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Cover: Low Temperature Resonant-Mass Gravitational Radiation Detector. This is a first-generation detector that operates at 4 kelvin. The article on page 10 describes the current efforts to build more sensitive detectors. (Courtesy of Stanford University)

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The Long Road to HERA

by PEDRO WALOSCHEK

The events that led to the construction of the large electron-proton collider in Germany are chronicled by one of its senior scientists.

THE PRESENT STANFORD LINEAR ACCELERATOR would need to be about 2000 miles long to reach the same collision energy (314 GeV in the center of mass) as HERA (Hadron-Electron Ring Accelerator), the electron-proton collider commissioned at the Deutsches Elektronen-Synchrotron Laboratorium (DESY) in Hamburg last year. The equivalent electron beam striking protons at rest would have to have an energy of 52,000 GeV, which is well beyond the range of our present techniques and resources.

However, the research to be done at HERA can be considered as the latest upgrade of the already epic SLAC/MIT experiments started at Stanford about 25 years ago, in which the existence of point-like electric charges inside the proton was clearly demonstrated. High energy electrons recoiling from protons, and losing a great deal of their energy in the process, were used at that time to discover this astonishing fact.

Aerial view of the DESY site and the HERA location.

Tiny details about the proton's internal structure can now be studied at HERA with an accuracy never reached before. At the same time, new and unexpected phenomena in the field of particle physics will be investigated. Two big international collaborations running the detectors H1 and ZEUS will start taking data this year. The developments that led to this modern and unique electron-proton experiment are summarized in this article.

The scattering method was originally used in 1910 by Ernest Rutherford and co-workers in Manchester to study the inner structure of atoms. He discovered the nucleus by bombarding thin foils of gold with 5-MeV alpha particles from a radioactive source. Higher resolution is obtained by increasing the collision energy, thereby decreasing the equivalent wavelength. An important step in this direction was made in the 1950s by the group led by Robert Hofstadter at Stanford, who directed electrons of a few hundred MeV against a hydrogen target. They were able to show that the hydrogen nucleus, the proton, has an extended size and therefore could have an internal structure—a rather important conclusion.

Around 1968, the results obtained at the Stanford Linear Accelerator Center (SLAC) by the SLAC/MIT group bombarding protons with electrons of energies up to 20 GeV were interpreted by James Bjorken and Richard Feynman as evidence for the existence of much smaller constituents inside the protons, the partons, that were later identified with the quarks already proposed by Murray Gell-Mann and others in 1964. (This work was recognized with the award of the 1990 Nobel Prize in Physics to Jerome Friedman and Henry Kendall of MIT, and to Richard Taylor of SLAC; see the *Beam Line*, Vol. 20, No. 3, page 18.) Data taken with 6-GeV electrons at DESY from 1964 on by the groups of Friedhelm Brasse and Gustav Weber also supported this conclusion. These were, in fact, the first of the so-called "deep-inelastic" scattering experiments, in which leptons strike the small constituents inside the nucleon. It was during this exciting period between 1965 and 1972 that two young physicists, Björn Wiik from Norway and Günter Wolf from Germany, were working as visitors at SLAC. Wolf, who had obtained his Ph.D. in Hamburg working at DESY, returned to DESY in 1970, apparently contaminated with the new quark-parton ideas, which were not at all popular at the time, particularly in Europe. Wiik joined him at DESY early in 1972.

IN JANUARY 1972, Wiik, Wolf, the late high-frequency specialist Horst Gerke, and Helmut Wiedemann (now at Stanford University) presented a detailed report proposing to use the electron-positron storage ring DORIS (just being built at DESY) as an electron-proton collider for test purposes. They also remarked in their paper that on the DESY site (about 700 m in diameter) a proton ring of 80 GeV and an electron ring of 10 GeV could possibly be built. For machines of this type the energy of the protons is limited by the strength of the bending magnets, and the energy of the electrons is limited by the amount of energy emitted as synchrotron radiation that must be replaced by the radiofrequency accelerating system. A few months earlier, in September 1971, fundamental and very concrete ideas for a high-energy proton-electron collider using the storage-ring technique had already been presented by Claudio Pellegrini at the International Accelerator Conference at CERN in Geneva, Switzerland. Besides Pellegrini, John Rees, Burton Richter, and Melvin Schwartz from SLAC, and Dieter Möhl and Andrew Sessler from Lawrence Berkeley Laboratory were the authors of this contribution. In a tunnel of 1.6 km circumference, protons of 70 GeV would collide with electrons of 15 GeV. They also mentioned that with superconducting magnets the proton energy could reach 150 GeV. In addition, ideas for an electron-proton collider were already in the air before 1971 at SLAC, where the name PEP was originally an acronym for a Positron-Electron-Proton machine, although the proton option was never built. And Björn Wiik continued developing this line at DESY.

In the following years scattering experiments with muon and neutrino beams of higher energy were performed. They provided important additional information about the partons in the nucleon. All this supported the present picture of the structure of hadrons, in which there are several main or "valence" quarks and many gluons holding them tightly together, and the gluons often transform into quark-antiquark pairs, which form a part of the so-called quark-gluon "sea."

To study this structure with even greater accuracy, higher scattering energies are required. At present, only storage rings with colliding beams can be used for this purpose. They provide at the same time sufficient reaction rates (luminosity). It is an historic curiosity that such a collider (with nuclear physics in mind) was originally proposed in Hamburg by Rolf Wideröe in 1943, in the form of an industrial patent. It was kept secret during the war and published in 1953. Bruno Touschek, well known for his idea of building the fifirst electron-positron ring AdA in Rome in 1960, was working in 1943 with Wideröe in Hamburg.

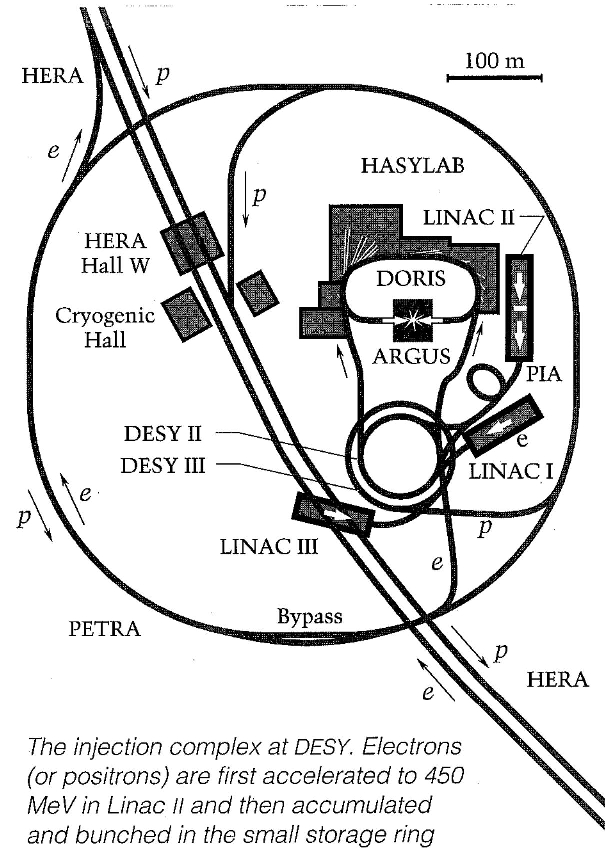
Björn Wiik always seemed to have a particular predilection for high-energy proton-electron collider experiments. The storage ring PETRA in Hamburg was initially proposed as a proton-electron collider for the DESY site; it was finally built as an electron-positron machine, with the "P" standing for positrons, probably as a result of the enthusiasm for such machines after the discovery of the J/psi. CHEEP was to be an electron-proton facility in the tunnel of the Super Proton Synchrotron (SPS) at CERN; it had been proposed by Wiik, John Ellis, and Kurt Hübner in 1978. PROPER included a superconducting proton ring to be built in the PETRA tunnel in Hamburg.

At the end of the seventies it became clear in Europe that a big electron-positron collider would be built at CERN as a next step after the PETRA ring at DESY. In 1979, a detailed plan for such a collider, the present LEP, was published at CERN. In the same year the European Committee for Future Accelerators (ECFA) recommended the construction of a proton-electron collider at DESY to complement the work to be done at CERN. DESY and ECFA organized a study group in which Wiik and Ugo Amaldi were the leading and driving forces.

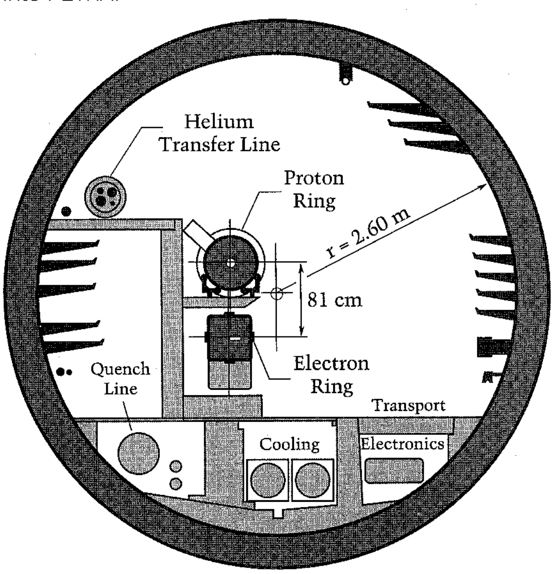
Several projects for proton-electron colliders were analyzed by the study group, including ideas from the United Kingdom, Japan, the United States, and the former USSR. In a first report (August 1979) it was pointed out that the collision energy for the optimal research potential of such an accelerator should be higher than that of most existing or planned projects, particularly those intended for DESY.

Subsequent studies indicated that an underground ring of 6.3 km circumference could be built in the neighborhood of the DESY site within acceptable costs. The tunnel would contain two almost independent storage rings, one for protons and one for electrons. Protons could reach an energy of 820 GeV using superconducting magnets similar to those developed for the Tevatron at Fermilab. A field of 4.5 Tesla provided by such magnets would allow steering the protons around HERA (iron magnets with copper coils saturate at about 1.8 Tesla). Electrons could be stored at about 30 GeV using conventional techniques.

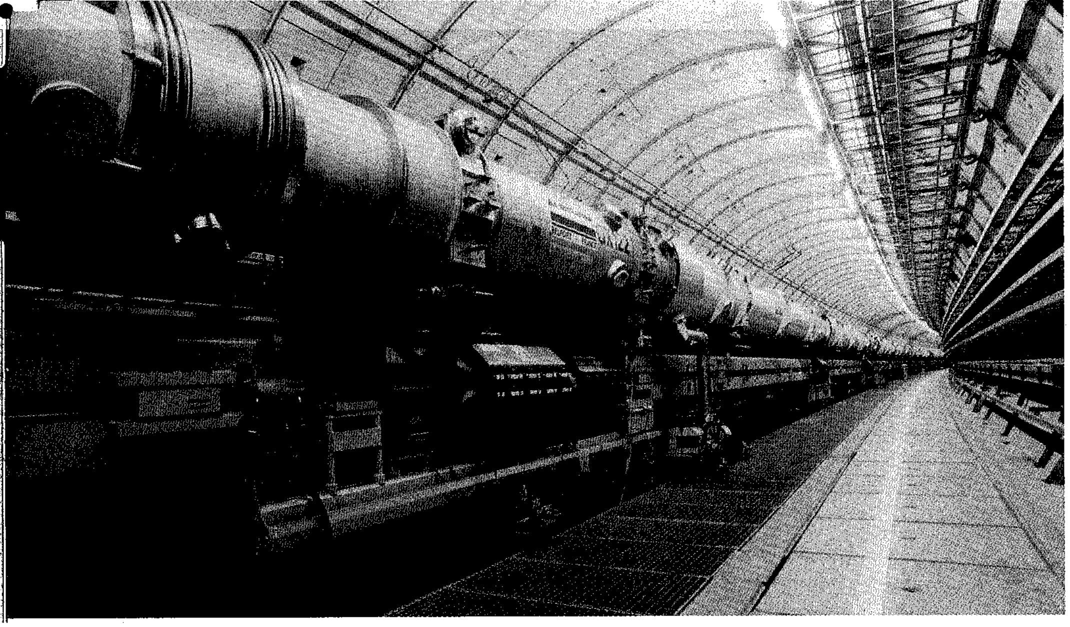
Central to the success of this project would be the superconducting magnets. Therefore, R&D was started at DESY to build superconducting deflection magnets, and at the Saclay laboratory in France for superconducting quadrupoles. Both centers had to demonstrate first of

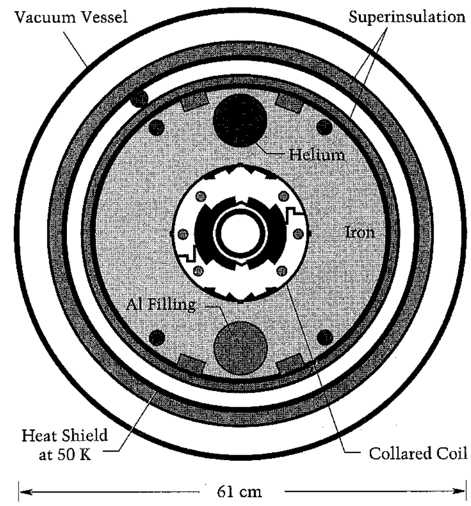


The injection complex at DESY. Electrons (or positrons) are first accelerated to 450 MeV in Linac II and then accumulated and bunched in the small storage ring PIA. In the synchrotron DESY II they are accelerated to 7 GeV before being injected in to PETRA, where they are accelerated to 13 GeV before injection into HERA. To be able to accelerate both protons and electrons, PETRA had to be modified through the addition of a bypass around the electron cavities. A new 50-MeV linac (Linac III) accelerates negative hydrogen ions, from which the electrons are stripped when they are injected into the 8-GeV proton synchrotron DESY III (constructed with the magnets of the first DESY synchrotron of 1964), which in its turn injects particles into PETRA.



Cross section of the HERA tunnel.





The HERA tunnel with conventional magnets (bottom) that bend the 30-GeV electron beam and superconducting magnets (top) that bend the 800-GeV proton beam.

Cross section of the superconducting dipole magnet for the HERA proton ring.

all that they were in fact able to build such magnets. In addition it was proposed that the magnets should be mass produced by industry, something that had never been done before. Siegfried Wolff and Hartwig Kaiser from DESY were sent to Fermilab to study how their magnets were built. The help of our Fermilab colleagues was very important, particularly in this first period.

In March 1980, a realistic proposal for a machine with the name HERA was published by ECFA and DESY. It was also presented to the physics community in meetings organized by ECFA at CERN and by DESY and the University of Bonn in Germany. The project was submitted by DESY to the German Ministry of Research and Development and to the authorities of the City of Hamburg. The Federal Government and the City of Hamburg normally cover the DESY budget in the ratio 9:1.

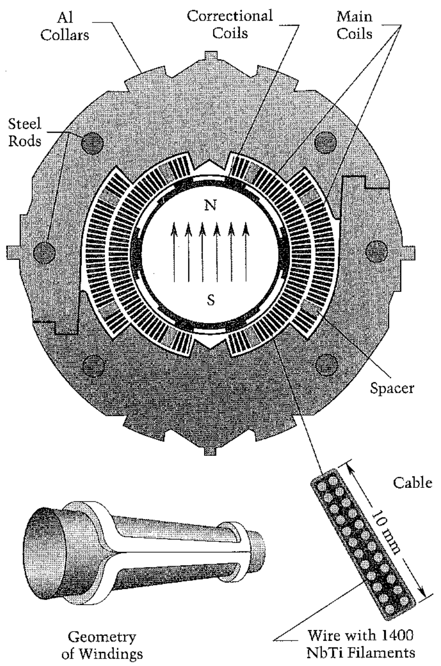
A scientific committee was nominated by the German Federal Government to judge the ten biggest research projects envisaged for the coming decade, including HERA for DESY and LEP for CERN. Of the eight members of the committee only Wolfgang Paul (Bonn) was a high energy physicist. The committee was led by Professor Klaus Pinkau. It finally arrived at a very positive conclusion regarding both the LEP and HERA machines, and recommended their construction in a report dated February 1981.

ORIGINALLY MOST particle physicists assumed that HERA would be built in the usual way (as in the case of PETRA): the accelerator by the host country and the experiments through international collaboration. However, the Pinkau Committee recommended that HERA itself should be built with substantial contributions from other countries in order to demonstrate their interest. This was an innovation; it was the first time a national machine was to be built with international contributions.

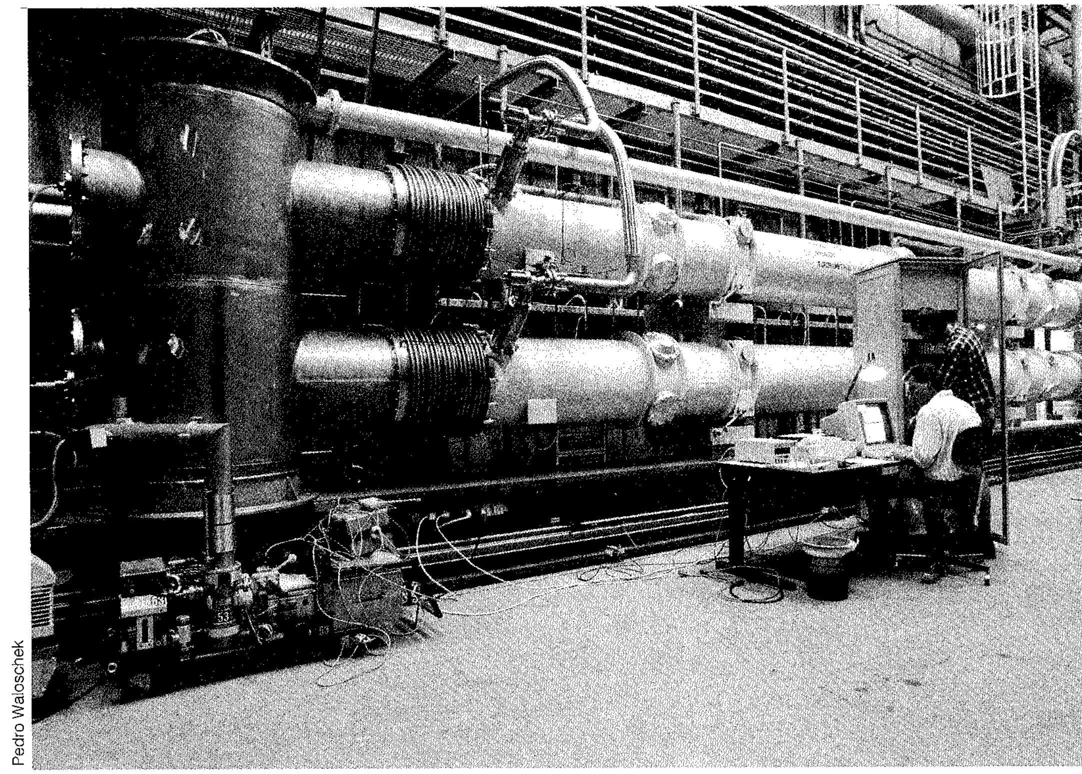
The difficult task of obtaining sufficient support from institutions of other nations was carried out by the DESY directors, in particular by Volker Sœrgel, obviously joined by Björn Wiik. The contribution that was probably decisive came from the Italian Istituto Nazionale di Fisica Nucleare (INFN), with particular sponsorship by Antonino Zichichi, who had excellent relations with Italian politicians like Giulio Andreotti, at the time Minister of Foreign Affairs and later on Prime Minister. INFN offered to provide a substantial fraction of the superconducting magnets for HERA.

In total, foreign contributions would eventually cover about 15% of the required costs, and as a result the German Federal Government and the City of Hamburg agreed to take over the remaining 72% and 13%. It should be emphasized that the physics arguments and the interest demonstrated in several international meetings by hundreds of physicists, mainly from universities, provided the rationale for the the project's approval. The high level of technological R&D required was also a positive argument.

The investment required for the project was estimated at 650 Million DM (about \$405 million dollars) at 1980 value. This sum agrees with the final cost (1991) of 1,010 Million DM (about \$610 million dollars), when inflation is taken into account. In addition, about 3000 man-years were needed for specialized work. In Europe this kind of calculation generally excludes the regular expenses (such as salaries and maintenance) of the involved institutes. It was taken into account that most of the existing accelerators at DESY could be used or modified as injectors for HERA. The available infrastructure and the expertise of the DESY staff would also be of great advantage.



Coil geometry of the superconducting dipole magnets for the HERA proton ring.



The two superconducting reference magnets used to survey and correct remanent eddy currents in HERA.

HOWEVER, BEFORE OBTAINING official approval, the problems related to construction of the superconducting magnets had to be solved, at least in principle. The cornerstones for this development were, first, the successful winding and testing of coils with sufficient accuracy and mechanical strength (February 1982); and later on the construction of several prototype magnets of 1 and 6 meters in length. The forces acting on the coils amount to about 100 tons per meter, and the windings must stay very accurately in place.

Two types of magnets were first explored for HERA: a warm-iron design modeled after the Fermilab magnet and, in collaboration with industry, a cold-iron magnet based on developments made at Brookhaven National Laboratory (BNL). Both types of prototype magnets fulfilled the requirements for HERA and were found to be suitable for industrial mass production.

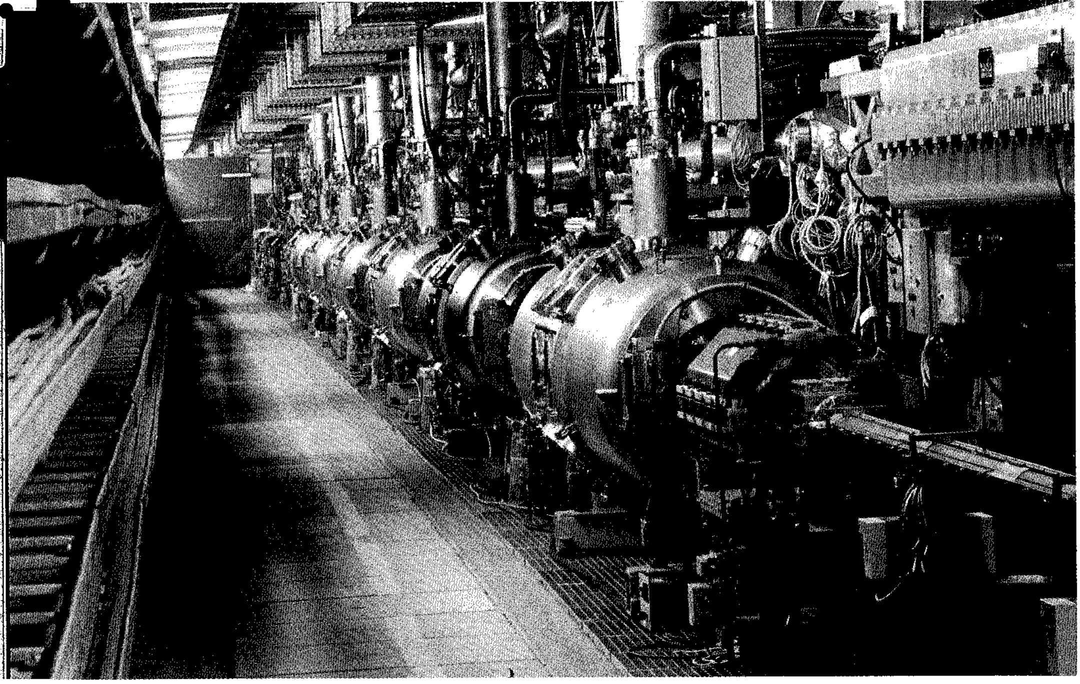
At this point a design was proposed that combined some of the advantages of both solutions. The mechanical support of the coils (rigid collars) of the Fermilab magnets was kept, and, as in the BNL magnets, the return iron was cooled down to liquid helium temperature. This final "HERA design" was later adopted for such accelerator projects as the SSC in the United States, the LHC at CERN, and UNK in the former USSR. In this design the temperature is kept at 4.2 K in a two-phase helium tube, while supercritical helium filling the gaps keeps good contact with all cold components without any gas bubbles disturbing heat conduction.

Finally, the length of the HERA bending magnets was fixed at 9 meters instead of the originally proposed 6 meters. For these magnets, the collars were of aluminum instead of stainless steel as used at Fermilab. The aluminum contracts more than other parts when cooling down, thus providing a convenient pre-tension. The vacuum pipe inside the superconducting magnets is also kept cold; it is used as an effective cryogenic pump, helping to reach an excellent vacuum. At that time the design of the electron ring was already in good shape.

This was the situation when the official agreement for the construction of HERA was signed on April 6, 1984, by the Federal Minister of Research and Technology, Heinz Riesenhuber, and the Hamburg Senator for Science, Hansjörg Sinn. Civil engineering work started a few weeks later. Planning and formalities had already been completed.

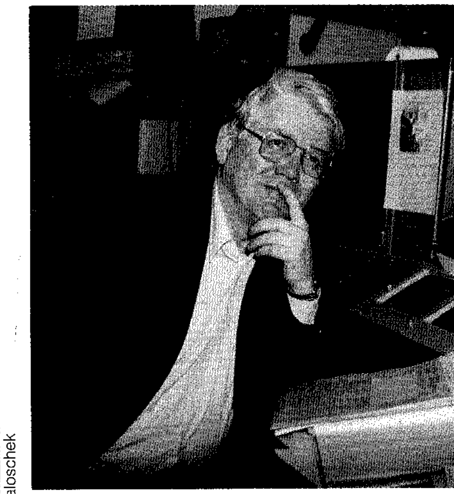
WORK WAS ORGANIZED into two groups that temporarily integrated many members of other DESY divisions. Gus Voss became responsible for civil engineering for the electron ring and for the injection channels between PETRA and HERA. Björn Wiik took over the construction of the superconducting proton ring, including the cryogenic plant and the proton injection system. Two international committees, a Management Board and a Machine Committee, were created to give advice during construction time. The Physics Research Committee of DESY (PRC) continued advising on the experimental program.

HERA was the first big accelerator to be built in a populated area of a town (see ærial photo on page 2).



Pedro Waloschek

Superconducting accelerating cavities installed in the HERA electron ring.



Petra Harms

Main Design Parameters of the HERA Storage Rings

	Electron Ring	Proton Ring
Highest energy (GeV)	30	820
Energy at injection (GeV)	13	40
Luminosity	$1.5\times10^{31}cm^{-2}s^{-1}$	
Beam current (mA)	58	163
Particles per bunch	3.6×10^{10}	10^{11}
Number of bunches	210	210
Time between collisions	96 ns	
Bunch length (cm)	2.5	44
Beam width at int. point (mm)	0.264	0.300
Beam height at int. point (mm)	0.017	0.095
Energy loss per turn	125 MeV	6 eV
Polarization time at 30 GeV (min)	27	—
Filling time (min)	15	20
Main ring dipole magnets	396	416*
Field (Tesla)	0.16	4.65
Main ring quadrupoles	580	280 (224*)
Accelerating cavities	84 + 8x8*2 + 4	
Radiofrequency (MHz)	599.7	52.05/ 208.2
Circumference (km)	6.336	
Free space for experiments (m)	11	

*superconducting

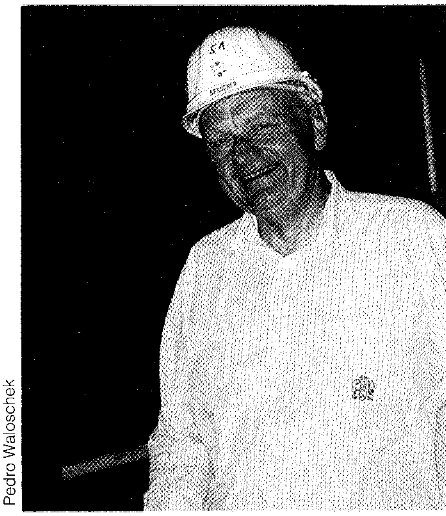
There were, however, no serious objections from the townspeople, who were always kept well informed about DESY projects. The civil engineering work was finished in 1987.

The tunnel, with a diameter of 5.2 meters, lies 10 to 25 meters underground. More than half of it is under the water table and therefore required a special drilling technique. The depth of the tunnel was chosen to avoid any danger of radiation reaching the surface.

Four large underground halls were prepared to house the experiments and the required supplies for the rings. Three of these halls are outside the DESY site. They have access through elevator buildings which are the only parts visible at surface level.

Installation of the electron ring started as soon as the different parts of the tunnel were finished. The electron ring is of the conventional type and capable of reaching an energy of about 30 GeV if all the space available for acceleration is filled with normal rf cavities. Most of the expensive high-frequency accelerating system was taken over from the PETRA storage ring where it was no longer needed. After several successful tests it was decided to replace some of the normal cavities with up to eight superconducting cavity groups of eight cells each that had been developed at DESY in close collaboration with industry. Cavities of this type were in fact installed and are at present running. The 9 m long bending magnets of the electron ring provide a field of 0.18 Tesla. This can be induced by a single aluminium conductor of about 10×10 cm^2 cross section running through all of the magnets in a long loop. Each of the 400 dipoles in the HERA arcs, together with the required quadrupoles, sextupoles, and correction magnets, was mounted on 12-m-long standard modules and adjusted in the laboratory before being installed in the tunnel. Special attention was given to the vacuum pipe. It was made of brazed copper shapes instead of aluminum (as in PETRA), a fact that allowed reduction of the gap (and cost) of the bending magnets. The electron ring was operated successfully for the first time in August 1988. It will be possible to inject, accelerate and store either positrons or electrons.

IN THE MEANTIME, EXACT specifications for manufacturing the superconducting dipoles for the proton ring (422 to be installed in the tunnel) had been prepared at DESY, and for the superconducting quadrupoles (224 to be installed in the tunnel) at Saclay. Several correction coils, beam monitors, and quench-protection devices had to be included in the cryostats surrounding the



Pedro Waloschek

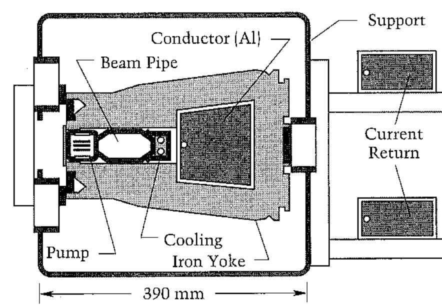
Left: Björn Wiik, leader of HERA Group B. Right: Gus Voss, leader of HERA Group A.

magnets. Half of the superconducting dipoles were built in Italy as an Italian contribution to HERA, and half of the quadrupoles were likewise built in France. Superconducting correction coils wound around the vacuum pipe were made in the Netherlands, and current leads for the cold coils in Isræl. Systematic tests of the superconducting cables used for the magnets were carried out at Brookhaven National Laboratory in the United States.

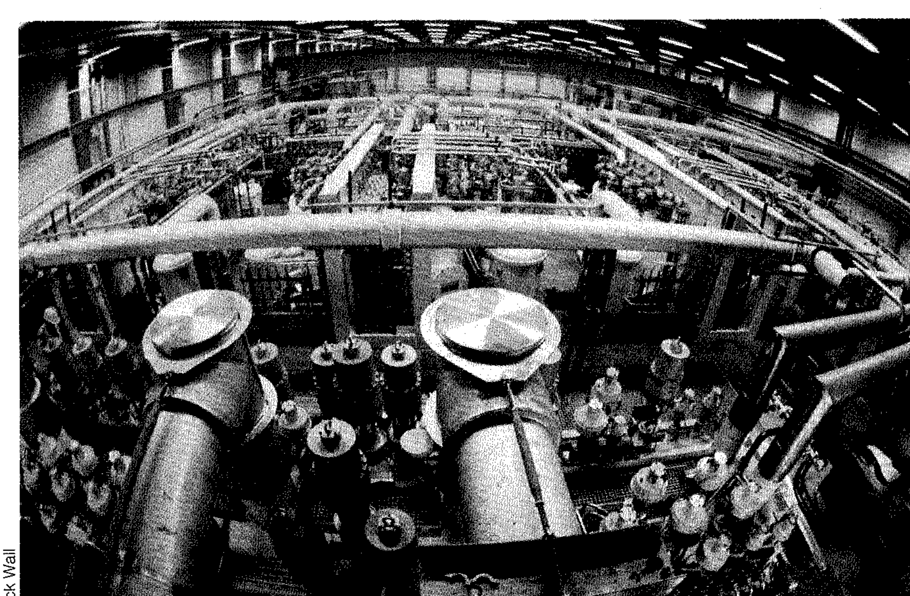
These were not the only foreign contributions to HERA: Canadian institutes provided the complete 52 MHz accelerating system for protons in PETRA and HERA, and also parts of the proton beam-transport system. In addition, physicists, engineers, and technicians from China (50), Poland (40), Czechoslovakia (3), the United Kingdom (3), and the former DDR (3) also participated.

To keep the superconducting magnets, rf cavities, and several other devices (in particular the superconducting solenoids of the two experiments) at liquid helium temperatures (4.2 K), a central refrigeration plant was built on the DESY site. The HERA cryogenic plant is the largest ever built in Europe. It has been in routine operation since 1987 without any unscheduled interruption. It was necessary to provide an early supply of liquid helium to test the superconducting magnets arriving from industry. This was done in a specially built hall. Accurate field measurements were also carried out for each magnet before it was accepted for installation in the tunnel. The performance of the magnets agreed well with the specifications, including their thermal insulation. Only a small number were rejected and had to be repaired. During the tests it was found that the semi-persistent eddy currents in the superconductors behaved differently in the magnets of Italian and German production. The currents in the correction coils, particularly at low fields, had therefore to be determined for the magnets in separated groups, following data from two reference magnets.

EXCEPT FOR THE STORAGE RING DORIS, all the accelerators at DESY are used as injectors for HERA In HERA, the proton bunches arriving from PETRA at 40 GeV are reduced to a length of about 40 cm, increasing the voltage and changing the frequency from 52 to 208 MHz. At the same time the protons are accelerated to the energy required by the experiments. At three points, in the halls North, East and South, electron and proton beams are directed head-on



Above: Section of a dipole magnet for the HERA electron ring. Bottom: View into the cryogenic plant of HERA.



Nick Wall

against each other, guided by special magnets. Big quadrupole magnets provide additional focussing at the interaction point to increase the luminosity. Cryogenic supplies are introduced into the tunnel in the West Hall on the DESY site. The two superconducting reference dipole magnets and a laser polarimeter for the electron beam are also installed in this region. In the East Hall the magnet system required to rotate the spins of the electrons will be installed as soon as a substantial polarization is detected. A clear effect of 18% has already been observed without any machine adjustments. A proposal has been presented for an experiment in which polarized electrons collide with a stationary target of polarized nuclei. It is called HERMES and could be installed in the East Hall. Needless to say, the HERA crew, the many helping visitors, and those preparing equipment in other laboratories were quite relieved when finally one component after the other started working regularly. The last superconducting magnet was installed in the tunnel in September 1990; in April 1992 both rings were ready to run at their nominal energies.

AS SOON AS THE specifications for HERA were known, and in parallel to its construction, the organization of experiments was started. Many laboratories interested in HERA physics were at that time engaged in LEP experiments. However, proposals for detectors were finally prepared by two international collaborations of reasonable size, "H1" and "ZEUS." In July 1986 the Physics Research Committee of DESY recommended the approval of the two projects, and in 1991 the detectors were commissioned in the assigned underground halls North and South. Up to 1991 they required the investment of more than 200 Million DM ($120 million dollars) and the work of about 800 physicists and engineers. Institutes from 17 countries had participated up to that time in the two projects. The speakers of the collaborations are Günter Wolf (ZEUS) and Franz Eisele (H1).

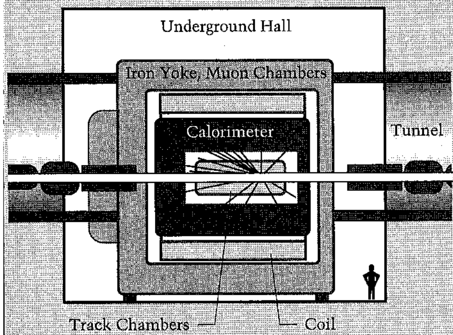
The main components of the HERA detectors show an asymmetry because of the higher momentum of the incident protons, which blasts the reaction products into one direction, usually called the "forward" region. The major challenge consisted of the construction of accurate calorimeters able to measure the energy and direction of high-energy jets of several hundred GeV. H1 installed a liquid argon calorimeter with iron and lead plates, while ZEUS opted for a compensating uranium calorimeter with scintillator read-out. Both detectors are provided with a magnetic field parallel to the beams, central tracking chambers, electron and muon identification, and a forward toroid iron magnet for muons. ZEUS included a vertex chamber from the beginning while H1 is proposing it as an improvement. Both detectors are now ready to take first data.

At press time (June 1) single bunches of protons of 820 GeV and electrons of 26.7 GeV were circulating in HERA. Luminosity and first collision events were observed in both detectors.

HERA Physics Revisited

PHYSICS HAS EVOLVED since HERA was first proposed. Some subjects are now less relevant for HERA, such as the search for certain kinds of exotic particles and for the top quark (for energy reasons); while others seem much more interesting, such as low-x physics in which partons carrying only a small fractional momentum (x) of the proton struck by an electron.

The elementary process in electron-proton collisions at the energies available at HERA is the electron-quark interaction. In a first approximation only the electromagnetic and the weak forces act here. For sufficiently high values of the momentum transfer (Q^2), these two forces are of comparable strength, and in addition the quarks can be considered nearly "free." The exchange of four field quanta must then be taken into account: photons, W^+, W^-, and Z^0 particles. Exchange of photons and Z^0 particles leaves the charges of the interacting particles unchanged, and therefore a recoil electron should be observed in the detectors. The exchange of W particles is a charge-exchange process: the incoming electron is transformed into a neutrino, the u-quark into a d-quark. To obtain W-exchange with d-quarks (charge $-1/3$), positrons must be stored in HERA instead of electrons, and this will be possible. The neutrino or antineutrino emitted in these reactions can only be observed as missing energy-momentum. The recoiling quark in general gives rise to a "jet" of particles (fragmentation) that must be carefully measured to identify the reaction.



Main components of a HERA experiment.

According to our present understanding, *W*-exchange happens only under particular configurations of the spin of the colliding particles and is a result of a left-right asymmetry of the weak force. HERA provides a unique facility to test this behavior at higher energies. Electrons circulating in the ring become vertically polarized after some time because of the emission of synchrotron radiation. With a set of special magnets it is possible to rotate the spins parallel or antiparallel to the line of flight, as is required for these experiments.

It is possible that the weak force is also mediated by particles (*W'*,*Z'*) that are related to but heavier than the well-known *W* and *Z*. This could be recognized in HERA collision events if the mass of these particles is not too large.

Elastic scattering of quarks and electrons might provide first information on a finite size for these objects. A positive result in this field would obviously be sensational, since extended objects must presumably have an internal structure. Theorists often speculate about a possible substructure of quarks and leptons.

Scattering of the incident electron from one of the three main quarks of the proton will not be the most frequent reaction at HERA. Several processes of higher order have a comparable or even higher rate. This includes collisions with quarks of the sea and collisions between virtual particles surrounding both the electrons and the partons.

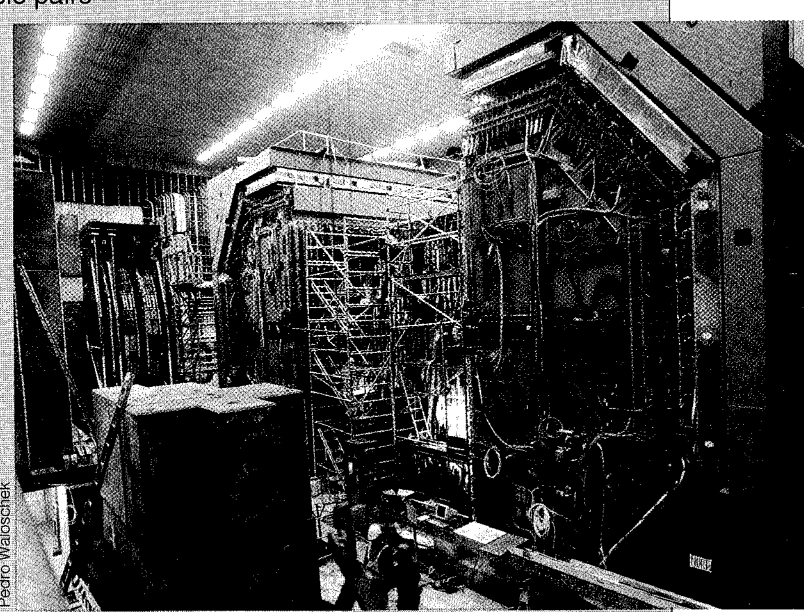
There is a large flux of almost real (massless) photons surrounding the incident electrons. Events caused by such photons (photoproduction processes) can be identified: the incident electrons are scattered at very small angles, lose some energy, and leave the interaction region through the beam pipe or very near to it. They can be separated in bending magnets (because of their lower momentum) and "tagged" by special counters placed along the beam. Interactions such as photon-quark Compton scattering and photoproduction of particle pairs ("photon-gluon fusion") might take place. Quark pairs of higher generations and resonant states such as the *J*/psi and upsilon particles can be produced. The almost real incident photons might also transform into quark-antiquark pairs that then interact strongly with the constituents of the proton at quite a high rate. This allows study of very particular properties of the photon.

There is little hope of finding exotic particles at HERA (as required in many unification theories) except for certain special cases such as "leptoquarks," which could be created directly in an electron-quark collision if their mass is not too large. All of the collision energy is available in this case, since the leptoquarks do not have to be created in pairs, and the search can cover a large region of possible masses.

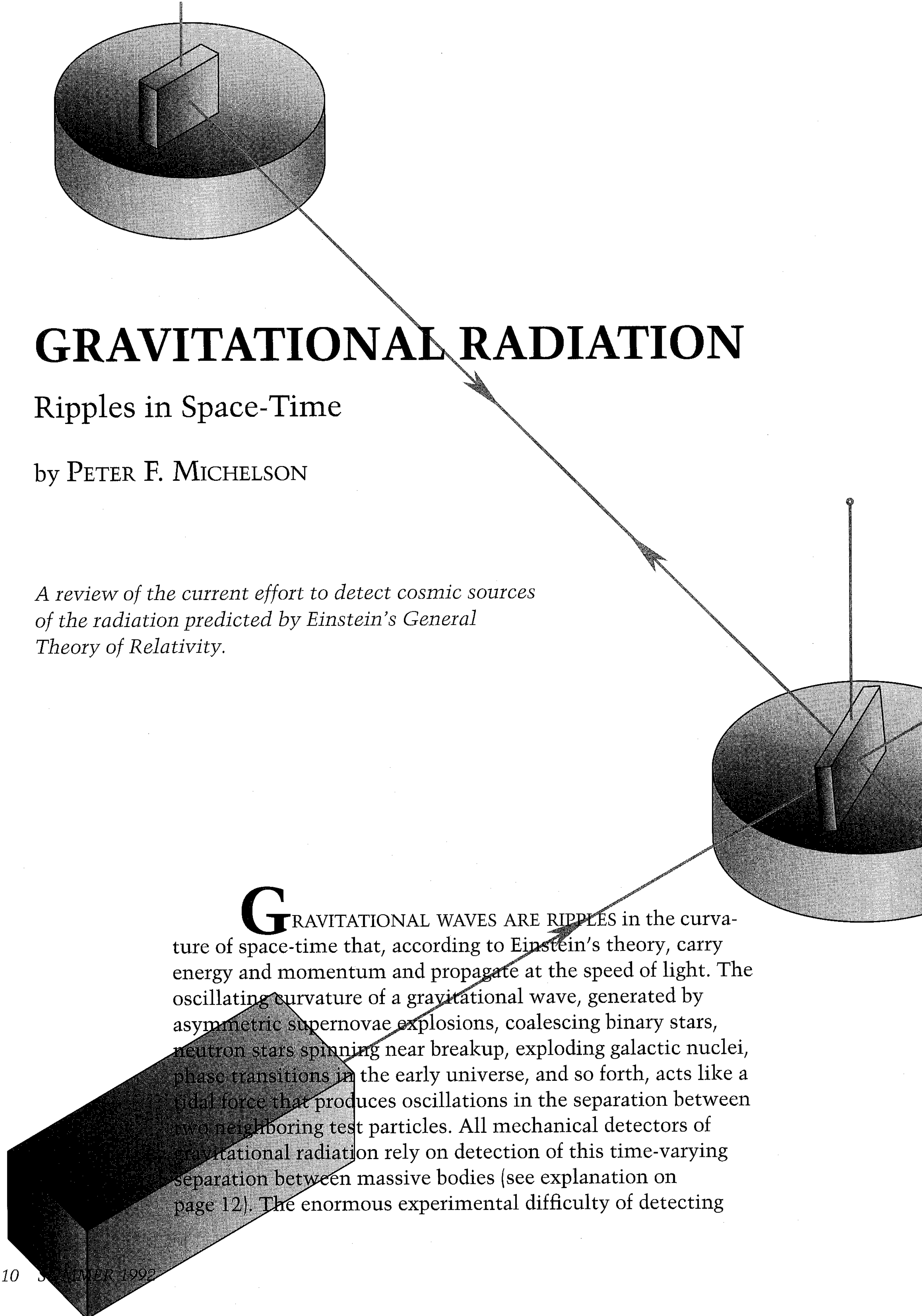
Special attention will certainly be given to events that cannot be understood with our present theories or prejudices. The kinematic range covered by HERA (high Q^2 and very small x) extends well out into regions that have never been explored before.

—P.W.

ZEUS just before being moved into the HERA beam line.



Pedro Waloschek



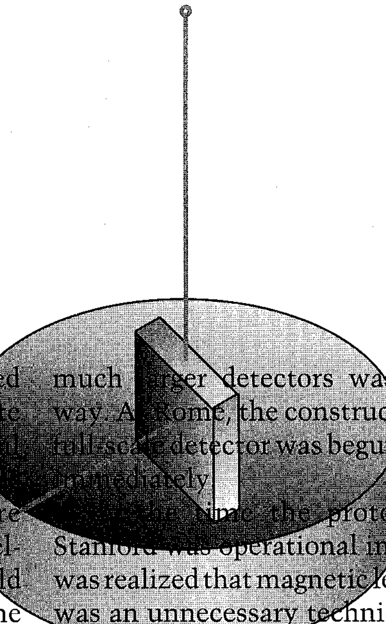
GRAVITATIONAL RADIATION

Ripples in Space-Time

by Peter F. Michelson

A review of the current effort to detect cosmic sources of the radiation predicted by Einstein's General Theory of Relativity.

Gravitational waves are ripples in the curvature of space-time that, according to Einstein's theory, carry energy and momentum and propagate at the speed of light. The oscillating curvature of a gravitational wave, generated by asymmetric supernovae explosions, coalescing binary stars, neutron stars spinning near breakup, exploding galactic nuclei, phase transitions in the early universe, and so forth, acts like a tidal force that produces oscillations in the separation between two neighboring test particles. All mechanical detectors of gravitational radiation rely on detection of this time-varying separation between massive bodies (see explanation on page 12). The enormous experimental difficulty of detecting



these waves can be appreciated by realizing how small the expected signals are: a gravitational collapse at the center of our galaxy that converts 1% of a solar mass into a gravitational wave pulse of 1 millisecond duration would cause a fractional change in the separation of two free masses located at the earth of about 3×10^{-18}. While it is unlikely that a supernovae collapse would produce a signal this strong, binary neutron star coalescences are expected to radiate this efficiently.

Beginning with Joseph Weber's pioneering work in the 1960s, efforts to detect gravitational radiation have been going on in several laboratories for over two decades. Except for indirect evidence of gravitational radiation from the binary radio pulsar PSR 1913+16 (see sidebar on page 14), these efforts have not yet been successful. Why? Is there reason to believe that gravitational radiation will be directly detected before the end of this decade? If the answer is yes, what will we learn?

FIRST, SOME HISTORY

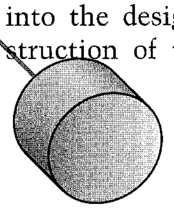
AFTER THE INITIAL EXCITEMENT that followed Weber's announcement in 1969 that he had detected gravitational radiation, it was soon realized that the energy fluxes implied by his measurements were, to say the least, extraordinary. This troubled theorists as they began to seriously consider models of gravitational radiation sources. Weber's results also encouraged groups at IBM, the University of Rochester, Moscow State University, and Bell Labs to build detectors. Disappointment followed as the new detectors failed to confirm Weber's claims. In spite of these negative results, several groups continued to develop more sensitive detectors. They were inspired partly by theoretical developments that suggested there would be detectable sources if only the sensitivity of the detectors could be improved by a few orders-of-magnitude. Most of the ideas for improving the detectors involved cooling them to liquid helium temperature or lower, thereby eliminating thermal noise. An added benefit of low-temperature operation was the availability of low-noise superconductive electronics based on the Josephson effect.

The first proposal for constructing cryogenic resonant-mass detectors was made in the late 1960s by William Fairbank of Stanford University and William Hamilton of Lousiania State University (LSU). Their ideas sparked the enthusiasm of Edoardo Amaldi and Guido Pizzella at the University of Rome. A three-way collaboration was formed to build a network of these detectors. In spite of the obvious technical difficulties to be overcome, such as cooling 5000 kilograms of aluminum to about 5×10^{-2} kelvin, Fairbank was characteristically optimistic that the first detector would be operational within a year. At Stanford, work was begun almost immediately on a prototype antenna weighing a few hundred kilograms. Because of the low operating temperature, the "advantage" of magnetically levitating the antenna to vibration isolate it was incorporated into the design. At LSU, the construction of the cryostats for the much larger detectors was underway. At Rome, the construction of a full-scale detector was begun almost immediately.

By the time the prototype at Stanford was operational in 1974, it was realized that magnetic levitation was an unnecessary technical complexity that offered no real advantages over a mechanical suspension system. Indeed, it made it all but impossible to diagnose problems at room temperature before cooling, since the suspension required low-temperature operation. The initial efforts at the University of Rome met a different fate: the large cryostat that was built to house the detector collapsed during an early cooldown because of thermal stresses. Fortunately, the large cryostats being built at LSU were of a different design that did not have this problem.

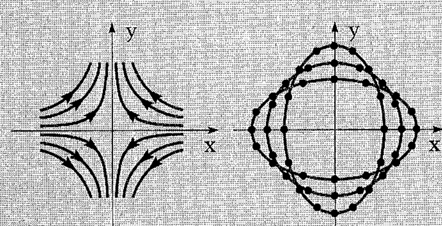
By 1981 the experimental efforts had almost recovered completely from the initial setbacks. At Stanford a 5000-kilogram detector with a mechanical suspension system was operated at 4 kelvin. It achieved a strain sensitivity of $h = 10^{-18}$, an improvement of more than four orders-of-magnitude in energy sensitivity over Weber's original room-temperature detectors. A few years later similar detectors were brought into operation by LSU and Rome, and coincident searches for gravitational-wave signals were done. Again, no evidence of gravitational radiation was found. The upper limits were orders-of-magnitude below the level of signals that Weber originally reported.

Theoretically, it was not surprising that the first observations with the cryogenic resonant-mass detectors

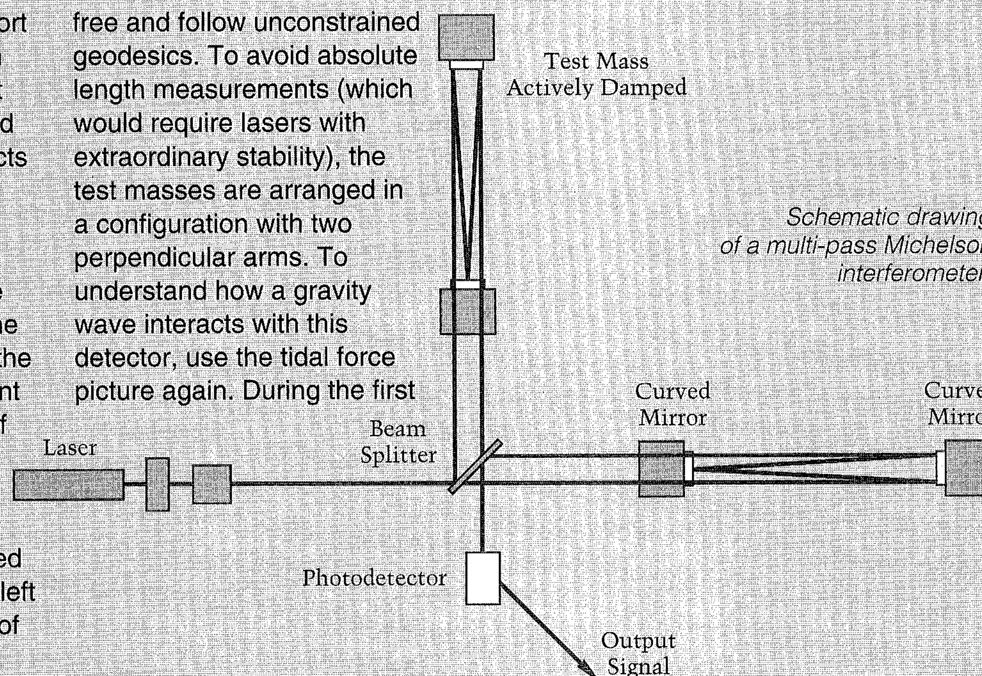


Gravitational Radiation Detectors

FOR DETECTORS that are short compared to the wavelength of the radiation (an excellent approximation for all ground-based detectors), a gravitational wave acts like a time-dependent tidal force. This force acts in a plane that is transverse to the propagation direction of the wave. To visualize the effect of this force, consider the circular hoop of beads shown on the right below. A gravity wave incident on the hoop will cause a motion of the particles as shown, with the relative change in dimension of the hoop being of the same order as the metric perturbation h caused by the gravitational wave. On the left is a picture of what the tidal lines of force look like for the so-called + polarization. To visualize the other independent polarization rotate the picture by 45 degrees.



Effect of gravitational waves on a circular hoop of masses. The tidal lines of force due to the passing wave are shown on the left.



Schematic drawing of a multi-pass Michelson interferometer.

Laser Interferometric Detectors. This kind of detector consists of masses with mirrors on them and a central beam splitter. The masses are suspended in order to support them in the earth's gravitational field and isolate them from local disturbances. At the gravity-wave frequency the masses are essentially free and follow unconstrained geodesics. To avoid absolute length measurements (which would require lasers with extraordinary stability), the test masses are arranged in a configuration with two perpendicular arms. To understand how a gravity wave interacts with this detector, use the tidal force picture again. During the first half cycle of the wave, one arm of the interferometer is lengthened while the other is shortened. During the next half cycle the opposite occurs. The gravity wave induces a differential displacement in the lengths of the interferometer arms.

If we inject light into the interferometer and measure the transit time in each arm, we will find that there is a difference in the transit times Δt that is proportional to the gravity wave perturbation h times the average transit time $t_{\mathrm{transit}} = 2L/c$. Since the relative time delay (or phase shift) is the measured quantity, we can increase the signal by making the interferometer longer. This works until the arms are half of the gravitational radiation wavelength long; any longer and cancellation of the signal sets in.

In practice, multiple bounces in a Michelson delay line interferometer or optical cavities in the arms of a Fabry-Perot interferometer can be used to increase the effective path length. The first generation optics in the 4 km LIGO detector will use Fabry-Perot cavities.

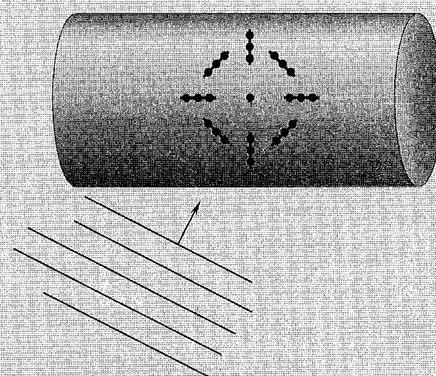
Resonant-Mass Detectors. Gravitational radiation detectors do not necessarily have to utilize free masses. A gravitational wave can also induce a dynamic strain in a suitable resonant mode of an extended massive object. The massive object commonly takes the form of a solid right cylinder, made from a material such as aluminum, with a fundamental longitudinal resonance near 1 kHz. With a low-noise motion transducer the excitation of the resonant mode can be detected. For the fundamental mode of a cylindrical antenna excited by a short pulse of gravitational radiation, the dimensionless strain induced is of order h.

Sensitivity Limitations: Noise Sources The gravitational-wave interaction with the detector is only half the story; detector noise is the other half. Both interferometric detectors and resonant-mass detectors are subject to thermal and seismic noise. Thermal noise can be reduced by increasing the baseline in interferometric detectors and by cooling to low temperature in resonant-mass detectors. In both detectors seismic noise is controlled by proper vibration isolation. Neither of these noise sources is likely to limit the sensitivities of planned detectors, at least for frequencies above several hundred Hertz. A more fundamental sensitivity limitation comes from the readout system used to monitor the relative positions of the detector masses in the case of an interferometer, or to monitor the longitudinal vibrational mode of a resonant-mass detector.

What are the ultimate sensitivity limits imposed by the readout system? If the readout is linear and quantum-limited, then the best achievable sensitivity can be estimated by Heisenberg uncertainty principle arguments as

$$h \simeq (1/L)\,(\hbar\tau/M)^{1/2},$$

where τ is the duration of the gravitational wave pulse, and L and M are the length and mass of the antenna, respectively. This formula applies to both kinds of detectors. It would appear that by making L as large as we like, we can get any sensitivity we want. Unfortunately, this is not so. The length of a resonant-mass antenna must be one-half of an



An incident gravitational wave pulse induces a dynamic strain in the longitudinal mode of a solid right-cylindrical antenna. The antenna has maximum sensitivity to waves that are incident at 90 degrees from the cylinder's axis.

acoustic wavelength $v_s\tau/2$, while the maximum length of a free-mass antenna is one-half of the wavelength of the gravitational wave $c\tau/2$. Here v_s and c are the speeds of sound and light, respectively. Thus the quantum limit of a free-mass interferometric detector is smaller than the corresponding limit for a resonant-mass detector by roughly the ratio $v_s/c \sim 10^{-5}$.

The experimental requirements to reach these limits are very demanding and very different for each of these detectors. Readout devices based on the Josephson effect have been developed that are within a factor of two of the quantum-limit (for frequencies near 1 kHz). These will be used on the ultralow temperature resonant-mass detectors. For a detector with a 5000-kg aluminum antenna, the quantum limit is $h \sim 3\times10^{-21}$. If an antenna were constructed from a material with higher sound velocity (diamond would be ideal) then this limit could be even lower.

In the case of an interferometric detector, the readout-noise limitations can be understood by considering the quantum nature of the electromagnetic field. At the output of the detector there are unavoidable quantum fluctuations of the number of photons detected per unit time. For fixed laser power, this photon-counting noise increases with the frequency of the gravity-wave signal, since higher frequency corresponds to shorter integration time. It can be reduced by increasing the laser power. Eventually we must contend with the quantum noise arising from the fluctuating number of photons bouncing off the mirrors and imparting an uncertain momentum to the mirror masses. This "back reaction" noise decreases with signal frequency. The quantum sensitivity limit is achieved when the photon counting noise contribution equals that of the back reaction noise. Because the required laser power to achieve this limit scales as frequency to the 4th power, prohibitively high laser power is required to reach the limit at high frequencies. Use of photon squeeze states could bring this limit closer by reducing the laser power requirements.

At present, the laser power used in interferometers is orders-of-magnitude less than the power required to achieve the quantum limit. For the forseeable future (at least above a few hundred Hertz) Poisson counting noise will be the limitation. Eventually the LIGO detectors, using 100 watt lasers and optical recirculation, are expected to achieve $h \leq 3\times10^{-22}$ for detection of bursts of gravitational radiation over a broad bandwidth. Even this sensitivity is several orders-of-magnitude from the quantum limit.

did not detect sources. At the sensitivity level of these detectors only a very strong signal from a nearby cataclysmic event, such as a supernova or the coalescence of a binary star system, would produce detectable signals. Such nearby events are extremely rare.

It was realized from the beginning that to detect events relatively often (i.e., several per year), much more sensitivity would be needed in order to see a greater volume of the universe. Even while the first generation of cryogenic resonant-mass detectors were being brought into operation, detailed plans were being developed at Rome and Stanford for second-generation detectors that would operate at 50 millikelvin, close to Fairbank's original goal, with energy sensitivity improved by another factor of more than 10^4. Not only would operation at this temperature virtually eliminate thermal noise as a sensitivity limitation, but new breakthroughs in transducer technology, techniques of vibration isolation, and superconductive electronics could also be incorporated.

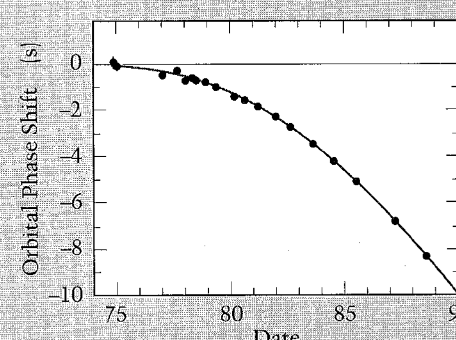
In the early 1970s, a parallel effort to develop laser interferometer detectors began. Robert Forward at Hughes Research Laboratory built the first small-scale laser interferometer gravity wave detector. At about this time Rainer Weiss at MIT began thinking about kilometer-scale instruments. By 1979 Weiss's group at MIT and a group at Caltech led by Ronald Drever were actively working on prototype devices with the aim of developing the technology needed for long-baseline interferometers. The MIT group initially focused on Michelson delay-line interferometers, while the Caltech group developed Fabry-Perot interferometers. By the end of 1991, a strain sensitivity approaching $h = 10^{-18}$ had been achieved with a 40-meter interferometer at Caltech.

CURRENT STATUS

DURING THE PAST TWO DECADES most of the experimental effort in this field has been devoted to developing the technology necessary to construct detectors with sufficient sensitivity to see predicted events. Since Weber operated his first detectors there have been technical breakthroughs leading to an improvement in energy sensitivity by about five orders-of-magnitude, but the objective of unequivocally detecting gravitational radiation has not yet been reached. Nevertheless, there are recent developments that give reason to be optimistic that at the beginning of the next millenium the effort will succeed not only in detecting gravitational radiation but also in exploiting it as a tool for observational astronomy.

What are these developments? First, the construction of resonant-mass detectors to be operated at 50 mK is nearing completion at Stanford University and at the University of Rome. The Rome group has already cooled an antenna weighing nearly five tons to below 0.1 K. Both of these detectors should be fully operational within a year, with sensitivity sufficient to detect events from within our galaxy that convert less than 10^{-6} of a solar mass into gravitational radiation. With anticipated improvements in transducer

THE BINARY PULSAR PSR 1913+16 is a system containing two gravitationally compact objects, probably neutron stars, gravitationally bound to each other in an orbit with a period of about eight hours. One of the neutron stars is a radio pulsar (a rotating, magnetized neutron star) that has a period of 59 milliseconds. The radio pulsar is a very good clock. Just like any moving clock, the pulsar's rate is modulated, because of the Doppler effect, by its motion in the binary orbit. By making precise timing measurements over a span of several years, Joseph Taylor and his colleagues have been able to measure the orbital parameters of this system and have found that the orbit is decaying with time. The solid line in the figure below (adapted from J.H. Taylor and J.M. Weisberg 1989, *Astrophysical Journal* **345**, 434) is the best-fit prediction of general relativity to the orbital phase shift caused by the gravitational radiation reaction. The dots are measurements carried out over a fourteen-year period. The agreement with general relativity is now better than 1%.



Decay of orbital period of the binary pulsar PSR 1913+16.

The Binary Pulsar PSR 1913+16

The precision of the radio-timing measurements is best illustrated by listing some of the parameters of this system as inferred from the measurements:

position: $19^h15^m28^s.00018$ (right ascension)
$16°06'27''.4043$ (declination)
period: 59.029997929613 milliseconds
rate of change of
period: −0.00000000000000000862713
pulsar mass: 1.386±0.003 solar masses
companion mass: 1.442±0.003 solar masses

If the binary system were subject only to the laws of Newtonian mechanics, several of these parameters would not be directly accessible with radio timing measurements. In particular, post-Newtonian, general relativistic effects allow an accurate determination of the mass of each of the compact objects. For PSR 1913+16 the neutron star masses inferred are remarkably close to the Chandrasekhar mass, the theoretical maximum mass of a white dwarf star.

What is the ultimate fate of PSR 1913+16? According to predictions of the general theory of relativity, for about the next billion years the binary system will continue to emit gravitational radiation at a relatively low frequency (twice the orbital frequency). At the end of this time, when the neutron stars are about 150 kilometers from each other and the orbital frequency is 50 Hz, the system will only have a few seconds left to live. The stars will then coalesce, emitting a chirp of gravitational radiation of increasing frequency and intensity. Finally, they will either collide or tidally disrupt one another. In these final few seconds about 3% of a solar mass will be radiated as gravitational waves.

A billion years is a long time to wait for PSR 1913+16 to coalesce. How many other binary neutron star systems are there that will coalesce on a more reasonable timescale? Observations of other pulsars in our galaxy provide a clue. Until very recently PSR 1913+16 was the only known precursor of a coalescing binary neutron star system. We now know of three other such systems in our galaxy. Based on these observations, Sterl Phinney, Ramesh Narayan, Tsvi Piran, and Amotz Shemi conservatively estimate that the rate of such coalescences is about 3 per year out to a distance of 200 Mpc. The rate could be as much as 1000 times higher.

This rate does not include possible coalescences of binary systems containing a neutron star and a black hole, or two black holes. Even though these systems are undoubtedly rarer than those like PSR 1913+16, they would be visible to much larger distances because of the larger signals expected. For example, a system with a 10-solar-mass black hole and a neutron star would be visible in a volume of space about 10 times larger than that for a two-neutron star binary.

Information obtained from the observation of gravitational waves from a coalescence will test predictions of Einstein's theory regarding the polarization states of the radiation and the speed of propagation. The detection of waves from the coalescence of two black holes would not only be the strongest evidence of the existence of black holes, but it would also test predictions of general relativity in the strong-field limit.

In addition to learning what happens when two neutron stars or black holes collide, Bernard Schutz has pointed out that the observation of chirped gravitational waves holds promise for cosmology as well. It is easy to see how. For a binary system with total mass M and reduced mass μ, and at a distance r, one finds that the gravitational wave amplitude h is

$$h = 1.02\times10^{-23}\mu M^{2/3} f^{2/3} r^{-1},$$

where the masses are measured in units of 1 solar mass, the distance is in units of 100 Mpc, and the frequency f of the waves is in units of 100 Hz. The timescale for decay of the orbit is given by

$$\tau = f/\dot{f} = 7.97\ \mu^{-1} M^{-2/3} f^{-8/3} \text{ sec.}$$

Since h and τ are both measurable quantities, one can find r by taking their product; the unknown masses M and μ drop out. Thus one can unambiguously measure the distance. This forms the basis of a new method of accurately measuring Hubble's constant.

[Editors' Note: For a brief review of the present status of General Relativity, *see page 25 of this issue.]*

technology an additional factor of ten improvement in sensitivity is likely. Further improvement would be possible with larger mass "spherical" antennas, or with antennas constructed from materials with higher sound velocity than aluminum which is currently used. (For fixed antenna frequency and shape, the antenna cross section is proportional to ρv_s^5, where ρ is the density of the material and v_s is the speed of sound.)

Even with this gain in sensitivity the rate of detectable events is likely, but not certain, to be less than one per year. While the significance of directly detecting a single gravitational wave event for the first time should not be underestimated, to use gravitational waves as an astronomical tool will require detectors that can see extragalactic events, such as supernovae in the Virgo cluster or binary coalescences out to a few hundred megaparsecs. (A megaparsec is about 3 million light-years.) This requires moving from the realm of an *experiment* to detect gravity waves to building a gravitational wave *observatory*.

This brings us to a second recent development: the approval by the National Science Foundation of the Laser Interferometer Gravitational Wave Observatory (LIGO). The FY 1992 National Science Foundation budget contains funding for the first part of LIGO's projected $211 million construction cost. The LIGO project, directed by Rochus Vogt of Caltech, will consist of two interferometer facilities, each with 4-kilometer-long arms. The recently selected sites are in Hanford, Washington, and Livingston, Louisiana. The major construction expenses are associated with building the required vacuum system capable of ultimately reaching 10^{-9} torr in a 1.2-meter-diameter pipe, 4 kilometers long. Construction is expected to take about four years, followed by first operation of the interferometers in 1998. The sensitivity of the initial LIGO receivers is expected to be $h \simeq 3\times10^{-21}$ at 1 kilohertz, and to approach 3×10^{-22} near 100 Hz. These are estimates based on technology that is essentially in-hand. With much improved optical technology, LIGO may eventually achieve two orders-of-magnitude improvement in energy sensitivity beyond these estimates. The planning of LIGO as a national facility includes the capability of housing interferometers of different optical designs in a common vacuum system. This will allow specialized experiments to be carried out simultaneously.

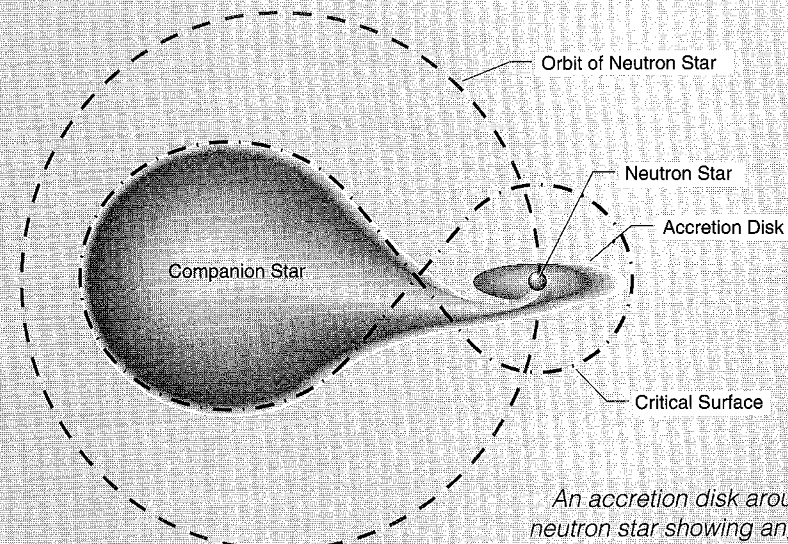
To obtain all of the information from a gravitational-wave signal (the direction of the source and the waveforms of the two independent polarizations) will require combining the outputs from detectors at three or more widely separated sites. Indeed, to obtain all-sky coverage with interferometers, a network of at least four detectors is required. Similar long-baseline detectors are now being planned or discussed in Europe, Japan, and Australia.

WHAT WILL WE LEARN?

IF THE HISTORY of astronomy is any guide, much of what we will learn from gravitational-wave detectors is impossible to predict; the safest expectation is that we will see the unexpected (see page 18). Almost everything we currently know about the universe comes from electromagnetic signals. Every band of the electromagnetic spectrum gives a different view of the universe. Historically, what was seen in one band has been a poor indicator of what would be seen in other unexplored bands. Much of what has been discovered in radio astronomy was unanticipated from optical astronomy. This in turn has been true of x-ray and gamma-ray astronomy. Surely it will be true for gravity-wave astronomy, because the most interesting and strongest sources of gravitational radiation likely involve coherent, relativistic motions of massive objects in regions where the curvature of spacetime is nonlinear. Electromagnetic signals carry little or no information about such regions, since they are easily scattered or absorbed by dense matter.

Most of what we know about gravity has been learned from observations in the solar system, where gravity is weak. What we know about strongly nonlinear gravity is mostly theoretical. For example, while many astrophysicists believe there is compelling evidence of black holes, the evidence is entirely indirect and depends upon the validity of general relativity in its extreme nonlinear limit. The most important promise of gravitational-wave observations is the opportunity to directly observe dynamical nonlinear gravity. Will general relativity survive the scrutiny of such observations? I don't know. Is it important to find out? Yes, if we want to take an important step towards understanding the relationship of gravity to Nature's other interactions.

A Hertz Experiment with Gravity Waves?



An accretion disk around a neutron star showing angular momentum transfer from the disk to the neutron star.

A LABORATORY experiment to generate and then detect gravitational radiation ideally might consist of a rotating-mass quadrupole source, for example a steel cylinder rotating about an axis perpendicular to its symmetry axis, and a sensitive receiver for detecting the coherent gravitational waves at the known frequency of the source. Because of the weakness of the gravitational interaction, it appears virtually impossible to perform this gravitational analog of the Hertz experiment in an earth-bound laboratory. For example, the gravity wave luminosity of a steel bar weighing 5 tons and rotating at 1 kHz, near the upper limit possible without exceeding the elastic limit of the bar, is 10^{-20} watts. This signal would produce a strain of 10^{-37} in a detector located about one wavelength (i.e., in the wave zone) away. This signal is almost 20 orders of magnitude in luminosity lower than what can be detected with any current or planned detector.

If instead of a rotating steel bar in the laboratory we substitute a distorted neutron star, rapidly spinning at a known frequency, then the gravity wave signal can be enormously larger even though the star is located thousands of light years away. For example, a weakly magnetized neutron star in a binary system may be spun up to a period near a millisecond by accretion of matter from the companion star. In this region the neutron star may acquire enough angular momentum to be unstable to nonaxisymmetric modes that grow by gravitational radiation reaction. These so-called Chandrasekhar-Friedman-Schutz modes are strongly damped by viscosity in normal stars. In neutron stars it is not known if the viscosity is low enough to allow these modes. If the modes are excited, a balance between accreted and radiated angular momentum will be reached. We can expect the x-ray emission from the system, generated by the accretion process, to be weakly modulated at the same frequency as the gravity wave emission.

Other mechanisms besides the instability mentioned could lead to continuous emission of gravity waves from a rapidly-spinning neutron star. A crack in the crust of the star, (a mountain) is one possibility. Detection of such an x-ray/gravity-wave pulsar might come from the detailed search for fast x-ray pulsars that will be made with an x-ray timing experiment being developed by the Naval Research Laboratory and Stanford University.* The Unconventional Stellar Aspect experiment will fly on the Advanced Research and Global Observation Satellite (ARGOS) to be launched by the U.S. Air Force in late 1995. If ARGOS detects a fast x-ray pulsar it will facilitate a sensitive search for gravity-wave emission with either LIGO or an ultralow temperature resonant-mass detector.

**The Unconventional Stellar Aspect Experiment team includes scientists from the Naval Research Laboratory (K. Wood et al.), the Stanford Linear Accelerator Center (E. Bloom et al.), the W.W. Hansen Experimental Physics Laboratory and the Department of Physics at Stanford University (P. Michelson et al.).*

The Nature of Cosmic Discovery

On many occasions, the astrophysicist Kip Thorne and Rochus Vogt, the director of the LIGO project, have both offered the opinion that the most interesting gravity-wave sources that will be seen have never even been thought of. Is this just wishful thinking? Perhaps not.

In his book *Cosmic Discovery** Martin Harwit argues that the discovery of new astronomical phenomena is driven primarily by technological innovation and not by astrophysical theory. Presumably this assertion applies to the discovery of fundamentally new phenomena and not necessarily to the "rediscovery" of a known phenomena disguised in a new context. In Harwit's own words,

> Astrophysical theory is a remarkably useful tool for dealing with a well-studied phenomenon. It guides us toward key analytical observations whose results help us decide between alternative models and thereby remove ambiguities and uncertainities in our understanding. But these theoretical steps have to be founded on observational data. Where no data base exists, the logic of theory alone provides no help. Rarely can we use theory to leap from a thorough understanding of one phenomenon to a prediction of the existence of a totally different, never-before-observed phenomenon. The span is too wide, and theory normally fails in the attempt.

The gulf between the observation of a new phenomenon and the theoretical models that explain it, while present in most fields of science, is probably largest in astrophysics. The reason is simple: astronomy** relies almost entirely on observations. The astronomical experiments have already been done. By contrast, in the physical sciences the experimentalist can design the experiment, analyze and interpret the results, and perform more refined experiments. Again, quoting Harwitt,

> The point to emphasize is this: The astrophysical concepts that lead to an understanding of cosmic phenomena have a history that is all but decoupled from the actual discovery of the phenomena. The phenomena are recognized largely because they exhibit observational features bewilderingly different from anything noted before. This was true of Tycho Brahe's supernova, of Galileo's Jovian satellites, of Saturn's rings studied by Galileo and Huygens, of the earth's motion around the sun discovered by Bradley, of clusters of nebulae first seen by William Herschel, of the nebular emission lines seen by Huggins, of Hess's discovery of cosmic rays, of Jansky's discovery of the Galaxy's radio emission, of Giaconni's and Rossi's discovery of X-ray stars, of Byram, Chubb, and Friedman's discovery of x-ray galaxies . . . Where was there but the vaguest connection between theoretical prediction and actual observed events?

Interestingly, of the 43 astronomical discoveries of new phenomena that Harwit identifies, approximately half were made by researchers who came from professions other than astronomy, about half were serendipitous, and nearly all depended on new instrumental power. Since World War II the fraction of new cosmic phenomena discovered by non-astronomers is closer to 70%. While many of the discoveries were initially isolated curosities, most eventually found themselves in the mainstream of astronomical investigation. Since World War II this has been true of radio, infrared, x-ray, and gamma-ray observations. Perhaps by the next millenium gravity wave astronomy will join this list.

* M. Harwit, *Cosmic Discovery: The Search, Scope, and Heritage of Astronomy*, MIT Press, 1984.

** I have not attempted to distinguish between *astrophysics* and *astronomy*. A reasonable definition is that astronomy is what astronomers do, while astrophysics is what physicists who do astronomy do. The term *astrophysics* appears to have been introduced by the astronomer George Ellery Hale, the founder of *The Astrophysical Journal*.

—*PFM*

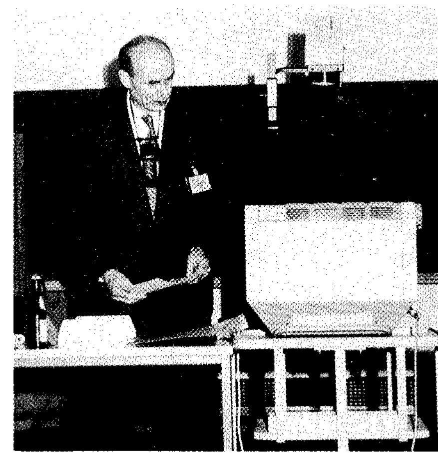
1992 European Particle Accelerator Conference

by STEPHEN MYERS

A review of the Third European Accelerator Conference by one of its participants.

THE THIRD EUROPEAN PARTICLE ACCELERATOR conference (EPAC) took place this year from March 24–28 in the Technical University of Berlin and attracted more than 700 participants, not only from Europe, but also from the USA, Japan, and many other countries. The economic situation in what used to be the Soviet Union would have made attendance for the Russians almost impossible had it not been for the efforts of the Conference Organizing Committee who chartered two train coaches to transport more than 70 participants from Moscow to Berlin and even sponsored their trip. Indeed in the opening session a spokesman for the Protvino laboratory presented a gift to the organizing committee as a gesture of their appreciation.

Far right: Donatus Degele of DESY reviews the HERA collider at the opening session of EPAC. Near right: Gunther Plass of CERN (right in photo) opens the conference.



The Conference was subdivided into 20 sessions and covered a wide range of topics on accelerator physics and technology as well as the use of accelerators for widely different applications such as the treatment of nuclear waste and medical applications. The program placed a strong emphasis on synchrotron light sources and their application to the material sciences and solid-state physics. In fact, it was clear from the audiences in the parallel sessions that the number of participants interested in synchrotron light sources far exceeded those interested in high-energy accelerators. The poster sessions in the afternoons were, as usual, a great success, and attracted large numbers of physicists and engineers who appeared completely at ease browsing around the posters in the airy atmosphere of the Technical University.

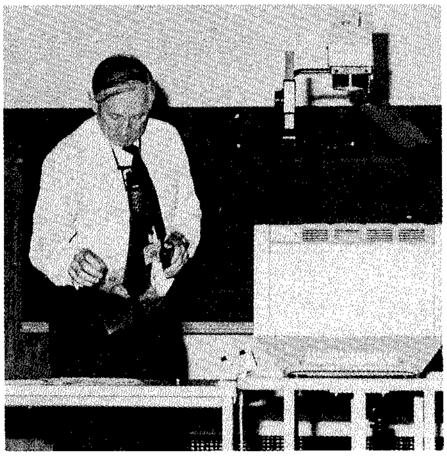
Although my main interest is in the field of high-energy accelerators, I will nevertheless include in this review not only high-energy accelerators but also, with my limited understanding of the subject, some of the presentations on synchrotron light sources and their applications.

HIGH ENERGY ACCELERATORS

GUNTHER PLASS, Chairman of the Organizing Committee, opened the conference by welcoming everyone to the Technical University. He added that it was a nostalgic occasion for himself and several other participants who had started their accelerator careers nearly 40 years ago in this very University, and had now come back to organize and participate in the Third European Particle Accelerator Conference in the reunited city of Berlin.

The first day of the Conference was dedicated to high-energy accelerators, and the opening presentation was by Donatus Degele on the impressive results from the electron-proton collider HERA. From his first transparency the message was clear: "HERA is ready." He then described the major HERA components including the 6.3 km tunnel that took only two years to construct under the city of Hamburg. The 820-GeV proton ring of HERA requires around 450 superconducting dipoles that were successfully constructed by industry; only 5 magnets were actually rejected, and in general the field quality and quench characteristics were better than design specifications. One of the main problems with superconducting magnets, inherent in their design, is associated with persistent currents, which are like eddy currents circulating within the coil filaments. These currents generate large sextupolar fields, which perturb the machine chromaticity and therefore require compensation down to the percent level. The compensation is complicated by the fact that the amplitude of the persistent currents depends on the excitation history of the magnet and decays logarithmically with time. The HERA electron ring uses eight 500 MHz superconducting cavities, which have all been tested without beam to 5 MV/m and run with beam at 2–3 MV/m. The good news here was that the superconducting cavities and the cryogenic plants are extremely reliable. In particular, the cryoplant had had zero down time in one year of operation. On the beam dynamics front, a multi-bunch instability that limited the intensity to about 10% of the design value has been cured by a feedback system that was reported upon in a later session by Rolf-Dieter Kohaupt. The dreaded beam-beam effect of electron-proton collisions has produced no real surprises, and beam-beam tune shifts of the design value have already been measured with single bunches. HERA starts up again in April 1992 and hopes to produce physics conditions later on in the year.

Grahame Rees had the unenviable task of giving "an outsider's view of the LHC and SSC machines," based on up-to-date information provided by CERN and the SSC laboratories. He highlighted the different approaches to the design of the superconducting dipoles: the LHC design is a twin bore, 10 Tesla magnet (2 K) with a 50 mm bore; while the SSC design is a single bore, 6.6 Tesla magnet (4.3 K) with a 40 mm bore in the old design and a 50 mm bore more recently. The luminosity of the LHC, which on paper is 17 times that of the SSC, is achieved by rather high bunch currents with more modest beam emittance, whereas the SSC



Grahame Rees of Rutherford Appleton Laboratory giving an outsider's review of large pp colliders.

calls for rather modest bunch currents but with very small beam emittances. The bunch current in the SSC could possibly be increased, but this would necessitate inner vacuum liners, which are already necessary for the LHC. These liners protect the cold bore of the magnets from the synchrotron radiation generated by the beams of protons and for vacuum reasons must have pumping slots. Rees came to the uncontroversial outsider's conclusion that the LHC and the SSC were "equivalent in degrees of safety in design." On a lighter note he then pointed out some of the other interactions available with these colliders: proton-proton, electron-proton, heavy ions, etc. He ended his talk with typical dry Welsh humor showing a photograph of Carlo Rubbia and Roy Schwitters in the LEP tunnel and suggesting that even director-director interactions might be available.

Eberhard Keil, definitely not an outsider, then gave an excellent review of the performance of the world's largest operating electron-positron colliders, CERN's LEP and KEK's Tristan. To emphasize his impartiality he declared that he would present the machines not in order of their size or energy or cost, but in strict alphabetical order, LEP therefore being first. The integrated luminosity (1991) in LEP was about one half that of Tristan, whereas the equality of the luminosity in the different experiments was much better in LEP. In both machines the synchrotron tunes, the betatron functions at the collision points and the bunch lengths are similar, whereas the synchrotron radiation losses are twice as much in TRISTAN because of the smaller (factor of 10) bending radius even though the beam energy is only two thirds that of LEP. The mode of operation of the two machines is significantly different, mainly because of the coasting beam lifetime. In LEP the filling time is on average around 3 hours followed by 8 hours of physics with a luminosity lifetime of typically 14 hours. In TRISTAN things happen much faster, with filling in 45 minutes followed by 2 hours of physics with a luminosity lifetime of about 4 hours. The beam-beam effect was the fundamental limitation to LEP in 1991, reaching an all-out maximum tune shift of 0.032, whereas TRISTAN has not yet been beam-beam limited up to tune shifts of 0.03.

On the polarization front, LEP has observed a maximum of 16% in 1991 and used resonant depolarization to calibrate the beam energy. In TRISTAN 40% polarization has been observed with a polarization time of only 2 minutes. The future plans for TRISTAN are to obtain an integrated luminosity of 300 pb^{-1} within three to four years at a beam energy of 29 GeV, and then later to convert to a fourth-generation light source with high brilliance provided by high phase advance in the arcs and the use of damping wigglers. In LEP the plans are to continue with Z^0 physics until 1994, with a luminosity upgrade provided by the Pretzel separation scheme installed during the last shutdown, and during 1994 to increase the energy (for W-pair physics) by the installation of at least 192 superconducting cavities.

SYNCHROTRON LIGHT SOURCES

IN AN IMPRESSIVE TALK Annick Ropert gave an up-to-date account of the status of the European Synchrotron Radiation Facility (ESRF). This facility consists of a 200-MeV electron linac, a 6-GeV fast-cycling synchrotron, and a low emittance 6-GeV storage ring optimized to produce high-brilliance x rays from insertion devices. The electron linac delivered its first beam in May 1991 and reached design performance during the first month of operation. Booster commissioning started in September 1991, and successful injection was obtained on the second day. Beam has now been accelerated to 6 GeV and extracted to the storage ring where a first turn was circulated within the first ten days and stored beam with a good lifetime within the first month. It is planned to fully commission the storage ring before the end of 1992 and then to install the first set of beam lines for operation in 1994.

The opening talk of the second day of the conference was by Vic Suller from the Daresbury laboratory, who gave a very informative review of the status of synchrotron light storage rings. He used "a statistical approach" to describe the various states, from conception to death, of a multitude of storage rings dating back to 1960. There are 17 sources in operation that are dedicated to synchrotron radiation research, 10

that are partly dedicated or shared with high-energy physics, and a further 9 that are used for restricted applications such as lithography or free electron laser (FEL) work. In addition, there are 18 sources under construction, with an additional 16 at the planning stage. Only 3 have been shut down. He showed an interesting plot of the circumference of the SRS storage rings as a function of time and concluded by extrapolation that LEP-size rings will be used in the not too distant future. He then went on to describe the various low-emittance lattices used in SRS storage rings. A figure of merit which compared the generalized minimum emittance with the design emittance showed that the more modern SRS lattices are approaching the design limit, while the multiple-bend acromats are not reaching their aims. Interestingly, FODO lattices have achieved extremely low emittances. In conclusion, synchrotron radiation sources are in a very healthy state, and while the choice of the optimum lattice is still rather open, there appears to be a convergence towards the double-bend acromat.

COMPACT SOURCES

FOR THE FIRST TIME in an accelerator conference the organizers planned a special session on compact synchrotron radiation sources. This special session was preceded by a fascinating review of the subject by Ernst Weihreter from BESSY. The three main applications for these machines are x-ray lithography, micro-mechanics, and medical applications. On the subject of micro-mechanics, an impressive photograph showed a stepping motor with a rotor of 200 μm radius.

The most important design parameters of these machines are compactness and low cost. In the quest for smaller and smaller machines, superconducting magnets with bending radii on the order of less than 1 m are being used. This raises many interesting technical challenges such as the coil tolerances needed, the reliability and safety of operation, the choice of warm or cold bore, and the compensation of sextupolar fields.

The opening talk of the special session on compact light sources was on the subject of a modular approach to superconducting rings. Here Gennady Kulipanov from Novosibirsk presented the subject with compassion and good humor. At the end of his talk he even offered "turnkey superconducting storage rings at bargain prices" because of the poor economic climate in his country. When asked from the audience to put a price tag on a 1.2-GeV superconducting ring, he replied that he would prefer to do this in private.

R.J. Andersen then presented the status of the first commercially produced synchrotron light source, Helios. This machine was produced by Oxford Instruments under contract for IBM. Testing was done initially at Oxford and then the storage ring was shipped to the USA where two months later a stored beam was circulated. The complex that weighs around 25 tons and uses superconducting magnets and a single rf cavity has surpassed nearly all design parameters. Based on this success, Helios II is now under design. The Mark II model will use a 100-MeV microtron as injector and non-evaporable getter strips for the vacuum pumping, and it will place great emphasis on accessibility, reliability, and productivity. Who knows, someday soon you may be able to buy one from your local DIY (Do It Yourself) shop!

Far left: (l. to r.) Heino Heinke, chairman of the local organizing committee; Lenny Rivkin, PSI; Bruno Zotter, CERN; and Ted Fieguth, SLAC, during one of the conference social events. Near left: Ernst Weihreter of BESSY reviews compact synchrotron light sources.

ACCELERATOR TECHNOLOGY

THE THURSDAY MORNING session reverted to accelerator technology, and in the opening session Claude Bovet of CERN gave a review of advanced beam-observation methods. He started his talk with a description of how the optics parameters are measured at the locations of the 500 pickups around the LEP circumference. The novel technique used is to excite a coherent sinusoidal oscillation on the beam and observe this motion at each pickup over 1000 turns. By doing harmonic analysis of the 1000 turns one can compute the betatron amplitude function and the phase advance. The momentum dispersion may be obtained in a similar way by inducing a coherent synchrotron oscillation. In the second part of his talk he showed a video recording of the motion of bunches in real time in LEP. The use of a streak camera with projections of the images into plan and side views allows very clear observation of not only coherent dipolar transverse and longitudinal oscillations but also "head-tail" oscillations.

The Friday morning session started with Joachim Tückmantel from CERN who gave a world-wide review of the operational experience gained to date with superconducting cavities. He detailed the accelerating gradients obtained at S-DALINAC (Darmstadt), CEBAF, MACSE (Saclay), DESY, KEK, and CERN. The most striking general result was that gradients obtained in the presence of beam are significantly lower than without beam. In addition, the average gradient of a group of superconducting cavities connected to a common power source is generally less than that of the individual cavities. The best results achieved with large numbers of cavities are at CEBAF, where the average gradient (test stand) was measured to be 8.2 MV/m with a Q of 5.3×10^9 on tests of their first 65 cavities that operate at 1.5 GHz.

All HERA dipoles exceeded the design field of 4.7 T without a quench, and a large percentage reached the critical current of the superconductor at the first or second attempt.

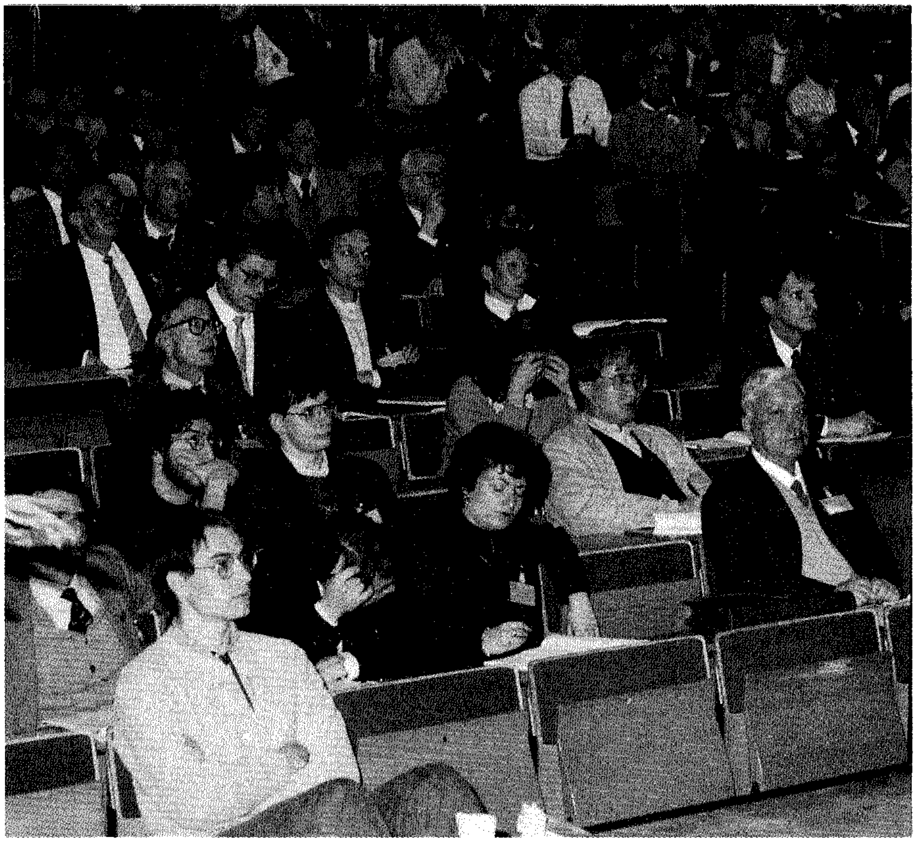
Peter Schmüser from Hamburg then gave an impressive review of the properties and practical experience of superconducting magnets. He concentrated on the extensive measurements made on the HERA magnets, which provided for the first time a wealth of information on the quench performance and field quality that can be achieved with large-scale industrial production of superconducting magnets. All HERA dipoles exceeded the design field of 4.7 T without a quench, and a large percentage reached the critical current of the superconductor at the first or second attempt. He stressed that superconducting magnets can be measured accurately and that persistent currents are manageable because they are reproducible. In conclusion, superconducting magnets now appear to be viable in the 5.5 to 6 T range and cost effective.

Romeo Perin then followed with an interesting review of the research and development towards high-field accelerator magnets. He highlighted the recent successes with the HERA superconducting magnets and the good results recently obtained at SSC and UNK and confirmed that the technology of accelerator superconducting magnets for fields in the range 4 to 6 T is now reliable for large-scale production. The 10 T field of the LHC is a bold step; however, the reduction of temperature from 4.3 to 2 K makes this advance in field possible. A twin-aperture 10 m magnet, made with HERA-type coils, went to the short-sample limit at the first quench at 4.5 K, showing no difference in behavior with respect to single aperture magnets, and reached 8.3 T at 1.8 K.

Four twin-aperture 1 m magnets have been built by European industry and tested at CERN. All magnets reached their short-sample performance at 4.2 K and went on to fields of 9 to 10 T at 1.9 K but with considerable training. Extensive research and development is continuing in order to understand the behavior of these short magnets, while in the meantime 10 full length (10 m) dipole prototypes are being built in industry. Eight of these will be assembled in a LHC prototype lattice cell for extensive testing.

EVENING SESSION AND CONCLUSIONS

THERE WERE TWO EVENING sessions. The first was the conference banquet that was an enormous



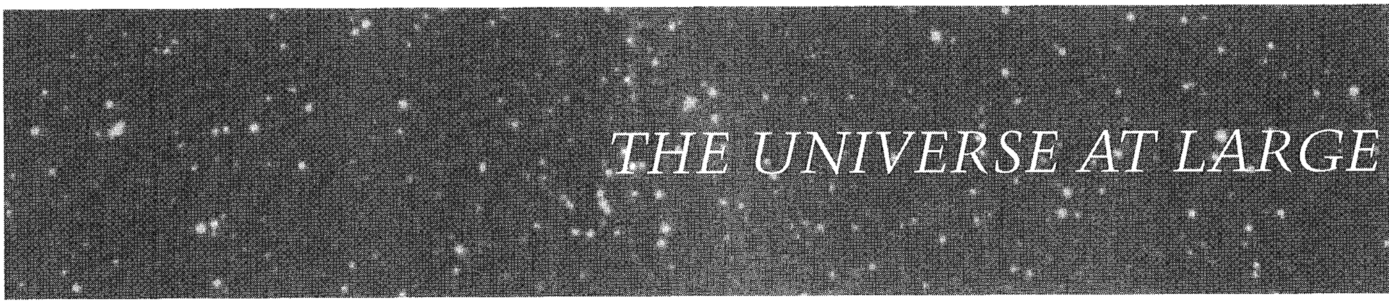
Attendees at the Third European Particle Accelerator Conference held at the Technical University of Berlin, March 24–28, 1992.

success with excellent food and wine as well as some very unusual entertainment. Bravo to the local organizers; this will be a hard one to follow. The second evening session was a public lecture by Carlo Rubbia to a packed auditorium on the fascinating and crucial subject of "Inertial Confinement Fusion—A Possible Contribution of Particle Accelerators to the World's Energy Problems." The enormous content in this lecture makes it, for me, practically impossible to review; however, there were two amusing moments in the presentation that I do remember. The first was when Rubbia jokingly dismissed the problems of dropping a small pellet into a chamber the size of a small church and blasting it simultaneously with 64 beams (or was it 256?) of heavy ions as mere "engineering details." The second occurred after about 45 minutes at his usual blistering pace, when Rubbia realized that he had only 15 minutes left before the scheduled end of his lecture and declared, "Let me go a little fast!"

This Third European Accelerator Conference was a success in providing a perfect atmosphere for informal discussion between participants. The University of Technology situated in the heart of the reunified city of Berlin was a fitting setting for European collaboration in the field of accelerators. As I mentioned earlier, the large Russian contingent made this occasion, on the site of the ancient East-West boundary, an altogether enriching experience for all.

The local organization team was composed of a mixture of former West and East Germans. It was headed by Heino Henke, the Chairman of the Local Organizing Committee. The Registration Desk counted some familiar faces from former EPAC conferences: Silvia Giromini and Pina Possanza from the Frascati Laboratory, Francoise Fein from the Centre Antoine Lacassagne, and Christine Petit-Jean-Genaz, the EPAC Executive Secretary based at CERN who also joined the team at the Particle Accelerator Conference last May in San Francisco (*Beam Line*, Vol. 21, No. 2, Summer 1991).

On a personal basis, I particularly enjoyed and benefited from the review talks and from the very well organized industrial exhibition. Needless to say, the poster sessions are the heart of all accelerator conferences nowadays, since they allow close interaction and idea interchanges between specialists in similar fields. I look forward with enthusiasm to the Fourth EPAC, which is scheduled to take place in London from June 27–July 1, 1994.



GEN REL IS ALIVE & LIVING IN PRINCETON

by VIRGINIA TRIMBLE

GENERAL RELATIVITY IS DEMONSTRABLY WRONG, in the sense that it is not a quantum theory and cannot be made into one, because it is not renormalizable.* It is also demonstrably right, in the sense that its predictions agree with all relevant experimental results. No other theory can make this claim, even some that were motivated by the desire for a quantum theory and unification with the other forces.

Einstein himself suggested three ways of distinguishing relativistic from Newtonian mechanics: gravitational redshift, deflection of light by the sun, and advance of the perihelion of Mercury. GR has long since won these battles (though gravitational redshift, at least to first order in GM/Rc^2, is now widely regarded as testing only the equivalence of gravitational and inertial mass-energy, which would not have offended Newton). One is, therefore, in some doubt about exactly what to test it against.

Einstein's theory of gravity, General Relativity, continues to pass its experimental and observational tests with flying colors.

**If you are looking down here to see whether I understand renormalization as well as you do, then get back to the top of the page where you belong—I don't. If you merely hoped for a hint of the meaning, then it is a prescription for subtracting off the infinite answers that you get when trying to use a classical theory, like Maxwell's electromagnetism or Einstein's general relativity, to calculate a quantum level phenomenon, like the self-energy of a point charge or mass. The prescription for E&M is called quantum electrodynamics and earned Tomonaga, Feynman, and Schwinger much deserved recognition. Credit for showing that no such prescription is possible in GR is somewhat difficult to apportion. Various colleagues here voted for Feynman, Salam, 't Hooft, Dyson, DeWitt, and "if I didn't do it myself, then I'm not interested."*

A few specific competitors (the Brans-Dicke scalar-tensor theory; Rosen's bimetric theory) have reared heads high enough over the years to attract fatal gunfire. But recent custom parametrizes possible deviations from GR in a fairly model-independent way. The parameters are designed to have values of 0 or 1 in general relativity and different values if, for instance, there are velocity-dependent forces, preferred reference frames, or differences between the gravitational and inertial mass of gravitational binding energy. The absence of that last feature is called the strong equivalence principle. Its presence, especially in the earth-moon system, is called the Nordvedt effect.

So far, all the ones are ones and all the zeros are zeros, at anything from 50% down to 10^{-4} levels. One further distinction is useful—between weak-field effects that might show up in regions with GM/Rc^2 much less than one, and strong-field effects that you expect to see only in the near vicinity of compact objects. Getting strong-field effects right counts for more brownie points (among both experimenters and theorists) than weak-field ones.

SOLAR SYSTEM TESTS

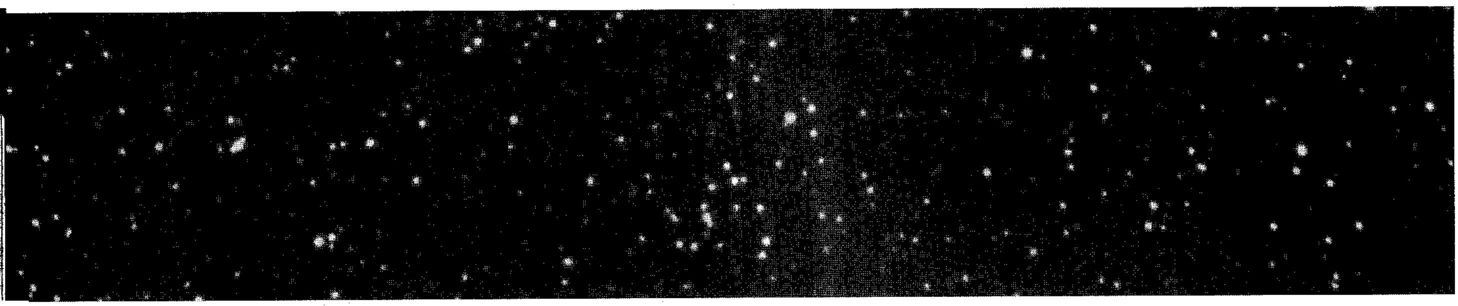
Since 1919 when Eddington went on his eclipse expedition, precision of the measurement of the 1.75 arc seconds expected deflection of light passing the limb of the sun has improved from 30% to better than 1%. The smallest error bars come from radio astronomers who don't have to wait for an eclipse. The delay in arrival time of a signal following this bent path (Shapiro effect) agrees with prediction even better. These results and lunar laser ranging data from 1971–90 together confine two of the weak-field parameters within ±0.002 of unity.

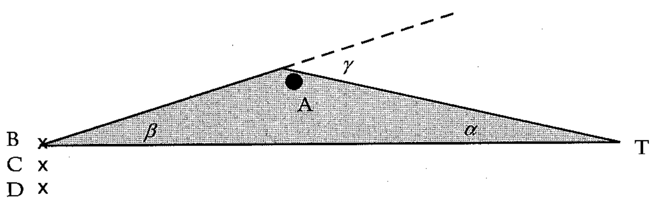
The perihelion of Mercury is still advancing at very close to the rate deduced by Leverrier in 1859. But its entanglement with Newtonian forces of other planets and a possible quadrupole moment for the sun (which would mimic the $1/r^2$ part of a weak-field GR potential) make this the least persuasive of the classical tests. The corresponding orbit rotation in binary pulsars can, however, be enormous—degrees per year rather than arc seconds per century. Thus, if you believe that gravity is the same here as around PSR 1913+16, the quadrupole moment becomes a derived parameter, and consistent with conventional solar models. A clock falling directly into the sun could explicitly separate the two effects. I am happy to volunteer my Timex but would prefer not to accompany it.

Other precision results from the lunar laser ranging effort include a Nordvedt effect parameter equal to 0 ± 0.0015; a limit on the time derivative of the gravitational constant, $\mathring{G}/G \leq 10^{-11}$ year^{-1}; and a measurement of the geodetic precession of the orbit of the moon at the predicted 2 arc seconds/century, to within 1%. This last is easily (but wrongly) confused with the Lense-Thirring effect, a small precession of things near the earth (or other rotating bodies) that arises because the rotator drags space time (inertial reference frames) around with it. The latter has not been seen but is among the goals of the Stanford gyroscope experiment (Gravity Probe B), proposed by Leonard Schiff in the 1960s and currently not scheduled for a 1993–94 Shuttle test flight.

COSMOLOGICAL CONSTANTS AND FIFTH FORCES

Einstein is supposed to have regarded the cosmological constant, Λ, as the worst mistake he ever made—though only after Hubble's work on redshifts of galaxies showed that it wasn't needed. But Λ has been resurrected as a solution to the nagging problem of stars in our galaxy that seem to be a bit older than the cosmic expansion time scale. In order to help, Λ has to have the sign of a cosmic repulsion and has to be about as large as the other terms in the Friedman equations for an expanding space time. This means about 10^{-56}cm^{-2}, 10^{-35} s^{-2}, 10^{-120} in Planck units, or one in units of $(H/c)^2$, where H is the Hubble expansion constant. You may





O. Chwolson's 1924 version of one star gravitationally lensing another. The frequently cited Einstein paper appeared in Science *in 1936.*

AIP Niels Bohr Library/Astronomical Society of the Pacific

Zwicky was not only the first person to recognize that gravitational lensing of one galaxy by another was more likely than that of stars but also one of the two discoverers of supernovæ (and their connection with neutron star formation and cosmic rays) and the first to compile firm evidence of the existence of dark matter in rich clusters of galaxies. He would occasionally describe a colleague who had displeased him as a "spherical bastard," meaning "no matter which direction you look from."

regard this sort of fine tuning as implausible. But just remember that, last time the age problem surfaced in 1948, Bondi, Gold, and Hoyle's solution was the Steady State Universe.

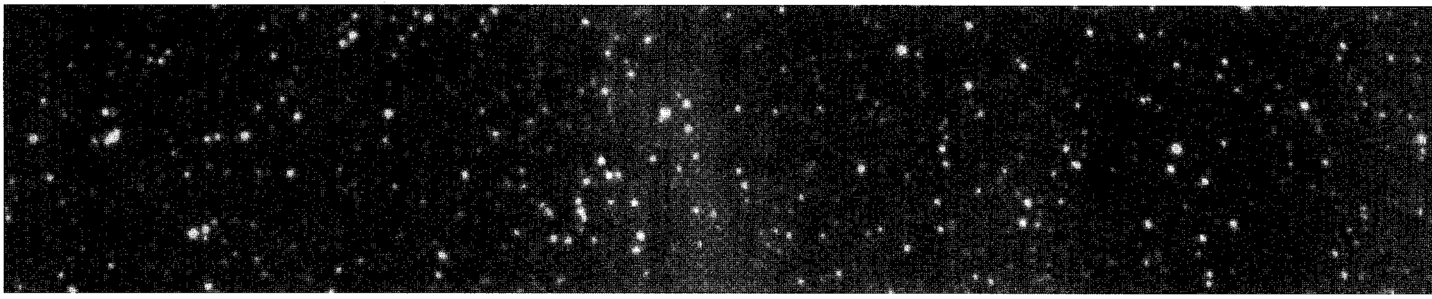
Einstein spent much of his life in a universe with only two well-defined forces. We are more or less used to four, interrupted by occasional floods of evidence for additional long-range, non-gravitational forces coupling to electrically neutral (but perhaps baryon, lepton, or isospin charged) matter. The most recent innundation showed signs of subsiding at the 1989 trienniel General Relativity and Gravitation meeting in Colorado. It seems now to have flowed away completely with a new set of data from a 300 meter high tower (also by chance in Colorado), which confirms purely $1/r^2$ accelerations, at least down to the level of 10^{-7} m/s^2 .

GRAVITATIONAL LENSES AND BLACK HOLES

If light is bent by passage through curved space-time, then optical systems become possible. Einstein contemplated the possibility of one star gravitationally lensing our image of another, though he was not first, and Fritz Zwicky showed that lensing of one galaxy by another was much more likely. Intuition based on experience with glass lenses can be rather misleading. In the gravitational case, a compact source (quasar) and an extended lens (galaxy or cluster) lead to 1, 3, or 5 point images; while a source that is also extended will show up as an arc or ring of emission around the lens.

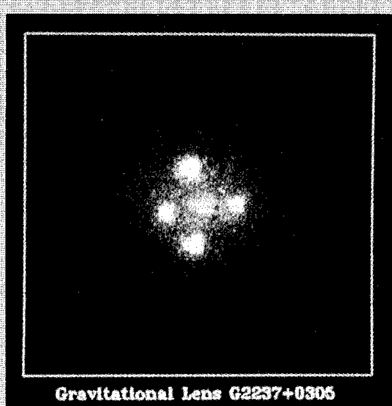
Enough of each have now been seen that new ones are not entitled to publication in *Physical Review Letters*.* Some show rapid temporal variability attributable to "microlensing" by individual stars within the lens galaxy. No real test of GR is implied, since any reasonable theory of gravity would lead to similar phenomena. There is, however, astrophysical interest in applied lensonomy. One possibility is microlensing by compact stellar or substellar objects making up the dark matter in our galaxy's halo. Another is determination of the cosmic distance scale using the multiple images of a variable source. Time delays between the images act as standard meter sticks from which distances to source and lens can be found.

**You may recall (if you are d'un certain age) a former editor's strictures on the discovery of a new effect, sequentially, in Whiffnium, Whaffnium, and Whoofnium, suggesting a rule that "one is a discovery; two is a confirmation; and three is a well-known class."*



A Gravitational Lens

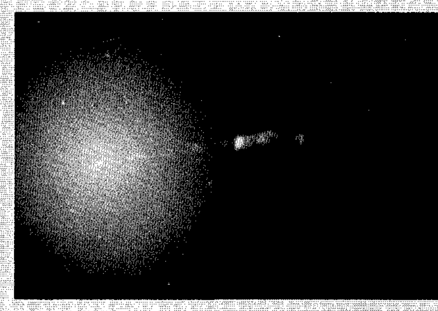
A HUBBLE SPACE TELESCOPE IMAGE of the Gravitational Lens G2237 + 0305, also referred to as the Einstein Cross. Light from a distant quasar is seen to be bent in its path by the gravitational field of the galaxy to produce four bright outer images. The diffuse central object is the bright core of the intervening galaxy. The quasar is at a distance of approximately 8 billion light-years, while the galaxy, at a distance of 400 million light-years, is twenty times closer. Gravitational lensing occurs when the light from a distant source passes through or close to a massive foreground object. Depending on the detailed alignment of foreground and background objects with the line-of-sight to the Earth, several images of the background object may be seen.



(Photographs courtesy of the National Aeronautics and Space Administration)

A Massive Black Hole?

A HUBBLE SPACE TELESCOPE near-infrared image of the central core and accompanying jet of the giant elliptical galaxy M87 showing the steady increase in brightness toward its center. The stars in M87 are strongly concentrated towards its nucleus, as if drawn in and held by the gravitational field of a massive black hole. The spot of light directly at the center of M87 appears to be a visible counterpart of the strong nuclear radio source, produced by relativistic electrons interacting with the magnetic fields. This phenomenon is possibly generated by a super hot disk of infalling gas expected to surround the black hole. Also visible are a number of faint star-like sources scattered around the center that are globular clusters orbiting M87, each composed of 100,000 to 1,000,000 stars.

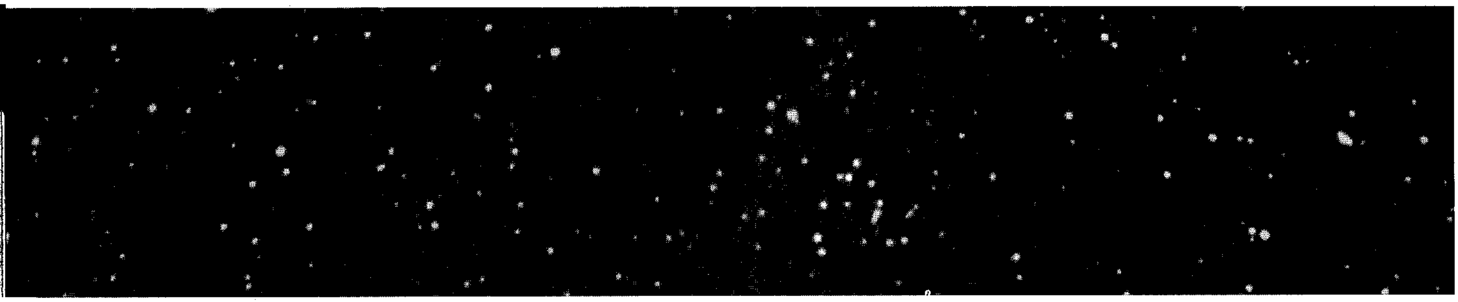


General Relativity permits the bending of light to become so extreme that none can escape from the immediate vicinity of sufficiently compact objects (black holes). This does not happen in all theories, and the interior space-time geometry, singularities, etc. are even more model-dependent. But astrophysical evidence for black holes doesn't really test GR either, because it is really only evidence for objects with GM/Rc^2 close to unity.

Such evidence exists for compact objects on two mass scales, stellar and galactic. The stellar ones are a subset of binary x-ray sources, in which gas from a normal star spirals down onto a companion too massive to be a neutron star, heating and radiating as it goes. We know a handful of good candidates, with ill assorted names like Cyg X-l, A 0620-00, and GX 2023+33. The galactic ones arguably reside in—and fuel—all quasars, Seyfert galaxies and so forth. But the most direct evidence pertains to a few nearby galaxies, whose optical images show very sharp, bright cusps at the center, suggestive of stars confined in a very deep, narrow potential well.

TIME MACHINES AND NAKED SINGULARITIES

One is inclined to feel that the right theory of gravity ought to prohibit both of these. In principle GR does not, and examples surface sporadically. But it generally



turns out that the configuration envisaged cannot occur in the real world. For instance, J. Richard Gott recently suggested that the region between two cosmic strings passing each other at close to the speed of light could contain closed time-like world lines, permitting the construction of a time machine (complete with the usual logical contradictions). But it seems that there is not enough mass-energy density in the whole universe (at least in an open one) to permit fabrication.

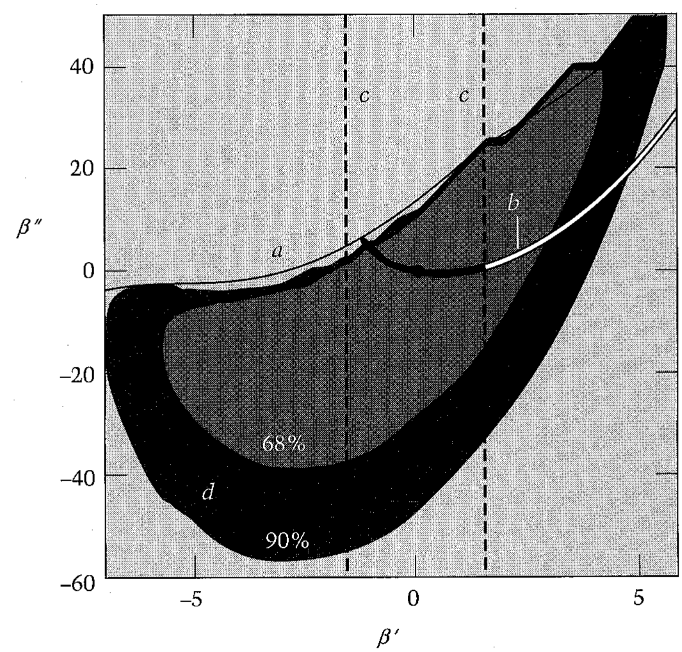
Other specific suggestions for constructing time-travel devices, worm holes (linking otherwise-distant regions of space-time), and singularities without horizons around them typically prove similarly impossible in the real world. This does not, however, prevent you from snatching away that portion of a black hole's energy associated with rotation (though its rest mass remains sacrosanct). Some models for central engines of quasars do precisely this.

GRAVITATIONAL RADIATION AND STRONG FIELD EFFECTS

Systems with changing mass quadrupole moments will lose energy via quadrupole gravitational radiation according to general relativity. The flux and dominant multipole differ in other theories. The trick to using this as a test is to find systems where the expected effect isn't utterly swamped by evolution due to electromagnetic and nuclear processes.

Neutron stars in close orbits around other neutron stars or black holes are the best bet so far. Not only do they carry exceedingly accurate clocks around with them (their rotation periods), they also send out time signals (pulsar radiation) every period. The gravitational radiation itself remains well below detectability, but we can watch the orbit period decrease as energy is lost. Such orbit decay has been followed in the binary pulsar PSR 1913+16 since 1983.* The decay rate

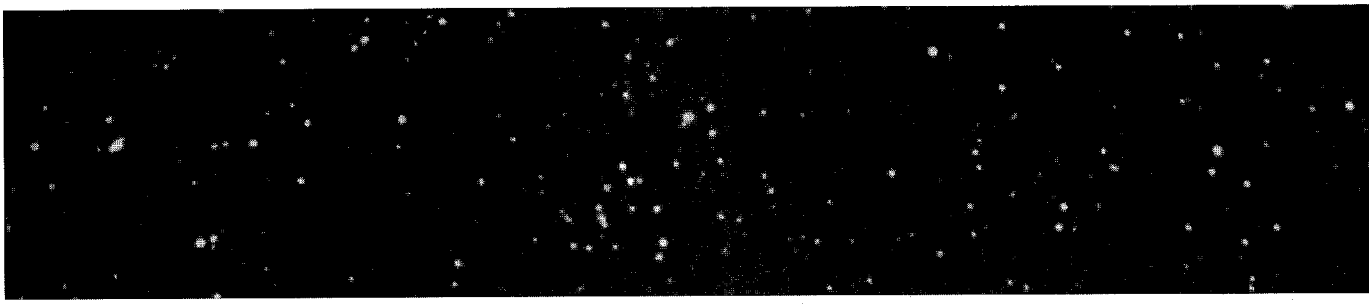
And you have another 10^8 year to get in on the act before the stars actually merge in a nasty mess of neutrinos, gravitational radiation, and neutron-rich debris.



Use of data from three binary pulsars to rule out large values of two parameters that describe strong-field, static deviations from general relativity. The vertical lines, c, *come from 1955+09 (a pulsar with a white dwarf companion). Data on 1913+16 are inconsistent with everything above contour* a, *and, with some model dependence, strongly favor the zone between the lines marked* b. *The contours d come, independently, from pulsar 1534+12. The general relativistic prediction of zero for both parameters is the dot in the middle. [Adapted from J. H. Taylor et al.,* Nature ***355****, 132 (1992)].*

is so close to the GR prediction that it puts tight limits on other theories (including scalar-tensor and bimetric ones) that permit dipole gravitational radiation. In order not to spoil the agreement, you also have to use something very close to the general relativistic prediction for weak-field effects, including periastron advance, gravitational redshift or time dilation, and Shapiro time delay.

It surprised me to learn that one can invent theories of gravity that have the same weak-field (solar system) and orbit-evolution characteristics as GR, but different



strong-field and radiation parameters when you separate them. This is true of a broad class of tensor-multiscalar theories that arise in attempts to quantize gravity and unify it with the other forces. The behavior of any one pulsar mixes up these static strong-field effects and the radiation ones. But the static and dynamic parts can be deconvolved and limits put on deviations from GR in each separately by looking at two or more pulsar systems with different degrees of compactness, and insisting that they all "obey" the same theory of gravity. As in the weak-field case, deviations can be parametrized. The parameters describe the amount of space-time curvature produced by a unit mass, non-linearity in the superposition of gravitational potentials, and so forth. They are equal to one in general relativity and something else for other theories.

Once again, GR comes through with flying colors. All three measured values are one. The error bars are now 10–70%, rather than the 1% characteristic of weak-field tests, but will shrink with a few more years of data. In summary, then, every experimental and observational test we can think of tells us that general relativity is the right theory of gravity. But we still know it is wrong.

Just the Facts, Ma'am

Additional details on most of the items mentioned in the accompanying article can be found in:

Lunar Laser Ranging: J. Müller et al., Astrophysical Journal **382**, L101 (1991).

Non-Zero Cosmological Constant: M. Moles, Astrophysical Journal **382**, 369 (1991).

Fifth Forces: C. C. Speake et al., Phys. Rev. Lett. **65**, 1957 (1991).

Gravitational Lenses: C. S. Kochanek, Astrophysical Journal **382**, 58 (1991).
F. Hammer et al., Astronomy & Astrophysics **250**, L5 (1991).

Microlensing: J. Wambsganss and B. Paczyński, Astronomical Journal **102**, 864 (1991).
R. J. Nemiroff, Astronomy & Astrophysics **247**, 73 (1991).

Black Holes in Galaxies: O. Bendinelli et al., Astrophysical Journal **103**, 110 (1992).

Time Machines: S. M. Carroll et al., Phys. Rev. Lett. **68**, 263 (1992).
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Binary Pulsars: J. H. Taylor et al., Nature **355**, 132 (1992).

Energy Extraction from Black Holes: I. Okamoto, MNRAS **254**, 192 (1992).

LINEAR COLLIDER R&D AT KEK

by KOJI TAKATA

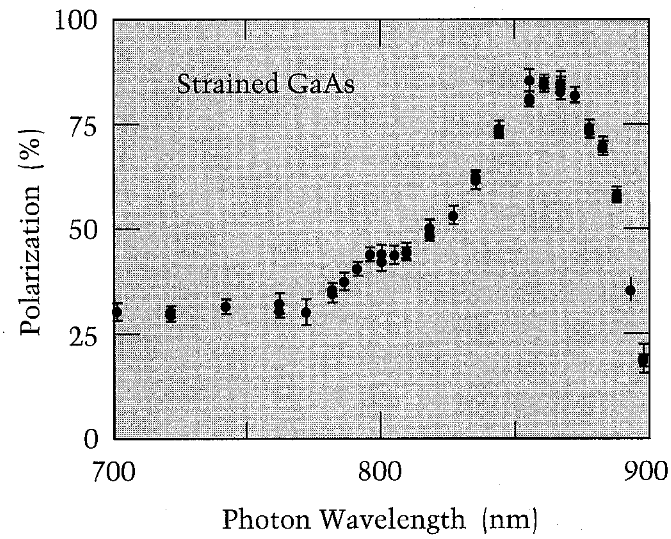
Japanese scientists are working on the design of a large electron-positron linear collider.

JAPAN'S NATIONAL LABORATORY for High Energy Physics' (KEK) master plan for the coming decade involves the construction of a TeV linear collider, the Japan Linear Collider (JLC), which is supported by the Japanese high-energy physics community. The accelerator test facility (ATF) has been the center of R&D work for the past several years (see the Fall 1991 *Beam Line*, Vol. 21, No. 3, page 18). At the ATF we have been constructing an S-band (frequency about 3 GHz) test linac, intended to advance linear collider technologies and to train young accelerator physicists who will build the future full-scale linac. As R&D progresses, however, we are involved in many other issues inherent in linear collider designs. In this article I will present a wider review of our R&D towards the JLC.

As I noted in my earlier article, the main design parameters of the JLC are similar to those of the accelerator that SLAC calls the Next Linear Collider or NLC, and we are carrying on our R&D work in close contact with the SLAC R&D team. This work falls into three categories: basic R&D work on individual items such as electron and positron sources, X-band high-power klystrons, X-band accelerating structures, and final focus systems including the design of the interaction region; promotion of the ATF project with emphasis on the construction of a test damping ring; and a continual optimization of parameters to include new results arising from progress in technology development.

CONCERNING NEW ELECTRON SOURCE technology, serious work is in progress on a radio frequency gun and on a polarized electron source. The former was first proposed at Los Alamos National Laboratory in 1987 and has been studied at many other laboratories since that time. It will generate a very low emittance electron beam using an intense microwave field instead of a conventional dc field. It accelerates electrons in a short distance to MeV energies, so that space-charge blow-up has little time to occur. Its key element is a photocathode that emits bunches as short as a few tens of picoseconds when irradiated by light from a mode-locked laser. At a very early stage of our R&D we studied the lasertron, a novel rf source. We developed techniques for photocathodes driven by a short-pulse laser system, which could then readily be adapted to the rf gun study. We use a cesium-antimony cathode 15 mm in diameter which is flashed with 532 nanometer laser pulses. Emitted electrons are accelerated in a single-cell S-band cavity. Recently we have observed the first relativistic electron bunches and are measuring various beam properties.

The polarized electron source was developed at Nagoya University. Polarized electrons are obtained by irradiating a gallium arsenide (GaAs) cathode with circularly polarized laser light. The polarization usually does not exceed 50% because GaAs's two states at the valence band, $P^{3/2}$ and $P^{1/2}$, are degenerate. A 100% polarization is, however, theoretically possible if this degeneracy is removed. The Nagoya group utilized both a super-lattice technique and also a lattice-mismatching technique to achieve high polarization. In the first case about one hundred layers of GaAs and gallium aluminum arsenide (GaAlAs) are alternately grown on a substrate. In this configuration the potential well is modulated and the energy levels split because the effective electron masses are different for each state. In the second case a thin layer of GaAs is grown on gallium phosphorus arsenide (GaPAs). The lattice constants of these two materials differ by a few tenths of a percent, and strain is thus created in the GaAs layer. This technique was invented by a team at the University of Osaka Prefecture. By optimizing lattice



Polarized electron emission from a thin GaAs layer deposited on a GaPAs substrate. The degeneracy of GaAs's spin states is removed by strain because its lattice constant is slightly different than that of the substrate's. A 100% polarized electron emission is theoretically possible when irradiated by circularly polarized laser light. This graph shows KEK's best record of 86% polarization at a wavelength of 850 nanometers.

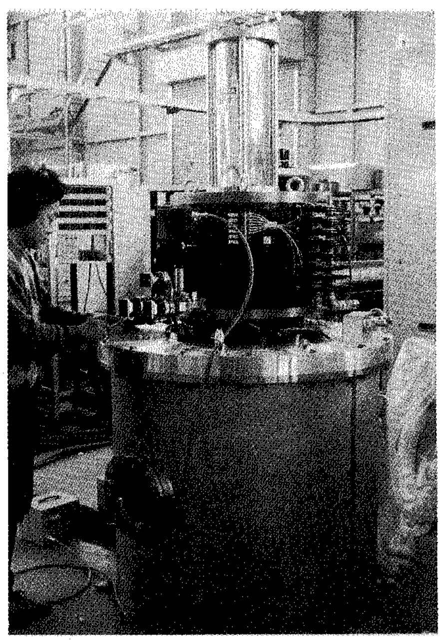
parameters, polarizations of 70% for the first case and 86% for the second (see graph on preceding page) have been achieved, although the quantum efficiency is still low. To improve the polarization further, it is necessary to investigate depolarization processes which affect excited electrons before they leave the GaAs surface. At KEK we are constructing a prototype gun based on this principle to get a practical number (on the order of 10^{10}) of polarized electrons per bunch.

THE DESIGN OPERATING FREQUENCY of the JLC is about 11 GHz (X-band). X-band high power klystron R&D is the most important and difficult task facing us. The JLC design requires about 7000 100-MW klystron tubes placed along the electron and positron linacs; each linac is 10 km long. State-of-the-art technology, established in the course of construction of the SLC at SLAC, is used in the fabrication of klystrons of this power level at S-band frequency. When we try to apply this technology to X-band klystrons, however, we encounter many new problems. These arise mainly because the rf frequency is four times that of the SLC and, roughly speaking, rf and beam-power densities become 16 times higher. At SLAC the design and fabrication of an X-band klystron in the 100-MW class was started some time ago. But at KEK we did not have the equivalent experience in manufacturing high-power klystrons, particularly at X-band frequencies. Therefore we started our R&D program with work on lower power (30 MW) tubes in order to understand key technical issues. There are three important points in designing high-power klystrons: the electron gun, the rf interaction section, and the rf output window. We set out by designing and fabricating a diode tube to check the gun behavior, and meanwhile carried out simulations and design studies for the rf section and the window.

In regard to the gun structure, we chose a design similar to that of the klystrons used on the SLC, which we considered as an excellent reference for our later work. While the SLC klystron operates at a beam voltage of about 350 kV, we wanted to raise it to 450 kV, and we made several modifications to reduce electric fields on electrode surfaces. We then had to specify the beam current level. It is characterized by a constant microperveance, the ratio of beam current in microamps to beam voltage in volts raised to the 3/2 power, according to the Child-Langmuir space-charge law. For instance, the SLC klystron has a microperveance of 2.0. To fix the perveance for our X-band tube, we must first consider that the emission of a conventional cathode is limited to around 10 A/cm^2. But the beam diameter normalized to the rf wavelength should not be too large or else the dc-to-rf power conversion efficiency will be seriously degraded. Therefore the beam focusing in the gun region becomes more and more difficult as the rf frequency increases. Taking these factors into account, we started the design of a diode tube with a rather small microperveance of 0.6 (corresponding to a dc beam power 81 MW at 450 kV). The cathode diameter was chosen to be 50 mm and the beam diameter 7 mm (corresponding to an area convergence ratio 51). The design of the beam focusing was optimized with the aid of the well-known code EGUN developed by William Herrmannsfeldt of SLAC. The first high-power test was carried out in the summer of 1989. The tube was successfully conditioned up to 450 kV by applying 1-microsecond high-voltage pulses. The microperveance was also confirmed to be the same as simulated. Encouraged by these results, we began manufacturing a klystron model with the same gun structure.

The design of the rf section was carried out by using the simulation code FCI developed by Tsumoru Shintake of KEK. This code calculates the radial dependence of the beam current density, which was neglected in previous codes. Such calculations will be essential to get accurate results for the bunching process and interaction with rf fields for klystrons with high current densities. For an optimized arrangement of cavities in the rf section, the code calculated an efficiency of about 45% for rf power generation (almost the same as typical figures for S-band klystrons), or an output power of 37 MW, at a beam voltage of 450 kV.

The output window, a dielectric disk usually made of high-quality alumina, is placed in the waveguide from the output cavity and functions as a vacuum seal for the tube. The window is the key component in determining the tube life. It must withstand temperature increases due to dielectric loss and surface degradation from secondary-electron bombardment, which inevitably occurs when high rf power passes through it. The window of the SLC klystron is an alumina disk 90 mm in diameter and 3.5 mm thick. Scaled to a frequency four times higher, however, the disk is only one-fourth as thick, which seemed too thin. Instead we adopted a several-millimeters-thick plate, although it required a different waveguide structure for matching. We tested the first model in the summer of 1990. Bright spots of light due to corona discharges were observed on the window surface as the output power increased, and it suffered cracks when the power reached 11 MW. We concluded that the failure was due to electric fields that were too strong on the surface. We then modified the window design to reduce the field strength. With this new window, we resumed high-power tests in the summer of 1991 and easily reached powers as high as 17 MW.

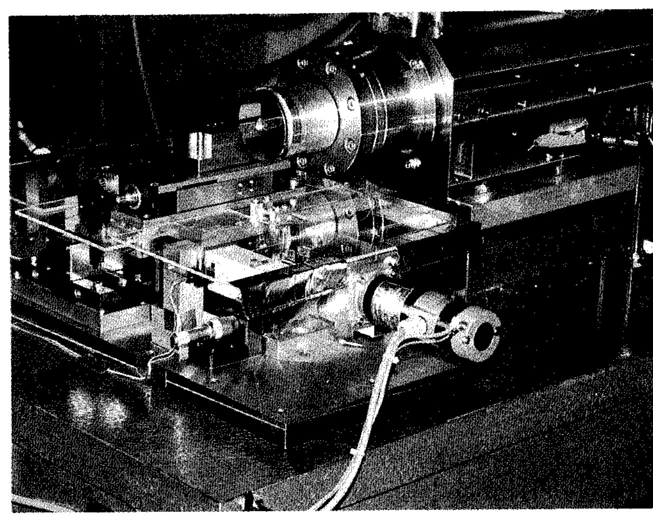


High power test set-up at KEK of the first 100-MW class X-band klystron At the bottom is the oil tank for the cathode assembly; in the middle is the focusing electromagnet; at the top is the klystron collector. Output power of 160 MW is expected for a beam voltage of 650 kV according to simulations.

IN PARALLEL, WE HAVE BEEN DEVELOPING a larger tube (see photograph above). We expect an output power on the order of 100 MW or more, as required by the JLC design specification. We increased the microperveance to 1.2 by increasing the cathode diameter to 72 mm, which doubles the area. The normal operating voltage is expected to be around 600 kV, where the simulated output power is 120 MW, but we think the tube should be designed so that it can be operated safely at voltages higher than nominal by about 10%. This margin will be very important in guaranteeing good stability for the thousands of tubes in operation on the full-scale linac. The first tube has already been delivered to KEK, and high-power tests are now beginning.

In klystron R&D we think feasibility studies for very high voltage tubes are important. As stated above, increasing the tube perveance to get a higher output power seems rather difficult because a higher current density is required. There are, of course, drawbacks in going in the direction of higher tube voltage. First, x-ray radiation from the tube would be serious. Second, the pulse-forming network requires many improvements for higher voltages. We will nevertheless pursue this direction, assuming those problems can be solved in separate R&D work. Another important study in developing a high-power klystron is to optimize the output cavity design. One serious issue is breakdown caused by the intense rf surface fields. Multi-cavity structures that reduce these fields are being studied at SLAC. We are pursuing a simple single-cell cavity whose gap is made fairly wide to reduce the surface field. Up to now such a structure has not been used because the rf conversion efficiency is thought to be low because of the small transit time factor. But simulations by the FCI code suggest efficiencies around 40%.

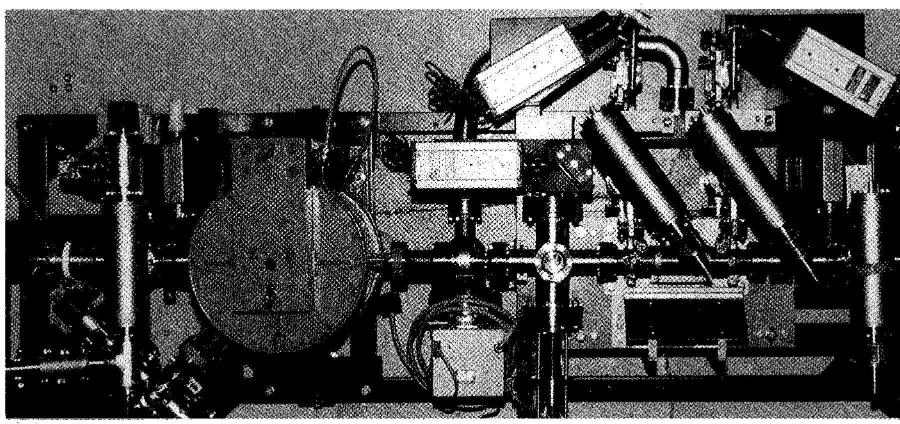
Even if we succeed in the 100-MW tube, we will still need peak powers several times higher than this to achieve the 100-MV/m accelerating gradient. This is only possible by using a special waveguide complex where the rf pulse height is increased by shortening the pulse width. Such an rf pulse compression technique is being seriously pursued at SLAC. We should also devise a klystron beam-focusing magnet which consumes much less power. Conventional electromagnets would consume more power than the average beam power of the klystron itself. Furthermore, we should also improve the rise time of the pulse-forming network to improve the overall efficiency. It is usually about 0.5 microseconds for conventional networks. But the flat top of the rf pulse in the JLC design will also be about this same value, and hence a shorter rise time is essential for good power efficiency. Although these problems are all very important, our team is not big enough to fully pursue all of them for the time being.



Machining of a unit cell of the X-band linac structure. At the center of an OFHC copper disk 9 mm thick and 80 mm in diameter, the acceleration cavity is bored 7 mm deep and 21 mm in diameter. Dimensional accuracies achieved are below 1 micron.

A ONE UNIT MODULE OF THE ACCELERATING structure for the X-band main linac will be about a 1-m-long cylinder loaded periodically by disks which separate it into more than 100 cells. R&D work for this covers machining studies, damped structure studies, and high accelerating gradient tests. The machining study is being carried on for a typical unit cell (see photograph above right). It is an open cylinder, 7 mm deep and 40 mm in diameter. One end is a 2-mm-thick disk having a center hole 9 mm in diameter as the beam aperture. Because of the shorter wavelength (one-fourth S-band), far better machining accuracies (on the order of 1 micron or less) are required than in the case of conventional S-band structures. In addition, copper of the highest grade is needed to achieve stable operation at a high gradient of 100 MV/m. However, such copper is usually soft and difficult to machine to an accurate finish. Furthermore, fine machining of such copper is not popular in industry. It is almost impossible to buy a precision lathe or milling machine for our purposes at a moderate price. Therefore we have prepared a conventional lathe for which we are developing special tables for mounting bits to achieve high-precision cutting using numerical control. We have achieved sufficient accuracy, in particular a few tenths of a micron in flatness, as long as machined pieces remain chucked on the lathe. But when they are removed from the chuck, they warp as much as a few microns. They will then be stacked together and brazed in a furnace, and we must expect further deformation in this process. In addition to dimensional tolerances, we must find the best conditions for the brazing process. It is thought undesirable to have any brazing alloys penetrate inside the cell because this can be a potential source of harmful field-emission electrons. On the other hand, we must achieve vacuum tightness at all brazed joints. We are only at a starting point for all these issues, and hope to carry out much more work during the next few years.

MOST OF OUR WORK on damped structures has consisted of simulation studies. Although we can obtain a very low-emittance beam from the damping ring, it is still necessary to suppress any emittance blow-up in the long linac to avoid a loss in luminosity. The JLC design assumes acceleration of multiple bunches per linac pulse to enhance the luminosity, as does the NLC design. A bunch will always be somewhat off the axis of the linac because of injection errors and linac misalignments. Thus it leaves behind transverse wakefields which will deflect the following bunches. It is therefore essential for multibunch operation to adequately suppress such dangerous wakefields. First of all, the beam aperture of the disk should be large compared with that of conventional structures, since the magnitude of the transverse wakefield is roughly proportional to the inverse cube of the aperture diameter. As the aperture becomes larger, however, more rf power is necessary to reach the design acceleration gradient. Therefore additional means must be devised to damp these unwanted wakefields. Two methods are known for this purpose: to extract the wakefield energy out of the structure between bunches by means of damping ports, or to make the wakefields sufficiently incoherent by detuning the deflection modes from cell to cell.



High-gradient test set-up of a 30-cm-long X-band structure (right). At the left is an analyzer magnet to measure the energy spectrum of dark current caused by field emission. Using the 30-MW-class klystron, it will be conditioned to an average gradient of about 80 MV/m.

An idea for efficiently extracting the wakefield energy was first proposed by Robert Palmer of SLAC at the 1988 KEK/SLAC Linear Collider Workshop. It was based on slots and damping ports cut at every disk to make the external Q values sufficiently low for deflecting modes. Since then we have carried out many calculations for various slot and port dimensions using a three-dimensional field calculation code. We have found it possible to achieve adequately low external Q values for the dominant deflecting modes. Such structures, however, have shapes that are too complicated to fabricate accurately. Also, deterioration of the unloaded Q value of the accelerating mode should not be overlooked. As is the case at SLAC, we are simulating much simpler structures where a few damping ports are machined only on the cylindrical part of a cell and the disk no longer has slots. We believe good results will be obtained soon

In the second method, every cell in a structure is made to have a different resonant frequency for the deflecting modes. Hence such a structure is called a detuned structure. The width of the detuning spectrum is on the order of the inverse of the time between successive bunches, which is 1.4 ns for the JLC design. A detuned structure would be much easier to fabricate than a structure with damping ports, but simulations so far are based on simple equivalent circuit models and the estimation of the wakefield effects might not be accurate enough. To get reliable results we have to calculate the wakefield profile for the whole length of a structure composed of about 100 different cells, which would be a very difficult job even for supercomputers. We can also consider a combination of the two methods to get a practical solution. In any case, some kind of test facility, such as the NLC test accelerator recently proposed at SLAC, would indeed be called for to evaluate these problems accurately by using actual high-energy electron beams.

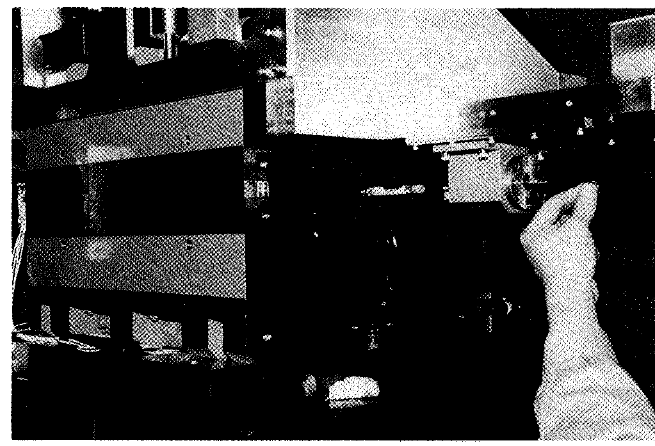
As described in my previous article, high-gradient tests have been completed at S-band because we did not have any high-power sources available at the X-band frequency. Of particular concern was the comparison of dark currents caused by field emission for different copper materials and fabrication processes. It became clear that a dust-free fabrication process greatly reduces the dark current. Only last December the first X-band tube became available, as mentioned above, and tests were begun with a 30-cm-long conventional disk-loaded structure, aiming to achieve a gradient of 100 MV/m at a 30-MW input level (see the photograph on the previous page).

A much more important issue is to enhance international collaboration. Any single laboratory would be unable to cover all of the linear collider R&D work now that it is so large and diverse.

THE DESIGN OF THE FINAL FOCUS SYSTEM has of course a great effect, not only on the maximum achievable luminosity and the design of the detector, but also on many specifications for the upstream accelerator. Hence we have long been devoted to optimizing the beam optics and evaluating background particle production at the interaction point. What we have stressed most is obtaining a design solution as simple as possible which does not impose any complicated conditions on the design of the upstream accelerator complex. To be more specific, we do not want options that would make it impossible to place the main linac in one straight tunnel. Therefore we rejected ideas such as the crab-crossing scheme, which require a rather large crossing angle of the two beams. In any event, a multibunch scheme requires a non-zero crossing angle at the collision point so that post-collision bunches in one beam will not hit pre-collision bunches in the oncoming beam. In our design, however, the angle would be only several milliradians. In the following, I describe some typical features of the present design, review some considerations concerning the background noise problem, and discuss the development of some of the final focus hardware.

As in the NLC design, we assume a flat or ribbon bunch shape at the collision point. This is a natural choice, since the vertical emittance obtained at the damping ring is much smaller than the horizontal. It also moderates the background problem because the space charge density can be made fairly small in a thin bunch. According to the present design, the bunch contains 1 to 2 times 10^{10} particles, is 3 nanometers thick vertically and 300 nm wide horizontally, and has a length of several tens of microns. While the bunch length is adjusted before injection into the main linac, the transverse dimensions are achieved by demagnifying the bunch shape by a factor of 300 vertically and 20 horizontally in the final focus transport line.

In designing the final focus system, we must consider several factors. First, there is a lower limit to the bunch size, even though a smaller size produces a larger luminosity. This effect is caused by the random deflection of particles by synchrotron radiation in the strong focusing fields of the final quadrupole magnet, as was first investigated by Katsunobu Oide of KEK. Second, we must consider the effect of resistive wall currents flowing on the pole surfaces of the magnet. The bunch suffers from serious emittance blow-up by fields caused by these image currents even if the pole surface is coated with copper. According to our estimation, the magnet aperture should be not less than 5 mm in diameter to avoid this blow-up, although this results in the loss of much of the focusing field strength. Third, the system should be achromatic over an energy range at least equal to the energy spread of the particles in a bunch. This energy spread is always on the order of 1% in the main linac. Such a spread is indeed essential to suppress transverse blow-up of a bunch in the main linac, since coherence is decreased in the betatron oscillations of the particles. Furthermore, we might need a rather long bunch because of the background problem at the interaction point as described below. The bunch length would then not be short enough compared with the rf acceleration wavelength, resulting in an additional energy spread. There are many ideas to make the energy bandwidth large enough, but we are investigating a scheme which is as simple as possible. According to our present design, the achromaticity can be achieved for a full spectrum width of 3% with only two families of sextupole magnets placed along the 500-m-long final focus line. The large aperture of the final quadrupole magnet will also make it unnecessary to insert any collimators to cut away off-momentum particles that would otherwise hit the magnet's poles.



Half-length model of the final quadrupole magnet to be installed at SLAC's FFTB. Its field properties are being measured with a rotating coil at KEK.

CAREFUL SIMULATION STUDIES of background noise are indispensable to fixing the beam parameters and the detector design. With extremely high-density, high-energy particles at the interaction point, many energetic photons are emitted by the particles in the presence of the strong electromagnetic fields of the oncoming bunch (beamstrahlung). These photons create many electron-positron pairs which become the primary component of the background. When such pairs accidentally hit the poles of the final quadrupole magnet, the detector will suffer from backscattered photons and neutrons which are the secondary background. A simulation code (ABEL, developed by Kaoru Yokoya and Toshiaki Tauchi of KEK in collaboration with SLAC) is used to evaluate the energy and angle of the electrons or positrons of the primary background. Simulations show that they are distributed within an area bounded by a curve $(\text{angle}) \times (\text{energy})^{0.8} = \text{constant}$, where the angle is typically 10 mrad and energy is 10 MeV. Particles with higher energies would not hit the poles, while those with lower energies would be trapped in the central region and would be harmless if a strong axial magnetic field is applied at the detector. For a center-of-mass collision energy around 0.5 TeV, a field strength of 1 Tesla seems sufficient to kill the background. Simulations, however, suggest that the angle-energy product noted above increases roughly in proportion to the collision energy. This means that a field of 2 Tesla is necessary for 1-TeV collision energy. This field strength is extraordinarily high, and we do not know how to establish it without affecting the characteristics of the final quadrupole magnets that are placed only 60 cm from the collision point. If a solution is not possible, we might be forced to reduce the number of particles in a bunch or to reduce the particle density by making the bunches longer. This would sacrifice the luminosity to some degree.

Hardware R&D for the final focus has been carried out mostly in collaboration with the SLAC Final Focus Test Beam (FFTB) project. The JLC team is in charge of manufacturing and mounting the quadrupole magnet family at the final focusing point. The most challenging task is to fabricate the final magnet, which is 1.1 m long and has a 13-mm aperture diameter. It must provide a quadrupole field of extremely good quality up to the maximum surface field at the pole tip, 1.4 Tesla. The four poles should be machined and assembled with an accuracy of about 2 μm. In 1991 we fabricated a one-half-length prototype (see photograph on page 38). The magnet was manufactured to the specified accuracy by an outside company. The field quality was also satisfactory according to careful measurements at KEK. The full-size magnet is also being fabricated outside of KEK and will be shipped to SLAC in the summer of 1992. This magnet, together with two other quadrupole magnets, will be mounted on a table with a precision stand. Precise positioning of the table will be achieved by piezo actuators which slide and rotate the table according to error signals. We have already tested this scheme with a prototype model. Externally applied random vibrations of 100 nm in rms amplitude or 1 mrad in rotation are reduced by about a factor of 20 with this feedback system. We are also carrying out R&D for the JLC final quadrupole magnet. It will be 1 m long with a 5-mm aperture as described above. The field gradient should be at least 500 Tesla/m, corresponding to a pole surface field as high as 1.4 Tesla. We fabricated a 10 cm test magnet, with poles made of an iron-cobalt alloy which has the highest saturation field among iron alloys. The field qualities were satisfactory enough, but the high axial magnetic field necessary for the detector is a very serious issue. An iron magnet will be of no use unless it can be shielded from this field. The shielding will be very difficult, however, when we consider that the final magnet is only 60 cm from the collision point. As an option we are considering using a permanent magnet whose magnetization is not affected by such a high external field.

Another important issue is to develop beam monitors with extremely good resolution, not only for bunch position but also for a bunch size in the nanometer range. For beam size monitoring a new idea was proposed by Tsumoru Shintake of KEK. It monitors Compton-scattered photons created by a bunch passing through a standing wave field of a laser beam. Modulation of the bunch position induces a modulation in the scattered photon intensity according to the electric field pattern of the standing wave, and thus gives information about the transverse bunch size. Commercially available lasers would provide adequate photon intensity. The first model will be tested at the FFTB next year.

WE THINK THE R&D ACTIVITIES DESCRIBED so far will continue for another three to four years to achieve some definite, not to say complete, results which would be the basis for proposing construction of the JLC. It would be absolutely impossible to reach this goal without strong collaboration with many groups outside KEK. First, we must continue good relations with industry, since we do not have a big enough machine shop at KEK and most of the hardware is fabricated by outside companies. An ideal situation for us is one where major companies are interested in developing small synchrotron radiation rings and are training a number of accelerator engineers. To maintain their interest in this field, our activities should cover, as before, a variety of areas of accelerator technology, although we have only a limited number of accelerator people at KEK. A much more important issue is to enhance international collaboration. Any single laboratory would be unable to cover all of the linear collider R&D work now that it has grown so large and diverse. In particular, the NLC and JLC designs have many common features compared with other proposals. Therefore R&D would be greatly accelerated if work at SLAC and KEK is well organized so that it is complementary and mutually useful to both laboratories for large-scale items.

FROM THE EDITORS' DESK

GEN REL IS ALIVE AND LIVING IN PRINCETON, starting on page 25 of this issue, is the first of a series of articles/columns in which astrophysicist Virginia Trimble writes about things that interest her. These will appear under the rubric of the "Universe at Large" as a regular department of the *Beam Line*. The prospect pleases.

The HERA machine described by Pedro Waloschek in our lead article is now in its early operational phase, with its first beam collisions recently reported. This is a unique facility, the first to produce colliding beams of electrons and protons. We look forward to the experimental results that should soon start to emerge from the ZEUS and H1 collaborations working at HERA.

The Third International Symposium on the History of Particle Physics was held recently (June 24–27) at SLAC, cosponsored with Fermilab. The two earlier Symposia in this series were held at Fermilab in 1980 and 1985. This year's event, "The Rise of the Standard Model," focused on the major experimental and theoretical advances that were made in our field during the period from 1964 to 1979. It was an occasion that brought together major contributors to particle physics with historians and other scholars of contemporary science in a very lively forum. We hope to have reports about, and perhaps even articles derived from, the presentations that were made at this memorable Symposium in future issues of the *Beam Line*.

Rene Donaldson

Bill Kirk

LETTERS TO THE EDITORS

Synchrotron Radiation and the Neutrino Mass

George Brown's article, "Synchrotron Radiation and the Neutrino Mass" in the Summer 1991 issue of the *Beam Line* was really well done, very lucidly written and interesting. We were delighted to see how he had captured the exciting flavor of this off-beat investigation.

We want to point out, however, that, in addition to SSRL and University of Oregon personnel, there were collaborators from Los Alamos and Lawrence Livermore National Laboratories on the experiment. Indeed, we at Los Alamos conceived the experiment, designed modifications to the Oregon apparatus, and brought some novel methods (for SSRL) to the experiment. Those included time-correlating the signal with PEP beam pulses to reduce random backgrounds a hundred-fold, and measuring scattering backgrounds in the Oregon specrometer to the 10^{-6} level with an off-line photoemissive source. We also were present and taking data throughout the entire duration of the experiment, analyzed the data, provided some of the funding, and wrote (with our Finnish collaborators) the paper describing the work. The paper, incidentally, was recently published in *Physical Review Letters* **67**, 2291 (1991).

Your readers may be interested to hear that we have recently improved our data to the point where a 9.3-eV mass is excluded at the 95% confidence level (see *Physical Review Letters* **67**, 957). This limit, which is in conflict with the 26-eV mass reported by a Soviet group, was made possible by the SSRL measurement. Although there are things we would have done differently if we had it to do again (such as trying to improve the resolution to the anticipated 2-eV level), it was overall a great success.

HAMISH ROBERTSON
Physics Division
Los Alamos National Laboratory

Peace Corps in Zimbabwe

Right now I am serving with the U.S. Peace Corps in Zimbabwe as a math and physics teacher. The courses I will be teaching are at A-level, and are of a similar scope and difficulty as the introductory physics and calculus classes taught at colleges in the States. (The syllabi are Cambridge A-level.). . . .Your publication would be a very useful source of information and interest arouser for my students and fellow teachers. It would let them know what was going on in a part of the outside world and maybe inspire them to do better so they might have a chance at the type of research that goes on at SLAC some day. . . .

MATTHEW SMITH
The Kwane Mission School, Zimbabwe

We have added Matthew Smith to the distribution list to receive copies of the Beam Line. *Contacts of this sort are important to us.*

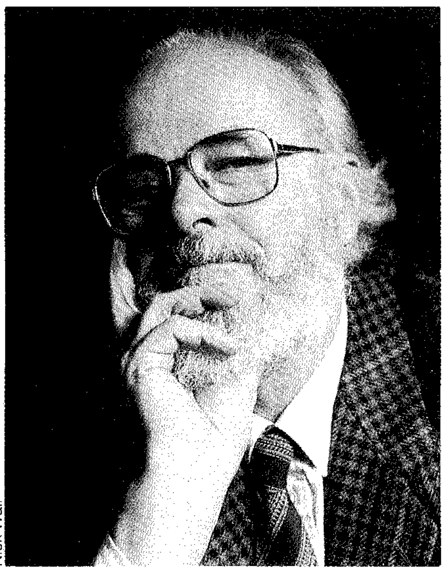
Plaudits

I was pleasantly surprised to see the new version of your *Beam Line* at the library of IHEP. It was the *Beam Line* who introduced me to the people and things of SLAC before I visited there in 1986-87. Then upon my return home I found a notice in a copy saying that no more issues of the *Beam Line* would be published. You may imagine how happy I am again to see the beautiful new *Beam Line*.

May the *Beam Line* link the whole high-energy physics community.

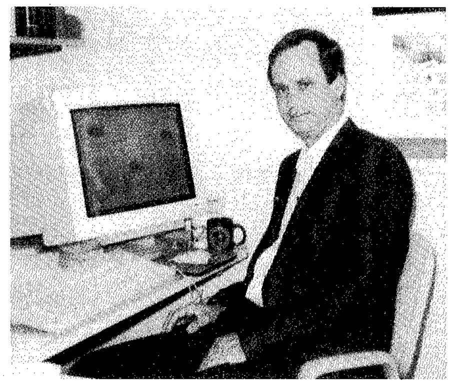
ZHANG CHUANG
Deputy Director, Storage Ring Division, IHEP
Beijing

CONTRIBUTORS



Nick Wall

PEDRO WALOSCHEK, senior scientist at DESY, began working in particle physics as a student in Buenos Aires in 1951. He spent 1955–56 in Göttingen, Germany, studying strange particles and then went to Italy where he organized the bubble chamber group at Bologna working with Jack Steinberger. Later he was affiliated with a group at the University of Bari. In 1968, after two years at CERN, he started developing proportional wire chambers at DESY and contributed to the design of PLUTO, a detector for the storage ring DORIS. Since 1978 he has written regularly for the general public and has directed the public relations group at DESY. Many articles and five books (in German), the latest one on HERA, testify to his prodigious activity, which he hopes to continue for many years.



PETER F. MICHELSON is Associate Professor of Physics at Stanford University and a member of the W. W. Hansen Experimental Physics Laboratory. He is the leader of the Stanford group currently constructing an ultralow temperature resonant-mass gravity wave detector. Since beginning that project he has also been involved in several high energy astrophysics projects that include the Energetic Gamma-Ray Experiment Telescope at the Compton Observatory and observations of bright galactic x-ray sources containing neutron stars and possibly black holes.

STEPHEN MYERS is deputy division leader of CERN's SPS-LEP Division. He has spent the last 20 years at CERN working initially on the ISR proton collider and since 1979 on the LEP collider. He played a key role in major aspects of LEP's design, building, and commissioning. He is presently responsible for the performance of LEP.

VIRGINIA TRIMBLE divides her time between the Physics Department at the University of California, Irvine, and the Astronomy Department of the University of Maryland, College Park. Her degrees come from UCLA (B.A.), California Institute of Technology (M.S., Ph.D.), and Cambridge University (M.A.). She was the 1986 recipient of the U.S. National Academy of Sciences Award for scientific reviewing and currently serves as editor of *Comments on Astrophysics* and associate editor of the *Astrophysical Journal*.

KOJI TAKATA is head of KEK's TRISTAN accelerator department. He came to KEK in 1972 and started to develop fast kicker magnets for the 12-GeV proton synchrotron. In 1977 he became responsible for design, construction, and operation of the rf system for the Photon Factory 2.5 GeV electron storage ring, and then in 1980 also of the TRISTAN 30 GeV electron-positron storage ring. Since 1982 he has been supervising R&D work at KEK for TeV linear collider technologies. He authored a previous article for the *Beam Line*, "The Accelerator Test Facility at KEK," in the Fall 1991 issue (Vol. 21, No. 3).

DATES TO REMEMBER

Jul 13–17	Particle Physics in the 90s: 1992 Gordon Research Conference, Andover, NH (Cynthia Sazama, Fermilab, MS 122, Box 500, Batavia, IL 60510 or SAZAMA@FNAL)
Jul 13–24	20th Annual SLAC Summer Institute on Particle Physics: The Third Family and the Physics of Flavor (School July 13–24; Topical Conf. July 22–24; Symposium on Tau Physics, July 24) Stanford, CA (Jane Hawthorne, SLAC, MS 62, Box 4349, Stanford, CA 94309 or SSI@SLACVM)
July 20–24	15th International Conference on High Energy Accelerators, Hamburg, Germany (by requested invitation) (F. Willeke, Conf. Secretary, DESY, Notkestr. 85, D-2000, Hamburg 52, Germany or HEAC92@DHHDESY3)
Jul 25–Aug 2	ECFA Workshop on e^+e^- Linear Colliders, Garmisch Partenkirchen, Germany (Mrs. Z. Kircanski, Max Planck Institut fur Physik, Fohringer Ring 6, W-8000 Munich 40, Germany or ZAK@DM0MPI11)
Jul 27–30	TeX Users Group 13th Annual Meeting: TeX in Context, Resources, Support Tools, and Comparative Studies, Portland, OR (TeX Users Group, Box 9506, Providence, RI 02940)
Jul 31	Fermilab Users Annual Meeting, Batavia, IL (Joy Miletic, Fermilab Users Office, MS 103, Box 500, Batavia, IL 60510 or USERSOFFICE@FNAL)
Aug 6–12	26th International Conference on High Energy Physics (ICHEP 92), Dallas, TX (by invitation) (Roy Schwitters, SSC Laboratory, MS 1070, 2550 Beckleymeade Avenue, Dallas, TX 75237-3997 or XXVICONF@SSCVX1)
Aug 17–21	5th Symposium on Pan-American Collaboration in Experimental Physics, Cartagena, Columbia [A. Pantoja, CIF, Apartado Aereo 49490, Bogota Columbia (CIF@ANDESCOL), or R. Rubinstein, Fermilab, Box 500, Batavia, IL 60510 (ROYR@FNAL). Working language to be English.]
Aug 24–28	LINAC 92, Ottawa Canada (M. Trecartin, AECL Research, CRL, MS 111, Chalk River, ON, Canada K0J 1J0)
Aug 30–Sep 12	1992 CERN School of Computing, L'Aquila, Italy (Mrs. Ingrid Barnett, CERN, CN Division, 1211 Geneva 23, Switzerland or BARNETT@CERNVM.CERN.CH)
Sep 13–26	1992 CERN School of Physics, Monschau, Germany (S. M. Tracy, CERN School of Physics, CERN, 1211 Geneva 23, Switzerland or TRACY@DGMAIL.CERN.CH)
Sep 21–25	10th International Conference on Computing in High Energy Physics (CHEP '92), Annecy, France (Christiane LeMarec, LAPP, BP 110, F-749491 Annecy-le-Vieux Cedex, France or CHEP92@CERNVM.CERN.CH)
Sep 29–Oct 2	3rd International Conference on Calorimetry in High Energy Physics, Corpus Christi, TX (Phyllis Hale, SSC Laboratory, MS 2080, 2550 Beckleymeade Avenue, Dallas TX 75237 or INTERCAL@SSCVX1)
Oct. 19–22	International Symposium on Neutrino Astrophysics, Takayama/Kamioka, Japan (K. Nakamura, Tokyo University, ICR, 3-2-1 Midoricho Tanashi, Tokyo 188, Japan or NEUTRINO@JPNUTINS)
Oct 27–31	IEEE Nuclear Science Symposium, Orlando, FL (J. W. Dawson, Argonne National Laboratory, Bldg. 362, 9700 S. Cass Avenue, Argonne, IL 60439)
Nov. 10–14	7th Meeting of the Division of Particles and Fields of the APS, Batavia, IL (Cynthia Sazama, Fermilab, MS 122, Box 500, Batavia, IL 60510 or DPF92@FNAL)

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