Superconducting magnets

Stable, reliable and homogeneous fields in the 50–100 kilogauss range are now readily available, thanks to a decade of development on superconducting materials and methods.

John K. Hulm, Don J. Kasun and Edward Mullan

In the last ten years we have seen the development of high-field superconducting magnet technology from the announcement, in 1961, of the first solenoids to the present day, when around a thousand magnet systems are in use in scientific laboratories throughout the world. A scientist interested in magnetic-field effects can now obtain a reliable magnet to generate a homogeneous and steady field in the 50–100 kilogauss range for a capital investment of about 25 cents per gauss.

That 1961 announcement (during a conference on high magnetic fields held at Massachusetts Institute of Technology) was seen by many observers as the dawn of a new era of electrical technology. Those superconducting solenoids, developed by Bell Telephone Laboratories, Atomics International and Westinghouse Research Laboratories, had fields of about 60 kG. They were seen as the vanguards of a revolution that was to sweep aside the "Faraday" copper-iron technology and replace it with a superconducting technology in which electrical apparatus would use operating magnetic fields of 50 kG or more. It didn't happen quite as quickly as some expected, but progress has been very encouraging. The erratic 1961 solenoids have now been retired as museum pieces. In their place are reliable, small-bore, high-field coils for scientific research and safe, predictable-performance, large magnets for industrial applications—thanks to major advances in understanding the behavior of superconducting magnets and the materials from which they are constructed.

The larger magnets, with working volumes of many cubic feet, are now beginning to find their way into industrial applications. Quite large motors and generators with superconducting magnets have been, or are being, constructed in several laboratories in the US and abroad. It is possible that this technology will be extended to large central power-station generators in the gigawatt range before the end of the present century.

Meanwhile, smaller research magnets have been greatly improved too. New materials have considerably diminished the stability problems arising from "flux jumping," the materials are used more efficiently, and we now know how to make very homogeneous fields.

Let us see who uses these research magnets, the type of magnets they use, how much the equipment costs to run and what operating problems can arise.

Who uses superconducting magnets?

Our experience relates primarily to small-bore (less than about 15 cm) magnets in the field range below 100 kG. We estimate that this type of magnet has been used principally in physics research (approximately 84% of all users) and predominantly in solid-state physics. Chemistry applications come next (about 9%), biological experiments (about 3%), metallurgy (about 2%). The remaining 4% of these research magnets were constructed for electrotechnological purposes, mainly in connection with satellite and space communication studies using masers.

Some idea of the range of experiments in which superconducting magnets have been employed can be gained from Table 1. In many of these experiments some special feature such as field homogeneity is important, and for this reason a magnet designed for one purpose may be completely unsuitable for another. However, where the requirement is simply a very high magnetic field, the magnet is a general-purpose tool that can be used for a variety of experiments. The larger research laboratories commonly use their magnets for several purposes, so that Table I should be regarded as only a rough guide to present-day use of magnets. Remember also that many large bubble-chamber magnets, beam-bending magnets and plasma research magnets constructed in-house by the Atomic Energy Commission are not considered in the above list.

Total sales of small research magnets probably do not exceed $2 million per year, worldwide. However, the magnet market has remained remarkably steady over the years; some applications have declined, but others have filled the gap. For example, although adiabatic demagnetization has declined because of the invention of the helium dilution refrigerator, interest in magnetic susceptibility measurements has grown steadily. Increased use of magnets by analytical chemists (in nuclear magnetic resonance and optical spectrometry) appears inevitable.

There is virtually no standardization—magnets are custom-designed for each application. This will probably continue to be the case for the foreseeable future, although a few standard magnets have been developed for magnetometers, NMR spectrometers, and optical spectrometers. The sheer variety of applications has necessitated close cooperation between the magnet manufacturers and the users with resulting benefits to both parties. We can not discuss here all of the special features that different experiments have required, but a few typical ones will be mentioned.

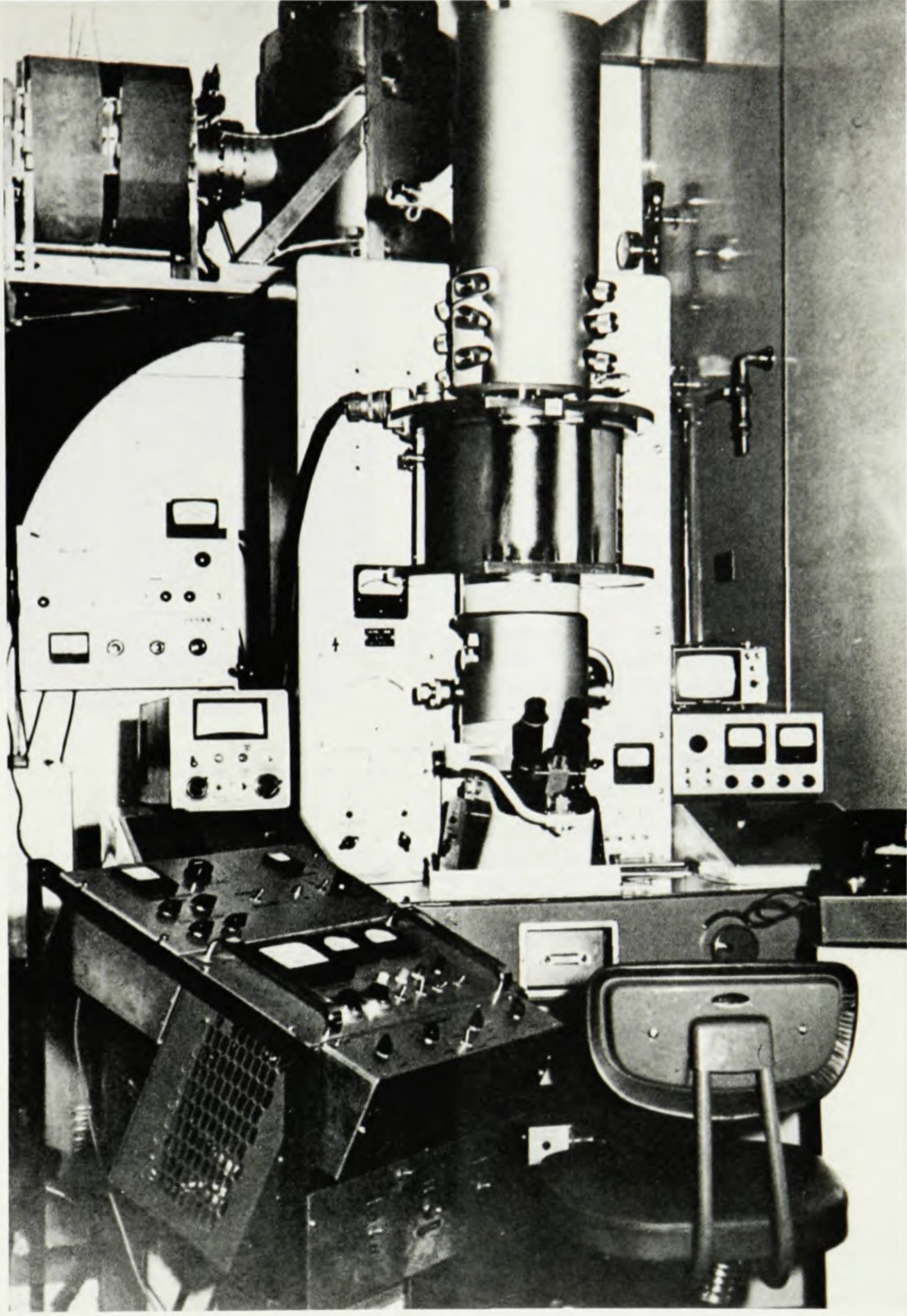
The superconducting magnet has two important features, aside from the main one of providing a high magnetic field with relatively low power input.

John Hulm, Don Kasun and Edward Mullan are all with the Westinghouse Electric Corporation in Pittsburgh, Pa.

First, it can be "corrected" with various auxiliary windings to give a field of very high spatial homogeneity (better than 1 in 10^8), and second, by operating in a short-circuited or "persistent" mode, quite remarkable time stability of the field can be achieved. Of course, high spatial field homogeneity is possible in ordinary copper–iron magnets, but for these magnets time stability requires quite elaborate current-controlling equipment, which becomes bigger and more complex as the degree of stability increases. All this is avoided in a persistent-mode superconducting magnet, and for some applications this feature is even more important than the high field itself.

In some applications high field, high homogeneity and time stability have been combined to produce a hitherto unobtainable level of performance. Perhaps the best example of this is nuclear magnetic resonance, where line resolutions of 1×10^{-9} have recently been achieved at 60 kG. Spatial field homogeneity is important in several other research areas; an example is the study of Fermi surfaces in metals by the de Haas-van Alphen effect, using the oscillatory part of the high-field magnetic susceptibility. The time stability of persistent-mode operation has proved to be beneficial for frequency stabilization in maser amplifiers used for satellite communications systems.

Electron-microscope designers have obtained increased resolution by using superconducting magnet lenses in the persistent mode (see figure 1). An additional benefit is the larger exposure time at lower beam intensities which can then be employed. Further improvement in resolution results from operating the magnet below the lambda point, to reduce vibration from the helium bath. An important feature of this type of system is that extremely



Electron microscope with a superconducting lens. Use of a superconducting magnet in the "persistent" mode—as here—gives increased resolution, with larger exposure time at lower beam intensities. (H. Fernandez-Moran, University of Chicago.) Figure 1 fine field-strength adjustments (a few parts in 10^7) can be made without leaving the persistent mode.

Special mechanical features are necessary for some applications. For example, neutron-diffraction work requires access to the magnetic field in both radial and axial directions, as in the magnet shown in figure 2. The design also requires that liquid helium be excluded from the beam path and that only thin-wall, low neutron cross-section materials are used there. Special shielding is also provided to reduce the solenoid's negative external magnetic field in the beam path.

Split coil for neutron diffraction studies, which require access to the magnetic field in both radial and axial directions. (South African Atomic Energy Authority.) Figure 2

Selecting the superconductor

Superconducting materials represent a high proportion of the basic costs of a magnet and must be carefully selected. Broadly speaking, the magnet designer has two classes of material to draw upon—superconducting alloys, such as Nb–Zr and Nb–Ti, and superconducting compounds such as Nb_3Sn, V_3Ga and so on. Some basic design criteria are summarized in figure 3, which shows the typical shape of the critical current density, J_c, versus field, H, curve for high-J_c type-II superconductors. It is necessary to operate below this curve, along an operating line characteristic of a given magnet. Thus J_c at P should be as high as possible, and H_{c2} provides an absolute upper limit of magnet field strength. At the same time, for thermal stability, t_{op} (the ratio of actual operating temperature T_{op} to the material critical temperature T_c) should be as low as possible.

Typical parameters for the two superconducting material classes are shown in Table 2.

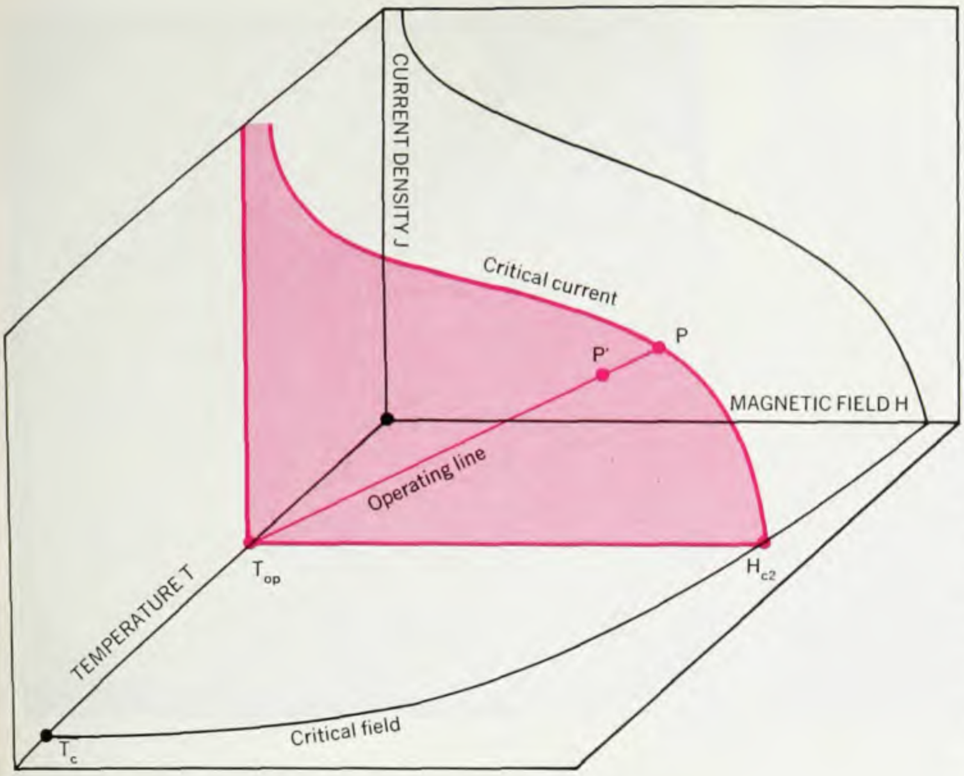
Although the compounds have better electrical and thermal performance than the alloys, the reverse is true for their mechanical properties. Whereas the alloys are ductile materials of great mechanical strength, the compounds are brittle and glass-like. This brittleness has definitely inhibited the use of compounds in magnet construction—in fact, most of the magnets in service now were built from alloy windings. Compound materials have found their major use in very high-field magnets operating above 100 kG, where alloys cannot be employed because of their comparatively low values of H_{c2}.

The critical current densities achieved in actual magnet windings lie considerably below the raw superconductor values quoted in Table 2. This is partly because of the inter-turn and inter-layer insulation materials (usually epoxy varnish and Mylar) and partly because the windings are never made of raw superconductors, but consist of superconductor–normal-metal composites. Generally the superconductor is bonded intimately with a good normal conductor such as copper, silver or aluminum. For alloy superconductors this is usually done by wire drawing of a single strand or multiple strands of superconductor embedded in a sheath or matrix of copper (figure 4). Compounds have been mainly available as thin films deposited upon supporting substrates of stainless steel or niobium (figure 4). The cross-sectional area of normal metal relative to that of superconductor can be as low as 0.1 or as high as 100, depending upon the magnet-design compromise.

Normal-metal–superconductor composites are used for two separate and distinct purposes; first, to protect the magnet from the consequences of normalization and, second, to ameliorate a long-standing problem of magnet operation, that is, premature entry to the normal state at some point in the superconducting region because of a "flux jump" in the winding. Let us

Table 1. Research Fields of Superconducting-Magnet Users

Transport phenomena (thermal conductivity, electrical conductivity, Hall effect, thermoelectric effect, etc.)	20%
Magnetic moment, magnetic susceptibility and magnetostriction studies	17
Nuclear magnetic resonance, electron spin resonance, and masers	16
Magneto-optical, infrared and ultraviolet phenomena	13
Adiabatic demagnetization	9
Fermiology, de Haas-van Alphen effect, magneto-ultrasonic absorption	8
Mössbauer effect and neutron-diffraction studies	6
Plasma research (solid state and gases)	4
Electron microscopes, biological research, heat-capacity studies and miscellaneous	7



Superconducting phase space. Color shows a critical current density, J_c, versus field, H, curve for a high J_c type-II superconductor. P' is a magnet operating point.
Figure 3

consider these problems in more detail.

We note first that for a magnet of known physical dimensions, the field per unit current H/I, or α, can be estimated from purely geometrical considerations. For example, in a long solenoid α is $4\pi/10$ times the number of turns per centimeter. The slope of the operating line (figure 3) is proportional to $1/\alpha$, with a proportionality factor dependent upon the fractional area of superconductor in the winding. Magnet users often want to drive their research magnets to the maximum possible field, which means up to and beyond the point P. When part of the winding becomes normal, joule heating tends to cause a rapid expansion of the normal zone. The stored magnetic energy is then dissipated quickly as joule heat.

When the superconductor is shunted with normal material, the latter provides a relatively low resistance path that the exciting current can switch into when normalization commences. This reduces the rate of local joule heating, which in turn slows down the speed of growth of the normal zone and the rate of dumping of the stored energy. The general effect is to distribute the total heat of normalization more uniformly throughout the winding. This prevents damage from local temperature rise or from excessive inductive voltage generated in the winding during the normalization process. Thus the magnet can be normalized as often as desired with no ill effects other than expenditure of refrigeration energy.

If one uses sufficient normal material (r, the ratio of normal conductor to superconductor, greater than about 30) and provides good internal cooling of the windings, loss of the magnet-stored energy may be entirely prevented by stopping propagation of the normal zone. This so-called "stabilized" design is popular for very large-volume, low-field magnets that store many megajoules of energy. The loss of this enormous quantity of stored energy is highly inconvenient, and in very large coils the increased winding thickness needed because of the lower effective J_c of the diluted superconductor can be tolerated. The opposite is true for most high-field research magnets; a higher effective J_c is essential to avoid excessive winding thickness, whereas dumping of the stored energy is merely a petty annoyance. Hence r values of 4 or less are typical in research magnets.

The second important function of the composite conductor, as mentioned earlier, is to inhibit premature normalization due to "flux jumping." When a magnet is excited, the field induces local circulating supercurrents within the type-II superconductor; in accord with Lenz's law these currents oppose the penetration of the field. Because of the high intrinsic J_c value, the circulating currents represent a stored energy density within the superconductor that approaches in magnitude the heat content of the superconducting state. Worse still, these circulating currents tend to be unstable. As the exciting field is raised, zones of circulating current collapse from time to time, releasing their stored energy and permitting flux to enter the superconducting wire in a flux jump. For a magnet operating at an exciting current close to J_c maximum, say at point P′ in figure 3, the energy released in the flux jump may be sufficient to nucleate a propagating normal zone. In this case premature normalization occurs at P′ for a magnetic field below the maximum design field.

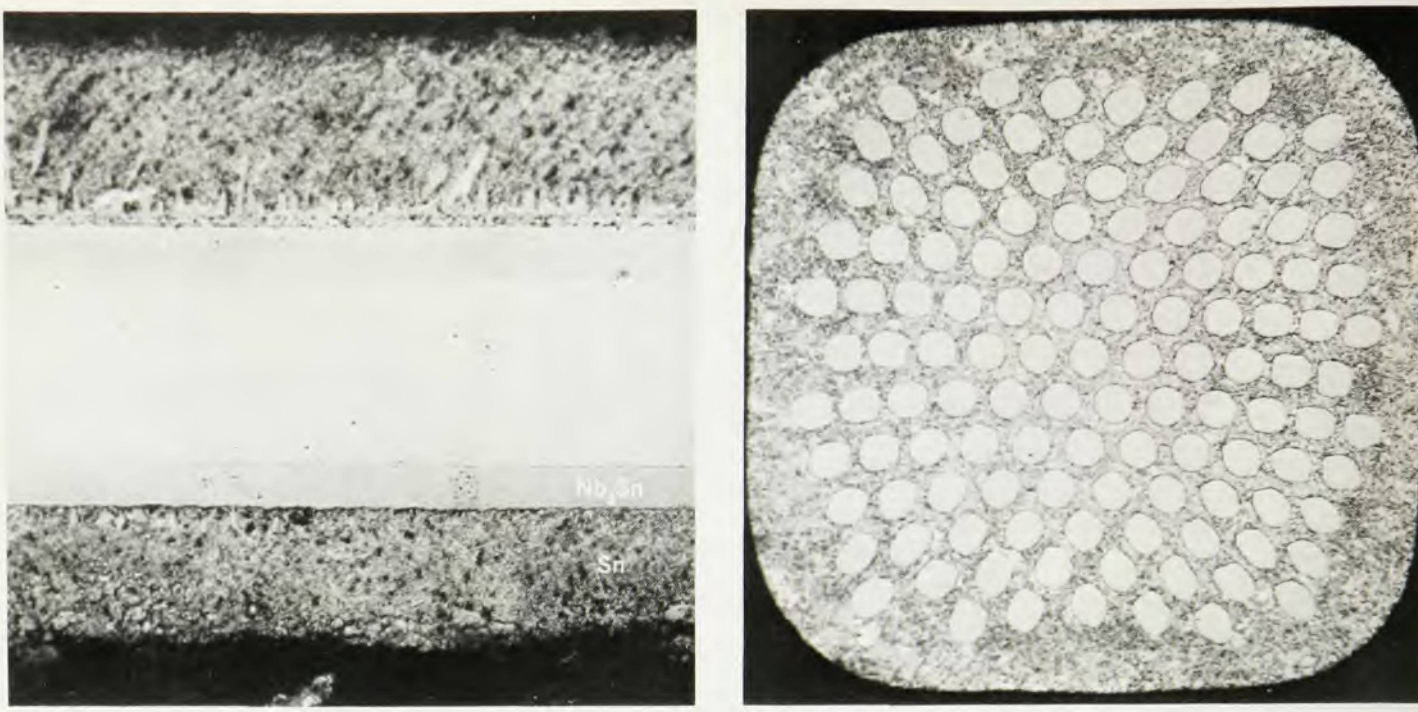
If the normal conductor to superconductor ratio, r, is deliberately increased, flux jumping is to some extent inhibited because of electrical shunting effects and the additional heat capacity of the normal material. However, as we have already seen, very high r values are not acceptable in research magnets. The best solution to the problem lies in breaking up the superconductor into many fine filaments separated from each other by normal metal. This is because the stored energy density of the circulating current is size dependent—in a superconducting wire of radius R the energy per unit volume is approximately $J_c^2\ R^2/8\pi$. Alloy composites have been produced in the past three years with hundreds of micron-sized filaments of Nb–Ti embedded in copper. In addition, the filaments are twisted or spiralled to minimize the lengths of the flux-jump zones. Magnets wound from these multifilament composites operate reliably up to the limit point P set by the basic J_c–H curve of the material.

Because of the extra metallurgical processing required, multifilament composites presently cost more than single-strand composites. However, the extra performance achieved (P′ to P in figure 3) justifies the use of multifilament material in the high-field region. The only drawback is that at present it is more difficult to make lossless joints with multifilament wire than it is with single-strand wire.

Field uniformity

The demand for research magnets of improved field uniformity has grown quite rapidly in recent years, particularly for de Haas–van Alphen and NMR experiments. At 60 kG, field uniformities of 2.5 parts in 10^8 have been achieved (figure 5) and will soon be commonplace.

The first cut at field design is usually made with a computer program that minimizes the superconductor weight for magnetic field, exciting current, bore and uniformity requirements. The program also yields the exact winding



Sections of typical superconductors. On the left is a diffused Nb_3Sn tape, at a magnification of $\times$ 500. On the right are drawn Nb–Ti filaments in a copper matrix, at a magnification of $\times$ 50. Figure 4

dimensions, shape and number of turns; it gives the field profile along the central axis of the magnet and over the surface of a specified uniformity region. This idealized calculation provides winding specifications for coil construction. After the base coil is wound, the calculation of the end-correction coils is refined to reflect the actual dimensions and number of turns in each layer of the base coil.

On a "parts-per-million" scale the field distribution in the center of an actual superconducting solenoid differs from this calculated distribution. For example, the ideal calculation ignores the magnetic influence of the superconductor winding, except for its role as carrier of the exciting current that generates the field. In reality the winding exhibits superconducting diamagnetism, modified by the presence of local circulating current, as we discussed earlier. These currents are subject to a complex magnetic hysteresis cycle, and their magnetic influence generally predominates over the basic material diamagnetism. The effects upon the resulting magnet field tend to be uniform with respect to the center of the magnet. One observes a "peaking" of the axial field profile, as the magnet is energized from zero up to about half the maximum field. At greater fields this peak effect declines steadily and is quite small at the maximum field level. Finally, when the system is de-energized, a dip in the axial-field profile appears as the field drops from maximum to about half of maximum and is present down to zero excitation current. At zero current there is also a residual field in the coil.

A second factor responsible for field distortion is the displacement of conductors from their correct positions in the winding. These displacements arise for a variety of reasons, including variations in wire diameter, winding nonuniformities, and so on. One result is the production of a first-order axial gradient, $\partial H_z/\partial z$, at the center, typically of about 10 gauss/cm. The gradient may be approximately corrected by adding a pair of coils in series with the main solenoid on its outside diameter. Occasionally second-order axial gradients, $\partial^2 H_z/\partial z^2$, appear also; they can be corrected by adding four exterior coils, also in series with the main solenoid. First-order radial gradients of around 5 gauss/cm are also present in most solenoids. Correction of these is more difficult, requiring a group of four separately excited "race-track" coils for the x and y axes.

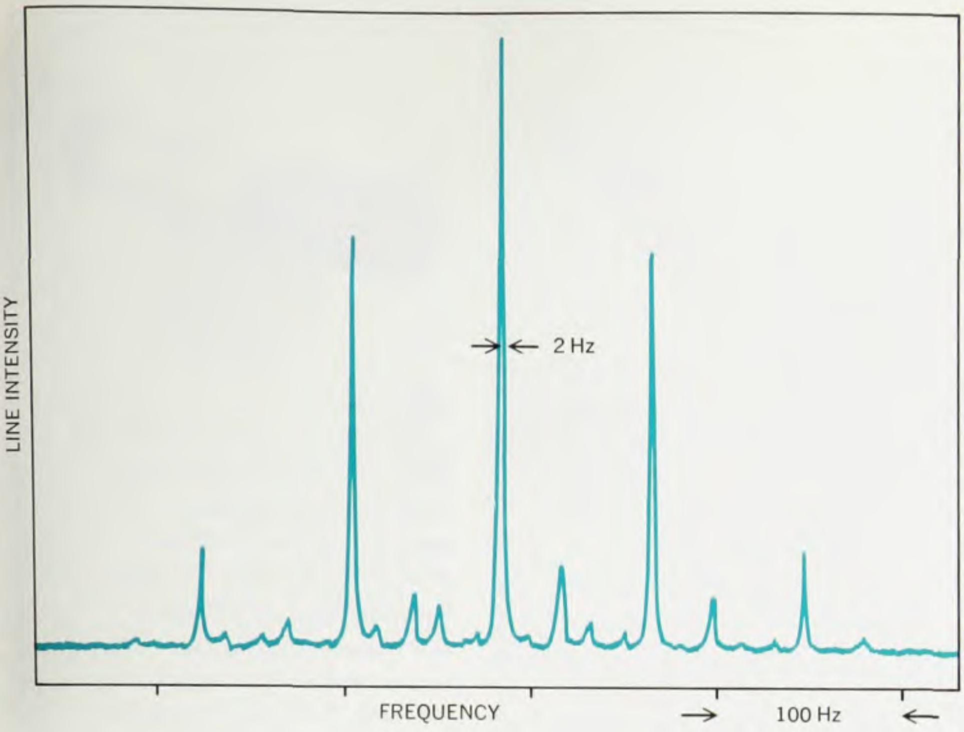
In addition to the built-in errors mentioned above, $\mathbf{J} \times \mathbf{B}$ forces in the winding cause small movements of the conductors when the solenoid is energized. The resulting field effects are dependent upon the magnetic and thermal history of the system; so that separately excited shim coils must be used to correct these transient effects during a given excitation of the magnet.

In summary, a complete magnet for high uniformity consists of a base coil producing the high magnetic field, two large end-correcting coils that destroy the second derivative of the axial field at the center (due to the finite length of the winding), a series first-order trim coil, a series second-order trim coil and separately excited coils for the first- and second-order axial corrections and for first-order radial corrections. Generally this type of system will yield a resolution of about 1×10^{-7}. Small copper coils in the room-temperature bore of the Dewar may be provided for further trimming.

Persistent-mode operation

Superconducting magnet fields are capable of exceptional time stability when the winding operates as a closed superconducting loop, that is, in the "persistent" mode. This is usually achieved with a thermal switch, consisting of a short section of superconducting wire close to a heater winding, connected across the magnet leads. During magnet energization the heater maintains the switch in its normal resistive condition. The usual research magnet has an inductance in the range 5–50 henries, and a switch resistance of a few ohms provides an adequate time constant. Because the division of input current between the magnet and the switch, under steady-current conditions, is inversely proportional to the resistance of the two circuits, no current flows in the switch. Of course, an $L\ di/dt$ voltage appears across the switch and produces a temporary current flow in the resistive link.

When a steady field has been reached ($L\,di/dt = 0$) the switch heater may be turned off, and the switch becomes superconducting. The external current supply may then be reduced to zero, being replaced by an equivalent current



Nuclear magnetic resonance line of boron II isotope at 80.2 MHz in a 58.6 kG field. This line was obtained with a standard 5-mm-diameter NMR sample, spinning in the superconducting magnet with no external shims. The linewidth is approximately 2.5×10^{-8}, which implies a constancy in the magnetic field of the same order as fluctuations in the local value of the earth's magnetic field. Figure 5

through the switch. This is the persistent mode.

Long-term drift tests show that it is possible to construct magnets that have no measurable resistance. For example, the test data in Table 3 were obtained on a Nb–Ti magnet by J. Dadok of Carnegie-Mellon University, who used proton resonance in a 250-MHz time-sharing spectrometer at 58.7 kG (see figure 6).

Here the initial drift in the field H_0 is attributed to a redistribution of flux in the windings (flux creep). The polarity and magnitude of the drift is a function of the polarity and magnitude of the previous change made in the magnet field, and the direction of the drift is fundamentally opposite to that of the field change. By "overshooting" and returning to a given field value, the drift could conceivably be reduced or eliminated.

The time-invariant nature of the field in superconducting magnets in the persistent mode is extremely important for NMR and electron-microscope uses. This mode is also good for most applications because of the low rate of loss of helium.

Magnet systems

Most research magnets are cooled by direct immersion in liquid helium at its normal boiling point, 4.2 K. The basic magnet system thus consists of a Dewar vessel with a suitable insert that supports the superconducting magnet and carries power and control leads to it, plus an external power supply. Essential auxiliary apparatus includes a supply of liquid helium in a separate storage vessel and vacuum transfer tube. The magnetic field may be monitored approximately from the exciting current, but an auxiliary field probe is frequently used as well. Much of this auxiliary equipment is more or less standard, but a few special features and problems relating to magnet operation are worth mentioning.

In principle, any controllable dc source can be used for energizing the magnet. Alloy magnets generally draw current up to about 50 amps, whereas Nb_3Sn tape magnets need about two or three times more current. An exciting voltage of 10 or 20 volts is adequate to give a run-up time of less than a minute for a typical small magnet. The detailed design of the power supply depends on what the magnet is to be used for. A few of the more common special features are as follows:

- ▶ A current regulator that maintains constant field (to about 1 part in 10^4) when the persistent mode (PM) switch is open or not part of the system.
- ▶ Capability of precise current setting (prior to PM operation).
- ▶ Special smoothing (on ac-powered units) to reduce the ac component of the field.
- ▶ Automatic current programming, to generate linear or special-function field sweeps at various predetermined rates.
- ▶ Automatic shut-down, which reduces the output current to zero in case of magnet normalization, to protect the PM switch.
- ▶ Automatic PM operation, which transfers the magnet in and out of PM and reduces operator errors.

Some degree of current regulation and filtering are necessary for proper operation of the persistent-mode switch. The ac component of the input current does flow in the switch and tends to keep the switch wire resistive after the heater has been turned off. Similarly, current drift in an unregulated supply will produce an $L\,di/dt$ voltage across the switch. The resulting joule heating may prevent the switch wire from becoming superconducting.

Precision measurement of solenoid-type high magnetic fields is still a difficult problem. Hall effect and magnetoresistive probes are useful for relative measurements of the axial field component but have little or no value

Table 2. Typical Parameters for Alloy and Compound Superconductors

	Alloys	Compounds
J_c	2×10^5 amp/cm^2	3×10^5 amp/cm^2
H_{c2}	100 kG	>200 kG
t_{op}	0.4	0.2

J_c values are at the middle (inflection) of the J_c–H curve in figure 3.

Table 3. Long-term Drift Test on a Nb–Ti Magnet

Date	Field Shift (relative to initial value)
20 June 1970	0
30 June	+ 9.8 ppm
10 July	+10.9
20 July	+11.7
15 October	+16.75
7 January 1971	+16.9
24 April	+15.8
15 June	+14.6

High-uniformity superconducting magnet with which the NMR spectrum of figure 5 was produced. Table 3 shows its long-term drift characteristics. (Carnegie–Mellon University.)
Figure 6

for absolute measurements. Rotating-coil gaussmeters need isolation Dewars, have rather large sensing elements and are somewhat suspect unless calibrated periodically at or near the operating field. Nuclear magnetic resonance is the most accurate method available, but requires a uniform field over the sample, room-temperature access, expensive equipment and skilled operating personnel. Precision measurement of the magnet current combined with a precise calculation of the coil constant produces a result that is accurate both in magnitude and distribution to better than 1% for all except low values (less than 10 kG) of magnetic field.

The cryogenic aspects of magnet operation still leave much to be desired, although quite dramatic improvements have occurred in the types and varieties of Dewar vessels available during the past decade. A few examples of the new designs include the short (10-inch) Dewar for electron-microscope coils (figure 7), Dewars with variable-temperature sample chambers (1.5 K to room temperature is common), vertical and horizontal room-temperature access Dewars, and Dewars with windows of quartz, beryllium, sapphire and Mylar. With improved stainless steels, good design practices, all-welded construction and adequate testing, units require little maintenance and provide years of trouble-free service.

Costs and reliability

In these days of research-funding shortages, some operating-cost data may be of interest. The following analysis applies to a Nb–Ti, 70-kG magnet system. The various contributions to helium evaporation are shown (as estimates) in Table 4.

From this list, we see that the overall system loss rates are expected to be 0.3 liters per hour in the persistent mode, 0.7 liters per hour in the regulated mode at 50 amperes, and 1.2 liters per hour if the field is swept at one volt excitation near peak field. Of course, if removable power leads are employed, the loss rate can be reduced to as little as 0.1 liters per hour for long-term persistent-mode operation.

These figures, combined with the average cost of cryogenic fluids and technician labor rates in the US, suggest that overall operating costs for an Nb–Ti, 70-kG magnet will range from about \$150 up to about \$500 per week. The lower figure applies to three-month-long persistent-mode operation with power leads removed, the higher figure to weekly cool-down and limited daily field sweep operation.

The nuisance of handling cryogenic liquids, especially helium, is often of more concern than the cost. Unless the operator is experienced, small procedural errors cause large problems resulting in equipment down time, delays

Table 4. Contributions to Helium Evaporation in a Nb–Ti Magnet System

Dewar conduction and radiation with plug in neck	0.1 liters/hr
Heat conduction down electrical leads	0.2 liters/hr
Joule heating in magnet power leads (50 amps)	0.3 liters/hr
Joule heating in PM switch heater (22 mA)	0.1 liters/hr
Joule heating in superconducting switch for 1 volt energization	0.5 liters/hr
Energy loss in windings for 10 000-joule coil (per cycle)	0.1 liters
Insert Dewar (conduction and radiation)	0.1 liters/hr

The hip pocket laser. $415.

Helium-Neon
Power at 632.8nm, TEM_{00}
Power supply: unregulated*
Cold cathode for longer life
Full one-year warranty (Typically 10,000 hrs. operating life)
Rugged, weatherproof construction
Sealed laser head (Ends optics cleaning)
No mirror adjustment required
Linear polarization
Delivery from stock
Quantity discounts available
3 milliwatts
1 ¾″ dia. x 12 ¼″
Model 3076H

Ditto. $355.

Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
Ditto
1 milliwatt
1 ¾″ dia. x 8 ½″
Model 3078H

Circle No. 27 on Reader Service Card

*Available Options: Regulated power supply. Regulated and modulated power supply. 230 VAC input voltage. Weatherproof cases. 12-volt DC in weatherproof case or OEM potted module. 10X collimator and mounting accessories.

HUGHES
HUGHES AIRCRAFT COMPANY
ELECTRON DYNAMICS DIVISION

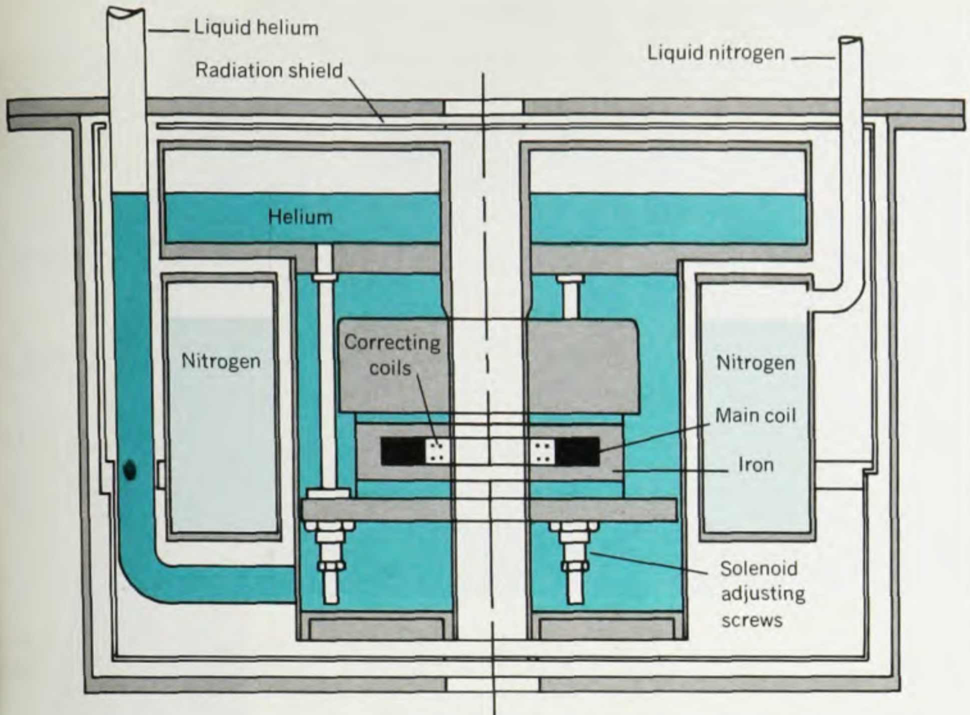
PT-8

☐ SEND INFORMATION
☐ I'D LIKE A DEMONSTRATION
☐ PLEASE RESERVE ___ (QTY.) OF 3706H, ___ (QTY.) OF 3078H.

COMPANY ______________________
ADDRESS ______________________
CITY ______________ STATE ______________ ZIP ______
NAME ______________________

SEND TO: Marketing Manager / Hughes Electron Dynamics Division / 3100 W. Lomita Blvd. / Torrance, CA 90509 / (213) 534-2121.

SEE THEM AT ELECTR **TH 301**



Short Dewar system for electron microscope lens, shown here in a simplified schematic view. The entire assembly is only ten inches high. Figure 7

in schedule, lost time and frustration. There is a real need for a relatively inexpensive "push-button" closed-cycle helium refrigerator. Desirable parameters would be: 0.5 watts cooling power at 4.2 K, 10 000 hours between overhaul and less than \$10 000 cost. Such a refrigerator would enable superconducting magnets to compete with lower-range conventional magnets, and would extend their use to areas where present cryogenic methods are inconvenient; for example, in electron microscopy, or in parts of the world where liquid helium is in tenuous supply.

Very few classes of scientific equipment possess the reliability and longevity of present-day superconducting magnets. The introduction of heavily shunted superconducting wire permitted the manufacture of coils that are consistent in performance and virtually incapable of being damaged by operator error or failure of related equipment. The superconducting switch is an exception; it can be damaged by excess voltage. However, the switch cost is usually only about 1% of the total system cost. There is no evidence that magnet performance changes with time, and no reason to suspect that any change would occur.

What next?

Looking to the future, one highly desirable goal is the development of a ductile superconducting alloy with usable current density in the 100- to 125-kG region. No obvious alloy candidate appears on the horizon for this job. The present compound tapes satisfy the field requirements but have many disadvantages. They are fragile, not easily joined in lossless joints, more expensive in terms of usable J_c, difficult to use in high-uniformity applications, and they require inconveniently high exciting currents. Some of these difficulties are gradually being overcome, and there is also hope for better properties in a new type of composite containing compound multifilaments that is now under development. For example, in Japan, vanadium filaments were embedded in a copper–gallium alloy and then converted into V_3Ga by solid-state diffusion. This material looks promising for magnet application. However, the research-magnet market is so small that there is little economic incentive for the development of new materials; any advances in this field will probably have to depend mainly upon spin-off from larger development, such as the possibility of power applications. □

Bibliography

Further information on the topics discussed in this article may be found in the three publications listed below:

1. P. F. Chester, Rep. Prog. Phys. **30**, 561 (1967).
2. *Superconductivity in Science and Technology*, (M. Cohen, ed.) U. of Chicago Press (1968).
3. V. L. Newhouse, in vol. 2 of *Superconductivity*, (R. D. Parks, ed.), Marcel Dekker, New York (1969).