Two Superconducting Accelerators: Physics Spurs Technology

Exotic new products derived from research on superconductivity have been predicted to revolutionize things ranging from railroads to power lines, but it is now virtually certain that the first major activity superconductivity will revolutionize will be that of accelerator building.

After debating the advantages of superconducting accelerators for a decade, physicists are now moving quickly to construct two of them. By 1981, Fermi National Accelerator Laboratory at Batavia, Illinois, plans to double the energy of its present 4-mile accelerator by installing a new set of superconducting magnets in the existing accelerator ring. By 1986, Brookhaven National Laboratory at Upton, Long Island, plans to complete a large new accelerator named ISABELLE, which will consist of a pair of 2½-mile intersecting storage rings. Preliminary research and development for the two projects has been under way for at least 5 years. They were just approved for construction, at costs of $38 million and $275 million, respectively, when the fiscal 1979 budget was announced in January.

By almost any measure, the new accelerators will be large-scale applications of superconductivity. Each will use enough superconducting wire to stretch around the equator. The cooling capacity needed for each project will match or possibly exceed the total world capacity for manufacturing liquid helium.

In a superconducting synchrotron, the "superconducting" refers to the properties of the wire used in the electromagnets that keep the particles orbiting in a circle. As the energy of the particles increases, the field of the magnets must increase appropriately to keep the particles in the proper track. The power dissipated in the magnet coils due to resistive losses is considerable, especially in an accelerator that has 1000 magnets, as the Brookhaven and Fermilab projects will. Though radio frequency cavities actually accelerate the particles in the ring, the magnets use most of the electrical power required by a modern synchrotron.

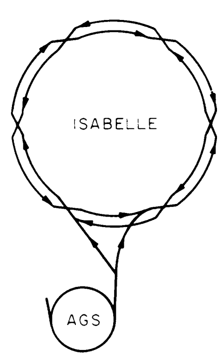

Fig. 1. Schematic of particle pathways for ISABELLE, an intersecting storage ring accelerator being built at Brookhaven National Laboratory. Protons injected at 30 GeV from the present synchrotron will be closely packed into two rings, then accelerated to 400 GeV. Head-on collisions will occur in six regions where the two rings intersect.

By replacing the copper wire in the magnet coils with niobium-titanium wire that becomes superconducting below 10°K, the magnets become nearly lossless and the power requirements are reduced dramatically. Officials at Fermilab estimate that their power bill will be cut in half, saving about $5 million per year. The same magnets will boost the laboratory's peak energy from 500 to 1000 gigaelectron volts (GeV). Officials at Brookhaven and Berkeley, where a small experimental superconducting synchrotron is being built, project equal or greater reductions in operating costs.

Another saving associated with superconducting accelerators occurs because their high magnetic field strength—double or triple that of conventional accelerators—allows the use of fewer magnets for a given energy. The result is smaller accelerator rings, and lower construction costs.

As new accelerators have been built at ever higher energies, it has been assumed that a time would come when the next machine would *have* to be superconducting. The only question was when. Magnet research had not progressed far enough to make a superconducting accelerator thinkable when the Fermilab accelerator, presently the most powerful U.S. machine, was built in the late 1960's. Even though small beam magnets and the magnets for small bubble chambers had been made with superconducting materials, they were designed for constant-field rather than pulsed-field duty. Large bubble chamber magnets and magnets for routine use in external beam lines were developed next. The shape of the long, narrow beam line magnets began to approach the extreme geometry that has evolved for accelerators, and research was begun on pulsed magnets that could be "ramped" upward over a period of seconds or tens of seconds as required for a synchrotron. Such operation creates stresses and heating losses that are not present in constant-field magnets.

Special multifilamentary wires that reduce the heating losses in pulsed magnets were developed, and by about 1971 magnets that could ramp at the rate of several hundred gauss per second (rather than a few gauss per second) were available. But the ramp rates had to be increased and the magnets were still far too small—only about 1/20 the length needed.

The European Centre for Nuclear Research (CERN), Geneva, seriously considered in 1971 building their 400-GeV accelerator with superconducting technology, but Fermilab already had a 5-year head start with an accelerator in the same energy range. The CERN management concluded that a superconducting accelerator could not be built nearly as rapidly as a conventional one, and, faced with a competitive situation, said no to superconductivity. About the same time, the Fermilab upgrading project was being studied and the first proposal for ISABELLE was being formulated. Neither proposed machine had a competitor in its particular regime of physics, and both projects had time for R & D—more time, due to the stringent funding of high-energy physics, than either laboratory was happy with. The research on prototype accelerator magnets thus began in earnest.

The two superconducting magnet re-

Fig. 2. View of the production line at the Fermi National Accelerator Laboratory for producing long superconducting dipole magnets for the energy doubler/saver project.

0036-8075/78/0414-0188$01.00/0

search projects that evolved at Fermilab and Brookhaven could hardly have exhibited more contrast.

Technically, the storage ring project planned for Brookhaven is generally agreed to be the more difficult undertaking—one appropriately ambitious for a completely new facility. No proton storage rings have been built before in the United States, and the only such facility built abroad, the ISR (Intersecting Storage Rings) at CERN, was designed for an energy and a particle collision rate at least ten times lower than those intended for ISABELLE.* Given its high performance criteria, ISABELLE (Fig. 1) will have to carry a larger current of particles than the Fermilab ring and carry them much longer (for 12 to 24 hours). This requirement places stringent limits on the uniformity and reproducibility of the superconducting magnet field, which is the ultimate measure of quality in both applications. Offsetting the field requirement, however, is the fact that Brookhaven will have considerably more money to spend on each magnet than will Fermilab.† Another technical difference is that Brookhaven's machine can be ramped very slowly to full energy, and it will remain at that point for long periods, but Fermilab's accelerator is to be ramped up and down rapidly.

Philosophically, the Fermilab approach to building a new accelerator is more daring and aggressive. Both laboratories had to make several important magnet design choices and Fermilab picked the more ambitious concept in each case. The Fermilab magnets are designed to have a cold bore—that is, the vacuum tube through which the beam passes is just as cold as the coils. This decision minimizes the size and cost of the expensive coils, because no insulation is needed between them and the tube, but it may introduce new operational problems since accelerators normally have room-temperature beam tubes. In deciding how to wind the coils,

Fig. 3. The inner assembly of a prototype magnet for ISABELLE, with one coil lifted off to expose the beam tube (left). The ribbons in the foreground are the ends of the superconducting wire braids that form the coil.

Fermilab opted for an elegant, easy-to-fabricate shortcut to approximate the ideal (cosine theta) distribution about the beam tube, while Brookhaven decided to carefully match the ideal distribution as closely as possible. In both instances, Fermilab chose a riskier concept with the possibility of substantial savings, while Brookhaven chose the more conservative design.

Tactically, the two approaches are even more distinctive. Brookhaven's approach has been to carefully handcraft a few magnets until they meet the quality requirements and then address the problems of mass production. Fermilab's approach has been to utilize a production line from the very beginning and to fine tune the process, using "cut and try" experimentation, until the magnets coming off the production line are satisfactory. The Fermilab approach, according to one physicist, was to choose a design that could be built cheaply and "then beat on it to see how close they could get it" to ideal performance. In the process, a large number of less-than-satisfactory magnets were produced.

The idea behind Fermilab's approach, which strongly reflects the style of its recently resigned director, Robert R. Wilson (*Science*, 10 March), was that after 50 to 100 magnets were produced, the requisite performance would be met. Brookhaven points proudly to the ingenious way it has found to perform certain crucial steps in its complex magnet assembly process, while Fermilab boasts of its ability to produce one magnet per day when its production line (Fig. 2) is running smoothly.

Although both projects will need a certain number of focusing magnets, the principal challenge is to build the bending or dipole magnets that will produce the circular orbits needed in an accelerator. Ideally, the field inside the beam tube should be perfectly uniform to avoid scattering particles out of the beam when they veer far from the tube center. Brookhaven has built up its magnet coils turn by turn, using a large number of jigs and spacers to ensure that the final coil will have its turns distributed to the cosine theta fashion necessary to produce a uniform field. After the coils are wound, they are heat-treated to solidify the epoxy in the wrappings so they hold their semicircular shape (Fig. 3). Identical coils laid precisely above and below the beam pipe carry about 4000 amperes of current and produce a field of 50 kilogauss. In the Brookhaven magnets, each wrap of the coil is actually a flat braid of superconducting wire, something like a braided belt. The individual wires in the braid are multifilamentary, with about 500 microscopic niobium-titanium fibers embedded in copper.

When the magnet coils are energized, enormous forces are generated that tend to push the coils outward. Restraining the coils so that they do not move even under such forces has proved to be one of the most challenging problems of superconducting magnet design. If the coils are not carefully packed, wrapped, and permanently compressed by some sort of metal sheath, the magnet will exhibit a phenomenon called "training." That is, as the magnet current is ramped upward a section of wire will shift under the building forces. The movement will generate enough heat that the wire section becomes normally conducting. This starts a cascading effect because the normally conducting wire has higher resistance and generates more heat, and soon the whole magnet coil has "gone normal." Fermilab's early prototype magnets exhibited severe training, requiring as many as 50 trials—each one reaching a higher field—before the maximum performance was attained.

Brookhaven's approach to the training problem has been to use the strongest structural element of the magnet—namely the iron yoke—to restrain the coils. The coils are assembled and wrapped tightly with fiberglass bands that are carefully ground to size. Then the entire assembly is cooled to 77°K in a bath of liquid nitrogen. The cylindrical iron yoke, also carefully honed to size, is suspended above the coil assembly. The coil is quickly shot up into the iron yoke by an air-drive system and, when they reach the same temperature, the coil is prestressed with a very high compression. The Brookhaven magnet has two zones of insulation just inside the coils and

*ISABELLE will consist of two intersecting magnet rings which will carry beams of 400-GeV protons circulating in opposite directions. At each of six intersections, the particle production rate is determined by the intensity of the beams and the degree to which they have been tightly focused into the same region—a combination of factors, known as the luminosity, which is intended to reach 10^{33} cm^{-2} sec^{-1} for ISABELLE. The ISR carries colliding beams of 28 GeV each and achieves a luminosity of 5×10^{31} cm^{-2} sec^{-1}.

†Fermilab management has a hierarchy of possible physics uses for the new magnet ring. They range from energy saving at 400 to 500 GeV, through energy doubling at 1000 GeV (at either the present or a reduced beam intensity), to the use of colliding beams at 1000 GeV. The latter modes of operation require considerably higher magnet quality than the simplest mode, which is one-turn injection of a single bunch of particles from the present ring into the new one. That mode would produce only about one-tenth the beam intensity of the present 400-GeV ring.

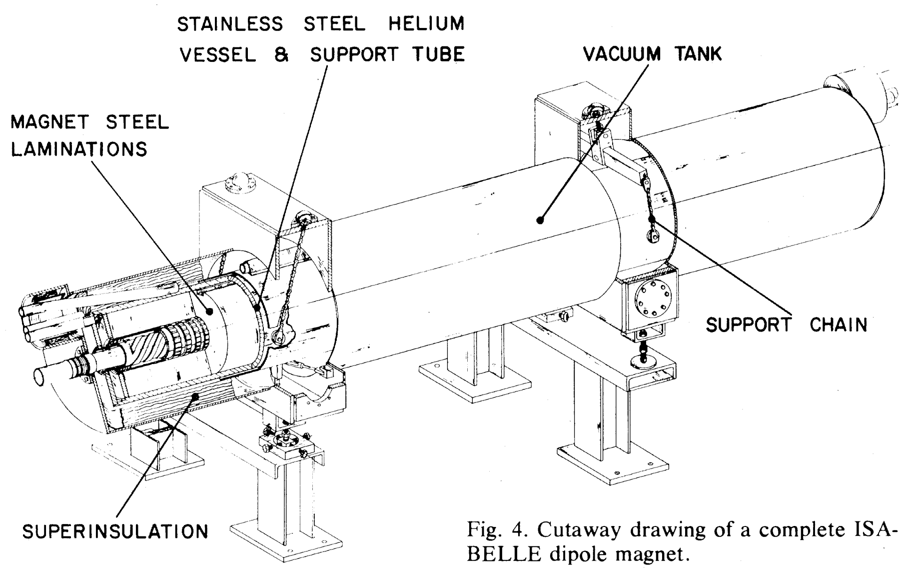

Fig. 4. Cutaway drawing of a complete ISABELLE dipole magnet.

outside the iron. It is commonly referred to as a "warm-bore, cold-iron" design. The entire assembly is encased in a vacuum tank (Fig. 4) and cooled with high-pressure helium gas. The principal source of heat in ISABELLE is expected to be leakage through the insulation and the support wires. Reducing the heat leak rate for each magnet has been an ongoing problem for Brookhaven. The latest tests have shown a nearly acceptable rate of 8 watts per magnet, according to Mark Barton, the physicist who is technical director of the ISABELLE project.

The design of the refrigeration system for a superconducting accelerator is just as crucial as the design of the electrical system—not only because helium has unusual properties that can produce severe thermal oscillations but also because the consequences when a magnet or a string of magnets goes normal can be spectacular. Each of the projects has had its share of dramatic failures during various tests. Brookhaven has burned out the coil of one smaller test magnet and had the coils of several more distorted from overheating, according to Al McInturf. Fermilab had a failure in a helium release valve when testing a string of four magnets. One magnet was lost, and the overpressure in the system caused the flexible bellows between the magnets to balloon up "like a string of sausages," according to one observer. The smaller experimental accelerator project at Berkeley has had similar problems. About 2 months ago, during a test of 12 magnets, some shorts occurred and forced the whole string normal, damaging several magnets.

When something occurs to warm up a superconducting magnet it does not follow that damage will be done, and in fact the experimental failures can be viewed as successful diagnoses of problems with the protection systems. The coils are designed with sufficient copper (about twice as much as superconductor by weight) that the wires in one magnet can carry the current of that magnet if it is shut off quickly and smoothly. In practice, when one magnet goes normal all the magnets in a limited string are also "quenched," and protective circuitry is designed to ensure that the adjacent magnets do not dump their current into the problem spot. In fact, it is desirable in some cases to use fast-firing electric heaters to quench all parts of a coil quickly when one region goes normal. In the Brookhaven design, up to 40 are quenched together. In the Fermilab system, only four magnets would quench when something malfunctioned in one.

Two areas of the ISABELLE program were singled out for more effort by a committee of the high-energy physics advisory panel (HEPAP) that reviewed both projects for the government last summer. They were the design of the cryogenic system and multimagnet tests. Although Brookhaven has tested two dipoles together, the committee said that tests of about ten magnets in a string with the vacuum systems, power supplies, computer control, and refrigeration system all operating would be a valuable engineering verification. Assessing the Fermilab project, the same committee singled out the field quality of the magnets themselves as the "major unknown" and indicated that the probability of success was difficult to predict for some of the modes of accelerator operation. The committee as a whole expressed confidence that the field quality goals could be met for two of the possible modes of operation.

The Fermilab program has produced a smaller magnet that has a much smaller cryogenic enclosure, and has also given early attention to many systems problems that will arise with the doubler/saver, including even the question of how to install the magnets in the present ring with a minimum of interruption of the ongoing experiments. The HEPAP committee generally gave Fermilab high marks for its systems work, particularly for the refinement of its cryogenic system design.

It is no accident that Fermilab's magnets are smaller in cross section. With space at a premium in the present accelerator ring (the new magnets will be squeezed underneath the old ones), the Fermilab team chose a small beam tube and adopted a "cold-bore, warm-iron" design, just the opposite of Brookhaven's. The cold-bore design makes the coils as small as possible, because there is no insulation between bore and coils, and reduces the size of the rest of the assembly accordingly. The warm-iron feature is achieved by putting the insulation and cryogenic enclosure between the coils and the iron yoke, reducing the problems of heat leakage. With a higher injection energy from the present accel-

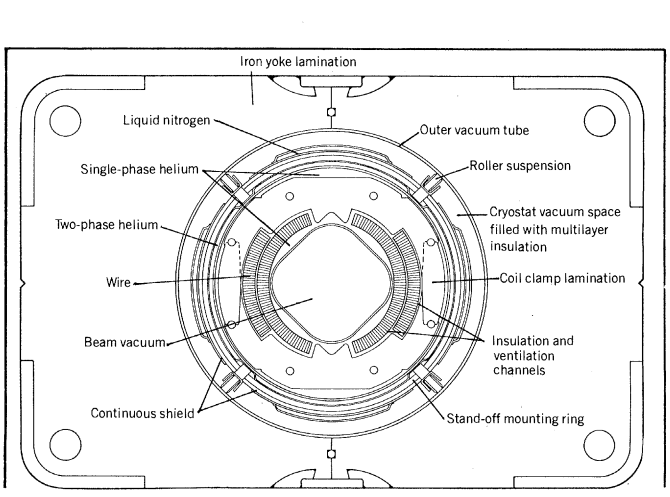

Fig. 5. Cross-sectional view of the dipole magnet for the Fermilab doubler/saver.

erator, Fermilab could tolerate a smaller magnet bore.

The first novel thing one notices about the Fermilab magnets is the geometry of the coils. Whereas Brookhaven has a single layer wrapped around the beam pipe, Fermilab has two layers of different azimuthal dimensions (see Fig. 5). Furthermore, there are no spacers of different sizes between turns of the coil to approximate the cosine theta distribution. All turns are evenly spaced. When properly adjusted, this coil geometry, conceived by Alvin Tollestrup of Caltech who has been working with the doubler/saver project for several years, produces a field that is remarkably uniform over 70 percent of the beam area, though it diverges rapidly at the outer edges. The trick then is to design the accelerator operation so that only the "good" region, about 6 cm in diameter, is used. With high-energy injection of a single turn of particles this is practical, although injection of multiple bunches of particles raises the questions articulated by the HEPAP committee.

With even spacings, the task of winding coils is immensely simplified. In fact, Fermilab winds its coils flat, then presses them into the necessary semicircular shape. What has occupied the Fermilab team for several years, however, is the problem of keeping the coils stable. This is a particularly severe constraint because the magnets will be cycled about 10^7 times during their lifetime. The iron yoke cannot be used for structural loading because of the insulation and vacuum gap between the coils and iron in a warm-iron design. Instead, Tollestrup devised a coil clamp. Made of stainless steel to be nonmagnetic, the clamp is a long cylindrical sheath made up of hundreds of laminations. After the coils are positioned properly, the laminations—which are interleaved for strength—are laid on the assembly by hand. Then the whole assembly is compressed in a huge press, edge-welded, treated with epoxy, and cured. When complete, the coils are prestressed at 18 tons per foot. They are then insulated and inserted in the rectangular iron yoke. A stack of finished magnets is shown in Fig. 6.

The refrigeration system for the doubler/saver must pump away heat that has been generated in the coils as well as heat that leaks in from the outside. In each magnet in the Fermilab design, about 6 watts of heat leaks into the cryostat from the outside, and a comparable amount of heat is produced by losses due to induced eddy currents. (Superconductors have no resistance to d-c current, but do have losses when

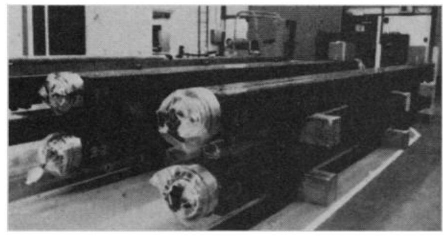

Fig. 6. Four prototype magnets for the Fermilab doubler/saver.

carrying a-c current. Virtually all superconducting magnets use multifilamentary wires in order to minimize eddy currents and thereby reduce the concomitant losses.) The 6-watt heat load due to a-c losses is the principal factor limiting the pulse rate of the Fermilab doubler to one per minute, as compared to one every 10 seconds for the present 400-GeV accelerator. If a faster repetition rate were possible, it would not be necessary to inject multiple beam bunches into the ring of the doubler/saver to match the intensity of the present accelerator.

While the repetition rate of the Fermilab project is refrigeration-limited, the Berkeley experimental accelerator, ESCAR, will not be. It is presently designed to operate at least three times as rapidly, according to Glen Lambertson at Berkeley. The ESCAR project began before the Fermilab one, but it has been funded more meagerly. It will be a cold-bore machine with 24 dipole magnets, capable of about 4 GeV. A cold-bore machine could have "all kinds of operational problems" because particles scattering off the walls could cause vacuum instabilities, according to James Liess at the National Bureau of Standards. In Lambertson's view, one of the functions of ESCAR will be to investigate these problems in an accelerator small enough that major modifications are economically viable.

The Fermilab refrigeration system will use both liquid and gaseous helium to cool the magnets. The requirement at 4°K is for a capacity of 15 kilowatts to cool 1000 magnets. Because of basic thermodynamic limitations, there is a 400-fold penalty for refrigeration at such low temperatures. The entire system, which will consist of a central helium liquefier and 24 satellite refrigerators, will require about 10 megawatts of power. Producing 5000 liters of helium per hour, it will easily qualify as the world's largest liquid helium facility.

Both projects are approaching their magnet quality goals. Brookhaven has built seven full-size (4.5 m) prototype magnets and three of them are suitable in quality for actual use in ISABELLE, according to project director Jim Sanford. The Fermilab effort does not have a single physics goal, and so the question of suitable magnet performance is more difficult. There is considerable debate over what level of magnet quality has been achieved. The laboratory has produced approximately 50 prototype magnets, and some of the latest ones are suitable for single-turn injection, according to Phil Livdahl, with the doubler project at Fermilab. James Liess, who was chairman of a group of accelerator physicists advising the HEPAP committee, says that the questions of quality were for the trickier modes and that his impression as an outside observer was that satisfactory magnets "for at least some of the modes" would be achieved by early 1978.

Challenges lie ahead for both Brookhaven and Fermilab in quality control during the production of the required 1000 magnets. A particular concern is that the higher-order field contributions be minimal and—to whatever extent they cannot be eliminated—repeatable. Fermilab plans to do this by introducing feedback into the production process. Brookhaven hopes that there are already enough constraints in its fabrication process to ensure it. For both projects, magnet quality reproducibility is essential so that any magnet can be inserted at any location in the ring. The tolerances required are near the state of the art.

There is heavy industrial participation in both projects. Whereas a few years ago it was nearly impossible to get timely delivery of niobium-titanium wire, now each project routinely gets wire of satisfactory quality from a number of suppliers. Brookhaven has also obtained two assembled coils from Grumman Aerospace that meet quality requirements. While many components for both magnet designs are subcontracted to industrial organizations, Brookhaven appears to favor doing the final assembly in-house and Fermilab is firmly committed to such a procedure. Nevertheless, the degree of industrial expertise in superconductivity that will result from the projects will be considerable.

After a very long incubation period, the age of superconductivity—for large R & D installations at least—has been born. The problems for big accelerators all seem to be of the type that methodical engineering will surely overcome, and the advantages are indisputable. "Looking back into the history of accelerators we see no superconducting machines," says Glen Lambertson. "Looking ahead we see nothing else."

—William D. Metz