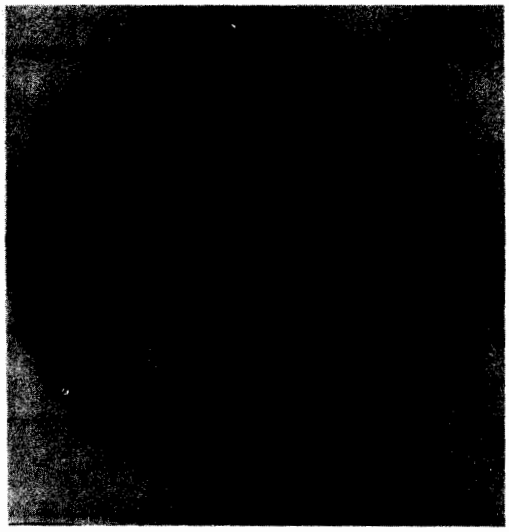
Magnet Project Boosts Superconductivity Expertise

By *Kate Metropolis*



Cross section of a superconducting strand used in Fermilab's low-beta magnets.

Striking advances in superconducting materials, wire manufacturing processes and cabling techniques have been realized in the development of a new series of focusing magnets for the Tevatron. The superconductor in the magnets has achieved the highest critical current density that has ever been seen in a working accelerator magnet: 3,100 amperes per square millimeter at 5 teslas, nearly twice that of the superconductor in the original Tevatron magnets. This accomplishment is the result of the combined efforts of three national laboratories, a university research group and American industry.

Fermilab's pioneering work in applied superconductivity began more than a decade ago, when the Laboratory began to design the Tevatron, the highest energy accelerator in the world today. The Tevatron's four-mile-long ring of superconducting magnets keeps two beams of particles circulating past accelerating stations that increase the particles' energy until they are traveling almost as fast as light. Much of what is known about the ultimate structure of matter has been revealed through the study of what happens when high-energy particles collide head-on—and there have been more immediately practical benefits from the research as well.

"Every program in superconductivity that there is today owes itself in some measure to the fact that Fermilab built the Tevatron and it worked," says Bob Marsh, of Teledyne Wah Chang, the world's largest supplier of superconducting alloys and a participant in the development of the new magnets. He cites high-energy physics as a driving force in the development of practical applications of superconductivity. Without the success of the Tevatron, he believes, "there would probably be no magnetic resonance imaging today. Fermilab provided the impetus necessary for industry to make better superconducting wire at a lower cost."

Although physicists have been running experiments with the Tevatron since the early eighties, their quest to learn more about the fundamental laws that shape the physical universe continues to spur the domestication of superconductivity. "We all knew that we could do better than the Tevatron magnets—that we'd just begun to tap their potential," says Fermilab physicist Al McInturff, who coordinated development of the new low-beta quadrupole magnets. Twenty will be installed over the next year to squeeze the particles together into tighter bunches just before the paths of the two beams cross. The factor-of-two increase in current-carrying capability doubles the probability that a proton and an antiproton will collide head-on, increasing the opportunity for physicists to record and study very rare events.

Improving superconducting wire

Funded by the Department of Energy's High Energy Physics Advanced Technology R&D Program, researchers at Fermilab, Brookhaven National Laboratory, Lawrence Berkeley Laboratory and the University of Wisconsin at Madison collaborated with their counterparts in industry to optimize the superconductor for the magnets. Although ultimately commercial contracts for the alloy and the wire were awarded on the basis of bids, several companies who are competitors in the marketplace joined forces in the research and development phase of this project.

Four years ago, a leading authority on superconductors, Professor David Larbalestier of the University of Wisconsin at Madison, took on the challenge

The University of Wisconsin at Madison collaborating group, under the leadership of Professor David Larbalestier, included: (l. to r.) K. I. Faase, P. J. Lee, D. C. Larbalestier, W. L. Starch and Y. E. High.

of improving superconducting wire so it could carry sufficient current for the new magnets. Larbalestier's group, which included a microscopist and both graduate and undergraduate students, succeeded in bettering both the intrinsic and the extrinsic properties of the superconductor. "If a chain is only as strong as its weakest link," Larbalestier explains, "you have to make the material of the link as strong as possible. But you also have to make sure that the links are welded properly—that it's mechanically strong."

To enhance the upper critical field of the magnets, the group decided to incorporate tantalum into the usual alloy of niobium and titanium. "This was the risky part," says Larbalestier. "It's difficult to melt these three metals in a chemically uniform fashion. But McInturff said, 'Let's gamble.' "

Mechanical stability was another issue. The University materials scientists learned that if titanium from the alloy diffuses into the copper that sheathes the superconducting filaments, brittle compounds can form that generally degrade the properties of the wire. To reduce this risk, the industrial partners suggested that the alloy be encased in a layer of niobium to create a diffusion barrier.

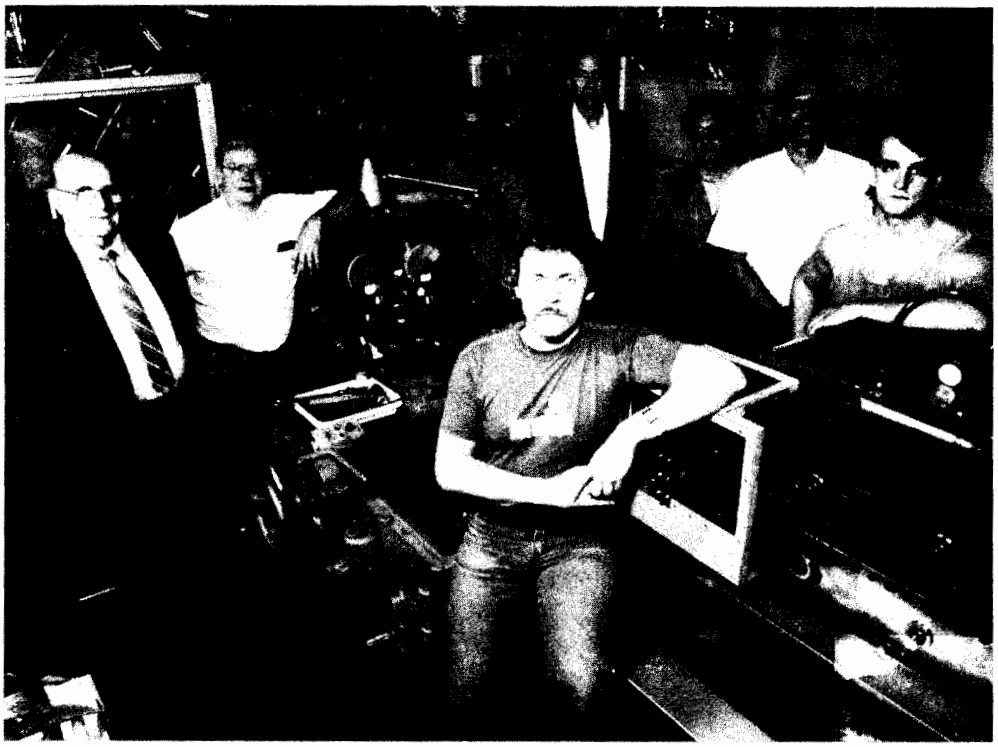
Daring new approach rewarded

Tests and detailed microscopy carried out at the University and the national laboratories confirmed that uniform samples of the superconductor could be made and that the current-carrying capability was very high. But it was by no means clear to the Intermagnetics General Corporation (IGC)—a company in Waterbury, Connecticut, specializing in commercial applications of superconductivity—that the techniques that worked in the laboratory would be economical for industrial production. Their concern was that the hotter, longer heat treatments prescribed by the Wisconsin group for the alloy—manufactured by Teledyne Wah Chang of Albany, Oregon—would render it too brittle for long lengths of the 21-mil-diameter wire to be drawn. One of the high points of Larbalestier's work on the project was the day he got "a very excited" phone call from IGC. The company had just drawn a 120,000-foot length of the wire. "They said they'd never had such a good piece," Larbalestier remembers.

"We had looked at these new techniques before the low-beta quad project came along, but we were unwilling to make the jump," said Dr. Hem Kanithi of IGC. He reports getting excellent results on a production scale. "This is probably the first time that anyone has made such a large quantity of fine superconducting wire. Having processed a batch of about four tons gives us the confidence to apply these techniques to other superconductors, such as those used in magnetic resonance imaging."

State-of-the-art cabling techniques

Fermilab turned to the Applied Superconductivity Group at the Lawrence Berkeley Laboratory (LBL) for help in twisting the wire into cable. Cabling superconducting wire is more demanding than cabling ordinary copper wire: the wire must be highly compacted to ensure a high over-all current density, but



The Applied Superconductivity Group at LBL included (back row, l. to r.) John Royet (LBL), Ron Scanlan (LBL), Hugh Higley (LBL), Clyde Taylor (LBL), Phil Rizzo (LBL), Scott Graham (LBL) and Bob Tuskey (Fermilab) and (front row) Bob Jensen (Fermilab).

the heat treatments that help ensure a uniform alloy also reduce its ductility. LBL's considerable expertise in cabling superconductor grew out of an early magnet design they had come up with for another accelerator. The group had had trouble getting the 30-strand wire their magnet required made commercially, so they decided to develop the technology themselves and then transfer it to industry.

"We wanted something that would allow us to make a precise rotation and then also transfer that motion to a linear drive to take up the cable," Ron Scanlan, a metallurgist in the LBL superconductivity group, explains. "One of our engineers realized that a lathe automatically does those operations, and we

were able to find a very large one in storage out in the Midwest. We had it shipped out and made a wheel to attach the spools to, and worked out the technique for making cable." This experience enabled LBL to write the specifications for a production cabling machine, which was installed at New England Electric Wire Company in the fall of 1988, where "it has worked out quite well," according to Scanlan.

Table I

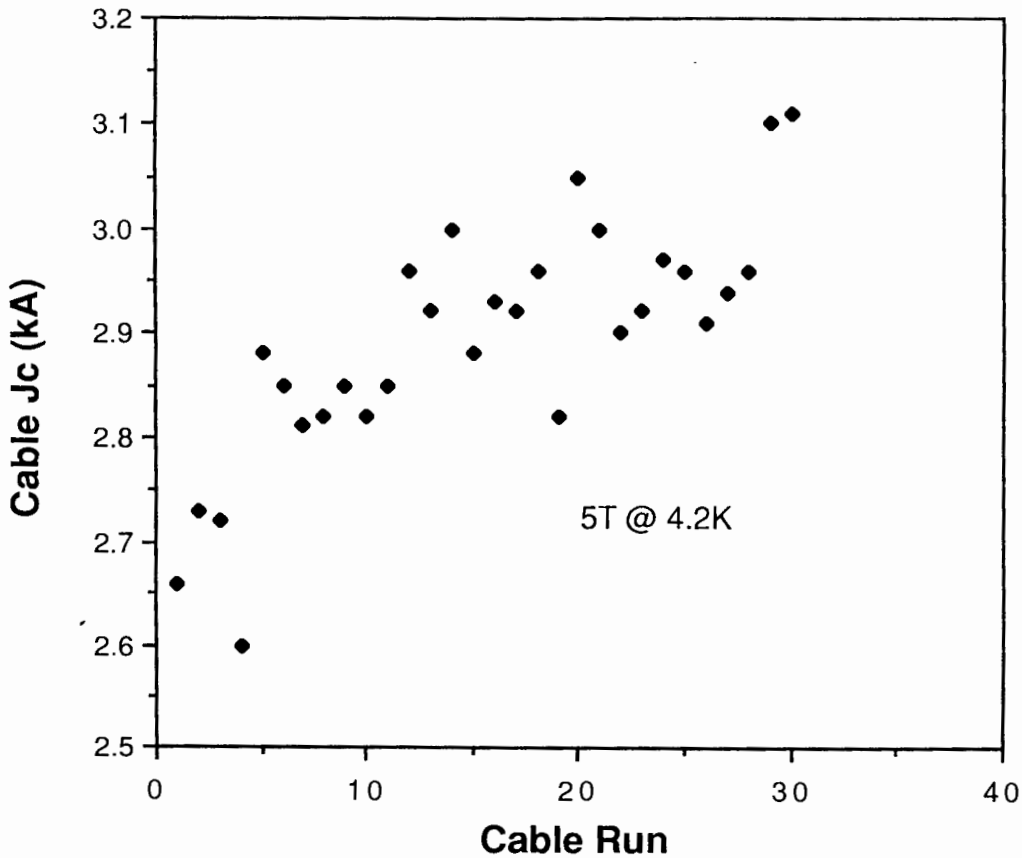


Table I: shows the increase in cable critical current density over the two-year cabling period.

Table II

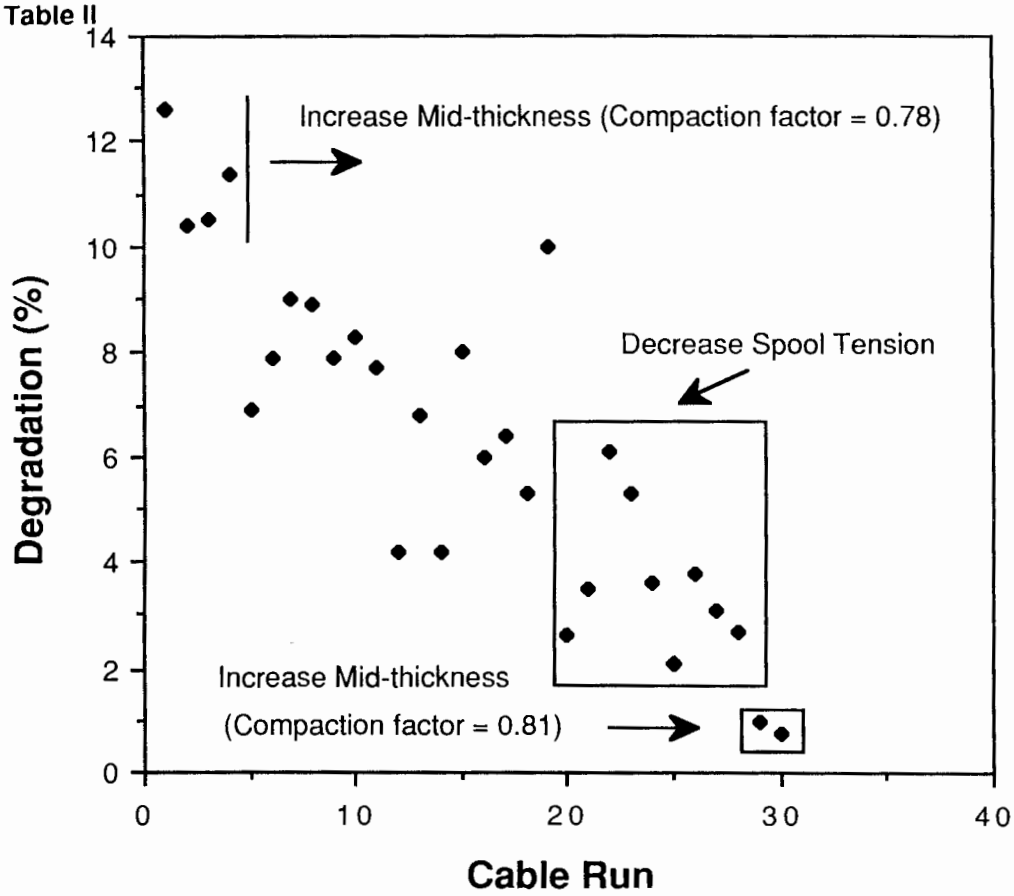


Table II: shows the reduction of degradation as a function of cable run.

To form a cable for the Fermilab low-beta quadrupoles, 36 strands of wire are carefully twisted together over a mandrel, so that each one lies next to, but doesn't cross over, the adjacent strands. It is then flattened in a Turk's-head roller, slightly more on one edge than on the other: in cross section it resembles a keystone. This shape allows the cable to be wound tightly into a magnet, for maximum current density and mechanical stability. However, this process must be performed with great care. If the cable isn't sufficiently flattened, it tends to spring back to its unrolled round cross section. On the other hand, rolling too hard can damage the strands. "Our cable could not have been made a few years ago," says McInturff.

In the meantime, both Fermilab and LBL came up with innovations to ward off the demons that can ruin cable. LBL developed specifications for how far the superconducting wire can be bent without breaking and how much variation in the springiness of the wire there can be to ensure that it can be cabled satisfactorily. A magnetic device controls the tension on each strand more accurately and precisely than the standard mechanical regulator. Sophisticated mathematical modeling by LBL's John Royet has improved the shape of the mandrel and its position relative to the Turk's-head roller to minimize the number of crossed strands. On-line quality sensors developed by John Carson at Fermilab have reduced deviations in the thickness of the cable by almost an order of magnitude, which is extremely important for such densely wound magnets.

Lighting the way for the SSC

The collaboration of superconductor experts and the physicists who will perform experiments with the upgraded Tevatron are not the only ones to benefit from the development of the new magnets. Many of the advances came at a crucial time in the work on magnets for the Superconducting Super Collider (SSC), a fifty-three-mile-long particle accelerator with twenty times the energy of the Tevatron that will be built by the Department of Energy near Dallas, Texas, over the next decade.

Like the SSC magnets—but unlike the original Tevatron magnets, the Fermilab low-beta quadrupoles have a "cold-iron" design, in which the cryostat surrounds the iron collars that restrain the coils under the tremendous Lorentz forces generated when the magnet is operating. The low-beta quadrupoles provided insight into the manufacturability of both the magnet and the cryostat.

The low-beta quadrupole work also blazed the trail for cabling 36-strand wire, which is a feature of the present SSC magnet design. In addition, according to David Larbalestier, the success of the superconductor for the low-beta quadrupoles suggests that no intrinsic limit to the material exists that might jeopardize the SSC magnets. "It's a very important proof of principle," he says.