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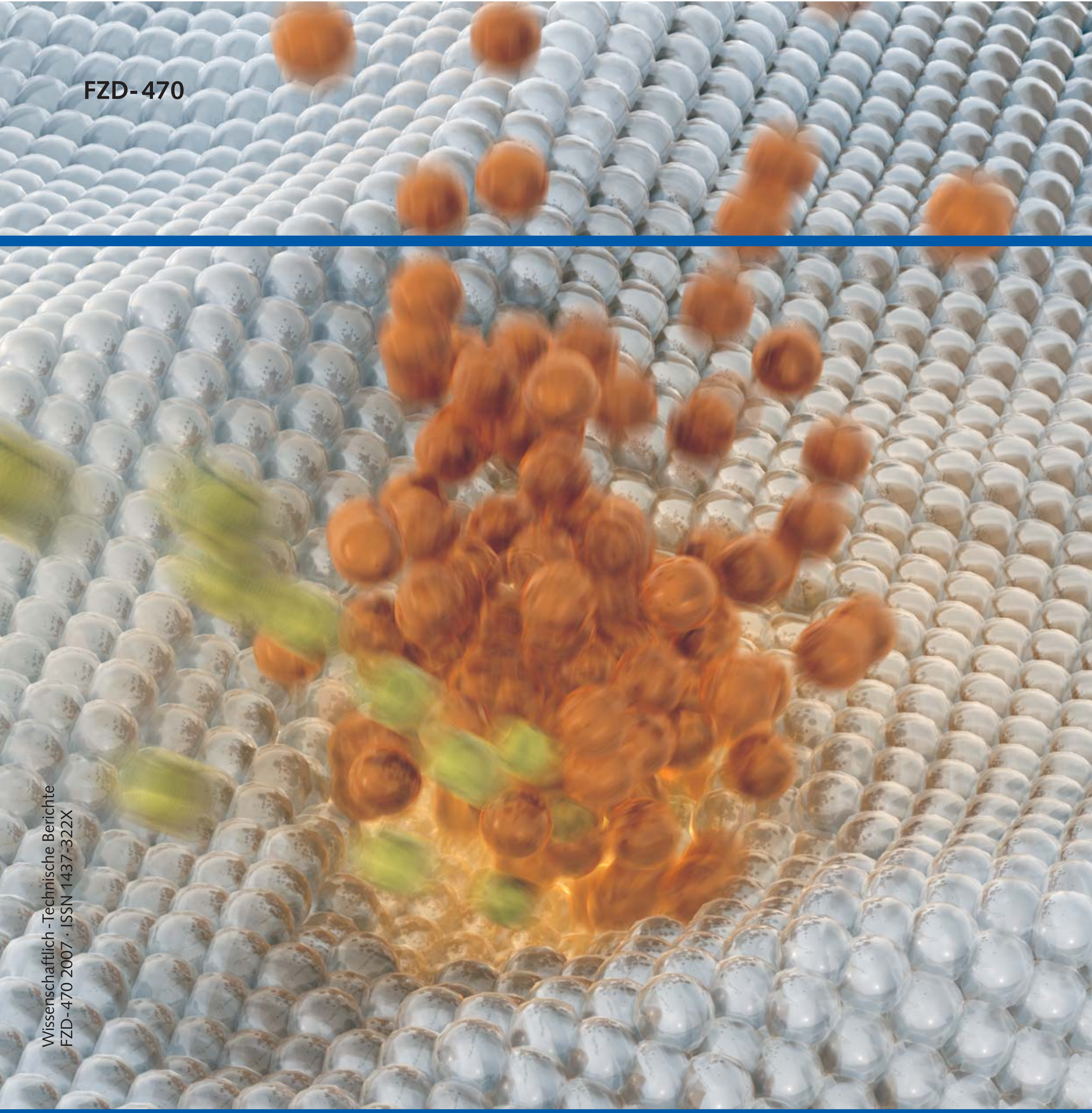

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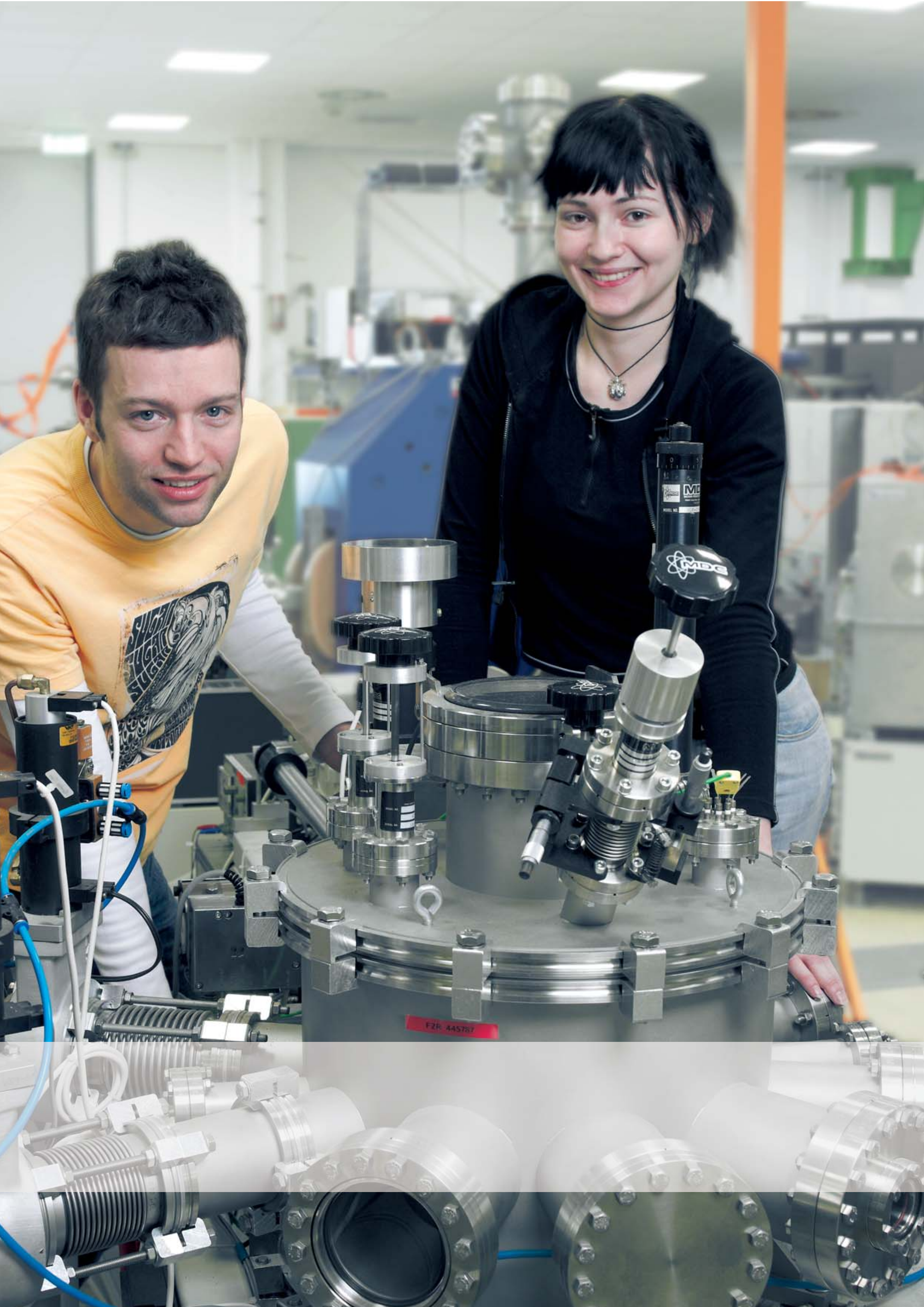
STRUCTURE OF MATTER

TRIENNIAL SCIENTIFIC REPORT 2004-2007 | Volume 1

Forschungszentrum
Dresden Rossendorf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Content

Cover picture: 3D scheme of an ion beam hitting the surface of a solid material (picture: Sander Münster)
Photo left: Sven Claus

Preface

Roland Sauerbrey I Scientific Director

This volume of the Triennial Scientific Report highlights the scientific output of the FZD research program "Structure of Matter", covering the years 2004 to 2007. It is the first out of three volumes that are published this year for the first time. In future, we plan to substitute our present Annual Report about all the research activities at the Forschungszentrum by Biannual Reports. These will be dedicated to the three research programs "Structure of Matter", "Environment and Safety", and "Life Sciences", respectively. They will provide the scientists of the FZD with the opportunity to present their research results to their colleagues, but also to a wider audience interested in sciences.

The first part of this Triennial Report introduces the "Structure of Matter" program as well as the large-scale facilities that are used for research within this program. The second part consists of ten articles on research projects that were conducted by scientists of the Institute of Radiation Physics, the Institute Dresden High Magnetic Field Laboratory, and the Institute of Ion-Beam Physics and Materials Research.

This report is primarily concerned with science. Nevertheless, we also want to take the opportunity and inform you about news from the FZD. During the last 18 months new programs for young and international scientists have been developed and some organizational changes occurred. In 2006, we launched the first Ph.D. seminar at the FZD with about 100 participants. As this seminar was a big success, the second Ph.D. seminar followed soon in September 2007. An outcome of these seminars was a series of FZD lectures that started at the beginning of 2007 and will continue on a regular basis throughout 2007 and 2008. Furthermore, special workshops have been offered to young scientists, e.g. communication to the media, presentation in English, training for young science managers, etc. Talented postdoctoral staff can benefit from a newly installed tenure track program that gives them financial freedom to lead a group of young scientists and full responsibility for the scientific success of the group. The FZD fellows program aims at working more closely together with highly renowned international cooperation partners who are invited for special research projects at the FZD.

The last 18 months were also characterized by an intense discussion about the future of the FZD. In meetings and seminars we debated about the status and the future of the Forschungszentrum Dresden-Rossendorf, asking questions like: "What are our future scientific objectives?" "Which research methods and facilities are required in order to reach those goals?" "How can new research activities be funded and who are our future cooperation partners?"

To successfully compete with other research institutions worldwide, it is important to participate in networks. On the one hand, these can be networks within the research center and, on the other hand, networks on the national and international level. For enhancing the interdisciplinary cooperation between the FZD institutes, the large-scale facilities have provided a strong unifying moment. To give one example: the Radiation Source ELBE is used for materials research and nuclear physics as well as for biophysical, medical, or radiochemical experiments. It is thus employed by all six institutes of the FZD.

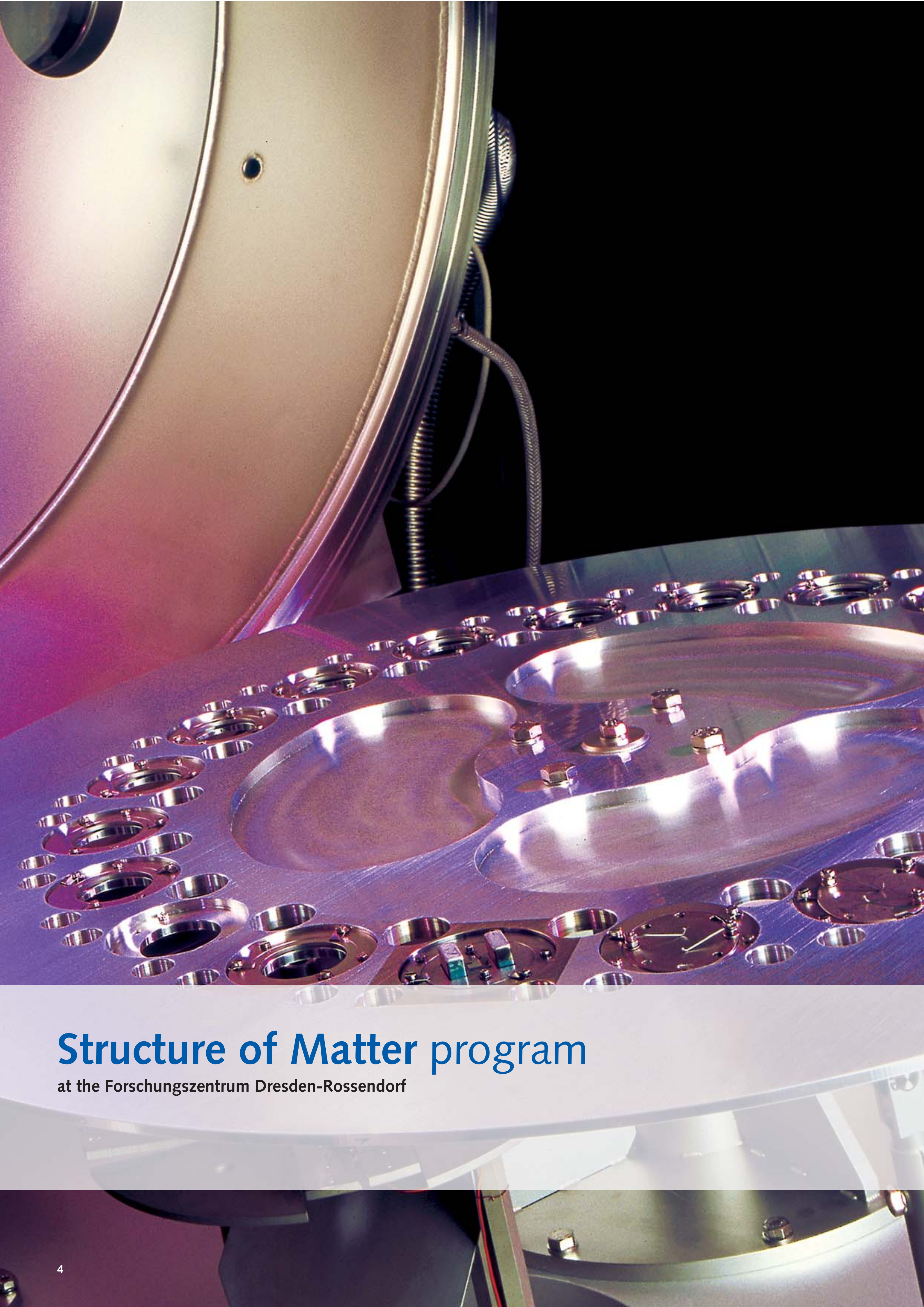
Furthermore, ELBE offers an excellent research platform for external users, which is mainly due to the two free-electron lasers that are operated as a user facility. The Universität Halle-Wittenberg is in charge of the positron beam-line whereas scientists from the Technische Universität Dresden generate neutrons for nuclear physics experiments and research on the transmutation of radioactive waste. In a special workshop, dedicated to the Radiation Source ELBE, in-house and external users together with scientists from leading accelerator laboratories discussed future prospects and tasks of the ELBE facility.

The Dresden High Magnetic Field Laboratory, which is a common project of five Dresden materials research institutions, welcomed its first user groups in 2007. As a member of a European network this laboratory provides a unique environment for measuring solid-state materials in high magnetic fields. Magnetism is also the focus of the "Nanoscale Magnetism" group employing the analytical methods of the High Field Laboratory, but also making use of ion-beam techniques at the Ion-Beam Center in Rossendorf. Here, the new research field "Nano-Spintronics" under the direction of Dr. Heidemarie Schmidt was established in 2007. This group of five scientists is especially interested in experiments with the Focussed Ion Beam—a perfect tool for producing nano-structures beneath the surface of almost any material— which can thus be applied to the fabrication of magnetic semiconductors.

A high-intensity laser laboratory is currently under construction and will be put into operation in the beginning of 2008. The Laser-Particle Acceleration Group was founded in November 2006 and comprises six scientists and laser engineers now. Besides basic research on the interaction of particles with matter their main goal is to generate new particle radiation for radiation therapy in the future war against cancer. In the very exciting new project "onCOOPtics", funded by the German Federal Ministry of Education and Research (BMBF), with laser physicists from Jena, medical doctors from the University Hospital Dresden, and scientists from the FZD we hope to explore the fundamentals for a new laser tool that can be applied for tumor research as well as for effective radiation therapy in ten to fifteen years. More information about this new research project is given in the third volume of the Triennial Scientific Report focusing on "Life Sciences".

Finally, I would like to thank our partners in both the state and the federal government for their continued support, our national and international scientific cooperation partners for many successful joint research endeavors and, last but not least, the entire staff of the FZD for their dedicated work for this fine institution.

Prof. Dr. Roland Sauerbrey



Structure of Matter program

at the Forschungszentrum Dresden-Rossendorf

Wolfhard Möller, Manfred Helm, Joachim Wosnitza, Burkhard Kämpfer

The FZD research platform consists of the Structure of Matter program, the Life Sciences program, and the Environment and Safety program. The activities of the Structure of Matter program are centered on the response of matter to extreme irradiation conditions and to strong electric and magnetic fields. Within the program areas of Materials Research with Ions and Semiconductor Physics, fast ions and thin-film deposition techniques are employed for the development of new materials with a prominent focus on nanosystems. In these program areas, novel structural and functional properties are investigated using a variety of macroscopic to nanoscopic diagnostics. Research with High Magnetic Fields is concerned with the electronic properties of solid matter using ultrahigh transient magnetic fields. The Subatomic Physics program studies rare hadronic processes in matter and nuclear processes which are relevant to nuclear technology and astrophysics.

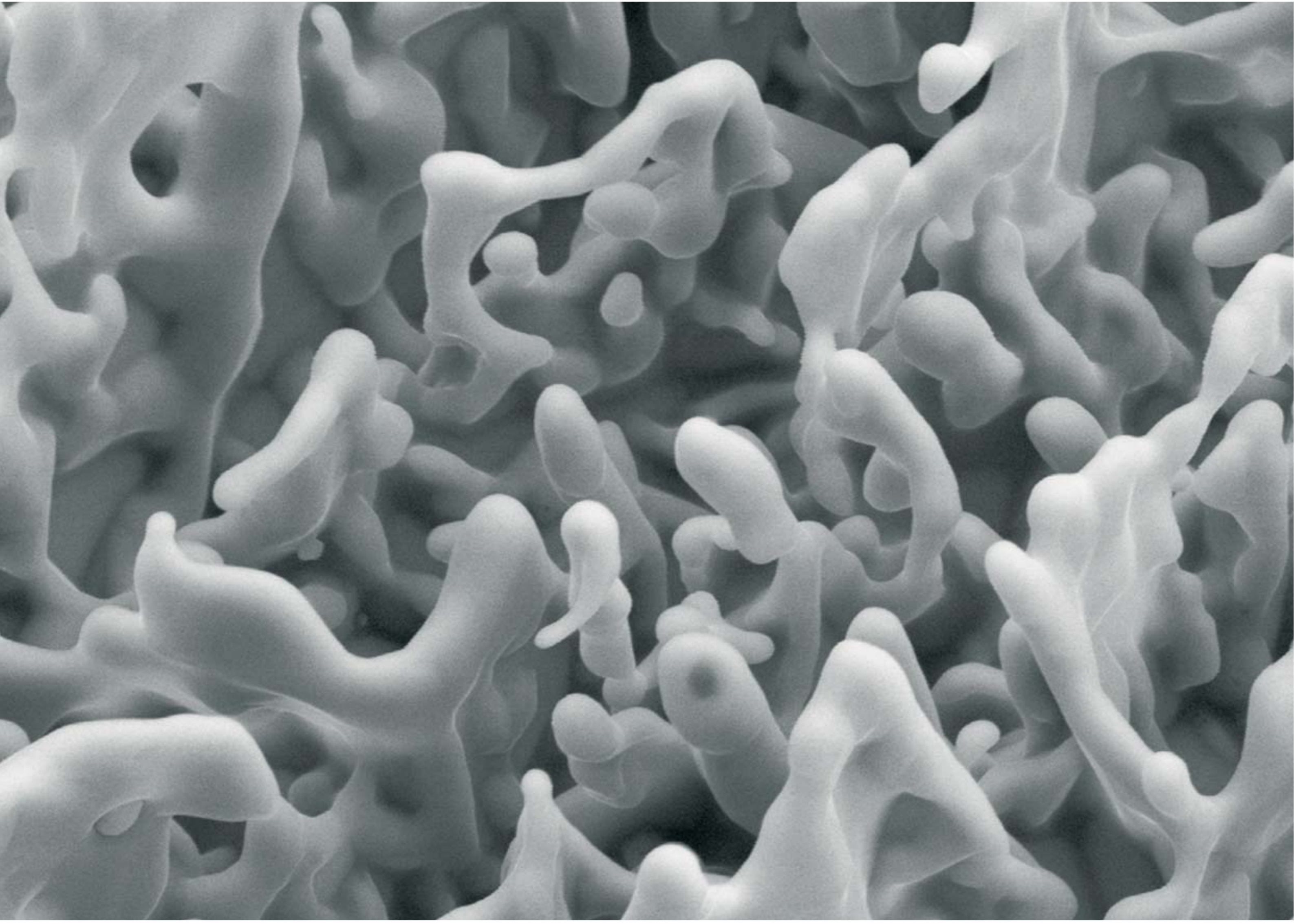
For these topics, the infrastructure at FZD offers four large-scale experimental facilities. The Ion-Beam Center houses ion-beam and plasma devices that deliver ions at energies between approximately 10 eV and 5 MeV for surface modification and analysis, as well as for thin-film deposition. Ion beams are used to create high-performance materials with specific and often nanostructure-based functions for electronic, optical, and magnetic applications. In addition to the in-house research activities, the Ion-Beam Center serves as a national and international user facility for research and industry, and is funded within the European Commission's Transnational Access.

The Rossendorf Beamline, located at the European Synchrotron Radiation Facility (ESRF) in Grenoble, contributes fundamentally to materials research at the FZD, offering X-ray diffraction and reflection, particularly in several real-time in-situ devices for thermal treatment and thin-film deposition.

The Radiation Source ELBE features numerous particle and photon beams. Its electron beam is applied both directly and through the production of high-energy photons, neutrons, and positrons. Two attached free-electron lasers deliver high-intensity coherent infrared light. They are also funded by the European Commission and provide transnational access to external users. The free-electron lasers' mid- and far-infrared radiation is well suited to studying semiconductor materials.

The Dresden High Magnetic Field Laboratory has set an ambitious goal to provide 100 Tesla in millisecond pulses for materials research in order to study the electronic properties of materials such as high-temperature superconductors, magnets, or semiconductors, even in combination with the ELBE free-electron lasers.

A **High-Intensity Laser Laboratory** is currently under construction. Laser-accelerated ions will be used there for multidisciplinary studies of non-linear particle-matter interaction. This topic underscores the goal of the FZD of increasingly interlinking the activities of its three programs. Biological templating of metallic nanostructures, physico-chemical characterization of radionuclide complexes, measurement of transmutation cross-sections, and tomographic characterization of pulsed magnet coils are additional examples of internal interdisciplinary cooperation with the Life Sciences and Environment and Safety program. The research activities of all three programs are also connected by the use of ELBE and the diagnostic facilities belonging to the Ion-Beam Center and the Rossendorf Beamline at ESRF.



SEM image at a tilting angle of 45 degrees showing the typical patterns of the nanostructures at the noble metal stent surface obtained with the new FZD technology.

Facilities for Europe

Center for Application of Ion Beams to Materials Research (AIM)

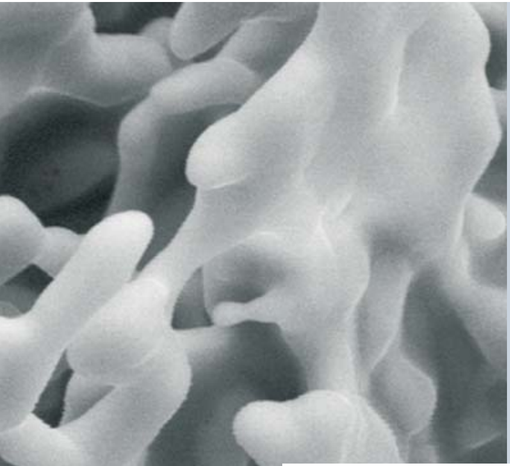
Andreas Kolitsch, Wolfhard Möller

The Center for **A**pplication of **I**on Beams to **M**aterials Research (AIM) is devoted to the application of ion beams to modify and analyze near-surface layers of materials. The ion-beam center (Fig. 1) operates three MV electrostatic accelerators, three ion implanters, a fine-focused ion-beam device, a highly-charged ion device, and several experimental installations for plasma immersion implantation as well as ion-assisted deposition of thin films. This broad spectrum of ion-beam equipment is available in the energy range from several eV up to several MeV. The main sections of the facility have been installed within the last 12 years and represent world-class quality.

The aim of the research activities at AIM is to contribute to the development of European materials research by using the diverse possibilities of ion-beam techniques. Basic research to explore new possibilities for surface modification of materials by ion irradiation is combined with the development of technological applications in cooperation with industry.

More than 40% of user time of AIM devices is made available to external users from universities and other research institutions. About 60 research projects from Germany, stemming from roughly the same number of research groups benefited from AIM facilities from January 2004 to December 2006. Moreover, 70 groups from the rest of the EU and its associated countries and 25 groups from other foreign countries made use of AIM. Fig. 2 demonstrates the widespread distribution of access in EU countries during this period. External users have requested use for almost all of the center's experimental facilities. In addition, a broad spectrum of research topics not only in materials science, but also in the life sciences, arts, archeology, and geology are covered as well.

During the past several years, AIM has continuously expanded its industrial cooperation projects and services. Industry plays a major role through partnerships in cooperative projects utilizing in-house research. From 2004 to 2006, there were direct cooperation projects and industrial



services with about 60 groups from German industry and 15 groups from foreign countries. Presently, direct industrial activities account for more than 20% of the capacity of AIM delivered to users. Direct industrial cooperation covers a wide range of industrial research dealing with the development of materials and components and the characterization of products. These are mainly applied in the semiconductor industry including microelectronics, tribology, biomaterials, optical coatings, and particle spectroscopy.

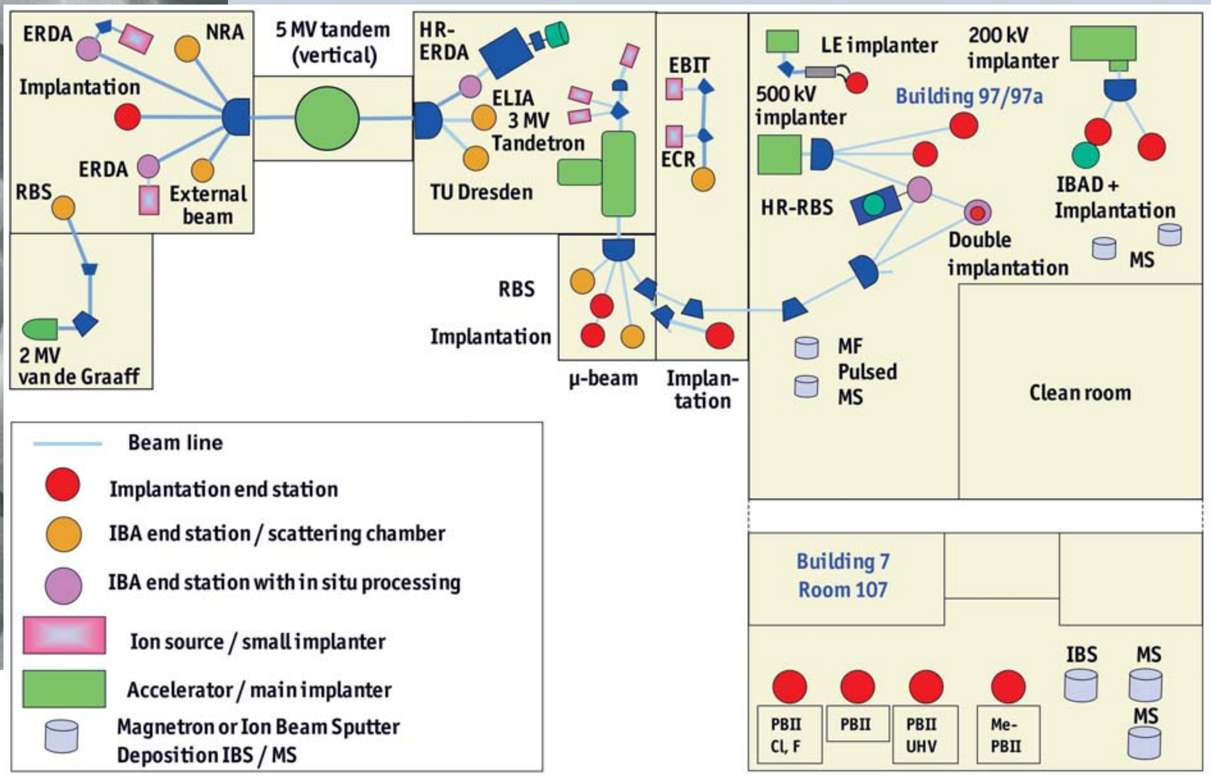


Fig. 1: Schema of the FZD Center for **A**pplication of **I**on Beams to **M**aterials Research (AIM).

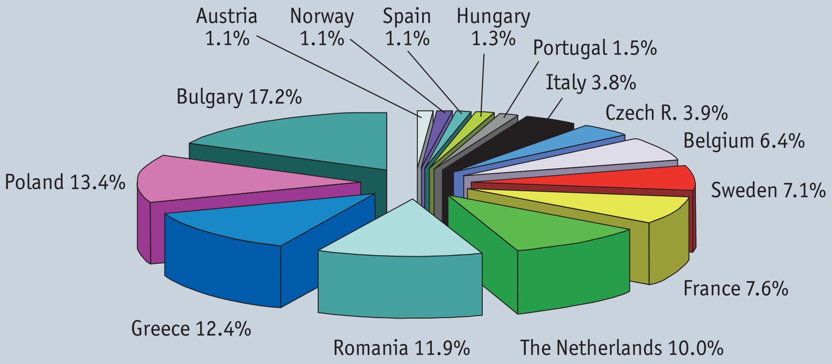


Fig. 2: Transnational access of 871 beam-time shifts granted to EU countries by AIM in the reporting period.

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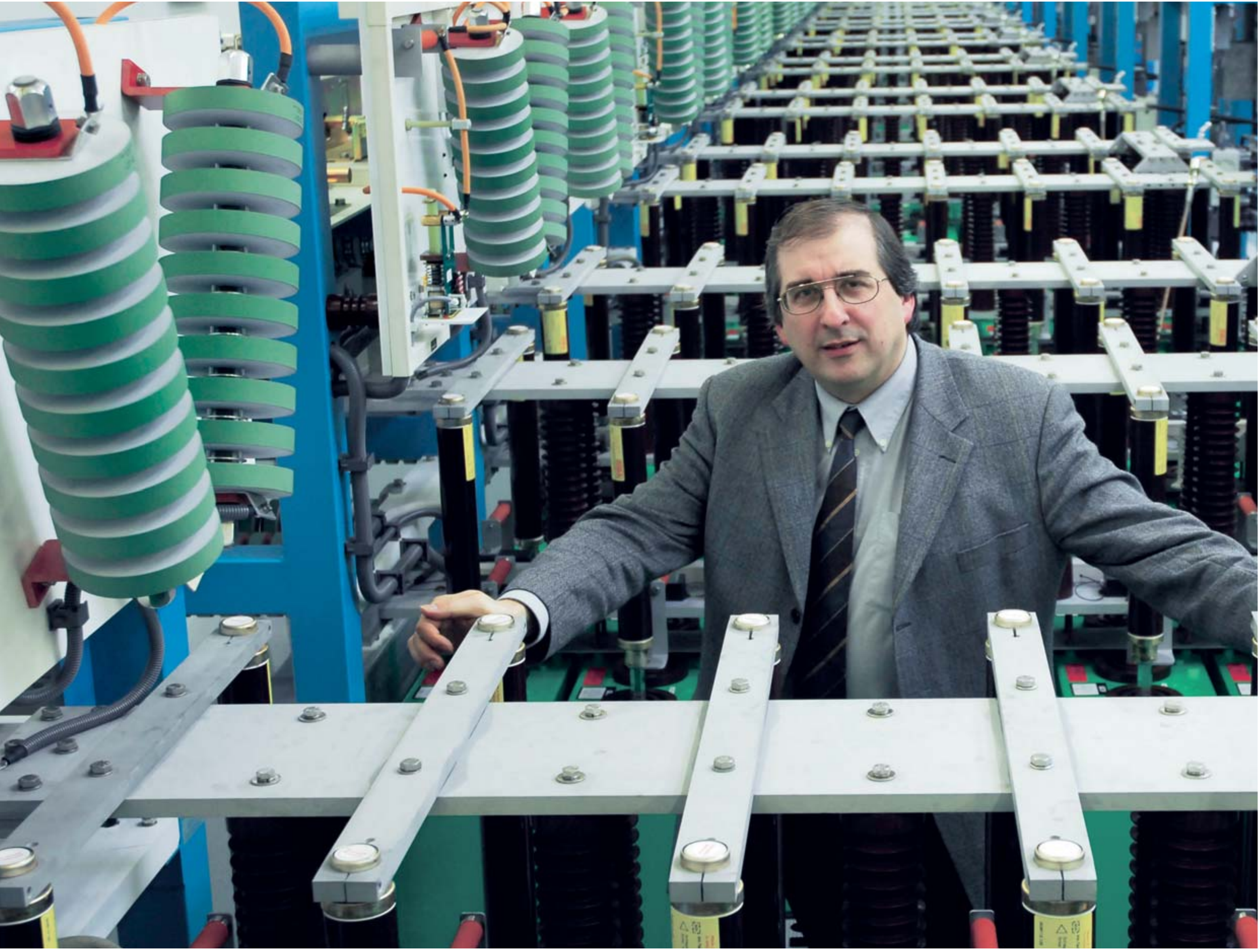
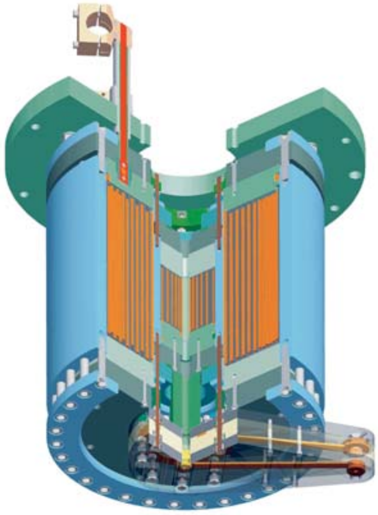

Joachim Wosnitza in the capacitor bank hall of the HLD.

The Dresden High Magnetic Field Laboratory (HLD)


3D animation of the dual coil system HLD100 which is designed for the generation of pulsed magnetic fields up to 100 Tesla.

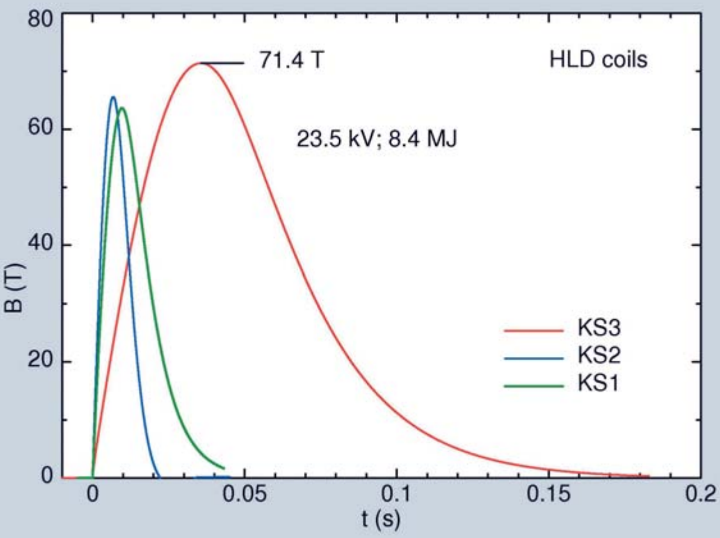
Joachim Wosnitza

High magnetic fields are one of the most powerful tools available to scientists for the study, modification, and control of the state of matter. This is fundamentally due to the unique property of the magnetic field to act universally on the charge and the spin of particles. In other words, it constitutes one of the few fundamental thermodynamic parameters (like temperature) which change the state of matter in a controlled way. Magnetic fields are particularly interesting since the induced changes are, almost without exception, reversible as static magnetic fields do not add kinetic energy to the system. Since these spin and orbital degrees of freedom control most of the electronic and magnetic properties of matter, it is natural to use the magnetic field to investigate and modify them. In general, the higher the field, the more clearly the field-induced changes can be observed and the more transitions to new fundamental states of matter become visible. Consequently, there is a growing demand for higher and higher magnetic fields in combination with a reliable and sophisticated sample diagnostics.

In 2002 the German Science Council therefore strongly recommended funding of the *Hochfeld-Magnetlabor Dresden* (HLD) at the FZD. The proposal for this pulsed-field facility was based on a collaborative initiative of five Dresden institutions. The construction of the

Photo: W.H. Schmidt

laboratory began in mid-2003 and was finished in 2007 within time and budgetary limits. Since the beginning of 2007, the HLD has been accepting proposals for magnet time and has hosted the first users. The coils available at the HLD produce both high magnetic fields (above 70 T with 150 ms pulse length) and smaller ones (60 – 65 T, with 25 – 50 ms pulse lengths). Energy for this is provided by a modular 50 MJ capacitor bank—the only of its kind in the world. The free electron laser facility ELBE next door allows high-brilliance infrared radiation to be fed into the pulsed field cells of the HLD, thus enabling unique high-field magneto-optical experiments in the 4 to 200 µm range. Additional high-energy magnets are under construction, the most challenging project of which is a pulsed magnet reaching 100 T, with a timescale of 10 ms in a bore of 20 mm. In-house research at the HLD focuses on electronic properties of materials at high magnetic fields. Research is being carried out on strongly correlated systems, such as novel superconductors, low-dimensional magnetic materials, and heavy-fermion compounds, as well as semiconductors and nanoparticles on biological templates.



Pulse forms of several magnets designed for the user program of the HLD. KS3 is in use for the generation of magnetic field pulses to above 70 Tesla in a sample-space diameter of 24 mm.

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Project partners

[1] Leibniz Institute for Solid State and Materials Research (IFW) Dresden, Germany
[2] Institute for Experimental Physics, Universität Leipzig, Germany

Max Planck Institute for Chemical Physics of Solids, Germany
Max Planck Institute for the Physics of Complex Systems, Germany
Institute of Solid State Physics, Technische Universität Dresden, Germany
Leibniz Institute of Polymer Research Dresden, Germany

Free-Electron Laser at FZD. Photo: Sven Claus

The Radiation Source ELBE

Peter Michel, Burkhard Kämpfer

By studying the interaction of various forms of radiation with matter in atomic and subatomic dimensions as well as with tissues, cells and their components, we can gain a wide range of new insights into their structures and functionalities. At the heart of ELBE (**E**lectron **L**inear accelerator with high **B**rilliance and low **E**mittance) is a superconducting linear accelerator consisting of two units which are cooled by liquid helium. It delivers a quasi-continuous electron beam of 5 to 40 MeV beam energy at beam currents of up to 1 mA. This primary beam is characterized by an especially low transverse emittance of better than 10 mm mrad (even less than 2 mm mrad has been achieved at low bunch charges) and short pulses (typically 2 ps bunch length) with low energy spread and flexible temporal structure.

Due to these unusual properties, a variety of secondary radiation types are available for experiments:

(i) Two Free Electron Lasers (FELs) with undulators of 27 mm and 100 mm period length deliver coherent radiation in the mid and far infrared. More precisely, the wavelength of the U27-FEL ranges from 4 to 22 µm while U100-FEL covers the range from 20 to 200 µm. Depending on the wavelength, several watts of optical power can typically be coupled out. The infrared light beams are transported to several optical laboratories, where a broad range of different experiments are conducted. The primary fields of research include semiconductor physics (ground-state vibration-population decay or experiments to determine the relaxation time of electrons in superlattices or self-assembled quantum dots), biophysics (IR-induced changes in thin DNA films), environmental and safety research, as well as experiments in ellipsometry and near-field microscopy. Furthermore, an additional transfer system directs the FEL light into the Dresden High Magnetic Field Laboratory (HLD) situated in a nearby building.

(ii) The high primary-beam current allows generation of intense secondary neutron beams, either in reactions with a rotating tungsten disc or a liquid-lead target. The emerging neutron pulses carry the time structure of the primary electron beam, making them well suited for time-of-flight experiments. Given this, neutron-induced reactions are used to complete the database for fusion-reactor materials, for transmutation of nuclear waste, and for certain steps in the astrophysical breeding processes of chemical elements.

(iii) By pair production from the intense gamma radiation field, positrons are produced in a stack of tungsten radiator foils. These will be extracted and delivered as a secondary beam for investigations in materials science.

(iv) The propagation of the well-collimated primary electron beam through crystals, such as diamonds, generates channelling radiation, i.e., X-rays in the 10 to 100 keV range. These X-rays are used within the Biostructures and Radiation program to investigate cell damage due to irradiation.

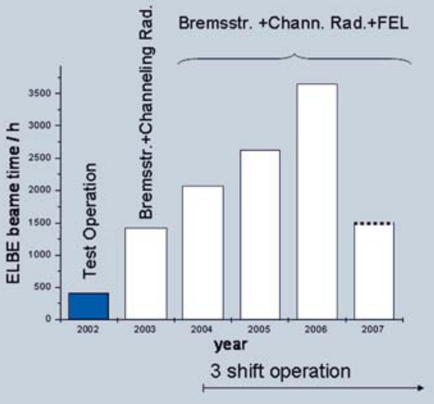
(v) Irradiating a thin foil with the primary electron beam generates hard X-rays with energies up to 20 MeV. By exposing selected isotopes to these X-rays, their excitation and transformation into other isotopes through various reactions can be studied. Understanding of what occurs in cross-sections such as these is important for understanding and modelling the cooking of chemical elements in explosive-star phenomena. These investigations complement those in item (ii). Further details can be studied by exposing isotopes directly to the electron beam.

(vi) Due to the excellent time structure and high intensity of the primary ELBE beam, state-of-the-art detectors with excellent time resolution (below 100 ps sigma) and sufficient stability in a high rate environment – between 10.000 and 50.000 charged particles impinging on the detector per cm^2 per second – are developed. These detectors fulfil the challenging requirements of new experiments at the future Facility for Anti-proton and Ion Research (FAIR), and of modern applications in neutron, particle, and medical physics.

The electron-beam quality strongly depends on the electron source (i.e., the gun). In the first years of the operation of ELBE, a thermionic gun was used. Research and development of a unique superconducting radio frequency gun is almost completed. It will be installed in 2007.

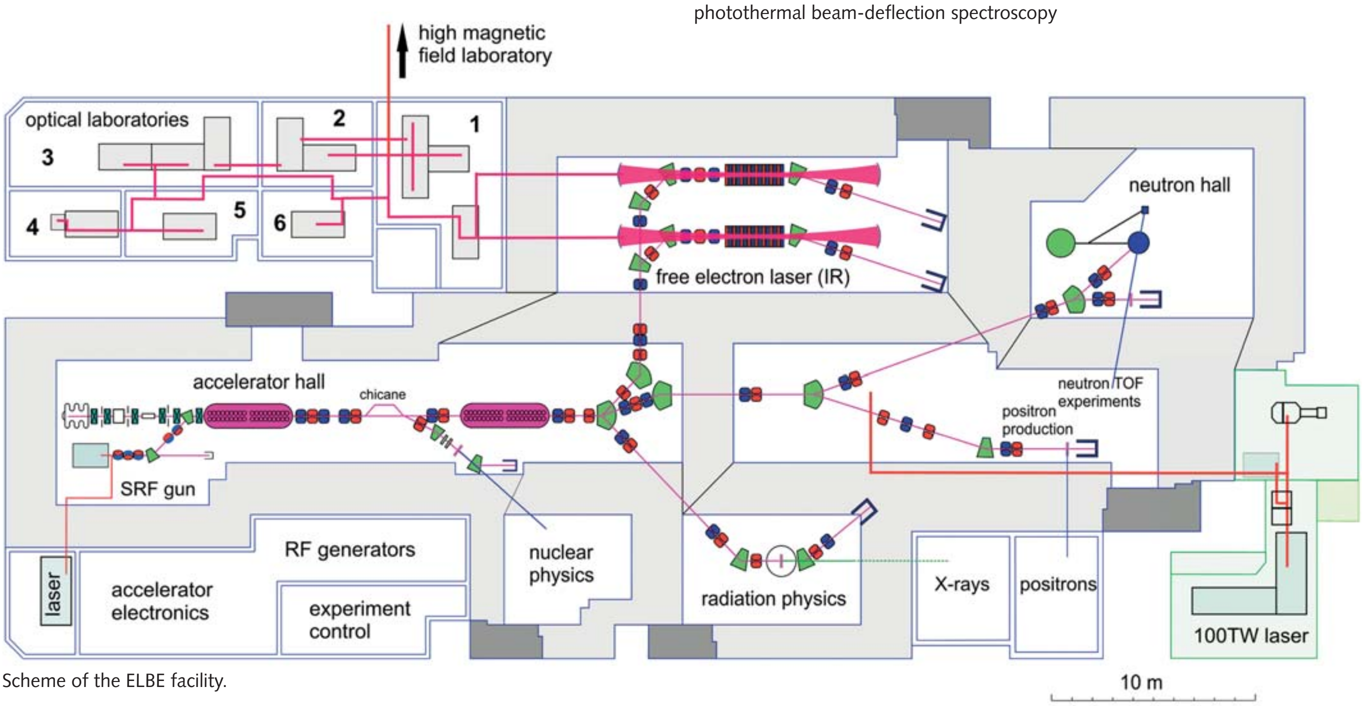
Table 1 displays the beam time statistics for each year up to the first quarter of 2007. The total available beam time in 2005 and 2006 was divided between 29% bremsstrahlung, 10% channelling radiation, and 36% FEL operation. In addition to the routine beam operation in scientific experiments, approximately 25% of the beam time was used for machine studies using the accelerator and secondary radiation targets.

At present, the ELBE user community is primarily composed of internal users at the FZD; external users account for about 20% of usage. Internal users come from almost all institutes of the FZD. Of these, about 65% are from the Institute of Radiation Physics. The external users are supported within the framework of the European Union-funded "Integrated Activity on Synchrotron and Free-Electron Laser Science" (IA-SFS) program. In addition to German groups from Technische Universität Dresden, Forschungszentrum Karlsruhe, and Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY) several external users came from other European Union and nearby countries (University of Linz, Sheffield University, Vilnius University, and so on).



Tab. 1: Beam-time statistics for years until 2006.

1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: FTIR, biological IR experiment
5: Near-field and pump-probe IR experiment
6: Radiochemistry and sum-frequency-generation experiment, photothermal beam-deflection spectroscopy



Scheme of the ELBE facility.

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European Synchrotron Radiation Facility.

Materials research
with synchrotron radiation at ROBL

Johannes von Borany, Carsten Bähtz,
Jörg Grenzer

Synchrotron radiation is one of the most versatile tools for structural diagnostics in materials science, as the X-ray wavelength (~ Å) matches perfectly with inter-atomic distances. Detailed information concerning crystalline phases, lattice parameters, particle (grain) sizes, texture, micro-stress, or surface and interface properties can be derived from X-ray scattering and diffraction experiments. When combined with X-ray fluorescence and absorption spectroscopy, the chemical composition and local bonding properties become accessible as well. Unlike transmission electron microscopy or probe measurements with near-atomic spatial resolution, X-ray methods usually deliver characteristic ("averaged") data on large areas, but X-ray micro-focus solutions also enable spatially resolved local information on patterned or inhomogeneous materials or microstructures. Depth profiling is possible via energy or incidence/exit angle variation.

The Rossendorf Beamline (ROBL), operated by FZD, is a bending magnet synchrotron radiation user facility located at BM20 of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. In operation since 1998, it offers two separate stations for X-ray scattering and absorption studies (5 – 35 keV, $6x10^{11}$ photons/s, $dE/E<1x10^{-4}$). Besides reviewed ESRF experiments, the beam-time at ROBL is predominantly used by FZD in collaboration with external groups for research on (ultra)thin films or ion-beam/plasma-treated surfaces. During the last

Photo: ESRF/Peter Ginter

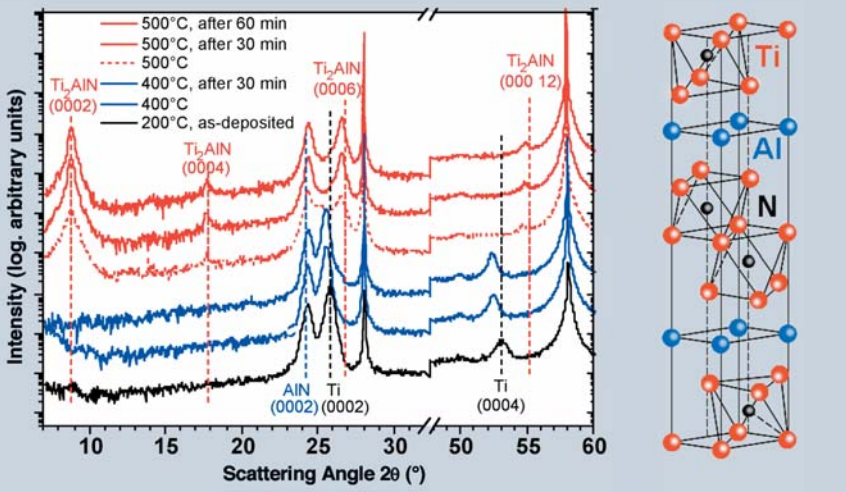

Fig. 1: X-ray diffraction data recorded during annealing showing the Ti_2AlN formation from an AlN-Ti multi-layer film onto Al_2O_3 substrate. The crystalline structure of Ti_2AlN MAX-Phase is shown to the right.

few years, the materials research station at ROBL has developed towards a special beam-line for *in-situ* and *real-time* studies of thin-film growth and/or their modifications during thermal treatments. For these purposes, the beam-line has been equipped with various processing chambers for magnetron sputter deposition, ion irradiation and/or annealing. Examples of such *in-situ* investigations are the synthesis of MAX-phase thin films [1, 2], NiTi shape memory alloys [3], transparent conductive films (ITO, ZnO) [4], magnetic materials (NiMn, FePt) or ion-implanted semiconductors (Fe, Mn doped ZnO, GaN) [5]. In close collaboration with Advanced Micro Devices (AMD) and Qimonda, leading companies in microelectronics, novel materials for gate capacitors ("high-k" dielectrics), conducting films, and metal interconnects are being characterized.

Based on the successful development of ROBL, investigation of nanostructures fabricated by self-organizing (ion irradiation, ion-beam synthesis), or patterning techniques will be a key issue of future activities. Furthermore, *in-situ* experiments with simultaneous measurement of structural and physical (device-relevant) properties (e.g., conductivity, magnetization) will be intensified to enable direct correlation. For a variety of these studies it is essential to determine long-range order structural properties by diffraction methods and short-range order parameters by spectroscopic investigations, both in combination with a high spatial resolution. Therefore, we proposed achieving a micro-focus capability at ROBL with a spot size ≤10 µm and to enable combined X-ray absorption, fluorescence, and scattering experiments. Research will focus on nano-structures and nanoparticles in semiconductors, organic (biological) templates, or thin films designed for magnetic or (opto)electronic applications.

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Research

Hadron mass: Why so heavy?

Frank Dohrmann, Burkhard Kämpfer

We need more mass!

The mass of objects that surround us in our material world is essentially made up of nucleons, i.e., protons and neutrons. Protons and neutrons belong to a group of particles that are called hadrons (from Greek, hadros = heavy, strong) due to their heaviness and strong interaction. Although we know the numerical values of these particle masses with high accuracy, it is not completely clear to modern physicists why particles actually have a mass. For instance, we do not know why an electron has a specific mass. Nor do we know why some quarks, which together with gluons make up the nucleon, have such a small mass: up and down quarks are relatively light (their masses are about a hundred times smaller than the mass of a nucleon). What's more, gluons do not have any mass at all.

Not only in the microcosm, but also in the macrocosm we are challenged to understand mass and energy. Since 1999, astronomical observations have revealed that the objects in the sky (stars, nebulae, galaxies, and clusters thereof) constitute only a small fraction of the matter contained in the universe. Indeed, most matter exists in forms which are unknown to us. Therefore, we call them "dark energy" and "dark matter", but we know almost nothing about them.

All these phenomena provide a strong motivation for physicists to understand the origin of the mass of nucleon matter. The key to this seems to be the strong interaction among constituents of nucleons. In a fictitious world, with massless quarks, the mass of nucleons and thus, atomic nuclei would only be 20 % smaller than in our real world.

Strange probes

Experiments addressing these questions often require specific probes. These are test particles that are created by collisions in the laboratory.

Kaons ($K^{\pm}$) have distinct properties which allow them to behave differently from other hadrons. Due to this, they were originally called "strange" hadrons. $K^{\pm}$ can be produced through collisions of nuclei. Once the electron orbitals of an atom are stripped in this process, the remaining charged nucleus (ion) may be accelerated, and an ion beam eventually impinges on target nuclei. The kinetic energy of these colliding nuclei is partially converted into the mass of newly produced particles. It is important to mention that for nucleus-nucleus collisions, K^+ or K^- are produced inside the nuclear medium. Upon collision, the nuclear matter of both nuclei is compressed and heated up; nucleons of the nuclei are mixed and they form a fireball in which a few newly produced particles are immersed.

The compression stage, subsequent expansion, and final disintegration only last for about 3×10^{-23} seconds in total. Due to this short time scale for the violent evolution of the fireball, theoretical interpretation is difficult. Therefore, after initial experiments with beams of nuclei and nuclear targets, it was necessary to perform a series of experiments in which a proton beam hit a nuclear target and produced $K^{\pm}$. The surrounding nuclear matter, through which the $K^{\pm}$ have to penetrate, behaves almost statically. The interpretation of such experiments is sophisticated. They were carried out by the Kaon Spectrometer (KaoS) collaboration [1], a group of scientists from FZD, Technische Universität Darmstadt, Universität Frankfurt, Gesellschaft für Schwerionenforschung Darmstadt, Jagiellonian University Krakow, and Universität Marburg. The experiments led to the conclusion that a K^- is modified in nuclear matter. It may thus be described effectively as an excitation with a mass reduced by 80 MeV relative to its vacuum mass, while the K^+ mass is effectively increased by 20 MeV. K^+ are always produced together with a Λ hyperon [2].

Di-electrons – Direct messengers

In experiments using $K^{\pm}$ mesons, these may mix in nuclear matter with other excitations with the same quantum numbers as $K^{\pm}$. Thus, some information is lost and the most interesting spectral distribution is barely accessible. In contrast, light vector mesons, ρ and ω—another group of hadrons—are better penetrating probes. A vector meson may decay into an electron-positron (e^+e^-) pair, which is called a di-electron. Measuring the momenta of e^+ and e^- yields access to the spectral distribution of ρ and ω mesons. e^+ and e^- only interact electromagnetically with nuclear matter. This interaction is so weak that the e^+e^- pair leaves the nuclear medium nearly undisturbed, thus, carrying the desired original information, which is needed for unravelling how the parent hadrons ρ and ω acquire their masses.

Although this approach appears very promising, a number of experimental challenges have to be tackled when using these direct probes: (i) only in one out of 10^5 (10^4) cases does a ρ (ω) meson decay into an e^+e^- pair. (ii) At energies, where ρ and ω mesons are produced, many other sources of e^+e^- pairs are generated unintentionally as well. (iii) The e^+ and e^- must be carefully separated from all other charged particles which occur much more frequently.

HADES

To build a detector which fulfills these challenging demands, more than 100 scientists from 19 institutions in 10 countries joined in an international collaboration to build the High Acceptance Di-Electron Spectrometer (HADES). It is installed at the Gesellschaft für Schwerionenforschung (GSI) Darmstadt and uses various beams delivered by the accelerator SIS18: nuclei, protons, or pions. Fig. 1 displays a cross-section of HADES.

The FZD contributed to the construction of HADES, building the third plane of tracking detectors. Each plane contains six multi-wire chambers, each of which consists of six anode and seven cathode layers. Inside each chamber, roughly 7000 thin wires (ø20 µm tungsten, ø 80 µm aluminum) are mounted with a spatial accuracy of 20 µm. The wire layers are enclosed in a chamber filled with a specific gas mixture. The chambers operate at high voltages—up to 2000 V. Fig. 2 gives an impression of the size of one chamber. Four planes of tracking detectors allow the reconstruction of the trajectories of charged particles—the momenta of which are then calculated.

Fig. 3 shows an initial important result of HADES [3]. Simulations of various sources of e^+e^- are displayed together with the data measured. Understanding these contributions is a demanding task and requires additional input from other experiments. This is adapted via models [4] which in turn ascribe the heaviness of hadrons to their intimate relation to the quantum chromodynamics (QCD) vacuum structure. In this way, the mass of hadrons and therefore, the visible matter in the cosmos is explained quantitatively by QCD, the theory of strong interaction.

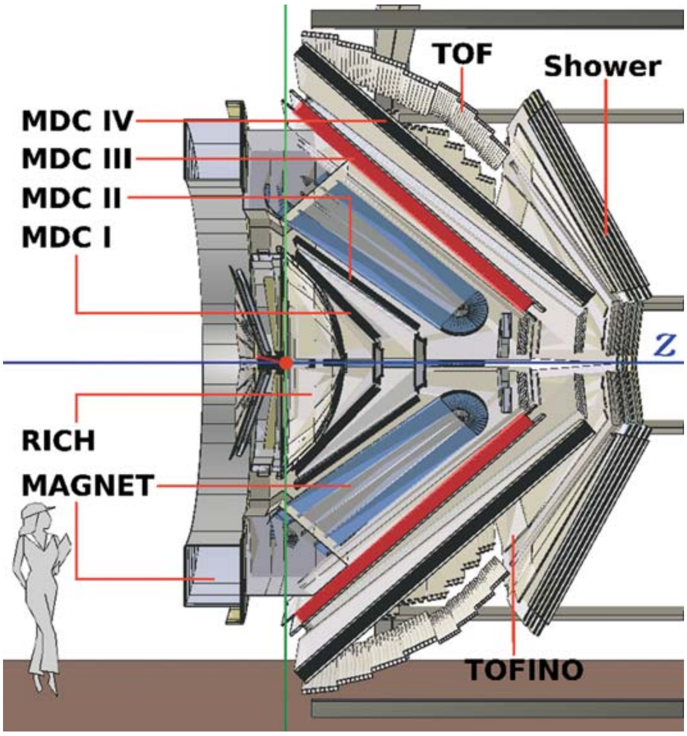


Fig. 1: Cross section of the HADES detector with acronyms denoting important components (RICH: Ring Imaging Cherenkov, MAGNET: superconducting magnet coils, MDC I-IV: Multi-wire Drift Chambers, TOF/TOFINO: Time-Of-Flight walls, Shower: shower detector). MDC III (highlighted in red) was built by the FZD. The detector is azimuthally symmetric around the Z-axis (blue horizontal line labeled Z, which depicts the beam direction; the orange dot indicates the target position).

Fig. 2: Mounting and testing one of the six multi-wire chambers in the detector workshop at the FZD. The six chambers are arranged hexagonally, forming a large frustum around the beam direction. Their position is colored red in Fig. 1.

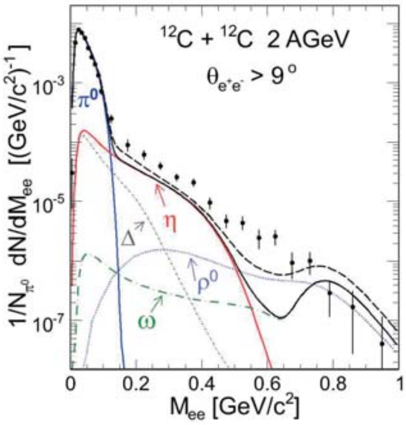
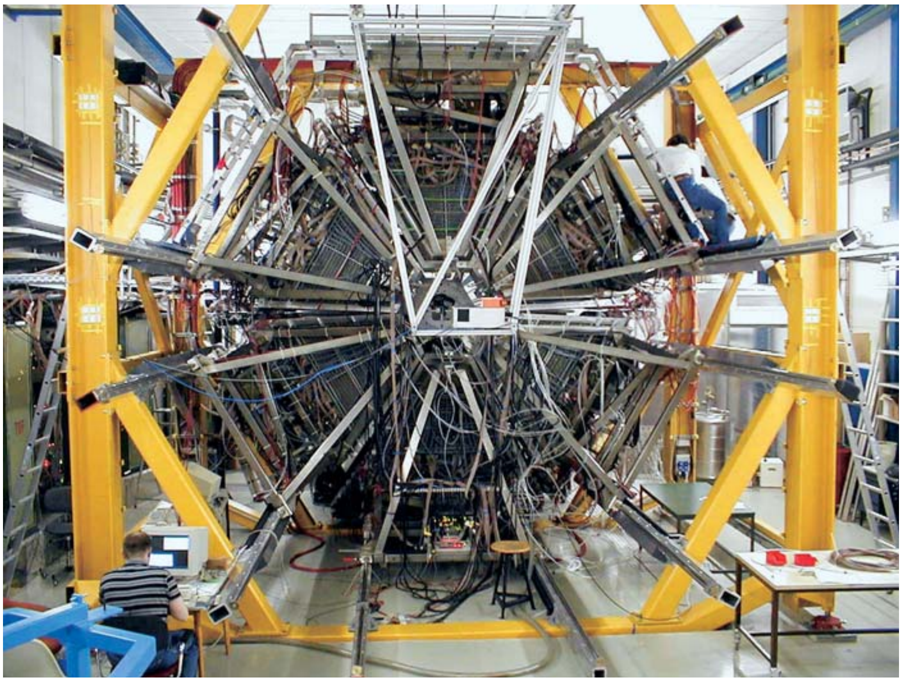


Fig. 3: The first physics results from HADES. On display: count rate of e^+e^- pairs, normalized to the number of pions, as a function of the invariant mass of e^+e^- pairs, M_{ee}. Symbols are for measured data, while curves depict estimates for various contributions to the spectrum. These estimates cannot account for the data. Sophisticated theoretical models are needed to extract information from data on the modification of the spectral distribution of ρ and ω mesons which are embedded in compressed nuclear matter arising from the collisions of carbon nuclei at beam energy of 2 GeV per nucleon.



Hades at GSI - two physicists testing parts of the installation.

Charming prospects

The results of KaoS and HADES have opened the door to answering the question about the origin of the masses of hadrons. New opportunities will soon exist to research much-needed supplementary information from the Facility for Antiproton and Ion Research (FAIR) which is under construction in Darmstadt. Among the core experiments of FAIR are nucleus-nucleus collisions. The accelerator SIS300 will deliver ion beams in an energy region in which the maximum compression of nuclear matter is expected. Moreover, FAIR provides a new degree of freedom: charm. Similarly to kaons, which are characterized by strangeness, D mesons carry a charm quark content. This makes them a very sensitive probe of the external strong interaction field and complements the information obtained from HADES and KaoS. Using this hadronic probe, further detailed insight into the complex architecture of hadrons and their mass generation is expected.

A large international collaboration has resulted in the building of the Compressed Baryon Matter (CBM) experiment at the FAIR site in Darmstadt. The task of the Rossendorf group is to develop Resistive Plate Chambers (RPC)—modern detectors with a time resolution shorter than 100 ps. They must function even at very high particle rates.

Due to the excellent timing properties of its electron beam (<5 ps resolution), the time resolution of RPCs is tested using electrons from the FZD linac ELBE. Moreover, the intensity of ELBE's electron beam offers an extremely valuable tool for testing the rate capability of modern detectors. Various test series with prototypes were already conducted at ELBE with promising results [5]. This necessary progress in instrumentation also provides cost-saving tools with application potential, e.g., for imaging devices in medicine. In this way, technology transfer and development is accomplished while the primary goal of addressing fundamental problems of physics, such as the heaviness of hadrons, especially protons and neutrons, is also tackled.

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ELBE γ-rays shed light
on the origin of the chemical elements

Andreas Wagner, Arnd Junghans,
Ronald Schwengner

Heavy chemical elements in the cosmos are produced by fusion reactions of two light atomic nuclei or by neutron-capture processes. Neutron-capture processes in red giant stars produce about half of all nuclei from iron to lead. The other half is produced during supernova explosions, which occur when heavy stars end their life cycle. During these cataclysmic events generating explosions brighter than an entire galaxy [1], rapid neutron capture processes and nuclear disintegration by photons lead to the formation of all elements in our solar system which are heavier than iron. Chemical elements with several stable isotopes serve as probes for our understanding of the cosmic nucleosynthesis by using their abundances as fingerprints of the various production processes. The origin of 35 neutron-deficient isotopes, for example around Molybdenum and Samarium, remains especially mysterious, as they are bypassed by stellar neutron-capture processes.

Recently, the question of nuclear disintegration induced by the high-temperature photon field present during supernova explosions has received growing attention. During these explosions, the outer layers of the exploding star are heated up to several billion Kelvin, extending the thermal photon spectrum beyond the neutron or proton separation energy of heavy nuclei. Under these conditions, the nucleosynthesis path proceeds through photodisintegration reactions as shown in Fig. 1.

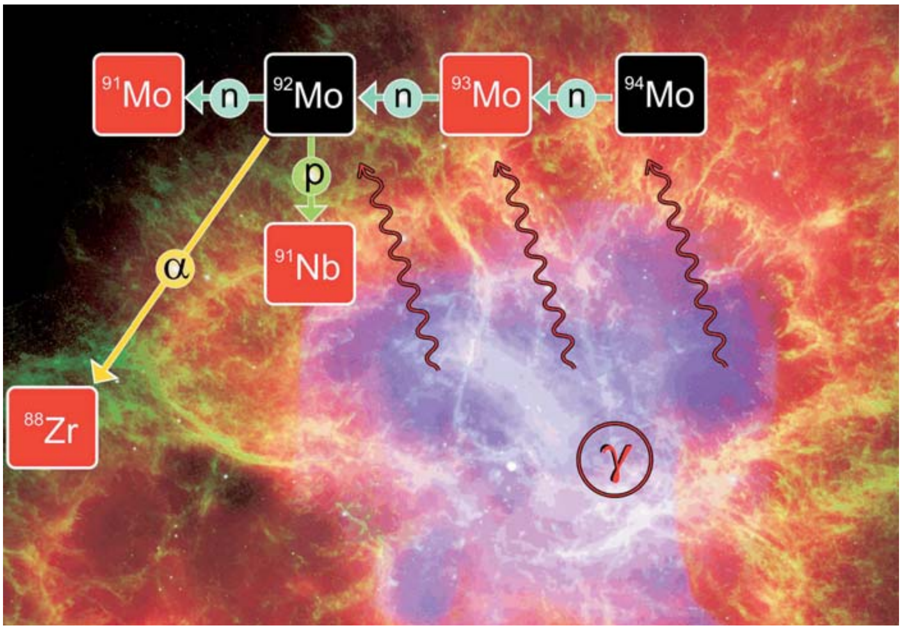

Fig. 1: Material driven outwards by the winds from supernova remnant Cassiopeia A (photo: courtesy of Hubble-STScI). The overlay indicates those nuclei studied at the FZD Radiation Source ELBE in the path of various nucleosynthesis reactions.

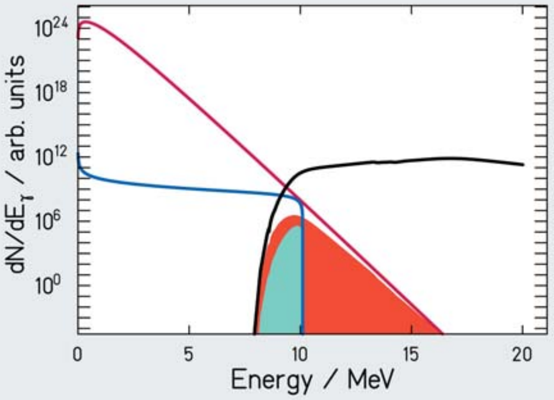

Fig. 2: Thermal distribution of photons at a typical supernova temperature of three billion Kelvin (red line) shown together with the bremsstrahlung at ELBE (blue line) in arbitrary units. The overlay of these two spectra together with a predicted nuclear photo-effect cross section shows that the region of interest can be scanned with bremsstrahlung of different end point energy.

Creating a supernova photon spectrum with ELBE bremsstrahlung

At the FZD Radiation Source ELBE, the thermal photon bath for temperatures of a few billion Kelvin can be replicated using electron bremsstrahlung. Scattered from a metal foil, the electron beam generates an intense continuum of γ-rays similar in energy to the field of γ-rays in a supernova as shown in Fig. 2. The ELBE γ-rays are then used to study nuclear reactions by experiments which aim at verifying or falsifying the input of nuclear theory for key astrophysical cases. In order to study

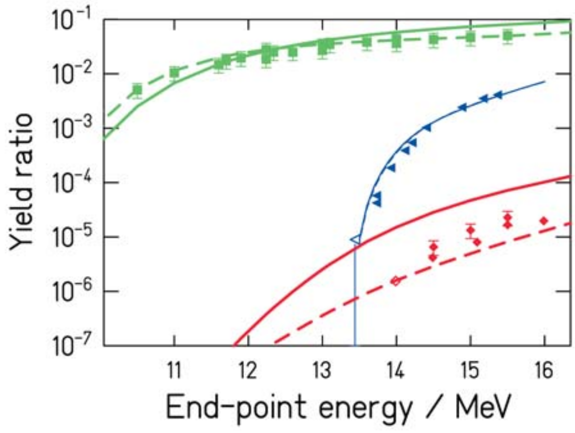

Fig. 3: Ratio of radioactive nuclei produced through bremsstrahlung with different electron energy for different photodisintegration processes on ^{92}Mo (^{92}Mo(γ,n)^{91}Mo (blue) ^{92}Mo(γ,p)^{91}Nb (green), and ^{92}Mo(γ,α)^{88}Zr (red), and the reference process ^{197}Au(γ,n)^{196}Au). The lines show the predictions of two different models for comparison.

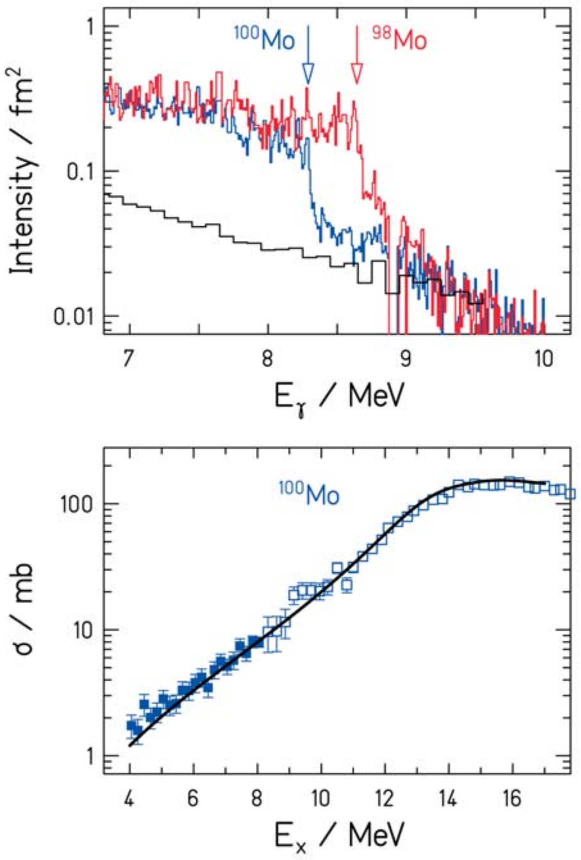

Fig. 4: Upper panel: Experimental energy distribution of scattered photons for the Molybdenum nuclides ^{98}Mo (red) and ^{100}Mo (blue). The dipole strength is deduced from the intensity above the simulated background (black line). Lower panel: Experimental photo-absorption cross-section from photon scattering data (full symbols) and photo-production of neutrons (open symbols). The solid line indicates the parameterization of the giant dipole resonance by Lorentzian distributions with constant widths.

the rare processes involved in γ-ray-induced cosmic nucleosynthesis, the uniquely high intensity of the ELBE radiation is necessary to get a sufficiently strong measurement signal.

One focus of the ELBE experiments is the role of the giant dipole resonance in photon-induced processes. The giant dipole resonance is the most important collective vibration of atomic nuclei. Sufficiently high photon energies lead to a strong absorption of photons in a characteristic energy interval. The cosmic nucleosynthesis is most sensitive to the low energy side of the giant dipole resonance. Thus, photon absorption directly above the energy threshold of the nuclear photo-effect, but below the peak of the giant dipole resonance, is particularly important. However, cross sections close to the threshold are small and difficult to measure. The detectors at ELBE which are used to measure the decay of irradiated samples have high detection efficiency and are shielded against background traces of natural radioactivity. A pneumatic system is used to transport the samples quickly from the irradiation positions to the detector. In this way, short-lived nuclides with half-lives of only few seconds can also be detected. From the data gathered at ELBE [2], cross-sections of the photon-induced emission of neutrons, protons, and even helium nuclei have been extracted (see Fig. 3). The latter were detected from heavy nuclei in the energy region of cosmic nucleosynthesis for the first time. The nuclides ^{92}Mo and ^{144}Sm serve as crucial test cases as their abundance predictions are off by more than an order of magnitude compared to the observations.

Photon scattering enables the experimental determination of the dipole strength function. In experiments at the bremsstrahlung facility at ELBE, we have determined the dipole strength up to the neutron-separation energy for the first time with high precision by including the contributions from resolved resonances as well as from a continuum of unresolved resonances, and by applying statistical methods to correct inelastic processes [3 ,4]. As a result of this novel technique, we have achieved a continuous connection of the dipole strength deduced from photon scattering to data deduced from photodisintegration reactions [3,4] (see also Fig. 4). Moreover, studying the chain of stable even-mass molybdenum isotopes from ^{92}Mo to ^{100}Mo has shown that the dipole strength depends on properties of the nuclei, such as nuclear deformation [5,6]. While studying closed-shell N=50 nuclei like ^{88}Sr [4] and ^{90}Zr, we have found resonance-like structures on top of the tail of the giant dipole resonance. This may influence photodisintegration reaction rates determining the production and destruction of specific nuclei in the cosmos.

Dipole-strength functions are also important for understanding the inverse process of radiative neutron capture. In this way, the dipole-strength functions in nuclei obtained from experiments will improve both the modeling of cosmic nucleosynthesis reactions and the

Andreas Wagner preparing an astrophysical experiment.

determination of cross sections of neutron-capture reactions which may be used for transmutation processes. In our experiments, atomic nuclei were made visible through their fluorescence light in the ELBE bremsstrahlung: they shine with a continuous spectrum in the ultra-far violet with a contribution from sharp resonance.

The experiments at ELBE are complemented by measurements with radioactive nuclei which are only possible at the Gesellschaft für Schwerionen-forschung (GSI) in Darmstadt. The disintegration of nuclei in the electro-magnetic field of a heavy target nucleus at high beam energies is used to determine the electromagnetic-strength function of nuclei with half-lives down to milliseconds. In conducting these measurements, we collaborate with GSI Darmstadt, the Institute of Nuclear Physics at Forschungszentrum Karlsruhe, and the Institute of Nuclear Physics at Technische Universität Darmstadt. The analysis is still in progress. Collaboration also exists with a group of Konan University in Kobe, Japan, which uses Laser Compton backscattered photons to investigate photodisintegration reactions.

Fostering scientific exchange on the questions of explosive nuclear synthesis described here, the Institute of Radiation Physics of the FZD organized the International Europhysics Conference "Nuclear Physics in Astrophysics III" in Dresden in March 2007. The conference highlighted the importance of the input of nuclear physics to astrophysical modeling and initiated many fruitful scientific discussions.

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Project partners

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[2] Universität Stuttgart, Germany
[3] University of Cologne, Germany

Charles University in Prague, Czech Republic

nELBE: Novel research on transmutation of radioactive waste

Arnd Junghans, Andreas Wagner,
Frank-Peter Weiss, Eckart Grosse

One—for many the strongest—of the arguments against a long-term commitment to nuclear power as an energy source is the need to permanently dispose of the long-term radioactive waste produced in nuclear reactors. Thus, significant efforts are being made worldwide in order to minimize, manage, and dispose of highly radioactive nuclear waste. Partitioning of nuclear waste and transmutation of long-lived isotopes into nuclides with a shorter lifetime are being investigated in the EURATOM FP6 program. Several transmutation schemes have been proposed and detailed numerical simulations are underway for an optimal solution. Regarding the development of new concepts to produce less waste via very high burn-up, different designs involving critical reactors or sub-critical accelerator-driven systems (ADS) are being studied in view of their transmutation capabilities. The Generation IV (Gen-IV) International Forum (GIF) has selected six nuclear energy systems which require additional research and development in order to confirm their viability. Also, their expected performance is to be demonstrated which, among other things, aims at producing less waste.

Different schemes have been proposed which may considerably reduce the radioactivity of the spent fuel after burn-up. Studies choosing the best options make extensive use of simulation methods in order to predict the system behavior in a great variety of possible configurations and running conditions. A fundamental prerequisite for these Monte Carlo computing techniques is the availability of reliable cross-section data. This is needed for processes and operating parameters which significantly differ from those of currently used operating systems.

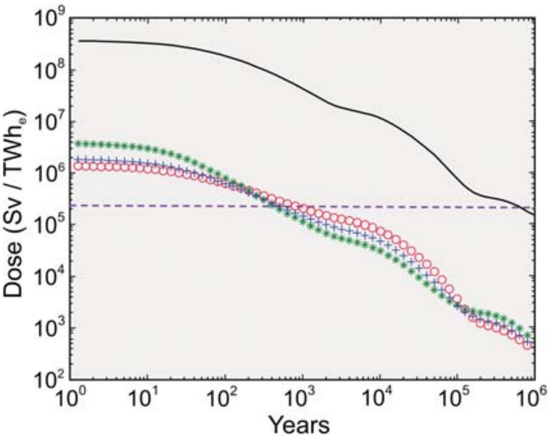


Fig. 1: The chart demonstrates how transmuting the waste from a traditional fission reactor may reduce the time needed until the radioactivity has reached the level of natural uranium (dashed line). The dose is plotted vs. the time after fuel removal from the reactor for three possible transmutation schemes [2]:

— Storage of spent fuel without treatment
+ Fast neutron reactors with recycling of the transuranium elements
o Transmutation of actinides in a separate compact fuel cycle
* Light water reactors with full recycling

Neutron time-of-flight at ELBE

In particular, accurate knowledge of neutron-induced nuclear reactions at appropriate energies is crucially important for predicting the capabilities of new systems. This means that for detailed waste-transmutation research and design work on Gen-IV systems, energy-dispersive studies are needed. To determine neutron energy, the time-of-flight method can be applied to a wide range of energies: starting with a broad spectrum, the neutrons are tagged according to their energy by measuring their velocity. The FZD Radiation Source ELBE with its ultra-short electron bunches is especially well suited for this method and time-of-flight measurements with high resolution can be performed here even for fast neutrons.

Regarding waste reduction, the possible use of fast (i.e., un-moderated) neutrons as they come directly from the fission process is highly important. The strong processes induced by these fast neutrons are known in principle, but reliable predictions of the relevant physical processes and phenomena depend on the availability of high-quality nuclear data. As the fission neutron spectrum bears great resemblance to the neutron distribution originating from the nuclear photo effect, a high-intensity electron beam, like the one at ELBE, allows cross-section measurements for capture and scattering of fast neutrons by structural materials, fuel and waste from fast reactors. The neutrons are generated by bombarding high atomic number material with electrons and thus producing bremsstrahlung which in turn causes the same material to emit neutrons.

Obviously the neutron flux, which determines the statistical accuracy of a cross-section measurement carried out in a given time, depends on the primary beam intensity and on the amount of converter target material put in the beam. At ELBE, flux as a limiting factor is restricted by the maximum beam power accepted on the neutron producing target; however, it is not limited by the available beam current from the accelerator. A technologically innovative solution for neutron converters suited for very high beam power deposition based on a molten-lead circuit (≈ 5 kW/g) was designed in a collaborative effort of the FZD Institutes of Radiation Physics and Safety Research.

The most important feature of this source, which is advantageous for transmutation-related measurements, is its extremely high flux at a reasonable time resolution: the neutron density of more than 10^7 n/cm^3 produced in the radiator by each micro pulse (at ≈ 1 MHz) results in nearly 10^7 n/(s·cm^2) at a flight path of roughly 5 m. By making use of the new superconducting RF-photo-gun at ELBE, the repetition rate can be adjusted to the neutron energy range studied at the given flight path. Due to the uniquely high bunch charge of up to 2 nC of this electron gun, the full neutron flux is available for neutron energies above 20 keV.

ELBE is the first superconducting electron linac combined with a neutron time-of-flight facility. A large advantage is that the radio frequency is permanently present, which allows accelerating nearly any pulse repetition rate delivered by the electron gun. At ≈ 1 MeV, a resolution $\Delta E/E$ of ≈ 2 % may be reached with detectors at ≈ 1 ns resolution. The time resolution of the e-beam is much better. Due to its small dimension of ≈ 1 cm, the radiator generates n-bunches shorter than 1 ns. The setup is devoted to measurements of transmutation-relevant data for actinides as well as for fission fragments. Measurements with targets of only 10 mg are planned.

EU-funded collaboration

The Rossendorf neutron time-of-flight setup called nELBE is part of the EU-funded Integrated Infrastructure Initiative (I3) "European Facilities for Nuclear Data Measurements" (EFNUDAT). It has been created by a consortium of European experimental facilities for nuclear data measurements. Joint Research Activities (JRA) within this I3 are concerned with the completeness, comparability, and quality assurance of the nuclear data produced by the ten participating institutions in seven European countries. FZD participates in three JRAs and heads one which is dedicated to neutron generators and targets. A major task of this JRA is to optimize the molten-metal radiator with the electron beam and to investigate how this design can eventually improve neutron production at the other facilities.

Transnational access to nELBE (as well as to the other neutron facilities) is supported by this I3, and some of the participating partners will perform experiments there.

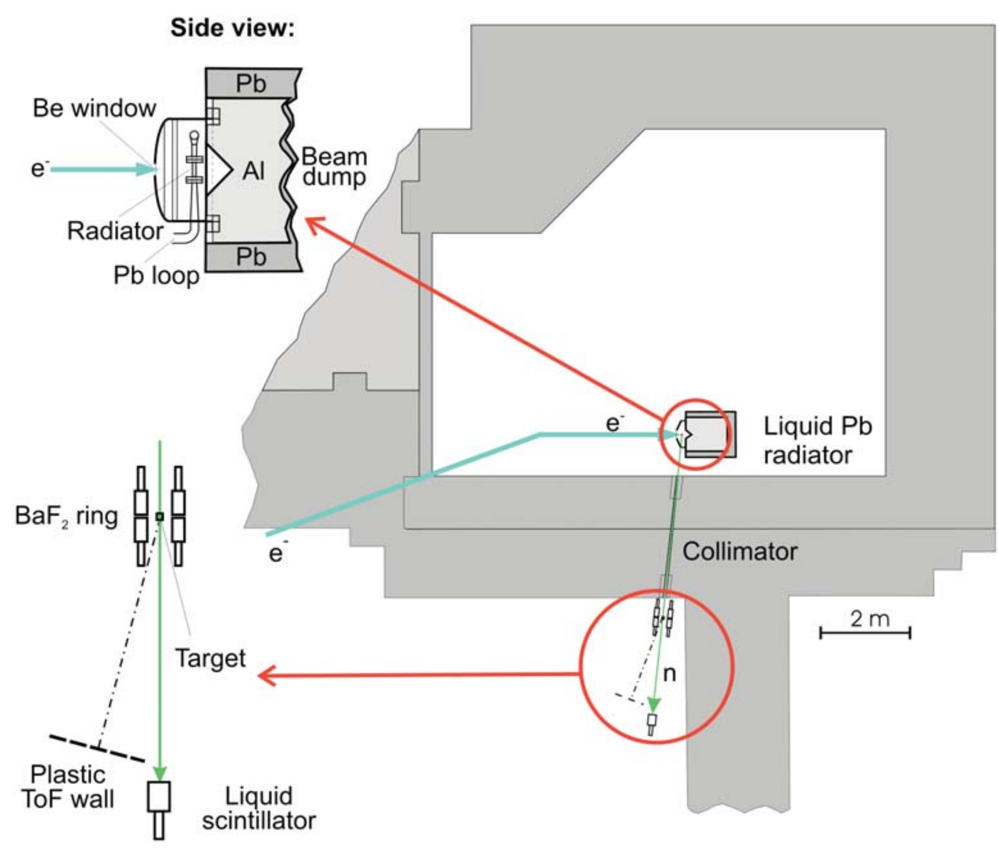
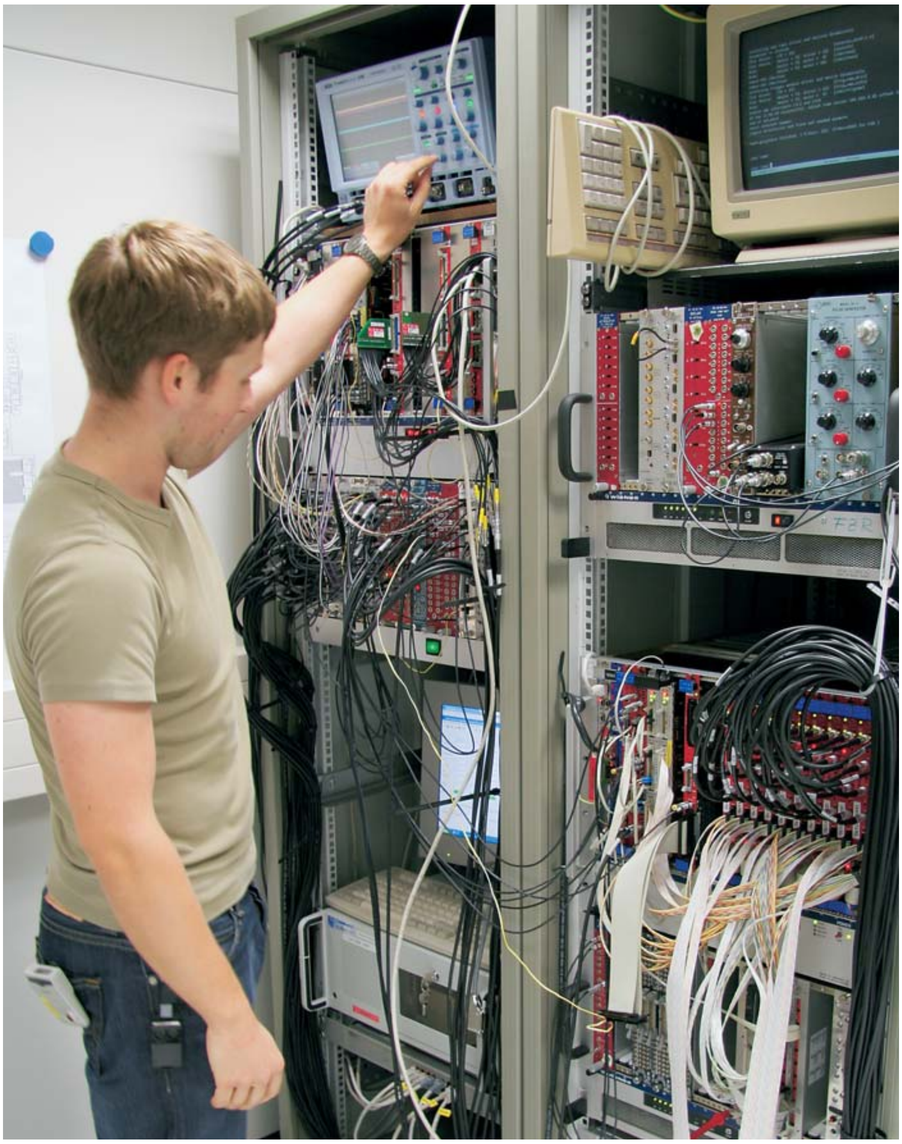


Fig. 2: This picture shows the setup for the measurements at nELBE. The neutrons are generated by the electron beam and are transferred through a massive concrete radiation shield (needed to warrant sufficient shielding between neutron radiator and experiment). The good emittance of ELBE in combination with an especially designed collimator results in a narrow neutron beam allowing the use of small targets and compact detector set-ups.
The measurements allow for photon detection following radiative neutron capture (4π-array of BaF_2 scintillators) and for the registration of neutrons scattered from the target (in specially equipped plastic scintillators). By using the photon and neutron detectors together, inelastic neutron scattering can be identified. Both detector types reach time resolutions below 1 ns and are thus well suited for time-of-flight tagging.



Roland Beyer setting up the data acquistion system for the nELBE experiment.

The only two other neutron time-of-flight facilities within EFNUDAT have concentrated on slower neutrons in the past (including moderated, i.e., thermal neutrons). The installation at the European Commission Institute of Reference Materials and Measurements (IRMM) in Geel has considerably less primary beam power and thus less neutron flux. At the proposed short (20 m) flight path of CERN/n_TOF, the flux will be somewhat larger than nELBE in the energy range accessible here, but the energy resolution is expected to be superior at FZD.

The FZD activities in the field of molten metal neutron converters parallel similar attempts in the USA and Japan which are carried out in view of the upcoming Spallation Neutron Source (SNS) and the Japanese Proton Accelerator Research Complex J-PARC, respectively. Both are built to deliver significantly higher particle fluxes than available today. The research performed at FZD will thus not only represent a significant step forward to upgrade the nuclear-data measurements within the EFNUDAT initiative, but, as many European scientists in the field of materials research hope, may also lead to results which can perhaps be used in the future European Spallation Source ESS.

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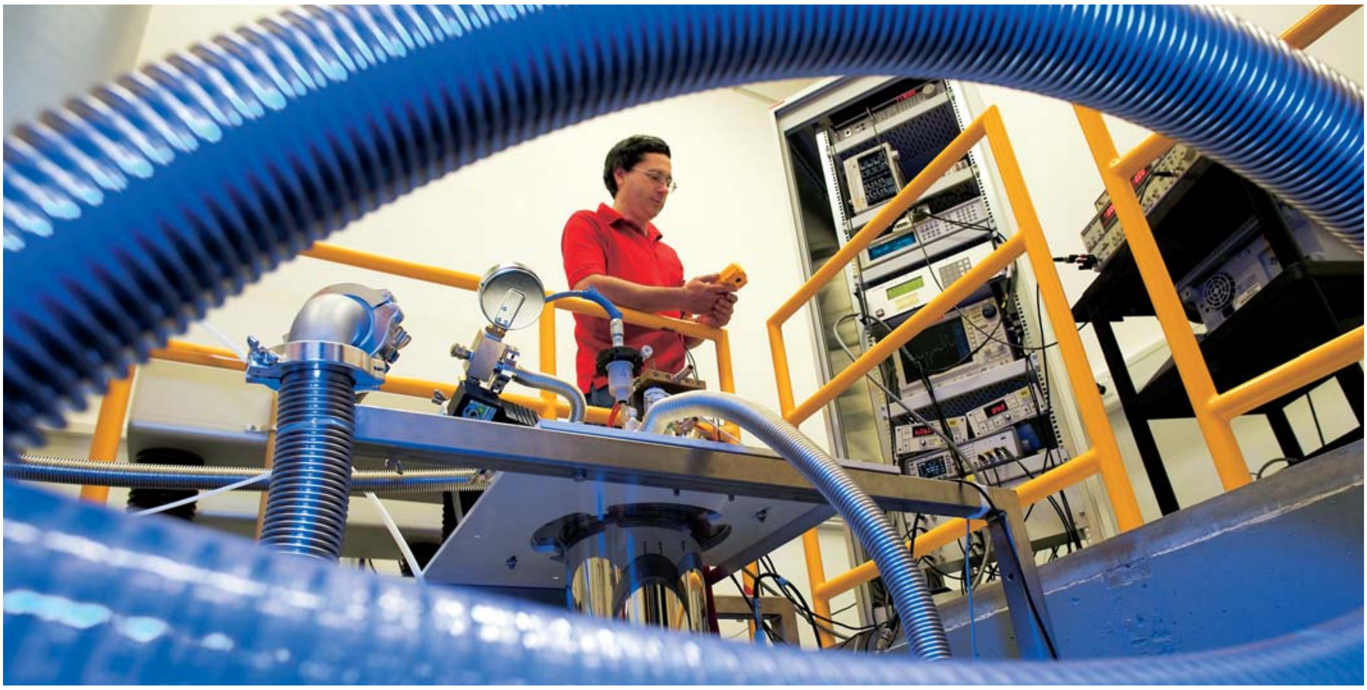
Quantum phase transitions
in an exotic metal



Sergei Zherlitsyn in one of the high magnetic field laboratory caves. Photo: Jürgen Lösel

Thomas Herrmannsdörfer

When cooled to low temperatures and exposed to very high magnetic fields, the properties and behavior of some materials can dramatically change compared to their properties at ambient conditions. The relevant mechanisms for changing their electronic, magnetic, and optical properties can be determined better under extreme conditions such as high magnetic fields. A fascinating demonstration of the quantum mechanical processes in metallic or semiconductor materials was performed by W. de Haas, L. Shubnikov, and P. van Alphen in the early 1930s. Their pioneering observation of oscillations of the magnetic susceptibility and electrical resistance of Bi as well as other materials in high magnetic fields prepared the way for determining microscopic electronic properties of conductive matter.

Thanks in part to their findings, today we know in detail how magnetic fields force conduction electrons in solids or, more precisely, in any kind of delocalized charge carriers on cyclotron orbits. In addition, we have gained insight into the changes of their energy spectrum, previously considered a continuum, and now understood as a set of quantized highly populated energy levels called "Landau" levels. We now understand that an increase in the magnetic field increases the cyclotron-energy splitting between the levels linearly as well as the number of charge-carrier states per Landau level. As each Landau level passes through the Fermi energy at a specific magnetic field, it depopulates—at the same time increasing the population of the lower states. This periodic population/depopulation scenario leads to quantum oscillations of magnetic and transport properties. Starting from L. Onsager's theoretical description in 1952, the monitoring of quantum oscillations in high magnetic fields has been developed from the early days of solid-state physics to a precise tool for the study of electronic band structures of metallic systems. With access to ever higher magnetic fields, the band structures of more and more classes of materials have been determined through high-field studies. In particular, spectacular changes of the period of quantum oscillations have been found in the presence of structural or magnetic phase transitions, which also affect the conduction electron density. However, there is plenty still remaining to be discovered. For example, changes of the band structure, (i.e., of the energy distribution of charge carriers in momentum space) which are caused solely by the application of high magnetic fields have not yet been observed. In conventional materials like copper, silver, or gold, the band structure hardly ever changes—even by applying the highest magnetic fields.

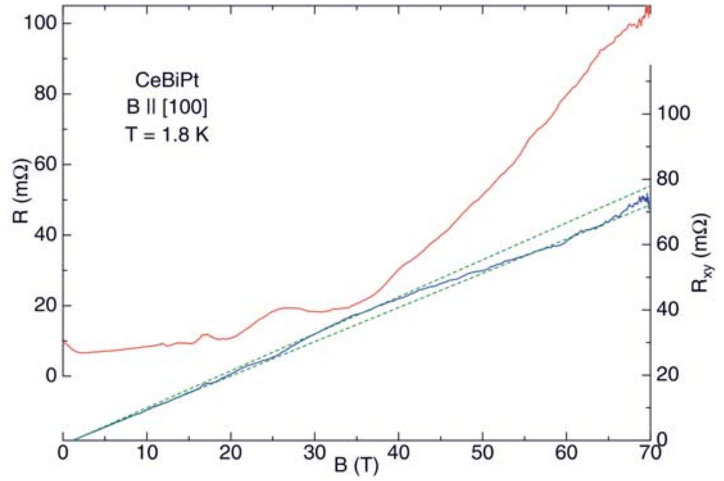


Fig. 1: Electrical resistance (red curve) and Hall-resistance (blue curve) of the metal CeBiPt. The green dotted lines indicate a change of the charge-carrier density.

New evidence of a Lifshitz quantum phase transition

Long-predicted, “Lifshitz” quantum phase transition has been demonstrated only recently. The first evidence of this phenomenon was observed in the exotic semimetal CeBiPt using very high magnetic fields [1]. Measurements of Shubnikov-de Haas oscillations in the electrical resistivity were performed at two laboratories involved in a project which is also included in the activities of a Collaborative Research Center (SFB 463) of the German Research Foundation (DFG) (“Seltenerd-Übergangsmetall-Verbindungen: Struktur, Magnetismus und Transport“). Initially, quantum oscillations up to 47 Tesla were investigated in the pilot facility of the Dresden High Magnetic Field Initiative at the Leibniz Institute for Solid State and Materials Research Dresden (IFW). Electrical transport up to 70 T as a function of the magnetic field applied was measured later at the High Magnetic Field Laboratory Dresden (HLD) situated at the FZD. In the second set of experiments at the HLD during 2006, the maximum field strength, field-pulse duration, accessible temperature range, and experimental resolution were improved significantly. In addition, a newly-prepared CeBiPt sample was investigated.

Magnetic field coil after testing.

Both experiments on the two CeBiPt samples with somewhat different impurity concentrations have demonstrated a field-induced change of the electronic band structure. This was clearly observed by the disappearance of quantum oscillations at fields above 40 Tesla (Fig. 1). In particular, the new experiments performed at the HLD have demonstrated that with fields of up to 70 Tesla, no new quantum oscillations emerge. This observation provides deeper insight into the exotic properties of the metal CeBiPt with highly sensitive Fermi-surface and band-structure parameters. This change of the charge-carrier density induced by the magnetic field is explained as an effect arising from both the low number of charge carriers and the special properties of the electronic structure influenced by the 4f electrons of the cerium atoms. The essential role of the cerium 4f electrons which are jointly responsible for the magnetic field-induced band-structure changes by polarizing the 5d conduction bands has been demonstrated by investigating LaBiPt for comparison purposes. LaBiPt is a compound with the same lattice geometry and similar properties; however, the cerium atoms have been replaced by lanthanum which possesses no 4f electrons. No evidence of a Lifshitz transition has been found in LaBiPt.

Additional evidence of a field-induced change of the charge-carrier density was found for CeBiPt. The slope of the Hall resistance (R_{xy} in Fig. 1), which is a direct measure of the charge-carrier density, was observed to change above 40 Tesla. The disappearance of the Shubnikov-de Haas quantum oscillations and the change of the Hall resistance at the same magnetic field, as well as the absence of quantum oscillations at fields between 40 and 70 T clearly indicate the occurrence of a Lifshitz quantum phase transition [1, 2].

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Searching for the magnetic Bose-Einstein condensate

Ph.D. student Mike Ozerov collecting and visualizing electron-spin-resonance data.

Sergei Zvyagin

Bosons, named after Satyendra Nath Bose, are particles with integer spin. In contrast to fermions (which carry half-integer spin), bosons obey Bose-Einstein statistics. One of the most fascinating aspects of these particles is the phenomenon of Bose-Einstein condensation (BEC). In this state, an unlimited quantity of bosons can share the same quantum state with wave functions remaining coherent on the macroscopic scale. The BEC phase, also referred to as the "fifth state of matter", was first postulated as a consequence of quantum mechanics by Albert Einstein, building upon the work of Bose in 1925. The Bose-Einstein condensate, and the process of condensation itself, was predicted to have many unusual properties and was indeed found to be responsible for a number of fascinating phenomena in quantum physics, such as the superfluidity of ^{4}He. For years, scientists have been looking for other manifestations of BEC in the laboratory. Finally, in 1995, conclusive evidence for BEC in a dilute gas of rubidium-87 atoms, cooled down to temperatures lower than 1 μK, was obtained. For this observation, the scientists Cornell, Ketterle, and Wieman were awarded the Nobel Prize in Physics in 2001.

Searching for BEC in other bosonic particles remains a formidable challenge in modern quantum physics. A possible example of this phenomenon may be found in the condensation of magnetic quasiparticles called magnons into quantum magnets. For many quantum systems, the magnetic field tends to suppress quantum fluctuations, leading to a system with a magnetically well-ordered state. By changing the magnetic field, the magnon concentration can be controlled. This provides access to a wide range of

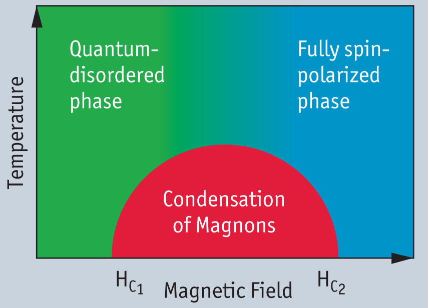

Fig. 1: Generalized temperature-field phase diagram of the field-induced condensation of magnons in quantum magnets.

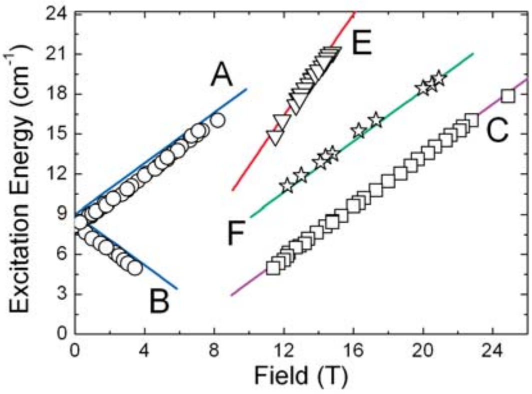

Fig. 2: Frequency-field dependence of magnetic excitations in DTN. Symbols denote the experimental results, and lines correspond to results of calculations. The modes F and E correspond to two-magnon bound state excitations.

magnon densities, from a dilute gas of particles to a strongly interacting Bose liquid. Fig. 1 shows a sketch of the generalized temperature-field phase diagram for the magnon condensation in quantum magnets.

Field-induced condensation of magnons in DTN

Recently, it has been suggested that the field-induced condensation of magnons can occur in the organic material $NiCl_2$-$4SC(NH_2)_2$ (known as DTN). At sufficiently low temperatures, DTN undergoes this field-induced transition at a magnetic field of 2.1 T. At 12.6 T, there is a second transition at which the magnetic moments become fully spin-polarized [1]. A thorough knowledge of magnetic material parameters is very important in understanding magnon condensation in DTN.

Measuring the electron spin resonance at high magnetic fields is one of the most powerful and sensitive tools for probing the magnetic excitation spectrum in exchange-coupled spin systems. Using the temperature and magnetic field as tuning parameters, we can obtain valuable information about the nature of the ground state, estimate important physical parameters and constants, and learn about magnetic interactions on a microscopic scale. The electron spin resonance technique is particularly important for studying physical phenomena at high magnetic fields where other spectroscopic techniques, such as neutron scattering or X-ray diffraction, are not yet available. We performed a number of high-field electron spin resonance measurements, investigating the magnetic excitations in magnetically low-dimensional materials [2-4]. In particular, we studied these excitations in DTN in magnetic fields of up to 25 T. A distinct advantage of the high-field approach is the availability of exact theoretical expressions used for determining the parameters of DTN. Analysis of the high-field excitation spectrum has enabled us to extract the spin-Hamiltonian parameters very accurately. This allowed us to calculate the temperature-field phase diagram and to qualitatively describe the magnon condensation in DTN. In addition, we found direct and conclusive evidence for "two-magnon bound states" in this spin-1 antiferromagnetic chain system with strong easy-plane anisotropy. These exotic states have been postulated since 1970 and have attracted a great deal of attention due to their possible connection to the intrinsic localized spin modes in anisotropic media. We were able to achieve excellent agreement between theoretical predictions and experimental data (Fig. 2).

The experimental part of this work was executed in large part at the National High Magnetic Field Laboratory in Tallahassee, Florida, USA. Recently, electron spin resonance measurements have become possible at the Dresden High Magnetic Field Laboratory (HLD) in pulsed fields of up to 70 T. This sophisticated equipment is available for the user research program at the HLD. It is also used for further in-house research on electronic properties of solids in high magnetic fields.

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Ions meet magnets –
tailor-made properties on the nano-scale

Kay Potzger adjusting the magnetic force microscope (MFM).

Jürgen Faßbender

The mission of the "nanoscale magnetism" group of the FZD is to understand the fundamental effects which determine the magnetic material properties of nanoscale elements. For their creation and modification, ion beam technologies are used. In addition to conventional topographic patterning approaches, pure magnetic material modifications on the nanoscale are emphasized. This way, devices with new functionalities can be created which could be applied in the fields of sensors and magneto-logic devices. The large variety of research topics in this area can be illustrated by three different examples on which we have been focusing.

Hybrid magnetic materials: microscopic origin – macroscopic results

We are investigating the correlation between artificially-generated magnetic-domain configurations and effective magnetic properties, i. e., magnetic anisotropy, exchange coupling, and interlayer-exchange coupling [1 – 5]. Artificial domain structures are produced by means of ion-irradiation techniques which allow modification of the magnetic parameters on a length scale similar to or even below the exchange-correlation length (typically ~ 10 – 1000 nm). In doing so, completely new domain walls and domain configurations, which are not possible in conventional thin films, are created. When they are further miniaturized, the domains vanish and an “effective” material with new properties, observed neither in fully irradiated nor in non-irradiated films, is designed. These are called hybrid materials. Fig. 1 shows an example of such an artificial magnetic domain configuration. Fig. 1 a) displays a

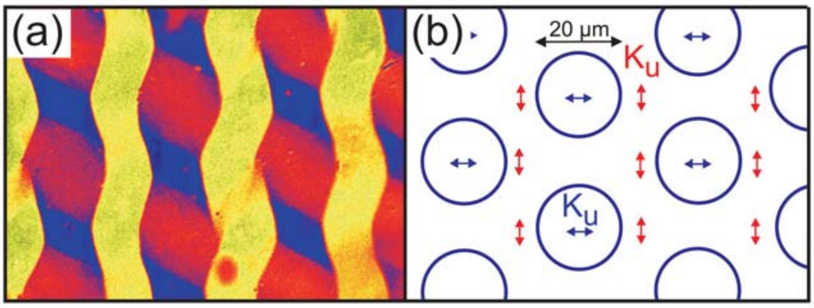

Fig. 1: a) Kerr microscopy image of the magnetization configuration of an artificial domain configuration created by means of local ion irradiation in an applied magnetic field. The magnetization direction is displayed color coded. **b)** Sketch of the local magnetic anisotropy direction. Comparing **a)** and **b)** immediately demonstrates that the magnetization does not simply follow the local anisotropy directions. Instead a complicated magnetization pattern is observed which depends strongly on the magnetic field history.

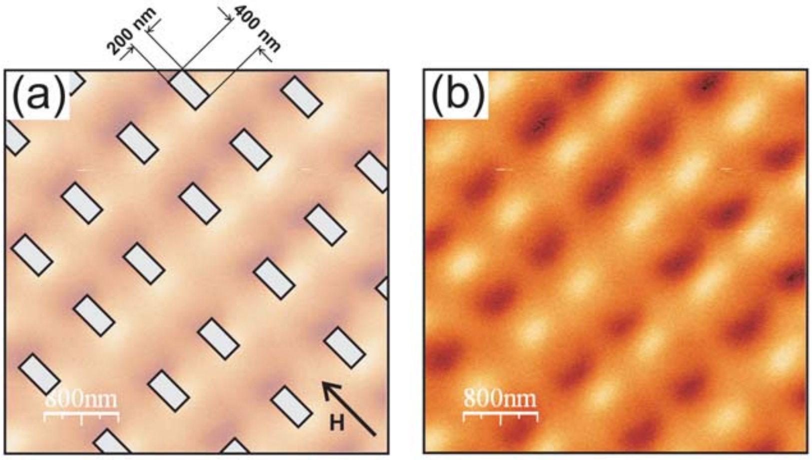

Fig. 2: a) Sketch of the FIB-irradiated areas (grey) of a FeAl alloy. **b)** Corresponding MFM images of the stray field distribution in an applied magnetic field. The ferromagnetic elements are in a single domain state. Hence a dipolar stray field distribution is observed.

Magneto-optic Kerr-effect setup for the investigation of the magnetization reversal behavior of thin magnetic films and structures.

color-coded image of the magnetization configuration which was visualized by means of Kerr microscopy. Fig. 1 b) sketches the imprinted local anisotropy directions.

In this project, our first goal is to gain a basic understanding of simple model systems such as at the transition between two different areas with different magnetic parameters, quasi two-dimensional structures, or magnetic point defects. Secondly, we are investigating the functional relationships between microscopic patterns and integral magnetic properties in close cooperation with J. McCord at the Institute for Solid State and Materials Research (IFW) Dresden. This cooperation is funded by the German Research Foundation (DFG). In addition, synchrotron-based imaging techniques are employed at the Advanced Light Source at Lawrence Berkeley National Laboratory/ USA.

Order-/disorder-induced ferromagnetism

The magnetic properties of a large variety of binary alloys are sensitively correlated to their chemical order. For example $Fe_{50}Pt_{50}$ exhibits a large magnetic anisotropy only in the chemically ordered $L1_0$ phase; however, by ion irradiation, a $Fe_{50}Al_{50}$ alloy can be prompted to transform from paramagnetic to ferromagnetic behavior. The origin of this effect is the transformation from the chemically ordered B2 phase, which is paramagnetic, to the chemically disordered bcc phase, which is ferromagnetic, due to ion irradiation. Local irradiation through focused-ion-beam (FIB) techniques allows creation of ferromagnetic nanoentities within a paramagnetic matrix [6]. The magnetization configuration and the stray field distribution of these nanostructures can be visualized using magnetic force microscopy (MFM/ Fig. 2). In this project, we are researching the modified magnetic properties accompanied by order-disorder phase transitions and are making use of these effects in order to create magnetic nanostructures. The project is partially funded by the European Union.

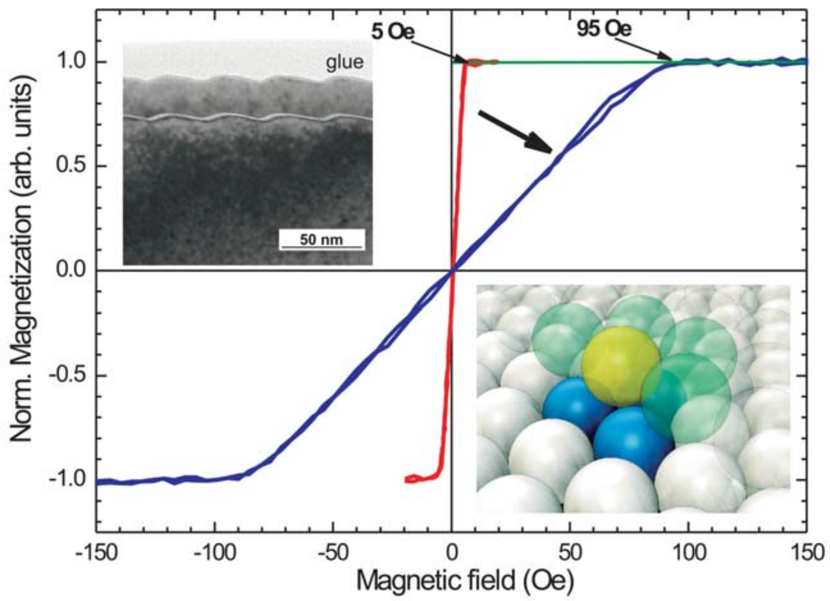

Fig. 3: Magnetization reversal curves along the hard magnetization direction of a thin Permalloy film deposited on a nominally flat (red) and rippled (blue) substrate. Left inset: Cross-sectional transmission electron microscopy image which shows that the magnetic film reproduces the ripple morphology well. Right inset: Sketch of a monoatomic step edge in order to visualize the atomic coordination.

Morphology-induced magnetic correlation effects

Ion erosion of semiconductor surfaces is a well-established technique in order to create a surface modulation based on a pre-defined modulation period (typically 10 – 100 nm) and amplitude (typically 1 – 10 nm). Since the modulation period can be varied easily by altering the ion energy, these surfaces are ideally suited to study roughness phenomena and material properties which depend on certain correlation lengths. We have been investigating the effect of a correlated roughness on the magnetic properties of thin magnetic films. Using cross-sectional transmission electron microscopy, we produced an image of a surface-ripple structure which has a period of 32 nm and a height of 2 nm and is covered by a thin soft magnetic film (see inset of Fig. 3). This image clearly demonstrates that the thin magnetic film reproduces the ripple periodicity and amplitude perfectly. Hence, a large step density perpendicular to the ripple direction is achieved, whereas the step density is negligibly small along the ripple direction. Since the atomic coordination at a monoatomic step edge is different from surface or bulk atoms (see inset of Fig. 3), a modified spin-orbit coupling is present at these locations. In addition, strong dipolar effects govern the magnetization reversal behavior. This is clearly demonstrated by comparing the magnetization reversal behavior of a thin magnetic film on a nominally flat substrate and on a rippled substrate [7]. There is approximately a twenty-fold increase in the magnetic anisotropy of the rippled film as determined by the saturation field, which refers to the magnetic field at which the magnetization is saturated. Our future goal will be to decompose rough films into their primary modulation-length components by means of Fourier transformation. We also want to explain their magnetic properties as a superposition on the basis of the individual modulation-length-dependent magnetic contributions. A new proposal for this at the German Research Foundation (DFG) is currently under evaluation.

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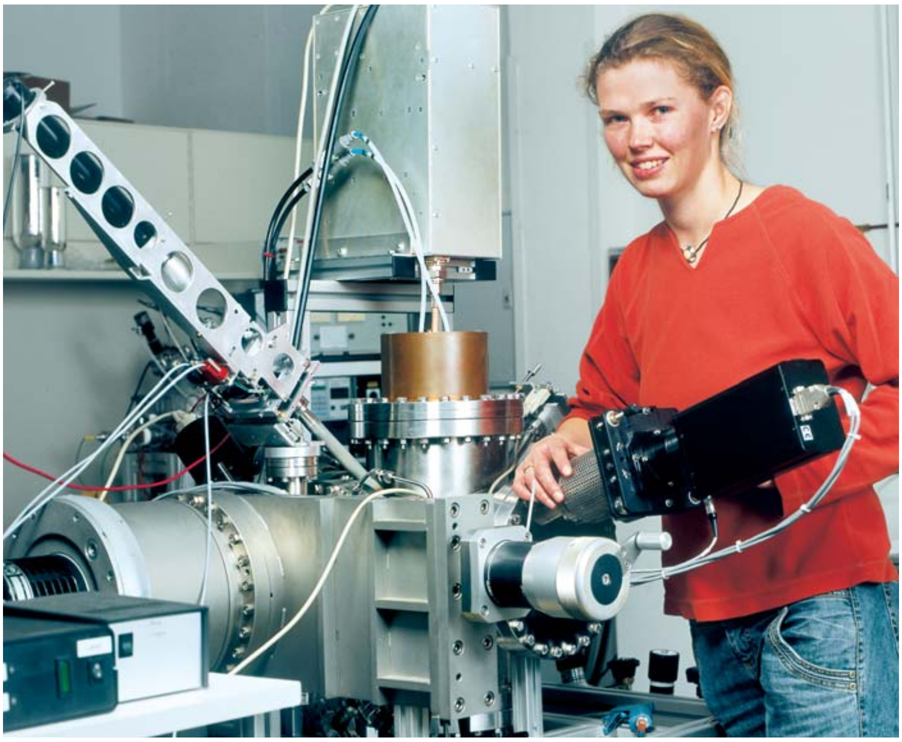
Cubic boron nitride:
Thin film physics moving toward a practical application



Barbara Abendroth in her laboratory.

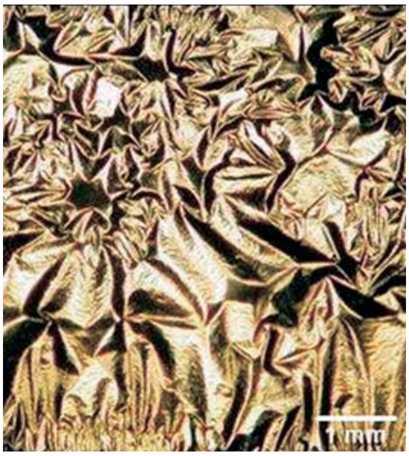


Fig. 1: Optical micrograph of a typical peeled-off cBN thin film with high compressive stress and poor adhesion.

Barbara Abendroth, Andreas Kolitsch, Wolfhard Möller

Cubic boron nitride: prospects and disappointments

Cubic boron nitride (cBN) belongs to the so-called "superhard" materials. With respect to its oxidation resistance up to temperatures of 1300 °C as well as its chemical inertness in hot contact with ferrous materials, it is even superior to diamond. Thus it would be an ideal wear-reduction coating for high-speed cutting tools. cBN thin films can be produced using a variety of standard processes even at relatively low temperatures (100 – 500 °C). Energetic ion bombardment in the energy range of 100 to 1000 eV is indispensable for the nucleation and growth of cBN against the soft hexagonal hBN phase. However, ion-induced densification results in an excessive intrinsic compressive stress in the layers often exceeding 10 GPa. In addition, the cubic phase nucleates on most common substrates only on a thin hexagonal interlayer. The combination of both the high intrinsic stress and the relatively weak substrate/film interface usually limits the achievable thickness of stable films to a few hundred nm. Delamination (Fig. 1) has been the frustrating result of numerous attempts to achieve higher film thicknesses in the micrometer range, which would be suitable for cutting tools. Thus, cBN is still waiting for its commercial application despite considerable worldwide efforts for more than 20 years.

The FZD story: From basic research …

Early studies in the 1990s at FZD contributed to the understanding of the growth mechanism using ion-assisted deposition with well-controlled deposition parameters. In previous investigations at the University of Ulm [1], significant stress relaxation had been achieved by stepwise deposition and intermediate 300 keV ion bombardment, resulting in film thicknesses exceeding 1 micrometer. Following this, a faster and continuous process was developed at FZD, using mid-level (several 10 keV) ion irradiation, which was applied during film deposition [2]. It proved essential to monitor the evolution of the intrinsic stress during film growth. This was related to the practical application because sufficiently high growth rates must exist for the process to be industrially feasible. Correspondingly, stress relaxation was demonstrated using magnetron sputtering

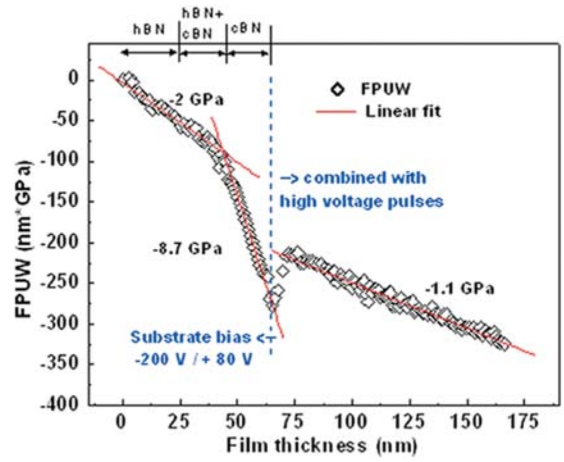


Fig. 2: The diagram shows the force per unit width (stress integrated over the film thickness) versus the thickness of the growing film. The gradients given by the linear regression fits (red) represent the compressive film stress in three phases, (i) growth of the hexagonal seed layer and cBN nucleation, (ii) growth of highly stressed c-BN, and (iii) growth of stress-released cBN using high-voltage pulsed substrate bias.

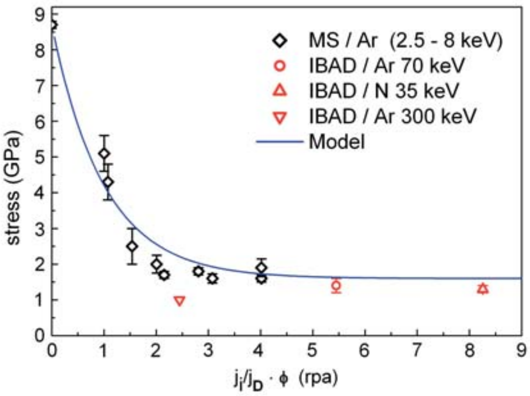


Fig. 3: Scaling of stress relaxation with ion-induced atomic relocation for different processes involving energetic ion bombardment. On the abscissa, j_i and j_D denote the incident flux of energetic ions and film-forming atoms, respectively, and ϕ the number of relocations per incident energetic ion. As ϕ is proportional to the ion energy, the stress relaxation scales with the product of ion flux and energy. The ion energies are indicated together with the different deposition processes (MS – magnetron sputtering, IBAD – ion beam assisted deposition).

combined with simultaneous bipolar-pulsed substrate bias at voltages down to 2.5 keV [3]. Systematic investigations of stress relaxation (Fig. 2) showed that bias voltage and pulse frequency, i.e., the energy and flux of the implanted ions, are the determining parameters. The studies were accompanied by compositional and structural investigations [4]. The cubic phase is stable under ion bombardment. The stress relaxation takes place within the cBN grains and is therefore not due to a phase transition to the hBN phase. The stress relaxation can be described by atomic relocation of strained interstitial film atoms and their transport to the grain boundaries of the nanocrystalline material which is due to binary collisions of the implanted energetic ions. In cooperation with the University of Sydney, Australia, a model of stress relaxation was developed which explains the dependence on the incoming ion energy and the threshold energy for atomic relocation [5] (Fig. 3).

…towards a commercial application

As indicated above, stress release is necessary but not sufficient for the deposition of thick and strongly adherent cBN films. Currently, FZD is working on a technology-transfer project which is fully financed by a leading German coating company. The goal is to commercially produce thick, low-stress protective cBN coatings on tools such as cutting inserts using a multi-step process. First, the pre-treatment procedure and the deposition process was optimized to eliminate any light-element contaminations such as H, O, and C. This led to reliable chemical stability of the films after exposure to air. Then, the microstructure and intrinsic stress of the hBN interlayer, which is necessary, was optimized to be able to bear the thick cBN top layer and the mechanical stresses occurring during tool operation. This was achieved by choosing the optimum bias voltages and bias pulse frequencies during deposition of the hBN interlayer, cBN nucleation, and the growth of the cBN top layer. Finally, growth and mechanical properties of cBN films are being investigated on a variety of tool materials including high-speed steel, cemented carbide, and TiN. Since the mechanical behavior and the interface properties are quite diverse for various tool materials, the interface engineering for the cBN coating has to be adapted for each material as well.

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Ion beam synthesis of nanostructures
for micro- and nanoelectronics

Bernd Schmidt, Karl-Heinz Heinig

If the dimensions of a solid shrink to a few nanometers, its properties change dramatically. Nanostructures can be two, one, or zero-dimensional objects corresponding to thin layers, wires, and tiny dots or precipitates. They can be fabricated by so-called top-down techniques using lithography or direct writing, as well as bottom-up processes involving self-organization, which are regarded as an attractive alternative. Ion-beam techniques represent a unique tool for the synthesis of nanostructures for electronic and photonic applications.

Ion beam synthesis of nanocrystals

An important goal of materials research using ion beams is to synthesize nanostructures, for example semiconducting or metallic nanocrystals in insulating films. Since ion beam synthesis of nanocrystals is compatible with complementary metal-oxide-semiconductor (CMOS) technology, great efforts are currently being exerted to apply this technique to micro- and nanoelectronic structures and devices.

One of the key challenges is to fabricate nanocrystals in the gate oxide of a transistor structure which can act as charge storing nodes for memory applications. These nanocrystals have to be small enough, should possess nearly identical size, and must be separated from the current-carrying channel by a few nanometers. Using the most straightforward method, we employed Si ions and implanted them at a relatively low energy (< 10 keV) into the SiO_2 gate oxide [1–4]. If the structure is annealed after implantation and the conditions are adequate, a phase separation occurs which means that Si nanocrystals are formed in the SiO_2 matrix. Fig. 1a shows a cross-sectional transmission electron microscopy (XTEM) image of the layer of phase separated Si in a 10 nm thick SiO_2 layer implanted with 1 keV Si^+ ions at a dose of $1x10^{16}$ Si^+ cm^{-2} [3]. When this experimental result is compared with an atomistic, three-dimensional kinetic lattice Monte Carlo (KLMC) simulation, the Si nanocrystals shown in Fig. 1b can be clearly identified.

Yet there is an alternative, more subtle way to fabricate Si nanocrystals in SiO_2 [2, 5] by irradiating the SiO_2 layer with energetic Si^+ ions (50-100 keV) of low fluences (10^{15}- 10^{16} cm^{-2}). As a consequence, the collision cascades cause substantial interface mixing of Si and SiO_2. Subsequent annealing restores the SiO_2/Si interface by phase separation. However, due to the finite diffusion length, the respective minority species in the tails of the interface mixing profile cannot reach the recovered interface. Thus, phase separation proceeds via nucleation and growth of nanocrystals. The competition between interface restoration and nucleation gives rise to an ultrathin layer of Si nanocrystals along the interface. This self-alignment process was first predicted by atomistic computer simulations, as shown in Fig. 2a. Fig. 2b displays an energy-filtered XTEM image of the MOS-like structure consisting of a polycrystalline layer of Si, a thin (15 nm) SiO_2 layer, and the Si substrate. The complete structure was irradiated with Si^+ ions (energy 50 keV, dose $7x10^{15}$ cm^{-2}). Both in the image and in the simulation, the nanocrystal layers are clearly visible. In collaboration with microelectronics industry, we have applied this method to fabricate non-volatile floating-gate memory devices [5]. The fabricated MOS transistors exhibit significant memory windows at low voltage programming conditions (programming voltage = ±6 V, programming time = 10 ms). The endurance of $>10^7$ write/erase cycles is excellent, but the data retention time is still too low for large-scale FLASH memory production. However, this fully CMOS-compatible fabrication process appears to be attractive for embedded nonvolatile memories.

Ion beam synthesis of nanowires

We directly fabricated electrically conductive nanowires with feature dimensions smaller than 100 nm using a writing process with a focused ion beam (FIB) and subsequent annealing. Such nanowires are very interesting for future nanodevices as well as for low-resistivity interconnect lines in highly integrated circuits.

We implanted a dose of $1x10^{17} cm^{-2}$ cobalt ions (Co^{++}) into (111) silicon substrates to directly synthesize metallic cobalt disilicide ($CoSi_2$) nanowires [6]. It turned out that the nanowire growth depends on the accuracy of FIB trace alignment relative to the Si crystallographic directions. When the FIB trace is aligned along a <110> direction, a continuous wire with a diameter of about 100 nm and a length of several µm is formed. This can be observed in the scanning electron microscope image shown in Fig. 3a. However, a small misalignment of a few degrees leads to the decay of the $CoSi_2$ nanowires into shorter parts. A larger deviation gives rise to the formation of a periodic chain of $CoSi_2$ nanoparticles (Fig. 3b). This behavior can be well explained by a Monte Carlo simulation shown in Fig. 3c for different crystallographic directions.

A lower implantation dose is expected to lead to even narrower wires, but in fact also results in reduced stability. Yet, we have discovered a method to circumvent this restriction: it is based on a self-organized process by FIB induced defects in a substrate which is super-saturated with cobalt [6]. With this method, we were able to synthesize wires as narrow as 20 nm. The physical mechanism is related to capillary forces which have also been shown to play a role in plasmon lithography [7]. The above research was supported by the German Research Foundation (DFG) within the priority program "Nanowires and Nanotubes" and by the European Commission in the FP5 GROWTH program, amongst others.

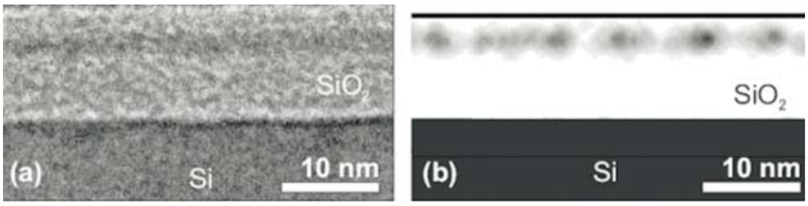

Fig. 1: Cross-section view of the layer of phase separated Si in SiO_2. **(a)** XTEM image for 1 keV Si^+ implanted SiO_2 at $1x10^{16}$ Si^+ cm^{-2} compared to **(b)** a cross-sectional kinetic lattice Monte Carlo (KLMC) simulation snapshot for $3x10^{15}$ Si^+ cm^{-2}.

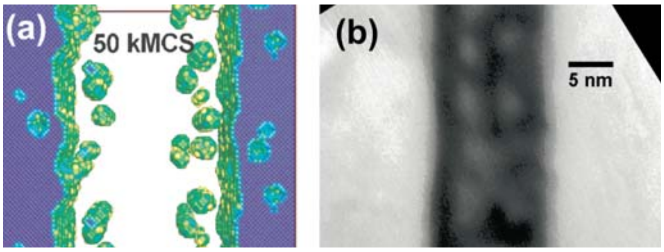

Fig. 2: Si^+ ion irradiation through a layer stack of 50 nm poly-Si, 15 nm SiO_2, into the Si substrate and subsequent annealing. **(a)** KLMC simulation snapshot referring to the stage of phase separation. **(b)** Energy-filtered XTEM image of the MOS-like $Si/SiO_2/Si$ structure referring to the state after Si^+ ion irradiation and post-irradiation annealing (energy = 50 keV, dose = $7x10^{15}$ cm^{-2}, T = 1050 °C, t = 120 s).

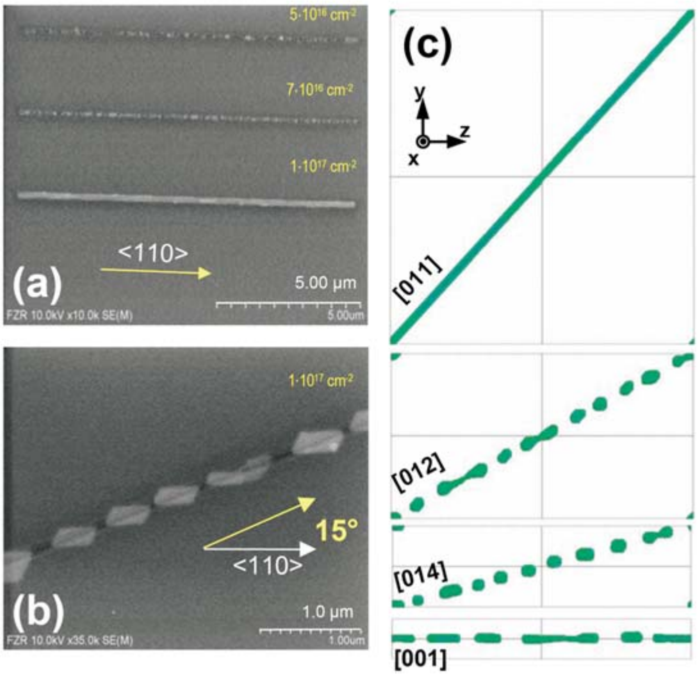

Fig. 3: $CoSi_2$ nanowires in (111) Si: **(a)** nanowire formation for different implanted Co^{++} fluences, FIB trace aligned in <110>-direction, and **(b)** with a misalignment angle of about 15° (Co^{++} FIB implantation dose was $1x10^{17}$ cm^{-2}). **(c)** Results of KLMC simulations of $CoSi_2$ nanowire growth and decay for different crystallographic directions in the Si crystal.

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Silicon based light emitters –
from infrared to ultraviolet

Ph.D. student Jarka Potfajova checking wafers for her research.

Wolfgang Skorupa, Lars Rebohle,
Manfred Helm

Combining silicon-based electronic circuits with optoelectronic functionality is one of the key challenges for the future of semiconductor technology. As the packaging density of transistors becomes higher and higher in ultra-large-scale integrated (ULSI) circuits, the total length of metallic interconnects also increases. This creates severe problems such as overheating and signal delay. One possible solution might be optical interconnects integrated with silicon (Si) technology. The implementation of silicon-based optical interconnections requires waveguides, modulators and photodetectors, as well as light emitters. Unfortunately, silicon is poorly suited to operate as a light emitter due to its indirect band gap of about 1.1 eV. However, the observation of red luminescence from porous Si in 1990 has triggered intense worldwide research activities focused on Si-based light emission. Since then, various approaches have been followed, some of which related to Si (or Ge) nanoclusters in SiO_2. In this context it has been demonstrated that ion beam processing of silicon and silicon dioxide can play an important role in the technology of silicon-based light emitters. For example, in 1997 we demonstrated strong electroluminescence (EL) in the blue-violet spectral region from Ge-implanted SiO_2 layers [1].

Rare-earth-based MOS light-emitting diodes

One promising approach is based on rare-earth ions incorporated into the SiO_2 layer of a metal-oxide-semiconductor (MOS) structure as depicted in Fig. 1. Rare-earth (RE) elements are known to exhibit strong

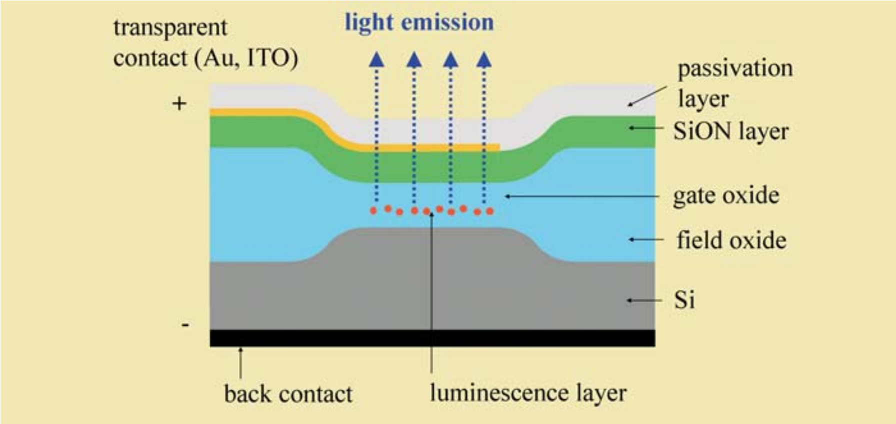

Fig. 1: Scheme of a rare-earth-doped MOS light-emitting structure.

and sharp luminescence lines related to transitions between levels within the unfilled 4f shell. The most famous and widely used example is trivalent erbium (Er^{3+}), which is commonly employed for fiber amplifiers operating in the telecommunication band at 1.54 µm. Other RE ions, due to their different energy level structure, can generate different wavelengths throughout the spectrum from the infrared (IR) to the ultraviolet (UV). These ions can be conveniently incorporated into the SiO_2 matrix by means of ion implantation. When applying a bias between the gate and the substrate of the MOS structure, the RE ions are impact-excited by hot electrons, which are accelerated in the SiO_2 conduction band by the high electric field after Fowler-Nordheim tunneling through the oxide barrier.

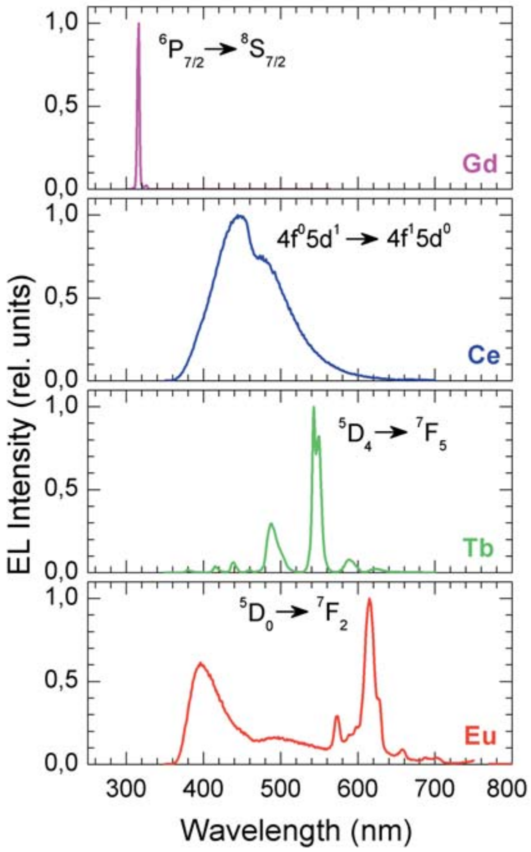

Fig. 2: Electroluminescence spectra from various rare-earth-implanted MOS devices. The transitions of the main emission lines are given in the diagrams.

In Fig. 2, electroluminescence spectra of MOS devices doped with different rare-earth elements are shown. Emitter structures doped with gadolinium (Gd, top panel) are quite remarkable since they exhibit a single, sharp emission line at a UV wavelength as short as 316 nm [2]. This spectral range cannot be reached easily by other semiconductor devices and may be relevant for exciting fluorescence in biosensing applications.

Terbium (Tb), which emits intense green light mainly at a wavelength of 541 nm [3], is the element among the rare earths with the highest external quantum efficiency of up to 15 %. Since this wavelength also matches the peak sensitivity of the human eye it could be applied for micro-displays. We also investigated the interaction of different RE elements implanted in the same oxide layer. If the emission band of one element matches the absorption band of the other, the EL intensity of the latter can be strongly increased. This is caused by a resonant energy transfer from one rare earth to the other. This phenomenon was demonstrated with cerium (Ce) implanted layers co-doped with Gd, where the excited Gd ions transfer their energy to the Ce ions [4]. The spectrum of a Ce-doped SiO_2 structure is also shown in Fig. 2, where the broad blue emission band is immediately noticeable. This stands in contrast to the sharp emission lines of the other RE elements. This is owed to the fact that the blue Ce luminescence does not derive from a 4f intra-shell but rather from an inter-configurational 5d-4f transition.

A very interesting phenomenon is observed with europium (Eu)-doped structures. While most rare earths occur in the RE^{3+} oxidation state when incorporated into a matrix, Eu exists in both the Eu^{3+} and Eu^{2+} state. While the former shows a red intra-4f luminescence, the latter gives rise to blue 5d-4f emission. Both are observed in our EL spectrum as seen in the bottom panel of Fig. 2. We have recently shown that the relative strength of the emission bands, and thus the color of the emitted light, changes with the excitation current. Hence, we have constructed a switchable multi-color light emitter [5].

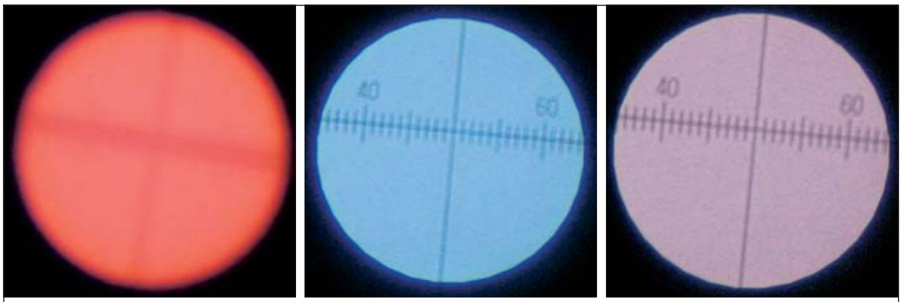

Fig. 3: Photographs of light-emitting SiO_2:Eu MOS devices with 200 µm diameter. The injection current was 20 µA **(a)**, 1 mA **(b)** and 2.5 mA **(c)**, respectively.

Fig. 3 shows the same device when excited with various currents: it appears red at low and blue at higher currents. At the highest current level, the color changes to violet again. This behavior can be tentatively explained by the variation of excitation efficiency upon changing the current and the electric field across the device.

Applications and other approaches

Light sources for optical interconnects are needed most urgently in the microelectronics industry. However, they must achieve stringent power consumption requirements which presently cannot be fulfilled by the devices discussed above. Yet other applications can be envisaged which could complement the use of LEDs based on common III-V semiconductors or organic materials. This is due to the various advantages shown by the RE-doped MOS emitters. They can be integrated well into common Si technology and electronics and both their size and design can be scaled according to specific needs. Last but not least, these light sources are inexpensive to mass produce. Due to these advantages, this type of light source is suitable for fluorescence analysis in sensor systems, especially for microarrays. In this case, a light emitter entirely encapsulated in SiO_2, is placed directly under the biological specimen to be investigated which contains dye-labeled analytes. The dye luminescence is then detected by a CCD camera or by a Si detector. This approach avoids the need for a separate excitation laser. Such a biosensing system is especially interesting for point-of-care applications.

The doping with rare-earth ions just described constitutes but one of the many possible variants for achieving efficient Si-based light emitters. It is important to mention that in SiO_2, layers which contain both nanoclusters and RE ions, the nanoclusters can act as sensitizers to enhance the rare-earth emission [6]. This is true in particular for Er^{3+} ions. Furthermore, not only can MOS structures be turned into light emitters, but also Si pn junctions heavily doped with boron (B) exhibit strong EL near the bandgap of Si—even at room temperature [7].

To conclude, silicon photonics, particularly with regard to efficient light emitters, is still a rapidly evolving field. The long-term goal of an electrically pumped silicon laser may remain elusive, but many new developments such as “photonic-bandgap engineering” may pave the way for viable Si-based photonic devices.

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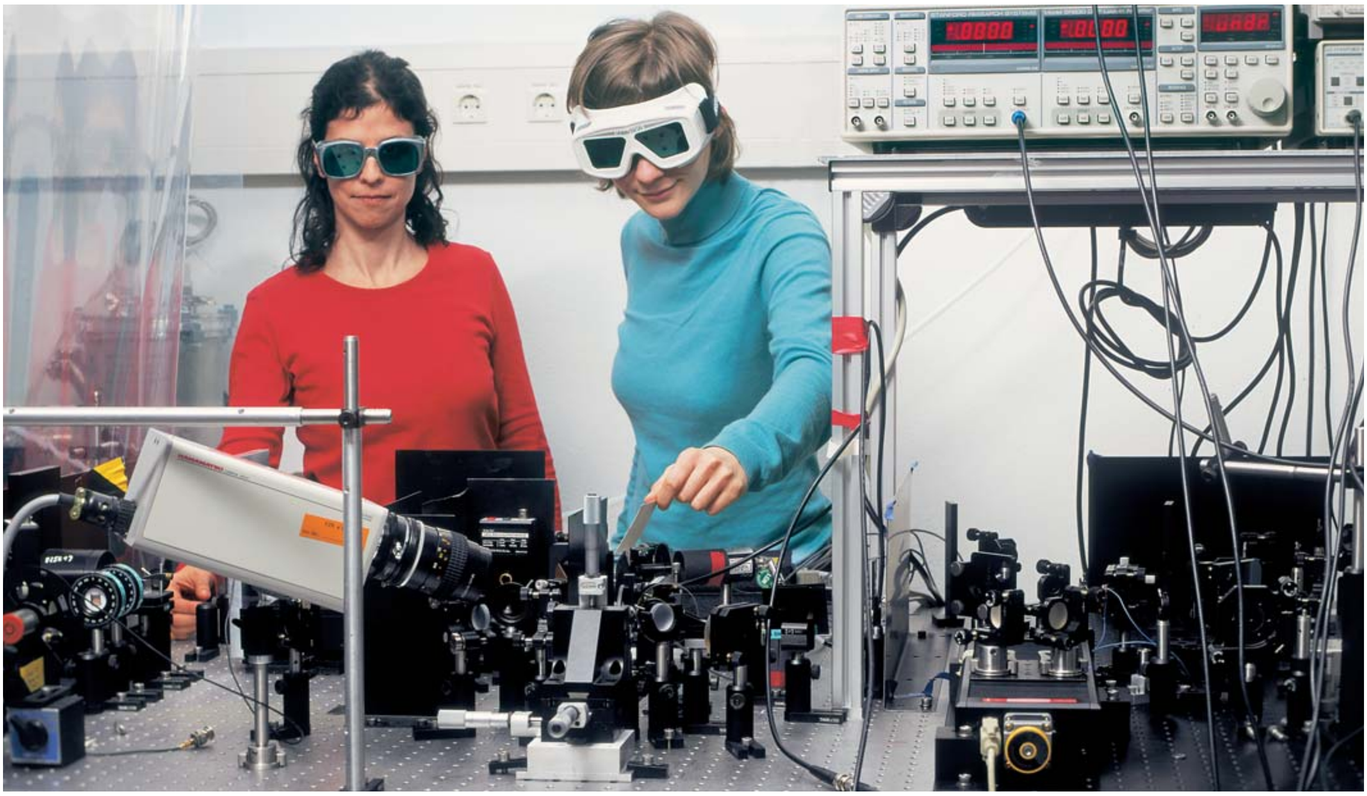
Ultrafast infrared spectroscopy of semiconductor quantum structures



Christiana Villas-Boas Grimm and Sabine Ohser in an optical laboratory.

Harald Schneider

Today's epitaxial-growth and nano-fabrication technologies enable us to realize semiconductor quantum structures with custom-designed optoelectronic properties. Quantum wells (QW) and superlattices, the conduction and valence bands of which are split by quantum mechanical confinement into two-dimensional subbands and minibands, respectively, are the most prominent examples for such band-gap engineered materials. While the QW laser, relying on electron-hole transitions between conduction and valence subbands, has already penetrated the visible and near-infrared optoelectronics market, unipolar devices for the mid-infrared spectral range have become available in commercial terms within the last decade. In particular, quantum cascade lasers (QCL) [1] and quantum-well infrared photodetectors (QWIP) [2] have performed well in applications such as thermal imaging, gas sensing, environmental sensing, quality control, and nondestructive testing. Major research efforts are advancing the technological standards towards mature quantum-wire and quantum-dot materials and are aiming at new applications, e.g., in the Terahertz (THz) region as well.

Because transitions between sublevels within the conduction (or valence) band generally occur on a picosecond to femtosecond time scale, any direct experimental access to their dynamic behavior requires "ultrafast" spectroscopic techniques in order to achieve sufficient time resolution. In this respect, the free-electron laser (FEL) located at the Radiation Source ELBE at the Forschungszentrum Dresden-Rossendorf, which can also be combined with synchronized near-IR tabletop lasers, provides valuable opportunities for ps spectroscopy in the mid-infrared and THz regions.

Intersubband relaxation dynamics at high transition energies

The InGaAs/AlAsSb material system, which is lattice matched to InP substrates, exhibits a conduction band offset as large as 1.6 eV and thus is promising for short-wavelength QCLs below 3.5 µm. A limiting factor arises from low-lying indirect-valley states (X and L) both in the QWs and barriers (AlAsSb is an indirect material), since intervalley scattering causes losses in short-wavelength QCLs. However, very recent work has demonstrated that lasing can still be achieved in InGaAs/AlAsSb at around 3 µm, where the upper laser level lies above some indirect minima [3].

We have conducted a pump-probe investigation of intersubband relaxation in doped narrow $\mathrm{In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}}$ multiple quantum wells with different thicknesses, ranging from 2.9 to 4 nm. These multiple quantum wells were grown by molecular beam epitaxy and were lattice matched to InP substrates [4]. A high-repetition-rate (78 MHz) optical parametric oscillator, tunable from 1.1 to 3.3 µm with a pulse length of 280 fs was used for the measurements. The extremely high signal-to-noise ratio enabled us to analyze the decay dynamics in detail.

In a well-doped 3 nm quantum well in which the second subband lies above the InGaAs X-minimum, intervalley transfer induces a non-exponential decay which can be very well reproduced by the two exponentials of 1.5 ps and 6.2 ps (Fig. 1). Analyzing this behavior with three-level rate equations (see inset), we assigned $\tau = 1.5$ ps as the combined decay rate from the upper subband to the lower one and to the X-state $(1/\tau = 1/\tau_{21} + 1/\tau_{2X})$. The slow component (6.2 ps) corresponds with the return time τ_{X1} from the X-level to the ground state. This suggests that the intervalley transfer time τ_{2X} is much longer (≥ 2 ps) than is known from bulk materials. It implies that population inversion in a QCL can persist, which explains how QCLs function at wavelengths as short as 3 µm.

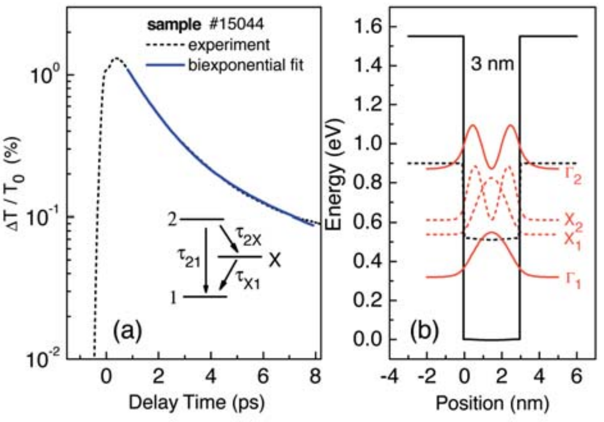


Fig. 1: (a) Probe transmission of a 3 nm InGaAs/AlAsSb multiple quantum well vs. delay time together with exponential fits of the decay curves. The inset displays the suggested relaxation path. **(b)** Band-edge profile at the Γ- (solid) and X-point (dashed) and probability densities (red curves) for the subband states.

Quadratic autocorrelation of FEL pulses using two-photon QWIPs

The two-photon QWIP comprises three equidistant subbands, two of which are bound in the QW and the third of which is located in the continuum (Fig. 2(a), inset). The intermediate subband causes a resonantly enhanced optical nonlinearity which is by about six orders of magnitude stronger than in bulk materials. The two-photon QWIP is used for quadratic detection of mid-infrared radiation. Here, time resolution is only limited by the sub-ps intrinsic time constants of the transition itself, namely the intersubband relaxation time and the dephasing time of the intersubband polarization [2]. These properties make two-photon QWIPs very promising for pulse diagnostics of mid-infrared lasers.

In a cooperation with the Fraunhofer Institut für Angewandte Festkörperphysik in Freiburg, we measured autocorrelation of ps optical pulses from the FEL at ELBE. For this purpose, a rapid-scan autocorrelation scheme at a scan frequency of 20 Hz was used [5]. As an example, Fig. 2 shows high-quality quadratic autocorrelation

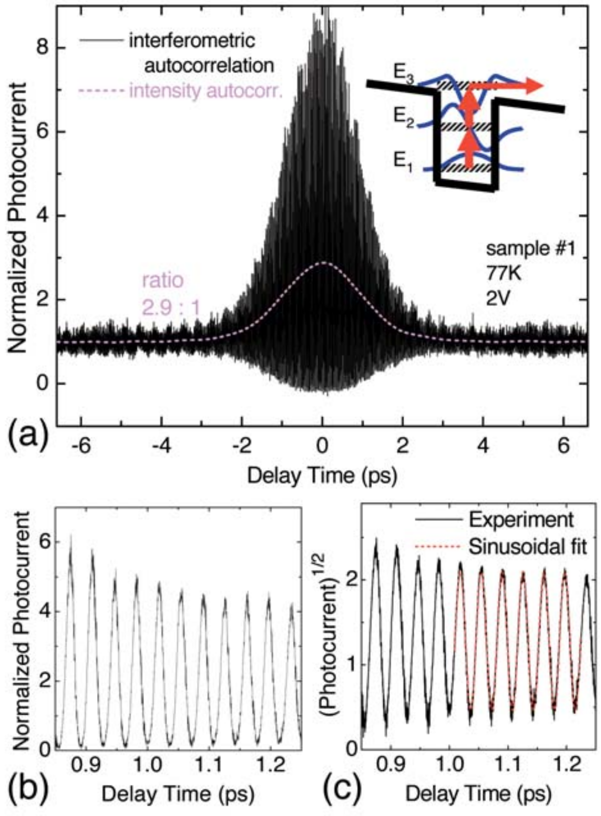


Fig. 2: (a) Interferometric and intensity autocorrelation of a two-photon quantum-well infrared photodetector at 10.4 µm FEL wavelength and 1.3 kW/cm^2 peak power density, **(b)** autocorrelation fringes, and **(c)** square root of the signal with sinusoidal fit. The inset of **(a)** indicates the operation of the device.

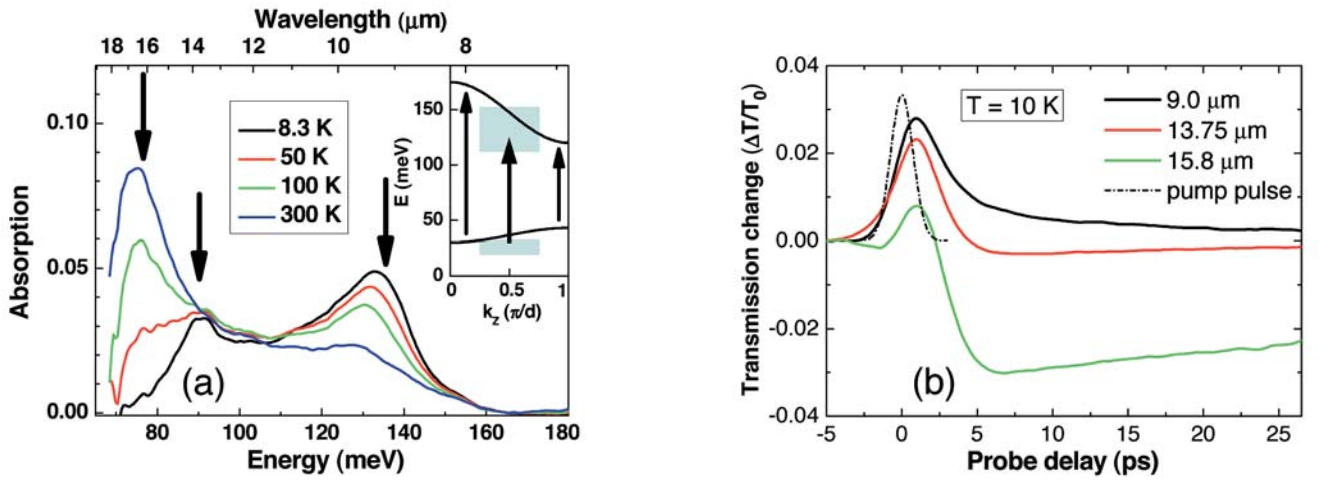


Fig. 3: (a) Interminiband absorption spectra of the superlattice at different temperatures. The inset illustrates the interminiband and impurity transitions, arrows indicate the excitation wavelengths.

(b) Probe transmission vs. pump-probe delay at T = 10 K for different wavelengths. The temporal pulse shape is indicated by the dashed line.

traces for both interferometric and intensity autocorrelation. They were obtained by using 7.6 nm wide GaAs quantum wells sandwiched between $Al_{0.33}Ga_{0.67}As$ barriers, and measured during one single scan within only 25 ms. Two-photon QWIPs thus provide an excellent approach for online pulse monitoring of the FEL.
In addition, we have investigated the saturation mechanism of the photocurrent signal which is due to internal space charges generated in the detector.

Interminiband relaxation and electron cooling in semiconductor superlattices

Superlattices, often used as a model system in semiconductor physics, can be applied as building blocks for Bloch oscillators and certain types of QCLs. We have investigated the relaxation dynamics of electrons in superlattice minibands [6]. A key property is the energy dispersion $E(k_z)$ along the growth axis (inset of Fig. 3(a)), giving rise to a spectrally extended interminiband absorption which also allows us to extract information on the electronic distribution function. Fig. 3(a) shows the interminiband absorption spectrum of a slightly doped (1.5×10^{16} cm^{-3}) GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice (well width 9 nm, barrier width 2.5 nm) for various temperatures. The spectral features result from the singularities at the center and the edge of the mini-Brillouin zone and from an impurity transition [7], respectively. The spectrum is changed due to thermal occupation of the bottom miniband.

We use the free-electron laser (FEL) at ELBE, providing ~2 ps mid-infrared pulses of up to 2 μJ energy at a 13 MHz repetition rate, for pump-probe measurements. Fig. 3(b) shows results for three different wavelengths. The fast positive part (increased transmission) is caused by bleaching and subsequent interminiband relaxation and thermalization at an electron temperature above the lattice temperature. The second, slower component is associated with the temperature of the electron distribution which cools down to lattice temperature. Consistent with the temperature dependence of the linear absorption, this latter component can be positive or negative. Temperature increases can either lead to a rise in transmission (at 9 μm wavelength) or to decreased transmission (at 15.8 μm). In this way, the experiment provides an intrinsic picosecond thermometer for the electron system in the superlattice.

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[6] Institut für Technische Physik I, Universität Erlangen, Germany

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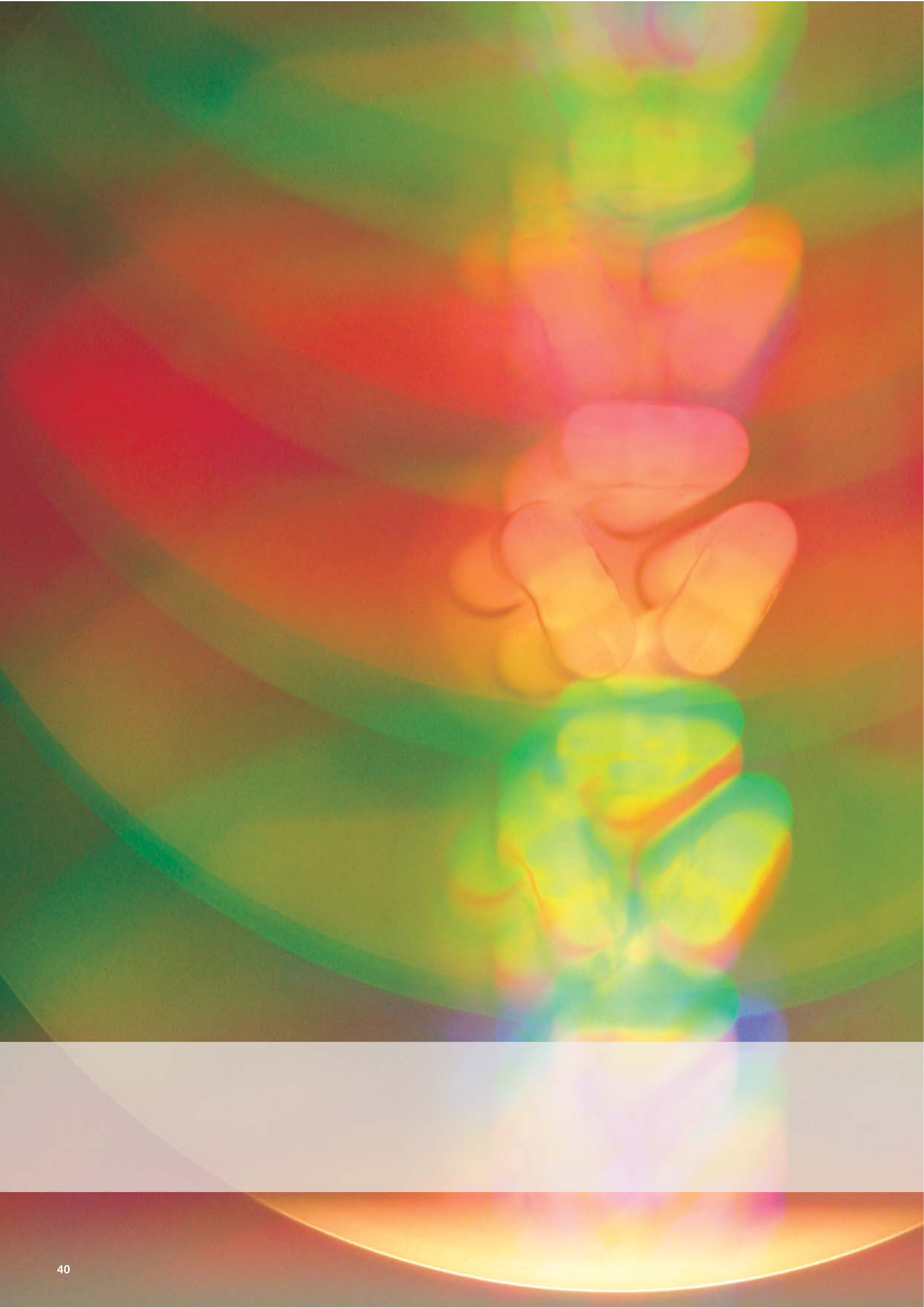
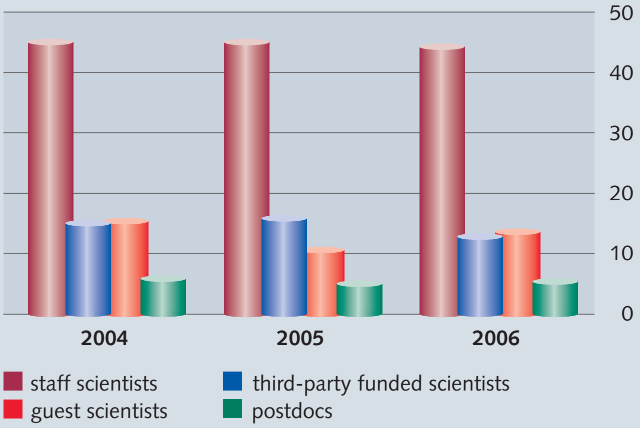


Facts & Figures

The Forschungszentrum Dresden-Rossendorf (FZD) is a multi-disciplinary research center for natural sciences and technology. It is the largest institute of the Leibniz Association and is equally funded by the Federal Republic of Germany and the Federal States, in particular by the Free State of Saxony. At the FZD, around 225 scientists are engaged in three different research programs of basic and application-oriented research. Scientists working in the Structure of Matter program investigate the reactions of matter when influenced by high fields and minuscule dimensions. Research and development in the Life Sciences program is focused on the imaging of tumors and the effective radiation treatment of cancer. How can humankind and the environment be protected from technical risks? – This question is in the center of research in the Environment and Safety program of the FZD.

In the following Facts & Figures section data presenting the scientific output in the Structure of Matter research program are given as well as information on staff and funding at the FZD.

Scientific staff

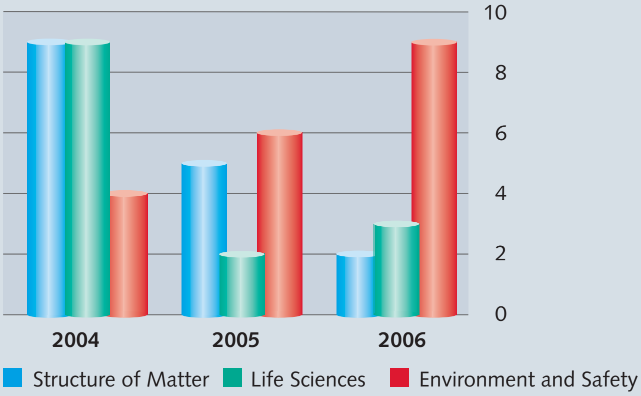


This chart shows the evolution of posts occupied by scientific personnel in the Structure of Matter program of the FZD. Third-party funded scientists, guest scientists, and postdocs represented by the corresponding figures are given in units of paid full-time posts.

Budget	2004		2005		2006	
Research Programs	Public Funding T€	Project Funding T€	Public Funding T€	Project Funding T€	Public Funding T€	Project Funding T€
Structure of Matter	**13.858**	**1.190**	**14.209**	**1.259**	**19.575**	**1.405**
Life Sciences	8.241	801	6.266	645	8.191	784
Environment and Safety	13.005	3.180	12.950	3.656	11.866	3.990
Facilities	20.721	911	20.428	756	17.988	1.643
Sum	55.825	6.082	53.853	6.316	57.620	7.822

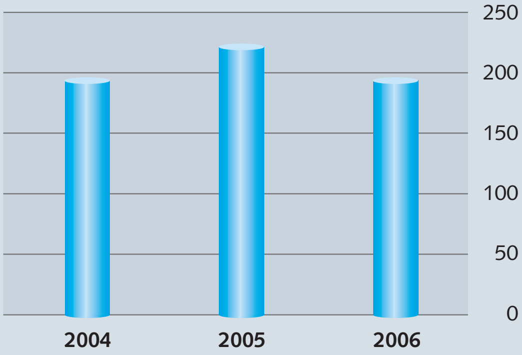
This table displays the share of each research program as well as the experimental facilities located at the FZD of both public and project funding during the last three years.

Patents



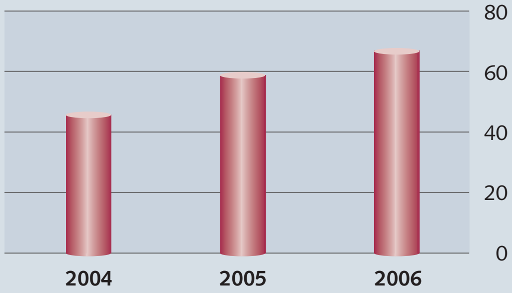
This figure shows the number of applications for a patent filed in each research program of the FZD during the last years. National and international applications for a patent of one and the same invention are only counted once.

Publications



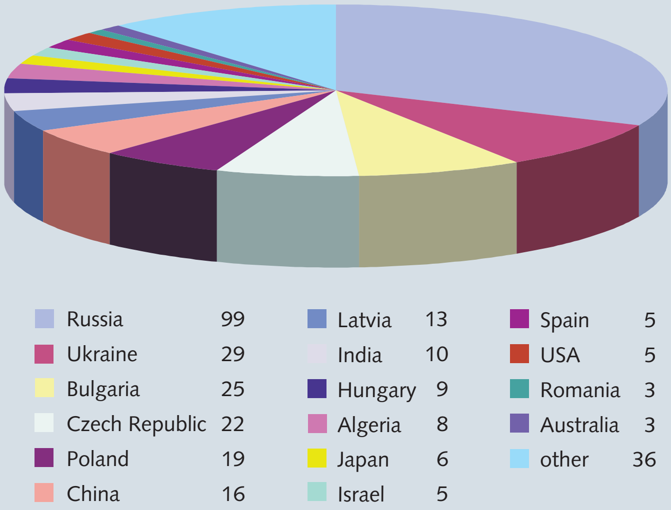
This chart displays the evolution of peer-reviewed articles by scientists from the FZD's Structure of Matter program.

Doctoral students



This figure shows the evolution of the doctoral students at the FZD from 2004 until 2006, which continues the rise of doctoral candidates in the previous years.

International guest scientists



Here, the distribution of the international guest scientists who visited the FZD for the purpose of research between 2004 and 2006 is shown according to their countries of origin.

Organizational Chart

General Assembly

Supervisory Board

Chairman: Dr. Gerd Uhlmann
Deputy: Dr. Jan Grapentin

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Scientific Technical Council
Chair: Prof. Frank-Peter Weiß

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Scientific Director	Administrative Director
Prof. Roland Sauerbrey	Dr. Dr. h. c. Peter Joehnk

Works Committee
Chair: Siegfried Dienel

Support Staff

Structure of Matter

Dresden High Magnetic Field Laboratory
Prof. Joachim Wosnitza

Institute of **Ion Beam Physics and Materials Research**
Prof. W. Möller and Prof. M. Helm

Life Sciences

Institute of **Radiopharmacy**
Prof. Jörg Steinbach

Institute of **Radiation Physics**
N.N.

Laser-Particle Acceleration
Dr. Ulrich Schramm

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Institute of **Safety Research**
Prof. Frank-Peter Weiß

Institute of **Radiochemistry**
Prof. Gert Bernhard

Research Technology
Dr. Frank Herbrand

Technical Service
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Administration
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Volume 3	Life Sciences

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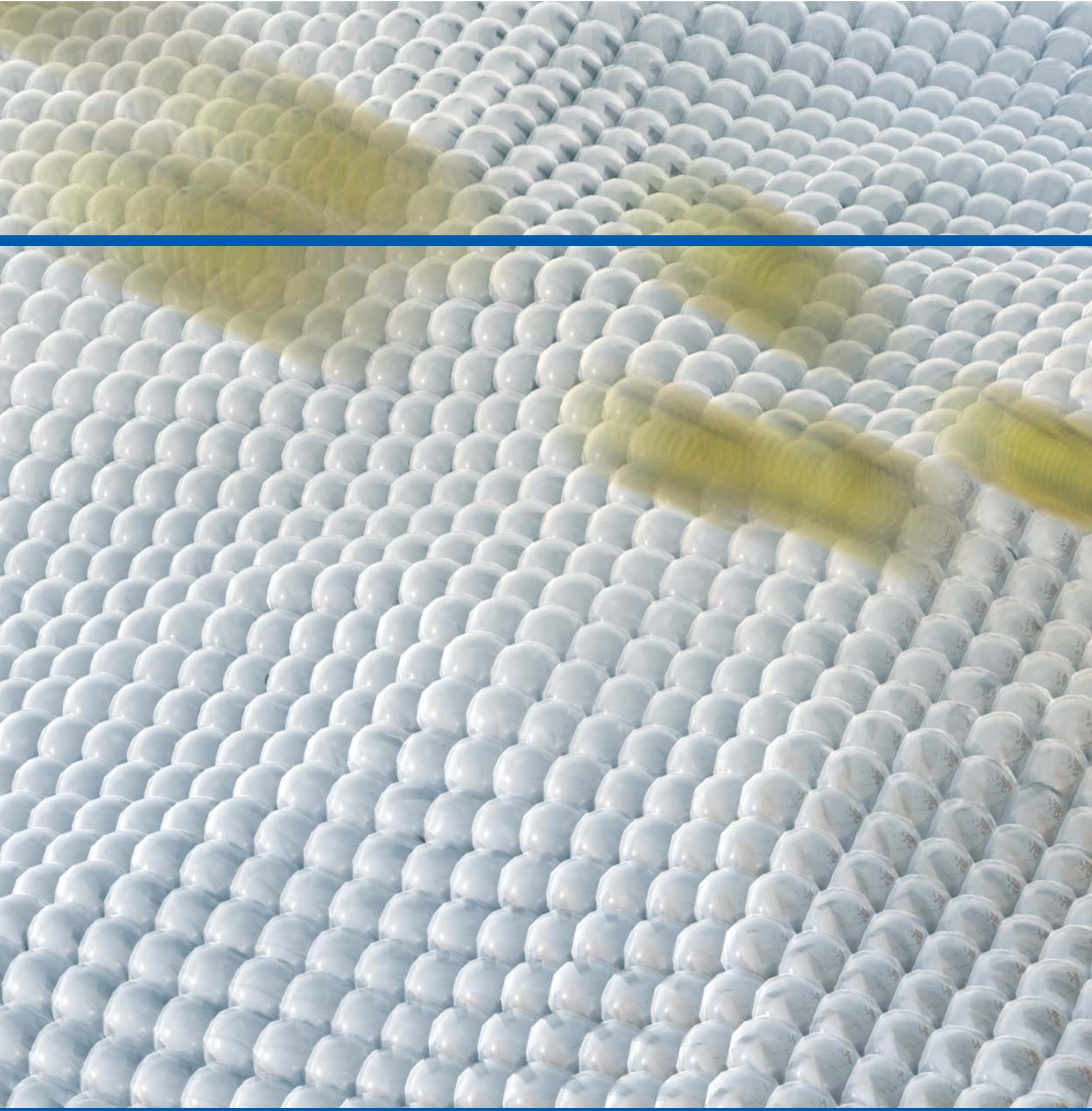

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