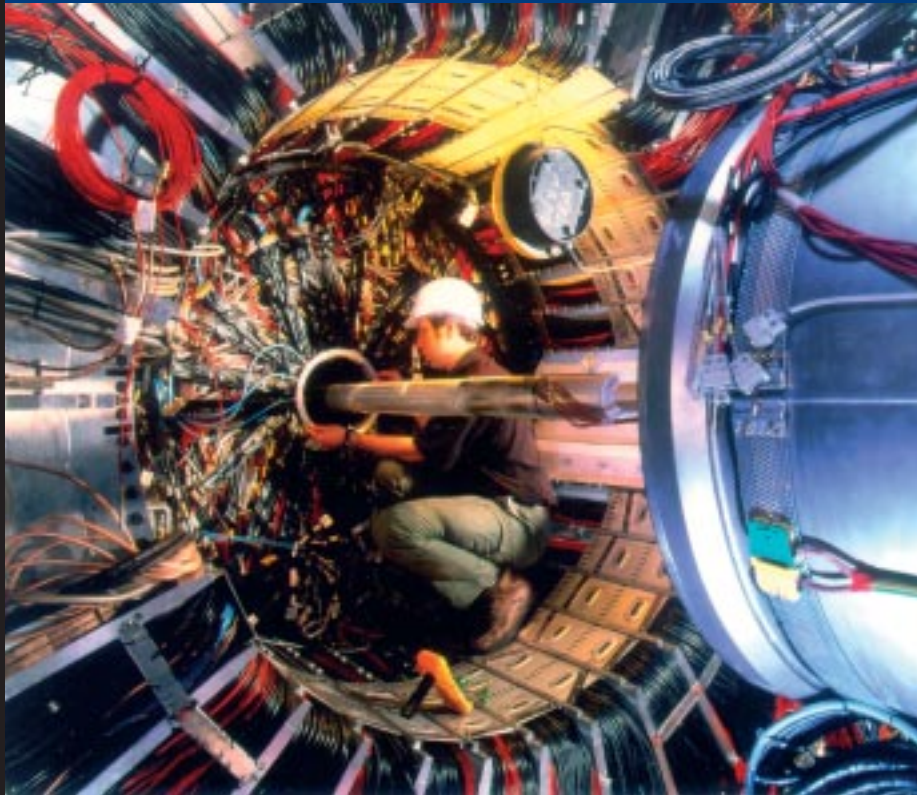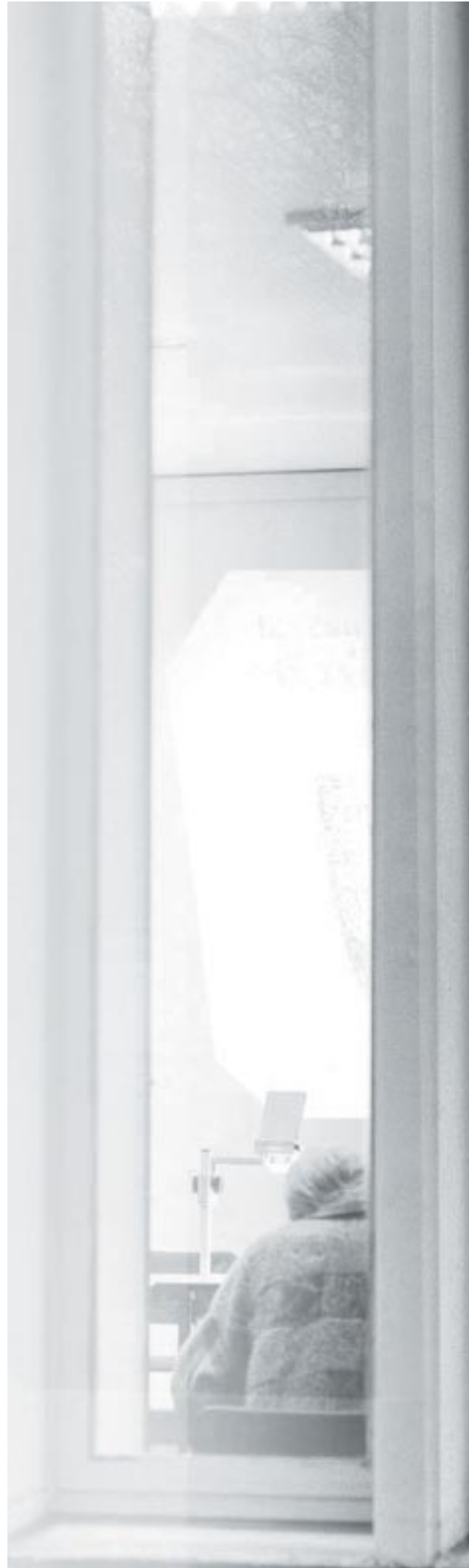# SUPER MICROSCOPE
HERA

Gazing into the Heart of Matter

DESY

THE SUPER MICROSCOPE
HERA

Ten years ago, the largest German research instrument, the particle accelerator HERA, began operations at the DESY Research Center. This means that for ten years, HERA has been the scene of collisions between electrons and protons underneath the city of Hamburg; for ten years, more than a thousand scientists from all over the world have been coming to Hamburg to take advantage of the unmatched research possibilities offered at HERA. Here, researchers find unique conditions that allow them to probe the innermost heart of matter.

HERA is the only accelerator in the world in which the two building blocks of the hydrogen atom, electrons and protons, are brought to collision at nearly the speed of light. The electrons penetrate the proton and scan its interior. HERA is thus a "super electron microscope," which deciphers the internal structure of the proton. Thanks to HERA, we now understand how the proton is constructed and with it matter itself, our own bodies, and the entire universe. The building blocks of matter are themselves held together by forces that we can also examine with HERA.
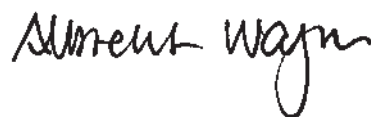
The results of the first ten years of the accelerator's operation have already made important contributions to expanding our knowledge of the universe. The accelerator was modified between the fall of 2000 and the summer of 2001 in order to produce a fourfold increase in its performance.

As a result, we expect to be able to see new things as we move into new physical realms with HERA over the next few years, much in the same way that one discovers surprising things when a stronger source of light is fitted to a conventional microscope.

But how does such a "super microscope" actually function? First of all, it involves a high-tech underground facility measuring 6.3 kilometers in length, in which tiny particles invisible to the naked eye collide with one another. How do the physicists make these particles and their collisions visible? How can they subsequently make statements about the structure of our universe and the forces that hold it together? And what exactly have they been able to find out with HERA over the last ten years?

This brochure is designed to answer such questions and thus provide you with a look behind the scenes at HERA — into the daily work of the particle physicists, the motivation of those who work with the super electron microscope, and the scientific successes that HERA has achieved over the last decade.

Pleasant reading!

Albrecht Wagner

Professor Albrecht Wagner
Chairman of the DESY Directorate

Hamburg, September 2002

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C O N T

E N T S

The DESY
Research Center

HELMHOLTZ
GEMEINSCHAFT

The **DESY** research center was established in Hamburg on December 18, 1959, as an independent foundation under civil law. The center is publicly funded, with 90 percent of the budget provided by the German Federal Ministry of Education and Research and 10 percent by the City of Hamburg and the state of Brandenburg (for the two **DESY** locations in Hamburg and Zeuthen near Berlin respectively). **DESY** Hamburg, which has 1390 employees, receives annual funding of € 145 million, while **DESY** Zeuthen with its workforce of 170 is allocated € 15 million. **DESY** is a member of the Hermann von Helmholtz Association of National Research Centers.

Objectives:

DESY's task is to conduct basic research in the natural sciences with special emphasis upon:
- the development, construction and operation of accelerator facilities
- the investigation of the fundamental properties of matter and forces (particle physics currently at HERA)
- the use of synchrotron radiation in the fields of surface physics, materials science, chemistry, molecular biology, geophysics, and medicine (currently at HASYLAB)

DESY is thus characterized by its broad spectrum of interdisciplinary research.

The Deutsches Elektronen-Synchrotron DESY was initially established as a particle physics facility for German colleges and universities. Over the years, it has developed into a research center of international renown, and its facilities are now open to scientists not only from Germany, but from all over the world. More than 1200 physicists from 25 countries are currently working on the four HERA experiments. A further 2200 guests from 33 countries come to DESY every year in order to conduct experiments in various areas of physics, chemistry, molecular biology, materials science, and medicine at the Hamburg Synchrotron Radiation Laboratory HASYLAB. DESY not only offers first-class research opportunities in particle physics at HERA; the synchrotron radiation generated by the storage rings DORIS and PETRA has also become an important and popular research tool since the mid-1960s.

Hamburg's Un
Racetrack for

Serious, analytical, mathematical and pragmatic — that's the typical stereotype of a physicist. So perhaps we shouldn't be surprised to discover that, at DESY, "HERA" doesn't stand for the Greek goddess — the quarrelsome, passionately jealous wife of ZEUS. Instead, the acronym stands for Hadron Electron Ring Accelerator, a tunnel with two particle accelerators beneath the city of Hamburg.

In our everyday lives, the world of the tiny particles on which HERA sheds light may seem just as remote as the mythical world of the Greek gods and goddesses. However, the research carried out here is of real relevance. HERA investigates quarks and gluons inside the proton. Protons and neutrons are the tiny particles that make up the atomic nucleus; nuclei and electrons in turn form atoms; and atoms are the building blocks of humans and everything in the world around us.

With a length of over six kilometers, the "super electron microscope" HERA is the largest particle accelerator at the DESY Research Center. Here, whole swarms of electrons fly through a ring accelerator at almost the speed of light. In the same tunnel, protons circulate in the opposite direction inside a second accelerator. The two particle beams are brought to collision in two places. Ten million times a second, the highly accelerated particles collide with such force that furious reactions take place in the microcosm. When the point-like electron hits the heavier proton, it acts as a tiny "probe" that elucidates the complex interactions of quarks and gluons inside the proton.

Particle physicists have been following these collisions beneath the city of Hamburg since 1992. To this end, they installed very special high-power "cameras" — detectors that are as tall as a three-story building, weigh half as much as the Eiffel Tower and contain hundreds of thousands of electronic components. These detectors can register ten million images of particle collisions per second. The experimental results are evaluated by international teams of researchers, each made up of hundreds of physicists, technicians, engineers and students.

The HERA storage ring has four large underground halls, one for each point of the compass. This is where the detectors are located, seven

derground Particles

stories below ground. The H1 detector in the north and ZEUS in the south investigate the high-energy collisions between electrons and protons. The accelerated electrons are used by scientists at HERMES in the east to study the spin of the proton. In the west, the HERA-B researchers make use of the accelerator's proton beam.

The HERA "microscope" provides the scientists with the world's sharpest view of the proton. They have observed structures as small as one two-thousandth the size of the protons themselves — that is 0.000 000 000 000 000 000 5 meters. At this incomprehensibly minute level, the research teams can also study the fundamental forces of nature that act between the particles. The insights they have achieved open up a whole new set of perspectives in space and time. The H1 and ZEUS experiments at HERA, for example, revealed how two of the four elementary forces of nature combine into a single force, thereby providing a glimpse back at the earliest moments of the universe itself. For, according to current theories, shortly after the big bang, a single primordial force governed everything in the cosmos.

"The results from HERA so far have provided decisive new knowledge that enables us to better understand the forces and the structures of particles," explained DESY's Research Director Robert Klanner on the occasion of the extensive modification work undertaken at HERA from September 2000 to June 2001. The aim of the major improvements was a fourfold increase in the number of electron-proton collisions. This will enable the experimenters to focus on extremely rare processes — and thus enhance HERA's view of possible unexpected effects beyond the scope of current particle theories.

In 2002, HERA embarked on a second round of experiments. This is just the right moment to look back at the results obtained in ten successful years and to turn our gaze to the promising future of Germany's largest research instrument.

DEUTSCHES ELEKTRONEN-SYNCHROTRON **DESY**

DESY 77/38
June 1977

(A)

Physics with Large Electron-Proton Colliding Rings

by
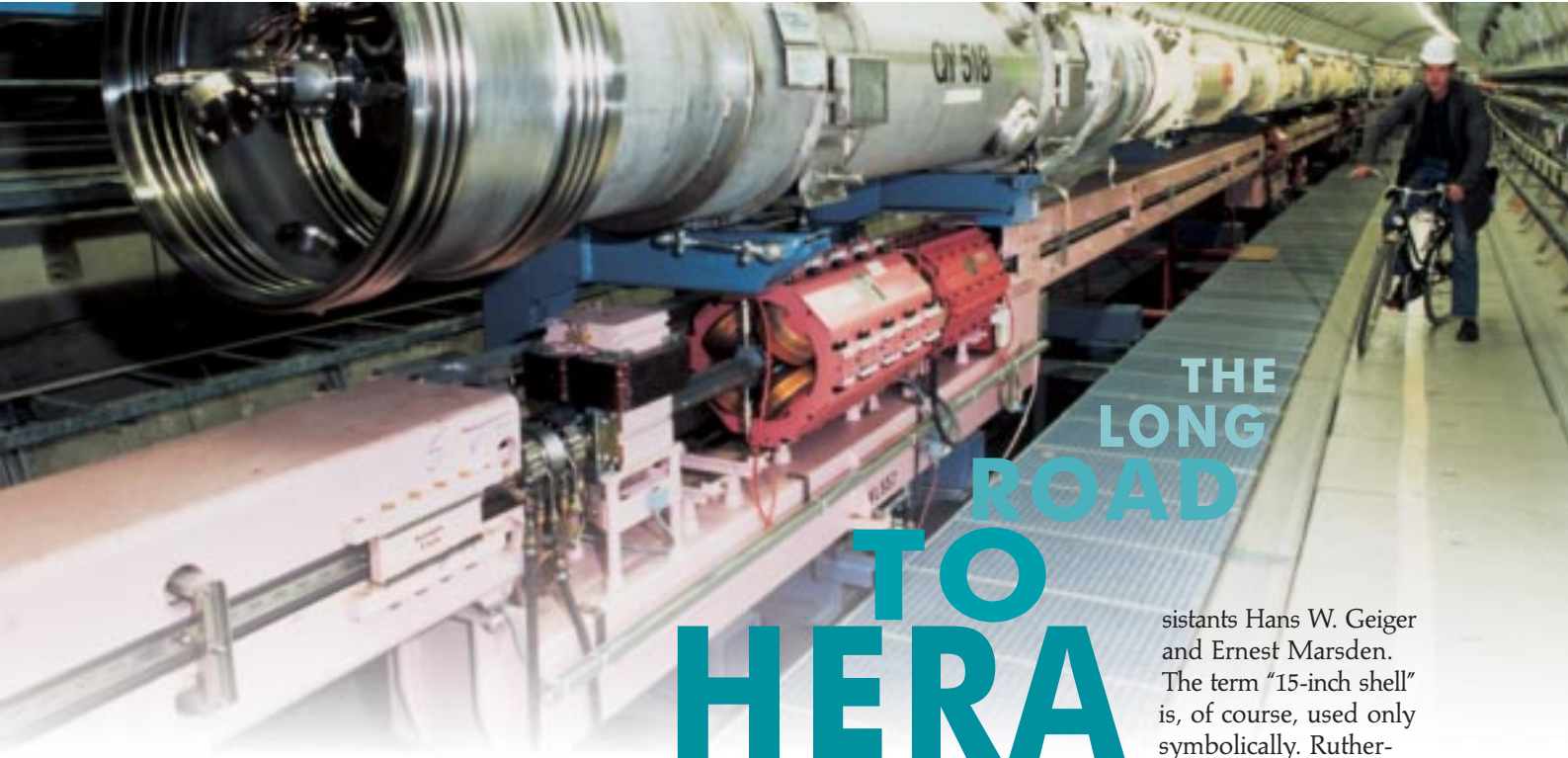
C. H. Llewellyn-Smith
University of Oxford

B. H. Wiik
Deutsches Elektronen-Synchrotron DESY, Hamburg

NOTKESTRASSE 85 - 2 Hamburg 52

The "Red DESY Report," in which Christopher H. Llewellyn-Smith, who later became Director General of CERN, and Bjørn H. Wiik first published their ideas for a large electron-proton accelerator in 1977.

When the Norwegian physicist Bjørn H. Wiik returned to Germany from the United States in 1971, he also brought a ground-breaking idea with him: He planned to construct a huge electron microscope for viewing protons — a facility that would allow physicists to discover the deepest secrets of the proton and of the fundamental forces of nature. To achieve this, a completely new concept was to be employed, in which electrons and the nearly 2000 times heavier protons would be stored in two separate accelerator rings and then smashed head-on into one another at very high energies.

At the time, no one had ever attempted such a thing. Instead, particle physics experiments either consisted of two beams of particles of equal mass colliding with each other within a single accelerator and in the same vacuum tube, or of a single particle beam directed at a stationary target. However, if the two types of particles move toward each other, the energy of the collision is far greater than if only one of the particles is moving. The higher the energy of the particle collision, the

**The tunneling machine
"HERAKLES"**

deeper the physicists can probe into the heart of matter and the smaller are the details that become visible. However, nobody knew then if it would be possible to accelerate two such completely different types of particles as electrons and protons in two separate rings and collide them in flight.

The idea of using particles as probes to uncover the structure of larger objects is quite old and is known as a "scattering experiment." At the beginning of the 20th century, Ernest Rutherford discovered the atomic nucleus using this method. "It was almost as incredible as firing a 15-inch shell at a piece of tissue paper and having it come back and hit you," is how Rutherford reportedly described the experiment conducted by his as-

sistants Hans W. Geiger and Ernest Marsden. The term "15-inch shell" is, of course, used only symbolically. Rutherford directed alpha particles at an extremely thin piece of gold leaf and watched in which directions the particles were diverted. The surprising fact that some of the particles bounced back could only mean that something small and hard — the atomic nucleus — was located at the center of the atoms.

Scattering experiments grew to become an even more successful research tool. The elementary, point-like electrons proved to be ideal "probes" for analyzing the structure of complex objects. Forty years after Rutherford's discovery, Robert Hofstadter conducted experiments at Stanford University, in California, in which he shot an electron beam at the nuclei of hydrogen atoms (which consist of single protons), and discovered that protons are not "points," but instead have a measurable diameter. This "smudging" proved that protons must have an internal structure. However, Hofstadter was unable to be more precise in 1954, since his "probes" did not have sufficient energy. Then, in 1967, physicists at the DESY synchrotron observed unusual reactions in electron-proton scattering experiments, which provided further indications that the proton possessed a substructure. By the same year, accelerator technology had advanced far enough to enable scientists at the Stanford Linear Accelerator Center, SLAC, to draw firm conclusions. During one experiment, Jerome

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DESY and its accelerators: The underground HERA ring along with the four experimental halls and the PETRA ring which surrounds the DESY site.

I. Friedman, Henry W. Kendall and Richard E. Taylor collided a beam of electrons at the highest available energy with liquid hydrogen, and were able to show for the first time that protons contained hard scattering centers. The scientists had discovered the quarks, the controversial building blocks of protons and neutrons that had been postulated by Murray Gell-Mann and George Zweig, but which most physicists of the time dismissed as purely mathematical fantasies. Like Hofstadter, the three physicists were awarded the Nobel Prize in Physics (1990) for their discovery.

The "father" of HERA: Bjørn H. Wiik, who went on to become director of DESY, in the accelerator control room.

However, scientists now faced the problem of continuing the success story. The main challenge was to find a way to substantially increase the collision energy in order to make the tiny quarks and any other substructures of the proton visible. Wiik's idea to accelerate electrons and protons separately and have them collide head-on showed the way. But much time would pass before the idea could be transformed into reality. In the meantime, physicists were obtaining a wealth of exciting results from experiments with electrons and their antiparticles, the positrons (DESY's specialty), so that the proton-electron concept slipped into the background. As a result, the meaning of the "P" in PETRA, an acronym which had stood for "Proton-Electron Tandem Ring Accelerator" when it was coined back in 1973, changed to "Positron" in the following year. However, once it became clear in the late 1970s that CERN — the European Laboratory for Particle Physics — in Geneva would also be delving into electron-positron physics with its LEP storage ring, scientists at DESY decided to adopt the new "super electron microscope" principle instead. The first project study followed in 1980 and the proposal was fully worked out and given a positive assessment a year later. On April 6, 1984, the German Minister of Research and Technology, Heinz Riesenhuber, and the Hamburg Science Senator, Hansjörg Sinn, met at DESY in Hamburg to sign the agreement for the construction of the new facility. The "Hadron Electron Ring Accelerator" HERA was born — the world's

only storage ring facility in which two types of particles with different masses are brought to collision.

April 6, 1984

The History of HERA

- Early 1970s: initial ideas for a "super electron microscope" for protons
- Late 1970s: initial technical preparations for the construction of superconducting deflecting magnets at DESY
- March 1980: first project study
- February 1981: positive assessment by the advisory committee of the German Ministry of Research and Technology (BMFT); the committee recommends a high level of international participation as a precondition for the facility's construction
- July 1981: detailed project proposal
- February 22, 1983: The BMFT provides the financial means for the construction of HERA
- April 6, 1984: signing of the agreement for the construction of HERA
- April 15, 1984: groundbreaking ceremony
- May 8, 1985: The tunnel boring machine begins digging the tunnel
- March 6, 1987: Construction of the electron ring begins
- August 19, 1987: The tunnel boring machine reaches its starting point again
- August 20, 1988: first electron beam stored
- March 1, 1989: Construction of the proton ring begins
- November 8, 1990: completion of HERA
- April 15, 1991: first proton beam stored
- October 19, 1991: first electron-proton collisions
- October 1, 1992: Research begins at HERA with the experiments H1 and ZEUS
- May 4, 1994: first longitudinal polarization of the electron beam
- 1995: commissioning of the third HERA experiment, HERMES
- 1999: commissioning of the fourth HERA experiment, HERA-B
- From September 2000 to summer 2001: remodeling of the facility to increase its luminosity (HERA-II)
- 2001-2002: commissioning and optimization of HERA-II

Inside the HERA tunnel: The normally conducting magnets of the electron ring are located beneath the proton accelerator with its superconducting magnets (beige).

October 19, 1991

The "HERA Model" of International Cooperation

HERA was to become the largest scientific project ever financed in Germany. But is a single country capable of realizing such a project alone? The German federal government had financed the construction of DESY's previous storage ring accelerator, PETRA, with the experiments being paid for by the participating institutes, both German and foreign.

The advisory committee that assessed the HERA project on behalf of the German Ministry of Research and Technology (BMFT) in the early 1980s was of the opinion that this program should be on a different footing than PETRA: "Since the construction of HERA will result in a second internationally competitive laboratory in Europe alongside CERN that will be operated on a long-term basis (something which the committee wholeheartedly recommends), it is only logical that DESY should not only be used by researchers from abroad, but that laboratories from other countries should also contribute to the construction of HERA. In its recommendation, the advisory committee assumes that such a contribution will be achieved in some form (materials, components, personnel), so that the human and financial resources which the Federal Republic has to provide will be substantially reduced."

This type of international cooperation was something completely new at the time, and it was not immediately clear if it would even be possible to obtain assistance from abroad for what was primarily a German accelerator project. The scientists at DESY — particularly the Heidelberg physics professor Volker Soergel, who became chairman of the DESY Directorate on January 1, 1981 — were now faced with the task of making foreign partners aware of HERA's scientific potential and interesting technology, as well as of

DESY Director Volker Soergel (left) welcomes Italian Prime Minister Giulio Andreotti (right) at DESY; standing behind them is Antonio Zichichi, then president of INFN.

the necessity of their contributing to the realization of the project. "We have never sold HERA research time to make money," said Bjørn H. Wiik, the "father" of HERA and project manager for the construction of the proton ring. "The people knew that

if they did not contribute anything, the whole project might not be realized. The fact that we managed to get so much support from abroad is evidence of the project's high quality." The plan was successful, and notable foreign partners contributed materials and services without any international treaties having to be signed or government agencies having to intervene. Of course, the partners benefited as well, as the project provided them with valuable knowledge and experience — particularly with regard to the technologies employed.

The people at DESY also made extraordinary efforts to ensure that the project was completed on time and within budget. Construction of HERA began at a time when the German parliament and the Ministry of Research had decided that the 13 national research centers should reduce the size of their workforces. No exceptions were made for DESY, despite the initiation of the new project. The management of DESY therefore decided to have the HERA electron ring constructed by the team headed by Gustav-Adolf Voss, which already had experience in building and operating electron accelerators. The new proton ring, on the other hand, was the responsibility of employees from the particle physics experiments division — a team of physicists and technicians headed by Bjørn H. Wiik, who took up their task with plenty of enthusiasm,

Worldwide participation in HERA: the international crew of the magnet measuring hall.

despite the fact that most of them had never before been involved in the construction of an accelerator. The team was supported by numerous physicists, technicians and engineers from abroad who worked in Hamburg for limited periods. Developing and completing the extremely sophisticated proton accelerator on time with such an ad-hoc crew was surely one of Wiik's greatest achievements.

The construction of HERA was a major international endeavor involving a total of eleven countries. Institutes from Canada, France, Italy, Israel, the Netherlands and the U.S. supplied and financed essential parts of the facility or conducted important tests. Meanwhile, Poland, the UK, Czechoslovakia, Switzerland, China and other German institutes (both from the FRG and the GDR) provided personnel to work on the project. At times, the foreign personnel — who received project-specific, fixed-term contracts — accounted for almost half of all the workers at HERA. "Although this might seem a strange way to build accelerators," Wiik said, "it all went very well, and I think the people benefited from it too, because they learned a lot and got good jobs afterwards. In this sense, the construction of

HERA was also a sociological experiment."

Interest in HERA was so great, in fact, that the German Minister of Research eventually found himself in a somewhat awkward situation. This was because the *Istituto Nazionale di Fisica Nucleare* INFN in Rome announced that it intended to deliver all of the proton ring's 422 superconducting deflection dipoles free of

Approximately 360 physicists from 51 institutes in 12 countries are working at ZEUS, one of the four experiments currently under way at the HERA ring.

charge as Italy's contribution to the project. Although such a plan would have saved a lot of money, it would also have precluded German com-

panies from acquiring the expertise needed to build large superconducting magnets. As a result, the Research Minister told DESY to accept only half of Italy's gift and use its own financial resources to have the other dipoles manufactured in Germany.

Altogether, 45 institutes and 320 companies (taking into account only those companies that received order volumes in excess of € 25 500) took part in constructing the facility. Over 20 percent of the costs of HERA were covered through financing from abroad.

As for the experiments, the extremely high foreign share of the funding — over 50 percent — makes this contribution much more than simple international participation. In fact, the experiments are international projects of the first magnitude — and are becoming even more so from day to day: Whereas 800 researchers from 16 countries participated in the HERA experiments back in 1992, this figure has since risen to approximately 1200 scientists from 25 nations. HERA thus plays a major role in promoting collaboration and networking among scientists across national boundaries. The "HERA model" of international cooperation is now a template for the conduct of other major international research projects.

The four underground HERA halls were constructed by open excavation.

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HERA is the only particle accelerator of its scale anywhere in the world to be operated in the middle of a major city. The complex comprises a 6.3-kilometer-long tunnel, four experiment halls 25 meters beneath the ground, and two connecting tunnels to the other accelerators on the DESY site. All in all, it took the HERA Working Group three years and three months to complete the construction work for this exceptional project. In November 1990, six and a half years after groundbreaking, DESY held a ceremony to mark the symbolic startup of the complex: The Hadron-Electron Ring Accelerator HERA had been completed on schedule and within budget.

The story first began next to the trotting course in Bahrenfeld, on a sand track behind the stables. Today, all that is visible of HERA above ground is a building surrounded by trees. Beneath the earth, however, a shaft surrounded by subterranean offices descends over eight stories before opening out into a substantial hall measuring 25 x 43 meters. This is the HERA South Hall, home today to the particle detector ZEUS. All in all, four such halls were excavated along the tunnel. This was a major undertaking, as all four were built by open excavation once the groundwater had been lowered. Meanwhile, work also commenced on the underground tunnel. Departing from the South Hall, a specially constructed tunnel boring machine known as HERAKLES tunneled through the earth at a depth of 10 to 25 meters

beneath the city of Hamburg. Six meters in diameter and around the same in length, the mighty steel boring machine was of the type normally used to build railroad tunnels.

At the head of the machine, a large pinion-type cutter chewed up earth and rock and mixed them with clay wash, which filled the front part of the drill under pressure. This mixture was pumped back through the section of the tunnel already excavated and then up to the surface, where sand and rock were removed. The advantage of using this type of tunnel boring machine is that only the area in front of the shield — where workers need to go only in exceptional circumstances — is under pressure. Apart from that, the underground crew was able to work without a pressure chamber, despite the fact that the bottom half of the tunnel actually runs below the level of the groundwater. As the drilling machine progressed, the tunnel behind it was lined with prefabricated concrete segments fitted with special rubber seals. These so-called tubbings fit so tightly against one another that there is no chance of groundwater penetrating into the tunnel. A muffled rumble was all that residents above noticed of the work below as HERAKLES steadily wormed its way beneath housing and commercial areas, roads and parks. The only problem that had to be remedied was one door that stuck. On August 19, 1987, the laser-controlled boring machine broke through the wall of HERA's South Hall, thereby closing the loop at the point where tunneling work had commenced exactly

Light at the end of tunnel: Work on the HERA ring advances; the boring machine HERAKLES can be seen in the background.

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28 months earlier. There was a devia-
tion of only two centimeters — well
within the allowed tolerance of 10 centi-
meters. In the course of its journey
under the Bahrenfeld racetrack, a
number of residential and commer-
cial areas, and Hamburg's Volkspark,
HERAKLES had removed a total of
180 000 cubic meters of earth.

As soon as HERAKLES had com-
pleted the first section between the
South and West Halls, the installa-
tion crew moved in to equip the bare
tunnel with all the necessary infra-
structure: cable shelves, water and
electricity lines, light and ventilation.
"At one of the preliminary meetings
to schedule the installation work for
the tunnel, I was given the responsi-
bility for project implementation,"
recalls Hannelore Grabe-Çelik, who
at the time was a member of the Ex-
periment and Accelerator Construc-
tion Group. "Luckily, I didn't realize
just what that involved!" In fact, there
were 24 800 gratings to be fitted as
well as 10 000 sections of anchor
rail, miles and miles of cable and
pipes, distribution boxes, telephones,
loudspeakers, emergency shutdown
systems and magnet mounts. Bus-
bars had to be welded, and magnets,
modules and accelerator resonators
transported to their respective loca-
tions and then hooked up. Wave-
guides had to be mounted and shiel-
ding stones installed. Grabe-Çelik
and her crew followed hard upon
the heels of HERAKLES as it made
its way around the ring. Indeed, the
first magnets for the electron accel-
erator were ready long before
drilling work had been completed.
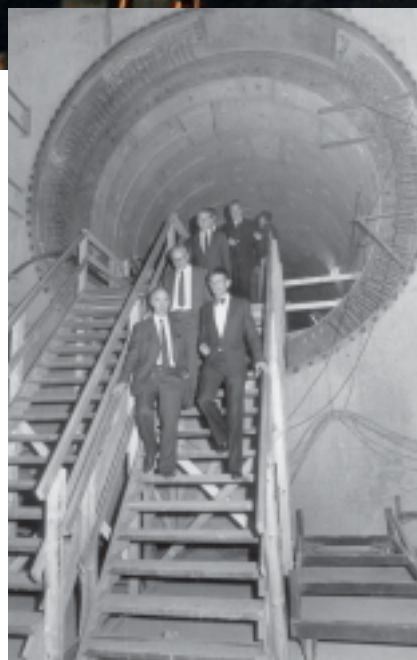By the time HERAKLES closed the

The tunnel boring machine HERAKLES is lowered into HERA's South Hall.

DESY Director Volker Soergel (front left) with German Research Minister Heinz Riesenhuber (front right) during a tunnel inspection.

loop in August 1987, almost half the electron ring was finished. One year later, it commenced operation.

This marked the start of the next major challenge: construction of the proton accelerator, complete with its new superconducting magnets and the complex helium cooling system. Everything had to be installed above the electron ring. Some 650 superconducting magnets were delivered by the suppliers and then tested for an average of 100 hours in DESY's test hall before being installed in the tunnel. On September 19, 1990, the final proton magnet was in place; the storage ring's completion and commissioning were celebrated on November 8. In the early hours of April 15, 1991, scientists succeeded in storing protons in the HERA ring for the first time. On the afternoon of October 19, 1991, a Saturday, the first electron-proton collision was recorded at HERA.

The Challenge of Superconductivity

In the control room of the HERA refrigeration plant

The decision to build HERA — the Hadron Electron Ring Accelerator — marked a new departure for DESY in a number of areas. To begin with, DESY had previously concentrated primarily on the physics of electrons and their antiparticles, positrons, and therefore had no experience in constructing a proton accelerator. Moreover, trying to bring particles as different as electrons and protons, which are 2000 times heavier, to collide with one another head-on was a challenge that no one had ever taken on before.

Essentially, particles and their corresponding antiparticles differ only in that they have opposite charges. This means that they can easily be stored and brought to collision in one and the same ring accelerator. With electrons and protons, however, two separate and

Large-scale cryogenics: HERA's 2500 m² refrigeration hall from a fisheye perspective.
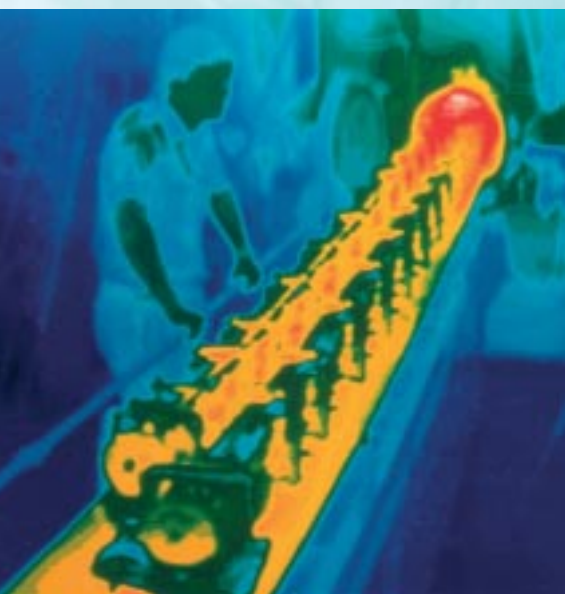
An infrared image of a vacuum chamber for the HERA electron ring.

completely different accelerators are needed, with a sophisticated beam guidance system to direct the particles onto each other at the interaction points.

DESY had already accumulated substantial experience in the field of electron accelerators so that, although HERA's electron ring would also feature a number of significant innovations, this part of the project was not likely to present major problems. The big challenge lay with the heavier protons. When operating at the high energies used by HERA, it takes very powerful magnetic fields to make such heavy particles follow the curve of the accelerator ring. Indeed, it requires magnetic fields around three times as strong as those that can be generated by conventional electromagnets with iron poles. The only practical way to produce a magnetic field of such strength is to exploit the phenomenon of super-

conductivity — i.e. the property exhibited by certain materials of having zero electrical resistance at extremely low temperatures. Superconducting wires also accommodate very large electric currents — around 10 000 times as large as copper wire of the same cross-section — without heating up. It is therefore possible to generate very powerful magnetic fields by using superconducting coils. At the time, this meant breaking new technological ground, since back when HERA was still in the planning stage, there was no such thing as a large superconducting accelerator. Although the Tevatron proton-antiproton storage ring at the Fermilab research institute in Chicago was already under construction, the magnets for that project were dogged by various teething troubles.

In other words, the HERA project involved not only the construction of a completely new accelerator system comprising the proton source, preaccelerator and superconducting ring. In addition, before this work could even begin, it was first necessary to develop the technology upon which it would be based. Here, DESY engineers were able to profit from the pioneering work done by their colleagues in the U.S. In fact, the magnets used for HERA are an advanced version of those used for the Tevatron storage ring. At the same time, however, DESY also broke new ground in two respects. On the one hand, it was the first time that a project to develop and produce superconducting magnets had involved close collaboration with private industry as well as government institutes

from a number of different countries. For European industry in particular, this presented a unique opportunity, for it was the first time that companies had had an opportunity to gain experience in superconducting technology and cryogenics on such a large scale. The HERA project marked the first time that all of the magnets had been supplied by industry. On the other hand, the design of the magnets proved so successful that it subsequently became the worldwide standard. Indeed, the magnets for the next large proton accelerator, the LHC in Geneva, are based on the principle used for the HERA magnets.

At first glance, however, it's not easy to identify a HERA magnet as such. Nine meters long and weighing 10 tons, it looks like little more than a thick yellow tube. The shape of the magnetic field is determined not by the conventional iron yoke but rather by the superconducting coils that directly surround the vacuum pipe containing the particle beam. With superconducting magnets, a

A complicated system of valves distributes liquid helium to the superconducting magnets of the HERA ring.

Europe's Largest "Refrigerator"

HERA's central refrigeration plant is located in a 2500-square-meter hall. The unit was the largest in Europe when it was built and has been in continuous operation since 1987, providing the superconducting magnets in the HERA ring with a reliable supply of liquid helium. The plant consists of three "lines" of compressors, refrigeration machines and gas purification equipment. Of these, only two are required for routine operation. Should one of the lines go down, however, the third one takes over the refrigeration.

In principle, the plant works like a huge refrigerator or the refrigerating unit of an air conditioner, the only difference being that it uses helium as a refrigerant. The gas is first compressed and purified before being expanded, cooled and liquefied in a system of heat exchangers and turbines. Finally, the liquid helium is transported via two specially insulated pipes to the northern and southern halves of the HERA ring.

When in a warm state, the helium is stored in 18 tanks beside the hall. Under normal operating conditions, however, ten of these remain empty. They are held in reserve as storage tanks for down periods or in the event that superconductivity should break down and the cold helium suddenly vaporize. HERA requires a total of 15 tons of helium, which is approximately equivalent to the world's daily production.

substantial effort is required to keep the coils cold. With the HERA magnets, for example, the operating temperature is minus 269 °Celsius — only four degrees above absolute zero. The magnets are therefore continually cooled with liquid helium. Similarly, the superconducting coils — surrounded by an insulating vacuum with thermal shields and fitted with

a safety system in case the superconductivity breaks down — are placed in a cryostatic temperature regulator, which is what gives the magnets their characteristic shape. In order to keep the magnet coils cold and so maintain their superconductivity over the 6.3 kilometers of the HERA accelerator, what was then the largest refrigeration plant in Europe was built at DESY in 1986. Here, helium gas is first liquefied before being directed around the HERA ring by a sophisticated distribution system.

A view into the "head" of a superconducting magnet and the technically complex connections within.

In the HERA tunnel: the superconducting resonators of the electron ring.

The superconducting cables from which the coils of the proton magnets are wound contain 28 000 filaments.

TECHNO DEVELO

Developing and constructing the superconducting proton ring was undoubtedly one of the most difficult tasks faced by the HERA designers. Superconducting accelerator magnets possess a whole range of properties that distinguish them from conventional, normally conducting magnets, and they require the highest degree of care during their design and production. Here, it is no longer possible to use precisely machined iron pole pieces in order to define the shape of the magnetic field. The shape is instead determined by the superconducting coils, which must be wound with an extremely high precision to ensure that the field errors remain within the required tolerances.

The coils themselves consist of delicate niobium-titanium filaments only fifteen micrometers in diameter, of which there are 1200 in a copper wire 0.8 millimeters thick — a special manufacturing challenge. Twenty-four of these wires are twisted into a flat cable from which the coils are finally wound. In order to keep the errors of the magnetic field within the prescribed range of 0.01 percent, the conductors in the coil must be within two hundredths of a millimeter of their design position. In addition, the strong electric currents in the superconducting coils give rise to powerful magnetic forces that try to separate the two halves of the coil with a force over 100 tons per meter. The coils are therefore clamped together with prestressed aluminum collars that absorb the strong forces and at the same time ensure the required mechanical precision.

The acceptance inspection of the finished magnets turned out to be just as elaborate and difficult. For two years, 70 people worked on it around the clock in three shifts, seven days a week. On average, each magnet was put on the test stand for about 100 hours. If any defects had first been noticed in the tunnel, the HERA team might
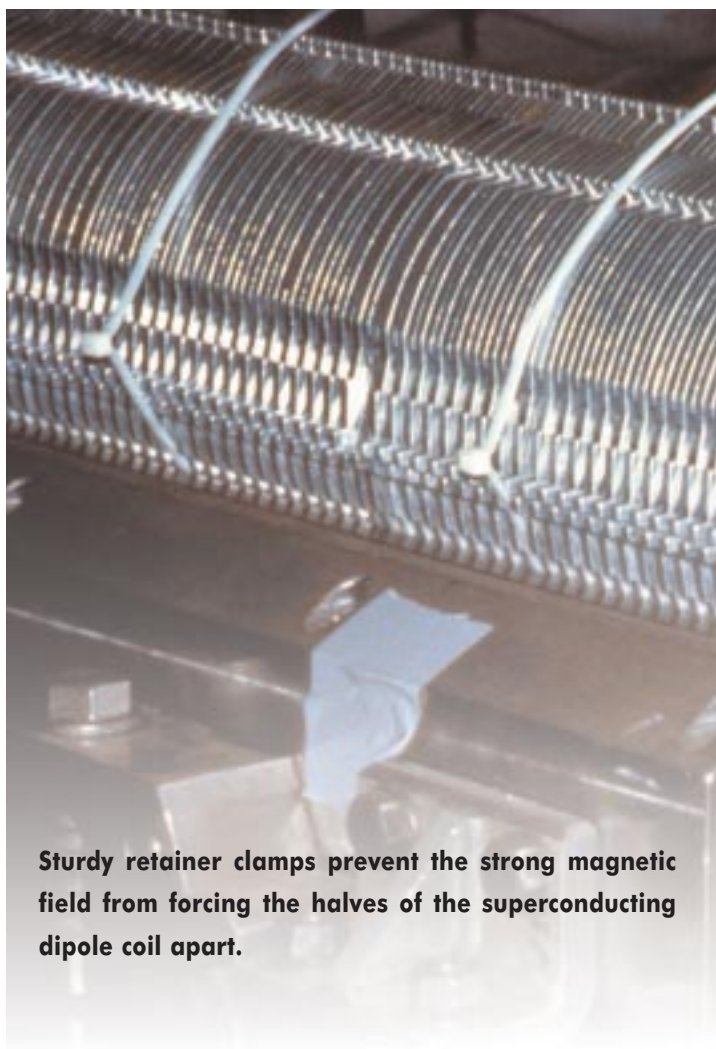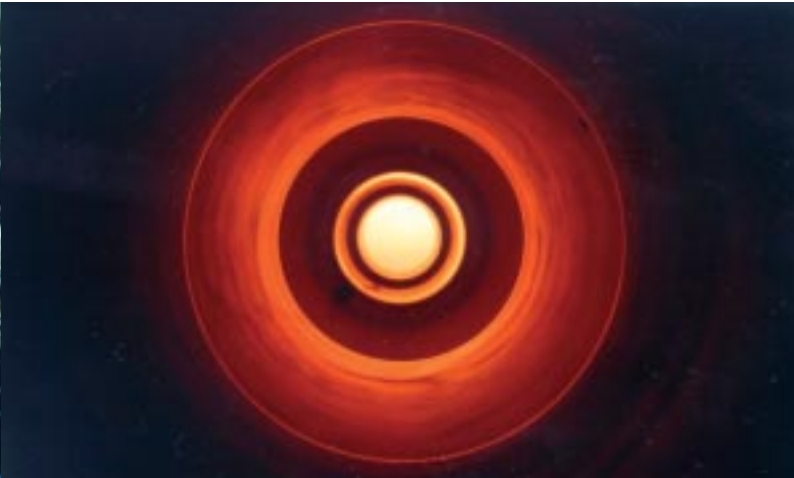
Sturdy retainer clamps prevent the strong magnetic field from forcing the halves of the superconducting dipole coil apart.
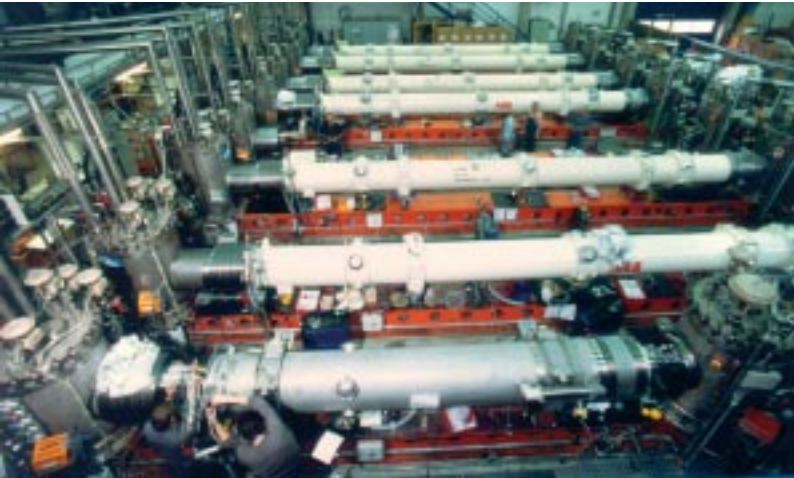
Final inspection of the superconducting proton magnets in the magnet measuring hall.

A glimpse inside a superconducting resonator.

LOGICAL
PMENTS

never have been able to get the accelerator running. Although all the individual components of the magnets and the magnets themselves were manufactured at a great variety of industrial firms around the world, the HERA magnets fulfilled expectations remarkably well. Of the 422 superconducting dipoles and 224 quadrupoles, only eight were initially rejected as unusable and subsequently repaired — far fewer than one would have expected in light of the experiences in the U.S. in this area. The industrial mass production of the HERA magnets was a complete success. All of the magnets significantly exceed the planned field strength of 4.7 tesla. Since 1998, HERA has been accelerating the pro-
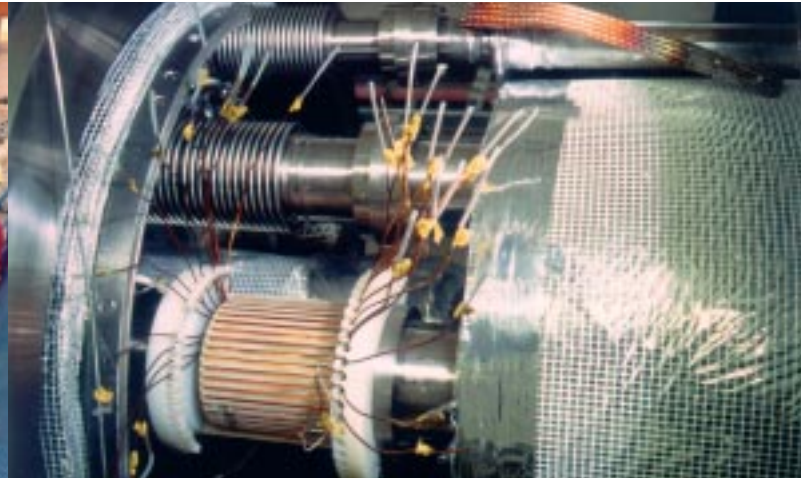
tons to energies as high as 920 gigaelectronvolts (GeV), instead of the 820 GeV originally planned. In order to achieve this, the magnets must be powered up beyond the originally planned field strength, to 5.3 tesla. The readjustment went smoothly, without the superconductivity breaking down in any of the magnets due to the strong electric currents.

For the electron storage ring of HERA, DESY was able to fall back on its experience with the electron-positron storage ring PETRA, which now serves as a preaccelerator for HERA. But here as well, essential technical innovations were introduced, such as the modular design of the magnets. A dipole magnet, quadrupole magnet and sextupole magnet each form one mechanical unit that was assembled prior to installation in the tunnel. This considerably facilitated the construction and adjustment of the electron ring.

For the first time, the vacuum chambers of the beam pipe in which the particles fly through their circuit were made not of aluminum but of copper, which offers better heat dissipation and better shielding against radiation. The majority of the acceleration sections in the electron ring
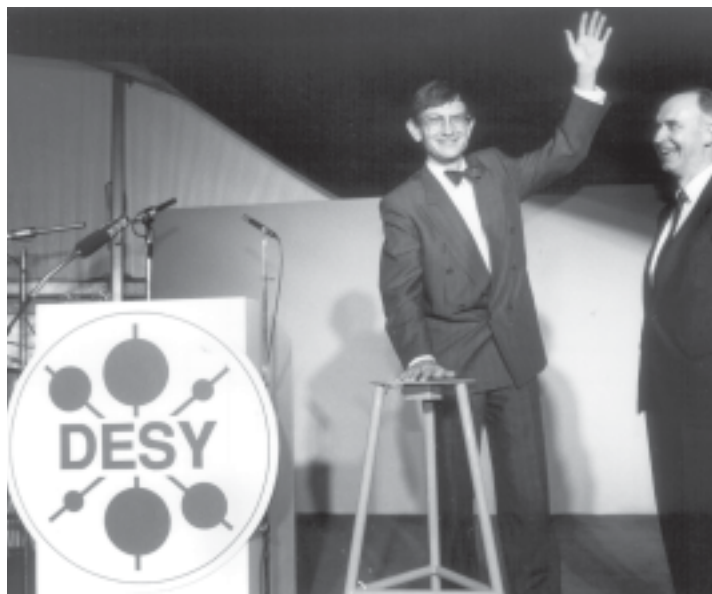
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Test of the superconducting proton magnets for HERA.

Utmost care was required: the connection between two proton magnets.

November 8, 1990: German Minister of Research Heinz Riesenhuber gives the signal for the startup of HERA by pushing a button (right: DESY Director Volker Soergel).

are normally conducting "resonators" in which a 500-megahertz electromagnetic wave accelerates the particles.

The designers also drew on superconductivity here in order to bring the electrons to the nominal energy of 30 GeV with an acceptable outlay of electrical power. The superconducting acceleration resonators made of niobium that were developed in Hamburg under the direction of DESY attained a maximum field strength of 5 megavolts per meter (MV/m), whereas conventional copper resonators provided at most about 1 MV/m at the time. HERA's electron accelerator now contains 16 of these niobium resonators.

HERA comprises two accelerator rings 6.3 kilometers in length — i.e. a total of 12.6 kilometers of beam pipe that must be evacuated to a pressure of 10^{-8} to 10^{-13} millibars.

The accelerator pipes in HERA then become as airless as the surface of the moon: The pressure corresponds to less than a quadrillionth of the air pressure on the surface of the earth. In order to reach it, HERA had to be equipped with an extensive system of vacuum pumps as well as a sophisticated vacuum control sys-

tem, primarily in order to monitor the impermeability of the many welded seams.

Operating an accelerator of such dimensions means regulating and controlling thousands of components, transmitting data over kilometers of cable, and processing that data in a central control room. The complexity of a system of this kind is almost inconceivable — but it works. On November 8, 1990, the startup was celebrated and, as Hamburg's Science Senator Ingo von Münch pointed out, the project came in exactly on budget. Despite the enormous technical challenges, HERA had indeed been completed on schedule and in accordance with the predefined cost boundaries.

HERA's Superconducting Magnets

The superconducting magnets for the proton ring of HERA no longer look like conventional magnets, since the iron yoke for focusing the field lines now plays only a subordinate role. What stands out instead is the effort invested in the helium cooling system, which keeps the superconducting coils of the magnets at their operating temperature of minus 269 °Celsius. The strong electric currents used to operate the HERA magnets give rise to powerful forces in the coils. During operation, the halves of the coils repulse one another with a force that corresponds to the weight of a heavy-duty truck. The coils are therefore held together with sturdy collars.

The HERA magnets are a logical development of the superconducting magnets for the Tevatron accelerator that went into operation at Fermilab near Chicago in 1987. The Tevatron magnets are of the "warm-iron" type, i.e. their iron yoke lies outside the superconducting coils cooled with liquid helium. The advantage of this design is that only the coils themselves must be cooled, not the iron. If, on the other hand, the iron yoke is in the immediate vicinity of the coils and, like them, at liquid helium temperature, the magnet is of the "cold-iron" type.

Although they are cold-iron structures, the HERA magnets are designed in such a way as to combine the benefits of both types. The cooling overhead is higher than in the case of the Tevatron, but the HERA magnets attain a higher field strength. The operational safety is also greater in the case of HERA, since the diodes that divert the current flowing in the coils if the magnetic field breaks down are also built into the cold area and hence provide better protection. The basic concept of the HERA magnets proved to be so successful that it has since won general acceptance.

Eddy Currents and "Flux Creep"

Keeping the field of superconducting magnets under control is not always easy. Powering the field up or down in a superconducting coil gives rise to eddy currents which, like any electric current, are accompanied by magnetic fields. In normally conducting coils, this does not lead to any problems, since eddy currents of this sort quickly die out due to the electrical resistance of the coils. Not so in superconducting coils, in which the eddy currents invariably persist. The interfering fields that result deform the main field — only minutely, of course, but with possible unpleasant consequences in a system as sensitive as HERA. Each of the 646 superconducting magnets of HERA is therefore equipped with a correction coil that is attached directly to the beam pipe, and which enables the interfering fields to be offset.

The difficulty, however, is this: The eddy current fields do not remain constant. When the accelerator is in operation for several hours, the magnetic fields in the proton ring "migrate"; they change their strength. This change is triggered by a special feature of the superconductors known as "flux creep." There are considerable differences in the speed at which this flux creep occurs — it depends on which production facility the superconducting coils come from. For HERA, therefore, two additional magnets — one each from the German manufacturer and the Italian manufacturer — were connected in series with the magnets of the proton ring for use as reference magnets. During operation, their fields are constantly measured by highly sensitive probes, enabling the changes in the ring as a whole to be immediately countered by appropriate adjustment of the correction coils. This system developed for HERA has likewise caught on: At CERN in Geneva, the principle was adopted for the LHC accelerator currently under construction.

HERA
Ready
to Go

The central accelerator control room at DESY could stand up to the bridge of the Starship Enterprise. There is one display screen after another; colorful diagrams alternate with tables, columns of figures, buttons, keyboards and trackballs as far as the eye can see. This is the beating heart of HERA: The two accelerator rings of HERA and all seven preaccelerators are controlled from here. The reason for this is that before the particles are shot into the actual HERA rings, they run through a whole starter system of smaller accelerators that put the particle beam into the right shape and bring it to the right energy.

The particles then reach their final energy in HERA's two large, 6.3-kilometer-long accelerator rings. Afterwards, they are "stored": They fly round their circuit for hours at nearly the speed of light. At the interaction points surrounded by the house-sized detectors H1 and ZEUS, the two particle beams meet head-on. When they do, some electrons and protons collide with full force. The particles arising from the collision scatter in all directions and are ultimately registered by the detection instruments.

All of this can be described so easily here on paper, but it actually verges on a technical miracle. The two 6.3-kilometer accelerators include over 800 deflecting magnets, 1340 focusing magnets, 1200 power supplies and 1500 vacuum pumps, all of which are controlled over cables that are kilometers long. Once the operation of the accelerator becomes routine, the physicists in the control

room know exactly what value the individual magnetic fields must have, what power supplies have which peculiarities, and how a particle beam that has gone astray is put back on track.

If, however, the system is new — and, as in the case of HERA, a new technological development besides — it is first necessary to patiently
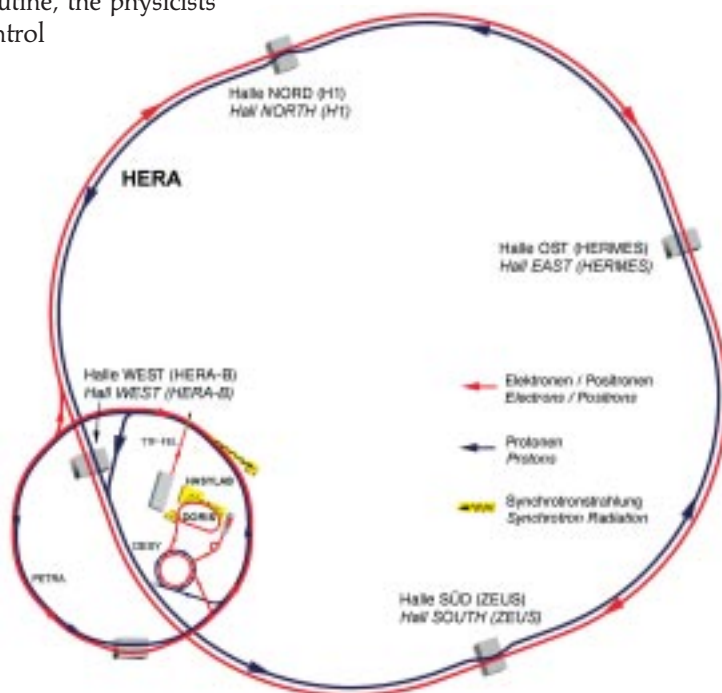
The system of preaccelerators and storage rings at DESY.

seek out the appropriate settings. A particle beam is not a cohesive entity. Instead, it consists of individual "packets" — also called "bunches" — which contain billions of electrons or protons.

The supervisor in the control room must therefore ensure that the bunches are held together, that they are guided around the curve on exactly the prescribed path, that the particles are not disturbed through collisions with residual gas in the vacuum pipe, that the electron and proton beams fly toward one another at the interaction points on trajectories correct to within fractions of a millimeter, and that the individual electron and proton bunches really do arrive there simultaneously! If you bear in mind that the particle beams are only fractions of a millimeter in diameter at the collision points — in other words, as fine as a human hair — this task seems practically insurmountable.

"At HERA, there is absolutely nothing on earth that guarantees the particles will actually collide," says Bernhard Holzer, one of the two coordinators responsible for the operation of HERA. "We accelerate two completely different sorts of particles in entirely separate rings. At two points, the particles are brought together via sophisticated systems of magnets. Things are different in systems in which particles and antiparticles are accelerated. Since those particles differ only in their electric charge, they can circulate in an individual beam pipe; they experience the same forces and automatically arrive at the right place at the right

moment. In our case, though, we first had to go through the trouble of trimming the machine for its job."

In order to be able to control the two particle beams at all, the HERA crew fills the accelerator in two stages: First, the proton beam is shot into the ring, accelerated and optimized. Once all the proton magnets have been adjusted and the beam parameters are at their target values, the protons are temporarily "parked." The beam then courses through the ring a few millimeters above the orbit it has when set for collision operation. This gives the HERA team time to fill the electron ring in the second step. This process is not without repercussions for the proton beam, however, since the latter is likewise flying through the electron magnets ahead of and behind the collision points — through the magnets that focus the electron beam and simultaneously guide it onto the path of the proton beam. As it does so, the fields of the electron magnets act on the protons too, and these disturbances suffice to throw the proton beam off track within a very short time. While the electrons are being shot into HERA and accelerated, the magnetic fields of the proton ring must therefore be constantly corrected in order to compensate for the disturbance. Once both particle beams have been optimized, the proton beam is brought down to a collision course and that mode of operation is "locked in." Holzer comments: "For a long time, this was a special problem peculiar to HERA, and we spent years to optimize the process. Today it's a
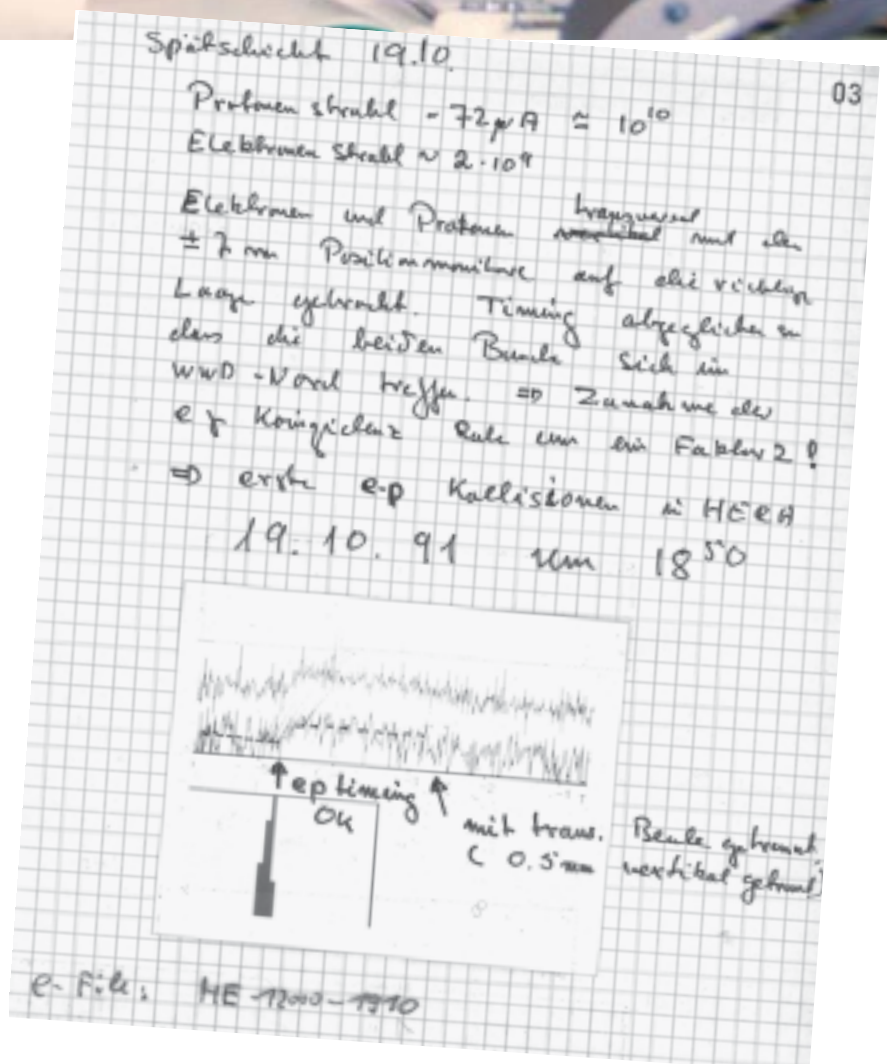
The late shift in the accelerator control room on October 19, 1991. Bjørn H. Wiik performs some final calculations.

routine matter. Meanwhile, our procedure has caught on elsewhere: This optimization process has been adopted at newer accelerators in Japan and the U.S. that also have separate rings."

The initial startup of such a complex system means sorting out one thing after another. Often there are weeks and months of tinkering, trial and error, setbacks and advances before everything is finally right and every magnetic field is positioned correctly, every vacuum pump holds out, and every power supply delivers the right current. On August 17, 1988, the HERA electron beam was up and running for the first time. In the fall of 1990, the last proton magnet was installed, and in the night from April 14 to 15, 1991, the HERA team stored the first proton beam. Then, on October 19, 1991, the announcement came that "HERA works!": For the first time ever, electrons and protons had collided head-on in the two interaction zones.

"HERA works!" Wiik's log entry: "The first e-p collisions in HERA, 10/19/91 at 6:50 p.m."

Bringing Particles up to Speed — the Accelerator Chain

The scene: the accelerator control room at DESY. After the annual winter break it's time to start HERA up again. The power supply units that feed the accelerator have already been started and tested several weeks ago. They perform best when they're running continuously, so they haven't been turned off in the meantime. In the control room, the operators — the physicists, technicians and engineers responsible for running the accelerator — are getting ready to fill HERA with electrons and protons. These particle beams are not boosted from zero to the speed of light solely inside HERA. The acceleration is achieved stepwise in a complex maze of preaccelerators that includes nearly every accelerator built during DESY's 40-year history.

The operators begin with the protons, whose high energy means their behavior remains relatively stable when the electron beam is subsequently added. The protons receive their initial acceleration in the **LINAC III** linear accelerator, which drives them to an energy of 50 million electronvolts. At this energy, they are injected into the **DESY III** synchrotron. Then, at eight billion electronvolts (i.e. eight gigaelectronvolts, GeV), they are transferred into the **PETRA** ring, where they're boosted to 40 GeV.

Ten of the 60 particle bunches from **PETRA** must now be transferred into HERA to optimize the proton ring.

That's no simple feat, since the superconducting magnets of HERA's proton ring are difficult to control. They require special treatment before they can produce the necessary magnetic field with an accuracy of 0.05 percent. This involves "massaging" HERA's superconducting magnets for 20 minutes in a special "warm-up" process without a particle beam, i.e. running them through a specific cycle of procedures. Only then can the operators be sure that the injected proton beam will encounter the correct magnetic fields inside HERA.

Those ten initial proton bunches are then injected into HERA so that the operators can use them to optimize the accelerator, test the beam parameters and minimize beam losses. The latter objective is aided by the experiments. Then at last it's time to finish filling HERA's proton ring — with three **PETRA** fillings of 60 particle bunches each — and accelerate the beam to its final energy of 920 GeV. At this maximum energy, the operators park the proton beam in a slightly higher trajectory by shifting it upwards just a few millimeters, where it can continue to orbit undisturbed while the electrons are fed into HERA.

The electron beam is likewise run through a series of preaccelerators — from **LINAC II** through the **DESY II** synchrotron to **PETRA II** — before it is injected in the form of 189 particle bunches into HERA's electron ring. If all goes well, this process takes only a few minutes, because the magnets of the electron ring are not superconducting and do not require special treatment.

As a final step, the operators must synchronize the timing of the particles in their respective paths: There would be no sense in having the proton bunches arrive at the interaction point while the electrons are somewhere else. To accomplish this, the proton beam is steered into the "inside track," where its particles begin to match the rhythm of the electron bunches traveling in the opposite direction. Once the particle bunches are moving in sync, the proton beam is shifted back to its normal path. Now the process has reached its operational stage: The particles collide at the interaction points — initially just a few of them. It takes another quarter of an hour of optimizing parameters and narrowing the beam diameter to fine-tune the operation to the requirements of each experiment.

This process calls for all the expertise and experience on the part of the operators, as well as excellent coordination between the accelerator crew and the scientists conducting the experiments. HERA is not a machine that can be operated by simply pushing a few buttons. It's essential to know the system and be aware of how to get the most out of it. In fact, it takes two years for a newcomer to master all the procedures and run the accelerator.

HERA IN OPERATION

The first particle collisions in a storage ring are a bit like the first words from the mouth of a small child: The parents are ecstatic, the relatives delighted — but it will take a good long time yet before the talented youngster learns to join up words to produce entire sentences. That's how it is with a large accelerator. The first particle collisions represent a milestone — they prove the machine is actually working. Then comes the learning curve, a period of getting the hang of the system. It takes several years before a system as technologically complex as HERA, with its dual accelerator rings, can be controlled with just a few keystrokes to provide the optimized conditions required for the various experiments.

It's not just a matter of getting the accelerator itself up and running: The operation must be tuned precisely to the requirements of the individual experiments that use the particle beams. In a system in which all of the experiments being conducted are alike — as was the case at the large LEP electron-positron collider at the CERN research center in Geneva — the boundary conditions of the experiments are essentially identical. HERA is the world's only accelerator in which two collision experiments and two beam-target experiments are conducted simultaneously. Each beam-target experiment uses only one of the two particle beams, which is made to strike a stationary target. The boundary conditions of these experiments differ substantially from one another. "Integrating all four experiments into daily operations has been pretty nerve-wracking at times," says Bernhard Holzer, who came to HERA in 1991 as a postdoctoral scientist and is now in charge of coordinating the operation of the system. "Both sides have had to practice and learn a lot, because the experimenters also need time to optimize conditions for their setups. To make this work, we've got to have close coordination between the experiment groups and the HERA crew. That's not always easy, but it's a lot of fun to join forces in finding solutions to problems."

When HERMES was first installed, the background of unwanted reactions was so high that none of the three experiments then installed were able to perform any meaningful measurements. So the experts from the HERA crew joined the HERMES coordinators to identify the origin of the problem. They were able to use the HERMES detector to identify the type, energy and direction of the interfering events, and after a few weeks the problem was solved. The process was similar when HERA-B, the fourth experiment, was integrated into the operation. Here the problem was that, after the intended collisions with the target wires in HERA-B, the protons would drift through the accelerator and trigger interfering signals in the

other three detectors. A task force was formed to tackle the problem. Experts from each of the four experiments met with the HERA team on a daily basis to determine who had made what changes, and how these changes had affected the detectors and the accelerator. In this case too, the consistent team-oriented approach was successful — and brought the task force a measure of celebrity even outside DESY circles.

HERA has been in operation since 1992. Throughout this period, the accelerator crew has been able to increase the power and efficiency of the storage ring, year after year. In certain parameters HERA even exceeds the original target values. An example is its luminosity — the reaction rate of the electrons and protons, i.e. the number of particle collisions produced by the accelerator in a given time span. "We started out very carefully," Holzer recalls, "with low intensities and therefore low luminosity. After all, we first

had to learn how to handle the high proton energy, initially 820 gigaelectronvolts." In a step-by-step process, the team then proceeded to reduce the cross-section of the particle beams and fill the ring with more particle bunches.

The annual winter breaks were used to keep improving HERA. As an example, there was a problem for a long time with actually operating the electron storage ring with electrons, and not just with positrons (their antiparticles): The lifetime of the stored electron beam was unexpectedly short. In the original design, the vacuum in the electron beam pipe was maintained by ion getter pumps. But such pumps can create positively charged dust particles, and these were probably being

Vacuum chambers stretching over a total of five kilometers had to be removed, modified and replaced to convert HERA for operation with electrons. The yellow "HERA Tram" hauls the heavy accelerator components to their proper location.

captured by the negatively charged electrons and consequently interfering with the particle beam. To circumvent this problem, HERA was temporarily converted in 1994 to operate with positrons. As a result, the lifetime of the beam was roughly doubled. To make HERA work well with electrons also, all of the electron storage ring's vacuum pumps were replaced during the 1997/98 winter break with absorption pumps, which do not require a high voltage and consequently introduce no troublesome charged dust particles into the vacuum pipe. In this project, a total of five kilometers of HERA's vacuum chambers had to be removed, modified and reinstalled. But the effort was worth it: The lifetime of the electron beam is now sufficient for the experiments.

Step by step, the HERA team also continued improving the reliability and user-friendliness of the facility. By 1998, the once cumbersome

control system of HERA had been completely converted to PCs. The new system requires far fewer actions on the part of control room personnel, and considerably simplifies the operation of the facility, including the four experiments. For example, the acceleration sections in the northern and southern parts of the HERA ring — where the two collision experiments, H1 and ZEUS, are located — can now be adjusted simultaneously, which was previously impossible. What's more, the installation of additional components has improved the stability of HERA across the board. This investment has really paid off: In 1997, the luminosity (integrated over one measuring period) exceeded its design value for the first time. In 1999, HERA reached the same reaction rate in electron operation that it had attained with positrons in 1997, even though the proton energy had in the meantime been increased from 820 to 920 giga-

electronvolts. The conversion was thus trouble-free, despite the increased stresses on the system components. After a superlative year of operation in 2000, when HERA produced more particle collisions than in any prior year, comprehensive changes were scheduled between September 2000 and the summer of 2001 to quadruple HERA's luminosity and to supply the H1 and ZEUS experiments with polarized electrons and positrons.

Everything under Control

HERA itself is an underground high-tech facility containing two particle rings, each of which are 6.3 kilometers in length. Add to this seven preaccelerators with a total length of several additional kilometers, and what you get is a gigantic complex of technical systems that must all run synchronously — with an accuracy of better than one billionth of a second — to transport the particles to the right place at the right time. Controlling this facility requires interrogating, monitoring and adjusting high-tech components within fractions of a second, some of them at distances of a few kilometers, where they are operated largely independently of each other.

"It wouldn't be possible to control a system of this scope with just a central computer and many long cables," explains Reinhard Bacher, Group Manager, Accelerator Control Software and Engineering. "Instead, the control of HERA relies on a distributed, largely PC-based system structured on three levels." On the first level, multiple stand-alone computers control local systems directly at the accelerator. These are known as FECs — Front-End Computers — and are located in the immediate vicinity of "their" component, where they independently manage its functions, i.e. control power supplies or read out measuring instruments. The FECs transmit their information to the other computers in the control system via the accelerator intranet. The mid-level computers perform general, cross-functional processes, such as logging alarms and archiving data. The computers at the third level constitute the human-machine interface: This is where different processes are displayed, settings are changed, subsystems monitored, and data analyzed.

This approach means that the design of the HERA control system is modular and locally intelligent. "If one of the computers fails, it doesn't mean that the entire system crashes, which is a possibility with a central computer," Bacher explains. "What's more, the distributed system gives the physicists and engineers the greatest possible freedom to achieve optimum control of the accelerator components. Everyone can select the very hardware and software elements best suited to a specific task." While all common operating systems can be found among the lowest-level computers, all those on the top level run Windows. After all, there's no point in constantly reinventing what's available shrink-wrapped at a lower price and with a wide range to choose from — it pays to take advantage of the products and standards available on the commercial software market.

HERA's is the world's largest PC-supported accelerator control system. It can be accessed and operated from any office at DESY, in principle even from anywhere in the world. "But ensuring efficient communication in such a system — between the most diverse processes on different types of computers running dissimilar operating systems — remains a major challenge," emphasizes Bacher. To master this challenge, DESY scientists have spent the last ten years developing TINE, a communications software package that enables all of the software systems at HERA to communicate with one another — a service far superior in performance to existing commercial software products.

The HERA storage ring passes through four immense underground halls, one at each point of the compass. Here, seven stories below the earth, are the detectors used by the international research teams to investigate the most minute building blocks of matter. In 1992, the first two experiments went into operation — H1 in the North Hall and ZEUS in the South Hall. Both experiments observe the high-energy collisions of electrons and protons in order to unravel the internal structure of the proton and the mysteries of nature's fundamental forces. The HERMES experiment has been located in the East Hall since 1995. It uses the HERA electron beam to investigate the intrinsic angular momentum — the spin — of protons and neutrons. Since 1998, the West Hall has housed the experiment HERA-B, which uses the proton beam from the storage ring to illuminate the properties of the heavy quarks.
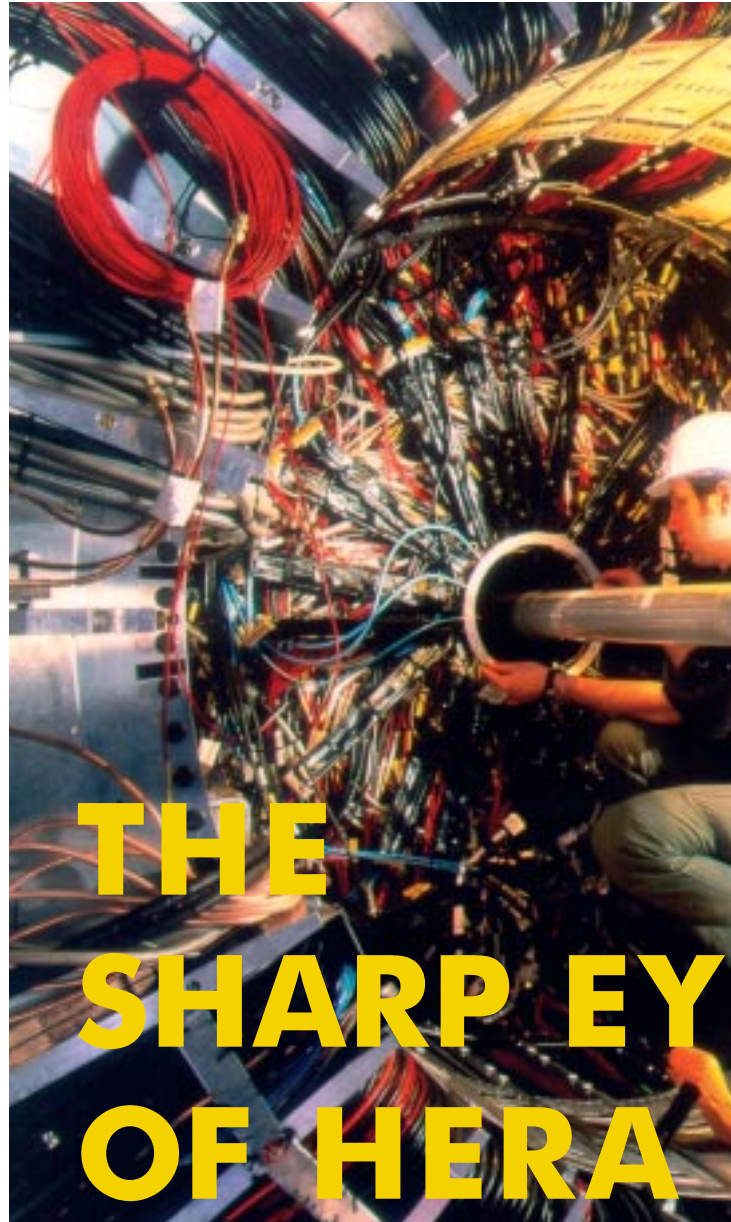
THE SHARP EY OF HERA

The detectors assembled in the underground chambers of the HERA ring are like giant high-power cameras. They are as tall as a three-story building, weigh half as much as the Eiffel Tower, and are packed with hundreds of thousands of electronic components. In order to detect as many of the particles released in all directions during the collisions as possible, the individual components of the H1 and ZEUS experiments surround the interaction point where the electrons and protons collide in successive shells. For the HERMES and HERA-B beam-target experiments, the individual detectors are arranged in consecutive layers. This is because in the latter case, the particle beams collide with a stationary target and the particles produced in the course of the collision only emerge in a narrow cone spreading out along the direction of the incident beam.

The detector components distinguish neutral particles from those with an electric charge and heavy particles from those with a lower mass. The particles are classified according to the degree of interaction they have with the material of the detector. Each detector component has a distinct function. Some components count the particles that pass through them, while others measure the curved particle tracks or bring some particles to a halt in order to determine their energy. The time of arrival of each particle is also recorded with high precision. After all, the measured signals have to be assigned to the correct electron-proton collision. Thousands of cables and optical fibers convey the infor-

14 000 gold-coated wires: the drift chamber of the H1 experiment, in which the tracks of particles passing through are recorded and measured.

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mation to the processing electronics.

The giant machines take ten million pictures of particle collisions, known as events, every second. Immediately after the events are recorded, the electronic equipment automatically selects the promising candidates according to criteria defined by the physicists. In any given second, some ten events might fulfill such requirements. This means that the H1 and ZEUS experiments produce more than 100 million pictures of particle collisions in a normal year of operation of HERA. These images are then analyzed and evaluated for various physical phenomena by the large, international research teams that operate the detectors.

H1 and ZEUS — Electrons Probe the Proton

In the H1 and ZEUS collision experiments, electrons that circle around the HERA ring in one direction smash head-on in the center of the detectors into protons coming from the other direction. In such collisions, the tiny, point-like electron acts as a miniscule probe that can scan the inside of the proton. It penetrates into the proton, where it may come up against one of the quarks from which the proton is made. This can lead to "communication" between the electron and the quark in the form of an exchange of a force particle. The quark is expelled from the proton in this process, forming a bunch of new particles that fly off in all directions along with the electron and the proton fragments.

The tracks that these particles leave behind in the detectors can be used to deduce what really occurs within the proton. This involves more than just learning about components that make up the proton; it also concerns the fundamental forces of nature acting between particles. At HERA, the proton acts as a microlaboratory for the investigation of various theories of modern particle physics. The energy available for these experiments is about ten times greater than that of similar experiments in the past. HERA thus functions like a "super electron microscope" with the world's sharpest view of the proton's interior. H1 and ZEUS can examine the details of proton structure ten times more precisely than was previously possible, right down to structures not even one two-thousandth the size of the proton itself — in other words, 0.000 000 000 000 000 000 5 meters.

As thin as one quarter the thickness of a single human hair: The readout wires of a silicon strip detector used for the HERA experiments.

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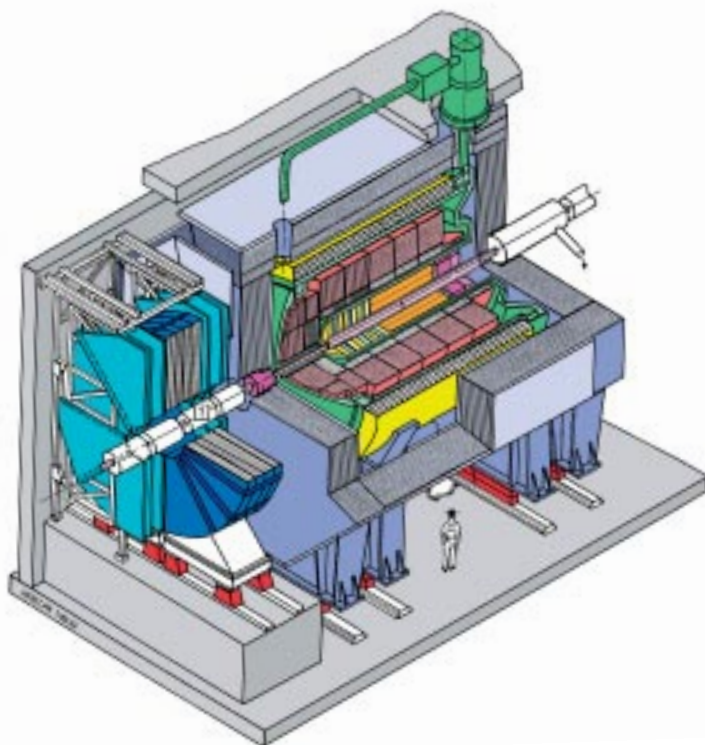
Keyword: Detector

A detector is the general term for a device that detects particles or radiation. In particle physics, this can also refer to an entire experiment, frequently a huge apparatus consisting of many detectors that detect, identify and measure the end products of particle reactions.

HERA's experiments with colliding particle beams — H1 and ZEUS — use universal detectors that record the maximum number of reactions and detect as many of the reaction products as possible. The interaction point where the particle beams collide is thus almost entirely surrounded by layers of highly sensitive detecting equipment.

The innermost layer detects the interaction point and the decay positions of the shortest lived particles with high precision using detectors made of semiconductor plates. So-called drift chambers record and measure the tracks left behind by electrically charged particles. A magnetic field deflects their course, allowing their momentum to be determined.
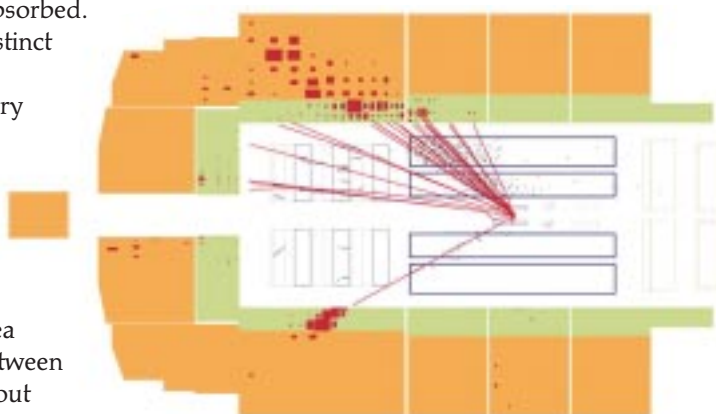
The next layer is formed by so-called calorimeters that measure the energy of individual particles or of whole jets of particles. Typically, 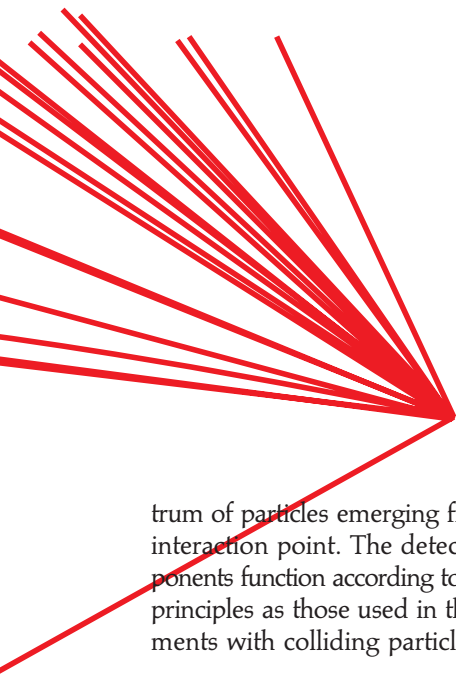the innermost, electromagnetic portion of the calorimeter measures the "particle showers" which electrons and photons (particles of light) create in materials with a high atomic number, such as lead, and which are recorded in various counters. The outer layer of the calorimeters detects the remaining hadrons, i.e. particles that interact with the material in the calorimeter via the strong force, causing avalanches of electrically charged secondary particles in plates made of very dense material. These particles are recorded by counters between the plates.

Muons, the heavier siblings of electrons, are frequently a clue that a reaction may be of interest. They can penetrate dense layers of material without being absorbed. This makes them distinct from other particles. Because it is necessary to use an iron yoke to channel the magnetic fields in the coils, this is often employed as an additional absorber, and large-area detecting devices between the iron plates pick out the tracks of muons passing through them.

Some particles, like neutrinos, do not leave tracks in the detectors. However, if the detector completely surrounds the interaction point, it is possible to infer the existence of such particles indirectly from the conservation of energy and momentum.

In the experiments where a single particle beam is aimed at a stationary target (HERMES and HERA-B), most of the reaction products emerge in a cone spreading in the direction of travel of the incident beam. Therefore, the "spectrometers" that form the detectors in this case do not fully surround the interaction point. They are actually composed of successive chambers for detecting the entire spec-

trum of particles emerging from the interaction point. The detector components function according to the same principles as those used in the experiments with colliding particle beams.
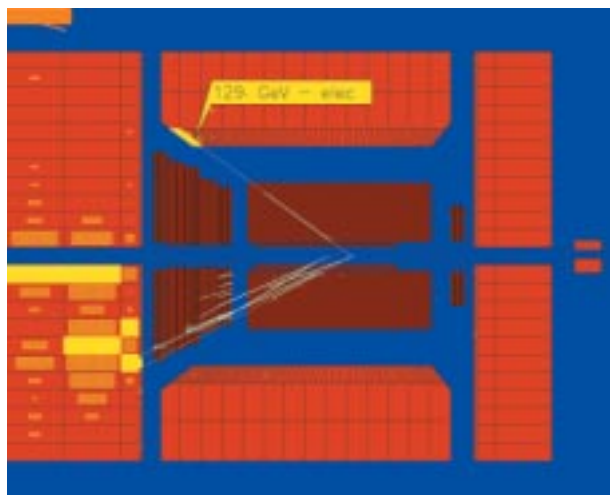
In order to distinguish interesting reactions from processes that are already well understood, as well as from unwanted background reactions, the signals from the detectors have to be analyzed for their properties in fractions of a second. Signals from the counters are thus fed initially into an electronic delay line, known as the "pipeline," where fast electronics determine whether there

are signs that a reaction will be of interest. The various stages of these analyses are performed in a few thousandths of a second, with each stage involving stricter criteria as to whether a certain reaction should be saved. The electronics therefore sort through 10 million events every second to emerge with about ten of the most promising.

The reactions that have been accepted are stored in compressed format at DESY's central computer center. They are primarily analyzed by physicists at the off-site institutes participating in the experiments. Several selection processes pick out the events according to relevant hypotheses, until the reactions featuring the physical processes to be investigated are filtered out.
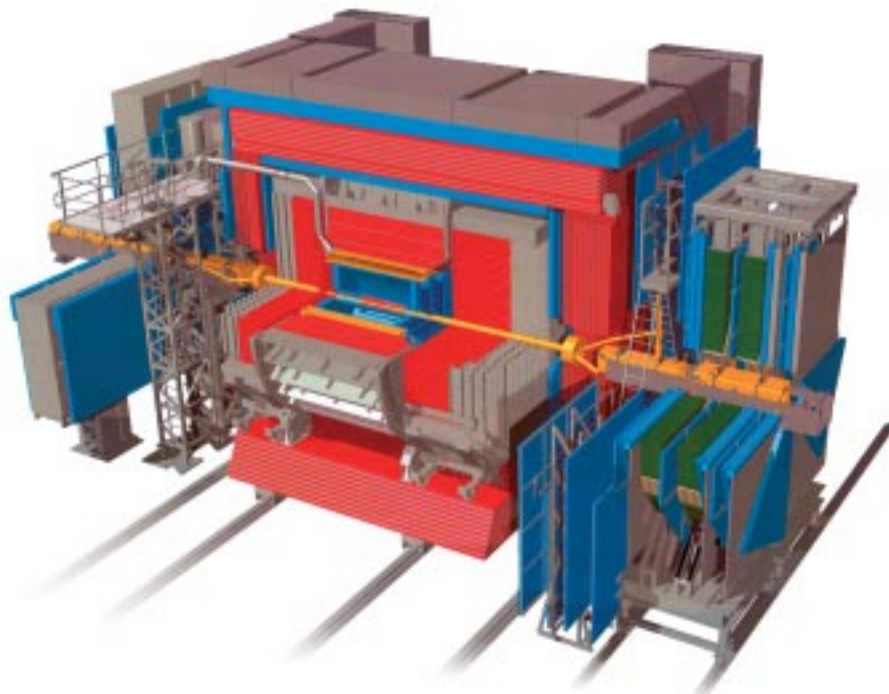
H1 and ZEUS: Two Detectors See More

Complex and difficult experiments on the scale of today's particle physics experiments can no longer be undertaken by a single country relying solely on its own resources. The detectors are therefore planned, constructed and operated by large international teams. The H1 group includes 330 physicists, technicians and engineers from 37 institutes in 12 countries. ZEUS has 360 members from 51 institutes in 12 countries. The experiments differ in their detailed designs, although they address similar research aims. This has a definite logic and is based on the unique aspect of HERA: Nowhere else in the world can electrons and protons be made to collide at such high energies. With two experiments, the number of rare processes identified in this new scientific territory can be doubled. In addition, it is essential for two independent research teams to make measurements to confirm each other's findings, thus cementing the results. As such, H1 and ZEUS both complement each other and serve to check each other's results.
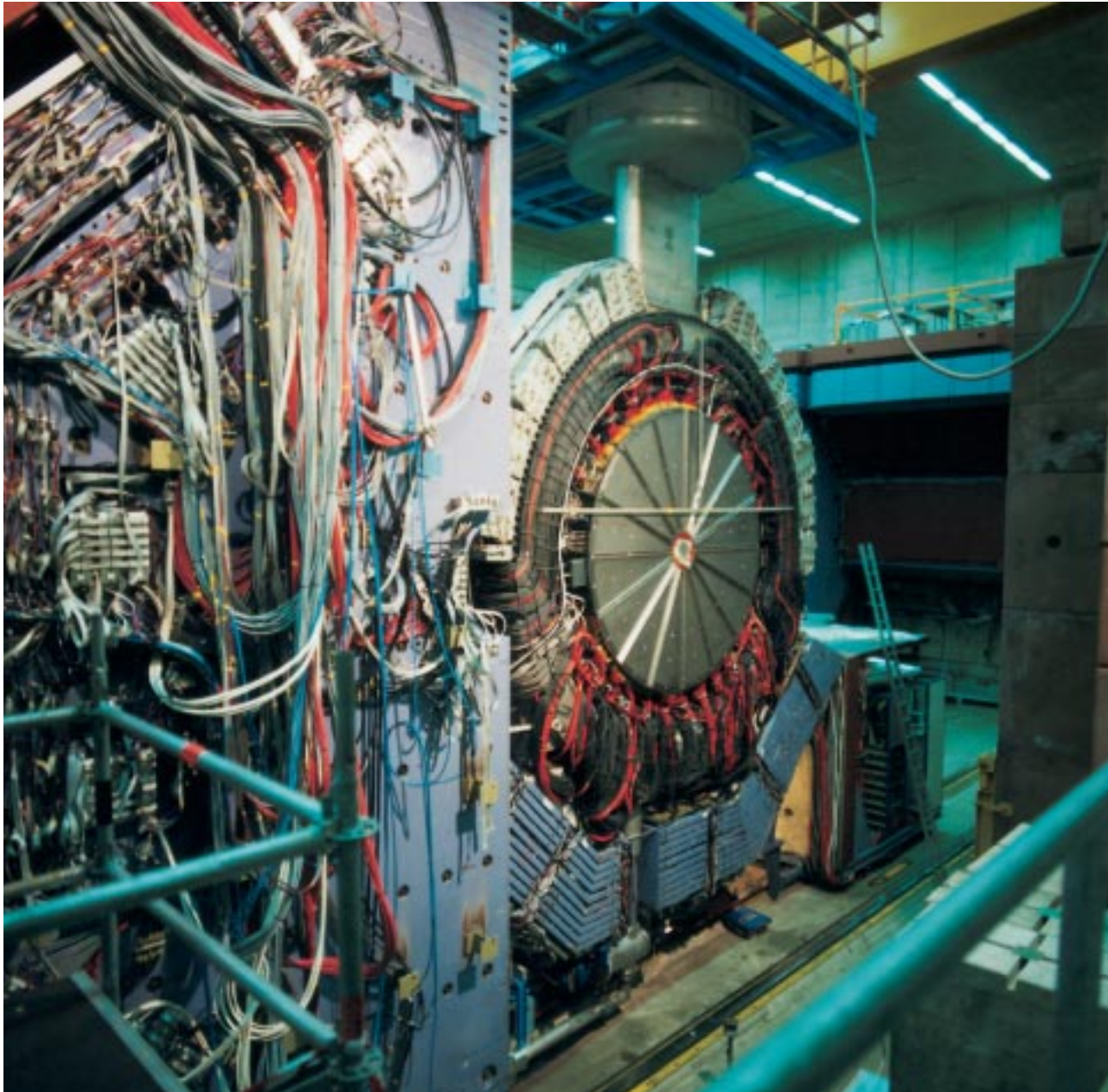
Under construction: the H1 detector in HERA's North Hall...

H1 and ZEUS use different detecting methods to pursue similar research aims. "We are determining the same physical quantities but are deriving them from quite different measurements," explains Eckhard Elsen, spokesman for the H1 group. The main difference is in the calorimeters — the detector components that slow down the particles produced and measure their energies. The H1 calorimeter consists of lead and steel plates, the space between which is filled with liquid argon. This enables particularly accurate measurements of particles that interact via the electromagnetic force, especially scattered electrons. "Our detector is also very finely divided into about 45 000 segments," Elsen says. "We can thus very accurately resolve the structure of the particle showers and even determine the direction of the particles' path. So there are many methods available to us for determining the course of a reaction process." In H1, the huge superconducting coil curving the paths of the particles also surrounds the calorimeter. "This means the particles don't have to pass through any other 'inactive' material before reaching the calorimeter," Elsen explains. That stops the particles from losing energy in the material of the coil, something that would require the energy measurements to be corrected.

H1 — Universal Detector in HERA's North Hall

In operation since 1992
12 m x 10 m x 15 m; 2800 metric tons;
from interior to exterior consisting of:
a silicon microvertex detector,
wire chamber system,
liquid argon calorimeter,
superconducting coil,
muon chambers in instrumented iron yoke,
muon spectrometer,
luminosity monitor,
forward direction proton detector
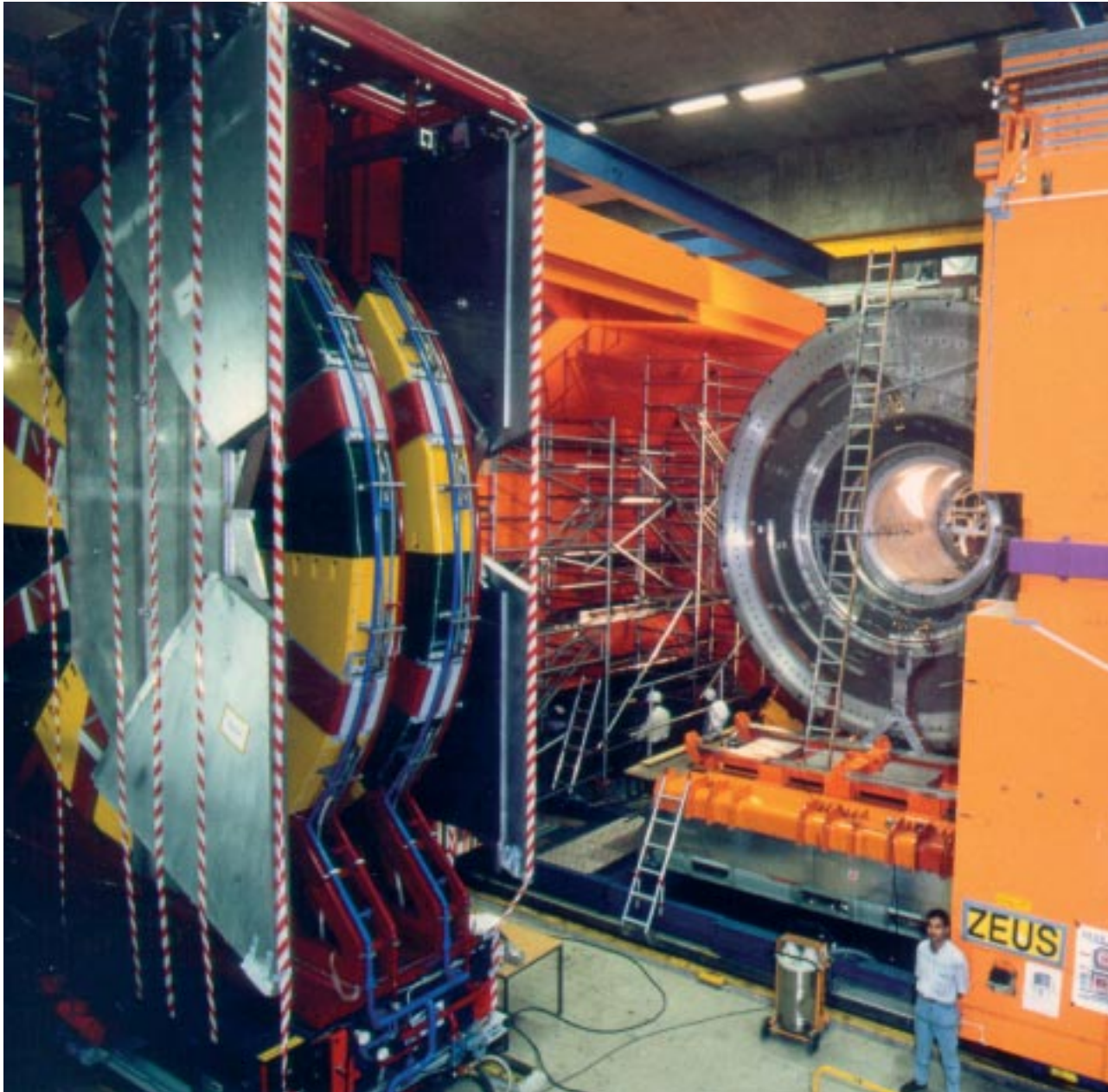
...and the ZEUS detector in HERA's South Hall.

Whereas H1 concentrates on measuring the properties of the electrons, at ZEUS we focus on the particles that interact via the strong force, the hadrons," says Wolfram Zeuner of the ZEUS experiment. These are formed from the quarks ejected from the proton by the collisions. They emerge from the point of collision as narrow bunches of particles — so-called jets. The ZEUS calorimeter consists of successive layers of depleted uranium and scintillator plates that emit bursts of light when the particles pass through them. The key feature is that electrons produce the same signals in the calorimeter as hadrons. "Unlike the situation with H1, we do not have to determine which particle we have halted before calculating its energy," says Zeuner. "We can more or less read off the energy of each particle directly." Furthermore, the energy resolution that ZEUS can achieve for hadron jets is particularly good, which is why the physicists working on ZEUS pay more attention to the measurements of such jets when analyzing results. "To ensure that we do not make any mistakes, we always check the results using the analyzing method of the other experiment," Zeuner explains. "However, we get the most reliable results from using our own procedures."

ZEUS — Universal Detector in HERA's South Hall

In operation since 1992
12 m x 11 m x 15 m; 3600 metric tons;
from interior to exterior consisting of:
a silicon microvertex detector,
wire chamber system,
superconducting coil,
scintillator-uranium calorimeter,
beam pipe calorimeter,
muon chambers,
instrumented iron yoke,
muon spectrometer,
luminosity monitor,
forward direction proton detector

HERMES and Nucleon Spin

HERA's East Hall is the site of the HERMES experiment, in which physicists are seeking to discover the secrets of nucleon

Spin:

The intrinsic angular momentum of particles. A particle's spin is perhaps best described by the motion of a spinning top, although this image has its limits in that particles such as electrons, quarks and gluons are currently believed to have no intrinsic size and therefore cannot really spin on their axis. In a magnetic field, the magnetic moment associated with spin causes the particles to act like tiny magnets and align themselves with the lines of the magnetic field.

spin. It is not presently known how the spin of nucleons — protons and neutrons — arises. It initially appeared as though almost all properties of nucleons (such as charge, spin and magnetic moment) could be explained in terms of their three main components, the so-called valence quarks. Since the end of the 1980s, however, it has emerged that the valence quarks can provide only about one third of the total spin between them. So where do the other two thirds come from? "Nowadays, it is assumed that not only the three valence quarks contribute to the spin of a nucleon but also the other particles that it consists of," says Manuella Vincter, former coordinator of physics analysis for HERMES. "These include short-lived quarks and antiquarks that appear from nowhere and then disappear again, as well as the gluons that are exchanged between the quarks. In addition, the motion of all these particles within the nucleon produces extra orbital angular momentum that also has to be taken into account." The origin of the missing two thirds of the spin remains an open mystery. The ability to determine each of the individual contributions is limited by current experimental and theoretical capabilities.

For HERMES, the high-energy electron beam of HERA is aimed at a target cell filled with gas, where the electrons collide with nucleons in the atomic nuclei of the gas. The key feature is that both the electrons from HERA and the atoms of gas can be polarized, i.e. they have a favored direction of spin.

"The nature and frequency of the particle collisions is dependent upon this polarization," says Vincter. "The various contributions to the spin of the nucleons can be derived by comparing the particle reactions occurring at different directions of polarization of the gas atoms."

Unlike older experiments, which could only identify the quarks' contribution to the spin as a whole, HERMES uses new technologies that allow the various contributions to the spin of the nucleons to be determined individually. This includes the gaseous target that is struck by the polarized electron beam from HERA. Unlike the usual targets, which are normally solid, the gas target contains no impurity atoms, allowing a very high degree of polarization. Moreover, unlike other experiments, the HERMES detector is able to capture and identify not only the electrons scattered in the collisions but also the particles created therein. This means that the distribution of nucleon spin as provided by the various kinds of quarks can be resolved. Nor is the spin of the gluons concealed from HERMES: It was the first experiment in the world to provide a direct indication of the contribution to nucleon spin made by the gluons, which bind the quarks together.

HERMES — Spectrometer in HERA's East Hall

In operation since 1995
Uses the longtitudinally polarized
electron beam from HERA
3.5 m x 8 m x 5 m; 400 metric tons;
polarized gas target,
spectrometer magnet,
Cherenkov counter (since 1998, a Ring
Imaging Cherenkov (RICH) detector),
planar drift chambers,
transition radiation detector,
lead-glass calorimeter
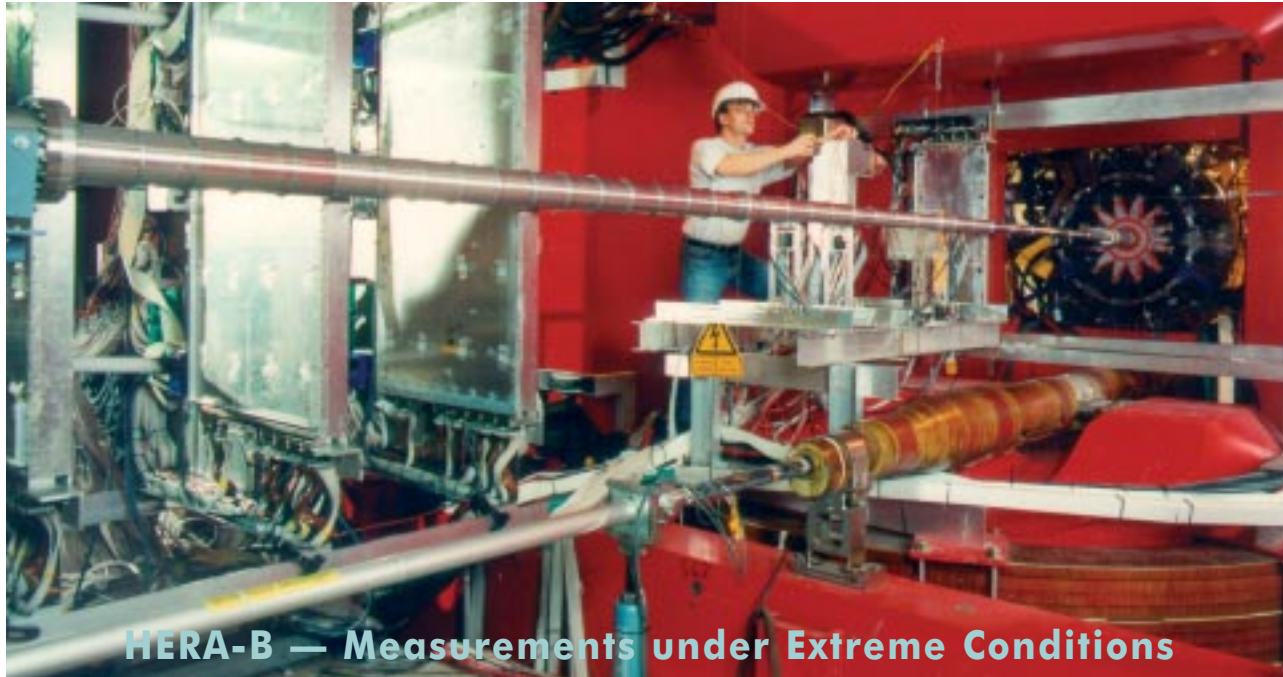
HERA-B — Measurements under Extreme Conditions

The newest member of the line-up of experiments at HERA is HERA-B, which is located in the western part of the storage ring. A detector 20 meters in length surrounds HERA's proton beam pipe like a giant funnel that fills the entire space available for experiments in the West Hall. HERA-B only uses HERA's proton beam, directing it onto a target of fine wires. This produces a cascade of particles that are

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Target:

An object against which particles are fired to trigger reactions that can then be observed.

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recorded within the detector. Among these are the very rare occurrences of pairs of particles composed of heavy quarks — the B mesons that give the experiment its name. "HERA-B was specially constructed to investigate certain decays of these B mesons," explains Bernhard Schmidt, HERA-B group leader at DESY. These processes are seen even much more rarely than the particles themselves, however. "From 100 billion events, only one will feature the desired reaction. So the detector has to process a vast number of particle tracks before one of these processes occurs." This flood of data that HERA-B has to deal with every second is equivalent to the entire flow of information that passes through Deutsche Telekom's entire network! "The huge particle flux places enormous technical demands on the

ability of the detector components and the electronic data acquisition system to withstand radiation," Schmidt emphasizes.

In the middle of the 1990s, when the experiment was first approved, there were still no proven means of detection in such extreme measuring conditions. This meant that the HERA-B team had to develop completely new technologies in order to filter out the desired processes from the vast quantity of data. The international research group had to design and build particle detectors with hitherto unattained resistance to radiation as well as electronic procedures for the rapid processing of data. In both areas, the HERA-B group conducted pioneering work for future experiments, where similarly harsh conditions will pertain. These will include experiments with the Large Hadron Collider (LHC) accelerator currently under construction at the CERN research center in Geneva.

HERA-B was originally designed to investigate the question as to why the universe is composed primarily of matter, although the big bang produced matter and antimatter in equal quantities. This puzzle may be studied using the aforementioned B mesons. It was clear from the beginning, however, that the experiment would be exceptionally difficult, especially with regard to the detectors to be developed. There were in fact unexpected difficulties during development, which led to delays. At the

same time, specialized electron-positron storage rings were being built in Japan and the U.S., each involving a single experiment, and both of which had already provided the first results regarding the matter-antimatter puzzle in 2001. The HERA-B group therefore got together at the end of 2000 to decide how their experiment should continue. Since 2001, the team has now been pursuing a different physics program that uses the existing capability of the detector to its maximum. Investigations are now concentrating on the strong force, one of the four fundamental forces of nature. For example, it is being examined how charm quarks are produced within the nuclei of atoms and how they react with other matter in the nucleus.

HERA-B – Spectrometer in HERA's West Hall

In operation since 1999
Uses the proton beam from HERA
8 m x 20 m x 9 m; 1000 metric tons;
internal wire target,
silicon vertex detector,
track chambers,
Ring Imaging Cherenkov (RICH) detector,
calorimeter,
muon chambers

Polarized
Electrons

A special technical feature of the HERA storage ring is the "polarization" of the electron or positron beam on which the HERMES experiment is based. It may help to visualize these atomic particles if you think of them as miniature tops whirling in the microcosm — although this is not the ideal comparison, since these elementary particles are point-like and therefore cannot really spin on their axes. In their professional jargon however, researchers speak of the "spin" of such particles. Even very complex structures like nucleons (protons and neutrons), which are composed of smaller components, have "spin." Exactly how this "spin" comes about is still not fully understood.

If we wish to solve this puzzle, it will not be enough to simply make elementary particles collide. At HERMES, the colliding particles — the electrons from the HERA storage ring and the atoms of the gas target — must be polarized; i.e. their spins must point in a single preferred direction. "Before the HERMES experiment could be approved, it had to be demonstrated that the electron beam from HERA could in fact be longitudinally polarized — that is, parallel to the electrons' direction of motion," explains Marc Beckmann, a postdoctoral scientist working at HERMES.

In the mid-1960s, the Russian physicists Arsenii A. Sokolov and Igor M. Ternov discovered that electrons in a storage ring automatically align themselves in a preferred direction antiparallel to the magnetic fields that keep them on their circular paths, and thus perpendicular to the direction in which the particles are moving. This effect was also observed at HERA shortly after the facility went into operation. "However, for the HERMES experiment we needed electrons whose spins pointed in a direction parallel to their direction of motion," says Beckmann. "So the aim was to change the direction of the electrons' spins just in front of HERA's East Hall, in which the experiment was to be set up, from the vertical direction to the electrons' direction of motion — and then reset them to their starting orientation a short distance behind the detector." For this purpose, DESY physicist Klaus Steffen, and Jean Buon from Orsay, France, developed a 60-meter-long "spin rotator" — a system consisting of eight deflection magnets lined up in a row, which divert the electron beam into a kind of "corkscrew path." In the process, the particles' spin makes a complicated reeling motion and finally ends up pointing in the desired direction when the exit of the spin rotator is reached. Behind the experimental area stands a mirror-image arrangement which returns the spins to the vertical orientation.
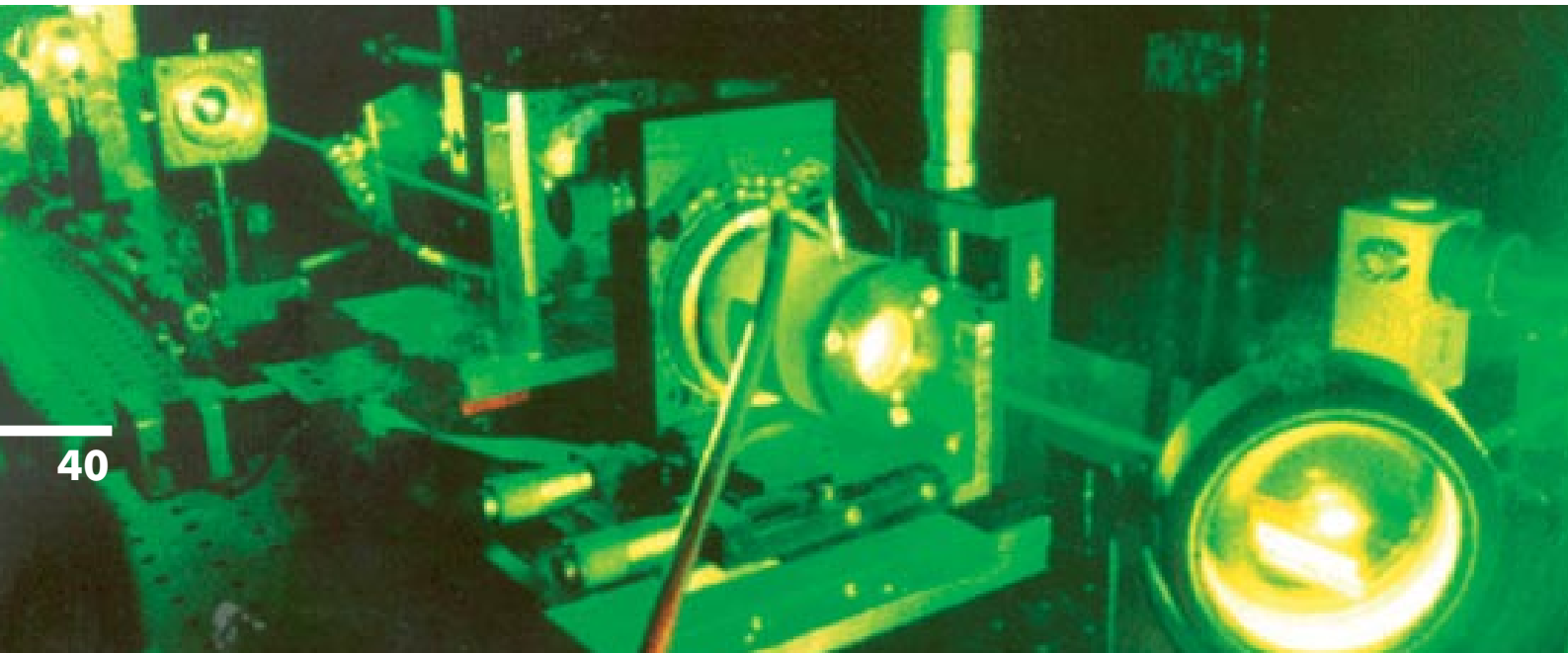
During HERA operation, the green laser beam is directed against the electron beam within the beam pipe in order to determine how well the electrons have been polarized. Here, the laser beam is outside the beam pipe so that adjustment work can be carried out.

In principle, the transverse polarization of the electron beam takes place on its own by means of the Sokolov-Ternov mechanism, but this effect is minuscule. It takes more than a half-hour — or about 85 million circuits made by the particles, in which they cover more than 500 million kilometers — to achieve a polarization of the electron beam of about 50%, i.e. to have three times more electrons with their spin pointing up than down. Moreover, the particle spins react extremely sensitively to every disturbance in the storage ring. The disruptive effects increase with the increasing energy of the particle beam; they are extremely hard to determine, so it is very difficult to calculate the behavior of the spins. The fact that a longitudinally polarized electron beam could actually be created at the high energies prevailing in the HERA storage ring was demonstrated in May 1994. During the interruption of operations at HERA in the winter of 1993/94, the sophisticated magnet systems of the spin rotators were installed in front of and behind the East Hall. On May 3, 1994, the HERA crew optimized the transverse polarization without spin rotators to 65%. The rotators were brought into position the next morning, and in the early afternoon of the same day, champagne corks were popping in the control room: The system had immediately achieved 55% longitudinal polarization — a very high value, marking the first time that a high-energy electron beam traveling in a storage ring was longitudinally polarized. For every circuit made by the particles, the rotators redirected the spins from the vertical to the horizontal direction and back again, 47 000 times a second. This set the scene for HERMES, which has since been reliably supplied with polarized electrons by HERA. The polarization of the particle beam routinely reaches 60% here, with top values of 70%. During the major remodeling of HERA from September 2000 to June 2001, additional spin rotators were installed in the north and south of the facility, enabling also the H1 and ZEUS experiments to use the electrons' spin for their own research activities.

How is Polarization Measured?

The magnitude of the polarization of the HERA electron beam is very important for HERMES. One reason is that the quality of certain measurements depends on the square of the polarization, so that in the case of half the polarization, the measuring process will take four times as long. A precise determination of the degree of polarization is also indispensable for the evaluation of the HERMES data. In order to be absolutely certain, the physicists installed two systems at the HERA ring, both of which can be used to study the polarization of the electron beam: a transverse and a longitudinal "polarimeter."

The older of these two systems stands in the western hall of the HERA facility. It measures the transverse polarization that automatically builds up in the storage ring. The longitudinal polarimeter, which was installed in 1996, measures the polarization between the spin rotators directly at the HERMES experiment. In both cases, a laser beam is directed by means of remote-controlled mirrors through a system of tubes that can be up to 200 meters long, until it meets the oncoming electrons nearly head-on. Some of the particles of light (or photons) are scattered backwards with full force and are finally snared by a detector.

These signals differ in accordance with the varying degrees of polarization of the photons in the laser beam and of the electrons in the acceleration ring. In the transverse polarimeter, the signal is displaced upward or downward, while in the longitudinal one the energy and number of the backscattered photons vary. This difference makes it possible to directly read off the degree to which the electrons have been polarized.

One advantage of this method is the speed at which the measurements are made. The polarimeters send one measurement per minute to the accelerator's control room, meaning that the progress of polarization can be observed and optimized more or less "online." While the transverse polarimeter has so far been able to deliver only an average value for all particle bunches traveling around the ring, the longitudinal polarimeter can determine the degree of polarization of each bunch. This has produced a surprising result: The polarization of the electron bunches varies depending on whether they collide with the corresponding proton bunches or whether they are non-colliding "control bunches" — an effect observed for the first time at HERA.

REMODELING FOR A BRIGHTER FUTURE

24.8.2000

1999

1997

1996

1995

1998

1994

1993

1992

Luminosity:

Luminosity is a measure of an accelerator's performance. It represents the number of events of a certain reaction that take place per second when elementary particles collide. At a given probability of a reaction (the "cross section" of the process under investigation), the greater the accelerator's luminosity, the more reactions will take place. Because the cross sections of the processes being examined today are extremely low, the luminosity must be correspondingly high in order to keep the measuring times within reasonable limits. In practice, the luminosity is often accumulated over a certain time period, e.g. a certain period of operation of the accelerator. In such a case, we refer to the integrated luminosity, which corresponds to a certain number of events produced.
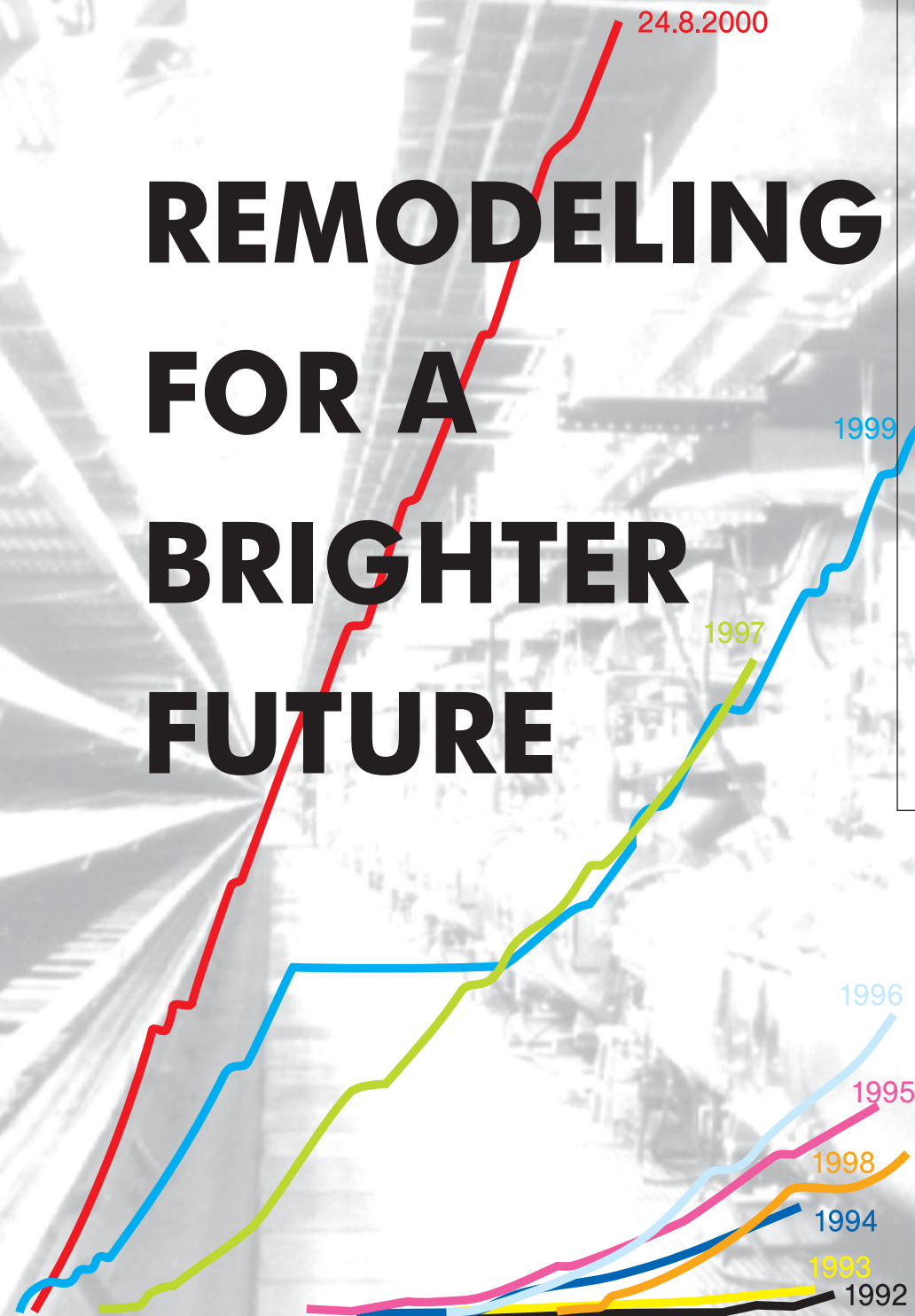
The **DESY accelerator crew can be proud of its accomplishments in 2000. The steeply ascending curves of the "hit rate" for each year show very clearly that ever since HERA went into operation in 1992, the performance of the accelerator facility has steadily improved — a development that ended on a pinnacle of tri-** umph in the measuring period of the year 2000. From the beginning of the measuring "run" on January 17, 2000, the HERA crew spent only 18 days on maintenance work and machine inspections. Almost all accelerator parameters reached their design values — and some even exceeded them. In particular, the inte- grated luminosity — a measure of the hit rate of the electrons and the protons in the storage ring, i.e. a measure of the number of collisions which the experiments can observe — was far higher in 2000 than were the values measured in previous years.

With the help of the "HERA tram," the new magnets, which weigh several tons, are transported and set up in the tunnel.
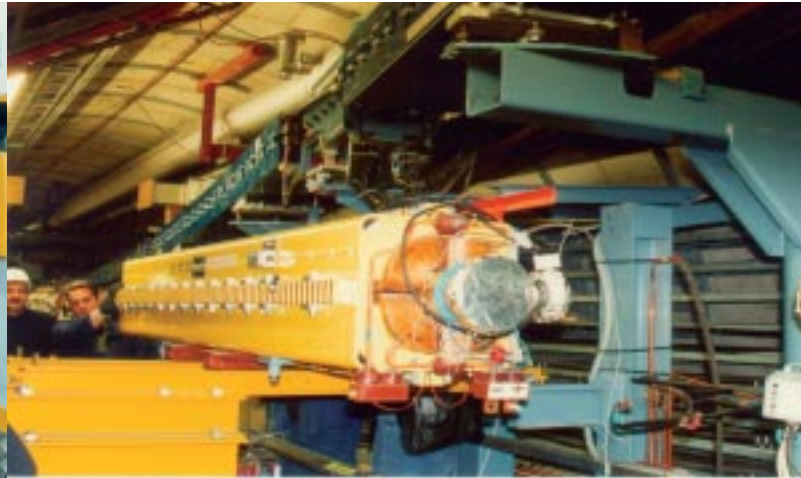
A quadrupole magnet is brought into position. It focuses the proton beam that whirls around in the accelerator.

From September 2000 until July 2001, HERA was remodeled in the "lumi upgrade." The purpose of this comprehensive program was to increase the luminosity of the storage ring by a factor of four in order to give the experiments access to extremely rare processes and thus further sharpen HERA's ability to "see" particles and forces beyond the limits of the currently accepted theory. This also enables the HERA experiments to investigate the structure of the proton and the fundamental forces of nature at even shorter distances than has previously been possible.

In order to increase the luminosity to such an extent, the cross sections of the electron and proton beams had to be reduced to a third of their previous size, i.e. from only one hundredth of a square millimeter to even tinier three thousandths of a square millimeter, before the collision took place. This feat required an extensive remodeling of the interaction zones in which the particle beams are directed toward each other — that is, the areas that are already among the most technically complex in the whole facility. In particular, the "magnet lenses" used to focus the electron beam, which were originally located 5.80 meters from the collision points at the center of the detectors, had to be moved to a distance of 1.90 meters from the collision points. The magnets are now located inside the detectors, which have therefore had to undergo considerable alterations. The HERA

Assessing the situation: Precise planning and implementation are essential if a project of this magnitude is to function smoothly.
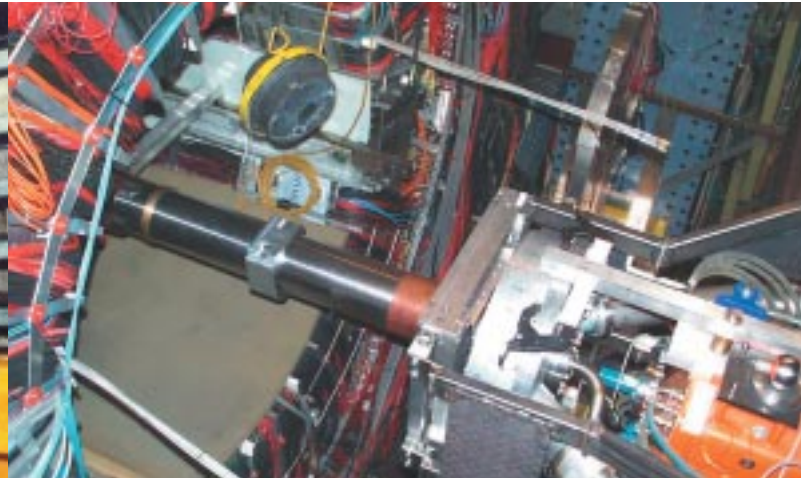
Assembling the spin rotator supports: This section of the accelerator can be raised and lowered as though it were on a platform lift.

Setting up the heavy magnets is a high-precision job. All the parts have to fit together with a tolerance of a few tenths of a millimeter.

The magnets that are closest to the collision point of the particles must be directly built into the detectors.

electron ring was also equipped with two additional spin rotator systems, so that now not only HERMES but also H1 and ZEUS can use the electrons' spin for their research activities.

All of this means that the increase of luminosity in HERA represented an enormous technical challenge not only for the HERA accelerator itself but also for the H1 and ZEUS experiments. The first set of magnets, which bring the particle beams together before the collision and direct them into separate paths again after-

wards, were built directly into the detectors. In the strong fields of these magnets, the electrons emit synchrotron radiation that can significantly impede the detectors' recording of data or make it altogether impossible. To solve this problem, a whole series of unconventional components were designed and built into the facility during the upgrade — for example, extremely small superconducting magnets that were integrated into the H1 and ZEUS detectors, and

keyhole-shaped vacuum chambers. It took nine months to complete the remodeling activities within the tunnel. In mid-2001, HERA was started up again — the operation with high luminosity and polarized electrons then become standard procedure in the course of 2003 after completion of the highly complex commissioning and optimization phase.

The newly installed spin rotators enable the H1 and ZEUS experiments to utilize the electrons' spin for their own investigations.

Remodeling finished: 25 meters in front of the collision point, the vacuum chambers for the particle beams already run through joint magnets.

Why Conduct Fundam
with Particle Accelera

People often — and rightly — ask whether we really need such large, expensive facilities as the accelerators used in particle research. But large-scale scientific equipment is by no means a recent phenomenon. As far back as the 16th century, the Danish crown provided the astronomer Tycho Brahe with an entire island, as well as almost unlimited financial aid and human resources, so that a large astronomical observatory could be established. This was where Brahe made his astoundingly accurate measurements of the positions of the stars. Johannes Kepler's use of Brahe's measurements paved the way not only for modern-day astronomy and cosmology — purely empirical sciences — but also for the mechanics of Galileo Galilei and Isaac Newton. This development thus provided the foundation for a type of science without which we would have no cars and no machinery today — in fact, none of the technology which we now have at our disposal would exist.

Large-scale equipment is required in many fields of science today. By taking research ships as an example, we can clearly see just what motivates the major research enterprises: pushing back scientific frontiers, the fascination of the unpredictable, and the assurance that the costs, efforts and risks involved are

all eventually worth it for society.

Some people complain that research equipment is becoming larger and in-

creasingly expensive, that experiments are taking longer, and that research work is carried out more and more like an industrial project. This is, however, not due to megalomania on the part of the researchers, but to scientific progress. We can now probe more deeply into the structure of matter, reach previously inaccessible parts of the cosmos, and approach increasingly complex issues. However, to achieve all this, there is no alternative but to use large-scale instruments and facilities and the most sophisticated technology — the fundamental laws of nature leave us no other choice. This is particularly evident in astronomy, for example, which requires increasingly large telescopes to be able to peer into the furthest regions of the cosmos, and continually gives us new, surprising

insights into our world as it probes further and further into the depths of the universe. Here, instruments such as the ROSAT X-ray telescope or the Hubble Space Telescope have made an enormous contribution to expanding our knowledge. The situation is similar in elementary particle research. The deeper we go into the innermost layers of matter, the more we find out about the interrelations in nature's functioning, and the more resources — in terms of ideas, instruments and effort — are needed. In particular, we require increasingly powerful "microscopes," namely the particle accelerators.

But what benefits does this type of research bring? To begin with, the effort and resources that people have invested in studying nature have always proved to be worthwhile

in the end. Tycho Brahe's huge astronomy project is an excellent example of this. We do not yet know how the
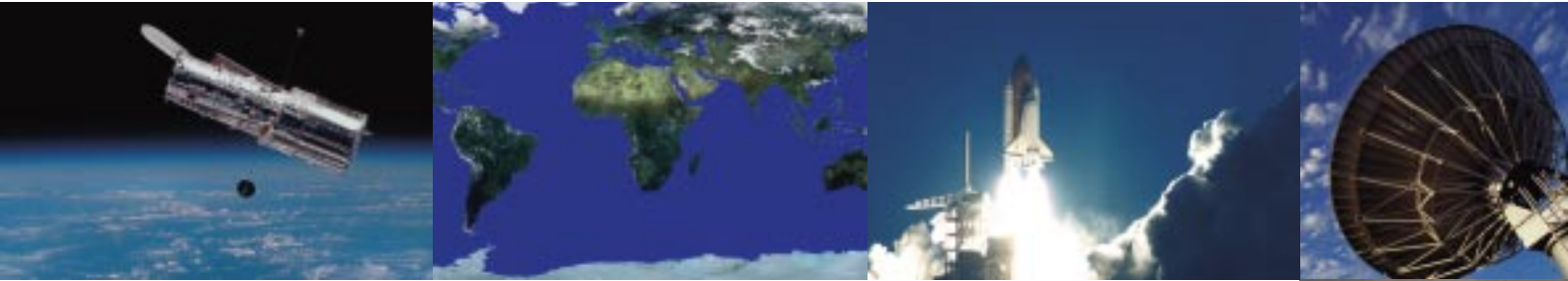
ental Research
tors? BY PAUL SÖDING

knowledge gained in particle research will one day rank against other human achievements. But there is one thing we can already say for sure about particle accelerators: Invented, developed and built to find out "what holds the world together in its innermost core," variations on them are already being used in the diagnosis and treatment of illnesses, as well as for the generation of synchrotron radiation and neutrons for research into the most wide-ranging disciplines — from physics and chemistry right through to geology, materials science, biology, medicine and even criminology. We will not be able to see their full potential exploited; that will be the task and the privilege of future generations. The manifold new technologies that particle physicists have developed for their experiments have proved to be beneficial in many ways. In fact, in the form of the WorldWideWeb, they have brought about a revolution in

the global networking of information and knowledge.

Although we know from experience that it is impossible to predict the entire extent of knowledge innovation and value creation that will arise from a given research project, past developments in new, large-scale research equipment have generally represented important milestones along the path of scientific knowledge and progress. At the same time, major developments in the natural sciences, and the discovery and exploitation of new areas of research, have usually been closely connected with the creation of new, specific instruments.

The HERA accelerator is one such new instrument. And now, after the first phase of the research work, we can already safely say that HERA has helped us to look significantly deeper into the structure of matter — particularly of protons and neutrons — than was previously possible. The complex, dynamic structure of the quarks, antiquarks and gluons that make up the innermost part of our matter is becoming clearer and clearer. And that means our chances of better understanding the structure of matter are also increasing. This involves more than just being familiar with the functions of and interaction between the smallest particles; it also includes comprehending why nature

is the way it is, and not somehow different. HERA can help us with this task, both now and in the future. In the meantime, we can look forward to finding out just what new insights and surprises are waiting around the corner for us on our journey of discovery into the innermost depths of matter.

Professor Paul Söding
DESY Research Director,
1982 – 1991
Head of DESY Zeuthen,
1992 – 1998

DESY and HERA — Their Econom

The Institute for Allocation and Competition at the University of Hamburg has taken a closer look at how DESY as a whole, and its HERA storage ring facility in particular, influence the German economy. Wilhelm Pfähler and Christian Gabriel published the results of the investigation in "The Economic Role of Basic Research: DESY in Hamburg" in February 2000. The aim of the study was to gather and process information on the significance of the research center to the regional economy, and to present the findings to DESY's management and financial backers as well as to governmental decision-makers and economic experts. The authors of the study examined the so-called demand effects which arose from DESY's operation in 1997, as well as the comparable effects caused by the construction of HERA from 1984 to 1990. These demand effects refer to revenues, income, employment and fiscal aspects.

The first step of the analysis was to take into account the "direct" effects arising from DESY's budget expenditure, such as the incomes and employment of DESY's staff and the revenues of its suppliers. Other, "indirect" effects become evident through the business connections between DESY's suppliers and other supplying companies and the latter's employment of workers. Both of these effects, direct and indirect, are specific to DESY. Their structure and relative significance are directly affected by the structure and level of the research center's expenditure and that of its direct and indirect suppliers. Furthermore, the direct and indirect income earned is subsequently expended once again. In turn, this expenditure leads to further revenue, income and employment effects, referred to by the analysts as "induced" effects. The state ultimately becomes part of this process as well through the higher tax revenues it gains.

The conclusion reached by the authors of the study is that DESY, including its HERA storage ring facility, is "a significant economic factor, not only for the region of Hamburg, where it is located, but also for the neighboring states of Schleswig-Holstein, Lower Saxony and Bremen, and for the rest of Germany:"

In order to determine the overall expenditure from the operation of DESY in 1997, it is necessary to add to the research center's € 133.8 million budget for human resources and equipment a further € 9.6 million — the amount spent by external DESY users (guest scientists, doctoral candidates and degree candidates). Through direct, indirect and induced effects, this overall expenditure of € 143.4 million led to € 198.6 million in terms of income throughout the country. This activity sustained and generated a total of 4244 jobs, around 70 percent of which (2862) were at locations other than DESY.

Of these 4244 jobs, 1340 (31.6 percent) were based in Hamburg, 1346 (31.7 percent) in Schleswig-Holstein, Lower Saxony and Bremen, and the remaining 1558 (36.7 percent) throughout the rest of Germany. In per-capita terms, Hamburg — DESY's primary location — is the largest regional beneficiary of operations at DESY. These operations generate an annual average of € 93 for every wage earner in Hamburg, € 12 for those in the rest of northwestern Germany, and € 2.60 for each worker in the remainder of the country.

Examining the individual economic sectors, it becomes clear that the service and retail sectors benefit the most from the work carried out at DESY, as the majority of the induced and directly earned income flows back into the consumption

ic Role

cycle. These sectors are followed, some way behind, by energy, chemistry, vehicles, machine construction and electrotechnology, which profit in particular from the research center's material expenditure and the business relations between DESY's suppliers.

Similar observations can be made with regard to the construction and equipping of HERA from 1984 to 1990. During this period, expenditure for human resources totaled € 78.2 million, while € 279 million was spent on materials (prices at 1984 levels). Through direct, indirect and induced demand effects, this figure led to total income of € 416.8 million (at 1984 levels) throughout Germany between 1984 and 1990 — corresponding to 14 205 jobs during the investment phase. Especially beneficial to Hamburg was the fact that around 90 percent of the expenditure for the construction of HERA flowed directly to the city.

All of these effects lead to additional tax revenues through income and sales taxes. A rough estimate of these "fiscal" effects for DESY operations in 1997 results in tax revenues throughout Germany of at least € 49 million, of which the federal government received slightly over half. For Germany as a whole, this effect accounted for almost 40 percent of DESY's running expenditure for human resources and materials, which means that the net burden on the taxpayer for financing DESY effectively fell by 40 percent. "To summarize, we can conclude that operations at DESY / HERA — 90 percent of which are funded by the state — finance themselves at a level of around 40 percent. Moreover, their economic impact primarily extends outside of Hamburg (i.e. 65 to 70 percent), and throughout a wide range of economic sectors," wrote the authors.
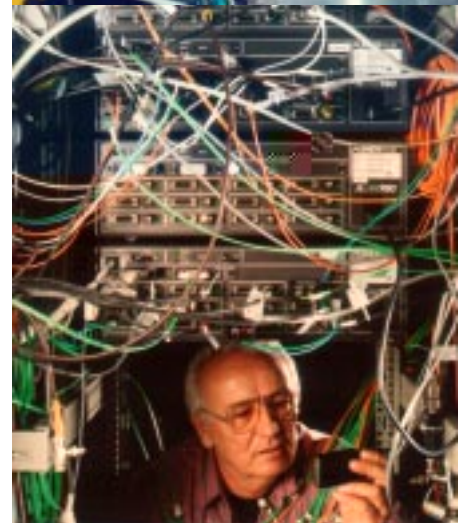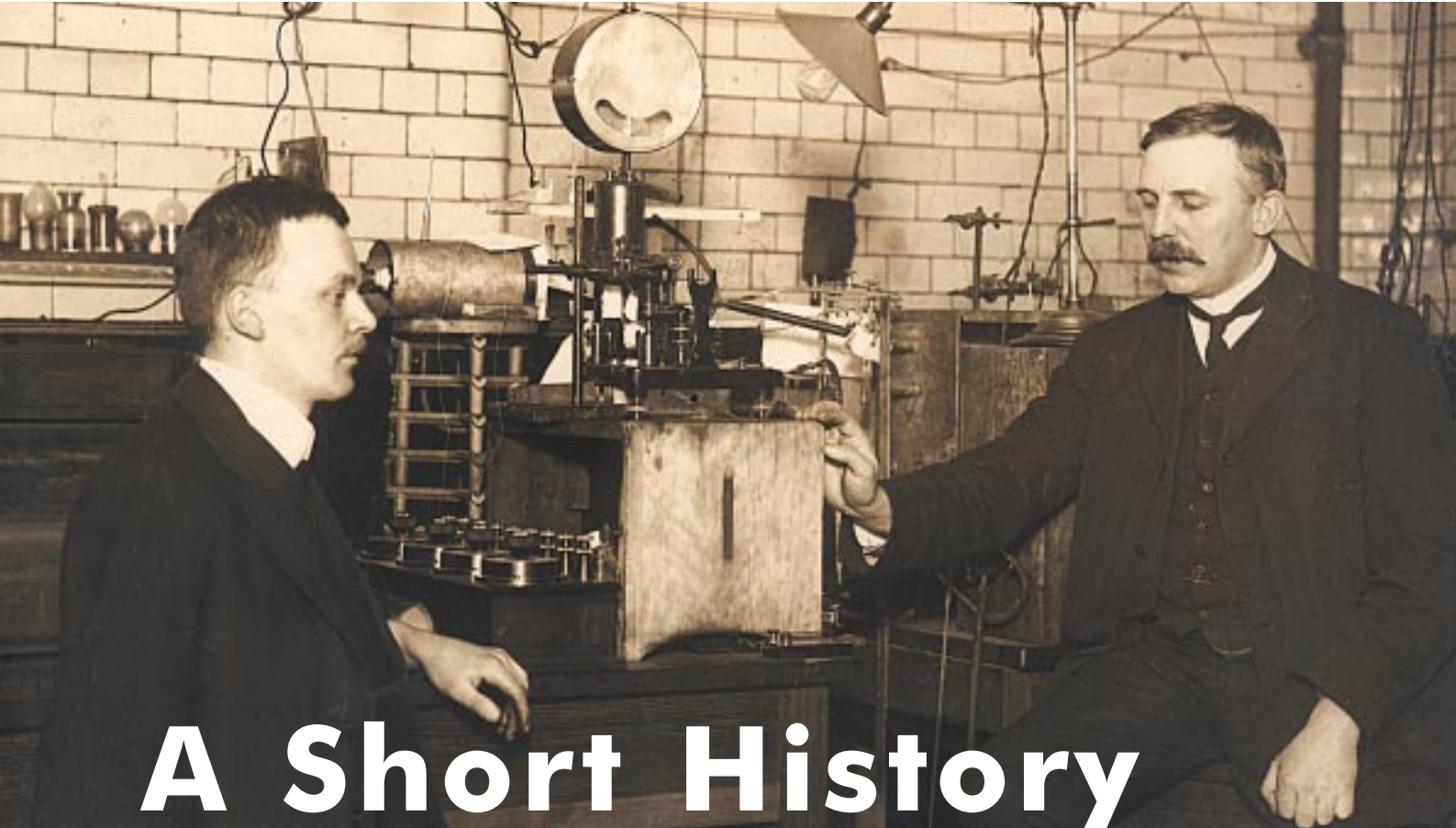
The Legacy of HERA - the First Decade

A. Levy

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Achievements up to 2000: HERA makes
crucial contributions to our knowledge of the world.

A Short History of Scattering Experiments

The principle is simple. In fact, one of our ancestors probably came up with the idea back in the Stone Age: To investigate the interiors of two objects, simply smash the latter together to see what the broken fragments reveal. During the millennia that have passed since then, technologies have grown more complex, the objects have become smaller and the difficulty of investigating them has increased. However, the principle remains the same. If we want to find out what is happening inside a piece of matter and whether the supposedly smallest components of our universe are perhaps actually made up of even smaller pieces, we smash two particles into one another and see what happens. In technical jargon, the process involved sounds a little less primitive: Physicists refer to "scattering experiments" — investigations in which one particle is used as a probe to investigate another

particle that scatters the first. The way in which the probe bounces off the target, the direction in which it is scattered, its energy and whether the target breaks up as a result of the collision all provide clues on how the target is put together.

One such scattering experiment, in which Hans W. Geiger and Ernest Marsden aimed alpha particles at a thin gold foil, revolutionized physics at the start of the 20th century. To the great surprise of the two physicists — assistants to Ernest Rutherford — some particles actually rebounded. "It was almost as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you," is how Rutherford later described the event. It was not until some weeks later that Rutherford was able to explain the astonishing phenomenon. The year was 1911. From the rate at

which alpha particles scattered at specific angles, Rutherford could see that most particles simply passed through the foil without being diverted. This, he deduced, meant that atoms of gold are largely made up of empty space. Those particles that
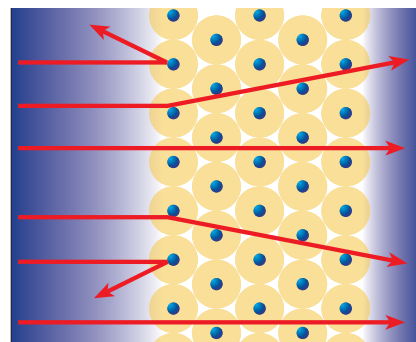

Alpha particles strike a piece of gold foil. If they hit an atomic nucleus, they ricochet backwards; otherwise they pass through the foil unhindered or only slightly deflected.

rebounded violently — i.e. at a large scattering angle — must, however, have encountered a small heavy core in which nearly all of the mass of the gold atom was concentrated. This meant that the prevalent model of the atom — a positively charged sphere containing negatively charged electrons — could no longer be regarded as valid. The atomic nucleus had finally been discovered.
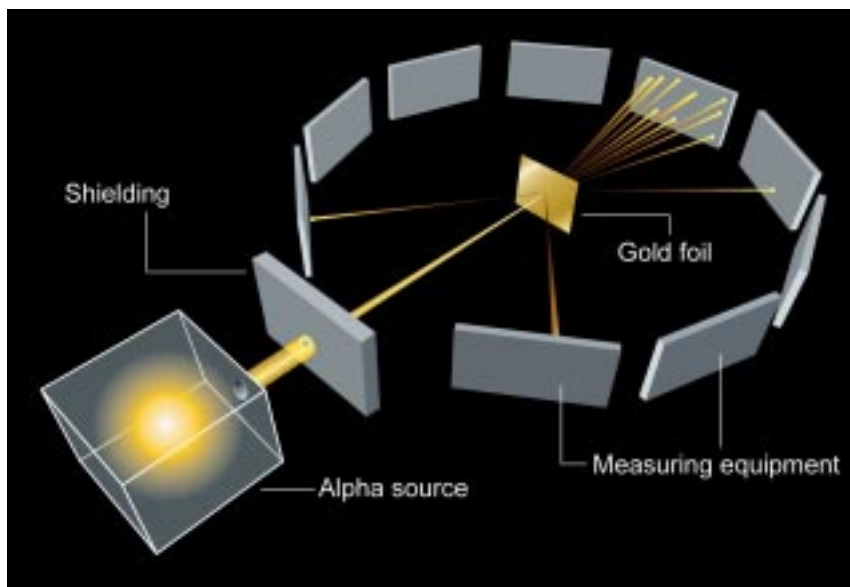
Atoms are too small for humans to "peer" into. However, using scattering experiments, it is possible to make the interiors of these tiny particles visible. In this way, Rutherford was not only able to determine that the atoms of gold contained smaller objects; he was also able to determine some of the latter's properties. Using fundamental observations, he managed to come up with a formula that described the collisions between very small, electrically charged particles. In this formula, the rate of occurrence of specific scattering angles depends on the charge of the particles involved. Using experiments
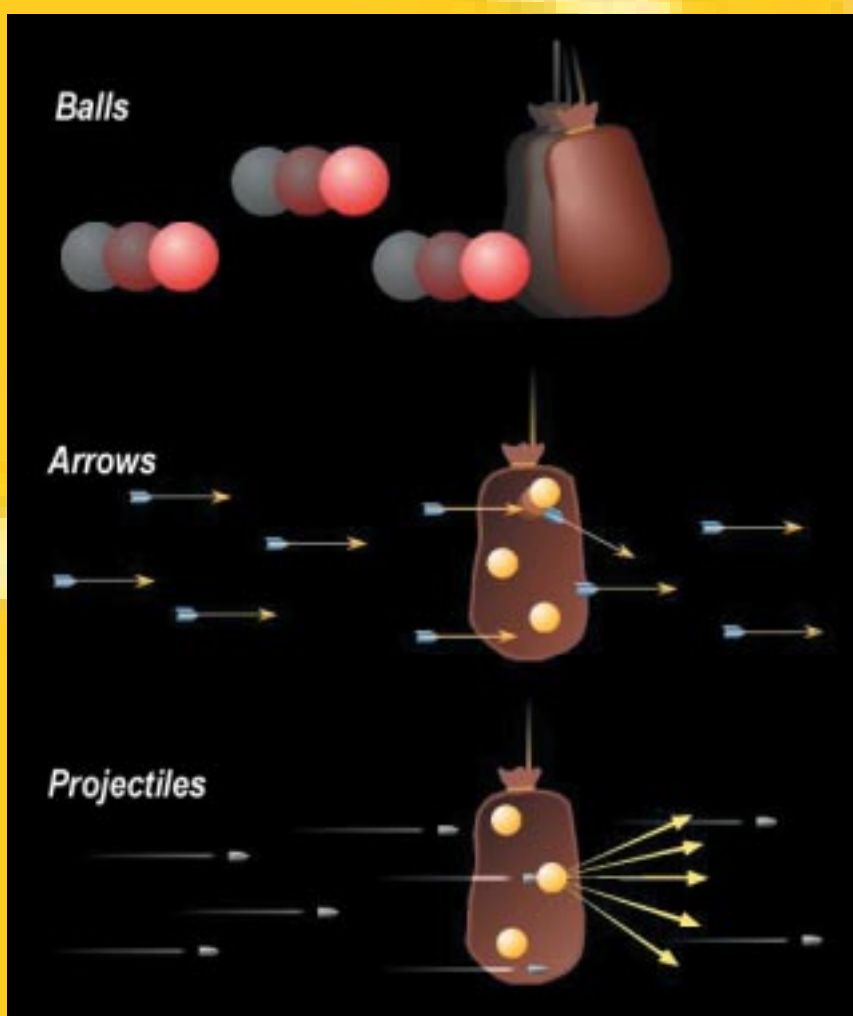
The more energetic the projectiles, the more information they can provide about the structure of the target object. The shape of a sack can be deduced from the deflection of the balls striking it; the arrows reveal the spheres within it. Highly energetic projectiles burst the spheres and thus reveal their internal structure.

Rutherford's experiment setup

Resolving Small Distances with High-Energy Particles

In 1924, the young French physicist Louis V. de Broglie put forward a revolutionary idea in his Ph.D. dissertation. Just as light waves sometimes behave as particles under certain conditions, as revealed by Einstein, de Broglie suggested that in certain circumstances, particles could behave as waves.
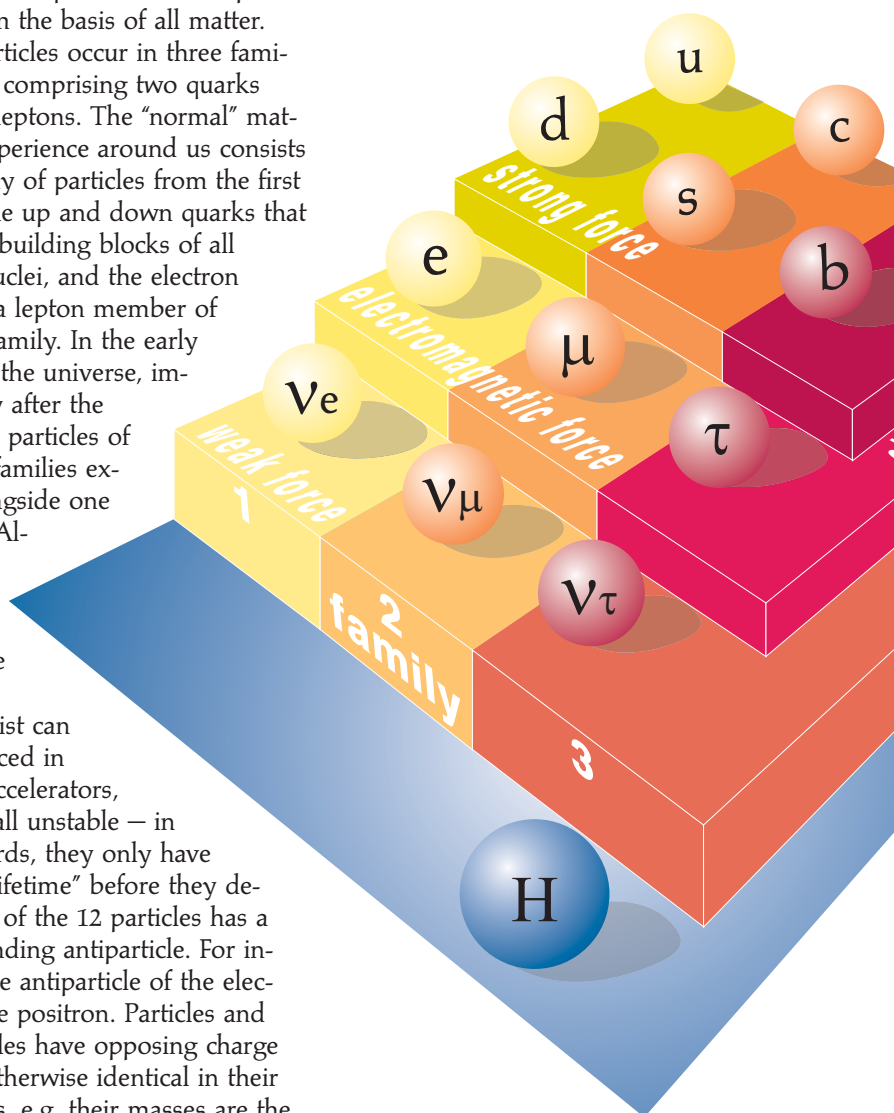
Up until then, electrons had been regarded as hard, impenetrable charged spheres. de Broglie's theory suggested that they should display refraction or interference effects just like light waves. This was proven to be the case three years later when Clinton J. Davisson and Lester H. Germer scattered a beam of electrons on a crystal lattice. Certain scattering angles exhibited maxima that could only be explained as the result of interference phenomena involving waves — in this case "matter waves."
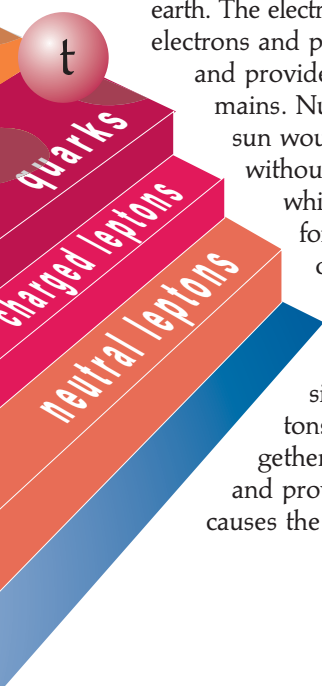
To complete the analogy, de Broglie stated that all particles possess a wavelength that is inversely proportional to its momentum. So the greater a particle's momentum and thus its energy, the smaller its wavelength. In the same way that light waves can be used to resolve structures of the same order of magnitude as their wavelength, particle beams can resolve distances of the same order as their de Broglie wavelengths. Whereas the smallest distances visible with a microscope using ordinary light are about 1 micrometer (10^{-6} m), X-rays with a wavelength of 10^{-10} m can be used to investigate individual atoms. The wavelengths associated with the particle beams in HERA are so short that physicists can recognize structures as small as 10^{-18} m.

with foils of various metals, researchers were now able to show that the atomic nuclei of each element had a unique charge. The key to this breakthrough was provided by Geiger and Marsden, who patiently sat in a darkened laboratory looking through a microscope and counting how many particles were scattered in each direction.

With the further development of particle accelerators, the projectiles became smaller and the collisions more energetic. As the energy of particles increased, scattering experiments were able to probe ever deeper and reveal increasingly fine details. In 1954, physicists discovered that protons are not simply "points," but instead have a measurable diameter. The end of the 1960s saw the discovery of the quarks — the building blocks of protons and neutrons. Today, the H1 and ZEUS experiments at the HERA storage ring are continuing the successful story of scattering experiments. Here too, electrons collide with protons, and the angle and the energy of the scattered elec-

trons provide valuable information about processes within the proton. Since the protons in the HERA experiments are not stationary, but are also accelerated to high energies, the energy available to the electrons during the collision is approximately 2600 times greater than that available in the SLAC experiment of 1969, and 9 000 000 times greater than that provided by Rutherford's alpha particles. In other words, HERA currently produces the most highly resolved view of the proton available worldwide. This "super microscope" can reveal structures as small as a billionth of a billionth of a meter — in other words, 2000 times smaller than the proton itself.

The Standard Model of Particle Physics

At the beginning of the 20th century, anyone who discovered a new particle could expect to be awarded the Nobel prize. Things changed dramatically in the 1950s, when the first modern particle accelerators went into operation and suddenly new particles were being announced every few months. By 1960, what had once been a relatively clear picture of particle physics had become an impenetrable jungle, populated by around hundred particles that could not be obviously classified. The situation was similar to that prevailing in chemistry a hundred years earlier, before Dimitri I. Mendeleev and Julius L. Meyer brought order to the chemical elements with the help of the periodic table. Thus it was in particle physics too, that order soon emerged from the chaos. In the last 50 years, the basic system has been taking on increasingly precise shape. Today, the knowledge we have gained is contained in the "Standard Model." However, the model is by no means as unspectacular as its name. Instead, it is based on an elegant mathematical theory that has proved very successful when it comes to describing all the verified experimental results from the field of particle physics. The basic assumptions of the Standard Model can be written down in a few lines — one of particle physics' great achievements.

The Standard Model proposes that six quarks and six leptons form the basis of all matter. These particles occur in three families, each comprising two quarks and two leptons. The "normal" matter we experience around us consists exclusively of particles from the first family: the up and down quarks that form the building blocks of all atomic nuclei, and the electron which is a lepton member of the first family. In the early stages of the universe, immediately after the big bang, particles of all three families existed alongside one another. Although the types of particle that no longer exist can be produced in particle accelerators, they are all unstable — in other words, they only have a short "lifetime" before they decay. Each of the 12 particles has a corresponding antiparticle. For instance, the antiparticle of the electron is the positron. Particles and antiparticles have opposing charge but are otherwise identical in their properties, e.g. their masses are the

same. When a particle and an antiparticle meet, they annihilate each other. All that remains is energy in the form of radiation, from which new particles can be created.

The particles of matter are subject to four fundamental forces: gravitation, electromagnetism, and the weak and strong interactions. It is the force of gravity that causes an apple to fall from a tree and planets to orbit the sun. The force of gravity prevents us from flying off the surface of the earth. The electromagnetic force binds electrons and protons into atoms and provides electricity from the mains. Nuclear fusion in the sun would not be possible without the weak force, which is also responsible for the radioactive decay of atomic nuclei. The strong force holds the quarks and gluons together inside the protons, protons and neutrons together in the atomic nuclei and provides the energy that causes the sun to shine.

The components of matter and the forces that hold them together. At present 12 matter particles are known, 6 quarks and 6 leptons. The Higgs particle is responsible for the mass of elementary particles. The particles at one "level" are also subject to the forces from the levels below.

The Standard Model comprises a second type of particle in addition to these "matter" particles: the "exchange" particles. The latter mediate between matter particles, conveying force and information. There are specific exchange particles for each type of force. The photon that we know as the quantum of light is the conveyor of the electromagnetic force; gluons mediate the strong force that operates between quarks; the neutral Z particle and the negatively and positively charged W particles are responsible for the weak force. According to theory, so-called gravitons convey the force of gravity. But gravity has not yet been included in the Standard Model.

The third kind of particle in the Standard Model are "Higgs bosons," which are responsible for the creation of particle masses. According to the Standard Model, matter and exchange particles start out massless — a state of affairs that clearly contradicts what we actually observe in nature. One solution to this problem is the "Higgs mechanism", named after the Scottish physicist Peter W. Higgs. According to his theory, the entire universe, including the vacuum, is filled with a background field, called the Higgs field, under whose influence a particle gains its mass. This field is associated with one or more Higgs particles. Despite intensive searches, these particles have not yet been observed. Only the discovery of these Higgs bosons will finally clarify how particles obtain their mass.

The Universe in a Coffee Cup

When you are breakfasting in the morning, you drop some sugar into your coffee, stir it and watch how the crystals of sugar gradually disappear. No matter how much you try, you will not be able to find any sugar in the cup with the naked eye. The molecules into which the crystals have dissolved are much too small, ten million times smaller than the crystals with which you began. To see the molecules you would need to peer into your coffee with a very powerful microscope.

What happens to the sugar in your coffee cup? Every individual sugar molecule consists of individual components about ten times smaller than itself: its atoms. If you look more closely at the atoms, you can see that each of the different types of atom has the same components. Electrons form the shell of the atom and the atomic nucleus is made of protons and neutrons.

The nucleus is astonishingly small compared to the size of the atom. If the atom were as large as a football pitch, the nucleus would still be no bigger than a pea. Yet even the protons and neutrons contained in the nucleus are not the smallest particles. They, in turn, are made up of components at least a thousand times smaller: quarks.

The "size" of a quark features an impressive numbers of zeros after the decimal point. A quark is less than an attometer across, i.e. less than 0.000 000 000 000 000 001 m. For comparison, the head of a pin is approximately 1 millimeter across, i.e. 0.001 m.

Quarks from inside an atomic nucleus and the electrons of the atomic shells are presently thought to be points without any physical size, making them perhaps the smallest components of the universe.
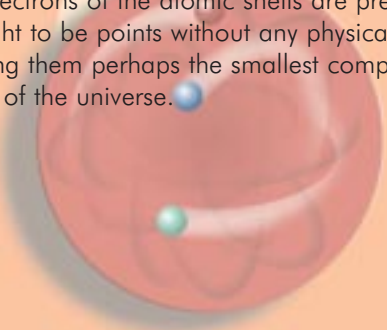
An Incomplete Picture

The Standard Model is one of the most successful scientific theories ever. Nevertheless, it leaves many questions unanswered, questions that an all encompassing "theory of everything" ought to explain. In general, it is nowadays assumed that the universe was created in the big bang from a center that encompassed everything. That means that all the forces observed today emerged from a single primeval force. In other words, it should be possible to describe them in a unified way. Although the Standard Model has unified the electromagnetic and weak forces into a single electroweak force, the strong force cannot yet be linked to the others. Gravitation has also obstinately resisted all attempts at unification.

The Standard Model also includes a large number of apparently arbitrarily defined "natural constants." These can be determined experimentally. However, why these numbers take precisely the values that experiments show them to have remains a mystery. We also don't know why particles of matter should be grouped into precisely three families or why the charge on an electron, a point-like elementary particle, is, as far as can be measured, so precisely identical in magnitude to that of the proton — a complex combination of quarks.

The model also fails to satisfactorily answer questions about the nature of the post big bang "soup" of quarks and gluons; nor does it explain why quarks never appear as free particles, but are always "confined" within protons or neutrons. Physicists assume, however, that all these answers are already included within the formulae of the Standard Model, and we only lack the appropriate mathematical tools to solve the problems.

The Standard Model obviously provides a good approximation for situations in which energies and particle densities are not too high. It will, however, eventually have to be replaced by a better, more comprehensive theory. In spite of huge experimental efforts, such a theory has not yet been developed. With their unique research program, the HERA e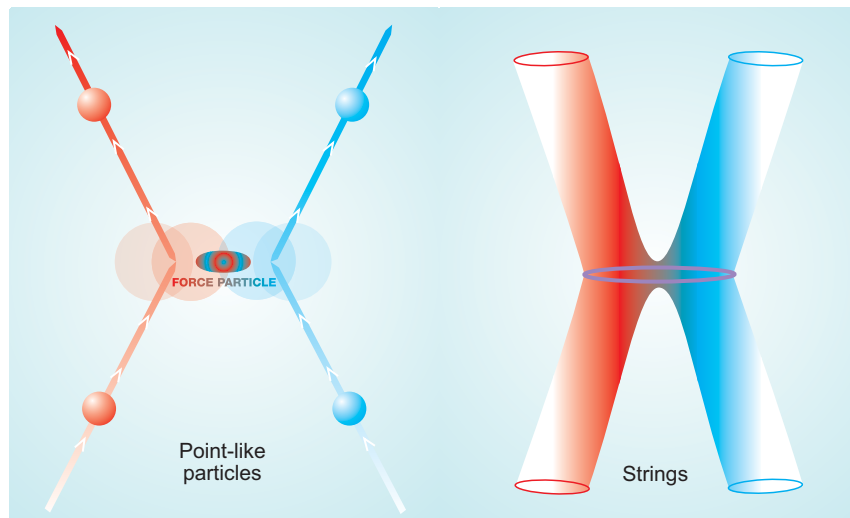xperiments could provide decisive insights when it comes to developing a theory that goes beyond the Standard Model. So-called Grand Unified Theories — theories that seek to describe the Standard Model's three forces of nature in a unified structure — propose, for example, the existence of hybrid particles (so-called leptoquarks) that combine properties of leptons and quarks. Since HERA is the world's only facility providing high-energy collisions between different types of particles — between electrons from the family of leptons and protons made up of quarks — the accelerator is well suited to studying the relationships between quarks and leptons. In particular, certain leptoquarks could be created and investigated at HERA.
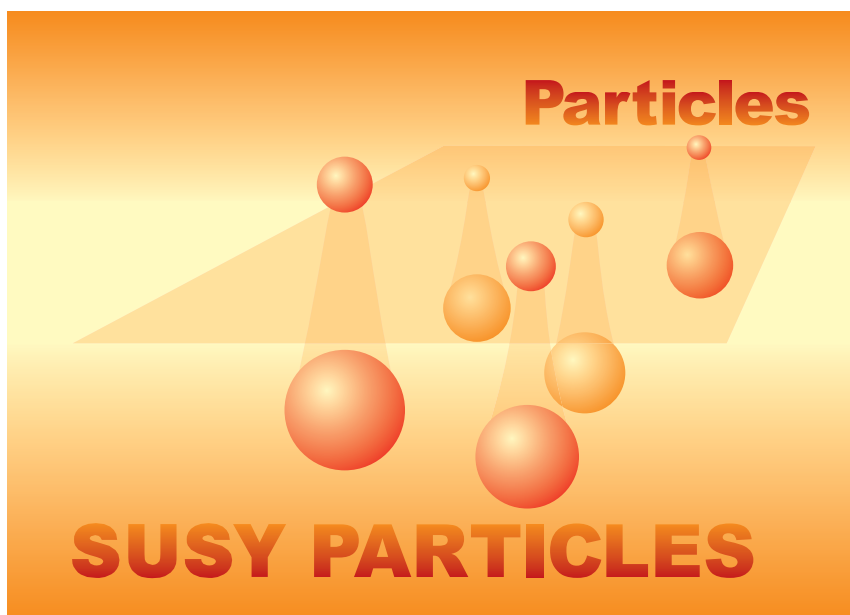
"Shadow partners": The theory of supersymmetry assigns every particle a supersymmetric partner.

Particles and strings: Two particles communicate by exchanging a force particle (left). The same interaction in the "string" model (right): Two "strings" join together to form one string before separating again.

A journey back through time to the beginning of the universe: The scale shows the age of the universe from the big bang to the present day alongside the average energy of radiation and matter particles.

Another idea that could provide the underlying principle from which the fundamental natural laws could be derived is the theory of supersymmetry. Also called SUSY for short, the theory links the matter particles and the force particles — they are strictly separated in the Standard Model — and leads to a closer connection between three of the four forces of nature. This is achieved in such an elegant fashion that many physicists believe that supersymmetry might play a key role in the quest to unlock the inner workings of matter. If supersymmetry is valid, there must be a whole range of additional particles, all of which must also have existed in the early universe. Some of them could still exist today, without having been discovered. Detection of such particles is difficult because their properties are completely different from those of the particles with which we are familiar. However, until one of these "shadow particles" is discovered, SUSY remains unproven. HERA is also making a key contribution in the search for supersymmetry.

An even more exotic possibility would be to use HERA to investigate the number and size of any additional spatial dimensions. Although such ideas might seem to come straight from the pages of science fiction, nothing could be further from the truth. The concept is the product of one of the latest developments in the fields of theoretical particle physics and cosmology. So-called string theories, for example, unify gravitation with the other three forces of nature by describing particles not as point-like objects but as tiny little strings. These do not oscillate in the three dimensions of which we are aware. Instead, they exist in up to ten spatial dimensions. Physicists believe that the extra dimensions are invisible to us because they are "curled up" on themselves into extremely tiny spaces. It may, however, be possible to detect their influence in the particle collisions at HERA. Such a contribution from the HERA experiments would not only show the limits of the Standard Model, but also offer important clues as to the nature of a new comprehensive theory whose scope extends beyond the Standard Model.

Just How Big Are Quarks?

In principle, HERA is a microscope. It might be a very large one, but the basic idea behind the particle collisions at HERA is really a logical progression from conventional microscopes using light. The following basic rule applies when investigating objects: The smaller the structure to be investigated, the shorter the wavelength of the light used to view it needs to be. With X-rays that have a wavelength of a few millionths of a millimeter, in other words, the same order of magnitude as the size of atoms, it is possible to resolve the structure of molecules. However, smaller structures remain invisible. To see them, even shorter wavelengths must be used.

If we want to investigate objects that are much smaller than atoms — a proton for example is about 10^{-15} meters across — we cannot use "everyday" electromagnetic radiation such as light or X-rays. This is where the large particle accelerators come into play. When an electron collides head-on with a proton — or rather with one of its building blocks — in the HERA storage ring, the two particles "communicate" with one another by exchanging a photon, for example. The more powerful the collision, the more momentum is conveyed between the two colliding particles by the exchanged photon. The more momentum the exchanged photon possesses, the shorter its wavelength. And this is where the microscopy principle comes in. The more violently the particles collide inside HERA, the smaller the dis-

tances that can be investigated. In other words, by increasing the energy involved in the collisions, it is possible to reveal even smaller structures.

By exploiting this principle, physicists have been able to penetrate ever further inside matter over the last 50 years. In 1954, Robert Hofstadter of Stanford University made electrons from an accelerator collide with a hydrogen target. By studying how often the electrons were reflected in each direction, he discovered that the scattering pattern was different from the one he would have obtained from the collision of two point-like, dimensionless particles. This deviation from the theoretical curve could only be explained by a "smearing" of the proton, in other words, by assuming that the proton has a finite diameter. In turn, this meant that the proton could no longer retain its status as an "elementary" particle, since the Standard Model specifies that such particles must be regarded as "points" with no size. Fifteen years later, it was possible to provide the electrons at SLAC with enough energy to allow physicists to take a look inside the proton. Suddenly, the scattering pattern they obtained was once again consistent with that of a point-like object — in other words, the electrons must have been striking tiny components inside the proton. The physicists had discovered

the quarks, the point-like building blocks of protons and neutrons.

With HERA, it is now possible to examine the quarks in detail. The region that can be explored is 100 times greater than that reached by previous experiments. In addition, the resolution of the particle collisions is ten times as high (see box p. 59). This means that HERA can investigate events in the microcosm at distances as short as 5×10^{-19} meters. It can thus reveal structures 2000 times smaller than protons themselves. Once again, physicists are measuring the scattering patterns. The aim is to compare the patterns with theoretical predictions for point-like particles and for quarks of finite diameter. From the results of other experiments, it is already known that electrons are even smaller than the smallest dimensions visible with HERA.

Analysis of the HERA measurements shows that the quarks are unimaginably tiny. It is certain at least that their diameter is not more than one thousandth of the diameter

## From Scattering Pattern to Results

The detector spews out a multitude of images from the various collisions. On the experiment screens, they look like snapshots of a firework display. But what can physicists deduce from them? How do they obtain a numerical result from all these colored lines?

Just as in Rutherford's first scattering experiments, the physicists working on the electron-proton collisions at HERA measure how often an electron is deflected at a certain angle by a proton. They also measure the energy it possesses after the collision. The fragments of the proton are also analyzed in terms of the direction in which they are propelled and the energy they possess. From these measurements, so-called kinematic variables that characterize the collision process can be calculated. The scattering of electrons by a quark inside a proton can be described by precisely two such variables: "x" and "Q^2." The symbol x represents the fraction of the proton's momentum that is carried by the quark which collides with the electron. Q^2 is a measure of the violence of the collision: It is the square of the momentum conveyed between the colliding particles, i.e. the square of the momentum of the exchange particle. Q^2 is therefore also a measure of the resolution of the HERA microscope. The larger the value of Q^2, the smaller the structures revealed.

If sufficient numbers of particle collisions are observed, it is possible to produce a graph depicting the rate at which the events occur within a certain interval of x or Q^2. This graph, the structure function, shows how the quarks in a proton are assembled. The Standard Model should actually predict the results of these scattering experiments. To date, this has, however, not been possible since the mathematical equations describing the strong force still remain unsolved. What has been achieved so far is a prediction of the way in which the structure function changes with the momentum transfer Q^2. If the function has been measured for a certain value of Q^2, appropriate predictions can be made for larger values of Q^2.

If the theoretical and experimental values agree, this would be celebrated as a success for the Standard Model. The assumptions behind the theory are then likely to be correct. Things get even more exciting, though, if the curve does not agree with the theory. Then very precise checks must be made to exclude any errors in the experiment and to see whether the result is only a statistical quirk — it might take several years until enough data has been gathered to ensure sufficient accuracy — or whether the discrepancy indicates something fundamental and thus the need to modify the theory.

of a proton — in other words, about 10^{-18} meters. No dimensions for the quark can be ascertained down to this value. There is therefore no evidence that quarks in turn could be made up of even smaller components. Within the reach of HERA's penetrating gaze, it seems that quarks are indeed points of matter, just as the Standard Model predicts. Up to now we have been descending along a chain of ever smaller, yet divisible particles of matter — a chain stretching from crystal to molecule, to atom to nucleus, to proton and neutron to quark and electron. Could it be that we have finally come to the end of our journey?
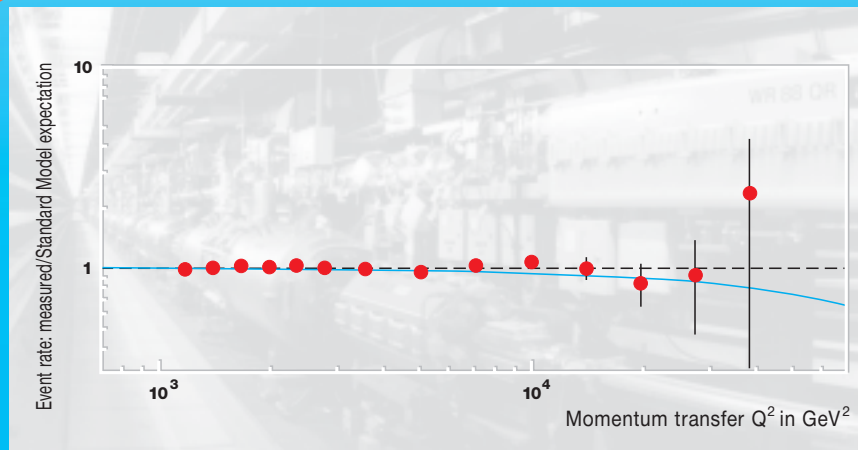
Comparisons between experimental (red) and theoretical results (the blue curve is for a quark radius of 8 x 10^{-19} m) can reveal the limits on the size of a quark.
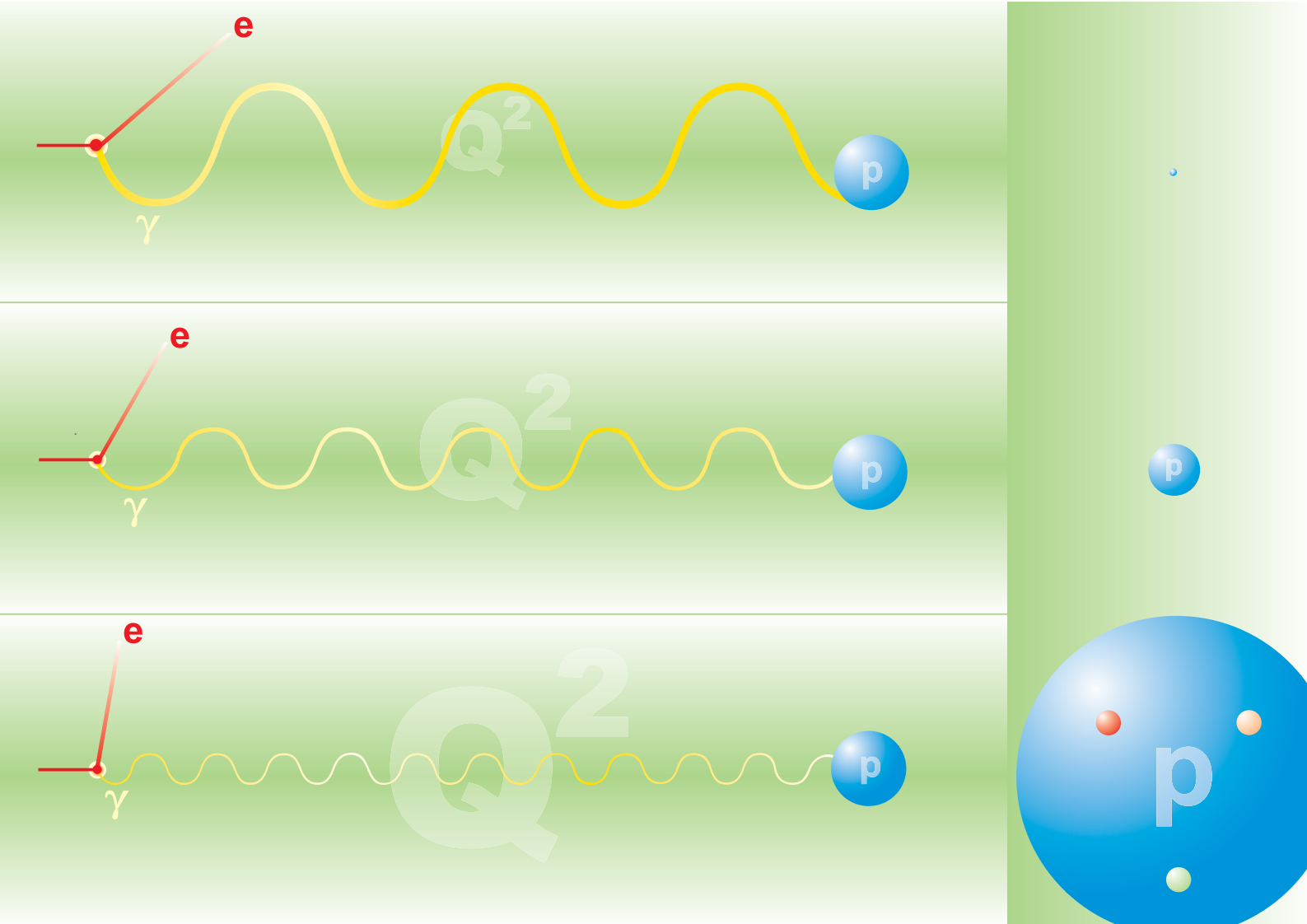
Energetic Particles Reveal More

The more energetic the electron-proton collisions in the HERA ring, the greater the resolution of the HERA microscope. To the left of the illustration: Electron (e) and proton (p) exchange a photon (γ). The photon "sees" the proton differently depending on the violence of the collision.

Top:

If the exchanged photon only communicates a small amount of momentum between the colliding particles (Q^2 small), its wavelength is longer. If the wavelength is greater than the size of the proton, the photon only "sees" the proton as a single point. The scattering pattern recorded by the physicists corresponds to that of two point-like particles.

Center:

The collision between the electron and proton is more violent, the resolution Q^2 increases. The wavelength of the photon becomes smaller until it reaches the dimensions of the proton. The proton now acquires form and appears to the photon as an extended object. Any structures within the proton however cannot yet be resolved with this photon.

Bottom:

When the energy of collision is at its highest, the wavelength of the photon is so small that the proton as a whole is no longer important. The photon penetrates the proton and is able to reveal the tiny building blocks inside: the quarks. As far as HERA is able to "see", the scattering pattern again corresponds to a collision between point-like particles.

HERA Shows the Way to the Unification of the Forces of Nature

As a "super electron microscope," HERA is a real all-rounder. The storage ring facility not only makes tiny particles visible, it also discloses the "communication" between particles to physicists. Today, four forces rule our world: gravitation, electromagnetism, and the weak and strong interactions. Gravitation, the force that influences our lives most directly, plays a subordinate role in the world of the tiniest particles because it is much weaker than the other three fundamental forces. In contrast, electromagnetism and the weak and strong interactions can be investi-gated in detail using HERA. In this regard, the proton is like a "microscopic laboratory" in which the researchers can thoroughly examine the characteristics of these three forces of nature.

Today, hardly anyone doubts that the universe was created in the big bang from an all-encompassing center about 15 billion years ago. This assumption, together with the results of particle physics experiments, implies that the forces that exist today also originated in a single primordial force. In other words, they are ultimately only different aspects of the one force. It should therefore be possible to describe the forces of nature within a single theoretical framework. It has, in fact, been possible to describe the electromagnetic and the weak forces together in terms of a combined electroweak force. This unification of the two forces can be followed "live" in the experiments being carried out at HERA.

When an electron collides with a proton in the HERA experiments H1 and ZEUS, these particles may interact with each other in a number

The Unification of the Forces
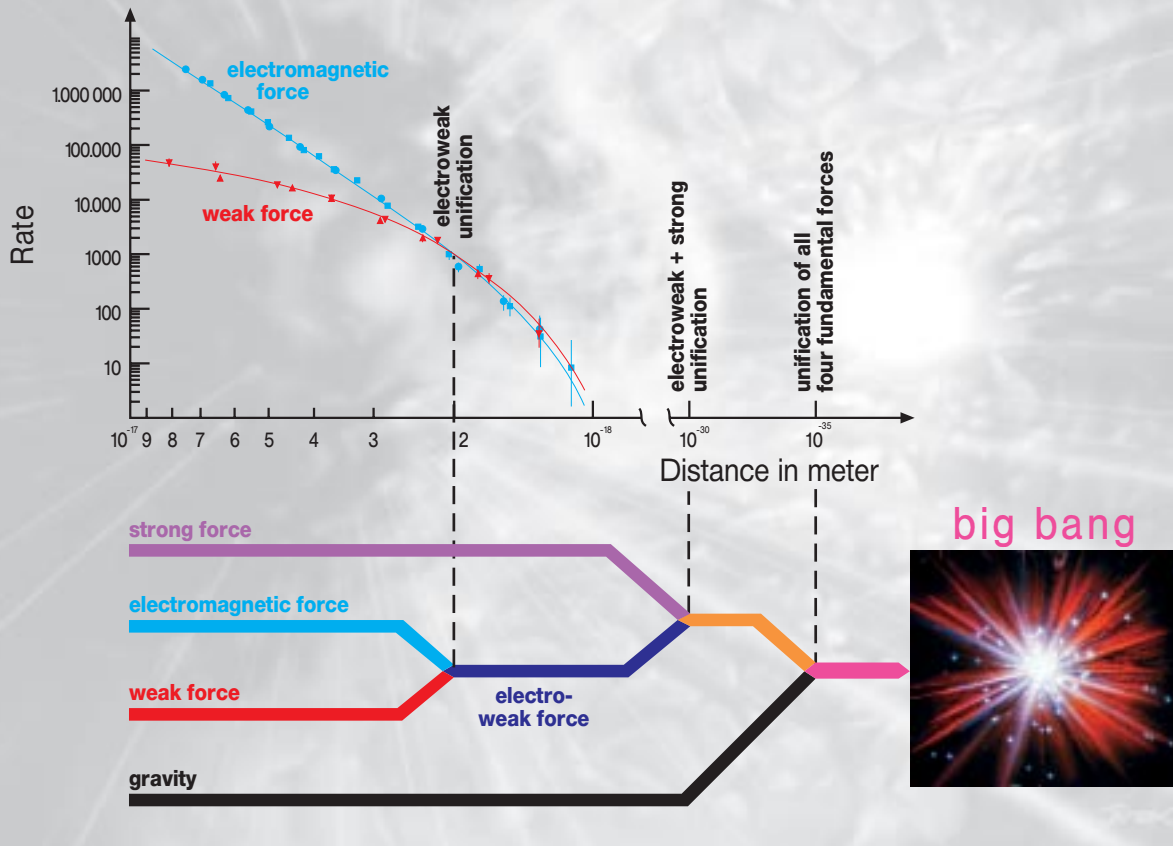
Electroweak unification — an important observation of the HERA experiments. The diagram shows the rate of occurrence of particle reactions due to the electromagnetic and weak forces respectively, as a function of the minimum distance of the particles at the time of their collision. As we move toward the right of the diagram the distances grow smaller. At distances greater than the range of the weak force (2×10^{-18} m), the electromagnetic reactions occur much more often than the weak ones. At smaller distances, the two reactions occur with about the same frequency. This means that the measurement directly indicates the electroweak unification, just as theory predicted (solid lines). The unification of the four forces of nature are symbolically represented in the lower part of the diagram.

of different ways: through either the electromagnetic or the weak force. In the first case, the two colliding particles exchange a photon, or particle of light. If the particles communicate with each other via the weak force, the exchanged force particle will be either an electrically neutral Z particle or an electrically charged W particle. When a W particle is exchanged, something remarkable happens: The electron changes into a neutrino, which leaves the detector unobserved. Thus two different kinds of particle reaction take place at HERA:

- An electron collides with a proton leaving an electron and other particles as the result of the collision. The mediators of this reaction are the photon and the Z particle — which means that here both the electromagnetic and the weak interactions are involved. Because both the photon and the Z particle are electrically neutral, we refer in this case to a "neutral current reaction."
- An electron collides with a proton leaving a neutrino and other particles as the result of the collision. The neutrino is electrically neutral,

subject only to the weak force and is created exclusively via the W particle. The rate at which this reaction occurs is thus a measure of the strength of the weak force. Because the W particle is electrically charged, we refer in this case to a "charged current reaction".

Researchers are now comparing the rate at which the two kinds of reaction take place as a function of the minimum distance of the particles when they collide in the HERA detectors. The smallest attainable distances correspond to the highest

Neutral Current Reaction
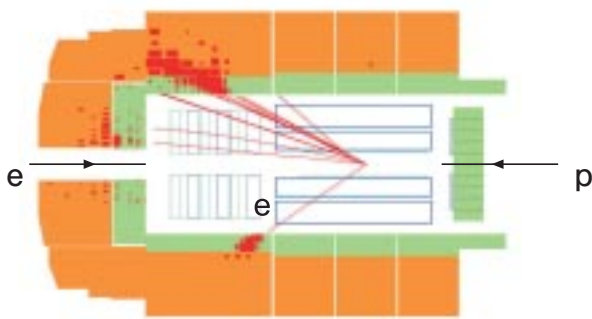
## Charged Current Reaction
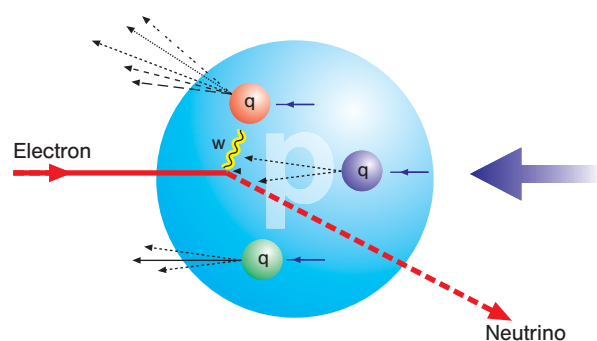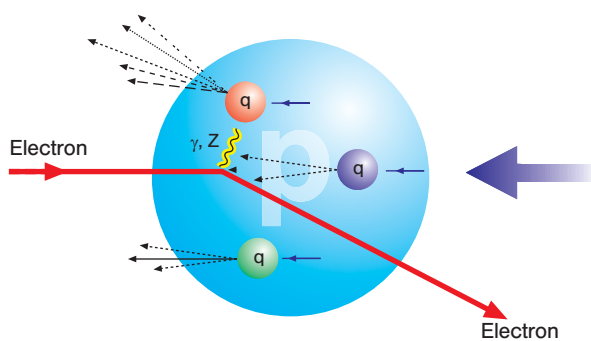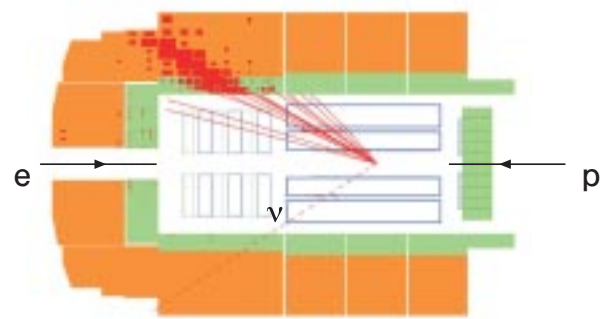
There are two kinds of collision: If an electron hits a proton, it can react with a quark (q) in the proton's interior, either via a neutral exchange particle — a photon (γ) or a Z particle — or via a charged W particle. In the first case, the electron is deflected and becomes visible in the detector (neutral current reaction, left). In the second case, it is changed into a neutrino (ν), which crosses the apparatus without leaving a trace (charged current reaction, right). The quark involved in the collision is blasted out of the proton and generates a particle jet.

momentum transfers delivered by HERA (see p. 53). At larger distances, the electromagnetic reaction occurs significantly more often than the weak reaction, because at these distances the electromagnetic forces operates much more strongly than the weak force. But at smaller distances (and correspondingly high energies), both reactions occur at about the same rate, i.e. both forces are equally strong. Thus the measurement directly indicates how the two forces of nature unite to form the electroweak force.

The reason why the electromagnetic and the weak force act with such different strengths at large distances becomes clear when we observe the mass of the exchange particles involved. The photon has no mass, and therefore it can deliver its "message," — the electromagnetic force — over a much larger distance than the heavy exchange particles of the weak force, the W and Z bosons. At energies that correspond to the mass of the W and Z particles, this difference disappears, and the two forces become equally strong.

Through this demonstration of electroweak unification, HERA in effect takes us a step backwards in time toward the big bang, when in the infancy of the universe the forces and particles of matter interacted at high energies similar to those generated today in the HERA collisions.

The Proton under the HERA Microscope
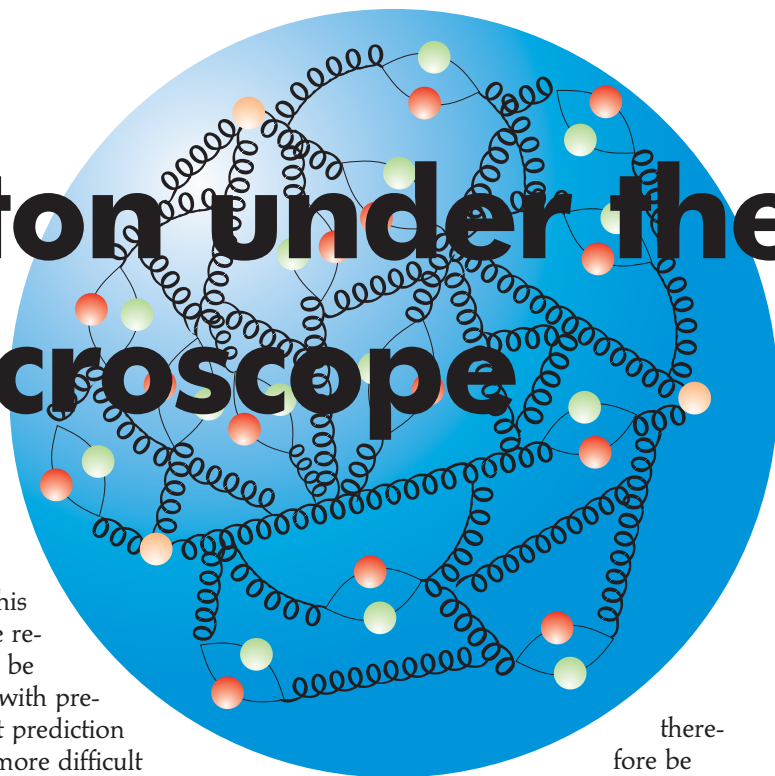
Measuring the inner life of the proton with the utmost precision was one of the key aims that led to the building of HERA. When electrons and protons collide in the H1 and ZEUS detectors, the electron functions like a tiny probe that can "scan" the inside of a proton by exchanging a force particle. Depending on what happens to the electron when it is inside the proton — which particles it collides with and what fraction of the proton's momentum these particles carry — the reactions recorded by the detector vary. But how do we get from these images of reactions to a concrete conclusion about the inner structure of the proton? How can the physicists interpret these colorful images to find out what is really going on inside the proton?

known from theory, and this part of the reaction can be predicted with precision. But prediction becomes more difficult with respect to the proton, whose complex composition from quarks and gluons was largely unknown. This previously unknown structure is now described by the structure function. Little is known theoretically about this function because the complicated equations that describe the strong force in the Standard Model are only partially solvable at present. What the structure function actually looks like must

therefore be determined by experiment. It is exactly this appearance — the characteristics of the structure function — that reveals to physicists what is hidden inside the proton (see box p. 66).

When HERA started up in 1992, nobody really knew what would be found in the depths of the proton. It was known that the quarks in the proton emit gluons (the particles that stick the quarks together) and that

The key to the proton's inner life is the so-called structure function. A typical particle reaction in HERA takes place as follows: An electron hurtles toward a proton, is scattered through the exchange of a force particle, and subsequently flies out of the interaction zone. The proton, by contrast, breaks apart in the collision and its "fragments" leave the point of collision as one or more bunches of particles. The mathematical description of the electron and the exchange particles are

A world first: H1 and ZEUS show that the number of quarks and gluons in the proton increases dramatically when the momentum fraction is small (at various resolutions Q^2 of the HERA microscope).
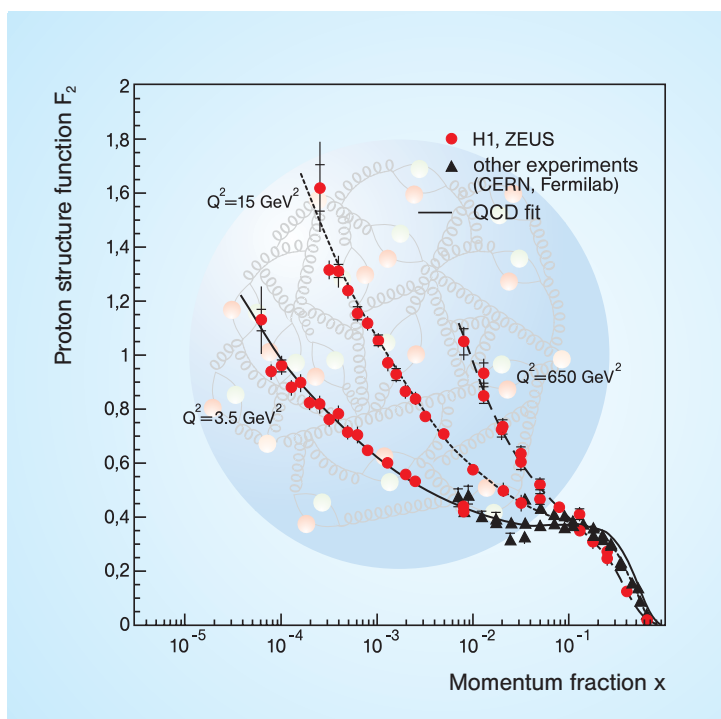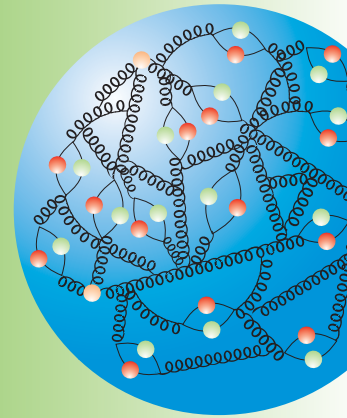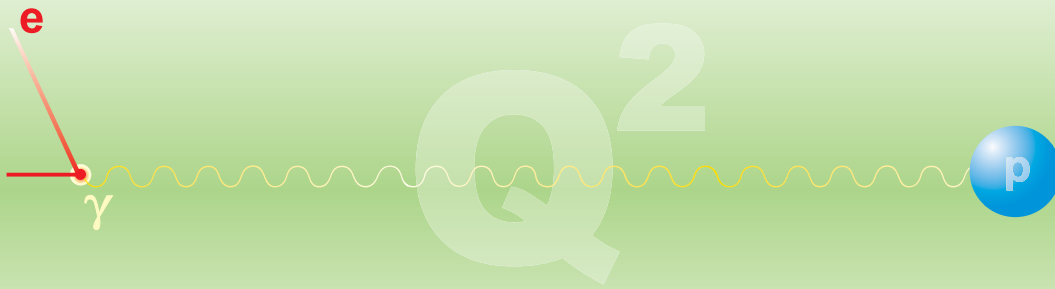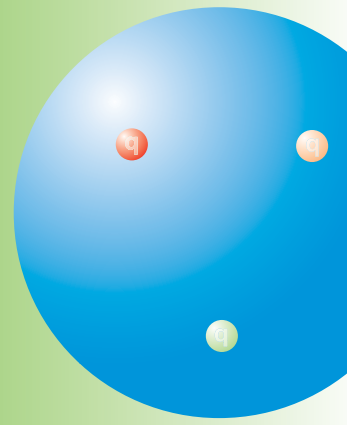
Electron-proton interaction at small quark momenta and impacts of different intensity:

Top: If the photon (γ) exchanged between the electron (e) and the proton (p) only transfers a little momentum (Q² small), the photon only "sees" the main components of the proton, the individual valence quarks.

Bottom: The greater the momentum transfer Q², the greater the resolution of the HERA microscope — the high-energy photon reveals the bubbling soup of quarks, antiquarks and gluons in the proton.

these gluons in turn create other gluons or pairs of quarks and anti-quarks. However, it was assumed that apart from the three quarks that are responsible for the charge of the proton — the "valence quarks" — there were only very few quark-antiquark pairs and gluons in the proton.

Thanks to the high energy of the HERA microscope, the H1 and ZEUS experiments go far beyond the regions that were measured in earlier experiments, right down to ever smaller spatial distances and ever decreasing momentum fractions. What was found there was a big surprise: The HERA measurements show that the interior of the proton closely resem-

bles a thick, bubbling soup in which the gluons and quark-antiquark pairs are continuously emitted and annihi-lated again. The smaller the momen-tum fractions of the quarks and gluons for which the HERA micro-scope is set, the more components there are in the proton.

To put this more simply: If the pro-ton is viewed through glasses that only show components carrying more than ten percent of the proton momentum, the main things that can be seen are the three valence quarks responsible for the charge of the proton. If, however, the protons are viewed using glasses that only show components that carry much

less than ten percent of the proton momentum, an enormous number of quarks and gluons suddenly ap-pear. This high density of gluons and quarks presents a completely new and previously uninvestigated state of the strong force — the force that holds quarks and gluons to-gether in the proton as well as pro-tons and neutrons in the atomic nu-cleus. It is probably as a result of this phenomenon that quarks and gluons are "confined" within the proton and can never be observed as free particles.
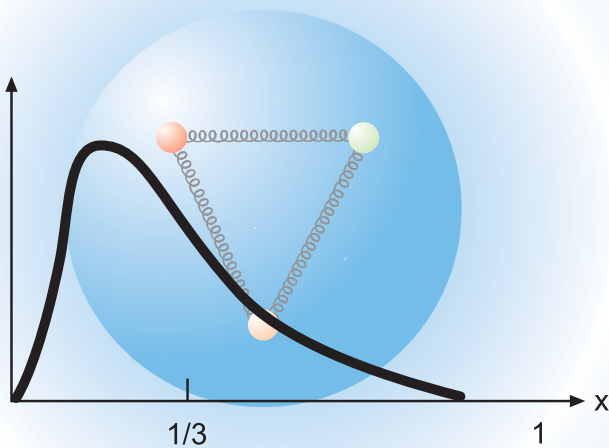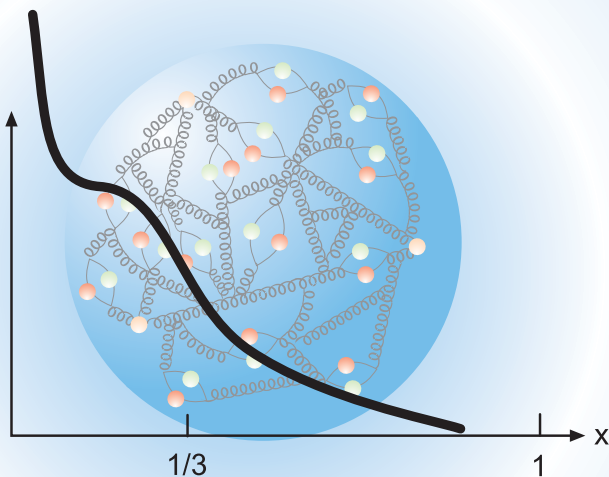
What the Structure Function Reveals
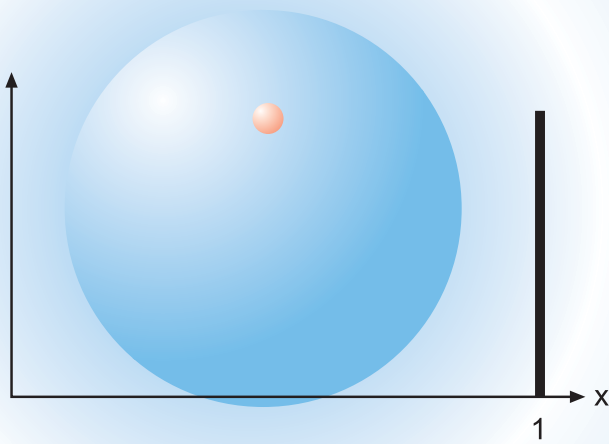
If the proton comprises only one quark, the structure function assumes the form of a dash at $x = 1$, because the one quark carries the entire momentum of the proton (x is the fraction of the proton's momentum that is contributed by the quark).
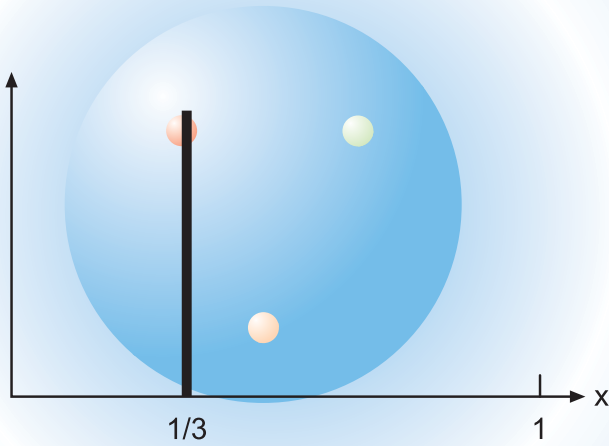
In the case of a proton made up of three independent quarks the dash is located at $x = 1/3$, because each of the quarks contributes a third of the proton's momentum.

If the three quarks communicate via the exchange of gluons, they transfer momentum to each other. This means that the quarks can have higher or lower momentum fractions — their structure function broadens. The gluons themselves are responsible for about half of the momentum. Because the structure function only indicates the momentum fractions contributed by the quarks, the maximum moves from 1/3 to lower values.

The more quark-antiquark pairs and gluons are to be found in the proton, the more the structure function increases toward lower momentum fractions — this is the insight revealed by results from the HERA experiments H1 and ZEUS that discovered the bubbling "soup" of quarks and gluons inside the proton.

Confinement — Inside the Proton

No one has ever seen an individual quark. Regardless of how much energy the particles possess when they collide in the accelerators, individual quarks have never been sighted. This is unusual, considering that they should be easily identifiable as a result of their fractional electric charge. The quarks always seem to appear in groups with integer charges. Protons and neutrons, for example, are made up of three quarks, whereas the so-called mesons are made up of a quark-antiquark pair. Even at HERA, when an electron collides with a quark in the proton, knocking the quark out of the proton with full force, the quark will never appear on its own. The detector reveals a whole bundle of new particles generated around the quark that has been forced out of the proton. It would appear as if the quarks are imprisoned within the particles, just as they are in the proton. But why is this so?

The strong force is responsible for keeping the quarks together in the proton. This force is transmitted by the gluons. The electron-proton collisions at HERA allow this force to be studied in detail; after all, the proton is just riddled with particles that communicate with one another via the strong force. Unlike the electromagnetic force, the effects of which can sometimes be calculated accurately to the tenth decimal
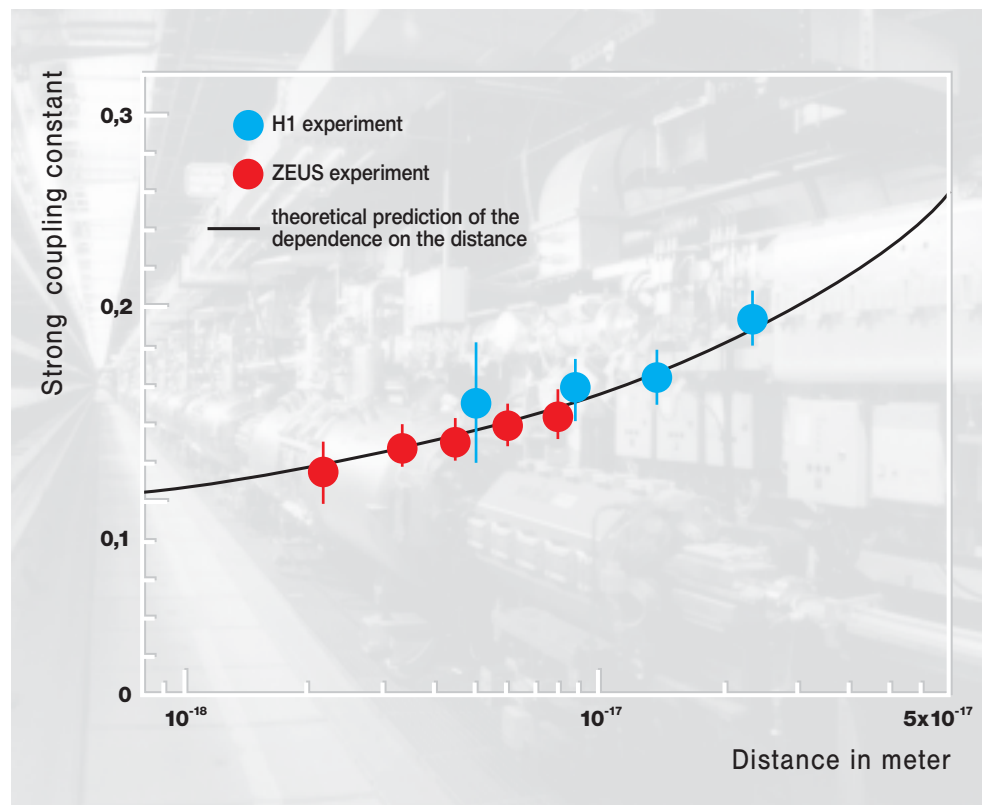

The strong coupling constant determines the strength of the force between the quarks. It is not actually a constant — accurate measurements taken at H1 and ZEUS have shown that it increases with increasing distance.
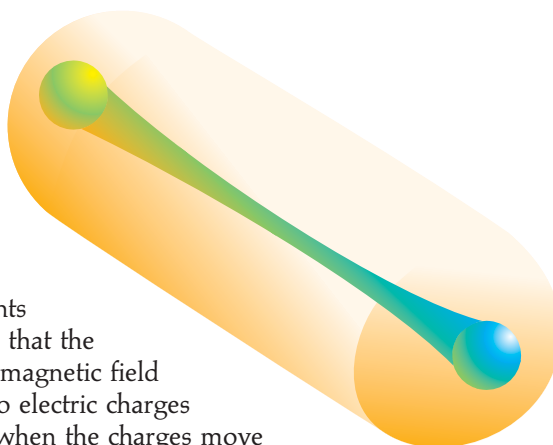
place, it is much more difficult to mathematically master the strong force. This is all due to one fundamental difference between the two forces: While the photons — the light particles that transmit the electromagnetic force — are electrically neutral and cannot, therefore

Experiments have shown that the lines of the magnetic field between two electric charges spread out when the charges move away from one another: The electromagnetic force between them becomes weaker. With the strong
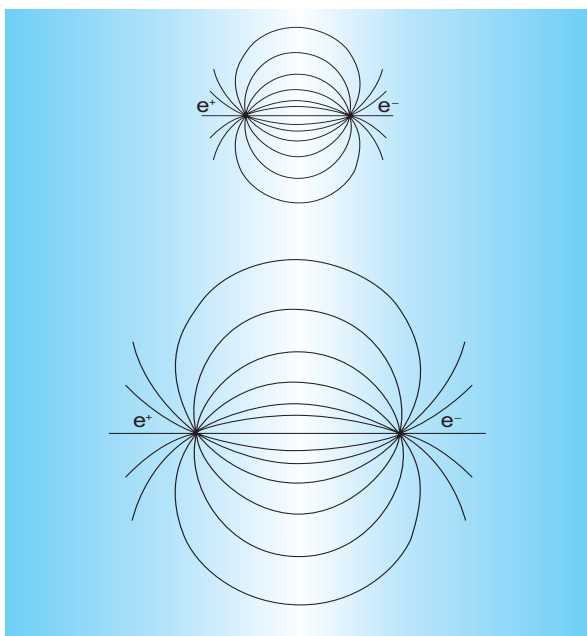
If two electric charges are moved apart, the electromagnetic force between them gets weaker — this means that the magnetic field lines spread further and further apart.
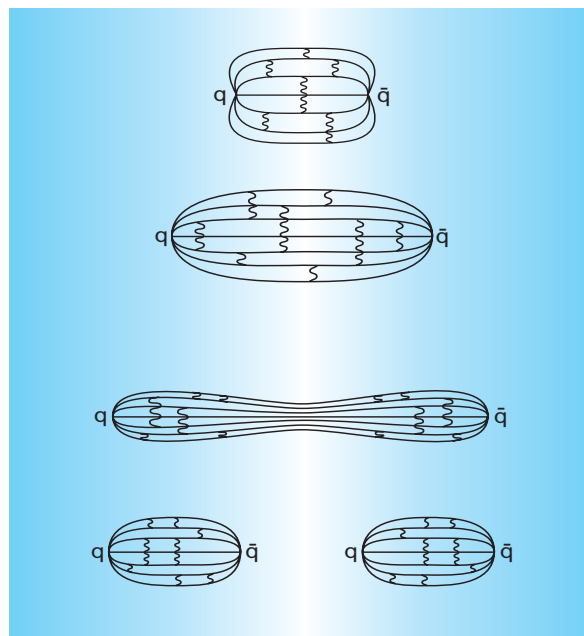

The opposite is true of the strong force: It gets stronger as the quarks move away from each other — until the field lines "snap" and a new quark-antiquark pair is created.

communicate with one another, the gluons, the exchange particles of the strong force, behave differently. They not only interact with the quarks; they also interact with each other — a property that has drastic consequences for the characteristics of the strong force.

force, on the other hand, the lines of the magnetic field are kept together as a result of the "self interaction" of the gluons. If two quarks are separated from each other, the magnetic field lines between them behave like rubber bands. The whole thing works like a sort of

"particle expander": The greater the distance between the particles, the bigger the force needed to separate them even more. Eventually, the system will have enough energy to create a quark-antiquark pair from nothing. As if the rubber band snapped, the original quarks separate.
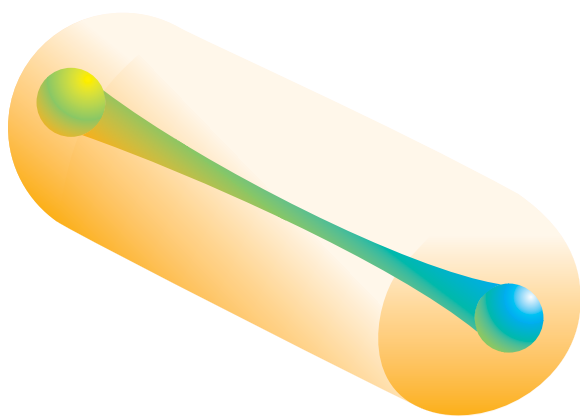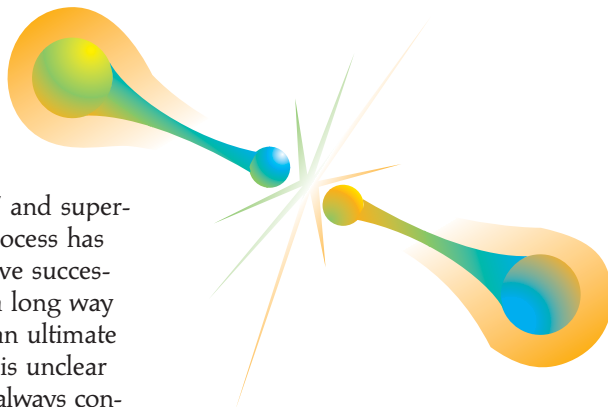
However, they do not do so individually but are always accompanied by another quark with which they combine to form a new particle.

The strength of both the electromagnetic force and the strong force depend on the distance between the particles. While the electromagnetic interaction becomes weaker as the distance gets larger, the exact opposite is the case with the strong force. It is only when the quarks are located particularly close to each other — for example, deep in the interior of a prot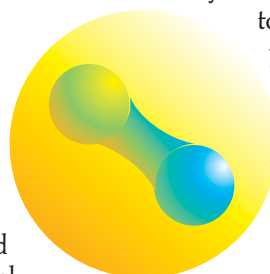on — that the force between them is weak. They then enjoy what is known in scientific jargon as "asymptotic freedom." In this system of virtually free particles, theory really shows what it can do. This is because only the interaction of particles subject to weak forces can be mathematically calculated within the framework of so-called perturbation theory. If the force is too strong, the mathematical process applied is no longer valid. In other words, when it comes to larger distances between quarks, the theoreticians are basically helpless. Attempts are being made to overcome this problem with the help of the "lattice gauge theory" and supercomputers. While this process has produced initial impressive successes, physicists still have a long way to go before they reach an ultimate solution. For example, it is unclear whether the strong force always continues to increase — this would mean that the quarks would be inseparable forever — or whether the strength of the force decreases again at large distances. In the latter case, increasing the energy of the particle accelerators should eventually enable us to observe the first free quarks.

To get to the bottom of quark confinement in the proton, experts currently rely on experimental investigations such as those being carried out at HERA. Like other experiments, H1 and ZEUS were able to accurately measure the strength of the strong force as a function of distance and therefore determine the "strong coupling constant" — a measure of the strength of the force — with respect to the distance between the particles.

To this end, physicists for instance use particle collisions featuring not only the scattered electron and a bunch of particles — a so-called jet — from the quark involved in the collision, but also an additional bunch of particles. This is generated by a gluon that is emitted during the collision. The probability of occurrence of such a gluon emission is directly proportional to the strong coupling constant — in other words to the strength of the force between the quarks. From the number of observed events with a gluon as a function of the momentum transfer during the collision, the dependence of the strong coupling constant on the distance can be measured. For values between 10^{-16} and 10^{-18} meters, the results are impressive confirmations of the large increase at greater distances predicted by the theory of quantum chromodynamics. The fact that the large number of measurements of the strong coupling constant made in various particle reactions at different accelerators produce values which are in agreement is a major triumph for the Standard Model. At the same time, it reassures physicists that they are right to put their faith in the theory of quantum chromodynamics as they strive toward a comprehensive description of the strong force.

Diffraction — File epX Remains Unsolved

Since HERA went into operation, it has been providing lots of important data — and the odd surprise. For example, physicists expected the protons to break up into innumerable new particles during the enormously powerful collisions in the accelerator — especially at the largest momentum transfers. But in about 15 percent of these collisions the proton remained completely intact, even though the interaction was extremely violent. That's about as surprising as if 15 percent of all head-on car crashes didn't leave a scratch on the vehicles. After all, such a violent particle collision does knock a quark out of the proton with enormous force, and, due to the special properties of the strong force, the quark should emit numerous other particles in the process. So how can the proton survive the collision intact?

Theoreticians and experimental physicists are still struggling to understand this phenomenon, which is referred to as "diffraction," a term borrowed from optics. But an explanation of this puzzling effect in the context of the theory of the strong interaction remains elusive, even though models now exist that describe these measurements well. The assumption in one of these models is that the proton contains a mysterious object referred to as a "pomeron" after the Russian physicist Isaac J. Pomeranchuk. While this model does describe the measurements properly, it still doesn't come close to explaining them. Eventually the cause of diffraction will probably have to be sought in the emission of a whole chain of gluons that causes the proton to ultimately emerge intact from the collision. It's likely that this extraordinary property of the strong force also holds the key to answering some fundamental and as yet unresolved questions: Why aren't free quarks found in nature? Why do quarks remain confined in the proton?

Colored Quarks

In the Standard Model of particle physics every force is caused by a characteristic charge: The electromagnetic force for instance is related to the electric charge of the particles. The strong force is related to a "color charge" — though this term has nothing to do with ordinary colors. Color charge is merely a convenient term for an abstract property of elementary particles.

Quarks for instance exist in the "colors" red, green and blue, antiquarks in antired, antigreen and antiblue. However, the only combinations that can be observed in experiments are color-neutral: like particles made up of three quarks — red, green and blue quarks — such as the proton, or quark-antiquark combinations with one color and the corresponding anticolor. Only colorless combinations like these exist as free particles. No single-color particle such as a blue, red or green quark or gluon has ever been observed. Physicists refer to this peculiarity of the strong force as "confinement." Why the quarks are confined within particles such as the proton remains one of the fundamental unanswered questions in particle physics.

e (scattered electron)

Created particles

X   p
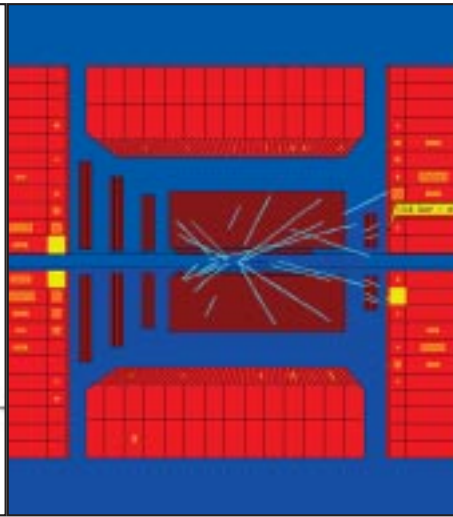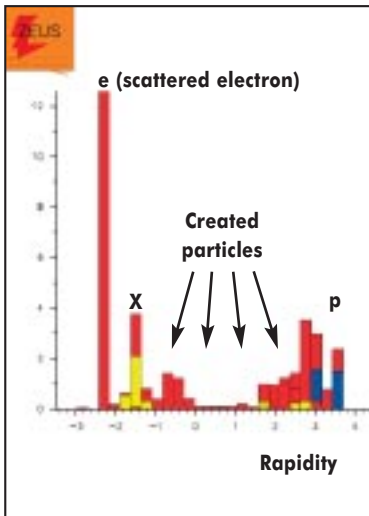
Rapidity

A "deep inelastic scattering" event at ZEUS.
(Right: particle tracks in the detector. Left: the measured energy as a function of the "rapidity," a measure of the angle at which the particles are created.)
Due to the special effect of the strong force, numerous other particles appear between the fragments of the proton (p) and the particle jet of the ejected quark (X).

RapGap at HERA

The scene is HERA: At the highest energies, an electron collides with a proton and knocks loose a quark. The electron rebounds, and the scattered quark creates a jet of other particles, as do the remnants of the proton. The electron and the two jets leave their observable tracks in the H1 and ZEUS detectors. It's characteristic of these "deep inelastic scattering" events that particles can also be found in the space between the two particle jets: As one quark is ejected from its group within the proton, the strong force between the quarks increases with the distance the ejected quark traverses. The strong force holds the group together much like rubber bands. But at some point the band breaks, and more particles are created from the released energy in accordance with Einstein's famous equation $E = mc^2$. In the detectors, these particles appear in the space between the particle jet from the scattered quark and the proton remnant.

This is precisely where a gap is apparent in the mysterious "diffractive events" discovered at HERA. An electron and a proton enter the detector at high speed. What comes out is the scattered electron (e), a narrow particle jet from the quark (X) ejected from the proton — and the intact proton (p). Nothing else. There is no sign of any remnant of the strong force's "rubber bands," nor of any change in the proton. This leads to the conclusion that the electron has collided with a color-neutral object — a particle not attached to the proton remnant by the "rubber bands" of the strong force. Particle physicists have been debating ever since what that might be.

In their vernacular, the name of these strange events has been derived from this particle gap: rapidity gap-events — RapGaps for short.

p at Rap = 7

e

X

No other particles
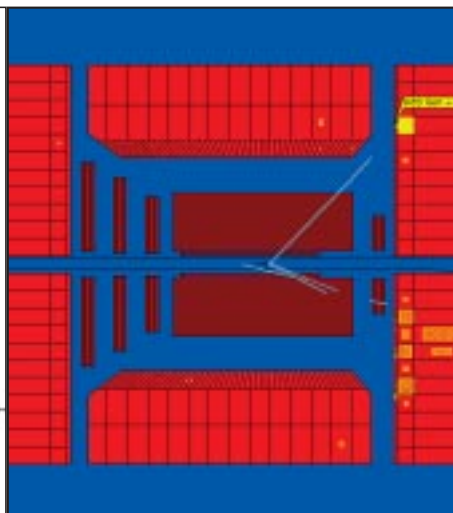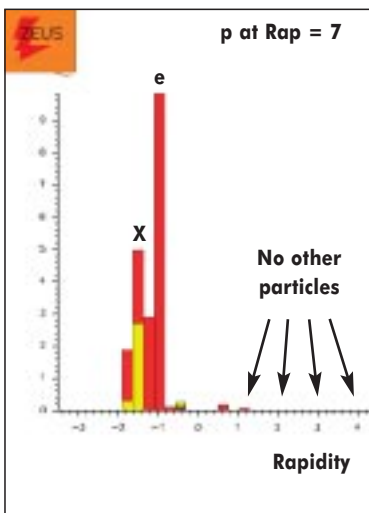
Rapidity

RapGap — a "diffractive" event at ZEUS. (Right: particle tracks in the detector. Left: measured energy as a function of the "rapidity").
Here the proton remnant (p) in the left part of the illustration is no longer visible — it should be located near a value of about 7. What's extraordinary is that no other particles are apparent between the particle jet from the ejected quark (X) and the proton remnant. This "gap" in the rapidity ("RapGap") is characteristic of diffraction.

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A Different Perspect With the Proton at Re

A fundamental postulate in physics states that the laws of physics apply anywhere in the universe — no matter from what perspective we view an event. Though the picture of an event as the observer views it does change with the reference system, the physical findings and ultimate results are independent of the perspective from which the process is described. Take the particle collisions in HERA: They can be analyzed from the perspective of the "laboratory reference frame" — the viewpoint of the observer sitting in the lab, watching the electron and proton rush towards each other at the center of the H1 and ZEUS detectors. But in many situations it's advantageous to be working in the "proton rest frame" — the reference system that moves along with the proton: The observer analyzes an event as though sitting

aboard the proton during its flight. To this observer the proton now appears stationary, while the electron is approaching it at nearly the speed of light.

From this perspective the proton carries no kinetic energy. Instead, the entire collision energy is delivered by the onrushing electron. While in the laboratory frame the electron carries only 27.5 gigaelectron-volts (GeV) of energy and the proton zooms around the HERA ring with 920 GeV, the perception from the proton rest frame is that the electron carries over 50 000 GeV as it impacts a proton that has a momentum of 0 GeV. The difference in perspective may at first sight seem insignificant, but it profoundly affects what the observer perceives when the particles collide.

The key to the further course of events is provided by Heisenberg's uncertainty principle. In the world of quantum

physics, a particle can split into several other particles for a very short time. The possible duration of these so-called quantum fluctuations can be derived from the uncertainty principle: The more energetic the original particle, the longer the life span of the quantum fluctuations. A photon for instance can split into a quark and an antiquark. These in turn can fragment into other particles — until the time span defined by the uncertainty principle is up and all of the fluctuations continue on their path once more in the form of the original photon. In the rest frame of the proton within HERA, the electron carries so much energy that its quantum fluctuations are very long-lived. Under certain conditions the photon can travel about a quadrillionth of a meter in the form of quarks and gluons. This distance equals about 1000 proton diameters.

During the collision of an electron and a proton in the HERA ring, the electron emits a photon, a quantum of light. Thanks to its high energy as viewed from the rest frame of the proton, the photon can transform itself into a whole cascade of quarks, antiquarks and gluons. And what finally interacts with the proton is no longer the original photon but a hadron — a particle composed of quarks which, unlike the photon, doesn't communicate with the proton through the electromagnetic force but through the strong force.

Viewing a physical result from this perspective can often lead to an alternative explanation of the event. For example, the rise of the structure function of the proton at low values
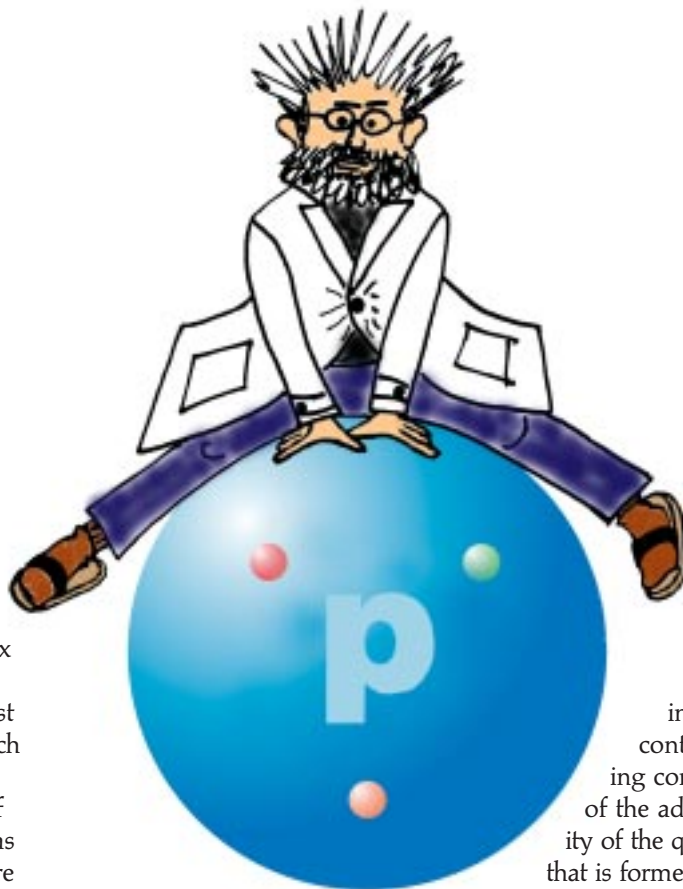
of the momentum fraction x (see p. 64) in this view of events is not ascribed to an increasingly complex internal structure of the proton — which remains unchanged in its rest frame. Instead, it's the photon which transforms itself at low values of x into an increasingly dense cloud of quarks and gluons that shows up as an increase in the measured structure function. Both views are complementary: The "viewing platform" is different, but the obtained result remains the same.

The mysterious diffraction too (see p. 70) can be explained when viewed from the rest frame of the proton. From this perspective, the photon doesn't encounter a color-neutral particle in the proton. Instead it's the photon itself which changes into a (color-neutral) hadron and is finally scattered as a hadron on the proton. The interaction can be so "soft" that the proton remains intact and is ultimately observed, together with the electron and the scattered hadron, in the detectors as a diffractive event. The reaction between the electron and the proton that began as electromagnetic scattering can therefore be demonstrated to be a hadron-hadron scattering event (the proton too is a member of the hadron family) — and this is confirmed by comparison with other hadron-hadron scattering experiments.

So far it has been possible to reproduce the physical results of such hadron-hadron scattering events quite faithfully by models. But these models fail to provide an explanation of how these results come about in

the context of quantum chromodynamics — the fundamental theory of the strong force. The HERA experiments can play a key role in resolving this issue. This is because the parameters of the experiment can be changed so as to alter the nature of the fluctuations into which the photon transforms itself. If one measures reactions with high momentum transfers (high Q^2), then the width of the quantum fluctuation is very small. In the extreme case it consists of a single quark-antiquark pair. The smaller the momentum transfer Q^2 of the reaction, the greater is the width of the hadron formed by the photon, and the more quarks and gluons are contained in the hadron. One could

say that in HERA it is possible to convert a photon into a hadron of continuously increasing complexity by virtue of the adjustable complexity of the quark-gluon cascade that is formed. The mechanism behind this transition from a single quark-antiquark pair to a complex hadron is a process controlled entirely by the strong force. By investigating this process, physicists can thus test the foundations of quantum chromodynamics. Ultimately this process can reveal exactly how the strong force holds the quarks and gluons together within hadrons — and thereby unveil the mystery behind the confinement of the quarks within the proton.

The Kinematic Variables x and Q^2:

x: fraction of the proton's momentum carried by the quark with which the electron collides;
Momentum transfer Q^2: square of the momentum transferred in the collision between the collision partners; a measure of the resolution of the HERA microscope ($Q^2 = 1$ GeV^2 corresponds to a resolution equal to one fifth of the proton radius).
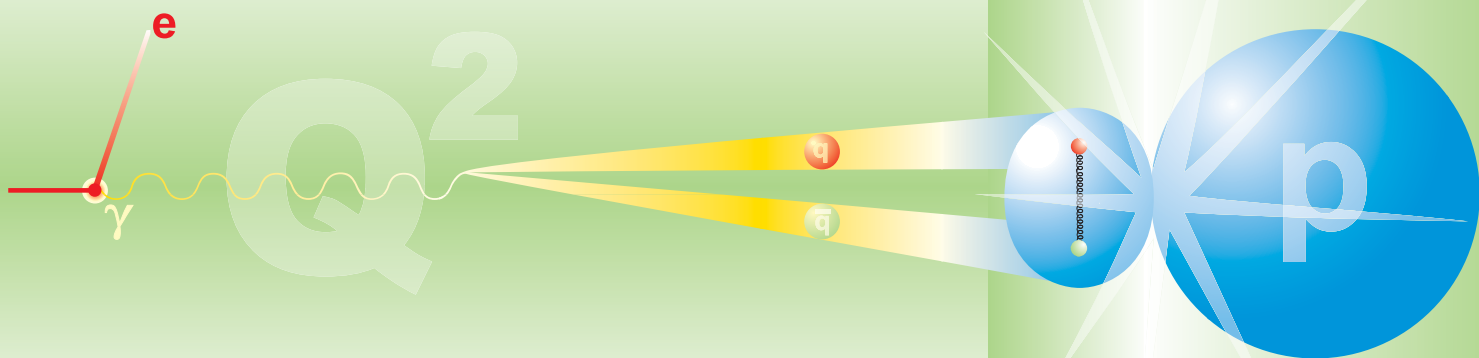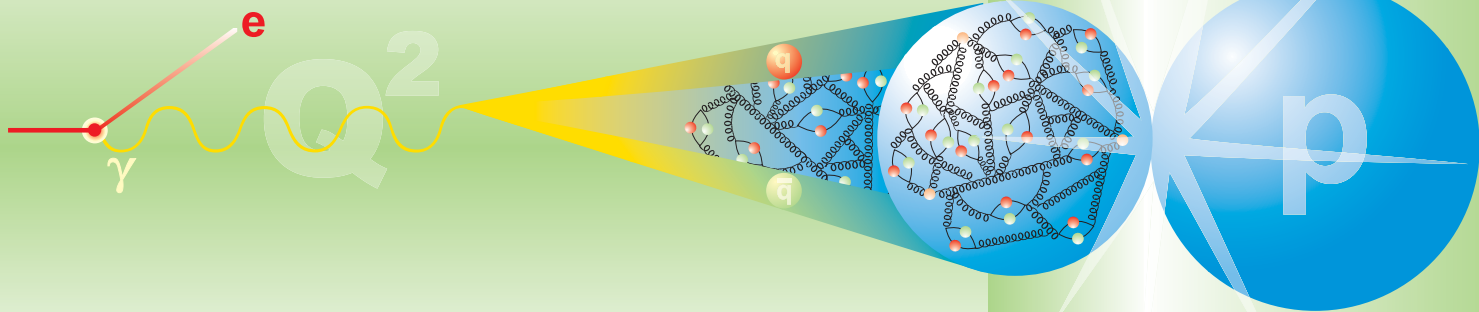
In the Rest Frame of the Proton

Viewed from the rest frame of the proton, the world looks different — but the physical results remain the same: In this case it's no simple photon (γ) that collides with a highly complex proton (see p. 65). Instead, the observer sees the photon transform itself into a complex particle consisting of quarks, antiquarks and gluons — a "hadron" that finally collides with the proton.

If the momentum transfer Q^2 is small (top), the photon forms a large, complex hadron. With a larger value of Q^2 the hadron is simpler. It can even consist of a single quark-antiquark pair (bottom).

The momentum transfer can therefore be used to adjust the complexity of the hadron that is formed. As a result, the HERA physicists can study in detail how such particles are formed and which properties of the strong force play a part in this process. It may even be possible to determine why the quarks are confined in the proton.

Tracking Down New Particles and Forces

With the discovery of the top quark in 1994 and the evidence for the tau neutrino in the summer of 2000 at Fermilab, Chicago, the particle zoo of the Standard Model is nearly complete. What's still missing is the Higgs particle, which is supposed to be responsible for creating the masses of the particles. So far, the Standard Model has described the events in the realm of the smallest particles with superlative success. Nevertheless physicists are not satisfied with the model. It leaves many questions unanswered. Gravity has no place in it. And too many apparently arbitrary natural constants have to be experimentally determined and plugged into the calculations. Ultimately physicists are searching for a more comprehensive theory — a "formula of the universe" that transcends the Standard Model and explains our world on the basis of few assumptions and constants.

There are several candidates for a more comprehensive theory (see p. 56). However, up to the present time, there have been no experimental indications of which of these theories conforms most closely to nature. Consequently the search is on in accelerator centers around the globe for effects "beyond" the Standard Model: The discovery of a new particle or force would probably provide the clearest indication leading toward an expansion of the Standard Model.

The two factors that determine whether a particle can actually be created in an accelerator are the types of the colliding particles and the collision energy — the "center-of-mass energy" of the accelerator. At HERA this amounts to about 320 gigaelectronvolts (GeV). Particles that are lighter than this center-of-mass energy can actually be directly produced thanks to Einstein's famous formula $E = mc^2$, which expresses the equivalence of mass and energy. Such newborn particles can be recognized by their "footprint" — the way they disintegrate into other particles — which can be directly derived from


the image of the particle tracks created in the collision. What's more, if we plot the distribution of the observed events as a function of the electron/colliding quark system, a new particle should reveal itself as a "peak" in this distribution. This is because at the energy that corresponds to the mass of the new particle there is an increase in the rate of the measured events. This "resonance" is a sure sign that something new has been created here.

Since HERA is the world's only electron-proton storage ring, the H1 and ZEUS experiments are uniquely well suited for the discovery of certain types of particles. As a case in point, certain theories beyond the Standard Model postulate the occurrence of leptoquarks — hybrid particles that combine the properties of leptons and quarks. Since in HERA a lepton (the electron) collides with the quarks in the proton, such leptoquarks could be created directly from the union of the two particles. Other accelerators would need to have enough energy to create leptoquarks in pairs. At HERA a vigorous search is also currently under way for supersymmetric particles, which have been predicted by the supersymmetry theory. So far, however, this search has been in vain, not just at HERA, but also at all other accelerators.

The direct search for new particles is limited by the center-of-mass
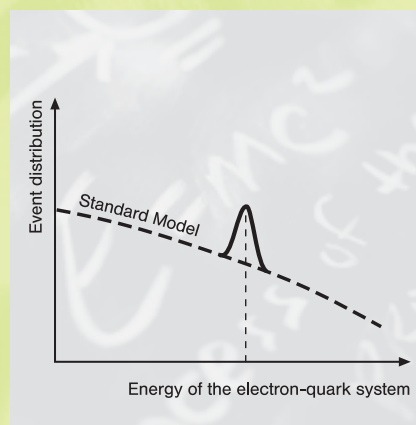
A "resonance" in the distribution of the observed events: A new particle has been created here.
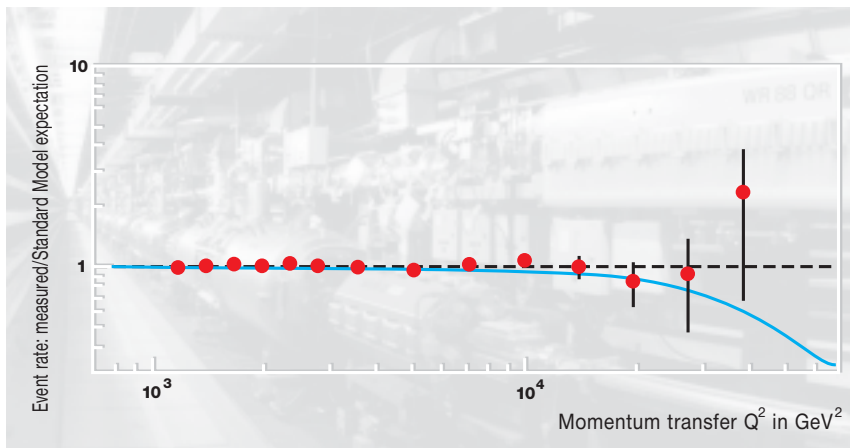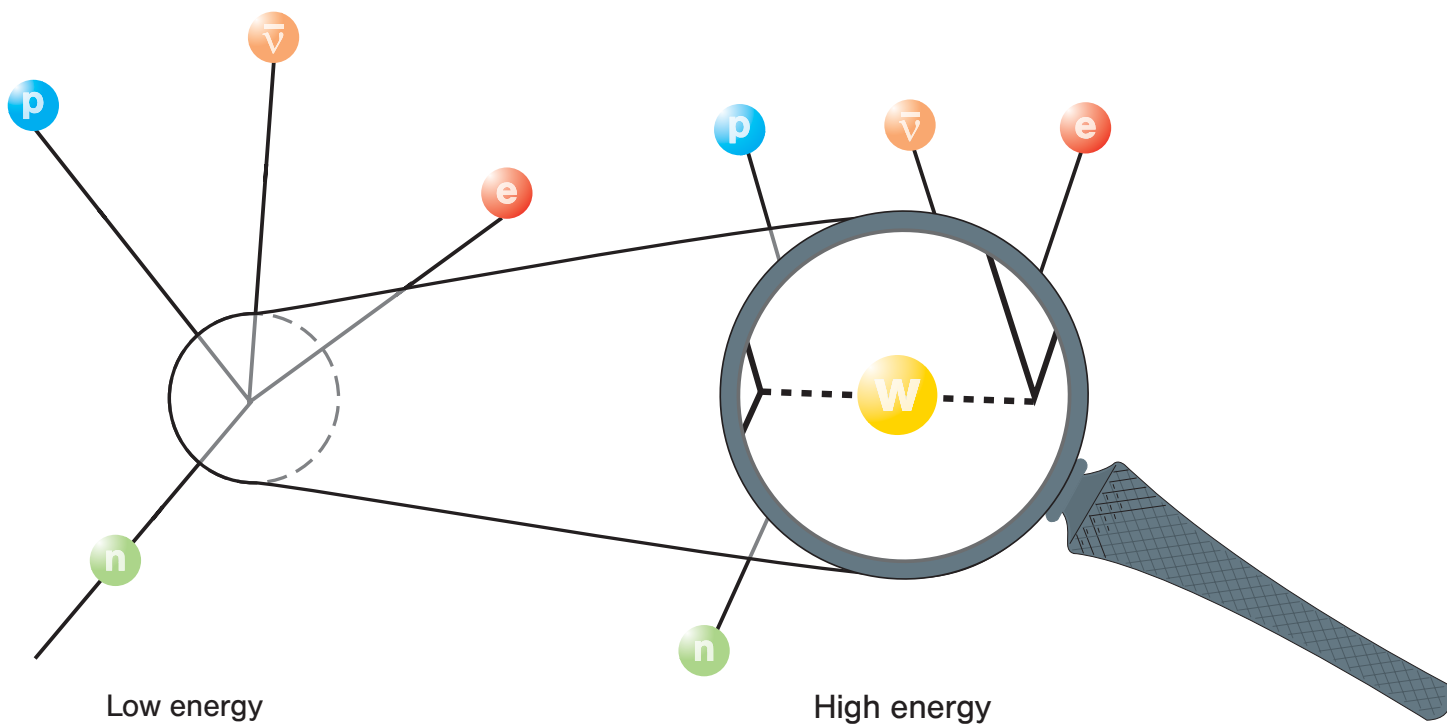
A comparison between measurement (red dots) and theory (blue line) enables physicists to exclude the existence of new particles such as leptoquarks with a mass greater than HERA's center-of-mass energy (blue line for a leptoquark with a mass of 900 GeV at strong coupling).
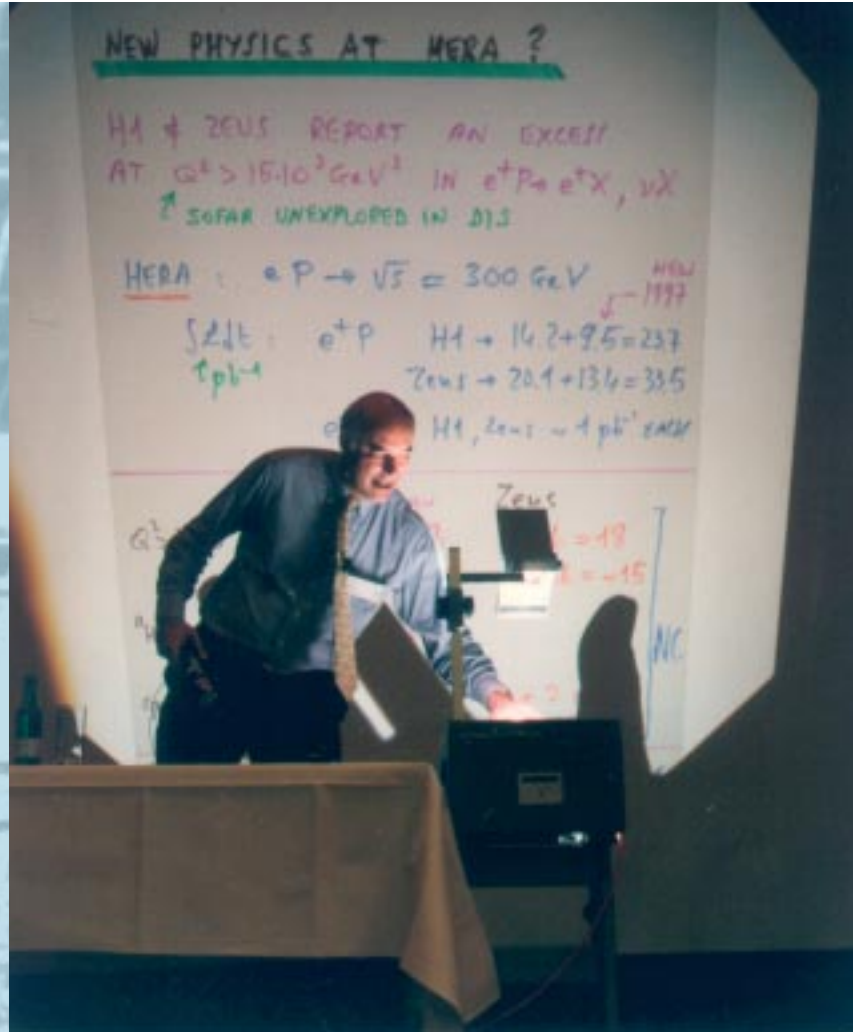
energy of the accelerator. But there is a maneuver that enables physicists to use their experiments, as it were, to "look around the corner" into a realm that lies beyond the presently available energy. This trick has already proven highly successful in the past: Well before the mediating particles of the weak force — the W and Z particles – were discovered at CERN in Geneva in 1983, physicists were able to predict them with considerable accuracy on the basis of experimental results.

The principle is based on the concept of the "contact interaction." When the energy of the accelerator is too low to resolve a given process, the interaction between the particles behaves as though it occurred at a point: Two particles converge to a single point, then two particles emerge from that point — but exactly what happened there can't be seen with the available energies. For example, the event might have been caused by the exchange of a particu-

Low energy   High energy

A neutron decays into a proton, an antineutrino and an electron: At low energies the interaction behaves as though it occurred at a single point. An energy increase enhances the resolution used to observe the disintegration and reveals that the event actually involved the exchange of a W particle.

In February 1997, H1 and ZEUS recorded an unexplained excess of events that seemed to point the way to a "new physics." The cause won't be unraveled until the luminosity increase at HERA has been completed.

larly heavy — new — exchange particle that mediates a previously unknown force. But such highly energetic, unobservable processes do leave their mark at lower energies too: They interfere with the known processes and thereby change the rate of occurrence of the measured reactions. So if the experimental data exhibit a deviation from the theoretical prediction as derived from the Standard Model, this difference may be a clue to a highly energetic process beyond the energy of the accelerator. Such analyses have so far ruled out the existence of any fundamental forces between electrons, quarks or gluons with a range greater than about one five-thousandth of the proton radius.

Any changes that are caused by new effects should become most readily evident at the maximum resolution — in other words, at high values of the momentum transfer Q^2, the very region where normally few reactions occur.

Not surprisingly, the search for such events has been a long, drawn-out undertaking. In February 1997 for instance the HERA experiments H1 and ZEUS listed an unexplained excess of high-energy events in their records. At the time there were wild speculations in the press about whether this deviation merely represented a statistical fluctuation or something really new. But the issue remained unresolved — the amount

of available data was insufficient to allow reliable conclusions. The deviation still exists in the currently available data volume, which is seven times larger. However, it has become less pronounced. A conclusive explanation of the cause will probably have to wait until the recommissioning of HERA has been completed. The experiments will then be able to make full use of the accelerator's fourfold increase in luminosity.

The Search for Extra Di

Left/right, back/front, up/down, we are clearly living in a space with three dimensions. Time counts as a fourth, yet many writers of science fiction novels are not content to leave it at that. Hardly have the heroes blundered into a hopeless situation in the regular four dimensions, when rescue suddenly appears in the form of a fifth dimension. In actual fact, the idea that our world may be embedded in a multi-dimensional space that goes beyond our familiar three is by no means the unfounded speculation of science fiction authors. Some theories that go beyond the Standard Model also postulate the existence of more than three spatial dimensions. String theories, for example, replace the point-like particles of the Standard Model with tiny strings that oscillate in up to ten spatial dimensions. The fact that these additional spatial dimensions remain hidden from us even has an explanation: Apparently, they are "curled up" on themselves. It's a bit like a drinking straw, which looks different when viewed from different perspectives. To us it may well look like a one-dimensional line from a distance. However, an ant scrambling around its two dimensional surface sees things very differently.

Behind these concepts lies the attempted unification of the forces of nature into a single primordial force (see p. 62). Whereas the electromagnetic and weak forces become equally strong at energies of 100 gigaelectronvolts (GeV) — energies that are already attainable today — the unification of the resulting electroweak force with the strong force does not occur until 10^{16} GeV. And that, unfortunately, is far beyond the range of any particle accelerator that could conceivably be built on earth. Moreover, gravity is very weak at our everyday energies. In fact, it only reaches the strengths of the other forces at 10^{19} GeV. This energy scale, the Planck scale, is associated with distances of just 10^{-35} meters, the Planck length. Physicists believe that it is only at such huge energies that gravity can be unified with the other forces in a "theory of everything." There are an entire 17 orders of magnitude between the energy scales of the electroweak unification and that of the unification with the gravitational force. This is an unsatisfactorily large difference and is not without difficulties for theoreticians, too. It would also put direct experimental testing of the unified theory hopelessly out of range for the foreseeable future.

However, in 1998 Nima Arkani-Hamed, Savas Dimopoulos and Georgi Dvali came up with a radical new idea at Stanford University in California. What if the decisive Planck scale were not 10^{19} GeV but effectively as low as the region around 1000 GeV? This possibility would
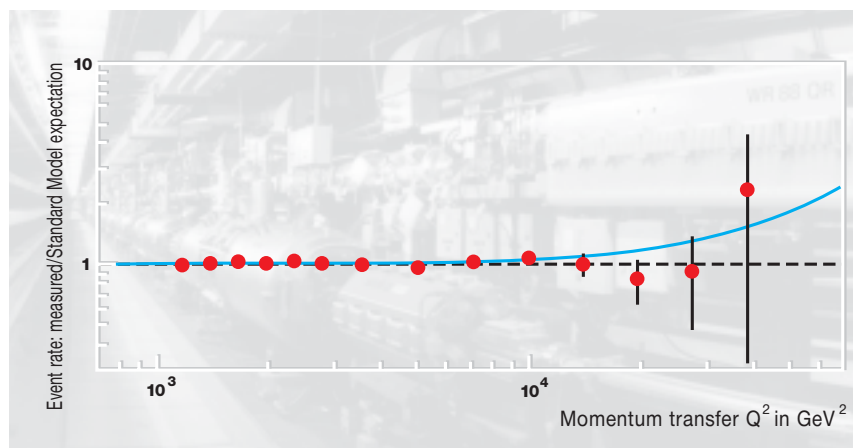
mensions

tional Planck scale of 10^{-35} meters is based upon the assumption that Newton's law of gravity — which accurately describes the case of solar systems and falling apples or human beings — is also valid at these minute distances. At the moment however, it has not yet been experimentally tested for distances below 0.2 millimeters. That the law of gravity is universally valid has hitherto only been generally assumed but has never been proven. What's more, it is necessary to extrapolate over 32 orders of magnitude to conclude that gravity only becomes strong at the Planck length of 10^{-35} meters.

If additional dimensions are added to the equation, dimensions that are "curled up" in less than 0.2 millimeters, the law of gravitation would be altered at such small distances, whereas for larger distances — above the 0.2 millimeter limit of current experimental determination — things would be as hitherto accepted. One effect of this change, however, is that gravity would increase in strength far more quickly than currently believed when distances are shorter and thus energies are greater. With the correct number and size of additional dimensions, the "effective" Planck scale could thus indeed move to within the region around 1000 GeV. This would mean that at least one part of string theory, namely the higher-dimensional framework in which the strings move, could be experimentally tested in existing or planned accelerators.

If these dimensions really are so large then the question arises, "why have they not been seen before?" The answer is simple and strange at the same time. All the particles which

put the unification of all the forces of nature and the theory of everything within the range of the next generation of accelerators — in other words, facilities such as the LHC at CERN in Geneva and the TESLA accelerator proposed by DESY. The idea is enormously attractive and astonishingly, no observations to date have excluded the possibility. Unification on a conven-

Are there more spatial dimensions? Comparison of data from HERA (red) with theoretical predictions (blue curve for an effective Planck scale of 800 GeV) can play a key role in answering this question too.
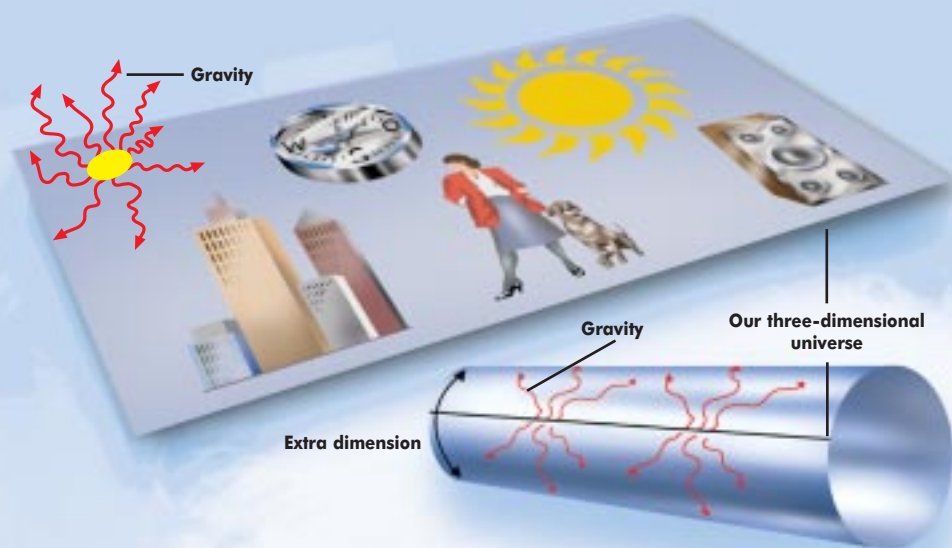
Our universe may exist on the surface of a wall or membrane that in fact is located within other dimensions. The line on the outside of the cylinder (bottom right) and the flat surface represent our three-dimensional universe — an environment that encloses all the known particles and forces with the exception of gravity. Gravity (red lines) spreads throughout all the dimensions.

have been experimentally investigated so far are still limited to the usual three dimensions — rather like flat objects on a two dimensional wall or membrane which itself is still embedded within a multi-dimensional space. Only gravitons, the hypothetical exchange particles that mediate gravity can move freely in the additional dimensions. The additional dimensions are thus detectable purely by gravitational effects.

The idea of large additional dimensions could therefore solve some of the riddles of particle physics and cosmology, for example what dark matter may be made of. More than 90 percent of the mass of the universe is invisible and not made of quarks and electrons. It can only be detected by its gravitational attraction. It is possible that this matter exists in parallel universes separated from ours by additional dimensions. Such matter would only affect our universe by gravity, the exchange particles of which can move freely through additional dimensions. The photons, gluons and W or Z particles used by physicists in their experiments would be irrevocably trapped within our universe and would thus be unable to reveal the dark matter.

Already particle accelerator experiments like H1 and ZEUS at HERA can search for these large additional dimensions indirectly. In this case too, the effect of extra dimensions on the HERA data is being calculated and compared to the actual measurements. So far the results show no evidence of extra dimensions beyond the familiar three spatial dimensions. As a result, the HERA experiments have shown that the effective Planck scale must lie above 800 GeV. After the recommissioning of HERA, the experiments will be able to explore the effective Planck scale up to about 1200 GeV.

Two extra dimensions curled up into a sphere.

HERA-B on the Trail of Charmonium

The HERA-B experiment was specially constructed to detect a particular needle in the proverbial haystack. The "golden decay" of B mesons — an event that only occurs once in 100 billion particle reactions between protons and atomic nuclei — is particularly suited to the study of possible causes for the unequal distribution of matter and antimatter in the universe. The international HERA-B group has lost the race for the B mesons against the so-called B meson factories at SLAC, U.S., and KEK in Japan. The delays caused by the enormous difficulties encountered during the construction of the detector and solving novel technological problems were just too big. Other ways of utilizing the specific strengths of the detector have emerged, however, which open up new fields of action for the "haystack" specialist from HERA's West Hall.

The proton hurtles along the beam pipe at almost the speed of light. A long curve to the left before the finishing straight, only 20 meters to the HERA-B target — bullseye! For a proton, the hair-thin wires that make up the target placed in the proton path by the HERA-B physicists are almost invisible. Between the atomic nuclei of the metal there is mostly empty space. The particle passes through the wire almost unaffected — however, now and again, there is a collision. The proton collides head-on with an atomic nucleus and smashes into one of the latter's components. Both the proton and the component "burst" apart to produce a firework of quarks and gluons. The matter particles get reshuffled into newly created particles that burst out of the wire, propelled by the impact of the proton, and end up in one of the sections of the detector.

In the collisions between protons from the accelerator and the wires of the HERA-B target, the physicists have been seeking a particular species of particle: charmonium particles, which consist of a charm quark and a charm antiquark. These particles are formed within an atomic nucleus during the collisions. Before emerging from the nucleus and continuing their journey into the detector, they must therefore first pass through the nucleus for a short distance. On their journey, however, they are obstructed by the components of the nucleus — in other words, by protons and neutrons that also consist of quarks and gluons.

There are various versions of the charmonium particle, some of which are more loosely bound than others. The charm quark and antiquark are most closely bound together in the so-called J/ψ particle (pronounced "j/psi"). The unromantic double name comes from its simultaneous discovery by two independent research groups. More loosely bound for example are the ψ' (pronounced "psi prime") and χ_c ("chi-c") particles. In scientific jargon, it is said that the particles have differing binding energies. The more loosely these charmonium particles are bound, the more easily they break apart when they interact with a nucleon on their way through the nucleus. The larger the nucleus, the longer the path that the particles have to travel and thus the lower the probability that the charmonium particles will emerge unscathed. Depending on its size, different numbers of charmonium particles will emerge from the atomic nucleus — a phenomenon that physicists call "charmonium suppression."

At HERA-B, four different target wires made of different materials can be placed in the proton beam at the same time. This means that the creation of charmonium particles can be simultaneously studied for different weights of atomic nuclei. Such an arrangement ensures that measuring errors in the results are far lower than when the measurements are conducted one after the other. Since the B mesons that HERA-B was originally designed to detect also decay to J/ψ particles, the detector is particularly suited to the study of such particles — in spite of, or perhaps because of its concentration on that particular type of particle. The phenomenon of charmonium suppression should largely occur for those particles

Particles are captured and identified in HERA-B's electromagnetic calorimeter, which is five meters high and six meters wide.
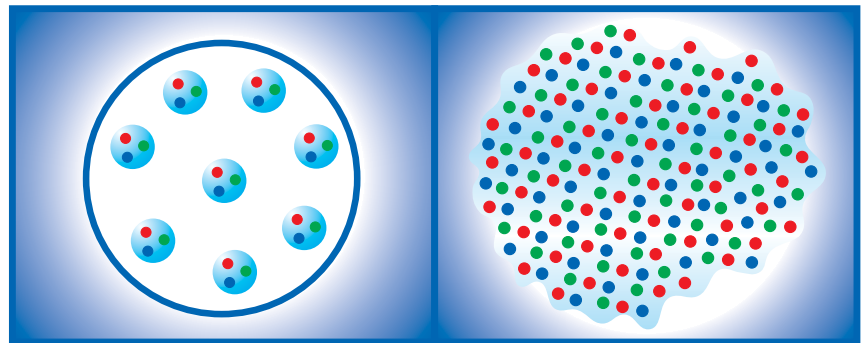
To do so, they are relying on collisions between highly accelerated heavy atomic nuclei. The evidence that such a plasma has been produced may only be indirectly determined, however. One method of providing such evidence is based on precisely the kind of charmonium suppression that HERA-B is able to study in detail. The rate at which J/ψ particles are created in a particle collision would be noticeably reduced by the presence of a quark-gluon plasma. Before the charm quarks and antiquarks form a J/ψ, they interact with the quarks in the plasma and are thus no longer available for particle formation. However, it is first necessary to precisely understand

which move most slowly through the nucleus since they remain in the nucleus longer. These particles are distinguished by their low forward momentum, which means that they are scattered into the detector at large angles with respect to the proton beam.

Early experiments at CERN in Geneva and Femilab in Chicago were limited to small angles when studying charmonium particles. HERA-B however opens up a hitherto unattained range of scattering angles covering precisely the area where the various theoretical models for the production and absorption of charmonium particles can be well tested.

The interaction of a charmonium particle with matter in the nucleus in which it was created provides clues to a range of unresolved questions in particle physics. The results obtained are equally of interest to particle physicists and cosmologists. For some time, experiments around the world have been searching for the so-called quark-gluon plasma, the "primal soup" of the universe. According to some theories, quarks and gluons existed as free particles a few

millionths of a second after the big bang before condensing into "normal" matter as the universe cooled. Such a plasma of free quarks and gluons could still exist today in extremely dense neutron stars. Researchers at CERN in Geneva and the Brookhaven National Laboratory in the U.S. are striving to create the necessary energy densities for a quark-gluon plasma in the laboratory.


The primal soup of the universe: Quarks in atomic nuclei are "confined" within the nucleons — the protons and neutrons (left). In a quark-gluon plasma the quarks and gluons exist as free particles (right).

the principle of charmonium suppression in conventional nuclear matter before a physical interpretation of quark-gluon plasma experiments can be developed.

HERMES and the Mystery of Spin

According to the measurements made in the HERA experiments H1 and ZEUS, the closer we peer into the proton, the more particles it seems to contain: The three valence quarks that give the proton its identity swim in a veritable sea of short-lived quarks, antiquarks and gluons. But the complexity goes a step further, for each of these particles has its own intrinsic angular momentum, its "spin." And all of them are moving — just like a carousel at a fair, where the riders are simultaneously spinning in their seats. Nonetheless, this bubbling, whirling "soup" forms a structure that also has a clearly defined spin of its own. How does the proton get its spin? Finding the answer to this question is the main focus of the HERMES experiment at HERA.
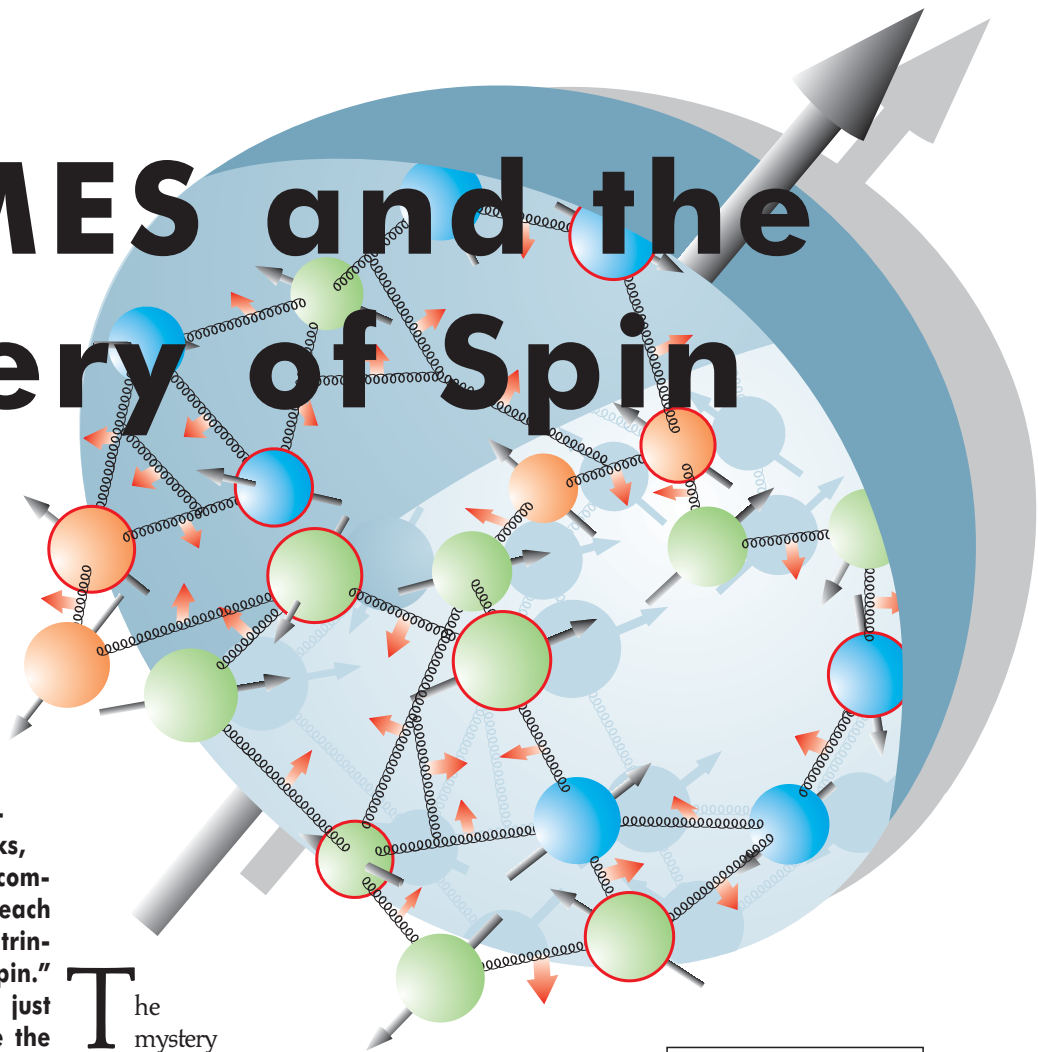
The mystery posed by the spin of the nucleons — i.e. protons and neutrons — has interested particle physicists for some time. In the simplest models, which were developed in the mid-1960s, it was initially assumed that the spin of the nucleons was generated by the spin of the three valence quarks. The theory was that two of the quarks "rotate" in one direction and the third rotates in the opposite direction, so that two of the spins cancel. The remaining spin determines the nucleon spin. This simple, elegant explanation was seldom questioned. However, since the end of the 1980s it has emerged that the valence quarks together provide less than a third of the total nucleon spin. This realization came as such a surprise that physicists initially referred to it as a "spin crisis." Since then it has become clear that in addition to the valence quarks, the sea quarks and gluons also contribute to the nucleon spin, as does the orbital angular momentum arising from the particles' motion. Yet finding out just how all this happens is not easy. Because HERMES, in contrast to earlier experiments, identifies the contribution made by the various types of quarks, this HERA experiment has yielded crucial insights into this question in recent years.
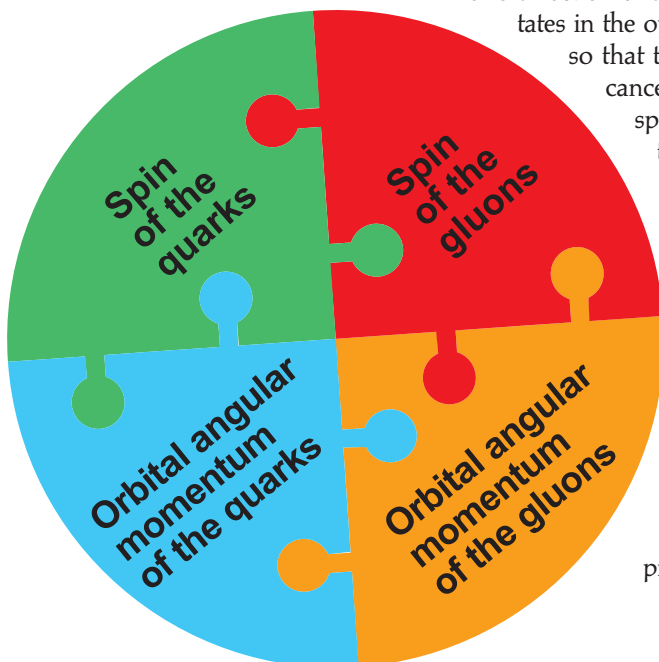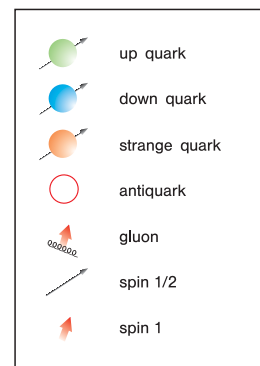
In HERMES, the polarized electron beam from HERA collides with a gas whose nuclei are also polarized — e.g. hydrogen, whose nucleus consists of a single proton, or deuterium, whose nucleus is made up of one proton and one neutron. By exchanging a photon, which partly takes on the polarization of the electrons, the electrons scatter upon impact with a quark in the interior of the protons or neutrons. However,
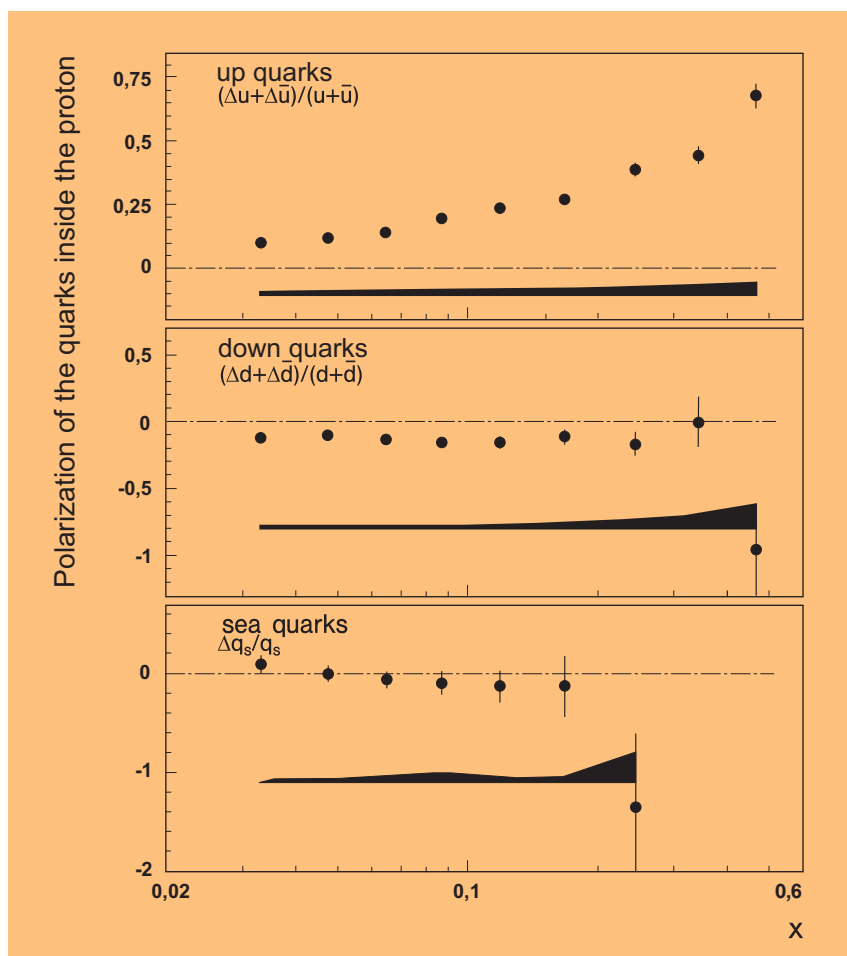
Precisely measured: the polarization of the up, down and sea quarks in the proton. The spins of the up quarks are preferentially aligned with the proton spins, while the down quarks' spins are preferentially opposed. The sea quarks hardly contribute to the proton's spin. (The black bands indicate the systematic errors in the measurements.)

they interact only with quarks that "spin" in the opposite direction from themselves. These quarks are ejected from the nucleon and form new particles, whose existence, just like that of the scattered electron, can be detected by the experiment. The scattering events occur at different rates, depending on how the directions of the electrons' and gas atoms' polarization are adjusted relative to one another. Measurements of this asymmetry enable researchers to determine the contribution made to the total spin by all of the nucleon's quarks. Because HERMES records and identifies not only the scattered electron, but also the particles originating from the scattered quark, the contributions made by the different types of quark to the nucleon's spin can be individually measured.

HERMES thus has been able to determine with a high degree of precision the polarization of the up, down and sea quarks inside the proton. The data shows that the spins

The HERMES detector in HERA's East Hall: In the foreground is the gas target area, behind it the large spectrometer magnet (blue).

of the up quarks tend to point in the same direction as the proton's spin, whereas the down quarks tend to point in the opposite direction. The sea quarks provide on average very little of the total proton spin — in fact, the data analyzed to date suggests that this value is close to zero. By fully evaluating the data gathered during the very successful 2000 measuring period, the HERMES physicists will probably be able to determine the sea quarks' contribution to the total spin much more precisely.

Nucleon:
The general term for protons and neutrons, the building blocks of the atomic nucleus, which themselves are made up of three quarks.

HERMES was the first experiment in the world to provide a direct indication of the contribution made by the gluons to the spin of the nucleon. This investigation is very difficult to carry out, because the impinging electrons do not "feel" the strong force of the gluons and thus can not directly "see" them — in contrast to the electrically charged quarks. Although it is possible to calculate the polarization of the gluons indirectly on the basis of the nucleon's polarized structure function, the range of data gathered globally has not been sufficient to permit a precise determination. Thus the researchers at HERMES resorted to a direct method — "photon-gluon fusion" — even though it was nearly as complicated as the calculation process. Here, the photon emitted by the electron interacts with the gluon via a quark-antiquark pair. The measured asymmetry of the scattering processes indicates a positive polarization of the gluon — i.e. the spins of the gluons seem to point in the same direction as the nucleon spin and thus to contribute at least a part of the missing spin. This experimental result provides a starting point for a reexamination of the theoretical models of nucleon spin, which disagree about the sign of the gluon's polarization.

To date, it has been impossible to experimentally investigate the orbital angular momentum of the particles in the nucleon. However, recent theoretical work suggests there is a way to determine the contribution made by these different orbital angular momenta to the total nucleon spin. So far, this approach has remained visionary — but the physicists at HERMES are determined to be at the cutting edge should this new approach prove to be feasible.

Spin:
The intrinsic angular momentum of particles. A particle´s spin is perhaps best described by the motion of a spinning top, although this image has its limits in that particles such as electrons, quarks and gluons are currently believed to have no intrinsic size and therefore cannot really spin on their axes. In a magnetic field, the magnetic moment associated with spin causes the particles to act like tiny magnets and align themselves with the lines of the magnetic field. The value of the nucleon spin measured in units of the elementary angular momentum is $1/2$ — hence the term spin-$1/2$ particles. Quarks and electrons, the building blocks of matter, are also spin-$1/2$ particles. In a different category we find the exchange particles such as photons and gluons: Their spin has the value 1.
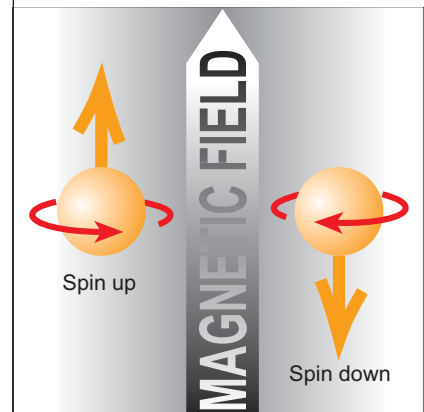
A Glimpse into the Atomic Nucleus

The main focus of attention at HERMES will remain the spin of the nucleon. But even in the project's initial years of operation, it was already evident that the insights gained through this experiment at HERA were applicable to a great variety of other areas. For example, the storage cell through which the polarized electron beam from HERA passes can be filled with a whole range of unpolarized gases of relatively high density. This means that, among other things, numerous investigations of the structure of nuclear material can be carried out.

One of these studies, for example, focuses on the question of precisely how the particles that consist of quarks, — the so-called hadrons — are created. Does the process by which they are generated vary according to whether the particles arise within a single free proton or in a nucleon that is "built into" an atomic nucleus as one of its basic components? In order to investigate this process of formation, physicists measure the number of particles that reach the detector after the collision with a specific energy. When an electron collides with a quark in the interior of an atomic nucleus, the quark initially moves through the nucleus and after a short distance forms a hadron. In the case of small nuclei such as the proton, the quark is practically outside of the nucleus by the time this happens. However, in heavier atomic nuclei the hadron is generated inside the nucleus, so that on its way out of the nucleus it collides with other nuclear particles. In every one of these "encounters," the particle loses some of its energy. If we now measure the number of particles with a certain amount of energy, we should be able to directly follow the formation of hadrons in the nucleus.

Thus in a sense the atomic nucleus is a mini laboratory to study the interaction of hadrons with nucleons. Of particular interest is the length of time it takes to form the hadrons in physical reactions at high energies. Knowledge of these formation times is vital for experiments in which heavy nuclei — e.g. lead or gold — are brought to collision to recreate the quark-gluon plasma. This is the "primal soup" that formed our universe a few millionths of a second after the big bang. The precise measurements made in HERMES are crucial for the interpretation of these experiments.

A hadron created in an atomic nucleus can interact with the nucleus' components on its way out, thus losing energy — and the larger and heavier the nucleus, the more frequent the interactions. Thus the number of hadrons observed in the detector should be lower in the case of heavy nuclei than it is in the case

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Hadron, Nucleon:

Hadron: The general term for particles that are made up of quarks; Nucleon: The general term for protons and neutrons — the building blocks of the nucleus — which themselves are made up of three quarks.

The photon blasts a quark out of a nucleon. The quark flies through the atomic nucleus, possibly losing energy in the process, and leaves the nucleus as a hadron. This process provides insights into hadron formation.
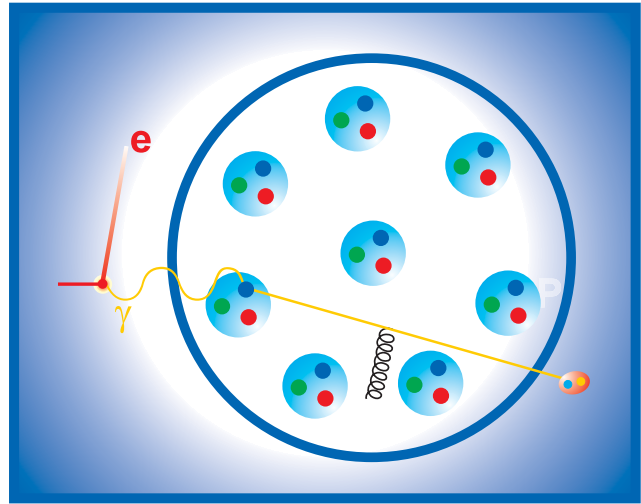
of individual protons. Moreover, this number should diminish in proportion to how early the hadron was formed, for the probability of a collision with the nucleons increases the longer the hadron has to travel through the nucleus. And this is exactly what the HERMES data shows. An additional unexpected observation, however, is that the length of time it takes for the hadrons to form clearly depends on their speed. The HERMES measurements show that fast hadrons are generated in a short period of time and are therefore — relatively speaking — weakened to a greater extent. These results contradict older theoretical models that were used to describe hadron formation.

The HERMES data also shows that positively charged hadrons are weakened much less than negatively charged ones, which means that they scatter considerably less often on the building blocks of the nucleons. This leads to the conclusion that positively charged hadrons are formed, on average, later than negatively charged ones. Because the formation times of positively and negatively charged particles consisting of one up and

one down quark — i.e. pions — are similar, this unexpected result must be due to the fact that the protons make a larger contribution than other positively charged hadrons. Apparently the protons require a much longer time to form than do the pions. The HERMES group will

be able to judge the correctness of this assumption after it has analyzed the data gathered using the "RICH detector". This component of the HERMES experiment, which was installed in 1998, enables physicists to directly differentiate between particles such as pions and protons.

The international HERMES team in front of the detector.

Ideas for the Future

The remodeling work conducted to increase HERA's luminosity will open up new research possibilities that promise exciting prospects for the coming years. In particular, activities will involve precision measurements of the strong coupling constant, the exact study of diffraction, research into the electroweak interaction, and the search for forces and effects beyond the Standard Model of particle physics. These studies will complete the current physics program at HERA. The long-term future of the facility is very much dependent on the realization of the TESLA project, which is being planned and developed as part of an international collaboration at DESY in Hamburg.

TESLA stands for TeV-Energy Superconducting Linear Accelerator. This planned 33-kilometer-long facility boasts a special feature: New superconducting accelerators will not only enable physicists to observe high-energy collisions of electrons and positrons; they will also serve as a source of intense X-ray light with laser properties. TESLA thus opens up new horizons for both fundamental and application-oriented research across a broad range of scientific fields. A decision regarding the project is expected to be taken sometime after the beginning of 2003.

The planned TESLA linear accelerator would enable scientists at DESY to bring electrons from TESLA into collision with protons from HERA. The resulting collision energy could be as much as five times as high as that achieved with

the current HERA facility. This combination of the two accelerators — known to the specialists as "THERA" — would make it possible to greatly extend the physical program at HERA into previously unattainable kinematic regions. Moreover, the HERMES research program could be continued by having the electrons from TESLA aimed at a fixed target. This option is known as "TESLA-N." Part of the linear electron accelerator at TESLA could also be used as a powerful particle accelerator for the HERA electron ring, which in turn

would enable the realization of a so-called stretcher ring. The latter is a facility that supplies a virtually continuous electron beam of the type required for beam-target experiments in nuclear physics. Such a link between TESLA and HERA could be used to create a particle beam with extraordinary properties, which to date have yet to be attained by existing or planned facilities in this area of research. As a result, a European center for fundamental research could be established in Hamburg, where researchers would focus on the interface between particle and nuclear physics — one of the most interesting scientific fields of modern nuclear physics.

DESY Research Director Robert Klanner Takes Stock

Ten years of operations at HERA — that's ten years of international cooperation between research groups from 25 countries, with the common aim of uncovering the secrets of the fundamental particles and forces of nature. The numerous results achieved and the new insights gained, some of which are presented in this brochure, were made possible by the untiring efforts, wealth of ideas, and scientific competence of the many technicians, engineers and physicists working at their home institutes and at DESY. Just as important, however, is the spirit of international cooperation and the common goal of exploring and uncovering the secrets of nature. The 200 master candidates and 600 doctoral candidates, who have found their own path into the world of research thanks to HERA have played a special role in the success of the facility.

The remodeling work on HERA and its experiments was completed in the summer of 2001. It was an ambitious project harboring many risks, one that again required the complete commitment of all members of staff. So what new knowledge will we gain from HERA-II, the only high-energy accelerator that will be in operation in Europe until the commissioning of the Large Hadron Collider LHC at CERN in 2007? Some things can already be predicted, such as precision measurements of the properties of the strong force, and new insights into the structure of protons and the behavior of the electroweak force at very short distances. But we also hope to move to new dimensions with HERA-II, to discover forces or particles beyond the Standard Model of particle physics. One thing is certain: The results from HERA will continue to have a key impact on the way we look at the world.

Robert Klanner

Professor Robert Klanner
DESY Research Director

Hamburg, October 2002

A Great Attraction for

A total of 3400 scientists from 35 countries are currently involved in research at DESY. Among them are more than 1000 young people — around half of them from abroad — who are attracted to DESY by the great variety of opportunities available here for further education and training. These young people begin as interns or as participants in excursions. They go on to active research as summer students, and work on their master degree or doctorate in a wide range of areas at DESY, culminating in independent post-doctoral research. Those who can take the initiative, are excited by scientific research, and are capable of taking on responsibility, have exactly what it takes to become part of an international DESY team, where they receive first-class training for launching their professional career.

Postdoctoral scientists at an experimental station in HASYLAB

The value of further education and training at an international center for basic research such as DESY becomes clear in times such as these, when the demand for rapid transfer of research results into practical applications is growing, jobs are becoming more scarce and largely practice-oriented, and the working world is becoming increasingly globalized. Here at DESY, the focus is on more than simply expanding one's specialist knowledge;

1000 Young People
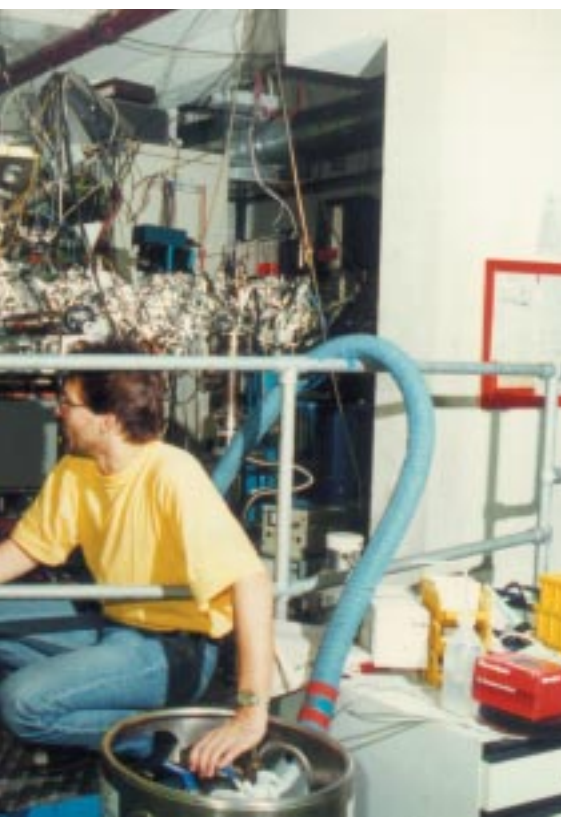
work in a DESY team offers an excellent opportunity to obtain the kinds of skills that are indispensable in the working world today. These include:

- the ability to work independently in international teams
- time and budget-focused project management
- the ability to "defend one's work"
- rapidly changing one's way of thinking and focusing on new questions and issues.

In the fields of both particle physics and research with synchrotron radiation, degree candidates, doctoral students and postdoctoral scientists are expected to independently solve specific tasks, whose results will be incorporated into the complex web of research at the center. The young people thus learn to coordinate and present their own work within a team in an environment marked by international cooperation. Armed with a high degree of quality-consciousness and the ability to find solutions to seemingly intractable problems, the young scientists are also extremely well prepared to assume responsibility in an industrial setting. Indeed, they often end up working in very "unphysical" sectors of the economy. Numerous DESY graduates are, for example, active today in the fields of corporate consulting, banking, the development of complex software, and process control technology.

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