Fermi National Accelerator Laboratory

1997

> Fermi National Accelerator Laboratory advances the understanding of the fundamental nature of matter and energy by providing leadership and resources for qualified researchers to conduct basic research at the frontiers of high-energy physics and related disciplines.
>
> —Fermilab Mission

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From the Director

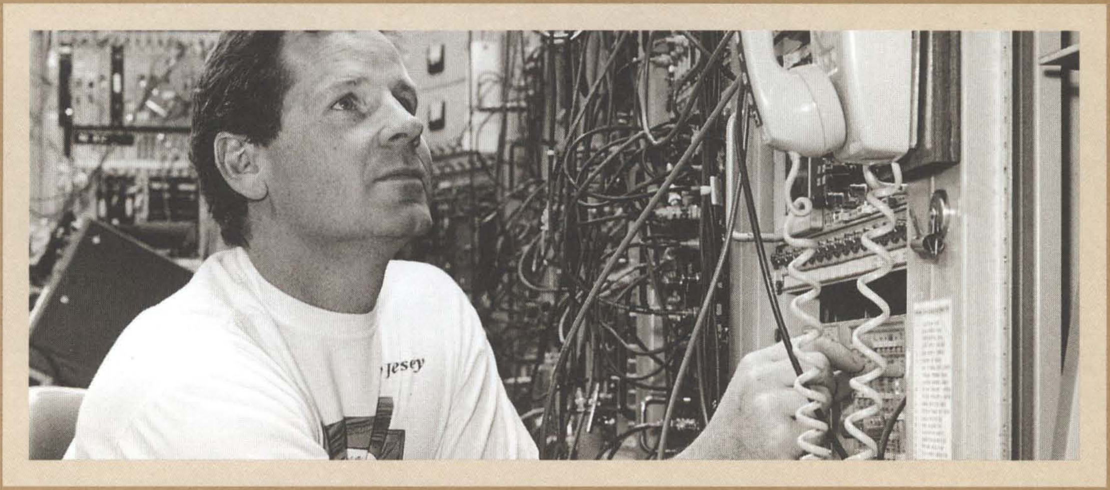
From the time human beings first began asking questions about the world around them, they have wondered about the nature and origins of the universe. Where did we come from? How small is the smallest piece of matter? How do all the pieces fit together? Today, scientists at Fermi National Accelerator Laboratory are using some of the most advanced research tools ever devised to explore these fundamental questions.

At Fermilab's Tevatron particle accelerator, physicists use beams of protons and antiprotons accelerated to the highest energies in the world as powerful probes of the smallest known particles of matter, the quarks inside the proton of the atom's nucleus. Intricate particle detectors weighing thousands of tons allow scientists to explore the ultimate particles and forces of the universe, both now and at the moment it began.

Thousands of university scientists from about 100 U.S. universities and 90 foreign institutions collaborate on experiments at Fermilab, a Department of Energy national laboratory. Universities Research Association, Inc., a consortium of 86 research universities, operates Fermilab under a contract with DOE. The 30-year partnership between universities and government at Fermilab has helped make the United States a world leader in the field of particle physics.

Discoveries of the past few years have given us a clearer understanding of matter and energy, but many critical questions remain: What gives the particles of matter their property of mass? Why is there more matter than antimatter in the universe? What is the dark matter that accounts for so much of the universe that we cannot see? Are there particles and forces that we have not yet discovered? In the years ahead, Fermilab's unparalleled facilities and scientific leadership will give physicists the best opportunity in the world to continue to explore these questions, in the ongoing search to understand the nature and origins of matter and energy, space and time.

JL Peoples



Dave McGinnis

Accelerator Engineer

Dave McGinnis has a vital intimacy with "the beam"—the stream of protons coursing through Fermilab's particle accelerators. He knows its tendencies and its idiosyncrasies; he knows when to help it along and when to leave it alone.

For fixed–target physics—in which the beam strikes stationary metal targets creating beams of secondary particles for research—a critical factor is intensity, reflected in the number of protons reaching the experiments. The more particles the experimenters receive, the more data they accumulate to gain new physics insights. McGinnis's job, quite simply, is to use his intimacy with the beam to cajole the intensity higher and higher.

In 1996, along with his team of engineers and technicians, the nine–year Fermilab veteran developed two types of beam enhancement devices, dampers and bunch spreaders. These innovations kept the particle beam stable as more and more protons circulated in the machine. Accelerator operators widely credited McGinnis's devices as main contributors to the record–setting intensities of the 1996–97 fixed–target run at the Tevatron.

When discussing the dampers and spreaders, the straight-talking McGinnis, usually seen in his signature jeans and t–shirt, sidesteps credit, choosing to focus on his team and the ideas that came before his time at Fermilab and upon which he built his expertise. And while McGinnis's work will continue to take place in the trenches made of metal, electronics and cryogenics, his contribution will be seen in the experimenters' insight, papers and discoveries made possible by the beam he improved.

In 1996–97, Fermilab conducted its last extensive 800-GeV fixed-target run before saying good-bye forever to the historic Main Ring.

The April 19, 1996, issue of *FermiNews* was a symbolic edition. On page two, the Laboratory newspaper chronicled the journeys of the two collider detectors, CDF and DZero, from their collision halls to their assembly stations after nearly four years of hard work and the discovery of the top quark. The article on the facing page detailed the first full test of the detector system for the Kaons at the Tevatron (KTeV) experiment, one of the major studies of the fixed-target run that began in 1996 and ran through late 1997.

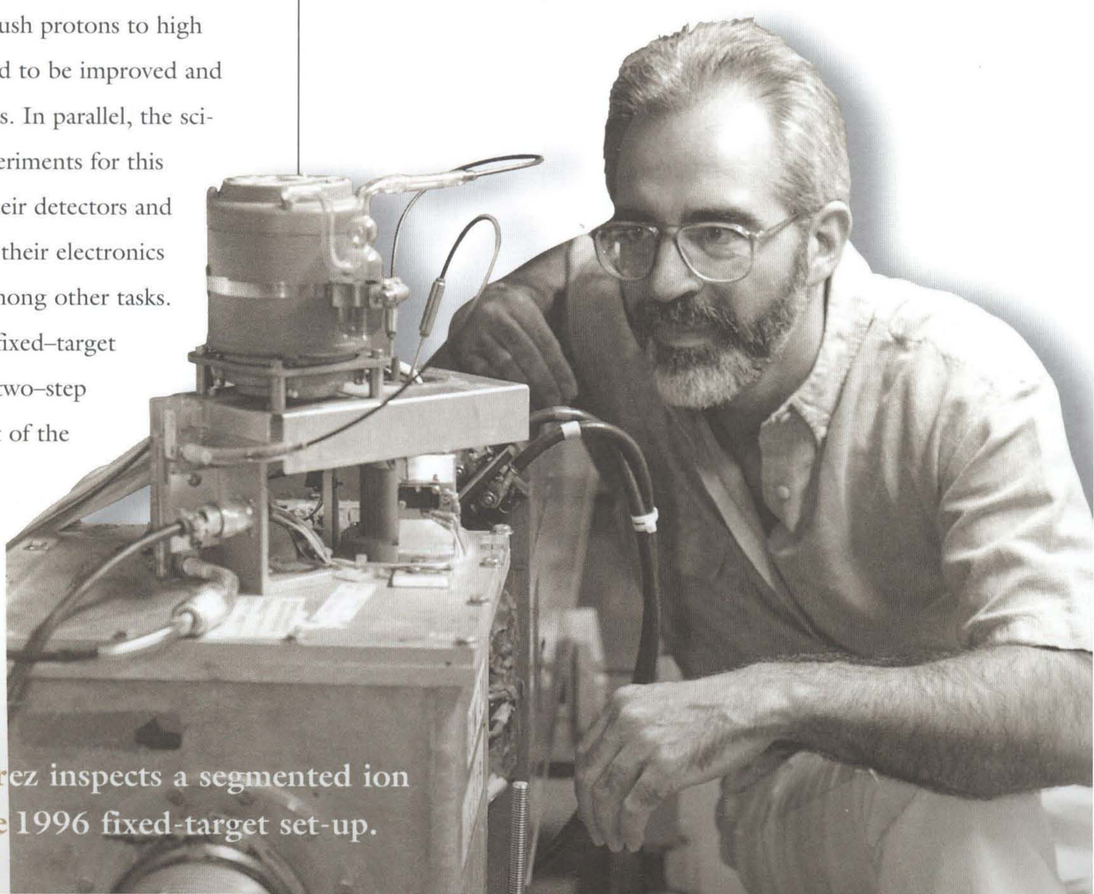
The transition from collider physics to the fixed-target style of operation was historic, because the 1996–97 800-GeV fixed-target run will be the last of its kind at Fermilab. Although the Laboratory plans to run a lower-energy fixed-target program in the future, this last series of experiments will in many ways close a chapter for Fermilab.

The 1996 transition unfolded along two paths. The series of accelerators that push protons to high energies for experimentation had to be improved and modified for fixed-target physics. In parallel, the scientists conducting the nine experiments for this fixed-target run had to build their detectors and beamlines and develop and test their electronics and data acquisition systems, among other tasks. The transition from collider to fixed-target physics was a familiar Fermilab two-step that reached its peak in the heat of the summer of '96.

IMPROVING THE ACCELERATOR

During the spring and summer of 1996, the Beams Division (known as the Accelerator Division before a fall 1996 Lab reorganization) met each Monday at 2 p.m. to discuss the progress of the changeover. Each shift of each day from the end of the collider run to the startup of the fixed-target run included complicated, choreographed tasks to complete the changeover.

Before the run began, Fermilab management presented the Accelerator Division with a challenge: Push the machine's intensity—or number of extracted protons—to a new record, allowing researchers to accumulate more data at a faster rate than ever before. The old intensity record stood at 1.8 x 10^{13} protons per pulse. The problem in raising intensity



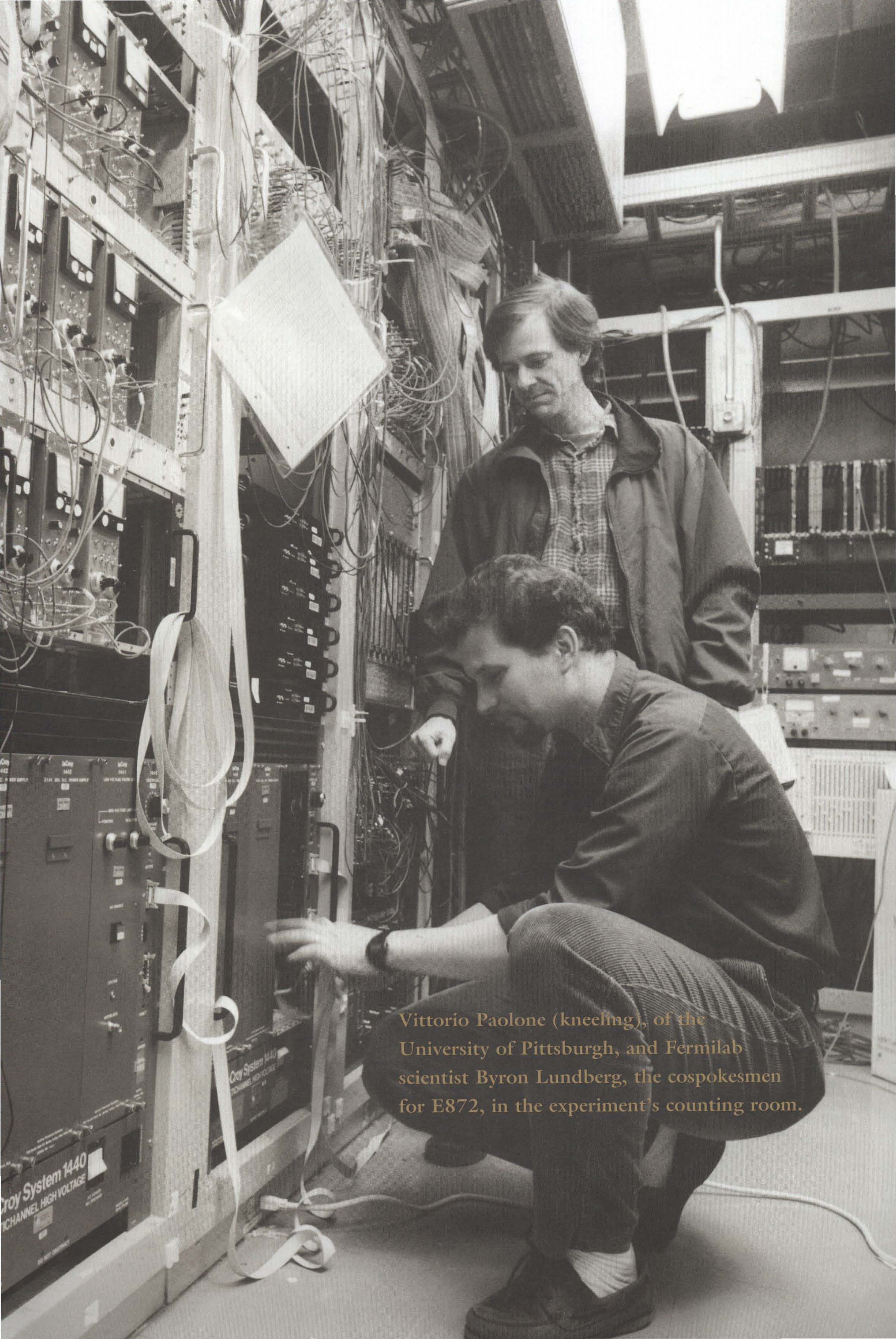
Fermilab's Gaston Gutierrez inspects a segmented ion wire chamber during the 1996 fixed-target set-up.

Craig Moore and Salah Chaurize, of the Beams Division, examine magnets in the Switchyard in May 1996.

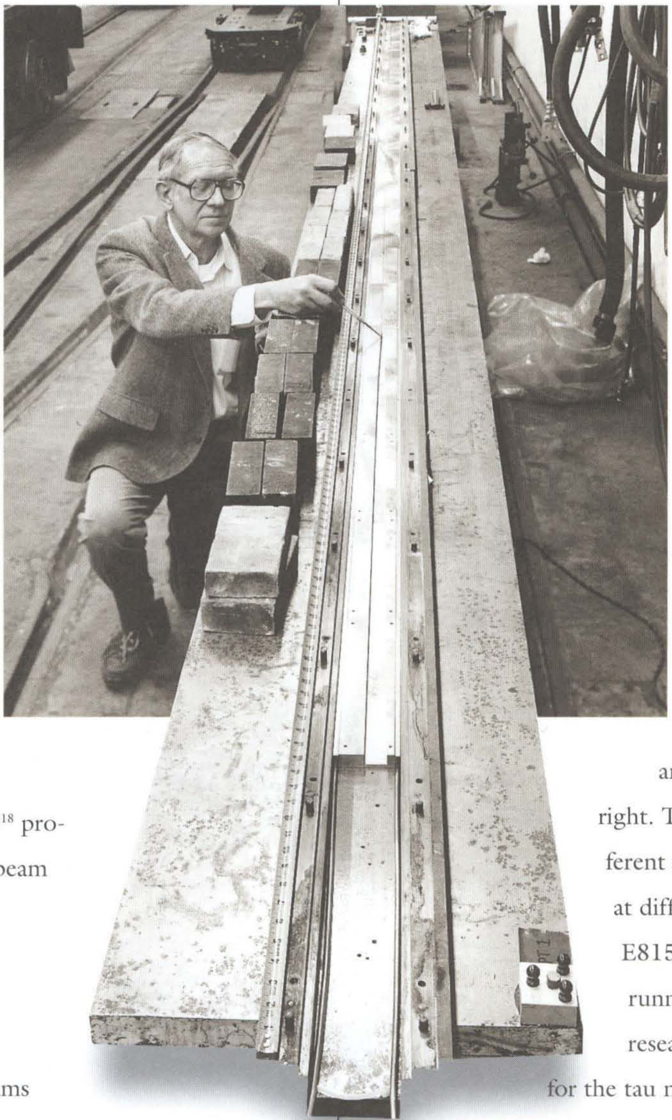
is that higher intensity in the machine generally makes for instability in the proton beam, causing it to wander from its designated path and eventually "blow out" of the beam pipe. This, in turn, shuts the accelerator down, bringing data collection to a halt. The perplexing question facing those intimate with the accelerator, simply stated, was how to raise the machine's intensity while keeping a stable beam for experimentation.

To meet the management challenge, the Accelerator Division tapped the skills and expertise of many accelerator physicists, engineers and technicians. Craig Moore, associate division head for systems in the new Beams Division, said many people and multiple factors contributed to the complicated task of improving the accelerator and making the transition to fixed–target physics. Mike Martens, head of the Tevatron Department in the Beams Division, led an effort that reduced beam loss, increasing the intensity. Martens and his team also found some misaligned Lambertson magnets in the superconducting accelerator. Dave McGinnis, along with his team of engineers and technicians, developed innovative beam enhancement devices that allowed the intensity to increase while retaining beam stability. Beamline specialists at Fermilab also vastly improved Fermilab's Switchyard, the area where the proton beam is split into several secondary beams for the experiments. One of the biggest challenges, according to Moore, was the "fast spill" the accelerator provided to the NuTeV experiment. In a fast spill, many high–energy protons are quickly extracted from the Tevatron, in contrast to the lower delivery rate of the slow spill that most experiments require. Moore said before this latest fixed–target run, Fermilab hadn't done high–intensity fast spills for nearly a decade. New hardware and software helped to achieve the fast spill at high beam intensity.

All of this work culminated in record-setting intensities in the accelerator. In early 1997, the machine set records for number of hours of high–energy physics beam time delivered in a week, intensity for a single pulse, average weekly intensity per pulse and total number of protons accelerated.



Vittorio Paolone (kneeling), of the University of Pittsburgh, and Fermilab scientist Byron Lundberg, the cospokesmen for E872, in the experiment's counting room.



Fermilab physicist Joe Lach works on a hyperon channel for E781.

"One of the few times that I have ever heard applause in an All–Experimenters' Meeting was on Monday [March 10, 1997] when Bob Mau [head of accelerator operations] gave these numbers," said Moore. "That was very gratifying, as a lot of people have worked long and hard over the last year to do this."

In the end, the Beams Division supplied 6.31 x 10^{18} protons and 5,767.3 hours of beam for the experiments.

FIXED-TARGET RUN

Setting up

The beneficiaries of the Beams Division's success with the accelerators were the hundreds of Fermilab scientists, university professors, postdocs and graduate students receiving the protons and secondary beams of particles for their experiments. However, before these researchers saw even one proton, they spent many months building their beamlines, detector halls and control rooms. Each collaboration worked countless hours to turn ideas and conceptual designs into working, efficient experiments. Collaborations marked progress in small steps, such as the positioning of steel, and in great leaps, such as the delivery and installation of major magnets. The researchers sighed in exasperation at setbacks and smiled when things went right. The experiments ran on different schedules and came on line at different times. For instance, E815, known as NuTeV, began running shifts in mid-May while researchers on E872, the search for the tau neutrino, were still installing their magnets and positioning steel. During the spring and summer of 1996, technical and engineering support was at a premium as all of the experiments worked to get up and running. The last experiment to begin taking data began in the spring of 1997.

Vassilios Papavassiliou, of New Mexico State University, checks equipment for his experiment, E866.

Running

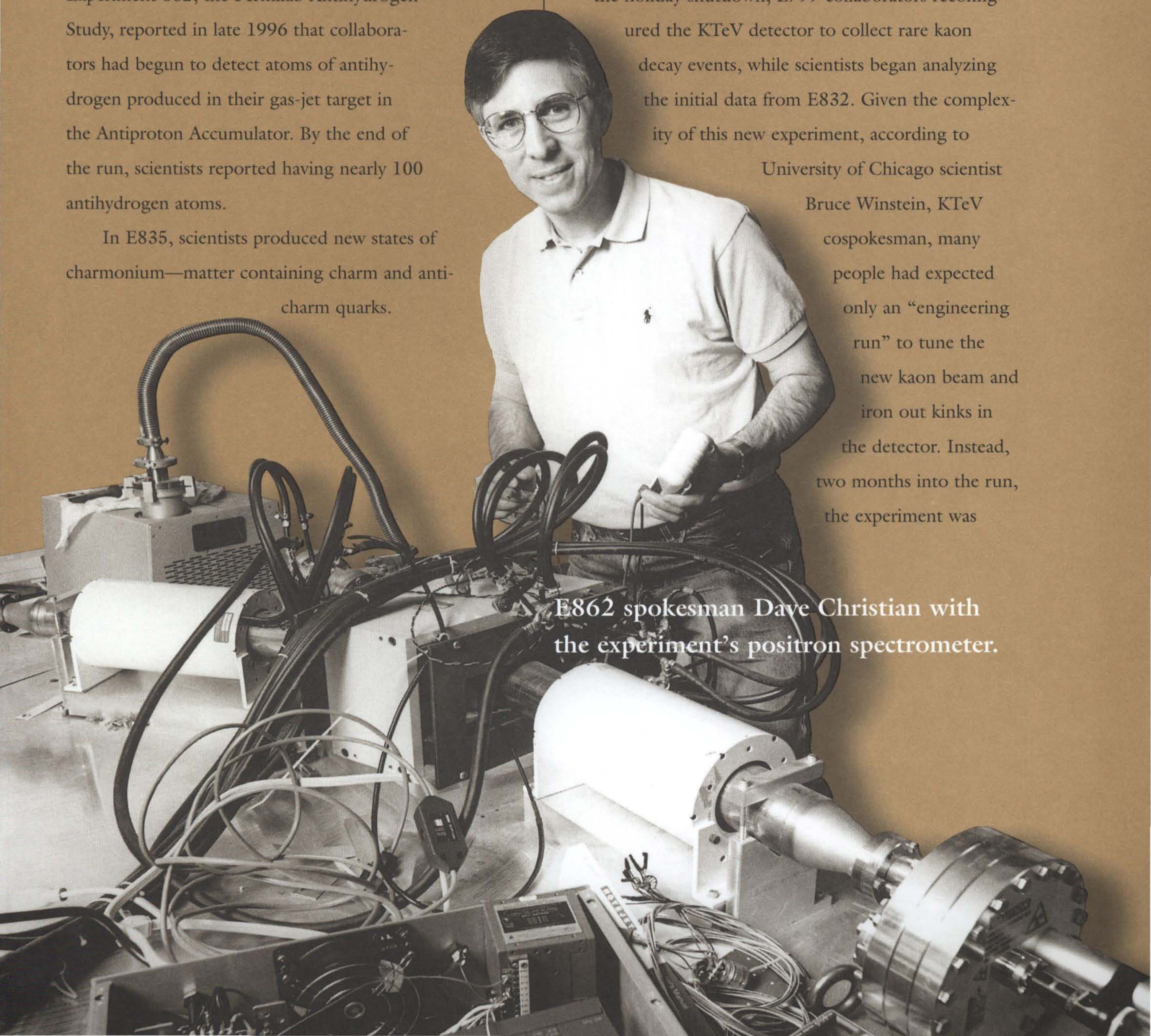
Once data began streaming in to all of the experiments, the Laboratory hit a stride of sorts. Experimenters ran their shifts 24 hours a day, seven days a week. Over the year of running, they spent their days and nights in the experiments' portakamps; in halls as cavernous as airplane hangars; in corridors stuffed with computers or crammed with logic units. They snacked on Twinkies during shifts.

They anguished over failing chips and channels and over signals that hadn't yet materialized. They repaired, installed, replaced, fiddled, adjusted and tuned. They reported, finally, operations so smooth as to be, in the words of one experiment's spokesperson, "wonderfully dull." And they shared those sunshot moments on shift when they witnessed the high-intensity pings—the signals of a neutrino slipping through the detector—or the signals of other long-awaited particles.

Although the bulk of the analysis is currently under way, some experiments reported early successes. Experiment 862, the Fermilab Antihydrogen Study, reported in late 1996 that collaborators had begun to detect atoms of antihydrogen produced in their gas-jet target in the Antiproton Accumulator. By the end of the run, scientists reported having nearly 100 antihydrogen atoms.

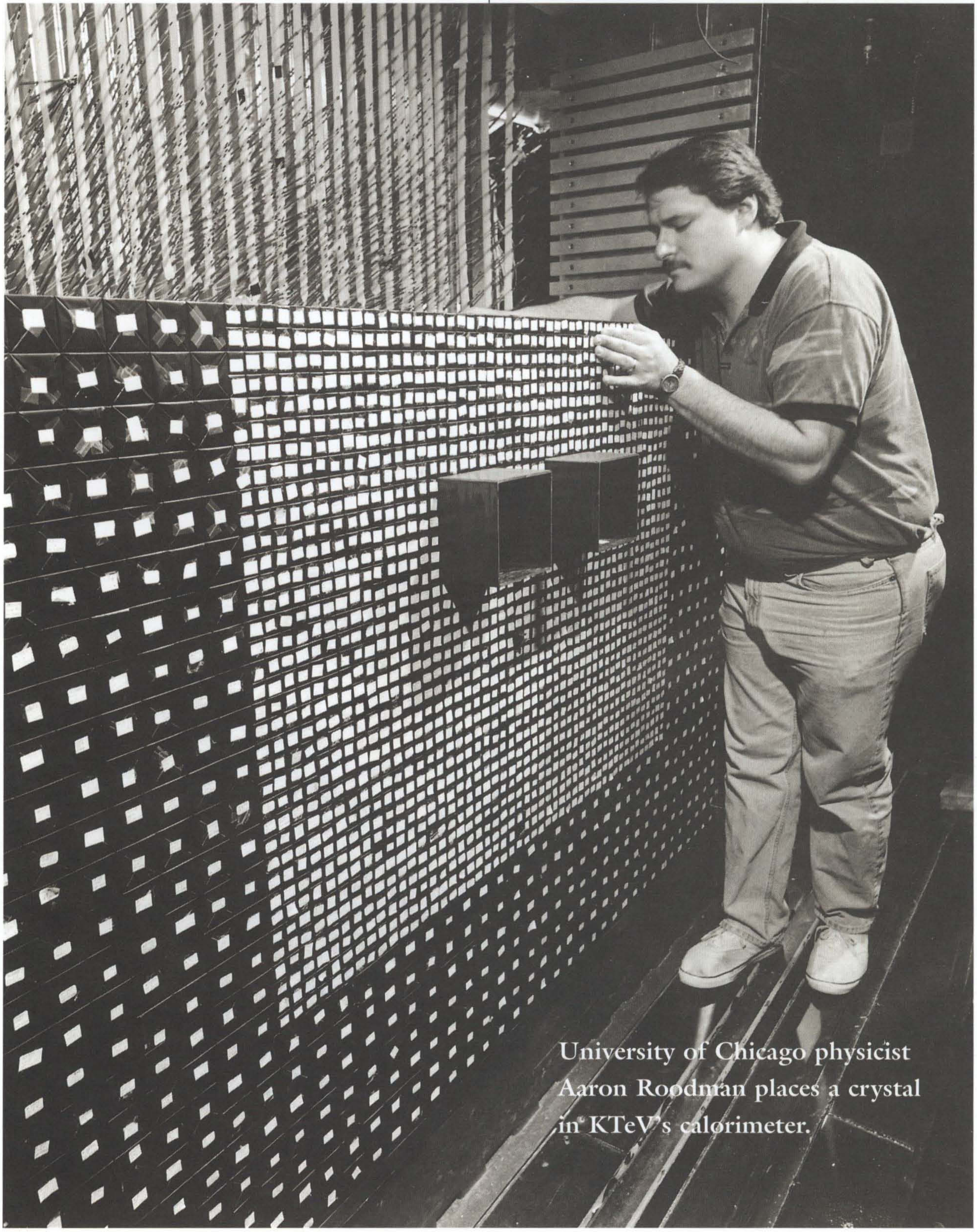
In E835, scientists produced new states of charmonium—matter containing charm and anticharm quarks. Collaborators forced protons to collide with antiprotons at a 90-degree angle in E835's detector. By precisely tuning the antiproton beam's energy, the experimenters detected charmonium in a small fraction of the interactions. They will begin analyzing their data for insights into the strong interactions binding the quarks—and, meanwhile, hope for "fame and glory," quipped collaborator Stephen Pordes of Fermilab.

By the 1996 holiday shutdown, KTeV collaborators reported collecting more than 1.3 billion kaon decay events, in the E832 portion of the study. After the holiday shutdown, E799 collaborators reconfigured the KTeV detector to collect rare kaon decay events, while scientists began analyzing the initial data from E832. Given the complexity of this new experiment, according to University of Chicago scientist Bruce Winstein, KTeV cospokesman, many people had expected only an "engineering run" to tune the new kaon beam and iron out kinks in the detector. Instead, two months into the run, the experiment was



E862 spokesman Dave Christian with the experiment's positron spectrometer.

collecting near-perfect data—thanks to equipment that remained faithful to design specifications. The detector eventually returned to its E832 mode, and, as of this writing, the experimenters have submitted their first results to Physical Review Letters.



University of Chicago physicist Aaron Roodman places a crystal in KTeV's calorimeter.

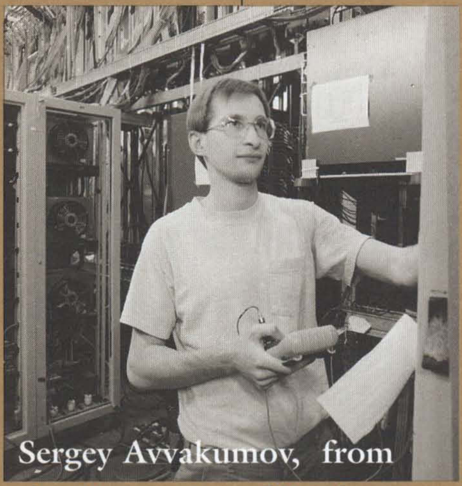
The cornerstone of the NuTeV experiment, E815, is the precise measurement of the weak mixing angle. When a neutrino and a nucleon interact, they exchange either a *W* or a *Z* boson, which are the carriers of the weak force. The ratio of these exchanges is related to the weak mixing angle. This information will tell scientists about the nature of the electroweak force. There are already measurements of the weak mixing angle, but experiments like E815 continue to narrow the margin of error, said experiment spokesman Bob Bernstein.

E866, which peered inside the proton at the "sea" of quark-antiquark pairs, has already published preliminary results. With negligible statistical and systematic error, experimenters measured the asymmetry of up and down antiquarks—the first such measurements in the world. Evidence had hinted at an asymmetry in these two lightest quarks, and E866 found that, as previously suspected, antidowns outnumber antiups.

E868, searching for signs of decay in antiprotons, achieved sensitivities of up to one million years for some decay modes—and, fortunately for the charge-parity-time-reversal invariance theorem, still found no decay. According to the CPT theorem, antiparticles should behave no differently from their corresponding particles. Steve Geer, the experiment's spokesperson, said the CPT theorem is still safe for the time being.

With a more efficient detector than a previous experiment had used and with increased beam intensity, E831 manufactured, as planned, over a million fully reconstructed decays of charm particles. To put it another way, the experiment compiled more than a million states of matter combining one or more charm quarks with light quarks (the strange, up and down). It is the largest such inventory in the world, giving the experimenters a distinct advantage over other physicists studying charm—and a better chance of observing certain rare phenomena associated with the strong and electroweak forces.

At the outset, E781 scientists were wondering whether their experiment was working at all. In designing their search for charm, said spokesman Jim Russ of Carnegie-Mellon University, they had carefully simulated the number of particles that would be detected, but when the beam turned on, they got twice as many particle "hits" as predicted. That meant twice as many events to be recorded, requiring twice as much computer space to store the information. Finally in April, the experimenters figured out how to handle the data overload—and figured out, too, that they hadn't "messed up," said Russ. In the end, the spectacular resolution in mass and time parameters amazed everyone.



Sergey Avvakumov, from the University of Rochester, checks drift chamber voltages for his experiment.

Experimeters in E872 are hoping to observe the tau neutrino. While firmly entrenched in the Standard Model the elusive particle has never been directly observed. Vittorio Paolone, cospokesman for E872, said two factors persuaded researchers to go after the tau neutrino. The first, quite simply, was to find the mysterious particle and understand its properties. Second, the experiment is a precursor to the NuMI project, the search for neutrino mass.

While many fixed-target experiments can process and analyze data as the information is collected, the tau neutrino scientists have to wait for awhile to see if they have success. The researchers had to complete the full run before removing the emulsion modules integral to the detection process. While scientists in the U.S. will analyze most of the data in the standard

Physicist Merrill Jenkins, of the University of South Alabama, works on E871.

electronic detectors, Japanese collaborators have taken the emulsion back to Japan for development, processing and analysis of its contents. Only by analyzing and comparing the information in all of the detectors will the scientists know if they have the tau neutrino in their grasp.

E871 looked for evidence of CP violation—that tiny flaw in nature's mirror that has bequeathed us more matter than antimatter—by comparing the decay parameters of hyperons and antihyperons, particles similar to protons. E871 recorded about 60 billion events to tape, said Craig Dukes, cospokeman for E871 and a University of Virginia researcher.

COMPUTING

During 1996, the Computing Division developed and subsequently implemented a new project to help the fixed–target experiments acquire, process and analyze data. All of the fixed–target experiments except two used the new data acquisition system, the product of a years–long collaboration between experimenters and Computing Division staff. The DART system, as it is known, ran smoothly for the fixed–target run, a tribute to the ability of the researchers to put their own specialized needs aside and take on the challenge of building one system to acquire and process the voluminous data generated by all of the experiments. Other Computing Division efforts involved networking upgrades in the fixed– target area to provide higher bandwidth for transmission of data from the experiments' counting rooms to the Feynman Computing Center; preparation for handling data after they arrived; increases in the capacity of the data-processing farms and in the use of robotic storage; the purchase, testing and diagnostics of new computing equipment for the experiments; and the reconditioning of existing equipment.

"Data acquisition problems were hardly mentioned during reports in the weekly experimenters' meeting—a testimony to the robustness of the DART system," said Ruth Pordes, project manager for DART. "The increased online scrutiny of the data collected, and the increased sensitivity of this round of experiment, placed more stringent requirements on the performance of various front-end modules."

SAYING GOOD-BYE

On September 5, 1997, the beam to the fixed-target area was cut, and on September 15, in a bittersweet ceremony, Fermilab shut off the beam to the historic Main Ring for the last time.

Physicist Robert Wilson, Fermilab's founding director, broke ground for the Main Ring on October 3, 1969. The first beam circled its four-mile circumference in 1972, and the Main Ring reached its peak operating energy later that year. For nearly a decade, thousands of researchers used the beam for dozens of experiments that helped uncover the mysteries of matter and energy in our universe. In 1977, physicist Leon Lederman used the Main Ring's beams in experiments that revealed the bottom quark, the first quark of the third generation of elementary particles that are nature's ultimate building blocks. Since 1983, the Main Ring has served as an injector to the Tevatron, Fermilab's superconducting accelerator, the highest-energy particle accelerator in the world.

"For twenty-five years, the Main Ring has been an essential part of our scientific program," said Fermilab Director John Peoples. "Now it is time to say farewell to the Main Ring. It is a moment to celebrate the Main Ring's past, and to prepare for the future."

Steve Holmes and Cathy Newman-Holmes

Physicists and Parents

First thing most mornings, Steve Holmes, Main Injector project manager, and Cathy Newman-Holmes, co-project manager for the CDF upgrade, talk about scheduling problems. They discuss conflicts in priorities, task assignments and deadlines that must be met.

Is a section of the CDF collider detector upgrade not progressing as hoped? Is construction on the Main Injector being held up? Actually, this particular meeting, taking place in the kitchen of the Holmes family, concerns getting their son, Eric, from school to his karate lesson. It's one step in a logistical dance Cathy and Steve, married 15 years, perform daily, as they attempt to coordinate family responsibilities and manage critical upgrades to Fermilab facilities.

Working with more than 400 scientists from 40 institutions spread among six countries, Cathy sweats the big picture and small details regarding CDF's upgrade, including the budget and schedules. She said the most difficult challenge is orchestrating numerous groups of scientists that are not part of a strict hierarchy. Moreover, each institution is working on a different part of the detector and is separated from the others by geography. Talk about logistics.

Conversely, Steve coordinates the activities of about 150 Fermilab staff members, all working somewhere on the site. With the Main Injector project about 80 percent complete, Steve said his team is at a critical stage, as Fermilab has entered a year-long Tevatron shutdown with many tasks to accomplish.

Both Steve and Cathy said the demands of work and family have increased as their daughter Stephanie, 14, and Eric have grown, and as the two physicists have progressed in their careers. However, they said the rewards of family life, with the added opportunity for directly influencing Fermilab's future, make those meetings in the kitchen worth every minute.

Fermilab continues to improve its physics tools and capabilities with innovative developments and efficient management, positioning the Laboratory for the next decade and beyond.

Like tomorrow, the goal of particle physics never arrives; it's always a day—or an accelerator—away.

The field of high-energy physics has its collective gaze ever fixed on the future, on the spot just over the horizon, where the next step forward in technology will make possible the next generation of experiments to explore the next new theoretical territory. Particle physics advances by the complex relationship of theory, experiment and technology, all moving forward together, by lurches and leaps, discoveries and missteps, beyond the horizon into the unknown. The work of accelerator physicists is never done; there is always the next accelerator to build, and the next one after that. For Fermilab, that next accelerator is materializing on the Lab's southwest quadrant in the form of a 2.25-mile ring, known as the Main Injector.

Civil construction continued in September 1996 on the 8-GeV line connecting the Booster to the Main Injector.

The Main Injector, which will begin operating by 1999, will greatly increase the luminosity of the Tevatron, resulting in many more collisions per second at the Lab's two collider detectors, thus greatly enhancing Fermilab's research capabilities.

As the fixed-target set-up and data-taking ran full bore during most of 1996 and 1997, Lab employees, users and contractors continued working on the Main Injector construction and the collider detector upgrades. The fixed-target run and upgrade work often ran concurrently, requiring carefully orchestrated accelerator operations, strict work schedules and more patience than usual from scientists. Laboratory managers shut the beam down occasionally, allowing the Main Injector crews to finish a section of the tunnel or test components. At the same time, collaborators carefully picked apart the two collider detectors, which were fresh from the successful Run I. CDF, in particular, looked eerily clean, as collaborators stripped away its signature wires, tubes, electronics, circuits and other components, revealing its bare, hard outer shell. Crews built and razed "dirty" rooms for construction work, while technicians, wearing white lab coats and hair nets, hovered over delicate silicon detectors.

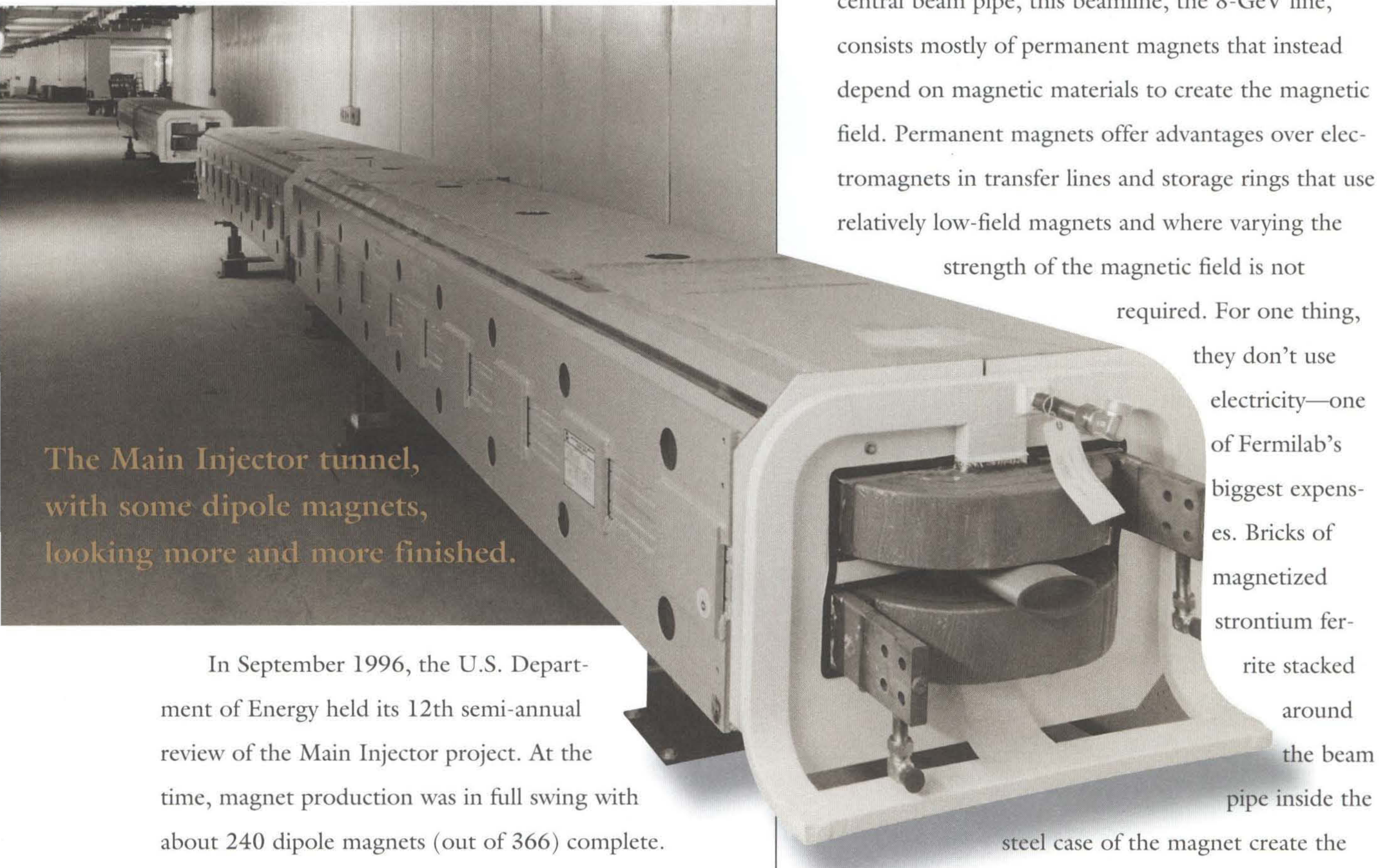
Fermilab's Bob Williams welds the final Main Injector dipole magnet.

And all involved were hurriedly working for deadlines that were, in some cases, years away.

MAIN INJECTOR CONSTRUCTION

The Main Injector construction progressed rapidly during 1996 and 1997. Large, empty trenches gradually filled with concrete tunnel segments, and workers transformed the Main Injector from a cold, dank tunnel to an atmosphere suitable for sophisticated and complex magnets.

In early 1996, construction crews continued to work on the 8-GeV beam enclosure connection that will couple the Booster to the 8-GeV transfer line needed to bring protons to the Main Injector. In late February 1996, the accelerator shut down for about 16 weeks to allow construction crews to finish the 8-GeV enclosure and connect with Fermilab's existing accelerators. Workers completed the 2.25-mile ring enclosure in July 1996 and the 8-GeV transfer line four months later.



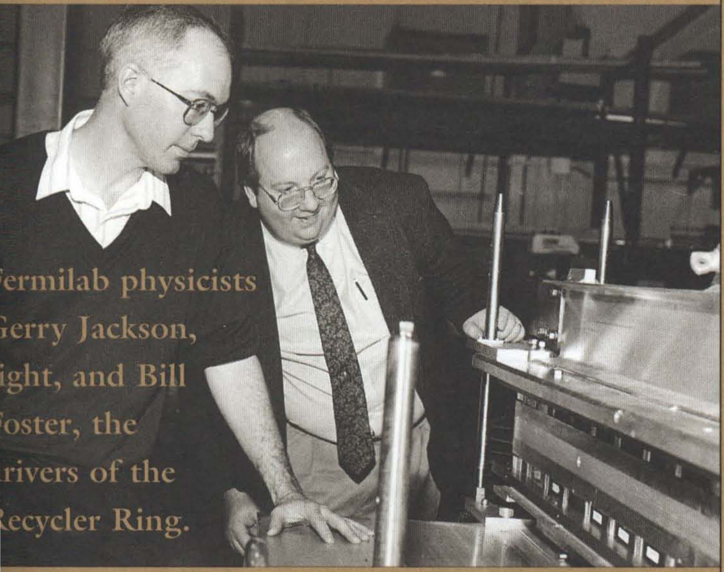
The Main Injector tunnel, with some dipole magnets, looking more and more finished.

In September 1996, the U.S. Department of Energy held its 12th semi-annual review of the Main Injector project. At the time, magnet production was in full swing with about 240 dipole magnets (out of 366) complete. Although the dipoles represent the most numerous type of magnet needed, quadrupoles, sextupoles, Lambertsons and trim magnets were rolling off the production lines as well.

Fermilab made accelerator history on a stormy night in February 1997 by sending a beam of particles down an accelerator beamline using a technology that no one had ever used on this scale for a beamline before: permanent magnets. Sending protons down beamlines is Fermilab's bread and butter. Accelerator operating crews have done it literally trillions of times. What made this attempt unique was the nature of the beamline itself. Instead of familiar electromagnets, wound with coils of wire to create a magnetic field for steering charged particles down a central beam pipe, this beamline, the 8-GeV line, consists mostly of permanent magnets that instead depend on magnetic materials to create the magnetic field. Permanent magnets offer advantages over electromagnets in transfer lines and storage rings that use relatively low-field magnets and where varying the strength of the magnetic field is not required. For one thing, they don't use electricity—one of Fermilab's biggest expenses. Bricks of magnetized strontium ferrite stacked around the beam pipe inside the steel case of the magnet create the permanent magnetic field. On that fateful day in February, the proton beam made it through the permanent magnets and struck a fluorescent tile, where a video camera recorded the flash; those involved celebrated with champagne.

Dixon Bogert, assistant project manager for the Main Injector, giving a tour to HEPAP subpanel members and DOE officials in the tunnel.

In July 1997, Fermilab completed construction of the 366 dipole magnets critical to the performance of the Main Injector and installed the final dipole in August 1997. The unusual production process for the dipole magnets—magnets that bend beams of high-energy particles around a ring—involved five vendors working closely with Fermilab staff. The Main Injector will have a total of 1,349 magnets, and the dipole magnets represent the most of any one kind in the accelerator. The dipoles account for approximately two-thirds of the total magnet cost, and will directly affect the performance of the machine.



ermilab physicists erry Jackson, ight, and Bill oster, the rivers of the ecycler Ring.

"The partnership [between Fermilab and the vendors] was extremely successful in that we built very high quality magnets below the originally established budget for these items. This is a good model for how we should conduct future large production runs of magnets and other work in high-energy physics," said Main Injector Project Manager Steve Holmes.

Also in the hot summer of 1997, construction crews built a new master power substation at the southeast corner of the new accelerator. Electricity at 345 kilovolts from Commonwealth Edison lines will be translated to 13.8 kilovolts for Lab use.

At the end of September 1997, Holmes proclaimed the project 80 percent complete. He said the major projects left included the construction of the 150-GeV transfer line between the Main Injector and the Tevatron, the FZero complex, as well as completing the beamline installation and the fabrication and installation of the Recycler Ring.

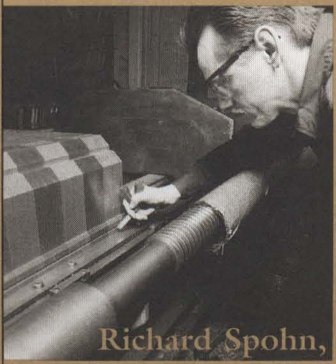
During Run II, the Recycler Ring, also made of permanent magnets, will retrieve, decelerate and store the unused antiprotons from a Tevatron store. During Run I, accelerator operators typically had to dump 80 percent of the particles produced. The Recycler will allow operators to increase the number of antiprotons available for collisions, thus further raising the critical Tevatron luminosity.

COLLIDER DETECTOR UPGRADES

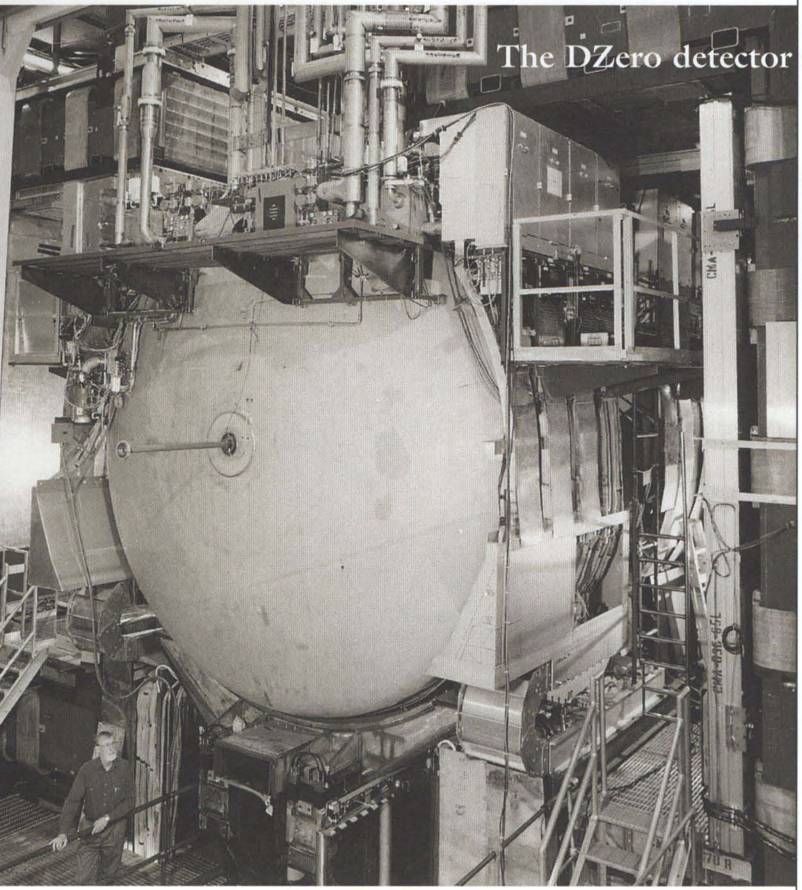
As Fermilab prepares for the Main Injector and the future in high-energy physics, the Laboratory must maintain a certain synergy. If technology and engineering advance in one field, other areas must progress in parallel, as with the DZero and CDF experiments and their future benefactor—the Main Injector.

Without upgrades to the sophisticated collider detectors, the finders of the top quark would not be able to keep up with the higher luminosity, and all those extra particle collisions would be for naught.

Each experiment has about 450 collaborators spread among various groups—each working on different parts of the detector. The challenge, according to Cathy Newman-Holmes, co-project manager for the CDF upgrade, is orchestrating all the groups and experimenters so that the upgrades get done in a timely and efficient manner. For CDF, experimenters are rebuilding all the data acquisition systems, triggers and every piece of electronics. Newman-Holmes said the tasks include installing the new silicon vertex detectors and scintillating fiber detectors, as well as



Richard Spohn, an employee of SVF Inc., working on the innards of a dipole magnet for Fermilab.



The DZero detector as seen in May 1997.

replacing the central drift chamber and plug calorimeters. Smaller projects include building a new beam pipe and replacing the ventilation/heating system in the collision hall. During an interview in October 1997, she said the project would soon be entering a critical transition in which the electronic devices will move from R&D and prototypes to production. Newman-Holmes said the detector should be assembled, except for the silicon vertex detectors, by summer 1999. The production and installation of the silicon chips is planned for late 1999 and early 2000, with commissioning to follow.

Among the myriad jobs at DZero, experimenters will position and test a superconducting solenoid magnet—what DZero cospokesman Hugh Montgomery called the core of the upgrade. The magnet arrived from Japan on May 12, 1997, and collaborators said it will help in the identification of electrons and open up new opportunities at DZero for the study of charm and *B* particles. The magnet will also improve identification of top quark candidates and will be especially useful for precision measurements of the momentum of muons, an important aspect of the physics of *W* and *Z* bosons and the search for the Higgs boson. DZero is also upgrading the triggering system and muon identification capability, among other tasks. The DZero detector is slated for completion in November 1999, when it will be rolled into the collision hall.

COMPUTING UPGRADES

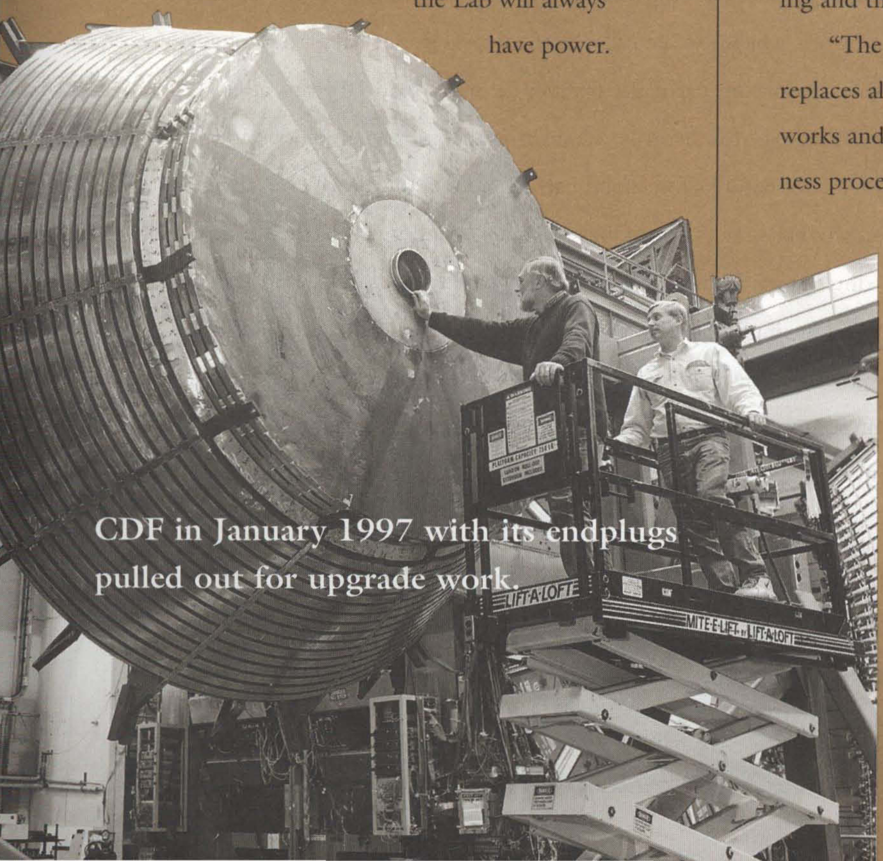
As mentioned earlier, upgrades at a cutting-edge science laboratory must proceed in parallel. Once the Main Injector places those extra particles into the Tevatron, resulting in extra collisions at CDF and DZero, the detectors, in turn, must hand over the increased data to the computers for reconstruction and analysis, among other functions. The computing infrastructure can expect 20 times more data than in Run I.

Computing upgrades for Run II are progressing along three paths. Each collider detector has a group devoted to specific computing needs, while the Computing Division has a large team in place to address common issues. Steve Wolbers, deputy head of the Computing Division, explained a flow chart detailing some of the challenges his division is addressing. He said embedded in the flow chart are nine major common projects. They include the Reconstruction–Input Pipeline, which brings data from the experiments to the Feynman Computing Center; supporting databases for calibration; visualization programs, such as event displays; code management, which involves a set of tools to organize the software; analysis tools for the scientists and students; and data simulation needs. Wolbers also said there will be four major hardware acquisitions, each guided by procurement teams. Fermilab must research and purchase production systems, such as "farms" for event reconstruction; mass storage systems, such as tapes and robot networks; analysis systems for scientists to study the data; and networks that will tie everything together.

IMPROVING THE INFRASTRUCTURE

David Nevin, head of Fermilab's Facilities Engineering Services Section, likes to peer into the future. He isn't hoping to find tomorrow's lottery numbers (although he says that would be nice). Rather, he is planning how best to position the Lab's infrastructure for the next five years. Put simply, the advent of the Main Injector and the addition of the upgraded collider detectors won't mean a thing if a 25-year-old electrical feeder fails, bringing the entire Lab to a halt.

Over the course of 1996-97, FESS identified the most problematic electrical feeders and has begun the multi-year project of replacing faulty wiring. In addition, Nevin hopes to run cable from the new Kautz Road substation near the Main Injector to Fermilab's main substation. When that is complete, Fermilab will be able to switch power between two main Commonwealth Edison lines, helping to ensure that the Lab will always have power.



CDF in January 1997 with its endplugs pulled out for upgrade work.

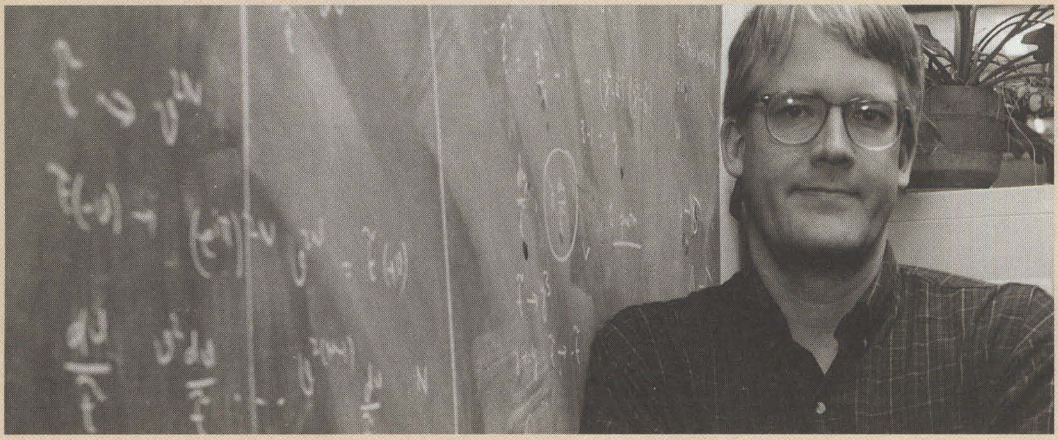
At the deteriorating Central Utility Building, the FESS team is now replacing all of the old instrumentation and controls for the Lab's entire utility system. When the complex task is complete, an operator will be able to monitor and control all utility systems from one location, and Nevin plans to staff that position 24 hours a day. FESS has many more projects on a five-year plan, including a Wilson Hall restoration project to fix structural problems in Fermilab's signature building.

BUSINESS, BUT NOT AS USUAL

As others have said in this chapter, the hope for new insight and advancement in science often rests on the development and implementation of new and better tools. That basic tenet of particle physics also applies to the science of doing business.

Fermilab's Business Systems Group recently completed the final phase of a five-year project to upgrade software and hardware essential to the Lab's financial management responsibilities. The systems that the group has overhauled include the general ledger, payroll, accounts payable, shipping and receiving and the old paper–heavy requisition process.

"The work we have done over the last five years replaces all of the hardware, application software, networks and databases that were used to run the business processes here at the Lab for the last 25 years," said Richard Karuhn, manager of the Business Systems Group. He added that the new systems support the Lab's mission by providing a reliable business environment for keeping employees and vendors paid, alleviating requisition bottlenecks and integrating processes that share similar data.



Joe Lykken

Theorist

Enter the office of Joe Lykken, a member of Fermilab's theory group, and you'll see an eight-foot blackboard nearly covered with scribblings. Equations, mathematical symbols and physics terms dazzle the layman's eyes and suggest a grand answer to a complicated question.

But Lykken says the blackboard is the product of confusion. The subject of the scribblings and calculations—and confusion—is superstring theory, which Lykken calls the theoretical frontier of particle physics. He has shared an outpost with other theorists on this particular frontier for more than 10 years, after what he called a revolution in thinking among particle theorists. Superstring theory is an ambitious and apparently unique framework for unifying all of nature's forces and particles into a "theory of everything."

Confused? You're in good company. Lykken said most of his colleagues spend much of their time perplexed about some piece of superstring theory. However, he says every so often a nugget of insight will surface and theorists will try to pursue its implications. Inevitably, those insights come as the result of working with other theorists, attacking the same questions from different angles. Lykken said people often think of theory work as an Einstein sitting alone at the Patent Office. It's just not true anymore.

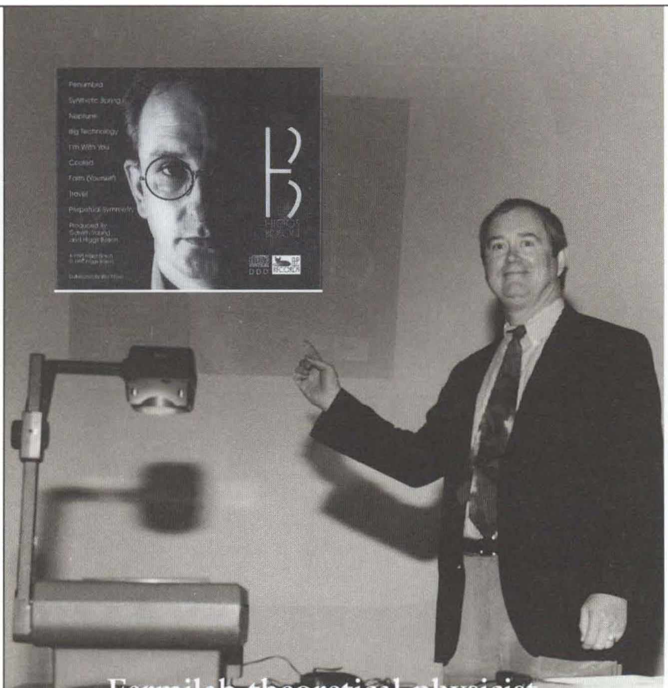
"Everybody relies on talking to other people," said Lykken. "Nobody is smart enough to figure this stuff out on his own."

You might think that Lykken is giving it a shot, though, if you spot him reaching high on his blackboard to complete one of those calculations.

For another decade or so, Fermilab's particle accelerator will remain the world's most powerful tool for exploring the high energy frontier. Physicists believe that many exciting discoveries are possible in the Main Injector era—discoveries that could shed light upon some of the fundamental mysteries of our universe.

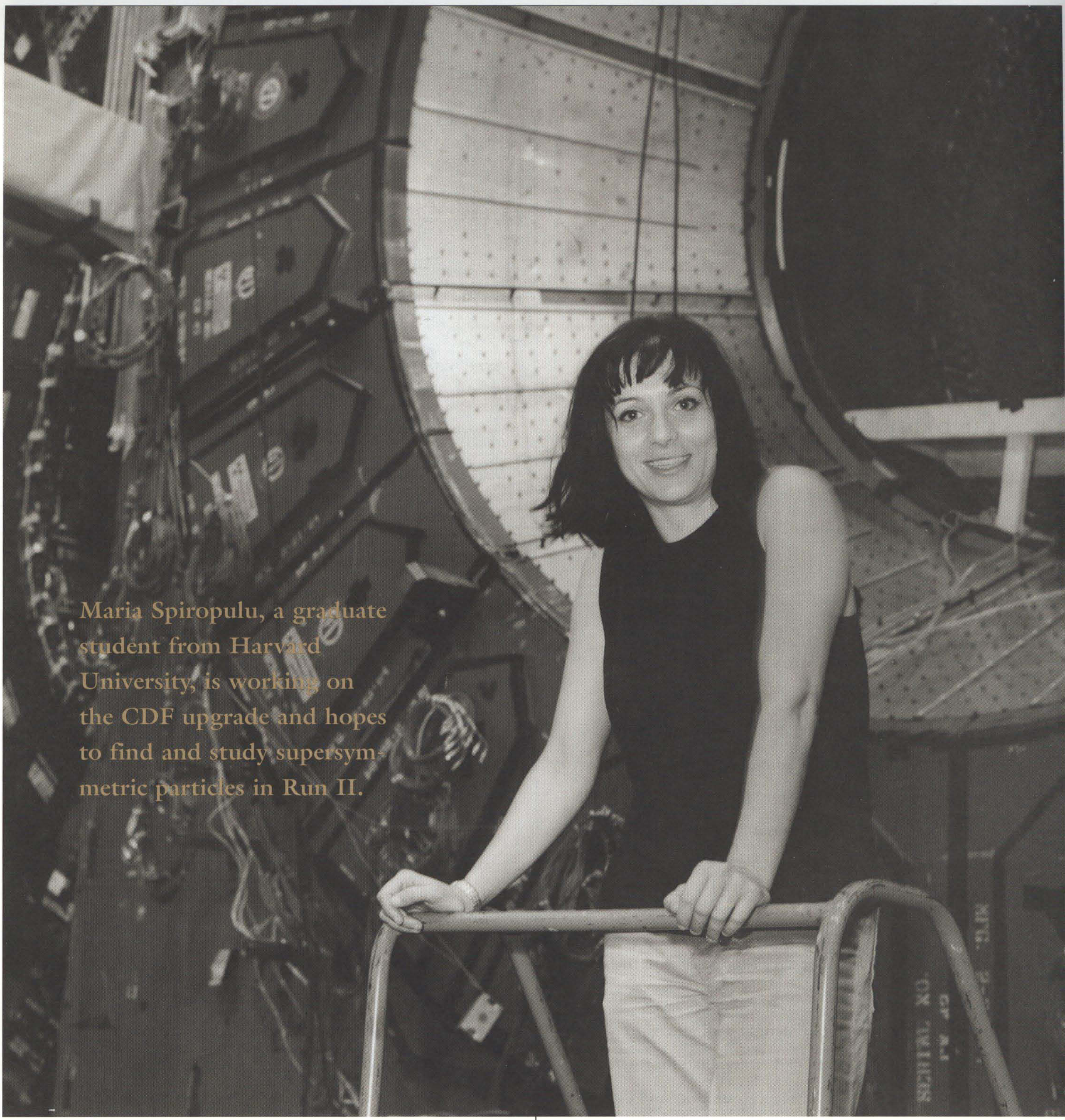
THE ORIGINS OF MASS

What is mass, and where does it come from? In the past 30 years physicists have learned that most of the mass in ordinary objects, such as people's bodies, is actually pure energy, produced by the powerful forces that bind quarks into protons, neutrons and the nuclei of atoms. But quarks, electrons and other elementary particles also carry an intrinsic mass, and this mass stays constant even when scientists smash particles together in accelerator experiments. In the Standard Model of particle physics, mass arises from a new kind of particle interaction that implies a new kind of particle: the Higgs boson. This hypothetical heavy particle has never been seen; it is truly the "missing link" of the Standard Model. Scientists will be able to search for Higgs bosons at the Tevatron, using the fact that it is produced together with the well-understood *W* and *Z* bosons, and that it decays to *b* quarks, which we can identify with efficient *b*-tagging techniques developed at Fermilab for the top quark searches. Even if Fermilab is unlucky and the Higgs is too heavy to detect at the Tevatron, physicists and their students here can probe for the Higgs indirectly by making precise measurements of the masses of the top quark and *W* boson. Within the Standard Model, scientists can use these precise measurements to predict a mass range where the Higgs should be found at future accelerators. If Fermilab can verify that the Higgs particle exists, and can study its properties, the Laboratory will have taken a major step toward understanding the origins of mass.



Fermilab theoretical physicist Chris Quigg announced he had found the elusive Higgs boson —in London. Higgs Boson is the name of a New Wave music group. Here, Quigg points to the album cover.

Another approach that may teach the world about the origins of mass is to study the top quark. Top is by far the heaviest elementary particle: 40 times heavier than the bottom quark and 350,000 times heavier than the electron. It seems whatever the mechanism that gives particles mass, top somehow sees it more directly. Most significantly, the mass of top is essentially identical to what in the Standard Model is called the electroweak scale, the energy scale associated with the unification of the weak nuclear force with electromagnetism. The Standard Model gives no explanation for the near equality of the top mass and the electroweak scale. But it could well be that the top quark itself is intimately tied up with the physics of electroweak unification and mass generation, perhaps through a new strong force called "topcolor." With thousands of identified top events produced in Run II, any new physics linked to top ought to show up as resonances or other peculiar phenomena.



Maria Spiropulu, a graduate student from Harvard University, is working on the CDF upgrade and hopes to find and study supersymmetric particles in Run II.

Yet another likely place to probe for the origins of mass is in neutrino oscillations. In the Standard Model, neutrinos have zero mass, but several experiments have found a deficit in the number of neutrinos expected from the sun and from cosmic rays striking our atmosphere. These neutrino deficits can be explained if the electron-, muon-, and tau-type neutrinos can oscillate (i.e., convert into each other), something that is only possible if neutrinos have mass. The NuMI experiments at Fermilab will help us resolve this puzzle.

ANTIMATTER

Fermilab is by far the world's largest producer of antimatter; the Lab has constructed simple antiatoms, and generates huge quantities of antiprotons for use in the Tevatron collider. However the fundamental physics associated with the existence of antimatter is still poorly understood. It was thought for many decades that the laws of physics applied to antiparticles should be just the mirror image of the laws of physics applied to particles. This assumption turns out to be false. There is at least one type of physical process—the production and decay of neutral *K* mesons—where nature treats particles and antiparticles in a more complicated, asymmetrical fashion. This effect, known as CP violation, has remained mysterious largely because of particle physicists' inability to find other physical processes that exhibit it.

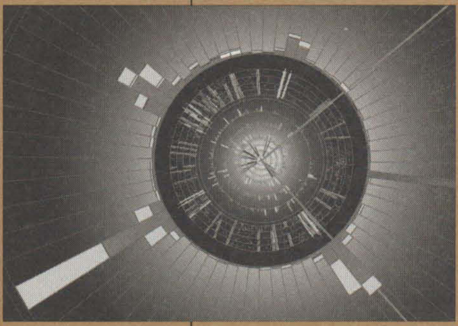
Fermilab scientists believe, however, that CP violation (and associated quark mixing effects) can be well studied in the decays of certain heavy particles known as *B* mesons (mesons that contain a bottom quark). The collider experiments in Run II will have tens of thousands of such events to study, providing ample opportunity to increase the understanding of this strange phenomenon. Even more could be learned by following up with a dedicated heavy quark program, which would exploit the full *B* physics potential of the high-luminosity Tevatron collider.

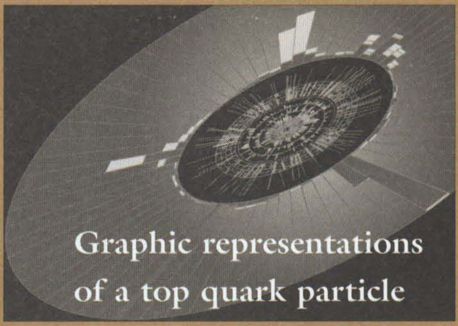
SUPERSYMMETRY AND UNIFICATION

One of the great triumphs of 19th-century physics was the discovery that electricity and magnetism are different aspects of a single unified force: electromagnetism. Similarly, a great triumph of the Standard Model was the prediction that the weak nuclear force combines with electromagnetism into a unified "electroweak" force. Theorists have since developed extensions of the Standard Model, called grand unified theories, that unify the electroweak force and the strong nuclear force in an elegant way. Even more ambitious is superstring theory, an apparently unique framework for unifying all forces, including gravity, into a final "theory of everything."

Both of these unification proposals seem to require a new principle of nature called supersymmetry. Supersymmetry requires that all of the elementary particles of the Standard Model have "superpartners:" as yet undiscovered particles whose interactions with ordinary matter are predicted by supersymmetry. A remarkable feature of supersymmetric models is that precisely in the case where the top quark happens to be very heavy (e.g., our universe) the superpartner masses can be tied to the electroweak scale. This puts the discovery of superpartners within the reach of collider experiments at the high-luminosity Tevatron.

Another remarkable property of supersymmetric models is that they put a strict upper limit on the mass of the Higgs boson. With sufficient high luminosity running beyond Run II, Fermilab collider experiments can cover the entire allowed mass range.





Graphic representations of a top quark particle interaction in the DZero detector. Scientists say understanding more about the top quark will lead to more profound physics insights.

THE CONSEQUENCES

Thus, with a continued vigorous collider program in the next decade, Fermilab will either discover the Higgs boson or rule out the theoretical possibility of supersymmetry tied to the electroweak scale. Either result will have profound consequences for the future of high-energy physics and the fundamental view of the universe.

Cosmore Sylvester

Engineer

"Just picture trying to stand upright a nine-ton magnet that is lying down," says Cosmore Sylvester, a mechanical engineer with the Magnet Test Facility in the Fermilab Technical Division.

Can't fathom how to do it? Well, neither could Sylvester at first, but he found a way.

That was among his first tasks when he joined Fermilab two-and-a-half years ago. A veteran of Brookhaven National Laboratory and the Superconducting Super Collider, Sylvester was recruited to help design a vertical test cryostat for magnets destined for Europe's Large Hadron Collider and for upgrades to Fermilab's Tevatron. The new cryostat is a vertical vessel holding a helium bath, into which multi-ton magnets, one at a time, are lowered for performance testing.

The first step was figuring out how to get those huge magnets vertical. For that, Sylvester invented an "up-ender". (He admits a lack of originality when it comes to naming.) He moved on to designing other components of the suspension system: for example, a plate that separates the normal helium from the still-colder superfluid helium in the vertical bath. He also designed a double-walled insulated cylinder—he calls it a "warm finger"—that descends into the magnet, and is now fashioning a coil that will thread through that finger into the magnet to test its magnetic performance. In hindsight, standing magnets on end probably doesn't look so hard.

Born in Grenada, raised in England, Sylvester lost his British accent at New York's Pratt Institute, where he earned a bachelor's degree in mechanical engineering. Today, in a polo shirt and blue jeans, he looks and sounds decidedly American, and is here to stay—determined, along with his colleagues, to place Fermilab at the forefront of superconducting magnet technology.

The future is always running away from you, the Zulus say. But in magnet technology, clever experiment ideas and designs for next-generation accelerators, Fermilab is not many paces behind.

MAGNET DEVELOPMENT

There are not many places in the world where magnets are designed, built, tested and then installed in an accelerator. Fermilab is one.

Once the home of cutting-edge superconducting magnet development, Fermilab temporarily lost its lead when engineers and physicists flocked to the Superconducting Super Collider.

"When the SSC collapsed, it took magnet development with it," said Peter Limon, head of the Technical Division, "and the U.S. was left without a program." However, Limon has restarted that program, building a team of engineers and physicists to advance the science of superconducting magnets. Magnet technology is crucial to building still more powerful accelerators that will take high-energy physics to a new frontier. Limon has now recruited talent from all over the world, and combined their skills with the deep experience and expertise of Fermilab's older guard to create a "dream team."

The team is focusing on designing, testing and building interaction-region quadrupole magnets with fields of 10.5 Tesla for the Large Hadron Collider, a new accelerator planned for CERN, the European Laboratory for Particle Physics. When operational, the LHC will take the energy frontier away from Fermilab and bring it to the Swiss-French border. To design the magnets, the Fermilab team is taking a fresh look at nearly every magnet component and every stage of development: from analysis of the stress on coils to cryogenics and quench protection.

For example, Gianluca Sabbi, from Italy, is performing magnetic field modeling for the quadrupole, calculating the field generated by the coils, the field quality, the manufacturing tolerances, the design of magnet parts and how best to correct errors. Chinese physicist Yuenian Huang is building a computer model to study temperature distribution in the magnets. The goal is to run LHC magnets at 1.8 Kelvin, even colder than the 4.4 Kelvin the Tevatron's superconducting magnets require. The lower temperature would allow for a higher magnetic field and acceleration to a higher energy. Later, Huang expects to conduct experiments on a magnet model to better understand the properties and confirm or adjust his computer calculations.

Imre Gonczy applies voltage taps to a high-field quadrupole magnet for the LHC.

LARGE HADRON COLLIDER

Magnet development is not the only activity Fermilab has undertaken to support CERN's LHC. Fermilab is also the host laboratory for the U.S. CMS collaboration, comprising 327 scientists from 39 institutions in the U.S. These physicists and their students are responsible for building major parts of the Compact Muon Solenoid, one of the two general-purpose detectors that will record the results of particle collisions in the LHC. The major parts include the endcap muon chambers, the hadron calorimeter and the trigger/data acquisition system.

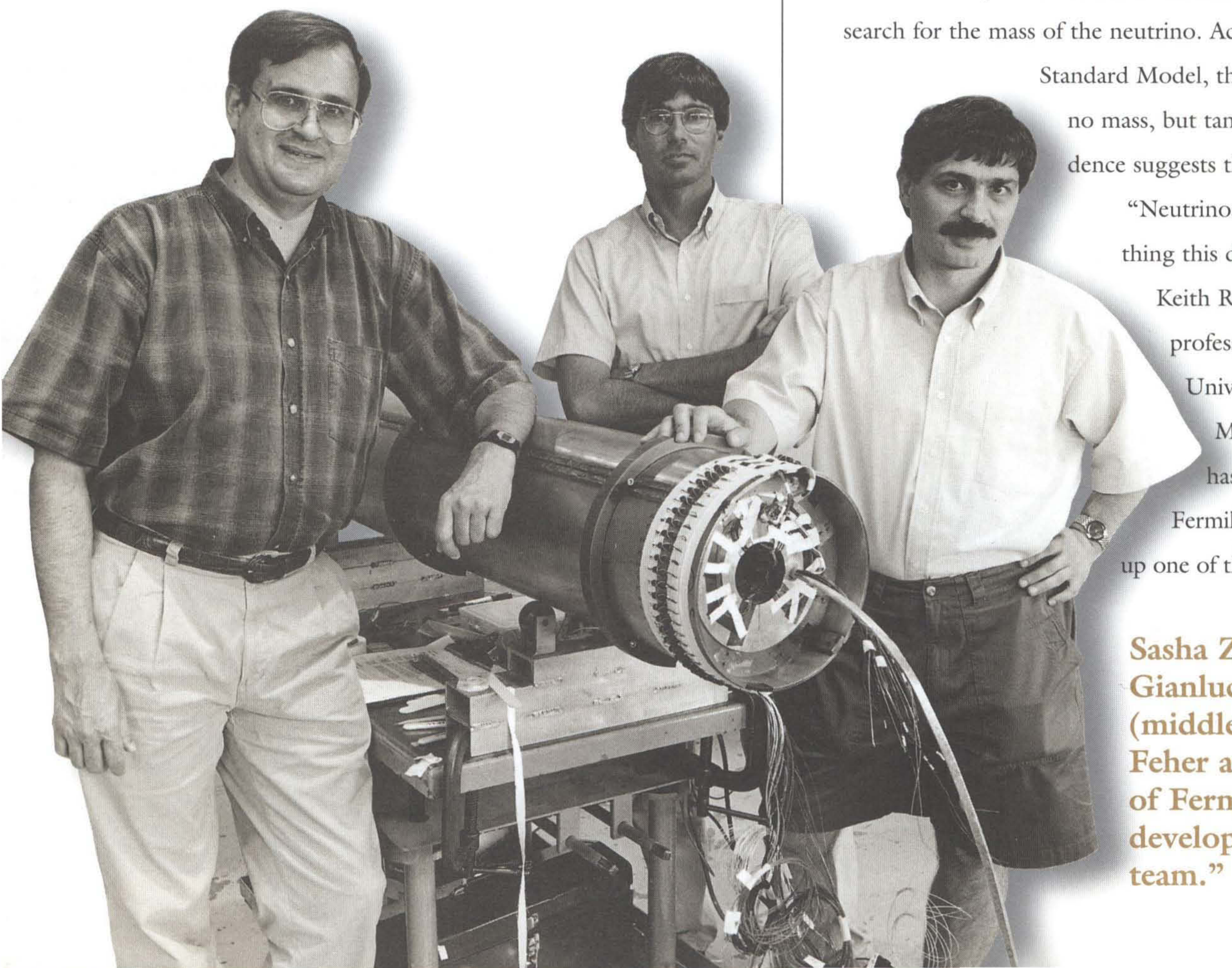
American physicists say U.S. participation in the construction of the LHC accelerator and its detectors is vital for the health of the U.S. high-energy physics program. Helping to build the accelerator and its detectors will advance critical U.S. technology. Moreover, when the new accelerator begins operating, it will represent the only opportunity for the U.S. particle physics community to work at the energy frontier.

A congressionally mandated cap on funding for the project will require managers to be especially prudent in managing the scope, costs and progress of the project.

Accordingly, the two funding organizations, the Department of Energy and the National Science Foundation, asked Fermilab to provide substantial oversight of the CMS project, citing Fermilab's proven record of successfully carrying out complex construction projects of both accelerators and detectors. Fermilab Director John Peoples delegated the oversight responsibility for the CMS project to Deputy Director Ken Stanfield, saying, "We will take all necessary measures to assure ourselves, DOE and NSF that the project has a good plan and the project is managed to that plan."

NEUTRINOS AT THE MAIN INJECTOR

While work on the LHC continues, scientists from Fermilab and many other U.S. and foreign institutions are planning two experiments, collectively called NuMI (for Neutrinos at the Main Injector), to search for the mass of the neutrino. According to the Standard Model, the neutrino has no mass, but tantalizing evidence suggests that it does. "Neutrinos are the sexy thing this decade," said Keith Ruddick, a professor at the University of Minnesota who has returned to Fermilab to help set up one of the experiments.



Sasha Zlobin (left), Gianluca Sabbi (middle) and Sandor Feher are all members of Fermilab's magnet development "dream team."

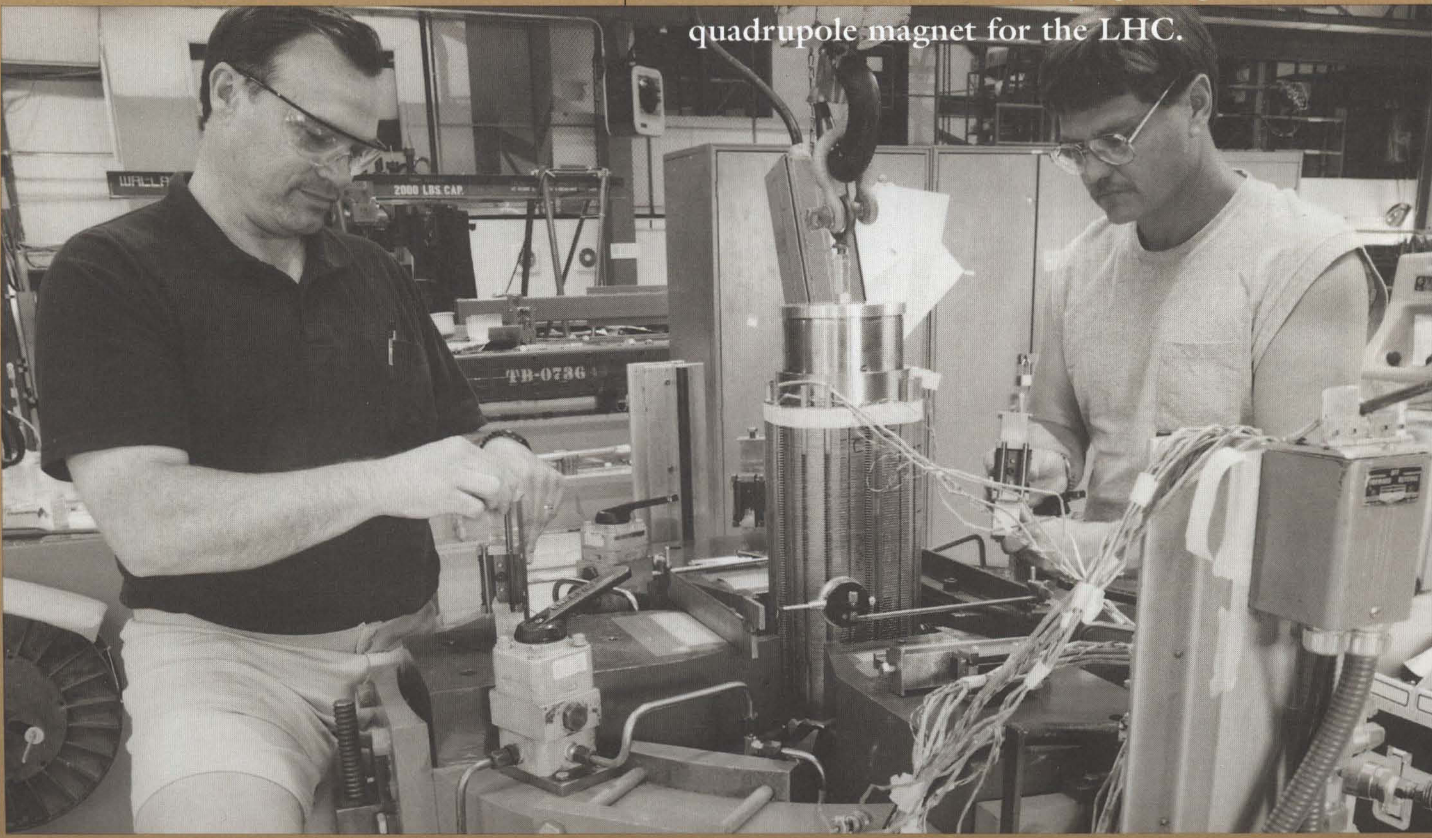
Neutrinos come in three flavors, and physicists will be looking for evidence of a phenomenon called neutrino oscillation—the change from one neutrino flavor to another. The experiments will take advantage of the capabilities of Fermilab's new particle accelerator, the Main Injector, scheduled to begin operating in 1999. The Laboratory plans to construct a new particle beamline to direct a nearly pure beam of muon neutrinos from the Main Injector toward both nearby and far-off detectors capable of counting all three types of neutrinos. The nearby detector, COSMOS, will be placed at the end of a new beamline on the Fermilab site, about one kilometer from the source of neutrinos. The far-off detector, known as MINOS, will be located in a mine 450 miles away in Soudan, Minnesota. Broadly stated, the goal is to see if neutrinos change from one flavor to another. If they do, experimenters will know that the neutrino has mass, bringing us a step closer to understanding the constituents of the universe.

POSSIBLE FUTURE COLLIDERS

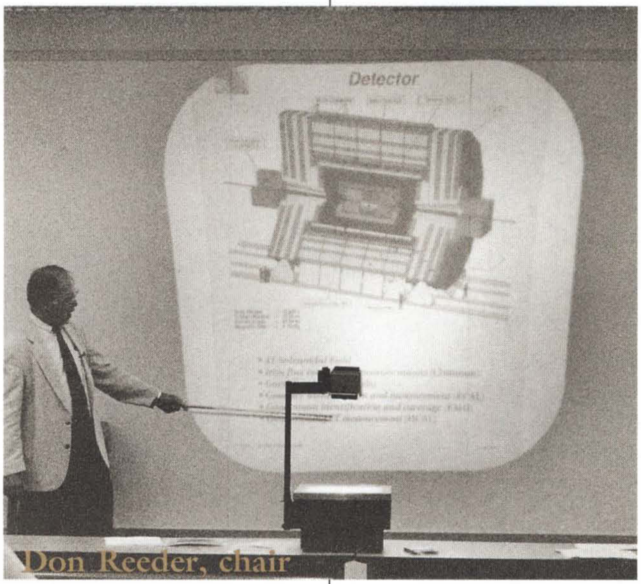
Reaching still farther into the future, Fermilab is already contemplating new designs for possible future colliders that will allow the study of physics beyond the Standard Model. The work has begun none too soon, for according to a Fermilab physicist, a machine could take "up to five years of serious R&D, then perhaps a decade of detailed design and construction."

One possible accelerator is currently referred to as a Very Large Hadron Collider. It would pit proton against proton at a center-of-mass energy of 100 TeV, seven times higher than in CERN's LHC. The machine would be so huge—from 62 to 300 miles in circumference, depending on details of the design—that it would have to extend far beyond the Laboratory's boundaries.

Steve Gould and Don Nurczyk, of the Technical Division, are keying a high-field quadrupole magnet for the LHC.



What kind of magnets the VLHC might use is one question Fermilab physicists have been exploring. A possibility is a new design by Fermilab physicist Bill Foster, called the low-field (2-Tesla), or super-ferric, magnet. According to Ernest Malamud, coordinator for a group studying the VLHC, this innovative magnet uses "the magic of iron." Its elegant design is surprisingly compact. For example, the magnet carries current in a single transmission line that powers the two gaps in which the proton beams circulate; typically, accelerators have two magnets, one for each beam. It also combines in one unit what most large accelerators allocate to two: the quadrupole, the magnet that focuses the beam, and the dipole, the magnet that steers the beam around the collider.



Don Reeder, chair of the U.S. CMS collaboration board, presenting the detector design at a DOE review in the summer of 1997.

A VLHC might also use magnets with fields of 9.5 Tesla or higher. The 9.5-Tesla design has a practical advantage, according to the Technical Division's Limon: "We know how to build it." No one yet knows how to create still higher-field magnets. High-temperature superconductors will be key to creating 12.5-Tesla magnets but are as yet a long way from industrial production.

Another possible accelerator is the Muon Collider. A dozen Fermilab physicists, along with scientists from Brookhaven National Laboratory, Lawrence Berkeley National Laboratory and U.S. universities, have been working for about two years on the design of a muon collider with a 4-TeV center-of-mass energy. The machine would use subatomic particles called muons. Muons are leptons and, because they have no substructure, produce "clean" collisions. Thus, all of the collision energy is available for conversion into new particles, at specified levels of energy. They have another advantage, too. Unlike electrons, they don't radiate, or lose energy. Moreover, unlike the VLHC, the Muon Collider could easily fit on Fermilab's existing site. However, muons live for only two microseconds before they decay into electrons and neutrinos. The trick in building a successful muon collider is to find a way to take advantage of the muon's useful qualities within its short lifespan—and to deal with the products of its decay.

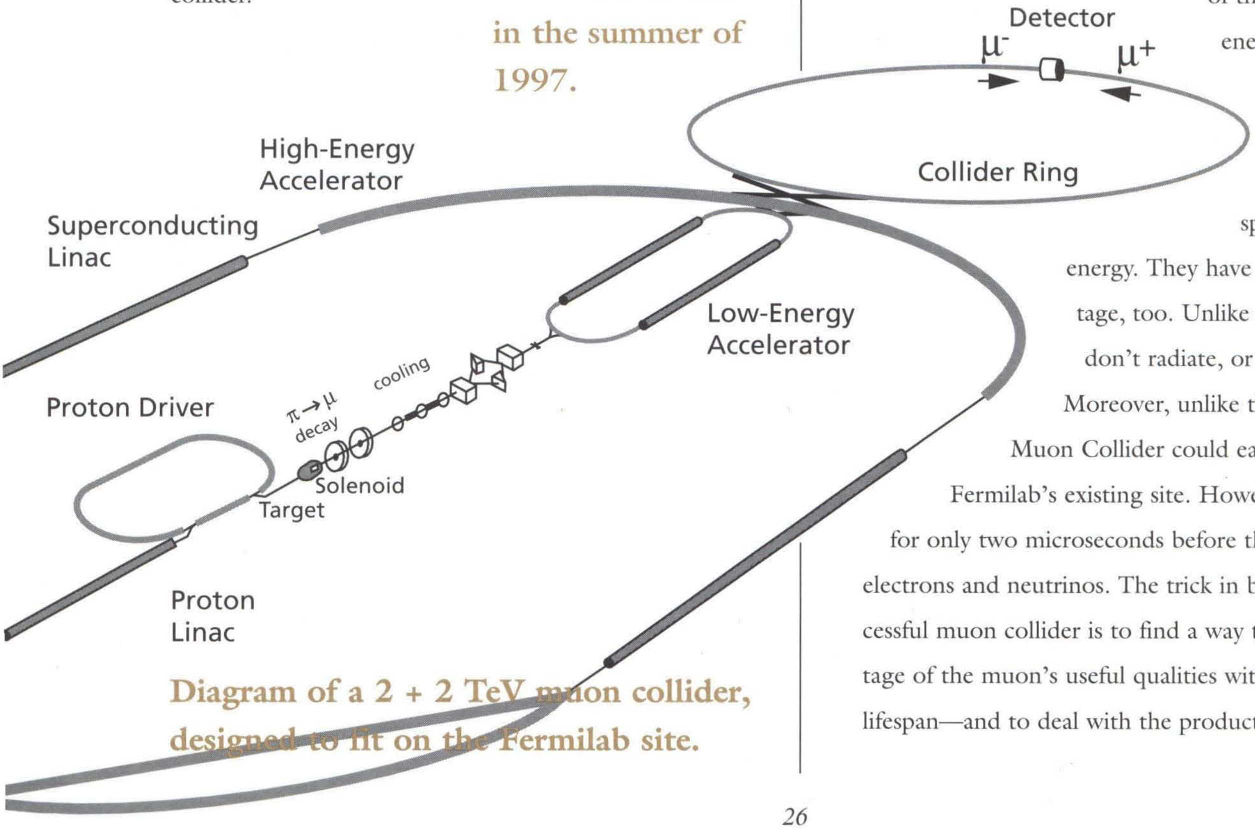
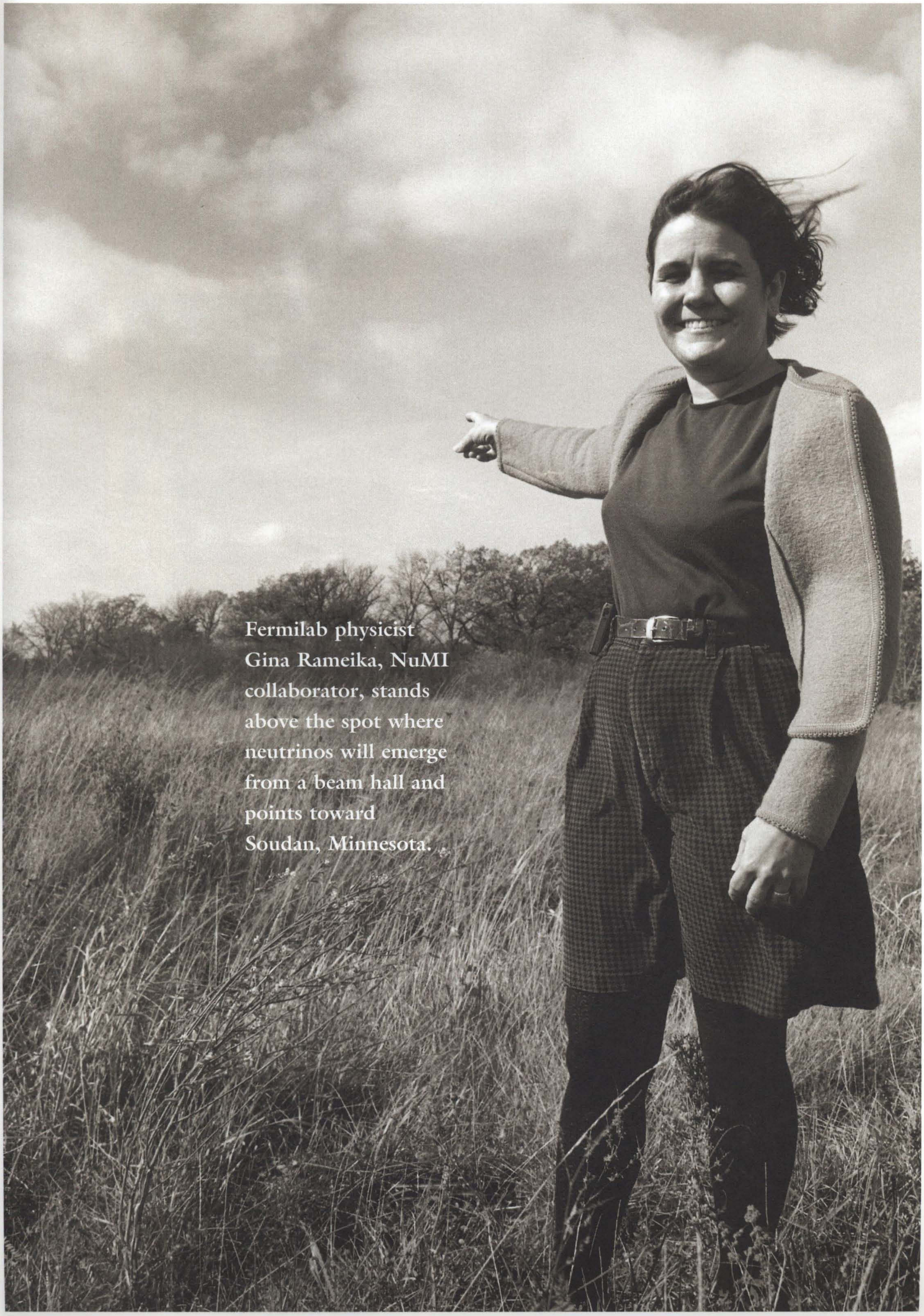


Diagram of a 2 + 2 TeV muon collider, designed to fit on the Fermilab site.



Fermilab physicist Gina Rameika, NuMI collaborator, stands above the spot where neutrinos will emerge from a beam hall and points toward Soudan, Minnesota.

Sam Zeller

Graduate Student

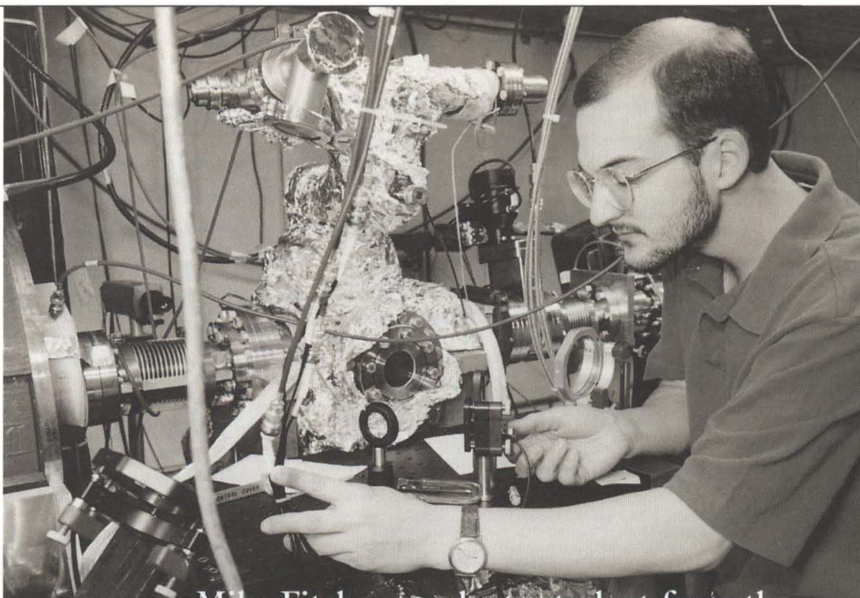
Sam Zeller's life took a dramatic, albeit expected, turn with the flip of a switch.

The switch in question turned off the beam from the accelerator to the fixed-target experiments, and as the protons stopped, so did the alarms, the frantic moments when the computers went down and the phone calls that pierced the night, interrupting her sleep.

The 25-year-old graduate student from Northwestern University now spends her days behind a computer analyzing the endless data from her experiment, getting eight hours of sleep at night and, surprisingly, missing shift work. Those eight-hour stints in the control room ranged from calm to feverish, especially on the owl shift, when Zeller often fell victim to the age-old experimentation axiom: "If something is going to go wrong, it is going to go wrong at 4 a.m."

The 14 months or so in which her NuTeV experiment received beam resulted in tape after tape of raw data. Somewhere in that data is her thesis (a precision measurement of the Weinberg Angle), the imposing document that will place the Dr. before her name. However, Zeller doesn't even want to think about the logistics of writing her thesis, nor is she encouraged by the job prospects in particle physics after it is finally done. But Zeller pushes on in NuTeV's portakamps–removed from family, friends and the bucolic Northwestern campus–with the goal of shedding a little light on the physical world around us.

As a basic research laboratory, Fermilab produces not just high-energy physics papers but also new scientists who receive their doctorates based on research at the Laboratory.

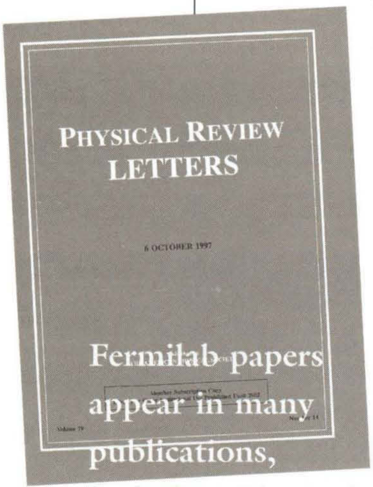


Mike Fitch, a graduate student from the University of Rochester, is working on his Ph.D. through a Fermilab program.

Part of doing science has always meant teaching science, and educating the next generation is a critical part of research life at Fermilab. Since Fermilab employees first got the beam of protons moving around the ring, scientists from universities all over the world have used those particles to conduct science experiments of the highest sophistication. Invariably, those university professors have had graduate students in tow to learn about particle physics as major contributors to each experiment. After 30 years, there is a legion of high-energy physicists around the world who wrote their doctoral theses based on research at Fermilab. Moreover, many of those graduate students have gone on to tenured positions at the nation's elite universities and to influential positions at Fermilab. Today there are still eager students ready to spend long days in dank experiment halls and sleepless nights in brightly lit control rooms. At present, the Lab has more than 600 graduate students from various universities working toward their Ph.D.s.

The benefit is mutual. How important are the graduate students to research at Fermilab? One veteran particle physicist said, "The research couldn't happen without them. Period."

The other common "product" that flows from the Fermilab site is the researchers' papers. These papers, most often written for particle physics journals and conferences, detail physics results from experiments conducted at the Laboratory. The publications are peer reviewed, providing legitimacy to the findings, and other physicists cite those papers in their own work. Some papers have titles that read like run-on sentences ("Determination of the Gluon Distribution Function of the Nucleon Using Energy-Energy Angular Pattern in Deep-Inelastic Muon-Deuteron Scattering"); other titles are simpler ("Measurement of the *W* Boson Mass")—one might not know what a *W* Boson is, but can still surmise that its mass was measured.



PHYSICAL REVIEW LETTERS

6 OCTOBER 1997

Volume 79

Fermilab papers appear in many publications, including Physical Review Letters.

The papers appear in well-known physics journals, such as Physical Review Letters, as well as in more focused publications, such as Advanced Cryogenic Engineering. Most of the papers are listed by the last name of the author; if a paper has multiple authors, the first one alphabetically is listed followed by et al., and that et al. can sometimes mean hundreds of others, especially on the collider experiments. How important are the papers to the high-energy physics community? The same physicist said, "The process of publication forces a rigor in interpreting and describing results that might be lost otherwise and is critical to getting it right." In 1996 alone, Fermilab researchers wrote more than 350 journal and conference articles.

This chapter lists those articles, as well as the students who received their Ph.D.s in 1996 based on research at Fermilab.

Fermilab 1996 Journal and Conference Articles

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Most Cited High-Energy Physics Papers

The following list represents the high–energy physics journal papers with the most citations from January 1994 to December 1996.

The ranking comes from the SPIRES database system at the Stanford Linear Accelerator Center. The list does not include the various editions of the Review of Particle Properties by the Particle Data Group. Listings in color represent papers based on work at Fermilab.

1. **SUPERSYMMETRY, SUPERGRAVITY AND PARTICLE PHYSICS**

   By H.P. Nilles (Geneva U. & CERN)

   Published in Phys.Rept.110:1,1984
   547 citations

2. **THE SEARCH FOR SUPERSYMMETRY: PROBING PHYSICS BEYOND THE STANDARD MODEL**

   By Howard E. Haber (UC, Santa Cruz & SLAC), G.L. Kane (Michigan U.)

   Published in Phys.Rept.117:75,1985
   525 citations

3. **ELECTRIC—MAGNETIC DUALITY, MONOPOLE CONDENSATION, AND CONFINEMENT IN N=2 SUPERSYMMETRIC YANG-MILLS THEORY**

   By N. Seiberg (Rutgers U., Piscataway & Princeton, Inst. Advanced Study), E. Witten (Princeton, Inst. Advanced Study)

   Published in Nucl.Phys.B426:19-52,1994 (Erratum-ibid B430:485-486,1994)
   465 citations

4. **OBSERVATION OF THE TOP QUARK**

   By D0 Collaboration (S. Abachi et al.)

   Published in Phys.Rev.Lett.74:2632-2637,1995
   462 citations

5. **ASYMPTOTIC FREEDOM IN PARTON LANGUAGE**

   By G. Altarelli (Ecole Normale Superieure), G. Parisi (IHES, Bures)

   Published in Nucl.Phys.B126:298,1977
   460 citations

6. **OBSERVATION OF TOP QUARK PRODUCTION IN ANTI-P P COLLISIONS**

   By CDF Collaboration (F. Abe et al.)

   Published in Phys.Rev.Lett.74:2626-2631,1995
   458 citations

7. **THE LUND MONTE CARLO FOR JET FRAGMENTATION AND E+ E- PHYSICS: JETSET VERSION 6.3: AN UPDATE**

   By Torbjorn Sjostrand, Mats Bengtsson (Lund U.)

   Published in Comput.Phys.Commun.43:367,1987
   407 citations

8. **QCD AND RESONANCE PHYSICS. THEORETICAL FOUNDATIONS**

   By M.A. Shifman, A.I. Vainshtein, V.I. Zakharov (Moscow, ITEP)

   Published in Nucl.Phys.B147:385,1979
   396 citations

9. **STRING THEORY DYNAMICS IN VARIOUS DIMENSIONS**

   By Edward Witten (Princeton, Inst. Advanced Study)

   Published in Nucl.Phys.B443:85-126,1995
   384 citations

10. **WEAK DECAYS OF HEAVY MESONS IN THE STATIC QUARK APPROXIMATION**

    By Nathan Isgur (Toronto U.), Mark B. Wise (Cal Tech)

    Published in Phys.Lett.B232:113,1989
    367 citations

Bob Lootens

Environmental Specialist

Bob Lootens felt as many others did when Robert Wilson, Fermilab's founding director, brought in Bob Betz, an ecologist, to turn the site's rich cropland into native tallgrass prairie.

"Why does this guy want to plant weeds in good corn ground?" they wondered.

Now Lootens knows. Not only does he know, but he has become the prairie's most ardent supporter.

"We feel like we're healing the ground," said Lootens. "It's going back to where it once was. It's a slow process, but it's going in the right direction." Thanks to Lootens and other members of the Roads and Grounds crew, Fermilab has restored 1,100 acres of prairie to the Prairie State.

Lootens has deep ties to this land. He grew up on a farm at the corner of Kirk and Wilson roads and remembers playing cowboys and Indians in the woods that now belong to Fermilab. He remembers, too, the bitterness of the families who resided here, including his own, when the state of Illinois bought the farmers' properties, forcing them to make way for what was then called the National Accelerator Laboratory.

But if Lootens now takes pride in the beauty of Fermilab's natural landscape, he guessed that his former neighbors would, too. In September 1997, he and a volunteer committee organized the first-ever reunion of the farmers who once plowed the fields here. They all came: the Erdmanns, who sold eggs at the end of Wilson Street; the Baumanns, who raised beef and hogs on Kautz Road; the Feldotts, who farmed the land now occupied by CDF.

And, like Lootens, they were "thrilled to pieces" that native prairie grasslands, and not strip malls, now cover their family farms.

Many people think of Fermilab as an island, a 6,800-acre site where 2,000 or so employees come each day to work, with minimal interaction with the "outside." In reality, though, Fermilab engages in vital partnerships in the neighborhood and throughout the world. For starters, the Lab serves 2,300 "user" scientists from 36 states and 20 foreign countries. These user scientists and their students use Fermilab's facilities to conduct sophisticated experiments and stretch the boundaries of knowledge of nature and energy. From science of various disciplines to the education of the next generation to the stewardship of the environment, the Laboratory relies on its links with the international science community, with area schools and with the Fox Valley community. This chapter gives a glance into a few of Fermilab's relationships with our myriad partners.

ASTROPHYSICS

Fermilab is one of eight academic and research institutions that are collaborating on a large-scale astronomical project called the Sloan Digital Sky Survey, designed to create an unprecedented map of the universe. Fermilab's partners in this effort include the Astrophysical Research Consortium, Apache Point Observatory, the University of Chicago, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, Princeton University, the United States Naval Observatory and the University of Washington. The Alfred P. Sloan Foundation, the U.S. Department of Energy, the National Science Foundation and the participating universities are providing funding.

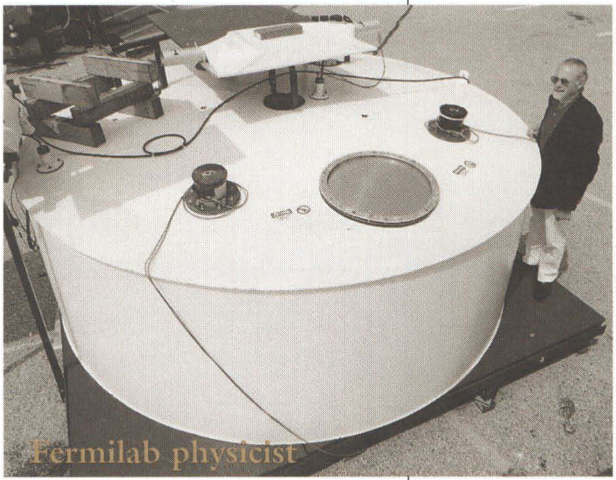
Fermilab scientists are leading the effort to develop what the Sky Survey calls data-processing pipelines—computer programs that process the digitized data to extract certain types of information. The pipelines are a collaborative effort. Princeton University scientists built the photometric pipeline; and University of Chicago experts created the spectroscopic pipeline. Fermilab's contributions include the monitor-telescope pipeline and the pipeline for selection of candidates for spectroscopy, as well as bringing the pipelines together into a working system.

Information processing for the Sky Survey begins with data acquisition. Photons from the stars hit the telescope's detectors and CCDs collect them. Charge "buckets" are then converted to digitized signals and written to tape on the mountain. The data travel from Apache Point to

The Sloan Digital Sky Survey site at Apache Point, New Mexico.

Fermilab via express courier—it's cheaper than over the Internet. The tapes go to Fermilab's Feynman Computing Center and thence into the various pipelines. Out of the pipelines comes information about the stars, galaxies and quasars, for inclusion in the Operations Database, written at Fermilab and the Naval Observatory, which collates the information to keep the Sky Survey running.

Eventually experimenters will pass the information in the Operations Database "over the firewall" to the database developed by scientists at Johns Hopkins University. The database will operate as a query engine to make the data readily usable by scientists in the project.



Fermilab physicist Peter Mazur with a prototype particle detector for the Pierre Auger Project.

The Pierre Auger Project, which will try to solve the mystery of high-energy cosmic rays, will build two giant observatories, one in Utah, the other in Mendoza, Argentina, to discover the unknown source of very-high-energy cosmic rays. Each observatory will contain 1,600 detectors spaced 1.5 kilometers apart over an area of 3,000 square kilometers. Fermilab scientists, with collaborators in the Pierre Auger Project, built a prototype particle detector. Fermilab, along with the U.S. Department of Energy and the National Science Foundation, also helped to fund the project's design study.

The project's two observatories will measure the nature, energy and direction of high-energy cosmic rays, the most energetic particles in nature, with more than 100 million times the energy of particles produced by the most powerful particle accelerators on earth. Physicists hope that tracking these rare particles will reveal the source of their enormous energies and provide new insight into the evolution of the universe itself. The collaboration includes scientists from 40 institutions in 19 countries.

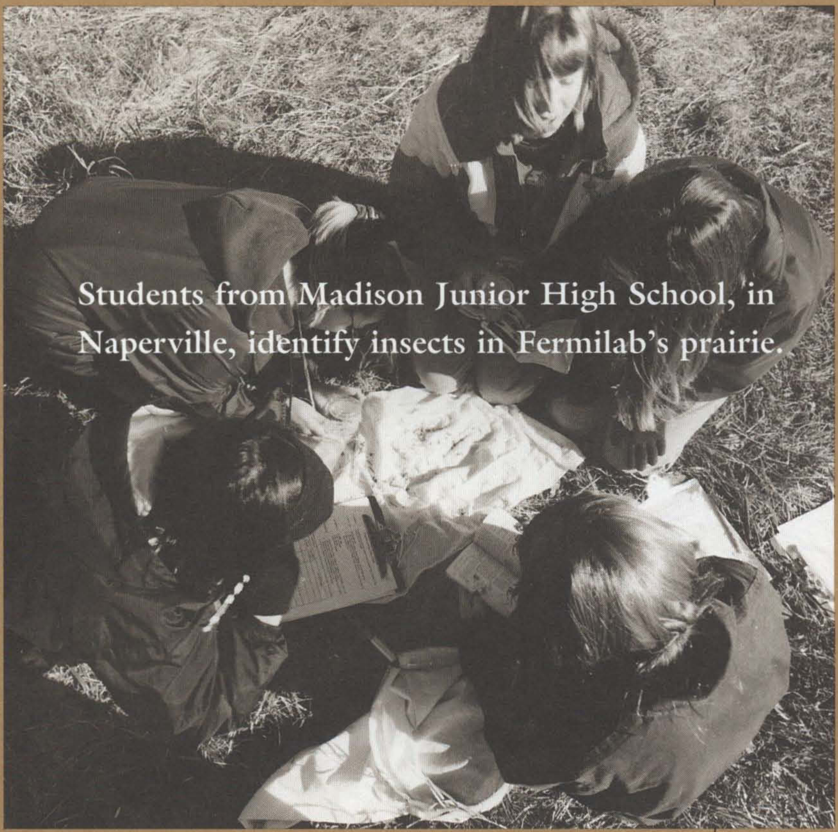
A small group of Fermilab physicists has recently joined the Cryogenic Dark Matter Search, an experiment to search for cold dark matter in the form of WIMPs (weakly interacting massive particles). The experiment is a collaboration of scientists from Case Western Reserve University, Fermilab, INR (Baksan in Russia), Lawrence Berkeley Laboratory, Santa Clara University, San Francisco State University, Stanford University, the University of California at Berkeley, and the University of California at Santa Barbara.

To detect dark matter, the experiment uses small, ultrapure crystals of germanium or silicon. Each crystal is about a centimeter thick and seven centimeters in diameter and weighs either 100 grams or 240 grams, depending on the material. The detector operates at a temperature of .015 Kelvin. If all goes as planned, experimenters will detect dark matter particles when they scatter, by means of the weak interaction, off a nucleus in one of the crystals, causing the nucleus to recoil. The recoiling nucleus will collide with some of the other nuclei in the crystal, knocking some electrons loose and creating ionization.

The bouncing and jiggling of the recoiling nucleus will also cause other atoms in the crystal to oscillate, making vibrations known as phonons. Extremely sensitive sensors mounted on the surface of each crystal will collect the energy deposited in the form of ionization and phonons. The information from the sensors is recorded, and scientists study the characteristics of the event to determine whether it is likely that a WIMP caused it.

EDUCATION AT FERMILAB

First graders roll balls down a ramp in the Science Education Center. Graduate students scribble in logbooks at 3 a.m. in an experiment's control room. An undergraduate builds a piece of a piece of a particle detector. Despite funding cuts that have shut down many of the Lab's education programs, students continue to learn about science, thanks to fundraising, support from the Lab's managers, and increasing volunteerism by employees and users. Fermilab's managers and education specialists speak of the education programs not as just a side benefit of the Lab, but as an obligation to the community—both the science community and the local community. While some might wonder why the nation's premier particle physics laboratory would engage in activities for kindergartners, Fermilab's education specialists say programs designed for kids expose students in their formative years to real science and allow access to preeminent scientists and cutting-edge research facilities not available to most school districts in the United States. While earlier sections of this report mentioned graduate programs, this area details just some of the opportunities available for the K–12 students.



Students from Madison Junior High School, in Naperville, identify insects in Fermilab's prairie.

In 1996, budget cuts at the U.S. Department of Energy eliminated a major source of funding for Fermilab's precollege education programs. Ambitious programs for the future and even some existing programs—such as the Outreach Program, which provided assistance for science education in local minority schools—had to be cut.

But Friends of Fermilab came to the rescue. Founded in 1983, Friends of Fermilab is a not-for-profit organization that secures public- and private-sector grants for Fermilab's precollege programs. While Friends of Fermilab has long raised money to support these programs, the grants were especially crucial in 1997 in ensuring the continuation of Fermilab's educational efforts for school teachers and their students. For example, a Science Literacy grant from the Illinois State Board of Education is supporting a second year of Fermilab's four-year ARISE (American Renaissance in Science Education) project. Six high schools, each with a team of three or four teachers, are participating in ARISE, two from the city of Chicago, two from suburbs and two from rural areas. The project helps teachers develop a three-year standards-based science curriculum that places special emphasis on demonstrating the links among physics, chemistry and biology. Details are left to the teachers. Two schools, for example, are teaching physics the first year, while four schools are integrating physics throughout the curriculum. The money, among other things, provides stipends for teachers so that they can spend summers developing their curricula and exchanging ideas with colleagues here at Fermilab and back in their schools.

Also, pending budgetary approval by Congress, Friends of Fermilab was expecting a $125,000 grant from the North Central Regional Technology in Education Consortium, one of six regional consortia funded by the U.S. Department of Education. NCRTEC's mission is to help schools develop the technology tools and skills to promote what is generally referred to as "engaged learning," or learning by doing.

Bob Betz, Fermilab's prairie consultant, helping a young prairie harvester at the Lab's annual harvest.

The grant will support several projects. One is The Fermilab LInC Online, the Leadership Institute Integrating Internet, Instruction and Curriculum, a program designed and taught by Laura Mengel, of the Computing Division, to create a network of leadership teams spurring educational changes that take advantage of new technology. The 80-hour LInC course, begun in 1995, develops participants' Internet skills and assists them in creating engaged-learning projects. While LInC originally was an on-site program supported by the state's Scientific Literacy Grant Program, NCRTEC is interested in having Fermilab run the course on-line so that teachers not just in Illinois but all across NCRTEC's eight-state region can benefit.

Two of the Science Education Center's most popular programs are Beneath the Ashes and Particles and Prairies. In one month alone (from September 15 to October 15, 1997), 4,450 children from 58 area schools came to Fermilab to experience the prairie.

The Beneath the Ashes field trip, for kids in grades 3, 4 and 5, includes a nature walk and a visit with the bison. Docents share Indian lore and information about the plant and animal life. They might have the children write a collective poem about the prairie, or play the parts of rabbits, foxes and hawks—predators and prey—learning why certain animals seek shelter in the part of the landscape called the transition zone.

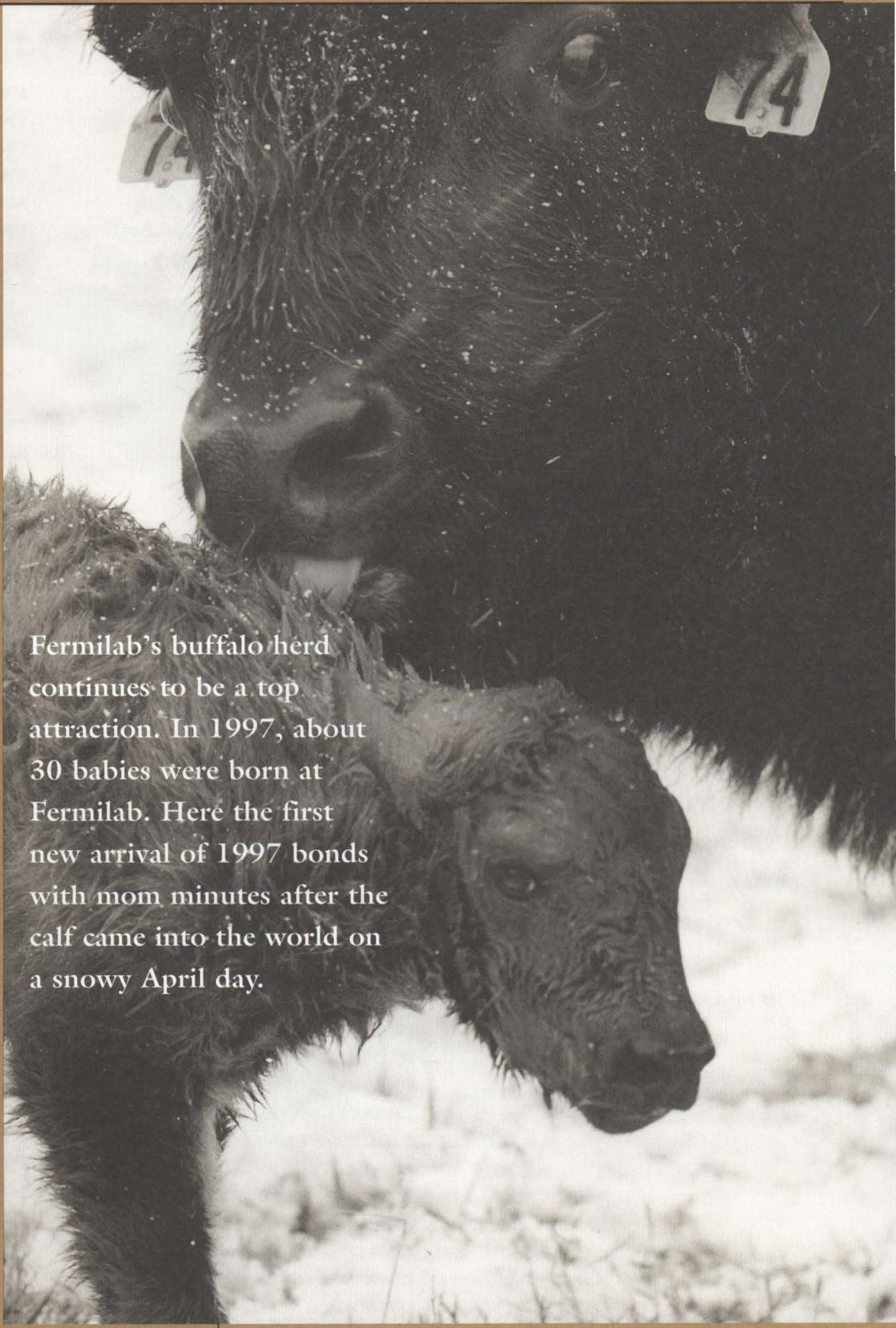
Particles and Prairies gives children in grades 6, 7 and 8 a unique opportunity to participate in ongoing research. Out in the field, the kids do studies, recording the diversity of plants in one-square-meter plots. They collect abiotic data, using light meters, psychrometers, and other tools; identify insects; and analyze the pond water, including its oxygen levels and animal life. The compiled information helps Fermilab staff monitor the evolution of the site's restored prairie ecosystem.

ENVIRONMENT

From the late 1960s to now, Fermilab has always encouraged stewardship of the environment. That ideal was set in motion by Robert Wilson, Fermilab's first director, and it continues today with a talented and dedicated crew of environmental specialists.

The most obvious example is the Fermilab tallgrass prairie. In the late 1800s, tallgrass prairie blanketed northern Illinois. But the arrival of the plow and the clearing of the land for agriculture stripped away much of the Prairie State's natural grasses. However, with the help of science, sound ecological management, and hard work, Fermilab has restored about 1,100 acres of tallgrass prairie on its site. Fermilab crews clean prairie seeds, burn large tracts to promote the growth of native species and test the soil, among other jobs. Critical to the prairie restoration effort has been the help of hundreds of volunteers who come to Fermilab to harvest prairie seeds each fall. The annual event has steadily grown in popularity over the years. Armed with gardening gloves and clipping shears, the volunteers charge into the prairie to look for certain species of flowering plants. The harvest, while fun, serves an important ecological function, according to Mike Becker, one of Fermilab's prairie experts. He said that the large combines Fermilab uses to harvest mechanically are effective in harvesting the prairie grasses, as they tend to be taller. However, the combine misses most of the shorter flowering plants, which the volunteers gather manually. The seeds are later cleaned and then planted the following spring in younger prairie areas at Fermilab to enhance their biodiversity. The Laboratory's dedicated environmental team also shares the seeds with other prairie restoration projects across Illinois and elsewhere in the Midwest.

Along with the prairie, Fermilab nurtures savannahs, woodlands, wetlands and other critical ecosystems. These sensitive areas are home to many creatures that complete the Fermilab ecological system.



Fermilab's buffalo herd continues to be a top attraction. In 1997, about 30 babies were born at Fermilab. Here the first new arrival of 1997 bonds with mom minutes after the calf came into the world on a snowy April day.

Fermilab's User Community

They're at the center of Fermilab's mission to provide "leadership and resources for qualified researchers to conduct basic research at the frontiers of high-energy physics and related disciplines." Those qualified researchers—nearly 2,300 scientists and their students—compose Fermilab's community of "users," as they are affectionately known.

They come from Texas and from Turkey; from Colombia the country and Columbia the university; from as nearby as Elmhurst, Illinois, and as far away as Beijing, China; from Oxford, England, and from Oxford, Mississippi; from university groups as large as 50 and as small as one.

Presented here are all of the institutions that send their scientists and students to the energy frontier, collectively representing the very reason the U.S. government built and operates Fermilab.

U.S. INSTITUTIONS (97)

ABILENE CHRISTIAN UNIVERSITY
UNIVERSITY OF SOUTH ALABAMA
ARGONNE NATIONAL LABORATORY
UNIVERSITY OF ARIZONA
BALL STATE UNIVERSITY
BOSTON UNIVERSITY
BRANDEIS UNIVERSITY
BROOKHAVEN NATIONAL LABORATORY
BROWN UNIVERSITY
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF CALIFORNIA, BERKELEY
UNIVERSITY OF CALIFORNIA, DAVIS
UNIVERSITY OF CALIFORNIA, IRVINE
UNIVERSITY OF CALIFORNIA, LOS ANGELES
UNIVERSITY OF CALIFORNIA, RIVERSIDE
UNIVERSITY OF CALIFORNIA, SAN DIEGO
UNIVERSITY OF CALIFORNIA, SANTA CRUZ
CARNEGIE-MELLON UNIVERSITY
UNIVERSITY OF CHICAGO
UNIVERSITY OF CINCINNATI
UNIVERSITY OF COLORADO AT BOULDER
COLUMBIA UNIVERSITY
CORNELL UNIVERSITY
DUKE UNIVERSITY
ELMHURST COLLEGE
FLORIDA STATE UNIVERSITY
UNIVERSITY OF FLORIDA
GEORGIA STATE UNIVERSITY
HARVARD UNIVERSITY
UNIVERSITY OF HAWAII AT MANOA
UNIVERSITY OF HOUSTON
UNIVERSITY OF ILLINOIS, CHICAGO CIRCLE
ILLINOIS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF ILLINOIS, CHAMPAIGN
INDIANA UNIVERSITY
IOWA STATE UNIVERSITY
UNIVERSITY OF IOWA
JOHNS HOPKINS UNIVERSITY
KANSAS STATE UNIVERSITY
LAWRENCE BERKELEY LABORATORY
LAWRENCE LIVERMORE LABORATORY
LOS ALAMOS NATIONAL LABORATORY
LOUISIANA STATE UNIVERSITY
UNIVERSITY OF LOUISVILLE
UNIVERSITY OF MARYLAND
UNIVERSITY OF MASSACHUSETTS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF MICHIGAN – ANN ARBOR
UNIVERSITY OF MICHIGAN – FLINT
MICHIGAN STATE UNIVERSITY
UNIVERSITY OF MINNESOTA
UNIVERSITY OF MISSISSIPPI
UNIVERSITY OF NEBRASKA
NEW MEXICO STATE UNIVERSITY
UNIVERSITY OF NEW MEXICO
SUNY AT ALBANY
SUNY AT STONY BROOK
NEW YORK UNIVERSITY
UNIVERSITY OF NORTH CAROLINA
NORTHEASTERN UNIVERSITY
NORTHERN ILLINOIS UNIVERSITY
NORTHWESTERN UNIVERSITY
NOTRE DAME UNIVERSITY
OAK RIDGE NATIONAL LABORATORY
OHIO STATE UNIVERSITY
OHIO UNIVERSITY
UNIVERSITY OF OKLAHOMA
UNIVERSITY OF OREGON
PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY OF PENNSYLVANIA
UNIVERSITY OF PITTSBURGH
PRAIRIE VIEW A&M UNIVERSITY
PRINCETON UNIVERSITY
UNIVERSITY OF PUERTO RICO - MAYAGUEZ
UNIVERSITY OF PUERTO RICO - RIO PIEDRAS
PURDUE UNIVERSITY
RICE UNIVERSITY
UNIVERSITY OF ROCHESTER
ROCKEFELLER UNIVERSITY
RUTGERS UNIVERSITY
UNIVERSITY OF SOUTH CAROLINA
SOUTWESTERN MEDICAL CENTER
STANFORD UNIVERSITY
UNIVERSITY OF TENNESSEE, KNOXVILLE
TEXAS A&M UNIVERSITY
UNIVERSITY OF TEXAS AT ARLINGTON
UNIVERSITY OF TEXAS AT AUSTIN
TEXAS TECH UNIVERSITY
TUFTS UNIVERSITY
VALPARAISO UNIVERSITY
VANDERBILT UNIVERSITY
UNIVERSITY OF VIRGINIA
UNIVERSITY OF WASHINGTON
WESTERN WASHINGTON UNIVERSITY
UNIVERSITY OF WISCONSIN - MADISON
XAVIER UNIVERSITY
YALE UNIVERSITY

Fermilab's User Community

FOREIGN INSTITUTIONS (90)

IHEP, ACADEMIA SINICA (TAIWAN)
AICHI UNIVERSITY OF EDUCATION (JAPAN)
UNIVERSIDAD DE LOS ANDES(COLOMBIA)
UNIVERSITY OF ATHENS (GREECE)
IHEP, BEIJING (PRC)
BOGAZICI UNIVERSITY (TURKEY)
UNIVERSITY OF BOLOGNA (ITALY)
UNIVERSITY OF BRISTOL (ENGLAND)
UNIVERSIDAD DE BUENOS AIRES (ARGENTINA)
CIPP (CANADA)
CBPF (BRAZIL)
CEN-SACLAY (FRANCE)
CERN (SWITZERLAND)
CHONNAM NATIONAL UNIVERSITY (KOREA)
CINVESTAV-IPN (MEXICO)
DELHI UNIVERSITY (INDIA)
UNIVERSITY OF FERRARA (ITALY)
INFN, FRASCATI (ITALY)
FREIBURG UNIVERSITY (GERMANY)
UNIVERSITY OF GENEVA (SWITZERLAND)
INFN, GENOVA (ITALY)
GIFU UNIVERSITY (JAPAN)
UNIVERSITY OF GUANAJUATO (MEXICO)
GYEONGSANG NATIONAL UNIVERSITY (KOREA)
HIROSAKI UNIVERSITY (JAPAN)
HIROSHIMA UNIVERSITY (JAPAN)
JINR, DUBNA (RUSSIA)
UNIVERSITY OF KARLSRUHNE (GERMANY)
KEK (JAPAN)
KINKI UNIVERSITY (JAPAN)
KOBE UNIVERSITY (JAPAN)
KOREA ADVANCED INSTITUTE OF SCIENCE (KOREA)
KOREA UNIVERSITY, SEOUL (KOREA)
INP, KRAKOW (POLAND)
KYOTO SANGYO UNIVERSITY (JAPAN)
KYOTO UNIVERSITY (JAPAN)
KYUNGSUNG UNIVERSITY, PUSAN (KOREA)
LAPP, D'ANNECY-LE-VIEUX (FRANCE)
UNIVERSITE DE LAUSANNE (FRANCE)
LEBEDEV PHYSICAL INSTITUTE (RUSSIA)
UNIVERSITY OF LECCE (ITALY)
MAX-PLANCK INSTITUTE (GERMANY)
MCGILL UNIVERSITY (CANADA)
INFN, MILANO (ITALY)
UNIVERSITY OF MILANO (ITALY)
MOSCOW STATE UNIVERSITY (RUSSIA)
ITEP, MOSCOW (RUSSIA)
NAGOYA INSTITUTE OF TECHNOLOGY (JAPAN)
NAGOYA UNIVERSITY (JAPAN)
NANJING UNIVERSITY (PRC)
UNIVERSITY OF OCCUPATIONAL & ENVIRONMENTAL HEALTH (JAPAN)
OKAYAMA UNIVERSITY (JAPAN)
OSAKA CITY UNIVERSITY (JAPAN)
OSAKA SCIENCE EDUCATION INSTITUTE (JAPAN)
OSAKA UNIVERSITY (JAPAN)
OSAKA UNIVERSITY OF COMMERCE (JAPAN)
UNIVERSITY OF OXFORD (ENGLAND)
UNIVERSITY OF PADOVA (ITALY)
PANJAB UNIVERSITY (INDIA)
UNIVERSITY FEDERAL DO PARAIBA (BRAZIL)
UNIVERSITY OF PAVIA (ITALY)
PNPI, ST. PETERSBURG (RUSSIA)
INFN, PISA (ITALY)
IHEP, PROTVINO (SERPUKHOV) (RUSSIA)
UNIVERSITYAUTONOMA DE PUEBLA (MEXICO)
UNIVERSITY FEDERAL DO RIO DE JANEIRO (BRAZIL)
INFN, ROME (ITALY)
RUTHERFORD-APPLETON LABS. (ENGLAND)
UNIVERSITYAUTO.DE SAN LUIS POTOSI (MEXICO)
UNIVERSITE OF SAO PAULO (BRAZIL)
SEOUL NATIONAL UNIVERSITY (KOREA)
SHANDONG UNIVERSITY (PRC)
SOAI UNIVERSITY (JAPAN)
SUSSEX UNIVERSITY (ENGLAND)
TATA INSTITUTE (INDIA)
TECHNION-ISRAEL INSTITUTE (ISRAEL)
UNIVERSITY OF TEL-AVIV (ISRAEL)
TOHO UNIVERSITY (JAPAN)
UNIVERSITY OF TORINO (ITALY)
UNIVERSITY OF TORONTO (CANADA)
INFN, TRIESTE (ITALY)
UNIVERSITY DI TRIESTE (ITALY)
UNIVERSITY OF TSUKUBA (JAPAN)
UNIVERSITY OF UDINE (ITALY)
UTSUNOMIYA UNIVERSITY (JAPAN)
VANIER COLLEGE (CANADA)
WASEDA UNIVERSITY (JAPAN)
UNIVERSITY OF WUPPERTAL (GERMANY)
YEONSEI UNIVERSITY (KOREA)
YOKOHAMA NATIONAL UNIVERSITY (JAPAN)

1997 Finances
Fermi National Accelerator Laboratory
Operated by UNIVERSITIES RESEARCH ASSOCIATION, INC.
under a contract with the U.S. Department of Energy

Laboratory Funding and Personnel Summary
For the Fiscal Year Ended September 30, 1997

OPERATING AND EQUIPMENT

Fermilab Operating	180,654,950
Other Projects	
• Waste management	2,185,000
• Education	0
• PET	3,250,000
• Work for others	172,074
• Tech transfer	0
• IHEM operating	0
• SSC closeout	5,531,000
Subtotal other	11,138,074
Total Operating	**191,793,024**
Capital Equipment	**22,908,000**

PROGRAM CONSTRUCTION

Main Injector	52,000,000
AIP/GPP	6,035,000
Total project construction	**58,035,000**
Total Laboratory Funding	272,736,024

LABORATORY PERSONNEL SUMMARY

Direct	1,638
Indirect	521
Total Laboratory Personnel	2,159

Credits
Writers/Editors: Sharon Butler, Judy Jackson, Donald Sena, Fermilab Office of Public Affairs; Joseph Lykken, Fermilab Theory Group;
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