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Cover: A montage of microwave-guiding components used in SLAC's Next Linear Collider Test Accelerator for transmitting high power microwaves from the klystrons to the accelerator.

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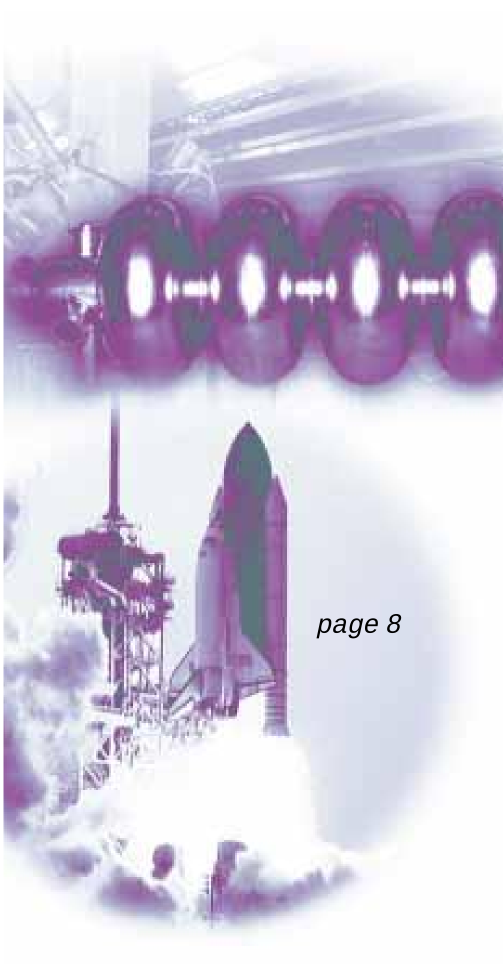
FEATURES

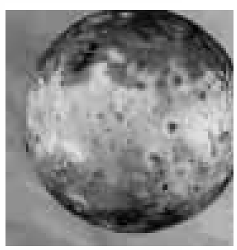
page 14

CONTENTS



page 2

page 8

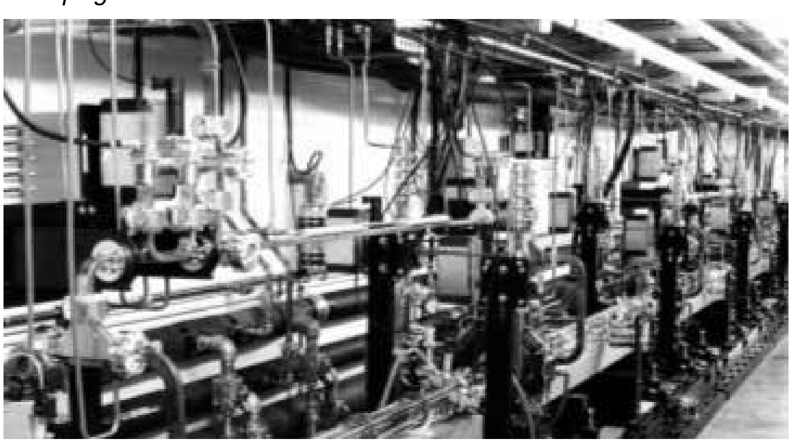


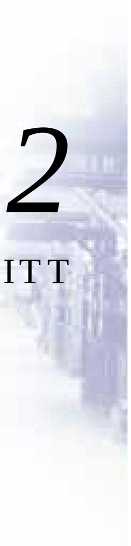
page 21

DEPARTMENTS

page 26

page 17





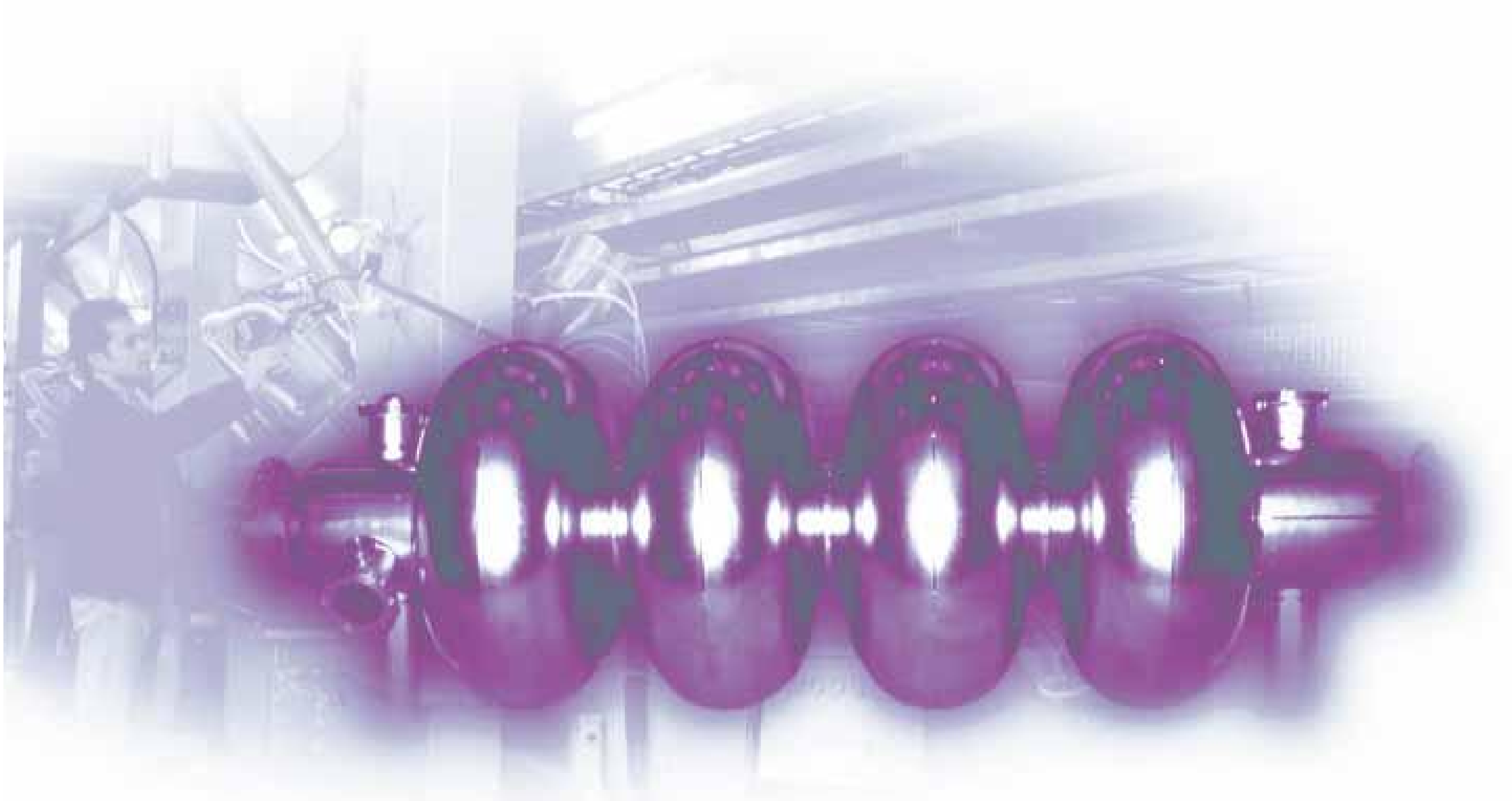
PHYSICS AT LEP 2

by MICHAEL SCHMITT

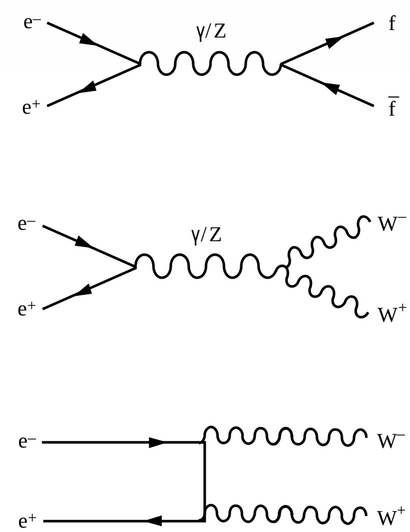
Particles colliding at CERN with a center-of-mass energy close to 200 GeV are changing the character of electron-positron physics. Here's what it means for new particle searches and precision measurements.

A NEW ERA IN ELECTRON-POSITRON collisions began four years ago at CERN. The center-of-mass energy of the Large Electron-Positron Collider (LEP) increased by half to 135 GeV—well above the peak of the *Z* boson resonance around 91 GeV, where LEP and its American cousin, the Stanford Linear Collider, have been taking data for years. Since then the energy has risen gradually to 189 GeV, making this collider, now called LEP 2, a unique high energy physics machine (see the article by Daniel Treille in the Fall 1992 issue of the *Beam Line*, Vol. 22, No. 3).

The first era of LEP physics began with the detailed study of the *Z* boson. When early hopes of discovering new phenomena were not realized, the four LEP collaborations—ALEPH, DELPHI, L3, and OPAL—concentrated on precision measurements and rare particle decays, leading to important results far beyond initial expectations. Perhaps the best examples are the measurement of the *Z* boson mass—now one of the best known quantities in all of particle physics—and the isolation of a small sample of $B^0 \rightarrow J/\Psi K^0_S$ decays with which to examine CP-violation. The main areas of study included electroweak processes, tau physics, the physics of "beauty" mesons and baryons, and quantum chromodynamics. Searches for new particles such as the Higgs boson or supersymmetric particles found nothing new within the limits imposed by kinematics, namely, that the sum of the masses of the particles produced is less than the total beam energy.



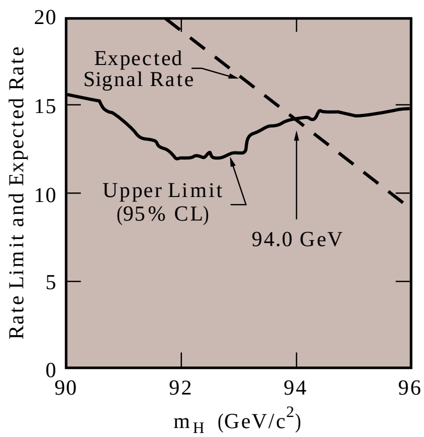
At LEP 2 the *Z* boson resonance is gone, and the previously huge production of two-fermion final states (pairs of leptons or quarks) is now accompanied by the appearance of four-fermion final states made large by the production of pairs of *W* bosons (see diagrams at right). The careful measurement of two-fermion cross sections and asymmetries continues, as tests of Standard Model predictions could well turn up deviations suggesting *new* physics. In addition, LEP 2 presents a wonderful opportunity to study the *W* boson, which previously had been produced in large numbers only at Fermilab. Most important, however, is the *direct* search for new particles—for should any such thing be discovered, particle physics would enter a new age.



Feynman diagrams of processes which dominated at LEP 1 (top), and those that are relatively more important at LEP 2.

SEARCHES FOR NEW PARTICLES

Theorists have proposed many new particles that might be discovered at LEP 2. Paramount among them is the Higgs boson, which in the Standard Model and its variants is the principal agent responsible for the masses of the known particles. This unique particle is not democratic with regard to the three generations of quarks and leptons: it couples more strongly to the heavy than to the light. Consequently, it prefers to decay into a pair of heavy particles that together are lighter than it. Unless the Higgs boson is



The expected rate of Higgs events as a function of the Higgs mass, compared to the upper limit derived from the direct search. These preliminary data from the OPAL Collaboration exclude a Higgs boson lighter than 94 GeV.

particularly heavy itself, this means mostly a pair of *b* quarks, with *c* quarks and tau leptons showing up 10 times less frequently.

A Higgs boson is thus expected to materialize most often as a pair of high energy "*b* jets"—a bundle of ordinary hadrons originating from a *b* quark. It would be produced when an electron and positron annihilate to create a supermassive *Z*, which would immediately "decay" into an ordinary *Z* and a Higgs boson. Although this would be a very rare process, it has advantageous properties: the *Z* decays to a pair of charged leptons, quarks, or neutrinos, all of which help physicists distinguish Higgs events from standard processes. The two *b*-quark jets emerging from the Higgs boson decay can be used to measure its mass; if Higgs bosons are produced at LEP 2, a peak should appear in plots of the two-jet mass.

Standard searches for Higgs bosons have been developed and perfected by all four collaborations, with each group competing for even modest improvements in their analyses. Unfortunately, no hint of any telltale excess of *b*-quark jets has appeared yet, and the researchers have had to be content with excluding ranges of possible Higgs boson mass. The combined data of all four experiments currently indicates that if the Higgs boson exists at all, its mass must be greater than 94 GeV (see figure on the left). With an ultimate LEP 2 collision energy of 200 GeV, these experiments can search for Higgs bosons up to a mass of about 109 GeV.

Supersymmetry (SUSY) is a collection of theories with many undetermined parameters and so far only *indirect* supporting evidence. Its basic premise can be stated easily: for every quark or lepton there are two new bosons, or scalar particles, and for every Standard Model boson there is a new fermion—including a partner for the as-yet unobserved Higgs boson! All these new particles must be very heavy, otherwise we should have discovered one by now.

The supersymmetric partner of the *W* boson, a charged particle called the "chargino," will be produced copiously if it is light enough. In the simplest scenario, the chargino decays the same way as a *W*, so one is looking for a second *W*-like particle that decays into pairs of quarks or leptons. In other scenarios chargino decays into leptons may be enhanced, but generally that poses no particular problem for experimenters. Charginos with masses less than 94 GeV have essentially been excluded by now.

Neutral sisters of the charginos, called "neutralinos," could enhance the signal for supersymmetry; if charginos are produced, one might expect also to observe neutralinos. The lightest neutralino plays a special role as the lightest of all supersymmetric particles. If it is stable, as usually assumed, then neutralinos left over from the Big Bang probably comprise a large fraction of the mysterious cold dark matter of the Universe (see article by Michael Turner in the Fall 1997 issue of the *Beam Line*, Vo. 27, No. 3) which is thought to clump together with the visible galaxies. Indirect limits on such a particle require its mass to be larger than about 28 GeV.

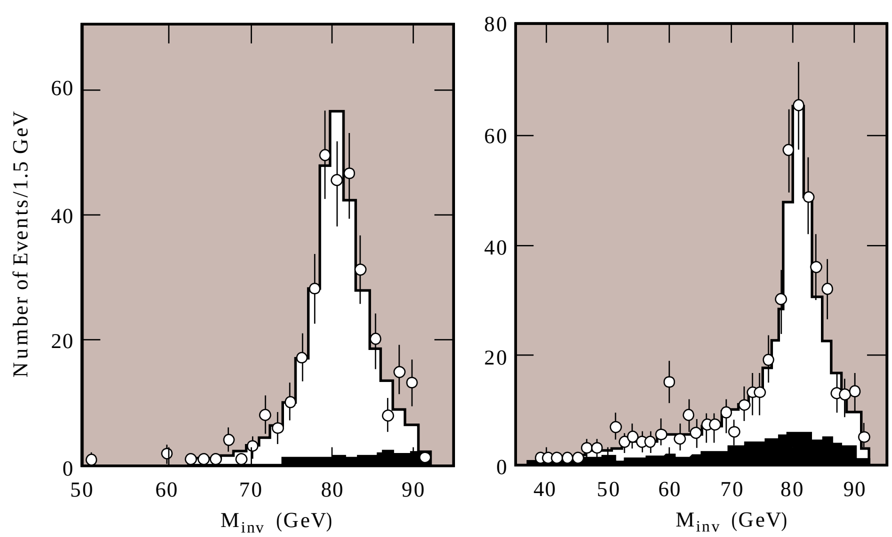
Other supersymmetric particles might be produced at LEP 2, including scalar leptons and quarks, which would show up as ordinary leptons and jets of hadrons plus missing energy. Ironically, the scalar top quark is the most promising of the scalar quarks; due to possible mixing of the two SUSY partners of the top quark, one light and one heavy mass eigenstate could result.

At the present time there is no whiff of supersymmetry in the data. Does this mean that this theory will soon be discarded? Probably not, as it does not specify precisely the masses of all the new particles—which might all be too heavy for LEP to produce. Their masses *should* come in largely below 1000 GeV, however, and the Large Hadron Collider will have a mass reach nearly that high. Supersymmetry, however, does place one important restriction on the mass of the lightest Higgs boson: it must weigh in at less than about 135 GeV, which is not far above the reach of LEP 2. And, judging from the indications gleaned from all the precision electroweak measurements, the Higgs boson may well fall within its reach.

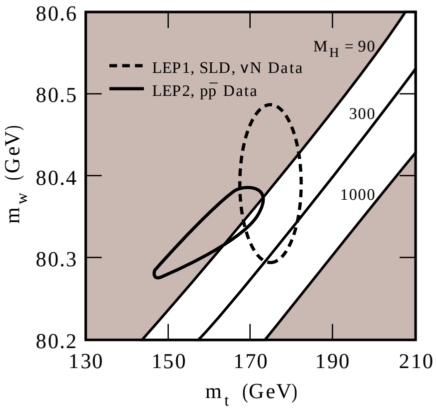
PRECISION MEASUREMENTS

The triumph of the precision measurements at LEP 1 is the mass of the *Z* boson, known now to one part in 30,000: $M_Z = 91.188 \pm 0.003$ GeV. As the mediator of the neutral weak force, the *Z* is produced naturally in electron-positron collisions. The mediator of the charged weak current is the *W* boson, which in electron-positron collisions is usually produced in pairs. Since a higher energy—more than 160 GeV—is required to produce a pair of *W*'s than a single *Z*, the study of the *W* has only become possible in the LEP 2 era.

The extraction of the *Z* mass was a question of measuring the event rate as the center-of-mass energy swept across the *Z* resonance, but *W*'s are another story. Since each event contains a pair of *W*'s, the resonance shape appears directly in the reconstruction of their masses. For example, if two *W*'s each decay to two jets, then in principle the masses of those two *W*'s can be reconstructed directly from the jet momenta. In reality there is a problem with jet confusion (How do you know which jets come from which *W* boson?) and the reconstruction of the jets themselves, so events that have a single charged lepton and two jets are easier to analyze. From fits to the resonance peaks measured so far (see graph below), the best *W* mass value is 80.37 ± 0.09 GeV. When the data taken in 1998 have been fully analyzed, the



Reconstructed W mass peaks. On the left, one W decays to a charged lepton and a neutrino while the other decays into a pair of quarks. On the right, both W's decay into quark pairs. These data come from the L3 Collaboration; the solid lines are fits to the data and the black areas represent background events.



Bounds on the Higgs mass from precision electroweak measurements from combined data presented at the 1998 Vancouver conference. The two round curves indicate the (68% confidence) constraints from indirect measurements of M_W and M_t (solid curve) and direct measurements (dashed curve). The white band shows the theoretical calculation. The data seem to favor low Higgs masses, which are, however, gradually being excluded by direct searches at LEP.

error will shrink substantially, so that the mass of the *W* will be known to one part in a thousand. By the end of LEP 2 running, this will be improved by another factor of two.

Of what use are very accurate values for the *W* and Z masses? Isn't it enough to know that they exist? Not in particle physics. We do not yet have a theory of everything; we have the Standard Model—which is not fully validated until we find the Higgs boson—and speculative extensions of it. In order to pick out the more worthy speculations, we need to "peer" from the energy scale of the experimental phenomena we observe (roughly 100 GeV) to much higher scales (such as 10^{16} GeV), where new phenomena would dominate. This procedure works because the new particles that are active at those high energy scales have indirect effects at these low-energy scales; we can see their impact in very subtle shifts of the interactions and masses of the known particles like the *W* and *Z*.

This procedure may seem rather speculative, but we know that it works. The top quark was found at the Tevatron in 1995 (see the article by Bill Carrithers and Paul Grannis in the Fall 1995 issue of the *Beam Line*, Vol. 25, No. 3), but before that no one knew for sure what its mass was. We could make a serious estimate, however, because it impacts the measurement of the mass of the *Z* boson and its decays. As it turns out, the value obtained indirectly agrees with the actual Tevatron measurement.

Now that we know the top quark mass, we can use the precision measurements to try to deduce an indirect value for the Higgs boson mass. This turns out to be much harder than for the top quark, because the Higgs boson has a weaker impact on things like the mass of the *Z* and the mass of the *W*. Consequently, improving the accuracy of the *W* mass measurement is vitally important. The bounds placed on the Higgs mass by the current measurements of the top quark and *W* masses (see graph on the left) are beginning to be significant. If the total error on the the *W* mass shrinks to 0.04 GeV, as anticipated, then the constraints on the Higgs boson mass will become much more stringent. If, for example, we find the mass of the *W* equals 80.48±0.04 GeV while the mass of the top equals 174±5 GeV—and still no Higgs boson is found with a mass less than 109 GeV— then the Standard Model will be in jeopardy.

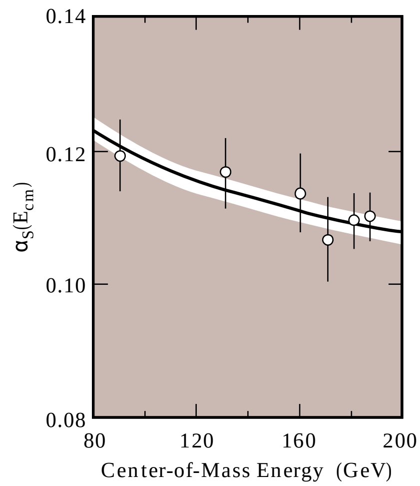
The calculation of these indirect "virtual" effects relies on field theory methods that predict that the strength of an interaction depends on its energy. In the parlance of particle physics, the "coupling constants run." In fact they run at different rates: the coupling constant for electromagnetism increases gradually with energy, the coupling for the weak force hardly changes at all, and the coupling constant for the strong force, α_s, actually decreases. One would like to know whether, at some high energy scale, all three have the same value. If they do, then they may be viewed as three aspects of a single, universal force, that is, they will be "unified." In the unaltered Standard Model, we already know that they do not unify, but in SUSY models, it looks like they do. To make a more stringent test, we need more precise measurements of the coupling constants, which in the case of α_S is experimentally challenging.

Fortunately, physicists have identified many indirect ways to measure α_S. For example, the emission of gluons, which shows up as "extra" hadronic jets, depends directly on α_S. A related feature is the overall "shape" of these hadronic events. They may be long and thin, indicating only two energetic quarks in the final state; broad and flat, indicating an additional gluon; or spherical, indicating two or more energetic gluons. It is impossible to make an absolute prediction for the shape of events or the number of jets, due to experimental and theoretical ambiguities. Fortunately, how these quantities *change* as a function of energy is well defined and easily measured. The doubling of LEP energy allows exceptionally clean observations of the running of α_S—better than 3 percent (see graph on the right).

There is a middle ground between direct searches for new particles and ultra-precise measurements of masses and couplings, and that is the measurement of cross sections and angular distributions for which the Standard Model makes clear and definite predictions. For example, we can easily calculate and cleanly measure the total cross section for hadronic events with center-of-mass energy well above the mass of the Z. If the measured value comes in larger than predicted, it might be due to the production of new particles somehow missed in the direct searches, or perhaps a deviation of the coupling constants that would point to new virtual effects. Of particular interest in this regard is the number of b-quark pairs produced, since this is the heaviest fermion produced at LEP. Thus far no deviation has been spotted, although the measurements have turned out to be more challenging than anticipated.

A more exotic corner of cross-section measurements actually tests the interactions among W's, Z's, and photons, rather than just their couplings to quarks and leptons. For example, a W boson can turn the incoming electron and positron into a pair of neutrinos—which escape detection—at the same time emitting a photon that generates a large signal in the electromagnetic calorimeter. A contribution due to this W-W-γ vertex can be isolated on a statistical basis, affording a direct test of the Standard Model in this important aspect. Other kinds of events test the W-W-Z vertex that contributes to W-pair production, and the Z-Z-γ vertex that should vanish to lowest order. These vertices lie at the very heart of electroweak symmetry.

The LEP collider will run through the year 2000, when its energy will reach 200 GeV. By the end of the program each experiment should have recorded more than enough data to complete searches for Higgs bosons and supersymmetric particles, and measure very precisely the properties of the W boson. Perhaps a genuine discovery will be made, or a new virtual effect uncovered. In either case the elucidation of any new phenomena would be carried out at future programs, such as future runs at the Tevatron, or at the LHC, or perhaps best of all, at the next generation of electron-positron colliders now in the design stages.



Variation of α_S with collision energy. This plot shows preliminary results from the ALEPH Collaboration.

LOOKING FOR COSMIC AN

by MAURICE BOURQUIN and GORDON FRASER

WHEN IT BLASTED OFF from NASA's Kennedy Space Center on June 2, 1998, the Space Shuttle Discovery carried the three-ton Alpha Magnetic Spectrometer (AMS), the first major particle physics experiment ever to go into orbit around Earth.

Despite its excitement and glamor, the 10-day flight of the Alpha Magnetic Spectrometer aboard the Space Shuttle was only a taste of bigger things to come. Although all AMS detector systems were up and working, the mission was a trial run to provide operational experience before deploying AMS on the International Space Station in the first years of the new millennium. This milestone mission could reveal the first evidence for nuclear cosmic antimatter, a major step towards resolving a long-standing puzzle about the apparent absence of antimatter in a Universe created in a Big Bang which supposedly produced matter and antimatter in equal amounts.

Stars and other powerful cosmic engines continuously blast out streams of high energy particles. These particles crash into nuclei in the upper atmosphere, producing showers of secondary debris which rain down from the sky as cosmic rays. To see the primary cosmic particles, messengers from distant parts of the Universe, detectors have to be flown high up into the atmosphere in balloons, or above the atmosphere in satellites. The largest pieces of antimatter seen in cosmic rays so far are antiprotons. Cosmic rays appear to contain no antinuclei, suggesting that their sources contain no nuclear antimatter.

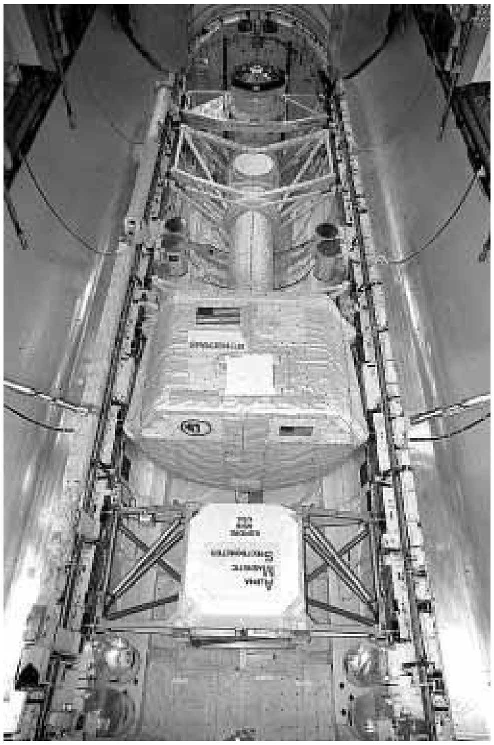
TIMATTER

Space Shuttle astronauts at CERN. Left to right are Mission Pilot Commander Dominic Gorie, Mission Specialist Franklin Chang-Diaz, Commander Wendy Lawrence, Mission Specialist Janet Kavandi, co-author Maurice Bourquin of the University of Geneva, and Mission Commander Colonel Charles Precourt.

This apparent absence of cosmic antimatter has been underlined in a careful appraisal of the implications of a balanced matter-antimatter Universe by Andy Cohen of Boston University, Alvaro de Rújula of CERN, and Sheldon Glashow of Harvard, published in 1998 in the *Astrophysical Journal*. They look at the consequences of matter and antimatter confined in separate and distinct domains.

Such a balanced Universe should have produced matter-antimatter encounters wherever and whenever the boundaries of the matter and antimatter domains touched. In such encounters, the separate pieces of matter and antimatter mutually annihilate to form bursts of energy in the same (but time-reversed) way that energy can create equal amounts of matter and antimatter. In the Universe, this matter-antimatter annihilation would provide a source of high energy cosmic radiation—gamma rays.

As the Universe expands, these annihilation radiation relics cool, giving a diffuse cosmic gamma ray background. But detailed calculations by Cohen, de Rújula and Glashow show that any such effect would be larger than currently observed gamma ray signals, such as those from the EGRET telescope aboard NASA's Compton Gamma Ray Observatory. Today's very low gamma background reveals no evidence for such annihilation processes ever having taken place on a large scale.



The AMS module installed in the Space Shuttle's payload bay. Above is the Spacehab module with supplies and logistics for the Russian Mir space station. This Discovery mission was the last of nine such dockings with Mir.

Detecting cosmic antimatter would be a new Copernican revolution, calling for a reappraisal of our picture of the Universe. However because of the limited sensitivity of the experiments, the existence of antimatter somewhere in the Universe cannot be completely ruled out. In the absence of any sighting, improving the limits on how much antimatter could exist and where it could be helps determine the fundamental parameters of particle theory and its cosmological implications.

AN ANTIMATTER EXPERIMENT IN SPACE

On its own, antimatter should behave like ordinary matter, with antiprotons and antineutrons forming antinuclei, and then attracting orbital positrons to form anti-atoms. Paul Dirac, the spiritual father of antimatter, pointed out that the spectra from atoms of antimatter should be no different from those of ordinary atoms, and antimatter stars would shine in the same way as ordinary ones. How then can antimatter be detected?

The only direct way is to look for stray particles of antimatter, just as Carl Anderson did in 1932 when he saw cosmic ray tracks bending the "wrong" way in a magnetic field and so discovered the anti-electron, better known as the positron. However any primordial cosmic antinuclei would be quickly mopped up by the earth's atmosphere. To see them means sending a magnetic detector into space.

In 1994 Samuel Ting of Massachusetts Institute of Technology presented an imaginative proposal to NASA. His Alpha Magnetic Spectrometer would be a space-borne equivalent of Anderson's historic experiment. Instead of using a cloud chamber to track cosmic particles, it would use sophisticated semiconductor technology.

Ting built up a diverse, skilled team of scientists from the United States, China, Russia, Taiwan, Germany, Italy, Switzerland, and other European countries. The experiment brings a novel symbiosis of space-borne and particle physics research.

Particle physicists are skilled at designing and building detectors to record particle reactions under controlled laboratory conditions. For AMS, the interactions would instead be supplied by Nature. However for AMS, the conditions are very different, calling for new solutions. As well as the size, weight, and electric power restrictions of a space-borne experiment, the detector has to respect stringent crew safety requirements and be compatible with delicate space shuttle systems (even in an airplane the use of electronic equipment by passengers is restricted!). AMS instrumentation has to withstand the huge forces when the space shuttle blasts off and lands, where accelerations reach 15 G and noise vibration levels attain 150 decibels. In flight, the detector has to withstand large temperature swings, high radiation levels and the intense vacuum of outer space. This was new territory for particle physicists used to the relative calm of their terrestrial laboratories. Instead of being on hand in a nearby control room, they would have to monitor their detector from the remote ground station, with an astronaut mission specialist as their space-borne representative.

A VERY SPECIAL DETECTOR

The AMS detector contains the usual components of a particle physics experiment—a central spectrometer with a magnet to bend the particle trajectories and tracking to record the paths of particles, particle identification capability, data acquisition systems to filter, compress, and record the information, and monitoring and control systems, as well as communications with the mother craft. Almost all these functions required special attention for a space environment.

To provide these capabilities, AMS uses a cylindrical permanent magnet, a set of six silicon tracking planes with double-sided readout, a time-of-flight measurement system with two pairs of scintillator arrays and an aerogel Cerenkov counter. An anticoincidence counter system around the tracker helps distinguish particles passing inside the detector from those interacting in the surrounding material.

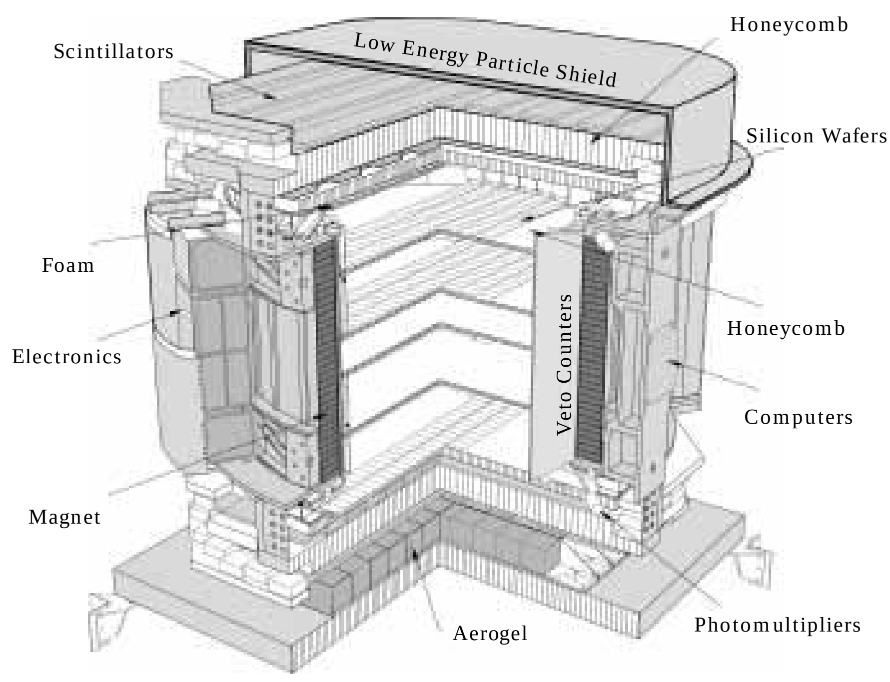
These components are assembled on an aluminum barrel structure, 1.14 m in diameter and 0.80 m in height, supporting the permanent magnet. The outside of the barrel carries electronic crates for the power supplies, trigger systems, data acquisition systems, monitoring and orbiter communication interfaces.

A charged antiparticle passing through the detector bends the "wrong" way in the magnetic field. However full identification comes from measuring the particle's momentum (from the exact curvature of its trajectory), its velocity (measured by the time-of-flight system) and its energy losses by ionization in the tracker and scintillators.

The magnet uses a neodymium-iron-boron alloy to optimize its field-to-weight ratio. The ferromagnetic material is shaped into 6000 small blocks (about 1 kg each) glued together into prismatic bars with suitably oriented magnetization. In the magnet aperture, the highly uniform magnetic field is of the order of 0.1 tesla. With such a magnetic field, the flux leakage has to be very small to safeguard the overall operation of the spacecraft. The magnet was built and space qualified using carefully chosen components and with stringent acceleration and vibration tests in China.

The core of the detector, the particle tracker, is based on the Silicon Microvertex Detector of the L3 experiment at CERN's LEP electron-positron collider, but most modules

Cutaway view of the AMS detector as flown on the Space Shuttle in June 1998. To track cosmic particles, the interior of the AMS detector contains semiconductor technology developed and perfected for the L3 experiment at CERN. As well as pinpointing cosmic tracks with micron precision, this instrumentation has to endure the extreme vibration and noise levels during the launch and landing of the Space Shuttle. Only half the silicon sensors were installed for this flight, thus providing valuable experience before deploying AMS on the International Space Station in the first years of the new millennium.



are much longer. These detector elements using arrays of high purity silicon wafers were developed to pinpoint particle tracks and so detect the decay products of very short-lived charged particles, which even when moving almost at the speed of light travel only a fraction of a millimeter before decaying.

The AMS tracker is made of 41×72 mm double-sided silicon sensors, 300 microns thick. The arrangement gives measurements in three dimensions. Charged particles can be pinpointed down to 10 microns. The modules are mounted on disk-shaped honeycomb supports. The front-end readout electronics uses hybrid circuits mounted perpendicular to the module planes. Cooling bars conduct the heat produced to the magnet. Flat ribbons of coaxial cables take the signals to the analog to digital converters and other data processing circuits in the outside crates.

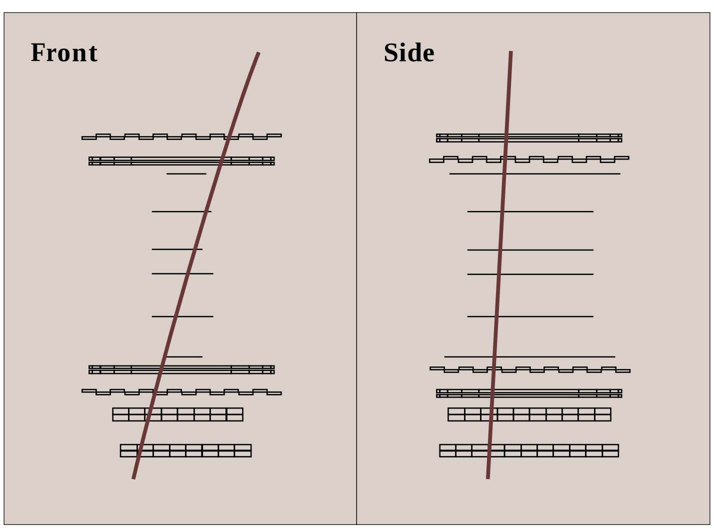
The time-of-flight system uses four planes of scintillators, two above and two below the magnet. It has three tasks: to trigger the detector by selecting single particles traversing the spectrometer; to measure their velocity and distinguish between upward and downward particles; and to perform four independent ionization measurements to separate particles carrying different electric charges. When the two independent measurements provided by the four planes are combined, the time-of-flight measurement is about 100 ps.

The threshold Cerenkov counter below the spectrometer uses a radiating medium made of 8 cm thick aerogel blocks optically connected to photomultipliers. The blocks are arranged in two layers of 8×10 and 8×11 matrices. As low energy protons and antiprotons do not produce Cerenkov light, they can easily be distinguished from positrons and electrons.

The anticoincidence counter system rejects sprays of neutrons and protons coming from comic ray interactions in the magnet body or in the detector material. This rejection considerably reduces background in the other systems and allows much more sensitive measurements. The system consists of a cylindrical wall of 16 plastic scintillators between the tracker and the internal face of the magnet.

For the space station mission, the silicon tracker has to be augmented to reach a total area of about 6 square meters, and additional detectors have to be built.

A candidate cosmic antiproton recorded by the AMS tracker.



Space qualification tests on the state-of-the-art detector were carried out in specially-equipped space laboratories. After final assembly at the Swiss Federal Technical Polytechnic (ETH) in Zurich, the initial version of the AMS detector was shipped to the US for final integration aboard the space shuttle.

Discovery's flight crew brought the space shuttle into land on schedule June 12, 1998. Although the orbiter's high speed data transmission link to earth failed during the flight, this did not affect actual AMS data taking: all data were safely recorded on board. Resourceful NASA communications specialists and the astronauts were also able to patch through some data via a link normally reserved for video pictures, and this 10 percent sample showed that the detector performed flawlessly. The valuable 100 million-event trawl of physics from outer space is being carefully analyzed.

Before publishing their final results, AMS scientists have to calibrate all their detectors with benchmark particle beams, including helium and carbon ions. This is being done at particle accelerators at GSI, Germany and CERN.

Is cosmic antimatter out there? Is it further away than we can currently see? As the curtain goes up on 21st century research, answers could soon be within reach. As Cohen, de Rújula and Glashow conclude in their milestone paper, "The detection of antinuclei among cosmic rays would shatter our current understanding of cosmology."

Toward a TeV Linear Collider. . .

Two large R&D facilities at KEK and SLAC are testing major subsystems for a next-generation electron-positron linear collider.

The JLC Accelerator Test Facility
SEIGI IWATA

The NLC Test Accelerator
THEODORE LAVINE

MOST HIGH ENERGY PHYSICISTS agree that the next major project after completing the Large Hadron Collider at CERN is to build an electron-positron linear collider operating at the trillion-volt (TeV) energy scale. Innovative designs for such a machine, which will stretch tens of kilometers and cost billions of dollars, have been evolving for over a decade. These design efforts have converged on a few favored approaches (see the article by Gregory Loew and Michael Riordan in the Winter 1997 issue of the *Beam Line*, Vol. 27, No. 4). An international collaboration headquartered at DESY has pursued one avenue that uses superconducting microwave cavities to accelerate electrons and positrons (see the article by Reinhard Brinkmann in the Fall/Winter 1998 issue of the *Beam Line*, Vol. 28, No. 3). Another promising approach, which employs copper cavities operating at close to ambient temperature, has been pioneered by the Stanford Linear Accelerator Center and Japan's High Energy Accelerator Research Organization (KEK, formerly the National Laboratory for High Energy Physics).

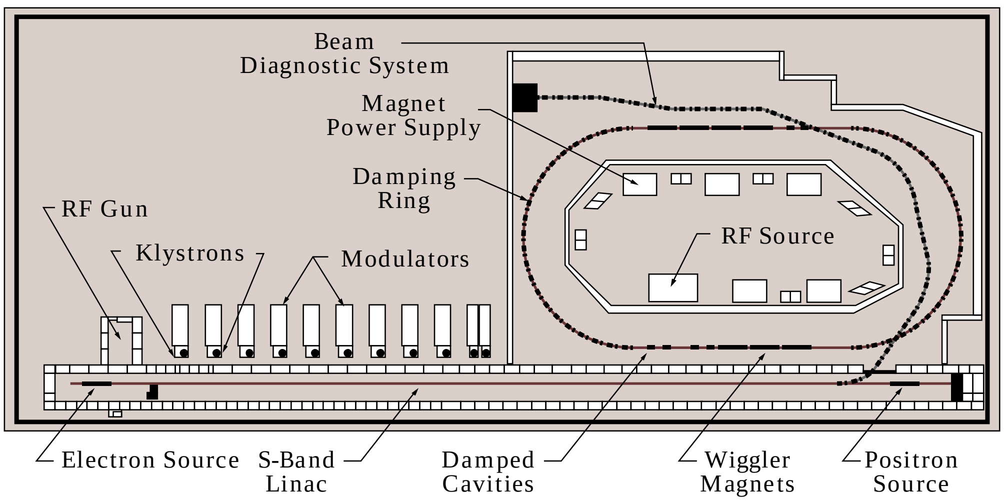
For more than a year, SLAC and KEK have been working closely together toward achieving a single design for such a next-generation linear collider. This joint R&D project occurs under an inter-laboratory memorandum of understanding signed in February 1998 by SLAC Director Burton Richter and KEK Director Hirotaka Sugawara. Well before this agreement took effect, however, researchers from both laboratories had built extensive R&D facilities to test some of the major subsystems required in such a TeV-scale collider. In the following articles, Seigi Iwata of KEK and Theodore Lavine of SLAC describe these facilities and the encouraging progress made with them to date.

—Michael Riordan

The JLC Accelerator Test Facility

by SEIGI IWATA

ONE OF THE MOST important experimental issues confronting physics today is the search for and study of the Higgs boson and other very heavy particles thought to be responsible for imbuing quarks, leptons, and gauge bosons with their various masses. This research can be done most effectively and efficiently at a high energy electron-positron collider. Thus the Japanese high energy physics community chose the construction of a large linear collider (called the Japan Linear Collider, or JLC) as its highest-priority project for the future. Research and development toward the design of such a machine has occurred at KEK for more than a decade. Two major areas of current accelerator R&D at KEK include the technologies needed to generate high-quality beams in an injector complex and high-power microwave technology required for the main linear accelerators.



Layout of the Accelerator Test Facility built at KEK as a prototype injector system for the JLC. Accelerator physics research is being conducted on this facility by an international collaboration with the goal of developing the technology of ultralow-emittance beams.

Because its particle bunches encounter another bunch only once, a linear collider must achieve very narrow beams (several nanometers thick for the JLC) at the interaction point in order to provide sufficiently high luminosities required for the intended physics research. Therefore KEK physicists made key contributions to the Final Focus Test Beam project at SLAC, which succeeded in squeezing a 50 GeV electron beam down to a thickness of only 60 nanometers. Its advanced magnet system performed as designed by Katsunobu Oide, while Tsumoru Shintake pioneered a new technique to measure such narrow beams using laser interference fringes.

One major improvement remaining to be demonstrated before a TeV linear collider can be built is the quality of the beams entering the final focus system. They must be sufficiently narrow and have small enough angular divergence so that the final focus magnets can compress the beams down to nanometer thicknesses. The injector systems must generate such high-quality beams and the main linacs must accelerate them to their final energies while maintaining the beam quality.

Clearly the injector system will be a key part of the JLC, determining the ultimate performance of its colliding beams. The KEK Accelerator Test Facility (ATF) was constructed in a large hall about the size of a football field; its purpose is to pioneer the state-of-the-art techniques needed to generate multibunch beam with unprecedentedly low emittance. (This is the conventional measure of beam quality, representing a one-standard-deviation divergence from the forward direction in the velocity vectors of individual particles in each bunch.) The principal components of the ATF are an electron source, a 1.54 GeV injector linac (operating at a microwave frequency of 2.9 gigahertz), an injection beam transport line, a 1.54 GeV damping ring, and an extraction line. In addition, various diagnostic instruments are included to measure beam performance. Much of the work on the ATF—from its design to current operations and research—has been done as an international collaboration with SLAC, PAL (Korea), IHEP (China), DESY (Germany), CERN (Europe) and BINP (Russia). In addition, university teams from Tohoku, Tohoku-Gakuin, Tokyo-Metropolitan, Tokyo-Science, Yokohama-National, Nagoya and Kyoto have been playing an increasingly important role in the project.

Since its speedy commissioning in autumn 1995, the injector linac has served as a facility for studying high-power microwave technology as well as production, acceleration, handling, and monitoring of various kinds of electron beams. It now routinely operates at an accelerating gradient of 30 MeV per meter—almost *twice* that of the Stanford Linear Collider and TESLA Test Facility. As an injector to the damping ring, this linac must generate a beam that is stable in energy, intensity, trajectory and size. Most of the early R&D work concerned improvements on these aspects. A drift in beam energy was suppressed by introducing an energy-feedback system based on information about the beam position at the transport line, and by stabilizing the temperature of the cooling water used in some of the klystrons. In addition, physicists and engineers have completed a systematic investigation of the stability of individual accelerator elements.

Another important goal was to show that one can stably compensate for the energy spread caused by the effects of multibunch beam loading. When a sequence of closely spaced bunches traverses an accelerating structure, each bunch carries away a small amount of electromagnetic energy; latecomers therefore suffer from successively larger losses in acceleration. In order to compensate for these deficits, two short accelerating structures with slightly offset resonant frequencies were included in the linac. The bunches passing through them are accelerated on the slope of the traveling electromagnetic wave—not its crest—in such a way that later bunches are accelerated more strongly. Tests performed with trains of 20 bunches spaced 2.8 nanoseconds apart successfully reduced the bunch-to-bunch energy spread to only 0.3 percent, thus verifying that this frequency-shift method works well in practice. Another way to compensate for beam loading is to feed amplitude-modulated microwave power into ordinary accelerating structures; preliminary tests have shown that this principle works well, too.

The goal of the damping ring is to generate a beam with ultralow emittance within a storage time brief enough to handle the successive beam trains coming from the injector linac. Circulating electrons (and positrons) exhibit oscillatory transverse motions known as betatron oscillations. Upon deflection by bending magnets, these particles emit synchrotron-radiation photons, thus losing a bit of their longitudinal and transverse momentum. But in passing through accelerating cavities every orbit, they regain the longitudinal component, thus narrowing the beam ever so slightly. After many orbits, the subtle imbalance between these losses and gains lowers the emittance exponentially to an equilibrium value independent of initial conditions.

The ATF damping ring was designed to reach a very low equilibrium emittance—about a *hundredth* that of conventional storage rings and a tenth that of advanced synchrotron-light sources. Eight multipole wiggler magnets were included in the ring to boost radiation damping by forcing the beam to oscillate in short steps. All round the ring's 140 meter circumference there are many

A portion of the Accelerator Test Facility Damping Ring. High precision alignment of individual components is important, although an automatic beam-based alignment system will ultimately be used.

small magnets in addition to the wigglers and microwave cavities. Its vacuum chambers have inner diameters as small as 24 millimeters in the arc sections and only 12 millimeters high at the wigglers—considerably smaller than the dimensions of conventional storage rings. But they are still large compared to the dynamic beam aperture arising due to nonlinear effects in an ultralow-emittance ring. Highly sophisticated beam control is naturally called for in such a situation, and the present ring is equipped with almost a hundred button-electrode systems to measure the bunch positions at every turn.

A team of physicists led by Junji Urakawa commissioned the ATF damping ring (see photograph above) in January 1997. After dealing with initial hardware problems, they established a sequence of successful operations from injection of a beam into the ring, its storage with the microwave cavities on, and extraction from the ring. So far, they have attempted only single-bunch operation at about 1 Hz repetition rate. Serious accelerator-physics research began six months after commissioning ended. To model the ring precisely, physicists conducted a systematic study in which they gave the beam small electromagnetic kicks and measured corresponding changes in the downstream orbit; the latest measurements agree well with calculations. These data are then used to adjust the field intensity of individual magnets. An automatic optimization procedure, using a similar beam-based alignment appoach, is about to become effective. Emittance damping times of 19 milliseconds (horizontal component) and 30 msec (vertical) have been observed with the wigglers off, in good agreement with design values. The damping time is expected to drop to 10 msec or less with the wigglers turned on.

A conventional synchrotron-light monitor was sufficient for measuring the beam profile in early stages of the research. But as machine tuning improved, this approach had to be abandoned due to the limited capability of such a monitor. As the beam gets very small, on the other hand, its synchrotron light begins to reveal a spatial coherence corresponding to the decreasing source size. Thus Toshiyuki Mitsuhashi developed and introduced a synchrotron-light interferometer that records the interference fringes formed behind a double slit. The size of the source is deduced from how the fringe contrast varies with the slit separation. So far the beam size has been measured (at a specific point in the ring) to be 39 μm wide and 15 μm high, compared with 40 μm and 6 μm expected from beam optics and the design emittance. Therefore the ring has essentially reached its design goal of 1 nm-rad—at least as far as the horizontal emittance is concerned. This conclusion was confirmed by measurement of an extracted beam, after correcting for beam jitter and spurious dispersion. The vertical emittance should be substantially smaller, as it is primarily determined by betatron coupling associated with magnet misalignments. Current estimates of this emittance, based on the beam-size measurement mentioned above, are about four times larger than the design value, although with a fairly large uncertainty.

After the first, hectic year of research at ATF, physicists have come close to achieving the ultralow-emittance beam needed for the JLC. At the same time, it has become increasingly clear that, even with a well-designed accelerator, stability and resolution are key issues. After scheduled improvements in these aspects, single-bunch operations will continue for some time before we move on to multibunch operation. Our immediate objectives are to achieve reliable, high-precision, one-shot and turn-by-turn beam measurements and to reach ultralow vertical emittance.

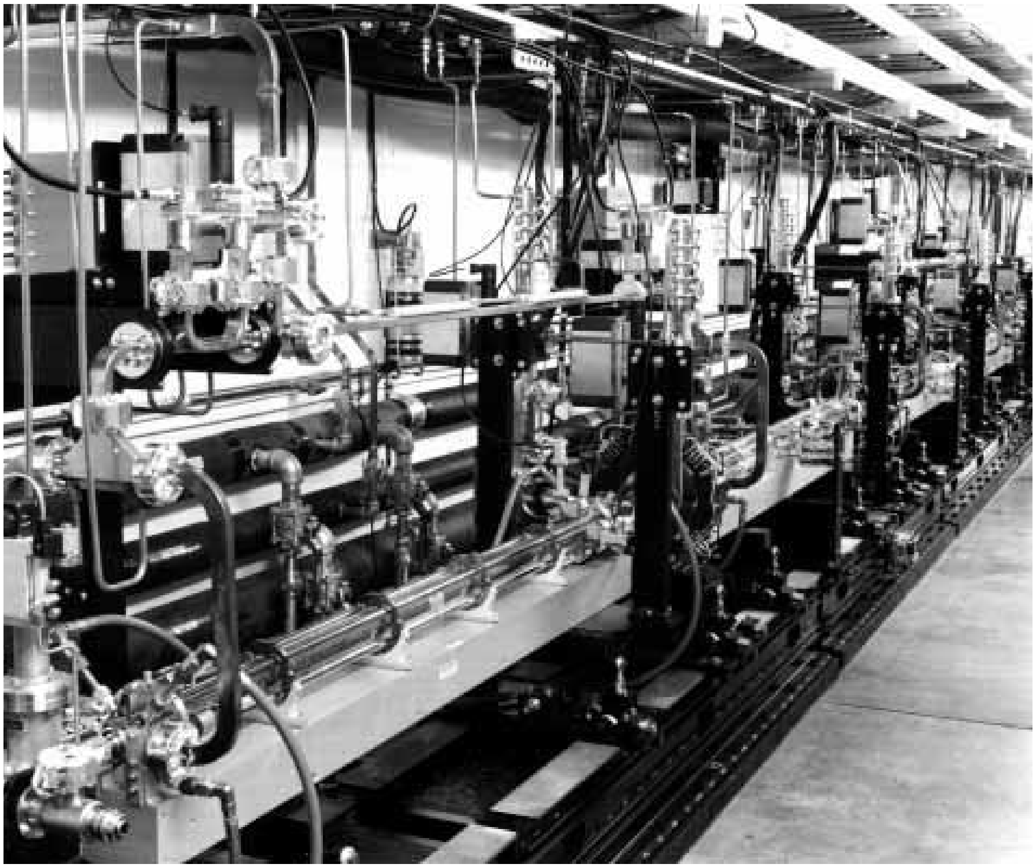
The Next Linear Collider Test Accelerator

by THEODORE LAVINE

THE NEXT LINEAR COLLIDER now under design consists of two independent linear accelerators aimed head to head, one for electrons and the other for positrons. Each accelerates its beam to hundreds of GeV, providing sufficient collision energy to create exotic new states of matter. The goal is to collide 250 GeV beams in the first few years of operation and to be able to support eventual upgrades to 500 GeV or more. To attain these beam energies with linear accelerators of reasonable length, we must achieve very high accelerating gradients. We need to learn how to generate microwaves of sufficient peak power to achieve the gradients, while keeping average power and operating cost down. And we must preserve the high quality and narrow energy spread of the beams during the acceleration process.

A linear-collider R&D program underway at SLAC and KEK has developed a new generation of microwave power sources and high-gradient accelerators equal to these tasks. As part of this program, the Next Linear Collider Test Accelerator (NLCTA) has been operating at SLAC since 1996 as a full-system test bed for these technologies. NLCTA is a high-gradient linear accelerator (linac) with its own dedicated electron injector. The accelerator structures and the microwave power systems that energize them are engineering prototypes for the linacs of a full-scale collider.

The forefather of the NLCTA linac is the three-kilometer-long SLAC linac, built in the early 1960s utilizing the 10.5 cm wavelength (S-band) klystron amplifiers and accelerator



The NLCTA linac currently has four 180 cm long accelerator structures installed between focusing magnets.

structures developed at Stanford during the 1940s and 1950s. Improvements in the klystrons powering the linac led to a continuous series of upgrades from the original, 24 megawatt (MW) tubes to 67 MW tubes developed in the 1980s—boosting the SLAC beam energy from 16 GeV in 1966 to 50 GeV today.

For the Next Linear Collider (NLC), accelerator designers have elected to use an X-band wavelength of 2.6 cm. The accelerator structures in the NLCTA are prototypes developed specifically for this shorter wavelength, which boosts the achievable gradient and reduces the cross-sectional area of the accelerator structure. The shorter wavelength also lowers the microwave filling time of the structure from 1 microsecond to 0.1 microsecond, reducing the needed microwave pulse length. While the SLAC linac achieves a gradient of 20 million volts per meter (20 MV/m), the NLC linacs will reach 50 MV/m for the same average electric power consumption (about 10 kW per meter of accelerator) at 120 pulses per second.

But many of the technical challenges for building the new accelerator and its power sources grow with the gradient because higher peak power is needed. The SLAC linac requires peak power of about 12 MW per meter of structure, while the NLCTA requires 50 MW per meter to achieve a gradient of 50 MV/m—or 100 MW/m to achieve 70 MV/m.

MAKING THE GRADIENT

The X-band klystrons for the NLCTA are the result of a decade of R&D on high-power klystron technology at SLAC. Each klystron generates 50 MW pulses of microwave radiation. As presently configured, the NLCTA operates with three 50 MW klystrons, each of which energizes a pair of accelerator structures. The energy in each klystron pulse is compressed to produce the full 200 MW required to achieve the 50 MV/m gradient in the pair.

The primary technical challenge of pulse compression is storing the microwave energy with low loss for the duration of the klystron pulse. The solution developed in the 1970s to boost peak power in the SLAC linac was to store the energy in oversized, cylindrical copper cavities. A major difference in the NLCTA is that the shorter microwave pulse length now makes it possible to use extended microwave transmission lines for low-loss energy storage. After the klystrons shut off, each storage line continues to discharge its pulse until the last part of the wave has traversed the entire line.

With higher peak power comes the challenge of handling stronger electromagnetic fields in the waveguides and other components that supply power to the accelerator structure. The NLCTA components are able to handle the peak power as a result of years of careful microwave engineering design and testing. Initial prototypes that suffered from electrical breakdown were redesigned to reduce the field strengths.

The accelerator structures were developed jointly by SLAC and KEK. Considerable attention went into copper-processing and machining techniques needed to achieve clean, smooth surfaces capable of sustaining high field gradients without emitting stray electron currents that can disturb the primary beam. Even after fabrication and installation, the internal surfaces of the structures must be conditioned by an aggressive regimen of high-power microwave processing to reduce surface emission.

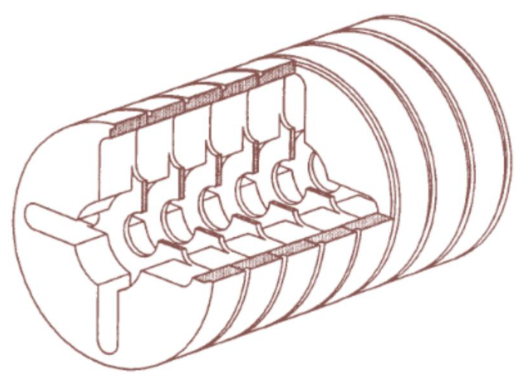
In 1997 we achieved the primary goal for the NLCTA power system: the NLCTA linac operated stably at the design gradient of 50 MV/m with tolerable electron emission. The maximum beam energy at this gradient (with four 180 cm structures and two 90 cm structures installed) is 450 MeV. The achievable energy at the design current is only 350 MeV because of beam loading.

Our next goals are to generate and test stable accelerating gradients up to 70 MV/m, which requires twice as much peak power. The first steps of this program are complete. A single 50 MW klystron (and pulse compressor) has been used to push the accelerating gradient in a single structure (not a pair) to 70 MV/m, and one of the klystrons has been operated at 75 MW (by increasing its high voltage). The next steps will be to use two klystrons to generate the 70 MV/m gradient simultaneously in a pair of structures and to test the stability of acceleration in that configuration.

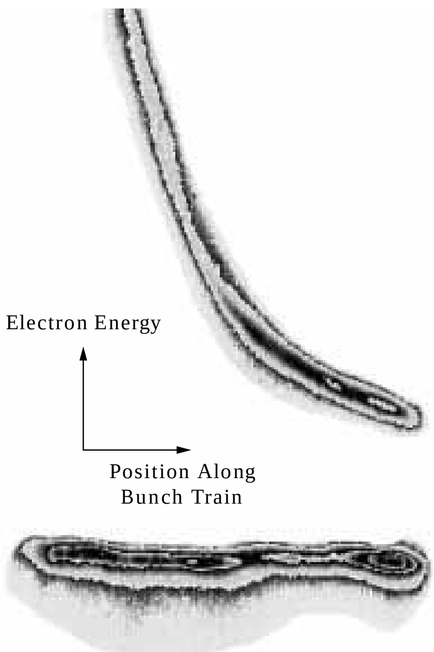
BUNCH TRAINS

In order to accelerate enough current on each machine pulse to create the event rates required for high-energy physics experiments, the NLC will accelerate a long train of 100 bunches, rather than a single bunch, on each microwave pulse. A challenge that designers face is the transverse instability that arises because a bunch can be deflected by the electromagnetic fields (wake fields) created by slight but inevitable offsets of preceding bunches from the central axis of the accelerator. The small size of the accelerator apertures for the 2.6-cm wavelength exacerbates this problem.

All the NLCTA structures are designed to suppress these wake fields by varying, in a precise pattern, the internal dimensions of the 200 cells that comprise a 180 cm structure; this spoils the coherence of the set of microwave modes that would otherwise contribute to the wakefield. The diameters of the irises in such a "detuned" structure vary from 8 to 11 mm. Two of the structures further suppress beam deflection by damping the undesirable modes by channeling them through slots that lead to microwave absorbers. Joint work at SLAC and KEK has developed the design techniques and manufacturing methods necessary to achieve



Cutaway view of part of a damped and detuned accelerator structure (top). The structure is fabricated from a stack of cells similar to the one shown above.



Digitized images of NLCTA beam spots showing the energy variations along the train of electron bunches. The images show the correlation of electron energy with position along the 36 meter long train. When the microwave pulses are not modulated (upper image), the electron energy drops off along the train by about 15 percent, approaching an equilibrium value that corresponds to steady-state beam loading. But when the microwave pulses are modulated to compensate for the transient beam loading (lower image), the energies of the electrons along the entire train are uniform to withn a few tenths of a percent.

the close tolerances needed for these damped and detuned structures.

The NLCTA injector makes trains of 1400 electron bunches spaced 2.6 cm apart. The strategies of detuning and damping have worked, for without them the accelerator structures could not transmit these trains. The future NLC injectors will probably distribute the same total charge into one-eighth as many bunches, spaced eight times further apart. Nevertheless, based on the stability of bunch trains in the NLCTA, we can predict stability in the NLC because the deflecting forces are proportional to the ratio of bunch charge to spacing, which will be the same.

Uniform acceleration of all the bunches in each train is required because only electrons and positrons within a narrow energy range (tenths of a percent wide) can be focused at the collision point. One of the most significant tests completed on the NLCTA has been to show that the bunch-to-bunch variation of energy along the train can be kept this small. This is a significant issue since, under the wrong conditions, the leading bunches in a train can extract too much microwave energy from the accelerator structure, and the trailing bunches will come up short. One strategy for achieving uniform acceleration is to fill the structure with microwave energy in a profile that matches what would occur behind an infinitely long train, so that all the bunches that follow get the same acceleration. The desired profile has been obtained by modulating the microwave pulses before the klystrons amplify them. With this approach, the energies of the electrons along the entire bunch train come out the same within a few tenths of a percent, as desired.

There are other potential applications for the NLCTA. A group at the Stanford Synchrotron Radiation Laboratory and SLAC has considered modifying the NLCTA to drive an X-ray free-electron laser into self-amplified spontaneous emission. The NLCTA can also be used to generate 2.6 cm microwaves or higher harmonics by decelerating the beam in resonant cavities or structures inserted in the beam line. Physicists from Harvard and SLAC are using the beam to excite 3.3 mm waves (the eighth harmonic of 2.6 cm) in a cavity with an aperture 1 mm in diameter. In future experiments, they plan to use a structure 25 mm long to excite 3.3 mm waves at multi-megawatt peak power levels and use them to generate accelerating gradients perhaps greater than 100 MV/m. Such high gradients are possible at these short wavelengths, but they raise the challenges of power levels, field strengths, and instabilities to new heights. These experiments with short, 3.3 mm wave structures will test advanced concepts for accelerators in the era beyond the NLC.

The experience gained by operating the NLCTA has been critical for understanding the performance and reliability of the complete systems of power sources, microwave components, and structures to be used in the NLC linacs. Future modification will continue to test new prototype components. Other applications as an experimental tool for studying accelerator and beam physics are only beginning to be exploited.

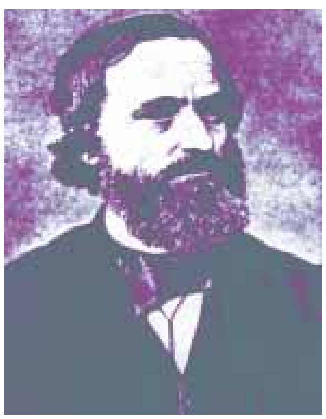
Part II
Can't You Keep Einstein's Equations Out of My Observatory?

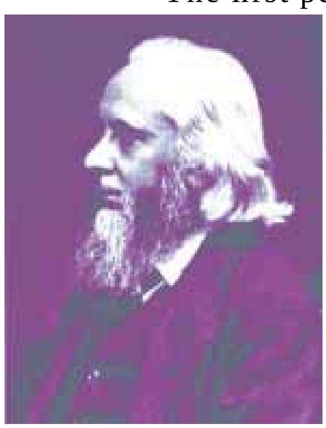
by VIRGINIA TRIMBLE

Part I of Virginia Trimble's two-part article was published in the Spring 1998 issue of Beam Line, *Vol. 28, No. 2. It can be accessed from our Web site at* http://www.slac.stanford.edu/pubs/beamline.

SPECTROSCOPY AND THE RISE OF ASTROPHYSICS

Our ability to recognize the chemical elements from their patterns of emission or absorption lines dates from 1859, when chemist Robert W. Bunsen (who had a burner) and physicist Gustav R. Kirchhoff (who had an assortment of laws) joined forces in Heidelberg to show that sodium in the laboratory mimicked a pair of yellow lines in the spectrum of the sun (called "D" by Fraunhofer and also by modern astronomers).





Gustav Kirchhoff, above, and Sir William Huggins, right. (Courtesy Yerkes Observatory and Lick Observatory, respectively)

The first people to aim their spectroscopes at the sun, stars, and nebulae were richly rewarded when (as described by Sir William Huggins) "nearly every new observation revealed a new fact, and almost every night's work was red-lettered by some discovery." (Huggins' own discoveries included the gaseous nature of many nebulae that had formerly been regarded as dense crowds of stars.) This was very different from the astrometry, celestial mechanics, and practical astronomy that generations of classical astronomers had labored over their equations and transit circles to accomplish. And it was correspondingly unwelcome among much of the existing community. Two reactions, one from each side of the Atlantic:

The Victorian astronomer royal, Sir George Biddle, declared that

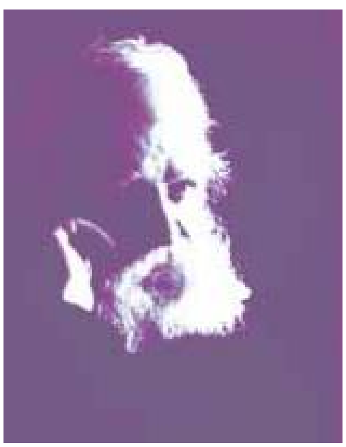
> what astronomy is expected to accomplish is evidently at all times the same . . . rules by which the movements of the celestial bodies, as they appear to us upon the earth, can be computed. . . . All else which we may learn respecting these bodies . . . possesses no proper astronomical interest.

Seth Chandler, a member of the National Academy of Sciences and calculator of comet orbits and Earth's polar motion, opined that the work of astrophysicists "will disappear like smoke in the air" and its "authors will lie in forgotten graves." Both were pontificating in the 1890s, and the bitter feelings between practitioners of traditional astronomy and of the new astrophysics nearly fractured the community and darkened efforts to form a single professional society (eventually the American Astronomical Society, but only after several iterations on names).

It was a rather motley crew of people with backgrounds in medicine, brewing, chemistry, physics, the silk trade, and occasionally even traditional astronomy who came rather quickly to constitute the community of solar physicists (by about 1870) and astrophysicists (by about 1890, with the *Astrophysical Journal* founded in 1899). Among the items they offered back were the discovery of the first element in a new column of the periodic table (helium; Jules Janssen at the eclipse of 1868), the demonstration of the existence of metastable atomic levels with exceedingly long radiative lifetimes ("nebulium" explained by Ira Bowen in 1927), and, down to the present time, accurate wavelengths and energy levels for molecules difficult or impossible to study in the laboratory. HCO^+ (initially X-ogen) and HC_9N are among those first seen in interstellar gas.

Left, Cecilia Payne Gaposchkin. The second edition of Cecilia Payne Gaposchkin *(ed. K. Haramundanis, Cambridge University Press, 1996) contains roughly equal numbers of her own words and those of friends and family. Right, Henry Norris Russell, who was, of course, the R of the HR diagram as well as the originator of the (very transient) giant and dwarf theory of stellar evolution. Judging from a 1939 conference photo, the two were exactly the same height. (Courtesy Yerkes Observatory)*

Quantitative spectroscopy was built upon two equations, named for Ludwig Boltzmann and M. N. Saha. These describe the fraction of atoms that ought to be in various states of excitation and ionization as a function of kinetic temperature (yes, I also offer egg-sucking lessons for grandmothers). The astronomical hero* here is Cecilia Payne (later Payne Gaposchkin), who, in her 1925 Harvard PhD dissertation applied the equations to the line spectra of stars of various colors (temperatures) and concluded, first, that nearly all stars have



Left, Jules Jansson (1824–1907) depended on temporary scientific jobs and stipends for his living until 1865, when his contributions to spectroscopy were recognized with an appointment to the chair of physics at the Ecole Speciale d'Architecture in Paris. He reached the eclipse of 1870 after escaping by balloon from beseiged Paris, only to be clouded out in Oran, North Africa. (Courtesy Yerkes Observatory) Right, Ira S. Bowen about 1968. For many years he was director of the Hale (Palomar and Mt. Wilson) observatories. (Courtesy Hale Observatories)

Personal taste still inclines very strongly to "heroine," for I can remember when the girl cast as Louise in Carousel accidentally said to the barker, "I want to be an actor," and it got a giant laugh. But modern usage seems to have abandoned the feminine forms for authors, actors, poets, and so forth—so, I suppose, also for heroes.

much the same chemical composition, and, second, that this is heavily dominated by hydrogen and helium, at least in the surface layers. So improbable did this dominance seem (remember Eddington) that the sun was allowed to have as much as 7 percent hydrogen only in 1929 when Henry Norris Russell applied the same equations and 75 percent (by mass) only in the late 1940s. Until then, the official excuse for the strong hydrogen lines was "anomalous excitation conditions," that is, a flat refusal to believe Boltzmann and Saha.

RELATIVELY SPEAKING

Each year, the annual meeting of the American Association for the Advancement of Sciences brings forth a coven of audience members who do not believe in special relativity. None, as far as I know, is currently employed as an astronomer, though one or two were in the past. Nor do I know exactly what they mean, because each year one of them starts the question period by saying that there are alternative explanations of the Michelson-Morley experiment, and I, or whoever is at bat at the time, start by answering that our confidence in special relativity does not today rest primarily on experiments from the nineteenth century. They then say that there are other explanations for everything else as well. And the chairman then says that further discussion will have to be deferred until after the session is over. Anyhow, all recent considerations of acceleration of particles to high energy, whether in the lab or in cosmic sources, of radio emission from jets moving at close to the speed of light, and all the rest have special relativity built in. It is even done correctly much of the time.

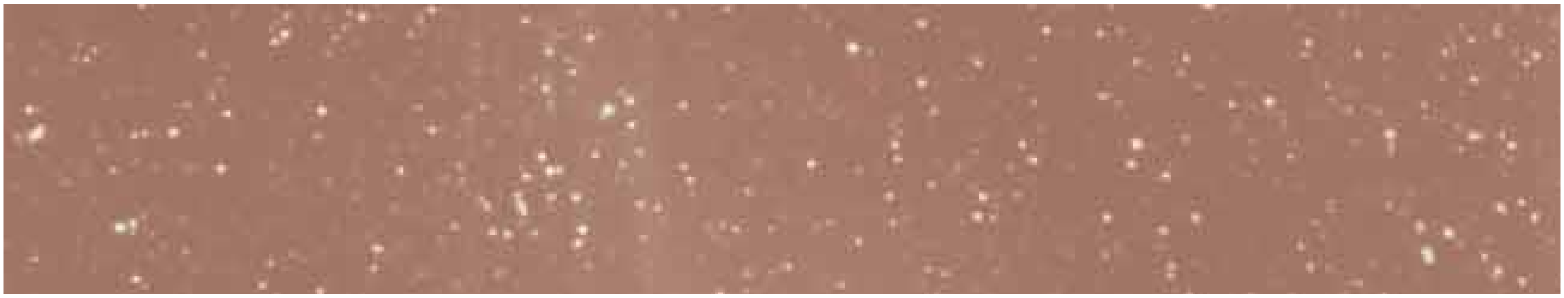
Karl, the elder Schwarzschild, published fundamental work on the analysis of stellar atmospheres, stellar kinematics, comet tails, and many other subjects as well as deriving the solution to the Einstein equations that bear his name. He also inspired H. Rosenberg (1910 Astron. Nach. 186, 71) to draw the very first example of what we now call a Hertzsprung-Russell diagram. (Courtesy Yerkes Observatory)

General relativity has a more checkered history. There was initial enthusiasm from at least parts of the astronomical community. Karl Schwarzschild devised the solution of the Einstein equations that still bears his name to describe the space-time around a spherical or point mass. Eddington undertook to make sure there were astronomers at the right places in 1919 to look for the deflection of light during a solar eclipse. There were and they did. The precise quality of the data has been debated on and off ever since; but it doesn't matter. The observation has been repeated and improved many times, especially at radio wavelengths, where you don't have to wait for an eclipse.

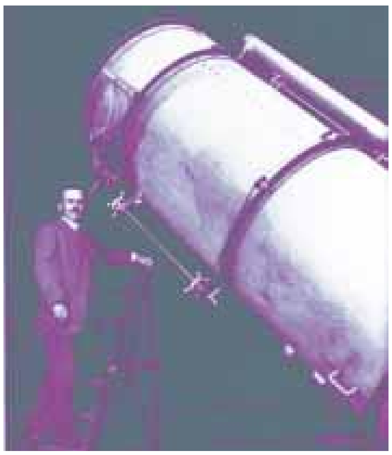
Thus, at the founding of the International Astronomical Union in 1919, one of the Commissions was devoted to General Relativity. Its founding president was Levi-Civita (who had a tensor). But, a couple of General Assemblies later, the Commission was disbanded for lack of need and interest, and GR did not come back to the IAU until 1970, with the establishment of Commissions on Cosmology and High Energy Astrophysics (meaning quasars, pulsars, and such).

Between 1916 and 1929, solutions of the Einstein equations to describe the Universe as a whole came from several people. Willem de Sitter (whose universe was expanding but empty) had previously worried about how to extract numbers for the mass of Mercury, the dipole moment of the earth, and similar Newtonian quantities from astronomical objects. Alexander Friedman(n) (whose universes contained ordinary matter and still expanded) was a man of many parts, mostly meteorological, and all sadly short-lived. Georges Lemaitre independently found one of the expanding models and also wrote down (as part of his PhD dissertation) what we now call the Tolman-Oppenheimer-Volkoff relativistic equation of state, useful for neutron star models.

After the 1929 announcement of the redshift-distance relation (Hubble's law or "the expansion of the Universe") other physicists and mathematicians, including



R. C. Tolman and H. P. Robertson, took up examination of the cosmological solutions and their implications. But their work was not somehow perceived as being part of mainstream astronomy. Even some of the people whom you might have expected to display great enthusiasm were doubtful. Hubble himself never took a strong stand in favor of cosmic expansion over tired light (proposed by Fritz Zwicky in 1929). Heber Doust Curtis, defender of the existence of external galaxies in the Curtis-Shapley debate of 1920, "never had much use for that fellow Einstein," according to Ralph Baldwin, one of his later students. And not all the early conversions were permanent. Sir William H. McCrea, who was writing about relativistic cosmology and Newtonian analogs as early as 1931, has recently expressed doubts about the correctness of the whole picture of a relativistically expanding universe.



Heber D. Curtis at the Crossley telescope, some time before 1921, when he left Lick Observatory to take up the directorship at Allegheny. Time has shown that Shapley and Curtis were right about roughly equal numbers of issues in their 1920 debate. Doust rhymes with "soused," according to Ralph Baldwin. (Courtesy Lick Observatory)

But an astronomer cannot evade GR forever. The first revival came with the discovery of quasars, leading to the invention of a subdiscipline called "gravitational collapse and other topics in relativistic astrophysics." Then came pulsars and X-ray emitting neutron stars. These forced us to think about how matter should behave in deep gravitational potential wells and how the radiation would come out. Today there are binary pulsars whose orbit evolution is precisely described by Einsteinian relativity and by no other combination of physics. And, as our telescopes have seen to larger and larger redshifts (5.64 is the record this afternoon), converting the fluxes and colors you see to energies and time scales is so model dependent that you have to assume some particular version of an expanding universe to make any sense at all of your data.

At the moment, the largest number of people earning their precarious livings by checking each others' relativistic calculations are probably the students and postdocs attempting to predict the gravitational radiation signal that should be seen by LIGO and its European cousins (a) when they are built and (b) when neutron stars collide. Most of these people do not think of themselves as astronomers, or even astrophysicists. Rather, they are part of the subset of members of the American Physical Society who recently formed a Topical Group on Gravitation, apparently because the larger Division of Astrophysics did not feel like home.

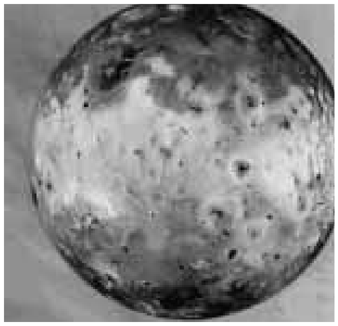
POSTMODERN PHYSICS

Like most things, interaction between astronomy and particle physics started just a little earlier than most of us noticed.* The year 1965 saw not only the discovery of the cosmic microwave background (by radio engineers!) but also the first calculation of a limit on neutrino rest masses from cosmological considerations and an explication of the conditions needed if we are to have more baryons than anti-baryons in the Universe, with credit to Zeldovich and Sakharov respectively.

An obituary of David Schramm mentioned that there had been a time when he was just about the only astronomer in the world interested in neutral currents and the correct form of the weak interaction (because of their role in driving supernova explosions). Still earlier in the 1970s, however, came the realization that model stars would evolve to match a particular observed class of hydrogen-poor red giants only if we included what was then called "the universal Fermi interaction." The idea came from Bohdan Paczyński, then in Warsaw, but I co-authored one of the relevant 1973 papers, so the "we" for once does not mean Queen Victoria.

More recently, non-baryonic dark matter, GUTS, axions, WIMPs, inflation, supersymmetry, and so forth have glutted the literature to the point where your desire to

**Would you believe that the first telecast from the Metropolitan Opera was March 10, 1940?! No, I wasn't there; but I did see the first, 1951, televised* Amahl.



You might think that Io has very little to do with our topic. It is, however, the only body known to be more volcanically active than Earth and so must be useful at the interface between astronomy and geophysics, not otherwise mentioned here.

(Courtesy NASA)

read about it all again is surely even less than my desire to write about it (but see the Spring 1997 issue of *Beam Line*, Vol. 27, No. 1 if appetite should revive). And, naturally, mainstream astronomy has welcomed the collaboration with the same enthusiasm it extended to spectroscopy, relativity, and all the rest. For instance, a generally outstanding 1991 encyclopedia of astronomy mentions both dark matter and Io. But Io gets four pages, and dark matter only one.

The following paragraphs could have been written by many of the people who are primarily interested in Io, stars, and other traditional subjects (but I think you will be surprised at who actually wrote them).

> We understand the concern of cosmologists that unbridled speculation should not take over the field, that it is better to persist with the standard model, warts and all, than for opinions to become splintered, with the decline of professional standards which would then almost inevitably ensue.
>
> Our response to this point of view, with which we have some sympathy, is that undesirable fragmentation has been permitted already, through the invasion of cosmology by Particle physicists. If the invasion had the precision and the certainty of earlier invasions of astrophysics by atomic theory and nuclear physics, the consequences would obviously be positive. However, one can have reservations about the advantages of becoming caught up in speculations from a different field, especially when those speculations are announced with an air of authority that will probably turn out to have been taken too seriously.

Notice that the earlier inputs, rejected by our astronomical ancestors, have been accepted. Only the most recent is being resisted. But the real startler is that these lines come from the pens or word processors of Sir Fred Hoyle, Geoffrey R. Burbidge, and Jayant Narlikar, who have championed other ideas from outside the mainstream, particularly steady state cosmology and noncosmological redshifts.

L'ENVOI

What should one make of these curious histories? Perhaps we have merely uncovered another of those "irregular verbs," of the form, "I evaluate new ideas carefully. You are a bit of a stick-in-the-mud. He is slightly to the right of Genghis Khan." Or perhaps the last word belongs to Darius Milhaud, who is supposed to have said (concerning music, of course) that the advance guard of today is the rear guard of tomorrow.

SOURCES & SINKS

THE FACTALS in the preceding pages and Part I came from many sources, most lost in the mists of time, but the victims of the most extensive plagiarism are the following:

Henry Norris Russell, Raymond Smith Dugan, and John Quincy Stewart, *Astronomy* (in two volumes) 1926, Ginn. & Co. Boston. This was the standard astronomical textbook for about twenty years.

George Ogden Abell, *Astronomy* (4th edition) 1982, Saunders College Publishing, a second-generation textbook.

Edward Harrison, *Darkness at Night*, 1987, Harvard University Press. Deals mostly with Olbers' Paradox.

Stephen P. Maran (Ed.) *The Astronomy and Astrophysics Encyclopedia*, 1991, Van Nostrand.

John Lankford, *American Astronomy*, 1997, Harvard University Press. Mostly about people.

Karl Hufbauer, *Exploring the Sun*, 1991, Johns Hopkins Press. Recounts the development of solar physics from Galileo to the present time.

More on the difficulties astronomers and astrophysicists had in getting together in the 1890s to found a society will appear in the centenary volume of the American Astronomical Society edited by David DeVorkin and scheduled for 1999 publication.

The quote from Hoyle, Burbidge, and Narlikar appears in *Monthly Notices of the Royal Astronomical Society* 286, 173 (1997).

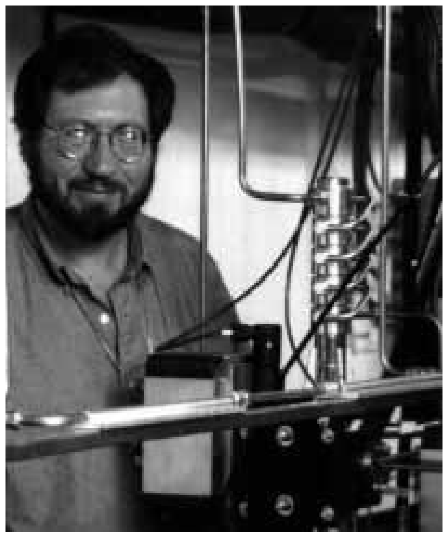
CONTRIBUTORS

MICHAEL SCHMITT received his PhD from Harvard University in 1991. He spent six years as a member of the ALEPH Collaboration at CERN, working first with Sau Lan Wu (Wisconsin) and later as a staff member. His physics interests ranged from the properties of tau leptons and *B* hadrons to searches for supersymmetric particles. In 1998 he joined the faculty at Harvard University and has become an active member of the CDF Collaboration at Fermi National Accelerator Laboratory, where he pursues Higgs searches while preparing a large section of the muon system for the next Tevatron run.

MAURICE BOURQUIN is Director of the University of Geneva particle physics department. After initial research at CERN for his PhD at Geneva, he became Research Associate at Columbia University and a member of Leon Lederman's group working at Fermilab. From 1974–1983 he returned to the University of Geneva, where he worked on hyperon experiments at CERN. Since becoming a full Professor at Geneva, he has worked on the MARKJ experiment at DESY, the L3 experiment at LEP, and most recently the AMS experiment for the Space Shuttle and the International Space Station. He is a member of the Swiss National Science Foundation's National Research Council and a Swiss delegate to CERN Council.

GORDON FRASER has been Editor of the CERN Courier for a long time. While a research student at London's Imperial College in the mid-1960s, he wrote short-story fiction as a respite from theoretical calculations and became side-tracked into journalism. He returned to physics as a science writer, eventually transferring to CERN. He is co-author, with Egil Lillestøl and Inge Sellevåg, of *The Search for Infinity* (New York, Facts on File, 1995) which has been translated into ten other languages; author of *The Quark Machines* (Bristol, Institute of Physics Publishing, 1997); and Editor of *Particle Century* (Bristol, Institute of Physics Publishing, 1998). He is currently writing a new book—*Antimatter*—and is a visiting lecturer in science communication at several UK universities.

SEIGI IWATA is Deputy Director of the Institute of Particle and Nuclear Studies and Head of the JLC Promotion Office at the High Energy Accelerator Research Organization (KEK). He received his undergraduate degree from Tohoku University and his PhD from the University of Tokyo. His involvement in collider physics began at CERN on the Intersecting Storage Rings. Then he served as the leader of the TPC subsystem and co-spokesperson for the TOPAZ experiment at the TRISTAN collider. Since 1988 he has been Director of the Physics Department at KEK.



THEODORE LAVINE has worked on developing high-power microwave pulse compression and other approaches for generating high peak power for linear colliders since he joined SLAC's Technical Division in 1987. He was responsible for the design and construction of the microwave energy compression system for the NLC Test Accelerator and has been responsible for operations and safety since the beginning of the project in 1993. He currently leads the Project Planning and Coordinating Group in the NLC design team.

He received his PhD from the University of Wisconsin in experimental particle physics working at SLAC on a PEP experiment.

VIRGINIA TRIMBLE of the University of California, Irvine and University of Maryland has now been writing regularly for the *Beam Line* for about 10 percent of her life. This spot has previously held pictures taken by her father, the late chemist Lyne Starling Trimble. This one is courtesy of her husband, physicist Joseph Weber. He is, as you can see, a "leg man." You may also be able to deduce that she is fond of books and turtles and tends to hang on to things, including father's ROTC hat, grandmother's papier maché elephant, and Mardi Gras beads from the New Orleans meeting of the Sigma Xi (from whose board of directors she has just retired).

DATES TO REMEMBER

Jun 7–18	Workshop on Physics at TeV Colliders, Les Houches, France (aurenche@lapp.in2p3.fr *or* belanger@lapp.in2p3.fr)
Jun 7–Jul 9	ICTP Summer School in Particle Physics, Trieste Italy (ICTP, Box 586, Strada Costiera 11, I-34100, Trieste, Italy *or* smr1141@ictp.trieste.it)
Jun 14–19	7th International Conference on Supersymmetries in Physics (SUSY 99), Batavia, Illinois (Cynthia Sazama, MS 122, Fermilab, Box 500, Batavia, IL 60510 *or* sazama@fnal.gov)
Jun 14–25	US Particle Accelerator School at Argonne National Laboratory, Argonne, Illinois (USPAC at Fermilab, MS 125, Box 500, Batavia, IL 60510 *or* uspas@fnal.gov)
Jun 27–30	12th IEEE International Pulsed Power Conference, Monterey, California (Teresa Montero ppc99@llnl.gov)
Jul 7–16	27th SLAC Summer Institute on Particle Physics: CP Violation in and Beyond the Standard Model, Stanford, California (Lilian DePorcel, SLAC, Box 4349, Stanford, CA 94309 *or* ssi@slac.stanford.edu)
Aug 9–14	19th International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California (by invitation only, Maura Chatwell, SLAC, MS 96, Box 4349, Stanford, CA 94309-4349 *or* lp99@slac.stanford.edu)
Aug 30–Sep 10	CERN Accelerator School Course on Accelerator Physics, Benodet, France (CERN Accelerator School, AC Division, 1211 Geneva 23, Switzerland, *or* suzanne.von.wartburg@cern.ch)
Sep 6–10	11th General Conference of the European Physical Society: Trends in Physics, London, England (Institute of Physics, Meetings and Conferences Dept, 76 Portland Pl, London W1N 4AA England *or* physics@iop.org)
Sep 12–25	CERN School of Computing, Stare Jabloniki, Poland (Jacqueline Turner, CERN School of Computing, CERN, 1211 Geneva 23, Switzerland, *or* computing.school@cern.ch)
Sep 21–24	International Workshop on Performance in Improvement of Electron-Positron Collider Particle Factories, Tsukuba, Japan (Yoko Hayashi, Secretary, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801 Japan *or* hayashiy@mail.kek.jp)
Oct 13–15	11th US National Synchrotron Radiation Instrumentation Conference, Stanford, California (Suzanne Barrett, Conference Administrator, SSRL, MS 99, Box 4349, Stanford, CA 94309-0210, *or* barrett@ssrl.slac.stanford.edu)