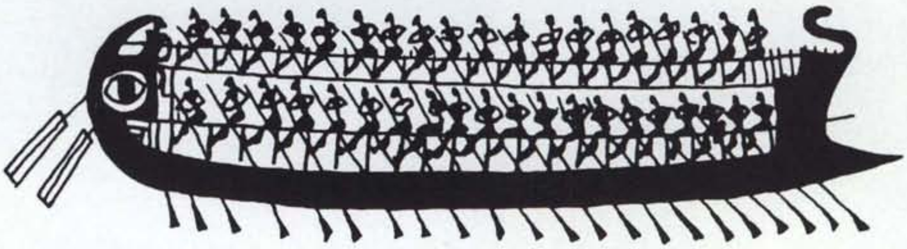

FERMILAB
1989



Fermilab 1989

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

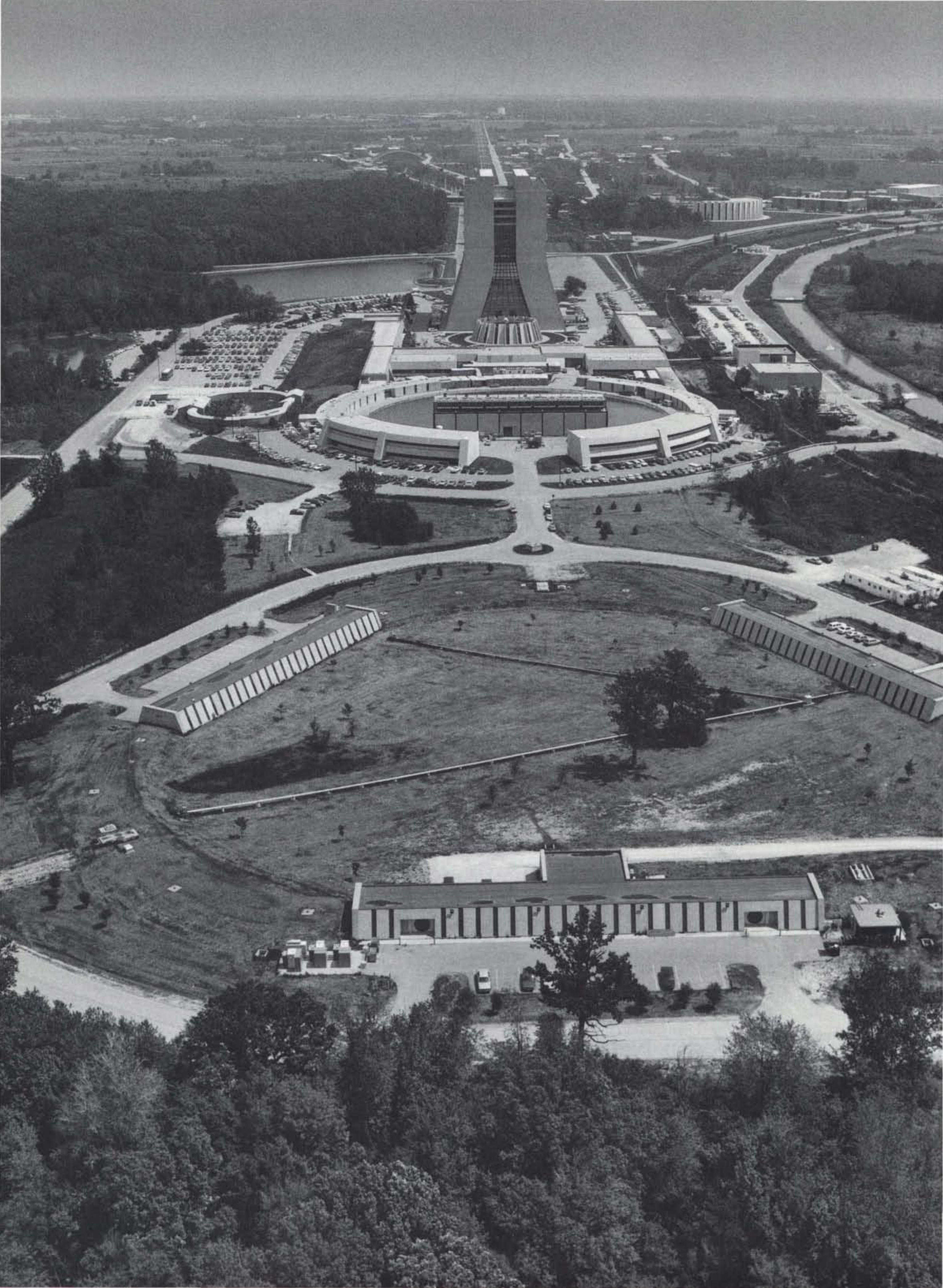
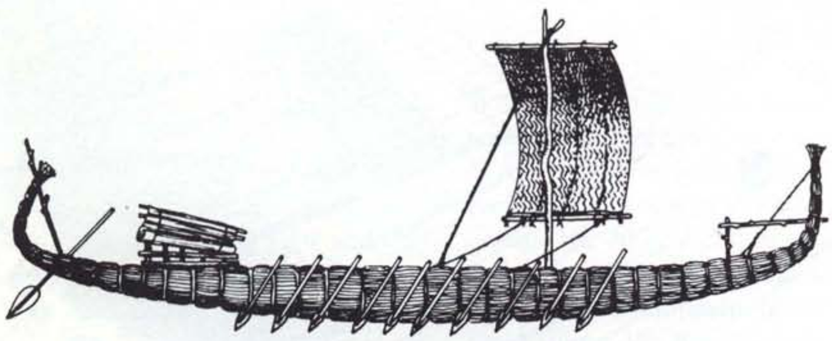
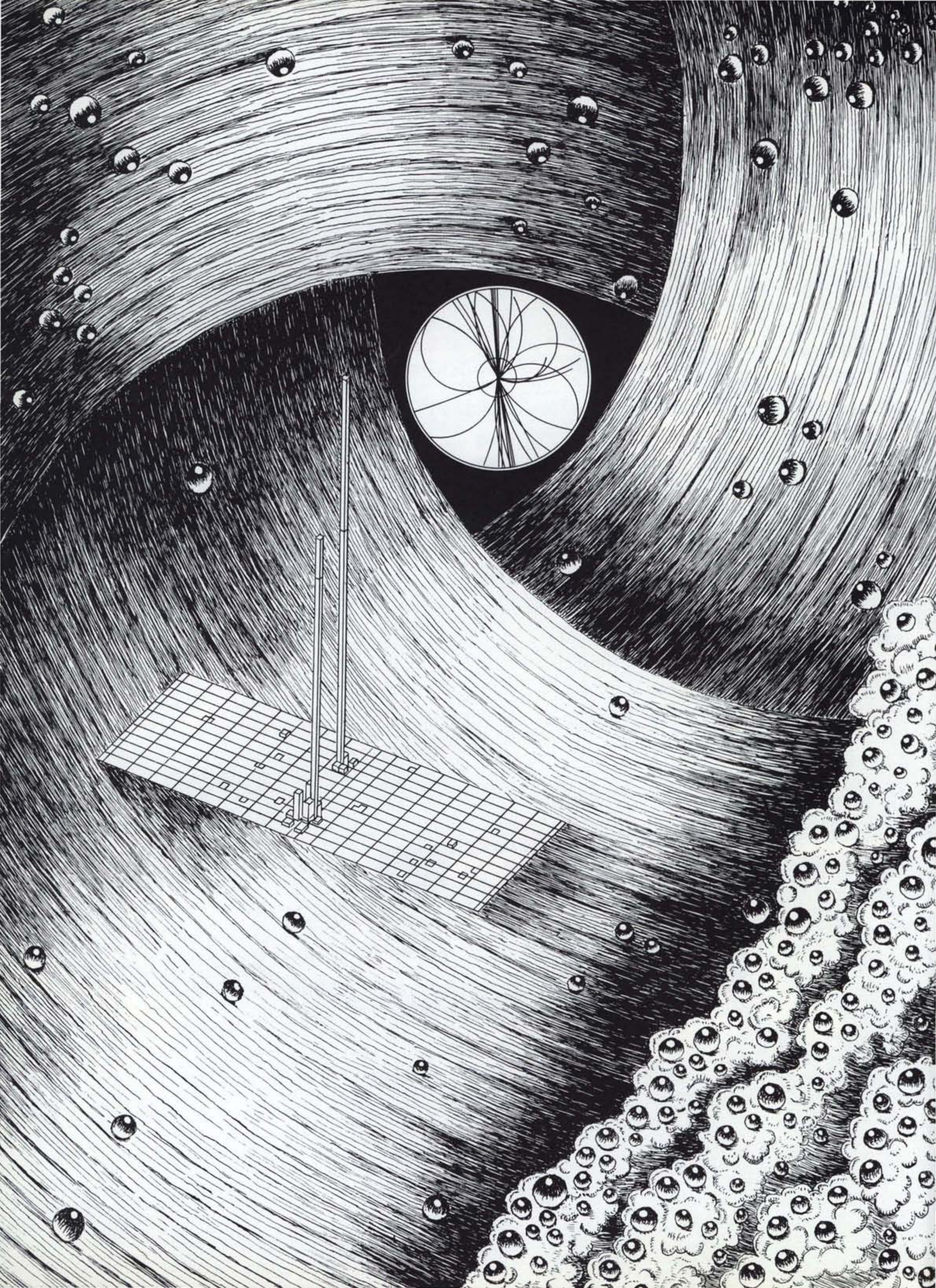


Table of Contents





Director's Statement

Exciting years have been a common occurrence at Fermilab. Over the years all of us have shared in the excitement of making the journey to the infinitesimal world of quarks and leptons and then discovering knowledge that we never imagined.

Nineteen eighty-nine was a truly exciting year — even by Fermilab's high standards. It was the year we completed our voyage toward becoming the foremost collider in the world. We did this by exceeding the design luminosity goal of the Tevatron by a factor of two. We did this by producing and analyzing the largest number of W and Z particles that ever had been produced in the Laboratory. President Bush recognized us when he awarded 1989 National Technology medals to Helen Edwards, Richard Lundy, J. Richie Orr, and Alvin Tollestrup.

The Tevatron and the Antiproton Source steadily and smoothly delivered a record number of proton-antiproton collisions to CDF. Of course the machines didn't do it by themselves, they were the ships that brought us to our destination. The people in the Accelerator Division set the course and kept us on it.

The CDF detector steadily stored the precious cargo of collisions on magnetic tape. The experimentalists analyzed these collisions more rapidly than our competitors had ever done. Within a month after the protons and antiprotons had finished traveling their circular path, the CDF collaboration reached its destination and submitted for publication the first measurement of the Z° mass with a precision of better than 1 GeV. Subsequent publications covered topics ranging from a precise measurement of the ratio of the W mass to the Z mass to a lower limit on the mass of the top quark. The CDF collaboration has shown that the elusive top quark is even more massive than 89 GeV.

Like Odysseus we have still other voyages to make. Over the past year the Accelerator, Research, and Computing Divisions, together with the CDF and DØ detector collaborations, have been preparing the next voyage in our search for the top. We will have a larger and swifter ship for this trip: two new sets of superconducting quadrupole magnets to focus the circulating beams of protons and antiprotons more tightly at CDF and DØ and new electrostatic separators to keep the beams from colliding except at the CDF and DØ detector locations.

The cargo of 30,000 data tapes from the 1987-88 fixed-target run and the newer cargo of 5,000 data tapes from the 1988-89 collider run are steadily being analyzed, thus refining the new data into new knowledge of quarks and leptons. Fermilab's computation and data-processing capability steadily increased during 1989. That capability will be increased still further to refine the shiploads of data that will be brought back from the voyages of 1990 and 1991. Already many of the initial results of the experiments from the last fixed target run and the last collider runs were presented at the Division of Particles and Fields Meeting at Rice University in January 1990. Many more results will be presented in the months to come.

Just as explorers have always set new sights at the end of each voyage of discovery, physicists prepare for data collection in a new cycle as the analysis of data from the last cycle is completed. Twelve groups of experimenters are now poised to begin the calibration of their detectors prior to data taking. The Tevatron's cargo of 800 GeV protons has already been delivered to all of the experimental areas and the experiments are in motion searching for charm, bottom, jets, and still other jewels of the subatomic world.

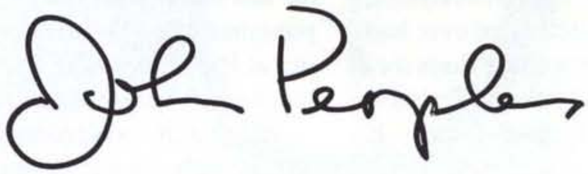
The destination of 1989 is only a port where we will prepare for a much longer voyage, the search for the top. Our new ship, Fermilab III, will exceed the design specifications of the accelerator complex in every measure. When we are finished building it we will increase the luminosity by a factor of fifty. The energy of the colliding beams will exceed 2 TeV, and the sensitivity of CDF and DØ to find the rarest of quarks will be extended by a factor of one hundred. With Fermilab III we will find the top quark although it may take three or four more trips.

And when we have found top, we will go to sea for more. Our staff will build one of the detectors to capture the 40 TeV collisions at the Superconducting Super Collider (SSC). Already we are helping the SSC in the development of full-length magnet assembly fixtures. We have already begun the fabrication of prototype magnets and plan to have the first full-length magnet ready for testing in 1990. Soon thereafter we expect to be guiding the SSC's industrial contractor in the construction of the first full-length

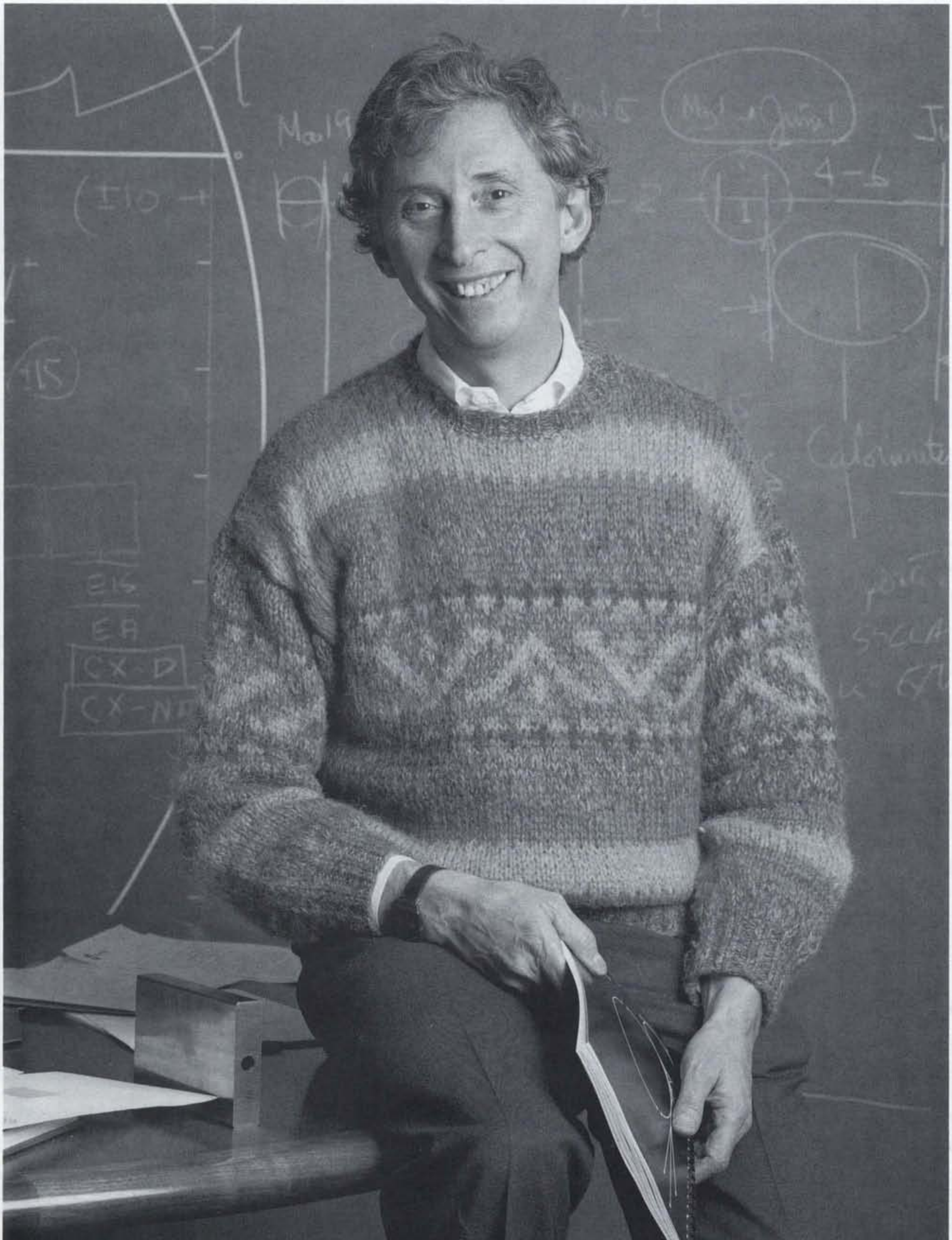
50-mm bore SSC dipoles using Fermilab magnet assembly fixtures in the Industrial Center.

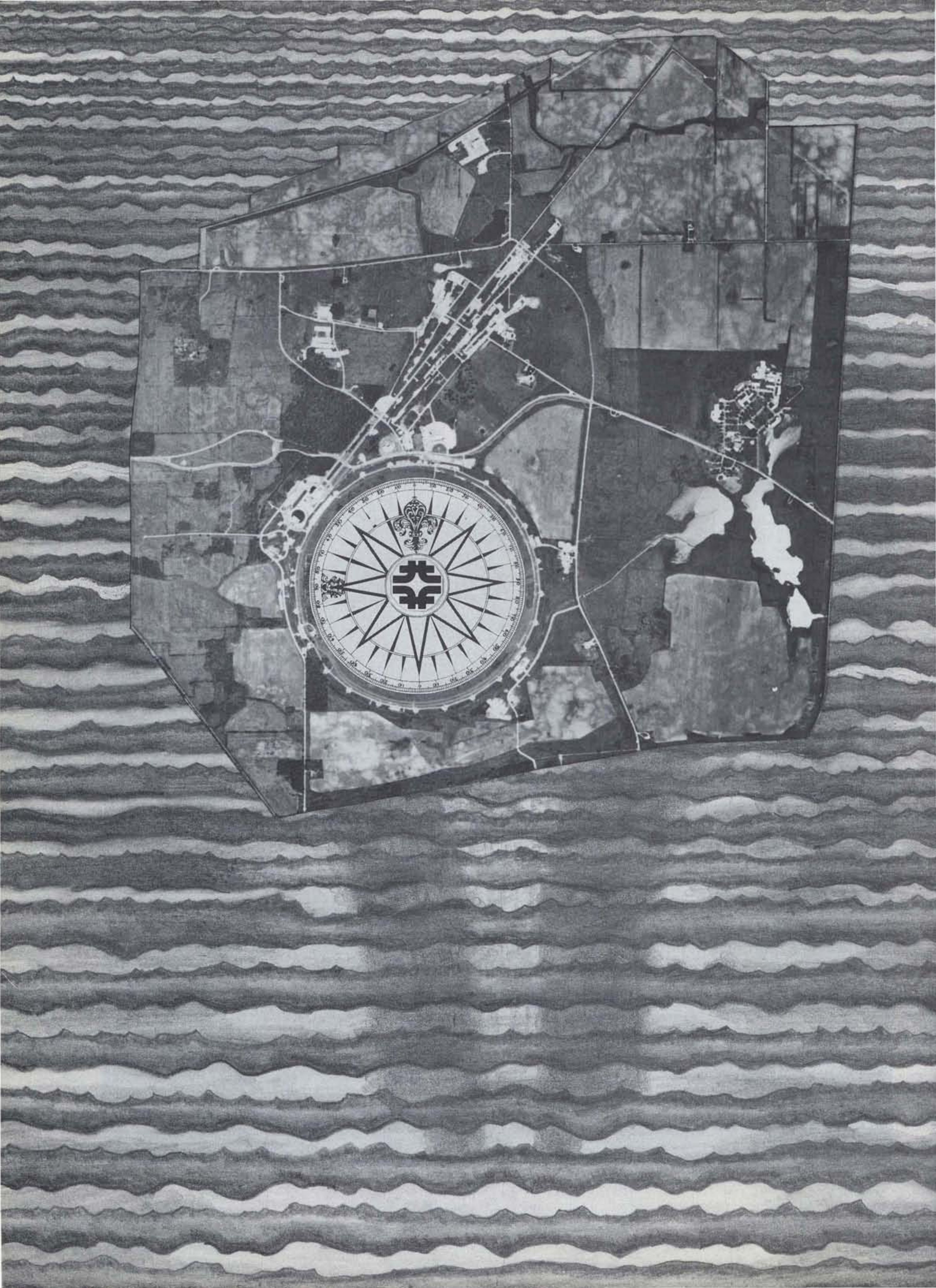
Finally, 1989 was a year of change. In July, Leon Lederman retired after 11 years as Director, only to begin a new career as educator extraordinary, Director Emeritus of Fermilab, and Professor of Physics at the University of Chicago. The mathematics and science education program he created while Director became the Education Office in October. In the same month, the Computing Division sprang full-blown from the brow of the Research Division. It is now developing its acquisition strategies in anticipation of the great cargoes of data that the 1990-91 fixed-target run and the 1991-92 collider run will return.

Yet all of our accomplishments seem so small when compared to the incredible changes taking place throughout the world. As turbulent as those changes may seem, participation by scientists from all of Europe and Asia is greater than it has ever been. We have learned from them that the responsibility for equitable government cannot be left to someone else, and we have learned that the dream of freedom cannot be extinguished. We live in interesting times.



John Peoples Jr., assumed his position as Fermilab's third director on July 1, 1989.





Introduction to Fermilab

Fermilab, the Fermi National Accelerator Laboratory, is one of the world's foremost laboratories dedicated to research in high energy physics. The Laboratory is operated by Universities Research Association, Inc., a consortium of 77 major research-oriented universities located in the United States and Canada, under a contract with the U.S. Department of Energy (DOE).

Fermilab is located on 6,800 acres donated by the State of Illinois to the U.S. government in 1969 for its construction. It is 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 this high-technology Corridor between Chicago and Aurora.

In 1989 the Fermilab staff consisted of more than 2,200 full-time employees, including 285 scientists and 164 engineers. In addition, there were 500 physicists and more than 220 graduate students from 53 American universities actively engaged in research here. Last year Fermilab also attracted scientists affiliated with 52 different institutions from 18 foreign nations.

Research at Fermilab

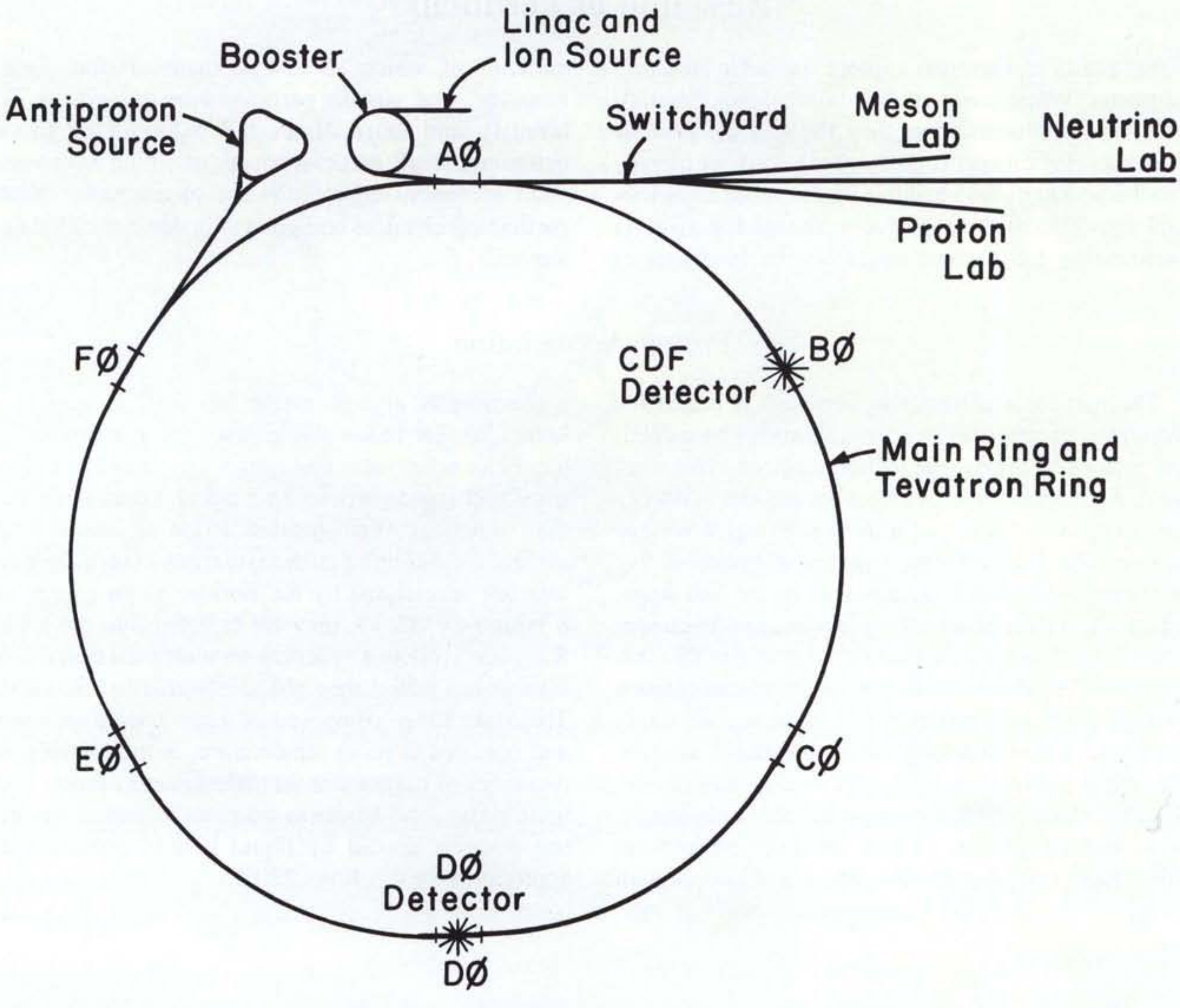
Physicists at Fermilab explore the basic structure of matter. When scientists first broke down the atom into its constituent parts, they thought the protons (positively charged particles) and neutrons (uncharged particles) making up the atom's nucleus and the electrons (negatively charged particles) surrounding the nucleus might be the fundamental particles of which all else is made. Before long, however, new, smaller particles were discovered. To identify and learn about the behavior of these extremely small particles, many of which have very short lifetimes, requires the use of machines called particle accelerators equipped with devices called detectors.

Proton Acceleration

The particle accelerator at Fermilab 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 first stage, a large dc voltage accelerates particles, hydrogen ions consisting of one proton and two electrons, to 750,000 eV (about 30 times the energy of the electron beam in a television set's picture tube). In the second stage, the Linac, a 500-foot-long linear accelerator, accelerates these particles to an energy of 200 million eV. The two electrons are then stripped off the hydrogen ions, leaving 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 is a circular accelerator that uses magnets to bend electrically charged particles in a circular path such that they experience the repeated action of accelerating electric fields during each revolution.) Once the protons are accelerated by the Booster to an energy of 8 billion eV (GeV), they are injected into the Main Ring accelerator, a synchrotron with a diameter of 2 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 operating at approximately 4.5 K (-270°C).

Antiproton Acceleration

The Tevatron's injector is also used to initiate production of the antiprotons used in Fermilab's particle research. An antiproton is a particle that has the same mass as the proton but opposite electrical charge. Because antiprotons are antimatter and do not exist naturally on earth, Fermilab produces them from batches of 2,000 billion protons that have been accelerated to 120 GeV in the Main Ring. The batches are removed, sent to the target station, and focused on to a production target. Of the many particles and antiparticles produced in the collisions, about 10 million antiprotons are collected in a Debuncher ring. The captured beam of antiprotons is then reduced in size by a process known as stochastic cooling. The antiprotons are then transferred to the Accumulator ring, where over 1,500 batches per hour of antiprotons are merged into a single beam, cooled further, and accumulated or stacked. Six batches of antiprotons, each containing 20 billion particles, are injected into the Main Ring at 8 GeV, accelerated to 150 GeV, passed down to the Tevatron, and accelerated simultaneously with a counterrotating beam of protons to nearly 1 TeV.



A schematic drawing shows the layout of various accelerators and experimental areas at Fermilab.

An aerial view of the Fermi National Accelerator Laboratory clearly shows the ring that houses the Tevatron. Fermilab's 6,800 acre site is located 35 miles west of Chicago's downtown area in the Illinois counties of DuPage and Kane. Because of its unique position in the world of high energy physics, Fermilab's close proximity to O'Hare International Airport is particularly advantageous for the many visitors who come to the laboratory.

Particle Research

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 impact on 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 is the most important factor. The amount of detail observed during a collision increases with the energy of the collision. For example, the energy at the center of a collision of two beams of particles traveling in opposite directions is equal to the sum of the energies of the beams. Thus, the energy produced at the center of a collision of a 1 TeV proton beam with a 1 TeV antiproton beam would be 2 TeV. These very high energy densities have the potential to produce very massive new particles in the collision.

The number of collisions between particles, or events, that takes place 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 nanobarns per second. (One nb equals 10^{-33} cm^2.) As the luminosity rises, the probability rises that a meaningful particle collision has occurred and that the researcher may discover something new.

The Standard Model

Fermilab theorists and experimentalists are studying the details of a description of the matter and forces in the universe called the Standard Model. In this model the strong, electromagnetic, and weak forces between quarks and leptons produce the interactions that we observe in nature. In 1989, all their experimentation, data analysis, design and installation of equipment, and theoretical investigations had one simple goal: the search for the ultimate structure of matter and energy by studying the forces and particles involved in high energy collisions.

Forces. According to current theory there are four forces in nature. Gravity is the force that holds us on the earth and keeps heavenly bodies in orbit. The force that holds atoms together is the electromagnetic force. The strong force binds protons and neutrons in the nucleus of an atom, and the weak force is seen mainly through the decay of unstable particles.

These forces are transmitted through the exchange of particles. For example, the electromagnetic force is transmitted by the exchange of photons, massless particles that travel at the speed of light. The weak force is transmitted by the exchange of three very heavy particles, W^+, W^-, and Z°. The strong nuclear force is produced by the exchange of particles called gluons. Finally, it is hypothesized that the force of gravity is transmitted by an as yet undiscovered particle called the "graviton," which, like the photon, is predicted to be massless and travel at the speed of light.

Particles. Subatomic elementary particles are divided into two families. Those that are not affected by the strong force are called leptons; they are among the lightest particles known. The electron is the most well known of this family; the muon and the tau lepton are heavier than electrons but carry the same negative charge. The three neutrinos are electrically neutral; neutrinos are the most common (but hardest to observe!) objects in the universe, possibly outnumbering atoms by a billion to one.

Quarks are subatomic elementary particles that are affected by the strong nuclear force. They carry a charge of $+2/3$ or $-1/3$ of the charge on a single proton. The lightest quarks are the up and down quarks, followed by the strange and charm quarks, and then the heaviest, the top and bottom quarks.

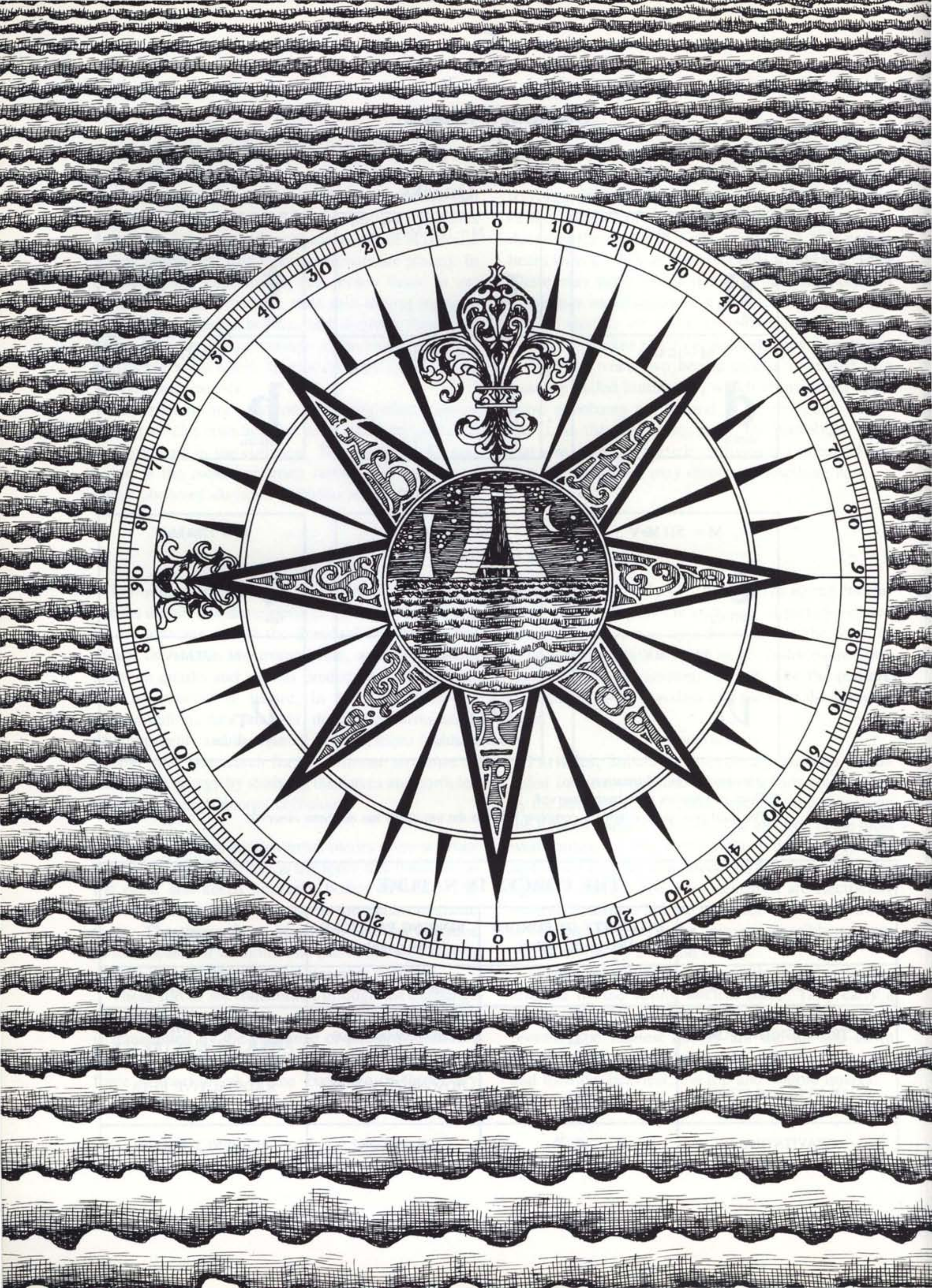
Standard Model

	I	II	III
	Quarks		
Q = +⅔	M ~ 5 MeV **u** up	M ~ 1500 MeV **c** charm	**t** top
Q = −⅓	M ~ 10 MeV **d** down	M ~ 300 MeV **s** strange	M ~ 5000 MeV **b** bottom
	Leptons		
Q = −1	M = .511 MeV **e** electron	M = 106.6 MeV **μ** muon	M = 1784 MeV **τ** tau
Q = 0	M < 30 eV **ν_e** electron neutrino	M < 350 keV **ν_μ** muon neutrino	M < 35 MeV **ν_τ** ray neutrino

- Q means charge. M means mass.
- Three generations have been observed.
- The third generation is not yet complete because the top quark has not been observed.

THE FORCES IN NATURE

TYPE	INTENSITY OF FORCES (Decreasing order)	BINDING PARTICLE (Field quantum)	OCCURS IN
STRONG NUCLEAR FORCE	~ 1	GLUONS (no mass)	ATOMIC NUCLEUS
ELECTROMAGNETIC FORCE	$\sim \frac{1}{1000}$	PHOTON (no mass)	ATOMIC SHELL APPLIC. OF ELECTRICITY
WEAK NUCLEAR FORCE	$\sim \frac{1}{100000}$	BOSONS Z^0, W^+, W^- (heavy)	RADIOACTIVE BETA DECAY
GRAVITATION	$\sim 10^{-38}$	GRAVITON?	HEAVENLY BODIES



Scientific and Technical Accomplishments

Nineteen eighty-nine was a banner year at Fermilab. We exceeded the design specifications of Tevatron I during the collider run. The Main Ring intensity of coalesced proton bunches was twice as large as in 1988, and there was a 50% increase in proton intensity to 1.8 x 10^{12} protons per cycle. We developed and implemented a system to reduce the size of the antiproton beam stored in the Accumulator and increased the yield of antiprotons delivered by the Debuncher accelerator.

Various accelerator improvements yielded more proton-antiproton collisions than had been anticipated by the Collider Detector Group (CDF), resulting in a very successful physics run. The 5,000 data tapes recorded during the run were processed and yielded many data-summary tapes for detailed analysis. While CDF has not yet found the top quark, they have determined that it is more massive than many had assumed.

After the completion of the fine collider run, we implemented unique techniques for diagnosis and repair of the Tevatron's superconducting dipole magnets. The subsequent inspection of and preventive maintenance on some 300 cryogenic magnets showed that, despite the complexities of superconducting dipoles, a superconducting accelerator can indeed be repaired and modified. The accelerator should now be in good repair for future extended data runs.

In the fixed-target areas, we assembled new experiments, improved beam lines, upgraded detectors, and published interesting results based on the analysis of data from the 1987-88 run.

Fermilab astrophysicists made important discoveries using the observations of supernova 1987a and have used advanced computing techniques to analyze the possible role of cosmic strings in galaxy formation.

We formed a new Computing Division and moved them and some of their equipment into a new building without interrupting service to the Fermilab research effort. In addition, we developed a powerful and successful computer system for lattice gauge theory computation and our technical groups designed the first fully custom chip for a time-to-digital convertor (TDC) project.

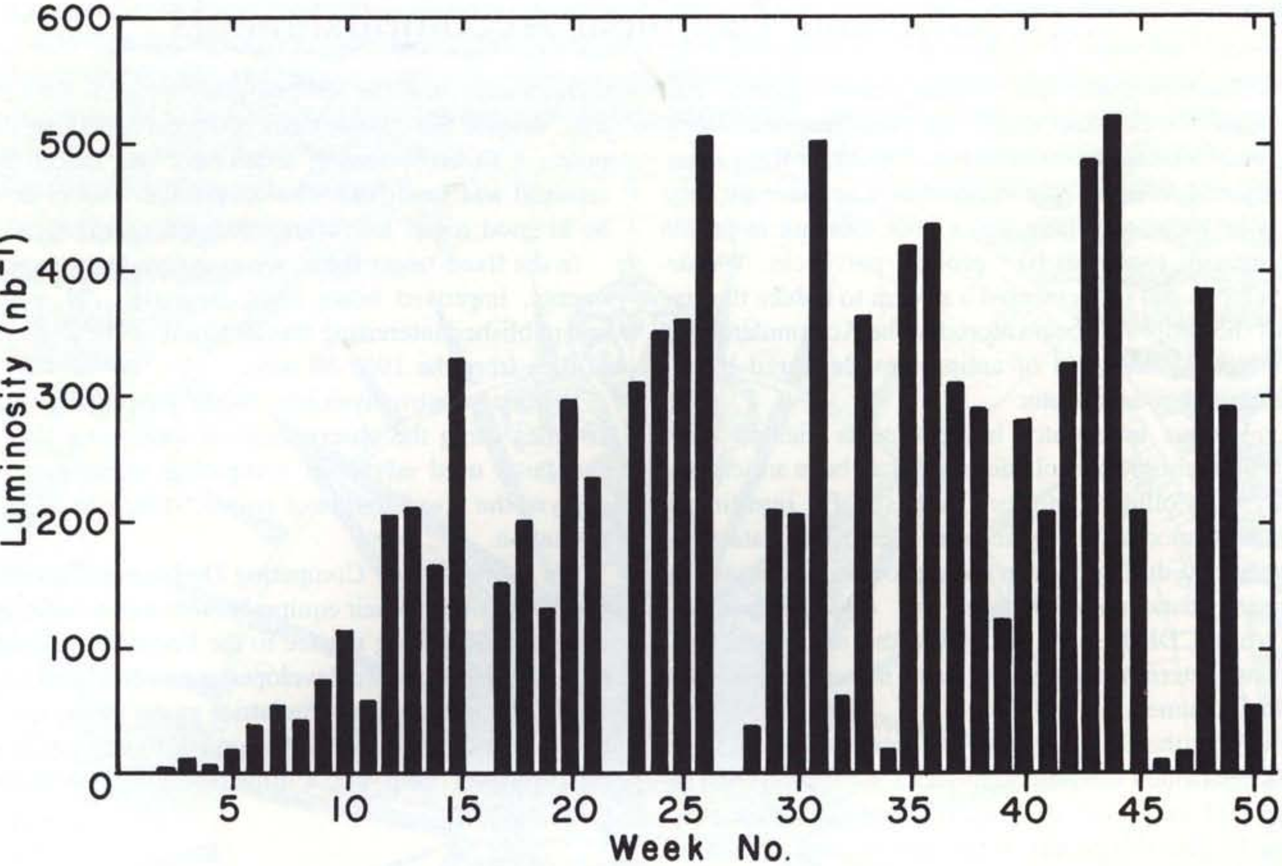
The 1989 Tevatron Collider Run

The Tevatron was operated in the proton-antiproton collider mode (TEV I) between June 1988 and June 1989. This report focuses on the accomplishments achieved during 1989. The 1988 part of the run was described in last year's Annual Report.

At the end of 1988, the collider had already achieved initial luminosities of greater than 2 x 10^{30}/cm^2/s. (The number of events (collisions) per second of a particular type is given by the product of the collision cross section and the collider luminosity; hence, high luminosities give us the ability to see rarer events.) Integrated luminosities, which also include machine reliability, had exceeded 500 nb^{-1} per week. The operation of the accelerator complex, although never completely routine, had a semblance of calm and order, especially when compared with the early days of the run.

At the beginning of the 1988-89 collider run, the activity in the Main Control Room was very hectic. Five-man "shot teams" were helping the operators with the various setups and "experts" were scattered all over the accelerator complex massaging critical pieces of equipment. (A "shot" refers to the process of transferring antiprotons from the Accumulator ring to the Tevatron.) The policy, during this initial period, was to take the time to understand every shot failure and take corrective action. Although this policy initially reduced the integrated luminosity, it was a spectacular success in the longer term. The reliability of all systems improved, and new software needed to automate procedures was continually implemented.

By the beginning of 1989 the shot teams were disbanded, the experts were called in on an as needed basis, and the accelerator was running at design specifications. A few numbers emphasize the phenomenal success of the run. The graph shows the integrated luminosity versus time, and Table 1 compares typical running conditions with the TEV I design specifications and summarizes collider performance for the run. The peak luminosity was twice design, and the total delivered luminosity was almost 10,000 nb^{-1}, far exceeding the 1000 nb^{-1} "expected" for

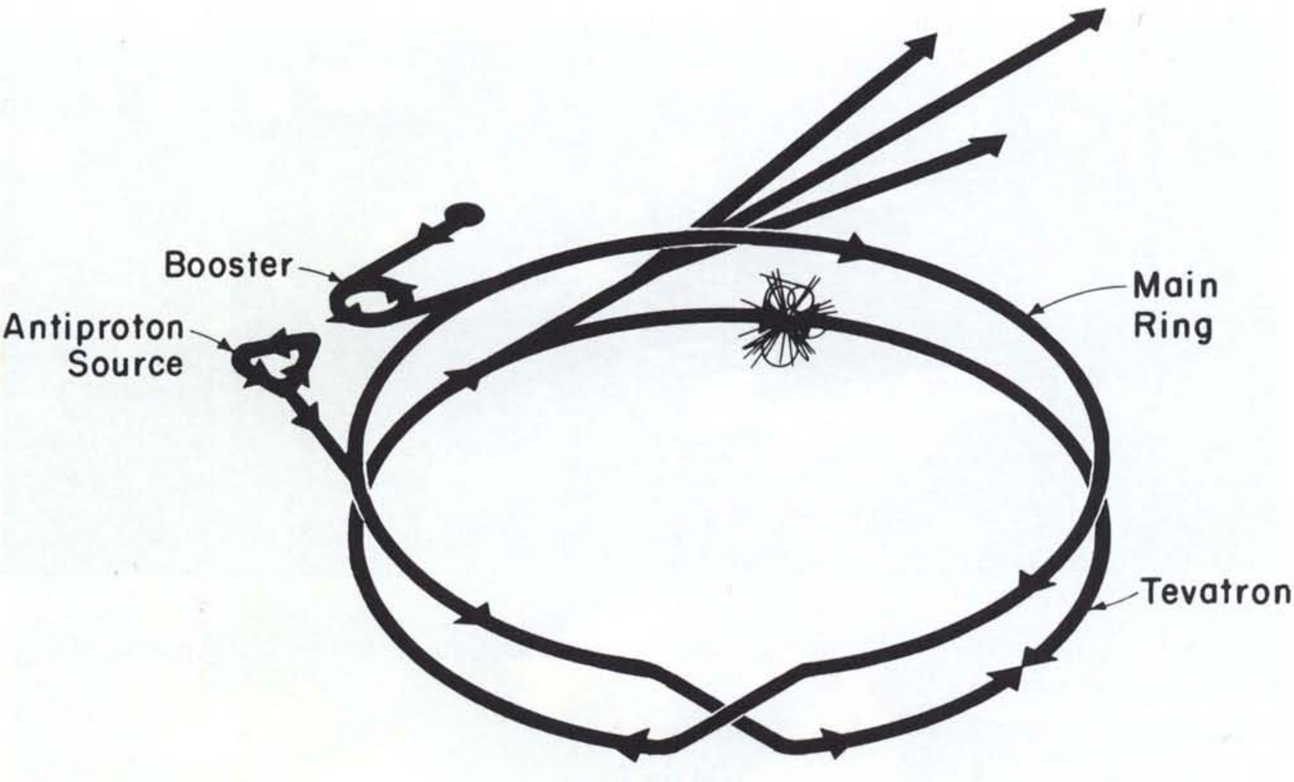


This graph shows the integrated luminosity of proton-antiproton collisions accumulated each week during the 1988-89 collider run.

the run. The data provided in Table 1 indicate that the antiproton source achieved a record production rate of 2.25 x 10^{10} antiprotons per hour, a record accumulation of 97 x 10^{10} antiprotons, and a record period of 53 hours for colliding a single fill of counterrotating protons and antiprotons in the Tevatron.

During the rest of the collider run we expended a large amount of effort trying to improve the performance of the Tevatron and found ourselves bumping into physics constraints in every new idea we tried. Specifically, the peak luminosity was constrained by limits on the proton and antiproton densities that could be delivered to the Tevatron. The presence of destabilizing resonances in the transverse oscillation of the counterrotating beams in the Tevatron (betatron oscillations) limits the phase space available for stable, long-lived orbits. We found that increasing the proton densities excited a seventh-order resonant oscillation in the antiproton beam due to the interaction of the electric field of the proton beam on the antiproton beam. This provides the rationale for building electrostatic separators in preparation for the next collider run. These separators will reduce the number of collision points in the Tevatron, thereby reducing the beam-beam interactions.

As the number of antiprotons stored in the Accumulator ring increases, the accumulation rate, the fraction of antiprotons extracted, and the efficiency of antiproton transmission to the collider decreases. These factors conspire to limit the antiproton density and, hence, the delivered luminosity. A planned series of upgrades in the Antiproton Source will improve on these limits. Unexpected store losses (Table 2) also limit the total integrated luminosity delivered.



A schematic drawing shows the paths of the proton and antiproton beams in the Fermilab accelerator complex. The long journey, at close to the speed of light, must be controlled with extreme precision to effect collisions at the proper place within the detectors. Note that the protons and antiprotons circulate in opposite directions.

Table 1. Tevatron Design Specifications and 1988-89 Run Data

Parameter	Tevatron Design	1988-89 Run
Protons per bunch	6.0×10^{10}	7.5×10^{10}
Antiprotons per bunch	6.0×10^{10}	2.5×10^{10}
Number of bunches	3 x 3	6 x 6
Low-beta (meters)	1.0	0.55
Initial luminosity (events/s/cm^2)	1.0×10^{30}	1.6×10^{30}
Lifetime (hours)	20	15-35
Antiproton stack	50×10^{10}	70×10^{10}
Maximum		97.2×10^{10}
Maximum stack rate in 1 hour		2.25×10^{10}
Integrated store hours		4257
Maximum integrated luminosity/week (nb^{-1})		518
Maximum integrated luminosity/ store (nb^{-1})		135
Peak store length (hours)		53
Typical shot setup (hours)		3
Typical controlled store length (hours)		21.5
Total number of stores		295
Abnormal store ends (%)		55

Table 2. Reasons for Store Terminations

Explanation	Times
Intentional, due to low luminosity	99
Abort kickers prefire	31
Tevatron power supplies	23
Maintenance and development	21
Quench protection system	17
Lightning and power glitches	15
Intentional for experimenters	13
Tevatron radiofrequency system	11
Human error	11
Cryogenics	9
Vacuum	9
Controls	8
Experimental area operations	7
Dipole correction system	5
Low beta quads	4
Pond water pumps	3
Miscellaneous	9

All five stages of the acceleration process are monitored in the Main Control Room. It is staffed year-round, twenty-four hours a day.

Main Ring

The intensity of coalesced proton bunches in the Main Ring for injection into the Tevatron was twice as large as that obtained in 1988. The intensity for antiproton production was increased by approximately 50%, to a typical single-batch intensity of 1.8 x 10^{12} protons. At the same time, there was considerable progress in reducing the effects of Main Ring losses at B0 for CDF experiments, at C0 for experiment E-735, and at E0 for E-710. Additional work successfully reduced the losses at D0 in anticipation of the 1991 run of E-740. (Experiments that scientists propose to undertake at Fermilab are given numbers such as E-735, E-736, etc. As of April 1, 1990, the Laboratory had received 817 experiment proposals, had approved a total of 386, and had completed 345 of those approved.)

Studies of the Main Ring focusing and betatron oscillations performed during the year centered around changing the Main Ring betatron tune, which was needed to optimize the performance of the D0 overpass that had been installed in 1988. Another effort involved the addition of special quadrupole magnets (beam focusing devices) to reduce the horizontal dispersion in the Main Ring leading to a larger momentum acceptance. Studies on the coalescing of proton beams into a few high-intensity bunches led to better insight into the limitations of beam-induced voltages on radiofrequency (rf) cavity performance.

The Accelerator Division made a number of changes during the 1989 shutdown in an attempt to improve the performance of the Main Ring. First, we replaced the 1972-vintage Main Ring controls system with a modern system that should increase Main Ring reliability and capability. Second, we replaced the old fixed-current correction-element power supplies, which were used to steer the injected beam along a tortuous path to avoid obstructions imposed by the overpasses and by extraction devices (i.e., abort, Tevatron injection, and antiproton production). The new power supplies have a computer-controlled variable-current output. Their response can be tailored to the varying conditions occurring during the acceleration process. As the main accelerator magnetic fields are increased (ramped) to match the increasing energy of the accelerated particles, time-varying and hence improved orbit control will be provided, leading to higher intensity beams and lower losses for the collider experiments. The new correction-element system will also allow better compensation for the effects of varying excitation in the Tevatron, which distorts the Main Ring orbit through magnetic and power-line coupling. Third, we installed fast computer-controlled tuning in the Main Ring rf cavities to reduce beam loading during the bunch coalescing. Finally, we replaced a number of magnets that had been identified as restricting the available apertures for stable proton orbits.

Antiproton Source

Although the antiproton source performance exceeded all expectations with record accumulation rates and a peak antiproton stack approaching a thousand billion antiprotons, the Antiproton Source Department continued working on ways to improve performance. One important improvement was in the efficient transfer of antiprotons through the Main Ring to the Tevatron. Large antiproton stacks are required to obtain high luminosity; however, the transverse emittance (physical beam size) increases with the

Joel Misek (left) and Michael Gormley examine and adjust a stochastic cooling cavity in the Accumulator ring.

stack size. Because the acceptance of the Main Ring is not much larger than the antiproton beam emittance, there is a decided drop in transfer efficiency for large antiproton stacks. To solve this problem, we attempted to improve beam cooling (i.e., to reduce the size of the antiproton beam coasting in the Accumulator ring). We developed and implemented a cooling system with a higher band width (4 to 8 GHz) than the original system (2 to 4 GHz). (A GHz is a unit of frequency equal to a billion cycles per second.) The new system already exceeds the performance of the original system. Further work is expected to lead to additional improvement.

The nature of high energy physics research is such that the successful collider run did not quench the thirst for high antiproton rates. A 30% increase in antiproton yield arose from the observation that the beam transfer line leading to the Debuncher and the Debuncher ring had only a few limiting apertures. The modification of a few magnets (the "left bends" in the beam line) and an increase in the gap of the stochastic cooling cavities increased the beam acceptance with an attendant increase in the antiproton yield. Because the electric field in the stochastic cooling cavities is proportional to the applied voltage divided by the gap, this modification required doubling the number of traveling wave tubes in order to double the microwave power.

While the Debuncher ring transverse cooling was being improved, we added a new Debuncher momentum cooling system designed to decrease the momentum spread of the antiprotons by 50%. The efficiency of antiproton stacking is increased as the momentum spread in the Debuncher is decreased. This new system is implemented with a new type of filter that employs a commercial bulk acoustic wave device, a compact module that generates delays at microwave frequencies. The performance of this filter is as good as or better than that of the superconducting cable filters used in a previous system, and the cost is an order of magnitude less.

Tevatron Magnet Repairs

The world's first and largest superconducting accelerator continues to be an important laboratory on long-term effects in high-field super-conducting magnets. The original development of the Tevatron laid the foundation for the modern superconducting wire and medical imaging industries. Fermilab has identified many problems and successfully developed techniques for repairing these "sealed" superconducting magnets. One-quarter of the 774 dipoles were repaired in 1986, and the rest were repaired in 1989. The entire ring of magnets was warmed to room temperature for the three classes of repairs made on the Tevatron dipoles.

The first class of repairs involved stopping excitation-dependent leaks from the single-phase liquid helium to the insulating vacuum. These leaks resulted from a fabrication choice that failed to allow for the dynamics of rapidly changing currents (ramping) in the dipoles. When a Tevatron dipole ramps up, the increasing magnetic force on the coils causes them to expand by about 1/16 of an inch on each end. In some magnets, round-head screws were used to attach a block to the end of the coil. The expansion of the coil during ramping caused these screw heads to push against a welded part, eventually cracking the welds and resulting in a helium leak. We solved this problem by replacing the round-head screws with flat-head screws and replacing the blocks with thinner blocks so there would be no contact during coil expansion.

A second class of repairs involved vaporization of the superconducting leads. This problem had two contributing causes. First, because the two leads emerging from the coil carry current in opposite directions, the magnetic force between them causes them to repel one another. If they are not tied securely together, they flex when the dipole is ramped. This motion causes the individual strands of superconductor making up the leads to crystallize and break. Second, the leads were abrading on the sharp corners of the blocks used to restrain them. This motion slowly rubbed away the insulation on the superconducting cable. Most of the leads with broken strands were repaired in place without removing the dipole from the tunnel. We prevented further damage by replacing sharp-edged blocks with blocks having beveled edges and by tying the two leads together securely enough to prevent motion.

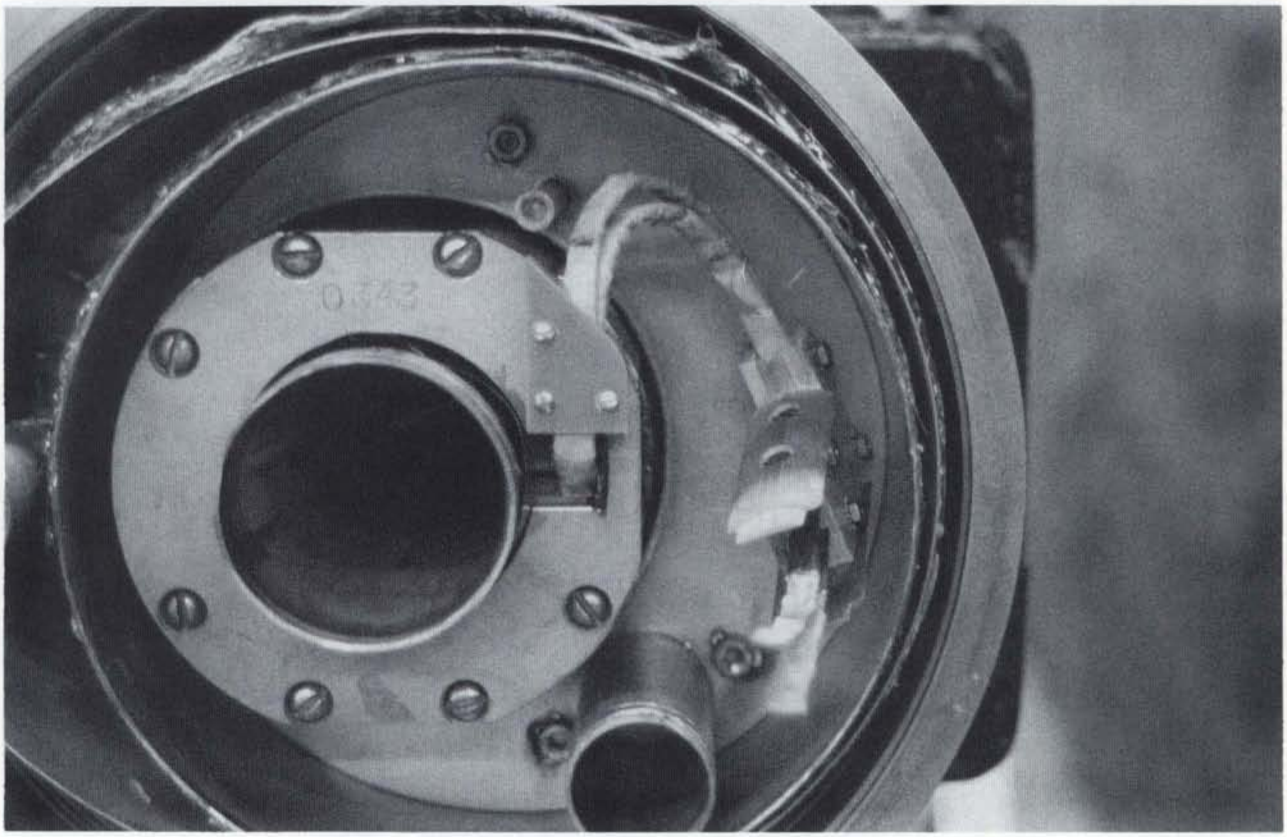
The third class of repairs could be called preventive maintenance. To prevent unraveling of the Kapton plastic film insulation wrapped around the beam tube, we attached it with glue, Kevlar ties, and shrink tubing. To prevent loosening of an L-shaped assembly

Bruce Hanna examines the inside of a superconducting dipole magnet. Fermilab has pioneered the use of these "remote surgery" techniques for repairing sealed superconducting magnets.

of pieces, which carefully positions the ends of the leads within the single-phase bellows, we replaced screws with rivets.

The physical replacement of 28 dipoles fell within previous estimates, although the reasons for replacement were not as expected. Most (24) dipoles were replaced due to leaks caused by warming the magnets from liquid-helium temperature to room temperature so that necessary repairs could be made.

During the dipole repair, we discovered corrosion in some of the Tevatron cryogenic transition pieces (spool assemblies) between neighboring superconducting magnets. This corrosion could conceivably develop in 141 of these 206 very complicated as-



An end view of a Tevatron magnet shows the superconducting current leads whose restraints were improved during the 1989 Tevatron repairs.

semblies. The corrosion occurs at a joint where a copper strap is brazed to a stainless steel pipe that separates the beam tube vacuum and the insulating vacuum. This kind of vacuum-to-vacuum leak would not be expected to cause operational problems; however, spare spools are being retrofitted using crimping rather than brazing to join the dissimilar metals. Moreover, the new low-beta (low-β) quadrupole transition pieces will not use this braze joint.

Collider Run Data

The superb 1988-89 collider run resulted in over 5,000 data tapes containing over five million events. New ground was broken in rapid data processing: *all* of these tapes were processed and reduced to data-summary tapes within seven months after the end of the run! These tapes were analyzed by a collaboration of 225 physicists, including over 60 graduate students.

Results of the run have been very exciting. The CDF detector has performed exceptionally well, allowing a result completely unexpected in the electron-collider community — measurement of the Z° mass to a precision comparable to that attained at the SLAC (Stanford Linear Accelerator Center) Linear Collider. A precise measurement of the mass of the $W^{\pm}$ has almost been completed, and quark-quark scattering has been studied at the highest energy yet achieved. These important data allow precision tests of quantum chromodynamics (QCD) — the theory of quark interactions. Precise measurements of the observed recoil spectrum of photons, W's, and Z's allow further quantitative tests of QCD.

There are, of course, some results yet to be achieved. So far, CDF has seen no indications that

Jay Hauser, Melvin Shochet, and Henry Frisch (from left to right) examine the special electronic sensing circuits and the many miles of cables in the trigger room of the CDF complex.

quarks or electrons have structure. To be more accurate, these particles exhibit no structure larger than one ten thousandth the size of the proton. If the sun were made up of three "partons" with the same scale as quarks in a proton, the "partons" would be less than 70 km in diameter whirling around in a 700,000-km sphere. It would have been exciting to get a first glimpse of structure within quarks or electrons, as this would necessitate a refinement of current theories and an even more interesting view of the universe.

The top quark continues to be elusive. The quest has become even more challenging since top is turning out to be unexpectedly massive. Data from the last CDF run indicates that the top quark is more massive than 90 protons! Top is likely to be even heavier than the Z°, which weighs in at a little more than 96 proton masses.

Moreover, there is a further clue in the treasure hunt. According to theory, the difference in mass of the W and Z° particles is a sensitive indication of the top mass. The CDF and D0 apparatus are capable of measuring the difference in the masses of the W and Z° particles with unprecedented accuracy. The present mass difference would place the top mass somewhere between 100 and 200 GeV. The next run will provide enough data to find the top if it is less than 150 GeV and will improve the accuracy of the W-Z° mass difference sufficiently to produce a reasonably accurate prediction of a heavier top mass.

If top is not in the sensitive range for the next run, CDF will have to wait for the completion of the Fermilab III improvements. With the Tevatron's increased luminosity provided by the new Main Injector, the CDF detector's mass sensitivity will be high enough to cover the whole expected mass range. CDF is thus hot on the trail of a direct confrontation with the theoretical models. Either CDF will find the top quark as predicted, or they will find the first deviation from the present Standard Model, which would indicate that they are probing beyond the theoretical model to the next level. CDF is looking forward to the test!

In addition to CDF, three smaller experiment groups (E-710, E-711, and E-735) took significant data at other interaction points in the Tevatron during the 1988-89 collider run.

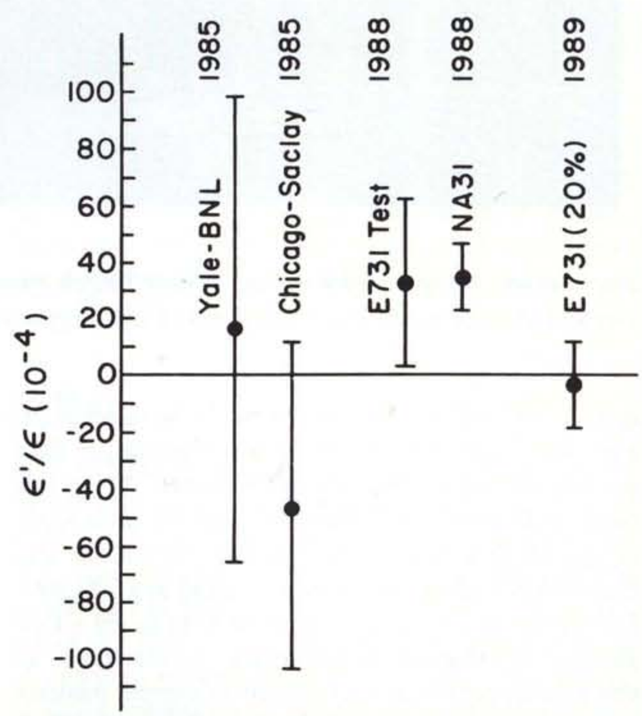
The Fixed-Target Program

Although there was no fixed-target experimental program at Fermilab in 1989, important results based on data taken in the 1987-88 run were obtained in 1989. After an analysis of one-fifth of their data, the E-731 group (a study of charge-parity symmetry, or CP violation) presented a value for the direct CP violation parameter, ϵ'/ϵ. Their analysis is impressively thorough, and the result, $\epsilon'/\epsilon = -0.0005 \pm 0.0015$, is different from that obtained in the only other experiment performed with comparable precision. In addition, the lack of asymmetry implies a high value for the top mass. The E-769 group (a study of charm quark production) has shown impressively clear signals of charm particles produced by a hadron (particles that interact via the strong force) beam. When this result, based on a small fraction of the E-769 data, is extrapolated to the full sample, it will play a major role in our understanding of the mechanism of charm production by hadrons. The combination of our modern detectors and the Tevatron is clearly capable of measuring detailed properties of the heavier quarks.

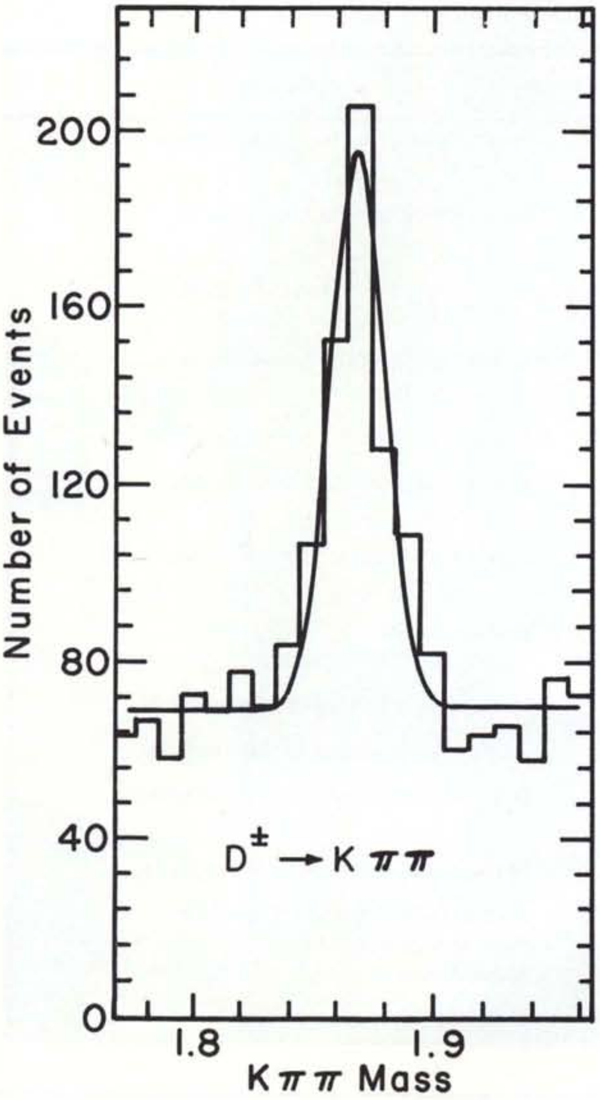
In addition to the analysis and reporting of existing data, 1989 was a year of expansion and major upgrades for the Fermilab fixed-target program. The performance of the beams and the new detectors in the first major collider run of the Tevatron confirmed that we have the technology to seek answers to basic questions and to refine our understanding of nature. The data obtained in the 1987-88 run have inspired experimenters to design and implement even more powerful beams and detectors.

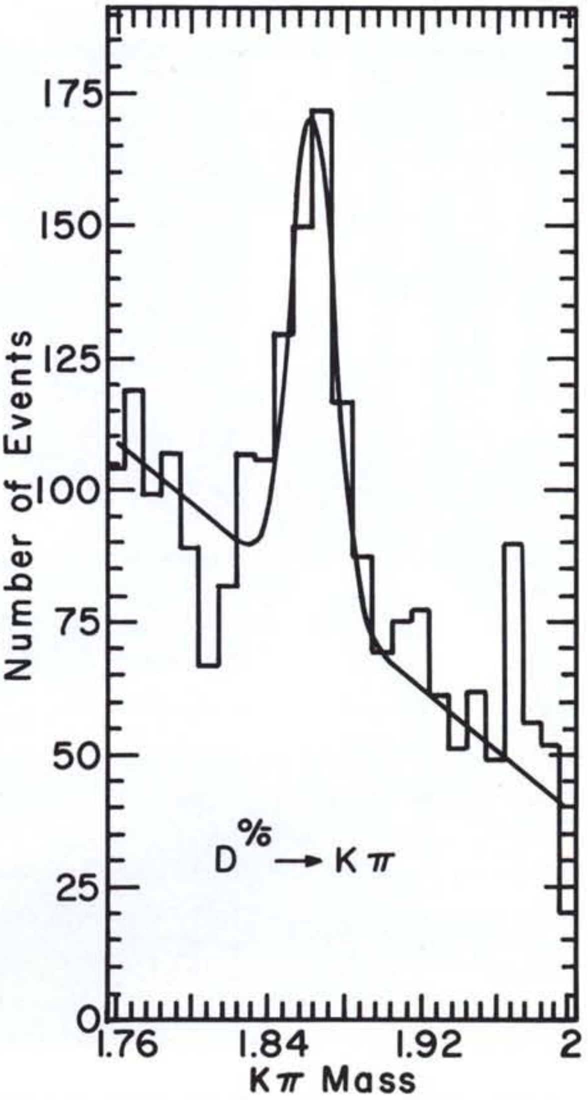
The program of fixed-target experiments investigates a whole range of issues in particle physics. The goals, as always, are twofold: to make increasingly incisive measurements to confront and refine theories of the structure and the interactions of the elementary particles and to discover processes and particles that are "not dreamed of." To this end, we constructed new experimental detectors in 1989 and made major improvements to existing beam lines to raise their operating energy and beam intensity.

The new experiments (Table 3) will address many unanswered questions in the world of elementary particles: What types of fundamental particles exist (E-



Previous attempts at a measurement of ϵ'/ϵ, the CP-violation parameter, are compared with the 1989 Fermilab result from E-731.





Graphs show events containing a strange K-meson and pi-mesons as seen in E-769. The peak indicates the presence of a charmed D-meson decaying into these final states.

774)? What are the masses and lifetimes of particles with charm and bottom quarks (E-687, E-690, E-760, E-771, E-789, E-791)? How do the quarks and the gluons that bind the quarks together behave inside matter (E-665, E-672, E-683, E-706, E-782), and how do they materialize into particles we see (E-665, E-672, E-683)? How well can one understand the decays and magnetic moments of particles containing strange quarks (E-761, E-800)? What property of quarks lies at the heart of the most mysterious asymmetry in the laws of nature, CP violation (E-773, E-799)?

To find answers to these questions, we use beams of protons, photons, electrons, muons, pions, kaons, polarized protons, and hyperons. Our cameras are complex electronic devices with thousands of detectors designed to record in as much detail as possible what happens in the instant when two elementary particles collide. The detectors were upgraded to operate with higher precision and at higher interaction rates in order to exploit the higher energy and higher intensity beams available from the Tevatron.

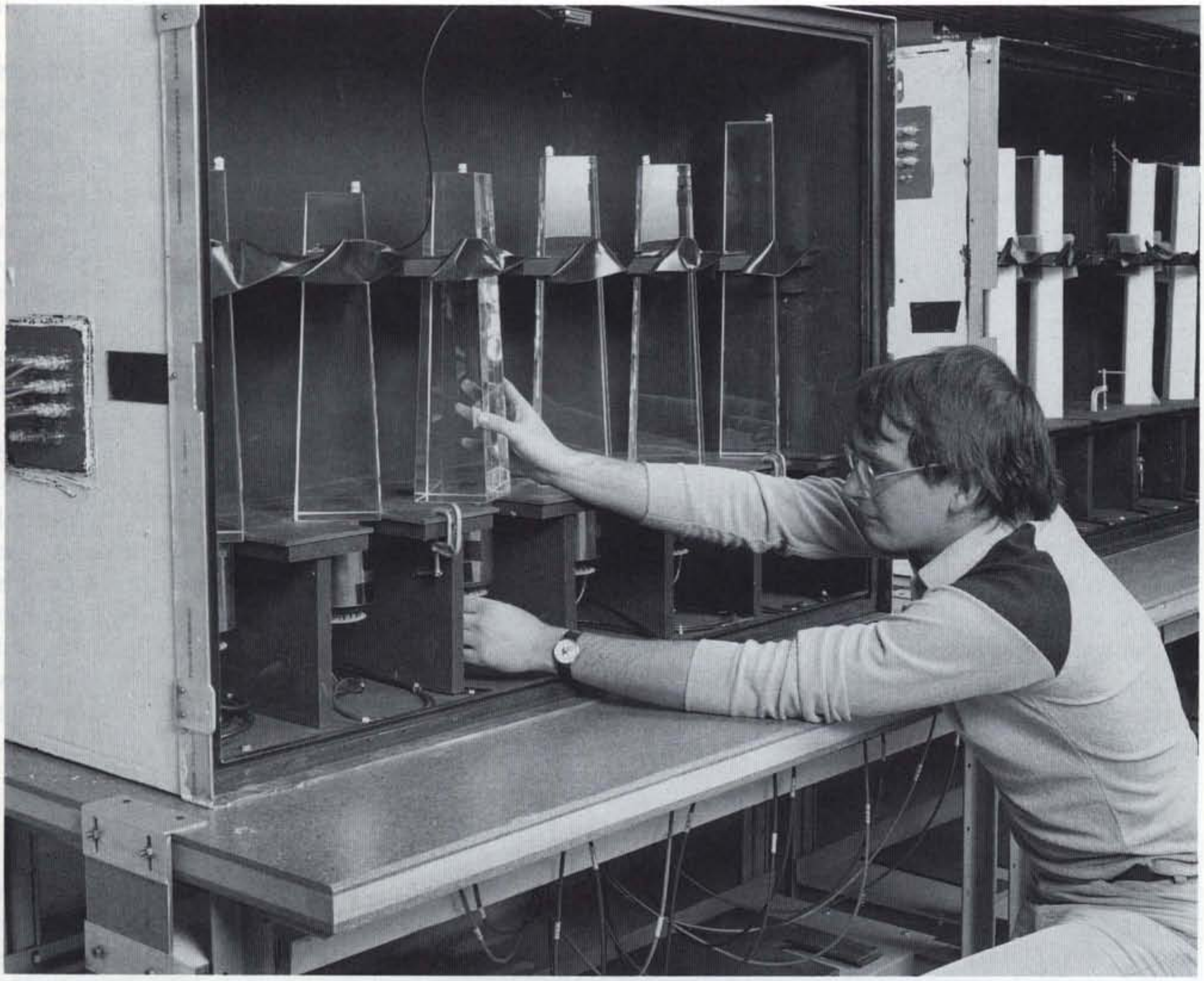
In 1989, the most dramatic improvement in beam lines occurred in the proton area. The P-West beam

Table 3. Experiments Prepared in 1989 for 1990 Operation

Exp. No.	Beam Line	Particles and Energy (GeV)	Goals
E-706 E-672	M-West	Protons at 800 Pions/kaons up to 500	Single photons, charm, and psi production
E-773 E-799	M-Center	Neutral kaons from 100 to 300	Kaon decay and origin of CP violation
E-741 et al	M-Test	Electrons, pions up to 300	Detector development and CDF calibration
E-581 E-704	M-Polarized	Polarized protons at 300	Spin dependence of proton-proton and proton-antiproton interactions
E-789	M-East	Protons at 800	Production of charm and bottom particles
E-740 (DØ)	N-West	Electrons, pions, kaons up to 250	Detector calibration and development
E-790 (Zeus)	N-Test	Electrons, pions, kaons up to 250	Detector calibration and development
E-782 E-690	N-K N-East	Muons at 200 Protons at 800	Proton structure Production of charm particles
E-665	N-Muon	Muons at up to 800	Proton structure and quark fragmentation
E-771	P-West	Protons at 800	Production of charm and bottom particles
E-761 E-800	P-Center	Protons at 800	Decays and magnetic moments of hyperons
E-791	P-East	Protons, pions, kaons up to 500	Production of charm and bottom particles
E-687 E-683 E-774	P-B	Electrons, positrons, and photons up to 500	Photon production of charm & bottom Photon production of "jets" Search for low-mass, short-lived particles
E-760	Anti-proton source	Antiprotons from 4 to 8	Detailed study of charmonium

was upgraded from 250 to 800 GeV; the P-East beam was upgraded from 250 to 500 GeV; and a positron channel was added to the P-B electron beam, thereby doubling the intensity it can deliver. In the neutrino area, we built the N-K beam, a low intensity muon beam for the Tohoku bubble chamber experiment. In the meson area, the M-West beam was redesigned to improve its transmission of secondary particles and to enable it to transport 800 GeV protons. In addition to these projects, we implemented a new beam-line control system. This system gives the operator better access to the beam-line information and, for the first time, integrates control of the cryogenic systems with the rest of the beam-line elements.

Much work has also been done in the area of direct support to experiments. We have installed and set up experiments in preparation for data taking, built and upgraded equipment to be used in various experiments, and contributed to the development and design of data-acquisition systems.



Keith Gollwitzer works on the polished lead glass photon detectors used by E-760 in the Accumulator ring. Each block must be carefully calibrated before final installation.

Physics Department

The Physics Department supports Fermilab staff physicists in their research efforts. During 1989, we had major responsibilities for construction and installation of detectors in nearly all the experiments scheduled for the 1990 fixed-target run. The Lab 6 Chamber facility constructed new detectors for five experiments and refurbished chambers for another three. The Mechanical Group provided silicon strip detector mounts for two experiments, and the Technician Group built gas systems for another two. The Lab 8 Group continued their three-year task of fabricating DØ calorimeter boards, while the Electronics Production Group made 1,000 photomultiplier tube bases for experiment E-687 and completed numerous small projects. The Scintillator Shop made counters for nearly every active experiment at Fermilab. We set up the test stand for the E-760 lead glass calorimeter and successfully installed half of the entire DØ muon detector. Other accomplishments included building a beam Cherenkov counter for one experiment, rebuilding neutral kaon regenerators for another, building new drift chamber electronics for two more, and building an entirely new vertex detector to replace the streamer chamber for yet another experiment.

An important 1989 accomplishment was the successful design of the first fully custom chip for the TDC (time-to-digital convertor) project. We also brought the TDC and ADC (analog-to-digital convertor) modules to the successful prototype phase in 1989. And, in a joint project with the Research Division, we completed the first FASTBUS smart crate controller (FSCC).

We organized the "Symposium on Particle Identification at High Luminosity Hadron Colliders" and a workshop in Breckenridge, Colorado, on "Physics at Fermilab in the 1990's." The latter was sponsored jointly with the Fermilab Users Executive Committee. A strawman design for FTD — the Fast Triggering Device, a detector to be used at the SSC — came out of the Breckenridge workshop.

As part of our service to the research community, the Physics Department sponsors the Fermilab Wednesday Colloquium, organizes academic lectures for graduate students and research associates, and hosts a monthly dinner to bring together research associates in experimental, particle theory, and accelerator physics, and in astrophysics. In July we sponsored a "fireside chat" between Fermilab physicists and the new Director, John Peoples, to discuss participation of Fermilab physicists in research at the SSC.

The engines that propel all of the accomplishments described here are the research associates. Because the task of data taking is continuous and analysis efforts usually exceed the duration of data collection, additional research associates are needed to staff the next round of experiments. We intensified our efforts to recruit the best new PhD physicists in 1989. Besides fulfilling a major role in doing physics, the research associates often move onto the regular Fermilab staff after an average of about four years. This infusion is crucial to the health of Fermilab and is perhaps the top priority of the Physics Department.

For the last twelve years, Fermilab has offered Wilson Fellowships to recent PhD graduates in accelerator science and to those with some postdoctoral experience in experimental high energy physics. The fellowships honor Robert R. Wilson, Fermilab's founding director. As a new initiative, the Lederman Fellowship was created in 1989. It will be awarded to new experimental research fellows who also show a talent for science education in honor of Director Emeritus Leon Lederman.

Theoretical Physics

Research problems addressed by the Theoretical Physics Department in 1989 range from fundamental mathematical problems in quantum field theory and the theory of superstrings to the phenomenology of proton-antiproton collisions at supercolliders. Significant progress in applying quantum chromodynamics (QCD) to physical problems has been achieved in both its perturbative and nonperturbative aspects. We also contributed to a broad spectrum of theoretical issues in 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) super-computer project for serious lattice gauge theory calculations focused on the nonperturbative physical properties of QCD. A 50-node processor system, on which the CANOPY software has been successfully implemented, has been operating at speeds in excess of 1 gigaflop (1 billion floating point instructions per second) and has been applied to a variety of physics problems. A particular emphasis of the present research has been the calculation of physical properties and decay parameters of particles containing the bottom quark. We have also studied the properties of postulated states containing gluons, the energy quanta of the chromodynamic force between quarks.

A full 256-node, 5 gigaflop, supercomputer system for lattice gauge theory is nearing completion by the Computer R&D Department in the Computing Division and will be applied to physics applications beginning in the next few months. Implications of this project on future designs for advanced supercomputer systems have been under active discussion in the Fermilab community and elsewhere.

The department has devoted a great deal of effort to studying 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 possible top quark and Higgs

$$\Phi_\ell = \Gamma(\ell + 1/2)\, b_\ell .$$

new

$$\Phi_{\ell+1} = \quad '' \quad ''$$

$$z \to \left(\frac{d}{d\xi}\right) \qquad \tilde{\Phi}_{\ell-1} = \qquad \tilde{b}_\ell ,$$

$$\frac{d}{dz} \to \xi$$

$$\ell_n = \alpha\, z^{n+1} \frac{d}{dz} + (1-\alpha) \frac{d}{dz} z^{n+1}$$

$$\tilde{\ell}_n = \alpha \left[\left(\frac{d}{d\xi}\right)^{n+1}, \xi \right] + (1-\alpha)\, \xi \left(\frac{d}{d\xi}\right)^{n+1}$$

$$+ \xi \frac{1}{\xi}\left(\frac{d}{d\xi}\right)$$

$$\tilde{\ell}_n = \alpha\, \xi^2 \left[\left(\frac{d}{d\xi}\right), \frac{1}{\xi} \right] \left(\frac{d}{d\xi}\right)^n + \quad ''$$

$$= \xi \left(\frac{d}{d\xi}\right)^{n+1} + \alpha \left(\frac{d}{d\xi}\right)^n$$

$$\int d\alpha = \int d\xi$$

particle events in proton-antiproton interactions. Expected experimental signatures of possible other aspects and extensions of the Standard Model of quarks and leptons also have been analyzed. These include the possible role of dynamical symmetry breaking in determining the masses of the top quark and the Higgs boson, the signature of new interactions beyond the chromodynamic force such as technicolor, the existence of neutrino masses or magnetic moments, and the possibility of observing CP violation in the decay of charm quarks.

We have also made progress in more formal areas of particle physics research, including many aspects of formal quantum field theories defined in both flat and curved space-times as well as the mathematical structure of fundamental string theories. The interface between astrophysics, cosmology, and particle physics has benefitted from the proximity of the Fermilab Astrophysics Group. Wormholes provided the focus of research in quantum cosmology and its implications for particle physics. 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.

Our staff, along with visiting scientists-in-residence, played an essential role in the intellectual life of Fermilab during 1989. Fermilab provides a focus for the research of several faculty members from surrounding universities as well as a number of long-term visitors from universities and research institutions around the world. 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 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 mutual interest, and department members contribute to the Fermilab Academic Lecture Series, which is addressed to the broader physics community at Fermilab.

We will continue to research a broad spectrum of physics issues, from questions of direct phenomenological interest to the more formal aspects of quantum field theory and superstrings. The completion of the 256-node lattice gauge supercomputer will make Fermilab a major center for realistic calculations in nonperturbative QCD and its application to the solution of many important physics issues.

Astrophysics

The largest and longest running experiment, the Universe, produced many interesting new results in 1989. One of the great astrophysical events of our time, supernova 1987a, continued to generate a great deal of interest. We have been able to rule out specific mass ranges for both neutrinos and axions based on observations of the evolution of this supernova.

However, astrophysical and cosmological constraints have drawn attention to very interesting "windows" in which the axion mass may still lie. We determined that if axions exist with a mass within one of the windows, they will produce a clear observable signal due to decays into photons. We have been granted telescope time to search for this signal in 1990.

Reports that a pulsar was observed at the location of supernova 1987a increased our interest. Calculations did not confirm our expectation that this was the neutron star expected to form after a supernova, and observational results regarding the pulsar have since been withdrawn.

A continuing problem in astrophysics is the origin and nature of dark matter. There is very strong evidence that most of the matter in the universe is *not* in the form of stars that we observe but in some form of dark matter. We investigated a variety of suppositions as to the nature and origin of dark matter, from the "conservative" possibility that it is made of very ordinary stellar remnants to exotic possibilities such as "nontopological solitons" formed in the early universe.

Another great problem in modern theoretical astrophysics is an explanation for the formation of large-scale structures such as galaxies and clusters and su-

Supernova 1987a.

perclusters of galaxies. We know from observation of the microwave background radiation that the universe was once extremely isotropic (having equal physical properties in all directions). Yet, new observations reveal anisotropic (nonuniform in different directions) distributions of matter on ever-increasing scales. The complex hydrodynamics that converts initial perturbations into the burning stars we actually observe is very important here. Unusual forms of matter such as cosmic strings or domain walls may play a role in identification of the source of the "initial" perturbations. We have made considerable progress in analyzing the properties of cosmic strings and domain walls. We investigated the suitability of these objects for forming the large-scale structure and examined more direct tests of their existence as well.

Going back to the early universe, we made progress in putting inflationary cosmology (the theory of a rapidly expanding universe) on a more solid formal footing with regard to gravitational forces. We also have been very excited about a new form of inflation called "extended inflation." An interesting feature of this new idea is the potential to produce distinctive bubble-like structures in the distribution of galaxies on large scales, similar to the observed distribution of galaxies.

Computing

The needs of high energy physics have always been the driving force behind the computing mission at Fermilab. The desire for higher data rates and the need to study rarer phenomena led the Computing Division to seek out, test, and implement a variety of new technologies during 1989. New data-storage media, improved on-line data-acquisition tools, rapidly increasing processing power, and the introduction of UNIX-based RISC (reduced instruction set computer) processors are a few of the changes we have made to improve both the speed and quality of physics at Fermilab.

A separate Computing Division was formed in 1989 by combining the Computing Department, the Advanced Computer Program (ACP), and electronic engineering groups in the Research Division strongly involved with data-acquisition projects. The new Computing Division consists of five departments: Central Computing, Distributed Computing, Data Acquisition Support, Data Acquisition Electronics, and Computer Research and Development. Its formation proceeded smoothly in parallel with normal day-to-day computing support as well as with the many equipment and software upgrades that were undertaken.

The basic three-pronged approach to computing at Fermilab has continued through the use of the central VAX clusters, the ACP production farms, and the general-purpose large Cyber and Amdahl mainframes. The Control Data Corporation Cyber computer complex was reduced as part of a plan to eventually phase out Cyber support. However, the Amdahl computer became available for general use, and its power was increased by updating its operating system to VM/XA. Moreover, the Japanese and Italian collaborations on CDF have added processors to both the VAX cluster and the ACP farms. (A computer farm is an arrangement of many compact computers or microprocessors inter-connected through a larger computer that "farms out" computations to its member computers based on their availability.) Taken together, this three-pronged platform of computers provides Fermilab scientists with the computing power of nearly 1,400 VAX 11/780 computers.

The availability of this computing power enabled the CDF group to complete half of the first stage of the analysis by the time its 1989 collider run was over in June and to complete the rest of the first analysis by the end of the year. The first stage of analysis was also completed on most of the backlog of data from the last fixed-target run in 1987-88.

To accommodate the 1989 growth in computing resources, the new Feynman Computing Center (FCC), dedicated at the end of 1988, quickly became the hub of computer processing. The new Amdahl computer was installed in the FCC, and the ACP farms and two VAX clusters were moved in. Despite this relocation, the total available computing power grew by almost a factor of three in 1989. One significant area in which this growth occurred was local VAX clusters, which are largely constructed from desktop work stations. In fact, many clusters located around Fermilab now account for more computing power than either the Amdahl or the ACP farms. Another significant aspect of the increase is a diversification of the type of processor farms in operation.

CDF brought into operation a farm of VAX 3100 computers providing a computing power of approximately 45 VAX 780s. In a more radical departure from the norm, event reconstruction for E-769 was begun on a farm of Silicon Graphics work stations providing a computing power of approximately 250 VAX 780s.

The Silicon Graphics machines represent an important transition: they are the first large-scale use of high performance RISC computers and the UNIX operating system at Fermilab. RISC machines have also made it possible to acquire additional computing resources at a greatly improved price/performance ratio. The Silicon Graphics farm has provided very valuable experience; by the end of 1989 it appeared that further use of RISC UNIX systems was likely to be the major source of increased computing power in at least the near future.

To support such UNIX-based farms, we developed the Cooperative Processes Software (CPS), which allows a single computational task to be performed by a set of processes running on a collection of computers. CPS is being used to coordinate E-769 event reconstruction processing on the Silicon Graphics farm. We have also started developing a new batch system that will submit jobs to a UNIX farm in a manner similar to job submission to an ACP farm.

This year saw a vastly increased use of 8-mm tape. Fermilab's leadership role in developing 8-mm tape for high energy physics applications has begun to pay off. Eight-millimeter tape is now being used as a primary on-line data-recording media, as input to microprocessor farm systems, as a distribution media for data-summary information, and for computer archiving. By the end of the 1989 collider run, the CDF group had started recording raw data on 8-mm tape. Many experimenters are now planning to use the tape for primary data recording for the next fixed-target run. As the year came to a close, we were investigating the use of 8-mm tape drives on both the central VAX clusters and the Amdahl.

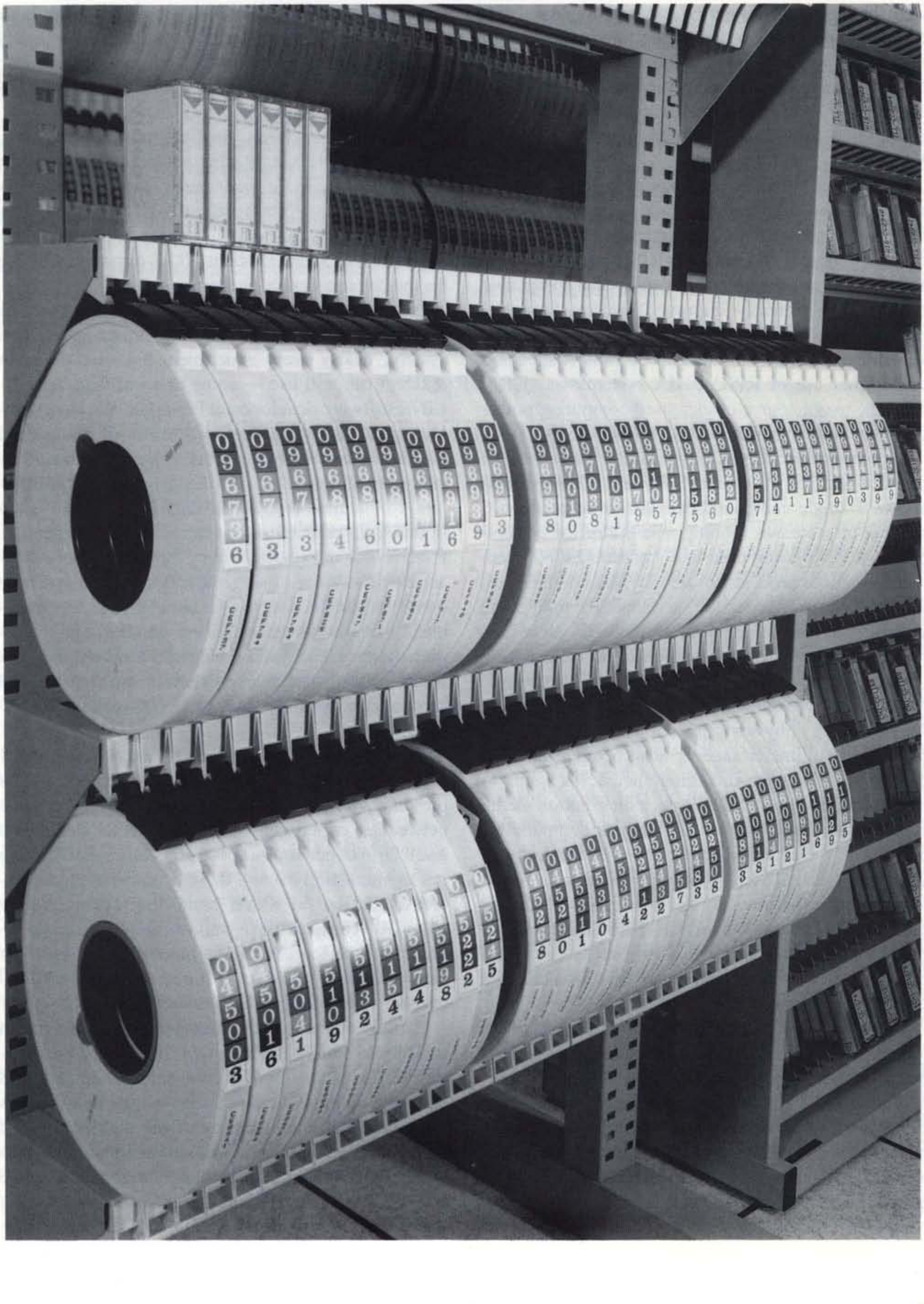
The 8-mm tape is more than a simple replacement for a 9-track tape. It allows computing applications that would have been practically impossible without it. The farm of Silicon Graphics machines used for E-769 analysis was easy for the experimenters to manage themselves because of its use of 8-mm technology. The use of 9-track tape would have required operator handling of tape mounts once an hour, compared to an average of twice a day for 8-mm tape. The towering bank of 40 8-mm tape drives built for use in the Tagged Photon Lab is designed to record data at a continuous rate of 10 Mbytes/second. Use of conventional 9-track drives would have required a 9-track tape change every 15 seconds.

While the new 8-mm medium provides low-cost, high-density storage, it also addresses the problem of how to handle the previously recorded data now stored on nearly 40,000 reels of 9-track tape. A tape-copy facility was used to transfer data from over 6,000 9-track tapes to about 700 8-mm tapes for use on the Silicon Graphics farm.

Important developments also occurred in the area of data acquisition during 1989. In its data-acquisition system, nearly every experiment has used — or in the next run will use — some or all of the VAXONLINE software developed at Fermilab. We have demonstrated that it is possible to use a lot of standard on-line software, although each experiment has different requirements. This view resulted in the first installation of a new distributed data-acquisition system (PanDA) in preparation for the next fixed-target run. PanDA was designed for very high throughput data-acquisition systems using either 9-track or 8-mm tape drives in conjunction with a farm of processor modules. It represents a transition to parallel data-acquisition systems designed to bring into a unified software framework distributed processors from front-end readout controllers to VAX-or UNIX-based work stations.

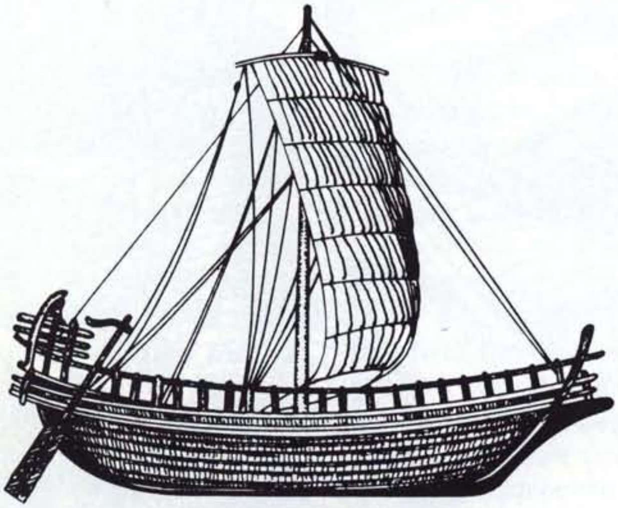
Design effort in 1989 also created a new parallel data-acquisition system. A so-called parallel switch provides a large number of parallel data-transfer paths between an experiment's particle-detector electronics and a farm of general-purpose processors. By filtering out uninteresting events, these processors greatly increase the rate at which interesting events can be recorded. The basic design allows the total data-transfer rate to be increased indefinitely by adding more data paths and processors. It can support total data-transfer rates of tens of gigabytes per second.

Particle-detector electronics support has also grown in 1989 to satisfy the needs of Tevatron-era experiments. The inclusion of processors and sophisticated controllers in many modern data-acquisition systems has added to the complexity of the distribution and maintenance of electronics modules. In an attempt to keep up, we have used continuous training and more powerful computerized test stands and are moving into the world of artificial intelligence. Expert system

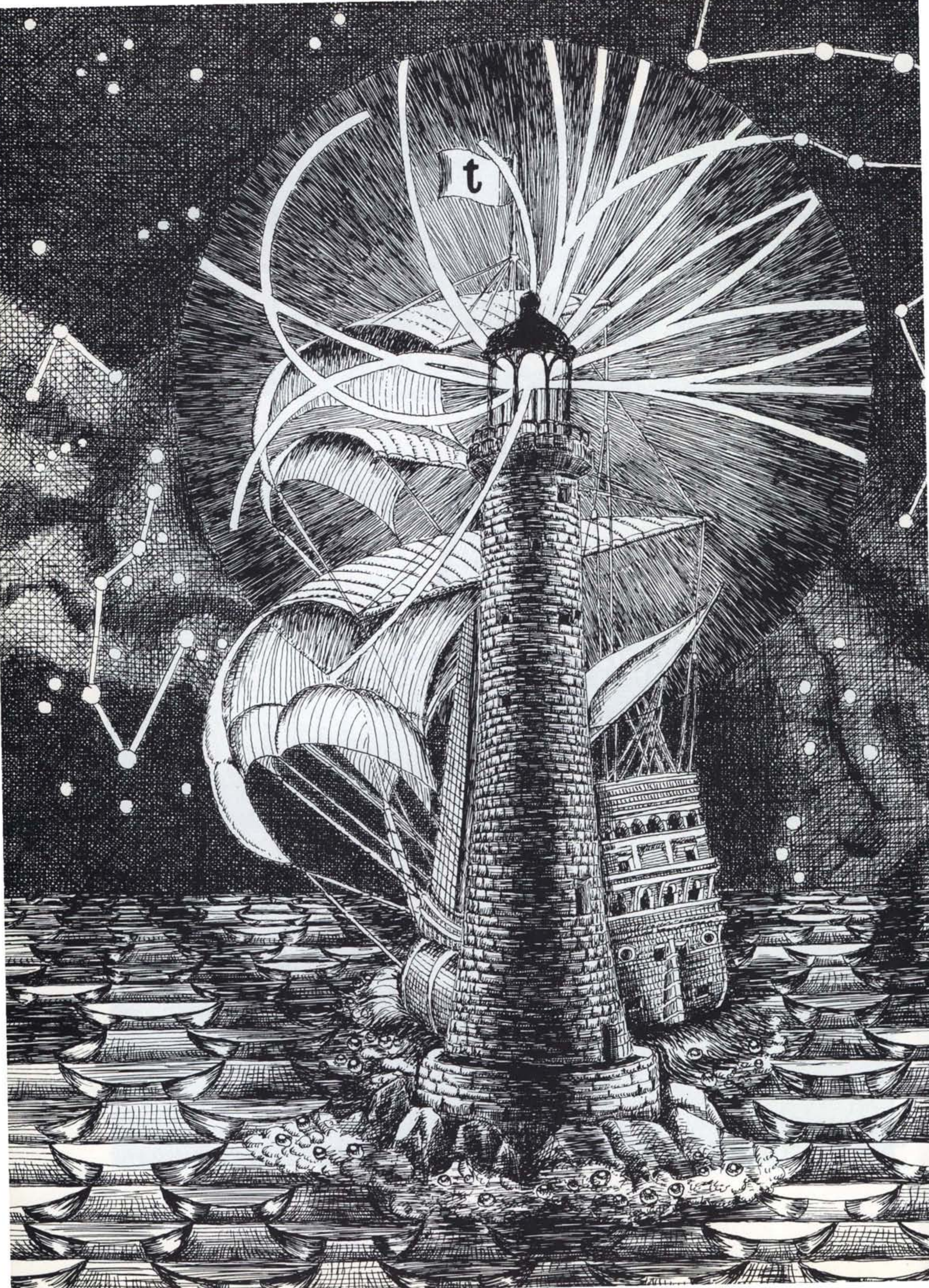


technology has been added to a prototype test stand for one of the more complicated data-acquisition modules.

In 1989 many additions were made to the networking connections available at Fermilab. We began to replace the medium speed (56,000 bits/second) HEPnet backbone links with the high speed (1,544,000 bits/second) ESnet links. ESnet, a DOE computer communications network supporting 20 facilities and energy research sites, will soon replace the strictly high-energy physics network HEPnet. Fermilab continues to maintain connections to Brazil, Canada, Europe, and Japan. All together, Fermilab has 39 direct DECnet links to universities and other laboratories. In addition, Fermilab upgraded its link to the National Science Foundation Network (NSFnet) to 1,544,000 bits/second.



The six 8-mm tapes resting on the rack in the upper left-hand corner hold as much data as the 60 regular magnetic tapes stacked below.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Fermilab III: Reaching for the Top

An important thrust in 1989 was the preparation for the 1991 collider running period. This thrust included design efforts on Fermilab III, a project to increase the capabilities of the accelerator complex well beyond the original design specifications.

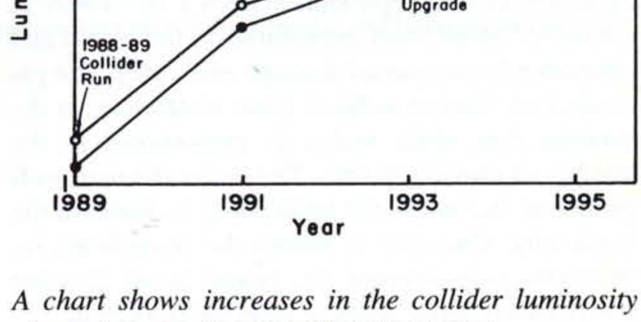
The production and observation of a top quark, with a mass in the range 100 to 200 GeV, as implied by our 1989 research results, are currently beyond the capability of any existing high energy physics facility in the world. Fermilab III is designed to create this capability. The changes required for implementation of Fermilab III include lowering the operating temperature of the superconducting magnets and placing electrostatic beam separators in the Tevatron, improving further the yield of antiprotons in the antiproton source, doubling the Linac energy, and replacing the Main Ring with a new accelerator, the Main Injector. We expect luminosity in the Fermilab III Tevatron collider to rise by a factor of five following installation of the separators and the Linac upgrade and by another factor of five following construction of the Main Injector.

Collider Luminosity

The physics research potential of a collider run depends directly on the luminosity, which is proportional to the brightness (phase space density) of the proton and antiproton beams as they pass through each other or collide at the experiment regions. Based on the technical studies of our accelerators done in 1989, we expect significant improvements in both proton and antiproton beam densities for the 1991 collider run. Proton bunch densities should increase by a factor of two due to improved Main Ring performance. Antiproton bunch densities will also increase by a factor of two, with increased antiproton stack intensities and reduced antiproton beam sizes. These changes should increase the initial 1991 collider run luminosity by a factor of four over the 1989 run and result in an integrated luminosity of approximately 40 pb^{-1} delivered during an eight-month running period. The number of bunches that collide with each other will remain at six.

Generating brighter particle beams is only the first step. We must be able to use them in a stable fashion. The ability to offer the higher interaction rates of these denser beams is provided by the beam-separation system, which ensures that the beams collide only at the experimental regions and not around the full machine circumference. Minimizing the number of collision points minimizes the disruption that results when the beams pass through each other (the beam-beam interaction). Separating proton and antiproton orbits inside the accelerator structure also allows the possibility of designing independent betatron oscillation control circuits for each beam, which will allow more flexible operating conditions. Smaller, denser particle beams will place greater emphasis on the accuracy of the beam manipulations and transfers from accelerator to accelerator.

During 1989 two new sets of superconducting focusing quadrupoles were constructed. These magnets will form a new strong focusing insertion, which will be installed at D0. The existing collision region at B0 will be retrofitted with a similar quadrupole insertion. These insertions are technically more complex but optically simpler and more powerful than the existing B0 quadrupoles. A major challenge will be to demonstrate that simultaneous experiments at D0 and B0 can be operated efficiently despite differ-



A chart shows increases in the collider luminosity planned during the Fermilab III project.

ing requests on beam properties from the two experiments. Problems of particle backgrounds in the detectors arising from the Main Ring in the new DØ experimental region were also studied in 1989.

We do not expect to achieve any significant increase in the overall efficiency of beam transfers beyond the 1989 run. During the 1989 run, 65% to 70% overall antiproton transmission from the Accumulator storage orbit to the Tevatron was achieved. It will be hard to do much better. However, reliability will continue to receive attention due to its crucial role in determining the total amount of data recorded by experimenters. The identification and elimination of unreliable components during the 1989 run resulted in a typical stable period of proton-antiproton collisions that increased from 10 hours to 15 hours as the run progressed. Routine data-collection periods of 20 hours should be achievable, given the luminosity lifetime of the beam.

Cryogenics

One means of increasing the luminosity would be to run the collider magnets at higher currents, producing higher magnetic fields and, consequently, higher energy proton-antiproton collisions. During 1989 we investigated lowering the operating temperature of the Tevatron. At lower temperatures the existing Tevatron magnets can be operated at higher currents, and hence, higher magnetic fields, without danger of losing their superconducting properties, an effect called quenching. We propose that it would be possible to lower the temperature by a few tenths of a Kelvin (e.g., from 4.5 K to 4.3 K, or even to 4.1 K) by introducing an additional "cold compressor" on the helium return. One cold compressor would be required at each of the 24 satellite refrigerator houses.

In 1989 we successfully tested this idea on one-sixth of the Tevatron, the minimum accelerator subsystem that can be tested at full power. After installation of two centrifugal and two reciprocating cold compressors, the test area was successfully cooled to approximately 4.3 K. Operation at magnetic fields equivalent to 1020 GeV was achieved. Moreover, the test provided considerable experience with the operating requirements of cold compressors.

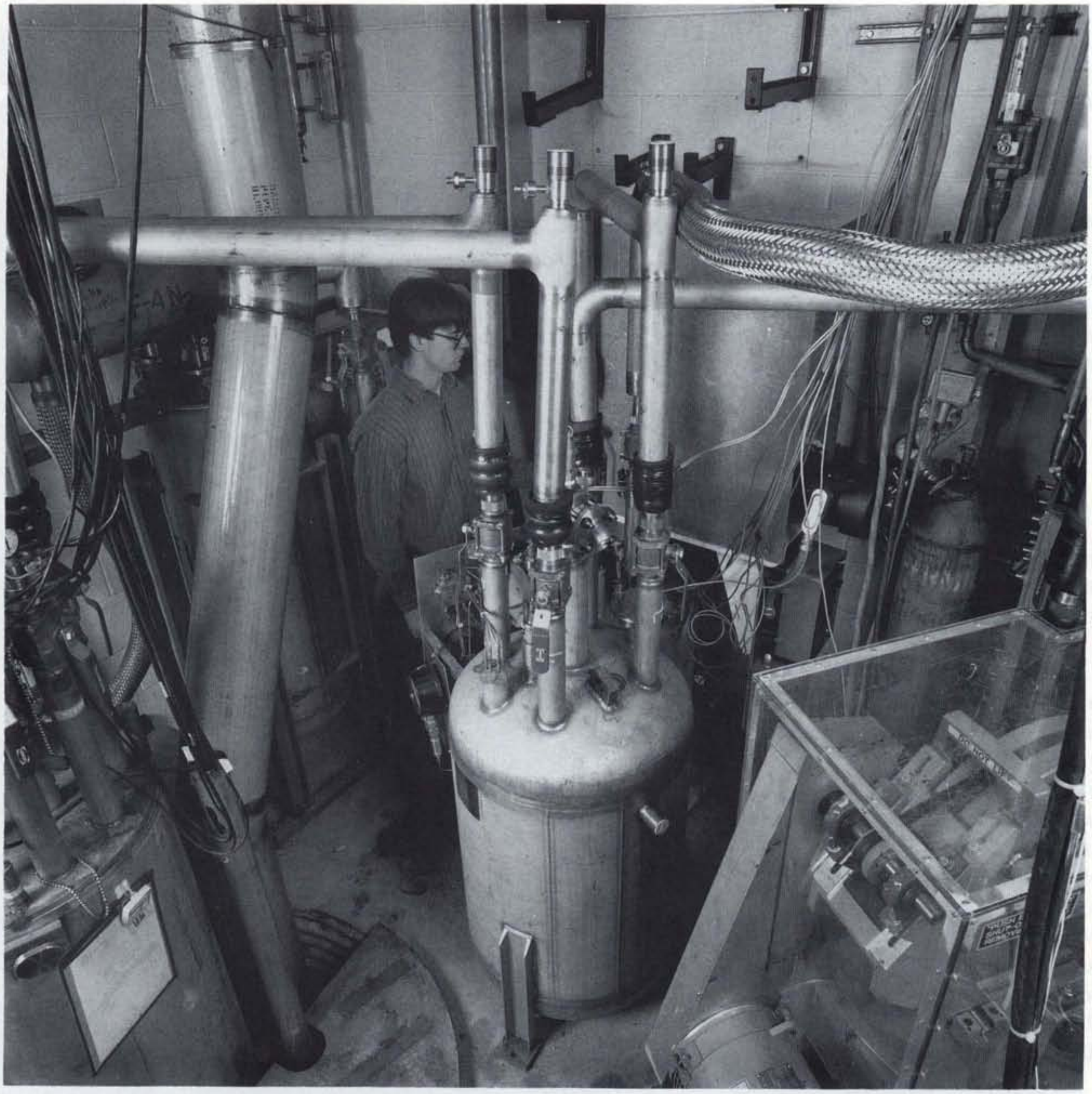
Beam Separation

We have also investigated ways of increasing the luminosity at existing Tevatron operating temperatures. One way to do this is to increase the number of proton and antiproton bunches simultaneously circulating in the Tevatron. Under this scenario, however, proton-antiproton collisions at the extra crossing points cause the beam to grow in size and thus limit the increase in luminosity.

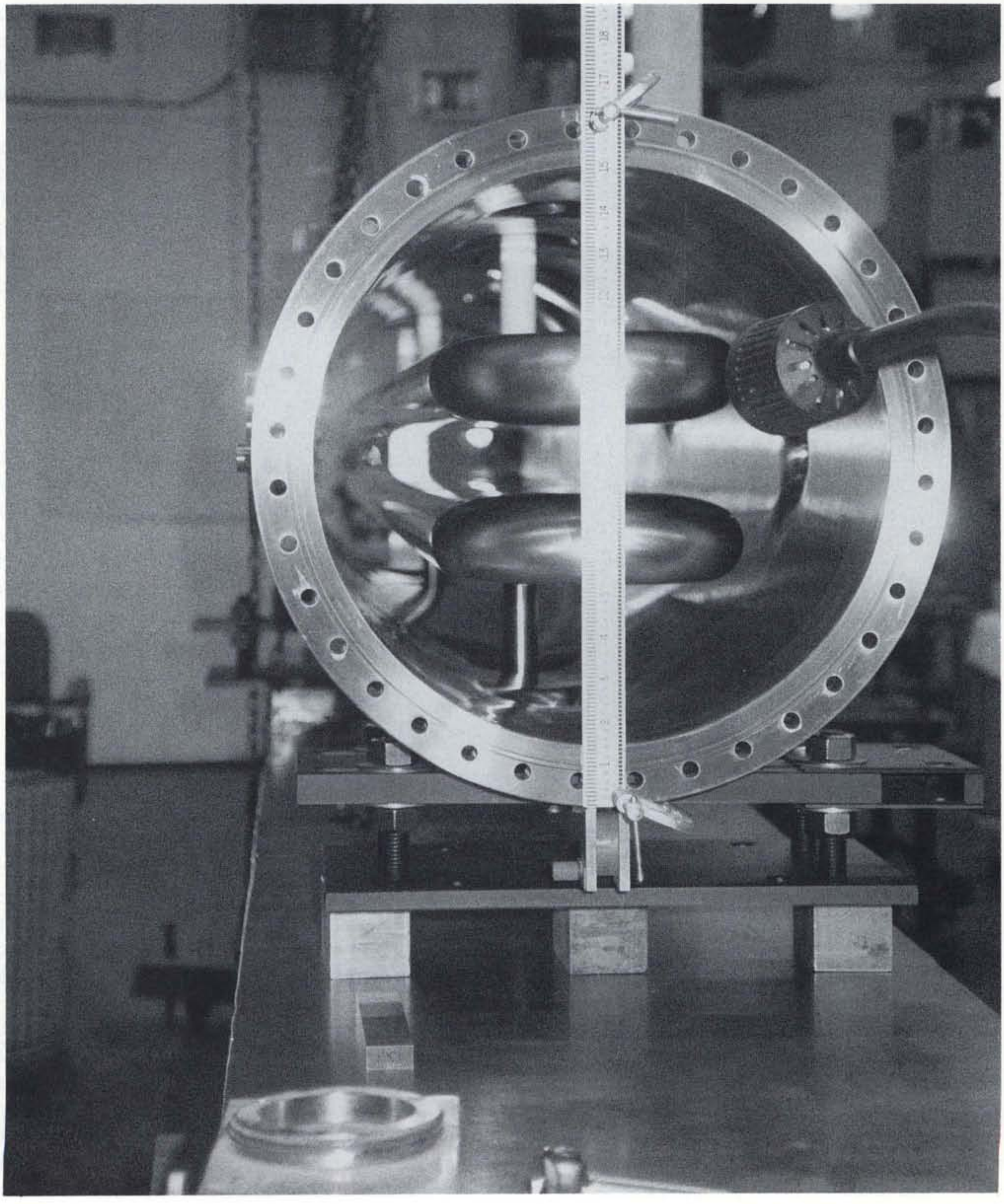
During the 1989 collider run, the Tevatron luminosity was limited to approximately $1.6 \times 10^{30}/cm^2/s$ as a result of beam-beam interactions as the proton and antiproton beams passed through each other. The parameter of concern in beam-beam interactions is the betatron tune shift, which is proportional to the number of crossing points. The larger the tune shift parameter becomes, the harder it is to increase the luminosity. One way to reduce the beam-beam interactions is to separate the beams at all crossing points except those where a detector is located.

There were six proton bunches and six antiproton bunches in the Tevatron during the 1989 collider run. Thus, there were 12 locations around the ring where the beams collided head on. By separating the beams everywhere except at the location of CDF (BØ), the beam-beam effect could have been reduced by 12 and the luminosity limit would have been increased by 12 to approximately $2 \times 10^{31}/cm^2/s$. We therefore proposed separating the beams, using electrostatic separators strategically located around the ring. When energized, the separators would separate the proton and antiproton orbits by approximately five times the natural width of the beam. To achieve this separation, the proton and antiproton orbits must make equal but opposite deviations away from the central orbit (the orbit that goes through the center of each magnet). Experiments performed in the Tevatron during 1989 to study such a scheme proved its feasibility.

In one series of experiments, we studied beam orbits that are not centered in the Tevatron magnets. As the particles move away from the center of the magnet, they experience nonlinear magnetic fields. Because these nonlinear fields can define the effective



Joel Fuerst of the Accelerator Division cryogenics group monitors the operation of a cold helium compressor in a satellite refrigerator.



A view of an electrostatic separator developed for the Fermilab III project.

aperture of the machine, they must be carefully measured. The effect of these nonlinear fields also depends on the direction of the deviation; therefore, the effect on protons and antiprotons would not be the same because the electrostatic deflection of protons is equal but opposite to that of antiprotons. This directional (or differential) sensitivity was also studied, as it prevents stable operation if left uncorrected.

In the experiments on noncentered orbits, we successfully produced orbit deflections that were 50% greater than those proposed. We found that theoretical predictions, based on the measured nonlinear fields in each of the dipoles, agreed with the observed differential effect. According to the calculation, sextupole nonlinear fields in the dipoles created the differential effects. Consequently, we designed a correction scheme that would cancel the effect of the sextupole fields in the dipoles. We implemented and tested this scheme, and experimental observations again agreed with the prediction.

In 1989 we also installed prototype electrostatic separators in the Tevatron. The locations of the separators were chosen to produce beam conditions and separations closely resembling those expected during the 1991 collider run. Both protons and antiprotons were injected into the Tevatron, and stable conditions were achieved with beam separations of five times the transverse beam size. The beam brightness increased and the observed beam-beam interactions decreased as expected.

Low-Beta Insertion

The collider luminosity can also be increased by reducing the transverse area of the beams at the point of collision. The luminosity is inversely proportional to the area of the proton and antiproton beams at the collision point. The transverse beam size of a beam of particles in an accelerator is usually given in terms of an effective focal length, β. Increasing the focusing power of nearby quadrupoles and hence decreasing the effective focal length β by a factor of two in each plane reduces the beam area and increases the luminosity by a factor of two.

The currently installed low-β quadrupole magnets at BØ operated during the highly successful 1988-89 collider run at a value of β = 55 cm. A low-β insertion is also being constructed at DØ for the experimental program associated with the large new detector being built there. For the simultaneous operation of two low-β focusing insertions in the Tevatron, their focusing must be matched precisely to the rest of the accelerator ring. A simple solution is to build two identical quadrupole insertions, one to replace the existing magnets at BØ and one to install at DØ.

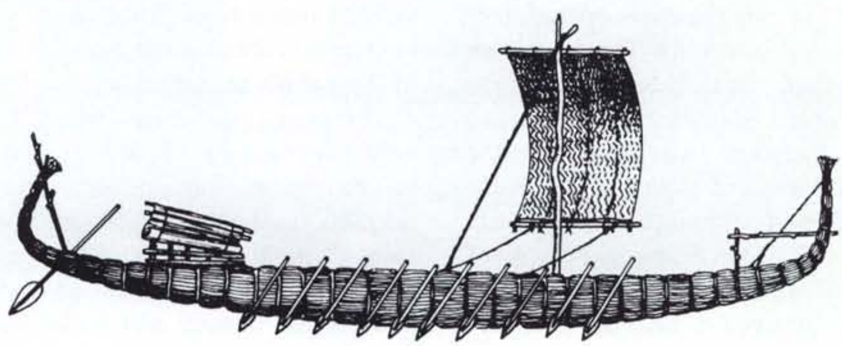
The mechanical support structures for the quadrupoles are different at BØ and DØ, partly because of the different geometry of the two detectors. The design of the DØ low-β insertion is also mechanically more complex than the one planned for BØ. Because the electrostatic septa for extracting the proton beam from the Tevatron for fixed-target experiments are also located at DØ, this straight section must be reconfigured each time we switch between fixed-target and collider runs. All production and testing of the components for the low-β insertion at BØ are geared for completion in time for installation in 1990.

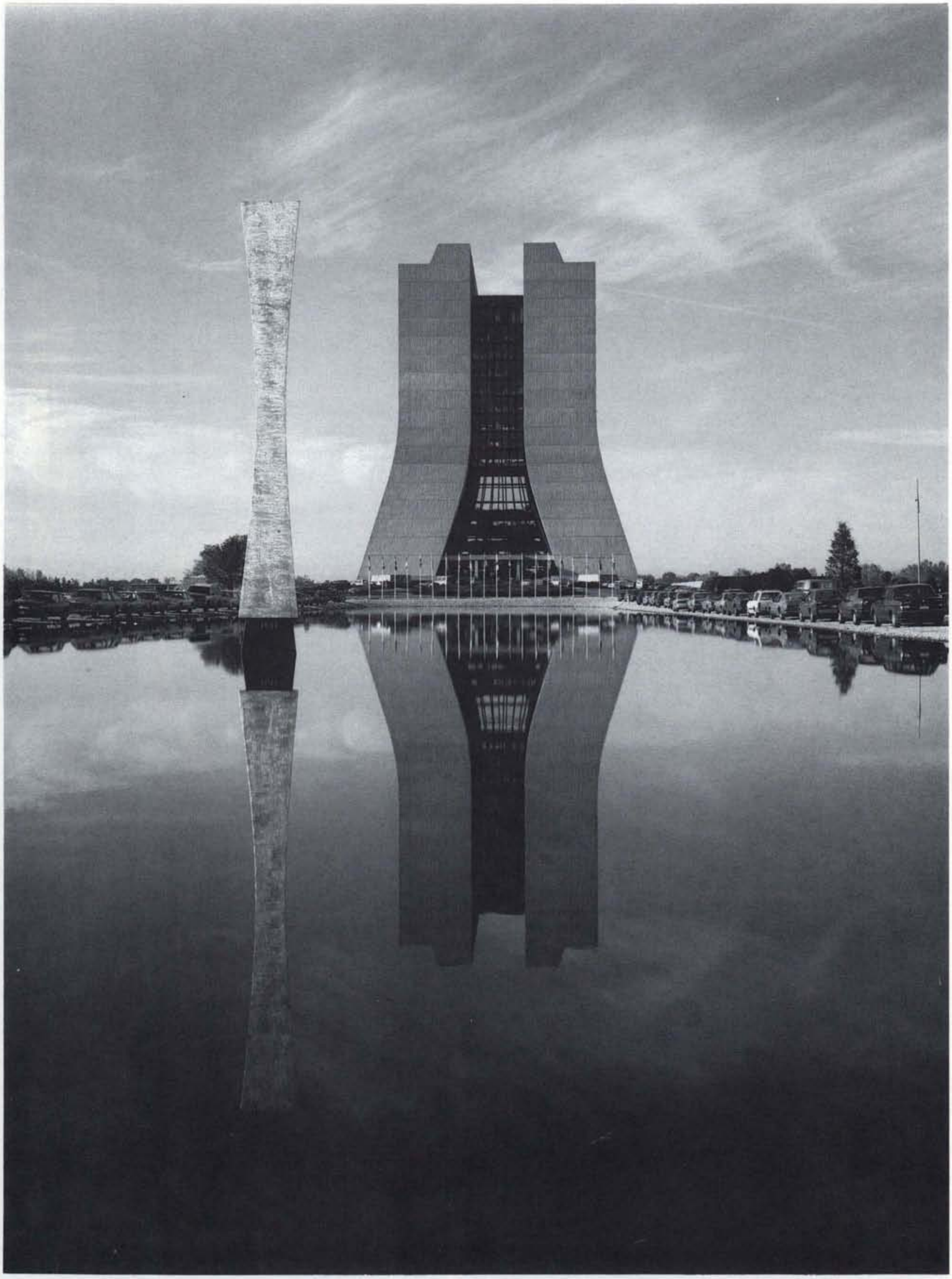
Magnets. The program to produce high-gradient quadrupole magnets for the BØ and DØ interaction regions was started a little over three years ago. By 1989 this program had progressed to the point where the magnets were in production; they will be installed in 1990. Two new magnets were developed for this program. The first was a high-gradient quadrupole that operates at 1.4 T (tesla)/cm; the second was a low-current "correction" quadrupole that operates at 0.7 T/cm. For comparison, the gradient of a standard Tevatron quadrupole at 1 TeV is 0.7 T/cm. (Tesla is the unit that defines the strength of a magnetic field. One tesla is about twenty thousand times the strength of the earth's magnetic field.)

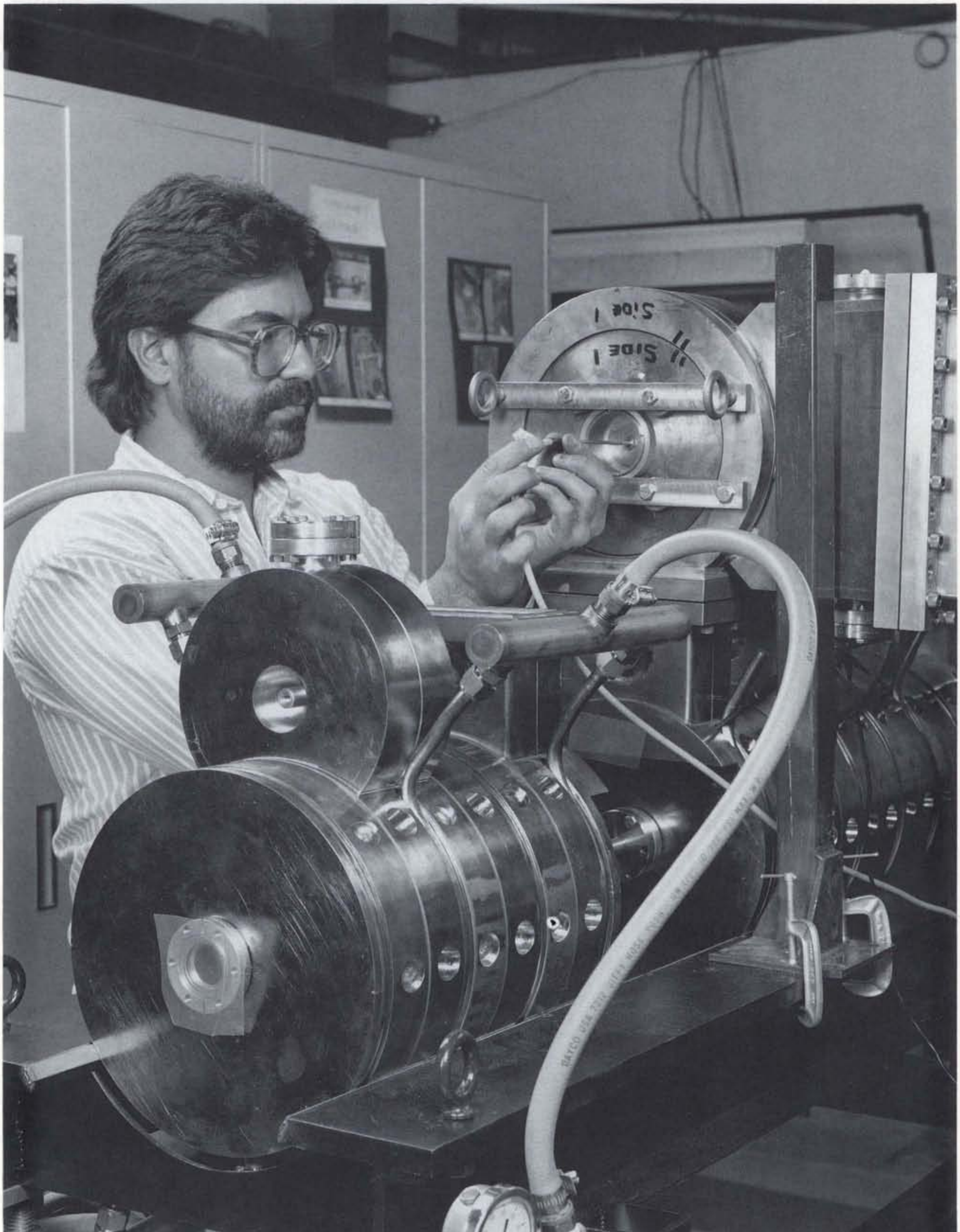
The high-gradient quadrupole is characterized by cold-iron, high current density, and precision conductor placement. The conductor developed for these magnets reached a new record in critical current density — more than 3100 Amps/mm^2 at 5 T. In addition, an all-Kapton insulation system increased the coil current density and improved the dimensional precision of the coil. The cryostats for these quadrupoles use the design concepts developed at Fermilab for the SSC.

The quadrupole corrector features a one-shell coil and cable made of five separately insulated rectangular monolithic conductors. After the coil is wound in the normal way, the conductors of each superconducting cable are connected in series to produce a quadrupole with an operating current of a little over 1,000 amps — one-fifth that of a magnet using the standard Rutherford-style cable.

Workers in the Magnet Factory surround one of the 20 new high-field quadrupole magnets. These magnets will more tightly focus the beams of protons and antiprotons at the CDF and D0 detectors, thus serving to increase the Tevatron luminosity.







Linear Accelerator

Improving the linear accelerator (Linac) is another way to increase luminosity in the collider. The Linac was conceived and built 20 years ago and has run without a major interruption since that time. However, steadily increasing demands have been placed on the Linac as a result of the growing complexity of the downstream chain of accelerators and the patient load of the Neutron Therapy Facility. Improvements to the Linac during the last 19 years have included the conversion from acceleration of protons to acceleration of hydrogen ions, installation of a new control system, and replacement of the radiofrequency (rf) control monitoring system. Other system improvements increased reliability and enabled the Linac to run 99% of the time in 1989. However, in the last 19 years, Linac technology has advanced, allowing an increase in the output energy of the Linac within the same physical length constraints.

We began construction of the new Linac for the Fermilab III program in October 1989. To increase the final Linac beam energy from 200 million electron volts (MeV) to 400 MeV, we will replace the last four drift-tube tanks of the nine in the present Linac with seven new accelerating modules operating at a higher frequency and higher accelerating fields. The new accelerator will be installed adjacent to the old Linac tanks as the new modules are completed and will be operated without beam until final conversion to 400 MeV operation (scheduled to begin in the summer of 1992). Some modifications in the beam transfer line to the Booster accelerator will be required to accommodate the higher energy beam. Seven 12-MW, 805 MHz klystrons (electron tubes) will supply the rf power to drive the new modules. Expansion of the Linac gallery will allow the installation of these systems without disruption of the currently operating Linac rf systems. The higher Linac energy will reduce the transverse size of the beam in the Booster and thus provide denser, more intense proton beams in the Booster.

The research and development effort required for the Linac improvements began in 1989. 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 series to form an accelerator module that is then powered by one klystron. Charged particles passing through a beam hole in each cavity are accelerated by the rf voltage in each cavity. The new Linac will have a total of 448 cavities, each providing an energy gain of 600 keV. Because of the high electric fields in these cavities (7.5 MV/m), a special six-cavity test model was built in 1989 to test sparking and x-ray production. These tests indicated that voltage conditioning with six million rf pulses (five days of conditioning at 15 Hz) would bring the sparking rate down to less than one spark per hundred pulses in the new Linac, and that continued voltage conditioning leads to a steady reduction in sparking. We found x-ray production to be low enough to not cause any component damage over the projected 20-year lifetime of the new Linac. A second six-cavity model was successfully fabricated to explore improved machining and tuning techniques.

Fabrication of a complete prototype accelerator module also began near the end of 1989. This prototype will be mechanically and electrically equivalent to the first accelerator module of the seven needed for the new Linac. This module will be power tested using a 12 MW prototype rf system. The modulator portion of this rf system was fabricated in the Fermilab Linac gallery during 1989 and successfully operated into a diode load at full power and repetition rate.

Rene Padilla works with the side-coupled accelerating cavities that will enable the Linac to increase its output energy from 200 MeV to 400 MeV. The doubling of the Linac energy is part of Fermilab III.

Main Injector

The centerpiece of Fermilab III is the new Main Injector accelerator (MI), which will be a more efficient replacement for the existing Main Ring accelerator. Many Main Ring components, including the rf, quadrupole magnet/power supply, and the correction element systems will be reused in the MI. However, the key elements of the MI are 300 new dipoles. Design and development of the dipoles for the MI began in 1989.

The MI will be constructed tangent to the Tevatron in a separate tunnel. It will be about half the size of the Main Ring but will allow the production of about five times as many antiprotons per hour as the Main Ring and will be capable of delivering three times as many protons to the Tevatron. The MI is expected to produce a luminosity of at least $5 \times 10^{31}/\text{cm}^2/\text{s}$ in the collider, a factor of 25 larger than achieved with the present accelerators.

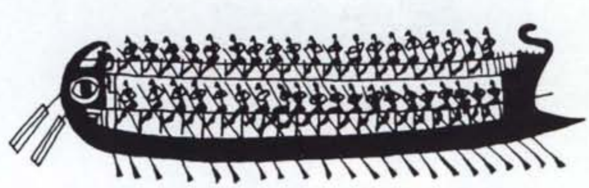
In addition to enhancing the search for the top quark and potential high-mass extensions to the Standard Model of the universe, construction of the MI will simplify and enhance operation of the Fermilab complex. Removing the Main Ring from the tunnel it shares with the Tevatron will eliminate interference with the experimental detectors being used to study proton-antiproton interactions. The MI will also support the delivery of very intense proton beams to existing experimental areas where the added proton intensities will allow precise studies of quantum number conservation laws and enhance experiments designed to observe the hypothesized tau neutrino. Finally, proton beams emanating from the MI 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.

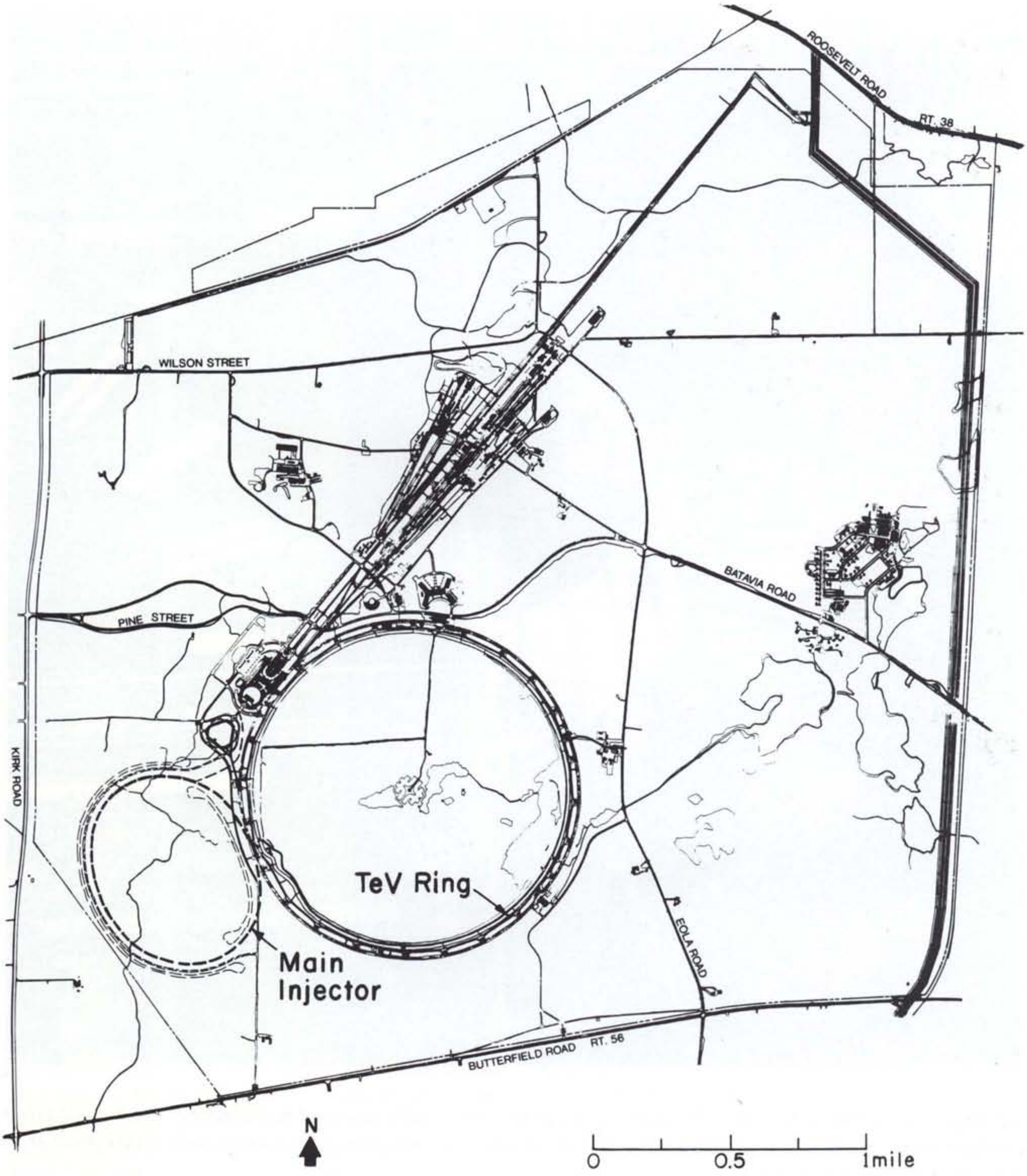
The MI will result in significant enhancements to Fermilab's collider and fixed-target programs. Benefits expected to accrue from construction of the MI include:

1. An increase in the number of protons targeted for antiproton production from 5×10^{15}/hour (following the Linac upgrade) to 1.2×10^{16}/hour.
2. An increase in the total number of protons that can be delivered to the Tevatron to 6×10^{13} protons per pulse.
3. The ability to efficiently accelerate antiproton bunches of 4×10^{10} particles for injection into the Tevatron.
4. The ability to produce proton bunches of 3×10^{11} particles for injection into the Tevatron.
5. The reduction of backgrounds at the CDF and DØ detectors through removal of the Main Ring from the Tevatron tunnel.
6. Provision for the extraction of proton beams to the fixed-target areas year-round and the potential for very high intensity (average and instantaneous) beams for use in high sensitivity K decay and neutrino experiments.

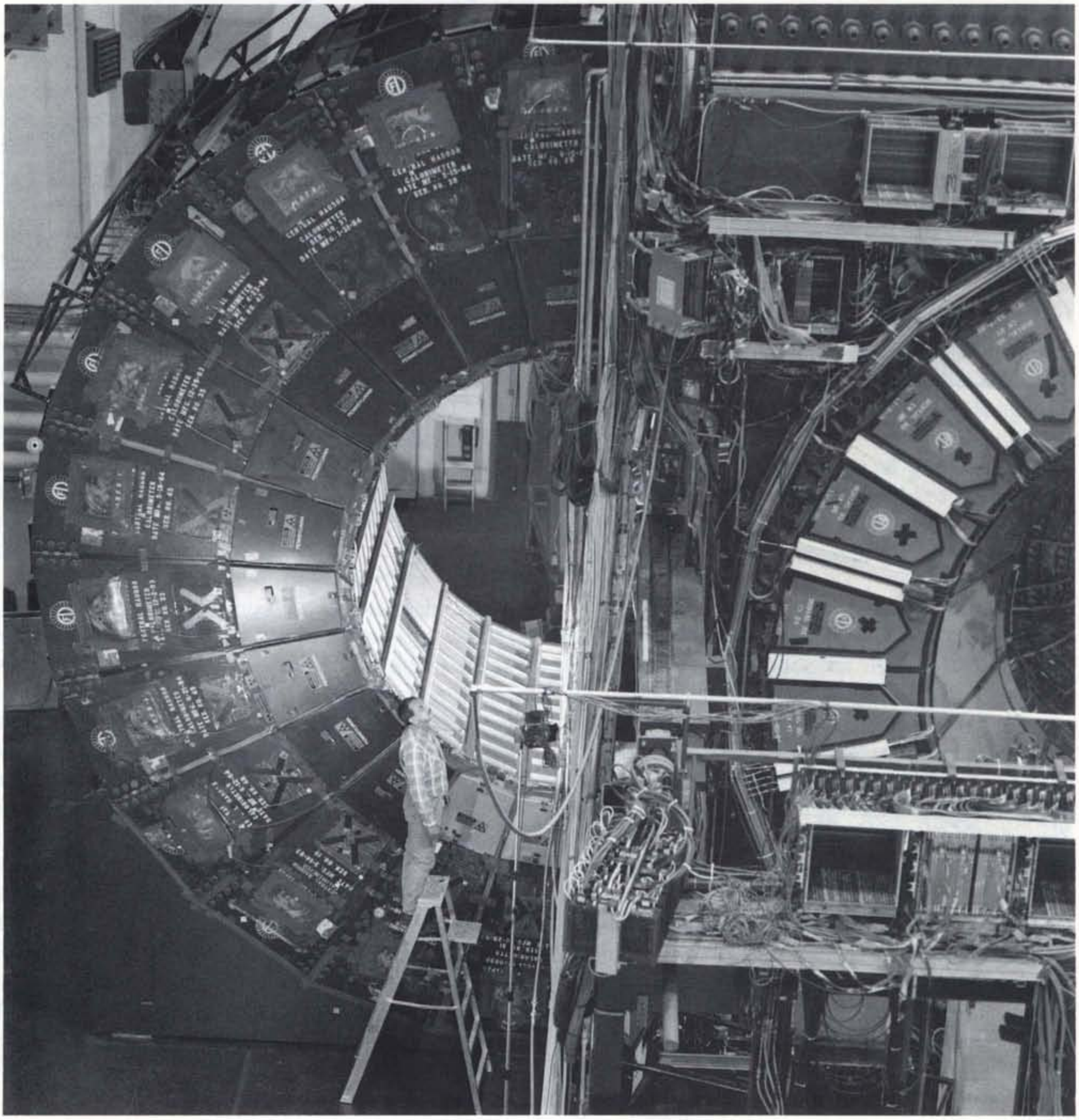
These expected improvements in performance are directly related to the optics of the MI ring. The MI will lie in a plane and will have stronger focusing than the existing Main Ring. The physical beam size will, therefore, be significantly reduced. The construction of mechanically simpler but more precise magnets is expected to yield a highly reliable machine.

The MI will be seven times the circumference of the Booster and slightly more than half that of the existing Main Ring and Tevatron. Six Booster cycles will be required to fill the MI, and two MI cycles will fill the Tevatron. The MI is designed to have a transverse aperture 30% larger than the Booster aperture (following the Linac upgrade) and three to four times larger than that of the Main Ring. The MI should be capable of accepting protons from the Booster and accelerating them without significant beam loss or degradation of beam quality.





A schematic drawing shows the layout of the proposed Main Injector, the centerpiece of Fermilab III. The Main Injector is designed to be a 150 GeV accelerator which will replace the Main Ring, the original 200 GeV accelerator built at Fermilab nearly twenty years ago. Scientists working at Fermilab expect that Fermilab III will enable them to discover the top quark and perhaps observe the interaction of the elusive tau neutrino with ordinary matter.



A central calorimeter arch of the CDF detector is opened up for calibration and maintenance. These calorimeter modules wrap around the collision point and thus can measure the energy emitted in various directions from the proton-antiproton collisions.

Detector Improvements

To reach the full potential of Fermilab III, we will need collider detectors capable of recording the proton-antiproton collisions produced at the increased luminosities. In 1989 improvements in the CDF detector were initiated and the DØ collaboration continued construction of the DØ detector.

The CDF Detector

Many of the changes planned for the 1991 collider run are a result of the increase in the luminosity of the Tevatron. Others derive from the operational experience of the 1989 run and are expected to improve the physics capabilities of the detector.

Extensive detector electronics changes are required to ensure that fast analog information from the particle calorimeters is available to allow a first level electronic logic decision (or trigger) between beam crossings. In addition, some of the calorimeters must be rebuilt to cope with the high rate of collisions. CDF intends to reduce the gain in the gas calorimeters and to speed up their integration times. Both changes require new electronics in the collision hall. Although the scintillation/photomultiplier-based central calorimeter is intrinsically fast enough to cope with the luminosity increase, some small modifications to the existing electronics are required to speed up the trigger signals. For these improvements CDF will have to build 24,000 channels of new electronics and modify 2,000 existing channels. CDF plans to test these electronics and recalibrate the calorimeters during the 1990 fixed-target run.

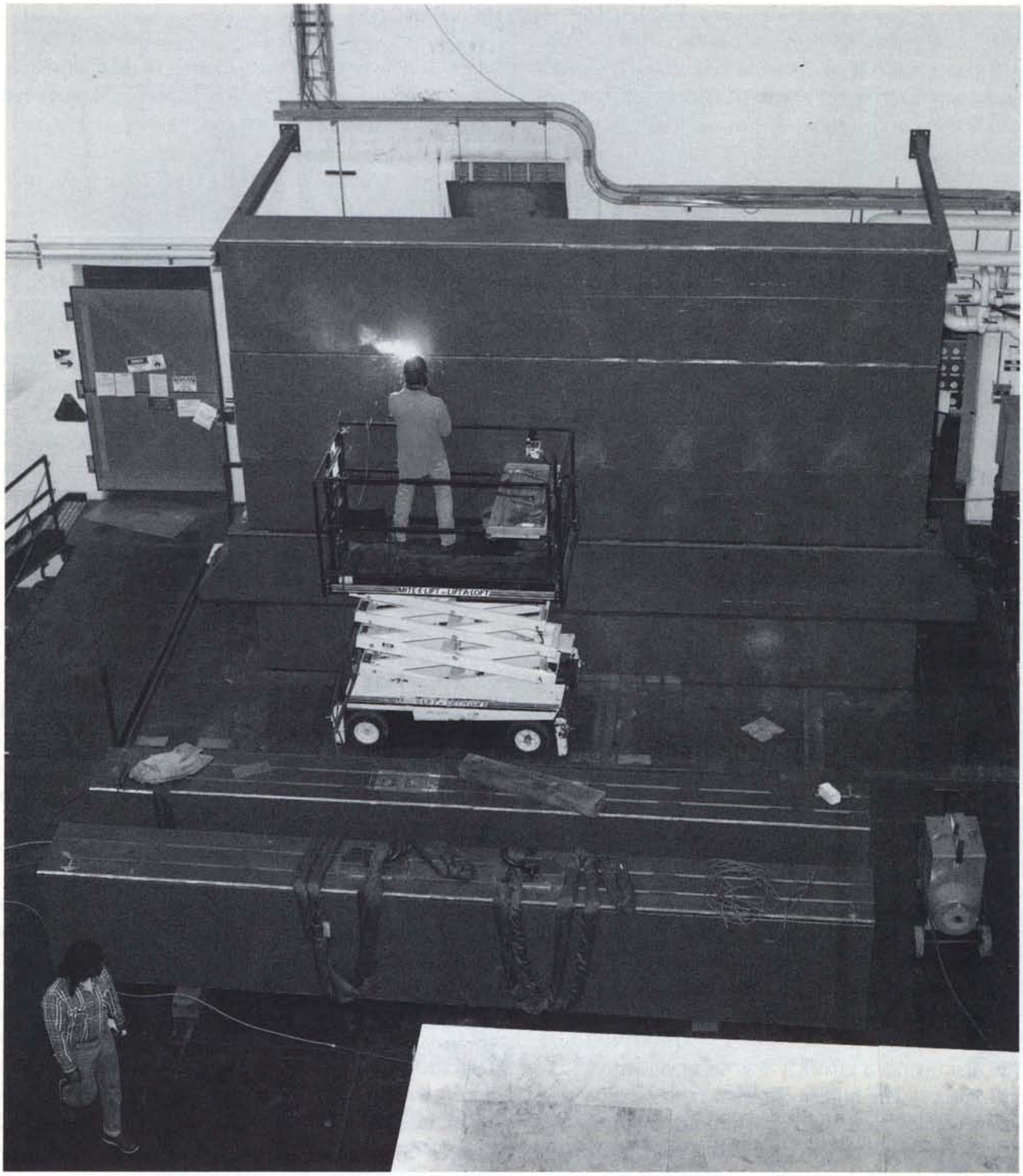
The particle-tracking detectors also need to be improved to function efficiently at the higher collision rates. First, CDF will have to replace the vertex time projection chambers (VTPC). These devices are used to locate the event vertices, measure event topologies, locate forward muon and electron candidates, and detect photon conversions. The VTPC system, which was first operated in 1985, was designed with 15-cm drift spaces. The higher collision rates would cause unacceptable space charge distortions within the detector. The new vertex chambers (VTX) will have 4-cm drift distances, and the number of active sense wires will be increased from 3,000 to 8,600, requiring new cables, amplifier-shaper-discriminator cards, etc. A new low-noise, higher gain, custom-integrated preamplifier was designed at Fermilab in 1989 to allow operation of the VTX at the low gas gains necessary to limit radiation damage to the chamber.

In 1988-89, the CDF detector ran at close to the maximum rate both for the data-acquisition system and the trigger level III processor farm. For a much larger luminosity, CDF must either raise the level II trigger thresholds or find additional selection criteria to lower the trigger rate. Because higher thresholds are unacceptable for many of the physics topics studied at Fermilab, CDF plans to apply additional selection criteria to lower the trigger rate. Most criteria effective in reducing the trigger rate must be made using fully digitized events in the level III processors. To increase the speed of the electronic digitization, they will replace the existing analog-to-digital electronics.

The real-time computing capability of the CDF detector will be increased by about a factor of four (for the 1991 run) to allow more detailed on-line monitoring. Many other on-line hardware and software computing improvements are planned to improve data-taking speed and efficiency. Based on experience from the 1989 collider run, CDF plans to write raw data only on 8-mm tape drives.

Off-line computing resources available for the detailed analysis of events will also need to be increased. A fourfold increase in available processor power is planned. This increase is needed because: (1) events will be more complicated due to the increased number of multiple interactions expected at higher luminosities; (2) the number of electronic channels in the CDF detector will increase due to the detector upgrades; (3) the improved level III trigger will only accept events of higher quality, allowing fewer events to be rejected off-line based on simple algorithms; and (4) the capability will exist to write events to tape at three times the previous rate.

A significant upgrade to the CDF muon system planned for the 1991 run is driven partly by the anticipated higher luminosities and partly by the desire to provide better physics capabilities. CDF plans to add a pair of two-foot-thick steel walls to the sides of the central detector and new chambers and trigger



Construction of a new steel absorber wall for CDF will allow the detector to more cleanly identify penetrating muons emitted in proton-antiproton collisions.

counters surrounding the central detector. The walls require 630 tons of steel, and the north wall must move in and out of the collision hall with the central detector. A new set of muon chambers and trigger counters behind these steel walls and above and below the steel magnet flux return legs will be used to reject low-energy muons. Additional chambers and trigger counters will be added to increase the muon coverage. The muon chambers will require 3,300 new electronic channels.

A silicon vertex detector (SVX) will add new physics capability by allowing CDF to identify events containing secondary vertices. In 1989 construction was started on a detector with four layers of 60-micron silicon microstrip detectors arranged in two 12-sided polygonal structures surrounding a new 1.5-inch beryllium beam pipe. The detectors themselves are located on a "ladder" structure that provides mechanical support and allows three detectors to be micro-bonded together. The detectors are then micro-bonded to a custom VLSI (very large scale integrated circuit) readout chip (MICROPLEX), which was developed at the Lawrence Berkeley Laboratory and Fermilab. The detector should allow the identification of a large sample of events with an unambiguously identified heavy quark decay separated from the primary vertex. The system will contain over 40,000 additional electronic channels.

The DØ Detector

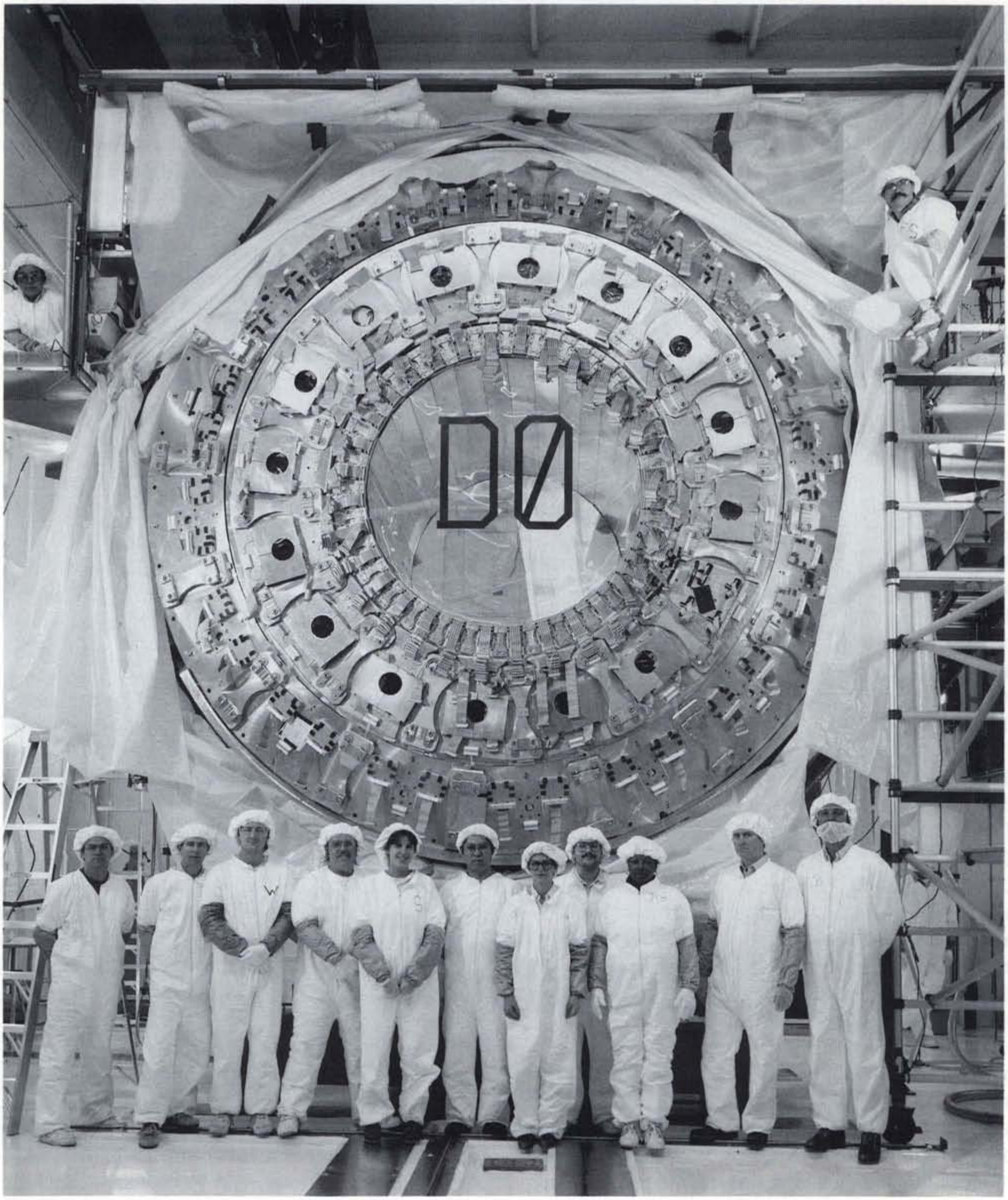
Assembly continued in 1989 on the DØ detector. It will complement the CDF detector and allow sensitive searches for departures from the Standard Model of quarks and leptons and open many new windows to look for particles in the mass region above 100 GeV. Searches for the top quark, for supersymmetric particles, and for detailed properties of the W and Z bosons all require the multijet, lepton, and missing transverse energy (E_T) detection for which the DØ detector was optimized.

During 1989 the DØ collaboration, which includes 22 institutions, worked hard on many fronts preparing the detector for operation in the 1991 collider run. Parallel efforts included detector installation in the DØ assembly building (DAB); detector fabrication in laboratory and university shops; tests of completed systems in cosmic ray and accelerator test beams; and development of the large variety of software packages needed to filter, collect, monitor, and analyze the data. Much of this work has been aimed at system tests of large parts of the detector during 1990.

Installation activity at DAB during 1989 was intense. The toroidal iron magnets for muon detection were completed in the spring; power tests went smoothly, and the fields in the iron and in the inner detector space were as expected. With the completion of all of the large muon chambers in April, attention turned to mating the detector electronics to the chambers and certifying them for installation. At year's end, 35% of the 164 muon chambers (with sizes up to 160 square feet) were installed and 20% were commissioned with full electronic readout. In parallel, the cable installation, construction of cryogenic services, and installation of electronics services for the full detector have proceeded. A major Soviet contribution to the DØ detector is SAMUS, the small angle muon system, which consists of over 5,000 proportional drift tubes. About half of these arrived at Fermilab in 1989 and were tested prior to assembly and installation.

The uranium-liquid argon calorimeters in the DØ detector are crucial for most of the anticipated physics signatures at high energy and bringing them into operation is a major effort of the collaboration. During 1989 the installation of the central calorimeter modules in the clean room at DAB was completed, and the pressure heads of the cryostat were given a trial fit. This followed an extensive and successful program of testing and cleaning of all the components to be inserted in the cryostat. In the meantime, work on the modules for the end calorimeters progressed rapidly. All of the stainless steel sections were delivered from the Soviet Union and are being readied for a trial installation at Fermilab. The first of two end electromagnetic modules arrived from Lawrence Berkeley Laboratories for a series of beam tests that will be performed together with the completed inner hadronic module fabricated at Fermilab. Hadronic module building, cold tests, and mechanical tests have been proceeding in parallel.

A full-scale test of one-fourth of the final central calorimeter electronics, from preamplifier to data acquisition and controls, was performed in 1989. These tests showed excellent performance. Linearity, stabil-



Clean room workers pose with the central calorimeter modules for the D0 detector. Because of the extreme sensitivity of the device, it is essential that utmost cleanliness be maintained during its final assembly. The detector is approximately eighteen feet in diameter.

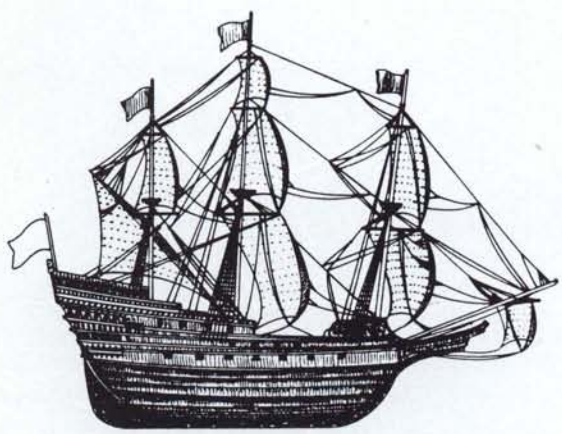
ity, reliability, and noise measurements all conformed to the stringent design specification.

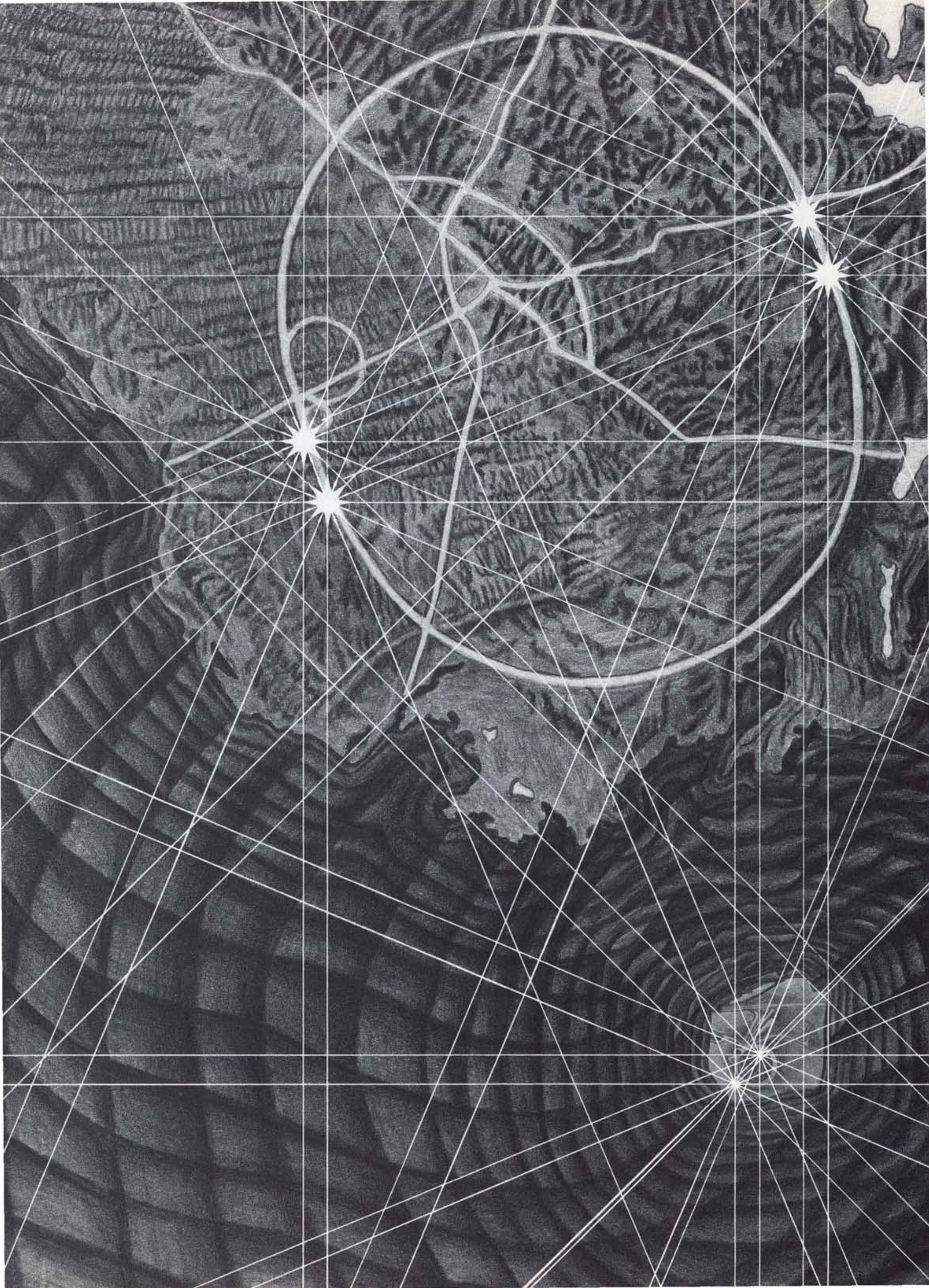
The tracking detectors that reside inside the calorimeters have been put to a variety of tests during this year. All but one of these chambers are complete, so the effort has been dominated by cosmic ray tests to determine resolutions and calibration constants and to exercise the complex digitization electronics. In addition, a sector of one chamber was installed at the DØ intersection region during the 1989 collider run to gain experience with radiation backgrounds in the final operating environment. The transition radiation detector has been completed at Saclay in France. Tests in a beam at CERN showed that its performance exceeded the design specification.

Increasing attention has been focused on the preparation of the software and hardware for data collection, hardware monitoring, and physics analysis. Major improvements in the data-acquisition software system were made in 1989 based on a 1988 run in the test beam. These were tested in DAB using the electronics and computers for the final full detector. A multiple processor farm was used to collect data from several independent data streams and to provide calorimeter calibrations on-line. The hardware control and monitoring systems were also tested.

During 1989 much progress was made toward finalizing and testing the full data-analysis software system. Development of data-reconstruction programs included generation of a large set of computer-simulated physics events including all mechanical and electronic detector details. The first version of the off-line program is now working with all detector reconstruction packages and the algorithms for particle, jets, and missing E_T in place. A jet is a collection of several particles evolving from a subconstituent of matter (a quark or gluon) and sharing the original momentum and energy. The jets seen at high energy tend to have their particles closely aligned with the direction of the original quark or gluon.

Much of the work accomplished in 1989 prepared for the large-scale tests of major detector systems planned for 1990. One beam test during the 1990 fixed-target run will provide valuable calibration data for the calorimeter electronic and hadronic modules, the intercryostat detectors, and the three types of tracking chambers. In addition, signal collection and digitization electronics will be put through their paces. The most important aspect of these beam tests is the opportunity to use the full system of trigger, data-acquisition, monitoring, calibration, and analysis software. The DØ collaboration will further test these systems during cosmic ray commissioning of the large-angle components of all detectors in the DØ hall late in 1990. Both beam tests and cosmic ray tests contribute to testing and upgrading the operating system and to training the full collaboration in running the detector.





Onward and Outward

One important part of Fermilab's mission is the transfer of newly obtained knowledge and recent discoveries to the private sector for development into commercial products. Another part of our mission is to put that information to work for the advancement of accelerator and particle physics worldwide. In 1989 we took impressive steps in both of these areas.

Technology Transfer

Technology transfer at Fermilab aids the development of broadly useful and marketable products from information and equipment designs generated by the Fermilab staff in the process of doing basic research. This transfer of research technology to a broader sector takes place in several ways.

Some of the most far-reaching Fermilab technologies have been an outgrowth of the Tevatron construction and operation. Development and then procurement of superconducting wire for the Tevatron spawned an industry that has continued and is now one of the main underpinnings of magnetic resonance imaging (MRI), an important new tool for medical diagnosis. The Tevatron nourished an industrial establishment that now manufactures between one-half billion and one billion dollars worth of product every year. To this day, the Tevatron remains the most successful research and development (R&D) investment ever made in superconductivity. The significance of the great technology effort was recognized this year when President Bush awarded 1989 National Medals of Technology to the major developers of the Tevatron.

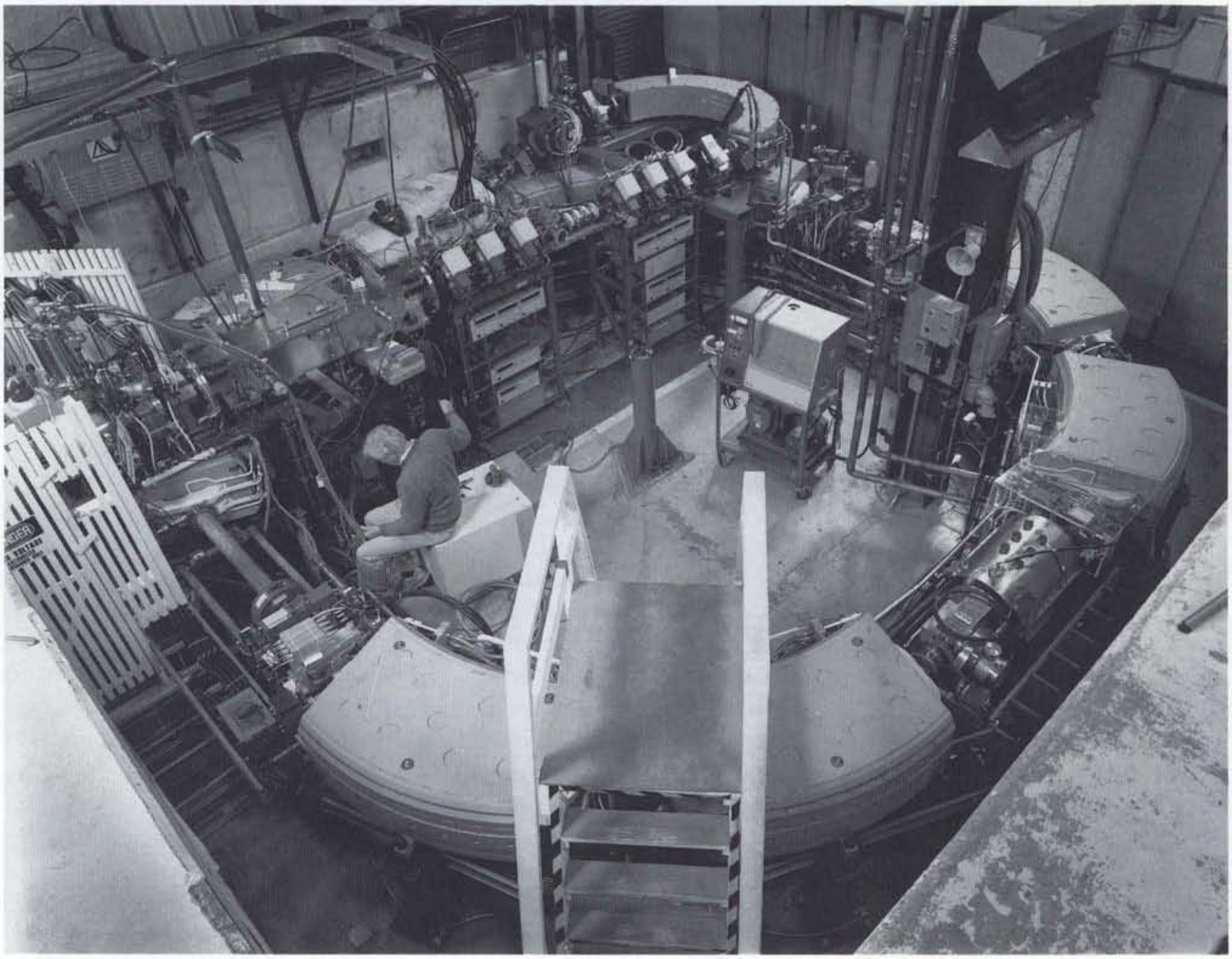
Superconductivity research continues at Fermilab as part of the R&D activity for the SSC. When the SSC becomes a full-scale construction project, that R&D will wind down and another of the Tevatron's children will have grown up and left home. If history repeats itself, new projects will come along and lead to creation of other technologies. Ensuring that the fruits of these technologies reach the U.S. public is an important part of Fermilab's mission.

Development of electronic systems whose technology is eventually modified and applied in the private sector is another successful area of technology transfer. One such example, the Advanced Computer Program (ACP) project, has now evolved through several generations. In 1989 the ACP group won their third prestigious R&D100 prize. This year's award was for the Advanced Computer Program Multi-Array Processor System (ACPMAPS), a very cost-effective, high-performance, parallel processing supercomputer. Many systems around the world are now in operation using ACP modules produced by a private company, and new ideas continue to evolve from the ACP group, which is now known as the Computer R&D Department.

Fermilab scientists provided the technology for another large project, the proton medical therapy accelerator at Loma Linda University Medical Center. The accelerator was completed at Fermilab in the spring of 1989, tested through the summer, and shipped to California in the fall. It is slated to be operational in the spring of 1990. Loma Linda has an industrial partner, Science Applications International Corporation, that will handle work on future medical accelerators.

A third technology transfer area where the Laboratory has been active is the Fermilab Industrial Affiliates. Publicity about accelerator technology at Fermilab engendered by the SSC created a flurry of interest in the Affiliates. In 1989 the traditional roundtable at the Affiliates meeting covered applications of accelerators. Discussion ranged from synchrotron radiation to medical applications to analyzing the pages of the Gutenberg Bible. A side-bar roundtable looked at computer and electronic initiatives for science. In 1990 attention will focus on specific Fermilab activities, including the new technologies in the Fermilab III project.

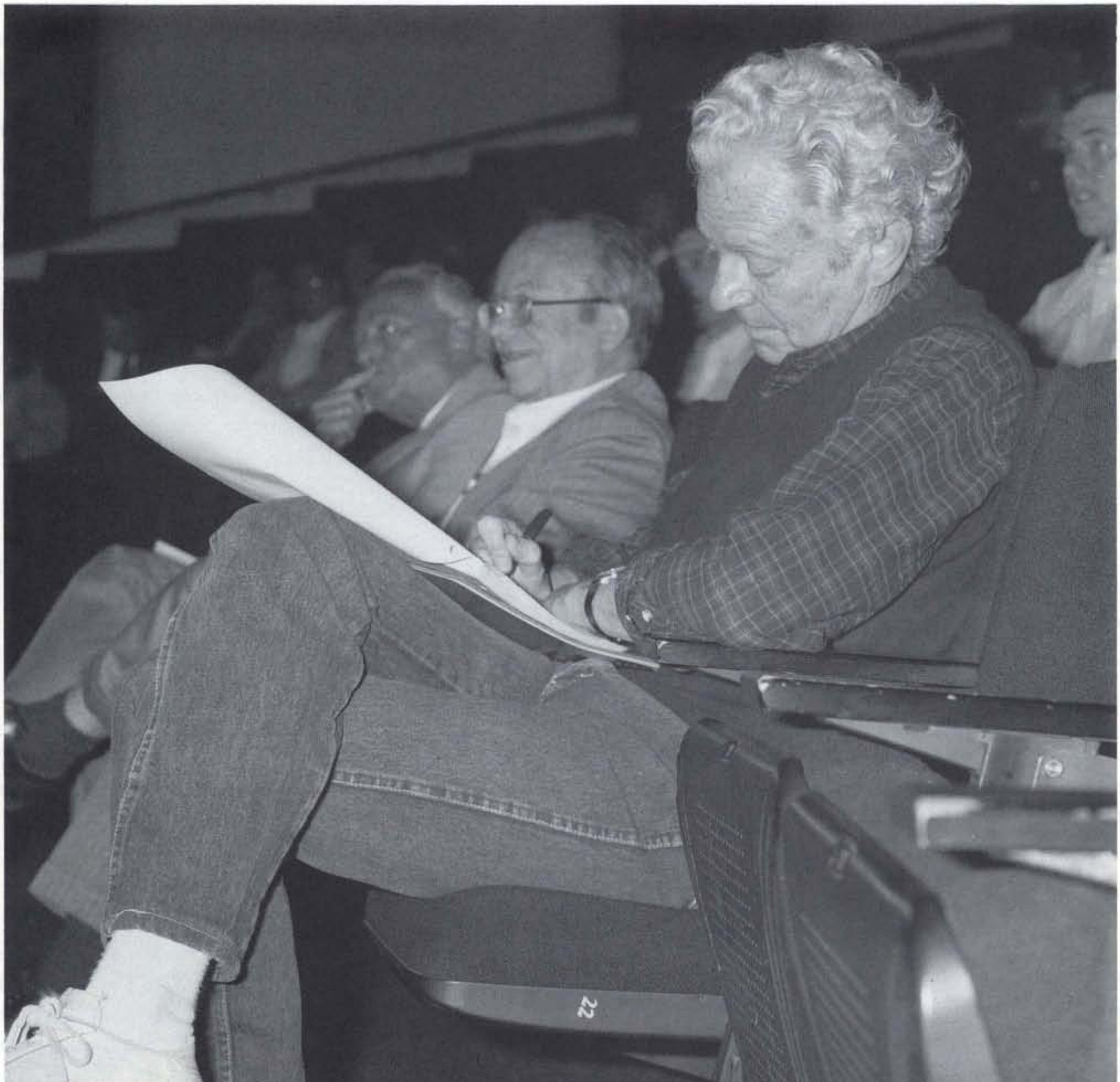
Big, orchestrated activities are important, but new technology emerges from every part of the Laboratory, including the Business Office. The Office of Research and Technology Applications (ORTA) assesses about one new technology or software development a week. Recently the ORTA completed the 600th Fermilab assessment. Perhaps 10% to 20% of these items are either patentable or can be copyrighted. Of those, perhaps 20% may be marketable.



This proton synchrotron, twenty feet in diameter, was designed and constructed by Fermilab for the Loma Linda University Medical Center where it will be used to treat cancer patients. This small accelerator provides a beam of protons whose energy, location, and intensity can be carefully controlled.

Nineteen eighty-nine was a milestone year for marshalling resources for licensing. DOE has now given University Research Affiliates, Inc. (URA), and Fermilab most of the administrative apparatus needed to commercially license particular software products. With a licensing officer now firmly in place, the Laboratory has several powerful new tools to channel good technology into the commercial sector.

One example of a new particle physics detector shows how this licensing activity develops. A Fermilab scientist pioneered the use of cerium fluoride as a scintillator for charged particle detection. The light output of cerium fluoride is faster than that from existing scintillating crystals. The scientist observed several years ago that cerium fluoride made an excellent scintillator for Positron Emission Tomography (PET), a medical diagnostic technique somewhat akin to MRI. PET, one of the first direct applications of exotic elementary particles, measures the antimatter annihilation of positrons with ordinary electrons. The



On June 15, 1989, Fermilab hosted a symposium in honor of retiring director, Leon Lederman. Dr. Lederman, a Nobel Laureate, was Fermilab's second director. In December of 1989, Governor James Thompson formally named him Illinois' first Science Advisor.

advantage of PET is that it allows physicians to monitor activity as it takes place inside the body. URA has filed a patent on the cerium fluoride technology. The patent application has stimulated unusual interest. Time will tell whether the technology makes its way into hospitals.

Fermilab III and other projects needed for the next decades of particle physics research will drive future technology transfer. The technology required for the high luminosity provided by the Main Injector emphasizes very fast electronics and computing resources greater than those now available commercially. It is possible that the computing needed to exploit the high luminosity from Fermilab III will result in new industries. Fermilab and a major computer manufacturer are now discussing ways to better investigate this type of computing. Supercomputers will be important in the emerging areas of neural networks, expert systems, and artificial intelligence.

Increasingly, society is coming to realize that the last great frontier left to exploit is knowledge. Fermilab's Director Emeritus, Leon Lederman, has now been appointed Science Advisor to the Governor of Illinois. Like many other states, Illinois has set up a multimillion-dollar challenge grant for high-technology programs. The State knows that the presence of Fermilab has been pivotal in the development of the I-88 Research Corridor. With the support of DOE and the State of Illinois, the exploitation of Fermilab technology should continue to thrive.

The Superconducting Super Collider

The experience of designing, building, and operating the Tevatron, the world's only operating superconducting accelerator and the largest superconducting facility in the world, has placed Fermilab in a unique position to support the SSC.

Detector Collaboration

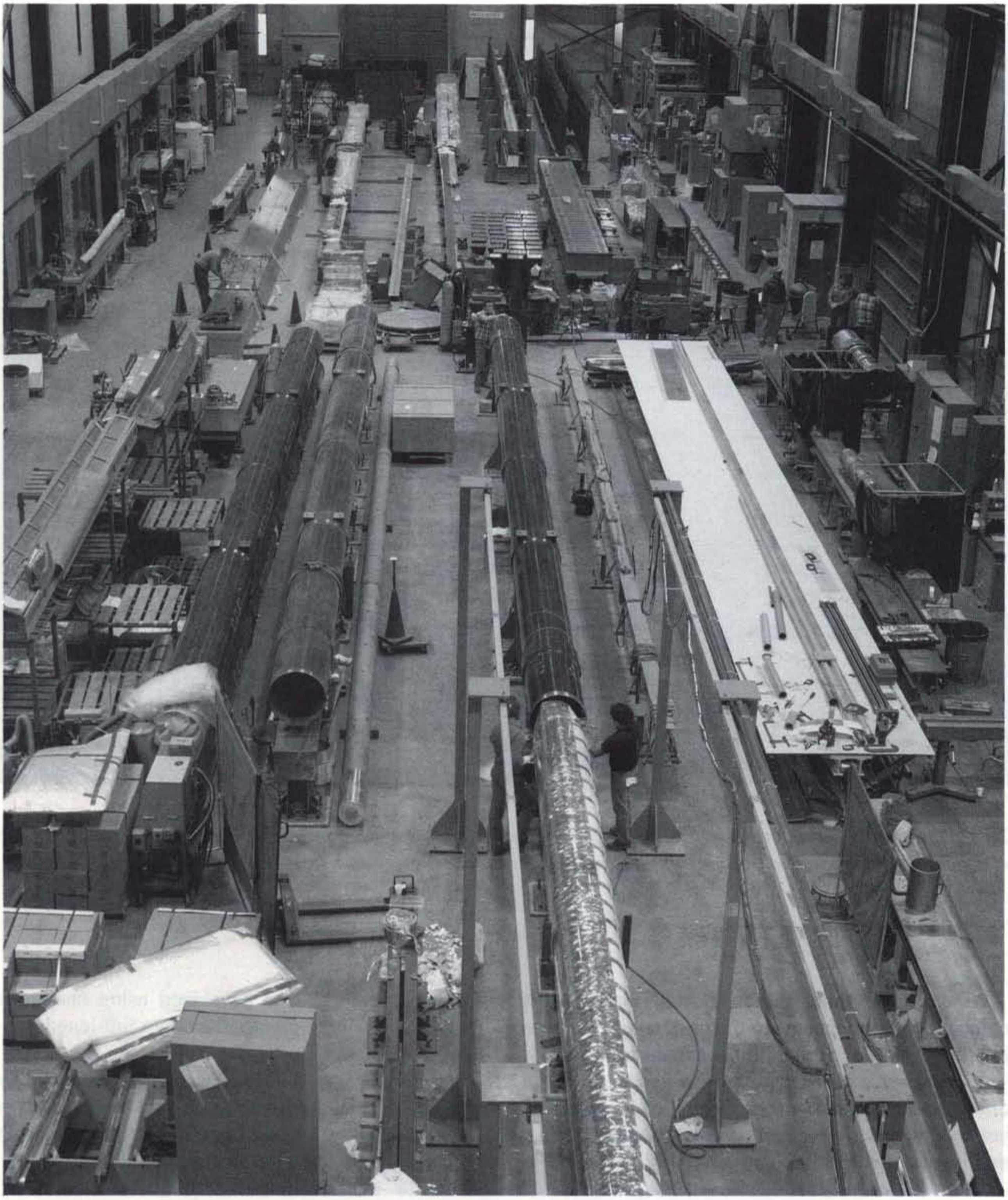
In September 1989, at a Fermilab-hosted workshop, an international collection of physicists agreed to collaborate on designing and building an SSC Solenoidal Detector. The first organizational meeting of this new collaboration was hosted by Fermilab in December.

Magnet Development

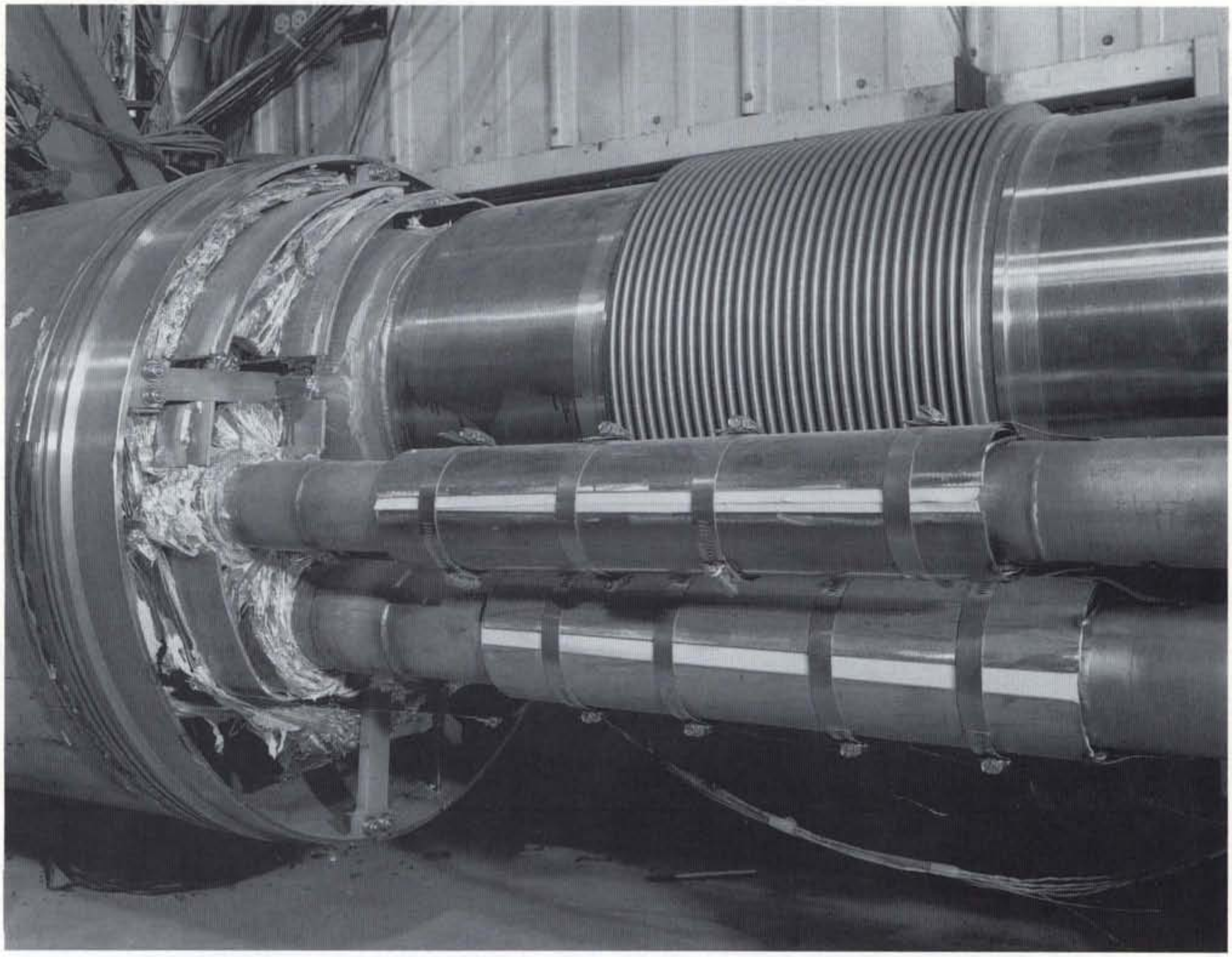
Over the past several years Fermilab has made important contributions to the SSC magnet-development program. When the SSC research and development program began in 1985, Fermilab undertook the task of developing a suitable cryostat to house the superconducting coil and magnet assembly being built at Brookhaven National Laboratory (BNL). Fermilab successfully completed the first-generation cryostat in time for the first cold mass to arrive from BNL in the summer of 1986. The very low-heat leak cryostat design features a folded post support using glass and carbon fiber composites, an effective radiant heat shield system, and a simple and continuous magnet-to-magnet interconnection. A second-generation cryostat of even simpler construction and improved performance was successfully tested in 1988. The cryostats have performed successfully on every magnet built to date.

Fermilab was also assigned the task of testing the full-length prototype dipoles made by Fermilab and BNL. The staff of the Magnet Test Facility (MTF) has been successful in continuously improving both the efficiency and the reliability of the SSC testing capability at Fermilab.

During the past two years the MTF staff has prepared to build both short (one-meter) and full-length prototype SSC dipoles. In particular they worked toward the development of a second set of full-length magnet assembly fixtures based on the proven design used for the Tevatron. The fixtures consist of full-length curing and collaring presses and a full-length press for applying the yoke and helium-containment skin. These fixtures will provide high-precision coil sizing and uniformity for better magnet performance and reliability. The fixtures are also designed for improved production efficiency.



The prototype SSC dipole magnets are being assembled in the Industrial Center Building.



This photograph shows the cryogenic connections at the end of a superconducting SSC dipole magnet. The cryogenic assembly and testing of the magnets take place at Fermilab.

At the same time, the MTF staff developed a number of improvements to the basic magnet design in order to improve reliability and manufacturability. These changes, also derived from experience with the Tevatron, included simpler, better ends; improved yoke-alignment; fewer coil parts; and better fabrication procedures with the new assembly fixtures. Design improvements are developed using one-meter models and will be incorporated into full-length prototypes as they are proven.

Development of the full-length magnet assembly fixtures was completed in 1989, and the fabrication of prototype magnets has begun. The first full-length magnet will be ready for testing in 1990.

As many as five SSC dipole magnets can be joined together in a string in this tunnel-like enclosure. They are then connected to and tested by utilizing the existing Tevatron cryogenic controls.

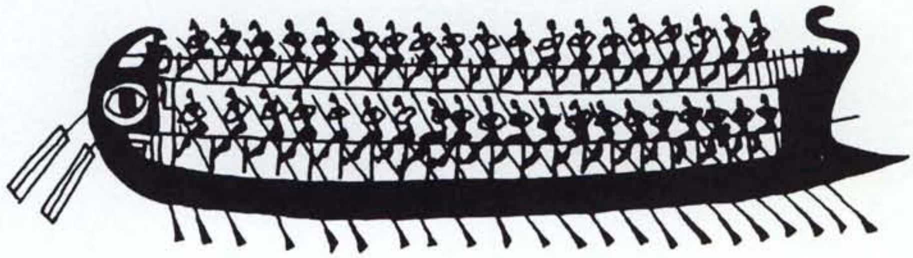
Magnet Testing

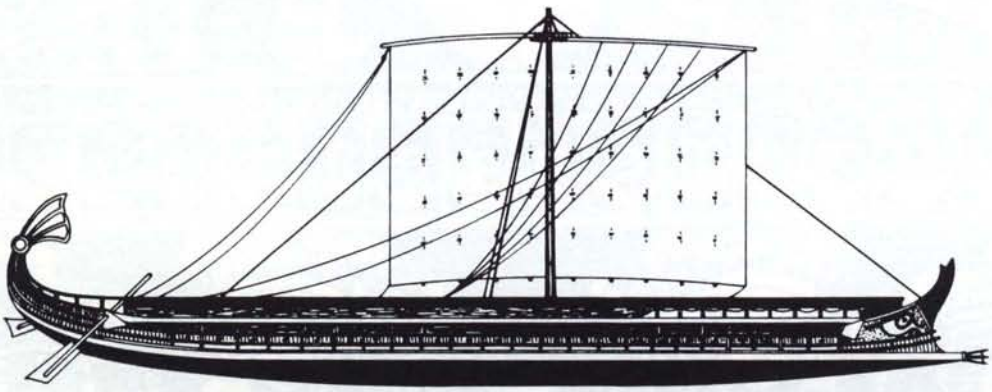
Design of a one-half cell test facility for prototype SSC magnets in cooperation with the SSC Laboratory was continued in 1989. For several years single full-length SSC prototype dipoles have been cooled to cryogenic temperatures and individually tested at the Fermilab MTF for operation at full field. However, it is not possible either to cool or power a "string" of several magnets at MTF (or elsewhere at this time). The operation of a number of magnets in a string is necessary for testing under conditions that mimic the actual operations and performance of an accelerator.

Several years ago the SSC Central Design Group (SSC-CDG) and the Fermilab Accelerator Division agreed to begin to create a site where a string of prototype SSC dipoles could be cooled, powered, and tested. This facility, physically located in the southwest quadrant of the Tevatron at location E4, utilized salvaged Main Ring tunnel arches to create a several hundred foot long tunnel-like enclosure. Additions to the Tevatron cryogenic plant at E4 were made and demonstrated. The facility was not used for its intended purpose because the SSC-CDG never produced enough working magnets to build the minimum string. In 1989, however, the SSC Laboratory decided to reactivate the project with the intention of achieving a minimum 5-dipole-string test in 1990. The Accelerator Division, therefore, reactivated the support work for this project, adding physical space for field offices and completing the "tunnel" enclosure. Assembly of an early two-magnet-string test was started.

Main Injector

It should also be noted that construction and operation of the new Main Injector as part of the Fermilab III project will provide a proving ground for many of the experimental techniques that need to be developed for use in the SSC preaccelerators. In addition, many of the beam-dynamics studies performed in 1989 in the Tevatron and Main Ring accelerators are directly applicable to the design of the SSC.



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Support

The effort, commitment, and dedication of many people are crucial to Fermilab's voyages of discovery. The following photoessay highlights just a few of the significant and important contributions of Fermilab's support personnel in 1989. The names and faces included are a salute to all those who enable our smooth sailing.

Three support groups — Laboratory Services, Business Services, and Safety — are designed and dedicated to providing services to the internal Fermilab community. Others reach out to a broader public.

Laboratory Services includes both human resources and information resources. Human resources includes medical services; employment, equal opportunity, and personnel; day-care, housing, and food services; and recreational activities. Information resources groups run the library, assist Fermilab authors with their publications, provide visual communications services, and disseminate information to the public. In October 1989, in a timely reflection of a nationwide concern with scientific education, the newly instituted Education Office joined the Laboratory Services Section.

The Business Services Section handles the business functions of accounting, payroll, and information systems. It also provides administrative support activities such as law, facilities management, and emergency services. During 1989, Business Services upgraded the payroll system, incorporated revisions to the Preventative Maintenance Manual, and elevated Emergency Services to a department within the section.

The Safety Section is responsible for monitoring the safety of Fermilab's employees, users, and visitors. In 1989, in addition to their usual duties, Safety employees contributed to the development of the DOE-wide Five-Year Plan for Environmental Restoration and Waste Management. They also conducted comprehensive internal appraisals of the industrial safety and health physics programs of the Research and Accelerator Divisions. In fulfillment of its ongoing commitment to a safe environment for all, the Safety Section maintained and tested fire protection systems, labeled radioactive materials, and handled hazardous waste of all divisions and sections.

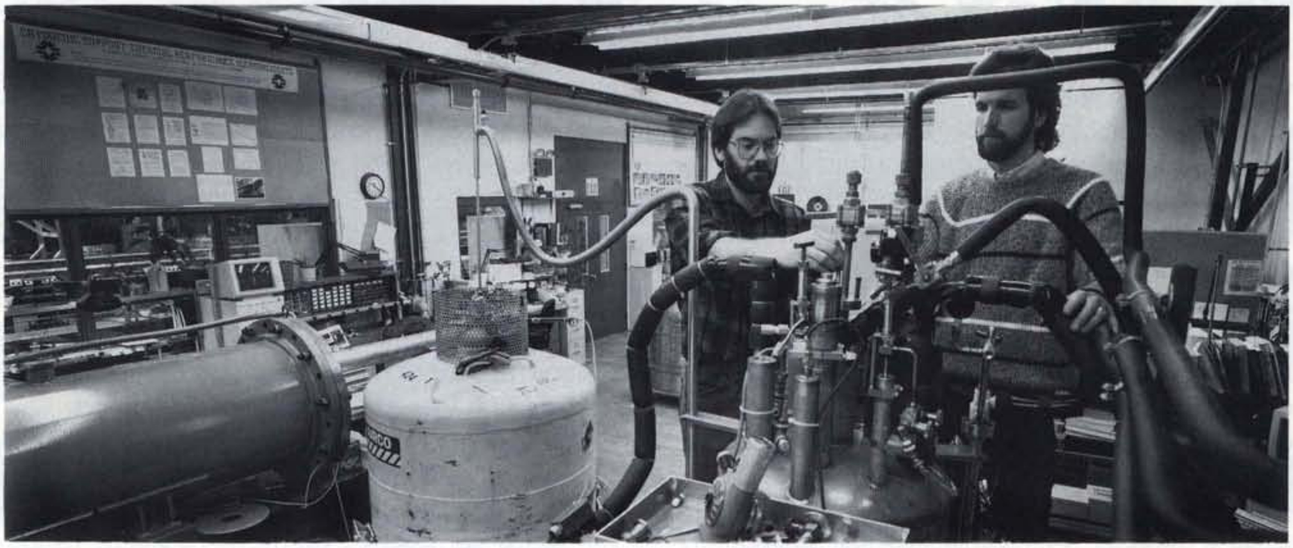
In 1989, Fermilab continued to contribute to the welfare of the surrounding community. Some of the Laboratory's more noteworthy programs include the Neutron Therapy Facility (NTF), educational offerings, and environmental research. Since 1976, NTF has been using the the Linac accelerator to treat cancer patients with inoperable radioresistant tumors.

Fermilab sponsors and/or participates in numerous educational activities designed to encourage young people to pursue careers in science and technology and to raise the overall scientific literacy of the nation.

Fermilab has developed an exciting and innovative collaborative effort with the education community to enhance the quality of precollege science education in public and private schools and to promote a broader public awareness and understanding of science. With support from Fermilab scientists, engineers, and Education Office staff members, local teachers develop, conduct, and evaluate programs both for their peers and for students.

College level programs support undergraduate and graduate students majoring in physics, related sciences, or engineering. Fermilab may provide some financial support during the school year and/or summer or academic year employment with scientists and engineers on research assignments and projects. Several of these programs target talented minority students.

Fermilab has taken an active part in environmental research and conservation for many years. Scores of volunteers participated in our 1989 "Prairie Work Days" — harvesting, sorting, and planting in the on-going effort to bring back a portion of the laboratory site to the native tallgrass prairie that flourished centuries ago. Dedicated as a sixth National Environmental Research Park, Fermilab serves as a research site for a variety of serious environmental and ecological studies.



Richard Kunzelman (left) and William Boroski of Technical Support conduct thermal performance measurements at the Engineering Laboratory Heat Leak Test Facility. The facility is commissioned to measure the performance of the superinsulation system for the SSC dipole magnets.

Drafting personnel (from left to right) Arnold Knapt, Simmie Meredith, Charles Grimm, Richard Dixon, John Rauch, Robert Andree (seated), and Donald Arnold train on a new work station based CAD (Computer Aided Design) system used for the design of superconducting magnets. These new work stations enable Technical Support personnel to distribute the computing load to individual users.

Rennie Bahr (left) and Michael Oudt serve a delicious meal at the annual Christmas Dinner Dance sponsored by NALREC, the employee recreational organization. The cafeteria staff serves breakfast, lunch, and dinner daily and provides catering for conferences and other special events.

Employment Office personnel include (from left to right) Warren Cannon, James Thompson, and James Lasenby. In 1989, the Employment Office interviewed approximately 1200 applicants, and 387 new regular employees joined the Fermilab staff. The office receives about 600 resumes and applications per month. These are reviewed and then circulated to hiring supervisors.

Once employees join the Fermilab staff, the Personnel Services office provides various services in the areas of benefits, training, compensation, and industrial relations. In 1989, major improvements were made in the Laboratory's retirement plan, and a new dental HMO was developed.

Teachers Andrea Judd (left) and Stacy Carpenter take care of children enrolled in the Infant Care Program at the Children's Center. The children in this group range in age from six to fifteen months. Three adults provide primary care to a maximum of twelve children. Primary care means meeting the basic needs of each child on an individual schedule.

Susan Stibal and Fredric Ullrich of Visual Media Services edit an in-house video program on computer-operated time-code editing equipment. Visual Media Services recently acquired the new equipment, which enables immediate retrieval and identification of file footage thus allowing for much greater precision in editing.

May West (left) and Lee Robbins check the circulation status using the on-line Patron Access Catalogue in the library. When fully implemented, the new system will allow Fermilab staff and visitors to access a "card" catalogue both from the library and from remote locations via the Laboratory's electronic mail. In addition, the new system will provide automation for many of the day-to-day tasks of the library staff such as checking books in and out, ordering, buying, and cataloguing.

Fermilab fire fighters (from left to right: John Babinec, John Steinhoff, and Joel Hurst) participate in the annual Site-wide Emergency Drill. Due to the importance Fermilab places on its ability to deal effectively with emergency situations, this year Emergency Services was elevated to a department level within the Business Services Section.

Brian Kane (left) and Kent Collins inspect the roof of Wilson Hall. In the fall of 1989, routine inspection of Wilson Hall revealed significant damage, the majority of which was repaired under warranty. In 1989, Business Services developed and implemented a formal facility inspection program. The annual structural, electrical, mechanical, and roof inspections provide greater accountability and help in the planning and prioritization of needed repairs. Major 1989 accomplishments included repairing several roads, upgrading Wilson Hall elevators, and roofing 19 village houses and multiple other structures on site.

Walter Canning empties resins from deionized water tanks into the main regenerating tank at the Central Utility Building. This regeneration procedure is a routine function that maintains the high purity level in the chilled water systems.

Payroll staff (from left to right: Jacqueline Hughes, Patricia Watson, Marshia Kaye, Constance Grubba, Jo Ann Baaske, Carol Alderson, and Deborah Dominguez) prepare to process payroll checks by checking the time sheet edit. In 1989, a new extensively-customized commercial package replaced the 20-year-old payroll processing software system. A human resources module was installed and will allow routine interfacing of personnel and accounting activities and the more efficient use of common data bases.

Fred Randazzo adjusts the water flow from the chilled water system in the Central Utility Building. The chilled water circulates through heat exchangers to cool the low conductivity water crucial for cooling the conventional magnets in the Booster and Main Ring. The chilled water also goes to air conditioning coils for Wilson Hall.

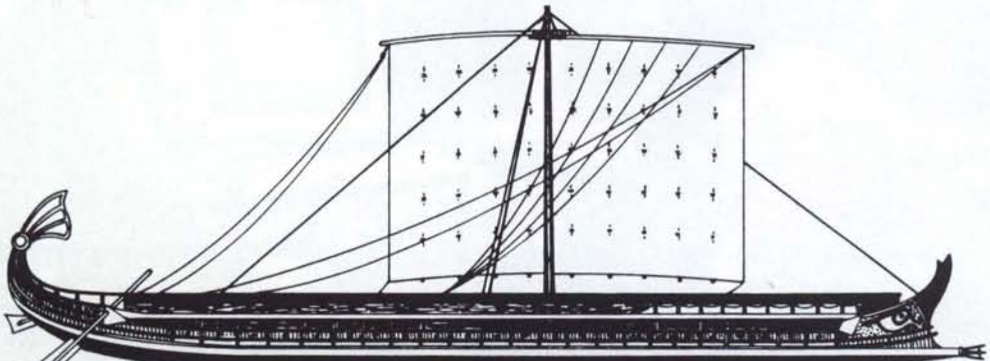
Anthony Bailey (left) and Gordon Bagby take stock inventory in the storeroom at Facilities Operations. This year numerous remote spare parts storerooms were consolidated, inventoried, and entered into the inventory system in preparation for the upcoming move into the new Parts Building. The new location will provide considerably expanded storage space at a centralized location for better control and access.

Glenda Boston (left), emergency dispatcher, and Michael Anderson, switchboard operator, work in the Wilson Hall Communication Center. In addition to handling local and international calls, the operators monitor various on-site and off-site radio frequencies and FIRUS, the lab-wide reporting system that alerts the Communication Center to fire and emergency alarms.

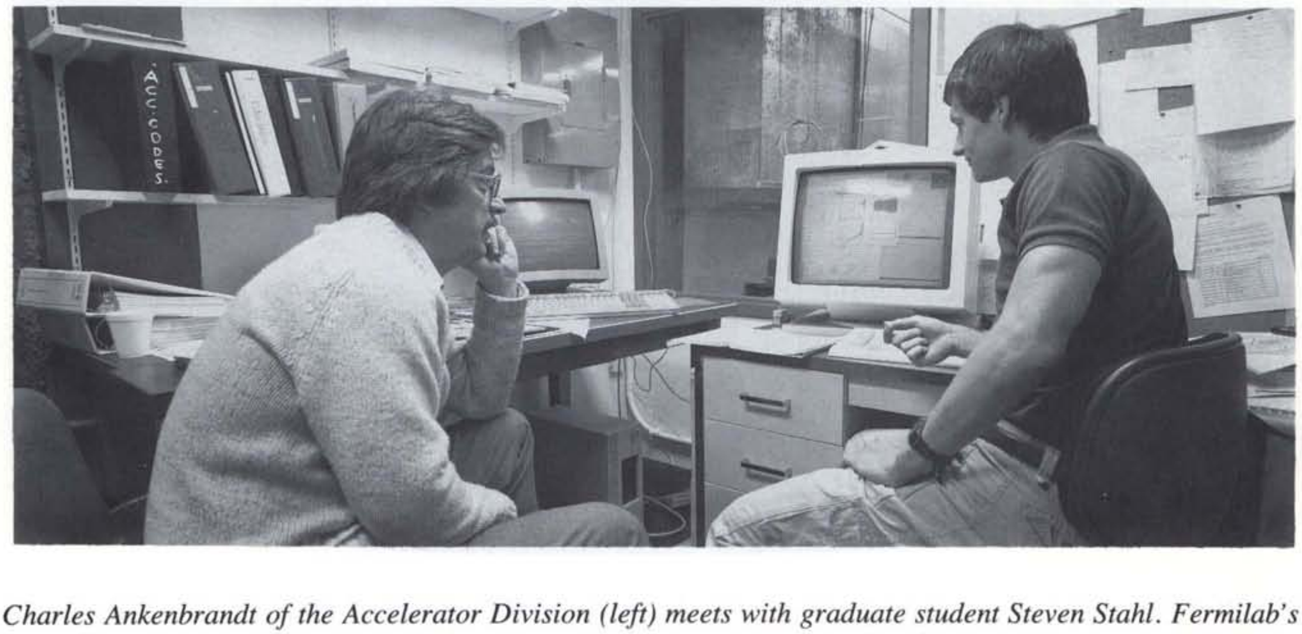
Myrtis Jenkins of the Safety Section organizes racks of film badges for distribution to designated site locations. This year, a significant part of the group's activities involved participating in the DOE Laboratory Accreditation Program for personnel dosimetry. Annual whole body exposures for Fermilab declined from the 43 person-rem recorded in 1988 to the 27 person-rem recorded in 1989.

Thomas Golaszewski of the Radiation Physics Technical Support Group performs the annual calibration of an area radiation monitor used by the Accelerator and Research Division. In 1989 this group, part of the Safety Section, continued its support role in providing reliable and well-calibrated safety instrumentation to the entire Fermilab community.

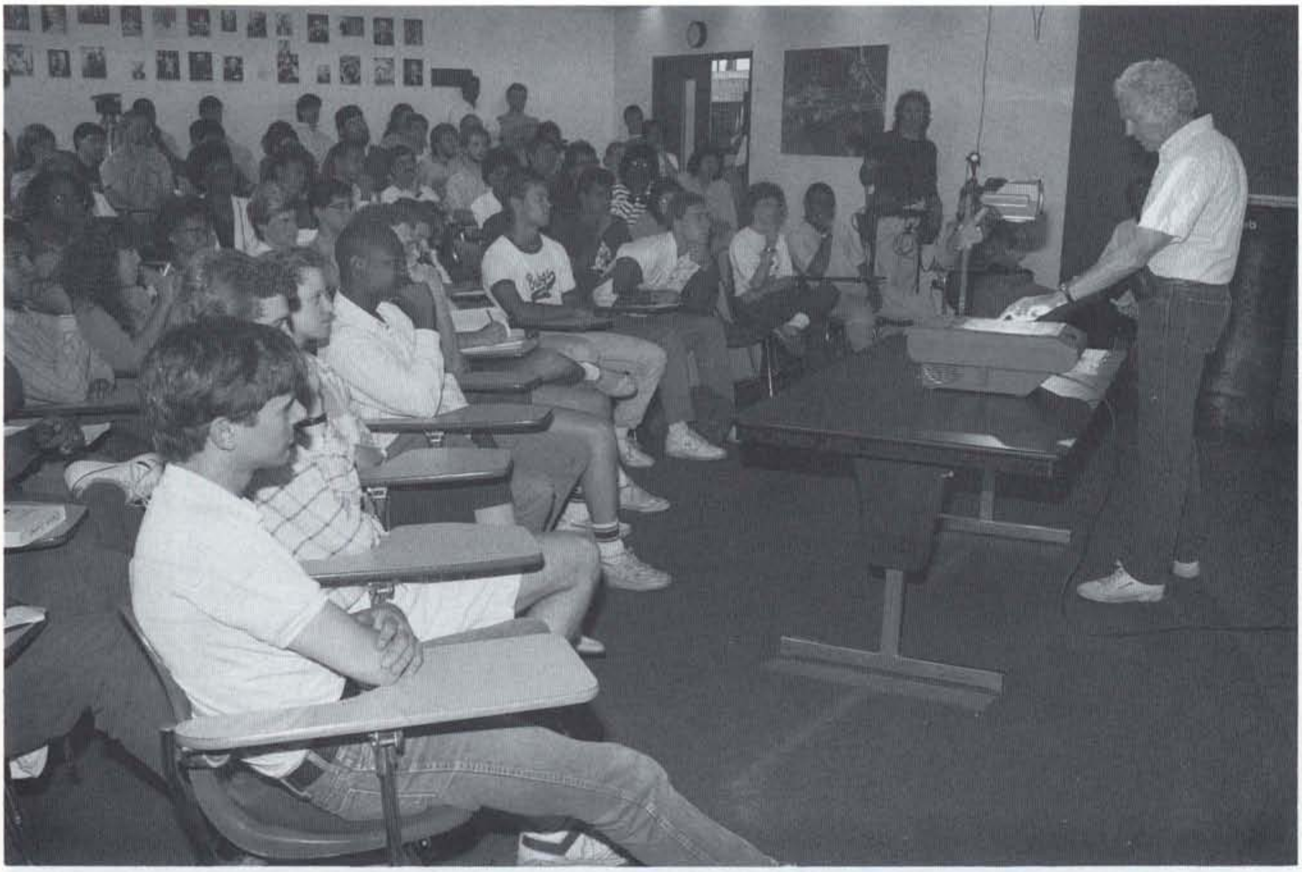
At the Ferry Creek site boundary, Paul Kesich takes surface water samples to test for radiochemicals. As part of a continued commitment to protecting the environment, the Safety Section performs these tests three times per year to ensure that Fermilab is not contributing to offsite pollution.



Secretary of Energy, Admiral James D. Watkins, is flanked by dignitaries and local students at the October 7, 1989, ground-breaking ceremonies for the Education Science Center. Shown from left to right: Jason Stevenson; Congressman Dennis Hastert of the 14th Congressional District in Illinois; Aaron Smith; Al'ishandrah Braneon; Stanka Jovanovic, Manager of Fermilab's Education Office; Admiral Watkins; John Peoples, Director of Fermilab; Leon Lederman, Director Emeritus of Fermilab; and Clare Sammells.



Charles Ankenbrandt of the Accelerator Division (left) meets with graduate student Steven Stahl. Fermilab's Accelerator Physics Ph.D. Program, a cooperative enterprise between Fermilab and various universities, is designed to improve the overall educational experience for students specifically interested in accelerator physics.



Leon Lederman, Director Emeritus of Fermilab, lectures to a group of high school students. Friends of Fermilab and the newly formed Education Office have sponsored a wide variety of programs for precollege students.

An Interpretive Trail through the restored prairie was formally opened in conjunction with dedication of Fermilab as a National Environmental Research Park. Open to the public during all daylight hours, the one-half mile long trail offers an opportunity to experience the Illinois prairie landscape as it was before the settlers moved west. In December 1989, the Prairie Committee named the trail in honor of Margaret M.E. Pearson, long-time manager of the Public Information Office at the laboratory.

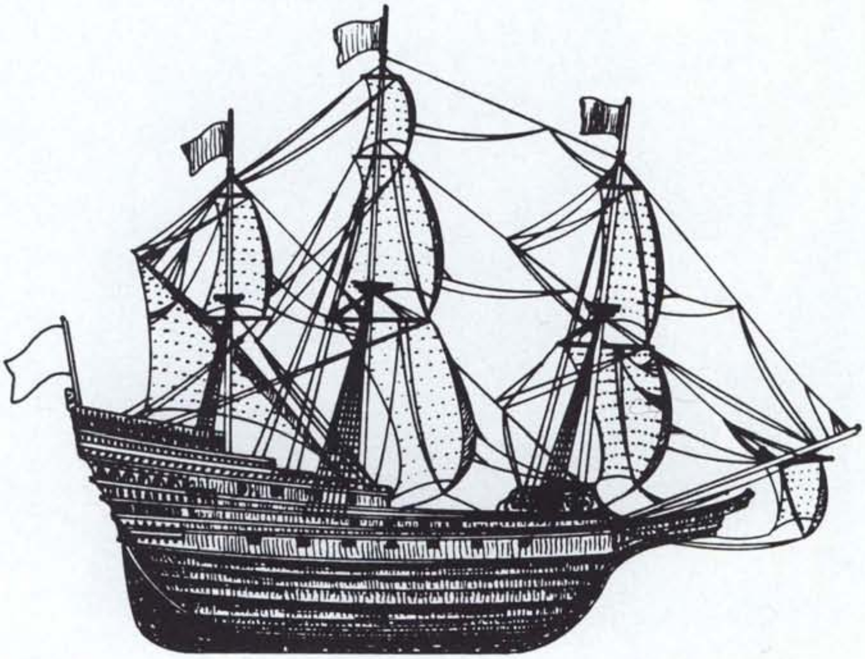
Earlier in 1989, the Department of Energy named Fermilab as its sixth National Environmental Research Park. These parks are protected outdoor laboratories suitable for studying and finding answers to some of the complex and poorly understood ecological issues confronting humanity. Qualified investigators from universities, environmental organizations, or the private sector are encouraged to submit proposals and use these public lands for such purposes. Environmental research at Fermilab is facilitated because it is an "open" site — free from controlled access for security purposes. Eleven environmental research projects are currently underway at Fermilab. Among the areas of investigation are: soil studies, root studies; bird and insect surveys; research into the diversity of springtails and spiders; studies of various plant-insect interactions; and a project on the restoration and management of woodlands.

The Fermilab site contains most of the major ecosystems representative of the Midwest — tallgrass prairie, oak savanna, agricultural fields, woodlands, grasslands, and wetlands. Since 1974, with contributions of hundreds of volunteers from the community, more than 600 acres of prairie have been planted on the Fermilab site. Further work on the project is intended to show that natural habitat supporting an abundance of wildlife can be preserved and coexist with massive, modern high-tech facilities.

Barbara Bennett and Brian Pientak of Fermilab's Neutron Therapy Facility (NTF) test the operation of a new magnetic contouring device. Donald Shea (left) developed its software.

The pencil-like probe senses a magnetic field generated by a source, and the position of the pencil point is displayed in 3D coordinates on the screen. The wand traces out a contour of a patient which is then utilized in calculating the dose distribution. The intersecting beam of laser light defines the central plane for the entry of the neutron beam.

This year the NTF staff has treated over 100 cancer patients and seen 500 follow-up patients. They are treating an increasing number of advanced prostate patients as local urologists become aware of the advantages of neutron therapy compared to other treatments for this form of cancer. Control rates for neutron therapy of salivary gland tumors, sarcoma of the bone, and melanoma exceed 50% based on international experience through 1987.



Acknowledgements

In an intentional departure from tradition, specific contributions from individual authors have gone unrecognized in *Fermilab 1989*. It is therefore appropriate to name, applaud, and thank those who have written the original papers, answered the follow-up questions, provided various suggestions, and reviewed the final copy. Heartfelt thanks to the following authors: Andreas Albrecht, William Bardeen, Vinod Bharadwaj, Dixon Bogert, Richard Carrigan, David Finley, Glenn Goderre, Paul Grannis, Daniel Green, Michael Harrison, Stephen Holmes, Robert Kephart, Ernest Malamud, Paul Mantsch, John Marriner, Philip Martin, Thomas Nash, Robert Noble, John Peoples, Stephen Pordes, and Alvin Tollestrup. Each contribution serves as an essential part of the log of Fermilab's voyage of 1989.

In continuation of tradition, Angela Gonzales has contributed the art that graces our report. Her unique, imaginative, and lively style of line drawings is synonymous with Fermilab itself.

Another hallmark of these yearly reports has been the excellent and multi-faceted photography — whether it be a mood picture such as Winter at Wilson Hall or a technical shot of an electrostatic separator. We are indebted to Reidar Hahn for his careful and creative work, which so visually documents our 1989 voyage. The entire Visual Media Services staff was most helpful in advising, researching, and selecting various photographs. Several Fermilab staff members — Donald Beatty, Donald Cossairt, Stanka Jovanovic, Arlene Lennox, Charles Marofske, and Cynthia Sazama — provided the text for the photoessay.

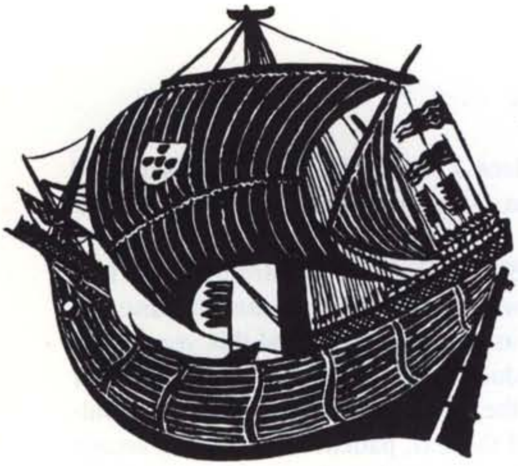
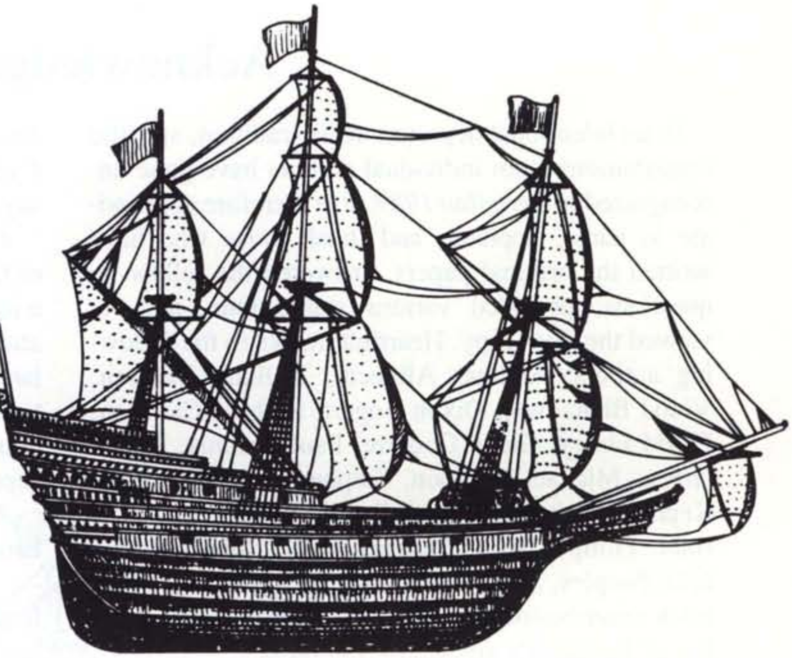
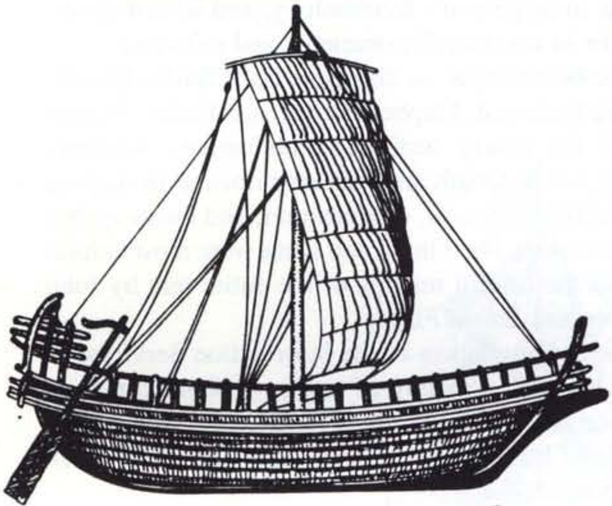
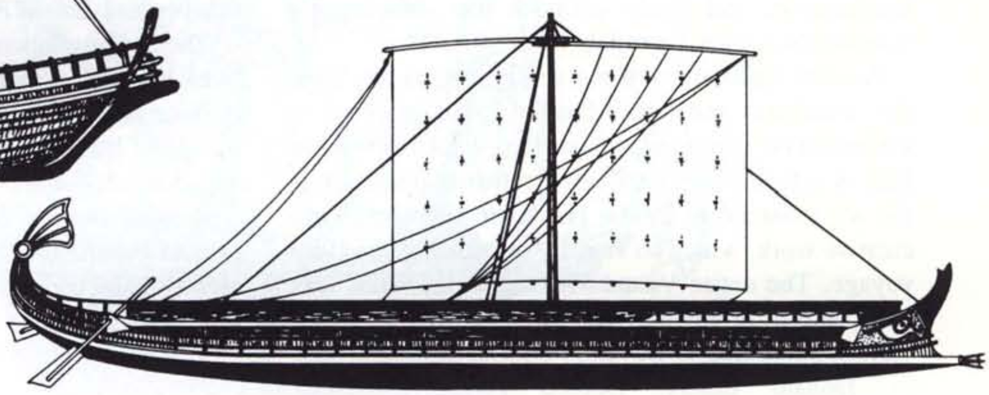
Fermilab 1989 greatly benefitted from the services of Charles Brown who served as Technical Editor — a role which was particularly critical this year as we attempted to reduce some of the jargon and technical language from the report. He was diligent in his multiple readings of the text, patient in explaining arcane points in layperson's terminology, and wise and perceptive in his overall comments and criticisms.

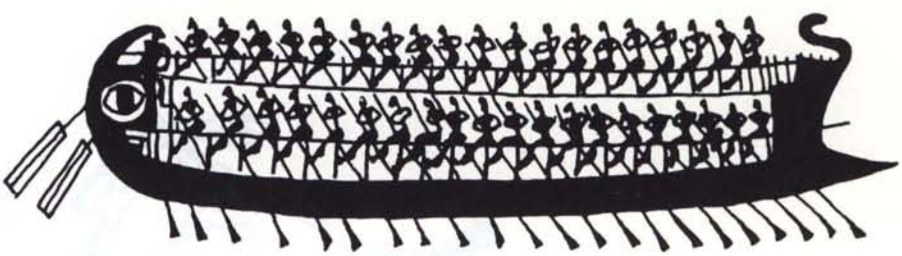
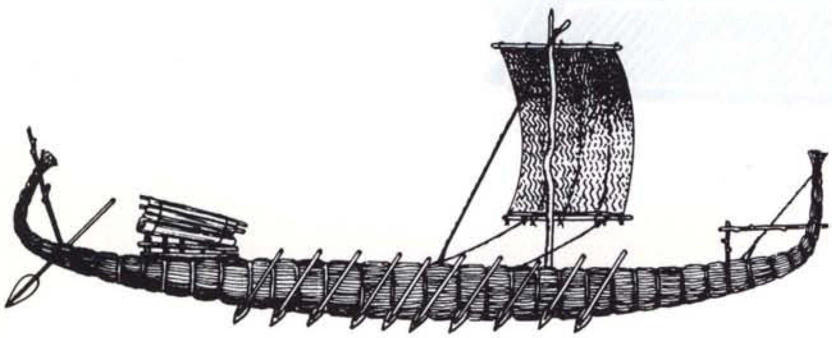
A subcommittee — comprised of Charles Brown, Ernest Malamud, Stephen Pordes, and Fredric Ullrich — of the newly instituted Publications Advisory Board met at length and was instrumental in shaping the overall emphasis, organization, and theme of this year's report. Their input and ideas were most helpful as was the careful reading of the entire text by John Cooper and David Finley.

The staff members of the Information Services offices handled a variety of tasks — photo captions, duplicating, typing, proofing, mailing — with energy and good humor. Their advice and support are much appreciated.

Richard Fenner, formerly Senior Editor and Manager of Fermilab's Publications Office, ably and efficiently launched *Fermilab 1989*. Carol Carlson and Joan Abern of the consulting firm TP&T, Inc., then guided the effort safely into home port.

Barbara Lach


Glossary

Abort System — The Main Ring abort system at Fermilab is designed to dump the beam instantly on an underground copper and concrete shield. The abort magnets are triggered by any one of several abnormal accelerator conditions or radiation alarms. It is routinely fired at the end of an accelerator cycle to purge the accelerator of any unextracted beam.

Accelerator — Any machine used to impart large kinetic energies to charged particles such as electrons, protons, or atomic nuclei. These accelerated particles are then used to probe atomic, nuclear, or subnuclear phenomena.

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 partner, called an antiparticle, identical in mass and with opposite charge-like properties. Some examples of particle-antiparticle pairs are proton-antiproton, positron-electron, and neutrino-antineutrino.

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

Baryon — A heavy, strongly-interacting particle made up of three quarks. The lightest baryon is the proton.

Beam — A slender unidirectional stream of particles or radiation.

Beam Dump — A massive object designed to totally absorb an unwanted beam and dissipate the resulting heat.

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.

BØ (B-zero) — A reference point on the Tevatron at which the Collider Detector at Fermilab (CDF) is located. The six sectors of the accelerator tunnel are labeled A to F.

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

Bubble Chamber — A device used for detection and study of elementary particles. High-speed charged particles traverse a super-heated liquid, leaving a trail of bubbles along their paths.

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

Collider Detector at Fermilab (CDF) — An apparatus designed to measure the results of proton-antiproton collisions in the Tevatron.

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 recirculate continuously through the interaction point to obtain a useful number of interactions.

Collision — A close approach of two or more particles — photons, atoms, or nuclei — during which energy, momentum, and sometimes charge are exchanged.

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

Cryogenics — The technology of the production of very low temperatures and the properties of materials at low temperatures.

Cryostat — A vessel for maintaining a very low temperature.

Cycle Period — The length of time between successive repetitions of a periodic phenomenon.

Decay — A transformation in which an atom, nucleus, or subatomic particle changes into two or more objects; the total mass of the decay products must be less than the mass of the particle that decayed.

Electron Volt (eV) — The amount of kinetic energy gained by an electron when it is accelerated through an electrical potential difference of 1 volt. It is a unit of energy, or work, not of voltage.

Elementary Particle — A fundamental constituent of matter.

Extraction — The process of removing the protons from an accelerator in a controlled fashion once acceleration has been accomplished.

Fixed Target — Any stationary spot to which the beam of protons is directed and with which the beam collides or interacts. This could be a metal target, liquid hydrogen (bubble chamber), or some other detector.

Gluon — The particle that transmits the strong force.

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

Injector — Refers collectively to the Pre-accelerator, Linac, Booster, and Main Ring as a chain of accelerators that first accelerates and then injects protons into the Tevatron acelerator.

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.

Lepton — A collective term for those particles that do not interact via the strong force. They are light particles including the electron, muon, and neutrino.

Linac — An accelerator for charged particles consisting of a linear series of radio frequency accelerating cavities.

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

Integrated Luminosity — The total number of collisions per proton cross-sectional area (collisions per second times the number of seconds). Integrated luminosity is often expressed as inverse nanobarns (nb^{-1}), a unit of cross section. One nb^{-1} of integrated luminosity yields one event per $10^{-33}cm^2$ of cross section.

Meson — One of a class of strongly-interacting short-lived elementary particles that are composed of a dissimilar quark-antiquark pair.

Neutrino — An electrically-neutral weakly-interacting elementary particle with a negligible mass.

Particle — A small piece of matter.

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

Quark — A fractionally-charged, strongly-interacting particle believed to account for hadron structure. In a simple quark model, the proton is composed of three quarks, each with a fractional charge.

Spark Chamber — An instrument for detecting and measuring the paths of charged elementary particles.

Storage Rings — An accelerator designed specifically to recirculate particle beams for long periods of time.

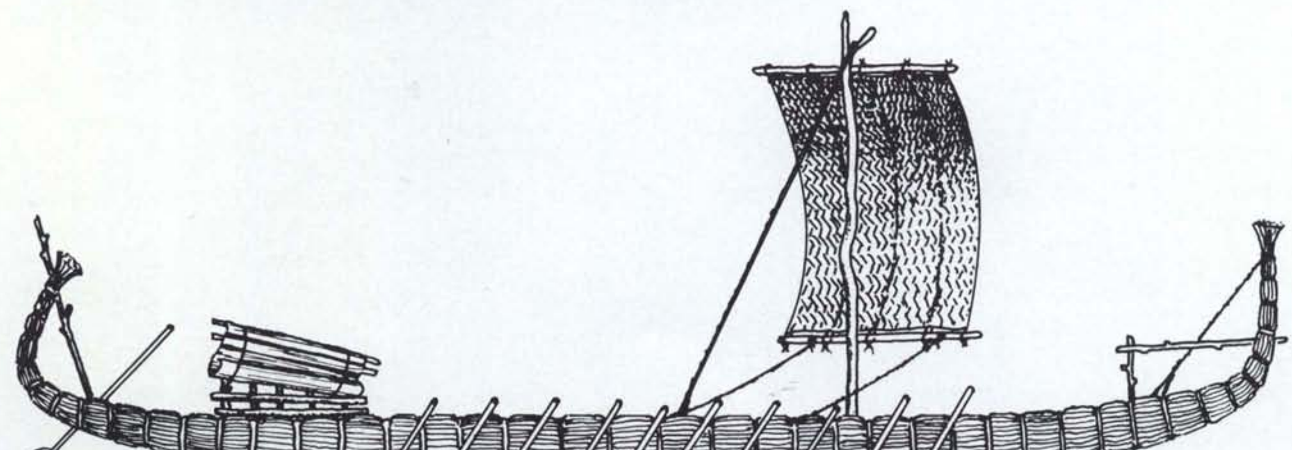
Superconductivity — A state of bulk matter characterized by the total absence of electrical resistance.

Supersymmetry — An hypothesized extension of the Standard Model which contains a complete symmetry between forces and particles. It would require the existence of as yet unseen new particles and forces.

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

Target — Material subjected to particle bombardment in order to induce collisions.

Tevatron — A synchrotron at Fermilab which is designed to accelerate protons and antiprotons to an energy of one trillion electron volts — 1 TeV.



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