Fermilab Installing Superconducting Magnets

The Illinois laboratory, with the highest energy accelerator in the world, will be the mainstay of U.S. high energy physics

As is only too well known by now, it can be difficult enough to construct individual superconducting magnets for high energy accelerators. But it is even harder to manufacture reliably many hundreds of identical magnets, all with the same high magnetic field uniformly distributed along the length of the magnet. Researchers at the Fermi National Accelerator Laboratory (Fermilab) west of Chicago have now accomplished this feat and are busily installing the magnets to make a new main ring for the laboratory's 500 billion electron volt (GeV) proton synchrotron.

All the magnets should be in place and the complete ring ready for testing at cryogenic liquid helium temperature this January. By March, physicists could be beginning the process of learning how to accelerate proton beams in the new machine. The first physics experiments are scheduled to be under way by September of next year.

The project is known as the Energy Saver because the superconducting magnets require very little electrical power as compared to conventional electromagnets. The superconducting magnets will be strong enough to guide 1000-GeV proton beams. By about 1985, more accelerating power will be added to the Energy Saver to allow it to reach this energy. The experimental areas will also be upgraded to allow handling the more energetic beams. Once titled the Energy Doubler, the improvement project is now Tevatron II because 1000 GeV is the same as 1 trillion electron volts (TeV). Finally, during 1986, Fermilab will obtain a proton-antiproton colliding-beam capability. This Tevatron I project (I because funding was authorized ahead of Tevatron II) will allow physicists to study collision energies up to 2000 GeV, almost a factor of 4 higher than the current world record holder, the proton-antiproton collider at the European Laboratory for Particle Physics (CERN) near Geneva.

Put together, the Energy Saver, Tevatron I, and Tevatron II will have a total project cost, including detectors, of over $300 million. Fermilab will be the mainstay of the U.S. experimental high energy physics program in the second half of the 1980's. There is also substantial overseas interest, with about 400 European physicists involved in proposals for Tevatron II experiments. There is a large Japanese contingent at Fermilab now, and physicists from China and the U.S.S.R. will be participating.

Fermilab's most recent superconducting magnet success is the A-sector test, which ran from January to June of this year in parallel with the normal experimental program. The new synchrotron ring is made up of six sectors containing 165 magnets each, 129 dipoles to bend the proton beam into its circular trajectory, and 36 quadrupoles to focus the beam so that it does not hit the surface of the vacuum pipe. A third type of magnet, the spool piece, contains correction coils of several types to offset the cumulative effects of small errors in the main magnets. There are 204 spool pieces. The A-sector begins at the point where protons are injected into the old main ring from a smaller booster synchrotron at 8 GeV. In the Energy Saver, the old main ring will then accelerate these protons to 150 GeV before transferring them to the superconducting ring for the final push.

> A full-ring quench in the A-sector produced gratifying results.

In January, a three-quarters completed A-sector with 120 magnets was cooled to 4.5 K, and several tests were begun. The heat generated by the huge magnet current (4000 amperes or more) passing through a normal conductor turns neighboring lengths of superconductor normal. The effect can propagate rapidly through an entire magnet, a phenomenon called quenching. According to J. Richie Orr of Fermilab's accelerator division, the energy stored in the magnetic fields of all the magnets in the synchrotron ring is equivalent to about 1000 sticks of dynamite. Moreover, the energy released if all of the liquid helium coolant were vaporized would be 15 times as much. A simulated full-ring quench in the A-sector, however, produced gratifying results. "Nothing broke," says Orr.

In a synchrotron, protons are accelerated by receiving an injection of energy on each turn around the ring from radio-frequency cavities. To keep the particles in orbit, the magnetic fields that confine and focus them must increase in synchronization with the rising energy. This procedure is ramping and is another critical performance characteristic of accelerator magnets. In A-sector tests, Fermilab researchers have demonstrated ramping for magnet currents up to 4000 amperes, which corresponds to a proton beam of 900 GeV. During the testing, the ramping cycle was 75 seconds long, which is considerably slower than the 10-second repetition rate of the old main ring. One reason for the speed limitation is the limited number of radio-frequency cavities. Another is the heat generated by eddy currents that are induced in the magnet by the changing magnetic field during ramping. Orr says that with eight radio-frequency cavities instead of the originally planned six, and with a larger compressor for the helium refrigeration system, a 50-second ramping cycle would be feasible.

Fermilab turned off its synchrotron on 15 June to finish the job of installing the superconducting magnets. Almost half of the new ring is in place. But each magnet must still be aligned to within less than 0.4 millimeter, followed by vacuum testing. The ultimate test, getting a beam of protons to circulate around the ring cannot begin until the spring, when some construction related to Tevatron II is complete.

Farther away are two operations that will determine how good the field quality of the superconductor magnets and the computerized control system that oversees them really are. The first is extraction of a 1000-GeV beam of protons from the synchrotron ring so that it can be guided to the dozen or more fixed-target experiments lying at the end of a fan-shaped array of beam tubes running tangentially away from the ring at the extraction point. The potential problem is that a 1000-GeV beam, if it struck the side of the beam pipe, would deposit enough energy to heat the surrounding magnets to the normal state, thereby causing a quench. The beam could go awry in this way during extraction if the magnetic field was not quite as it was designed so that the orbiting protons wandered slightly and struck a wire (septum) in the beam pipe that initiates the extraction process.

One solution, devised by Helen Edwards of Fermilab, is to build a dogleg into the beam pipe at the septum location, with conventional magnets to bend the beam. In this way any scattered beam misses the superconducting magnets. Orr notes that the strategy works on the computer but there is no way to know for sure until actually trying it.

The second critical operation is storing a beam for the proton-antiproton collider. In this mode the beam is not accelerated and immediately extracted, but is held in the ring for several hours. The experimental events are provided by collisions between beams of protons circulating in one direction and antiprotons circulating in the other. Only a minute fraction of the particles actually collide, so it is the magnetic field uniformity that keeps the particles in orbit and the residual gas pressure in the highly evacuated beam pipe that mainly determines the lifetime of the stored beam. Again, says Orr, it all works on the computer.

All in all, Fermilab director Leon Lederman foresees a schedule for bringing the Energy Saver and Tevatrons into operation as follows. Three months of

Brookhaven Magnet Progress

Brookhaven National Laboratory has been struggling with superconducting magnets for its ISABELLE proton-proton intersecting storage rings project (*Science*, 21 November 1980, p. 875; 21 August 1981, p. 846). The laboratory had to abandon its original magnet design after 4 years of work. But in the last year, its new Palmer magnets, named after their inventor Brookhaven physicist Robert Palmer, have exhibited none of the faults of their ill-starred predecessors. In particular, the Palmer magnets all exceed the magnetic field strength required for ISABELLE, and all behave nearly identically. Only the uniformity of the field needs to be improved slightly.

Palmer was working in Brookhaven's physics department and not on ISABELLE in mid-1980 when the new magnet idea was born after a visit to Fermilab. Along with another Brookhaven and a Lawrence Berkeley Laboratory group who had devised alternative schemes for superconducting magnets, Palmer and his associates got the go-ahead to begin making model magnets that December. By July 1981, the group had produced a 1.5-meter-long dipole magnet that surpassed the required 5-tesla magnetic field on the first try. A second magnet followed shortly and was equally successful. By October, when the researchers tested their first full-length ISABELLE dipole (4.6 meters long), all work on alternate designs had been stopped, and Palmer had become chief of ISABELLE's magnet division.

Last May, Palmer reported to the Department of Energy's (DOE's) High Energy Physics Advisory Panel (HEPAP) that six full-length dipoles, four short dipoles, and one quadrupole magnet had been tested, all with comparably sanguine results. The major remaining problem is field quality, which is a little below that needed for ISABELLE. A dipole magnet, for example, is not a pure dipole but also exhibits a small quadrupole moment, and so on, that make the field slightly nonuniform. Recently, a 1.5-meter dipole was tested that exhibited the required field quality, and a full-length, field-quality dipole is to be tested soon. Also to be demonstrated is the ability to make large numbers of magnets with identical properties. ISABELLE will need about 1100 in all.

Palmer's Fermilab inspiration boiled down to two main changes to the original Brookhaven magnet design. The first was to switch from braid to cable superconducting wire. In both cases, individual superconducting wires (which are complex multifilamentary entities in themselves) are laid to make a flat tape-shaped conductor. The braid is wider and the individual wires are rigidly held in place, whereas the fewer wires in the cable (which originally was developed at the Rutherford Appleton Laboratories in the United Kingdom) are floppy. Palmer's first magnets were made directly from Fermilab's excess cable, with two layers of cable replacing one of braid.

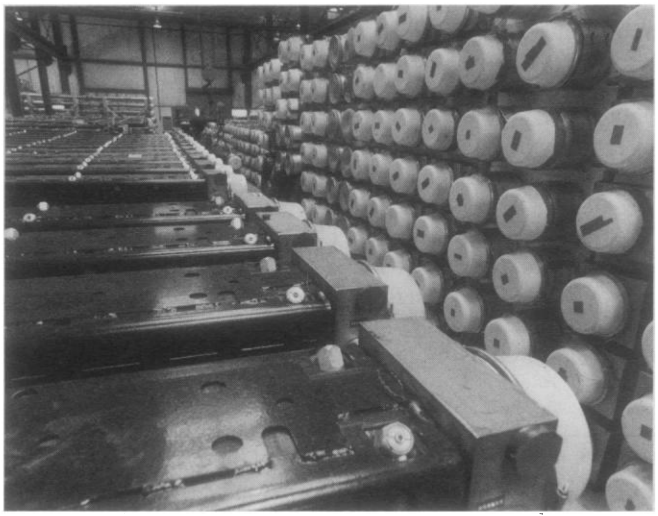
The second switch was to adopt a way to immobilize the magnet windings by a method somewhat similar to Fermilab's. The iron magnet yoke was split into halves, the magnet coil inserted between them, and the split yoke compressed around the coil by means of bolts. The idea, says Palmer, is to stop coil motion at all cost, so "you squeeze like hell." Although the split yoke could work with braid, the more flexible cable superconductor is better suited.

In other respects, Brookhaven has stayed with its original magnet concept. For example, the entire magnet—yoke and coil—sits in the liquid helium cryostat, but the beam pipe through which the accelerated particles pass is kept at near room temperature. Both characteristics are just the reverse of Fermilab's magnet concept.

Despite the inspiring magnet progress at Brookhaven, ISABELLE is still in peril. All construction will have stopped by 1983 pending a solution to the magnet problem. Next spring, DOE is to begin the process of deciding whether to reactivate ISABELLE, and, if so, in what form. A January report from a HEPAP subpanel estimated that it would take $500 million to complete the machine as designed, including all remaining R & D, particle detectors, and pre-operational commissioning. However, at the May HEPAP meeting, DOE officials discussed "realistic" budget scenarios for the next several years that allowed for approximately $350 million for a "major new facility."

Palmer discussed, at the meeting, some options for lowering ISABELLE's cost. One was to use a single magnet yoke and cryostat with two sets of coils, instead of a separate magnet for each of the intersecting storage rings. Another was to combine the dipole bending and quadrupole focusing functions into a single magnet. A third was to leave out some magnets and run the accelerator at a lower energy. Palmer estimated that using the first two tricks and also only partially equipping the six planned experimental areas at first would knock down the cost to complete ISABELLE to $350 million.

Brookhaven has begun making double-yoke magnets, and they seem to work fairly well in early tests. Can ISABELLE still be revived?—A.L.R.



Magnet warehouse

Completed superconducting dipole magnets awaiting installation in Fermilab's Energy Saver.

running at 400 GeV could begin in September 1983, during which time some experiments that are left over from the most recently completed run would be completed. In early 1984, the laboratory would start an 8-month period of 800- to 900-GeV experiments. And about a year later, a similarly long run at 1000 GeV would commence. In late 1985 or early 1986, the first attempts at colliding-beam operation are to get under way. Once the Tevatron I and II projects are both fully up to speed, the two modes of operation, fixed target at 1000 GeV, and colliding beam at 2000 GeV (1000 GeV in each beam), would alternate.

There remains considerable apprehension until the superconducting ring tests out, for it took Fermilab a long time to master the art of superconducting magnets. The laboratory's builder and first director, Robert Wilson, now at Columbia University, began R & D on superconducting magnets in 1972. Wilson's approach was to build a magnet production line, fabricate a large number of magnets, and test them. The test results would then feed back to the production line.

The idea seemed to be working, and by 1977 Fermilab was one of the largest consumers of superconducting wire in the world and was boasting of producing superconducting magnets at the rate of one per week. Wilson wrote at the time that the Energy Saver could be ready for physics in 1980, if the $38 million needed to built it were forthcoming together with $13 million of R & D money for the A-sector magnets and their testing.

The funding was not granted in full, and in 1978 Wilson carried through with a threat to resign if Fermilab's overall finances were not boosted considerably (*Science*, 10 March 1978, p. 1052 and 13 October 1978, p. 195). Lederman became the second Fermilab director and immediately launched an analysis of the Energy Saver project. A more complete machine that could serve as the basis for the two Tevatrons would cost $80 million. The final cost, with the end in sight, is $95 million or more, depending on what year's dollars the accounting is in.

If the financial situation did not permit meeting Wilson's goal of a 1980 start-up for the Energy Saver, neither did the technological. Superconducting magnets are air coil devices—that is, there is no iron core to shape the magnetic field. Hence, the superconducting wire in a magnet coil must be precisely placed to within 0.075 millimeter. But when current flows through the wires, immense forces are generated that tend to deform the coil, leading to premature quenching due to the heat generated by the motion. The problems are worst in the dipoles because they are larger and the magnetic fields are also higher. In 1978, Alvin Tollestrup, who was then head of the magnet group, helped solve part of the problem of coil motion with the development of a stainless steel collar that fit around the magnet coil inside the helium cryostat. The collar was built up out of 1.5-millimeter-thick laminations that were welded together. Because each lamination could be machined very precisely, the overall shape of the collar, and hence the coil of the magnet, was similarly well controlled.

One of the last problems to be corrected was a rather subtle one in the dipoles. The cryostat containing the magnet coil and the stainless steel collar rests inside a vacuum tube embedded in a laminated iron yoke 5.1 meters in length. The yoke returns the magnetic flux from one side of a dipole to the other and also slightly increases the strength of the field. The cryostat is suspended inside the vacuum tube by spacers made of a material that does not conduct heat well. When a magnet is cooled, the cooling starts at one end and propagates to the other. The magnet also shrinks by about 2 centimeters in its length and 0.5 millimeter in its diameter. This shrinkage propagates from one end of the magnet to the other in such a way that its position shifts enough to eventually break the locating spacers. The effect is so small that it takes 100 cycles of cooling and warming backup to be noticed, and it takes almost 6 hours to cool a dipole.

After 6 months of effort, a solution was found in 1980 by Richard Lundy of Fermilab—the "smart bolt." These are spring-load fixtures that keep a constant force on the spacers and thereby prevent rotation. The bolts also allow physicists to precisely adjust the magnet coil to eliminate imperfections in the magnetic field (quadrupole and skew quadrupole moments). Thereafter, magnet fabrication at Fermilab was shifting into high gear, and the laboratory reached a production rate of 40 dipoles and 20 quadrupoles per month. Reducing the time needed to test each magnet from 25 to 14 hours helped considerably because testing had been a bottleneck. About 95 percent of the magnets pass the tests, which are made at half a dozen points during manufacture.

As the Energy Saver eases into operation, Fermilab will be able to devote more attention to the Tevatron projects, which have had second priority up to now. Last February, the Tevatron I group headed by John Peoples designed a new antiproton source at the request of Lederman. A study panel led by Maury Tigner of Cornell University had criticized the earlier source as not ambitious enough. The new scheme will permit the production and accumulation of antiprotons much faster than the old one (2 hours rather than 24 to gather up the 2×10^{11} antiprotons needed for a beam), but it costs about $40 million more.

Detectors for colliding-beam experiments surround the beam pipe of the synchrotron. Fermilab plans two. The first is a 4000-ton monster being built by an international collaboration of 90 physicists from the United States, Japan, and Italy. The U.S. share comes to $33 million. It will sit in a detector building that is in the early stages of construction now. The second detector has not been selected, but will be a more modest device.

A large part of the Tevatron II project will involve upgrading the beam lines leading from the synchrotron to the fixed-target experimental areas so that they can handle the higher energy beams and, also, the experimental areas themselves. Fermilab's fixed-target complex consists of three main areas: meson, neutrino, and proton. Each of these, in addition to upgrading, will also receive at least one new beam line and associated new facilities.

Superconducting magnets have already played a major role in the upgrading of the beam lines. The beam lines leading to the meson and proton areas have to be bent by dipole magnets to the left and right, respectively, of the straight beam line to the neutrino area. Fermilab's first large superconducting magnet experiment was the "left bend," a string of 22 magnets that began operating a year and a half ago under the direction of Roger Dixon of Fermilab. Among the lessons learned in commissioning the left bend was how important the helium refrigeration system can be. With the Energy Saver taking up most of researchers' attention, the left bend refrigeration system was originally barely adequate. Only after it was improved did the left bend work well.

These kinds of details are the sort of thing that Lederman refers to when he says Fermilab is "running scared" as the time to break in the Energy Saver approaches. While there is a feeling of hopeful expectation, Lederman says that the new superconducting synchrotron "has the highest risk of something going wrong of any accelerator so far."

—ARTHUR L. ROBINSON

Long-Awaited Decision on DNA Database

Molecular biologists can look forward to having access to a national DNA database now that NIH has at last awarded a $3-million contract

A long period of indecision and uncertainty in the field of molecular genetics has been brought to a close with the award of a $3-million, 5-year contract to Bolt, Beranek and Newman, a Cambridge-based company with expertise in computer communications. The company, which is subcontracting Los Alamos National Laboratory with Walter Goad as principal investigator, will be responsible for compiling and distributing a national database of DNA sequences.

The need for the database was first perceived urgently in 1979, but various circumstances combined to delay a decision on a national scale until now. Meanwhile, several groups around the country, and in Europe and Japan too, began independently to establish rival facilities. Although there has been considerable cooperation between the Europeans and groups here, their main effort, at the European Molecular Biology Laboratory (EMBL) in Heidelberg, came to fruition in April this year when their Nucleotide Sequence Data Library became freely available. EMBL's early success causes considerable embarrassment on this side of the Atlantic.

Ever since DNA sequencing became virtually a routine procedure in most molecular biology laboratories, the need for handling the inexorable information tide became obvious and pressing. Practitioners needed a way of compiling sequences with some kind of standard annotation showing known functional regions, such as transcription signals and splice sites. At least as important, however, is the facility to search for homologies between a new sequence and all existing sequences and to do sophisticated analytical procedures that might reveal other significant regions.

Until the middle of last year, when budget tightening intervened, the National Institutes of Health (NIH) had intended to support compilation and distribution of the DNA database as one project and the development of analytical software systems as a second, related, project. The contract to Bolt, Beranek and Newman covers just the first of these two, with the second, which might have cost around $2 million over a period of 5 years, on hold, perhaps indefinitely. As a result there seems likely to develop some sharp competition in originating and offering analytical expertise.

The momentum to establish a national DNA database got under way in March 1979 when the Rockefeller University was host to a workshop sponsored by the National Science Foundation. Carl Anderson of the Brookhaven National Laboratory had initiated the meeting and was its chairman. He recalls a unanimity that something should be done, but a diversity of opinion as to how to proceed. Should there be an extensive computer network, with centralized data collection and storage together with a big effort for the development of analytical software? Or would a much more modest and limited data-collection system be more prudent, at least to start with?

Opinions were sharply divided between these two conceptions. In addition, many people were uncomfortable with the prospect that sequences might become freely available before principal investigators had had time to work with them and therefore benefit from their sequencing efforts. Concern over potential violation of a researcher's right to prior access to his or her own data was deeply felt. Computer anxiety was still strong in the molecular biology community at the time.

For these several reasons the impetus of the Rockefeller meeting was dissipated, thereby exacerbating rather than avoiding one of its prime aims—avoiding the duplication of data-collection efforts.

By the end of 1979 the NIH had received proposals for data collection and analysis from several groups, including those of Margaret Dayhoff of the Biomedical Research Institute, Washington, D.C., and Walter Goad at Los Alamos. Dayhoff and her group already had considerable experience in compiling and distributing data on amino acid sequences of proteins. The Los Alamos group had begun serious work on DNA sequence collection in mid-1979.

As these several proposals involved a substantial service component in addition to research, the NIH realized that its support for any national facility would have to be by contract rather than as a research grant award. Primarily at the instigation of Elvin Kabat of the National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases, a series of NIH workshops was organized by the National Institute for General Medical Sciences (NIGMS). The aim was to prepare the ground for two requests for proposal (RFP's) for a national DNA data facility and for sequence manipulation software. In the meantime, Dayhoff and Goad received separate small grants to develop a system for data collection as an interim measure.

The first workshop was held at NIH in mid-July 1980, 1 month after the EMBL had decided to set up its own sequence data center. Subsequent workshops, in

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