High-field superconductivity

Rapid strides in the development of composite superconducting materials have encouraged the widespread use of high-field superconducting magnets in high-energy physics, fusion and medical imaging—fulfilling Kamerlingh Onnes's 75-year-old vision.

David Larbalestier, Gene Fisk, Bruce Montgomery and David Hawksworth

One does not often read original research communications that are 50 or 75 years old. Preparing an article to commemorate the 75th anniversary of the discovery of superconductivity seemed to be an appropriate occasion for reading some of Heike Kamerlingh Onnes's original articles. Two years after his discovery, Onnes made a report to the third International Conference of Refrigeration in 1913. He reviewed the recent research of his Leiden group. This article is quite astonishing, and only extensive quotations can convey the breadth of Onnes's conception of the possibilities of the superconducting state. Onnes commences his description of the superconducting state by describing his initial 1911 experiments on mercury, but he proceeds rapidly to sketch whole segments of the technology of superconducting magnets:

> Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state.... The behavior of metals in this state gives rise to new fundamental questions as to the mechanism of electrical conductivity.
>
> It is therefore of great importance that tin and lead were found to become superconductive also. Tin has its step-down point at 3.8 K, a somewhat lower temperature than the vanishing point of mercury. The vanishing point of lead may be put at 6 K. Tin and lead being easily workable metals, we can now contemplate all kinds of electrical experiments with apparatus without resistance....
>
> The extraordinary character of this state can be well elucidated by its bearing on the problem of producing intense magnetic fields with the aid of coils without iron cores. Theoretically it will be possible to obtain a field as intense as we wish by arranging a sufficient number of ampere windings round the space where the field has to be established. This is the idea of Perrin, who made the suggestion of a field of 100 000 gauss being produced over a fairly large space in this way. He pointed out that by cooling the coil by liquid air the resistance of the coil... could be diminished.... To get a field of 100 000 gauss in a coil with an internal space of 1 cm radius, with copper cooled by liquid air, 100 kilowatt would be necessary.... The electric supply, as Fabry remarks, would give no real difficulty, but it would arise from the development of Joule-heat in the small volume of coil... to the amount of 25 kilogram-calories per second, which in order to be carried off by evaporation of liquid air would require... about 1500 liters of liquid air per hour....
>
> But the greatest difficulty, as Fabry points out, resides in the impossibility of making the small coil give off the relatively enormous quantity of Joule-heat to the liquefied gas. The dimensions of the coil to make the cooling possible must be much larger, by which at the same time the electric work and the amount of liquefied gas required becomes greater in the same proportion. The cost of carrying out Perrin's plan even with liquid air might be about comparable to that of building a cruiser....
>
> We should no more get a solution by cooling with liquid helium as long as the coil does not become superconductive.
>
> The problem which seems hopeless in this way enters a quite new phase when a superconductive wire can be used. Joule-heat comes not more into play, not even at very high current densities, and an exceedingly great number of ampere windings can be located in a very small space without in such a coil heat being developed. A current of 1000 amps/mm^2 density was sent through a mercury wire, and of 460 amps/mm^2 density through a lead wire, without appreciable heat being developed in either....
>
> There remains of course the possibility that a resistance is developed in the superconductor by the magnetic field. If this were the case, the Joule heat... would have to be withdrawn. One of the first things to be investigated... at helium-temperatures... will be this magnetic resistance. We shall see that it plays no role for fields below say 1000 gauss.
>
> The insulation of the wire was obtained by putting silk between the windings, which being soaked by the liquid helium brought the windings as much as possible into contact with the bath. The coil proved to bear a current of 0.8 ampere without losing its superconductivity. There may have been bad places in the wire, where heat was developed which could not be withdrawn and which locally warmed the wire above the vanishing point of resistance....
>
> I think it will be possible to come to a higher current density... if we secure better heat conduction from the bad places in the wire to the liquid helium.... In a coil of bare lead wire wound on a copper tube the current will take its way, when the whole is cooled to 1.5 K, practically exclusively through the windings of the superconductor. If

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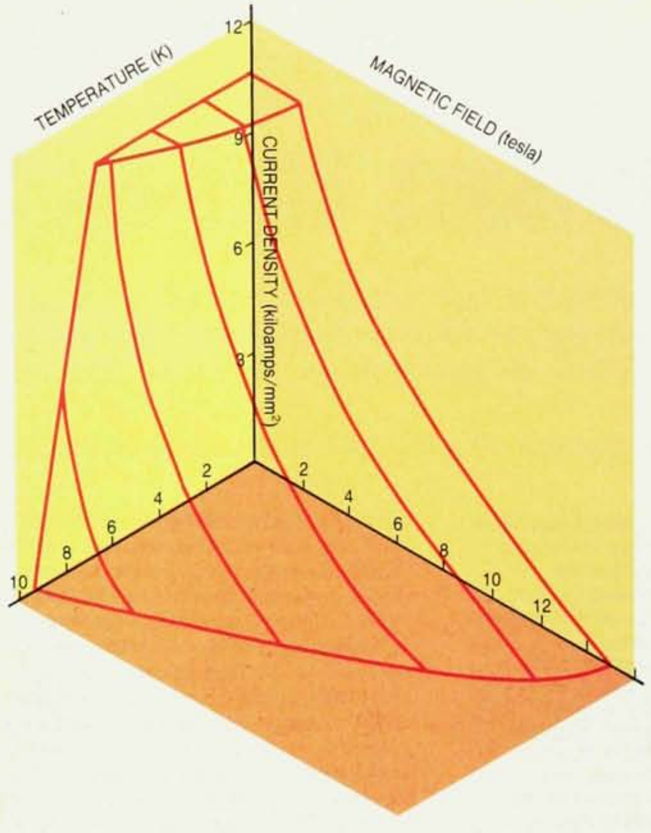
Magnetic resonance imaging for medical diagnosis has produced the first large-scale commercial market for superconducting devices. Clinical MRI systems require high-intensity magnetic fields of rigorous uniformity over dimensions on the order of a meter. These clinical images are a frontal section of an abdomen (top) and two sections of a head. Figure 1

> the projected contrivance succeeds and the current through the coil can be brought to 8 amperes . . . we shall approach to a field of 10 000 gauss. The solution of the problem of obtaining a field of 100 000 gauss could then be obtained by a coil of say 30 centimeters in diameter and the cooling with helium would require a plant which could be realized in Leiden with a relatively modest financial support. . . . When all outstanding questions will have been studied and all difficulties overcome, the miniature coil referred to may prove to be the prototype of magnetic coils without iron, by which in future much stronger and . . . more extensive fields may be realized than are at present reached in the interferrum of the strongest electromagnets. As we may trust in an accelerated development of experimental science this future ought not to be far away.

What a description! So many of the points described in the present article were sketched out by Onnes already in 1913. The conception of powerful magnets, the problem of heat removal from compact windings, the attractive economic feasibility of superconducting, as opposed to resistive, magnets, operation at current densities of 1000 amps/mm^2 and temperatures down to 1.5 K—all of these are crucial aspects of our present technology. Elsewhere in the same article, Onnes describes the melting of superconducting wires following an abrupt transition from the superconducting to the normal state, and he perhaps prefigures modern composite conductors by considering the properties of a resistive constantan wire coated with a superconducting layer of tin.

It is perhaps only the last sentence quoted that strikes a false note. High-field superconducting magnets remained unbuilt until the 1960s, and it is only in the last 10 or 15 years that the



Superconductivity exists only below a critical surface defining maximum tolerable temperature, current density and magnetic field intensity in *TJB* space. Only type-II superconductors have critical fields high enough for use in high-field magnets. This critical surface for a commercial niobium–titanium alloy, for example, shows that its superconductivity will persist at liquid-helium temperature in a 5-tesla field at current densities exceeding 3 kiloamps/mm^2. Figure 2

technology has progressed to the reliable construction of high-field magnets. Onnes described a major obstacle only in a footnote—namely that superconductivity was destroyed in lead wires at a magnetic field intensity of about 60 millitesla (600 gauss) instead of the hoped-for 10 T. As we now understand well on the basis of the Ginzburg–Landau–Abrikosov–Gorkov theory, superconductors fall into two classes. The pure elements, with which Onnes first worked, all have critical fields H_c less than 100 mT. Only after Eugene Kunzler's 1958 discovery of high-field superconductivity at 8.8 T in Nb_3Sn was the dream of constructing high-field magnets rekindled.

Much of the R&D necessary to develop superconducting composites suitable for high-field magnets was carried out under the pressure of the worldwide high-energy-physics community's continuing drive for ever more powerful accelerators, as exemplified by the Tevatron at Fermilab and the planned mammoth Superconducting Super Collider. During the 1970s, the world fusion community designed and began to construct enormous superconducting magnets, and in the early 1980s a major new market developed with the introduction of magnetic-resonance imaging devices for medical diagnosis (figure 1). After discussing the development of high-field superconducting materials, we will return to the present state of these applications.

The impossibility of realizing Onnes's dream with lead is clearly brought out by a consideration of figure 2 and the table on page 30. Superconductivity exists behind a surface defined by a critical field H_c or H_{c2}, a critical temperature T_c and a critical current density J_c. Type-I superconductors, which exclude flux from their interiors, all have critical fields below 0.1 T. However, type-II superconductors, which allow flux to penetrate in quantum "fluxoids," can have critical fields as high as 60 T. (See introduction by Michael Tinkham, page 22). It is to this latter class of materials (see the table) that high-field superconductivity must turn.

While T_c, H_c and H_{c2} are relatively fixed parameters for alloys or compounds of given composition, J_c is extremely structure sensitive, its value varying over three to four orders of magnitude—from 1 to 10^5 amps/mm^2—depending on the defect microstructure of the material.

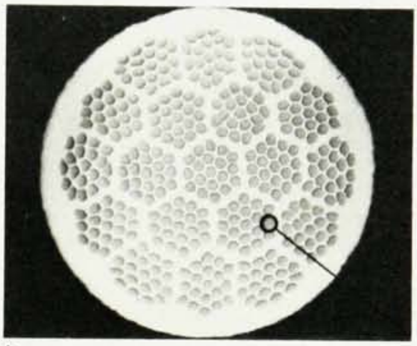
Superconducting composites

Discovery of a suitable high-field superconductor is only one step along the path to a conductor suitable for the construction of a high-field magnet. The multiple and sometimes conflicting requirements that the magnet conductor must fulfill dictate many aspects of the magnet design, as we shall see. What are some of these requirements?

High critical current density J_c is important for achieving efficient use of space and raw material. (Superconducting composites cost about $100 a pound.) Values of J_c typically range from 500 to 5000 amps/mm^2, lower values being obtained at higher magnetic fields. To obtain such high values of current density requires that the microstructure support a fluxoid gradient against the Lorentz force of the magnetic field, and this can only be achieved by pinning the fluxoids at microstructural heterogeneities. Very sophisticated processing sequences are used to develop such microstructures, as one can see in the transmission electron micrograph of figure 3a. The microstructure of the Nb–Ti composite shown here has two phases; normal particles of α-Ti less than 5 nm thick attract the normal cores of the fluxoids, pinning them. The high density of the particles, produced by special metallurgical treatments, can produce values of J_c as high as 3500 amps/mm^2 at 5 T; such a large value of J_c is highly desirable, for example, for the magnets of the proposed Superconducting Super Collider. Flux pinning is most effective when the pinning centers have dimensions and separations on the order of one to five superconducting coherence lengths, that is, approximately 5 to 25 nm or less for all high-field superconductors. Microstructures of the compounds shown in the table are generally simpler than that in the micrograph of figure 3. The microstructural feature responsible for flux pinning is the grain boundary; thus one needs very fine grain sizes (100 nm or less). Low-temperature solid-state diffusion can sometimes provide this. Various new rapid-quenching techniques can produce grain sizes of less than 50 nm in compounds such as Nb_3Al. High-field superconductors have structural subdivision on a real microscale!

The Lorentz force of the magnetic field exerts large macroscopic stresses on the windings. These stresses must be supported by the conductor itself or be transmitted to a support structure.

a



b

Composite superconductor (right) consisting of 15-micron-diameter Nb–Ti filaments embedded in a copper matrix. In the high-resolution micrograph (top, 600 nm across), the light ribbon-shaped features in the Nb–Ti are microscopic precipitates of normally conducting α-titanium, which serve to pin the quantized fluxoids of the magnetic field. At 5 tesla, these fluxoids seek to form a regular array with a spacing of about 20 nm. Achieving superconducting composites with high critical currents requires sophisticated processing that produces a high density of such pinning centers. (Micrograph by P. J. Lee) Figure 3

Such stresses store large amounts of mechanical energy, and small fractions of this energy are continually being dissipated in the superconducting windings as the field is varied. Because of the very small enthalpies of solids at helium temperatures, such energies can provoke local transitions to normal resistance, which, if left unchecked, will provoke a "quench"—a coil-wide transition to the normal state.

The conductor must therefore also provide stabilization against harmful energy inputs that might provoke a quench. Such inputs fall into three classes. First among these are the electromagnetic disturbances associated with the magnetic field gradient in the conductor—the supercurrents themselves. The field gradient entails an energy difference $\Delta B^2/2\mu_0$ per unit volume between inside and outside, where ΔB is proportional to the product of the critical current and the depth to which the current flows. This yields an expression for the energy difference proportional to the conductor radius squared. Roughly speaking, the conductor can be protected against the collapse of the flux front (a "flux jump") if the stored energy of the current is less than the enthalpy change the conductor undergoes as it changes from its operating temperature to T_c. This is the rationale for subdividing the cross section of a superconductor wire into many fine filaments—as shown in figure 3b.

The simplest form of superconducting conductor is one in which many filaments with diameters on the order of 10 microns are embedded in a high-conductivity copper matrix. The copper has multiple functions: It is a good thermal conductor, transferring heat produced by local energy release to the cooling medium and minimizing Joule heating under conditions where the superconductor is temporarily above T_c. It also protects against the meltdown noted by Onnes during a quench. Indeed the ratio of the copper to the superconductor cross section must be chosen to provide such protection, and this is generally the limiting factor in large-magnet design.

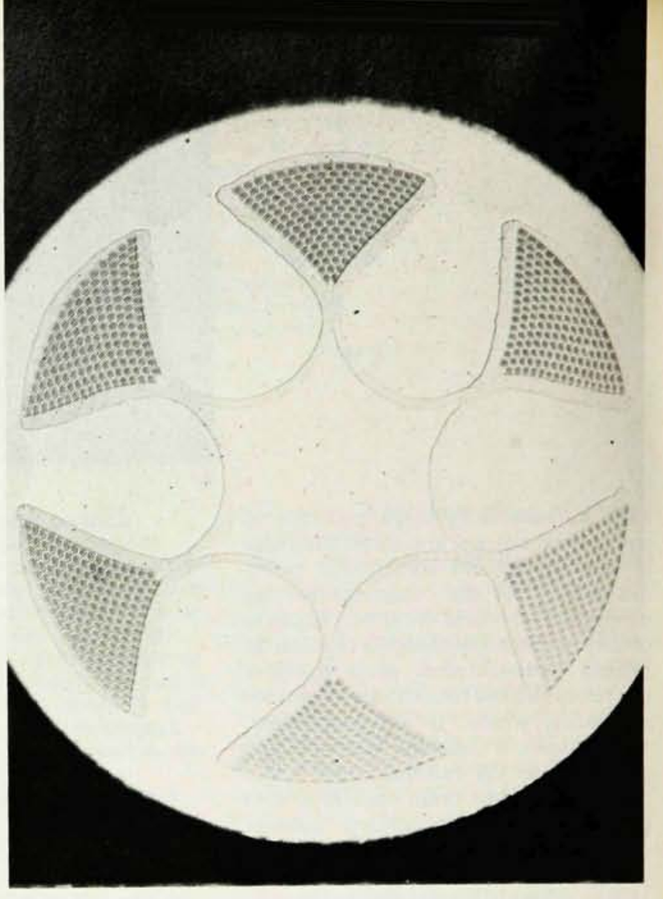
In the design of a superconducting composite conductor one must also consider the response of the conductor to a changing magnetic field. Even magnets designed for dc operation must be charged and discharged. Under these conditions, the flux change couples the individual filaments back into one large filament by providing the voltage necessary to drive coupling currents across the matrix. The solution to the problem—and the development of the intrinsically stable conductors from which virtually all superconducting magnets are wound nowadays—was provided in the late 1960s by Peter Smith, Martin Wilson and their colleagues at the Rutherford Laboratory. Twisting a conductor about its axis causes the voltage between any pair of filaments to reverse periodically, greatly limiting the cross-matrix current. For fast-ramping magnets the twist pitch must be tight and the transverse resistivity of the matrix must be greatly increased over that of pure copper. Figure 4 shows a particularly elegant solution. This "tulip" conductor has resistive barriers of cupro-nickel separating one filament from another, as well as barriers that break up the large center region of copper required to prevent magnet burnout.

Magnets for high-energy physics

In the early 1960s, as physicists perfected visual techniques for finding new particles by measuring the curvature of tracks in bubble-chamber magnetic fields, the development of superconducting magnets was in its formative stages. As particle momenta increased, higher fields and larger chamber volumes became desirable. The promise of higher-field magnets and the fact that superconducting magnets and bubble chambers both required cryogenic systems led to their integrated development. The first example of such an integrated system, now on view at the Smithsonian Institution, was the 10-inch liquid-helium bubble chamber and superconducting magnet developed jointly by Argonne and Carnegie Tech. This was followed by much larger efforts, culminating in the Fermilab 15-foot bubble chamber and the Big European Bubble Chamber at CERN in the early 1970s. These magnets and their modern counterparts, the large solenoids (with volumes approaching 200 m^3) that are used as momentum analyzers in colliding-beam experiments, are made from Nb–Ti superconductors stabilized in copper or aluminum. In general they are operated at full field over long periods of time, and they can be charged slowly to their top field level without concern over ac loss or flux jumping. At Fermilab there are several superconducting spectrometers, the largest of which are the Multiparticle Spectrometer and the Chicago Cyclotron magnet used in deep-inelastic muon scattering experiments.

In addition to these spectrometer solenoids, beam-line magnets have been built for dc operation at all the world's high-energy-physics facilities. Superconducting coils have also been

"Tulip" conductor designed for the poloidal field coil of the TORE SUPRA tokamak in France. For such fast-ramping ac magnet applications, the transverse resistivity of the embedding matrix must be much higher than that of pure copper, lest the voltage induced by the time-varying field drive coupling currents across the matrix. The Tulip solution, devised by the Nuclear Research Center, Karlsruhe, and Vacuumschmelze GmbH, Hanau, is to break up the large central region of copper with resistive barriers of the same cupro-nickel alloy that separates the superconducting Nb–Ti filaments from one another in each of the six filament bundles. Thus the transverse resistivity is high, while the axial resistivity is low—maximizing thermal conductivity and minimizing Joule heating. Figure 4



used in several polarized-proton targets, and they are the basis of the Michigan State and Chalk River superconducting cyclotrons.

The invention of twisted fine-filament Nb–Ti wire with low ac losses and high current density was crucial to the development of magnets that could be cycled, and thus to the application of superconducting magnets in the accelerators themselves. (These high-energy synchrotrons, unlike cyclotrons, require time-ramped bending fields.) Combining individual strands into a twisted flat cable makes it possible to construct bending and focusing magnets in a cost-efficient way. Thus, cost and field-strength considerations almost compel modern accelerator builders to choose superconducting magnets. In cases where magnet or tunnel length is important, producing a high field is the more important consideration. In other cases, the operating costs for conventional magnet systems become insupportable, so that, despite the cryogenics, superconducting magnets are cheaper to run.

The Tevatron superconducting ring (figure 5) is a good example of a facility where both increased field intensity and reduced operating costs dictated the choice. In 1982, when the four-mile-long conventional magnet ring was operating at 400 GeV, the electric power consumed in 26 weeks of operation was 158 GW hrs. With this conventional ring, about half the power was consumed during the 9×10^5 seconds of maximum-field "flat top," when the beam is actually available to experimenters. During the first 35 weeks of 1985, when the new superconducting ring operated at 800 GeV, the electricity usage, including refrigerator power, was 151 GW hrs for a total flat-top time of 4×10^6 seconds. Thus the number of useful seconds per gigawatt hour was increased about fivefold, and the beam energy doubled, by using superconducting magnets.

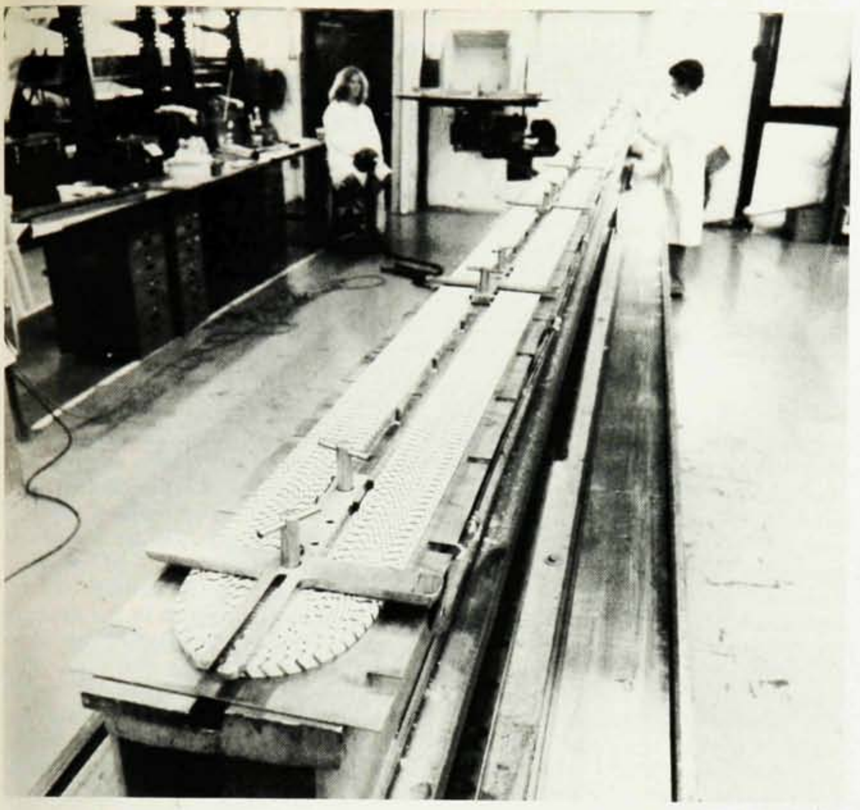
In designing superconducting magnets one must deal with special problems of field homogeneity and quality, cryostat design and construction, and quench protection. The field quality of unsaturated iron magnets is dominated by the shape of the iron. Typical iron laminations can be stamped to tolerances on the order of 25 microns. In most superconducting magnets, the field shape is dominated by the precise location of conductors. If field inhomogeneities of less than a part in 10^4 are required over roughly half the bore of the magnet, one must place and secure conductors with an accuracy of about 25 microns.

Because the superconducting coils operate at temperatures below 10 K, the winding assembly is surrounded by liquid helium in a cryostat. Given the Carnot efficiency for extracting heat at 4 K (about 1.3%) and the mechanical efficiency of refrigeration equipment (about 20%), it costs about 400 watts at room temperature to extract 1 watt at 4.2 K. Economics thus dictates a cryostat design that includes a 77-K temperature shield to intercept heat from the cryostat's room-temperature environment. Careful attention must also be paid to coil supports, superinsulation, insulating vacuum, current leads and instrumentation to minimize heat leakage.

Accelerator bending magnets are very much longer than their aperture diameters. This implies that the magnet design is essentially two-dimensional. The size of the aperture is determined by the requirement that the beam inside the vacuum chamber be able to perform its transverse motions without encountering significant nonlinear magnetic fields. In the Tevatron bending magnets, the quadrupole, sextupole, octupole and higher-order components of the field must be less than 2×10^{-4} of the central dipole field out to a distance of one inch from the beam axis.

Lorentz forces on the conductors and the supporting structure of these high-field magnets can be very large. It is not unusual for the forces to exceed a hundred pounds per linear inch of cable. This means the support structure must be able to withstand more than a ton per inch! At the same time, the requirement for helium flow channels in the coil implies that the magnet coil must have 10–15% empty space. To give the winding structural stability, the cabled strands are wrapped with about 100 microns of kapton insulation and spirally overwrapped with fiberglass tape impregnated with epoxy. After winding, the coil halves are molded under heat to give them proper dimensions, and the magnet is then assembled with pre-punched stainless steel or aluminum collars placed outside the coil to constrain the conductor motion when the magnet is powered. In fact, the collars are used to preload the coils with force sufficient to keep the conductors from moving and generating heat that would quench the coil.

The successful demonstration of superconducting accelerators and the continuing efforts of particle physicists to understand the unification of the basic forces have led to the proposal for the Superconducting Super Collider (PHYSICS TODAY, March 1985, page 28). Two



Superconducting bending magnet coil being wound for the Tevatron at Fermilab. These 20-ft-long magnets, arrayed along the 4-mile circumference of the Tevatron ring, provide the 4.5-tesla bending field that keeps TeV protons circulating around the ring. The superconducting ring was completed in 1983. Improved superconducting cable now makes it possible, with 6.6-tesla bending magnets, to build a 20-TeV proton ring—the proposed SSC—with a circumference of "only" 60 miles. Figure 5

magnet rings, each 60 miles in circumference, would accelerate protons in opposite directions to 20 TeV. The countercirculating protons would then be brought into collision with a center-of-mass energy more than 20 times that currently possible. Special detectors set up at the collision points would witness the outgoing particles and record data for later analysis. The discovery of the vector bosons $W^{\pm}$ and Z^0 at the 240-GeV CERN collider in 1983 confirmed the "standard model" that unifies the weak and electromagnetic forces. Further evidence for unification would be the observation of scalar Higgs particles that are expected at the energies that would be available with SSC. Undoubtedly SSC would lead to other discoveries that would shape our fundamental understanding of particle interactions and the early Universe, because 40 TeV would allow the simulation of the state of matter at 10^{-16} sec after the Big Bang.

The magnet proposed for SSC has a $\cos\theta$ winding and reaches 6.6 T central field (see PHYSICS TODAY, December, page 58). Because SSC's energy is significantly higher than that of the Tevatron, the SSC magnets can make do with a smaller beam aperture. Magnetic field measurements of SSC prototype dipoles show that a 4- or 5-cm bore will suffice, with consequent cost savings.

Another factor that will reduce costs is the use of better superconductors. The critical current density for the cable used in the Tevatron magnets was a maximum of 1800 amps/mm^2 at 5 T and 4.2 K. Recently manufactured SSC prototype cable performs at 2400–2700 amps/mm^2, indicating that the magnets will exceed design performance standards for 6.6-T operation.

The superconductor shielding currents that flow in the filaments, causing induced magnetization and consequent field imperfections, are large enough in the prototype SSC dipoles to require corrective action. The magnitude of this persistent-current effect is proportional to the diameter of the superconducting filaments. One solution, therefore, is to reduce the filament diameter to 3–5 microns from its present value of 10–20 microns. Producing strands with 10 000 ultrathin filaments has required a basic understanding of the metallurgy of the interface between the Cu matrix and the Nb–Ti filaments. In fact, the achievement of high current density has required high chemical homogeneity in the Nb–Ti alloy, and this in turn has resulted in much more uniform filaments. Great progress has been achieved in the last year, but the final decision will depend on economics. If the cost of fine-filament wire is too great, the unwanted persistent-current fields can alternatively be dealt with by using low-current superconducting correcting coils on the beam tube.

A significant challenge to the 60-mile-long cryogenic system is posed by the 8 kW of synchrotron radiation generated by each of the countercirculating 20-TeV proton beams. Although high-energy electron rings generate much more synchrotron radiation, none of these is, as yet, superconducting. To remove the heat deposited at liquid-helium temperatures by the synchrotron radiation from the circulating SSC protons will require refrigeration power on the order of 10 megawatts.

If SSC goes ahead as planned, Kamerlingh Onnes will have been right in his expectation of "stronger and at the same time much more extensive fields. . . . in an accelerated development of experimental science."

Magnets for fusion

Fusion was not quite so quick off the mark as high-energy physics in its demand for superconducting magnets. In contrast to particle physics, where most magnets now tend to be relatively small (on the order of a ton, although hundreds or thousands may be required), fusion magnets are individually massive, and this has inevitably stretched out the time scale of magnet development for fusion devices.

The very large copper-magnet tokamak fusion devices that have come into recent operation—JET, JT-60 and TFTR—are so substantial that a decade has passed since their inception. Their normal magnets, with coil dimensions on the order of 3 m, produce maximum field intensities of about 8 T. By the same token, the superconducting integrated prototypical reactor tokamaks now being planned, such as the Fusion Engineering Reactor in Japan and the Next European Torus, will require a decade to bring into operation.

In the meanwhile, several superconducting devices on a somewhat smaller scale, such as TORE SUPRA in France, T-15 in the USSR and the tandem mirror MFTF-B in the US are nearing completion. There is also a variety of test facilities available to help build the future superconducting-magnet database.

Another generation of major tokamaks is deemed necessary between the copper machines typified by JET and the first commercial fusion reactors. These superconducting-magnet devices, generally referred to as integrat-

Selected superconducting materials

Material	Type	T_c kelvin	H_{c2} tesla at 4.2 K	Comments
Pb	I	7.3	—	Superconductivity confined to fields less than 0.1 T
Nb(45–50 wt%)–Ti	II	8.9–9.3	10.5–11	Most widely used material
Nb_3Sn*	II	17–18	19–25	Also in production
Nb_3Al*	II	16–20	20–35	Possible new conductor
NbN*	II	16–18	20–35	Possible new conductor
$PbMo_6S_8$*	II	14	40–55	Possible new conductor

*These are all brittle compounds. Their compositions can vary from the stoichiometries noted.

ed test facilities, include the proposed intercontinental collaboration INTOR as well as NET and FER. These machines would have prototypical reactor components, for example tritium breeding blankets and power-generating modules. They would be approximately a factor of two larger in linear dimensions than the largest existing tokamaks, with maximum magnetic field intensities of about 11 T.

There is also a strong interest in exploring more compact magnetic systems in the push toward attractive fusion power systems. TIBER is a proposed advanced superconducting experiment that would achieve ignition with dimensions no larger than the biggest present-day tokamaks. It would, however, require magnet current densities of 40 amps/mm^2, almost twice as high as INTOR or the current machines. Still, 40 amps/mm^2 is a factor of 50 less than the 1000 amps/mm^2 anticipated by Onnes. He did not, however, count insulation, coolant or the copper stabilizer that has proven so necessary. To meet these ambitious goals will take a substantial R&D effort on top of the existing investment in superconductor development.

The next year or two will see several important events in the development of superconducting magnets for fusion. Three superconducting tokamaks will be in operation: major machines in Europe (TORE SUPRA) and the Soviet Union (T-15), and a lesser-scale but higher-field machine in Japan (TRIAM-IM). Two of these machines use Nb_3Sn, and one employs superfluid helium as a coolant. Only the small Japanese machine, with a peak magnetic field of 11 T, comes close to the projected field requirements of the integrated-test-facility devices. In recent weeks the very large MFTF-B tandem-mirror machine at Livermore has completed its magnet testing, and the Large Coil Test Facility at Oak Ridge has begun the six-coil test for which it was built.

The largest superconducting magnets in the fusion program are contained in the MFTF-B tandem-mirror facility at Livermore. The first of its two 340-ton Nb–Ti yin–yang coil pairs, shown in figure 6, was successfully tested to a peak field of 8 T in 1982. The central plasma region between these two gargantuan magnetic mirrors contains six sets of Nb–Ti 5-m-bore solenoid-coil pairs with peak fields of 3.5 T. The two high-field end-plug coils have 12.5-T peak fields and inner diameters of 36 cm. Their inner coils were wound with prereacted Nb_3Sn pool-cooled conductor, and they have an overall winding-pack current density of 20 amps/mm^2.

The complete magnet system of MFTF-B was successfully tested for the first time last month—a major technological achievement. Ironically, that was also the month in which the President's FY 1987 budget made its appearance, with a sufficiently drastic cut in the magnetic-fusion budget that MFTF-B has been placed on standby.

The conductors used in a superconducting magnet as large as MFTF-B generally contain sufficient copper and helium coolant to provide what is called "unconditional stability." To satisfy this stability condition, an arbitrarily long length of conductor must be able to recover from a temperature excursion above the critical temperature of the superconductor. This means that all the current will momentarily flow in the copper stabilizer, and that there must be sufficient cooling capacity to reduce the temperature back to the operating point. For the MFTF-B yin–yang conductor operating at 5800 amps, this requires 7 times as much copper as Nb–Ti superconductor and 8.17 cm^2 of cooling surface per centimeter of conductor length. The conductor, were it a simple square 1.24 cm on a side, would have a cooling surface of only 5 cm^2/cm of length, and hence a novel conductor configuration with extended surface was necessary. Simply flattening the cable to increase surface area would not have done, because the yin–yang coil configuration requires that the cable be twistable about both transverse axes.

The unconditional-stability criterion implies that a sufficient supply of helium will be present to remove both the initial energy perturbation and the Joule heating that occurs while the conductor is not superconducting. This requires a structure open enough that passages do not become choked with vapor or deprived of coolant. By and large, designs for large fusion magnets leave approximately 25% of the winding cross section for helium coolant. (This can be compared to the approximately 15% found in high-energy-physics dipoles, where the stored energies are smaller.) The important design solutions for stability were derived only during the 1960s and 1970s, but we can note with interest the hints at problems of stability given by Onnes in his original work.

The future challenges in magnet requirements for tandem-mirror reactors are posed by the plug coils. The overall power-reactor economics are dependent on how much field can be produced, and designs have been done for 24-T fields in a 1.2-m-diameter coil. These very-high-field coils would be produced by insertion of radiation-resistant copper coils into background superconducting coils that produce 16 T. Livermore is working on developing high-current alloyed Nb_3Sn conductors for these coils, and will examine both He I internally cooled cable conductors and He II pool-cooled conductors.

The simultaneous testing of six large (40-ton) superconducting coils of different design at full 8-T field begins this month at the Large Coil Test Facility in Oak Ridge, culminating a decade of large-test-coil development in the US, Japan and Europe. The six coils are tested together in order to approximate the magnetic environment of a fusion reactor. The six coil designs encompass most of the realistic alternative construction techniques: Five of the coils were built with Nb–Ti and one with Nb_3Sn; five use support cases and one employs a distributed plate structure; three of the coils use conductors in which the coolant flows internally. All the coils operate at 4.5 K.

The three different conductors employed in the three American coils involved in the Oak Ridge large-coil test are shown in figure 7. The General Dynamics Nb–Ti conductor was fabricated by soldering a flat Rutherford-

The yin–yang coils that plug the ends of the MFTF-B tandem-mirror facility at Livermore are the largest superconducting magnets in the fusion program. This 340-ton, nested pair of yin–yang coils, seen before installation, provides the complex 8-tesla field that plugs one end of the mirror machine. A second pair plugs the other end. The entire magnet system of the MFTF-B was successfully tested last month, just in time for the project to be relegated to standby status by budget cuts. Figure 6

type cable of 26 strands into a premachined monolithic channel. Of particular interest is the "extended" surface, a series of triangular grooves on each face, which improves the heat transfer by a factor of 1.65 over an ungrooved flat surface. The General Electric Nb–Ti conductor was fabricated by cabling 16 square sub-elements around a copper core, then compacting and soldering them. The spaces between sub-elements serve to extend the available cooling surface. The Westinghouse conductor differs from the other two US conductors by being cooled internally and by using Nb_3Sn, a choice made to provide experience with brittle high-field conductors.

The Westinghouse conductor was fabricated by Oxford Superconducting Technology Ltd from a cable surrounded by a rolled and welded sheath. After compaction the cable occupies about 70% of the cross section, leaving the remainder for the supercritical-helium coolant. (Liquid helium has a critical point at a pressure of 2.5 atmospheres; that is, it remains in a single phase as the temperature is raised. Heat must then be removed by local increases in fluid velocity rather than by the usual bubble-rising mechanism that operates in a two-phase system.) Heat-transfer measurements for the Westinghouse conductor suggest that the conductor will be extremely stable.

The three conductors used at the Large Coil Test Facility reflect the alternative paths open to the magnet designer: Bath-cooled designs reflect the widely held view that open baths are much simpler than systems requiring manifolds and pumps; internally cooled designs reflect the view that such conductors can be better insulated and supported.

This year's test will bring the peak fields of the six coils up to the full 8 T and will subject them to pulsed fields, simulating the tokamak environment. Extensive instrumentation will monitor stress, winding-pack motion, quench propagation, pressure and acoustic emission. This will augment the already important comparisons of theory and practice coming out of the European and Japanese domestic large-coil test programs and the earlier two-coil test at Oak Ridge. A 120-m length of the Westinghouse conductor fabricated into a 1-m-diameter test coil at MIT has been tested to 12 T in the High Field Test Facility at Livermore. A large Japanese Nb_3Sn coil has also recently attained 12 T.

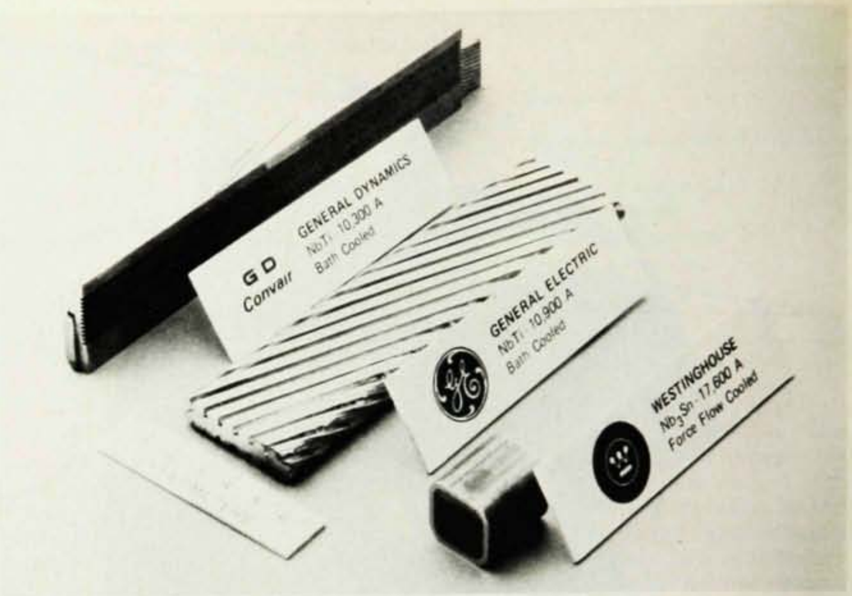
In spite of these great strides in superconducting magnets for fusion, the next fusion device in the US is likely to be a compact copper ignition device, whereas the next-generation machines in Europe and Japan will probably be larger superconducting devices. Thus it seems that most of the near-term development of fusion-related superconducting magnets will be done overseas. However, it remains in the long-range interest of the US to maintain a strong domestic program. If it wishes to join overseas colleagues in the important next step embodied in these superconducting machines, the US must be seen to have something of value to contribute. Furthermore, if fusion is to have a long-range future, we must continue to improve the promise of future reactors by continuing to improve the magnets.

Magnetic-resonance imaging

Magnetic-resonance imaging (MRI), with its requirement for large-diameter (1 m), high-intensity (1–2 T) magnetic fields of rigorous uniformity, has produced the first large-scale commercial application of superconductivity. The growth in the market for such magnets has been very rapid (from \$10 million in 1982 to \$110 million in 1984), reflecting a general anticipation in the medical community about the ability of MRI to provide information about the chemistry of human physiology noninvasively and without exposure to ionizing radiation.

A magnetic-resonance image is a representation of the spatial distribution of the amplitude and phase of the nuclear-magnetic-resonance signal from a heterogeneous sample. The possibility of such an image was first demonstrated by Paul Lauterbur, who produced two-dimensional nmr pictures of water vials at Stony Brook in 1973. After several years of experiments on animals, a number of groups almost simultaneously considered scaling up these experimental methods to human subjects. Early whole-body imaging studies were performed with resistive-magnet systems of field strength 0.2 T or less. In 1979 Oxford Instruments Ltd delivered the first superconducting whole-body imaging magnets of strength 0.3 T to Hammersmith Hospital in London and the University of California Medical Center in San Francisco. In 1982 Oxford manu-

The three conductors employed in the three 40-ton superconducting test coils built by US firms for the Large Coil Project. Together with three similar large coils from overseas, they are currently being tested at full 8-tesla field at the Oak Ridge Large Coil Test Facility. Figure 7



factured the first 1.5-T, 1-m-bore magnet, which was delivered to the General Electric Research Center at Schenectady, New York. Although MRI systems with resistive and permanent magnets have been developed by several medical-instrument manufacturers, superconducting magnets have so far dominated the MRI market. The advantages of superconducting magnets lie in their relatively high field strengths and their great stability and reliability. Over 600 superconducting-magnet systems have now been manufactured for magnetic-resonance imaging. Recent MRI images of various cross sections of the human body are shown in figure 1.

The manufacturing and functional requirements of medical-imaging magnets are rather different from those of superconducting magnets for laboratory use (small 8- to 15-T systems), dipole magnets for accelerators and large plasma-containing devices for fusion. Furthermore, because MRI magnets must operate in clinical settings, where operators are not familiar with superconducting-magnet technology, the magnets must be very reliable, easy to maintain and safe to operate, with controllable failure modes.

The main features of whole-body MRI magnets are:

▶ dc field strengths of 0.15–2 T (stored energies up to 7 MJ)

▶ large uniform field volumes (inhomogeneities of less than 0.1 ppm over a 10-cm-diameter sphere for spectroscopy, and 25 ppm over a 50-cm-diameter sphere for proton imaging)

▶ good temporal stability of the field (drifts of less than 0.1 ppm per hour).

Each of these parameters affects the signal-to-noise ratio of the nmr signal. Although there is general agreement on the requirement for high field uniformity and temporal stability, the optimal field for proton imaging is still the subject of considerable debate, involving, among other things, concern about the possible adverse biological effects of high-intensity dc fields. Fields of 1.5–2 T are currently required for spectroscopy. Future developments may require fields of 4 T or more.

A clinical MRI magnet system is shown in figure 8. One approach has been to use a standardized cryostat vessel for all magnets. The system has a room-temperature bore of 1 m and is 2.3 m in length. The weight varies from five tons for 0.5-T systems to seven tons for 2-T systems. The system is about eight feet high, so it can be installed in normal clinical sites.

To ensure simple and reliable operation mechanical refrigerators were avoided at first. After several years of trials, however, several magnet manufacturers now offer refrigeration as an option. Refrigerators are finding particular application in mobile MRI systems.

The cryostat is designed to minimize thermal losses. It has five major components: the outer vacuum vessel, which provides the structural strength of the system, a liquid-nitrogen vessel, the magnet tank, a series of radiation shields and a turret for electrical and cryogen access. A three-dimensional array of glass-reinforced rods, designed to minimize the conduction heat load on the helium vessel and withstand shipping forces, secures the vessels to each other. The typical boil-off loss of an MRI cryostat is less than that of many laboratory cryostats: A helium loss of 0.4 liters/hr and a nitrogen evaporation rate of less than 1 liter/hr are typical.

Compared with some high-energy-physics and fusion magnets, MRI magnets are modest in size and stored energy, and the technology of their coils is conventional. However, the real challenge is to produce a design of the precision needed for high field uniformity that can nonetheless be reliably manufactured by routine industrial processes and sold at an affordable price relative to the diagnostic benefits of MRI.

Specific problems overcome in the design of whole-body MRI magnets include:

▶ fabrication and assembly of large structures to the precision required by magnet physics—generally ±0.1 mm per meter

▶ design and specification of a cost-efficient superconducting composite wire capable of being manufactured consistently in large quantities

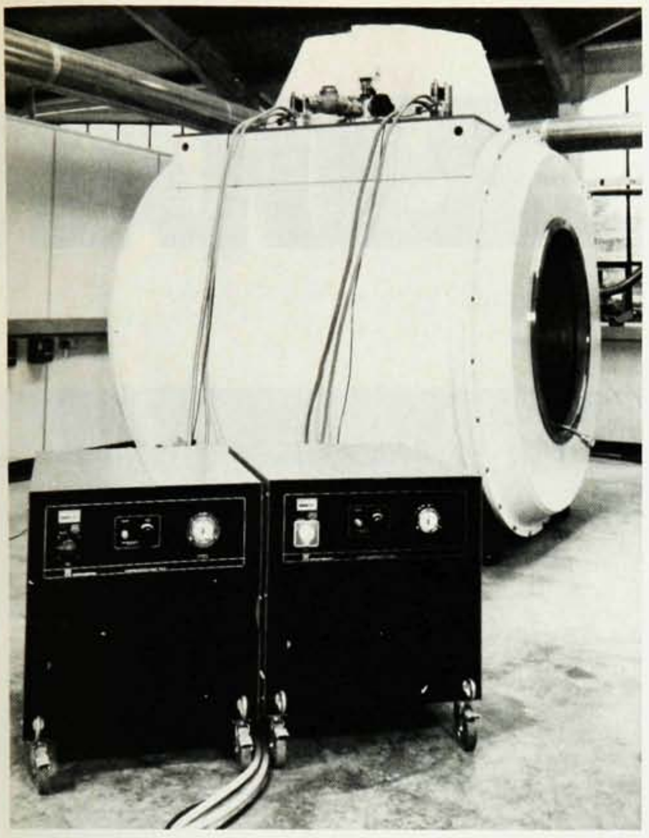
▶ development of methods of joining random lengths of conductor with resistances of less than 10^{-10} Ω to produce coils that meet field-decay specifications of 0.1 ppm/hr

▶ development of superconducting switch systems that reliably maintain the magnet in persistent-current mode.

A typical MRI magnet comprises six circular coils of a Nb–Ti–Cu composite conductor wound onto a precision-machined Al bobbin of 1.3-m radius. The coil positions are chosen to optimize the field uniformity over the specified volume under the constraints of minimum conductor mass, acceptable stress level and magnet geometry. Each coil is circumferentially clamped against the Lorentz force acting when the coil is energized. The winding is impregnated with a specially selected epoxy resin.

In addition to the requirements common to all superconducting-magnet conductors, MRI magnets require very uniform conductor dimensions and continuity of filaments over many kilometers to achieve persistent-mode operation. Monolithic conductor designs are used for 0.5-T and 1.0-T magnets. A typical conductor operates at 150 amps at 50% of the maximum rated capacity. The high-field 1.5-T and 2-T magnets use a soldered cable with a high ratio of copper to superconductor at operating currents up to 400 amps.

Although the theoretical uniformity of the magnetic field, as defined by the idealized coil positions, is such that field errors are zero, in practice manu-



Clinical magnetic-resonance imaging system. More than 600 MRI systems have already been built for medical imaging. The heart of the system is a superconducting magnet coil of 1-m diameter, producing a highly uniform and stable field on the order of 1 tesla. Figure 8

facturing tolerances and field perturbations arising from environmental iron at the clinical site give rise to inhomogeneities up to a part per thousand over the 50-cm-diameter spherical volume specified. To correct for these errors, MRI systems employ a set of correction coils—typically an array of 13 shim coils capable of correcting selected low-order error terms in the zonal-harmonic field expansion. The shim set is usually resistive, typically requiring about 500 watts to achieve adequate field uniformity. Where the additional complexity is warranted, the shim coils may be superconducting.

The stray magnetic fringe field of an MRI system poses a serious problem in a hospital environment. Ideally, one would like to put the magnetic-resonance facility close to other medical imaging modalities, in an area easily accessible to patients. However, Federal Drug Administration guidelines limit the maximum field for general public access to 0.5 mT. Furthermore, x-ray CAT scanner gantries must not be placed in fields exceeding 1 mT. These factors have significant impact on possible locations for the MRI system.

The most obvious solution to the fringe-field problem is to surround the magnet with a symmetrical yoke of iron having virtual pole pieces at each end of the solenoid. Such systems are offered commercially, a typical yoke shield weighing more than 20 tons. Extensive computer modeling is required to ensure that the homogeneity of the magnet is not impaired by the presence of such a shield.

An alternative approach has thus far achieved more widespread commercial application. This is the "room shield," in which iron plates in specific locations provide limited screening of selected areas. The advantage of this approach is that the iron plates have little effect on homogeneity, do not exert large forces on the magnet, and they can be customized to suit particular situations.

The future

Returning to our excerpt from Kamerlingh Onnes's 1913 review, we can indeed say that the last 15 years have witnessed an accelerated development of the experimental science of high-field superconductivity: magnets in hospitals, a four-mile-long ring of superconducting magnets at Fermilab, magnets individually weighing as much as 300 tons—not quite as heavy as a cruiser, nor as expensive as a warship. These are achievements that one suspects would fit well into Onnes's conception of the uses of superconductivity.

Superconducting laboratory-scale magnets would also be close to his heart. Compact superconducting magnets of Nb–Ti providing 5–9 T are widely dispersed in scientific laboratories. Magnets made from Nb_3Sn are available up to 16 T. However, dealing routinely with brittle materials for magnet construction has taken longer than expected. The world's highest-field superconducting magnet was constructed by Intermagnetics General some 10 years ago. It gives 17.5 T, but only now are there serious plans to raise the record to 18 or 20 T. Nonetheless, superconducting magnets remain crucial to further developments in dc magnetic fields. The maximum steady fields from resistive magnets are of order 23 T, requiring 8 to 10 megawatts. The central field of such resistive magnets can be raised to 30–31 T with an assist of about 10 T from 1-meter-bore superconducting magnets.

Further developments await new developments in superconducting composites. As the table on page 30 shows, Nb_3Al, NbN and $PbMo_6S_8$ are all superconductors with the potential for more than 20 T. More exotic materials may hold even greater promise.

In pondering why Onnes's conceptions took so long to come to fruition, let us review the various scientific and engineering advances that were required. The path around the limits of type-I superconductivity was not discovered until the 1950s—though it was almost discovered in the 1930s. It then took about 10 years to control the electromagnetic instabilities that caused coils to perform much worse than short samples of superconducting cable. After the developments of the 1970s we can now build and operate coils storing hundreds of megajoules in a few cubic meters, using materials with enthalpy margins of only a few millijoules per cubic centimeter. Onnes's conception of the widespread use of high-field, ironless magnets may fairly be said to have been realized.

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