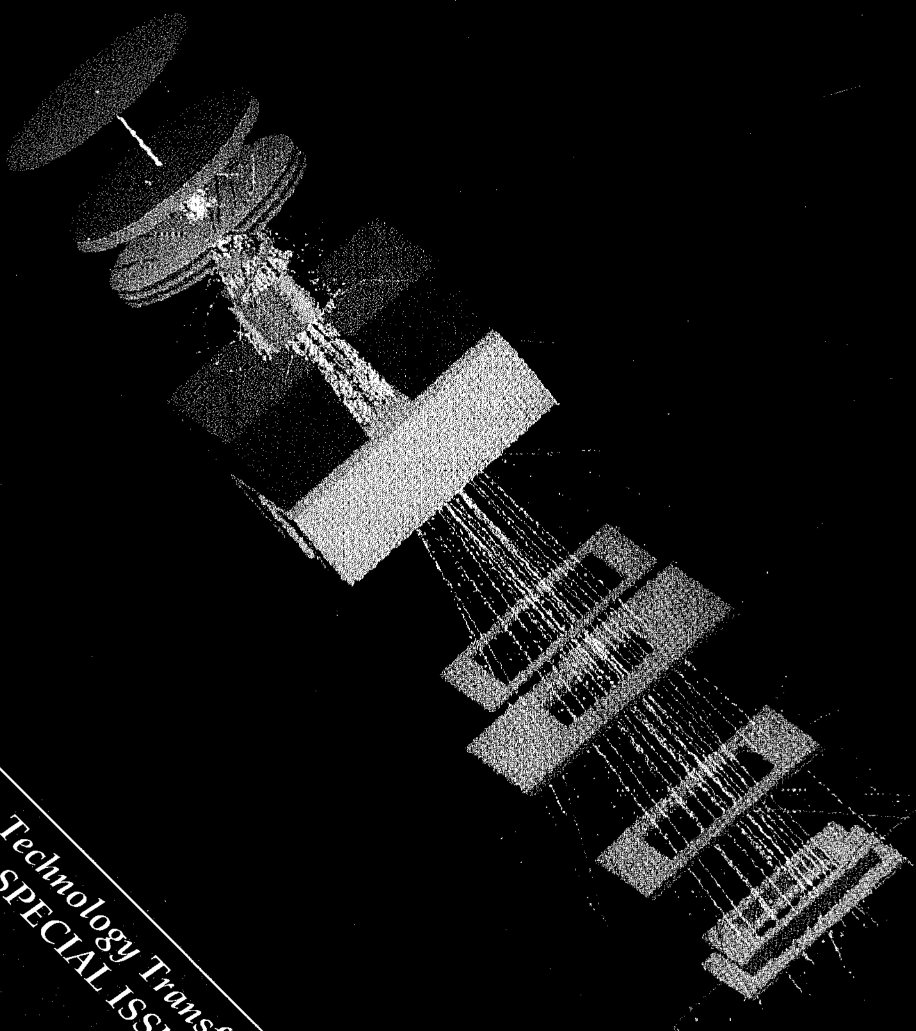
STANFORD LINEAR ACCELERATOR CENTER

Beam Line

Spring 1993, Vol. 23, No. 1



Technology Transfer
SPECIAL ISSUE

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

SPRING 1993 VOL. 23, NUMBER 1

The *Beam Line* is published quarterly by the Stanford Linear Accelerator Center,
P.O. Box 4349, Stanford, CA 94309.
Telephone: (415) 926-2585
INTERNET: BEAMLINE@SLACVM.SLAC.STANFORD.EDU
BITNET: BEAMLINE@SLACVM
FAX: (415) 926-4500
SLAC is operated by Stanford University under contract with the U.S. Department of Energy. The opinions of the authors do not necessarily reflect the policy of the Stanford Linear Accelerator Center.

Cover: An EGS4 computer simulation of a cancer-therapy accelerator operating in the electron mode. An initial group of 100 electrons (blue lines), each of 20 MeV, strike a scattering foil (dark blue and green), then pass through an ion chamber. Some x rays (yellow lines) are produced, and the beam is shaped by a succession of collimators. This simulation was created by Alex Bielajew and George Ding of the National Research Council of Canada.

Printed on Recycled Paper

CONTENTS

FEATURES

by JUDY JACKSON

Building Fermilab's Tevatron accelerator brought science and industry together in a partnership that took superconducting technology

DOWN to the WIRE

THE FIRST SPOOL of superconducting cable had an airline ticket and a seat of its own on the Boston-to-O'Hare flight early one summer afternoon in 1974. Robert Remsbottom, in the seat beside it, didn't let the cable out of his sight. There wasn't another such spool on Earth. The Fermi National Accelerator Laboratory would use that spool of cable and thousands more (most traveling with lesser accommodations) to build the first superconducting synchrotron, the world's highest-energy particle accelerator—and to save five million dollars a year on the Laboratory's electric bill. In the process, Fermilab brought experts in superconductivity like Remsbottom together with physicists, engineers, materials scientists and manufacturers in a collaboration that fast-forwarded the infant superconducting magnet industry to a full-grown role in the billion-dollar world market created by magnetic resonance imaging.

As the United States wrestles with how best to use results from basic scientific research to strengthen our country's economy and lead to a better way of life, "The Case of the Superconducting Wire" shows plainly both the power and the pitfalls of the arranged marriage between Science and Industry—and the remarkable, even unexpected, progeny they sometimes produce. Almost 20 years ago, Fermilab's procurement from industry of large quantities of material manufactured using just-emerging technology raised critical questions for government, science and private industry: How do we reconcile the undeniable requirement to control costs in taxpayer-supported national laboratories with the indisputable need for businesses to earn a reasonable profit? How do we balance the free flow of scientific information with the protection of technological know-how?

OVERNIGHT, A NEW MARKET

"Technology transfer" suggests the orderly flow of information from the laboratory bench to the factory to the marketplace. Pure scientist makes important discovery, passes it on to applied scientist who uses new knowledge to develop technology for new products, creating new markets, better economy, new jobs. Like all real-life human endeavors, technology transfer is more complicated and less orderly. Fermilab's advancing research in high-energy physics, for example, required large quantities of superconducting wire and cable, creating overnight a market for products that didn't yet exist. It was this "demand pull," rather than a particular new discovery, that sent technological development and large-scale production zooming up the learning curve. Meeting this demand created an industry with the capability to supply a commercial market—driven by the important new medical diagnostic tool called magnetic resonance imaging (MRI)—that no one had foreseen at the start. To build the Tevatron, the world's first superconducting particle accelerator, Fermilab used 135,000 pounds of niobium-titanium-based superconducting wire and cable between 1974 and 1983. At the project's start, annual world production of these materials was a few hundred pounds. Fermilab brought together a collaboration of scientists and manufacturers who improved the properties of the superconductor and developed a large-scale manufacturing capacity. Today, annual production has climbed to 200,000 pounds, about half of which finds commercial applications, principally for MRI.

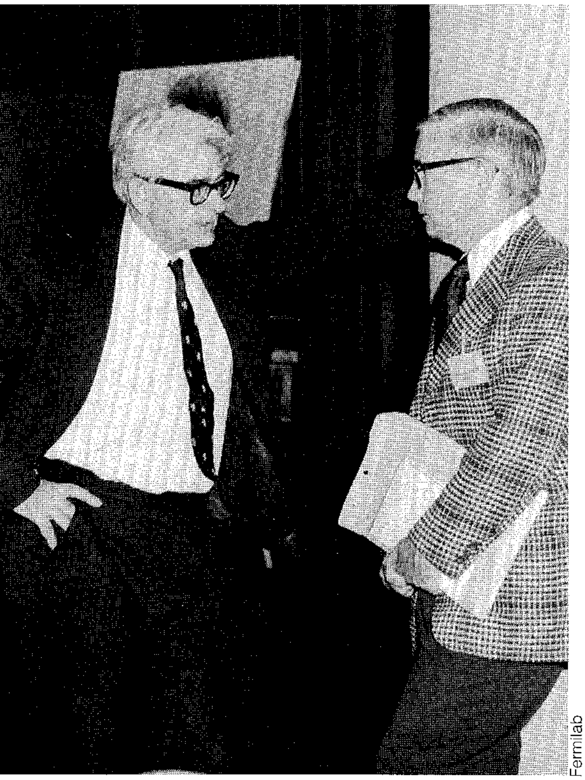
MILLIONS OFF THE ELECTRIC BILL

From its beginning, physicists planning Fermilab (called the National Accelerator Laboratory until 1974) west of Chicago had conceived of using superconducting technology to achieve an accelerator energy level of 1 trillion electron volts (1 TeV). But the people who met in 1967 to plan the Laboratory realized that it was not yet technically feasible to build superconducting magnets of accelerator quality. Instead, they designed a machine to achieve 400–500 GeV using only conventional magnets. The first 200 GeV proton beam passed through the Main Ring on March 1, 1972. That September, with the Main Ring well on its way to an energy of 400 GeV, Director Robert R. Wilson established an informal working group to begin investigating technical issues involved in building the next-generation accelerator, the Doubler.*

Renowned for his parsimony, Wilson thought Fermilab's power bill was too high. It was high in 1972, when the first beams passed through the Main Ring, and it got higher. By 1976, the Laboratory's consumption of electric power had nearly doubled—and the electric bill had shot up by a factor of six to nearly $10 million a year. Using superconducting magnets would take much less power than conventional magnets and cut Fermilab's electric bill by an estimated $5 million a year, while at the same time doubling the energy of the accelerator.

These magnets use less power than conventional magnets, because superconducting materials do not resist the flow of electric current when they are cooled to temperatures a few degrees above absolute zero.

**The superconducting accelerator at Fermilab has had more names than a character in a Russian novel. First it was generally called the "Doubler," or sometimes the "Energy Doubler," in recognition of the goal to increase accelerator energy from 500 to 1000 GeV. Later, during the 1974 gasoline shortage, it was called the "Saver," or the "Energy Saver," to emphasize the savings in power it would make possible. Physicist Peter Limon remembers attending a meeting devoted to long and heated debate of the relative merits of "Doubler/Saver" and "Saver/Doubler." Its current name, the "Tevatron," reflects its status as the first 1 TeV accelerator.*



Above: Charles Laverick, left, Argonne National Laboratory, and William Fowler of Fermilab during a 1974 conference on applications of superconductivity.

Because electric current that flows through superconducting wire doesn't lose energy to resistance, magnets made with such wire use less electric power to achieve the high magnetic fields required by particle accelerators. It does take energy to cool the magnets, however, so the net reduction in power use is less than 100 percent.

Shortly after Heike Kamerlingh Onnes discovered superconductivity in 1911, he also discovered the bane of superconducting materials: quenching. This phenomenon occurs when a superconducting material reaches a certain critical current, temperature or magnetic field; it suddenly "goes normal," that is, returns to its nonsuperconducting state, releasing its stored energy—and sometimes melts. His discovery of this phenomenon also quenched Kamerlingh Onnes's enthusiasm for the practical uses of superconductivity. It was not until the late 1960s that superconducting technology reached the stage where it began to interest the builders of particle accelerators.

BETWEEN MAGIC AND WITCHCRAFT

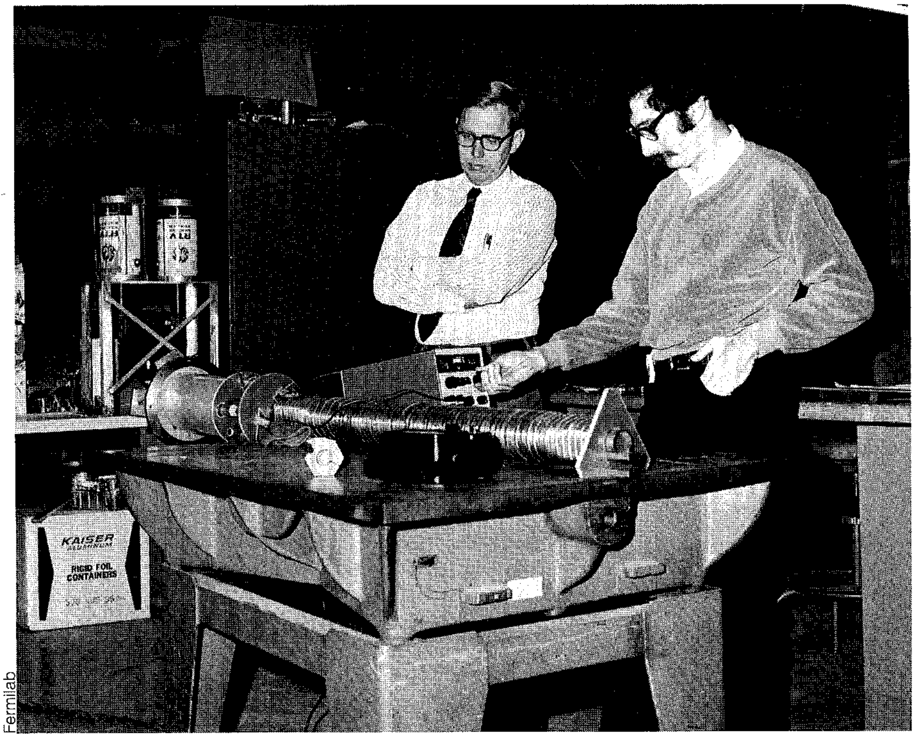
Many have credited Wilson with a genius for bringing the right people—with the right skills and knowledge—together at the right time in order to accomplish scientific goals that were, to say the least, challenging. He never used this talent to better effect than in the design and building of the Doubler.

In the mid-1970s, when physicists and engineers at Fermilab began trying to design and build superconducting magnets, the technology of manufacturing superconducting wire and cable was still "exotic," as Leon Lederman, who became Director of Fermilab in 1978 after Wilson resigned, has written. "Somewhere between magic and witchcraft," is where University of Wisconsin metallurgist David Larbalestier places it.

Using his own brand of magic, Wilson brought together his available sources of expertise in superconducting technology for the task of designing and making the wire and cable. Fermilab physicists William Fowler, Paul Reardon and Russ Huson and metallurgist Bruce Strauss had gotten their feet wet in superconducting technology by building magnets for the 15-foot bubble chamber. John Purcell, a physicist from Argonne National Laboratory brought to the project his experience in building its 12-foot bubble chamber.

The Applied Superconductivity Laboratory at the University of Wisconsin gave Fermilab another entree into the field of superconductivity. Attracted partly by the wire-fabricating facilities designed by specialist Remsbottom, Larbalestier had come to Wisconsin from Britain's Rutherford Laboratory, where he had worked on superconducting materials in the effort to understand how they work at a microscopic and molecular level. "Larbalestier was our mentor in superconductivity," says retired Fermilab Associate Director J. Ritchie Orr. "He made it his business to understand how it really worked."

Sixty years after Kamerlingh Onnes's disheartening discovery, *Engineer Willard Hanson and metallurgist Bruce Strauss test an early superconducting magnet.*



Fermilab

quenching still caused problems for magnet builders at Fermilab, explains physicist Alvin Tollestrup, who, along with Orr and Fermilab physicists Richard Lundy and Helen Edwards, received the 1989 National Medal of Technology for their contributions to the Tevatron. A superconducting magnet uses coils of cable made of strands of superconducting wire to induce a magnetic field. The performance of a magnet made of such wire—its ability to reach and maintain a prescribed magnetic field without quenching—depends on many factors but fundamentally on the critical current of the superconductor, that is, on the amount of current the wire can conduct, at its operating temperature and field, without quenching. Thus, says Tollestrup, the object of making superconducting wire is to achieve workable wire—that bends easily, for example, and has precise dimensions—with a high critical current.

IT'S NOT SO EASY

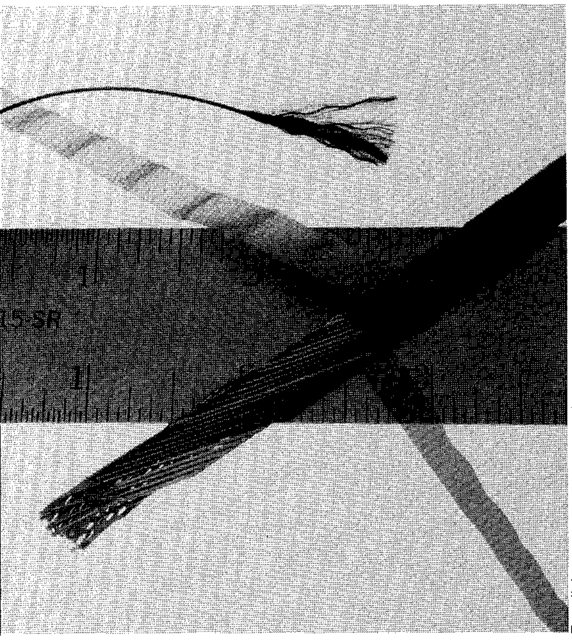
The would-be wire maker must combine the right alloy of the right superconducting materials in the right configuration with a conventional conductor, such as copper; then find the right methods of heating and drawing the materials into wire, in order to achieve the requisite critical current and mechanical properties that will allow the wire to be formed into cables. Finally, those materials and methods must be adapted for mass-production of wire of uniform quality. The problem to solve in cabling the wire is to find the right number of strands of wire, in the right configuration, with the right materials on the surface of the strands and on the cable itself to achieve the highest critical current and appropriate mechanical properties so that it can be wound into magnet coils.

What kind of cable works best in superconducting magnets? Particle accelerators have lived and died by the answer to that question. For years, magnet builders at Brookhaven National Laboratory struggled to build superconducting magnets for the ISABELLE collider using not flat cable but a braid of superconducting wire. Many point to this choice of braided cable as a fatal flaw that led to ISABELLE's demise when the Department of Energy withdrew funding for the project in 1983.

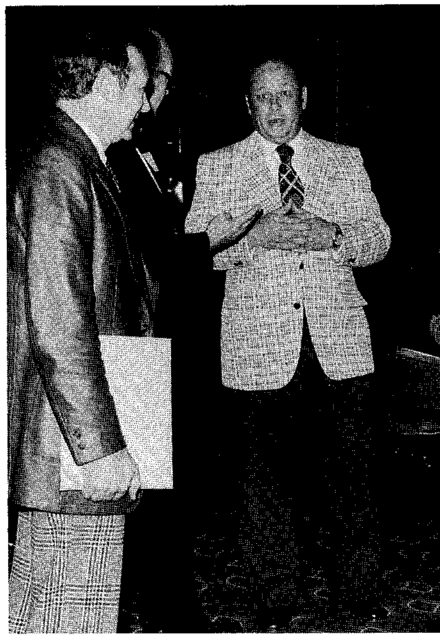
These were problems that members of Wilson's Doubler group took on in the early 1970s. "When it comes to making superconducting magnets," says metallurgist Strauss, "a let's-try-it" approach works better than a theoretical one based on calculations alone. If you think about superconductivity too long, you'll realize it won't work." By early 1975, Fermilab's highly systematic and tightly organized "let's-try-it" approach had made enough progress to fix important wire and cable specifications. The cable would be a 23-strand, flat, twisted "Rutherford cable." The superconductor itself would be an alloy of 53.5 percent niobium and 46.5 percent titanium, proportions chosen to be non-proprietary and in the middle of the range of proprietary alloys of the various wire vendors. (Later research would show that the exact ratio of niobium to titanium was not critical in wire performance.) The work of Fermilab physicists Fowler, Reardon and Donald Edwards, metallurgist Strauss, technical consultant Remsbottom, and others ultimately produced not simply a set of specifications for superconducting wire but a sort of "build-by-numbers" wire-making assembly, the so-called Fermilab Kit.

BY THE TON?

As the needs of the magnet-development program increased, Fermilab researchers began looking for manufacturers who could work with them to supply large quantities



Fermilab



Argonne National Laboratory

Above left: Each wire strand contained 2100 filaments of superconductor. The New England Electric Wire Company wove the wire into 23-strand, flat Rutherford cable which was wrapped in Kapton insulating material. Above right: Paul Reardon, right, at a 1974 conference in Illinois. Opposite left: The "Fermilab Kit" for making superconducting wire comprised a copper can filled with 2100 niobium-titanium rods in hexagonal copper tubes (foreground), capped with a tailpiece and a nose piece. Employees of Intermagnetics General Corporation assemble the kit. Opposite right: A Fermilab machinist winds superconducting cable to form the outer shell of a Doubler magnet coil.

of superconducting wire and cable that would meet the specifications of the evolving magnet design. Having previously served as Fermilab's business manager, Reardon played a central role in putting together the collaboration between the laboratory and the manufacturers of superconducting alloy, of wire and of cable to produce the materials the project required. Orr sees Reardon as another of Wilson's strategic choices, another person with the right skills at the right time, a man with "organizational brilliance and guts. He didn't mind gambling a little with the taxpayers' money when he believed it would mean substantial benefits in the end." Reardon's gambles usually paid off for Fermilab.

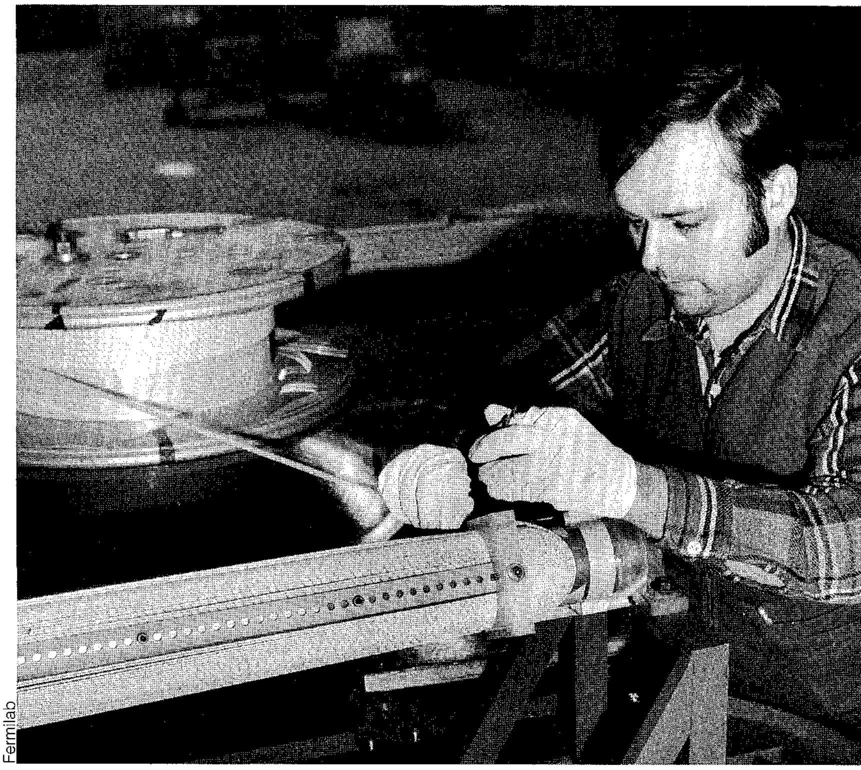
Niobium-titanium is an alloy formed at high temperatures by melting in a vacuum with an electron beam. In 1974, when Fermilab first went looking for superconducting alloy, the Teledyne Wah Chang Albany Corporation in Oregon was the major supplier of niobium-titanium in the United States—and the Laboratory was virtually the only buyer. Strauss and Reardon once constructed a bar chart showing that Fermilab had bought 95 percent of all the niobium-titanium ever produced since the beginning of time. Niobium is mined in only a few places on earth—Brazil, Canada and China. In the 1970s China was not a practical source, and the ores with the highest concentration came from Brazil. Most of Fermilab's niobium alloy came from Brazilian ores until climbing export taxes sent Wah Chang to Canadian sources.

In the spring of 1974, Reardon, Strauss and contracts manager Edward West made a trip, legendary in Fermilab lore, to the Northwest to buy niobium-titanium from Wah Chang. "How much is it by the ton?" Reardon is supposed to have asked. Strauss remembers him explaining, "If we order it by the pound, they'll never learn how to make it in quantity." That early decision to buy a large amount of niobium (an initial order of about 15,000 pounds) proved significant in defining the relationships Fermilab established with the companies that made the alloy into superconducting wire.

FROM MINE TO MAGNET

Fermilab requested delivery of the alloy from Wah Chang as straight 24-inch rods, an eighth of an inch in diameter. The rods were the first piece of the Fermilab Kit, which consisted of a "billet" of 2100 niobium-titanium rods inserted into hexagonal oxygen-free, high-conductivity copper tubes with round bores, all packed into a 10-inch diameter copper "can." Nose and tail pieces were welded onto the can. The niobium-titanium rods came from Wah Chang. The Small Tubes Products Company made the hexagonal copper tubes.

Fermilab



Fermilab

The Phelps-Dodge Company furnished copper for the cans, which were made by the Janney Manufacturing Company.

Fermilab bought all these kit materials for delivery to the wire manufacturers, whose task was to push and pull each 10-inch billet of copper-tubed niobium-titanium into a strand of superconducting wire 27 thousandths of an inch in diameter. Each strand would thus contain 2100 filaments of copper-coated niobium-titanium superconductor. Theoretically, each billet would produce 220,000 feet of superconducting wire. In practice, Fermilab paid a premium for any usable lengths over 210,000 feet that met specifications.

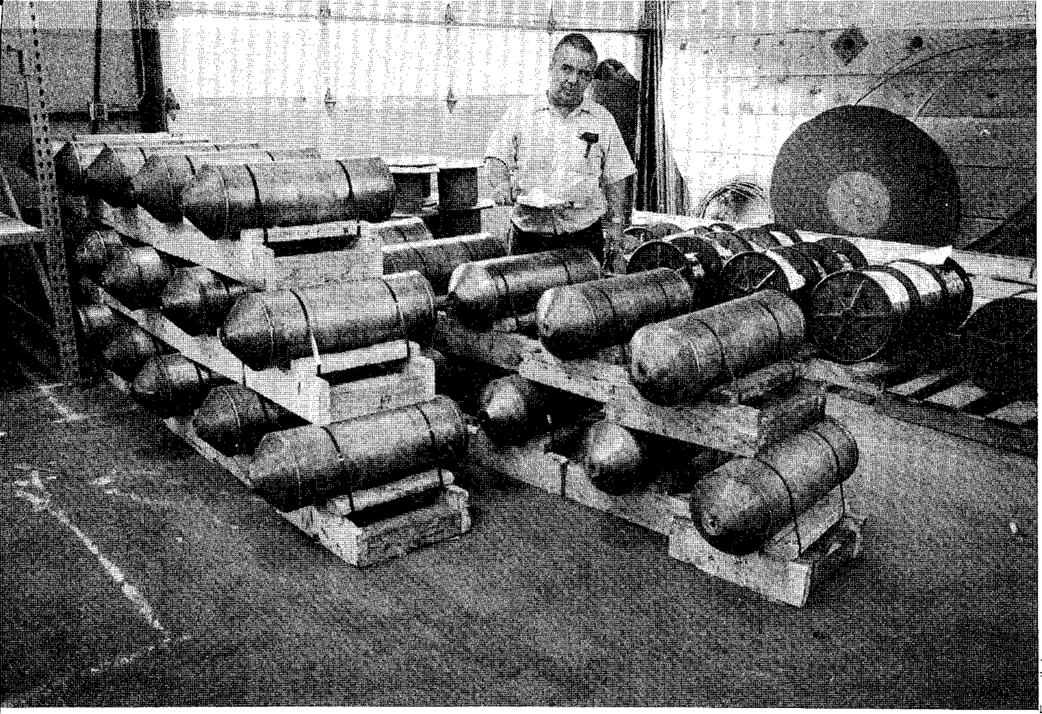
After the wire had been tested for dimension and superconducting properties, it went to the New England Electric Wire Company, where it was formed into flat 23-strand Rutherford cable. Fermilab magnet builders worked with the cable manufacturer to develop tooling and methods to "keystone" the cable, slightly changing its shape to fit the curve required by magnet design. To the finished cable they added a wrap of the insulating material Kapton. Tollestrup had discovered that wrapping with Kapton not only eliminated short circuits in the cable but insulated the superconductor against thermal transference that led to quenching. Both Fermilab inventions—keystoning and the Kapton wrap—played significant parts in the success of the Doubler magnets.

New England Electric Wire delivered the cable to Fermilab's Magnet Fabrication Facility for winding into coils for magnets. Each magnet used 110,400 feet of wire, twisted into 4,800 feet of cable. The 796 dipole magnets and 224 quadrupoles in the Doubler used enough wire to circle the earth 2.3 times, says contracts manager Lawrence Vonasch. In addition, prototype and experimental magnets used millions more feet of wire.

"We had learned very early," says Larbalestier, "that the properties of the conductor determined the properties of the magnet." The process of making 10-inch billets into 0.027-inch wire takes many steps, including an initial extrusion into two-inch diameter rods, various heat treatments, and "cold-working," drawing the wire into ever-finer diameters. No single step is more crucial in determining the critical current than the heat treatment the wire receives. How hot should the wire be heated? For how long? At what wire diameter should the heat treatment occur? Each wire company had its own proprietary recipe.

Fermilab dealt with four manufacturers of superconducting wire—Magnet Corporation of America, Supercon, Airco and Intermagnetics General Corporation (IGC). The first orders gave only a few billets to a manufacturer to make into wire. Fermilab would test it, rejecting wire below a certain level of performance. The vendors' early efforts yielded wildly erratic results. As a company's performance improved and the needs of the magnet program increased, Fermilab furnished more billets. By the project's end in 1982, IGC—the remaining wire vendor—was processing 150-billet orders into highly uniform wire.

Close communication between Fermilab and the manufacturers influenced the success of the



Fermilab

Above: Billets at Intermagnetics General Corporation (IGC), manufacturer of most of the wire for the Energy Doubler. Each 10 inch billet yielded about 200,000 feet of 0.027 inch superconducting wire, on spools in background. Opposite: IGC employee winds superconducting wire onto a spool.

Laboratory-industry collaborations, says physicist Lundy, who put together and ran its mass-production assembly line for superconducting magnets. Wisconsin's Remsbottom, a skilled hands-on veteran in the superconducting field who, says Lundy, "knew as much about how to make superconducting wire as anyone in the world," spent most of his time on the road, traveling from Wah Chang to IGC to New England Electric Wire and back again. "If you were a Fermilab vendor, you knew that every two weeks or so, Bob would show up." Often Lundy, who was himself a practical and inventive engineer as well as a high-energy physicist, accompanied him on these trips. "They let me in because I was with Bob," he says. These personal visits provided a direct channel for the back-and-forth flow of information that helped improve the quality of the wire.

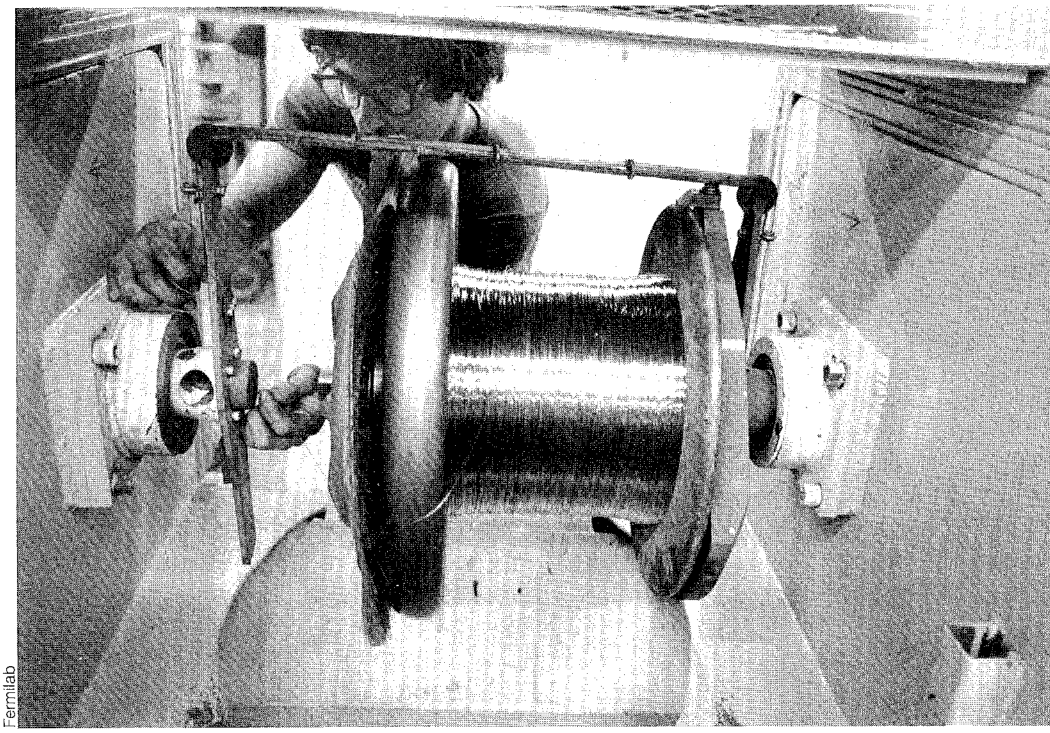
ASSUMING THE RISKS—AND CUTTING THE PROFIT

Fermilab's decisions not only to purchase the raw materials for the superconducting wire but to require the wire manufacturers to use the Fermilab Kit were key factors in determining the nature of the working relationships that evolved. These decisions had important and controversial consequences, worth examining for their effect on the success—and the limitations—of Fermilab's major procurement of superconducting wire in creating and encouraging the superconducting wire industry in the United States.

The greatest cost component in producing superconducting wire is the cost of the alloy. It was expensive—about $100,000 a ton—when Fermilab began buying it in 1974. For large corporations with deep enough pockets to assume the level of financial risk required to buy large quantities of alloy, the Doubler represented a relatively limited market that did not justify the necessary investment in research and retooling. They just weren't interested. Smaller, specialized companies that did find the Doubler market worth pursuing lacked the financial resources to buy large quantities of alloy. From Fermilab's point of view, the Laboratory's purchase of alloy helped the fledgling industry by assuming one of the major financial risks for these small manufacturers, that operated, recalls Orr, "on the ragged edge of nothing."

"Sure they took away some of the risk," says Carl Rosner, president of IGC, the manufacturer that ultimately supplied most of the wire. "They also took away most of the profit. By refusing to allow us to buy the alloy ourselves, to our own specifications, and mark it up, they took away our major opportunity to make any money on the contract."

"It's true we didn't have the cash on hand to buy niobium," he adds "but with an order from Fermilab we



Fermilab

could have gone to the bank for a loan. That's how it's supposed to work."

By furnishing kits to the wire manufacturers, Fermilab eliminated many technical variables in an enterprise in which systematic control of the parameters of superconducting magnets was absolutely crucial to success. But the kits also took away most of the opportunities for vendors to use their own proprietary materials and methods—and thus even more of the opportunities to profit.

"Fermilab helped us enormously," says Rosner. "They forced us to accelerate our learning curve in superconducting technology. But our experience making wire for the Doubler should have positioned us as a world leader in superconducting technology." Instead, he believes, Fermilab's refusal to allow vendors to profit left U.S. superconductor manufacturers like IGC ill equipped to compete in the world market that took off in the 1980s with the advent of magnetic resonance imaging.

Maybe so, says Bruce Chrisman, Fermilab's Associate Director. "But if we had let those guys mark up the niobium, it would have sent the cost of the Doubler up so high that DOE would have told us to forget it. The Doubler would never have been built, and there wouldn't be any market to talk about today."

WHY IT WORKED

Another thorny issue in this rocky marriage between science and commerce concerned who would have custody of the information that the partnership engendered. What tradition is more hallowed in science than the free dissemination of the results of scientific investigation? What commodity is more precious to a technology-based company than hard-won technical secrets? To Fermilab scientists, it seemed only natural and ethical to share what they learned about superconducting wire with the world. To the wire makers, it seemed like giving away the farm. From their point of view, the scientific community simply handed foreign firms a state-of-the art recipe for making superconducting wire, effectively eliminating the leg up that U.S. companies had gained from their fast and arduous scramble up the learning curve.

If "The Case of the Superconducting Wire" raises difficult questions, it also shows that science and industry can find common ground where both can thrive. Although it didn't work perfectly, the collaboration between Fermilab and the superconducting technology industry did indeed work.

Asked why, Wisconsin's David Larbalestier says, "I think it came down to honesty—good old-fashioned intellectual honesty. In all the organizations, there were people who could focus on the things that were real. It's all too easy in this business to get egos into play. But the question is, 'Will the game be played in an honest fashion?' "It's not a trivial thing—simply to understand," he adds, "In the long run in this country, we need a long-term commitment to understanding."

Successful companies in the collaboration had the motivation to innovate and experiment and invest resources to supply the materials to build the world's highest-energy particle accelerator, and in doing so they built a new industry. High-energy physics did not invent MRI, but it did push superconducting technology out of the nest so that when MRI came along, the industry was ready to fly. For the future, we can't predict the exact flight plan, but we can be sure that superconducting technology has just begun to soar. In the words of the late Robert Marsh, of Teledyne Wah Chang, still the world's largest supplier of superconducting alloys, "Every program in superconductivity that there is today owes itself in some measure to the fact that Fermilab built the Tevatron and it worked."