LHC MAGNETS: From MODEL to PROTOTYPE

by Kurt Riesselmann

Magnets are crucial components of every particle accelerator around the world. Like tracks guiding trains, they force charged particles to follow a path prescribed by magnetic forces. The higher the energy of the particles, the stronger the magnetic forces needed to steer them around a ring.

The Large Hadron Collider, which will be the world's most powerful particle accelerator when finished in 2005, will feature the world's largest assembly of powerful magnets. Thousands of magnets will assure that protons, traveling at almost the speed of light, will stay on track as they zip around a 17-mile-long circular track at CERN, the European particle physics laboratory near Geneva, Switzerland.

Operating a particle accelerator requires two main types of magnets: dipole and quadrupole magnets. Dipole magnets are able to bend a particle beam. Quadrupole magnets work like lenses, focusing particle beams. Locating them next to the collision detectors, physicists use quadrupole magnets to direct as many particles as possible to a tiny area at the center of their detectors, called the interaction point. The number of beam particles and the quality of the quadrupole magnets determine the number of collisions an accelerator can produce.

Fermilab is one of the world's top laboratories in magnet research and development. Three years ago, as part of a $531 million U.S. commitment to the LHC, it joined a collaboration with CERN; Japan's prime research laboratory, KEK; and Lawrence Berkeley National Laboratory, to develop and build the eight final focusing sections for the LHC. Each section is almost 100 feet long and has a peak magnetic field of more than eight Tesla, twice the strength of the Tevatron magnets and a 100,000 times stronger than the earth's magnetic field.

"Each section consists of four main quadrupoles," said Jim Kerby, project manager for Fermilab's magnet construction. "KEK and Fermilab will each be responsible for two quadrupoles in each section."

CERN will build magnetic correctors, which will serve as magnetic fine-tuning lenses between the main magnets. Fermilab will receive the KEK and CERN magnets and assemble the final configuration, which it will ship to CERN for installation in the LHC tunnel.

Building powerful magnets is not a straightforward task. Precision machines

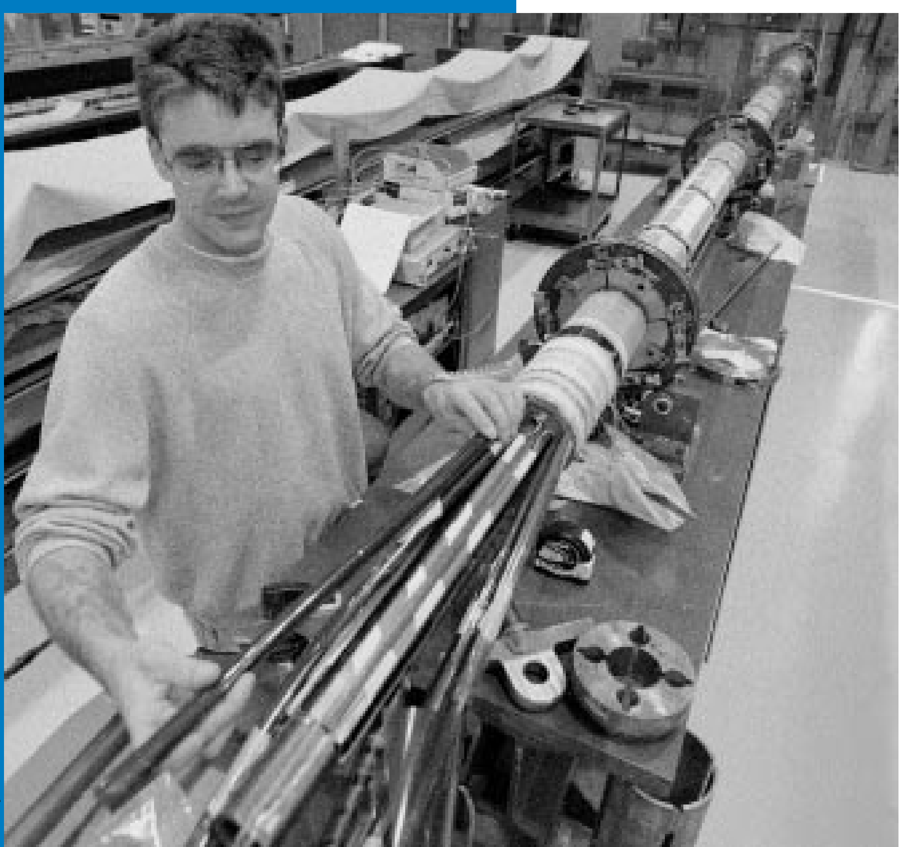
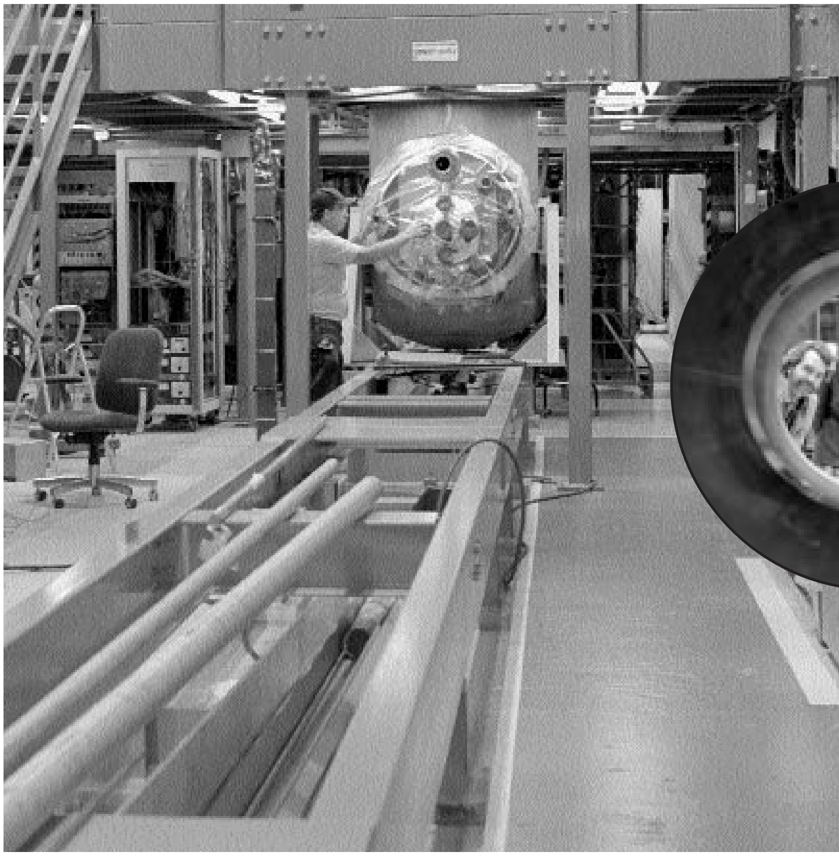


Photo by Reidar Hahn

Magnets for powerful particle beams are an intricate construction of wound coils, pressed together by precision collars. Paul Mayer checks one of the leads to a coil prior to final assembly.



Photos by Reidar Hahn

The Magnet Test Facility prepares for cooling and testing LHC superconducting magnets. Charlie Hess covers the liquid-helium pipes and other connectors with plastic to protect them from dust. When finished, the vessel containing the first prototype will be placed on top of the rails in the front of the picture.

“These MAGNETS are touchy **WIDGETS**.”

– Jim Kerby

Arnold Knauf (front), Tom Nicol, Christine Darve, Tom Page and Marsha Schmidt (from left) will see that this empty vacuum vessel houses the first superconducting LHC magnet and its cooling system.

carefully wind and cure superconducting cables into elongated coils, placing the cables accurately to within thousandths of an inch. Technicians take the coils and pack them tightly together. Specially designed collars keep the coils in place, protecting them from the strong magnetic forces that try to drive the coils apart as electrical currents flow through the cables. A massive iron yoke, which wraps around the collars, stabilizes the magnetic field. When completed, a steel skin covers the final assembly. In the case of the LHC quadrupole magnets, the assembly is about 16 inches in diameter and 20 feet long.

“These magnets are touchy widgets,” Kerby said. “We spent about two years to build and test 6-foot-long models.”

The coil and magnet ends are the most difficult parts to design. Studying short models saves time and money, and produces reliable test results. In March of this year, the ninth model produced by the Fermilab team provided confirmation that it had met all technical requirements. The project leaders decided to move on and build a full-length prototype, which is currently under construction.

The strength of the magnetic field is determined by the amount of electrical current flowing through the coils. The 8-Tesla magnetic fields of the LHC quadrupole magnets require currents of 12,000 amperes, about 50 times more than the engine-cranking current delivered by a car battery. Finding materials that can conduct and withstand such extreme currents in a limited volume is an important field of research. The LHC magnets rely on a niobium-titanium compound, which is an excellent conductor at ultra-low temperatures. At about 10 kelvins, a temperature only slightly above the lowest temperature possible in nature, the niobium-titanium compound becomes superconducting and carries electrical currents without resistance.

For accelerator magnets, this still isn’t good enough. Further decreasing the temperature, the current-carrying capability of the compound improves. Fermilab operates its 4-Tesla Tevatron magnets at 4.8 kelvins. Because the LHC pushes niobium-titanium technology to its limits, engineers had to take another step down on the temperature scale, lowering its operating temperature to 1.9 kelvins to achieve higher fields in the magnet design.

Creating and maintaining these temperatures is a major challenge. Scientists use helium as coolant since all other materials are solid at temperatures close to absolute zero.

“Testing the full-length magnets will be more difficult than testing the model magnets was,” said Tom Peterson, who is responsible for cryogenics at the Magnet Test Facility. "The model magnets were tested in a 12-foot-deep dewar filled with liquid helium at 1.9 kelvins. The prototype is too long to fit in our vertical dewar, so it has to be tested in its own liquid-helium container."

Peterson is now involved in setting up the test facility for the full-length prototype. Like the magnets destined for the LHC, the prototype magnet will be mounted inside a cryostat, a vacuum vessel three feet in diameter that contains liquid-helium pipes and special heat shields.

The magnet is mounted at the center of the cryostat. Minimizing the number of contact points between the magnet and the surrounding vessel reduces the amount of heat flowing toward the magnet. In addition, cryogenic experts need to remove heat generated by the particle beam from the vacuum vessel.

"Because they are so close to the interaction points, these quadrupole magnets are exposed to much more heat than any other LHC magnet," said Christine Darve, a thermomechanical engineer working on the cooling system. "In each final-focusing section, we constantly need to get rid off about 200 watts of power."

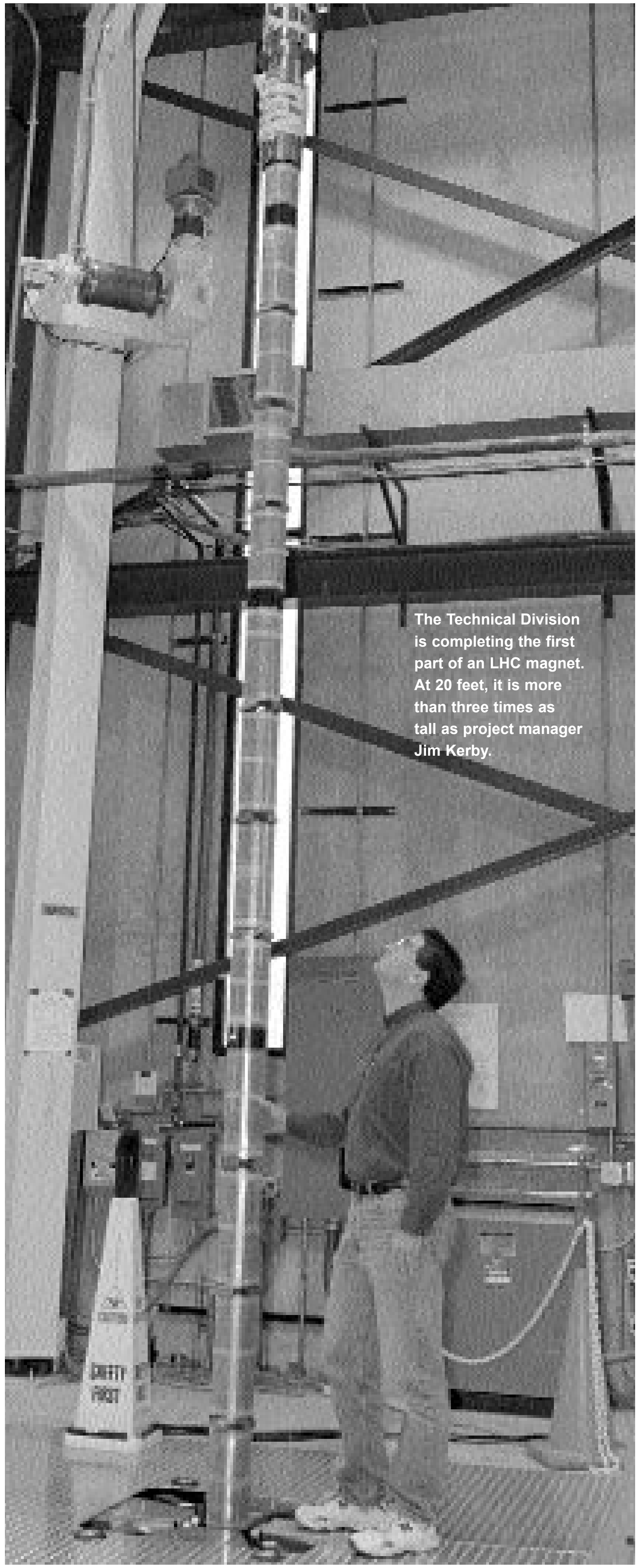
This corresponds to the heat generated by a couple of strong light bulbs, assuming they burn inside the beam pipe. At ultra-low temperatures and in the middle of a superconducting magnet, this is a major engineering challenge. Fermilab designed a full-scale model of the cooling system for the final-focusing sections and successfully tested it at CERN.

To keep the magnets at their ultra-low temperature, they are bathed in 1.9-kelvin superfluid helium. The helium absorbs the excess heat generated by the beam, transports it to a heat exchanger inside the vacuum vessel, and a separate stream of liquid helium carries the heat outside the vessel, where refrigerating units re-cool the helium.

Fermilab's first LHC prototype magnet will be ready around the end of the year. Technicians currently install the superconducting coils. Soon the steel yoke will be in place. Next, they will outfit the prototype with supports and pipes of the cooling system.

"We build the cooling system around the magnet core," explains Darve. "Once all equipment is installed, we carefully slide the whole construction into the vacuum vessel."

Next summer, after completing the prototype tests, production and final assembly of the magnets will start. Fermilab will ship the last quadrupole magnet to CERN in 2004, allowing physicists there to continue exploring the secrets of matter at the smallest scales. □



The Technical Division is completing the first part of an LHC magnet. At 20 feet, it is more than three times as tall as project manager Jim Kerby.

Photo by Reidar Hahn