discrete geometry, and classical integrable systems. All this is presently a bit aside of our main research, but we supervise Bachelor and Master of Science students writing their thesis in the area of general relativity, for example.

Fig. 2: Part of a surface generated (as parametric plot) by a 2-soliton solution of a system of two simple PDEs, closely related to the short pulse equation as well as the sine-Gordon equation.

List of Publications:

http://www.mueller-hoissen.de/publ.html

Folkert Müller-Hoissen

Folkert Müller-Hoissen did his Diploma in Theoretical Physics in 1979 at the University of Göttingen and continued on to obtain his PhD in 1983, also in Theoretical Physics in Göttingen. He had his first post doc from 1983 - 1985 at the Max-Planck-Institute for Physics, Munich, followed by a stay as a Postdoctoral Fellow from 1986 - 1987 at Yale University, USA. Returning to Göttingen in 1988, he was an Assistant Professor and completed his Habilitation in 1993. Besides his employment at the Institute of Theoretical Physics in Göttingen, in summer of 1994 he also took a Lectureship at the University of Hannover. In 1995 followed a position as a Research Scholar at the Max Planck Institute for History of Science, Berlin. Since 1996, he has been a scientific staff member at the Max Planck Institute for Flow Research (now called the Max Planck Institute for Dynamics and Self-Organization) in Göttingen. Since 2000, he has been an Extraordinary Professor at the University of Göttingen.

Network Dynamics

Many complex systems consist of a large number of units that are coupled via a non-trivial interaction network. The resulting dynamics are typically genuinely emergent, that is, they cannot be explained from considering the dynamics of the individual units. Examples come from a wide range of spatial and temporal scales and include global telecommunication and transportation networks, complex disordered systems in physics, the activity of neuronal circuits in the brain, as well as gene regulatory networks on a sub-cellular level. All of these multi-dimensional systems immediately impact our everyday lives, yet their cooperative dynamics and the mathematics underlying them are still poorly understood.

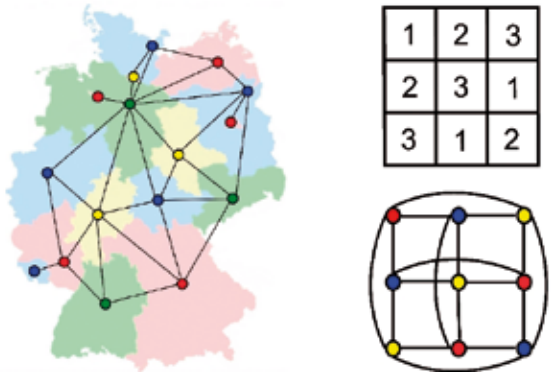


Fig. 1: © Max Planck Insitute for Dynamics and Self-Organization

In the Network Dynamics Group, we are trying to understand the structure and dynamics of complex networks in physics, biology and engineering with a focus on the analysis and modeling of the activity of neural networks in the brain. For instance, spatio-temporal patterns of neural spiking activity is a key ingredient for information processing in the brain. We investigate the theoretical fundamentals underlying the mechanisms for generating such patterns in complex neural networks.

We also develop new mathematical and computational tools required for understanding these highly complex systems. Furthermore, we work on foundations and applications in the areas of computer science, statistical physics of disordered systems, artificial neural networks and robotics, and, more recently, gene evolution and modern power grids. As one example, we recently developed a novel method to exactly compute the number of different ground states for complex systems exhibiting ground state entropy, an exception to the third law of thermodynamics.

The Network Dynamics Group was established in 2006. Some of the main projects run within the Bernstein Center for Computational Neuroscience (BCCN) Göttingen. The group collaborates with researchers at Harvard University (USA), the University of Exeter (UK), the RIKEN Brain Science Institute (Japan), Cornell University (USA) and the Warwick Mathematics Institute (UK). It is supported by a major grant by the Max Planck Society, by the Göttingen Graduate School for Neuroscience and Molecular Bioscience (GGNB), a visitors grant by the German Academic Exchange Service (DAAD) and by the Federal Ministry for Education and Science (BMBF) Germany.

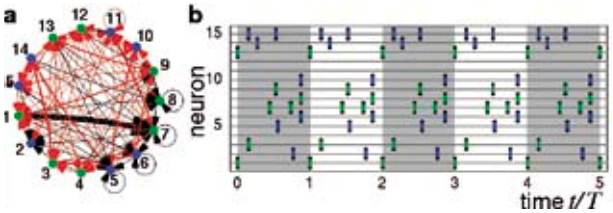


Fig. 2: The American Physical Society; Phys. Rev. Lett. 97:188101 (2006)

Marc Timme

Marc Timme studied physics at the University of Würzburg, Germany, at the State University of New York at Stony Brook, USA, and at the University of Göttingen, Germany. He received an MA in physics in 1998 (Stony Brook) and a doctorate in theoretical physics in 2002 (Göttingen). After working as a postdoctoral researcher at the Max Planck Institute for Dynamics and Self-Organization, Göttingen, from 2003, he was a research scholar at the Center of Applied Mathematics, Cornell University, USA, from 2005 to 2006. He became the head of the Max Planck Research Group Network Dynamics in October 2006.
He is a faculty member of the Georg August University School of Science (GAUSS), the International Max Planck Research School (IMPRS) Physics of Biological and Complex Systems (PBCS), and the Program for Theoretical and Computational Neuroscience (PTCN). He was named Adjunct Professor by the University of Göttingen in 2009.

Principles of Self Organisation

Our group deals with the Statistical Physics of Non-Equilibrium Processes and Nonlinear Dynamics. Recent work focuses on dynamic phase transitions:

- At which angle does a metastable packing of grains topple? How does the angle of this toppling transition change when the grains are wet, and what happens upon wiggling the pile?
- Under which conditions does the flow through a pipe go turbulent? How is this transition controlled by small pertubations, and is there any regularity left in turbulent flow?
- What controls the number and the size of droplets in a vapour? And how do droplets merge and grow when attached to surfaces (like dew droplets), or when freely evolving in the volume (like cloud droplets)?

A common theme in these studies is the close interlocking of a) analytical calculations which provide insight in basic mechanisms leading to the respective transitions, b) numerical studies to test assumptions and verify how the suggested principles work in more realistic settings, and c) comparison to experimental studies. Two examples are shown in the figures. In the near future we plan to further broaden the scope of applications by resuming studies on the stability of membranes, and on the transition between qualitatively different patterns of motion in swarms of active swimmers.

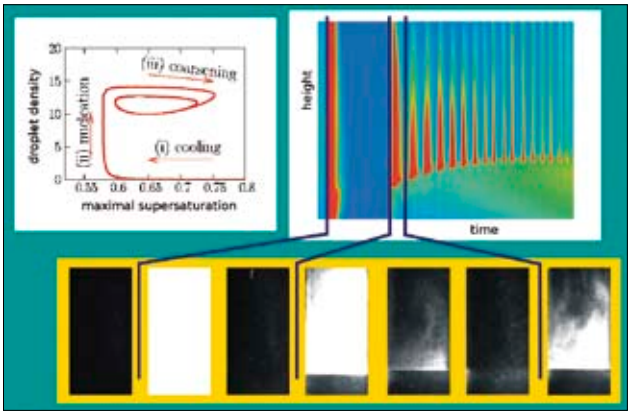


Fig. 1: Similar to humid air being rapidly lifted in a thunderstorm cloud, a continuously cooled binary mixture undergoes nucleation, coarsening and sedimentation (cf pictures of a demixing fluid in the bottom). For a fixed control parameter [JCP 123, 2005] this process repeats in a limit cycle, which can be visualized in terms of a space-time plot of the horizontally averaged turbidity (top right). Focussing on the maximal supersaturation and the droplet density provides a simple model for this surprising finding (top left [PRL 98, 2007]).

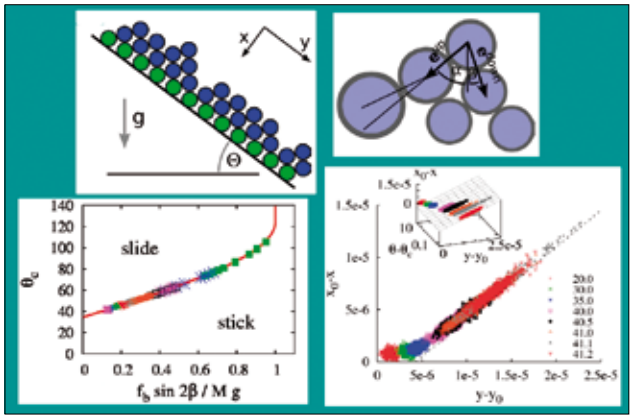


Fig. 2: Capillary bridges can substantially increase the stability of granular piles. For a regular packing with random mass and height distribution (top left) we discussed the force balance and propagation (top right) in a Green-function formalism [EPL 87, 2009]. This provides an explicit prediction of the tilting angle, θ_c, where the pile starts to topple (bottom left) in terms of the capillary bridge force, f_b, and it also sheds new light on the softening of vibrational modes (right) immediately before the transition.

Jürgen Vollmer

Jürgen Vollmer holds a Doctoraal degree in Theoretical Physics from the Universiteit Utrecht (NL), where he prepared an experimental thesis in surface science and a theoretical one on 2d electron gases. In 1994 he finished his dissertation under the supervision of Prof. H. Thomas at the Universität Basel (CH). Since that time he applies non-linear dynamics methods to condensed matter problems. His expertise was further developed while being a a DFG fellow at the Universität Essen, a post-doc in Prof. G. Nicolis group at the Universite Libré de Bruxelles, and a Schloessmann research fellow at the MPI for Polymer Research in Mainz. In 2001 he earned a habilitation from the Universität Essen, and from 2003 - 2007 he held a position in the AG für Komplexe Systeme at the Philipps Universität Marburg. Since 2007 he heads a research group at the MPI for Dynamics and Self-Organization in Göttingen, and in the winter term 2009/10 he was appointed an apl. professorship at the Georg-August Universität Göttingen.

Theoretical Neurophysics

The focus of our research in theoretical neurophysics is Self-Organization in the dynamics of biological neural networks. We are developing novel approaches to model and analyse the dynamics of information processing and learning in the cerebral cortex of the brain. To connect theory and experiment in this system, we are designing methods for the quantitative characterization of cortical networks. In collaboration with biological researchers, we are applying these in particular to the large scale imaging of neuronal activity in the intact brain. Mathematical work in the group is focused on the analysis of the dynamics of large and complex networks of pulse-coupled neuron models and on field theories of neuronal learning processes.

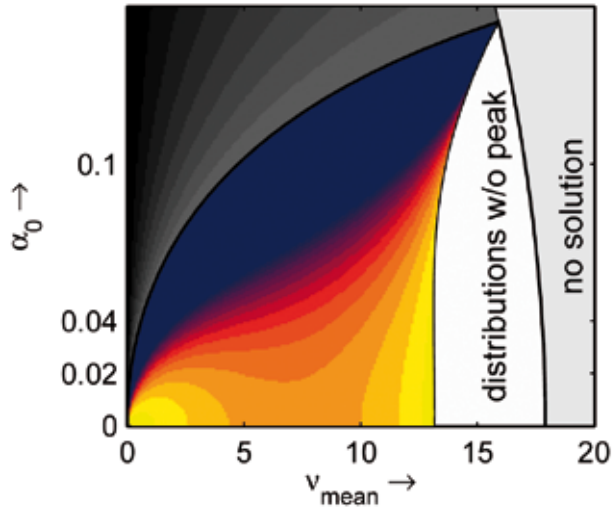


Figure: Phase diagram of activity in a random network of strongly interacting neurons. Colours code the fraction of inactive neurons as a function of network average firing rate and cell to cell variability. Gray region: singular firing rate distributions.

Motivation

The brains of humans and animals arguably are among the most complex systems in nature. Even during the neuronal processing of the most elementary sensory stimulus large ensembles of interacting nerve cells distributed throughout the brain are activated. Understanding neuronal information processing thus requires analysis of the collective dynamics of large strongly interacting and spatially distributed systems of nerve cells. Theoretical neurophysics serves this purpose by developing quantitative theories, mathematical models and quantitative data analysis methods for the study of brain function.

From Neurons to Networks

The operation of a network of nerve cells is influenced by the topology of the entire network and the dynamics of the individual nerve cells. To understand how these factors interact, we are developing models for the dynamics of individual nerve cells embedded in active networks and for their collective activity states. We are also designing experimental approaches to probe the properties of individual nerve cells under in vivo-like conditions.

Self-Organization of Neural Circuits

Genetic information is insufficient to completely specify the wiring of circuits in the brain. Nervous systems thus use dynamical network self-organization to set up their precisely organized wiring patterns. We are studying this type of network self-organization using analytically solvable models, large scale network simulations, and live brain imaging methods.

Fred Wolf

Fred Wolf, born 1965 in Darmstadt, studied physics and neuroscience at the University in Frankfurt, where he received his doctorate in theoretical physics in 1999 (1999: Altdorf-Leibniz Award, Amos de Shalit Fellowship), 2000: Schloessmann Fellowship). After postdoctoral research at the MPI für Strömungsforschung (Göttingen) and the Interdisciplinary Center for Neural Computation of the Hebrew University of Jerusalem (Israel), he became a research associate at the MPIS in 2001. He spent various periods as a visiting scientist at the KITP (Santa Barbara, USA). Since 2004 he is head of the research group Theoretical Neurophysics. He is a faculty member of the International Max Planck Research Schools "Neurosciences" and "Physics of Biological and Complex Systems" and serves on the boards of the Bernstein Centers for Computational Neuroscience and the Bernstein Focus Neurotechnology.

How to contact the research groups of the Faculty of Physics

Faculty of Physics

Georg-August-Universität Göttingen
Friedrich-Hund-Platz 1, 37077 Göttingen
Internet: www.physik.uni-goettingen.de

First Institute of Physics

Prof. Dr. Philipp Gegenwart
Phone: +49 (0) 551 39-7607
E-mail: pgegenw@gwdg.de

Prof. Dr. Markus Münzenberg
Phone: +49 (0) 551 39-13112
E-mail: mmuenze@gwdg.de

Prof. Dr. Konrad Samwer
Phone: +49 (0) 551 39-7601
E-mail: konrad.samwer@physik.uni-goettingen.de

Second Institute of Physics

Prof. Dr. Ariane Frey (Lichtenberg Professor)
Phone: +49 (0) 551 39-14153
E-mail: ariane.frey@phys.uni-goettingen.de

Dr. Carsten Hensel (Emmy Noether Group)
Phone: +49 (0) 551 39-7667
E-mail: carsten.hensel@phys.uni-goettingen.de

Prof. Dr. Hans Hofsäss
Phone: +49 (0) 551 39-7669
E-mail: hhofsae@uni-goettingen.de

Prof. Dr. Arnulf Quadt
Phone: +49 (0) 551 39-7635
E-mail: aquadt@uni-goettingen.de

Third Institute of Physics

Prof. Dr. Jörg Enderlein
Phone: +49 (0) 551 39-13833
E-mail: J.Enderlein@DPI.physik.uni-goettingen.de

Prof. Dr. Ulrich Parlitz
Phone: +49 (0) 551 39-7716
E-mail: U.Parlitz@DPI.physik.uni-goettingen.de

Dr. Iwan Schaap
(Center of Molecular Biology of the Brain, Junior Research Group)
Phone: +49 (0) 551 39-22816
E-mail: I.Schaap@DPI.physik.uni-goettingen.de

Prof. Dr. Christoph F. Schmidt
Phone: +49 (0) 551 39-7740
E-mail: C.F.Schmidt@DPI.physik.uni-goettingen.de

Prof. Dr. Florentin Wörgötter
Phone: +49 (0) 551 39-10760
E-mail: F.Woergoetter@DPI.physik.uni-goettingen.de

Fourth Institute of Physics

Prof. Dr. Angela Rizzi
Phone: +49 (0) 551 39-4545
E-mail: rizzi@ph4.physik.uni-goettingen.de

Prof. Dr. Claus Ropers (Courant Research Centre, Junior Research Group)
Phone: +49 (0) 551 39-4549
E-mail: cropers@gwdg.de

Prof. Dr. Michael Seibt
Phone: +49 (0) 551 39-4553
E-mail: seibt@ph4.physik.uni-goettingen.de

Prof. Dr. Susanne Schneider
Phone: +49 (0) 551 39-4538
E-mail: sschnei@gwdg.de

Prof. Dr. Rainer G. Ulbrich
Phone: +49 (0) 551 39-4541
E-mail: ulbrich@ph4.physik.uni-goettingen.de

Institute for Astrophysics

Prof. Dr. Stefan Dreizler
Phone: +49 (0) 551 39-5041
E-mail: dreizler@astro.physik.uni-goettingen.de

Prof. Dr. Wolfgang Glatzel
Phone: +49 (0) 551 39-9989
E-mail: wglatze@astro.physik.uni-goettingen.de

Prof. Dr. Wolfram Kollatschny
Phone: +49 (0) 551 39-5065
E-mail: wkollat@astro.physik.uni-goettingen.de

Prof. Dr. Jens Niemeyer
Phone: +49 (0) 551 39-13802
E-mail: niemeyer@astro.physik.uni-goettingen.de

Dr. Ansgar Reiners (Emmy Noether Group)
Phone: +49 (0) 551 39-13825
E-mail: areiners@astro.physik.uni-goettingen.de

Institute of Geophysics

Prof. Dr. Karsten Bahr
Phone: +49 (0) 551 39-7453
E-mail: karsten.bahr@geo.physik.uni-goettingen.de

Prof. Dr. Andreas Tilgner
Phone: +49 (0) 551 39-7482
E-mail: andreas.tilgner@geo.physik.uni-goettingen.de

Institute for Materials Physics

Prof. Dr. Christian Jooß
Phone: +49 (0) 551 39-5303
E-mail: jooss@ump.gwdg.de

Prof. Dr. Reiner Kirchheim (Lower Saxony Professor)
Phone: +49 (0) 551 39-5001
E-mail: rkirch@ump.gwdg.de

Prof. Dr. Hans-Ulrich Krebs
Phone: +49 (0) 551 39-9642
E-mail: krebs@ump.gwdg.de

Prof. Dr. Astrid Pundt
Phone: +49 (0) 551 39-5007
E-mail: apundt@ump.gwdg.de

Prof. Dr. Cynthia Volkert
Phone: +49 (0) 551 39-5011
E-mail: volkert@ump.gwdg.de

Institute for Nonlinear Dynamics

Prof. Dr. Eberhard Bodenschatz
Phone: +49 (0) 551 5176-300
E-mail: Eberhard.Bodenschatz@ds.mpg.de

Prof. Dr. Theo Geisel
Phone: +49 (0) 551 5176-401
E-mail: geisel@ds.mpg.de

Institute for Theoretical Physics

Dr. Andreas Honecker (Heisenberg fellow)
Phone: +49 (0) 551 39-7693
E-mail: honecker@theorie.physik.uni-goettingen.de

Prof. Dr. Reiner Kree
Phone: +49 (0) 551 39-9565
E-mail: kree@theorie.physik.uni-goettingen.de

Prof. Dr. Marcus Müller (Lichtenberg Professor)
Phone: +49 (0) 551 39-13888
E-mail: mmueller@theorie.physik.uni-goettingen.de

Prof. Dr. Thomas Pruschke
Phone: +49 (0) 551 39-7683
E-mail: pruschke@theorie.physik.uni-goettingen.de

Prof. Dr. Karl-Henning Rehren
Phone: +49 (0) 551 39-7690
E-mail: rehren@theorie.physik.uni-goettingen.de

Prof. Dr. Kurt Schönhammer
Phone: +49 (0) 551 39-7681
E-mail: schoenh@theorie.physik.uni-goettingen.de

Dr. Richard L. C. Vink (Emmy Noether Group)
Phone: +49 (0) 551 39-7684
E-mail: Richard.Vink@theorie.physik.uni-goettingen.de

Prof. Dr. Annette Zippelius
Phone: +49 (0) 551 39-7678
E-mail: annette@theorie.physik.uni-goettingen.de

Institute for X-ray Physics

Prof. Dr. Tim Salditt
Phone: +49 (0) 551 39-9427
E-mail: tsaldit@gwdg.de

Prof. Dr. Sarah Köster (Courant Research Center, Junior Research Group)
Phone: +49 (0) 551 39-9429
E-mail: sarah.koester@phys.uni-goettingen.de

Further Research Groups in other institutions

Faculty of Chemistry

Prof. Dr. Andreas Janshoff
Tammannstr. 6, 37077 Göttingen
Phone: +49 (0) 551 39-10633
E-mail: Andreas.Janshoff@chemie.uni-goettingen.de

Faculty of Medicine

Prof. Dr. Dr. Detlev Schild
Department of Neurophysiology and Cellular Biophysics
Humboldtallee 23, 37083 Göttingen
Phone: +49 (0) 551 39-5915
E-mail: dschild@gwdg.de

German Aerospace Center
Bunsenstr. 10, 37073 Göttingen

Prof. Dr. Andreas Dillmann
Institute of Aerodynamics and Flow Technology
Phone: +49 (0) 551 709-2177
E-mail: Andreas.Dillmann@dlr.de

Prof. Dr. Martin Rein
Institute of Aerodynamics and Flow Technology
Phone: +49 (0) 551 709-2671
E-mail: martin.rein@dlr.de

Max Planck Institute for Biophysical Chemistry
Am Fassberg 11, 37077 Göttingen

Prof. Dr. Bert L. de Groot
Computational Biomolecular Dynamics
Phone: +49 (0) 551 201-2308
E-mail: bgroot@gwdg.de

Prof. Dr. Helmut Grubmüller
Theoretical and Computational Biophysics
Phone: +49 (0) 551 201-2300
E-mail: hgrubmu@gwdg.de

Prof. Dr. Stefan W. Hell
NanoBiophotonics
Phone: +49 (0) 551 201-2500
E-mail: shell@gwdg.de

Prof. Dr. Erwin Neher
Membrane Biophysics
Phone: +49 (0) 551 201-1079
E-mail: eneher@gwdg.de

Max Planck Institute for Dynamics and Self-Organization
Bunsenstraße 10, 37073 Göttingen

Prof. Dr. Stephan Herminghaus
Dynamics of Complex Fluids
Phone: +49 (0) 551 5176-200
E-mail: stephan.herminghaus@ds.mpg.de

Prof. Dr. Stefan Luther
Biomedical Physics
Phone: +49 (0) 551 5176-370
E-mail: stefan.luther@ds.mpg.de

Prof. Dr. Folkert Müller-Hoissen
Phone: +49 (0) 551 5176-715
E-mail: folkert.mueller-hoissen@ds.mpg.de

Prof. Dr. Marc Timme
Network Dynamics
Phone: +49 (0) 551 5176-440
E-mail: timme@nld.ds.mpg.de

Prof. Dr. Jürgen Vollmer
Principles of Self Organisation
Phone: +49 (0) 551 5176-210
E-mail: juergen.vollmer@ds.mpg.de

Prof. Dr. Fred Wolf
Theoretical Neurophysics
Phone: +49 (0) 551 5176-432
E-mail: fred@nld.ds.mpg.de

Max Planck Institute for Solar System Research
Max-Planck-Str. 2, 37191 Katlenburg-Lindau

Prof. Dr. Jörg Büchner
Sun and Heliosphere
Phone: +49 (0) 5556 979-295
E-mail: buechner@mps.mpg.de

Prof. Dr. Ulrich Christensen
Planets and Comets
Phone: +49 (0) 5556 979-542
E-mail: christensen@mps.mpg.de

Prof. Dr.Laurent Gizon
Helio- and Asteroseismology
Phone: +49 (0) 5556 979-439
E-mail: gizon@mps.mpg.de

Prof. Dr. Manfred Schüssler
Sun and Heliosphere
Phone: +49 (0) 5556 979-469
E-mail: schuessler@mps.mpg.de

Editorial

Editor

Georg-August-Universität Göttingen
The Dean of the Faculty of Physics
Prof. Dr. Hans Hofsäss
Friedrich-Hund-Platz 1
37077 Göttingen
Phone: +49 (0) 551 39-4095
Fax: +49 (0) 551 39-4583
E-mail: dekanat@physik.uni-goettingen.de
Internet: www.physik.uni-goettingen.de

Managing Editor

Dr. Ralph Behrends

Editorial staff

Prof. Dr. Stefan Dreizler
Prof. Dr. Hans Hofsäss
Dr. Karl Ahlborn
Dr. Udo Kaatze
Gisa Kirschmann-Schröder

Proof-Reader

Adam Roe

Photos

Kirschmann/Schröder
Illustrations regarding content of research group portraits: respective research group leaders

Design

Domino Werbeagentur GmbH, Göttingen

Circulation: 3,000 copies

Published: January 2010