

Lawrence Berkeley National Laboratory

Recent Work

Title

Superconducting Magnets 1992

Permalink

<https://escholarship.org/uc/item/2zm50807>

Author

Chew, J.

Publication Date

1993-06-01

Supercon- ducting Magnets

1992

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

June 1993

LBL-34253
LOAN COPY
Circulates
for 4 weeks

Bldg. 50 Library
COPY 1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Superconducting Magnets

1992

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

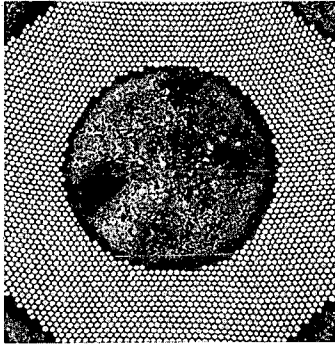
June 1993

Reprinted from *Accelerator and Fusion Research Division 1992 Summary of Activities*,
LBL-33377 (December 1992).

This work was supported principally by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Support came from the Director, Office of Energy Research, through the Office of High Energy and Nuclear Physics (High Energy Physics Division) and the Office of Superconducting Super Collider.

Contents

5. Superconducting Magnets	5-1
SSC Magnet Industrialization	5-2
Collider Quadrupole Development	5-2
Advanced Magnets	5-7
D19: A Record-Setting Magnet	5-7
D20: The Push Beyond 10 T	5-9
Nonaccelerator Applications	5-10
Advanced Materials and Design Techniques	5-10
APC Materials Development	5-10
High- T_c Superconductor at Low Temperature	5-13
Cable and Cabling-Machine Development	5-14
Analytical Magnet Design	5-14
Publications and Presentations	5-15



5.

SUPERCONDUCTING MAGNETS

THOUGH PERHAPS MOST FAMILIAR IN ACCELERATORS such as the Superconducting Super Collider (SSC), superconducting materials are currently or potentially useful in many other fields, ranging from magnetic-resonance imaging to magnetically levitated trains. The Superconducting Magnet Program in AFRD takes an integrated approach to these magnets, with involvement at all phases from basic development of superconducting materials to evaluation of finished magnets.

One of our most significant 1992 accomplishments was the completion of the SSC Magnet Industrialization Program, in which industry representatives worked alongside LBL engineers and technicians to learn how to build the technically challenging collider quadrupole magnets. This degree of technology-transfer activity is inherent in the program's operations, which rely at all levels upon two-way interaction with industry.

The SSC work largely culminated in 1992 with the exhaustive (and successful) testing of six full-length collider quadrupoles. As this effort diminished, the program's emphasis shifted toward other areas: generic R&D that will benefit future accelerators, for instance, as well as nonaccelerator applications of superconducting magnets and basic investigations of materials.

C. Taylor (*program head*)
L. Amerman*
B. Ardenyi*
R. Armer**
P. Barale*
B. Benjamine*
R. Benjegerdes
B. Bensiak*
P. Bish*
J. Boehm*
V. Brady**
S. Caspi*
J. Cortella*
S. Dardin*
D. Dell'Orco*
D. Dietderich
B. Ghiorso*

W. Gilbert*
M.A. Green*
M.I. Green*
L. Hawrysiw*
M. Helm*
H. Higley*
E. Hiss**
J. Iler*
R. Lafever*
J. Laslett**
X. Li
A. Lietzke
R. Meuser**
K. Mirk**
J. O'Neill*
R. Oort*

A. Pekedis**
F. Perry*
J. Rechen**
J. Remenarch*
K. Rencher*
J. Royet*
C. Saunders**
R. Scanlan
D. Schafer**
J. Sopher*
D. Thewlis**
N. Twigg*
D. Van Dyke*
H. Van Oort
A. Wandesforde*
J.S. Zelver*

Administrative Support
S. Pereira
J.A. Zelver

Students
C. Brown
K. Etter
S. Eylon
E. Kornblum
P. McManaman
M. Sixta
H. Tsui
C. Wang
N. Wilco*
P. Wong

* Engineering Division
** Retired
* Babcock & Wilcox
† SSC Laboratory
** Contract

SUPERCONDUCTING MAGNETS

Among the highlights was a field-strength record for accelerator-type magnets: just over 10 T in the magnet D19, made with niobium-titanium superconductor.

The 10-T regime, however, appears to be near the practical limit for niobium-titanium. In the push toward 13 T and beyond in accelerator magnets, we are exploring other materials that are not currently as well-proven and economical, but hold the promise of higher fields. They include brittle materials such as niobium-tin, as well as "high-temperature" bismuth-oxide superconductors operated at liquid-helium temperatures.

Innovative approaches are also being taken in ancillary fields. A new method that uses fiber optics to measure strain through optical interferometry is being investigated. Also being developed is an analytical approach that better integrates magnet design and accelerator physics.

The SSC, the largest scientific instrument man has ever attempted to build, entails many technical challenges. Some of the most significant challenges arise from the superconducting magnets. The magnets have to meet exacting specifications for precision and durability. Furthermore, the most-used magnet types, especially those in the main collider rings, must lend themselves to industrial mass production; the pair of 52-mile-circumference collider rings will need more than 10 000 magnets, mostly dipoles and quadrupoles.

Our program at LBL has contributed to both of these types of magnets. In 1989, we resumed work on the quadrupole (focusing) magnet, which had begun in 1987 but had been suspended so that we could concentrate on the dipole. Because the full-scale quadrupoles are only 5 m long (in contrast to the 17-m dipoles), it was feasible to conduct the entire effort in the LBL facilities, including fabrication and testing of prototypes and subsequent transfer of the technology to industry.*

By the end of 1992, we had exhaustively tested all six full-length quadrupole prototypes. The fabrication and testing effort often involved the close cooperation of engineers and technicians from Babcock and Wilcox and from Siemens under the auspices of the Magnet Industrialization Program. They worked alongside their LBL counterparts, beginning in August 1991, to learn how to build and test these magnets.

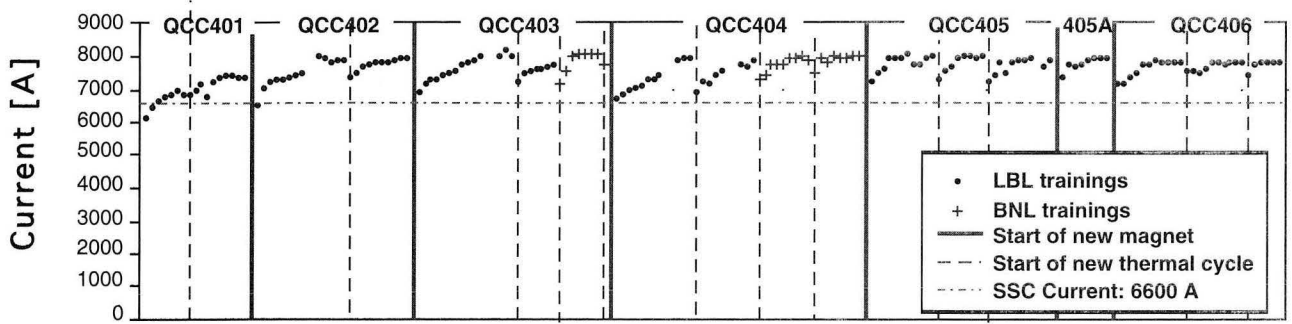
The Magnet Industrialization Program resulted in the transfer of both know-how and manufacturing technology to the Babcock and Wilcox team, which has contracted with the SSC Laboratory to design, build, and test 1-m working models and 5-m prototypes, thereby positioning themselves to bid on mass production later in the SSC project. Our SSC collider-quadrupole effort, except for some probable ongoing consultation and assistance, was thereby successfully concluded.

The results of "training" the six 5-m prototypes are shown in Figure 5-1. The last five fully met the SSC's specification for quadrupole training behavior, which requires that the magnet exceed the operating current of 6560 A by 5%

SSC Magnet Industrialization

Collider Quadrupole Development

* At first, we worked with 1-m functional "models" of the SSC quadrupole as well as the 5-m prototypes. The 1-m models, which are quicker and cheaper to make, were useful for many of our research activities. The Babcock and Wilcox effort will also begin with 1-m models. Our base program of non-SSC magnet research is performed mainly with short dipoles.



XBL 931-4709

Figure 5-1. Training results for full-scale SSC collider quadrupole prototypes show that the desired field (horizontal dashed line) was usually achieved on the second quench or sooner, with subsequent performance well in excess of requirements. QCC 401 was the first "throwaway" prototype; QCC 405 examined a modified yoke. The vertical dashed lines indicate experiment interruptions during which the magnet was brought back up to room temperature.

after no more than three quenches and subsequently reach the operating current without quenching. They achieved 6560 A, corresponding to a field gradient of 211 T/m across the 4-cm bore,* on or before the second quench. After a modest amount of training, they far exceeded the design requirements.

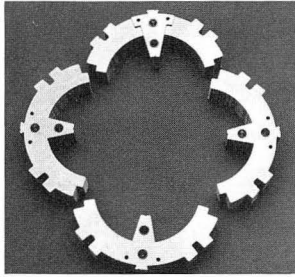
Figure 5-2 shows successive stages in the fabrication of one of these magnets. First, the superconducting cable is formed into the proper shape on a mandrel. For short magnets the cable supply spool and tension control remain stationary while the mandrel revolves. In 1989, for making 5-m magnets, we developed the equipment shown here, in which the mandrel remains stationary while the cable spool travels around in a "racetrack" path. The cable and mandrel are inserted in a precisely machined molding cavity where heat is applied. A heat-activated B-stage epoxy on the windings holds them in place until laminated-metal collars can be installed with a hydraulic press. The result is a low-cost yet rigid structure that maintains the coil positions accurately even under the stress of multi-tesla magnetic fields. Finally, iron yokes and a welded stainless-steel jacket are applied.

Each of these magnets is slightly different, for engineering them is an iterative process. Although physicists and engineers understand quite well how to build adequate magnets of this type, a great many potentially beneficial innovations have yet to be tested. (Now that our SSC work has ended, the final design will be determined by Babcock and Wilcox or other industrial companies that will mass-produce the 1664 collider quadrupoles.) Each magnet—a typical completed unit is shown being inserted in its cryostat in Figure 5-3—incorporates some feature that we think will improve performance, reliability, or manufacturability.

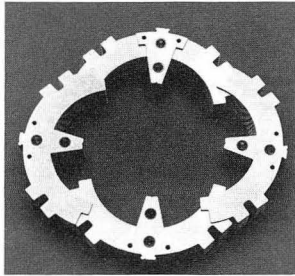
An example is QCC 405. In it, we tried out a different design in which the iron yoke is clamped down onto the pack of interlocking collars, hoping that this would improve the magnet's training behavior—an approach that

* In the original SSC design, all the principal magnets in the main collider lattice had a 4-cm bore. Later, the dipole bore was changed to 5 cm to ensure a sufficient transverse "good-field" region. The concerns were not applicable to the much shorter collider quadrupoles, so there the less costly 4-cm design remains in use.

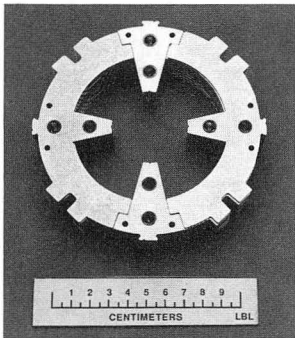
SUPERCONDUCTING MAGNETS



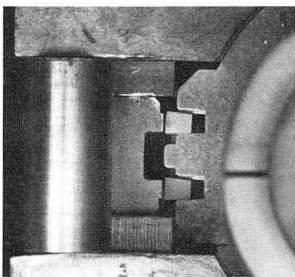
CBB 905-3690



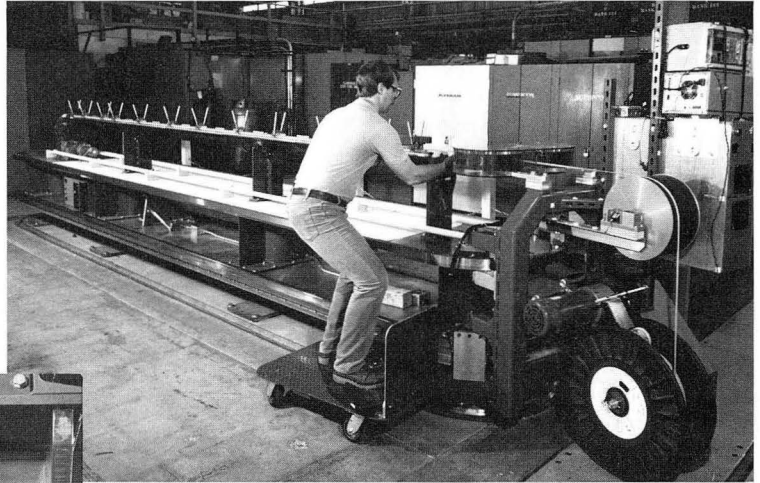
CBB 905-3686



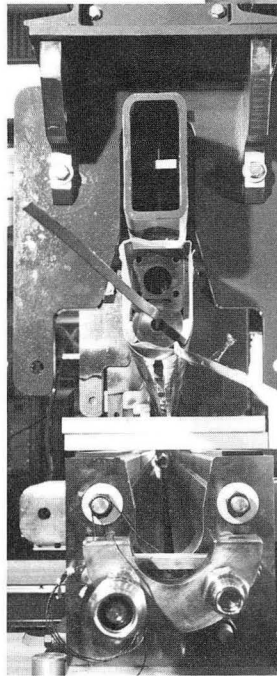
CBB 905-3688



CBB 878-7135

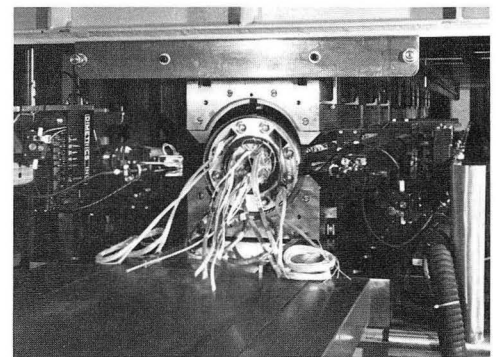


CBB 905-4515

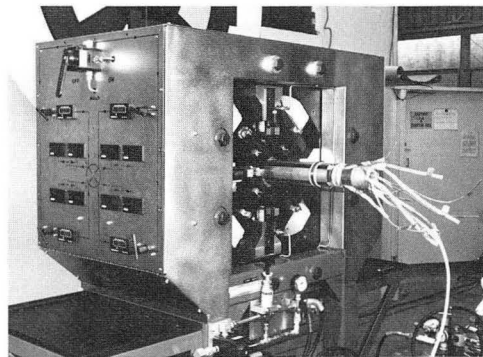


CBB 904-3490

Figure 5-2. Stages in the assembly of a magnet include (counterclockwise from top right) winding the layers of superconducting cable on a mandrel, compressing and heating this assembly inside a precision mold, installing collars, and finally applying and welding the stainless-steel jacket at the outer edge of the cold mass. During magnet collaring, a hydraulic press compresses the collar pack enough for tapered keys to be driven into the slots in the collar as the external pressure is relieved. The collar pack is thus drawn tightly around the coils, resulting in a stable assembly that puts a pressure of several thousand pounds per square inch on the windings. The details at far left show how the parts of the collar pack for a quadrupole fit together.

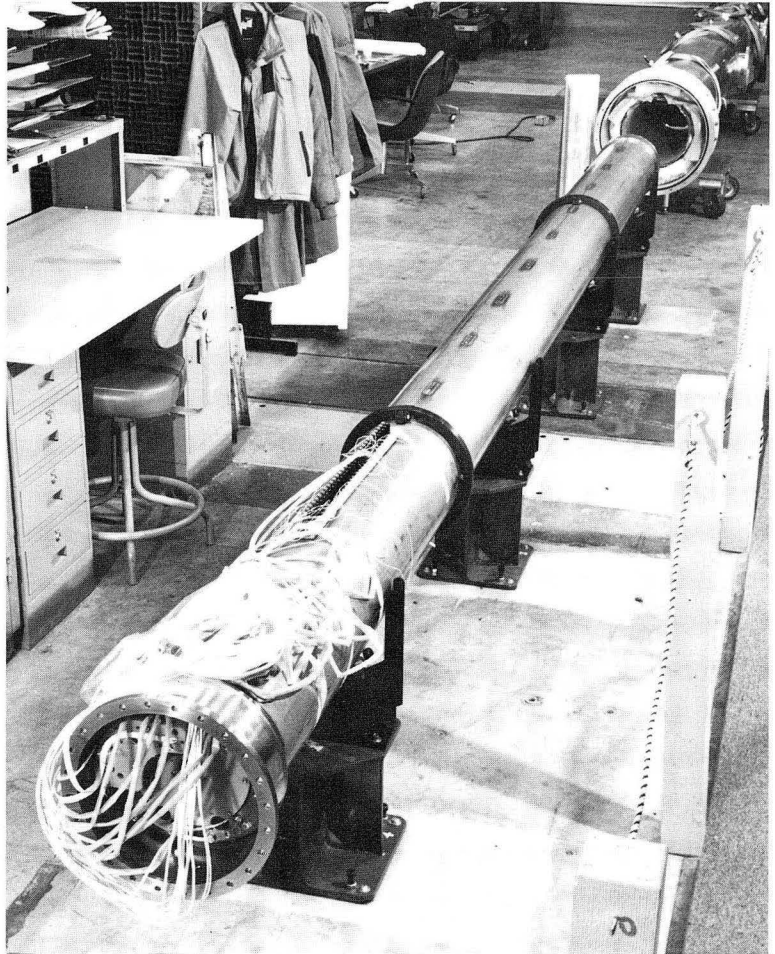


CBB 915-3865



CBB 900-8619

Figure 5-3. A prototype SSC collider quadrupole magnet is inserted in its cryostat for testing.



CBB 913-1209

was originally suggested by the SSC Laboratory for the dipoles. However, the training behavior of the inherently more-rigid quadrupole was improved little, if at all. The lack of substantial improvement in the already-acceptable training behavior suggests that the idea will not be applied to the collider quadrupoles.

After a magnet has been fabricated, it is operated in a cryostat at ever-increasing current until we detect a "quench," which is a rapid heating and consequent loss of superconductivity. Each unit is equipped with extensive instrumentation, such as load cells to measure the forces developed in the windings and voltage taps to pinpoint the origin of quenches. This information can be used to improve design and fabrication in the search for greater reliability and predictability.

In keeping with the highly applied nature of the SSC program, quality assurance and quality control are carried to great lengths. The emphasis begins in engineering, where we strive to create designs and procedures that reduce the need for skilled craftsmanship and the variability it entails. Precision tooling is another key feature. Coils are wound to a uniformity of ± 0.001 to 0.0015 inch (azimuthal) over the 5-m length of each magnet, and similar degrees of reproducibility from one magnet to another are sought. Each of the major manufacturing fixtures—the molding, collaring, skinning,

and yoking presses—is built to close tolerances, and automated, numerically controlled processes are used whenever possible. The result is a final assembly that is true to within ± 0.005 inch in straightness and ± 0.25 milliradian in twist. Each coil is measured at 20 locations along its length, using a semi-automated, numerically controlled measuring machine.

The uniformity of the magnetic field is also measured, as is its purity, or freedom from undesirable higher-order fields. The magnetic measurements are usually made at room temperature, which is much easier; correlations with measurements made in a cryostat show that room-temperature measurements of these parameters provide a good indication of cryogenic performance.

Measurement and documentation are also important factors in quality. Each magnet is made according to standard procedures and is accompanied by a logbook where some 1000 electrical and mechanical measurements are recorded. This kind of information constitutes a knowledge base of normal readings and critical parameters that will be useful during mass production.

“Breaking In” a New Magnet

Nearly all of our tests involve training, the process by which a very strong superconducting electromagnet is brought up to its full capability in several steps. The mechanism of training is not definitively understood. The predominant hypothesis centers on small, unavoidable mechanical instabilities in the windings. When the magnet is first energized, the windings, which are themselves affected by the magnetic field, move slightly as they bed in. This motion, although minuscule, is enough to cause frictional heating, and at liquid-helium temperatures even a small amount of heat can make a small part of the winding go from a superconducting state into a normal, resistive state. Then, at high currents, the entire magnet heats up, or “quenches,” and the energy has to be removed from it quickly. Measures can be taken to control a quench gracefully and avoid ruining the magnet, but a quench in any of the thousands of magnets in an SSC collider ring would halt operation for several hours while the problem was resolved and the ring was reloaded with accelerated protons.

The need for training can be circumvented, or at least greatly reduced, through a procedure called conditioning, which we demonstrated in 1986. To condition a magnet, we temporarily reduce the temperature below the design value, which enables us to increase the current and therefore operate for a time at a higher magnetic field than the magnet was designed for. This results in considerable overpressure; once a magnet has been conditioned, the remaining quench-causing mechanical instabilities will not be triggered by normal operation. Nonetheless, we continue to work with nonconditioned magnets that must be trained; the training behavior of a magnet offers great insight into design and performance, and such detailed knowledge may point the way to building magnets that give their full performance without either training or conditioning.

In 1988, we learned that very small changes in the coil-support structure can cause significant differences in training behavior. For example, when the collars are removed from a trained magnet and then put back around the same coils in even a slightly different fashion, the magnet must be retrained. Thus we can test the influence of changes on training without having to build completely new magnet parts for each test.

The SSC is planning to use conditioning if necessary. However, the last four of our unconditioned SSC collider quadrupole prototypes reached the field strengths required by the SSC without quenching, as have full-length dipole prototypes built at Brookhaven National Laboratory and Fermilab.

Advanced Magnets

Although applied development work for the SSC dominated our activities in recent years, we have continued to investigate other aspects of superconducting-magnet science and technology. The findings will be relevant to accelerators other than the SSC and to superconducting-magnet applications other than accelerators.

These investigations also represent the future of our program as the SSC magnet effort shifts its focus away from laboratories and R&D toward private industry and mass production. Our current and future directions include advances in high-field magnets; specialty magnets such as interaction-region focusing quadrupoles for "particle factory" colliders; and magnets that are stronger, more reliable, and easier to assemble.

D19: A Record-Setting Magnet

To advance the state of the art in magnets and to support our development of superconducting cables and the machines to make them, we build experimental magnets comparable in size and shape to those actually used in accelerators. The aforementioned field-strength record for such magnets of 10.06 T central field (approximately 10.4 T near the conductor) was set using D19, a high-field dipole. Figure 5-4 shows the training behavior of D19 en route to 10 T.

D19 uses the same niobium-titanium cable as the SSC dipole magnets: 30 strands in the inner layer of windings, 36 in the outer layer. The field-record attempts were made at 1.8 K, with a current of about 9.4 kA. It reached the

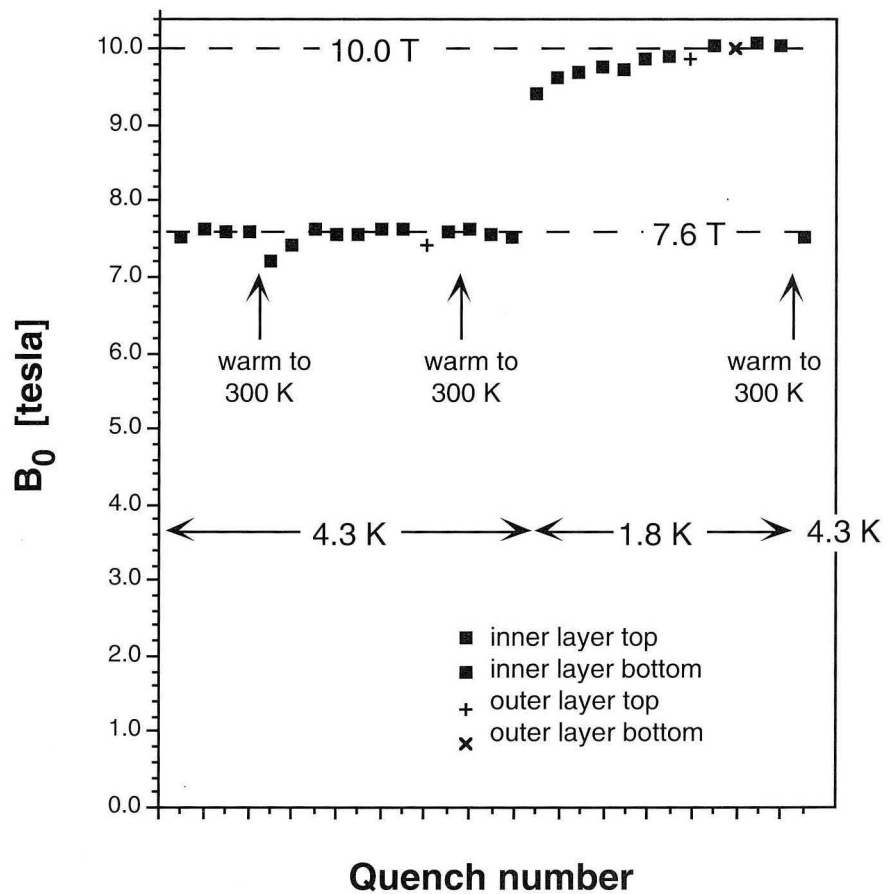
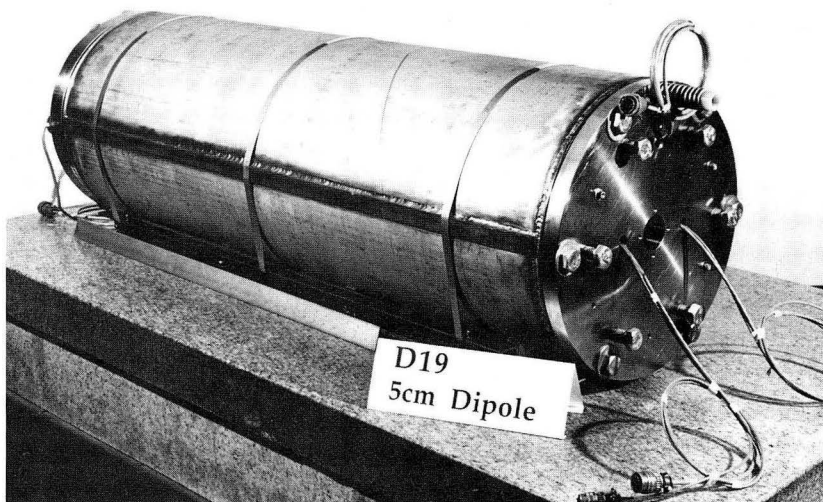


Figure 5-4. This graph shows the training behavior of dipole D19 on its way to an ultimate field of 10.06 T in the middle of the bore—a record for accelerator-type magnets.

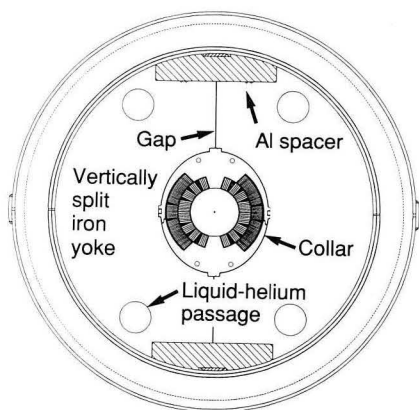
SUPERCONDUCTING MAGNETS

SSC dipole field of 6.6 T at 5.8 kA and 4.3 K. This is considerably better efficiency than could be obtained from an earlier design such as the SSC collider dipole, which requires 6.6 kA, also at 4.3 K, to produce the same field.* The cross section in Figure 5-5 reveals the noncircular inner profile of the iron yoke. This shape, an existing idea not previously applied to accelerator-type magnets, maximizes the magnetic-field contribution of the iron while keeping high-field saturation effects down to reasonable levels.

Currently in the works is D19B, a follow-on project using the same design but incorporating superconductor that has artificial flux-pinning centers for higher critical current.



CBB 921-248



XBL 9112-6875

Figure 5-5. Dipole D19, the 10-T magnet, is more efficient than the similar SSC magnets because of the noncircular inner profile of the iron yoke. This shape maximizes the magnetic-field contribution of the iron while keeping high-field saturation effects down to manageable levels. Another interesting feature is the vertically split iron yoke with aluminum-alloy spacers between the halves. The spacers maintain a predetermined gap between the halves at room temperature but allows them to shrink together tightly at cryogenic temperatures. This maintains the high compressive load on the coils and prevents the windings from shrinking faster than the iron yoke during cooldown. Such differential contraction would relieve the compression of the windings and thus undo the "training" process that allows the ultimate magnetic field to be reached.

* A large, high-technology apparatus that must be completed in a timely manner, be it an aircraft, supercomputer, or accelerator, cannot necessarily incorporate all the latest innovations. As improvements are invented, the advantages they offer must be weighed against schedules and budgets, a rule that has become more and more stringent as the project progresses and components go into mass production.

D20: The Push Beyond 10 T

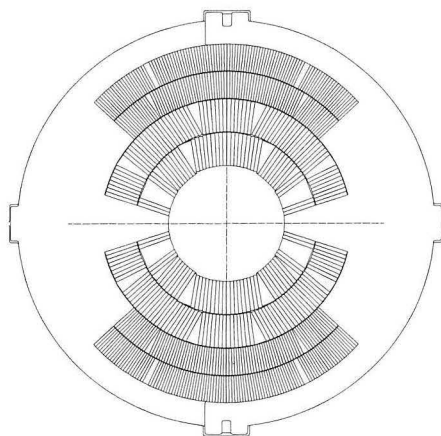
Another advanced magnet, D20, is now being designed. It will press through the 10-T barrier (and hopefully well beyond) by using niobium-tin superconductor. The goal of D20 is a “short-sample” field of about 13 T at 1.8 K. (The short-sample field represents the maximum performance of the superconducting cable and is determined by measuring the conductivity of a short sample in an external magnetic field. An actual magnet incorporating the cable might, if designed and constructed well, approach the short-sample limit near the edge of the aperture, where the field is strongest.)

The effort to reach beyond 10 T in accelerator-type magnets presents a number of challenges above and beyond magnetic design. Mechanical stresses become far greater than those in the SSC magnets, for example. This can have a variety of adverse effects. In its most severe form, the strain can distort the magnet. It can also cause the small movements of the cable that lead to quenches, and can reduce the critical current of the superconductor (an effect that we are investigating).

Most importantly, Nb_3Sn in its finished, superconducting form is much more brittle than the widely used NbTi and cannot be wound into cable. Instead, cable containing the ingredients is wound onto magnet forms and then heated to 700 °C to make the ingredients react (which also causes embrittlement). This magnet-making procedure is essentially a new technology, and an important one, since all of the other materials potentially useful for these high-field magnets also require heating after winding. (Ductile “ternary,” or three-part, compounds like NbTiTa might offer small improvements over NbTi, but the high-field frontier clearly belongs to brittle superconductors. The brittle compounds, at least theoretically, hold the potential for current densities four or five times greater than that of NbTi.) Therefore the techniques developed for D20 will be widely applicable to future R&D. D20 is diagrammed in Figure 5-6. Although intended solely as an Nb_3Sn “trial horse,” it has many characteristics generically applicable to future hadron colliders. These characteristics include the high field itself (which would permit higher energies and/or more-compact layouts) and an iron flux-return yoke that could accommodate twin bores. Twin bores might

prove more economical than the approach used in the SSC and present-day colliders, in which, variously, two beams rotate in opposite directions through the same pipe or two pipes run through separate lattices of magnets.

Figure 5-6. With dipole D20, we will use Nb_3Sn superconductor in the push toward field strengths previously unachievable in accelerator-type magnets. Two layers of superconducting cable—47 strands in the outer layers, 37 in the inner layers—will be wound in a double-pancake configuration. The mechanical design is similar to that of D19. However, because Nb_3Sn is embrittled by the heat treatment that makes it superconducting, we will have to anneal the cable after winding. The goal of D20 is 13 T, representing a short-sample limit for the Nb_3Sn material of about 13.3 T.



XBL 9211-5829

Although our program grew up alongside high-energy physics and is strongly oriented toward service to the accelerator community, there are many other applications for high-field superconducting magnets. One of them is the field of nuclear magnetic resonance (NMR) and magnetic-resonance imaging (MRI).^{*} We are exploring a cooperative project with Wang NMR of Livermore, CA and the Bitter National Magnet Laboratory at the Massachusetts Institute of Technology to develop the conductor for a gigahertz NMR spectrometer. This proton spectrometer would be part of the Molecular Science Research Center, an initiative proposed by Pacific Northwest Laboratory, and would be especially well suited to studying the large molecules and systems of molecules that are of interest to biologists. The spectrometer design requires a large 23.5-T magnet.^{**}

As part of a “vertically integrated” approach to superconducting magnet R&D, we conduct a diverse program of investigations in superconducting materials. Current projects explore artificial pinning center (APC) materials and investigate still-embryonic but promising applications of high-T_c superconductors. Other projects include a novel interferometric method of measuring strain in magnets; it uses optical fiber not in its conventional role as a “light pipe” for imaging, but rather as a physical sensor. We are also embarking upon an innovative approach to the design of magnets that better integrates this process with the methods and conventions used for beam-dynamics calculations by accelerator physicists.

As we look toward the future of superconducting-magnet development, we realize that materials-science research plays a key role in achieving higher, more-uniform, and more-predictable magnetic fields. A promising recent line of inquiry involves the APC concept. In APC superconductors, the random distribution of pinning centers, which ordinarily arise from precipitation, is replaced with a more-precise distribution that matches the magnetic fluxoid lattice for a given field strength.

A fluxoid is the site of one quantum of magnetic effect and may be thought of as the place where a line of magnetic flux penetrates the superconducting wire. Ordinarily, fluxoids can move through the superconductor in response to an applied magnetic field, and energy is dissipated. In artificial flux pinning, a material (niobium in the case of our niobium-titanium wire) is introduced as a normal-conducting phase in the superconducting material. The flux lines are localized to these regions. Artificial flux pinning allows some measure of control over the final microstructure of the superconducting material—an intrinsic characteristic that cannot be altered

^{*} Generally speaking, NMR refers to the nonimaging scientific tool and to the underlying physical principle, whereas MRI refers to the imaging technique used for applications such as medical diagnosis.

^{**} Note that the 10-T record mentioned earlier was for an accelerator-type magnet. The magnets for high-energy accelerators must exert their field over a considerable length in order to bend or focus the extremely “rigid” particle beam, and the field must be extremely homogeneous. Their design is also constrained by many mechanical and economic factors. NMR magnets, although challenging in their own way, are much different physically, so the apparent tremendous leap from 10 T in accelerator magnets to 23.5 T in this project is misleading.

Nonaccelerator
Applications

Advanced
Materials and
Design Techniques

APC Materials
Development

by the way the superconducting material is formed into wires. (The significant intrinsic factors are filament microstructure and composition. Extrinsic factors, such as the cross-sectional area, integrity, and uniformity of the superconductor, are also important.) Figure 5-7 illustrates this principle.

The ultimate application of this research is to enable the fabrication of multifilamentary superconducting wire that has higher critical-current density (J_c) and is more economical to produce. We are examining niobium distribution and pinning strength as key intrinsic factors that may offer opportunities for further understanding and progress. We are also working with several industrial companies on ways of producing APC superconductor by the strictly mechanical means of cold-working, rather than the time-consuming and expensive heat-treatment technique that is used today.

In 1991 and 1992 we studied two such approaches, selecting one proposed by Supercon, Inc., that improves the high-field performance of the APC superconductor and also promises to reduce the cost of the material. Microstructural examination of the wire (Figure 5-8) showed that it had a uniform structure despite a local area ratio (copper matrix to superconductor filaments) of about 0.6. Such a low ratio would have caused "sausaging" with conventional manufacturing techniques. It is desirable to make this ratio as low as possible to increase the J_c of the wire. (Superconducting magnets retain the desired electrical properties only up to a certain critical

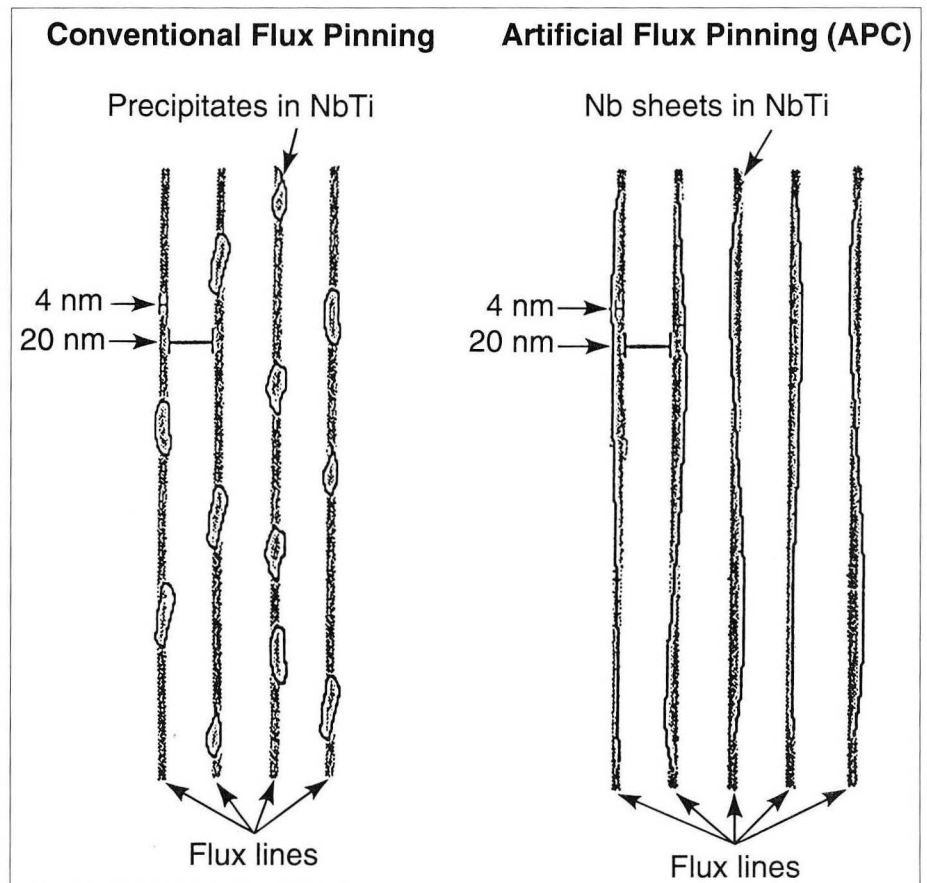
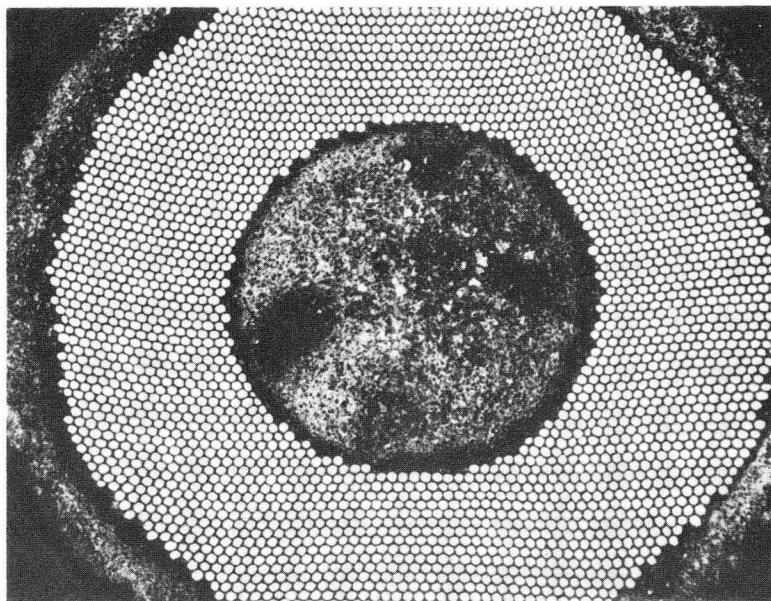


Figure 5-7. In conventional flux pinning (*left*) the fluxoids are localized at the randomly distributed points where precipitates were formed by heat treatment. (These sites are elongated, as shown here, when the material is drawn into wire.) In artificial flux pinning, normal-conducting metal sheets are interleaved with the superconductor in the manufacturing process and drawn down to nanometer scale. This provides better matching between the pinning sites and the flux lines. It also obviates the formation of pinning centers as a reason for heat treatment.

XBL 9211-5830

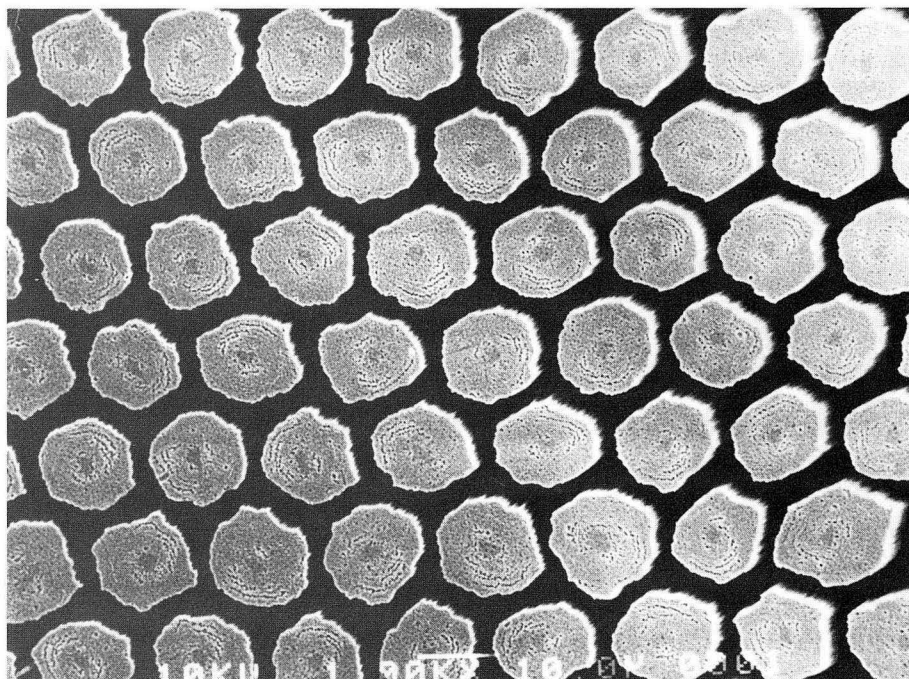


XBB 921-30

Figure 5-8. APC wire produced by Supercon, Inc. with a proprietary process showed a uniform structure despite a local area ratio (copper matrix to superconductor filaments) of about 0.6. Such a low ratio would have caused "sausaging" with conventional manufacturing techniques. It is desirable to make this ratio as low as possible to increase the critical current density. The whole wire is shown at *top*, an electron photomicrograph of the filaments at *bottom*.

current; above that level, they regress to ordinary conduction. Current density, temperature, and magnetic field interact in this regard; the superconducting regime is often graphed along three axes and referred to as the " J_c , T_c , B_c surface." Field and current density can be limited by fundamental properties of the superconductor.) Increased J_c allows the use of smaller, cheaper cable or, alternately, the achievement of higher fields.

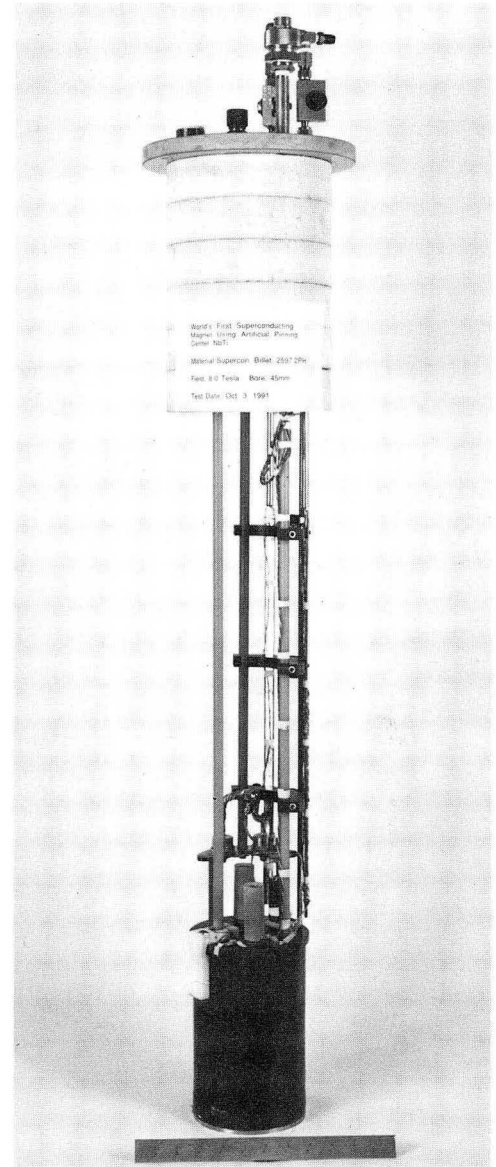
The solenoid shown in Figure 5-9 allowed a simple test of this wire; it achieved an 8.5-T magnetic field across its 45-mm bore diameter at



XBB 928-6094

4.2 K. The solenoid was built with NbTi APC wire made by Supercon, Inc., under contract to LBL. The 8.5-T field has been achieved not only in a continually driven mode, but also in a persistent-current mode. In persistent-current mode, the coil is cut off from the power supply after being energized and the leads are shorted with a piece of superconductor, so a supercurrent circulates through it almost indefinitely. (This effect should not be confused with the undesirable, small-scale persistent eddy currents that can occur when the field strength is varied at low field and current.) This test provides an important confirmation of the uniformity of the APC wire.

Figure 5-9. This 8-T solenoid was built as a simple test of the new wire from Supercon, Inc., shown in Figure 5-8. Tests with persistent current (continuing circulation of a current after the power supply was disconnected) provided an important confirmation of the uniformity of the APC wire. As a result of this successful demonstration, we have ordered enough of the APC wire to fabricate cable and build a 1-m-long dipole, D19B, that will give us further information on the performance, reliability, and cost-effectiveness of this type of material.



CBB 910-8236

As a result of this successful demonstration, we ordered enough of the wire to fabricate cable and build D19B. Testing this 1-m-long dipole magnet will give us further information on the performance, reliability, and cost-effectiveness of APC material, which is needed to realize the full potential of NbTi and may prove useful in Nb₃Sn and other brittle superconductors as well.

High- T_c Superconductor at Low Temperature

Although nearly all the emphasis in the program has been placed on traditional Bardeen-Cooper-Shockley superconductivity, we also have a promising investigation into so-called high- T_c superconductors. These materials, which we actually use at liquid-helium temperatures in order to achieve high magnetic fields, might someday be useful for accelerator and other magnets.

However, many challenges will have to be overcome in order to turn them into useful engineering materials for devices such as accelerator magnets that must withstand great stress or must be built up into complicated shapes.

In an effort currently funded with Laboratory Directed Research and Development monies (and interesting to at least one potential industrial partner), we are examining phase equilibria and microstructural texture in thick films of the bismuth oxide (BiSrCaCuO) family of compounds. In particular, we are studying ways of creating and preserving an aligned microstructure in the $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_2$ or "2212" phase throughout the phase transformations that occur during processing, both within the bismuth-oxide compound and between it and its silver substrate. Earlier work indicated a J_c of greater than 1000 A/mm^2 for 2212 bismuth-oxide material. This figure seems to be on the same order as the J_c of NbTi conductor (albeit at a low magnetic field), though the sample was too small for incorporation in a coil. Whether formed into tapes for windings or deposited onto surfaces as a coating (e.g., for superconducting rf cavities in accelerators), high- T_c compounds represent a promising area of development.

A longtime goal of our superconductor R&D program has been to develop improved techniques and tooling for the fabrication of Rutherford-style cable. The R&D cabling machine we developed to meet the needs of the SSC, and which is now available in a commercial version, continues to serve our R&D needs. In 1991 we upgraded it with a new spool and Turk's-head so that it could fabricate cables with as many as 48 strands of superconducting wire. With this new equipment, we have been able to fabricate cables that are 30% wider and contain 25% more strands than the cable we developed in the late 1980s for the SSC dipole magnets. In addition to furthering cable manufacturing, this upgrade has provided our magnet designers with additional flexibility in their choice of superconducting materials and cable designs.

The easy in-house availability of this machine, along with the expert assistance of its operators, has paved the way for innovative materials experiments. For example, we will use it to make the 48-strand Nb_3Sn cable for D20; the cable can be made in the usual fashion because the wire is ductile. Later, after magnet winding, it is heat-reacted in place; this coincidentally makes it brittle.

In the attempt to better integrate two quite different fields that depend on one another, we are exploring an analytical approach to magnetic design. The goal is to use the same notation that is common in beam dynamics, expressing the three-dimensional fields produced by electromagnetic lenses in terms of a single function $A_n(Z)$ and its derivatives. Thus far, by applying the Biot-Savart law and using both a differential algebra package developed in part at LBL and a numerical method, we have achieved success in three-dimensional modeling of magnetic fields. A longer-term goal is to extend this technique to guide accurate conductor placement and to use simulation codes to study the resulting particle motion.

Cable and Cabling-
Machine Development

Analytical Magnet
Design

Publications and Presentations

- P. Barale, "Quadrupole centering correction," abstract accepted for the International Industrial Symposium on the Super Collider (San Francisco, CA, 1993); LBL-33012a (1992).
- S. Caspi, "An approach to 3D magnetic field calculations using numerical and differential algebra methods," LBL-32624 (1992).
- S. Caspi, "Non-linear beam dynamics," Spring Meeting of the American Physical Society (Washington, DC, 1992); LBL-31719a (1992).
- J. Cortella, "Mechanical performance of full-scale prototype quadrupole magnets for the SSC," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32788 (1992).
- D. Dell'Orco, "A 50 mm bore superconducting dipole with a unique iron yoke structure," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32071 (1992).
- D. Dell'Orco, "Design of the Nb₃Sn 13 T dipole D20," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32072a (1992).
- D. Dietderich, "Noble metals and Bi₂Sr₂Ca₁Cu₂O_x," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32104a (1992).
- D. Dietderich, "Nucleation and growth of Bi₂Sr₂Ca₁Cu₂O_x in textured thick films," Materials Research Society (Boston, MA, 1992); LBL-32635a (1992).
- M.A. Green, "UCLA Phi Factory detector, the integration of superconducting compensation solenoids and the final focus interaction region quadrupoles," International Cryogenic Engineering Conference (Kiev, Ukraine, 1992); LBL-32635 (1992).
- A. Lietzke, "Quadrupole magnet for the SSC," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32790 (1992).
- A. Lietzke, "SSC quadrupole magnet performance at LBL," abstract accepted for the International Industrial Symposium on the Super Collider (San Francisco, CA, 1993); LBL-33002a (1992).
- J. Royet, "Recent developments in cabling technology used to manufacture superconducting accelerator magnets," LBL-32069a (1992).
- R. Scanlan, "Characterization & coil test results for a multifilamentary NbTi conductor utilizing artificial pinning center technology," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32074 (1992).
- C. Taylor, "Construction and test results on 40 mm bore 5 m long quadrupole magnets for the SSC," LBL-32074a (1992).
- J. van Oort, "A fiber-optic strain-gauge with absolute readout using the strain-dependent frequency-shift of the transmission spectrum of a fused biconical tapered 2x2 coupler," LBL-32623a (1992).
- J. van Oort, "A superconducting pressure test-station for material property tests at 4.2 K," LBL-32620a (1992).
- J. van Oort, "An absolute fiber-optic strain gauge using white-light interferometry of an extrinsic fiber-optic Fabry-Perot cavity," LBL-32622a (1992).
- J.M. van Oort, "The application of extrinsic Fabry-Perot fiber-optic strain sensors in accelerator dipole magnets," LBL-32184a (1992).
- J. van Oort, "The design of a 13 T, Nb₃Sn, 1 m model dipole using a window-frame coil layout," LBL-32621a (1992).
- J. van Oort, "The reduction of the critical current in Nb₃Sn cables under transverse loads," Applied Superconductivity Conference (Chicago, IL, 1992); LBL-32070 (1992).

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720

ABH279

LBL Libraries