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*The policy at Fermi National Accelerator Laboratory is to pursue its scientific goals with an emphasis on equal employment opportunity and a special dedication to human rights and dignity.*

*Fermilab attracts scientists not only from this country, but from many other nations all over the world. Foreign visitors, laymen as well as scientists, come to the Laboratory to participate in its work. They represent a wide variety of races, nationalities, cultures, and beliefs. It is essential that we provide an environment and maintain an atmosphere in which both staff and visitors can live and work with pride and dignity without regard to such differences as race, religion, sex, or national origin.*

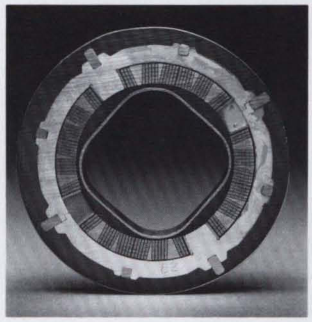
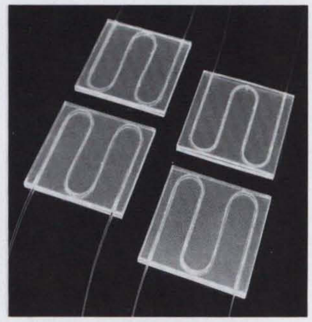
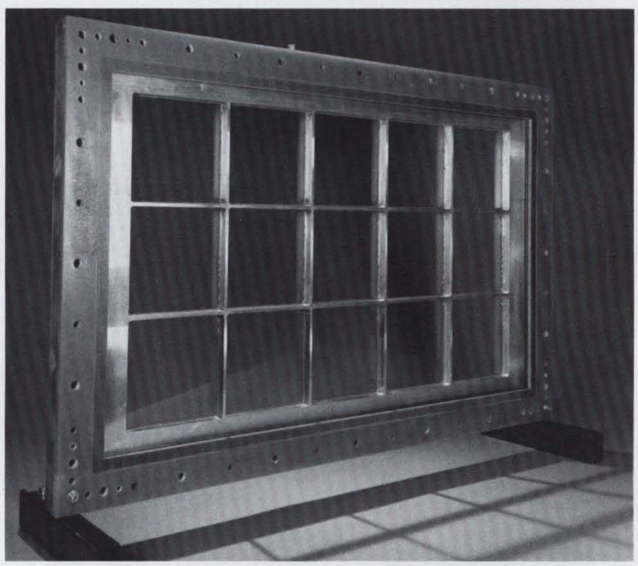
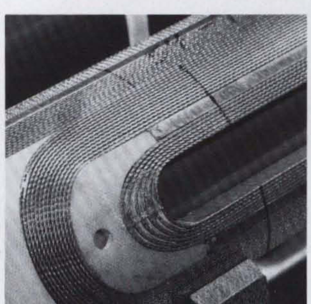
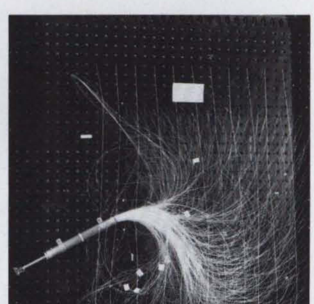
AAB2470

# Fermilab 1990

## Annual Report of the Fermi National Accelerator Laboratory

Fermi National Accelerator Laboratory
Batavia, Illinois

*Operated by Universities Research Association, Inc.*
*Under Contract with the United States Department of Energy*

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## From the Director…

This was the year that the high energy physics community took the measure of the opportunities for discovery in the 1990s. We were delighted that the Department of Energy's High Energy Physics Advisory Panel concluded that the Tevatron is the premier high energy facility in the nation and that **Fermilab III** could make the nation's high energy physics program preeminent in the world during the 1990s. They "assigned the highest priority in the base program to the immediate commencement and speedy completion of construction of the Main Injector."

The Department of Energy accepted this recommendation, and as the year ended it had included $43.5 million for the Main Injector in its FY 1992 Congressional budget request. While Congress has the final say on this request, we are hopeful that they will support it. We are very pleased that the Department has recognized that **Fermilab III** is essential for the future of Fermilab and the nation's high energy physics program. The plans for the three major elements of **Fermilab III** – the Linac Upgrade, the Main Injector, and substantial improvements to CDF and the DØ detector – are complete. Plans for the fourth element – fixed target physics with the

Main Injector, have begun in earnest. The fact that the Linac upgrade is nearly half complete is strong evidence that we are beyond the planning stage. Prototype development for the substantial improvements to CDF and the DØ detector that will make them sensitive to the top quark has already begun. We have even cut metal for the Main Injector. The first full-scale prototype dipole magnet was built and tested. **Fermilab III** is rapidly emerging as a reality.

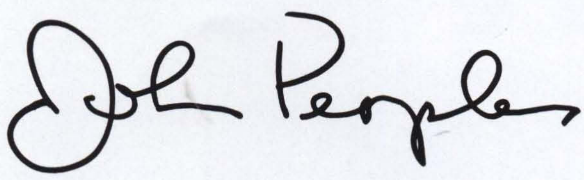
The highlight of our 1990 accomplishments has to be the extremely successful fixed target run that began in February and continued until the beginning of September. The Tevatron flawlessly delivered a steady stream of protons to the experimental areas. Records were set for efficiency and hours of operation. Ten experiments took extensive data, four more experiments started the commissioning of their detectors with beam, and ten collaborations tested detector subsystems for use at the Tevatron collider and other colliders present and future. Many of these detector tests have the same level of complexity as medium size fixed target experiments.

While beam was being delivered to the fixed target experiments, preparations for the winter 1991 collider run continued at a hectic pace. The massive DØ detector, the results of a seven-year effort by the DØ collaboration, dwarfs those who visit the DØ assembly building. This massive detector will be ready to move into place in the Tevatron in the fall 1991. Soon thereafter it will join CDF in recording collisions of protons and antiprotons. The CDF collaboration also made full use of the past year to make major improvements to its detector, to continue the analysis of the data it acquired in 1988 and 1989, and to prepare for the collider runs beyond 1992. During the last four months of 1990, the Accelerator Division installed superconducting quadrupoles and electrostatic separators, the ingredients needed for the collider run that will start in 1991. The success of these efforts gave us confidence that the Tevatron luminosity will reach the very ambitious goals that are set for **Fermilab III**.

This year was the first full year of operation for the Education Office as we witnessed its successful transition from Friends of Fermilab, the volunteer effort that fostered Fermilab's impressive precollege education programs. The Secretary of Energy's commitment to engaging the national laboratories in precollege education has enabled Fermilab to continue bringing its growing precollege programs to the Fox Valley as well as the broader national scene. Friends of Fermilab continues to be a crucial part of reaching out to the community, since it can move nimbly where the bureaucracy cannot.

Fermilab reached for the stars this year with the formation of an experimental astrophysics group. The first goal of this group will be to fulfill Fermilab's commitment to the Digital Sky Survey, a proposal to measure the red shifts of a million galaxies in the northern galactic hemisphere. Astrophysicists at Chicago, Princeton, and the Institute for Advance Study initiated this proposal in order to understand the large-scale structure of the universe. Since that structure may be intimately connected with the dark matter and the particle content of the early universe, we elected to join this effort after the invitation was extended.

In this year's *Annual Report* we are exploring all of the different connections that stitch the fabric of our Laboratory together. There are the connections that bind us to the many communities that we draw from and give to. There are the connections that link a discovery in one part of science to a seemingly unrelated one in another branch of science. There are the connections that bind science and technology together. All of these connections can be thought of as pathways for communication. Of all of the pathways, electronic networks are becoming the most ubiquitous. We hope that you will enjoy learning about these connections as you read on.



April 1991

*(Opposite) Director John Peoples stands before his wife Nancy's work, Two Galaxies and Snail Landscape.*

# Introduction to Fermilab

Fermilab, the Fermi National Accelerator Laboratory, is one of the world's foremost laboratories dedicated to high energy physics research. The Laboratory is operated for the U. S. Department of Energy by Universities Research Association, Inc., a consortium of 78 major research-oriented universities in the United States and Canada. Fermilab is named in honor of Enrico Fermi, a pioneering physicist whose work led to the first self-sustaining chain reaction.

Fermilab is located on 6,800 acres about 30 miles west of Chicago, slightly north of the Illinois East-West Tollway (I-88) whose route defines the Illinois Research and Development Corridor. Fermilab's construction has contributed greatly to the development of the high technology Corridor between Chicago and Aurora.

The headquarters of Fermilab are in Robert Rathbun Wilson Hall, a 16-story structure named after Fermilab's founding director. At the end of 1990 Fermilab employed more than 2,300 people, including 326 scientists and 184 engineers. In addition, 882 physicists and graduate students from 83 American universities were actively engaged in research here. Last year Fermilab also attracted scientists affiliated with 44 different institutions from 18 foreign nations.

## Fundamental Interactions and Fundamental Particles

Research at Fermilab is driven by human curiosity about what we and the universe are made of, on finding the ultimate building blocks of the universe and on understanding the forces acting between these fundamental particles. Physicists are constantly searching for ways to explain nature with a small number of laws. In the current theoretical framework, there are four fundamental interactions, called gravitational, electromagnetic, strong, and weak which are responsible for everything we observe. The familiar gravitational interaction, or force of gravity, keeps us on the earth's surface and explains the motions of the planets and stars. The electromagnetic interaction is responsible for holding atoms, as well as familiar macroscopic objects, together. The strong and weak interactions are less familiar in everyday life but are very important at the level of atomic nuclei or particles. The strong force holds quarks permanently together inside of particles called hadrons, such as the proton, neutron or pi meson. This leads to a residual force between protons and neutrons which causes them to form atomic nuclei. The weak interaction is responsible for nuclear beta decay. Weak interactions are essential for the synthesis of chemical elements in stars. Without them life could never exist.

Four forces may seem like a small number to explain everything but physicists who search for unity and simplicity in nature would prefer if everything could be explained with one force. In the past 20 years a unifying principle that underlies all of the known forces has been uncovered. This is called local gauge invariance. Prior to 1972, all textbooks treated the four forces completely differently, while today physicists have uncovered nature's basic principle underlying all forces, including gravity.

This suggests that there is really only one underlying force in nature that gives rise to the four different forces at low energies (and maybe others not yet seen!) through symmetry breaking. Thus theorists are led to incredible ideas which unify all the four forces into one underlying symmetric object. The difference in forces at low energies is a bit like the difference between Antarctica, or the Amazon; only when you go to very high altitudes (energies) do you see that they lie on a common spherical globe. The dominant question physicists seek an answer to now is: Why are the weak interactions weak at low energies? or: Why are the W and Z bosons massive while the photon is massless? We think the mechanism may involve something like a Higgs particle and is intimately related to the phenomenon of superconductivity.

Physicists at Fermilab explore the basic structure of matter. When scientists first broke

| THE FORCES OF NATURE | | | |
|---|---|---|---|
| FORCE | RELATIVE STRENGTH of FORCE Decreasing Order | BINDING or MESSENGER PARTICLE Field Quantum | IMPORTANT IN |
| Strong Force | 1 | Gluons (no mass) | Holding Quarks in Hadrons<br>Atomic Nucleus |
| Electromagnetic Force | 1/100 | Photons (no mass) | Atomic Shell<br>All Electric and Magnetic Phenomena and Technology |
| Weak Force | Varies (actually stronger than electromagnetic at Fermilab energies) | Bosons $Z^0$, $W^+$, $W^-$ (heavy) | Nucleosynthesis (without this force carbon would not exist)<br>Stars |
| Gravitation | $10^{-38}$ | Graviton (no mass) | |

down the atom into its constituent parts, they thought the protons (positively charged particles) and neutrons (uncharged particles) making up the atom's nucleus and the electrons (negatively charged particles) surrounding the nucleus might be the fundamental particles of which all else is made. Particle physicists have been discovering new particles for some time, but it is believed now that there are only two basic kinds of matter: the quarks and the leptons. There are three pairs of quarks, called up-down, charm-strange, and top-bottom. There are also three pairs of leptons – the electron, muon and tau, each with its own neutrino. The top quark has not yet been observed, but its existence is essential to make the picture complete. The leptons participate in weak interactions and in electromagnetic interactions if they have charge. They are not subject to strong interactions. Quarks participate in the strong interaction as well as the weak and electromagnetic interactions. We ignore gravitational interactions between the particles. Their small masses make these forces negligible.

# Particle Research

Study of the behavior of these incredibly small and sometime short-lived particles has become possible through the use of high energy accelerators. Fermilab's accelerator, the Tevatron, is capable of accelerating protons to energies approaching one trillion electron volts (TeV). The accelerator is also used to produce a beam of antiprotons that circulate in an opposite direction than the protons in the same vacuum chamber. When the two beams collide, the highest energy collisions in the world are produced.

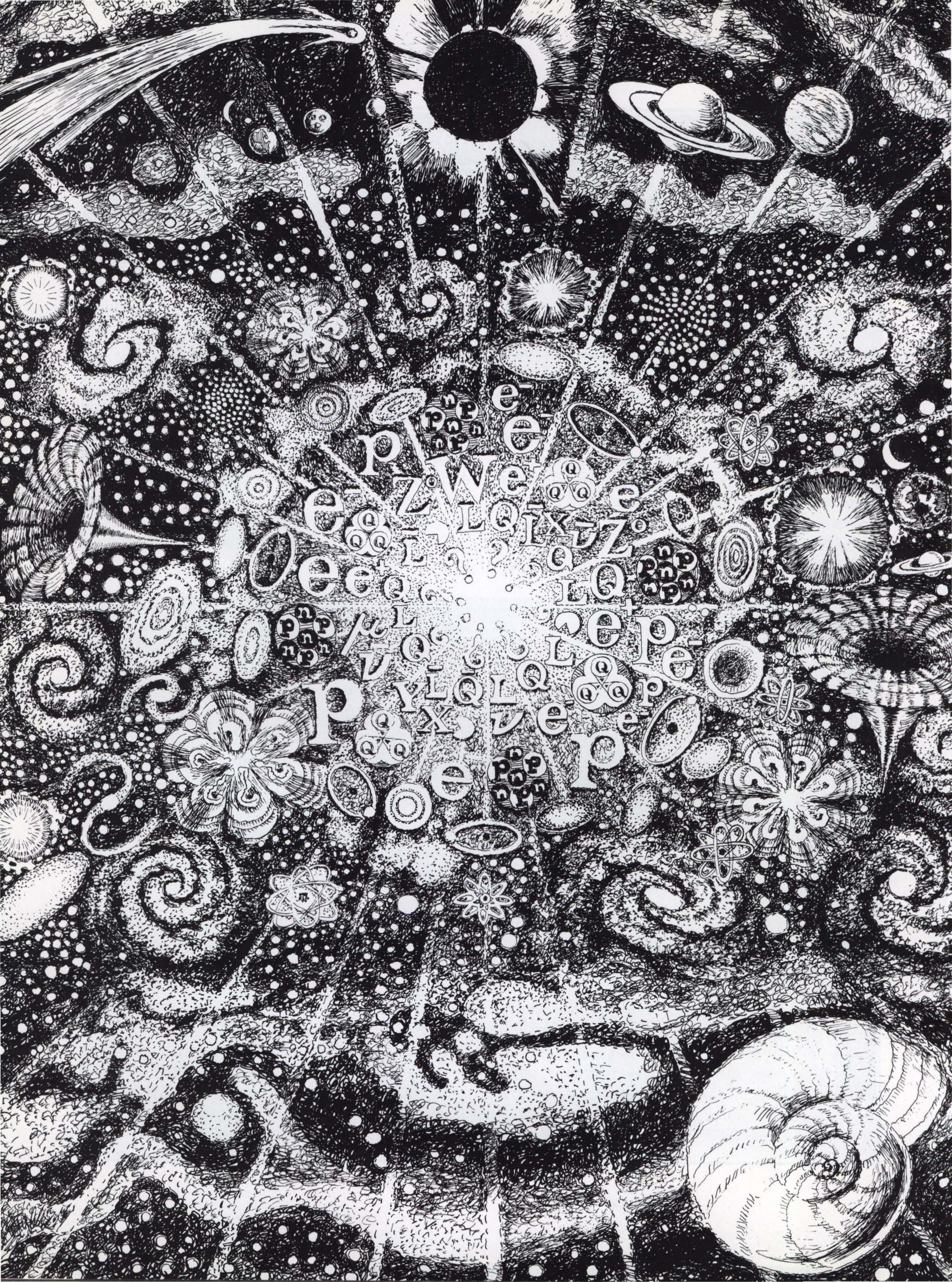
Fermilab operates its experimental program in two basic modes: colliding beam and fixed target. In a colliding beam experiment, a beam of protons and a beam of antiprotons circulate in opposite directions within the Tevatron and are made to collide at specific points around the ring where detectors are placed. In a fixed target experiment, the proton beam is extracted from the Tevatron, then split into as many as 15 different proton beams, and directed through a series of underground tunnels to the fixed target experimental areas where the protons strike a variety of stationary targets.

Experiments are based on observing what happens to the particles colliding and what additional particles are produced in the collision. The energy of the collision determines the possible set of outcomes. Large detectors are used to study and record collisions of interest.

The number of collisions between particles per second when a beam hits a target or when two beams collide is related to a quantity called luminosity, which is measured in inverse picobarns per second. (One picobarn equals $10^{-36}$ $cm^2$.) As the luminosity rises, the probability rises that a particle collision of interest has occurred and that the researcher may discover something new or be able to measure an important parameter more accurately.

| | ELECTRIC CHARGE PROTON IS +1 UNIT | M = MASS IN ENERGY UNITS | | |
|---|---|---|---|---|
| THE QUARKS | +2/3 | M = 5 MeV<br>**u**<br>up | M = 1500 MeV<br>**c**<br>charm | M > 89 GeV<br>**t**<br>top<br>NOT YET DISCOVERED |
| | -1/3 | M = 10 MeV<br>**d**<br>down | M = 150 MeV<br>**s**<br>strange | M = 5000 MeV<br>**b**<br>bottom<br>DISCOVERED at FERMILAB |
| THE LEPTONS | 0<br>(neutral) | M = 0 or very small<br>$\nu_e$<br>electron neutrino | M = 0 or very small<br>$\nu_\mu$<br>muon neutrino | M = 0 or very small<br>$\nu_\tau$<br>tau neutrino<br>NOT YET OBSERVED |
| | -1 | M = 0.511 MeV<br>**e**<br>electron | M = 105 MeV<br>$\mu$<br>muon | M = 1784 MeV<br>$\tau$<br>tau |

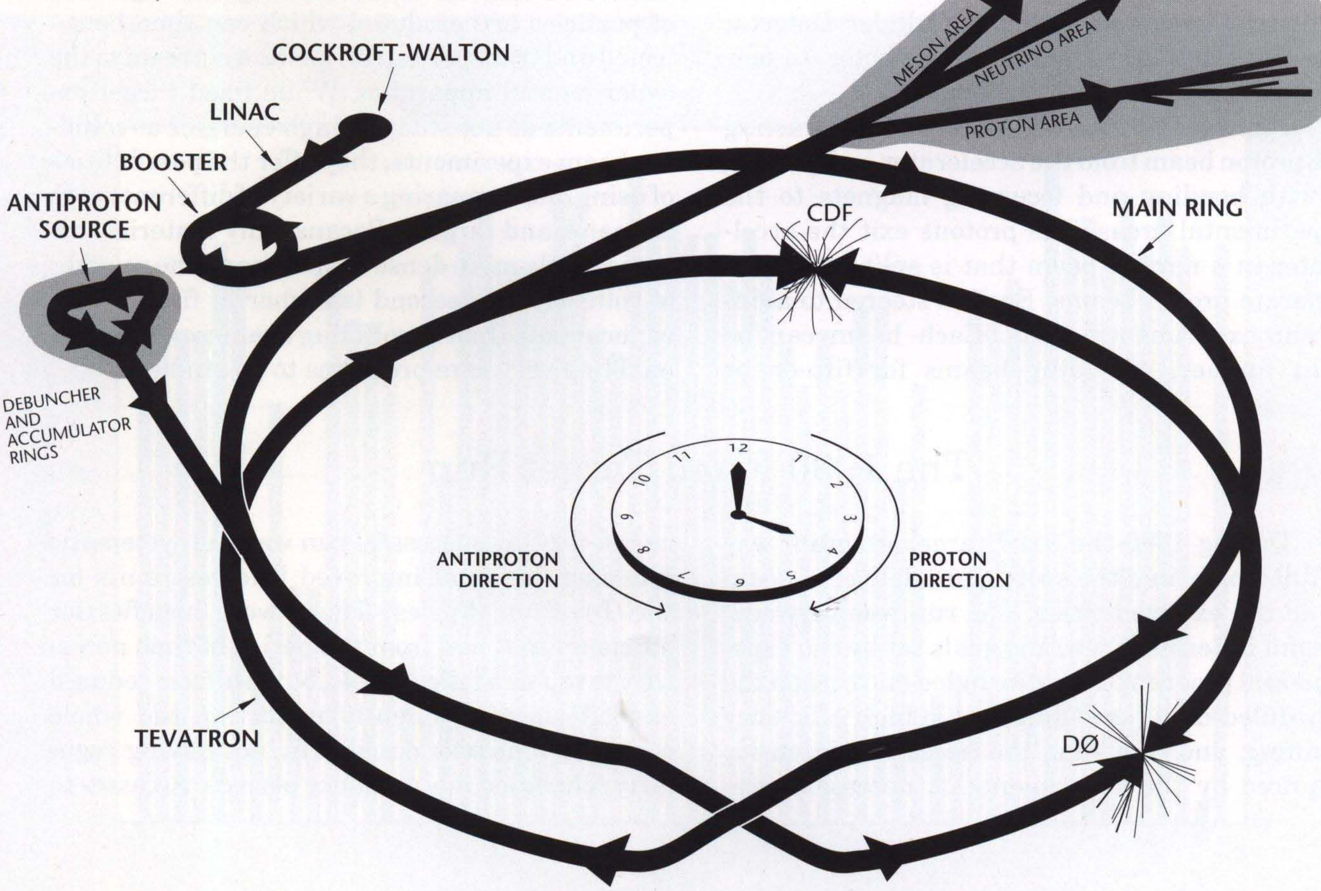
Antiparticles are indicated with a bar such as: $\bar{p}$ antiproton $\bar{c}$ anticharm



# Fermilab Physics Programs

## Accelerators at Fermilab

The particle accelerator complex at Fermilab as well as the last and highest energy accelerator in that complex is called the Tevatron. Its name derives from its ability to accelerate protons to nearly one trillion electron volts, or 1 TeV. (An electron volt, or eV, is the amount of energy gained by one electron as it moves through a voltage of one volt.) The Tevatron is part of a system of five accelerators that work in sequence. In the Cockcroft-Walton, a large dc voltage accelerates hydrogen ions consisting of one proton and two electrons to 750,000 eV. This is about 30 times the energy of the electron beam in a television set. In the second stage the Linac, a 500-foot-long linear accelerator, accelerates these particles to an energy of 200 million eV. (The energy will be raised soon to 400 million eV.) The two electrons are then stripped off the hydrogen ions, leaving bare protons, which are injected into the third stage, known as the Booster, a synchrotron with a diameter of approximately 500 feet, located in a tunnel 20 feet below the ground. A synchrotron uses magnets to bend electrically charged particles in a circular path so they repeatedly experience accelerating electric fields. Once the protons are accelerated by the Booster to an energy of eight billion eV (8 GeV), they are injected into the Main Ring, a synchrotron with a diameter of two kilometers, where they are accelerated to 150 GeV. The Main Ring, composed of water-cooled magnets and operated at room temperature, is the top ring of two rings of magnets in an underground tunnel. The bottom ring, the Tevatron, consists of superconducting magnets cooled by liquid helium to approximately 4.5 K (-270° C). The superconducting magnets in the Tevatron can produce much stronger magnetic fields than the copper-iron magnets of the Main Ring while consuming less electrical energy.



## Antiproton Acceleration

An antiproton is a particle that has the same properties as the proton except for its electrical charge which is negative (like an electron). Antiprotons do not exist naturally on earth; they must be produced by converting energy into matter and antimatter in high energy collisions.

The Tevatron's injector is also used to initiate production of the antiprotons. Every two seconds, approximately two trillion protons are accelerated to 120 GeV in the Main Ring accelerator and then directed to an antiproton production target. Of the many particles and antiparticles of different types produced in collisions the protons make in the target, about ten million antiprotons are collected in a Debuncher ring. The captured beam of antiprotons, circulating in the Debuncher ring, is then made more dense by a process called stochastic cooling. The antiprotons are then transferred to the Accumulator ring, where over a period of hours or even days, the antiprotons are merged into a single beam, cooled further, and stored. The Debuncher and Accumulator rings operate at 8 GeV, the same energy as the Booster accelerator. About once a day intense, very dense bunches of antiprotons are extracted from the Accumulator ring, injected into the Main Ring at 8 GeV, and accelerated to 150 GeV. The antiprotons circulate counterclockwise in the Main Ring and the Tevatron, whereas the protons circulate clockwise. From the Main Ring the antiprotons are passed to the Tevatron, and accelerated simultaneously with a beam of protons to nearly 1 TeV.

## Colliding Beam and Fixed Target Experiments

In colliding beam experiments, where collisions between two beams travelling in opposite directions are observed, the energy of the collision is much higher than in a collision between a moving beam and a fixed target. Fermilab has built two large detectors, the Collider Detector at Fermilab (CDF) and the DØ detector, to perform colliding beam experiments.

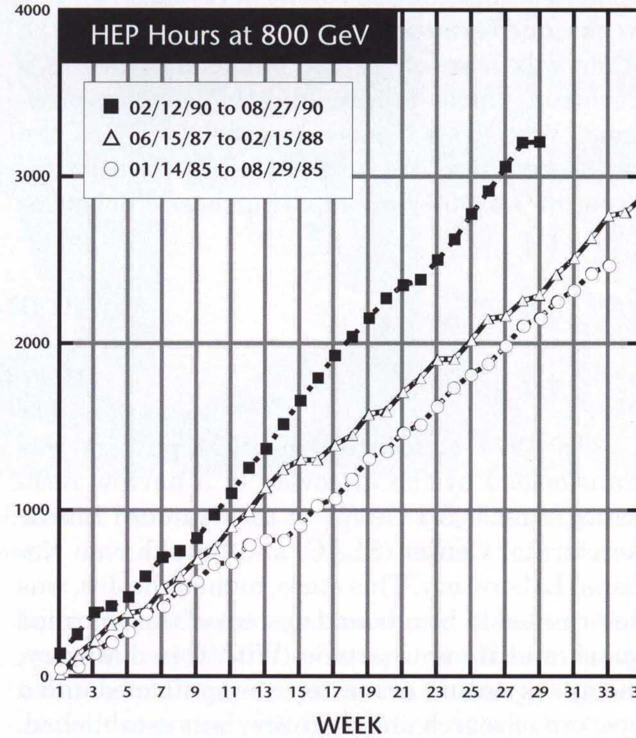
Fixed target experiments involve extracting the proton beam from the accelerator and guiding it with bending and focussing magnets to the experimental areas. The protons exit the accelerator in a narrow beam that is split into three separate proton beams. Each is steered to a different experimental area. Each beam can be split further, providing beams for fifteen or more experiments simultaneously. Many experiments use particles other than protons. This is accomplished by first steering the primary beam of protons into a stationary target. As the protons interact with the atoms in the target, many kinds of particles are produced which can then be selected and transported further downstream to the experimental apparatus. While fixed target experiments do not study as high energies as colliding beam experiments, they offer the possibilities of using and comparing a variety of different types of beams and targets. Because any material target is vastly more dense than a beam, the number of collisions per second is higher in fixed target experiments than in colliding beam experiments, enabling very rare processes to be studied.

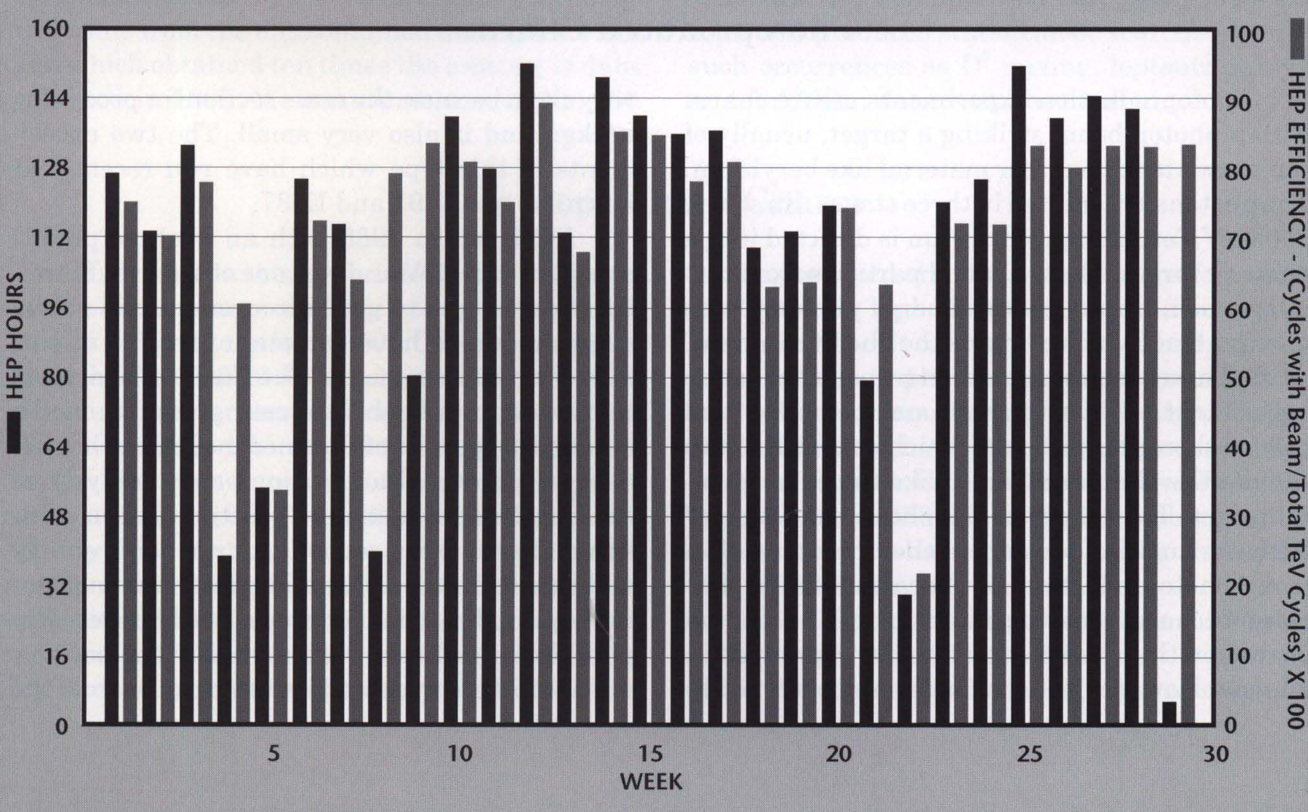
## The 1990 Fixed Target Run

During 1990 the fixed target program was in full bloom, and the switchyard delivered beam to all the external areas. The run was very successful in terms of meeting goals set by the experimental program. These included starting on the scheduled date, providing stable high efficiency running, and providing the necessary intensity required by the experiments. A necessary precursor for this successful run was the systematic implementation of improved lead restraints for the Tevatron dipoles. There were benefits for efficiency, not just from the period of time necessary to repair a failed dipole, but also from reduced end effects of frequently restarting the whole complex. This was possible by not having regularly scheduled maintenance periods. Accesses to the accelerator tunnels were made only when some necessary element failed, and other work was permitted under tight control. The machine study periods were longer in duration than in previous runs, but fewer in number which also helped reduce end effects. In addition, a very important component of success was failure tracking which ensured that no systematic or repetitive problems were occurring. Having high efficiency meant that when some occurrence affected the efficiency, resources could be marshalled and attention focussed on the problem.

The fixed target program started on schedule in February 1990. The graph on the right compares this fixed target run with the two previous runs in the number of High Energy Physics (HEP) hours. As is evident from the graph, not only did we start on schedule, but we started well. This running start was made possible by a great deal of effort from many people throughout the whole accelerator complex, systems groups, support groups and especially the operations group.

Since we did not schedule maintenance and development periods one might expect that on occasional weeks one could have many HEP hours. In fact, of the 22 weeks (since January 1, 1973) in which the accelerator has provided greater than 140 hours of HEP, seven of these weeks occurred in this last run, including the two best weeks ever. But of perhaps even more interest is the ability to



deliver beam when scheduled, i.e., the efficiency which factors in beam study time. The large graph on the preceding page shows the HEP efficiency for the run. The average efficiency was 73%, with a median efficiency of 76%. There were two bad weeks; one resulted from a feeder failure and the other was a result of the single instance of a Tevatron dipole failure (due to vacuum problems). We had six weeks between 60% to 70%, ten weeks between 70% to 80%, and 11 weeks between 80% to 90%. In comparing these efficiencies and number of HEP hours delivered with earlier runs, one should remember that these recent results have been achieved with the addition of another accelerator in the chain, a cryogenic accelerator at that.

The weekly integrated intensity steadily increased over the run. This increase was dictated by the needs of the experimental program. For the bulk of the run the intensity of the machine was equal to or greater than the sum of the experimental requests.

# Charm Physics

## Introduction

In 1974 elementary particle physics was transformed by the discovery of a narrow resonance of mass 3.1 GeV/$c^2$ at the Stanford Linear Accelerator Center (SLAC) and Brookhaven National Laboratory. This state, named the J/ψ, was determined to be a bound system of the charmed quark and its antiparticle. With this discovery, the quark nature of matter was confirmed and a new era of search and discovery was established.

Since then, detailed studies of the production, spectroscopy, and decay of states containing the charmed quark have been of paramount importance at Fermilab and other laboratories around the world. Charm quarks are produced in high energy photon and hadron beams. This charm then condenses into various charmed hadrons, which are indirectly detected and whose properties are measured. Details of the way the charm quarks are produced, how they clothe themselves with light quarks to become observable charmed particles, and the way these charmed particles decay can be studied.

## Photoproduced Charm

Photoproduction experiments create charm with a photon beam striking a target, usually of some low atomic number material like beryllium. The photons are created in three stages. First, the 800 GeV Tevatron proton beam is directed into a primary target. Then, neutral particles from this interaction, including high energy photons, pass through lead, which converts the photons into $e^+e^-$ pairs. These electrons are then transported to the experiment with a conventional beamline and passed through more lead which causes them to radiate the photons which strike the experimental target. The energy of the photons is "tagged" from the angle and energy of the remaining electron. Photoproduction is characterized by low rates because both the intensity of the photon beam and the cross section for charm production is small. However, the charm signals observed are very clean because the cross section for producing background is also very small. The two experiments of this type which have run recently at Fermilab are E691 and E687.

E691 ran in 1985 with an average photon energy of 145 GeV and was one of the first Fermilab experiments to use silicon microstrip vertex detectors which have become invaluable in current charm experiments. The E691 collaboration continues to publish interesting results on the detailed properties of charmed meson and baryon decays, photon-gluon fusion, and analysis of charm photoproduction. By fitting to the measured charm cross section, its rise with energy and the Feynman-x ($x_F$) and transverse momentum squared ($p_t^2$) distributions, E691 has recently published results on the gluon distribution.

E687 has presented its first results from the

*Penelope Kasper from the Illinois Institute of Technology and Donald Summers from the University of Mississippi prepare to install 8 mm tapes in the E791 data acquisition system.*

1988 running period during which 60 million event triggers were obtained and is anticipating a much larger data set from the 1990-91 fixed target period. The beam used by E687 is the highest energy photon beam in the world, with average energy of 250 GeV. Production and decay characteristics were studied with the 1988 data, and even more interesting results from this experiment will come from the data obtained during the 1990 run which obtained ten times the amount of data collected in 1988. We anticipate nearly 100,000 fully reconstructed charmed particles from this new data set! With this sample production, properties of photoproduced charm in energy regions not yet explored will be studied. Also, the large number of events will enable a search for and study of rare charm states, some of which have not been observed, others about which little is known. With this large sample very rare decay modes of copiously produced states can be searched for and such occurrences as $D^0$ mixing, leptonic decays, and forbidden decays can be studied.

## Hadroproduced Charm

Hadroproduction experiments create charm with a hadron beam striking a target. This beam can be either the primary 800 GeV proton beam from the Tevatron or a secondary beam created by directing the pi mesons, K mesons, and protons from a primary interaction to the experimental target. The momentum and charge of the secondaries are selected by the optics of the beamline. The type of particle striking the experimental target can be "tagged" with detectors which provide different responses for pi mesons, K mesons and protons. Hadroproduction is characterized by high rates, because very intense hadron beams can be produced and the cross sections for charm production is high. However, the charm signals are more difficult to obtain and have higher backgrounds than in photoproduction because the total hadronic cross section is also high. Hadroproduced charm has become better understood in the past year as the results from two Fermilab experiments, E653 and E769, begin to appear. A high-statistics charm hadroproduction experiment, E791, ran in 1990.

E653 employed a hybrid silicon microstrip detector (SMD) and emulsion target, which enabled them to study the event vertices very precisely. With the information from their spectrometer used in conjunction with the vertex information, they are able to study charm events. With these data they can examine the production characteristics of charm for 800-GeV protons and 600-GeV pi mesons. This experiment has recently produced very interesting results on the correlation between charm particle pairs ($c\bar{c}$).

Another major experiment, E769, employed the same detector facility used by E691 with some upgrades. During the 1988 fixed target run they collected 400 million event triggers and results from this sample are becoming available. E769 is primarily focussed on production of charm and has two features that distinguish it from other hadrocharm experiments of its type. First, the target consisted of 26 thin foils of four different materials (beryllium, aluminum, copper, tungsten) that were simultaneously exposed to study the dependence of charm production on the atomic number of the target material. (This is significant because the behavior of the quarks in the target might depend on the number of nucleons in each nucleus). Second, the hadron beam used for this experiment was tagged, which means the cross section and other details of charm production can be studied as a function of incident particle type. Also, the data obtained from E769 represents one of the largest samples of hadroproduced charm to date from which cross sections for rare states such as D's ($c\bar{s}$) and the charmed baryon Lamda$_c$ (cud) will be measured.

An experiment, E791, just began to take data during the 1990 running period. This experiment employs the E769 detector with several upgrades, faster readout electronics and a 500-GeV pi meson beam. During the first half of the 1990 fixed target run E791 successfully demonstrated that, with their new readout electronics and data acquisition system, they will be able acquire data at a rate of 10,000 events per second. During the next half of the run they expect to exceed the amount of data obtained in E769 by at least 20 times! This will provide almost 100,000 fully reconstructed charmed particles.

Another experiment which has explored the dependence of charm production on atomic mass number is E772, employing a high-precision "double arm" spectrometer. This experiment has measured the production of the $J/\psi$ in a high rate 800-GeV proton beam incident on five different target materials. About 7% of the $J/\psi$s produced decay into $\mu^+\mu^-$ pairs which are focussed in the detector by high-field dipole magnets and uniquely identified with Cerenkov, calorimetry, and muon counters. They find that $J/\psi$ (and $\psi'$) production is suppressed in proton-nucleus collisions at this energy and that the amount of this suppression depends on the transverse momentum and $x_F$ of the $J/\psi$.

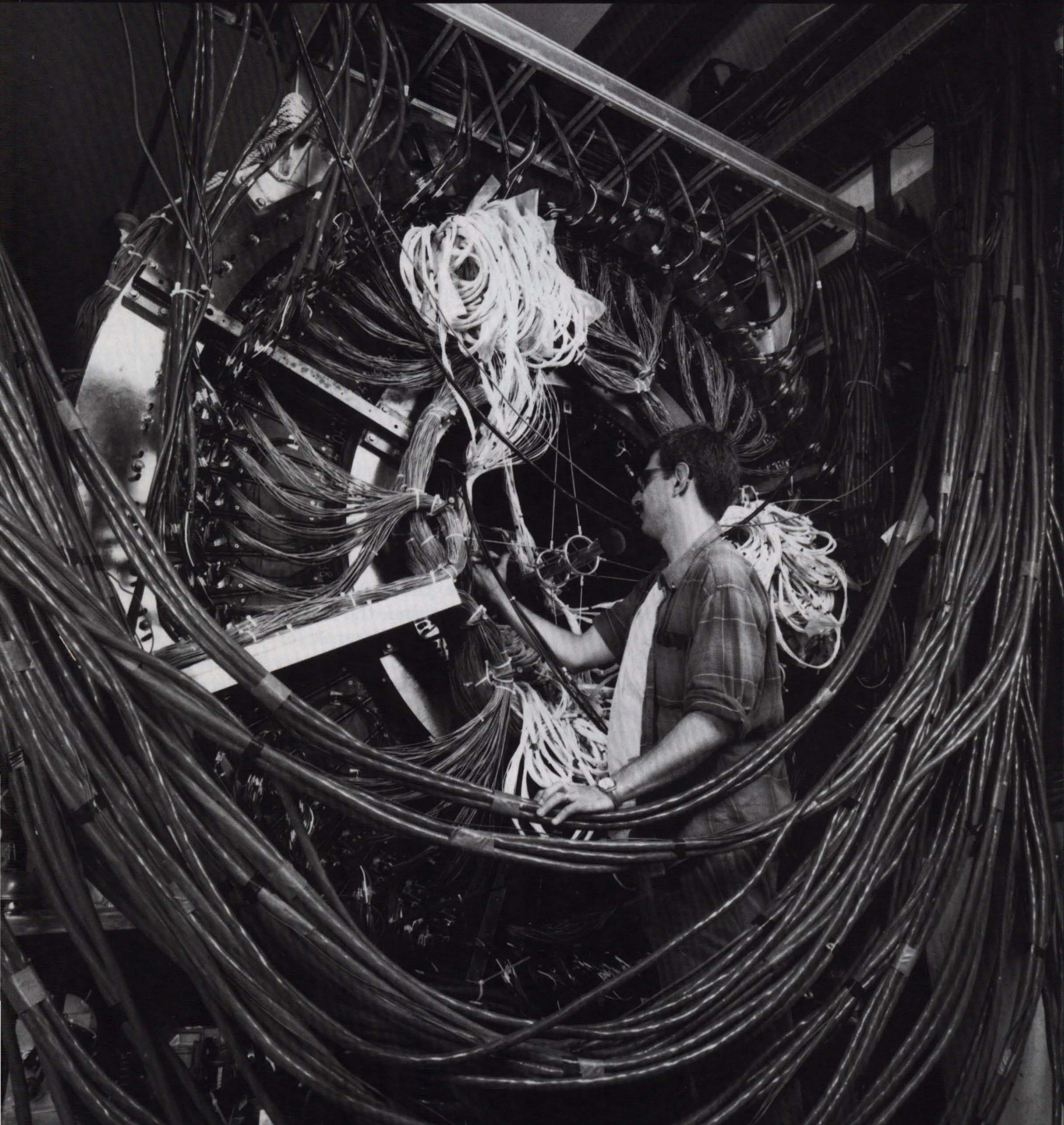
## E760: Exclusive Charmonium Production in the Accumulator

One of the most striking examples of the connection between two rather distant fields of physics is the similarity between the spectrum of positronium (the bound states of an electron positron system) and charmonium (the bound states of a system composed of a charm quark and a charm antiquark) despite vast differences in the energy scales. The study of charmonium provides a field for precision studies of the theory of the forces between quarks, quantum chromodynamics, in exactly the same fashion that the study of positronium allows for some of the most stringent tests of quantum electrodynamics.

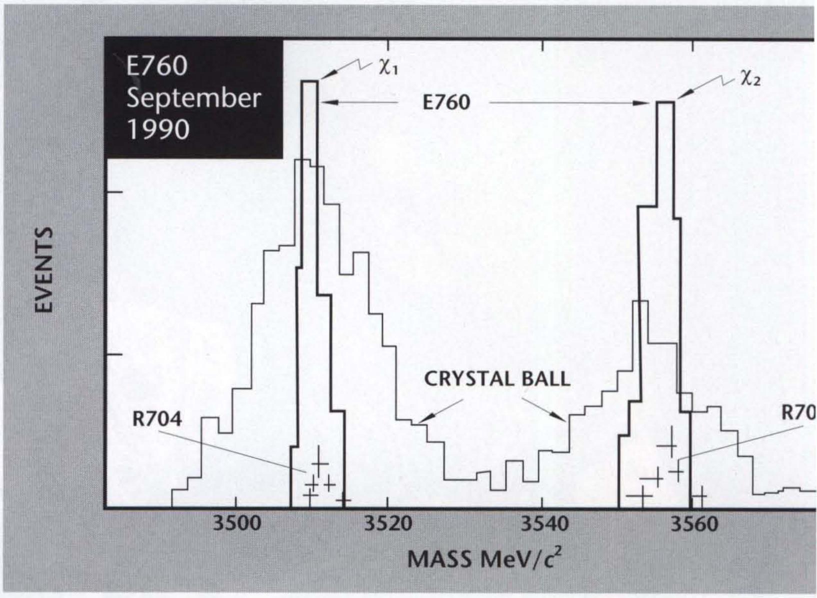
Studies of charmonium have been carried out in $e^+e^-$ colliding beam experiments at SLAC. Such experiments have provided a wealth of information, but only states of charmonium with a specific set of quantum numbers, the $\psi$s with $J^{PC}=1^{--}$, can be produced in $e^+e^-$ annihilation. The other states have to be studied by observing them as intermediate decay products. In addition, one has to rely on the energy resolution of the detector system to determine the masses and widths of these intermediate states.

E760, the study of resonant charmonium production in antiproton-proton collisions in Fermilab's antiproton Accumulator ring, offers a way to overcome these limitations. Charmonium

*(Opposite) Mechanical engineer Larry Bartoszek adjusts the "spider" which supports and aligns the beam pipe in the calorimeter for E760.*



is a short-lived charm quark-anticharm quark pair bound together by the strong force (gluons). In a manner analogous to the hydrogen atom or positronium, the interaction of the two charm quarks produces a rich spectrum of states, many of which have never been seen before, and many of which have been only poorly measured. It is this spectrum of states that E760 explores. Why choose the antiproton source at Fermilab? Because antiprotons colliding with protons can produce *all* charmonium states directly and because the Fermilab antiproton source is currently the *only* antiproton facility in the world capable of being tuned to all energies necessary for this experiment.

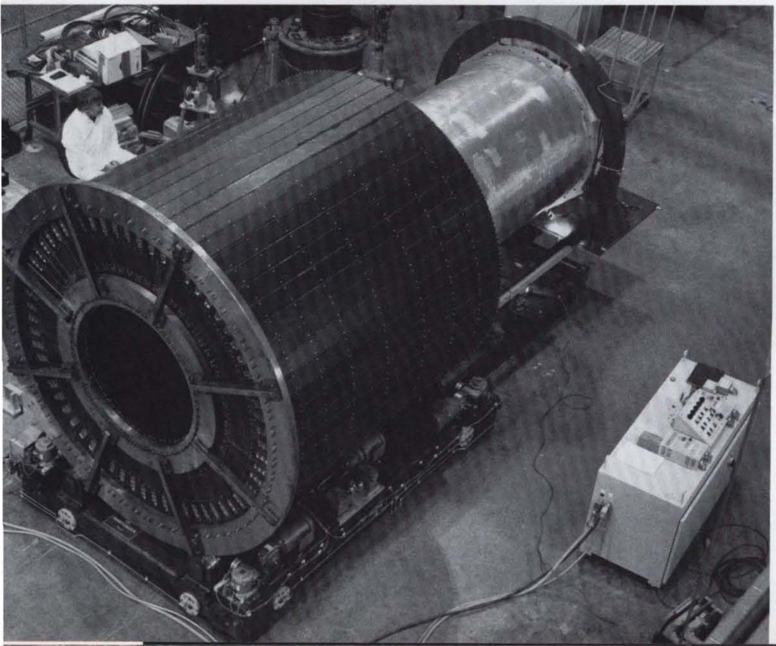



During the fixed target period of Fermilab's program, the Main Ring is idle most of the time. During this "idle" time it is used to accelerate protons to 120 GeV which, in turn, are used to produce and store antiprotons in the Accumulator ring. After some $3.0 \times 10^{11}$ antiprotons have been collected over a period of a day, the beam energy is reduced to the desired value and the antiprotons are allowed to interact with a 0.5-cm-thick gas jet of molecular hydrogen with a density of $10^{14}$ atoms/cm$^2$. Data from these interactions, at a peak luminosity of $10^{31}$cm$^{-2}$s$^{-1}$, are collected for two days, after which the cycle repeats.

The excellent definition of the energy of the antiprotons allows a high accuracy measurement of the energy of the initial state ($\Delta E_{c.m.} \approx 0.2$ MeV) and thus for a measurement free from any dependence on detector resolution. The use of a tenuous gas jet target permits the most economical use of the antiprotons, since protons which have not interacted keep on circulating in the Accumulator and cross the jet target a multitude of times.

However, there is no such thing as a free lunch. The price we have to pay is a ferocious background of nonresonant hadronic interactions. The background is almost a million times higher than the reactions we are interested in (e.g. 70 millibarns for pp $\rightarrow$ hadrons versus 240 nanobarns for pp $\rightarrow \chi_2$). The solution is to have a detector that is highly selective to the electromagnetic decays of charmonium into an $e^+e^-$ or $\gamma\gamma$ high mass state.

The detector consists of three scintillation counter arrays, a Cerenkov counter for detecting electrons, five separate wire chambers used for tracking charged particles, a lead glass electromagnetic calorimeter consisting of 1,280 precision-machined blocks of lead glass used to measure electromagnetic energy, and a forward calorimeter consisting of 144 lead scintillator stacks to measure electromagnetic energy in the downstream direction. In order to achieve a compact design the lead glass blocks have a tapered shape; they are supported by a lightweight structure made from stainless steel sheets that utilizes the glass itself as a load-bearing element. This rather elaborate construction pushed the manufacturing techniques of both glass cutting and laser welding of steel to their limit. Fermilab physicists, engineers, and technical support personnel worked with colleagues in industry to



*(Left) E760's lead glass calorimeter waits to be mated to its inner detectors prior to shipment to the antiproton source.*

solve the various pesky problems that were encountered.

E760 is a collaboration of approximately 60 physicists from seven different institutions in Italy and the United States. The successful running of E760 during the fixed target period of 1990 owes a great deal to the exceptional performance of the Accumulator. During the past three years the Accumulator operating procedures have been expanded to include the option of decelerating the stored cooled antiprotons from their normal momentum of 8.9 GeV/*c* down to momenta corresponding to the $E_{c.m.}$ of charmonium (6.2 to 3.7 GeV/*c*). In the process, we have succeeded in changing the scope of Fermilab from being an *accelerator* laboratory to being both an *accelerator* and *decelerator* laboratory!

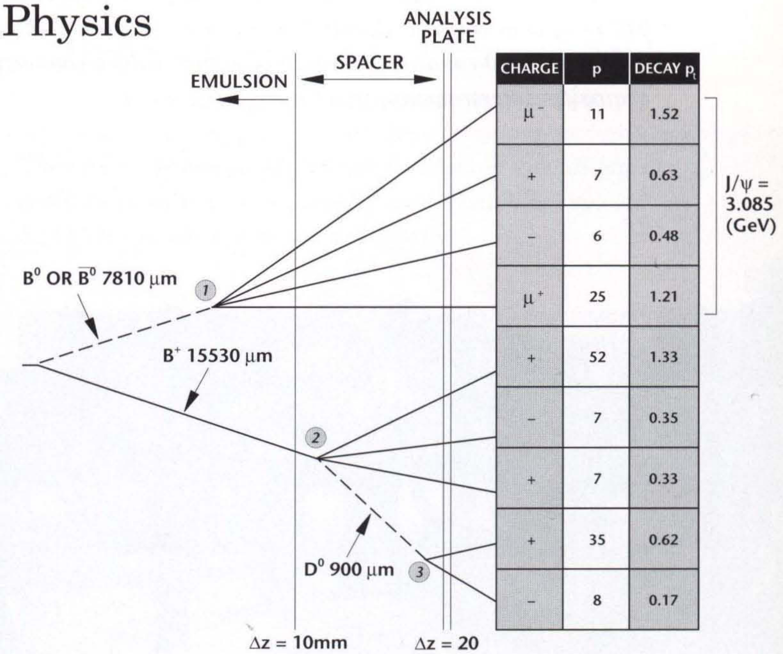
The experiment ran for two periods, February and March 1990, with an incomplete detector, and for two and a half months with the full detector starting in mid June 1990. The first run served as a calibration run. The $J/\psi$ was rediscovered at the first attempt and served as an energy calibration point. During the second run 6.3 $pb^{-1}$ of integrated luminosity were accumulated at the $J/\psi$, $\psi'$, $\chi_1$, $\chi_2$, and at background points. The quality of the data is excellent, as shown in the figure that compares the E760 data with the CERN R704, and SLAC Crystal Ball data for the $\chi$s.

We already have preliminary new results on the $J/\psi - \psi'$ mass difference, the $\chi_1$ and $\chi_2$ masses and total widths, and the first *direct* measurements of the total width of the $J/\psi$ and the $\psi'$. All of these results have errors smaller than the currently accepted values. E760 is well on its way in providing a stringent test for quantum chromodynamics. In the upcoming run we will concentrate on a search for the one undiscovered bound state of charmonium, the $^1P_1$ state, and on measuring the poorly known $\eta_c$ and $\eta_c'$.

# Bottom Physics

Bottom physics (B physics) is the study of the properties of particles containing b quarks or b antiquarks. 1990 was an interesting year in B physics, and for the first time Fermilab was a part of the excitement. The Cornell electron storage ring has provided record luminosity for the newly finished CLEO II experiment. First results display its excellent physics potential. Enthusiasm continues to build for a very high rate B factory, needed to observe charge-parity (CP) violation in the B system. Meanwhile, here at Fermilab, we have had two very exciting "firsts." CDF showed the first ever B reconstruction from hadron collisions. In addition, E653 became the first Fermilab fixed target experiment to produce a B signal. These results have reminded the physics community that a vigorous B physics program is planned at Fermilab for the 1990s.

E653 is an emulsion target experiment. In 1987 the U.S.-Japan-Korean collaboration took $10^7$ muon triggers from 600 GeV incident pi mesons. A few hundred of the muon candidates were from secondary vertices, a signal of heavy quark

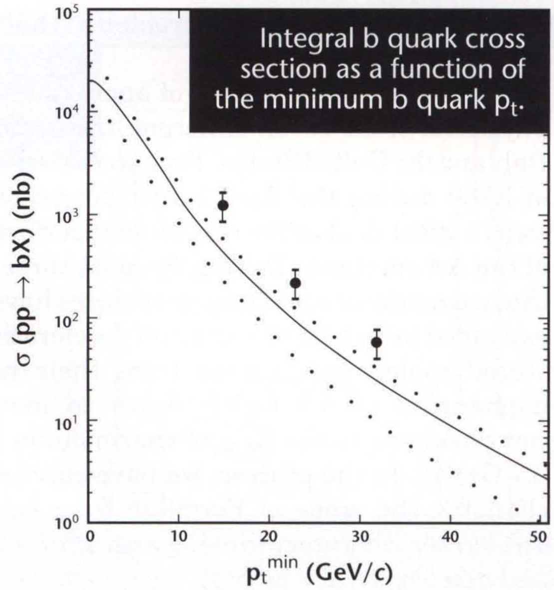



| | $p_t$ BAL | | $M_{min}$ | $P_{est}$ | T(ps) |
|---|---|---|---|---|---|
| 1 ($B^0/\bar{B}^0$) | 0.57 | | 4.81 | 61 | 2.2 |
| | | | | | |
| 2 $B^+$ | 0.4 | | 5.2 | 164 | 1.7 |
| 3 $\bar{D}^0$ | 0.45 | | 1.5 | 83 | 0.07 |

*An event display of a $B\bar{B}$ Candidate event from E653. The muon pair from the neutral B reconstructs to the $\psi$ mass.*

decays. Events with three or more secondary vertices are a clean signal of bottom, and its subsequent decay to charm. Seven such events have been observed in the data analyzed so far. The final B sample is likely to triple as the rest of the E653 data are analyzed. The diagram on the previous page shows one such event. The E653 sample is already the largest fixed target B signal with good particle decay vertex information. It is the vertex information that allows particle lifetimes to be measured. E653 has used this sample to measure the neutral and charged B meson lifetimes and the b quark production cross section. Production properties of the B mesons will also be measured. This measurement will be important both to theorists and to other Fermilab fixed target experimenters interested in B physics.

E789 and E771, two fixed target experiments that will receive beam in 1991 and the following




*The CDF data points are compared to a theoretical calculation by Nason, Dawson and Ellis.*

*Derek Lane (front) of Abilene Christian University and Los Alamos National Laboratory leads his E789 collaborators, (front to back following Derek) George Gidal, Jen-Chieh Peng, Martin Schub, Dick Preston, G. C. Kiang, Peng-Yung Woo, Shi Lan, Dan Kaplan, Randy Schnathorst, Nathan Yanasak, Don Isenhower, Pat McGaughey, as they transport and install a 2,500-conductor bundle of signal cables connecting the detectors near the production target with the data acquisition electronics.*

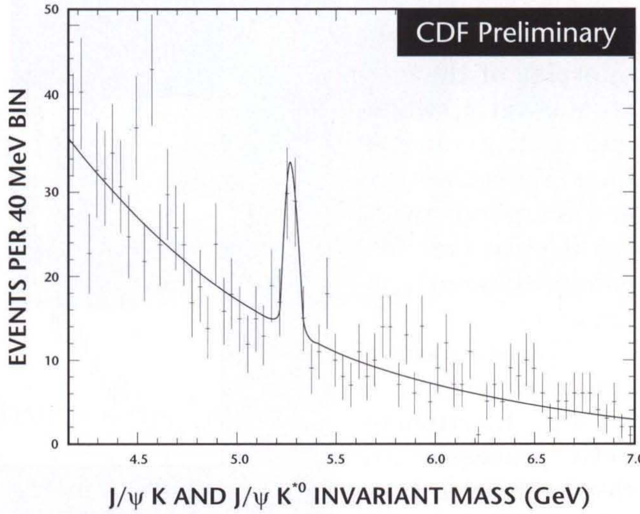
fixed target run, anticipate collecting many thousands of B events. E789 will search for rare two-body decays of B mesons. These rare decays, if observed, will give important information about the fundamental decay parameters of b quarks. E771 will collect a large sample of b decays to one and two muons. One of the physics goals of E771 is to observe new particles with b quarks and measure the lifetimes of these and other long-lived particles.

Meanwhile, CDF has been able to conduct B physics in a qualitatively different way than any previous hadron collider experiment. Very good tracking resolution and excellent lepton identification have allowed CDF to observe $D^0$ decays in association with lepton triggers. This is a clear signal of the decay of bottom to leptons and charm. Using the observed lepton rate, properly subtracted for W and Z decays, CDF has measured the b quark production cross section and the transverse momentum ($p_t$) dependence of the cross section shown in the graph above left. This result confirms that the b quark production rate at the Tevatron is very large. In the 1988-89 run of 5 $pb^{-1}$, roughly 400 million b quarks were produced and decayed in the central detector of CDF.

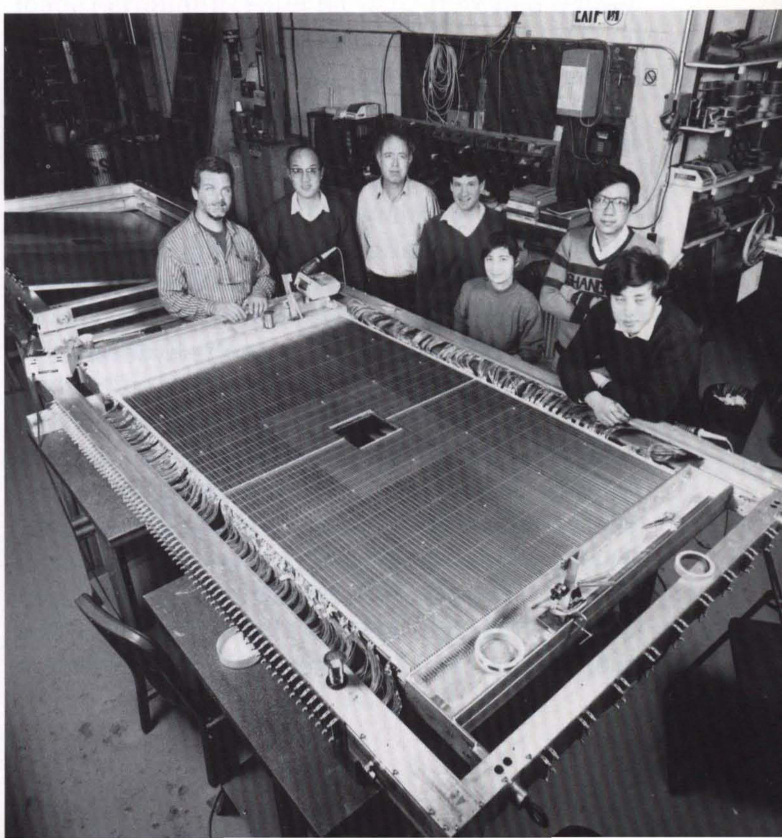
Given such high rates of b production combined with the high performance of CDF, it is not surprising that simple, but relatively rare, B decays can be reconstructed, despite the confusion caused by other particles from the hadronic interaction. So far, CDF has reconstructed about 40 B mesons to a ψ and a K meson. Shown in the graph above right is the mass plot for the sum of the two observed modes, which clearly shows the B signal at 5.279 GeV.

CDF has almost completed upgrades that will improve its b physics potential. One of these upgrades is a silicon secondary vertex detector. This device will separate the long-lived daughters of b quark decays from the rest of the particles in the event, much as is done already in fixed target experiments. The commissioning of DØ, with excellent muon detection, will also enhance the b opportunities at Fermilab.

The CDF results are only the beginning of the planned exploitation of the huge b cross section provided by the Tevatron. In the future our goal is that Fermilab's own b factory, the Tevatron, will provide the huge numbers of b quarks needed to address the most interesting b physics issues.



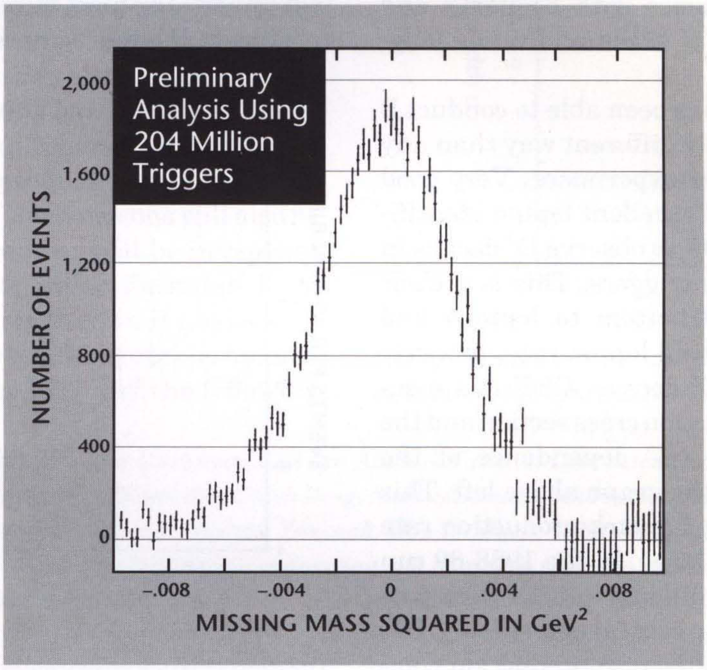

*The sum of two mass distributions for dimuon ψ candidates combined with a $K^{\pm}$ or neutral $K^{*0}$ candidate. The excess at 5.279 GeV is 39± 9 B meson candidates.*



*(Right) From the left, Charles Serritella of the Physics Department, Zhang Nai Jian of Shadong University, Harvey Bruch of the Physics Department, Leonard Spiegel of the Research Division, Gloria Corti of Northwestern University, Cao ZiLi of Shadong University, and Wei Chao of Shandong University surround the central pad chamber for E771.*

# E761: Rare Hyperon Decays

Fermilab E761 completed data taking in Proton Center in August 1990. This represents the end of a journey which started over 30 years ago. Radiative decays of hyperons are a class of reactions which are simple in their kinematics. One baryon decays into another with emission of a photon. Yet they are also complicated in that they probe the interplay of the electromagnetic, weak, and strong interactions. The connections and interplay between these forces is fundamental to understanding them.




The simplest of these reactions is $\Sigma^+ \rightarrow p\gamma$. Electromagnetic processes are clearly important as a photon is involved. The decay is a weak process since the baryon strangeness changes. The strong forces must also be involved: they provide the fundamental distinction between the proton and $\Sigma^+$.

What can we measure? One possible measurement is the probability of a $\Sigma^+$ decaying to a $p\gamma$ compared with other allowed decays. A series of early experiments with very limited statistics indicated this branching fraction is small: $\approx 1 \times 10^{-3}$. Even more challenging for the experimenter is the confusing background of a major decay mode, $\Sigma^+ \rightarrow p\pi^\circ$, with the subsequent decay, $\pi^\circ \rightarrow \gamma\gamma$. A basic limitation of this low energy technique is the short distance the hyperon travels from its creation to its decay.

E761 is an international collaboration from Leningrad, Moscow, Sao Paulo, Rio de Janeiro, Beijing, Bristol, Mexico, and three U.S. institutions (University of Iowa, Yale and Fermilab). The apparatus uses the Fermilab hyperon beam of $\Sigma^+$ at $\approx$ 350 GeV/*c*. Because the $\Sigma^+$s are produced with large energies, they travel $\approx$ 8 m from their origin; hence they are well separated from the clutter of the production region. The momentum and direction of the $\Sigma^+$ and the decay proton are used to reconstruct the mass squared of the missing neutral track. There is a large peak at the mass of the $\pi^\circ$ and a small enhancement near a missing mass of zero corresponding to a single photon, signaling the decay of interest. It was very difficult for early experiments to reconstruct 100,000 $\Sigma^+$ events of all decay modes; one such experiment might yield about 100 $\Sigma^+ \rightarrow p\gamma$ events. However, in E761 we have over a million events per bin! E761 measures the photon energy with a unique calorimeter and the photon position with a novel application of a transition radiation detector. Applying this additional information the events are separated from the $\Sigma^+ \rightarrow p\pi^\circ$ background. Crucial to this separation was the photon detector. It includes in its central region crystals of bismuth germanate, which were provided by the Institute of Theoretical and Experimental Physics in Moscow and fabricated in Shanghai, China.

More information may be gleaned from the decay if the $\Sigma^+$s are polarized and the correlation of the direction of emission of the $\gamma$ relative to the direction of the $\Sigma^+$ polarization is measured. This quantity, $\alpha_\gamma$, is zero if there is no correlation, as is predicted by the simplest models. However, the early experiments, with statistics of only a few hundred events, indicated that $\alpha_\gamma$ was large and negative. These results confounded theorists and worried some experimenters, since it might be explained by an unexpected contamination of the $\Sigma^+ \rightarrow p\gamma$ events with an unresolved background from the much more copious $\Sigma^+ \rightarrow p\pi^\circ$ decays. The Fermilab hyperon beam produces polarized $\Sigma^+$ and, even more important, the direction of polarization can be easily changed, providing control of potential systematic errors. Preliminary results from E761 indicate $\alpha_\gamma = -0.69 \pm 0.11$ (statistical). The systematic uncertainty is of comparable size.

E761 is connected to the rest of the physics community by the thread of time forcing us to look back carefully at the previous experiments. Since E761 touches on the interplay of three basic forces, there has been a natural connection to the theoretical physics community. At this time the large number of theoretical papers far outweighs the few experimental results. The connections on an educational, cultural and personal level may be even more important.

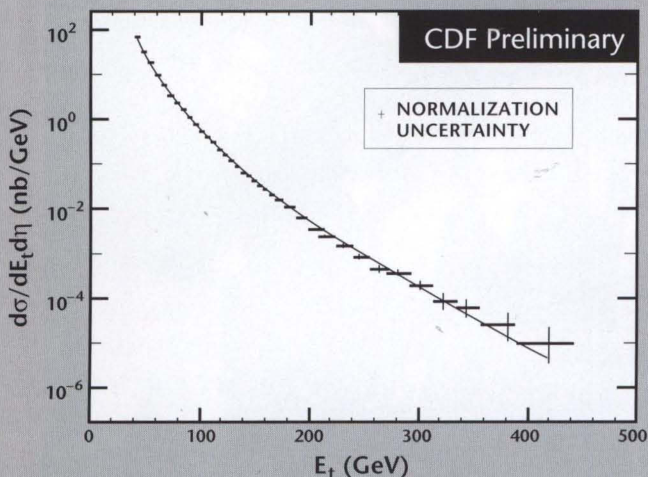
*(Right) From left to right, Michael Kubantsev, Dai Lisheng, Zhao Wenheng, and Shi Huanzhang, members of the Chinese and Soviet groups, stand beside the E761 photon calorimeter.*

# QCD Physics

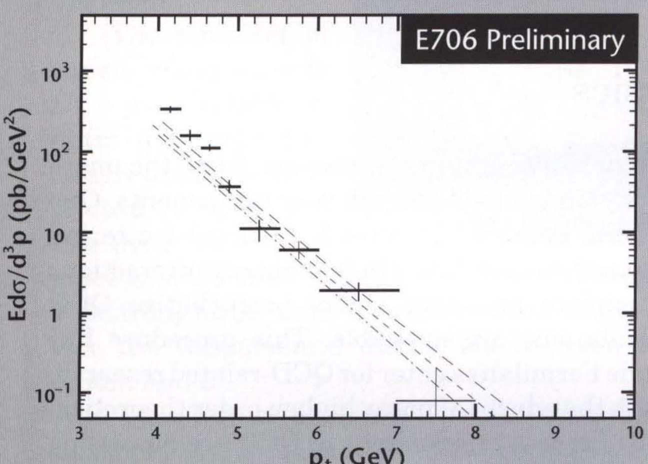
At first glance, the wide variety of experiments that have been performed, are being performed, or will be performed at Fermilab appear to study many wildly different phenomena. However, the one thread that connects nearly all of these experiments is the Quark Parton Model as modified by Quantum Chromodynamics (QCD). From studies of jet production as seen in the world's highest energy collisions to structure function measurements obtained in neutrino deep-inelastic scattering, from direct photon observations in fixed target and collider experiments to the photo and hadroproduction of charm, from the study of atomic mass number dependence in $J/\psi$ production back to the study of jets produced in muon deep-inelastic scattering, the experimental program at Fermilab is successfully extending our understanding of the theory of strong interactions, as well as pushing the boundaries in the search for new and unexpected phenomena.

While perturbative techniques have been successfully employed to perform QCD calculations for so-called "hard-scattering" processes, it has been very difficult to make detailed quantitative calculations for "soft" processes. Thus, many experiments have tried to isolate the non-perturbative physics processes from the more easily understood perturbative components. One general approach to get into the hard-scattering regime has been to use higher energy interactions to explore processes where perturbative QCD calculations are available. This procedure has made Fermilab a center for QCD-related research. With the advent of many higher-order theoretical calculations, precise tests of QCD are now being performed with a wide variety of interactions.

Dominating the high energy tests of QCD is the collider program at Fermilab. CDF is studying the hardest collisions yet observed. An example of the tests being performed by CDF is shown in the graph on the following page where the measured inclusive jet cross-section is compared to a recent next-to-leading order calculation (absolute normalization). Notice that the data span a range of seven orders of magnitude and reach transverse energy ($E_t$) values as high as 400 GeV. There is remarkable agreement between data and theory over the full range of jet $E_t$. In addition to testing the QCD calculations, these data can be used to look for new effects beyond the Standard Model, such as quark compositeness. This effect would manifest itself as a distortion in the jet cross-




*Inclusive jet cross section from CDF compared to the next-to leading order calculation. The theoretical prediction is absolutely normalized. Only statistical errors are shown for the data.*




*Preliminary E706 direct photon results from the reaction, $p + Be \rightarrow \gamma + X$, compared to theoretical predictions from Aurenche et al., (PMS) using different gluon distributions.*

section at the high $E_t$ end. By characterizing this effect as a four-Fermion interaction with scale $\Lambda^*$, CDF has set a limit of $\Lambda^*$= 950 GeV (95% confidence level).

Additional tests of QCD performed by CDF include the study of di-jet invariant mass and angular distributions. These measurements not only test the QCD calculations but are also sensitive to non-Standard Model effects. With di-jet invariant masses as high as 950 GeV, CDF is able to set a limit on the mass of axigluons.

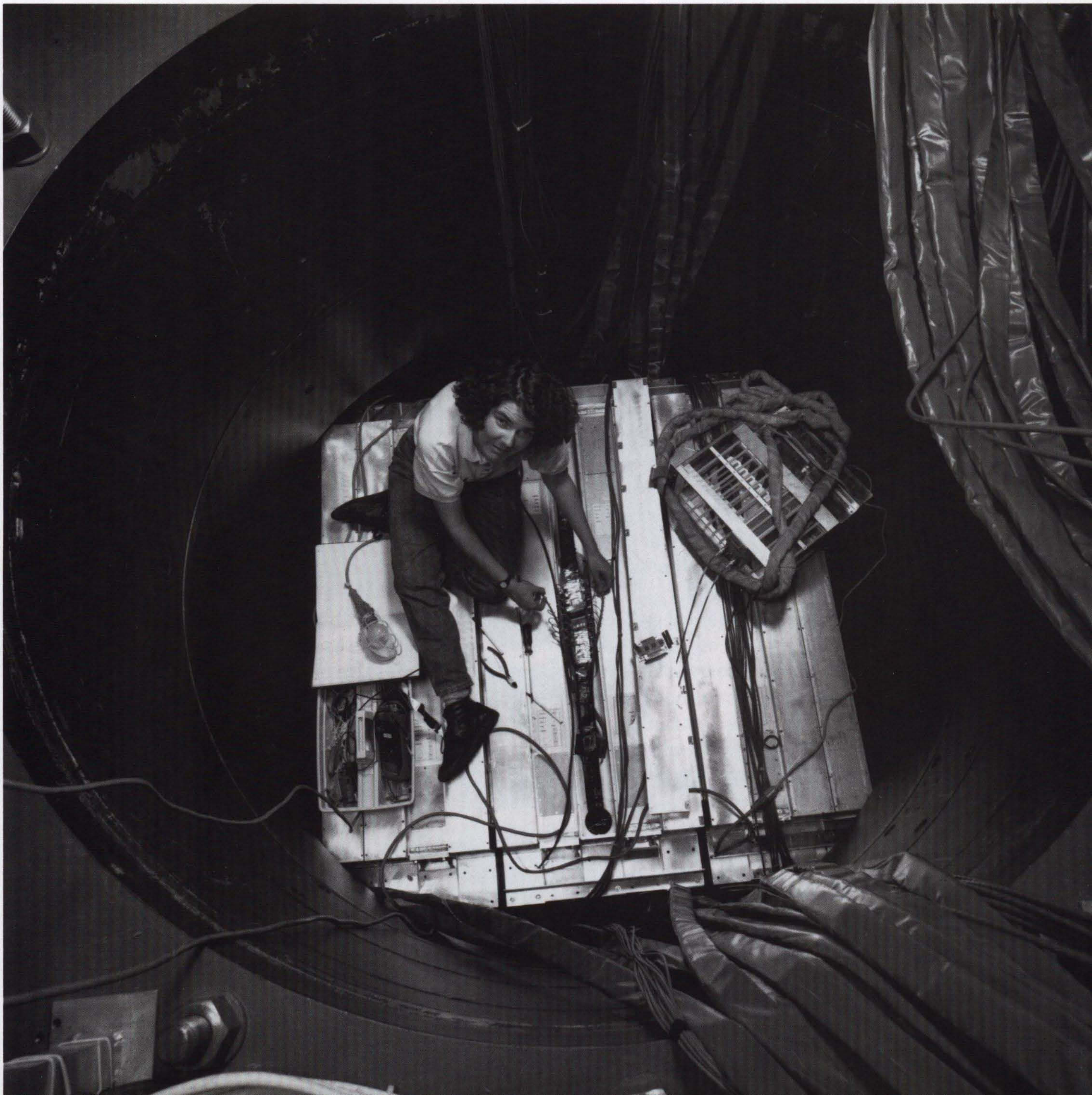
Illustrating the connectivity among experiments is the dependence in all of the above analyses on the knowledge of the underlying parton distributions. In fact, the dominant source of error in the inclusive jet cross-section calculation comes from uncertainties in the structure functions. The cornerstone for extracting parton distributions has always been deep-inelastic-scattering experiments and, until recently, ultra-high statistics deep-inelastic scattering experiments have been confined to muon beams. With the advent of the quadrupole-triplet beam, the University of Chicago/Columbia University/Fermilab/University of Rochester (CCFR) collaboration has established that neutrino deep-inelastic scattering can yield high statistics as well. In addition to the extraction of the structure functions $F_2$ and $F_3$ (final results expected within a year), CCFR has performed a test of the Gross-Llewellyn Smith (GLS) sum rule, which predicts that the integral of $F_3$ is the number of valence quarks in the nucleon, modified by perturbative QCD and higher twist effects. The value obtained is $2.66 \pm 0.03$ (stat) $\pm 0.08$ (syst), agreeing with the predicted value of 2.63 (using $\Lambda$ = 250 MeV). This is the first result of the GLS sum rule with a sensitivity to observe a deviation from the naive quark model prediction.

While the deep-inelastic-lepton-scattering experiments are directly sensitive to quark structure functions, they are much less sensitive to the gluon structure functions. As the energy of the hadron colliders has increased, dependence on the knowledge of the gluon distribution has also increased, and thus it has become very important to pin down this quantity. One process that is directly dependent (at leading order) on the gluon distribution is direct-photon production. This process is being studied both in fixed target experiments (E705, E706) and at the collider (CDF), affording a very wide range in the kinematic regime explored. Shown in the graph are preliminary E706 results for direct-photon production from protons on beryllium, compared with various theoretical predictions containing different gluon distribution parameterizations. With an order of magnitude (and more) increase in statistics taken in the 1990 fixed target run as compared to the 1988 run, and with even more coming in 1991, detailed tests of QCD should be achievable in the fixed target direct-photon experiments.

*(Opposite) Physicist Heidi Schellman from Northwestern University shown with the vertex drift chamber of E665 tests the system for electronic noise. The high-precision tracking chamber is located directly downstream from the target and contains 2,000 channels of electronics.*

An example of an experiment that probes the overlap between perturbative and non-perturbative QCD is the measurement of the atomic mass dependence of J/ψ and ψ′ production. Simple perturbative arguments predict little or no atomic mass dependence. In a recent publication, E772 reported a depletion of the yield per nucleon from heavy nuclei for both J/ψ and ψ′. Using the standard parameterization of $\sigma_A = \sigma_N A^{\alpha}$, they obtain the best fit to the data with $\alpha = 0.92$. In addition, the depletion exhibits a strong dependence on $x_F$. Different models have had varying degrees of success in attempting to understand these data. Ultimately, QCD must be able to predict such effects if it is to be accepted as the theory of strong interactions.

As at the collider, jet production can also be used to study QCD in fixed target experiments. Using the world's highest energy muon beam, E665 is exploring new kinematic regimes where the contributions from leading-order QCD subprocesses (gluon bremsstrahlung and photon-gluon fusion) become significant. When the angular energy flow is plotted for planar events, two



clear forward jets are observed. These data are sensitive to both gluon fragmentation as well as to the gluon structure function. With an order of magnitude more statistics to analyze from the 1990-91 runs, E665 should be able to make unique tests of QCD.

With the completion of the 1991 fixed target run and the upcoming collider runs at the Tevatron, the experimental program at Fermilab promises to push our understanding of the strong force, and its corresponding theory, QCD. With the upgrade of the Main Injector, the possibilities will be even more exciting. At the collider, continued investigations with jet production into non-Standard Model phenomena will be able to probe beyond the 1 TeV scale. Studies of direct photons will reach $E_t$ values as high as 400 GeV. In the fixed target arena, a new generation deep inelastic neutrino scattering experiment would push the precision testing of QCD to a new level. Such an experiment would have the opportunity to determine $\alpha_s$ to 1% at three or four different $Q^2$ values. And of course the most interesting possibilities may still be awaiting discovery. What is certain is that Fermilab will continue to lead the way in QCD physics.

# Electroweak Measurements and the Search for Top

## The Tevatron and CDF

One of the detectors constructed to examine the particles produced in the energetic collisions of protons with antiprotons is CDF. CDF is made up of many parts built by many different institutions. The detector must have several different components because the fundamental particles are detected in different ways. The detector parts are of two types: tracking chambers and calorimeters. The tracking chambers measure the paths of charged particles. The tracking chamber is inside of a magnet. The effect of the magnet is to change the trajectories of the charged particles so they follow curved paths rather than straight lines. The particle's momentum may be determined from the curvature of the track. The second component of CDF is a calorimeter. Calorimeters measure the particle energies.

So how are the fundamental particles identified? Electrons deposit all of their energy in the front part of the calorimeter. Since electrons are charged, they leave tracks in the tracking chamber. The "signature" of an electron is a cluster of energy in the front part of the calorimeter with a track pointing to it. The track's momentum must match the calorimeter cluster's energy. Muons also leave tracks in the tracking chamber, but they behave differently in the calorimeter. Muons have the property that they pass through large amounts of material without interacting very much. A muon detector is located on the outside of the detector so that particles have to penetrate a lot of material to get there. The signature of a muon is a track in the tracking chamber pointing to a track in the muon chamber with very little energy in the calorimeter in between.

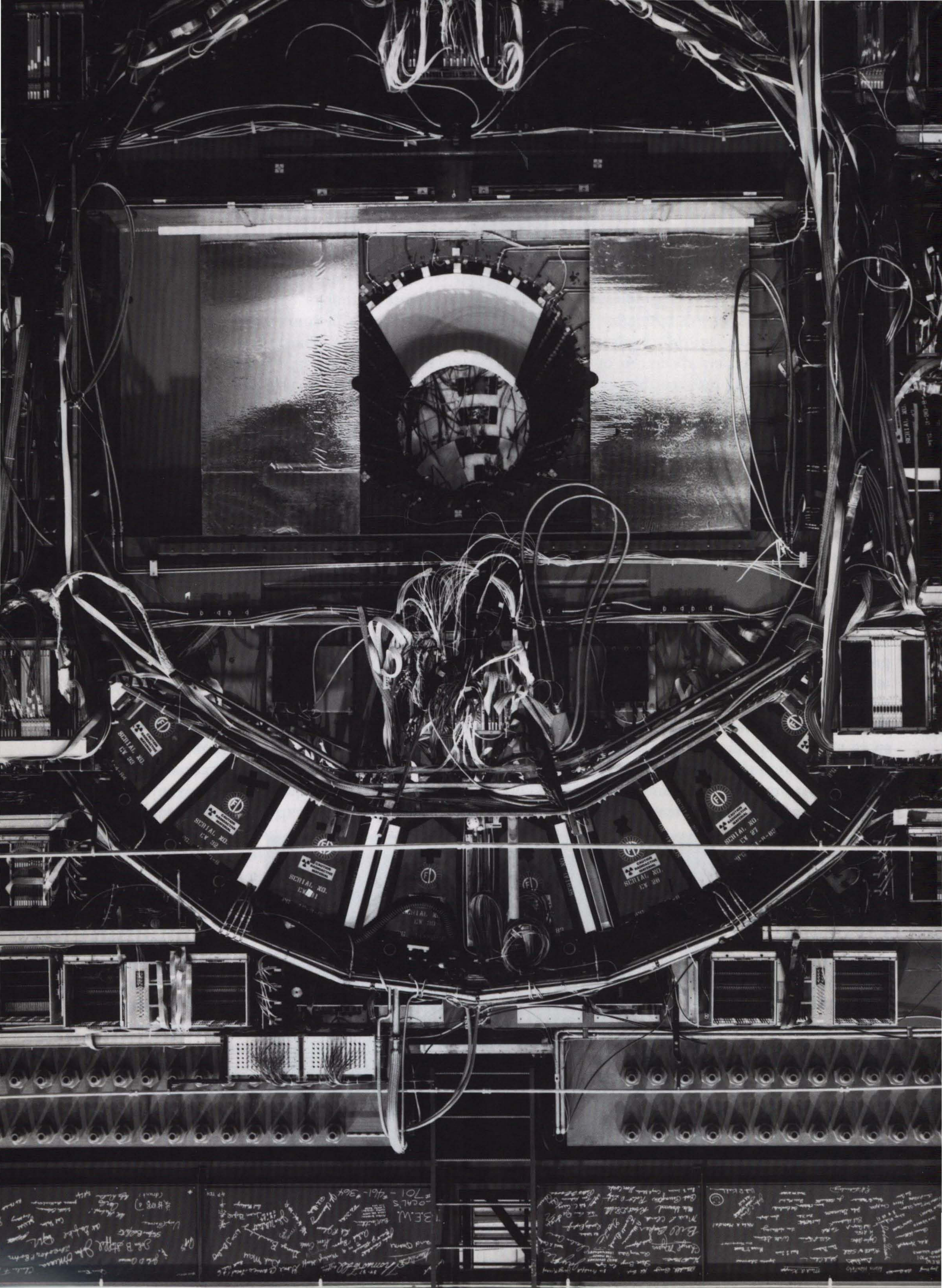
Detecting neutrinos is difficult. They pass through material without interacting and do not leave tracks in the tracking chamber or deposit energy in the calorimeter. Their presence is not measured directly but is inferred by measuring the energy imbalance. After the proton and antiproton collide, produced particles fly off in all directions. If the observed energy is not symmetrical, then it is assumed that a neutrino is present. The signature of a neutrino is "missing" energy.

The quarks are not detected individually but as clusters of energy in the calorimeter. These particle "jets" generally have several tracks pointing to the calorimeter energy cluster.

## Looking at W's and Z's

One of the jobs for which CDF was designed is the study of W's and Z's – the heavy particles which are the carriers of the weak force. Because these particles are so heavy, very energetic colli-

*(Opposite) The Collider Detector Facility. The CDF collaboration reported a new, more precise mass for the W boson.*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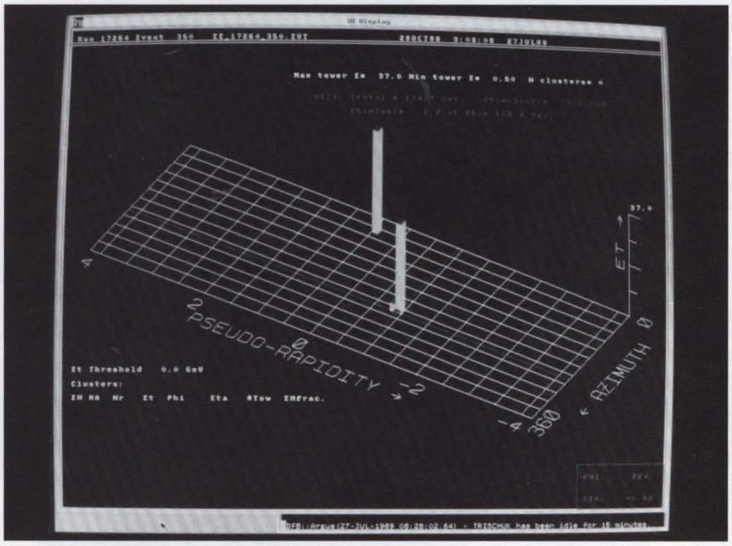
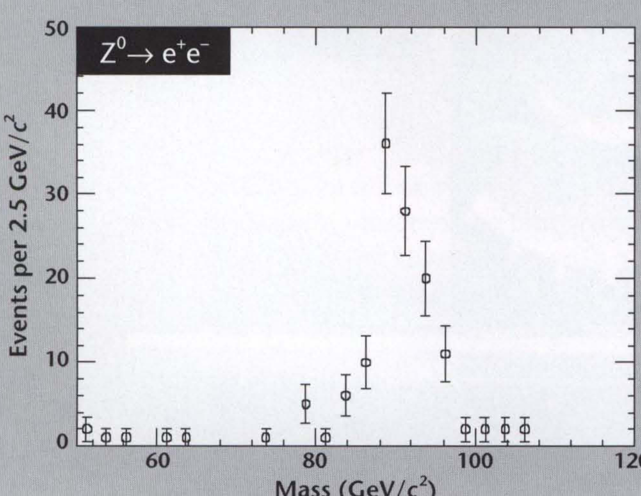
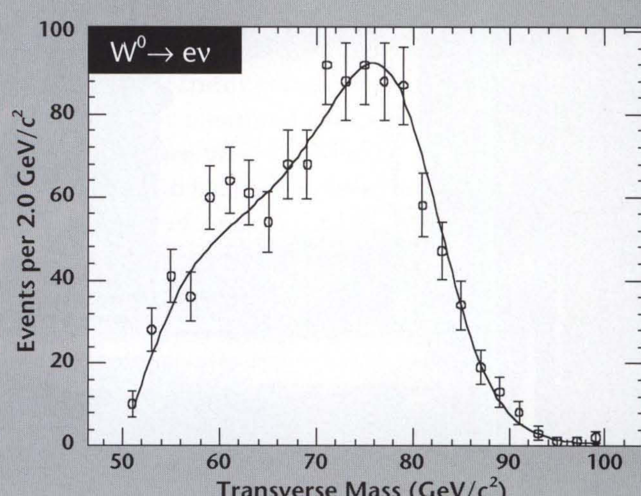
sions are required to produce them. The W's and Z's decay to other particles shortly after they are produced so the detector must be able to recognize their decay products and reconstruct the W or Z from what it leaves behind.




The Z particle has no electric charge and may be observed through its decay to two electrons ($e^+e^-$) or to two muons ($\mu^+\mu^-$). Both decay modes are quite striking in CDF. The photo shows a Z decaying to electrons in CDF. The two tracks in the tracking chamber are almost straight, indicating very high momentum. The calorimeter shows two energy clusters. From the momenta of the two particles, one may calculate the mass of the Z particle, for several electron pair events. The different events all give masses that are almost the same, indicating a particle with the mass of the peak in the mass plot below. The best information about the mass of the Z now comes from CERN where Z's are produced in high energy electron-positron collisions.

Unlike the Z, the W particle is charged, so it can decay to an electron plus a neutrino or a muon plus a neutrino. The W signature is still striking – a W event has an isolated energetic electron or muon and a large amount of missing energy. Because the second lepton is a neutrino rather than a muon or electron, one cannot calculate the mass for many W events and look for a bump in the mass distribution as one does for Z's since the neutrino momentum cannot be completely determined. We know something about the neutrino's energy from looking at the energy imbalance in the event, but this gives us information only about the neutrino's energy (or momentum) perpendicular to the beam direction. So we have no knowledge of the neutrino's momentum along the beam direction. Instead of calculating the mass, we calculate a quantity called the transverse mass. The transverse mass distribution for $W^- \rightarrow e^-\nu$ events is shown in the graph below. Then we use a computer simulation of W production in the detector to tell us what W mass value gives a transverse mass distribution that matches the one we observe.



## Searching for the Top Quark

An important piece of the Standard Model picture is missing. The top quark has not yet been observed. But how do we look for it? If top quarks were produced in antiproton-proton collisions, they would quickly decay to other particles. As we do for the W's and Z's, we must infer their existence from the particles that do show up in the detector. First, we assume that t quarks will be produced in pairs, a top with an antitop. Each of the t quarks can decay in several ways. Most of the time, the t (or anti-t) just decays to other quarks. If both decay this way, we have a final state containing several jets. The problem is that we can get similar multi-jet events from $p\bar{p}$ collisions with no t quarks involved at all. So it is not easy to identify the t quark this way. Another possibility is that one or both of the t quarks decays "semi-leptonically," which means that its decay products include an electron or muon. If both t's decay this way, we will have two energetic charged leptons in the event, and there are not very many known processes which produce events like this. In particular, if the top quark exists, we should see an abundance of events containing both an energetic electron and an energetic muon. We can calculate how many of these events we should see in the detector as a function of the top quark mass. A search for such events in CDF concluded that the top quark must be more than 70 times heavier than the proton. If it were lighter, more e-μ events would have been found.

The masses of the W and Z also tell us something about the top quark mass. We can calculate an upper limit for the top quark mass using information about the mass of the W combined with Z mass information from CERN. The result is that for the Standard Model to be consistent, the top quark mass must be less than about 230 times the mass of the proton. So even though the top quark has not been found, we are narrowing the range where it must be seen or the Standard Model will be in serious trouble. Future experiments will either find it or force the theories to be modified.

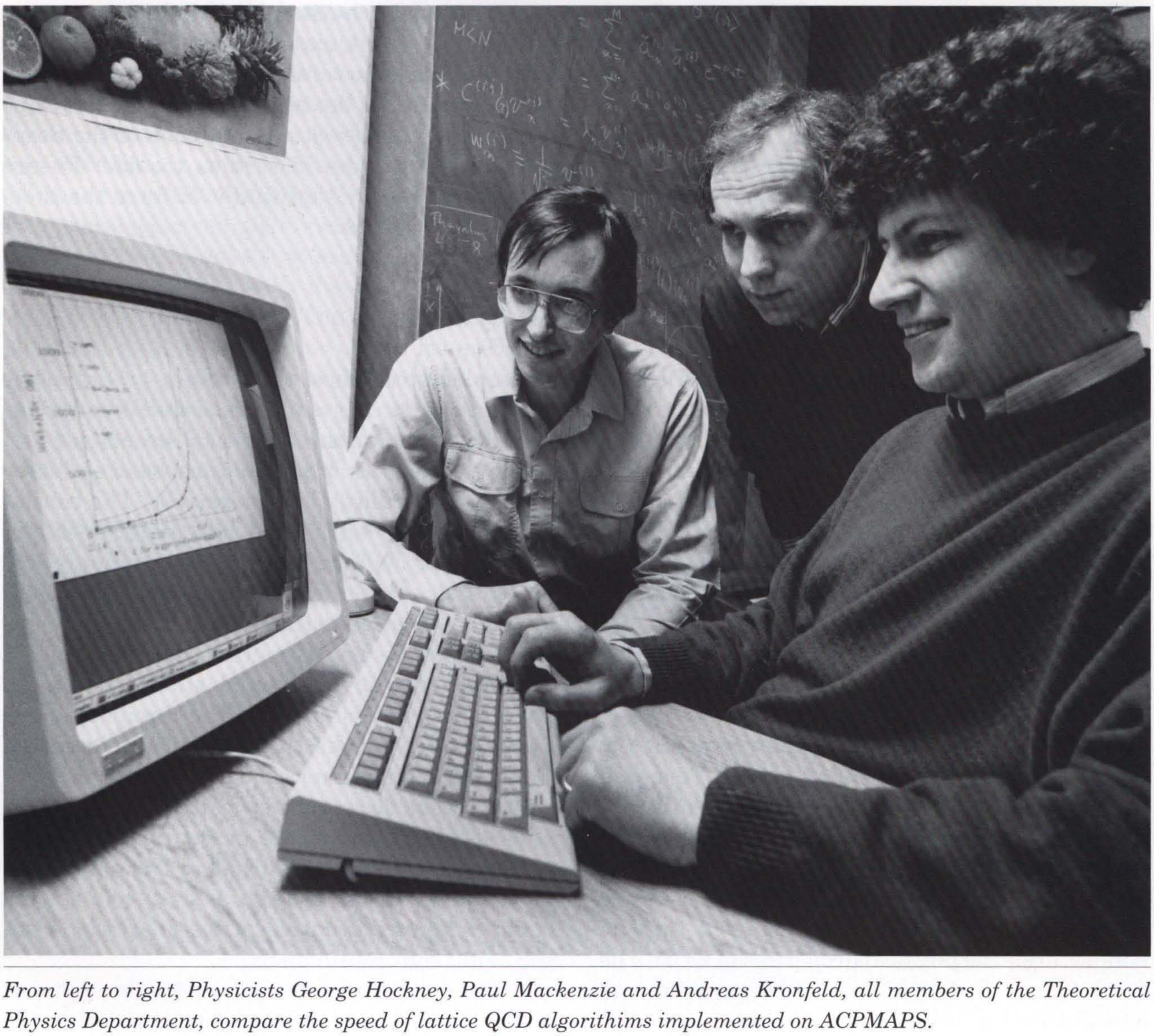
## Theoretical Physics

Members of the Theoretical Physics Department pursue independent research programs in theoretical elementary-particle physics. Research problems addressed by the Theory Group in 1990 ranged from the phenomenology of antiproton-proton collisions at supercolliders to fundamental issues in nonperturbative string theory. Significant progress has been achieved in applying perturbative QCD to physical problems. We also contributed to a broad spectrum of theoretical issues related to understanding the structure and interactions of elementary particles.

The Theoretical Physics Department and the Computer R&D Department of the Fermilab Computing Division have been collaborating on the development of the Advanced Computing Program Multi-Array Processor System (ACPMAPS) supercomputer project for lattice gauge theory calculations focussed on the nonperturbative physical properties of QCD. The full 256-node, five-gigaflop processor system with its software has been certified, and the systematic implementation of the physics program has begun. A particular emphasis of the research has been the calculation of physical properties and decay parameters of particles containing heavy quarks, particularly bottom quarks. The continued development of the lattice gauge supercomputer project will make Fermilab a major center for realistic calculations in nonperturbative QCD and its application to the solution of many important physics issues. The group has also studied the properties of postulated states containing gluons, the energy quanta of the chromodynamic force between quarks, the topological structure of QCD, and the numerical simulations of semi-leptonic weak decays of mesons, including various D-meson decays that are currently being measured at Fermilab. Perturbative calculations of lattice guage theory have studied the connections between nonperturbative lattice simulations and the usual continuum analysis.

The department puts considerable emphasis on the perturbative approach to calculating the strong QCD force between quarks. Perturbative QCD calculations of the production rate of W particles accompanied by jets of light particles have been important in understanding the experimental problems involved in isolating the possible top quark and Higgs particle events in $p\bar{p}$ interactions. Higher-order calculations of heavy quark production cross sections continue to play an essential role in the search for the top quark at the Tevatron. We continue to analyze expected experimental signatures of other aspects and possible extensions of the Standard Model of quarks and leptons. These include the signatures for new interactions beyond the chromodynamic force, such as technicolor or possible strong interactions of the vector bosons at high energy; the existence of neutrino masses or magnetic moments; the structure of the quark mass matrix and its implications for quark mixing.

We are studying mechanisms for electroweak symmetry breaking to determine the fundamental source of all known particle masses. The Higgs sector of the Standard Model may be replaced by condensates formed by new attractive interactions between the normal quarks and leptons. The possible role of condensates of fourth-generation quarks has been studied as well as the implications of neutrino condensates on the neutrino mass matrix and mixings. A spinoff of this research involves the analysis of radiative correc-



*From left to right, Physicists George Hockney, Paul Mackenzie and Andreas Kronfeld, all members of the Theoretical Physics Department, compare the speed of lattice QCD algorithims implemented on ACPMAPS.*

tions to electroweak observables, which is highly relevant to the exciting physics objectives of CDF and DØ in the forthcoming collider runs.

We have also made progress in more formal areas of particle physics research, including the problems of quantizing gravity defined in two dimensions, the construction of conformal field theories, and the development of new matrix models for the analysis of nonperturbative string theory.

The connection between astrophysics, cosmology, and particle physics has benefitted from the proximity of the Fermilab Astrophysics Group. Research has emphasized the important role very light particles could play in "late-time" phase transitions affecting the evolution of the universe. Progress has also been achieved in understanding the possible origin, observational implications, and experimental detection of cold dark matter.

Fermilab's traditional Theory Visitors Program, which provides hospitality and support for a large number of physicists from the local, national, and international physics communities, makes Fermilab a central crossroads for the exchange of the newest theoretical ideas. It also provides an opportunity for useful interaction between the theoretical community and the many experimental physicists who find Fermilab the home of their research. To that end, our department organizes the weekly Theoretical Physics and Joint Experimental-Theoretical Physics Seminars. We also organize an annual workshop for the study of new theoretical developments of interest, and department members contribute to the Fermilab Academic Lecture Series, addressed to the broader physics community at Fermilab.

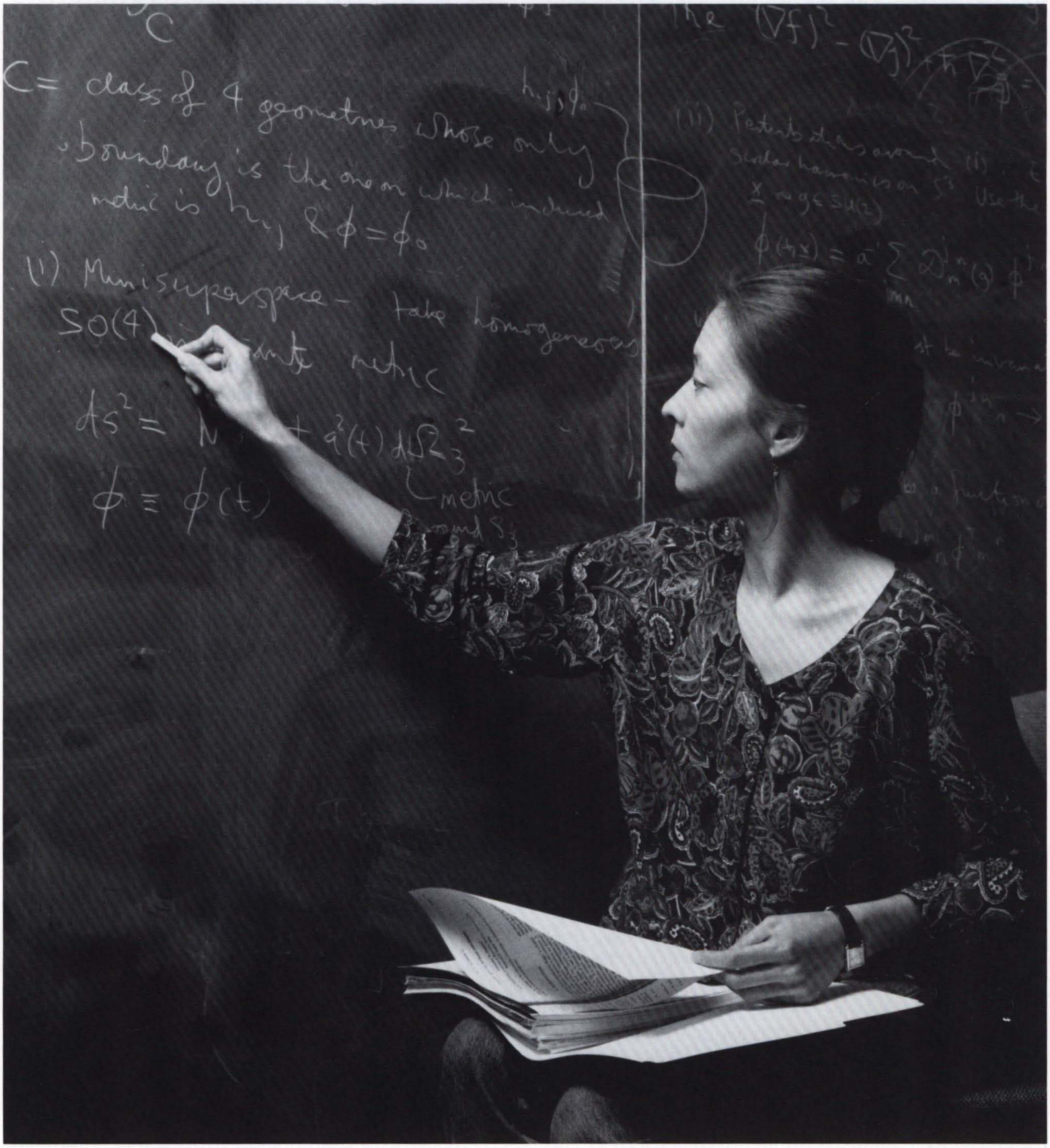
## Theoretical Astrophysics

In the past decade the importance of the symbiotic relationship between elementary-particle physics and astrophysics/cosmology has become very clear. Understanding the behavior of matter at high energies and densities is necessary to understand the evolution of the universe at very early times. Average particle energy is related to the age of the universe. Conversely, both the early universe and contemporary astrophysical sites provide unique Heavenly Laboratories for probing Fundamental Physics in regimes that are inaccessible to terrestrial laboratories. The activities of the Theoretical Astrophysics Group have involved the Theoretical Physics Department, experimental groups, and the Department of Astronomy & Astrophysics at the University of Chicago. The Map of the Universe project (discussed on page 68) represents a new direction to this important relationship.

### The Blueprint

The standard hot big bang cosmology provides a reliable and tested account of the history of the universe from about 0.01 sec after the bang ($T \sim 10$ MeV ) until the present ($T = 2.74$ K). The evidence in support of the model includes the universal expansion (Hubble flow of galaxies), the existence of the cosmic microwave background radiation, and the predictions of primordial nucleosynthesis for the abundances of D, $^3$He, $^4$He, and $^7$Li. In addition, the model provides a general framework for understanding the formation of structure in the universe: the gravitational amplification (by the Jeans instability) of small primeval density fluctuations. This amplification process began when the universe became matter-dominated, about 1,000 years after the bang. In many respects, structure formation is just an initial data problem; given the amount and composition of matter in the universe and the spectrum of initial inhomogeneities, the problem can be solved (e.g., by numerical simulation). Conversely, this means that by studying the structure that exists in the universe today one can hope to infer the initial data.

Many now believe that understanding the initial data involves the study of the early universe. In particular, "the blueprint" for structure formation was laid down very early and involves funda-




*In her study of quantum cosmology, Fay Dowker, a research associate of the Astrophysics Group, applies quantum mechanical principles to the study of the universe.*

mental physics beyond the Standard Model. To be specific, the inflationary scenario predicts the universe today is flat ($\Omega_{TOT} = 1$) and has a particular form for the primeval inhomogeneity (Harrison-Zeldovich spectrum). Since the successful predictions of primordial nucleosynthesis only hold if $\Omega_B \leq 0.12$, this line of reasoning implies that the bulk of the mass density must exist in nonbaryonic matter ($\Omega_{NB} \sim 0.9$). Many of the theoretical speculations that go beyond the Standard Model predict the existence of new stable particles, whose relic abundance is about right to provide most of the mass density today. Among the most well-motivated candidates are a $10^{-6}$ eV to $10^{-4}$ eV axion, 20 GeV to 1 TeV neutralino, and a 20 eV to 90 eV neutrino.

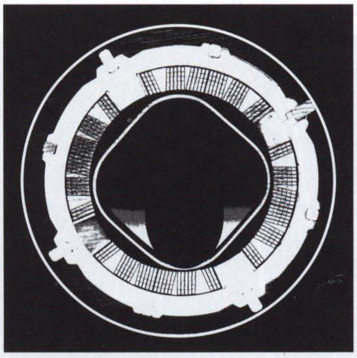
The idea that the blueprint for structure formation involves fundamental physics in the early universe has served to focus the problem. A number of interesting blueprints have been developed: cold dark matter and inflation-produced inhomogeneity; hot or cold dark matter and cosmic-string-produced inhomogeneity; hot or cold dark matter and inhomogeneity produced by a very recent, low-temperature phase transition. (Cold dark matter refers to slowly moving relics such as the neutralino or axion; hot dark matter refers to fast moving relics such as a light neutrino). Provided that the blueprint did involve fundamental physics in the early (or late) universe, the study of the structure that exists today offers a unique opportunity to probe fundamental physics, which of course is the motivation for the Laboratory's involvement in the Map Project.

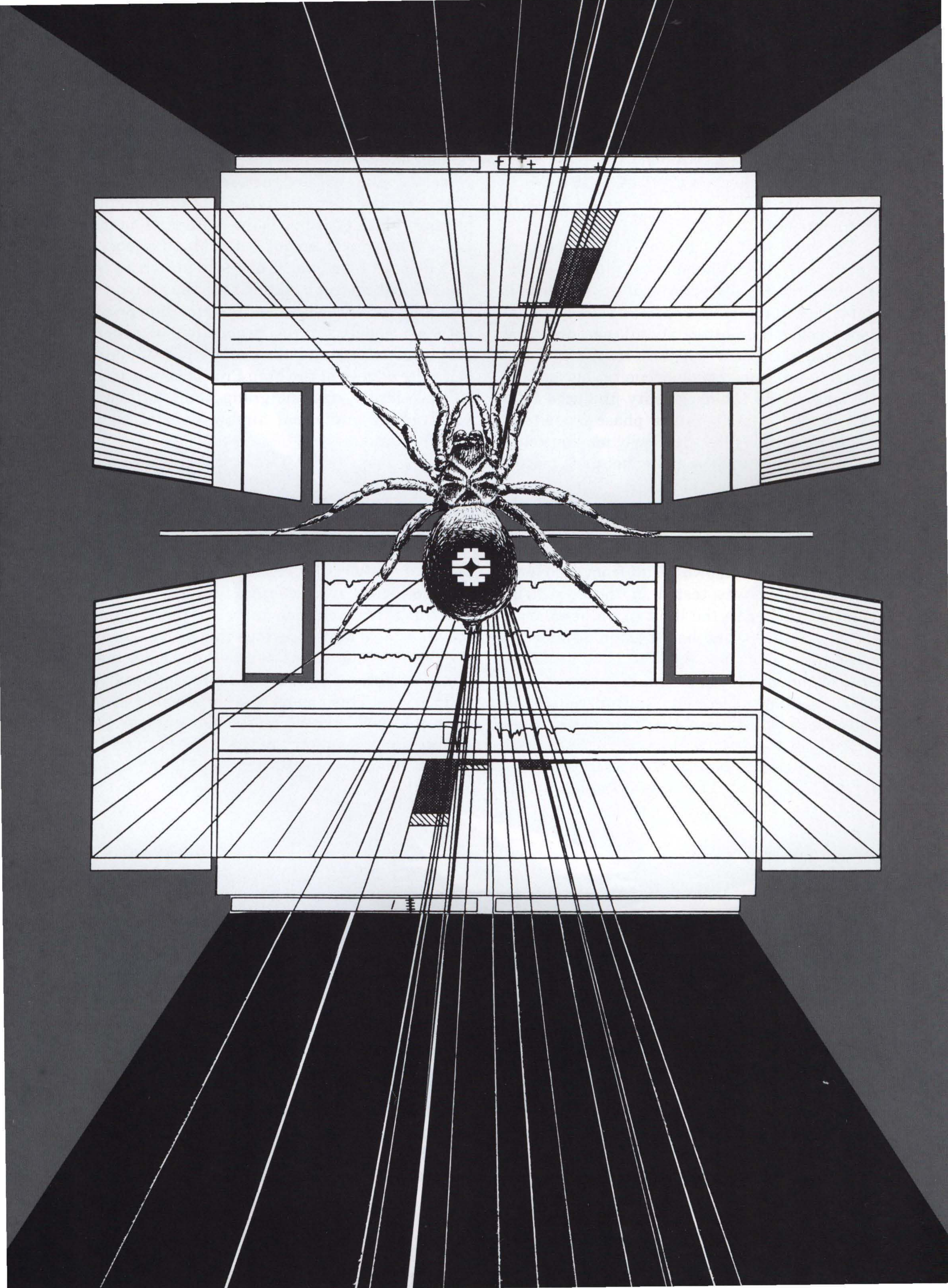
In past years much of the research in the Theoretical Astrophysics Group has involved the study of various early universe blueprints; both as models for the production of density inhomogeneities and dark matter candidates. With the advent of the Map Project that activity will accelerate, and the group plans to become involved in numerical simulations of structure formation.

## The Heavenly Laboratory

The most well-known result from the Heavenly Laboratory was tested in the terrestrial laboratory this year; the limit to the number of light neutrino species based upon primordial nucleosynthesis, is $N_\nu \leq 4.0$. Precision measurements of the properties of the $Z^0$ boson at both SLAC and Large Electron Positron collider at CERN (LEP) confirmed this early-universe result: $N_\nu = 2.89 \pm 0.1$.

Since its inception, the Theoretical Astrophysics Group has led the way in exploiting the Heavenly Laboratory. Results over the past year include the use of primordial nucleosynthesis to exclude a tau-neutrino mass in the range of 0.5 MeV to 20 MeV (provided that $\tau_\nu \gtrsim 1$ sec) and the closing of one of the two remaining axion mass windows through a telescope search for decaying relic axions. This means that if the axion exists, it is the dark matter and constraints to low-energy supersymmetry mode is based upon the relic neutralinos.





# Preparing for the 1991 Collider Run

## Tevatron Collider Upgrades

The goal of the Tevatron collider upgrade program is to provide two high-luminosity interaction regions for the detectors at the BØ and DØ straight sections. The major physical components of the upgrade are new superconducting quadrupole magnets to focus the proton and antiproton beams tightly in the middle of the detectors and new electrostatic dipoles to keep the beams apart outside of the detectors.

The luminosity is proportional to the rate of interactions. By focussing the beams to a smaller volume, the luminosity is increased. This increases the sensitivity to rare processes like the production of the top quark. In quite another way, the luminosity can be increased by separating the beams outside of the interaction regions with the electrostatic separators.

In past collider runs, the proton and antiproton beams have each consisted of six bunches of particles circulating in opposite directions on the same orbit in the Tevatron. Each time a bunch passed through a counter-rotating bunch, the opposing electromagnetic fields perturbed the trajectories of the particles in the bunch, leading to a growth in the transverse beam size. Thus the interaction volume in the middle of the interaction region grew and the luminosity diminished. In these past collider runs, the beam brightness has been limited by this beam-beam interaction; if the number of protons in a bunch increased or the transverse size of the bunch decreased, the electromagnetic fields would influence the opposing bunches, reducing the luminosity lifetime.

In future runs, the electrostatic separators will separate the two beams at all crossing points except those at DØ and BØ. This will allow the beam brightness, and therefore luminosity, to be increased. Another aspect of the collider upgrade program, then, is the improvement of the brightness of both the proton and antiproton beams.

A first step has been taken by improving the antiproton source to increase the antiproton beam brightness. These improvements, which included higher-frequency stochastic cooling systems and increased apertures, led to record stacks of 1.2 x $10^{12}$ antiprotons in December. A future step for proton beams involves the new Linac upgrade to increase the injection energy of the Booster synchrotron. This in turn should lead to a significantly brighter proton beam.

Electrostatic separators have been used at other colliding beam laboratories with great success, but up to now the separation has been in only one plane. The orbits in these cases look a bit like a pretzel. The Fermilab scheme has electrostatic deflection in both the horizontal and vertical planes, which leaves the proton and antiproton orbits winding around each other forming something like a double helix. The advantage to this scheme is most apparent when there are many bunches, as in the 36 on 36 scenario contemplated for more distant collider runs. With so many bunches there would be too many near-by passages in a pretzel scheme. As the luminosity increases, the number of interactions seen by a detector per bunch-bunch crossing can get quite large. By increasing the number of bunches, the event overlap and confusion in the experimental detector can be reduced.

The design of the previous CDF low-beta insertion, or configuration of quadrupole magnets around the interaction region, was clever and relatively simple. It was composed of only four additional quadrupole circuits. Unfortunately, it was not flexible enough to use with another low-beta insertion at DØ. A new design for the insertion using nine circuits was developed that could be replicated almost exactly for the DØ experiment. It allows simultaneous operation of both insertions. The new design required the development of three new types of quadrupoles, the strongest of which is capable of 1.4 Tesla/meter compared with 1.1 Tesla/meter used in the old design. In principle, these higher-strength quadrupoles can squeeze the beam to half the transverse area of the older insertion.

## Implementation Strategy

The DØ straight section is used for the electrostatic splitting septa needed to extract the Tevatron beam for fixed target experiments. Since the fixed target program is to continue for another five months into 1991, the DØ low-beta insertion has to be the last piece of the collider upgrade plan. But past experience has shown that collider operation can be pretty tricky, sometimes with unanticipated complications. It was decided to interrupt the 1990 fixed target run, install the BØ low-beta quadrupoles and roughly half the needed electrostatic separators, and gain as much experience as possible in machine study sessions during the 1991 fixed target run.

Such an interruption did take place, and many heroic efforts produced all the parts to reassemble a very different Tevatron. Magnets were made, tested, measured, and installed. Separators were constructed, tested, and conditioned. Power supplies, quench protection, cryogenics, controls, and safety systems were added to integrate the upgrade components into the Tevatron. By early December, the Tevatron was ready to go.

One particular aspect of the machine that was as new as any part of the upgrade hardware was a revolution in the control system. At the upper end of the system the operator consoles were changed into powerful workstations. This change accomodated new programs necessary to meet the demands of the Tevatron upgrade with its many new elements. At the lower end of the control system, a new generation of function generators was available, which allowed a new approach to collider operation. With these microprocessor-driven devices, hundreds of power supplies are coordinated using the Tevatron clock system for the 12 or so different sequences of steps needed for collider operation.

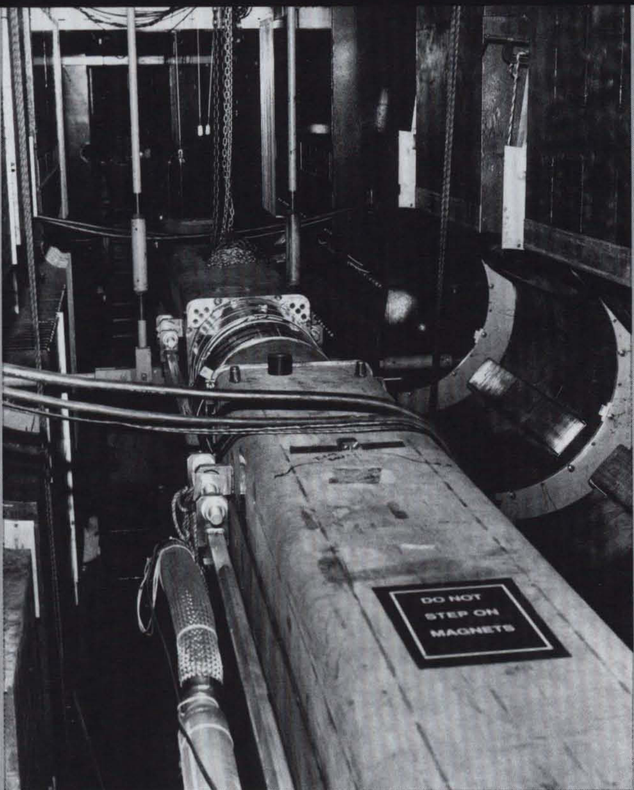
As examples of the powerful new applications programs, there is the Tevatron Orbit Program (TOP) and an on-line lattice calculation program. TOP can gather the closed-orbit data from one Tevatron ramp for each of nine energies, calculate the settings of the 240 or so correction dipoles for each energy, and load the values into the function generators so the orbit is corrected for the next ramp. The lattice calculator, needed for the TOP program, runs as a subroutine and takes about five seconds to generate a full description of the lattice from the magnet current settings. This subroutine includes the higher-order multipoles from the magnet test facility measurements of each of the 772 superconducting dipoles in the ring, a feature necessary to understand the helical orbits at injection energy.

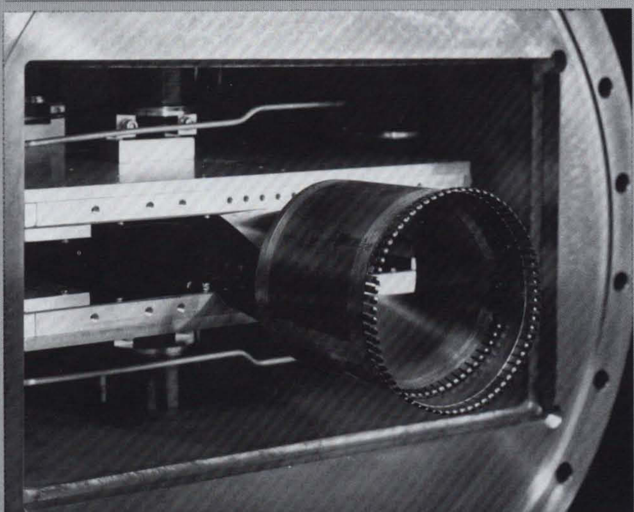
## Progress as of the Year's End

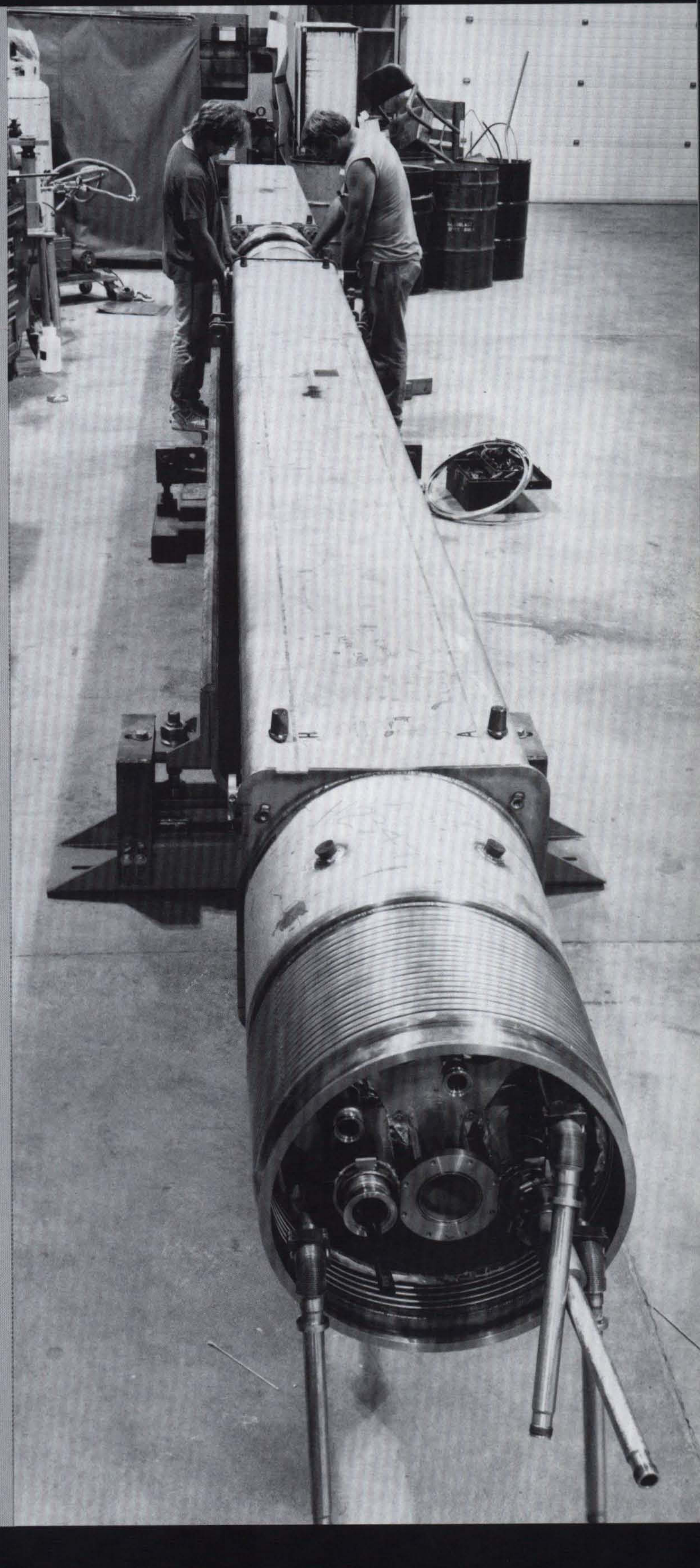
The highest priority after the shutdown was to confirm that the Tevatron could function as a fixed target machine again. This is always an interesting question after a long shutdown in which only routine maintenance is performed. Indeed, a couple of unanticipated problems did occur, relatively unrelated to the upgrade devices, which delayed things a few days. Nevertheless, fairly efficient extracted beam at 800 GeV was established within one week of the start of the commissioning.

Some of the new quadrupoles at BØ and DØ that were installed during the shutdown are necessary for fixed target operation. And, of course, they change the focal properties of the machine. In particular, the orbits between the electrostatic splitting septa at DØ and the magnetic septa at AØ were modified enough that a new study of the extraction process was needed. New settings had to be derived for the driving 39th harmonic quadrupoles used for the 1/2-integer slow resonant extraction process.

Having tuned the Tevatron to fixed target mode, the next priority was to resurrect the collider mode of operation with the new controls and to test the low-beta insertion at BØ. This meant dealing with more magnets, more circuits, and another new lattice. In fact, in the collider injection lattice the low-beta insertions are almost fully energized. For example, in the old collider lattice, the beta function (proportional to the square of the beam size) at the center of BØ was



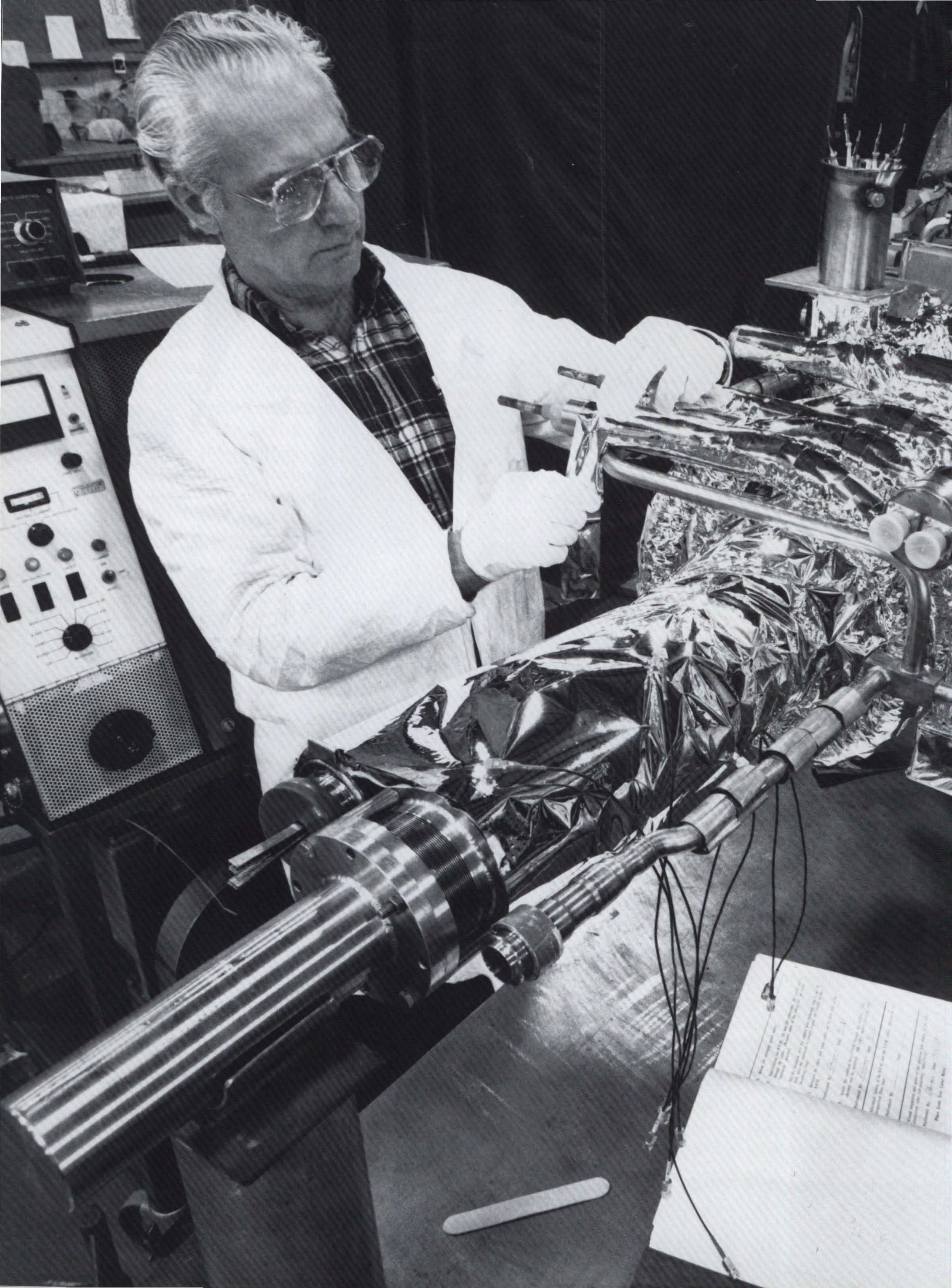



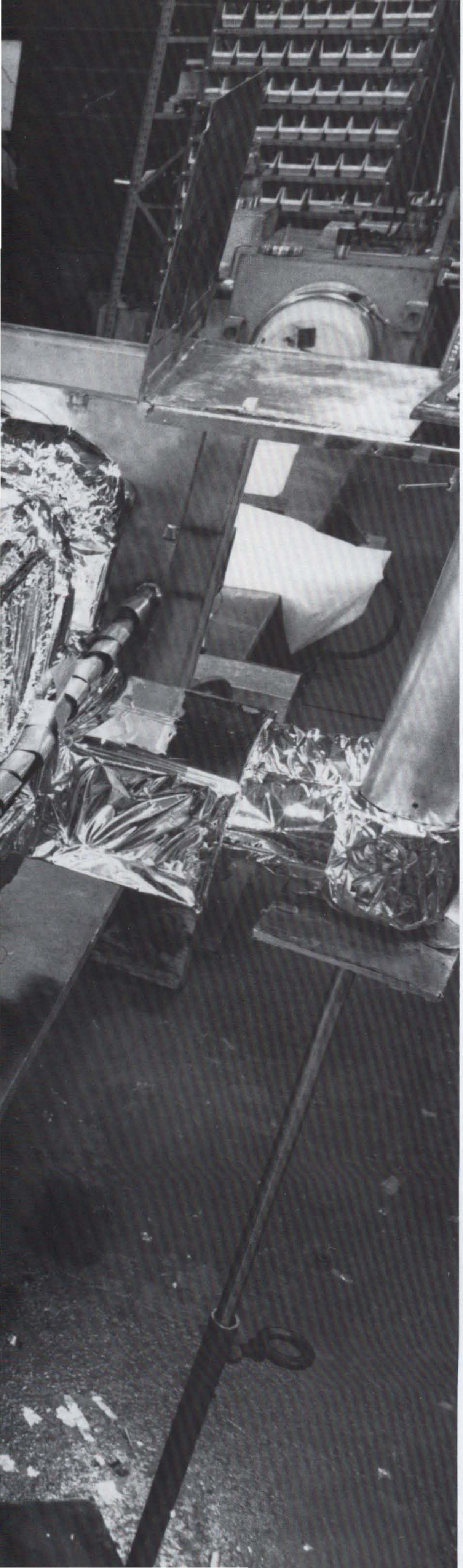


*(Top Left) New low-beta quadrupoles were installed in the CDF collision hall in 1990 to increase the luminosity for the Tevatron collider.*

*(Bottom Left) A cross-sectional view of a bunched beam stochastic cooling tank installed in the Tevatron.*

*(Right) Scott Adner (l) and Roger Thomas (r) fabricate vacuum connections between two six-meter-long low-beta quadrupole magnets located at CDF.*





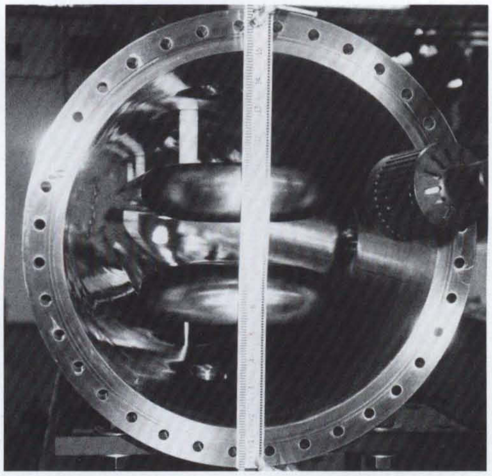
72 meters. With the new low-beta insertion the corresponding beta function is 1.7 m, to be compared with the final design value of 0.5 m. That is, the injection lattice has a luminosity potential a factor of three less than the design operating value.

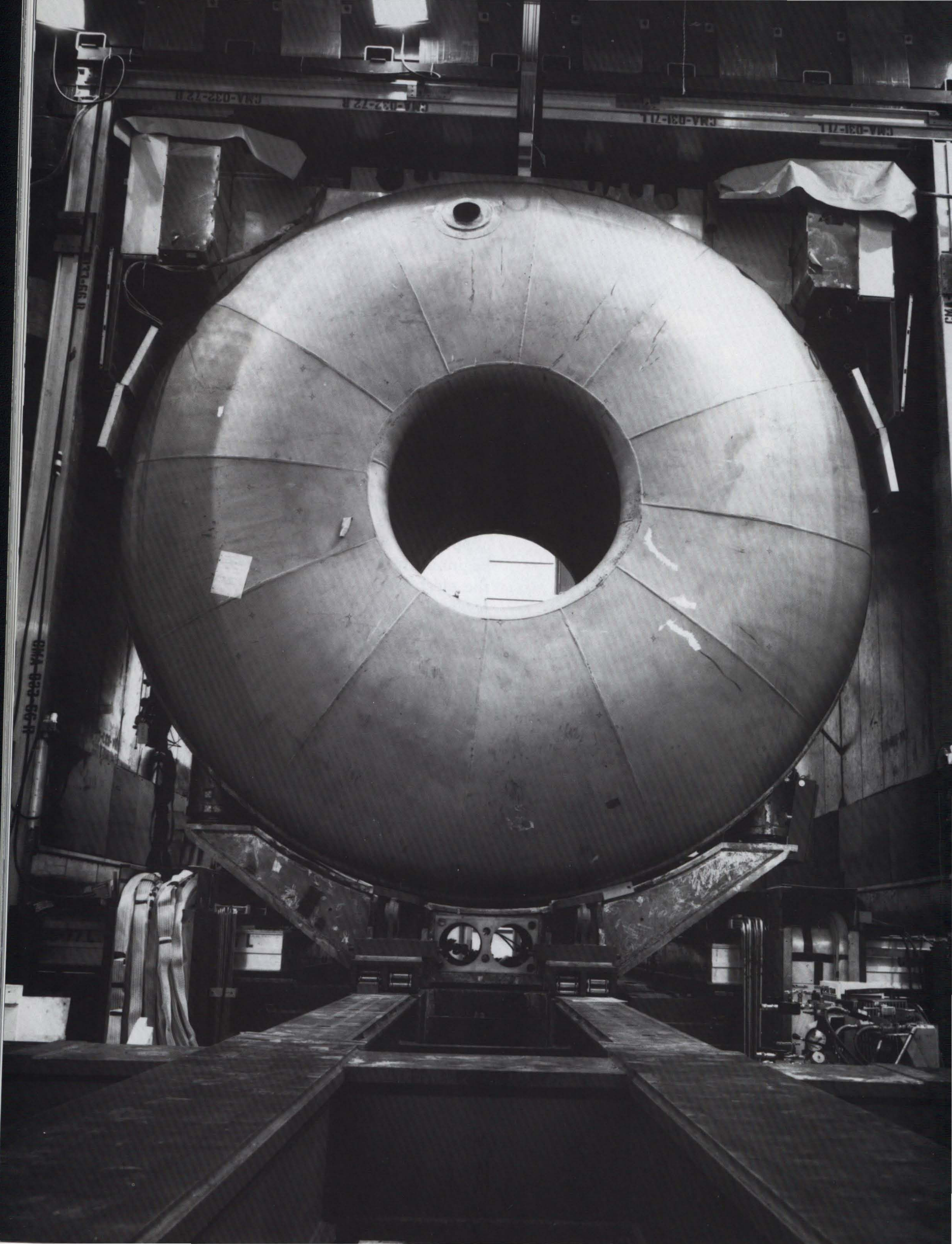
One very worrisome aspect of the fully energized quadrupoles in the insertion is due to the sensitivity to surveying errors. If the quadrupoles are misaligned transversely so that the beam passes off the center of the quadrupole, the beam sees an effective dipole field which causes a closed orbit distortion. Superconducting correction dipoles were included in the design to compensate for this effect, yet it was known that an error of 250 microns could cause an uncorrectable orbit distortion at full energy.

These and other worries were overcome and, by years end, beam had been accelerated to 900 GeV and stored, and studies of the details of the new lattice were underway. The collider mode of operation with the controls upgrade was just beginning to work reliably and beam studies with the electrostatic separators were just about to begin. The commissioning studies had gone so well that it seemed very likely that all the preparations for tests with protons and antiprotons on helical orbits could be finished before the fixed target program resumed.

*(Left) Steve Kovacs applies insulation to the last low-beta spool piece to come off the production line. The spool piece contains a correction magnet package and a high-gradient quadrupole.*

*(Below) An electrostatic separator controls proton and antiproton collisions in the ring, reducing beam-beam interaction and increasing luminosity.*





# Expectations for the First Run of the DØ Detector

As the date of the next collider run rapidly approaches, monumental preparations are underway to complete Fermilab's second collider detector, to be located at the DØ interaction region. The DØ detector has been designed as a complimentary counterpart to the existing CDF, to augment the output of collider physics from Fermilab's collider runs over the next ten years. Detector design began well after the CDF design had been completed and after the first runs of CERN's UA1 and UA2 detectors, enabling DØ to take advantage of the experience gained in building and operating those three detectors.

The DØ detector is a large (~5500 tons) hermetic ($4\pi$ solid angle coverage) detector, consisting of three primary subsystems. The central region is filled with tracking chambers and a Transition Radiation Detector (TRD) to aid in electron identification. A salient feature of this region is the absence of a magnetic field. Completely surrounding the central region is the liquid argon/uranium calorimetry, which contains both electromagnetic and hadronic sections, and comes in three major parts, approximately equal in size: one central and two end calorimeters.

Four layers of proportional drift tubes (PDTs) track the particles that penetrate through the six to eight absorption lengths of the calorimetry. These chambers are followed immediately by a large iron toroid, which bends muons as they traverse its one meter of magnetized steel. The muons then encounter three more layers of PDTs on the outside of the toroid followed by a one-meter drift length and another three layers of proportional tubes. The PDT/toroid combination allows the momentum of the muons to be determined to 20% or better.

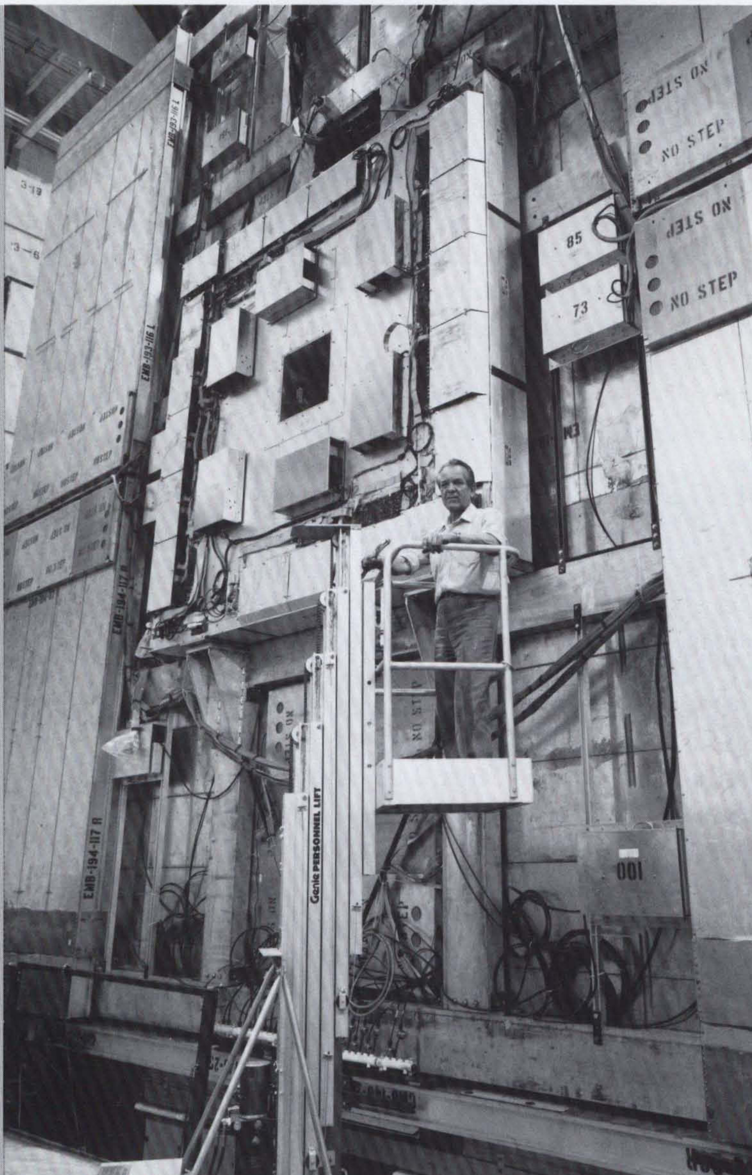
The DØ detector was designed to have specific advantages over its counterparts. A design with no central magnetic field was chosen because the primary measurements being made were of jets and leptons. Good calorimetry resolution is more important in measuring the energy of a jet than momentum determinations, which require magnetic fields. A liquid argon calorimeter, uniform in all directions and with fine segmentation, was chosen for its superior resolution properties and the fact that the response of this type of calorimeter requires no recalibration. It is only necessary to keep track of the argon purity and the electronics gains. Also, the variation in response from module to module is negligible. Because intramodule variations do exist, it is important to calibrate each type of module. These assertions have been verified in two test beam runs. In the second run, the response of modules that will be used in the DØ calorimeter was measured. A major advantage of the DØ detector is its superb muon coverage, which extends down to approximately four degrees. The thickness of the detector varies from 13 to 18 absorption lengths, depending on the angle of emergence of the muon. This is roughly twice as thick as the best of the previous detectors. Far fewer pi mesons will penetrate to the outer layer of PDTs to generate a false muon signal.

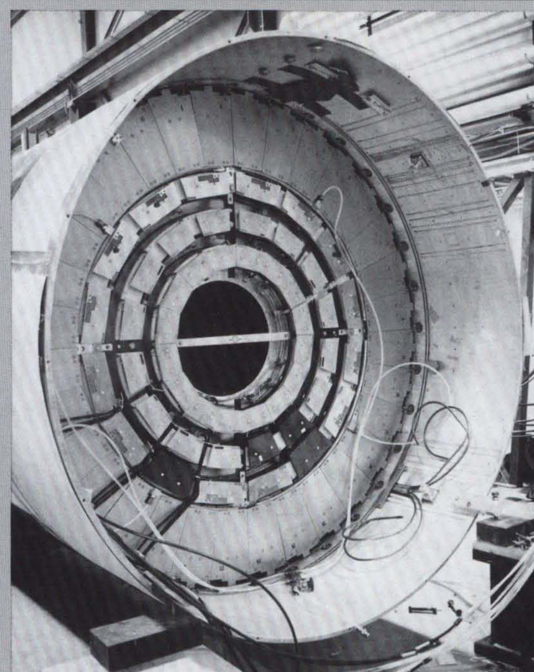
At the end of 1990 many of the essential components of the detector were already in place. All of the central tracking chambers and the associated electronics have been built, tested, and installed. The central calorimeter has been assembled and moved onto the main detector platform where it is being cabled and readied for cooldown. The cryostats for the two end calorimeters have been made and delivered. All of the modules for these calorimeters have also been completed. One of the cryostats is currently in a clean room at DØ where modules are being loaded into it. The second is being prepared to move to DØ; both calorimeters will be complete by fall 1991.

The muon toroid and all of the muon PDTs are complete. The toroid has been power tested, and most of the PDTs have been installed and commissioned. Much of the data acquisition system, including the host computer and hardware trigger system, has been installed and tested.

The schedule for the next few months consists of a cosmic ray commissioning run to be followed by completion of the detector. The commissioning run to begin in spring 1991 is designed to test all of the major components of the detector by studying cosmic rays that pass through it. The elements of the detector that can be tested in the commissioning run include the central tracking chambers, the central calorimeter, central por-

*(Opposite) The DØ central calorimeter (17 feet in diameter and 300 tons) was assembled in a special clean room. In September, a milestone in DØ history was reached when the central calorimeter was moved into the center of the detector.*



*(Left) Pavel Kostromin, a technician from IHEP in the Soviet Union, shown in front of one of the steel end pieces of the DØ detector. The square insert above left is the SAMUS (Small Angle Muon System) portion of the muon detector fabricated at IHEP.*

*(Top Right) Physicist Norman Amos checks wiring installation for a module of the DØ end calorimeter.*

*(Bottom Right) This eight-foot aluminum circle, containing the central drift chamber and transition radiation detector, fits inside the "donut-hole" of DØ's central calorimeter.*

tions of the muon system including the toroid and a number of the PDTs, and subsets of all of the electronics, trigger, data acquisition, and on-line software. This run will undoubtedly be of great use in preparing for a smooth turn on of the detector when it moves into the DØ collision hall.

In addition to preparing for the commissioning run, a great deal of work has gone into generating and analyzing 100,000 Monte Carlo events. This exercise has allowed much of the off-line software to be tested on data which is very similar in nature to the real data that will be accumulated during the first run.

The early start on the commissioning should allow a transition to a data taking mode within a few months. At that time DØ will join CDF in the hunt for the elusive top quark, and begin work on a large menu of other physics topics including the study of jets and photons to test strong interaction theory. In addition, there will be detailed measurements of W/Z properties including masses, widths, and asymmetries. Completing the list of topics are B physics and, of course, the search for new and unexpected phenomena.

# Improvements to CDF and Potentials for Discovery in the Next Collider Run

The next Tevatron collider run is expected to provide antiproton-proton collision rates well above the original Tevatron and CDF design goals. Indeed, peak luminosities are expected to approach $10^{31}$ cm$^{-2}$ s$^{-1}$, which could allow CDF to accumulate a fivefold or more increase in the total integrated luminosity from this run compared to the sum of all previous CDF runs. This increase, when combined with such detector improvements as a silicon microvertex detector, an expanded muon system, and new preradiator chambers will significantly enhance the capability of the experiment to make precision tests of the Standard Model as well as to search for new physics phenomena.

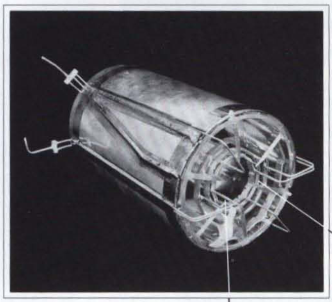
Antiproton-proton collider experiments at CERN in the early 1980s led to a number of new physics discoveries, most notably confirmations of many of the basic predictions of QCD and the Standard Model description of the electroweak interactions including the discovery of the W and Z bosons that mediate the weak interactions. Yet many questions remain unanswered. These same experiments and more recently CDF at the Tevatron collider have not revealed the expected sixth subatomic constituant, called the top quark. As a result the mass of the top quark appears to be much greater than originally anticipated. (Indeed, the entire question of how such particles obtain their mass is a mystery that may require even more powerful accelerators such as the SSC to unravel.) However, the best current theoretical limits on the top quark's mass put it well within range of discovery by an upgraded Tevatron collider program at Fermilab, and much of the recent CDF effort has been aimed at optimizing the detector to insure that, if the top quark is within the expected mass range, then CDF will find it! However, it is paradoxical to note that if the top quark is not found at the Tevatron, that may create an even more exciting puzzle for our theorist friends to solve. In addition, CDF's plans include a wide range of physics exploration, ranging from precision tests of the electroweak theory to searches for exotic new particles. This article briefly describes the changes being made at CDF as well as physics opportunities that lie ahead.

The present CDF upgrade story began as an 11-month physics run with a fully operational CDF detector which ended in May 1989. During this run, the CDF detector, by every significant measure, met or exceeded its original design goals. The recent flood of CDF physics papers is a tribute to the many people who worked so hard to make the detector and the Tevatron collider work so well. But life goes on...and there are new challenges ahead. The CDF collaboration realized that to upgrade the detector while at the same time analyzing data from previous runs, the collaboration would have to grow. New institutions from the U.S., Japan and Italy have joined and CDF now includes 28 institutions and more than 275 collaborators. These people have their work cut out for them! The spectacular performance of the Tevatron collider as it delivered peak luminosities in excess of $2.0 \times 10^{30}$cm$^{-2}$ s$^{-1}$ during the 1989 run pushed the detector and its data acquisition system hard; it was clear that improvements were mandated for future runs.

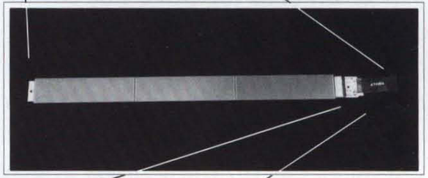
Many of the detector upgrades in progress are required for the detector to function efficiently at a luminosity an order of magnitude higher than its original design. One such upgrade is a new high-luminosity vertex tracking system (VTX) being built at Fermilab in collaboration with INFN (Instituto Nazionale di Fisica Nucleare), Frascati, and Duke University. Twenty-eight VTX modules are needed, along with 8600 channels of new low noise preamps and custom readout electronics connected to commercial TDCs. Similarly, new front end electronics for the CDF forward and plug gas calorimeters will allow the detector to trigger more rapidly. One hundred fifty new digitizer boards will allow event digitization and readout more than ten times faster than in the last run. Other improvements include a new event builder and a new, more powerful level III trigger processor farm. The level III trigger in 1991 will use much more sophisticated algorithms to obtain the required level of event rejection and will employ UNIX-based processors that will deliver more than an order of magnitude more computing power than those used in 1989. The level III upgrade is a collaborative effort of Rutgers, Tufts, and Fermilab.

Other upgrades are based upon our experience from analyzing existing data and our desire to improve the detector's basic physics measurement capabilities. One such improvement is the silicon microvertex detector (SVX). This device consists of four layers of silicon strip detectors surrounding a new 1.5-inch-diameter berylium beam pipe. The detector is expected to have an impact parameter resolution of 30 microns, which should allow the collection of a large sample of events with an unambiguously identified heavy flavor decay away from the primary vertex. This resolution is achieved by using microstrip detectors that have a 60-micron pitch on the innermost layers. The detectors are microbonded to a custom VLSI (Very Large Scale Integration) readout chip. The SVX system contains about 40,000 channels multiplexed out to a set of custom built memory modules located in FASTBUS. (The SVX is a collaborative effort of Fermilab, INFN/Pisa, LBL, and Johns Hopkins.) This device is expected be important in verifying the discovery of top and also gives CDF the ability to carry out a number of basic heavy quark measurements at the collider.

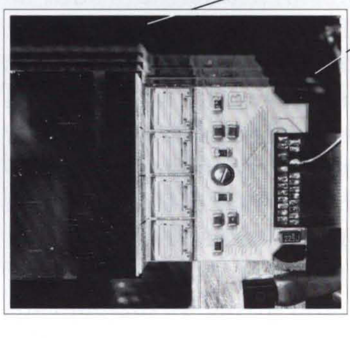
A significant upgrade to our muon system is in progress. Part of this upgrade is driven by the anticipated higher luminosities and part by the desire to increase the coverage of the system to provide better physics capabilities. The central muon system will be upgraded with additional steel walls to the north and south of the central detector. These walls require 630 tons of steel and 856 new muon chambers. These chambers and



*A mechanical model of a SVX detector awaits testing. The actual detector will fit around the beam pipe at CDF. Four layers of silicon "ladders" lining the barrel will track particle paths.*



*One of 96 silicon ladders shows the three silicon panels that observe particles.*



*A close up of the readout end of the SVX detector's test wedge. The four ladders (layers) pictured contain microscopic strips that detect particle activity.*

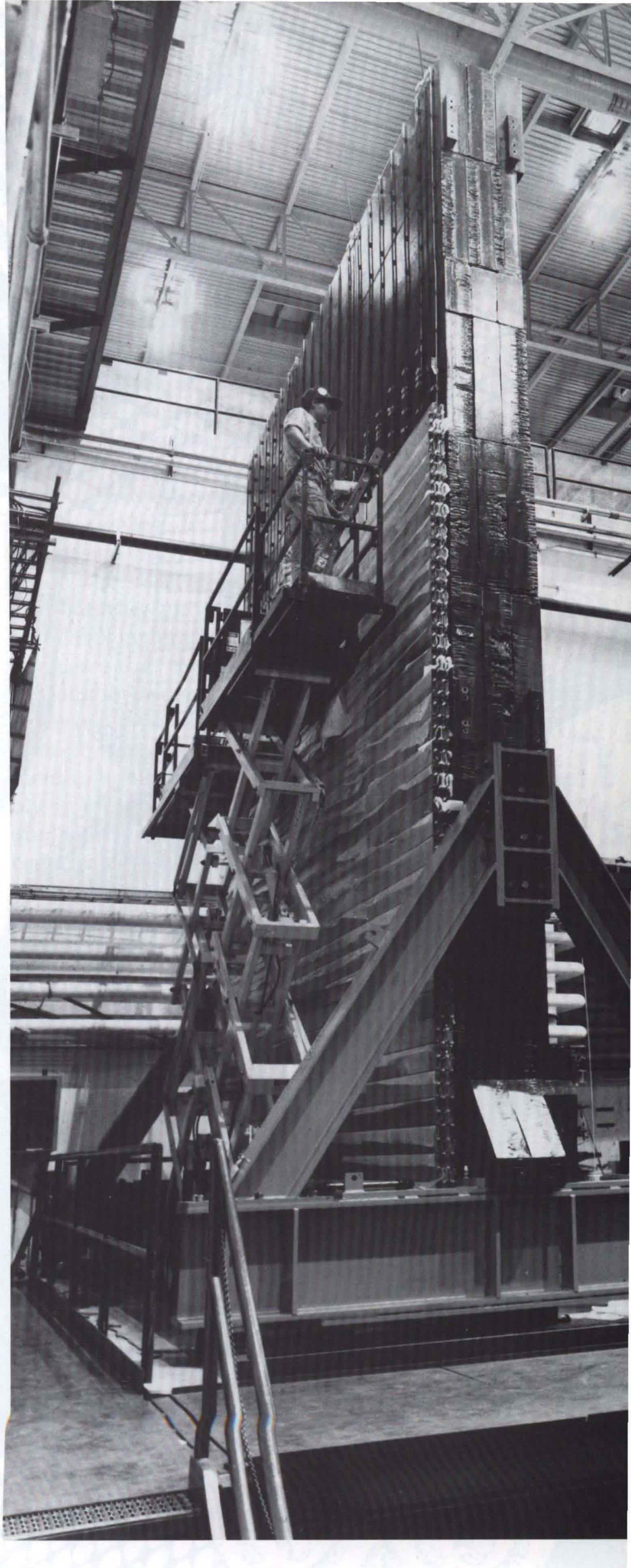
*(Left) From front to back, Technicians Ines Ramos, Deborah Quintero and Tamara Hawke in the IB4 Clean Room wire the individual VTX drift chamber modules.*

new trigger counters behind the steel walls and above and below the steel magnet flux return legs will be employed to stiffen the central muon trigger. In addition, 1,632 new chambers will be added to extend the central muon coverage beyond the present central system. The CDF muon upgrade is truly a worldwide effort, with chambers, electronics, trigger counters, and steel walls being made by CDF's Japanese and Italian collaborators, as well as by Harvard, the University of Illinois, and Fermilab.

Another new system adding physics capability to CDF will be the extension of the central electromagnetic calorimeter strip chamber system with an additional set of chambers between the solenoid and the existing calorimeter modules. These preradiator chambers will sit behind the 1.0 radiation length CDF coil/cryostat. They will be used to measure the rate of photon conversions in that material to measure prompt photon signals at large $p_t$. A total of 96 chambers (1,920 channels) are being built for CDF by our collaborators from Argonne, with help from the Fermilab Technical Support Section.

Lastly, CDF's computing resources are being upgraded. The online computing capability for the 1991 run will need to be quadrupled to allow more detailed online monitoring. In addition, off line resources available for production computing will be increased. What physics do we hope to accomplish with the improved CDF? The many possibilities include electroweak studies such as precision measurement of the W boson mass and weak mixing angle, searches for new heavy bosons, the discovery of the top quark or limits on its mass, study of b quark production and decay, studies of QCD, jet physics, direct photon production, high-$p_t$ W and Z production, the search for supersymetric particles and other exotic particles using missing $E_t$ information. The list goes on and on!

In summary, CDF has in progress a comprehensive program of upgrades for the next run. These are the first steps in a program of upgrades planned to take full advantage of the physics opportunities made available by the upgraded *Tevatron collider. Together, the machine and de*tector upgrades should yield exciting new results. Further improvements are planned to keep Fermilab at the technical and physics forefront of high energy hadron collider physics.



*(Above) A technician inspects the chamber installation of the Central Muon upgrade. The wall acts as an extra filter, allowing physicists to better detect and track muon activity.*

# Supporting Fermilab Research

## Technical Support Section

### Introduction

Frontier research in high energy physics depends on access to facilities to build specially designed components for accelerators, beam transport, and experiments. The Fermilab Technical Support Section was organized more than a decade ago to build over a thousand superconducting magnets required for the Tevatron. Later, a similar number of conventional magnets was built for the Antiproton Source for the collider and for the higher energy beam lines for the fixed target experimental areas. More recently, participation in the SSC magnet program included the design of the collider dipole cryostat, development of the dipole coil assembly with associated tooling, and the testing of completed magnets. Over the past several years Technical Support has also built numerous components for experiments.

There is a common thread in all these projects. The leading-edge technology needed to meet project requirements is not readily available in industry. Strong engineering design and development capability, as well as advanced fabrication resources, are needed to effectively confront these projects.

Projects undertaken by Technical Support typically require basic R&D, engineering design, materials development fabrication, and performance testing. In some cases the development and design originate elsewhere in the Laboratory or, in the case of experimental equipment, in collaborating universities. As a project's design and development advances, prototypes are made to ensure that the design and its fabrication are thoroughly understood. The subsystems are then analyzed to decide which parts are best made in industry and which, because of special requirements, should be made at Fermilab. Final assembly is often done at the Laboratory to control quality and precision crucial to performance. The connection to industry is strong from procurement of parts made in small local machine shops to the fabrication of major assemblies.


*The National Medal of Technology was presented by President Bush on October 18, 1989 to Helen Edwards, Richard Lundy, J. Richie Orr and Alvin Tollestrup. They were cited for their achievements in the design, construction and initial operation of the Tevatron.*

## Instrument Making for Research Design and Development

A strong research program uses instruments whose requirements usually approach or exceed the limits of existing engineering and fabrication capabilities. In designing superconducting magnets with increasingly higher fields, careful investigation of the conditions that establish stability at the corresponding higher force levels and conductor current densities is required. At Technical Support, physicists and engineers work together to develop the designs that will meet performance requirements.

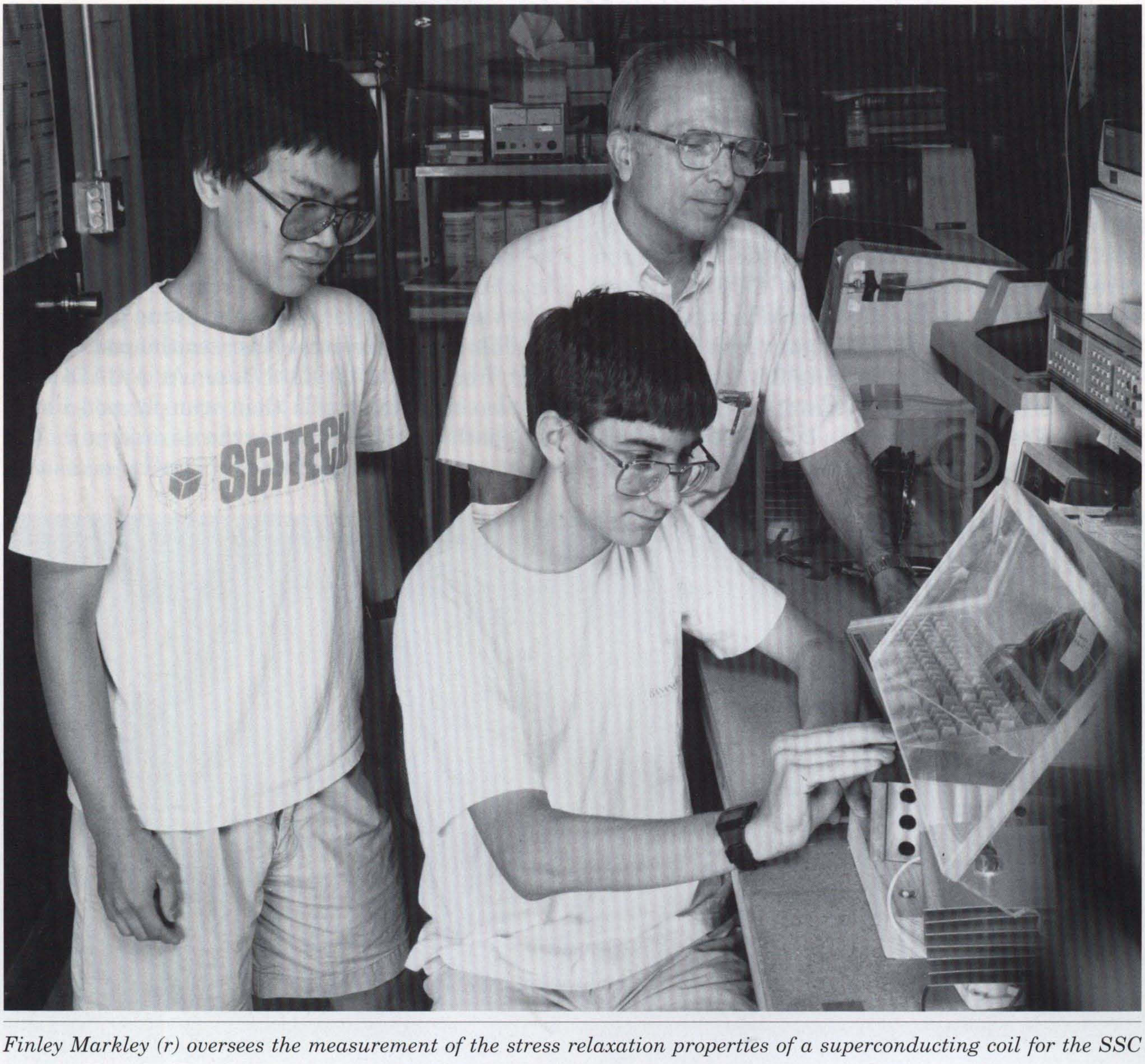
The Technical Support Engineering Group turns the design into drawings for fabrication using the latest CAD (computer-aided design) equipment. Current CAD tools include Sun work stations, VAX 3200 work stations, and other terminals tied to IDEAS CAD software on central computers. Structural integrity is verified using the finite element code ANSYS. The engineering effort is supported by the Engineering Laboratory where engineering designs are modeled and tested to assure the necessary performance.

*George Zielbauer, a designer in Technical Support, operates a CAD station to make a design for tooling fixtures used on the SSC project.*

## Learning and Teaching

Training in skills such as CAD, CAM (computer-aided manufacturing), quality assurance and safety are a continuing activity for Technical Support personnel. Technical Support has set up a CAD training facility that serves not only Technical Support but the rest of the Laboratory as well. The need for CAD/CAM qualified machinists has led to a revised training syllabus for apprentices which includes training in both programing and operating computer-controlled machine tools.

Technical Support is also deeply involved in the co-op, summer student, and teacher programs offered by the Laboratory. Of particular significance is the program in the Material Development Laboratory where about ten students work on individually tailored projects. They work on materials studies important to ongoing Technical Support projects and at the same time learn laboratory techniques. Participation in seminars, discussions and the preparation of a report of their work have given these students an excellent exposure to science as a career.




*Finley Markley (r) oversees the measurement of the stress relaxation properties of a superconducting coil for the SSC project. Choudet Khuon (l) and Laurent Stadler (foreground) were Fermilab summer employees in 1990.*

## Material Development Laboratory

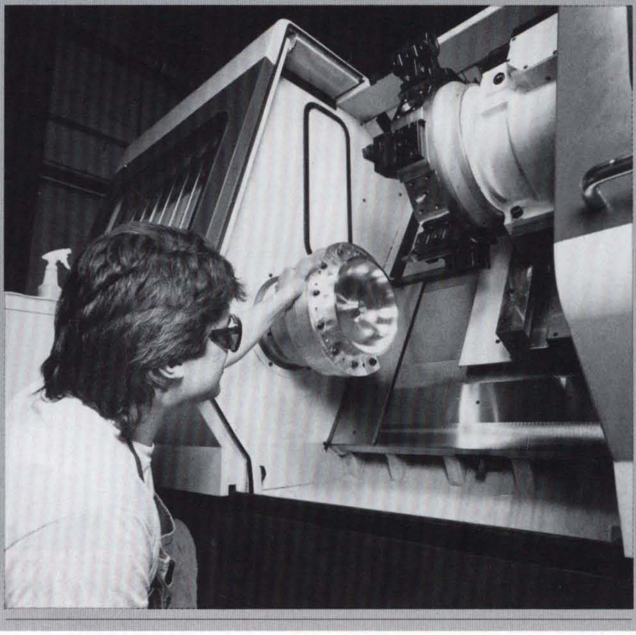
Understanding the properties of materials and how to improve them are crucial resources to design. The mechanical properties of material at low temperature, for example, are important to modeling the performance of superconducting magnet coils. Magnet cryostats require special composites tailored to the requirements of high strength and low thermal conductivity. Insulation systems for magnets must be thin and strong to protect against puncture and dielectric breakdown. Leak-tight chambers for particle detectors often require custom adhesives.

Such problems are the province of the Material Development Laboratory. Equipment in this laboratory includes a state-of-the-art tensile testing machine (to 4.2 K), metallographic sample preparation equipment, and injection molding equipment. The Materials Lab can prepare a variety of epoxies and adhesives.

## Fermilab Machine Shops

Instruments used in research at Fermilab often demand parts that are difficult to make. A new Linac is being built at Fermilab whose accelerating cavities require surfaces machined to tolerances of tenths of thousandths of an inch. An extremely precise, very thin support resembling a spider web is needed to hold the delicate silicon vertex detectors at the heart of CDF. End spacers of complex shapes are needed to support end turns of superconducting magnet coils.

Meeting such challenging fabrication tasks keeps Fermilab at the forefront of scientific research. The Laboratory has one of the most advanced computer-aided design machining and inspection facilities of its kind. Over the past six years the machine shop has acquired eight CNC (Computer Numerical Control) machine tools, including two turning centers, three machining centers, two mills, a horizontal boring mill and an electrical-discharge machining system. Twenty-seven Fermilab machinists are trained in CNC machining. Five can both program and operate the machines. In the CNC machining process the machinist/programmer accesses the part "drawing" from the CAD data base. At a CAD work station the drawing is then transformed into a tool path that will produce the desired part. The tool path is then translated by a post processor to



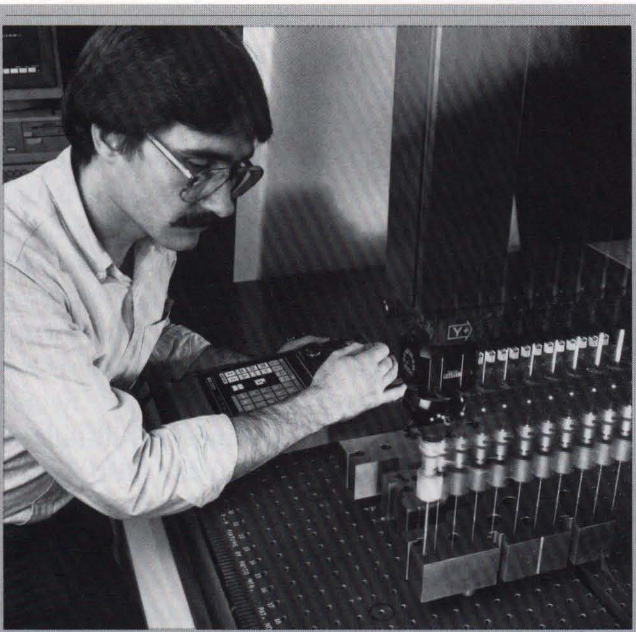
the sequence of instructions understood by a particular machine. Finally the program is transferred to the CNC machine via floppy disk. Although computer controlled machines can easily do repetitive production jobs, they can also draw on a library of programs of parts.

Perhaps the most difficult part of the programming of these machines is transferring the drawing from the CAD image to machine instructions. The software available is still rather new, the CAD tool path and post processors are not well integrated, and different machine tool controls follow different instruction protocols. The success in CNC machining at Fermilab derives from its access to the computer and software-intensive environment of the Laboratory.

The Fermilab shops are intended to service the special needs of the Laboratory that cannot readily be met by outside shops. The shops must also make sure machinists are available on short notice to physicists and engineers to allow rapid fabrication of crucial parts. In order to ensure timely access to the shops, a large burden of shop work is assumed by the shop task order operation under the Technical Support Material Control Group. The task order operation has over 70 shops under contract to respond within 24 hours to fabrication orders. These shops cover specialities from sheet metal work to CNC machining. The task order operation has allowed rapid turn around on a wide variety of fabricated parts. Often, once machining techniques are developed in the Fermilab shops, jobs are transferred to these outside shops.

## Inspection

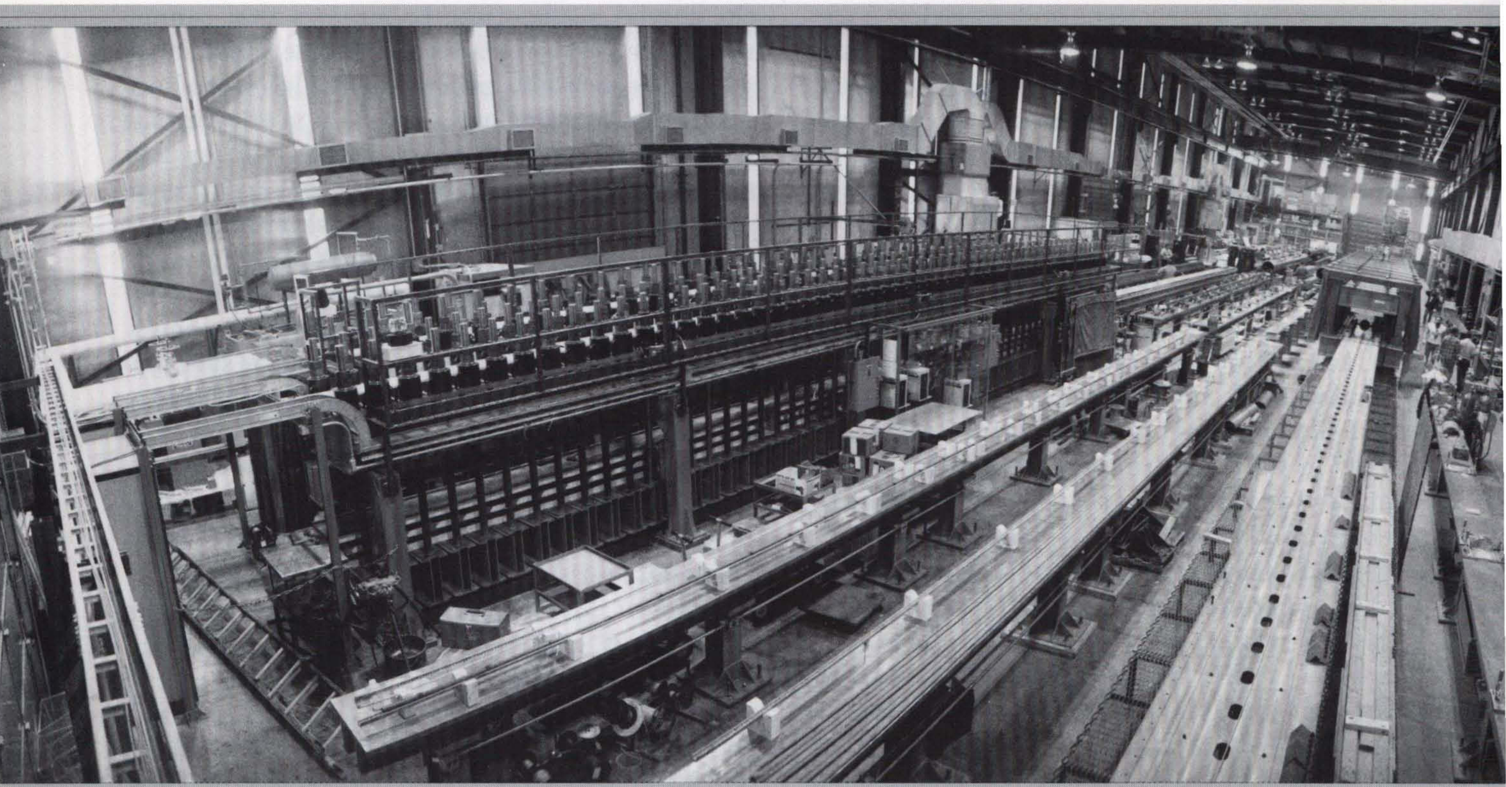
A key part of any project is the supply of quality parts: parts that are correct and ready to assemble. The schedule and cost of a project typically suffer most from delays in parts flow. During the Tevatron construction period Technical Support built up a quality control laboratory for incoming parts inspection. The capabilities of this laboratory have grown with Fermilab. In addition to a large collection of small measurement tools, the lab has one manual coordinate measuring machine (CORDAX), one computer-controlled contour projector measuring machine, and a computer-controlled CORDAX. The job of the Quality Control Inspection Laboratory is to make sure that the part meets the dimensions and requirements specified on the drawing. In the case of CNC machining the part must be compared with its CAD image. The complex shapes



*(Left) Ray Meisner of Technical Support's Machine Shop tests the DC circuitry of a lathe.*

*(Center) Charles Matthews of Technical Support Section machines a Linac cavity as part of the Linac upgrade.*

*(Right) Technician Robert Riley measures winding and curing tooling for the SSC 50-millimeter dipole magnets on the Cordax machine.*



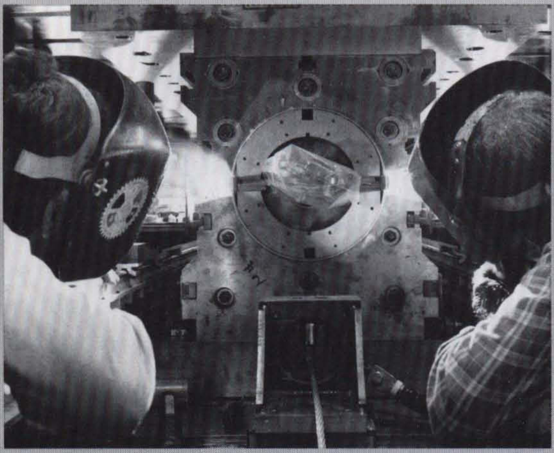
that are typically made via CAD/CAM require that the part image be fed to a computer-controlled inspection device (usually a CORDAX) to accomplish the comparison.

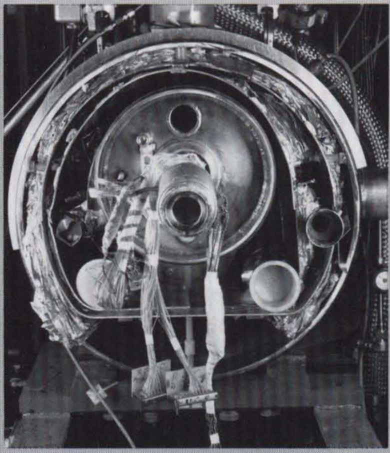
The steps from concept to finished part may be illustrated by the recent task of making end spacers for superconducting magnet coils for the SSC collider dipoles. The topologies of the conductors around the end of a superconducting magnet coil are vitally important to both the stability and the quality of the magnetic field. The end geometry is devised by determining analytically the minimum-stress trajectory of the cables around the magnet end that are consistent with a uniform dipole field. The output of these computer codes is fed to the CAD system, where drawings of the ends are produced. The drawings are accessed from the drawing data base by the tool path software at the machine shop. The resulting tool path is translated to machine instructions and transferred to the machine tool. When the part is finished, it is sent to the Inspection Laboratory where the CORDAX, again with access to the original CAD drawing, verifies the quality of the part. Once the machining processes have been proven in the shop, the CAD drawings – or sometimes the tool paths – are taken to outside CNC shops. The finished parts are measured in the Inspection Lab to complete the sequence.

## Major Projects

During the past year three major projects were under way in Technical Support: the SSC dipole development program, the low-beta quadrupole magnet program, and the start of the Main Injector program.

Fermilab has been involved in the development of the SSC collider dipole, the dipole cryostat, and production-style tooling for full-length (17m) magnets. In March 1990 the SSC Laboratory decided to increase the magnet aperture from 4 cm to 5 cm. Our new task was to redesign the magnet coil assembly, the cryostat, and the associated tooling accordingly. The objective was to have a short model magnet completed by De-





*(Left) The Industrial Center Building contains presses for coil molding, collar keying, and for assembling and welding the helium containment vessels.*

*(Center Left) Betty Phillips loads a wound and packaged superconducting coil in preparation for coil curing in the Industrial Central Building.*

*(Center Right) Michael Reynolds (l) and John Jones (r) of Technical Support weld the two half shells of an SSC dipole magnet together.*

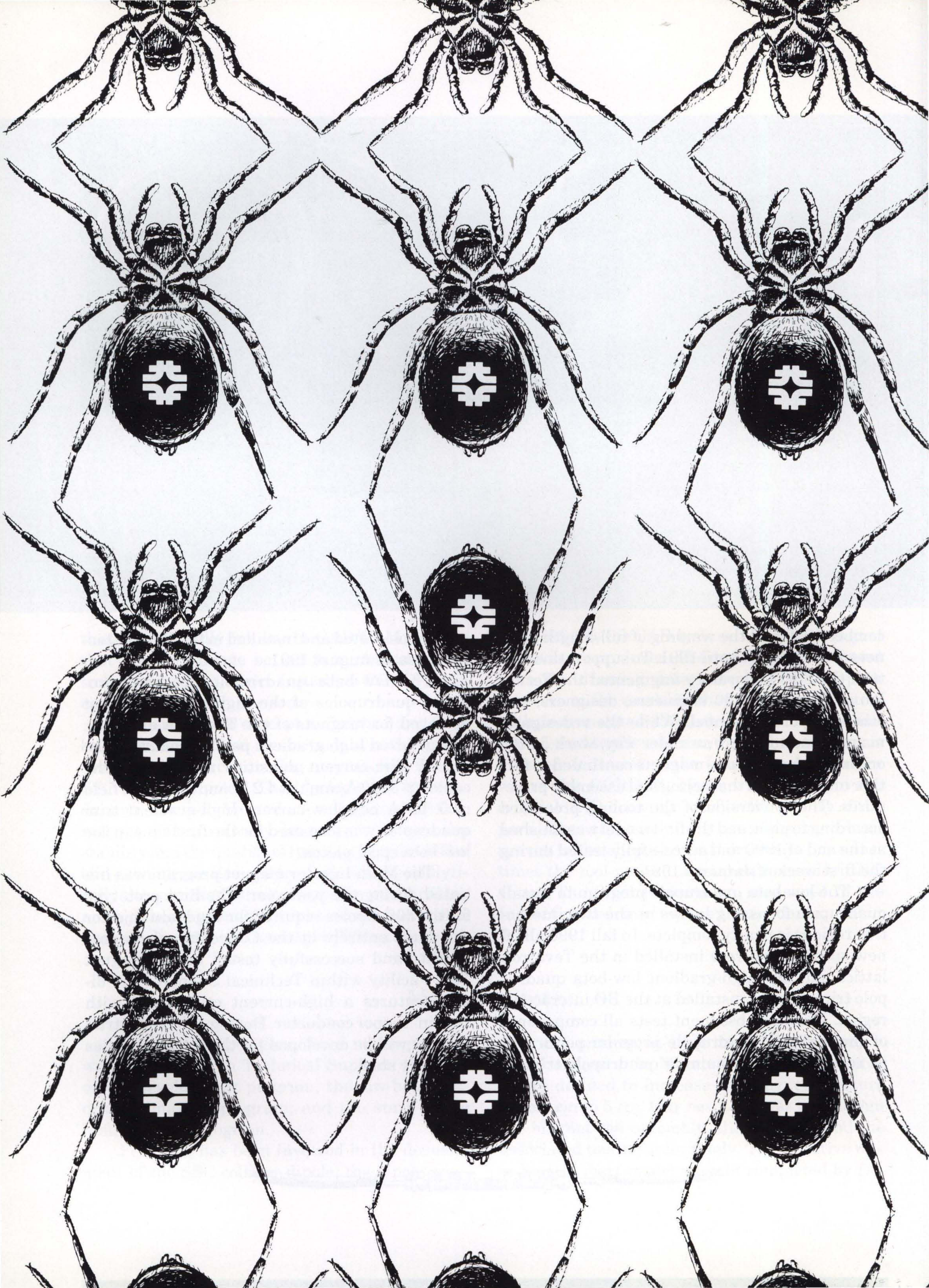
*(Right) End view of the stand-4 turnaround can at the Magnet Test Facility shows the connections which join the can to an SSC test magnet for testing to as low as 3.5 K.*

cember 1990 and the winding of full-length magnets under way by April 1991. To support this new task the SSC Laboratory augmented the Fermilab staff by about 30 engineers, designers, and other support personnel. While the redesign of magnet and tooling was under way, work on the original 4-cm aperture magnets continued to further improve both the tooling and assembly procedures. The conversion of the tooling proceeded according to plan, and the first model was finished at the end of 1990 and successfully tested during the first week of January 1991.

The low-beta quadrupole program to install quadrupole focussing lenses at the two interaction regions is nearly complete. In fall 1990 all 26 new spool pieces were installed in the Tevatron lattice and two high-gradient low-beta quadrupole triplets were installed at the BØ interaction region. During subsequent tests all components of the low-beta quadrupole program performed as required. The remaining quadrupole triplets will be completed and installed in the DØ interaction area in August 1991.

The low-beta quadrupole program produced quadrupoles of the highest gradient yet achieved for magnets of the Tevatron aperture. We achieved high gradient partly because of the record high-current densities achieved in the cables (> 3000 A/mm$^2$, at 4.2 K, and magnetic field of 5 T). A new low-current high-gradient trim quadrupole was also used for the first time in the low-beta spool pieces.

The Main Injector magnet program was initiated during the past year. The first prototype for the 300 dipoles required for the Main Injector was built entirely in the Conventional Magnet Facility and successfully tested in the Magnet Test Facility within Technical Support. The dipole features a high-current coil wound with $1 \times 4$ in$^2$ copper conductor. During 1991 industrial sources will be developed for the coil assemblies and yoke steel.



# Computing Division

## Introduction

High energy physics often involves large experimental collaborations of hundreds of researchers whose home institutions can span the globe. Data collected in a large experiment sometimes amounts to tens of terabytes ($10^{12}$ bytes) per year, which must be reconstructed, analyzed, and published. Researchers need to work collaboratively to develop designs for these experiments, develop the software for taking and analyzing data, examine the data, hold technical meetings, and write papers disseminating their discoveries.

Computer networks are one way in which the challenge of tying together far-flung collaborations has been met. High energy physics laboratories have long taken a leading role in providing computer networks, beginning with the first links between laboratories installed over a decade ago. Since then, computer networks have played an increasingly important and integral role in high energy physics research.

Computer networks and, more recently, remote conferencing are helping to reduce the time and money spent on travel. Electronic mail is used widely in many ways: as a means of avoiding telephone tag; as a faster and more reliable alternative to paper mail; and, most significantly, as a general forum for discussion of ideas. Computer networks also allow transfer or sharing of files containing data or programs and enable computers at remote locations to be used. More recently, the costs of video and other forms of remote conferencing have dramatically declined. An experimental project has demonstrated that video conferences among collaborators at Fermilab, SSC, and LBL can be an effective aid to research. Plans are under way to expand this capability to include other laboratories and universities.

## Future Computing and Networking

The diversity of computers, operating systems, and networks of collaborators from different institutions poses impediments to getting work done. Moreover, networking, computing technology, and the ways of doing computing over networks are evolving rapidly. An experimental collaboration, which often lasts for years, may see several generations of networking or computing paradigms.

Packet-switched wide-area and local-area networks are providing ever-increasing connectivity and data rates and helping standardize interoperability among dissimilar computing systems. At Fermilab, Ethernet local area networks will be supplemented by fiber-optic interconnections based on the Fiber-Distributed Data Interface (FDDI) standard, which provides an order-of-magnitude increase in data rate. Wide-area networks like HEPnet and ESnet are able to take advantage of new telephone company offerings that provide very significant increases in performance at reasonable cost. Costly, dedicated direct links are being replaced by lower-cost shared regional and nation-wide networks, often with increased performance.

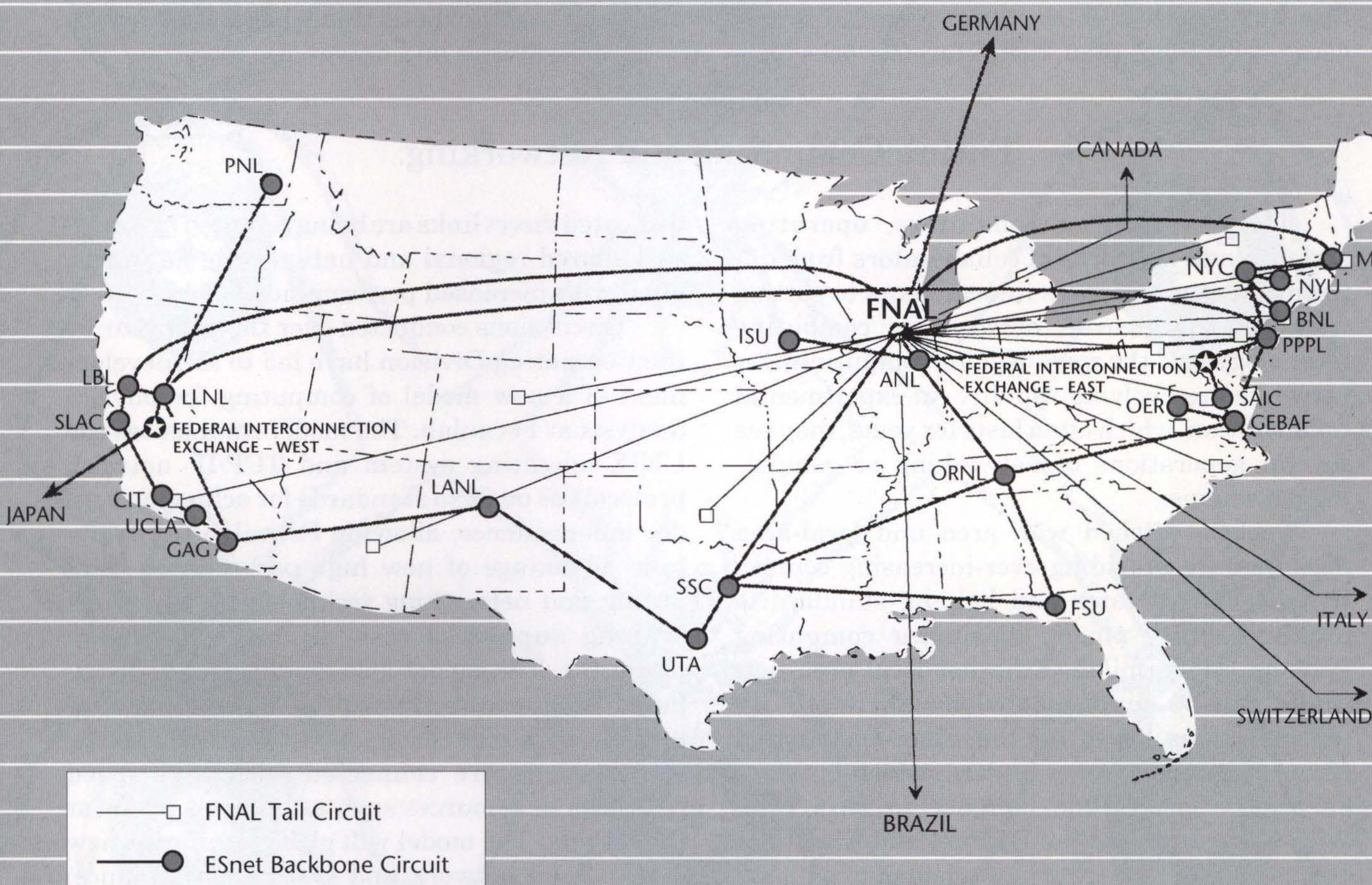
Discussions conducted over the past year by the Computing Division have led to the development of a new model of computing for physics analysis at Fermilab. The model emphasizes the UNIX operating system and TCP/IP network protocols as de facto standards for achieving vendor independence, allowing Fermilab to rapidly take advantage of new high-performance computing and networking technologies, while leveraging support across different hardware platforms. The model also emphasizes a distributed architecture, known as workgroup computing, in which local clusters of physicists' workstations are connected with high-speed networks to resources such as analysis farms or file servers. The model will place significant new demands on network and system performance, support requirements, and application and system software design.

# National HEPnet Management

Planners trying to coordinate efficient data communication among all of the numerous research programs of DOE's Office of Energy Research have, since 1987, struggled to create order in a world where chaos has heretofore existed. The random growth of networks in the HEP community, driven by the escalating needs of individual research groups and collaborations, had reached a critical state where communication problems attendant to dissimilar networks, computers and paradigms had to be corrected. In September 1990, the U.S. Department of Energy's HEP Networking Committee formed the National HEPnet Management organization to address these concerns.

Headquartered at Fermilab, HEPnet Management seeks to implement orderly migration from dedicated communication facilities to shared networks, a shared network information center specifically for the high energy and nuclear physics communities, and a methodology for modeling the communities' needs both in terms of shared network migration and for developing future networks.

While HEPnet Management is primarily interested in studying methods by which dissimilar computer systems interoperate across national networks, the urgency to communicate between HEP laboratories and research institutions around the world has made international networking a necessity. The task of applying future networking paradigms to national and international experimental collaborations lies on the immediate horizon.



## Future

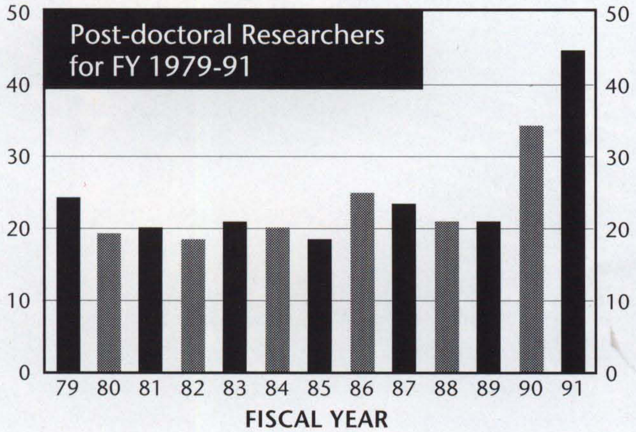
Technology and need are forcing moves toward networking and distributed computing approaches that will entirely transform computer interconnection before the end of the decade. Proprietary computer architectures are rapidly disappearing along with the tight linkages between computing and networking that couple a vendor's computer systems and applications to their own proprietary networks. Replacing them will be multivendor, multiprotocol "networks of networks" with global reach that will meet a broad spectrum of user requirements and applications to which almost all vendors will adhere.

Bit rates are increasing and costs are decreasing. Local area networks (LANs), such as Ethernet that currently run at 10 Mbps (million bytes per second), will gradually be replaced by FDDI running at 100 Mbps and spanning much larger distances. By the end of the decade, FDDI will begin to be replaced with LANs having bit rates of a gigabit per second or more. Wide-area network links that are now moving from 56 kbps to 1.5 Mbps will move, by the decade's end, to 44 Mbps or more at little or no increase in cost. Moreover, these bit rates, which are dedicated now, will be available on an on demand basis, thus reducing the cost even more. Delays across all these networks will decrease to the point where the limiting factor in many cases will be the speed of light.

# The Fermilab Physics Department

The Physics Department supports Fermilab staff physicists in their research efforts. During 1990, we had major responsibilities for construction and installation of detectors in nearly all the experiments scheduled for the 1990-91 fixed target run as well as major efforts for the two large collider experiments. In reviewing the year's activity, connections to other efforts at the Laboratory and around the world become apparent. These connections appear in the realm of physics, as one would expect, but also in many service and cultural areas as well.

One of the most significant developments of the year was the increase in the number of research associates and fellows (post-doctoral researchers). Part of the reason for the increase was the first Lederman Fellow. The fellowship, named in honor of Director Emeritus Leon Lederman, is awarded to new experimental researchers who also show a talent for science education. In addition to the first Lederman Fellow, Vaia Papadimitriou, there is a continuation of the tradition of excellence in new Wilson Fellows, who are, in general, more senior than Lederman fellows. The total number of post-doctoral researchers in the Department now stands at 45. It was only in the low 20s for nearly all of the 1980s.




A second significant development was the completion of scanning and measuring of all the film assigned to Fermilab as part of the bubble chamber and streamer chamber experiments at the Laboratory. Following this work, the Film Analysis Facility (FAF) was decommissioned. The dedicated staff have all been reassigned, receiving training for new careers as data aides and technicians, and in computing support roles. The FAF equipment has been disassembled and scavenged for useful parts.

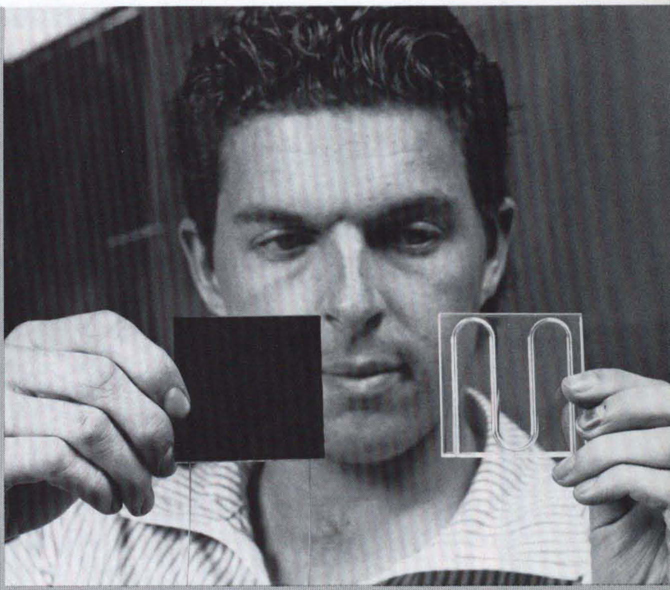
Among the more traditional activities in the Department, we have expanded the clusters of computers provided for researchers. There is now a cluster of VAX computers (18 stations totalling 43 MIPS with 17 Gbyte of disk storage), a cluster of UNIX workstations (three stations totalling 85

MIPS (million instructions per second) with 9 Gbytes of disk) and a cluster of Macintoshes (15 stations). Each is supported by a local system manager and shared hardware support. Additional support is provided by the Computing Division. These clusters are dedicated to hands-on computing with user mounting of data sets on 8 mm cassettes, providing a useful adjunct to the large batch-processing capability supplied by the Laboratory in the Feynman Computing Center.

Also continuing a tradition of technical prowess is the large variety of specific projects for experiments and research and development efforts. In 1990, these included silicon microstrip systems, Cerenkov counters, pad/wire chambers, xenon and other gas systems as well as the more traditional scintillation counters, photomultiplier bases, and custom electronics boards. A major new involvement has been in the assembly of prototype calorimeters made of exotic new materials and concepts: tiles with fiber readout and scintillating fiber-based "spaghetti" calorimeters. There is also an effort in support of using scintillating fibers for tracking systems. Here the Department has focussed on the readout problems. Another new technology receiving Department support is a neural network project for developing experiment triggers, the first being implemented with the CDF collaboration. Some of the projects of earlier years have become so popular that they have been adopted for support by the electronics pool (PREP) of the Computing Division. The Department has manufactured dozens of visual scalers, prescalers, and level converters for PREP during the year.

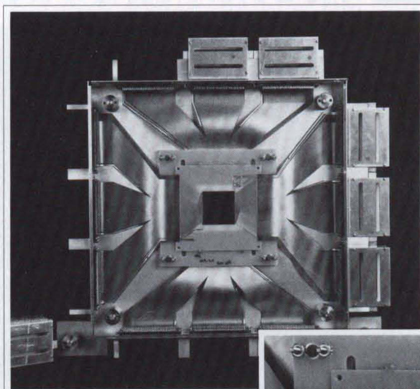
As part of our service to the research community, the Physics Department sponsors the Wednesday Colloquium, organizes academic lectures for graduate students and research associates, and hosts a monthly dinner to bring together the many research associates in experimental particle physics, theoretical physics, astrophysics, and accelerator physics. The Department is also now the organizer of large conferences sponsored by Fermilab.

*(Opposite) Technician Harvey Bruch assembles part of the copper-clad G-10 boards used in E771's pad chamber. This is a combination of a conventional chamber and a supplier of signals for the trigger processor, acting as a detector.*

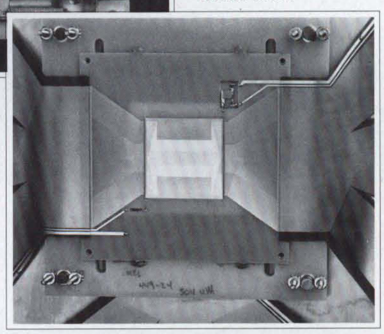


*(Above) Drafter Daniel Bart of the Physics Section holds two scintillation tiles, the one on the left wrapped and the one on the right showing its wavelength shifting fibers inside.*

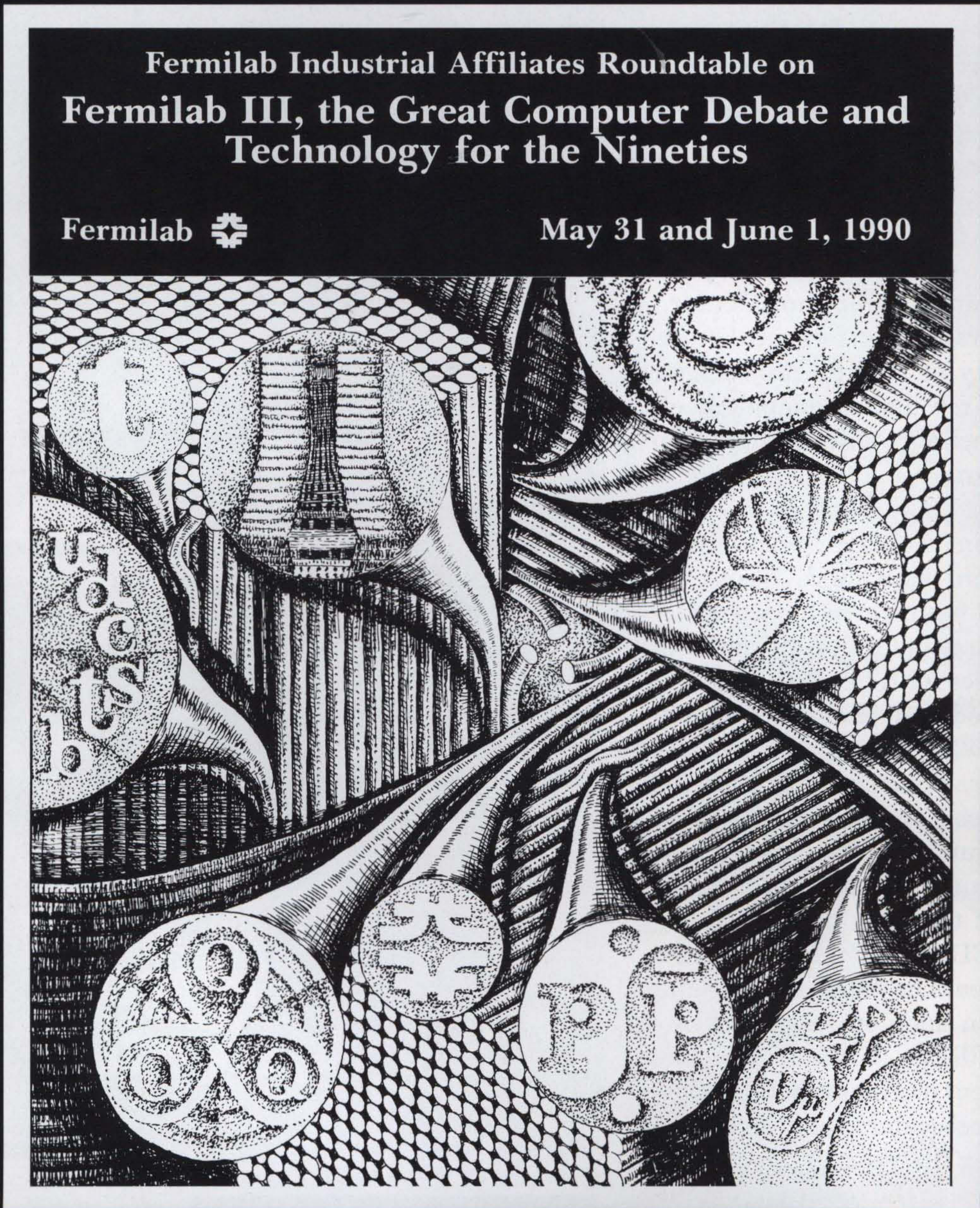
*(Right) Technician Eileen Hahn injects epoxy into scintillation tile to hold wavelength shifting fibers.*



*An amplifier sits apart from a silicon strip microvertex detector (SMD). The SMD detects charm and bottom particles as well as mesons and hadrons.*



*25 micron silicon strips radiate outward to amplifiers from the active region of the SMD.*




*Brig Williams of the University of Pennsylvania addresses the annual Fermilab Industrial Affiliates meeting held in May. The meeting's theme was "Fermilab in the Nineties" and his presentation centered on electronics for future colliders and the need for industrial involvement.*

# Technology Transfer, the Ultimate in Connections

"Technology transfer!" These are words to brighten men's souls and make America competitive again. In this glowing picture great networks link industry, universities, and government laboratories in a vast exchange of problems and solutions.

Here at Fermilab, technology transfer has taken on real meaning. Like the man who discovered he could speak in prose, Fermilab entered into technology transfer long before we knew the meaning of the words. Superconducting wire developed for the Tevatron became a cornerstone of the greatest business opportunity to emerge out of Department of Energy work, the billion-dollar-a-year magnetic resonance imaging industry. The same wire is the technological springboard for the SSC. In 1990 the Loma Linda University Medical Center Proton Synchrotron, designed and built by Fermilab, treated its first patients. In years to come, thousands of patients will use the machine. Patented cerium fluoride technology developed for particle physics detectors here may one day emerge as an important adjunct for positron emission tomography.

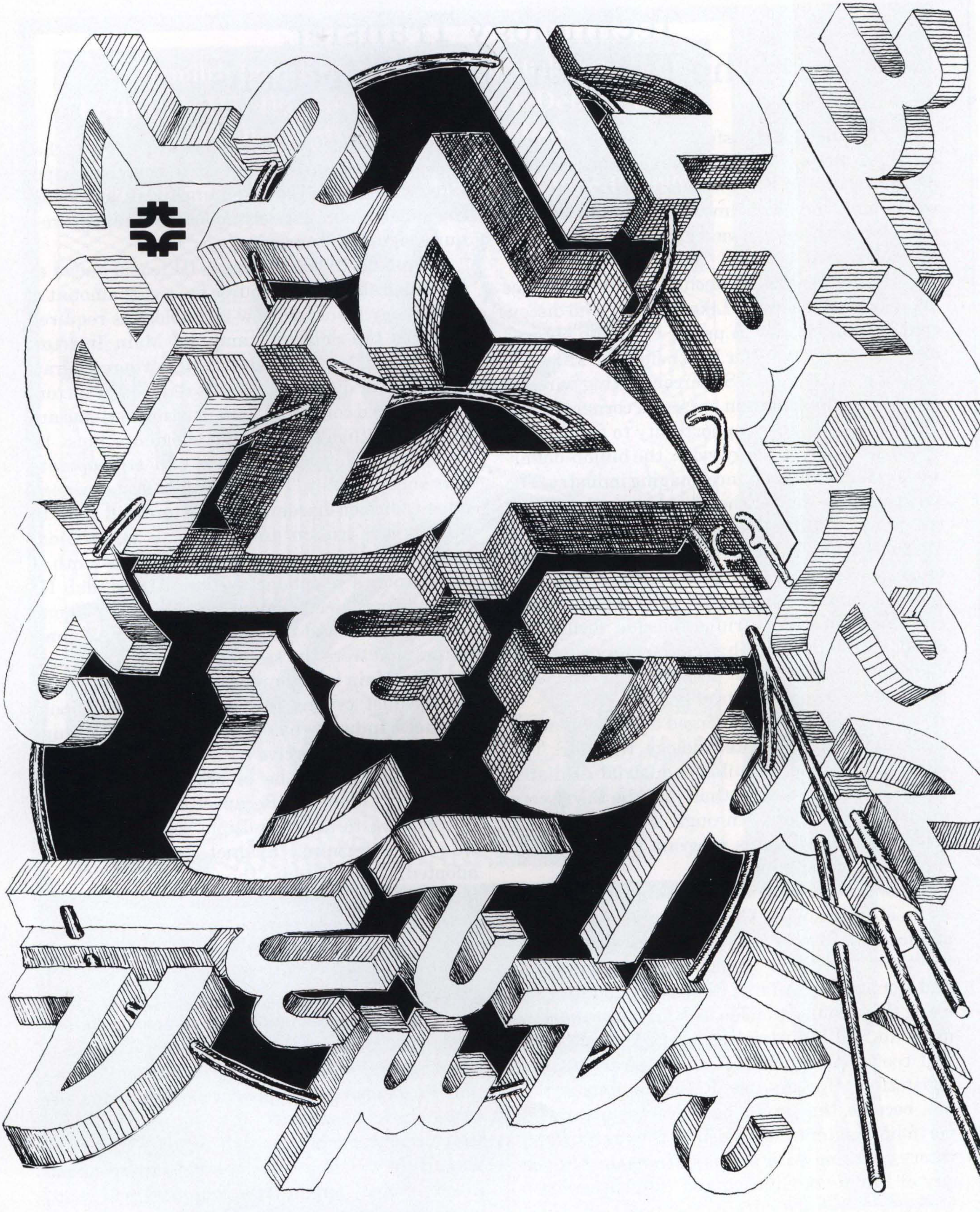
The Laboratory has forged a powerful net of connections to foster technology transfer. The centerpiece is the Fermilab Industrial Affiliates which has become more than just the thirty core industrial members. Through newsletters and meetings, the Affiliates program reaches out to thousands of companies.

Connections are also stimulated by a network of Technology Centers at Fermilab, Argonne, and Illinois universities established by the State of Illinois Department of Commerce and Community Affairs. Now the Laboratory is using these connections to look for more opportunities to find industrial partners for exchanges and cooperative R&D. Through recent federal legislation, Universities Research Association has become the proud possessor of a growing portfolio of patents. A licensing office at the Laboratory, working with students from the University of Illinois at Chicago and Northern Illinois University, markets these technologies. Three licenses are now in place. Hints are building that some may be important. A small company populated with former Fermilab employees is developing superconducting technology that may have a quite significant market.

For the 1990s, Fermilab III looms ahead as the Laboratory's next source for a vast amount of technology transfer. New technology is required for both the detectors and the Main Injector. High-speed, low-noise electronic systems operating at power dissipation levels reduced by factors of a hundred compared with existing systems are needed. Millions of detector elements must be crammed into a small space and still operate extremely reliably. The electronics systems need to be radiation-hardened. Detectors will have to process one trillion analog signals per second, roughly equivalent to the capacity of one-tenth of the country's telephone system. A Fermilab III detector may need computing equivalent to one hundred thousand to a million of the VAX computers that were the standard several years ago.

The Main Injector requires high quality steel for the fast cycling, extremely uniform dipole magnets. Industry has already been able to supply steel with a coercive force of 0.6 oersted. The next challenge will be to provide hundreds of tons of this material. Because the Main Injector is called on to serve multiple roles, a sophisticated four-terminal magnet design has been adopted, which doubles the voltage between adjacent wire turns in the magnet wires, making new demands on magnet insulation. Other technical challenges for the Main Injector include radio frequency power and exploiting new advances in beam monitors.

All of these technologies are needed. Industrial experience and cooperation should be able to help. Several of these Fermilab III technologies may find important applications outside physics research. Just as important, experience indicates that other technologies will develop along the way. If they yield as much as the superconducting technology for the Tevatron, they will easily offset the entire cost of the Main Injector project.



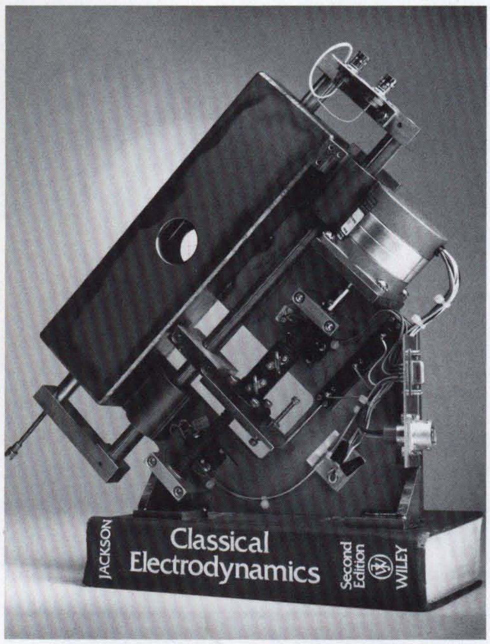
# Fermilab III: Building for the Future

## The Fermilab Linac Upgrade

The Fermilab linear accelerator (Linac), conceived 21 years ago, produced its first 200-MeV beam of accelerated protons on November 30, 1970, and has run without major interruption since. Greater demands have steadily been placed on it by the added complexity of the downstream chain of accelerators and by the increased patient load of the Neutron Therapy Facility. The major improvements during the last 20 years have been the conversion from the acceleration of protons to the acceleration of negative hydrogen ions, a new control system, and replacement of the radio-frequency control monitoring system. Minor improvements have resulted in an increase in reliability; during 1990 the Linac ran reliably 99% of the time. However, as gratifying as the record may seem, the technology has advanced in the last 20 years to the point where the performance could be vastly improved to the benefit of all systems downstream of the Linac.

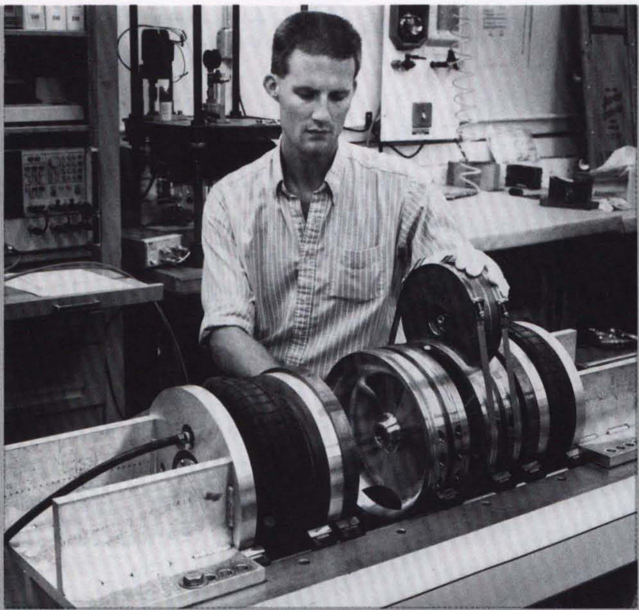
An upgrade of the Linac was approved by Congress in 1989, and accelerator fabrication reached peak production by the end of 1990. The plan of the upgrade is to replace the last four drift-tube tanks (total 60 meters long) of the nine in the present Linac with seven new accelerating modules operating at a higher frequency and higher accelerating fields so as to double the final beam energy from 200 MeV to 400 MeV. The new accelerator will be installed adjacent to the old Linac tanks as the new modules are completed and operated without beam until final conversion to 400 MeV. Some modifications will be required in the injection line to the Booster to accommodate the higher energy. The radio frequency power to drive the new accelerator modules will be supplied by seven 12 MW, 805 MHz klystrons. An expansion of the Linac gallery, completed in December 1990, will allow the installation of these systems without disruption of the presently operating Linac radio frequency systems. The higher Linac energy will reduce the tune spread due to beam space-charge forces at injection in the Booster, thereby improving the ratio of the total number of particles in the accelerator (N) to the normalized transverse emittance ($\varepsilon$). At 400 MeV this ratio, $N/\varepsilon$, should be increased by 75% compared with the ratio at 200 MeV.

The accelerator structure for the Linac upgrade is the side-coupled cavity structure originally used on the Los Alamos Meson Physics Facility (LAMPF) Linac 20 years ago. The basic fabrication unit for the new Linac is a set of coupled resonant cavities brazed together into a 16-cavity section. Four such sections are connected in a series to form an accelerator module, which is then powered by one klystron. Charged particles passing through the beam hole are accelerated across the voltage gap in each cavity. There will be a total of 448 cavities in the new Linac, each providing an energy gain of about 600 KeV. The past year saw eight of the 28 accelerator sections needed for the new Linac successfully fabricated. Four of these sections were fabricated as prototypes earlier in 1990 but are now intended to be used in the new Linac in the first of seven accelerator modules. All accelerator sections are brazed together in hydrogen furnaces (1800°F) at the industrial firm of Pyromet in San Carlos, California. Copper for the accelerator cavities is supplied by Hitachi Industries, Japan.

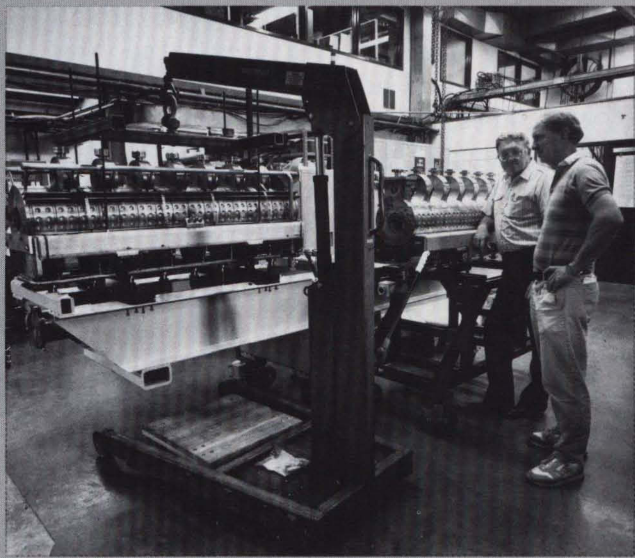



*A textbook gives scale to a wire scanner used to measure beam emittance in the new Linac.*

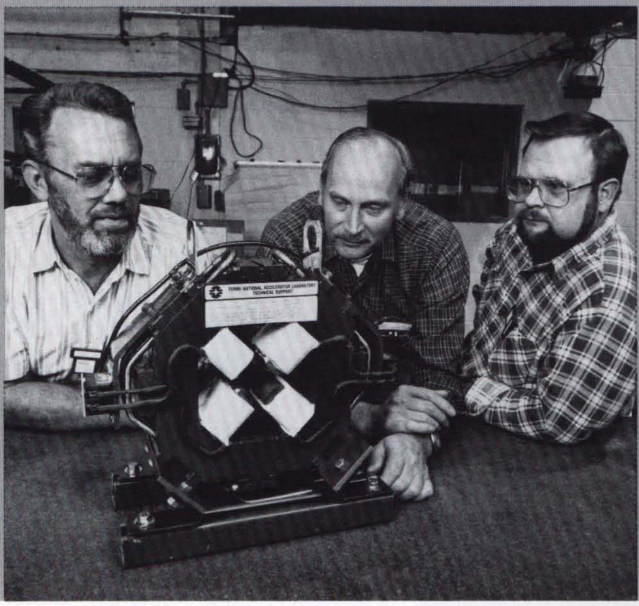
Because of the high electric fields in the new Linac



(Top Left) *Technician Raymond Ryan measures the resonant frequency of side coupled cavities in a 64-cell accelerating module for the Linac upgrade.*



*(Above) Mechanical Engineer Michael May (r) and RF Electrical Engineer William Miller (l) watch one of the accelerating modules as it is prepared for mounting on a girder in preparation for power testing.*



*(Bottom Left) From left to right, Shift Leader Gene Underwood, Associate Engineer James Humbert and Draftsman James Jablonski inspect a prototype quadrupole magnet for use in the Linac upgrade.*

(7.5 MV/m), two of the prototype 16-cavity sections have been separately voltage conditioned to test sparking and x-ray production. Both sections indicate that after about 20 million radio-frequency pulses, the sparking rate extrapolated to a full Linac will be less than one spark per thousand radio-frequency pulses. Continued voltage conditioning leads to a steady reduction in sparking. The production of x-rays is about one-hundred times more than the existing Linac but too low to cause any component damage over the projected lifetime of the new Linac.

Each of the seven accelerator modules will be powered by a 12 MW (peak power) klystron to be supplied by Litton Electron Devices. The prototype klystron is one year behind schedule having suffered two failures common to new tubes: a cathode failure and a high-voltage ceramic insulator failure. The expectation of such difficulties was one reason that the prototype development was started early in 1988. Design improvements have been completed and the prototype is scheduled for delivery in January 1991. Also scheduled for 1991 are the delivery of production klystrons and the power testing of the Prototype R accelerator.

*(Opposite) New wave guide penetration (horizontal black pipe) feeds into cement casings (vertical blocks) enroute to the dirt mound (far left) covering the Linac tunnel.*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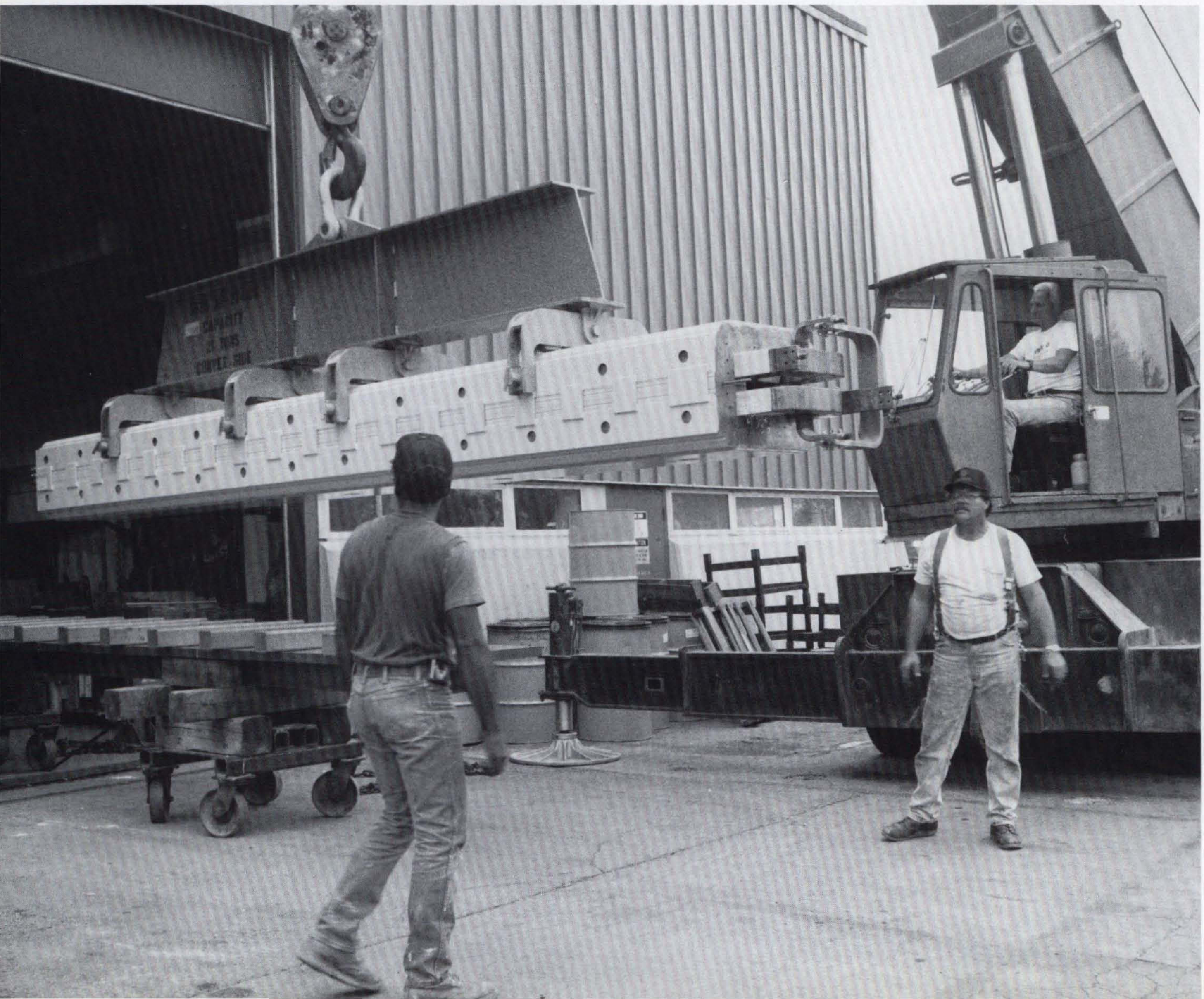
# The Fermilab Main Injector

The Fermilab Main Injector is the centerpiece of the Fermilab III initiative. Specifically, this new accelerator is designed to support a luminosity in excess of $5x10^{31}cm^{-2}sec^{-1}$ in the Tevatron antiproton-proton collider. The concept of the Main Injector has been developed over the last two years. A Conceptual Design Report was prepared and submitted to the U.S. Department of Energy in January 1990, accompanied by a request for a Fiscal Year 1992 construction start. The total project cost is estimated at $194 million. Fermilab has proposed to complete the project over a 38 month period starting in October 1991. Construction will require a seven month disruption to the Fermilab high energy physics program starting in April 1994.

The Main Injector is specifically designed to carry out, in a much more efficient manner, the support functions currently being provided by the Main Ring — the original 400 GeV Fermilab accelerator. Through the 1970s the Main Ring was the primary high energy physics accelerator at Fermilab. However, with the construction of the Tevatron during the early 1980s, the Main Ring was reconfigured in order to provide support for the Tevatron-based collider and fixed target programs. This reconfiguration included the addition of vertical overpasses around the BØ and DØ interaction regions, and the addition of several new extraction areas required for operations with antiprotons. These modifications reduced the available aperture in the Main Ring to the extent that today the Main Ring represents the primary bottleneck in the delivery of high-



intensity proton and antiproton beams to the Tevatron, and in the delivery of protons onto the antiproton production target. Construction of the Main Injector is designed to remove this bottleneck once and for all.

The Main Injector will be constructed tangent to the Tevatron in a separate tunnel on the southwest corner of the Fermilab site. The Main Injector is roughly half the size of the existing Main Ring yet will boast greatly improved performance. The Main Injector will allow the production of about seven times as many antiprotons per hour ($1.5 \times 10^{11}$/hour) as are currently possible and will have a capability for the delivery of five times as many protons to the Tevatron (at least $3 \times 10^{11}$ protons/bunch for collider operations). Additionally the Main Injector will support the delivery of very intense proton beams ($3 \times 10^{13}$ protons every 2.9 seconds with a 33% duty factor) to existing experimental areas where they can be used for state-of-the-art studies of CP violation and rare k meson decays, and for experiments designed to search for transmutation between different neutrino generations. Low intensity proton beams emanating from the Main Injector will support test and calibration beams required for the development of new experimental detection devices which will be required both at Fermilab and at the SSC. In contrast to the present situation at Fermilab, simultaneous antiproton production and Main Injector slow spill operation will be possible during normal operations. Delivery of beam from the Main Injector to all experimental areas will be compatible with Tevatron collider running, while delivery of beam to a dedicated neutral K and neutrino area will be compatible with Tevatron collider and fixed target operations.

The goals and timeliness of the Fermilab III program have been affirmed by the Department of Energy's High Energy Physics Advisory Panel (HEPAP). In October 1989 HEPAP was asked by the Department of Energy's Office of Energy Research to offer guidance on research directions for U.S. High Energy Physics during the period leading up to utilization of the SSC. In April 1990 HEPAP presented its recommendations to the Department of Energy, including as its highest priority "...the immediate commencement and speedy completion of construction of the Tevatron Main Injector at Fermilab."

Accomplishments for 1990 included development work on a new dipole magnet required for the Main Injector, initiated in October 1989. The first full scale prototype was built at the Technical Support Section's Conventional Magnet Facility, and was delivered to the Magnet Test Facility (MTF) in September 1990. Initial measurements indicate that this magnet will operate with the required field quality.

Fermilab has, since its inception under Director R.R. Wilson, attempted to create facilities harmonious with the existing environment. Every effort is being expended to continue this tradition in the planning for the Main Injector. A major activity during 1990 was the study of design enhancements which would minimize negative environmental impacts of the Main Injector, and the initiation of preparation, in concert with relevant state and federal agencies, of the required environmental documentation and permit applications. This effort has been largely funded through the State of Illinois Technology Challenge Grant Program and will continue in 1991.

*(Left) From left to right, crew foreman Samual Jaskin of Blackhawk Industrial Services, Inc. supervises ironworker Terry Milligan and operator David Smiley as they transport a Main Injector dipole magnet from IB2 to IB1.*

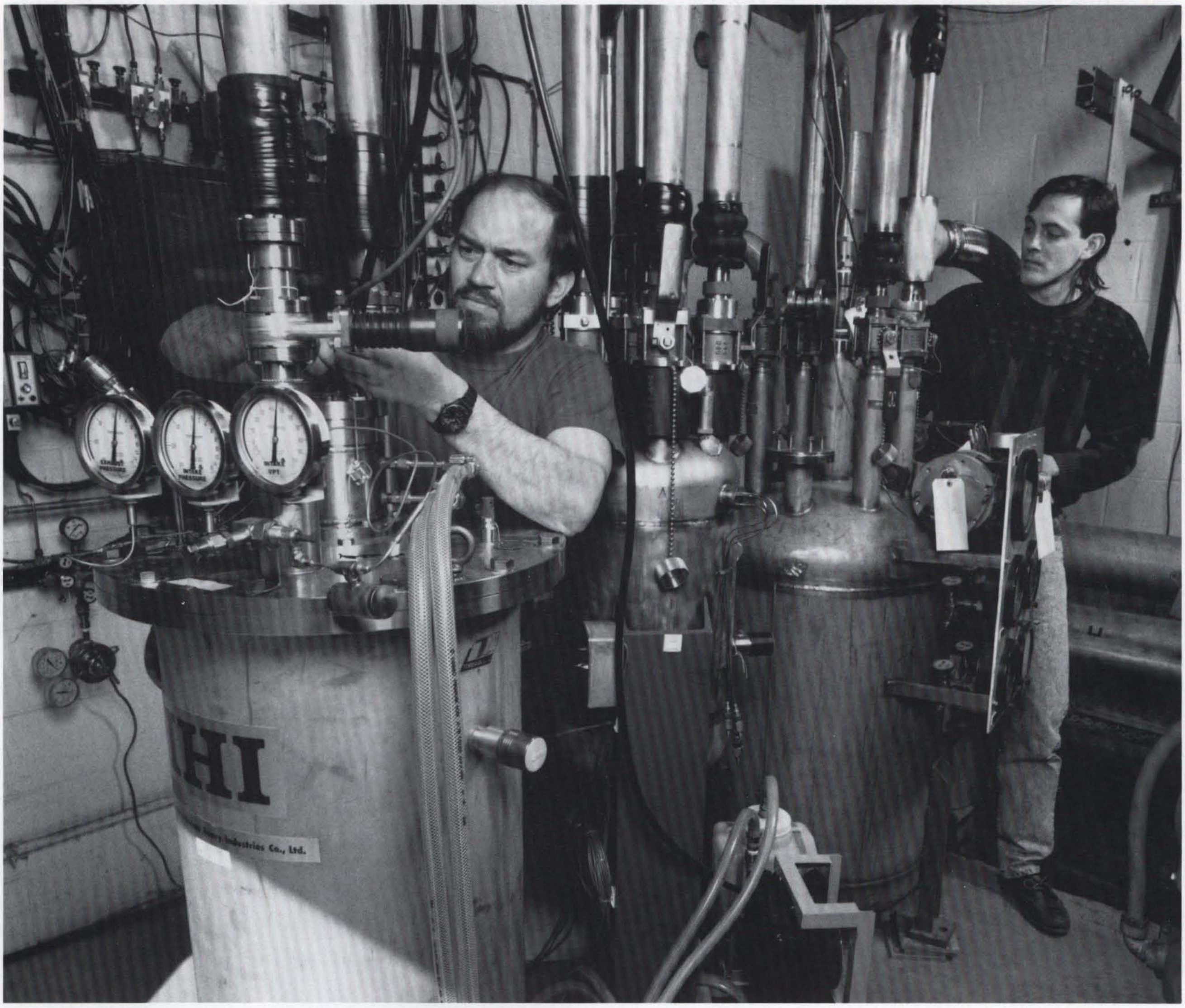
*(Right) Technician Patsy Sanchez wraps insulation around the coils of a prototype Main Injector dipole magnet.*

# Tevatron Higher Energy Upgrade

This project provides for the design, procurement, and installation of a cryogenic upgrade to lower the temperature of the superconducting Tevatron. The anticipated result will allow for 1.0 TeV operation for collider physics and 0.9 TeV for fixed target physics beginning in 1993. The system is designed to allow future operation up to 1.1 TeV and 1.0 TeV in collider and fixed target physics, respectively.

An increase in magnetic field is achieved by lowering the temperature of the superconducting coils. Lower temperature increases the superconductor critical current, the current level at which the conductor is no longer superconducting at a given magnetic field. For the Tevatron, this enhanced current carrying capability amounts to about 15% per degree Kelvin.

The current operation threshold of the Tevatron is 935 GeV with a peak coil temperature of 4.9 K. A coil temperature reduction of 1.0 K is expected with the new system. Assuming that no mechanical limits are reached in the magnets,



*Technicians Kenneth Olesen (l) and Barry Norris (r) test new equipment in a refrigerator building. The liquid helium dewar near Barry collects gaseous and liquid helium returned from the superconducting magnets, and the cold compressor lowers the pressure of the helium.*

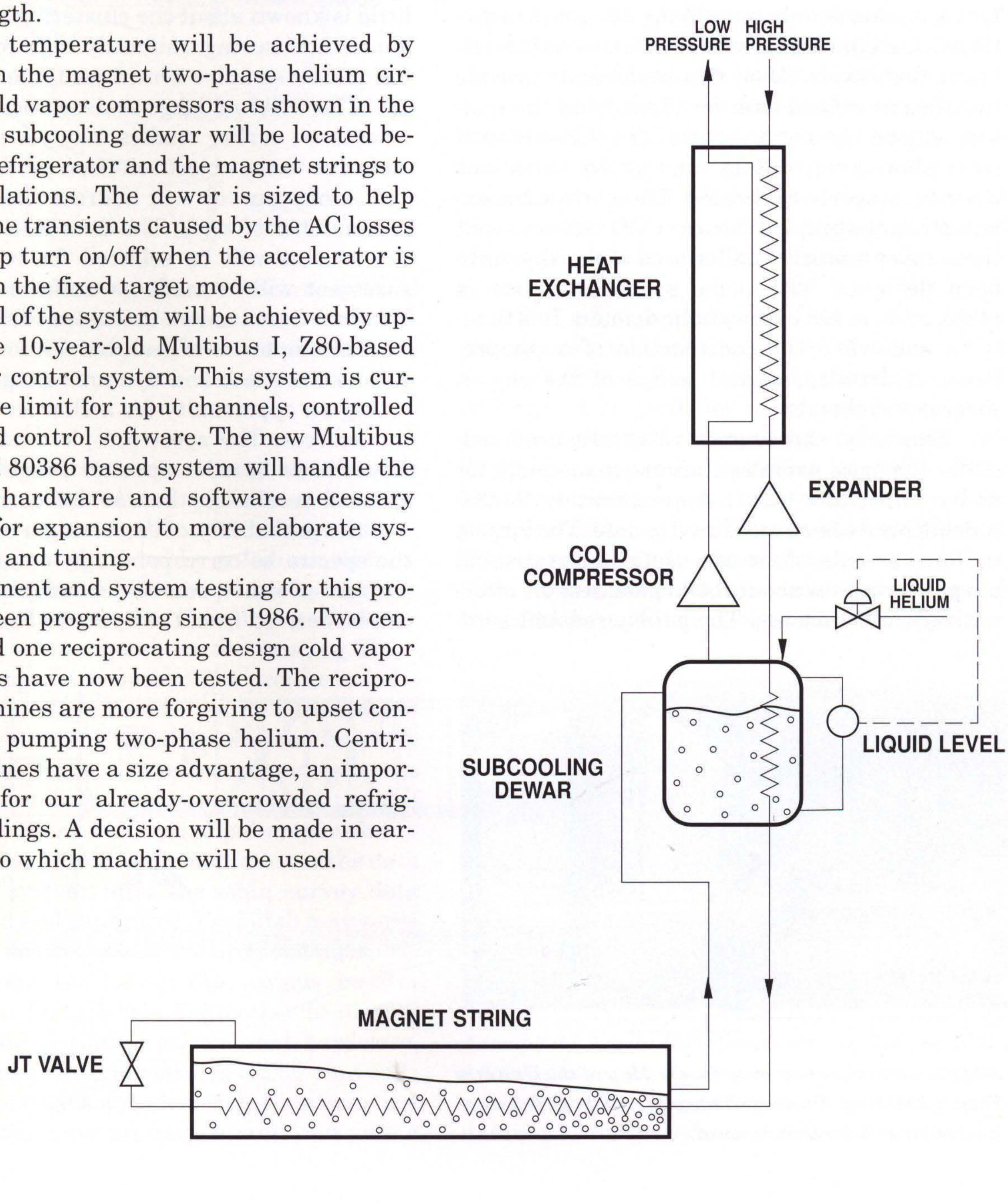
this will result in 15% increase in energy, or 1075 GeV. In reality, mechanical limits and weak splices will be encountered between 935 GeV and 1075 GeV. It is estimated that a two-month study period will be necessary to identify and replace weak magnets. Future studies to identify weak magnets should allow operation up to 1.1 TeV (collider) with a reasonable number of magnet replacements. This represents the operational limit of several major subsystems of the Tevatron: cryogenic system capacity, power supply, power lead current, and magnet collar strength.

Lower temperature will be achieved by pumping on the magnet two-phase helium circuit with cold vapor compressors as shown in the diagram. A subcooling dewar will be located between the refrigerator and the magnet strings to buffer oscillations. The dewar is sized to help minimize the transients caused by the AC losses during ramp turn on/off when the accelerator is operating in the fixed target mode.

Control of the system will be achieved by upgrading the 10-year-old Multibus I, Z80-based refrigerator control system. This system is currently at the limit for input channels, controlled devices, and control software. The new Multibus II and Intel 80386 based system will handle the additional hardware and software necessary and allow for expansion to more elaborate system control and tuning.

Component and system testing for this project have been progressing since 1986. Two centrifugal and one reciprocating design cold vapor compressors have now been tested. The reciprocating machines are more forgiving to upset conditions and pumping two-phase helium. Centrifugal machines have a size advantage, an important issue for our already-overcrowded refrigerator buildings. A decision will be made in early 1991 as to which machine will be used.

System tests in two sectors of the Tevatron have also taken place: F-sector in 1989 and A-sector in 1990. After one magnet replacement, F-sector quench current improved from 940 GeV to 1021 GeV with a 0.43 K temperature reduction. A-sector did not perform as well, improving from 930 GeV to 989 GeV with a 0.5 K temperature reduction. This was not a surprise since A-sector was known to have the worst distribution of magnets in the Tevatron.



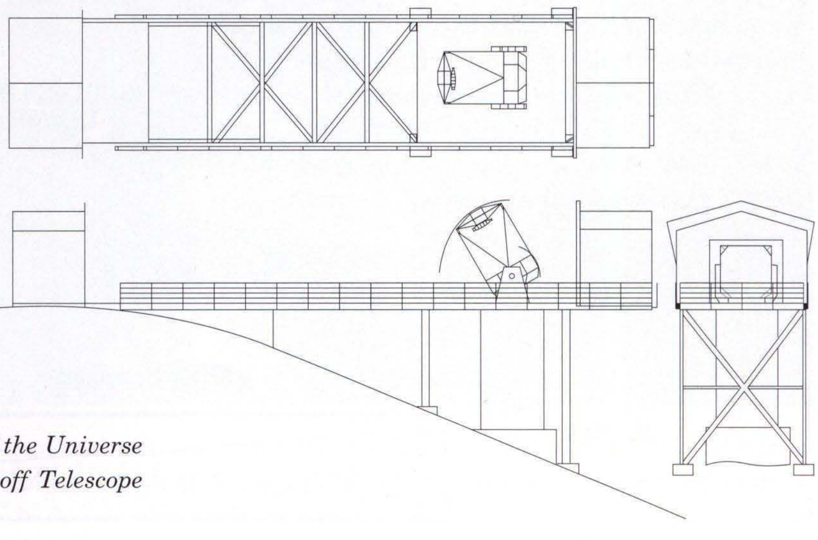
# Experimental Astrophysics

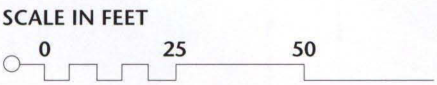
## Map of the Universe Project

The current state of astronomical maps and source catalogs leaves much to be desired for studies of large-scale structure. The existing all-sky maps are in the form of a published collection of a few thousand photographs in two wavebands. The digitization of these photographs is laborious, the dynamic range is small, and the angular resolution is only marginally adequate to distinguish stellar images from galaxies at the relevant flux levels. Also, two wavebands provide insufficient information for identifying the quasars among the normal stars. The sensitivity of each photograph differs, and these variations must be properly calibrated. There are some existing charge-coupled device (CCD) surveys, but these cover a much smaller area of the sky, have been designed with some special purpose in mind, and are not in the public domain. It is timely to undertake the construction of a comprehensive, detailed, digital image of the sky in several wavebands.

Similarly, the sources with measured redshifts comprise samples that are inadequate for many important tasks. Approximately 25,000 redshifts have been measured to date. The largest uniform samples that are useful for statistical purposes contain about 5,000 galaxies, or, alternatively, 500 quasars. The galaxy redshift samples cover very roughly 1 steradian; in one such study, this area is covered in patches that occupy only 25% of the total area, and in the other extant study, the flux limit for the galaxies is not well defined. The quasar samples are somewhat better in this regard, but the surveyed area is much smaller, of order 0.01 steradian. As a result, very little is known about the clustering properties of quasars. Ensuring uniformly high completeness for quasar samples continues to be problematical. The view of large-scale structure derived from these earlier studies may yet contain artifacts due to the object selection procedure.

A new survey will address these problems in a number of ways. The data base from which the sources will be selected for redshift measurement will be made as uniform as possible. The data base is more extensive than previously available in terms of multiband information, angular resolution, and dynamic range, thus providing an opportunity for a sharper selection of the sources. The spectroscopic data will themselves have broader spectral range and higher spectral resolution than is the norm. Not only will the probability of extracting a redshift from the spectra be correspondingly enhanced, but a number of other source-dependent parameters can be derived from the spectra. The proposed π






*Site plan and elevation view for the Map of the Universe Project building. Diagram shows the Roll-off Telescope Enclosure with building opened.*

steradians of the survey will allow large structures to be identified even in the relative foreground, and the area will be covered fully.

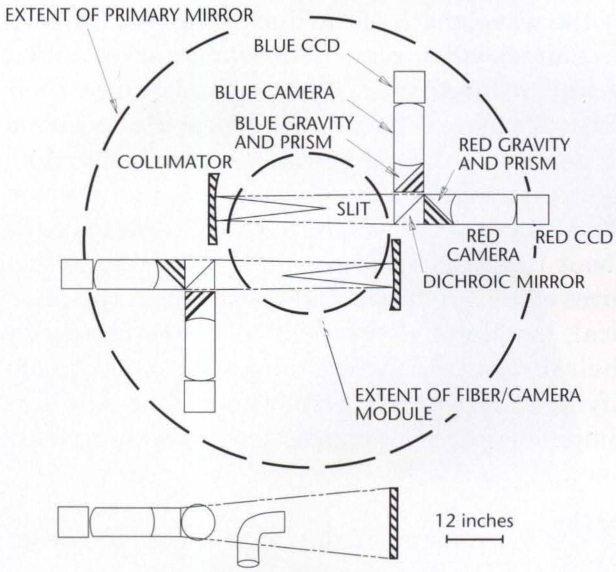


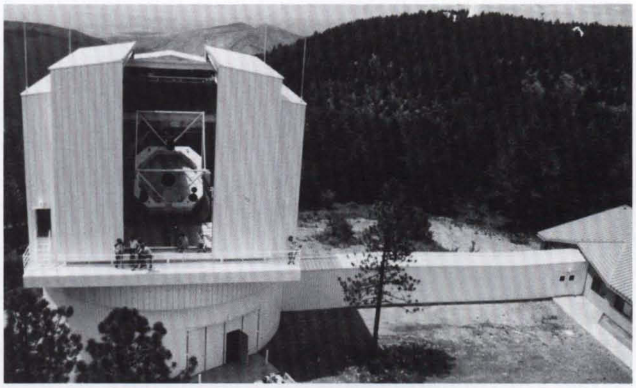

*Diagram shows two spectographs, permanently mounted at the focus. Note the accessible free volume within the central dashed circle. The plug plates and the imager are positioned at the focal plane via a module that occupies this volume.*

The cornerstone project is the construction of a telescope and data acquisition system for studies of structure in the universe on cosmological scales, as delineated by galaxies and quasars. This project will be carried out by a newly assembled group in the Computing Division. Their work will complement the existing Theoretical Astrophysics Group. The project is to be undertaken in cooperation with the University of Chicago, Princeton University, and the Institute for Advanced Study. The telescope and detectors will be located in the Sacramento Mountains of New Mexico. Fermilab's principal responsibility will be the design and implementation of the data acquisition system; after the main survey data are obtained and calibrated, Fermilab may serve as a center for analysis of the archived data.

Representatives from the various institutions met at Fermilab in September to discuss the scientific priorities, the needed hardware, and the implementation strategy. The plan calls for a telescope with a modest collecting aperture (2.5-meter-diameter primary mirror), but with a very wide field of view (3 degrees diameter). The technically novel parts of the project concern the instrumentation in the focal plane, namely a large array of large-format CCDs, and a fiber-optics system for directing light from hundreds of sources at a time into a pair of spectrographs.

A two-dimensional map of the sky will be produced in four or five wavebands in the visible spectral range. This will be done by scanning the sky repeatedly in strips, using only the nights with best observing conditions. There will be about $10^8$ galaxies detected within the $\pi$ steradian survey region. Moreover, there are expected to be about $10^6$ quasars measured with sufficient accuracy to be distinguished from ordinary stars. A subsample of sources will be chosen based on analysis of the images in the map, and redshifts for about $10^6$ galaxies and quasars will be obtained with the fiber-fed spectrographs. Current plans call for full operation to begin in 1995, and the project can be completed in about five years of observations.

The major opportunities for a digital sky survey are enabled by technologies developed in the past decade. These include the development of large CCDs with low electronic noise backgrounds; affordable computers and storage media that are capable of handling large data rates and data volumes; robotic systems (required for positioning the optical fibers in the focal plane of the telescope); and progress in telescopic design that, among other things, takes advantage of the economies of light-weight mirror designs.



*A view of the Apache Point Observatory in Sunspot, N.M., 9,200 feet above sea level in the Sacramento Mountains overlooking White Sands Desert. Photo courtesy Kurt Anderson Astrophysics Research Consortium (ARC).*

# Map of the Universe Connections

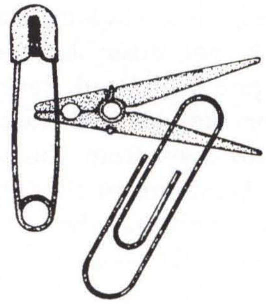
The sky survey project provides for a number of connections with other fields, both practical and intellectual.

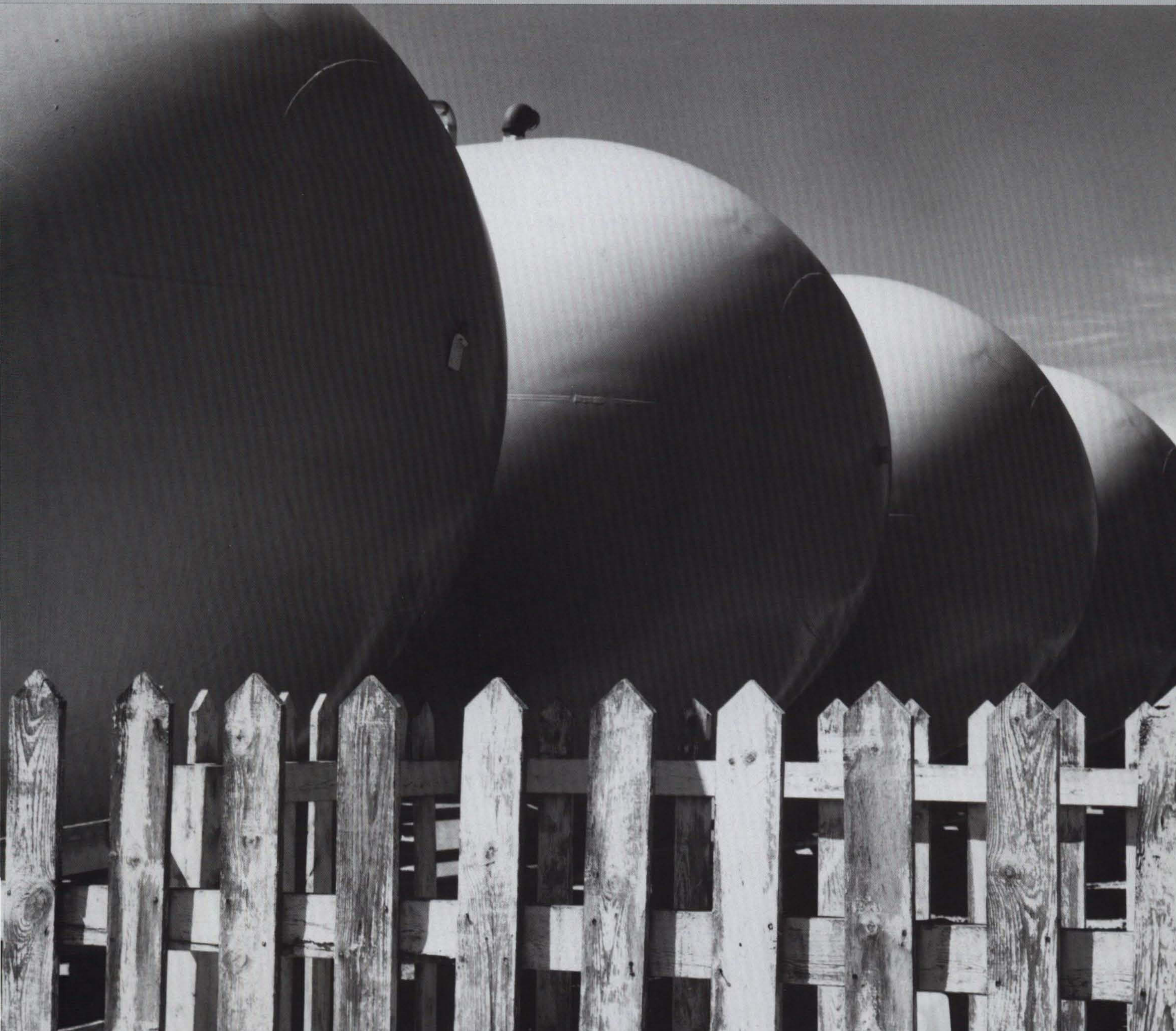
**1** Dynamical studies of galaxies reveal the existence of large amounts of matter that is not otherwise visible – the so-called dark matter. The match between the observed cosmic abundance of the light elements and the predictions of big-bang nucleosynthesis provides an upper limit on the total amount of matter that can be composed of baryons. Otherwise, the nature of the dark matter continues to be elusive. One constraint can be derived from the distribution of the dark matter with respect to the distribution of luminous matter (ordinary stars in galaxies or star light reradiated by gas or dust). Current dynamical studies do not yield a clear picture, but progress can be made with a much larger sample of galaxy phase space positions, such as will be provided by the proposed survey. This astronomical approach is complementary to laboratory searches for dark matter candidates in the form of exotic particles (or not-so-exotic particles, as in the case of a massive neutrino).

**2** Relics of the universe as it was at very early times have in general not survived the subsequent thermalization: the COBE satellite has dramatically shown that the cosmic radiation is thermal to high precision and is accurately isothermal. The matter distribution is evidently nonuniform, and at the large scales it may provide a glimpse of the state of the primordial universe in the form of relic density fluctuations, assuming that the relation between the distribution of luminous matter and dark matter can be determined. (At the smaller scales, say individual galaxies and clusters of galaxies, the visible structures are dominated by the action of gravity and hydrodynamical processes, which makes the interpretation much more problematical.)

**3** The image of the sky will comprise a 10 terabyte ($10^{12}$) data base, from which the position and other parameters for the sources will be automatically extracted. Quasars at the highest redshifts are a good example of rare events – perhaps only 1,000 quasars with redshift $z > 4$ ($z$ is the shift in wavelength of a spectral line divided by the wavelength of the line in the rest frame of its source) will appear in the whole survey, and it is important to find these reliably since their statistics place constraints on the early spectrum of density enhancements. The corresponding "background" is the detection of ordinary stars in the Milky Way, of which there are expected to be about $10^8$ to the same flux limit. The image structures of high-redshift quasars and stars are identical, but these classes can be discriminated by their respective spectral indices. The task of identifying rare events in enormous data bases is similar to the challenges faced by experiments like CDF and DØ.

**4** Charge-coupled devices are not only excellent photon detectors (offering quantum efficiency better than 50% over a wide range of the visible spectrum, low noise, high stability and linearity); they are also good particle detectors. The diodes are sufficiently isolated so that a particle incident on a thinned chip will generally appear in only one pixel. Pixels are typically manufactured in sizes ranging from seven microns to 30 microns, and the formats of the diode arrays are typically square with 1024 to 4096 pixels on a side. The time required to clock the charge off the CCD depends on the design of the particular device; there is a trade-off between speed and noise. At the high end, CCDs can easily match video rates. It is reasonable to expect that the development of CCDs for astronomical applications, namely the low-noise regime, will also benefit the development of particle detectors.





## *The Ties That Bind...*

### *Connect. Link. Reach out.*
### *Weave. Interrelate.*

*These verbs describe the ways in which the Fermilab community operates as a whole. More specifically, they underscore the activity of the various structures and personnel that support the Laboratory's basic mission. While the research into the essence of matter and energy receives the most acclaim, the work of the people who support Fermilab's mission deserves continued recognition.*

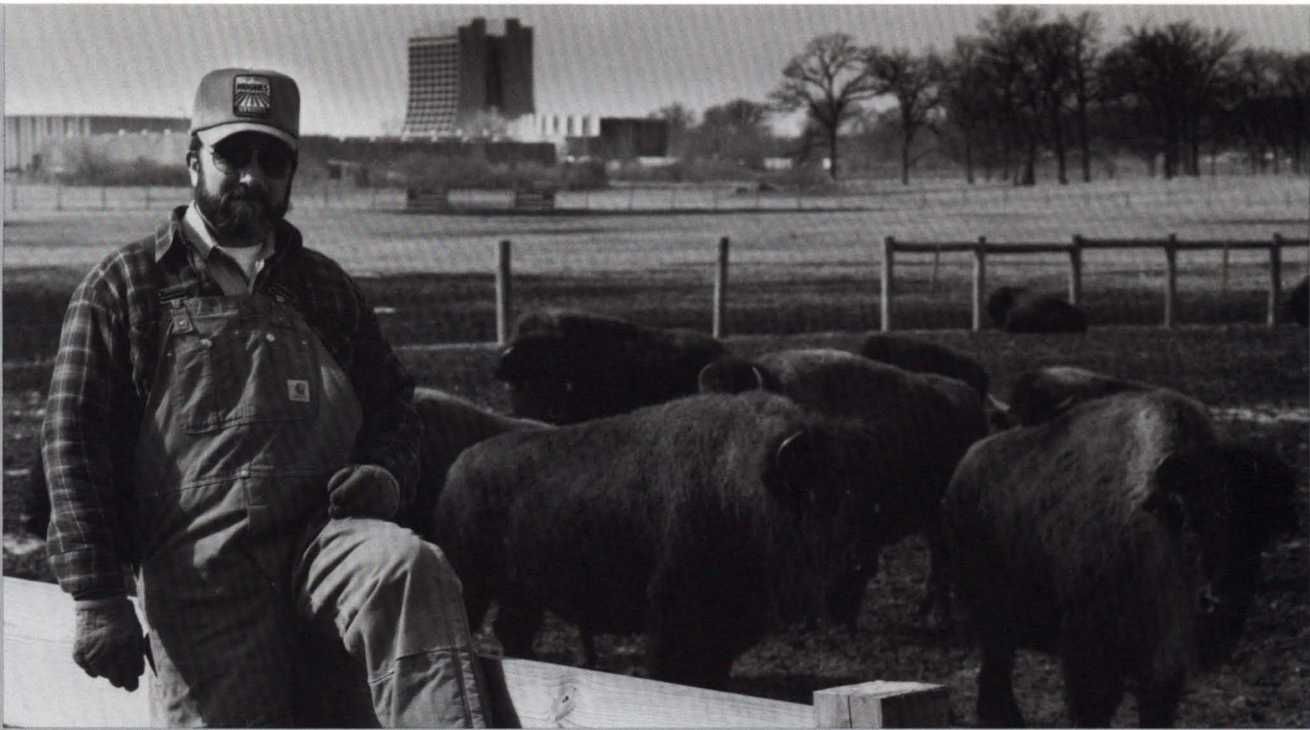
*The following pages highlight only a few of the individuals who have contributed to the development of Fermilab's network of connections in 1990. They represent countless others who enable the Laboratory to connect with and impact on not only our immediate community but our entire world.*

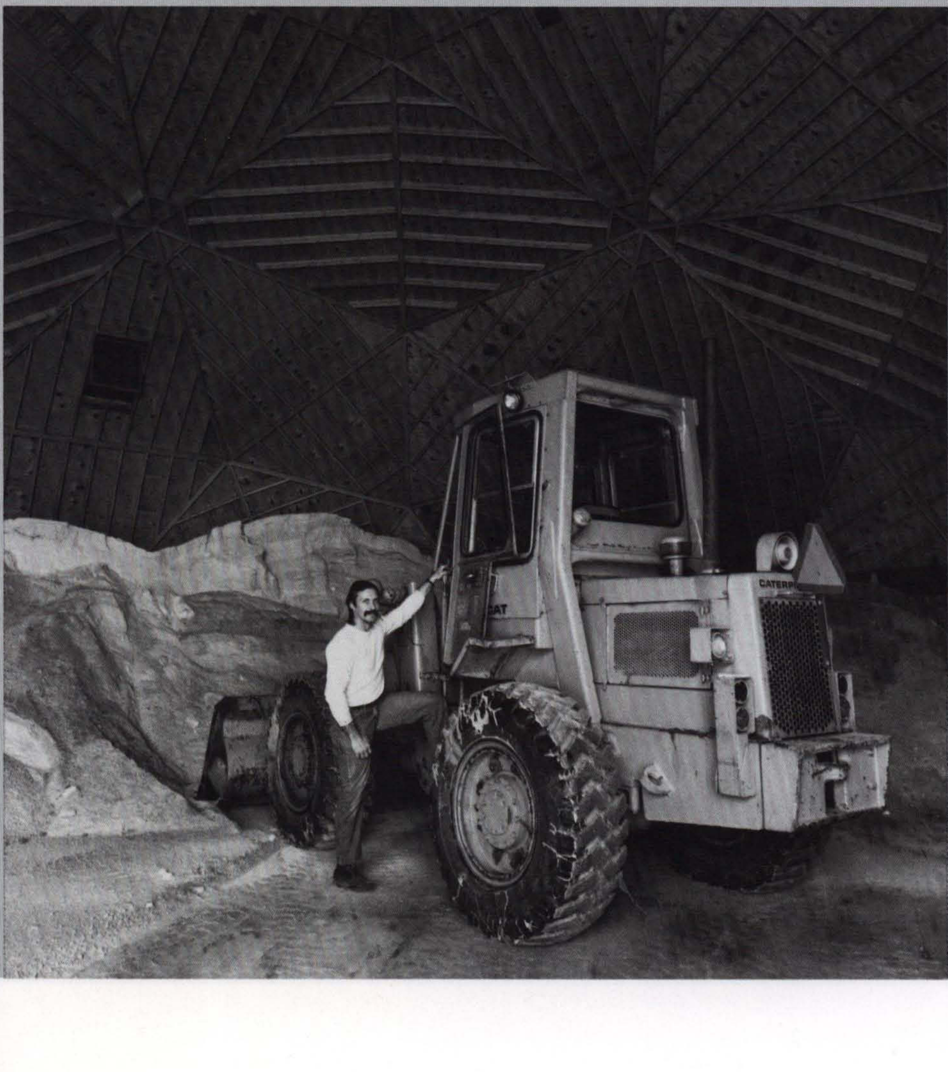
*Fermilab connects with neighboring communities via a variety of tours and a rich, varied cultural arts program. Sending vehicles and personnel to aid in the clean-up effort, Fermilab reached out in a very special way to its neighbors in Plainfield who were devasted by a tornado in August 1990.*

*Fermilab connects with its experimenters world-wide via teleconferencing, computer networks and the gracious personnel of the Users and Accomodations offices.*

*Fermilab connects with a far-ranging educational community via a wide array of educational opportunities offered to students and teachers at all levels.*

*Fermilab connects with its past via the History of Accelerators project, the reconstruction of the prairie, and the reality of the buffalo herd. Fermilab connects within its own boundaries via the telephones, mail, and the roads which bring us all together.*



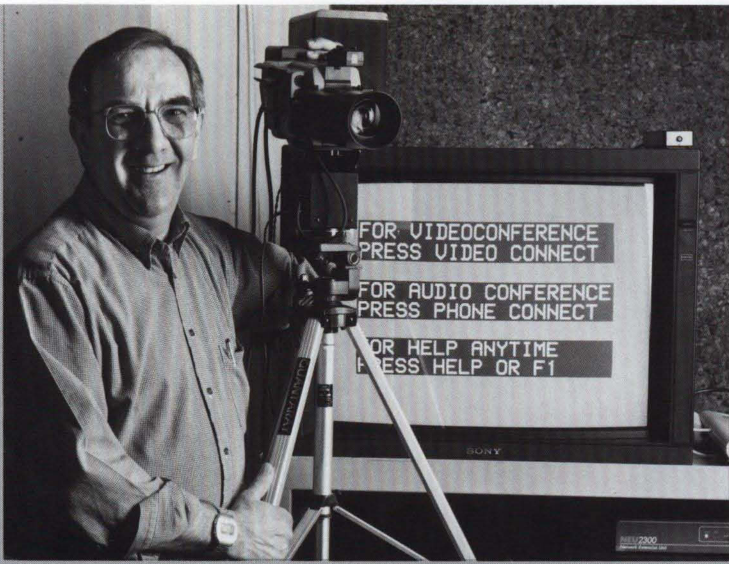


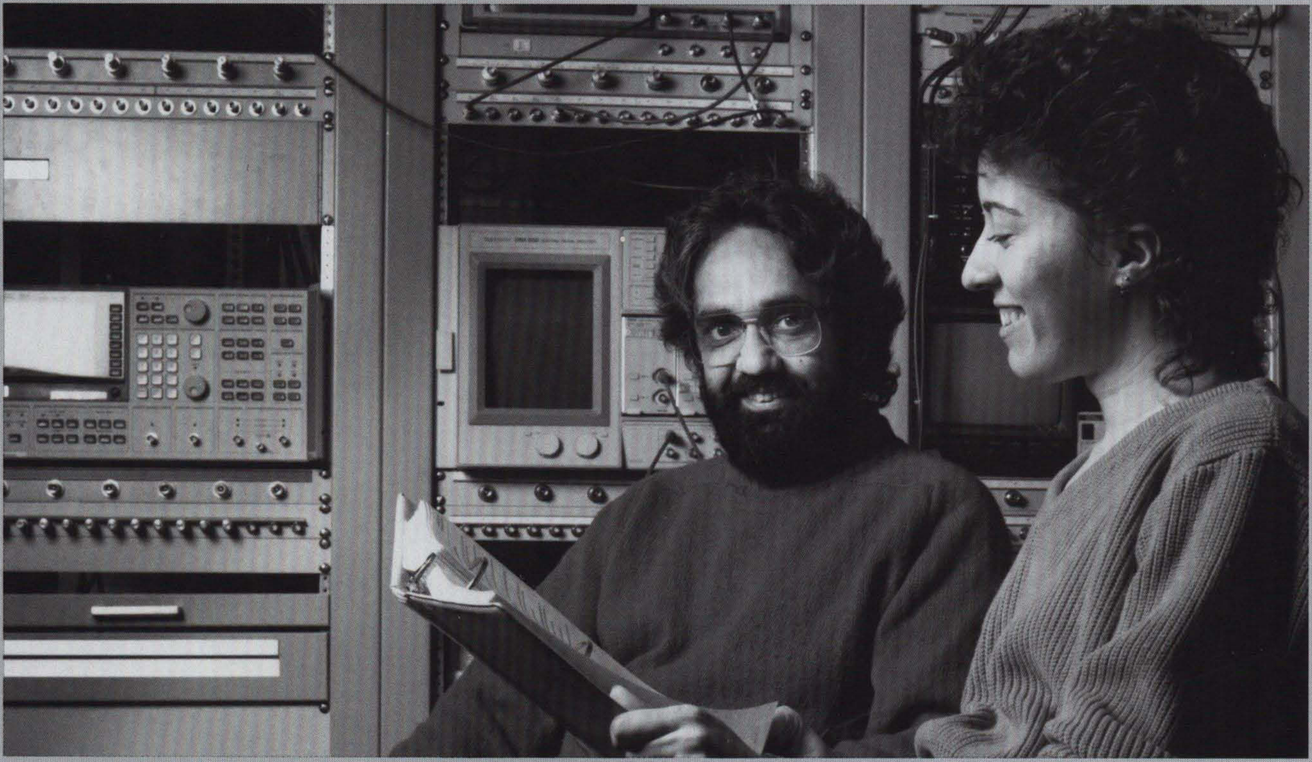
*(Above) Chief Herdsman Donald Hanson shows off some of the Fermilab buffalo in a holding corral. The buffalo are an attraction to casual passers-by and Fermilab visitors who participate in tours of the Laboratory.*

*(Left) Groundsman Bryan Needham climbs into a loader inside Fermilab's salt storage area where 200 tons of salt are kept. The loader breaks up the salt before it is dumped into salt-spreading trucks for distribution during periods of inclement weather. Fifty-seven miles of roads link all of the buildings and facilities on-site, and the Roads and Grounds crew maintain the roads by clearing them in the winter and patching them in the summer. Snow and ice storms often demand that crew members report to work at odd hours on an emergency basis to clear roads to enable Fermilab employees to get to work.*


*Outreach Coordinator Robin Dombeck of the Education Office joins in the science activity of sixth graders at McWayne School in Batavia. The Education Office coordinates collaborative efforts between the Laboratory and local school districts. The Education Office coordinates workshops and institutes to familiarize teachers with effective science teaching strategies and inquiry-based instructional materials, provides informal science experiences for young students, assists in the development of long-range plans to improve the quality of school science programs and offers assistance in locating resources for the science classroom.*


*Nancy Lanning of the Public Information Office (PIO) conducts a tour of Wilson Hall's 15th floor for students from the University of Western Ontario. The PIO regularly conducts guided tours of the Laboratory for high school age students and adult groups. Fermilab's open-laboratory policy means that visitors may come to the Laboratory 365 days a year.*

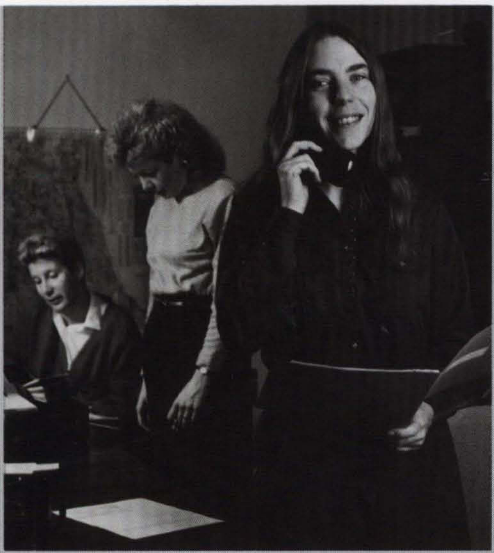


*(Top Left) James Szyplik of Visual Media Services sets up for a video conference. Pictured is one of the two video monitors used to communicate with remote sites. Fermilab began video conferencing in 1990 and now participates in about 15 events per week with most divisions having made use of the technology.*

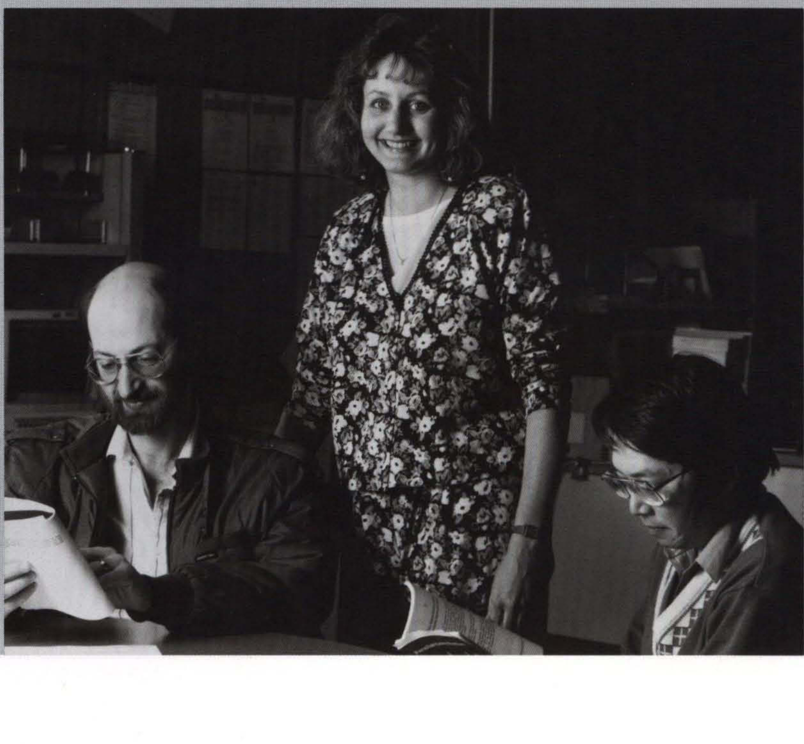
*(Top Right) Pictured in the gym, Jeanmarie Guyer, Recreation Manager, designs, promotes and implements programs for Fermilab employees and users and their families. The Recreation Facility has 800 members and is a gathering place for Fermilab employees to work out and socialize.*

*(Bottom) Booster Department Head Vinod Bharadwaj confers with Purdue University Ph.D. student Katherine Harkay in front of a digital oscilloscope in the Booster Control Room. They are working together in the Joint University-Fermilab Doctoral Program in Accelerator Physics in which established scientists instruct doctoral candidates in a physics topic supplemented with field experience at the Laboratory.*



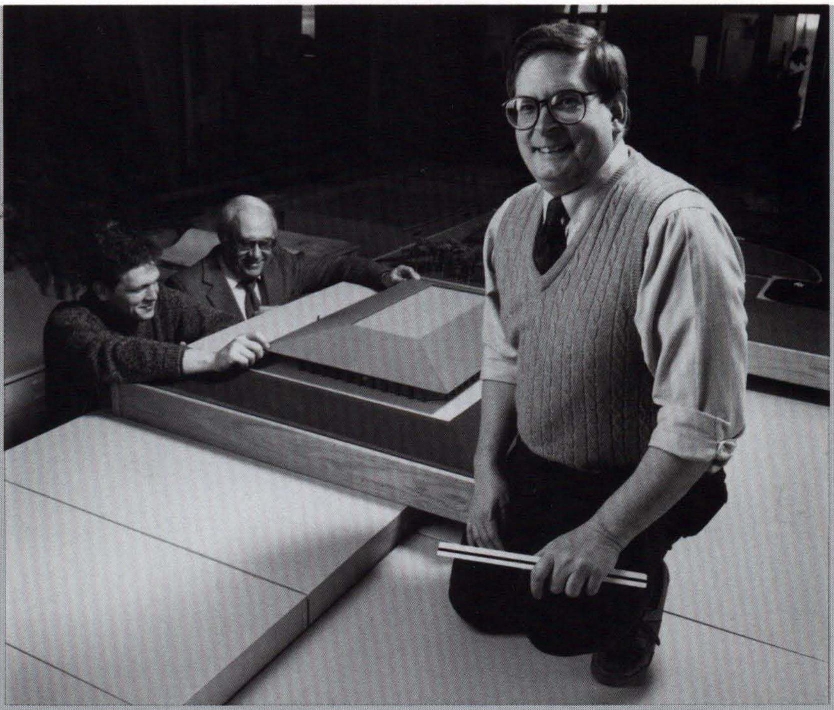
*(Above) Pam Fox, Linda Olson-Roach and Cheryl Bentham from the Housing Office in Aspen East provide visitors to the Laboratory with on-site and off-site housing. The office works in conjunction with local apartment complexes to accomodate users from the U.S. and various foreign countries who will be at Fermialb for at least one month. In addition, the office matches short term users with on-site accomodations in the dorm and in the Fermilab village.*

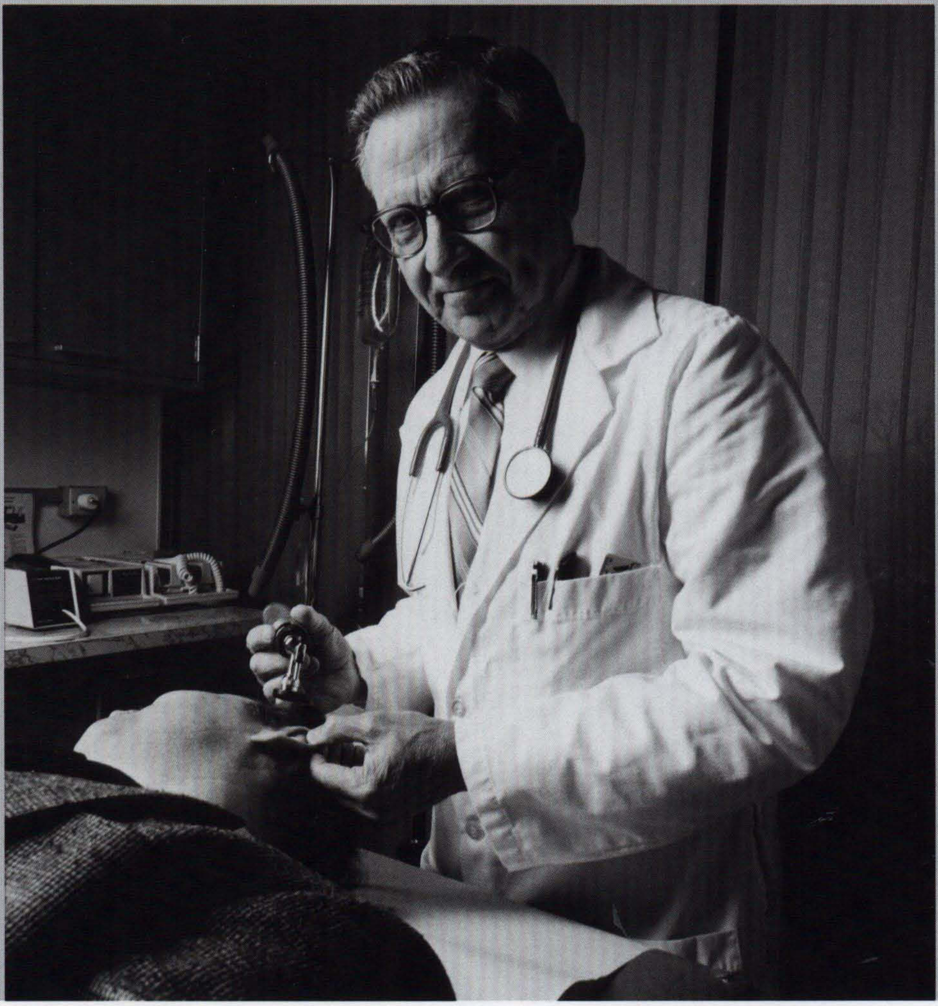
*(Top Right) Chef Tita Jensen stands at the entrance to the dining room of Chez Leon. The restaurant, located in the Users' Center in the village, offers a unique and comfortable place where members of the Fermilab community and their guests can relax and enjoy freshly-cooked, all-natural cuisine.*



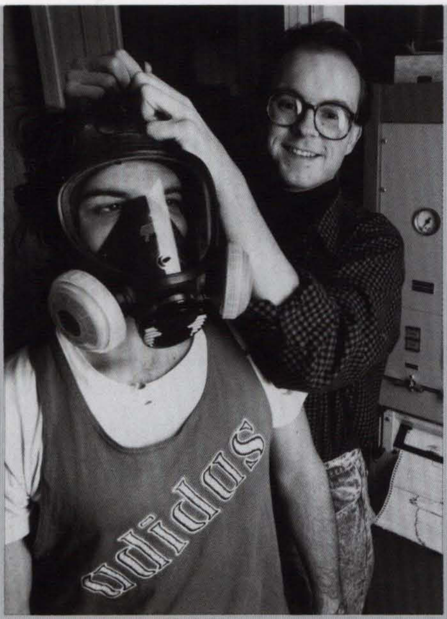
*(Right) Joy Miletic of the Users Office assists Daniel Kaplan of Northern Illinois University with his application for a Fermilab user identification card while Yee Bob Hsiung of the Physics Section waits his turn. The Users Office assists and informs the approximately 1,000 visitors who come to the Laboratory for research and research-related functions every year.*

*Edward Crumpley (foreground), lead architect of Construction Engineering Services Section, with apprentice architect and model builder Tim Burke (l) and Section Head Wayne Nestander (r) review a model of the Fermilab Science Education Center. The Center will house Fermilab and Friends of Fermilab precollege education programs and is scheduled for completion in late 1991. The Construction Engineering Services Section is involved in the design and building of on-site construction or remodeling. Models such as the one pictured help give a three dimensional understanding of how space useage affects the entire Fermilab community.*



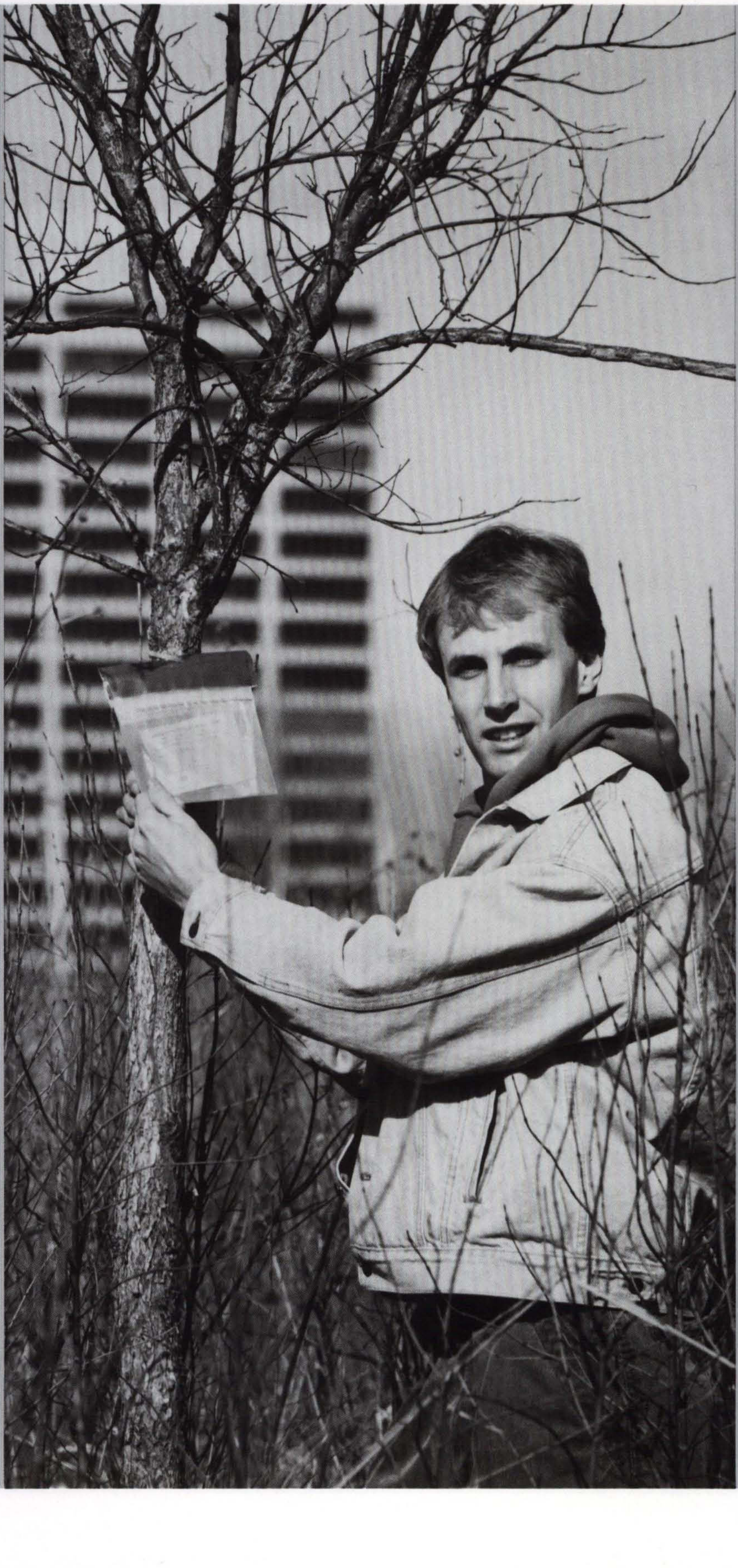


*Dr. David Morrison examines a patient in the Fermilab Medical Office centrally located on the first floor of Wilson Hall. The Medical Office provides a valuable service to Fermilab employees by providing them with easily accessible on-site medical attention and health screening. All Laboratory employees receive pre-employment physicals. The Medical staff coordinates regular audiogram programs and oxygen deficiency hazard (ODH) physicals as well as offering free annual physicals to employees over 45 years of age.*




*(Above) Joe Kenny (r) helps technician Christopher Exline (l) into a full face respirator during a fit test. They are members of the Health and Safety Group which is responsible for industrial safety, industrial hygiene and fire protection. Laboratory employees who work in contaminated areas wear masks inspected by the Health and Safety Group when working with asbestos, lead contamination, or when they transfer materials between waste disposal containers.*

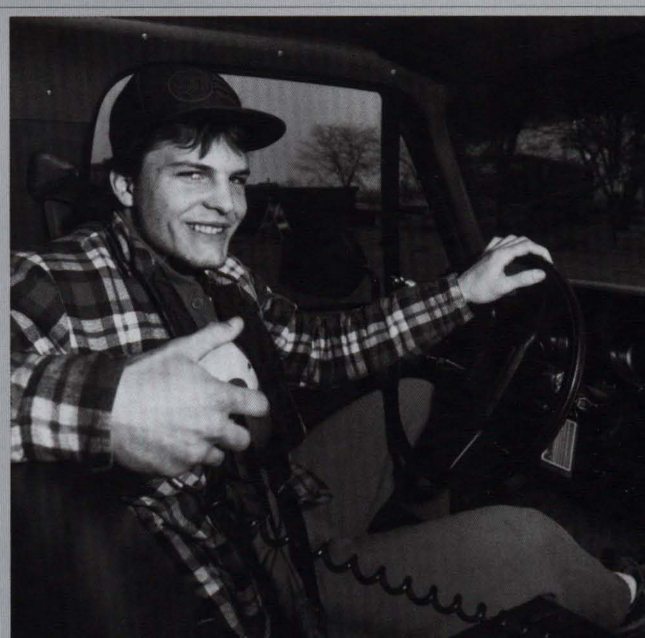
*(Right) Eric Mieland, a technician with the Environment, Safety and Health Section, inspects one of Fermilab's 75 on-site thermal luminescent dosimeters. The dosimeters are distributed at various locations site-wide to gauge any atmospheric radiation emission to the immediate area that could affect the neighboring community. This measuring program ensures that Fermilab maintains and protects the local environment's integrity for the welfare of its inhabitants.*



*(Left) Telephone technician Jess Rugg runs a wire through the telephone switching system in the basement of Wilson Hall. Telecommunication links all Laboratory buildings and offices on the 6,800-acre site via the wall of framework that connects over 3,000 individual telephone lines.*

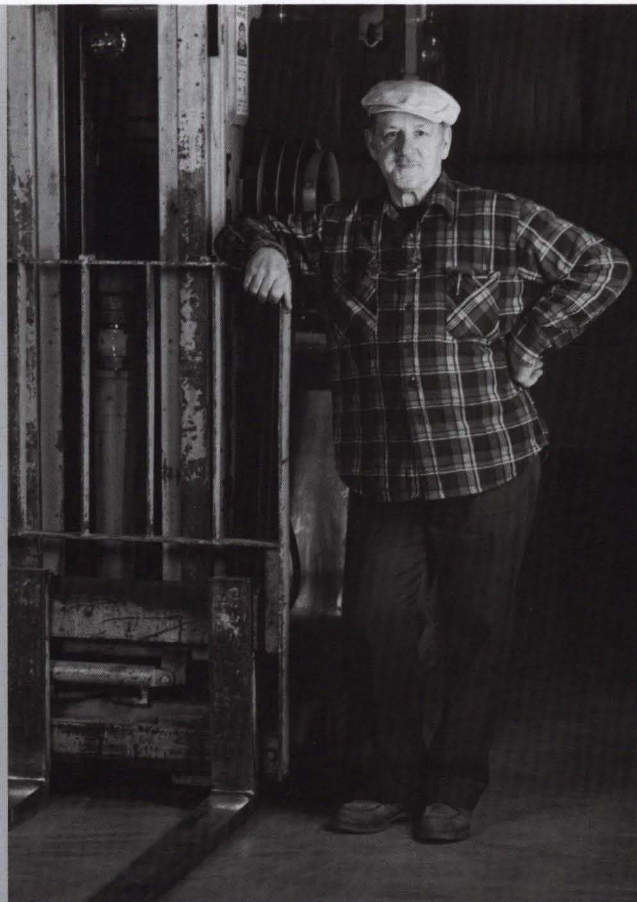
*(Below Left) Dispatcher Roger Braun fields one of the many requests the Dispatch Office handles daily. Operating out of an old cow barn, he directs Fermilab's taxi service as well as trucks that respond to on- and off-site requests for material pick ups and deliveries. The continual flow of requests keep Dispatch's fleet of about one dozen drivers and two taxis continually on the move.*

*(Below Right) Taxi driver Robert Kobiella at the wheel of the Fermilab taxi. The two taxis make an average of 110-115 on-site runs per day. Because of shifting demands, drivers need to be versatile, and most are licensed to drive vehicles that range in size from taxis to semitrucks.*

*(Left) Martha Garcia (l) and Leighann Nurczyk (r) prepare the mail for delivery in Wilson Hall. Four mail carriers trade off on the weekly delivery of two routes per day to Wilson Hall and one to outside Laboratory sites, ensuring timely delivery and pick up service. The Mail Room ships 1,400 outgoing first class letters and packages daily and has window hours to serve Fermilab mailing needs.*

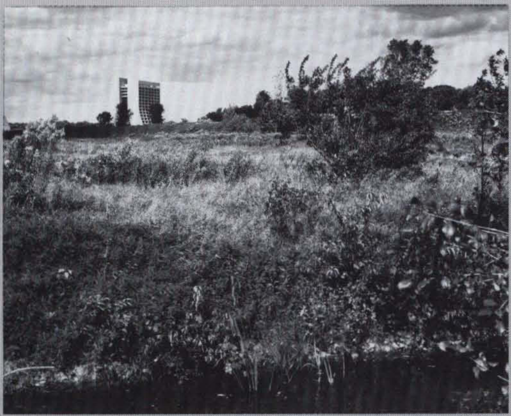
*(Below) Richard White (background) and John Pratscher of the Carpenter Shop work together on a project to replace some of Aspen East's wooden trim. In addition to performing preventive maintenance and carpentry repairs to all site-wide structures, the Carpenter Shop also constructs specialty wood items designed and built to meet the specifications of experimenters.*

*(Above) George Benedetti, storekeeper in the Receiving Department, stands beside a forklift he uses to unload some of the heavier packages shipped to Fermilab. The Laboratory receives, on the average, 5 tons of material daily in all shapes and sizes - ranging from letter-sized packages to bulk steel.*

*(Left) Storekeeper Archie Beasley logs in UPS packages at the Receiving warehouse. Semitrailers deliver an average of 200 UPS packages per day to Receiving, including Air Freight from around the world. Not only does Receiving routinely and efficiently unload, weigh and register all incoming packages, but the Department also identifies and locates addressees to whom unmarked or undecipherable packages have been sent .*

# Honors and Awards



***Illinois Technology Challenge Grant***

*On April 16, Universities Research Association learned it was the recipient of an Illinois Technology Challenge Grant totalling $200,000 for FY 1990 and $2,000,000 for FY 1991. The monies will be utilized at Fermilab for preconstruction, design and environmental assessment for the Main Injector slated to be built on the southwest corner of the site. The Challenge Fund, administered by the Department of Commerce and Community Affairs, is designed to accelerate the process of state economic growth through investment in science and technology research and development. The purpos of the program is to identify, develop and commercialize technology which will permit Illinois to successfully compete in today's global marketplace.*

***President-Elect of AAAS Lincoln Award***

*In 1990, Leon Lederman, Nobel laureate and Fermilab director emeritus, was named President-Elect of the 133,000-member American Association for the Advancement of Science. In addition, Governor James Thompson bestowed the Order of Lincoln on Dr. Lederman at a ceremony in the University of Chicago's Rockefeller Chapel on April 22. Lederman was one of six Illinoisians who received the state's highest award as recognition for bringing honor to Illinois.*

*(Top)*
***Margaret Pearson***
***1924 - 1990***
*Manager, Public Information. In recognition of her years of service to the Laboratory, the trail through the restored prairie was named The Margaret Pearson Interpretive Trail.*

*(Bottom)*
***William Riches***
***1927 - 1990***
*Energy Management Coordinator. Recipient of the 1990 Regional Engineer Award from the Association of Energy Engineers.*

***Awards in Energy Conservation***

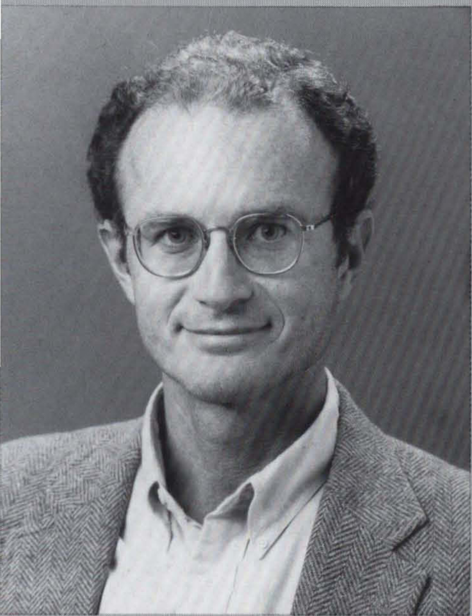
*(Above ) From left to right back, Dennis Theriot, Richard Graff, Fred Rittgarn, Andrew Mravca, Ado Adami Charles Anderson, and John Peoples. From left to right front, Kenneth Kittleson, Jack Mills, and Romesh Sood. In 1990 seven Fermilab employees received energy conservation awards for ideas which, when implemented, will save the Laboratory more than $500,000. Romesh Sooc of the Research Division received the maximum award for his suggestion to install automatic controls in all three beam lines to reduce the ramping magnets to zero current during no-beam conditions.*

*On October 25, the Association of Energy Engineers gave its Energy Efficiency Corporate Award to Fermilab. The Laboratory received the award in large part for conservation programs that improved energy efficiency in buildings, metered processes, vehicles and equipment.*

*On October 26, Assistant Secretary for Conservation and Renewable Energy, Michael Davis, presented the Laboratory the Department of Energy In-House Management Program Award in recognition of Fermilab's "extraordinary achievements, initiatives and resourcefulness in planning and implementing a highly effective energy management program."*

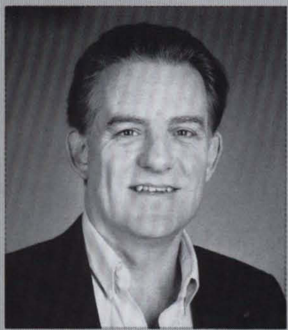
***500th Cooperative Education Employer***

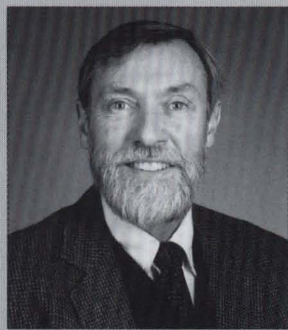
*At a ceremony held March 16, the College of DuPage recognized Fermilab as its 500th Cooperative Education Employer. Students employed at Fermilab during the summer have received college credit for their work experience. Representative Harris Fawell of the 13th Congressional district (left) presented the award with Dr. Harold McAninch, President of the College of DuPage (right) to James Lasenby (center) of the Employment Office who accepted on behalf of the Laboratory.*

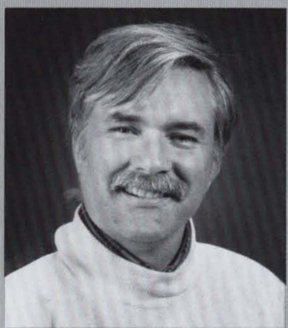


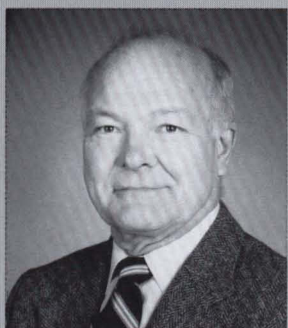
***1990 W.K.H. Panofsky Prize***

*Michael Witherell, Professor of Physics at the University of California, Santa Barbara and collaborator on Fermilab Experiment 691, was named winner of the 1990 W.K.H. Panofsky Prize for his outstanding contributions to the field of elementary particle physics. The prize, awarded by the American Physical Society's Division of Particle and Fields, went to Witherell for his pioneering studies of charmed particles. Working with a team of physicists, Witherell developed experimental techniques based on silicon-microstrip vertex detectors to extract nearly 100 million charmed particles from photon-nucleus collisions, allowing the Fermilab experimenters to determine charmed lifetimes with great precision.*









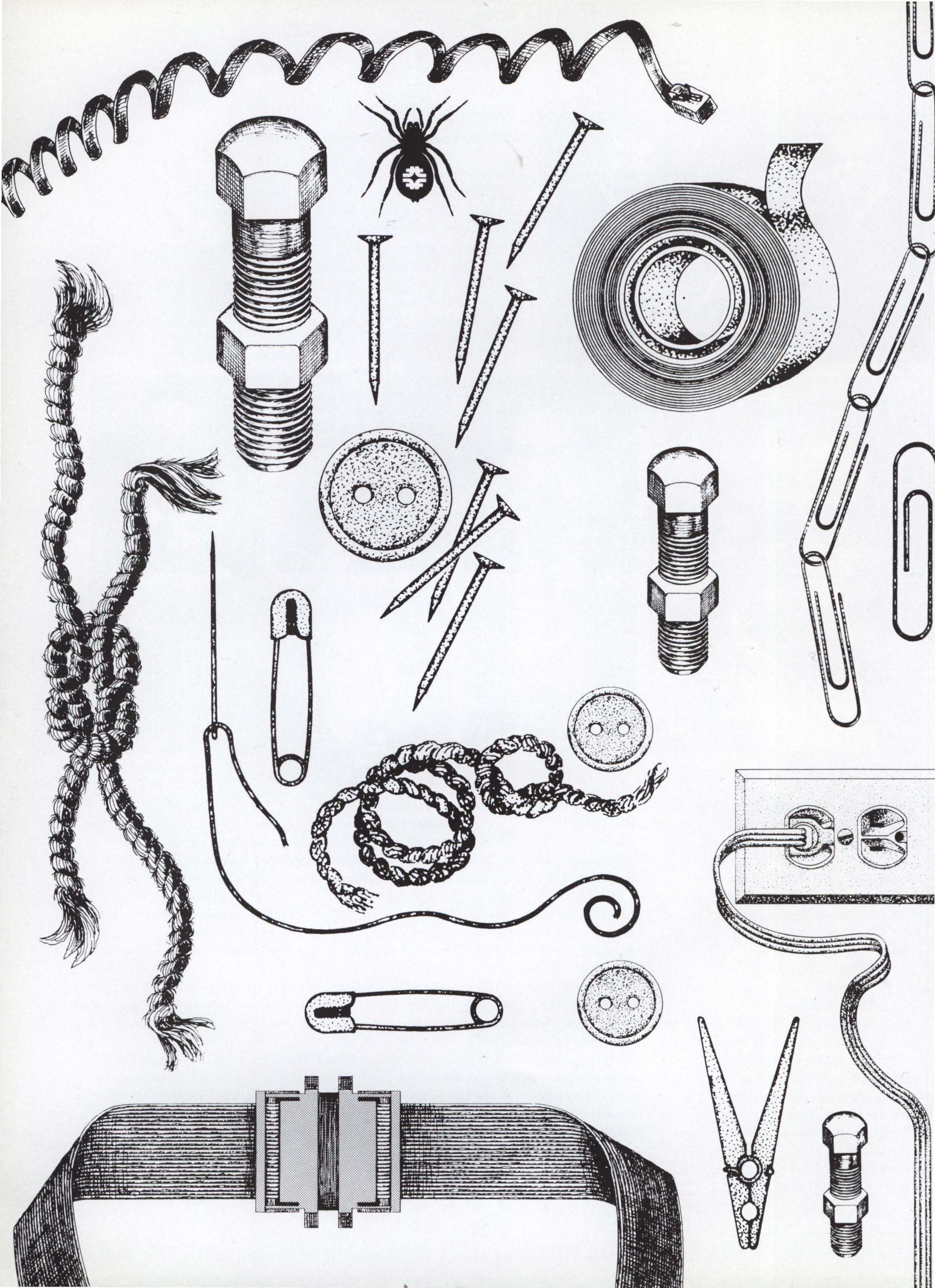
*(Top left to right)*
*Charles Brown*
*Joel Butler*
*H. E. Fisk*

*(Bottom left to right)*
*Christopher Hill*
*Donald Young*

***American Physical Society Fellowship***

*The American Physical Society designates for Fellowship those members who have contributed to the advancement of physics by independent, original research, or who have rendered some other special service to the cause of science.*

***Charles Brown**, Physics Section, elected "for his leadership in a series of experiments studying dimuon production by high energy hadrons."*
***Joel Butler**, Computing Division, elected "for his leadership in the study of charm quark states."*
***H. E. Fisk**, Research Division / DØ Construction Department, elected "for his leadership in neutrino physics research, and his skilled management of large scientific projects including superconducting high-gradient quadrupoles and Fermilab's DØ detector."*
***Christopher Hill**, Theoretical Physics, elected "for elucidating the mechanisms of shaping the spectra of ultra-high energy cosmic rays and neutrinos, and for contributions to the understanding of nonleptonic weak interactions."*
***Donald Young**, AD / Linac, elected "for contributions to the science of linear accelerators including the development of computer programs for RF fields and beam dynamics in accelerating structures, thereby advancing their design and construction."*



# Acknowledgements


Angela Gonzales. I first met Angela in the 1950s when I was a graduate student at Cornell and she was the Nuclear Lab's artist and draftsperson. For all these years I have been in awe of her and admired the breadth of her talents, but this is the first occasion I have had to work with her. She has continued the grand tradition of the Fermilab Annual Reports and provided this year's issue with a wonderful assortment of beautiful and whimsical fine art pieces and vignettes on the theme of connections. Besides these original creations, she has educated me on many of the finer points of layout and printing. I thank her most warmly for her key contribution.

Reidar Hahn's superb photography produces a handsome souvenir of Fermilab activities in 1990. He has contributed 89 educational and aesthetically pleasing photographs. Besides his photographs, he has helped me greatly with his broad technical knowledge of activities at the Laboratory. It has been a pleasure to collaborate with him and to acknowledge his contribution.

I want to thank most warmly each and everyone of the authors for their well written contributions. They have recorded for posterity the many Fermilab accomplishments of 1990. Their patience with me in answering my questions is appreciated. I apologize to these authors, if, in the editing process, I have introduced an inaccuracy or removed some subtle intention.

The authors of the 1990 Annual Report are:

Jeffrey Appel
William Bardeen
Richard Carrigan, Jr.
Michael Church
Roger Dixon
Christopher Hill
Catherine Newman Holmes
Stephen Holmes
Rolland Johnson
Mark Kaletka
Robert Kephart
Richard Kron
Barbara Lach
Joseph Lach
William Lidinski
Lee Lueking
Paul Mantsch
Harry Melanson
Craig Moore
Robert Noble
John Peoples
Petros Rapidis
Jay Theilacker
Paul Tipton
Michael Turner

As I discovered part way through this project, there are many things to learn and and do well in producing a book of this sort. Kate Metropolis read the manuscript and made important suggestions and caught many errors. Carol Renaud of The Renaud Group did the layout and made all the pieces mesh. Members of the Publications Advisory Board made many wise suggestions and offered encouragement. Fred Ullrich, its Chair, was always available to me for advice. Members of Media Services and Information Services contributed to the production and distribution of this report. I thank all of these people for the time and effort they have devoted to this project.

Finally, Barbara Lach, the Technical Editor, has worked as a partner to edit and produce this book. Without her tenacity, knowledge, and hard work, this report would still be languishing. She deserves the bulk of the praise and none of the blame.

Ernest Malamud, Editor



For information about Fermilab and subscriptions that are available write:
Public Information Office, MS 206, Fermilab, PO Box 500, Batavia, Illinois 60510.

**Accelerator** - Any machine used to impart large kinetic energies to charged particles.

**Annihilation** - A process whereby a particle and its antiparticle interact and disappear; their total energy coalesces into other pairs of particles and antiparticles.

**Antiparticles** - Each particle has a mirror image called an antiparticle, identical in mass and with opposite charge and other quantum numbers (e.g., proton-antiproton, positron-electron, neutrino-antineutrino).

**Atom** - A particle of matter indivisible by chemical means. It is the fundamental building block of the chemical elements.

**Axion** - Hypothetical weakly interacting particle that may exist in some formulations of the Standard Model.

**B-meson** - Contains at least one b-quark or b-antiquark.

**BØ** (pronounced "B-zero") - A reference point on the Main Ring at which the Collider Detector at Fermilab is located.

**Baryon** - Heavy, strongly-interacting particle made up of three quarks. The lightest baryon is the proton.

**Beam** - Narrow unidirectional stream of particles or radiation.

**Beam Intensity** - *The average number of particles in a beam* passing a given point during a certain time interval (e.g., the number of protons per pulse or protons per second).

**Beam Line** - A collective term referring to all the devices used to control, monitor, and produce a beam having particular characteristics. The common elements of a beam line are magnets, intensity monitors, beam position monitors, and collimators.

**Beam Space Charge Forces** - When the density in a charged particle beam becomes large, the charged particles exert forces on each other which tend to defocus the beam.

**Booster** - The rapid cycling synchrotron which receives 200 MeV protons from the Linac, accelerates them to 8 GeV, and injects them into the Main Ring for further acceleration.

**Boson** - An elementary particle with an integral number of spin units (measured in units of Planck's constant).

**Bremsstrahlung** - Electromagnetic radiation emitted when a charged particle is deaccelerated (loses momentum).

**Brightness** - Intensity per unit volume in phase space.

**Calorimeter** - A device used to determine particle energies by sampling the ionization deposited when a particle is totally absorbed in a heavy metal block, often made of iron or lead.

**Cerenkov Radiation** - Electromagnetic radiation emitted by a charged particle whose velocity in a medium (gas, liquid, solid) exceeds the velocity of light in that medium.

**Charge-Coupled Device (CCD)** - A solid state device used to convert visual analog information into digital information.

**Charmonium** - A bound state of a charm quark and an anti-charm quark. Charmonium states are mesons.

**Collider Detector at Fermilab (CDF)** - Apparatus designed to measure the results of colliding beams of protons and antiprotons, located at BØ.

**Colliding Beams** - Oppositely-directed particle beams brought together at small or zero angle to produce high energy collisions. Because even the most intense beams are dilute compared to ordinary solid matter, the beams must be recirculated many times through the interaction point to obtain a useful number of interactions.

**Collision** - A close approach of two particles – photons, atoms, or nuclei – during which energy, momentum, and sometimes quantum numbers, such as charge, are exchanged.

**Color** - A mnemonic used to indicate the threefold nature of quark interactions.

**Cross Section** - Measured in units of area. This is the fundamental term describing the probability for a reaction to occur. A large cross section signifies a probable outcome. A small cross section signifies a rare process.

**Cryogenics** - The technology of the production and effects of very low temperatures.

**Cryostat** - A vessel for maintaining a constant low temperature.

**DØ** (pronounced "D-zero") - A reference point on the Main Ring at which the DØ Detector is located.

**Decay** - A transformation in which an atom, nucleus, or subatomic particle changes into two or more other objects.

**Deep-Inelastic Scattering** - A violent collision between two *particles in which the target particle absorbs lots of energy and momentum from the beam particle.*

**Dewar** - A vessel for maintaining a constant low temperature.

**Dipoles** - A magnet with a north pole and a south pole. Dipoles are used to bend charged particles in a circular path.

**Duty Factor** - Fraction of time a system is operating correctly.

**Electron** - The least massive particle carrying electric charge and a constituent of all ordinary atoms.

**Electron Volt (eV)** - The amount of kinetic energy gained by an electron when it is accelerated through an electric potential difference of 1 volt.

**Elementary Particle** - A fundamental constituent of matter.

**Extraction** - The process of removing protons from an accelerator in a controlled fashion.

**Fastbus** - A mechanical and electrical standard for a type of high speed electronics.

**Fermion** - An elementary particle with a half integral number of spin units (measured in units of Planck's constant).

**Fixed Target** - Any stationary spot to which the beam of protons is directed and with which the beam collides or interacts.

**Flux** - Number of particles per second per unit area.

**Forbidden Decays** - Decays which violate one or more conservation law and therefore are observed rarely or not at all.

**Function Generator** - An electronic device which generates a varying voltage. Often used to control magnet systems.

**Gluon** - The particle that transmits the strong force.

**Hadron** - A particle that interacts via the strong force, either a meson or a baryon.

**Hard Scattering** - A particular type of collision which enables the study of phenomena at very small distances.

**Higgs** - Higgs mechanism and yet-to-be-discovered Higgs particle are a key to the unification of the weak and electromagnetic forces and a way to explain the mass of the W and Z bosons.

**Injector** - Refers collectively to the Cockroft-Walton, Linac, Booster, and Main Ring, a chain of accelerators that first accelerates and then injects protons into the Tevatron accelerator.

**Integrated Luminosity** - The luminosity added up over a time span, such as the length of an experimental run. Integrated luminosity is often expressed as inverse picobarns ($pb^{-1}$).

**Ion** - An atom or molecule that is not electrically neutral.

**Ion Source** - An electrical arc in hydrogen gas located in the high voltage electrode (dome) of the Cockcroft-Walton pre-accelerator.

**Jets** - Narrow clusters of subatomic particles resulting from collisions of quarks and antiquarks.

**Klystron** - An electron tube used for the generation and amplification of very high frequency electrical voltages and current.

**Lattice Gauge Theory** - A computational method for making calculations involving the strong force.

**Lepton** - A collective term for those particles that do not interact via the strong force, such as the electron, muon, and neutrino.

**Lifetime** - The time it takes for approximately 2/3 of a sample of unstable particles or radioactive nuclei to decay.

**Linac** - Linear accelerator. A radio frequency voltage is applied to the electrodes at the correct phase so that charged particles passing through them receive successive increments of energy.

**Liquid Helium** - The coldest substance that is still a liquid and the only refrigerant at temperatures of a few degrees Kelvin.

**Low-Beta Magnets** - Special quadrupole magnets used to focus the beam to create collisions of high luminosity.

**Low-Beta Insertion** - A series of low-beta magnets at one of the Tevatron straight sections.

**Luminosity** - The number of events (collisions) per unit of time per proton cross-sectional area.

**Luminosity Lifetime** - The characteristic time for a decrease in luminosity by a factor of about 2/3.

**Meson** - One of a class of strongly-interacting short-lived elementary particles composed of a quark-antiquark pair.

**Monte Carlo Events** - Data simulating real collisions or events that can be generated on a computer. These simulated events are used to test computer programs and evaluate biases in the detectors.

**Muon** - A lepton, very similar to an electron except for its larger mass. Muons are found commonly in the cosmic rays which impinge on the earth's surface.

**Neutrino** - An electrically-neutral, weakly-interacting, elementary particle with zero or negligible mass.

**Neutron** - An uncharged elementary particle with a mass slightly greater than that of the proton, found in the nucleus of every atom heavier than hydrogen. A free neutron decays into an electron, proton, and antineutrino.

**Nucleus** - The small, positively-charged core of an atom.

**Particle** - A small piece of matter.

**Phase Space** - A space whose coordinates define the dynamical state of a system, (e.g., [position, velocity]).

**Photon** - A "bundle" or particle of electromagnetic energy.

**Positronium** - A bound state of an electron and a positron.

**Proportional Drift Tube (PDT)** - A gas detector. When a charged particle passes through the PDT an electrical signal is generated from which the coordinate(s) can be determined.

**Proton** - One of the particles constituting all nuclei. Protons do not decay.

**Quadrupole** - A magnet with two north and two south poles arranged so there is no magnetic field at its center. Quadrupoles focus beams of charged particles.

**Quantum Chromodynamics (QCD)** - A mathematical description of the strong force acting between quarks and gluons.

**Quantum Electrodynamics (QED)** - A mathematical description of the electromagnetic force.

**Quark Compositeness** - The hypothesis that quarks may themselves be composed of some smaller, even more elementary building block.

**Quarks** - A fractionally-charged particle hypothesized to explain hadron structure. In a simple quark model the proton is composed of three quarks.

**Quench** - The name assigned to the phenomenon of going from the superconducting state to the normal resistive state.

**Septum** - A special type of magnet used in extracting a beam from an accelerator.

**Slow Spill Operation** - The usual mode of operating the Tevatron for fixed target physics. The beam is extracted slowly and smoothly over a period of several seconds.

**Soft Processes** - Collisions in which the momentum transferred between the colliding particles is small.

**Solid Angle** - The angular space intercepted on the surface of a sphere measured in steradians. A solid angle of $\pi$ steradians is the angular space intercepted by 1/4 of a sphere.

**Stochastic Cooling** - A technique used in the antiproton source to reduce the beam size.

**String Theory** - The latest theory of fundamental physics in which the basic entity is a one-dimensional object rather than a "zero-dimensional" point object.

**Structure Function** - Mathematical function which describes the size and shape of a particle such as a proton.

**Superconductivity** - A state of matter that many metals and alloys reach at very low temperatures (i.e., a few degrees K). This state is characterized by the total absence of electrical resistance.

**Switchyard** - A system of devices through which the primary proton beam is removed from the Tevatron and transported to the external (fixed) targeting stations.

**Synchrotron** - A circular machine that accelerates charged particles to high energy by the repeated action of electric forces on the particles during each revolution.

**Toroid** - A type of magnet approximating the shape of a donut.

**Tune** - A term which describes the strengths of the focussing magnets in a synchrotron.

**Tune Spread** - The electric forces between the particles in an accelerator beam cause a spread in the tune.

**Two-Phase Helium** - A mixture of liquid and gaseous helium.

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