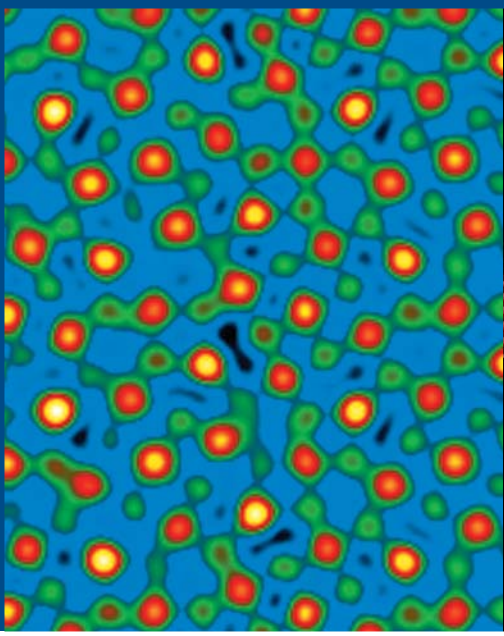
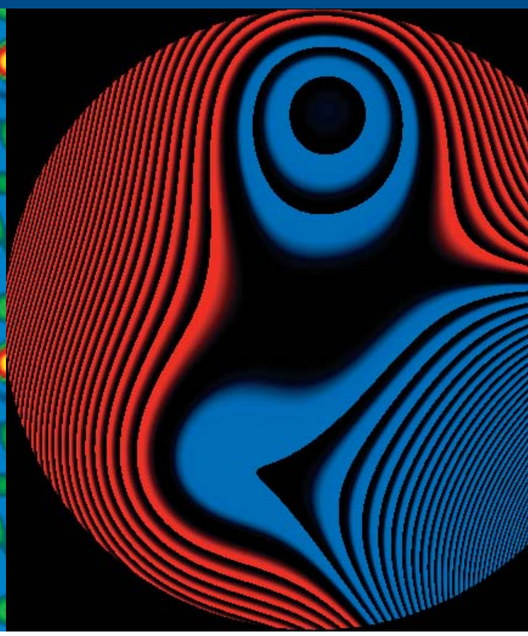
Ernst Ruska-Centre

Microscopy and Spectroscopy with Electrons





RWTH AACHEN UNIVERSITY

JÜLICH FORSCHUNGSZENTRUM

Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons

ER-C

At a glance

Operators	Forschungszentrum Jülich and RWTH Aachen University
Mission	The Ernst Ruska-Centre (ER-C) means that Forschungszentrum Jülich and RWTH Aachen University operate a centre of excellence for atomic-resolution electron microscopy and spectroscopy on the highest international level. ER-C develops scientific infrastructure and advanced methods for present and future materials research. ER-C is at the same time the first national user centre for ultrahigh-resolution electron microscopy. It provides researchers from science and industry with access to the most powerful electron microscopes currently available and guarantees competent support.
Named after	Ernst Ruska (1906 – 1988), Nobel laureate for physics and developer of the first electron microscope
Founded	27 January 2004
Location	Forschungszentrum Jülich
Directors	Professor Dr Knut Urban, Forschungszentrum Jülich Professor Dr Joachim Mayer, RWTH Aachen University
User quota	50 % operators and 50 % external users from universities, research institutions and industry
Allocation of measuring time	According to scientific criteria by a panel of reviewers appointed by the German Research Foundation (DFG). Details – also on how to submit a proposal – can be found in the separate user rules and fee table.
Equipment	High-performance electron microscopes of the Titan 80-300 class permitting a spatial resolution of 80 picometres and an energy resolution of 0.1 electronvolts; facilities for data analysis and sample preparation such as focused ion beam and low-voltage ion milling facilities; conventional transmission and scanning electron microscopes for preliminary investigations of specimen quality
Research priorities	Together with its cooperation partners, ER-C is concerned with providing a basis for the further development of electron optics with respect to methodology and application thus creating the necessary conditions for innovation in other branches of technology. In-house research programmes concentrate on the physics of condensed matter and on materials for information technology and nanotechnology.
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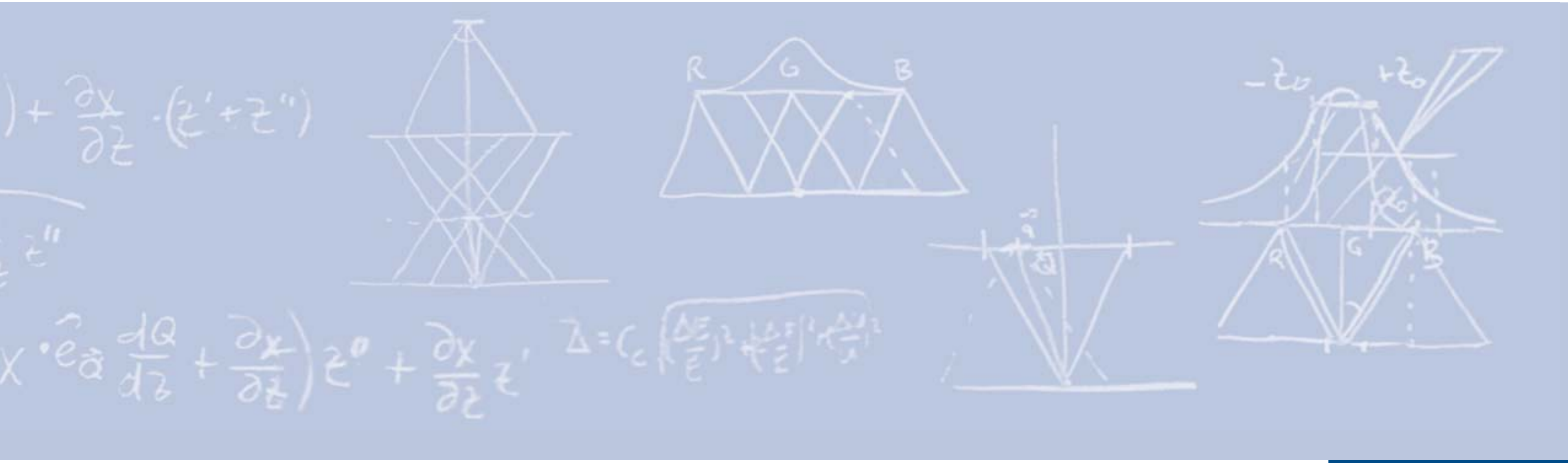

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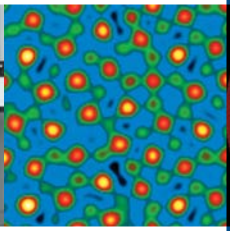
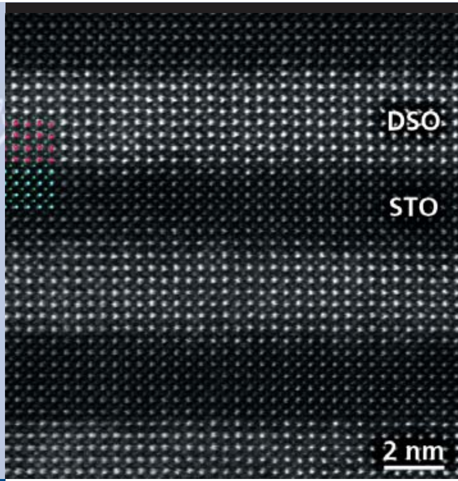
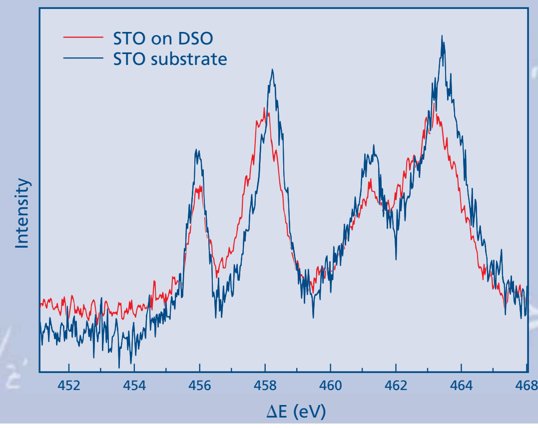


Left: Ultrahigh resolution electron microscope of the “Titan 80-300” class.

Centre: Lattice representation of the complex oxide $Ca_{0.28}Ba_{0.72}Nb_2O_6$ (CBN-28). The green circles correspond to the oxygen atoms.

Right: Phase plate measured by means of the ATLAS software (p. 11) while fine-tuning an aberration-corrected electron microscope.





Prefaces

From nanotechnology to new materials, from energy technology to memory chips – innovations in all fields require the ability to obtain well-focused insights into the atomic world since the interaction of individual atoms determines the properties of materials and components.

With the Ernst Ruska-Centre (ER-C) founded in 2004, Forschungszentrum Jülich and RWTH Aachen University operate a centre of excellence for atomic-resolution electron microscopy and spectroscopy on the highest international level. ER-C develops scientific and technical infrastructure and methods for present and future materials research. ER-C is at the same time the first national user centre for high-resolution electron microscopy. At ER-C we provide researchers from science and industry with access to the most powerful electron microscopes currently available.

Investigations using the highest resolution, below 80 picometres, and the highest precision, less than a few picometres, enable scientists to study materials – atomic position by atomic position. The high-precision optics required for this purpose was developed in the 1990s together with scientists at the European Molecular Biology Laboratory (EMBL) in Heidelberg and Darmstadt University of Technology. The aberration-corrected electron optics realised for the first time at Jülich in cooperation with the partners in Heidelberg and Darmstadt has been very successfully applied in industry. Starting in about 2004, all four of the world's largest electron optics companies have launched a completely new generation of instruments onto the market based on this technology. Demand is so great that the companies have long delivery times.

Our Jülich and Aachen scientists at the Ernst Ruska-Centre have thus succeeded in retrieving for European industry the initiative in electron optics that, as in other fields of technology, had been lost to the Far East.

From 2010, in its new building, ER-C will be able to put into operation a unique ultrahigh-performance electron microscope. The funding for the so-called PICO project, costing € 15 million, is divided between the federal state of North Rhine-Westphalia, the Federal Ministry of Education and Research, and the German Research Foundation. The new equipment means that the Ernst Ruska-Centre will continue to operate at the forefront of ultrahigh-resolution electron microscopy.

Professor Dr Achim Bachem, Chairman of the Board of Directors of Forschungszentrum Jülich

In multilayer systems of complex oxides, lattice strains can be used to increase the polarisability of materials. Left: Chemically sensitive "Z contrast" representation of a layer system of dysprosium scandate (DSO) and strontium titanate (STO). Right: The characteristic energy loss ΔE of the L edge excitation of the titanium displays a chemical shift in the strontium titanate within the layer system which is associated with a distortion of the titanium-oxygen bonds.

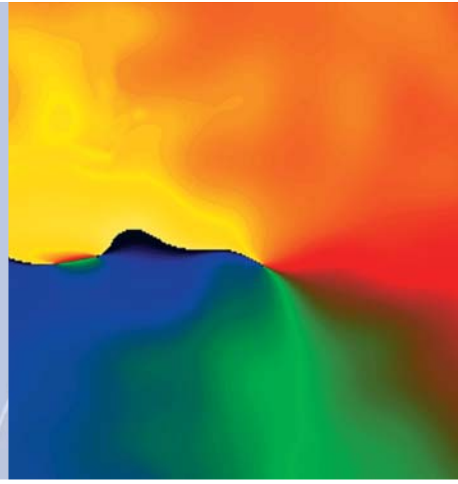
The basis for new knowledge, and thus a necessary prerequisite for progress in the sciences, is the development of new research tools. The Ernst Ruska-Centre represents a particularly productive collaboration between RWTH Aachen University and Forschungszentrum Jülich in this field.

Microscopy symbolises the dawn of modern science. Since the early 17th century, scientists have made use of microscopes to make visible what was until then inaccessible to the human eye. The Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons represents a further development of these "imaging" scientific instruments.

Today, it is even possible to resolve atomic structures. However, the technical efforts required and the skills of the laboratory technicians have increased by several orders of magnitude. For example, in order to analyse the structure of a human hair in a transmission electron microscope, the hair must first be cut into thin sections thousands of times thinner than the hair itself. Such demands on the staff and instrument can only be fulfilled and the resources use meaningfully if large research institutions combine their efforts in joint facilities.

ER-C thus represents a collaboration between Forschungszentrum Jülich and RWTH Aachen University. This cooperation takes a variety of forms. Apart from special collaborative programmes and transfer projects, the "Aachen Institute for Advanced Study in Computational Engineering Science" and the "German Research School for Simulation Science" have also been established. The partnership between Forschungszentrum Jülich and RWTH Aachen University has been placed on a new basis by the creation of JARA – the Jülich Aachen Research Alliance. The aim of this close collaboration is to establish high levels of performance in large interdisciplinary research fields. After all, only by means of interinstitutional forms of organisation is it possible to address the grand research challenges of our time. The ER-C represents a significant component in this endeavour.

Professor Dr Ernst Schmachtenberg, Rector of RWTH Aachen University



The Ernst Ruska-Centre:

Ultrahigh-resolution electron microscopy has a wide range of scientific applications. The interplay of the atoms determines the properties of materials and components. An understanding of the fundamental phenomena and processes is a decisive basis for developing novel combinations of materials for applications ranging from nanotechnology and microelectronics to energy technology. Selected findings from ER-C research projects can be found at the top of each double-page spread in this brochure.

The rapid development in the field of information and communications technologies, for example, is based on the progressive miniaturisation of the components. In computer chips of the next generation there will be structures that are smaller than 45 nanometres. This corresponds to roughly 200 silicon atoms in a row. Decisive factors for understanding the functional mechanisms of structures that are becoming increasingly smaller are powerful microscopes and instruments which reveal the physical properties of the nanoworld. International efforts at establishing new research areas in the world of nanodimensions and thus deriving innovative applications lead directly to atomistic concepts. Nanophysics, nanoelectronics and nanotechnology mean synthesis and production in quasi-atomic dimensions.

With the aid of ultrahigh-resolution electron microscopy, researchers at ER-C seek new materials which will facilitate the construction of zero-emission power plants.

Innovative nanomaterials must be understood on a scale that is continuously being reduced in size since each atomic fault and each distortion of the atomic arrangement can influence the properties of individual components. In order to investigate these phenomena and to develop high-performance materials, ultrahigh-resolution microscopic techniques are required permitting nanoscale systems to be precisely controlled in atomic dimensions.

Cooperation between Forschungszentrum Jülich and RWTH Aachen University

With the establishment of the Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons. Forschungszentrum Jülich and RWTH Aachen University have created an excellent basis for identifying future demands on atomic-resolution electron microscopy as early as possible and thus for making a decisive contribution at the cutting edge of developments in instruments and methodology.

Located in Jülich, ER-C was founded in January 2004 as the first national centre of excellence for methodological developments and applications in high-resolution electron microscopy and spectroscopy and was officially opened in May 2006. A foundation agreement defines

Gallium arsenide (GaAs) is used for high-frequency applications and for the conversion of electrical into optical signals. Left: The high-resolution micrograph of GaAs (magnified 16.3 million times) was produced at ER-C with the first aberration-corrected transmission electron microscope worldwide and shows an extrinsic stacking fault which in an electronic device would lead to a short circuit on the atomic level. Right: Quantitative analysis of the underlying lattice distortions.

cooperation between the equal partners – Forschungszentrum Jülich and RWTH Aachen University.

The institutes involved – the Institute of Solid State Research in Jülich and the Central Facility for Electron Microscopy of RWTH Aachen University – ensure the scientific and technical competence of the Centre. Even before the foundation of ER-C, both institutions had extensive electron microscopy resources. Furthermore, one of the few theoretical groups worldwide working in the field of electron optics can be found in the Jülich institute. With the goal of exploring the ultimate limits of electron microscopy imaging techniques, this award-winning group takes on a key function in international competition in basic research and the electron optics industry.

50 percent external users

The close collaboration between ER-C and the German Research Foundation (DFG) ensures that the Centre is oriented both to university requirements and also practical applications. DFG was already involved in the discussions on establishing ER-C, it is represented on the board of trustees and it also funded one of the two ultra-high performance microscopes at ER-C.

In consultation with DFG, it was laid down that 50 percent of user time should be reserved for universities, research institutions and industry. This time will be allocated by a panel of experts appointed by DFG after examining the quality of the applications. The remaining time is divided between RWTH Aachen University and Forschungszentrum Jülich.

With the operation of ER-C, Forschungszentrum Jülich has fulfilled one of its central tasks defined in the mission of the Helmholtz Association of German Research Centres: the provision of cost-intensive infrastructure requiring extensive supervision which would exceed the capacities of individual scientific institutions.

Official opening of ER-C on 18 May 2006 with members of Ernst Ruska's family, from the left: Klaus Heinz, Professor Dr Burkhard Rauhut (Rector of RWTH Aachen University until July 2008), Irmela Ruska, Dr Jürgen Ruska, Professor Dr Joachim Treusch (Chairman of the Board of Directors of Forschungszentrum Jülich until October 2006) and the Directors of ER-C Professor Dr Knut Urban (Jülich) and Professor Dr Joachim Mayer (Aachen).

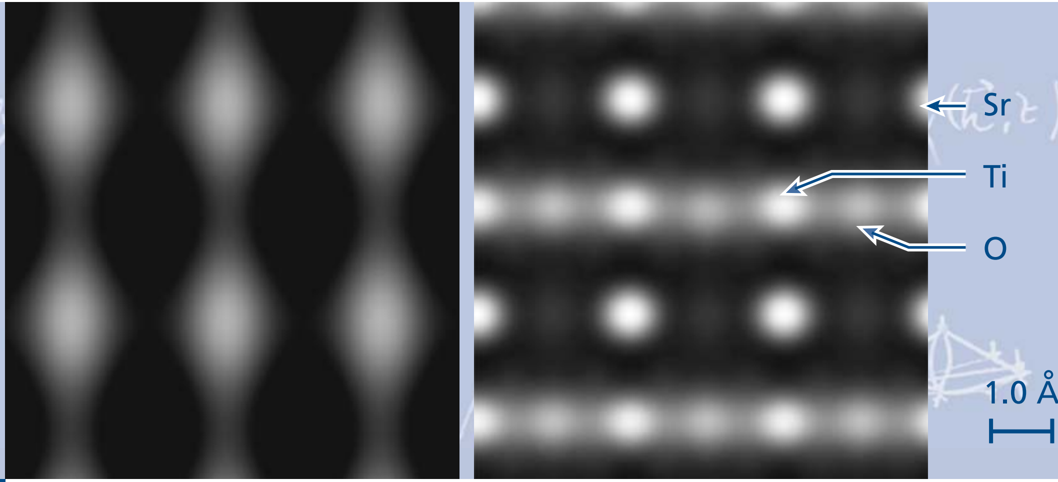


Image formation in a high-resolution transmission electron microscope (TEM) is basically comparable to phase contrast imaging in an optical microscope. However, the shorter wavelengths – compared to the light waves of an optical microscope – of the high-energy electrons used for imaging lead to significantly higher resolution.

TEMs operate with electromagnetic lenses which focus the electron beam, guide it onto the specimen to be investigated and finally enlarge the object structure. However, in the same way as their glass counterparts, electromagnetic round lenses have an unfavourable property which severely restricted the resolution of electron microscopes for decades – so-called "spherical aberration". Electrons which penetrate the beam-forming condenser or the imaging objective lens at a distance from the optical axis, that is to say close to the edges of the lens, are deflected much too strongly. This results in "fuzzy" images with correspondingly reduced resolution.

Spectacles for electron microscopes

In optical microscopes this problem was solved long ago by using additional concave lenses, but the development of a diverging lens for electron optics caused problems for a considerable time. Only in the 1990s did a research group from Darmstadt University of Technology, the European Molecular Biology Laboratory (EMBL) in Heidelberg and Forschungszentrum Jülich, funded by the Volkswagen Foundation, succeed in developing a specially shaped magnetic lens system – the so-called "hexapole" corrector. An additional reversal of the contrast transfer mechanism moreover significantly improved the image contrast. When the prototype of this aberration-corrected electron microscope went into operation in Jülich this meant that for the first time researchers were able to image single rows of superimposed light oxygen atoms in the vicinity of heavy atoms and were even able to precisely measure their local concentration fluctuations in atomic dimensions.

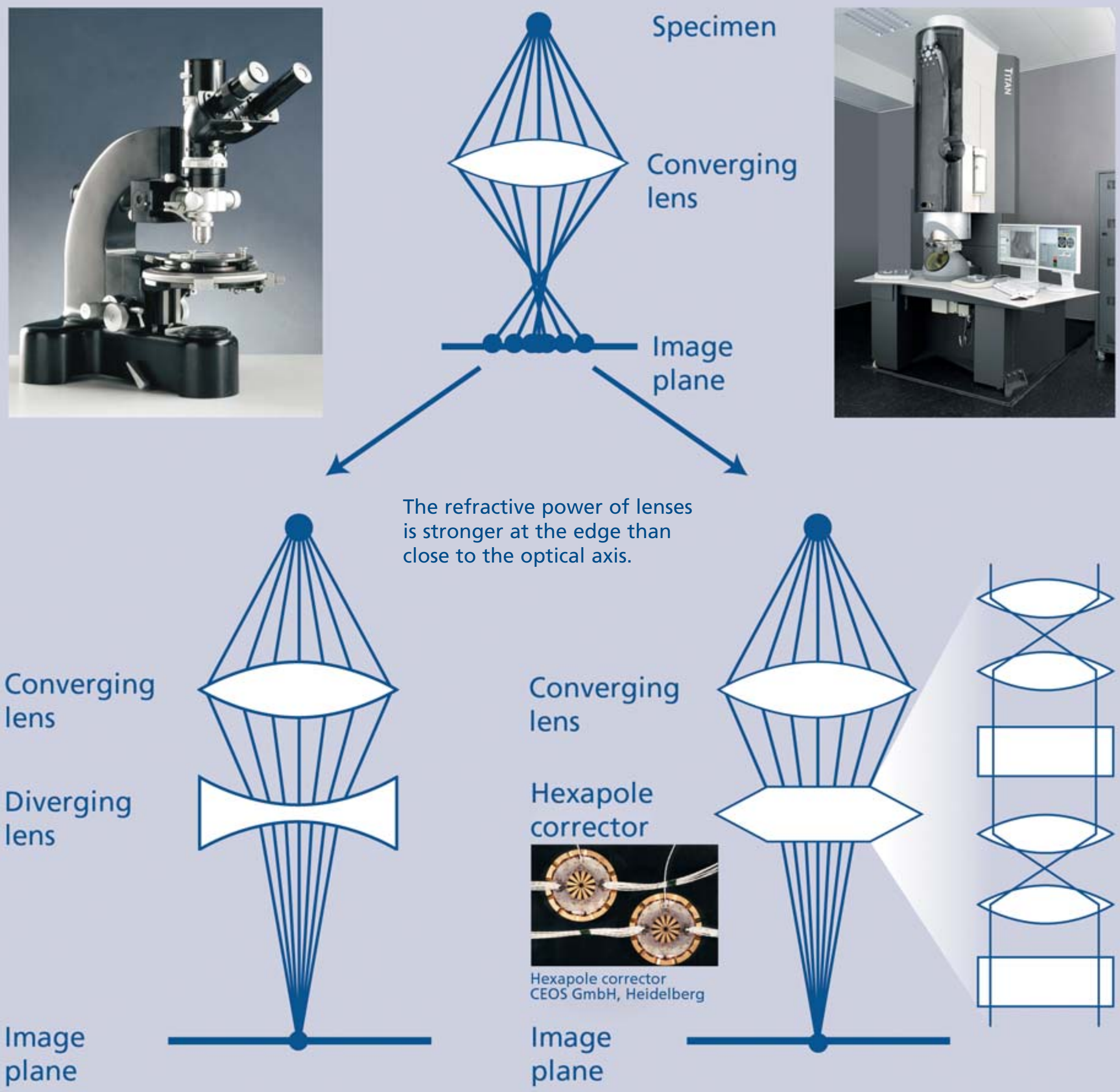
Software solution "Made in Jülich"

However, scientists at ER-C took a further decisive step since the rules of quantum physics come into play in nanodimensions. In practical terms, this means that visual image interpretation is no longer sufficient as scientists approach the physical limits of resolution. What looks like an image in the conventional sense is actually an encoded result of the quantum-physical interaction of the electron waves with the atoms of the sample. The researchers therefore developed software-based methods which made it possible to reliably evaluate the ultrahigh-resolution image data. In this way, the object wave function can be reconstructed from a series of successively recorded images with the aid of numerical calculations (more information on the "TrueImage" software: page 10/11).

With the aid of the ingenious "spectacles" for their microscopes, scientists at ER-C are now able to precisely measure atomic distances down to a few picometres. This is a dimension that roughly corresponds to one tenth of an atomic diameter.

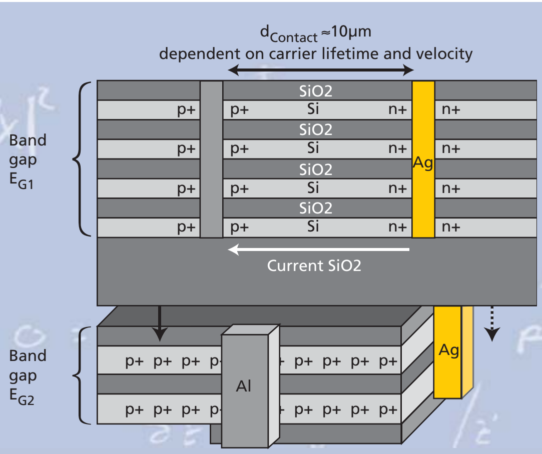
Strontium titanate – left viewed in an uncorrected electron microscope, right in an aberration-corrected microscope. Only the image on the right shows the atomic structure. The possibility of directly imaging oxygen for the first time with electron microscopes opens up new opportunities for studying oxides – an important class of materials for information technology.

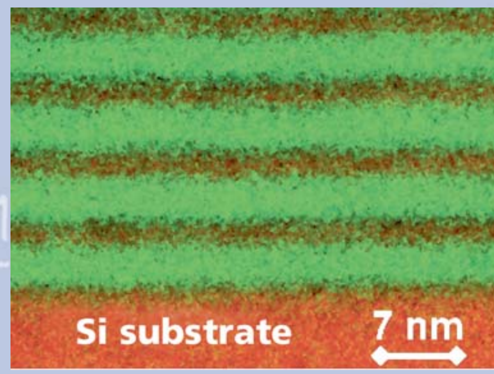
Spherical aberration: the problem of edge deflection



In optical microscopes, a diverging lens ensures that the edge deflection of the converging lens is corrected.

A complex system of electromagnetic lenses, the so-called hexapole corrector, compensates edge deflection in an electron microscope.





Aberration-corrected electron optics:

The development of aberration-corrected electron microscopes has led to a unique boom in the electron optics industry. Based on this technology, all of the four world leaders in electron optics – the American-Dutch company FEI, the two Japanese companies HITACHI and JEOL, and also Zeiss in Germany – launched a completely new generation of instruments onto the market starting in about 2004. Demand is so great that the companies have long delivery times. Up to the beginning of 2009, more than 100 instruments had been ordered from FEI alone. Depending on the configuration of instruments, this corresponds to a volume of orders worth € 3 to 4 million each.

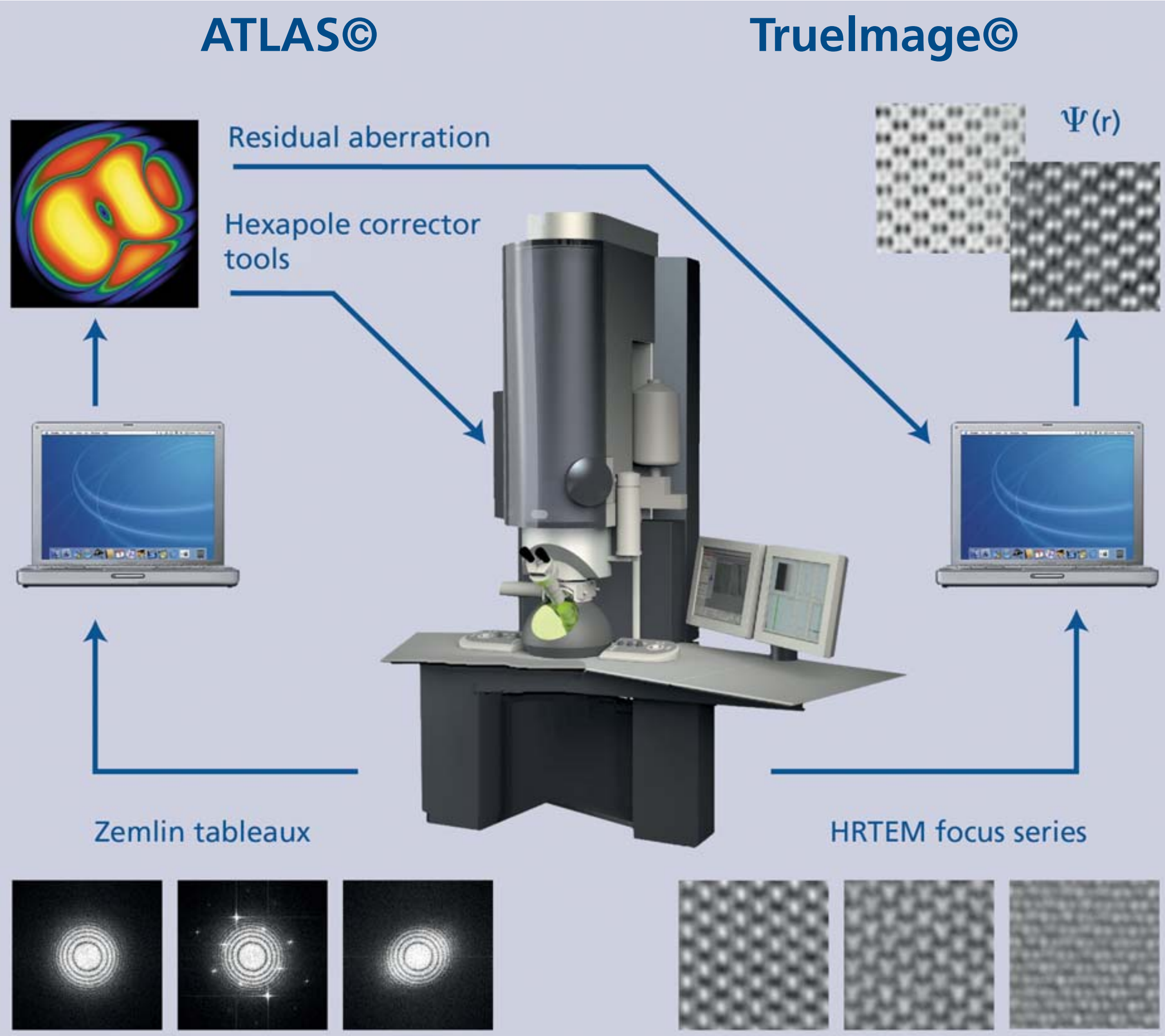
Some of the latest generation of electron microscopes do not only have an image corrector but also a corrector in the beam-forming system as well as monochromators and electron spectrometers. The majority of correctors for the new generation of instruments are licensed from or supplied by CEOS GmbH in Heidelberg. This company was founded after the successful conclusion of the Jülich-Darmstadt-Heidelberg project (page 8) by Dr Maximilian Haider, one of those responsible for the project.

A profound understanding of the atomic origins of macroscopic material properties will provide the basis to tailor materials to the specific problems of modern information technology.

ER-C as an industrial partner

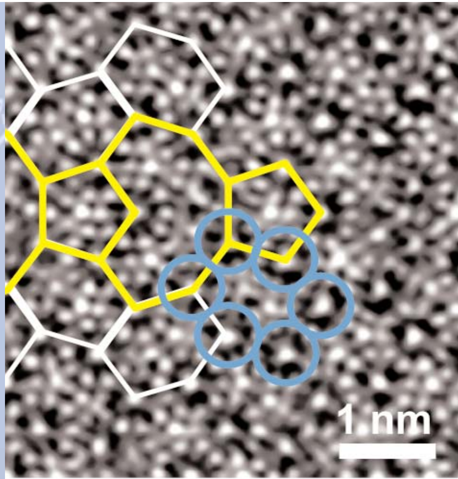
On the basis of a cooperation agreement, ER-C collaborates with FEI, one of the most innovative enterprises in the electron optics sector. FEI was granted a licence to software that has a key function in atomic-resolution electron microscopy. In this way, Jülich researchers developed a technique for the computer-based retrieval of the quantum-mechanical object wave function from focus series which has proved indispensable for work at the limits of electron microscopy. The result of this research work – an extensive software package for quantum-mechanical optical image analysis – is marketed as "TrueImage" and used throughout the world. The most recent product is the "ATLAS" diagnostic software, for which FEI has also obtained a licence, that enables fast and high-precision analysis of residual electron optical aberrations and is thus a prerequisite for a subsequent correction of these aberrations.

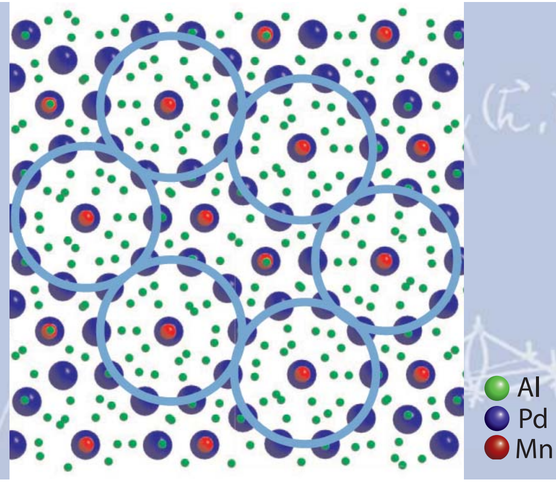
New high-efficiency solar cells may be produced on the basis of silicon (Si) nanostructures. Multilayer systems (left) are under construction in which the absorbency is adjusted by varying the thickness of the Si layers. Between these layers, SiO_2 layers are applied as a barrier. In the element distribution image (right), the SiO_2 layers (green) may be distinguished from pure silicon (red) by their oxygen content. The energy loss signal is recorded by an imaging energy spectrometer.



The "ATLAS" software package developed at ER-C enables precise characterisation of the actual optic state of the electron microscope from an analysis of Zemlin tableaux. If the aberrations measured in this way are linked to the controls of the hexapole corrector then the transfer properties of the instrument can be optimised to a large extent.

Residual aberrations can be completely eliminated by applying the "TrueImage" package to numerically retrieve the object wave function Ψ(r) from a focus series of high-resolution images.
In combination, the two packages directly decipher the "true" structure of the specimen investigated – for the first time in the history of high-resolution electron microscopy.

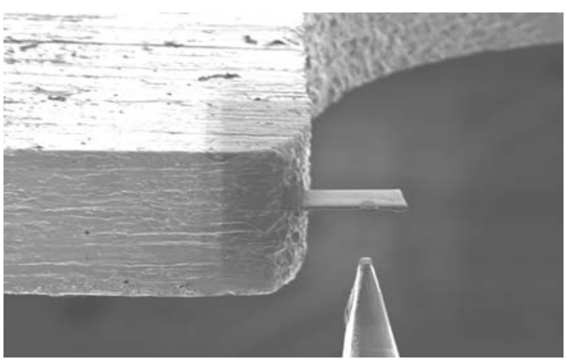




Research at the limits:

The application of state-of-the-art methods of ultrahigh-resolution electron microscopy requires special expertise and operating experience – only in this way is it possible to achieve useful results at the limits of electron microscopy. This is why ER-C provides both top technology and also internationally outstanding know-how. This unique combination ensures an efficient and targeted application of the instrumentation.

At ER-C, the scientific expertise of the Institute of Solid State Research at Forschungszentrum Jülich and the Central Facility for Electron Microscopy at RWTH Aachen University complement each other in an ideal manner. The two institutions work together at ER-C in the field of ultrahigh-resolution electron microscopy and spectroscopy. As regards external user services, ER-C does not only have top electron optical instruments available but also facilities for sample preparation and for preliminary examinations of electron microscope specimens. Additionally ER-C offers comprehensive support for the analysis of experimental data.



Critical step: sample preparation

The preparation of electron-transparent specimens is a particularly critical step in electron microscopy. This is especially true at the limits of atomic resolution. For example, usually the sample thickness must not significantly exceed five nanometres.

For this reason, ER-C has state-of-the-art equipment for sample preparation, such as a focused ion beam system and low-voltage ion milling facilities with an integrated scanning electron microscope as well as conventional transmission electron microscopes, which if necessary can be applied before the subångström studies to verify the sample quality.

Microscopes of the latest generation

The core equipment at ER-C is composed of aberration-corrected microscopes of the "Titan 80-300" class with an accelerating voltage of 300 kilovolts. The imaging "Titan 80-300" TEM provides a primary resolution of 80 picometres and permits measurements to be made with a precision of less than 5 picometres in determining atomic positions.

Fitted with a Gatan imaging filter, the "Titan 80-300" scanning transmission electron microscope (STEM) achieves a spectroscopic energy resolution of less than 0.1 electronvolts and a spatial resolution of 100 picometres.

TEM specimen preparation: A roughly 10-micrometre-long sample lamella prepared by FIB technology (centre) is soldered onto a carrier gauze (top). Bottom: The tip of the manipulator.

Novel complex alloys have unusual physical and chemical properties. Due to their high structural complexity, as here in the ϵ_6-Al-Pd-Mn phase with 320 atoms per unit cell (right), these materials cannot be properly studied using conventional electron microscopy.

For the first time, structural details of this phase were imaged with the aid of aberration-corrected scanning transmission electron microscopy. Decadentate palladium cluster columns along the [010] direction are visible in the form of overlapping rings (left).

According to the cooperation agreement between the operators of ER-C, the range of instruments will be continuously modernised. From 2010 onwards, an electron microscope with almost twice the performance of the Titan 80-300 microscopes characterised by a record resolution of less than 50 picometres will be available.

Support for users

External users receive support from the scientists and engineers at ER-C, who accompany them during the demanding microscopic investigations. ER-C dedicates about 50 percent of its scientists' time for this supervision at the highest scientific level.

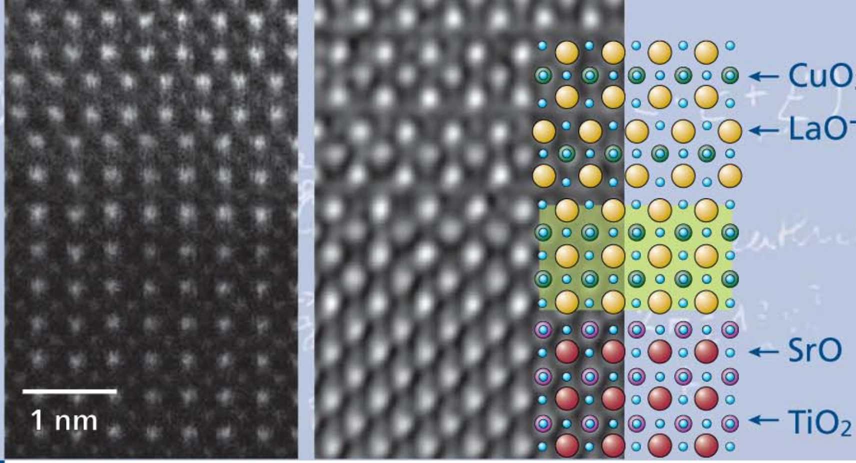
Challenge: the evaluation

Electrons "see" in a different way to that familiar to the human eye from light optics. Electron microscope images provide encoded information on the interatomic potential. Deriving structural and element-specific information from these images requires a quantum-physical understanding of the overall imaging process and also of the interactions of the electrons with the atomic object itself.

Apart from a few borderline cases, an electron microscope image can rarely be interpreted directly and intuitively. In practice, computer-aided analyses are therefore required to evaluate primary image data.

In close cooperation with in-house methodology and theory groups, ER-C offers efficient evaluation in order to enable external users to gain maximum information from the experimental images. This type of comprehensive user support takes on a key function in evaluating the reliability of the measured results.

In addition to state-of-the-art equipment, excellent support forms the basis for successful top-class research at ER-C.



About us

Forschungszentrum Jülich

Forschungszentrum Jülich makes a decisive contribution to solving the grand challenges facing society in the fields of health, energy and the environment as well as information technology. Its work is based on two key competencies: physics – which has a long tradition at Jülich – and the promising new discipline of simulation sciences. Work at Jülich focuses on both long-term fundamental research, as well as on specific technological applications. Forschungszentrum Jülich is a member of the Helmholtz Association and with an annual budget of some € 360 million and a staff of about 4,400 it is one of the largest research centres in Europe.

Since 1970, the Institute of Solid State Research has been holding an annual spring school on contemporary issues of condensed matter physics. Young scientists from all over the world take the opportunity to learn from leading representatives of their subject in Jülich.

RWTH Aachen University

More than 31,000 students are enrolled in the 106 degree courses offered by RWTH Aachen University. RWTH Aachen University focuses on science and engineering. The university provides employment for 7,100 people: 420 professors, 2,000 scientific staff and 1,850 other employees, more than 2,000 members of staff financed by third-party funds, and 713 trainees. RWTH Aachen University is thus the biggest employer in the region and also has the largest number of trainees. Its annual budget amounts to over € 570 million. More than € 190 million of this total is acquired by the university in the form of so-called third-party funds – funding for research projects provided by government and industrial clients. RWTH Aachen University thus takes a leading place among the German universities.

Ernst Ruska-Centre

ER-C is the first centre of excellence for ultra-high-resolution microscopy and spectroscopy with electrons to be jointly operated by a research centre and a university. It provides external users from science and industry with access to the most powerful electron microscopes of our time. Together with its cooperation partners, ER-C is concerned with providing a basis for the further development of electron optics with respect to methodology and application. ER-C thus creates the necessary conditions for innovation in other branches of technology, for example nanotechnology. In its own research programmes, ER-C concentrates, on the one hand, on the development of electron optical technologies and methods and, on the other

The reorientation of atomic bonds at interfaces between complex oxides can lead to unusual electronic properties originating from phenomena taking place within a few atomic layers. The example shows the atomic structure of the interface (shaded green) between strontium titanate and lanthanum cuprate. In order to maintain charge neutrality, an oxygen-deficient perovskite lanthanum copper oxide phase is formed, which represents an electronically independent interlayer.

Publication details

hand, on the investigation of solid-state phenomena focusing on the physics of condensed matter and information technology. This work provides a solid basis for developing new concepts in micro- and nanoelectronics.

By organising and holding conferences and summer schools, ER-C is also involved in training young scientists. Examples of these activities are the "European Microscopy Congress 2008" in Aachen and the "IFF Spring School 2007" in Jülich on the topic of "Probing the Nanoworld". External users' research fields are very varied and range from basic studies of the structure and electronic properties of internal interfaces up to analyses for evaluating functional mechanisms in component prototypes.

Staff

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