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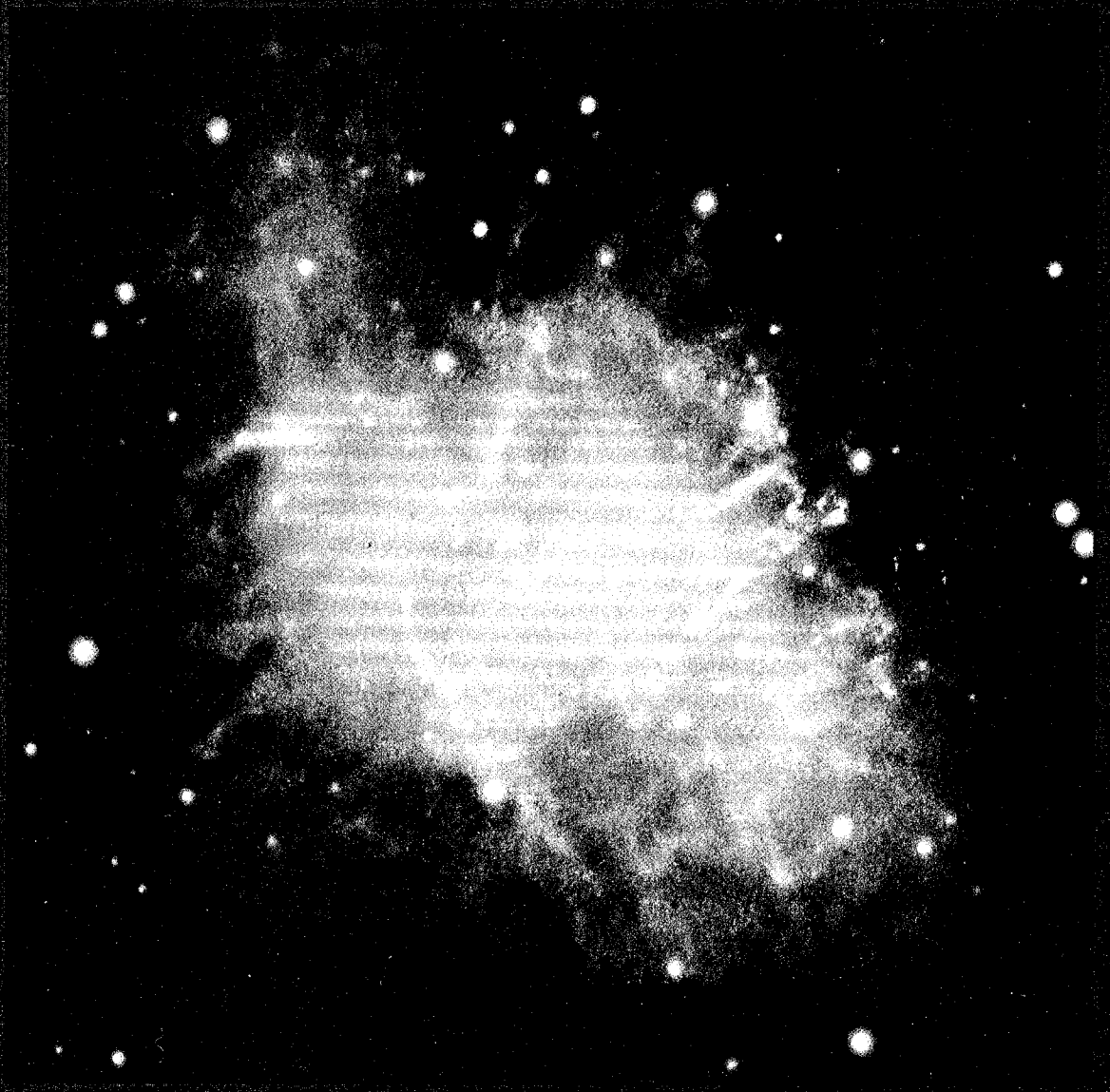

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

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Cover: The Crab Nebula, a confirmed source of very high energy gamma rays. Ground-based observation of such energetic photons is described in Leslie Rosenberg's article on page 10 of this issue. (Photograph courtesy of Lick Observatory)

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COOPERATION IN HIGH ENERGY PHYSICS RESEARCH BETWEEN THE UNITED STATES AND JAPAN

Joint research projects have helped establish mutual trust and understanding between physicists on both sides of the Pacific.

by MICHAEL RIORDAN and KASUKE TAKAHASHI

FOR OVER A DECADE SCIENTISTS from the United States and Japan have been collaborating on joint research in the field of high-energy physics. Most of this work has occurred within the framework of an agreement signed in November 1979 between the U.S. Department of Energy (DOE) and the Japanese Ministry of Education, Science and Culture (Monbusho). Since then, more than $100 million has been devoted to research activities of Japanese physicists at U.S. accelerator laboratories and to R&D efforts in Japan on advanced concepts for particle accelerators and detectors. Included in this total are amounts spent on equipment fabricated by Japanese scientists and industry for use in cooperative high-energy physics research at five U. S. national laboratories: Brookhaven National Laboratory (BNL) in New York, Fermi National Accelerator Laboratory (Fermilab) in Illinois, Lawrence Berkeley Laboratory (LBL) and the Stanford Linear Accelerator Center (SLAC) in California, and, most recently, the Superconducting Super Collider Laboratory (SSCL) in Texas.

The AMY detector and part of the collaboration immediately after installation of the central drift chamber in late 1986. Akihiro Maki (standing at left center under Korean flag) and Stephen Olsen (leaning on I-beam at right center) served as spokesmen for this project. (Courtesy of Alan Sill)

The Japanese efforts, led by Professor Tetsuji Nishikawa, the Director General of the National Laboratory for High Energy Physics (KEK) in Tsukuba until 1989, and coordinated by Professor Ken Kikuchi of KEK, have included contributions from physicists at universities throughout the country. In 1989, Professor Hirotaka Sugawara succeeded Nishikawa as Director of KEK and assumed leadership of this program. The U.S. contributions to this joint program were coordinated through the mid-1980s by James Leiss of the DOE office of High Energy and Nuclear Physics; in 1986 he was succeeded in this responsibility by Wilmot Hess.

In parallel with this research, the DOE has been supporting a team of about 40 U.S. physicists from eight universities who work together with Japanese, Chinese, and Korean physicists in the AMY collaboration at KEK. Since 1985, the United States has devoted a total of more than $10 million toward construction and operation of the AMY detector, one of three general-purpose particle detectors installed on the TRISTAN electron-positron collider at KEK. In addition, Monbusho has helped support research activities of the U.S. scientists in the AMY collaboration.

During the 1980s, this program of cooperation between the U.S. and Japan evolved from one that focused on a few joint high-energy physics experiments at U.S. laboratories to one that also includes extensive accelerator and detector R&D as well as experiments at Japanese accelerator facilities. The result has been research of high quality, as evidenced by the number of significant scientific papers that have been published. Based on this research, many students have earned Ph.D. degrees, in both the U.S. and Japan.

This program has been also extremely helpful in establishing mutual trust and good working relationships between physicists from the two countries. It provides an excellent model for future cooperation in the field of high-energy physics. This article summarizes the major achievements of this program, with emphasis on Japanese contributions to research conducted mainly in U.S. laboratories.

THE EARLY YEARS

FOR MANY YEARS before 1979, Japanese high-energy physicists were involved in experiments in the United States, but mainly on an informal basis, working as visiting scientists at U.S. institutions or analyzing data back at home. Discussions to put these exchanges on a firmer foundation began in Tokyo in 1978, during the International

Conference on High Energy Physics. These preliminary discussions soon led to the Implementing Arrangement on the U.S./Japan Cooperation in the field of High Energy Physics, signed at SLAC between officials of the Department of Energy and Monbusho on November 11, 1979, the fifth anniversary of the discovery of the ψ particle at SLAC.

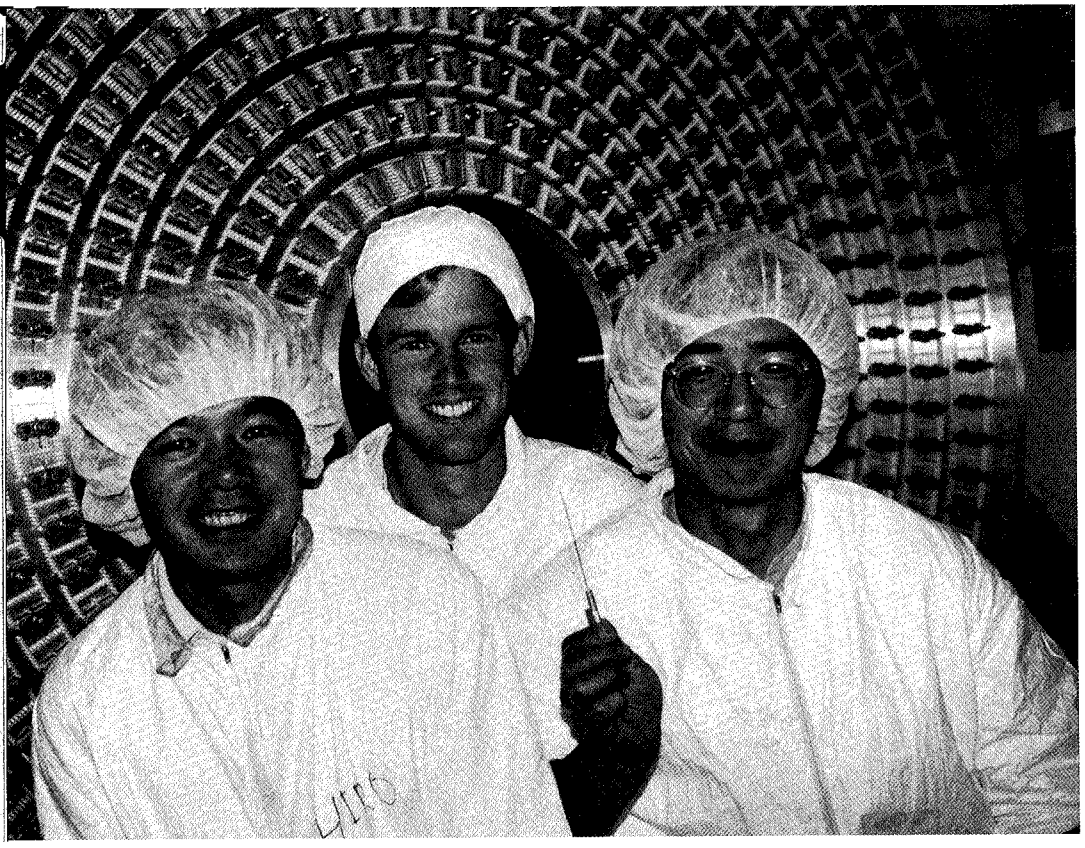
One of the earliest experiments to take advantage of this cooperative agreement occurred on the SLAC Hybrid Facility (SHF), a combination of a 100 cm rapid-cycling hydrogen bubble chamber with electronic particle detectors. The bubble chamber helped reveal the fine details of particle tracks emanating from the point of collision between incoming high-energy photons and target protons, while the electronic detectors aided in triggering the chamber and identifying the particles that emerged from it. The spokesmen of this experiment were Ken Moffeit of SLAC and George Kalmus of Rutherford Appleton Laboratory (one of the collaborating institutions). Under the leadership of Professor Toshio Kitagaki of Tohoku University, Japanese physicists (including one of the authors) from KEK, Nara Women's University, Tohoku Gakuin University, and Tohoku University made important contributions to this facility and to the analysis of data taken with it. From 1980 to 1983, this collaboration used the SHF to study the production of charmed particles in collisions between energetic photons and protons. Among other contributions, these physicists determined the lifetimes of neutral and charged *D* mesons.

Another series of SLAC experiments that involved major Japanese contributions occurred from 1978 to 1984 on the Large Acceptance Solenoidal Spectrometer (LASS), which was built under the leadership of SLAC physicist David Leith. This spectrometer is designed to study particles containing strange quarks (such as kaons and lambda particles) that are produced in collisions between high-energy kaons and protons. With its large acceptance and high-rate capability, LASS allowed physicists to make important advances in the understanding of strange particles. Scientists from KEK, Nagoya University, and the University of Tokyo played key roles in this collaboration. Led by Professor Ryoichi Kajikawa of Nagoya, they helped to upgrade the LASS particle detectors and took a major responsibility for the extensive data analysis that occurred after the experimental runs were completed.

Another early collaboration, this time at Fermilab, involved groups of scientists from Japan, Europe, and the United States; they worked together in an experiment led by Chuck Brown of Fermilab and later by John Rutherfoord of the University of Washington that studied pairs of leptons produced in very high-energy collisions between protons and nuclei. The proton beams used in this research had the highest energies then available in the world. Physicists from KEK and Kyoto University contributed to this work, with Professor Kozo Miyake of Kyoto serving as their spokesperson. A major result of this research was a high-resolution study of the upsilon particles, a family of mesons that are composed of a bottom quark plus its antiquark, which can disintegrate into a pair of leptons.

Two other Fermilab experiments were done by collaborations between U.S. high-energy physicists and Japanese physicists who had been using photographic emulsions to study particles produced in cosmic rays. Among their number was a group from Nagoya University that in 1971 had obtained the first evidence for a charmed particle in cosmic rays using these techniques, which enabled physicists to study particles with short lifetimes, such as mesons containing charmed or bottom quarks. Together with groups from several Canadian and Korean universities, these scientists combined photographic emulsions with standard electronic detectors. The spokesman for this hybrid emulsion/counter experiment was Bill Reay of Ohio State University. Led by Professors Koyoshi Niu of Nagoya, Goro Fujioka of Kobe University, and Osamu Kusumoto of Osaka City University, the Japanese scientists played a key role in this collaboration, developing the photographic emulsions and the high-speed data-analysis techniques needed to extract information from them rapidly.

In the early 1980s, a group of U.S. and Japanese physicists led by spokesman D. H. White of Brookhaven National Laboratory cooperated on an experiment that examined the scattering of neutrinos from matter. Led by Yorikiyo Nagashima of Osaka University, groups from Hiroshima, KEK, Osaka, and Tokyo helped design and build a combined target-detector consisting mainly of



Standing in front of the endplate of the SLD central drift chamber are (l. to r.) Hiroaki Masuda, Mike Fero, and Akira Sugiyama. (Courtesy of SLD)

180 tons of liquid scintillator. In 1982–83, this unit was exposed to an intense beam of fairly low-energy (about 1–2 GeV) neutrinos at Brookhaven, in order to study events in which these particles rebounded elastically from atomic electrons and protons in the target materials. From about 100 such events, the group extracted a measurement of the Weinberg angle, a parameter in the Standard Model that determines the degree of mixing between the electromagnetic and weak forces. A subsequent run in 1986 helped them refine this measurement.

Led by Professor Kitagaki, a team of Japanese scientists has worked with U.S. physicists in a long series of bubble-chamber experiments at Brookhaven and Fermilab. In the first experiment, which occurred in 1979–80 at BNL, a beam of low-energy neutrinos was passed through the chamber, and almost a million events were photographed. Two of these revealed the production of a charmed baryon (i.e., a heavy, composite particle similar to the proton in which one of the constituent quarks is a charmed quark). The Tohoku group then moved its operations to Fermilab, where it teamed with physicists from the United States, France, and Israel in using a 76 cm long bubble chamber to study interactions of 200 GeV pions, kaons, and protons with matter. This group also built its own high-resolution Freon bubble chamber in Japan. Featuring laser holographic optics in addition to the three standard views, it was used on the Fermilab Tevatron from 1985 to 1990 to examine collisions of very high-energy neutrinos with atomic nuclei.

COLLIDING-BEAM EXPERIMENTS

BY THE MID-1980S the emphasis in cooperative research between the U.S. and Japan had shifted to colliding-beam experiments, in which two beams of high-energy particles clash with one another and detectors situated around the point of interaction record the outcome. At the time, KEK physicists were also building TRISTAN, the first such collider in Japan. Research continued in fixed-target experiments, in which particle beams strike stationary targets, but the focus of the cooperative program had clearly changed. Japanese groups began working on two large detectors employed in electron-positron colliders at SLAC, and on another big detector being built for the Tevatron proton-antiproton collider at Fermilab.

Led by Professor Tuneyoshi Kamae of Tokyo, a group of Japanese physicists from KEK and Tokyo teamed with Lawrence Berkeley Laboratory physicists to build the

TPC detector for the PEP electron-positron collider at SLAC. Pioneered by LBL scientists led by David Nygren, the TPC was the first instance of a revolutionary type of detector that permits physicists to reconstruct particle tracks in all three dimensions, a feat that had never before been achieved in colliding-beam experiments. It also allowed excellent discrimination among the various kinds of charged particles emanating from the collisions. The Tokyo contingent had major responsibility for the calorimeter used in the TPC to distinguish electrons, positrons, and photons from heavier particles. The initial running with the TPC occurred in 1982–83, with follow-up runs in 1984–85 after this detector had been upgraded with a superconducting magnet. The data gathered in these experiments allowed the TPC collaboration to make perhaps the most detailed studies then available for the mechanisms by which hadrons are produced in electron-positron collisions, and to examine the production of hadrons containing charmed and bottom quarks. The experience gained by Japanese physicists working on the TPC was later applied to the design and construction of the TOPAZ, one of the three general-purpose detectors on the TRISTAN collider.

Groups from Nagoya and Tohoku led by Professors Kajikawa and Haruo Yuta, who had worked on the LASS and SHF experiments, continued their SLAC involvement by participating in the construction of the SLAC Large Detector, or SLD. A state-of-the-art general-purpose detector completely surrounding the interaction point of the Stanford Linear Collider or SLC, the 4000-ton SLD is designed to provide detailed reconstructions of subatomic particles that emerge from high-energy electron-positron collisions. (See *Beam Line* Vol. 20, No. 3, 1990, page 10, for more details.) Led by Charles Baltay of Yale and Martin Breidenbach of SLAC, the SLD Collaboration includes more than 150 physicists from 33 institutions in the U.S., Japan, Canada, Britain, and Italy. The solenoidal magnet coil for the SLD was built by Mitsubishi, and Kawasaki Heavy Industries manufactured most of the iron parts for the magnet support yoke. Japanese physicists have worked on the central tracking chamber in the SLD and on its Cherenkov detector, which helps physicists determine what kinds of particles emerge when Z particles decay. They are also working on a gun to supply polarized electrons for acceleration on the SLC itself.

Perhaps the most interesting of all the experiments to which Japanese physicists have contributed in the U.S. is the research done since 1987 on the big Collider Detector at Fermilab (CDF). A contingent led by Professor Kunitaka Kondo of the University of Tsukuba, which includes groups from KEK, Saga University, and Tsukuba, has been a crucial part of this large international collaboration since the late 1970s, even before the U.S./Japan Implementing Arrangement was signed in 1979. These physicists have made important contributions to the calorimeters and worked with Hitachi Industries to fabricate the solenoidal superconducting magnet at the core of this detector.

Led by Alvin Tollestrup of Fermilab, Roy Schwitters (then) of Harvard University, and Melvin Shochet of the University of Chicago, CDF physicists designed and built this huge general-purpose detector, which is almost 10 meters high and weighs over 5000 tons. Their goal has been to study the results of proton-antiproton collisions on the Tevatron at energies up to 2000 GeV, or 2 TeV, the highest collision energy currently attainable in the world. So far, this collaboration of more than 200 physicists from 18 institutions in the U.S., Japan, and Italy has made the most accurate measurement of the properties of the W boson, a very massive particle almost 90 times heavier than the proton that acts as the carrier of the weak nuclear force responsible for radioactive decay. CDF has also established the world's most stringent limit on the mass of the top quark, whose existence is required by the Standard Model but which has yet to be discovered. In 1992 this collaboration will continue its search for the top quark and should eventually isolate this elusive particle.

Led by Professors Shoji Nagamiya (now at Columbia University) and Ryugo Hayano of Tokyo, physicists from Hiroshima, Kyushu University, Saga, Tokyo, and Waseda University have been working with U.S. physicists since 1984 to produce beams of heavy ions in the Alternating Gradient Synchrotron (AGS) at BNL. Atoms of oxygen and silicon are stripped of their electrons and the resulting bare nuclei accelerated to high energy (234 GeV for oxygen and 409 GeV for silicon) in the AGS, a machine that was originally designed to accelerate protons. In a series of experiments begun in 1987 and

The solenoidal magnet coil for the Fermilab CDF arrives at Chicago from Japan in 1984. (Courtesy of Fermi National Accelerator Laboratory)

continuing to the present day, this group of physicists led by Ole Hansen of Brookhaven have directed these beams onto targets of aluminum, copper, and gold in order to study the behavior of nuclear matter at high energy densities. So far they have witnessed an enhancement in the ratio of kaons to pions produced in such heavy-ion collisions (over what is observed in proton-proton collisions), which may be evidence for a new state of nuclear matter.

The work of this collaboration in developing heavy-ion beams has paved the way for a new kind of collider called the Relativistic Heavy Ion Collider (RHIC), in which two beams of heavy ions will be accelerated simultaneously and then brought into collision. Far more extensive studies of the behavior of nuclear matter under conditions of extreme temperature and density will become possible when RHIC, now under construction at BNL, is completed in about 1997.

DETECTOR R&D

SINCE THE EARLY 1980S physicists from the United States and Japan have worked together in a continuing program to develop advanced systems and components for the sophisticated particle detectors required to perform high-energy physics experiments. Much of the early Japanese contribution to the CDF collaboration, for example, involved such detector R&D. Between 1982 and 1986, KEK, SLAC, and several universities in both countries jointly developed new systems and techniques that have been incorporated into the detectors built to observe electron-positron collisions at TRISTAN and the SLC. Recently, groups from KEK and Japanese universities have become heavily involved with U.S. groups doing important detector R&D for the Superconducting Super Collider (SSC) under construction in Texas.

Led by one of the authors, physicists from KEK and several Japanese universities collaborated with SLAC on detector R&D for electron-positron colliders then under construction at the two laboratories. Included in this program was the development work that went into the SLD. Several of the new or improved techniques for particle detection that emerged from this program were used in the VENUS and TOPAZ detectors at TRISTAN. Both of these general-purpose detectors, for example, contain calorimeters made of a dense type of lead glass whose properties were studied at KEK and SLAC, where a prototype calorimeter was tested in high-energy electron beams. VENUS and TOPAZ have precision

vertex detectors (devices positioned very close to the beam pipe that record the fine details of particle tracks as they emerge from the point of collision) based on prototype models built and tested at SLAC under the leadership of John Jaros. (See article in the *Beam Line*, Vol. 20, No. 1, 1990, page 8.) And the first particle detector used at the SLC, the Mark II, had a vertex detector based on this design. The cooperative detector R&D performed in this program played a major role in the new generation of collider detectors that came on line during the late 1980s at KEK and SLAC. In addition, some of the data-acquisition systems used on the SLD and all three TRISTAN detectors are based on cooperative R&D efforts that occurred in the mid 1980s at KEK, Fermilab, and SLAC.

The third general-purpose detector on the TRISTAN collider, AMY, was another beneficiary of the cooperative detector R&D program. Constructed by an international collaboration of scientists from the United States, Japan, Korea, and China under the leadership of Professor Stephen Olsen of the University of Rochester and Akihiro Maki of KEK, AMY is a compact detector optimized for the study of electrons and muons. A group of about 40 U.S. physicists from Rochester, the University of California at Davis, Louisiana State University, the University of Minnesota, Ohio State University, Rutgers University, the University of South Carolina, and Virginia Polytechnic Institute form the core of this team. United States agencies have spent more than $10 million on AMY, which includes over $5 million on detector components alone.

This collaboration was able to build such a compact detector because it used the expertise of Japanese industry in fabricating solenoidal superconducting coils. The high magnetic fields (3 Tesla) thereby generated allowed AMY to be built much smaller than the other TRISTAN detectors with comparable powers of particle detection. A unique detector that sits just inside this solenoidal magnet coil is derived from prototypes that were built and tested as part of the cooperative detector R&D program; this work was done by the University of Rochester and Fermilab together with KEK and Niigata and Saitama Universities. As electrons and positrons trace out curved paths under the influence of AMY's strong magnetic field, they emit energetic x rays that are recorded by this detector. Because heavier particles do not emit nearly as many x rays, the new detector gives physicists an extra way to distinguish electrons and positrons from pions and kaons.

Since 1986, a group of Japanese physicists led by Professor Shigeki Mori of Tsukuba have worked with U.S. physicists on detector R&D for the SSC. At first this R&D project was supervised by M. G. D. Gilchriese of the SSC Central Design Group headquartered at LBL; after the SSC was approved by the U.S. government in 1989, this role passed to the new SSC Laboratory in Texas. In addition to KEK and Tsukuba, Japanese groups involved in this project are Hiroshima, Kyoto, Niigata, Osaka, Tohoku, and Tokyo; on the U.S. side are major groups from LBL and the CDF collaboration. The principal concerns of this project are to devise components and data-acquisition systems able to function in the anticipated SSC environment of high radiation and event rates. One subgroup is building vertex detectors from radiation-hardened strips of semiconductor material; another is examining how to build suitable calorimeters; and a third is developing the ultrafast electronics needed to extract data from the detectors. The Japanese groups working on this detector R&D form an important part of the Solenoidal Detector Collaboration, a group of over 700 physicists from 100 institutions in 12 countries that is proceeding with the detailed design of a general-purpose detector for the SSC.

ACCELERATOR R&D

SINCE THE EARLY 1980S, the United States and Japan have worked together upon research and development of advanced techniques for particle acceleration. Such efforts help scientists and engineers in both countries (and around the world) build better and more powerful particle accelerators and colliders while keeping costs down. As part of this research, Japanese scientists have cooperated with their U.S. counterparts on high-field superconducting magnets, on superconducting cavities, and high-power klystrons for generating microwave power, and on a variety of other projects whose ultimate goal is to facilitate the next generation of linear electron-positron colliders.

Under the leadership of Professor Hiromi Hirabayashi, scientists at KEK have worked for over a decade with

groups at BNL, Fermilab, LBL, and the SSCL to advance the state of the art in superconducting magnet design and fabrication. A major goal has been to develop dipole magnets with fields approaching 10 Tesla, more than twice the operating field in the magnets that presently guide protons and antiprotons around the Tevatron at Fermilab. By working closely with Furukawa Electric and other companies, this collaboration has developed the industrial techniques needed to produce large quantities of copper-cladded niobium-titanium wire, which becomes superconducting at very low temperatures (below 4.4 K). Such wire can be reliably manufactured with a diameter of 6 microns, and its current-carrying capacity is almost twice that of the wire used in the Tevatron magnets. Further R&D efforts are directed at reducing the wire diameter, which will help to reduce the undesirable "eddy currents" that occur, while maintaining its ability to carry high currents.

Another important aspect of this joint magnet program has been learning how to form this wire into cable, and then to wind and clamp the cable firmly in place to make current-carrying coils for the dipole magnets. Tiny movements of the coils under the stresses that occur when high currents flow through them can generate enough heat to make the magnet quench (i.e., suddenly lose its superconducting property). Overcoming these tendencies while carrying the thousands of amperes needed to generate the high fields required is one of the keys to building successful SSC magnets. A 1 meter long prototype built at KEK in 1990 was the first magnet to achieve fields at the high levels that are needed to ensure a sufficient operating margin for the SSC. Since then, full-scale prototypes built subsequently at BNL and Fermilab (based on similar designs) have given accelerator physicists confidence that industrial firms, such as General Dynamics and Westinghouse, will be able to manufacture the superconducting magnets that are required to keep 20 TeV protons on track in the SSC.

By doing cooperative research for more than a decade, scientists in both countries developed the mutual understanding and trust necessary to work in the large collaborations that do the most significant research in particle physics today.

Superconducting materials also make important contributions in accelerating cavities where microwave power is applied to keep beams circulating in storage rings such as TRISTAN. Because the energy loss per circuit grows as the fourth power of the energy, these cavities must operate efficiently if power costs are to remain reasonable. Superconducting cavities have far smaller losses in their walls than cavities operating at room-temperature; most of the power goes into the beam. Led by Professor Yuzo Kojima, KEK physicists worked with SLAC physicists led by Gregory Loew and Cornell physicists led by Maury Tigner to develop the niobium-coated cavities now installed in TRISTAN, the first superconducting cavities to be used extensively in an operating storage ring. These cavities generate an accelerating field of up to 9 million volts per meter, allowing the TRISTAN energy to be raised to 32 GeV.

A burgeoning area of cooperation between the U.S. and Japan has been joint R&D on linear electron-positron colliders. Pioneered by SLAC, this is a relatively new approach to colliding-beam accelerators in which the two beams of particles are boosted to their collision energy by two linear accelerators, rather than in a storage ring. As electron and positron energies exceed about 100 GeV, a linear collider becomes the preferred approach because these particles will not lose energy by the copious emission of x rays, as they do in storage rings. Now that the feasibility of linear colliders has been demonstrated at SLAC by the SLC, physicists in the U.S., Japan, Europe, and the Russian Republic are working together on developing the techniques and equipment needed to design and build the next-generation collider.

Early work on this area came in attempts at KEK and SLAC to develop high-power klystrons (which generate the bursts of microwave power needed to accelerate electrons and positrons) whose peak power exceeded 100 megawatts. Led by Professor Jiro Tanaka, KEK physicists worked with engineers at Mitsubishi and Toshiba from 1983 to 1985, achieving 150 MW peak power output for a klystron operating at about 3 GHz, the frequency used on the

SLAC accelerator. More recent R&D has focused on developing high-power klystrons that operate at 11.4 GHz; prototypes have thus far been able to achieve an output of 72 megawatts for short bursts lasting about a tenth of a microsecond.

Extensive research and development on the next-generation of linear colliders continues at KEK under the leadership of Professors Yoshitaka Kimura and Koji Takata. In addition to the klystron development mentioned above, this effort includes theoretical analysis of advanced magnetic optics needed to focus particle beams down to sizes smaller than a micron. KEK physicists are also developing ultrahigh-precision alignment systems and focusing magnets to be installed on the Final Focus Test Beam, a major facility now under construction at SLAC that will test these advanced optics and magnet systems using the 50 GeV electron beams available at SLAC. The goal of this project, which is led by SLAC physicist David Burke, and also involves contributions from Europe and the Soviet Union, is to generate beams with dimensions of 60 nanometers by 1 micron.

SUMMARY

OVER THE PAST TWELVE YEARS, high-energy physics research performed under the auspices of the United States/Japan Agreement has run the gamut from fixed-target experiments with electron, proton, and heavy-ion beams to those using colliding beams of electrons or protons with their antiparticles. In addition, there have been extensive efforts devoted to developing sophisticated new technologies for building the particle accelerators, colliders, and detectors needed to do research at the frontiers of this field.

The scientific results of this cooperative research have led to important advances in our understanding of matter. The Standard Model has become the dominant theory of elementary particle physics—against which all high-energy phenomena are compared. Scientists from around the world are now deep in the process of building the SSC to push this theory to its limits in the hopes of catching a glimpse of what lies beyond.

Equally important progress has been achieved in building the infrastructure of organizations and human relationships among the U.S. and Japanese scientists involved in this program—while helping to educate the next generation of high-energy physicists in both countries. As of the end of summer 1991, more than 130 U.S. and 50 Japanese physicists have earned their Ph.D. degrees based on research that was supported by this program. By doing cooperative research for more than a decade, scientists in both countries have developed the mutual understanding and trust that is absolutely necessary to work in the large collaborations that do the most significant research in particle physics today. These partnerships between U.S. and Japanese scientists will form the basis of continued cooperation on future projects at the SSC and on a full-scale linear collider that will likely be built early in the next century.

MESONS AS CARRIERS OF THE NUCLEAR FORCE

THE MESON THEORY started from the extension of the concept of the field of force so as to include the nuclear forces in addition to the gravitational and electromagnetic forces. The necessity of introduction of specific nuclear forces, which could not be reduced to elecromagnetic interactions between charged particles, was realized soon after the discovery of the neutron [1932], which was to be bound strongly to the protons and other neutrons in the atomic nucleus. As pointed out by Wigner, specific nuclear forces between two nucleons, each of which can be either in the neutron state or the proton state, must have a very short range of the order of 10^{-13} cm. . . . .

[In 1934] Fermi developed a theory of beta-decay based on a hypothesis of Pauli, according to which a neutron, for instance, could decay into a proton, an electron, and a neutrino, which was supposed to be a very penetrating neutral particle with a very small mass.

This gave rise, in turn, to the expectation that nuclear forces could be reduced to the exchange of a pair of an electron and a neutrino between two nucleons, just as electromagnetic forces were regarded as due to the exchange of photons between charged particles. It turned out, however, that the nuclear forces thus obtained were much too small, because the beta-decay was a very slow process compared with the supposed rapid exchange of the electric charge responsible for the actual nuclear forces. The idea of the meson field was introduced in 1935 to make up for this gap. . . .

—Hideki Yukawa
Nobel Lecture
December 12, 1949

Ground-Based Gamma Ray Astrophysics

by LESLIE J ROSENBERG

Sensitive ground-based instruments herald a new astronomy based on detecting cosmic gamma rays with energies upwards of a TeV.

THIS ARTICLE IS A SUMMARY OF GROUND-BASED TeV, PeV and EeV gamma ray astrophysics. Photons in this very high energy region of the electromagnetic spectrum are the result of ultra-relativistic processes occurring in the neighborhood of energetic celestial objects; the nature of these processes and the nature of the objects themselves are of keen interest to particle and astrophysicists. This field has recently gained legitimacy with the detection of steady emission of TeV gamma rays from the direction of the Crab nebula. Newer and more sensitive detectors are extending these searches to higher energies.

INTRODUCTION

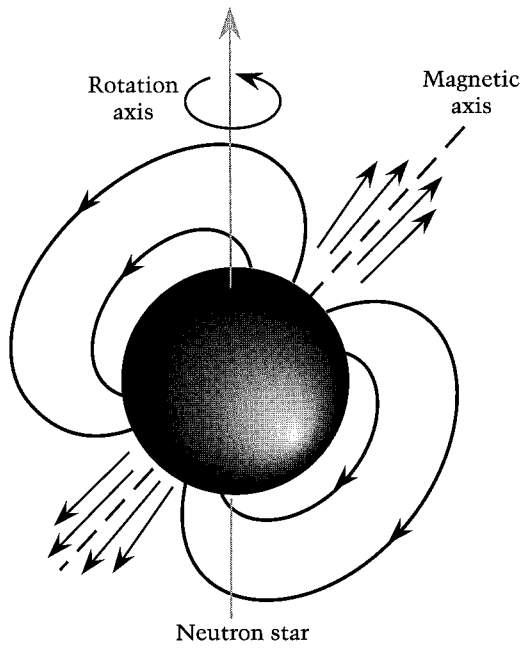
A NEW FIELD, particle astrophysics, has developed in the last decade. This field has undergone tremendous growth, fueled by discoveries as diverse as neutrinos from supernova 1987A, the uniformity and blackbody character of the microwave background, the solar neutrino deficit, and evidence for dark matter from missing mass on the galactic scale. One specialization in this field is the search for cosmic gamma rays with TeV (10^{12} eV) through PeV (10^{15} eV), EeV (10^{18} eV) and greater energies. This is the field of ground-based gamma ray astrophysics. These gamma rays probe conventional astrophysical objects such as pulsars and accreting binary systems; they might be emitted by unusual and exotic objects like evaporating black holes and cosmic superstrings. The production and interactions of these gamma rays extend experimental particle physics to enormously high energies. Accordingly, the researchers in this field are a mix of particle physicists and astrophysicists. The detector technology, though, would be most familiar to particle physicists, with instruments such as calorimeters, Cherenkov counters and tracking chambers.

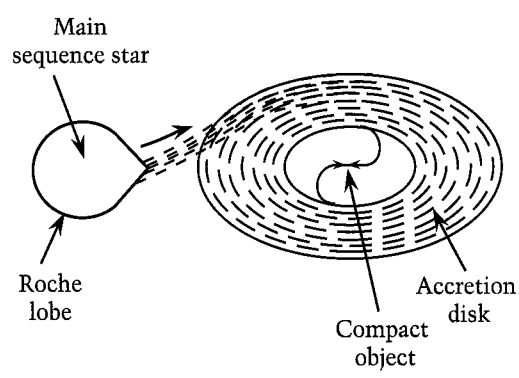
The idea of looking for sources of energetic gamma rays originated with the pioneering experimenters of cosmic ray physics. Interest in the field waned as accelerator-based physics overtook high energy cosmic ray physics in the late 1950s. In the last decade there has been a resurgence of interest in this field, driven perhaps by a sense that there is new physics, beyond the range of present accelerators, apt to be explored with the current and next generation of gamma ray detectors.

I cannot hope to do full justice to the breadth of this field in the space of this one article. More detail may be found in the "Suggestions for Further Reading" at the end of this article.

SOURCES OF TeV AND HIGHER ENERGY GAMMA RAYS

ENERGETIC GAMMA RAYS could arise from interactions of cosmic rays with extended objects (giant molecular clouds, interstellar matter, etc.) or from production near compact objects. Attention centers on compact objects because the gamma radiation is expected to be more intense, and the point-like signal will stand out against the background cosmic rays. One compact source of gamma rays is a rapidly spinning bare neutron star, as illustrated top right. These stars have a large magnetic dipole moment with surface fields of order 10^{12} gauss, and a radius of order 10^6 cm. The neutron star rotation period might be as small as a few milliseconds for very young stars, but periods on the order of seconds are more typical. The spin axis need not coincide with the axis of the magnetic dipole. The spinning $\vec{B}$ field induces an $\vec{E}$ field, which, coupled with the surrounding plasma, is presumed to drive particle acceleration. The radiated electromagnetic power, in characteristic neutron star units, is given by 4×10^{43} erg/s (B^2/P^4), where the magnetic field B is given in units of 10^{12} gauss and the rotation period P is given in milliseconds (ms).





Two possible sources of energetic gamma rays. Top: a bare neutron star; the spin axis is offset from the magnetic dipole axis. Bottom: an accreting binary system; matter from the main sequence star falls onto the compact object, a neutron star or a black hole.

Despite this enormous radiated power, the maximum particle energy is limited. Most models of particle acceleration near pulsars limit the particle energy to $\lesssim 10^{14}$ eV. The Crab Pulsar is a famous example of a bare neutron star. It is about 2 kpc from Earth (1 parsec $\approx 3\times10^{18}$ cm ≈ 3 light years), with mass of $\gtrsim 1.4\ M_{\odot}$ ($M_{\odot}$ is the mass of the Sun). The pulsar period is approximately 33 ms.

Another potential source of gamma rays is an accreting compact binary system, as shown in the bottom sketch on page 11. These objects are composed of a dense neutron star (or black hole) and a normal optical companion. Matter from the normal companion falls onto the compact object, where the temperature of the accreting plasma reaches perhaps 10^7–10^9 K. Here the kinetic energy of the accreting matter is realized in the form of x rays, with perhaps some component radiated as higher energy photons. The maximum steady-state power available from this mechanism is given by the Eddington limit, the output power level at which the outward radiation force on infalling electrons just balances the gravitational force on infalling protons, given by 1.4×10^{38} erg/s$(M/M_{\odot})$, where M is the neutron star mass (this much simplified picture assumes isotropic matter infall and isotropic radiation). Even though the maximum available power from accretion is less than that from fast spinning neutron stars, the coupling of this power to particle acceleration could be more efficient, and the maximum particle energy is greater. Some models of acceleration in accreting systems can generate particles with energies of 10^{16} eV and more. Hercules X-1 is an example of a binary system composed of a neutron star and normal companion. It is about 4 kpc from Earth, with neutron star mass of $\gtrsim 1.4\ M_{\odot}$. There are several x-ray periods associated with this object. There is a 1.24 s rotation period of the neutron star, a 1.7 day orbital period, and a 35 day period possibly associated with neutron star precession or wobble of the accretion disk.

What mechanism couples this power to particle acceleration? The predicted gamma ray energy spectrum from thermal and Compton-synchroton processes dies off beyond about a TeV. Above this energy, true particle acceleration mechanisms come into play, as in energy transfer from moving shock fronts. Understanding these mechanisms is one of the key goals of the field.

Particles that Reveal their Source

Particles that reveal their source are neutral. The few parsec Larmor radius of PeV cosmic rays in the ambient μgauss galactic magnetic field is small compared to the size of the galactic disk, so charged particles lose their source directionality by the time they reach Earth. Of the known neutral particles, only the photon and neutrino (and possibly the neutron at the highest energies) live long enough to survive the journey to Earth.

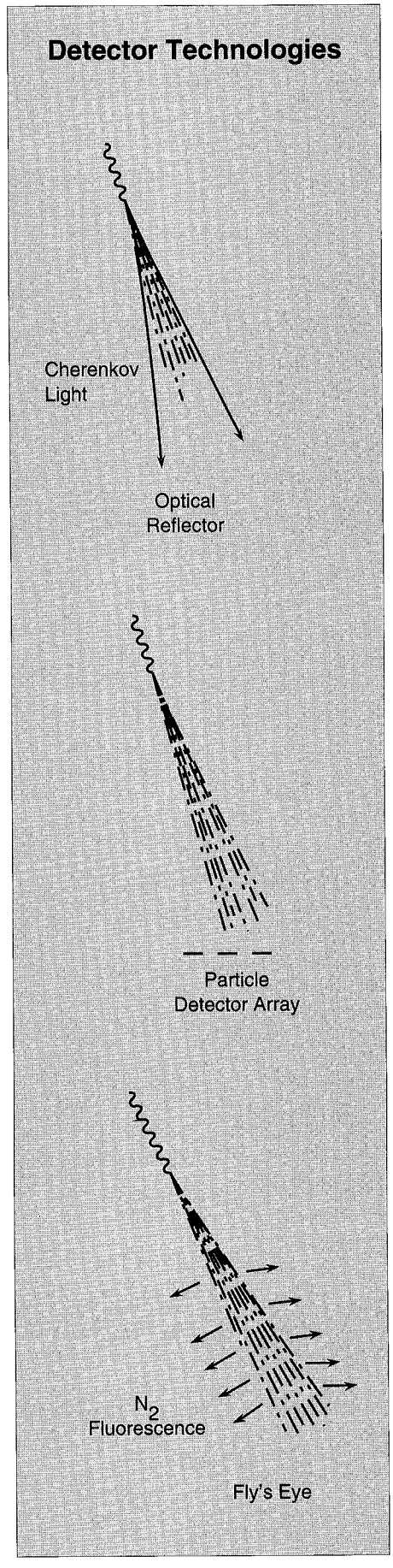
Unlike neutrinos, gamma rays have a short interaction length in the Earth atmosphere. Every energetic gamma ray incident on the atmosphere initiates an Extensive Air Shower (EAS). These air showers are detected with 100% efficiency for initiating gamma rays above some minimum energy. On the other hand, the neutrino detectors record only a small fraction of the incident flux, so all else being equal, their sensitivity to point sources is much poorer. The flux of gamma rays expected from steady-state sources is small, and the number of detected neutrinos will in all likelihood be smaller still. These TeV and more energetic sources will probably be detected initially by gamma ray detectors. Compare for example the expected TeV sensitivity of DUMAND (Deep Underwater Muon and Neutrino Detector) of perhaps 5×10^{10} neutrinos cm^{-2}s^{-1} with the achieved gamma ray TeV sensitivity of better than 5×10^{-12} photons cm^{-2}s^{-1}.

Propagation of Gamma Rays from the Source to the Earth

The gamma rays must escape from matter in the immediate neighborhood of the source, and the attenuation factor accounting for this is unknown. There is always a chance that the obscuring matter is sufficiently thick so that neutrinos may be more powerful than gamma rays for revealing the source. Perhaps this is true for some sources. Nonetheless there are many accreting binaries which emit x rays and MeV gamma rays, so it is reasonable to assume these objects are similarly transparent to photons of higher energy.

Probably more of a worry is the attenuation of gamma rays on the 2.7K microwave background. The gamma rays are absorbed through the process $\gamma + \gamma(2.7\text{K}) \rightarrow e^+e^-$. This absorption is most severe, with an attenuation length of ~ 7 kpc, near

Sketch of three different detector technologies: (Top) at TeV energies, the number of shower particles reaching the ground is small, but Cherenkov light from the shower is abundant; (middle) at PeV energies, many shower particles reach the ground; (bottom) at EeV energies, fluorescence light from the shower dominates scattered Cherenkov light at large impact parameters from the shower axis.



gamma ray energy of 2.5 PeV. This is not a problem for the many reasonably close potential sources, and not a problem at all for detectors with energy thresholds well below the absorption peak at 2.5 PeV. However, there will be significant attenuation of the gamma ray flux from distant sources at higher energies, and PeV gamma ray astronomy is therefore limited solely to the study of galactic sources.

DETECTION OF TeV, PeV, AND EeV GAMMA RAYS

FOR THE PURPOSES of gamma ray interactions, the atmosphere may be considered flat, with a $1/e$ pressure scale length about 8 km.There are no peculiar properties of the atmosphere up to altitudes of several tens of km where air showers start. One radiation length of sea level air is about 37 g/cm^2, and the critical energy is 84 MeV.

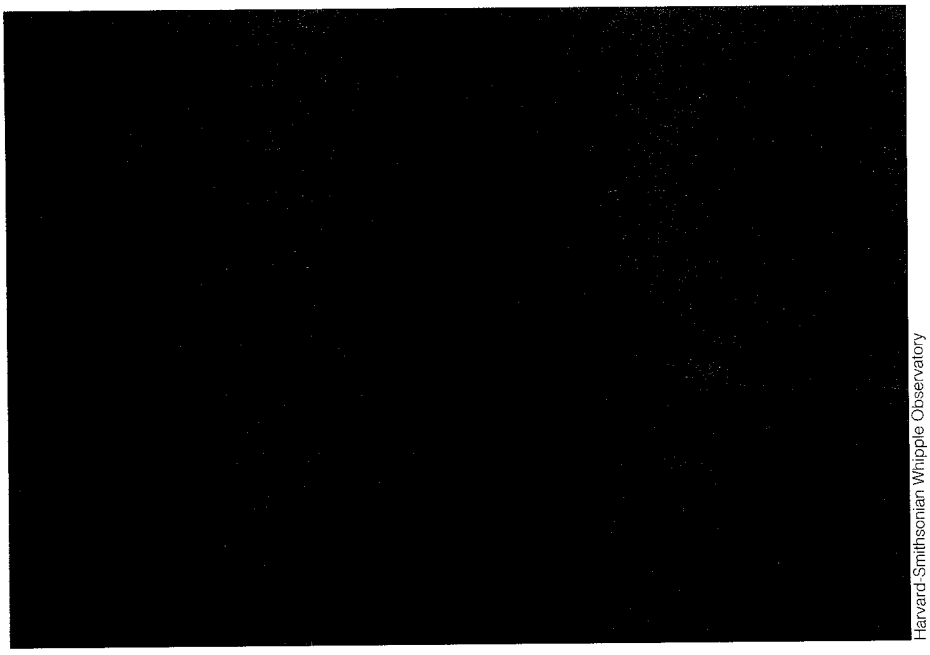
An incident gamma ray strikes the atmosphere, producing an e^+e^- pair, which in turn radiate additional gamma rays, a multiplicative process continuing until the energies of the electromagnetic particles in the shower are below the critical energy of air. At this point, the energy losses are dominated by atomic processes, and the shower slowly dies out. Direct detection of particles in sub 100 TeV gamma ray-induced showers is difficult in present detectors, as too few electrons and positrons strike the ground.

There is an isotropic background of mostly hadronic cosmic rays. The problems inherent is seeking discrete sources in this enormous background have been compared with attempting optical astronomy in the daytime. Many methods have been proposed for revealing point source and gamma ray-induced showers. The most obvious is to improve the instrument angular resolution or phase lock the arrival time of showers to known lower energy periodicity of an object. A powerful though unproven technique at PeV energies exploits the low relative muon content of gamma ray-induced showers (where background rejection factors of 10^{-2} are expected). A proven technique at TeV energies exploits the shape differences between the Cherenkov light footprint of electromagnetic and hadronic-induced showers (where background rejection factors of at least 10^{-2} have been achieved).

The operation of the three common detector technologies, Cherenkov detectors, EAS arrays, and N_2 fluorescence, is shown on the right, and together they span the cosmic ray range from sub TeV to above 100 EeV. Other technologies, such as large-area water Cherenkov detectors and tracking chambers, are proposed for the next round of gamma ray experiments.

Cherenkov Light Detectors

This technique is useful from sub TeV incident particle energy through perhaps 10 TeV, where the dwindling source flux becomes too small for the collection area and limited observation time. These detectors work best on dark moonless nights and isolated locations free of city lights, and the live time is reduced accordingly. A typical year-long study of a single source (and these



Harvard-Smithsonian Whipple Observatory

The Cherenkov detector of the Whipple Observatory Collaboration. The mirror, 10 m across, focuses light on a cluster of 109 photomultiplier tubes. (Photo courtesy of Trevor C. Weekes.)

Whipple Collaboration

Iowa State University
University of Leeds *(Leeds, UK)*
University of Michigan
Purdue University
St. Patrick's College *(Maynooth, Ireland)*
University College *(Dublin, Ireland)*
Whipple Observatory, Harvard-Smithsonian Center for Astrophysics

detectors view just one object at a time) yields perhaps 100 hours of observation time.

In a typical Cherenkov detector, the face of a bare photomultiplier tube (PMT) is placed in the image plane of a mirror, the assembly pointed into the night sky. The PMT dark current is 10^3–10^4 photoelectrons/s from a typical photocathode, increasing to ~10^8 photoelectrons/s when aimed at the night sky. Although this photomultiplier tube's signal resembles an alarming light leak, most counts with pulse heights greater than 20 photoelectrons are registered by atmospheric Cherenkov light. The Cherenkov light strikes the ground in a patch of some 100 m in radius, for a large area of about 3×10^4 m^2 from a single device.

An advantage of the Cherenkov technique is that the energy of the incident primary is determined in a calorimetric way, as Cherenkov light yield is related in a well-understood way to the total charged-particle track length in the shower, which is in turn simply related to the incident gamma ray energy.

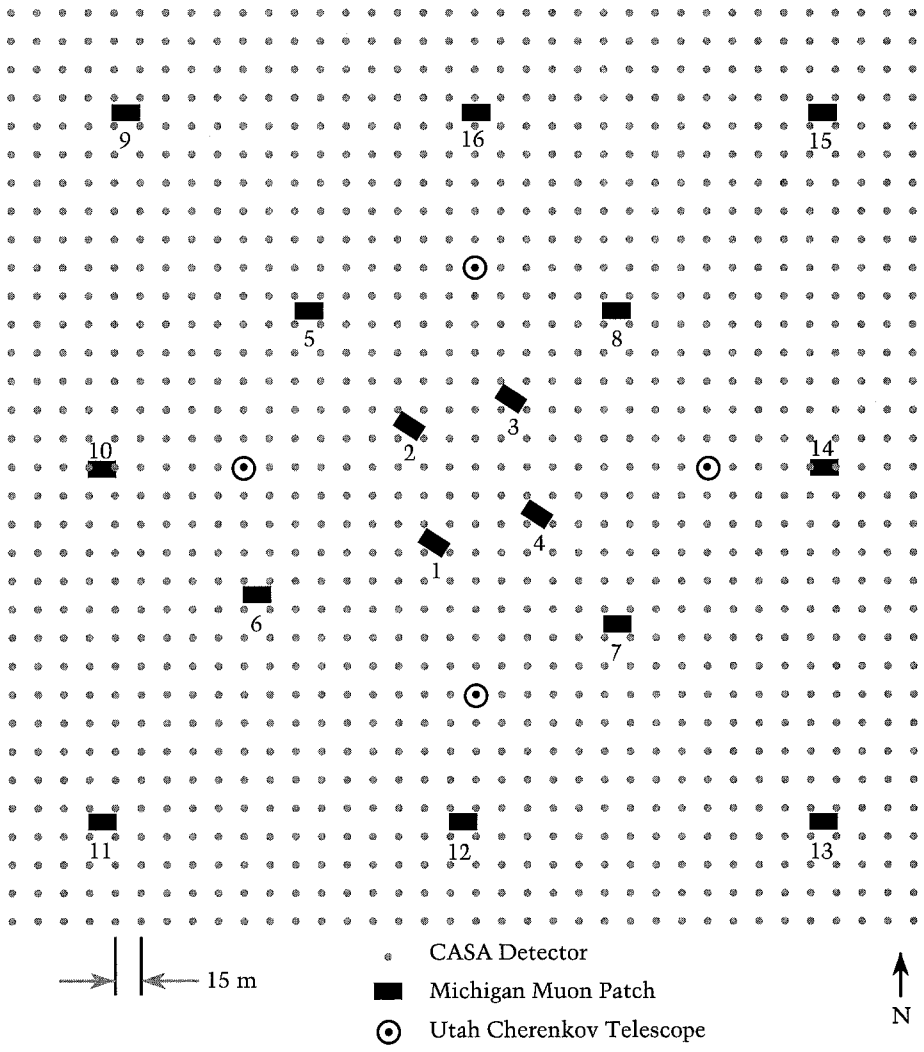
The most successful TeV detector, the Cherenkov telescope of the Whipple Observatory Collaboration, is shown in the photograph on this page. This is an imaging detector, where a 10 m mirror focuses light on a cluster of 109 photomultiplier tubes. The total field of view is 3.5° across. Larger photomultiplier tubes on the periphery have a 0.5° field of view, and smaller PMTs near the center have a 0.25° field of view. This imaging capability proves extremely powerful in differentiating, according to event shape, gamma-ray induced showers from background hadron-induced showers. The angular resolution is approaching the arcminute level, which is a record for gamma ray astronomy in any energy range

Surface Arrays

Surface arrays are used to study gamma rays of energy upwards of approximately 100 TeV, energies where an appreciable remnant of the shower reaches the Earth's surface. For distances reasonably close to the shower core, the "pancake" of particles forms a sharp timing front. It is this sharp front that allows reconstruction of the shower direction from differences between arrival times at various points of the shower. The lateral extent of the shower is related to the Molière radius in air, some 80 m at sea level.

The typical surface array measures time-of-arrival differences between many points near the shower core. Each time difference is simply related to a direction cosine of the shower arrival direction, and the ensemble of many direction cosines provides a space angle resolution of better than 1°.

Surface arrays are rather poor at determining the incident particle



Schematic aerial view of the CASA experiment. Each dot represents a scintillator station of the array. The scintillator stations are 15 m apart. The boxes represent underground muon detectors. The circles represent Cherenkov telescopes.

energy since, unlike the calorimetric measurements possible with Cherenkov and nitrogen fluorescence detectors, the shower development is sampled at just one depth. Therefore, the type of incident particle and fluctuations in shower development have an adverse effect on determining the incident particle energy for a specific shower. The mean incident particle energy of many showers is limited by uncertainties in modeling the initial stages of shower development at high energies.

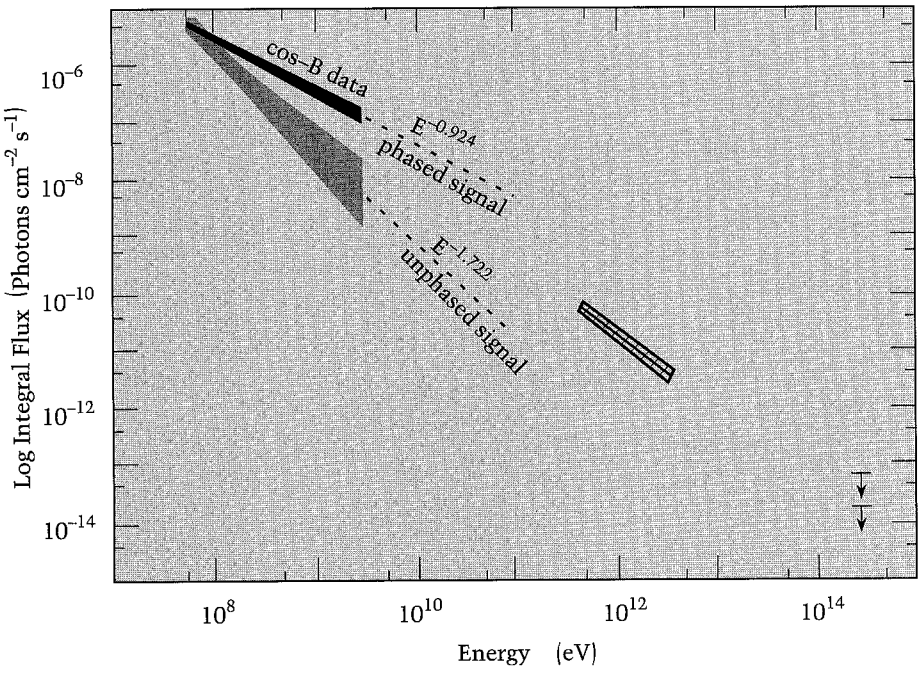
There are many shower arrays searching for sources of PeV gamma rays. Of these, the CASA detector is the largest and most sensitive. It was built by a collaboration of physicists from the Universities of Chicago, Michigan, and Utah. The CASA experiment consists of 1089 scintillator stations, each containing 1.5 m^2 of active area, distributed on a square 15 m grid, for a total enclosed area of 2.3×10^5 m^2. The angular resolution is better than 1° for most events. The illustration above right shows the scintillator stations as dots. The boxes are patches of muon counters, of total area 2500 m^2, buried 3 m beneath the ground. The circles represent four Cherenkov telescopes, used to cross-calibrate the pointing accuracy and energy response of the array. The trigger rate is nearly 10^9 events/year at a cosmic ray energy threshold somewhat below 10^{14} eV.

Atmospheric Fluorescence

This technique, useful from around 10^{17} eV through the highest energies, relies on the fluorescence of air molecules, mostly N_2 and N_2^+, excited by the nearby passage of relativistic particles in the air shower. The N_2 $2p$ and the N_2^+ $1n$ band systems may de-excite by isotropically emitting optical photons. The light-yield efficiency (the total energy released as optical photons normalized to the energy released in the shower) is quite poor, around 0.005. However, the energy released in an EAS initiated by an energetic primary is large (a shower induced by a primary of 100 EeV releases on the order of 1 Joule in 20 μs) and can be thought of as a 5 watt blue light bulb flying by at the speed of light.

The fluorescence light is viewed at large impact parameters, perhaps 2–20 km, so the effective active area of a single detector is therefore enormous, 10^3–10^4 km^2 steradian. The Cherenkov light emitted by the shower is approximately 100 times greater, but is beamed forward, away from the viewer. For cosmic rays of EeV energies, the light output from N_2 fluorescence in the atmosphere excited by the EAS exceeds the output of the scattered Cherenkov light at large angles to the axis of the shower. However, Cherenkov light scattered at large angles still makes up a non-negligible fraction of the light reaching the observer. Other backgrounds include scattered starlight, diffuse galactic radiation, subthreshold stars, other galaxies, intergalactic matter, photochemical processes in the atmosphere, airplanes, smokestack strobe lights, meteors, fireflies, etc.

Like the Cherenkov detectors, the experiments work best on dark moonless nights, so the fractional



The integral flux of photons from the direction of the Crab nebula. The flux measured by the Whipple Collaboration is indicated as the cross-hatched line near 1 TeV. Also shown to the left is the unphased and 33 ms phased (solid colors) photon flux from satellite observations at lower energies. There is no evidence in the Whipple data for the 33 ms pulsar periodicity. In the lower right corner are recent 90% upper confidence limits on the unphased Crab nebula photon flux reported by the CASA group. The higher limit is for all data; the lower limit is from events with low muon content [Adapted from G. Vacanti et al., Astrophys. J. ***377****, 467 (1991).]*

live time is small, about 5% to 10%. But unlike the Cherenkov instruments, a large fraction of the 2π steradian of the night sky is under view.

These detectors are able to reconstruct much of the longitudinal development of a shower. From this, and the known electron dE/dX in air, the energy of the incident primary is determined in a calorimetric sense, independent of the worst aspects of Monte Carlo shower simulation.

The University of Utah's Fly's Eye Detector is the only 2π steradian atmospheric fluorescence detector in operation. It is located in Utah (one of the Fly's Eye installations is located at the center of the CASA experiment). The newer Fly's Eye II 36 mirror detector at the center of the CASA experiment contains a total of 464 photomultiplier tubes. The projection of the hexagonal light cones into the night sky resembles the compound eye of a fly, and hence the name of the experiment. A cosmic ray track appears to the Fly's Eye as a great circle on the celestial sphere. The Fly's Eye observes some 20 cosmic ray events/year with energy above 10 EeV. Just the pattern of photomultiplier tubes hits recorded from a single shower is sufficient information for reconstructing the shower-detector plane. Adding photomultiplier tubes timing information allows full reconstruction of the track geometry, including the point of shower maximum. The original Fly's Eye I detector is 3.3 km away, allowing stereo reconstruction of the track geometry, including the depth of shower maximum, from just the pattern of the combined photomultiplier tubes hits in the two devices.

TeV GAMMA RAYS FROM THE DIRECTION OF THE CRAB NEBULA

THE MOST CONVINCING detection of TeV gamma rays makes use of the Cherenkov telescope of the Whipple Observatory Collaboration. When they pointed their instrument in the direction of the Crab nebula, they found a 5σ excess of showers relative to background. When they then select those showers having the expected gamma ray-like light pattern, the significance of the excess rises to 20σ. They give a gamma ray flux of $N(E)\,dE = 2.5\times10^{-10}(E/0.4\text{TeV})^{-2.4\pm0.3}$ photons cm^{-2}s^{-1} TeV^{-1}. The integral form of this flux (the total flux above some energy) is indicated in the illustration above left as the cross-hatched line near 1 TeV. Also shown to the left is the unphased and 33 ms phased photon flux from satellite observations at lower energies. There is no evidence in the Whipple data for the 33 ms pulsar periodicity. That their cuts so dramatically improve the significance of their observation supports the hypothesis that the particles from the direction of the Crab nebula are in fact gamma rays.

Further, the Whipple Collaboration finds a significant excess from the direction of the Crab nebula in all their data samples taken at widely separated times. The Crab nebula is now the "standard candle" of TeV gamma ray astrophysics. Does this form of the spectrum continue to higher energies? Theorists anticipate that the spectrum cuts off below a PeV. At the lower right corner of the illustration on the preceding page are recent 90% upper confidence limits on the unphased Crab nebula photon flux reported by the CASA group. The higher limit is for all data; the lower limit is from events with low muon content. These limits on the PeV gamma ray flux are approaching the extrapolated TeV photon flux. After several years of operation, the CASA sensitivity will be better than 10^{-14} photons $cm^{-2}s^{-1}$, and we will know whether or not the spectrum continues.

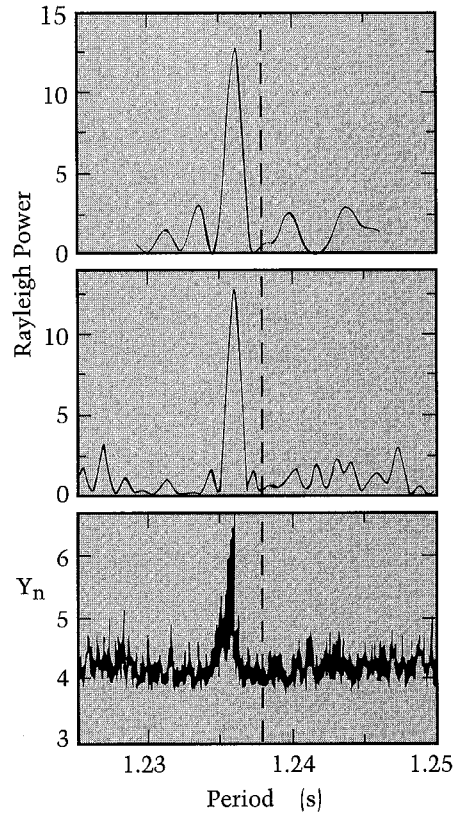
ARE THERE OTHER SOURCES OF GAMMA RAYS WITH ENERGY UPWARDS OF 1 TeV?

THERE ARE MANY REPORTS of episodic emission of TeV through EeV cosmic rays from a variety of other objects. These reports all suffer from problems of marginal statistics or lack of confirmation, or they demand implausible new physics. Although Cygnus X-3 is perhaps the most notorious of these objects, I highlight reports of episodic TeV and PeV emission from Hercules X-1 (Her X-1) because I consider its case more interesting.

The illustration at the right shows frequency amplitudes (from the shower arrival times corrected for the motion of the Earth around the Sun) of Her X-1 data from three experiments. The upper plot is from the Haleakala experiment, a TeV Cherenkov detector; these data are from a 15 min burst occurring on May 13, 1986. The middle plot is TeV data from the Whipple Cherenkov telescope; these data are from a 25 min burst on June 11, 1986. The lower plot is PeV data from the CYGNUS air shower experiment; these data are from two 30 min bursts on July 24, 1986. The dashed line is the measured x-ray pulsar period of 1.2378 s, which contrasts with the value measured by these three experiments of 1.2357 s.

The Whipple Collaboration then applied their gamma ray selection to the Her X-1 data. Since their cuts selectively remove hadronic background, the significance of a gamma ray signal is expected to increase. Quite surprisingly, the opposite occurred for this data sample, and all their previous Her X-1 data samples.

The CYGNUS experiment at the time relied on multiwire proportional chambers for muon detection. The events from Her X-1 are expected to be gamma rays and hence muon poor. With the 11 events in the phase peak, they predict a background contamination of 0.13 events. From this background combined with accidentals, they expect 2 detected muons from the 11 events. In fact, they detect at least 62 muons. This is also surprising. As a consistency check, they detect 40 muons from an ensemble of background events selected to be otherwise similar in



The possible episodic observation of Hercules X-1 plotted in the frequency domain. The upper plot is from a 15 minute burst on May 13, 1986, observed by the Haleakala TeV Cherenkov experiment. The middle plot is from a 25 minute burst on June 11, 1986, observed by the Whipple TeV Cherenkov experiment. The lower plot is from two 30 minute bursts on July 24, 1986, observed by the CYGNUS PeV experiment. The peak frequency power, at a period 1.2357 s is displaced from the x-ray period 1.2378 s. The signal events observed by the Whipple and CYGNUS experiments have a hadronic character. (Reproduced with permission from the Annual Review of Nuclear and Particle Science, Vol. 38, © 1988 by Annual Reviews Inc.)

character to the 11 events in the phase peak.

There are suggestions that the unexpected effect of gamma ray selection on the Whipple data, and the surprisingly high muon content in the CYGNUS experiment, could be due to an increase in the hadron content of photons at high energies, an effect allowed by the standard model. However, the expected size of this effect should not provide nearly enough of an increase in the hadron content, although this conclusion can be tested soon with HERA data. There are other suggestions that these observations are attributable to an undiscovered particle. To account for the surprising aspects of the data, this particle must be stable, neutral, relatively light (preserving pulsar phase coherence), and act hadron-like with regard to muon production. It is hard to believe that such a particle would go undiscovered in accelerator experiments. The demand for this implausible new particle forces me to question the elevation of Her X-1 to the status of established episodic source.

THE FUTURE

THERE IS ONE CONVINCING source of TeV gamma rays, from the direction of the Crab Nebula, observed with greatest significance by the Whipple Collaboration. Further, these events have the expected photon-like behavior. There are no other absolutely convincing TeV or higher energy observations. There are many less convincing cases for other sources. For example Her X-1 is reported to be an episodic source, although the hadron-like character of the signal is worrisome.

A major goal of gamma ray astrophysics over the next several years is expanding the catalog of TeV sources and the discovery of convincing PeV sources. In particular, should the gamma ray spectrum from the direction of the Crab nebula not cut off below a PeV, surface arrays should be sensitive enough to observe the Crab in a few years. There are plans for many new detectors (improved Cherenkov telescopes, a high-resolution Fly's Eye, particle-tracking surface arrays, water Cherenkov, and ever larger scintillator surface arrays) to exploit the recent discovery of TeV sources, and the hoped for discovery of PeV and higher energy sources. Many of these planned detectors have good sensitivity to gamma rays from TeV through PeV energies, filling the gap in the electromagnetic spectrum between the TeV "standard candle" of the Crab and relative silence at a PeV.

Suggestions for Further Reading

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Thomas K. Gaisser, "Gamma Rays and Neutrinos as Clues to the Origin of High Energy Cosmic Rays," *Science* **247**, 1049 (1990).

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THE SDC DETECTOR

by LAURA P. BAUTZ
and
GEORGE H. TRILLING

One of the proposed SSC detector designs is described.

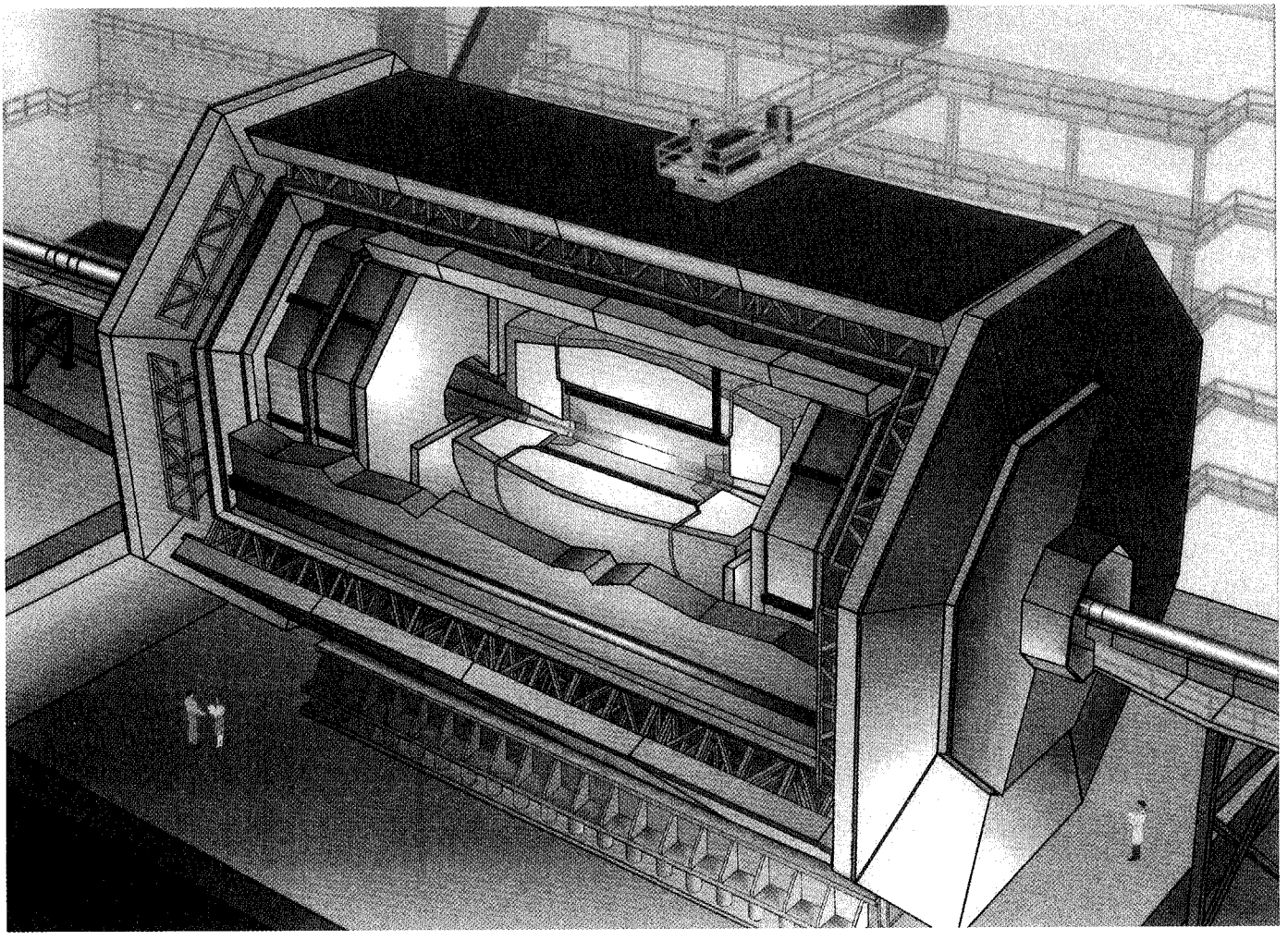
IN AN EXCELLENT ARTICLE published in the Summer 1991 issue of the *Beam Line* ("Why Are We Building The SSC?), Michael Riordan provided a detailed description of many of the physics motivations for building the Superconducting Super Collider (SSC). The pursuit of these new physics directions requires the design and construction of detectors of power and sophistication well beyond our past experience. Indeed it is sometimes said that in electron-positron physics the major challenge is the collider, with the detector being straightforward, whereas in hadron physics the major challenge is the detector, with the collider being straightforward. While it is a gross oversimplification to suggest that either a hadron collider (such as the SSC) or a detector for a large e^+e^-

collider is "straightforward," there is a germ of truth in the above comment. The extraordinary challenge for an SSC detector is to identify with high and measurable efficiency interesting but extremely rare events in an ocean of uninteresting background. To give but one example, the identifiable Higgs events that one might look for are expected at the rate of one such event in about 10^{13} (!) normal events. In this article we describe briefly the design of such a detector proposed by the SDC (see illustration on the next page).

THE INITIALS SDC stand for the Solenoidal Detector Collaboration, a group of over 700 physicists and engineers from around the world who are working together to design and build the detector. This seems like a large group, but the detector challenges are correspondingly large, and many of the group are also involved part-time in ongoing particle physics experiments. The collaboration grew out of several initially independent efforts in the United States and in Japan aimed at designing a detector with broad capabilities for the SSC. The SDC currently includes collaborators from the United States, Japan, countries of the Commonwealth of Independent States, France, Italy, the United Kingdom, Canada, the Peoples Republic of China, Bulgaria, Czechoslovakia, Romania, Israel, and Brazil. In the United States, about 50 groups from national laboratories and universities are participating. The collaboration has been growing continuously since it was formed in 1989 and further growth is likely.

The SSC will provide counter-rotating beams of protons with energies of 20 TeV each and a design luminosity of $10^{33}\text{cm}^{-2}\text{sec}^{-1}$. These figures represent a 20-fold increase over presently available energies and a 1000-fold increase over present luminosities. As described in Riordan's article, these properties open a whole range of new opportunities for physics discovery, including the Higgs boson or bosons, new spectroscopies such as supersymmetry, new massive gauge bosons, and searches for effects of compositeness. While the top quark may have already been discovered at Fermilab by SSC turn-on, study of its decay properties will greatly benefit from the high statistics available at the SSC. Furthermore, there are likely to be discoveries totally unrelated to the specific theoretical directions presently in fashion. Simulations of searches for the phenomena suggested by the Standard Model or its proposed extensions are providing guidance to the design of the detector subsystems to ensure that these phenomena will be convincingly detectable. Doing this for a sufficiently broad array of processes gives confidence that the detector will be sufficiently powerful for the discovery of entirely new phenomena. The power of the SDC detector derives from its multiple capabilities which permit the measurement of a large number of independent quantities for each trigger event and also the observation of interesting processes through several independent signatures. When combined, these redundant elements of information should provide the ability to establish, rather than just suggest, new unexpected phenomena even in the presence of the high backgrounds anticipated at the SSC.

THE GENERAL LAYOUT of the SDC detector is shown schematically on page 22. The name "solenoidal detector" refers to a large cylindrical volume (1.7 m radius by 8 m length), concentric with the beam, and surrounded by a superconducting solenoid coil that produces a magnetic field of 2T. This volume is filled with tracking detectors that record the passage of charged particles coming from the interaction region. The magnetic field of the solenoid deflects these particles, allowing precise measurements of their momenta, directions and signs of charge. This tracking system can measure particles emitted over the angular interval between 10 and 170 degrees relative to the beam, an interval much larger than what we are accustomed to in detectors for e^+e^- colliders. This choice reflects the fact that, in hadron collisions, a significant fraction of the interesting physics occurs at relatively small angles. Outside of the solenoid and tracking volume, there is an hermetic central calorimeter providing total energy measurements for electrons, photons, and hadron jets. Great care is exercised to make the solenoid coil as thin as possible to minimize degradation of the calorimeter measurements. The calorimeter includes a special "shower-maximum" detector that provides high-resolution position information on electromagnetic showers. By connecting this information to charged-particle tracking measurements, one can identify electrons with high efficiency and excellent rejection of background. The central calorimeter measures particles emitted between 6 and 174 degrees relative to the

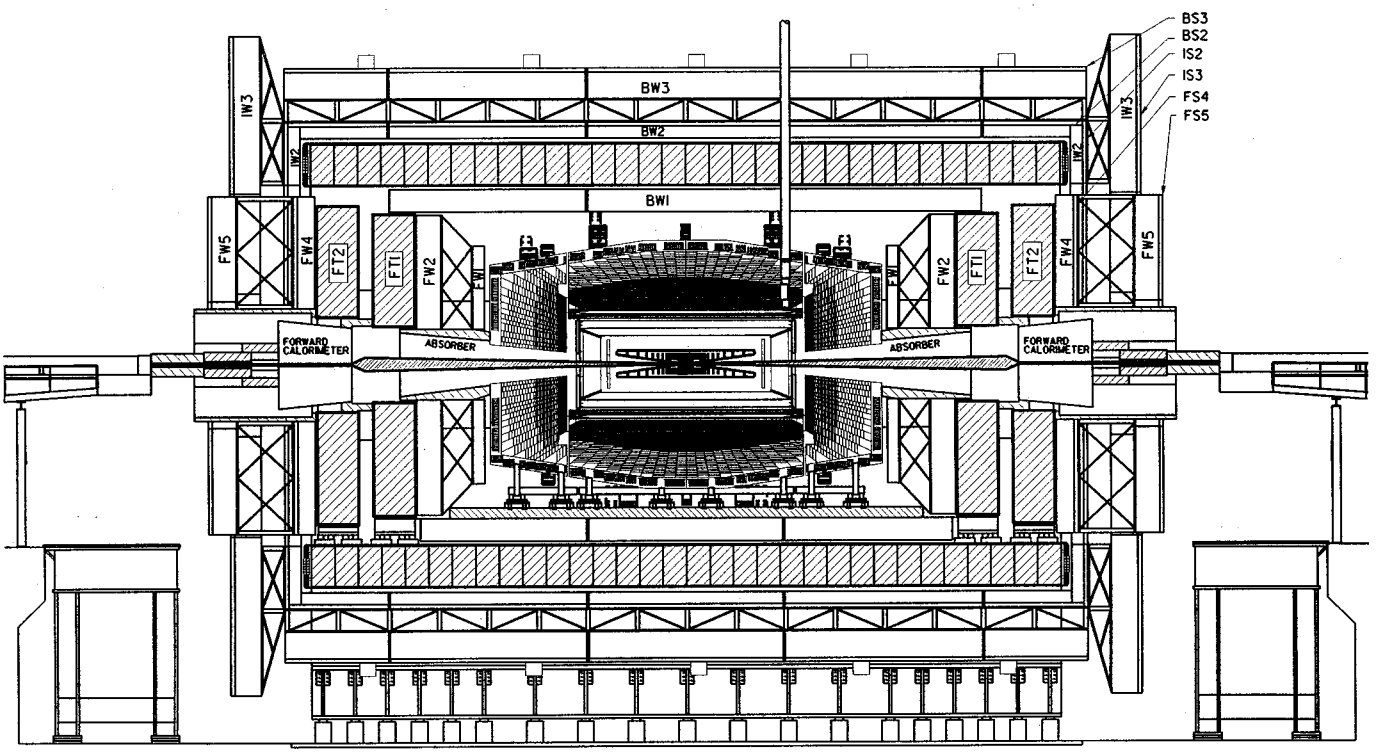


Artist's rendition of the proposed SDC detector at the Superconducting Supercollider (SSC).

beam. This coverage for calorimetry is extended down to 0.5 degrees and up to 179.5 degrees with two forward calorimeters, allowing the detection of neutrinos or perhaps new non-interacting neutral particles through apparent violation of transverse momentum balance. Finally, on the outside of the central calorimeter there is an extensive system for identifying and triggering on muons emitted within the same 10 to 170 degree interval already discussed in connection with the tracking system.

In the initial design process, several possible candidate technologies were considered for many of the subsystems. Over the course of the past two years, R&D and engineering design efforts funded through the SSC Laboratory (SSCL) have provided sound technical bases for making technological decisions or at least reducing the numbers of options under consideration. The criteria for choosing particular technologies include feasibility, adequacy of performance, survivability in a high radiation environment, acceptable technical risk, affordable cost, and the interest of SDC members to build with the chosen technology. In a few areas, final technological decisions are still deferred until further R&D efforts are completed.

WE NOW GIVE A FEW MORE details on the subsystems. The tracking system includes inner (radius below 50 cm) and outer (radius between 50 cm and 1.7 m) sections. The inner silicon-strip section consists of a set of cylinders concentric to the beam for large-angle tracks and a set of circular disks perpendicular to the beam for measuring tracks emitted at small angles. The silicon detectors have strips on both surfaces



Elevation view of the SDC detector. The dark structure near the center is the silicon tracking system. The labels BW, IW, and FW refer to various muon tracking systems, and BS, IS, FS to muon scintillation counter systems (B=barrel, I=intermediate, F=forward).

to provide maximum information for the least amount of material in the tracking volume. The 17-square-meter area of the proposed SDC silicon system dwarfs all existing silicon strip tracking detectors. This system will provide excellent pattern recognition, even within very complex events, partial momentum information, and detection of heavy quark decays through high-resolution vertex reconstruction. Silicon pixel detectors are under development and, if successful and affordable, will replace the two inner layers of silicon strips. A major challenge for this large silicon system will be the maintenance of few-micron tolerances while removing heat produced by several kilowatts of electronics power.

For the outer tracking section, several technologies are still under consideration. The most conservative is a drift chamber consisting of multiple layers of 4-mm-diameter gas-filled "straws" with wires running down their axes, these axes being parallel or at a small angle to the beam. Under development are "gas-microstrip" detectors (which in some sense are a cross between drift chambers and silicon-strip detectors); these may be particularly applicable to the difficult angular region between 10 and 26 degrees relative to the beam. Also under development are scintillating-fiber tracking detectors. The fibers, 1 mm in diameter, have the advantages of high speed (no drift to wait for) and excellent granularity. The proposed readout is a fast and efficient solid-state device, the Visible Light Photon Counter (VLPC), under development by the Rockwell Corporation. The final technology choices for outer tracking will depend on the outcome of continuing R&D and engineering efforts.

The central calorimetry technology chosen by the SDC (see illustration above) consists of tiles made from plastic scintillator with wavelength-shifting fibers imbedded in grooves in the tiles. These fibers are spliced to clear fibers that carry the signal photons to phototubes. The advantage of this design is that the dead space can be made very small. The scintillator tiles are sandwiched between layers of absorbers,

which are thin lead in the electromagnetic sections and thicker iron in the hadronic sections. An elaborate calibration system is necessary to monitor performance and provide correction capability in case of radiation damage to the scintillator. Since radiation damage is a particular concern, there is an extensive international program, using electron beam facilities in China, France, and Japan, to study the effects of radiation exposure on the performance of tile/fiber electromagnetic calorimeters.

The muon system consists of magnetized iron toroids and enormous areas of tracking chambers and scintillation counters. The toroids and tracking chambers provide a second momentum measurement independent of the central tracking system, for muon identification and also for trigger information. The scintillation counters are used to identify the beam crossing with which the muon-tracking information is associated. If further study suggests excessive backgrounds at small angles to the beam, Cherenkov counters may be added near the forward direction.

In order to read out the relevant information from all the subsystems, several electronics systems are being developed, including front-end electronics, the three-level trigger system, the data-acquisition system, and the control system. The overall event rate (10^8 per second at design luminosity, and more if the luminosity is raised) provides a daunting challenge, especially in triggering on only a small fraction of the interactions, with well-understood efficiency and with no losses of potentially interesting events.

All subsystems are planned to be fully functional at the design luminosity of $10^{33}cm^{-2}sec^{-1}$. With some modifications and somewhat reduced functionality, the detector will also be capable of attacking specialized physics problems which require higher luminosity. It is part of the design criteria that the detector components be able to survive operation at 5–10 times design luminosity for long periods, and that there be sufficient monitoring capability to allow correction for potential radiation-damage effects.

The SDC detector will, according to present plans, be installed in an underground hall at Intersection Region 8 on the East Campus of the SSC Laboratory. In as much as possible, subsystems will be assembled above ground and lowered into the hall through shafts. According to detailed month-by-month CAD simulations, the installation and initial checkout will take about three years after occupancy of the hall. It is the SDC's aim to have its detector ready for physics operation when the SSC turns on.

IN SUMMARY, the Solenoidal Detector Collaboration is proceeding well toward the design of a large and powerful detector for the SSC. It submitted its Technical Design Report to the SSC Laboratory on April 1, 1992, and hopes to initiate construction by the end of 1992. The fabrication of the SDC detector will require a major investment of effort from the international high-energy physics community over the coming decade. The anticipated physics rewards from exploration of an entirely new domain of energy and luminosity should amply justify this effort.

DETECTOR SCHEDULE

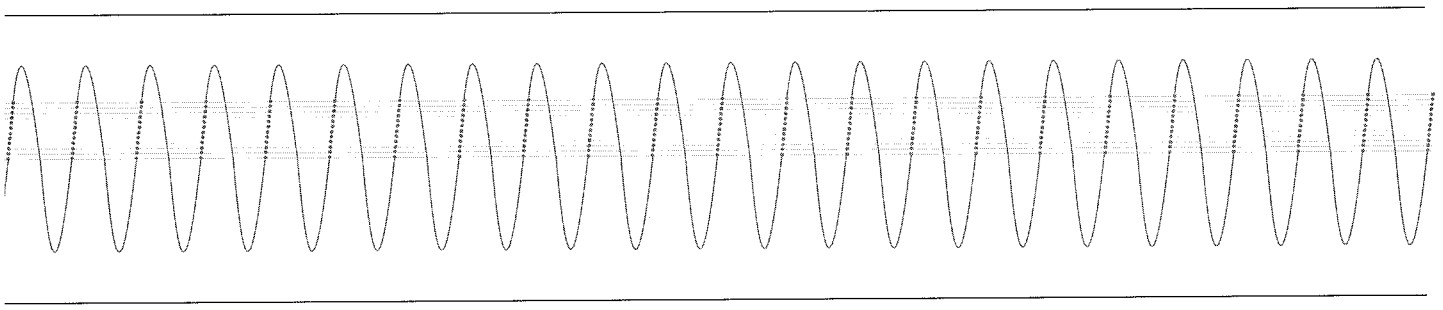
AS STATED IN THE ARTICLE, the SDC submitted its Technical Design Report (TDR) to the SSC Laboratory on April 1, 1992. Accompanying the TDR are other documents including a Draft Project Management Plan and a Cost/Schedule Summary. An Experimental Facilities Users Requirements Report describing the required underground and surface facilities for the SDC detector has been prepared by the SSCL Physics Research Division and approved for initiation of detailed design. The SDC Project will be reviewed in depth by the SSCL Program Advisory Committee, SSCL staff, and consultants during May 4–9, 1992. The review will particularly focus on physics and technical issues. Issues raised at the May Review, and the SDC's responses to them, will be further considered by the PAC at its Summer meeting in July. A DOE cost/schedule/management review is scheduled for mid-September 1992. Over this same period, the assignment of responsibilities, the development of subsystem organizations, and the formulation of a detailed funding plan will be taking place. The SDC hopes to initiate construction in early 1993, commence installation of detector components into the underground hall in 1996, and begin commissioning in early 1999. Physics operation is scheduled to start near the end of calendar year 1999.

A 500 GeV S-Band Linear Collider Based on SLAC Technology

by GUS VOSS and THOMAS WEILAND

Physicists at the Deutsches Elektronen Synchrotron laboratory (DESY) in Hamburg are developing a design for a large electron-positron linear collider.

ELECTRON-POSITRON ACCELERATORS HAVE PROVEN to be an excellent tool for high energy physics. Because of synchrotron radiation losses, the energy of circular e^+e^- accelerators can not be significantly increased beyond the energy range of LEP II, which is designed for 200 GeV center of mass. Today the only known way to reach center-of-mass energies of 500 GeV or more is with linear colliders. A linear collider consists of two opposing linear accelerators, one accelerating electrons, the other positrons. With an almost straight beam path, such an accelerator does not suffer from the synchrotron radiation losses mentioned above. In principle, there is no obvious reason why such an accelerator should not be able to produce e^+e^- collisions in the TeV range. Compared to seemingly simpler proton accelerators, which can achieve energies in the multi-TeV range, e^+e^- physics has a number of advantages in the kinds of high energy physics experiments that can be carried out.



The overall length of a linear collider is approximately given by the ratio of the desired collision energy to the accelerating gradient in the linear accelerator. Thus a 1 TeV linear collider 10 km long would require a gradient of 100 MeV per meter. The fact that high gradients were thought to be essential for this type of machine was considered to be the major issue in the late 70s and early 80s. Numerous ideas have been published on new methods for obtaining these high gradients: laser accelerators, laser-plasma accelerators, wake-field accelerators, two-beam accelerators, inverse free-electron lasers, and many more. During the years from 1980 to 1990 some experimental work was done on high gradients at various laboratories. While in the early '80s it was quite uncertain whether gradients in the order of 100 MeV/m could be reached, experiments by Juwen Wang and Greg Loew at Stanford Linear Accelerator Center (SLAC) did show that it was relatively easy to reach even several hundred MeV/m in "normal" copper structures.

Most of the new ideas described above have now been shown to be impractical for various reasons. The most important reason is that laser, plasma, and wake-field accelerators all have efficiencies that are too low to provide gradients at an affordable power consumption.

After the initial work had focused on achieving high gradients no matter at what cost, later research has concentrated more on the design of a complete linear collider, and specifically on minimizing the total power consumption.

Initially the operating mode envisaged was identical to the one now used at the SLAC Linear Collider (SLC), where with each pulse of radio-frequency power one bunch of electrons and one bunch of positrons are accelerated and brought to collision. In this operating mode the energy efficiency is a real problem. An upper limit is given by the acceptable energy spread in the bunch, which is of the order of a few percent only. Thus the total stored energy in one rf pulse is a very important quantity. After each shot the remainder of this energy is completely lost.

An obvious way to reduce the stored energy is to make the linac smaller in diameter, which in turn means increasing the operating frequency. (The operating frequency of the present SLAC accelerator is about 3 GHz, which is also known as "S-band.") Not only do higher frequency structures reduce the stored energy, they also have the advantage of increasing, in principle, the shunt impedance (the quantity which measures the effectiveness of producing an accelerating field from a given rf input power).

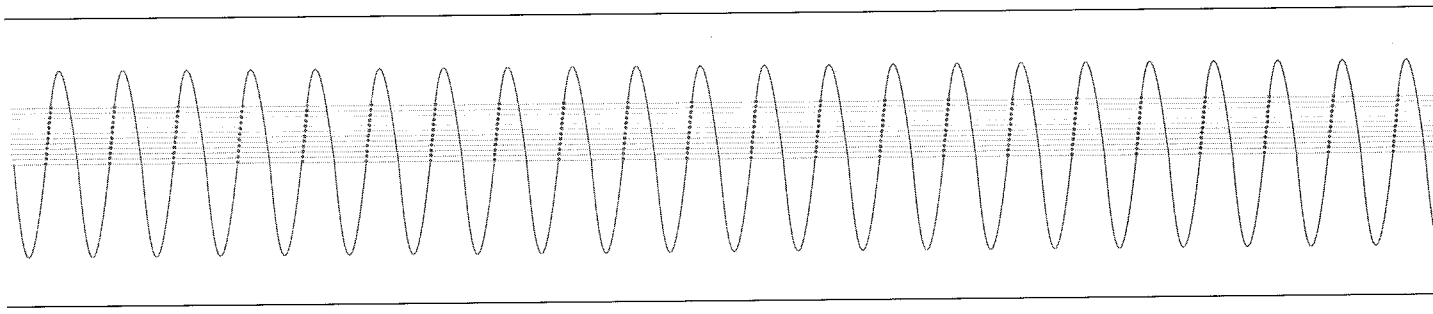
These considerations led to a frequency choice of about 11 GHz for the advanced linear collider development work at SLAC and KEK and 14 GHz for VLEPP in Protvino; frequencies as high as 30 GHz were suggested by Andrew Sessler of LBL and Wolfgang Schnell of CERN.

AT DESY, WE BEGAN to think about a linear collider design based upon what had been learned during the decade of the 1980s, but starting with no stringent *a priori* assumptions. Our general conclusion is that there seems to be no need to go to higher frequencies and that, in contrast to the above statements, higher frequencies than SLAC's S-band lead to even lower efficiencies than those that can be achieved at 3 GHz.

By running a linear collider in a very long pulse mode, with about 200 bunches per rf pulse, the stored energy no longer plays an important role. The effective "rf power to beam energy" efficiency, measured by the shunt impedance, also is found to be almost constant when going from 3 to 11 or even 14 GHz, when one takes pulse compression schemes and large aperture cavities into account.

Instead of filling a cavity once and accelerating one or a few bunches at a time, we propose to run the accelerator in a quasi-continuous mode: bunches in a long pulse are accelerated continuously, while the rf power supplies replenish the energy in the cavities. Since a true continuous mode would require far too much wall plug power (and would in fact destroy the linac for thermal reasons), we have to switch the accelerator on and off but in such a way that within any one pulse all the operating conditions are close to dc (continuous).

After all, if the increase in frequency does not help, why should



Tentative Parameters for Two Different Versions (100 mA and 300 mA) of the Proposed DESY Linear Collider.

		100 mA	300 mA
General Parameters			
energy	GeV	250+250	250+250
luminosity	$(cm^2\ sec)^{-1}$	4.1×10^{33}	2.2×10^{33}
active length	m	29 411	
repetition rate	Hz	50	
number of particles per bunch		7×10^9	21×10^9
Particle Production and Damping Rings			
damping ring energy	GeV	3.15	
ring circumference	m	650	
invariant emittance $\gamma\varepsilon_{x,y}$	$m/10^{-8}$	410/4	1000/100
wiggler peak field	T	2.0	
wiggler total length	m	84	
dynamic acceptance	m	4×10^{-6}	
Main Linac			
wave length	m	0.10	
average shunt impedance	MΩ/m	53.6	
attenuation	neper	0.57	
structure length	m	6	
group velocity	% of c	4.1–1.3	
filling time	μsec	0.825	
maximum energy width (peak to peak)	%	0.33	1.0
klystron peak power	MW	112	145
number of klystrons		2451	2451
structures per klystron		2	
klystron efficiency	%	45	
total rf pulse length	μsec	2.8	
zero current energy	GeV	540	613
mean power	MW	86	110
rf peak power	MW	275 000	355 000
average pulse current	mA	100	300
current pulse length	μsec	2	
number of bunches per pulse		172	
bunch length (rms)	mm	0.2	0.5
Final Focus and Interaction Point			
β function at IP $\beta^*_{x,y}$	mm	3, 0.3	5, 0.8
beam dimension at IP $\sigma^*_{x,y}$	nm	169, 5.48	316, 40
crossing angle	mrad	±0.8	
momentum acceptance	%	±1.8	
Efficiencies			
rf → beam	%	18	43
wall-plug → beam	%	6	14

one choose any other than SLAC's S-band frequency, since more than 25 years of experience with a running accelerator have shown that this technology is well understood and practical? This seems to be the most effective choice not only in terms of wall plug power but even more in terms of the required research and technical development efforts that are clearly minimized when one uses existing hardware.

THE TENTATIVE PARAMETER list (left) of the proposed DESY S-band collider shows that many operating conditions have been chosen to be close to what has already been achieved at SLAC. Two linacs, used to accelerate the electrons and positrons from approximately 3 GeV up to 250 GeV, are the main components of this collider. Two bunch trains of 172 bunches with 7×10^9 particles per bunch (or 21×10^9 for the 300 mA case) have to be accelerated and focused into the interaction region with a repetition rate of 50 Hz. The average pulse current (either 100 mA or 300 mA) is higher than what has been reached at SLAC, but the single-bunch charge is considerably smaller than what can be stably accelerated today.

Both cases (100 mA and 300 mA) produce about the same luminosity. The 100 mA version has relaxed tolerances on single and multi-bunch dynamics, whereas the 300 mA version allows reduced demands on ground-motion feedback in the linac,

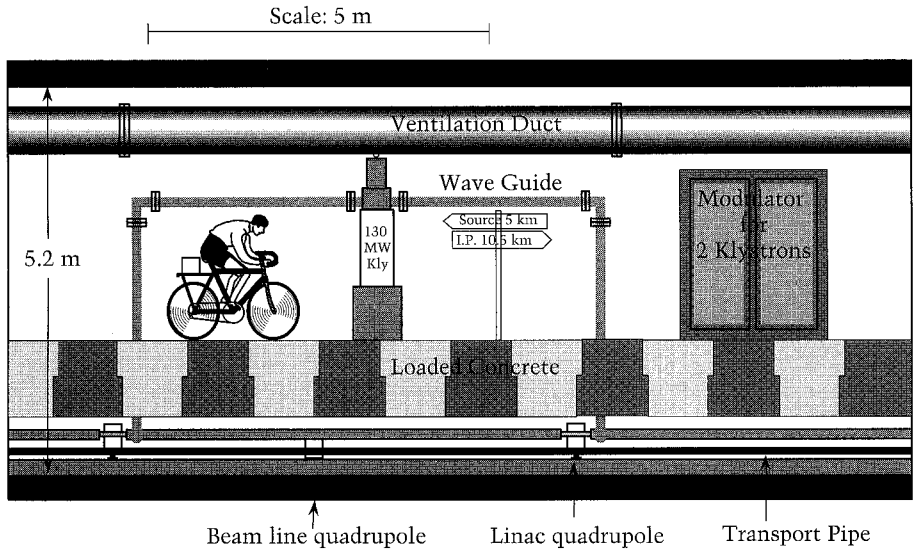
tolerances for the final-focus alignment, and emittance preservation during acceleration. In fact, the spot sizes at the interaction region for the 300 mA case are comparable to the spot size aimed for in the Final Focus Test Beam Facility now under construction at SLAC.

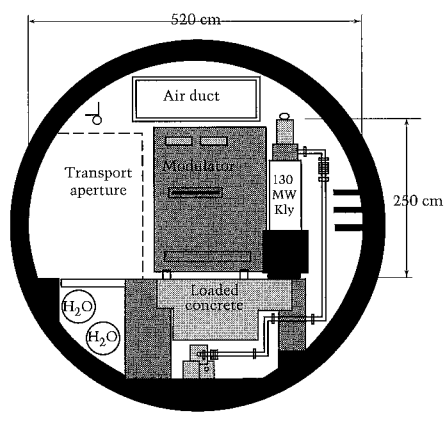
The electron particle production is almost trivial, as the bunch charge and average current are state of the art; however, such is not the case with positron production. Work has been started on new target material and a scheme to produce positrons by a photon beam, generated by the spent beam after interaction (similar to Novosibirsk's helical undulator scheme). In addition, recycling strategies have been investigated that give us confidence that the required 2×10^{13} positrons per second can be reached.

Damping rings for producing low-emittance beams are already known to work in the present SLAC linear collider. As the requirements for future linear colliders are much higher than what is available today, detailed studies were necessary. The importance of alignment tolerances, shown by appropriate computer simulations, have led us away from the commonly used FODO lattice to a modified Chasman-Green lattice with wiggler insertions. Such a damping ring design seems to fulfill all requirements under realistic assumptions.

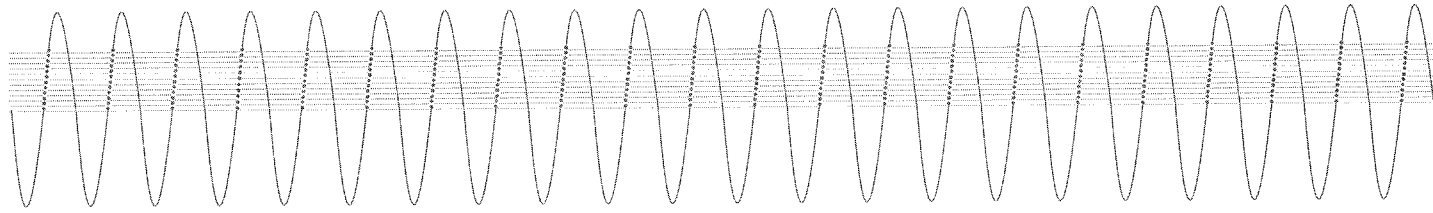
The accelerating structure is basically a doubled SLAC structure, six meters long and of a constant-gradient type. Various technologies are under investigation for cheap mass production of such structures. First offers by industry for test structures indicate that the price for the accelerating sections will be only a minor fraction of the total accelerator cost. The detailed design of the structures is dominated by multi-bunch instability considerations.

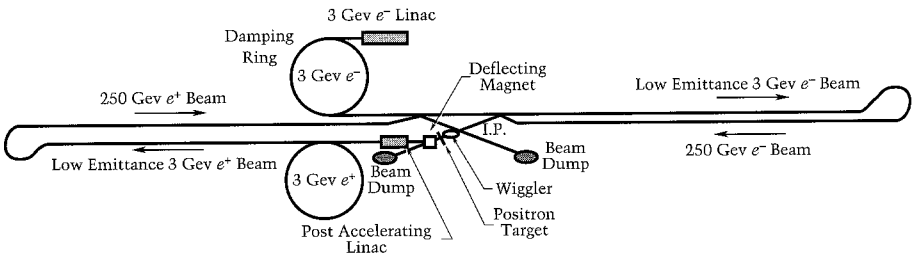
Beam-dynamics studies were focused for many years on single-bunch beam breakup, a well-known phenomenon at SLAC. However, in the proposed DESY S-band collider the single-bunch charges are smaller than those in the present SLC, and breakup investigations have shown that there is no such problem in this machine. Even BNS damping does not seem to be necessary. (Balakin-Novokhatsy-Smirnov or BNS damping





Side and cross-sectional views of the accelerator tunnel for the proposed DESY linear collider.





General schematic layout of the proposed DESY linear collider (not to scale).

is a technique used at the SLC to minimize the disruptive effects of wake fields acting on the electron or positron bunches.)

However, a wide new area of possible beam instabilities is opened by the long beam pulse intended for the DESY collider. With a train of 172 bunches, multi-bunch beam breakup seems to be the limiting instability in such an accelerator. This effect, called "pulse shortening" at the time when SLAC first came into operation (late 1960s), was reduced in the early days of the SLAC linac by detuning the accelerator sections in such a way that the accelerating mode was not affected but the higher order dipole modes were shifted slightly in frequency in order to lead to cancellation of deflecting forces. More elaborate ideas have since been developed at SLAC for the proposed multi-bunch X-band collider using structures with higher order mode dampers in each cell.

For the DESY S-band collider the detuning method seems to be effective enough to suppress beam break up, and we envisage the use of only a single higher order mode coupler per 6 m of accelerating structure for damping and diagnostics simultaneously. An important area of research is required to find a suitable detuning strategy. Only a rather small amount of detuning will be needed (about 10 MHz), and only small variations in the structure parameters will suffice to account for the appropriate shifts in dipole frequencies. Elaborate evolutionary methods combined with tracking simulations are used and have so far shown satisfactory results.

The energy spread in the S-band collider is intrinsically small because of the low bunch charge and the large cavity aperture. Although it is not necessary from the beam dynamics point of view, the energy spread can easily be minimized by moving the bunches a few degrees away from the crest of the accelerating wave.

Radiofrequency power generation will be accomplished with one high voltage power supply per klystron. As these power supplies seem to be the most costly ingredient of the collider, studies are now under way to decide between the hard-tube pulser or optimized conventional pulsers. Construction of a test hard-tube pulser is now being carried out in collaboration with SLAC and Varian Associates.

The klystron parameters used in the S-band design are state of the art in terms of output power, as demonstrated at SLAC many years ago. The required pulse length needs to be increased to about 3 microseconds. A collaboration with SLAC is being

discussed to work on the development of such tubes. As the total number of klystrons needed is very large (2500), even the (normally neglected) power consumption of the solenoid focusing coils becomes an important problem and consequently a focusing scheme using permanent magnets is under investigation.

The final focus system leading to the interaction region is mainly characterized by the acceptance in terms of the width of the energy distribution of the particles within one bunch. This acceptance was considered to be a significant constraint on linear colliders for quite some time. The reason is simple: When a particle bunch extracts a certain amount of energy from an accelerating cavity, the reduction in stored energy causes a drop in accelerating voltage and thus the particles at the head of the bunch see a higher voltage than the particles at the tail of the bunch. As a consequence, the final focus energy acceptance (typically 0.5%) determines the overall efficiency of the linac.

We began our work on final-focus design starting from the CLIC (CERN Linear Collider) lattice, designed for 1 TeV. Additional sextupoles have been inserted and the entire lattice has been computer-optimized. As a result we obtained an enormous bandwidth of 1.8%, which is in fact much more than what is needed in our design.

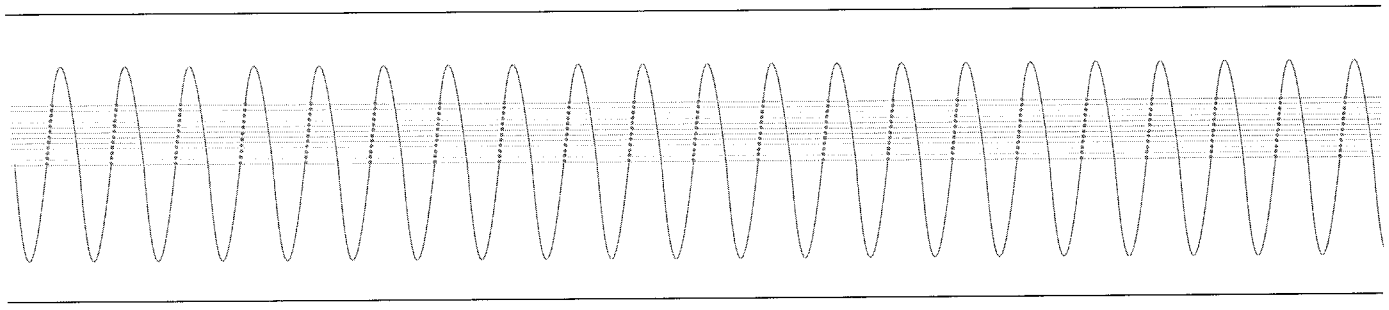
At the recent conference on high energy physics at 500 GeV, held in Saariselka, Finland (*Beam Line*, Vol. 21, No. 3), a sizeable fraction of the discussion was concerned with looking into the physics prospects at 300 GeV. In order to have good resolution in this energy region where the still-undiscovered top quark is expected to be studied, the particle physicists asked for a rather low energy spread within the bunches. Without major hardware changes we find that the proposed S-band collider can provide excellent beam parameters for these kinds of experiments. The energy spread can be made very small. The fraction of beam particles that do not lose energy through "beamstrahlung" can be as high as 70%.

In the other direction, extending towards higher energies, it has often been claimed that an S-band collider cannot simply be expanded beyond about 500 GeV. However, it has recently been shown that doubling the number of klystrons and employing the usual SLAC pulse-compression technique, the proposed S-band collider could reach a collision energy of 1 TeV without an increase in length.

The two 500 GeV parameter sets in the sidebar on page 26, the 300 GeV operation mode shown above and the possible 1 TeV extension shown on the next page show clearly how flexible an S-band collider can be.

Operational Parameters at 300 GeV.

General Parameters		300 mA
energy	GeV	150+150
luminosity	$(cm^2\ sec)^{-1}$	1.0×10^{33}
repetition rate	Hz	50
number of particles per bunch		21×10^9
Particle Production and Damping Rings		
damping ring energy	GeV	3.15
invariant emittance $\gamma\varepsilon_{x,y}$	$m/10^{-8}$	1000/100
bunch length σ_s	mm	3.6
Main Linac		
maximum energy width (peak to peak)	%	0.44
bunch length (rms)	mm	1.0
Final Focus and Interaction		
β function at IP $\beta^*_{x,y}$	mm	11.5,1.5
beam dimension at IP $\sigma^*_{x,y}$	nm	632, 51
critical radiation parameter		0.020



Parameters for the Energy Upgrade.

General Parameters	300 mA
Luminosity	2.7×10^{33}
number of bunches	50
number of part. per bunch	2.8×10^{10}
beam pulse length	500 nsec
effective gradient	34 MeV/m
No. of klystrons	2×2451
average current	448 mA
klystron output peak power	150 MW
power/beam	5.6 MW
average power	220 MW
beam dimension at IP	223/28.3 nm
disruption	0.9/10.1
SLED* and RF Parameters	
external Q, Q_e	18 000
unloaded Q, Q_0	200 000
rf pulse length T_{rf}	3.7 μsec
$\beta = Q_0/Q_e$	11
$\alpha = 2\beta/(1+\beta)$	1.834
length of accel. section	6 m
attenuation (τ)	0.57 neper
unload. accel. grad. without SLED and 150 MW input	30 MeV/m
unload. accel. grad. with SLED	45 MeV/m (at max)
average current within pulse	448 mA
filling time T_f	825 nsec
injection time before max	-440 nsec

**SLED is the rf pulse compression scheme developed at SLAC.*

The beam quality and luminosity are very high, while only relatively moderate spot sizes are required.

Probably the most important parameter for any future linear collider is the overall efficiency, given by the ratio of beam power to wall-plug power. Because of the quasi-dc operating mode, the proposed S-band collider can reach an enormous efficiency of up to 43% for the rf power to beam power conversion, and 18% for wall plug to beam power conversion (assuming 45% klystron efficiencies). These numbers are in fact very close to the efficiencies reached by superconducting linear colliders. This advantage of the long-pulse operation is attributable to the fact that a major fraction of the rf power goes directly to the beam, and the cavity wall-losses become consequently less important.

In summarizing this design study, we find that an S-band collider is very flexible, needs a minimum of R&D work compared with superconducting linacs or higher frequency linacs, uses moderate beam sizes at the interaction region, and provides the highest overall power efficiency of all normal-conducting collider species.

In our mind "10 times SLAC" is a reasonable, effective, and practical way to reach 500 GeV or even 1 TeV collision energy.

MOST CITED WORKS IN SPIRES HEP DATABASE

by HRVOJE GALIC

SPIRES DATABASE SYSTEM AT SLAC is a treasure-chest of information. One of the most popular databases is HEP, a joint project of the SLAC and DESY libraries. HEP contains almost 250,000 entries with bibliographic data on articles and preprints in high energy physics. Among other things, HEP tracks the number of times a paper is cited by later works. The list of the 'top thirty' cited papers in HEP (1974 to present) shows two remarkable features: almost half were published in a period of three years, 1973–75, and only two experimental papers made it to the list. The first column below shows number of citations, the second lists the author(s), title, and journal reference of the cited paper. SPIRES/HEP also runs at DESY, KEK, and Yukawa Institute, Kyoto and is accessible to a wide community of particle physicists via SPIRES' remote server, QSPIRES. For more information send electronic mail to QSPI@SLACVM.SLAC.STANFORD.EDU.

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FROM THE EDITORS' DESK

ELEMENTARY-PARTICLE PHYSICISTS often take note of, and pleasure in, the international character of their field of science. It is thus a matter of pleasure for us to note here that the present issue of the *Beam Line* contains several examples of international cooperation. One such example occurs in the article on the DESY (German) linear collider development program, in which Gus Voss and Thomas Weiland point out contributions to their design from American, Russian, Japanese, and European colleagues.

The second example is the review of the U.S.-Japan cooperation in experimental particle physics, detector development and accelerator development, by Michael Riordan and Kasuke Takahashi. Japanese and American particle physicists have been collaborating for many years, at first informally, and more recently under the auspices of the Implementing Arrangement on the U.S./Japan Cooperation in the Field of High Energy Physics (1979).

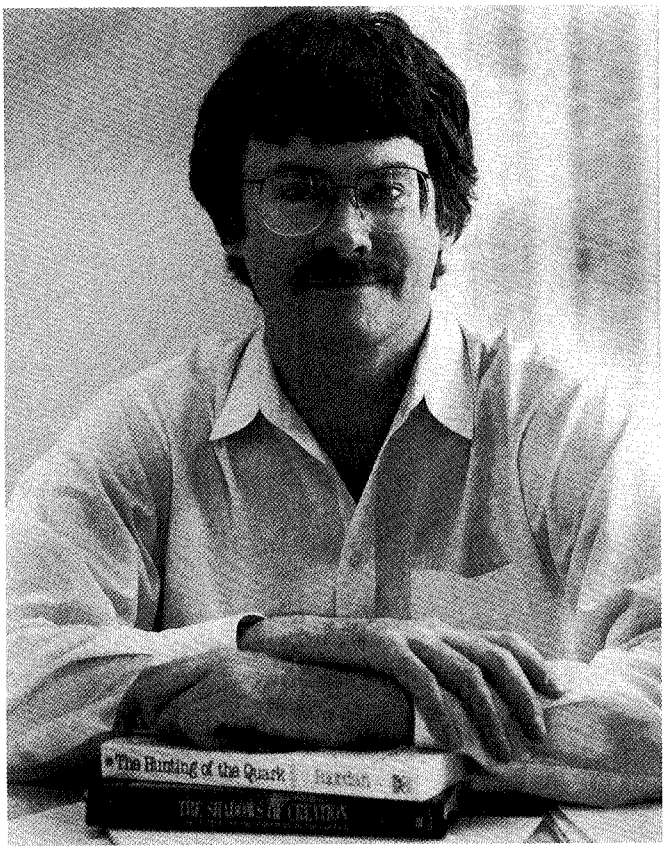
The last example is in large measure a product of the extensive international cooperation that has gone before. This is described in the article on the Solenoidal Detector Collaboration (SDC) by Pat Bautz and George Trilling. The schedule for the SDC shows that this very large detector system, intended for use at the Superconducting Super Collider in Texas, is about seven years away from its SSC installation date of 1999. But already it has assembled a collaboration of some 700 scientists and engineers from around the world to design and build the detector. The SDC crew presently consists of members from France, Italy, several of the countries of the new Commonwealth of Independent States, the United Kingdom, Japan, Canada, the Peoples Republic of China, Bulgaria, Czechoslovakia, Romania, Israel, Brazil, and the United States. Participants from the U.S. number several hundred, consisting of about 50 groups from different universities and national laboratories. The Japanese contingent is particularly large with 24 institutions and over 80 individuals represented. As this issue goes to press, the U.S./Japan working group formed to establish Japanese participation in the SSC is holding its first meetings.

In high energy physics, the objects of study get smaller, the machines and detectors get larger, the facilities become fewer, and the collaborating groups grow correspondingly larger. That the collaborating groups also become increasingly international is indeed one of the pleasant aspects of the field.

Bill Kirk

Rene Donaldson

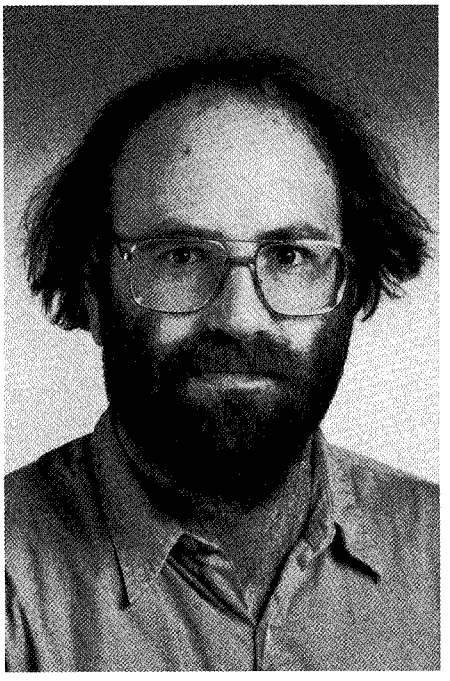
CONTRIBUTORS



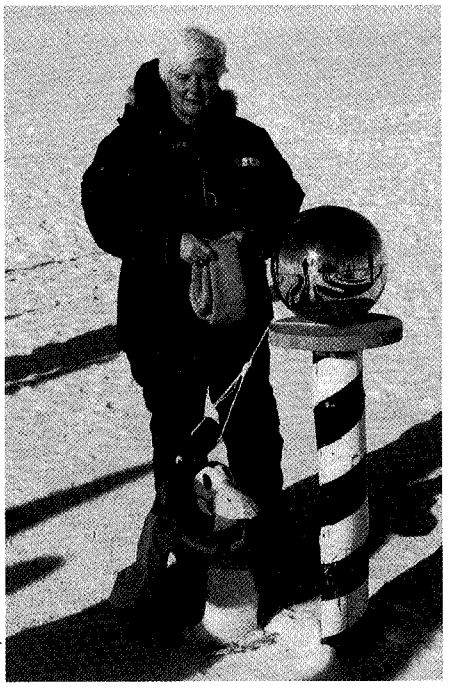
MICHAEL RIORDAN, contributing editor of the *Beam Line*, has returned to the Stanford Linear Accelerator Center after a year's leave of absence as Assistant to the President at Universities Research Association in Washington, DC. In his new position as Assistant to the Director, he is responsible for coordinating external affairs, including media and government relations. If it isn't already obvious, he is the author of *The Hunting of the Quark* and co-author of *The Shadows of Creation*, which will be available in paperback this fall. He is presently working on a history of the transistor.

In April, KASUKE TAKAHASHI became the new Vice Director of the National Laboratory for High Energy Physics (KEK) in Tsukuba, Japan. Prior to that he served for a year as Director of the Washington Office of the Japan Society for the Promotion of Science, and before that he was Director of the TRISTAN e^+e^- Collider Detector Department at KEK.

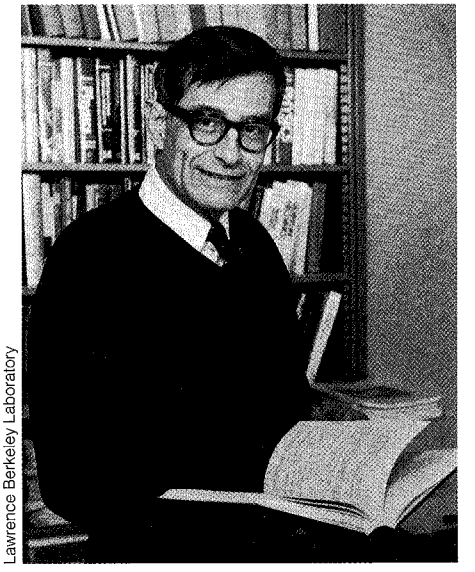
In 1962, Takahashi earned his Ph.D. in Physics from the University of Tokyo, remaining there as a Research Associate until 1966. He worked mainly in bubble chamber research until the early 1980s, including extended periods in the United States at the Carnegie Institute of Technology (1964–65) and Stony Brook (1968–70). As Professor of Physics at KEK after 1971, he was deeply involved in the SLAC Hybrid Facility mentioned in the article. He has also been working since 1980 on the Kamiokande underground experiments.



LESLIE J ROSENBERG received his Ph.D. in Physics from Stanford in 1985 where Professor David Ritson supervised his studies of QCD and jets based on MAC Detector calorimeter data from the PEP ring at SLAC. He continued on with straw tube vertex chamber development, furthering MAC studies of hadrons containing the *b* quark. He is now a Senior Research Associate at the Enrico Fermi Institute of the University of Chicago and one of the founding members of the Chicago Air Shower Array detector.



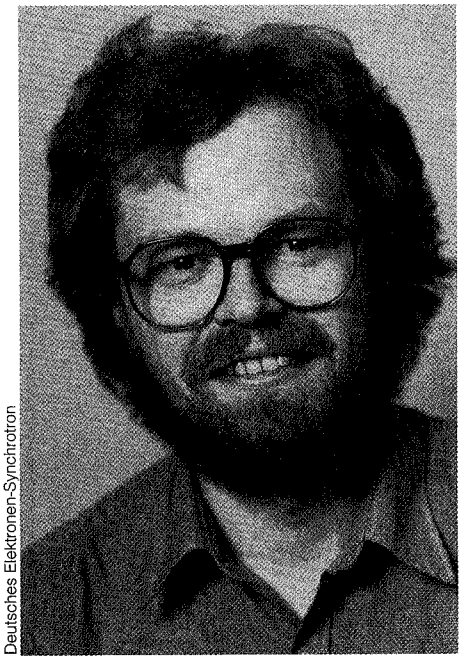
LAURA P. (PAT) BAUTZ received a B.S. in Physics from Vanderbilt University and a Ph.D. in Astronomy from the University of Wisconsin at Madison. She was on the faculty of Northwestern University for ten years before joining the National Science Foundation in 1975. There she spent six years in the Physics Division before being named to head the Astronomy Division. In 1990, Bautz was assigned to the Lawrence Berkeley Laboratory to assist the Solenoidal Detector Collaboration. Her stay was extended from one year to two to enable greater participation in the project. She expects to return to NSF as deputy director of the Physics Divison in October of this year.



Lawrence Berkeley Laboratory

GEORGE TRILLING is a physics professor at the University of California at Berkeley and a member of the Physics Division staff of the Lawrence Berkeley Laboratory. He worked with the Mark I and Mark II groups on electron-positron experiments at SPEAR, PEP, and SLC from the early 1970s until 1989. Since then he has been deeply involved in the organization of the Solenoidal Detector Collaboration to design and construct a detector well matched to the physics opportunities presented by the Superconducting Supercollider.

Deutsches Elektronen-Synchrotron



Deutsches Elektronen-Synchrotron

GUSTAV-ADOLF VOSS studied physics at the University of Technology in Berlin where he received his Ph.D. in 1955. As assistant director at the Cambridge accelerator from 1964 until 1972, he proposed, together with Ken Robinson, the CEA Bypass project. In 1973 he became a member of the DESY directorate responsible for the accelerator division. He served as project head on the construction of the PETRA storage ring that came into operation in 1978. His next major project was the construction of the HERA electron ring which has been running since the end of 1990. In addition to his involvement with circular accelerators, since 1982 he has also worked on linear collider problems.

THOMAS WEILAND studied electrical engineering and mathematics at the technical university of Darmstadt and received his Ph.D. in 1977. He started his accelerator career at CERN working on the design of the LEP storage ring. In 1981 he joined DESY to work with Gus Voss. He is the principal author of many accelerator design codes (TBCI, URMEL, MAFIA). As a member of the PETRA group he contributed to the solutions for many accelerator instability and impedance problems. Together with Voss he has worked on linear colliders, and since 1989 he is a professor at Darmstadt and coordinates with Voss the S-band collider study group.

DATES TO REMEMBER

May 27–Jun 3	Summer School on QCD Analysis and Phenomenology, Batavia, IL (Treva Gourlay, CETQ School, Fermilab, MS 122, Box 500, Batavia, IL 60510 or CTEQSCHOOL@FNAL)
Jun 15–19	CEBAF 1992 Summer Workshop, Newport News, VA (Lynne Chamberlin, CEBAF Physics Div., MS 12H, 12000 Jefferson Avenue, Newport News, VA 23606 or LYNNE@CEBAF)
Jun 15–26	US Particle Accelerator School, Stanford, CA (US Particle Accelerator School, Fermilab, MS 125, Box 500, Batavia, IL 60510 or USPAS@FNAL)
Jun 24–27	3rd International Symposium on the History of Particle Physics (N. Adelman Stolar, SLAC, MS 70, Box 4349, Stanford, CA 94309 or NINA@SLACVM)
Jul 6–10	13th International Conference on Cyclotrons and Their Applications, Vancouver, BC, Canada (Cyclotrons '92, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada, 604-222-1047, ext. 439, FAX 604-222-1074, or CYC92@TRIUMFCL)
Jul 6–31	Aspen Physics Program: Massive Neutrinos in Particle Physics and Astrophysics, Aspen, CO (Sudip Chakravarty, Aspen Secretary, Physics Dept., UCLA, 405 Hilgard Avenue, Los Angeles, CA 90024-1547 or SUDIP@UCLAPH)
Jul 13–17	Particle Physics in the 90s: 1992 Gordon Research Conrerence, Andover, NH (Cynthia Sazama, Fermilab, 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. Jul 22–24; Symposium on Tau Physics, July 24) Stanford, CA (Jane Hawthorne, SLAC, MS 62, Box 4349, Stanford, CA 94309 or SSI@SLACVM)
Jul 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@DMOMPI11)
Jul 27–Jul 30	TeX Users Group Annual Meeting: TeX in Context, Resources, Suppport Tools, and Comparative Studies, Portland, OR (TeX Users Group, Box 9506, Providence, RI 02940)
Aug 6–12	26th International Conference on High Energy Physics (ICHEP 92), Dallas, TX *(venue of this conference has been changed from Moscow to Dallas)* by invitation (Roy Schwitters, SSC Laboratory, MS 1070, 2550 Beckleymeade Avenue, Dallas, TX 75237-3997 or XXVICONF@SSCVX1)
Sep 29–Oct 2	III International Conference on Calorimetry in High Energy Physics, Corpus Christi, TX (Phyllis Hale, SSC Laboratory, Users Office, MS 2080, 2550 Beckleymeade Avenue, Dallas, TX, or PHYLLIS@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)

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