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Superconducting Magnets in High-Energy Physics

Large-scale magnets that dissipate no electrical power are under construction for high-energy physics research.

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Research in the physics of elementary particles is centered in the national laboratories that build and operate the high-energy accelerators, but major participation by university research groups is an integral part of the program of every laboratory. Beams of secondary particles originating from targets bombarded with the primary particles of the accelerator are steered and focused by magnetic fields; hence all experiments in high-energy physics require many magnets. Rectangular magnets having a uniform field bend the secondary beam to select its momentum. Focusing is accomplished with quadrupole magnets in which the magnetic field is zero on the beam axis and increases linearly with radius. A typical secondary beam may use three or four bending magnets and six to ten quadrupoles. The fields in these beam-transport magnets do not normally exceed 18 to 20 kilogauss since the iron yokes, which provide a return path for the flux of low magnetic reluctance, saturate at about that flux density. Higher magnetic fields can be obtained only by using excessive amounts of electrical power. The bending magnets are typically 2 meters long, and the quadrupoles are 1 meter long, both with apertures of about 20 centimeters. A field of 18 kilogauss over a 2-meter length will bend a beam of momentum 10 Gev/c through 10° (*1*). The 200-Gev accelerator will provide secondary beams of momentum in the range of 100 Gev/c, so even longer magnets will be required in the future.

An experiment in high-energy physics usually consists of observing the interaction or decay of the beam particles in a detector. The detector, placed at the end of the secondary beam, often uses an additional magnetic field. The bubble chamber is one of the most important detectors. In this device the beam particles pass through a superheated liquid, and bubbles are triggered by the energy deposited by the particle. These bubbles, when photographed, show the trajectories of the beam and any secondary particles arising from interactions with the nuclei of the liquid. Liquid hydrogen provides a pure proton target and so is most often used as the sensitive liquid. Deuterium, helium, neon, and hydrocarbons are other liquids that have been used for specific experiments.

High magnetic fields are more important in the detector than they are in the beam transport system for two reasons. First, the detector always consists of some material, whereas beams are usually transported in vacuum. For the detector the multiple coulomb scattering of the particles in the medium distorts the trajectories. The relative accuracy of measurements of momentum, $\delta p/p$, in a homogeneous medium is given by:

$$\frac{\delta p}{p} = \left[\left(\frac{c}{H l^{\frac{1}{2}}}\right)^2 + \left(\frac{c' p}{H l^2}\right)^2\right]^{\frac{1}{2}}$$

where p is the momentum, H is the magnetic field, l is the length of the particle trajectory, and c and c' are constants. The first term within the brackets represents the error from multiple coulomb scattering, and the second represents the error from uncertainties in measurement. The occurrence of momentum in the second term means that, for particles of high momentum, the measurement error dominates; for low momenta, multiple scattering gives the largest contribution to the error. The second reason that high magnetic fields are more important in the detector results from the fact that most particles are unstable, some of them having such short lifetimes that the possible length of track is restricted to a few centimeters. For such particles, and for those in which multiple scattering is most important, a stronger magnetic field is the best way to increase the accuracy.

The beam transport and detector magnets commonly used at the large accelerator laboratories consume more electric power than the accelerator itself. For example, at the Argonne Zero Gradient Synchrotron (ZGS), the accelerator complex consumes a mean power of 20 megawatts whereas the magnets in the experimental area require 30 megawatts; the power requirement will probably double as more experimental areas come into use.

These general considerations show why, as soon as the early results of work on the "hard" superconductors, such as niobium-zirconium and niobium-tin, became known, there was interest at the various laboratories in the technological possibilities of building large magnets that dissipate no electric power.

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Superconductivity in Metals and Alloys

The phenomenon of loss by certain materials of all electrical resistance at temperatures of a few degrees Kelvin has been known for more than 50 years (*2*). The early materials, such as mercury and lead, were all examples of what are now called type I superconductors, in which the current ceases to flow at low magnetic fields; these "soft" superconductors are therefore of no use in making high-field magnets. It was only with the discovery of the properties of other materials, since about 1955, that large, high-field magnets became a real possibility (*3*). The most often used materials at present are various alloys of niobium with zirconium or titanium, and the intermetallic compound niobium-tin, Nb_3Sn. These examples of "hard" superconductors, or type II materials, not only exhibit superconductivity in a high field, but also carry substantial currents.

When placed in a magnetic field, a type I superconductor excludes the magnetic flux from its interior (*4*). Exclusion is achieved because loss-free surface currents which shield the interior are set up. The currents attain a certain depth, and the flux therefore penetrates the materials a short distance. As the magnetic field is raised, the Lorentz force between the surface currents and the field increases; finally, at some critical field H_c, the flux penetrates the superconductor, and the material again becomes a normal conductor. The superconductivity is then said to be quenched. In a type II material, the flux starts to penetrate at a lower critical field, but the superconductivity is not quenched completely until a much higher critical field is reached. When the superconductor is in the intermediate state, between the lower and upper critical fields, it behaves as if there were small superconducting regions embedded in a matrix of normal material.

Superconductivity only becomes possible below a critical temperature, T_c, which is characteristic of the material. At this point, the electrons in the material rearrange themselves in a configuration of lower energy. This energy difference sets up the surface currents that exclude the magnetic flux. The best superconductors are those with the highest critical temperature and the largest density of electron states. Although superconductivity is well understood generally, many important points remain to be investigated.

Table 1. Characteristics of the three most used superconducting materials.

Critical temperature (°K)	Upper critical field, approx. (kgauss)	Current densities, typical (amp/cm²)
	NbZr	
10	70	4×10^5 at 20 kgauss
	NbTi	
9	120	10^5 at 40 kgauss
	Nb_3Sn	
18	250	10^6 at 20 kgauss 10^5 at 100 kgauss

The important properties of the three most-used materials are shown in Fig. 1 (*5*). Such characteristic curves can be obtained by placing a short sample of the material in an external magnetic field and keeping it at the specified temperature by means of a liquid helium bath. The current is increased until the sample becomes resistive. Repeating the experiment at different magnetic fields gives the whole curve. Above the curve, the conductor is resistive or normal. As the temperature is decreased, the sample carries a greater current before a transition from a superconducting to a normal state occurs (Fig. 2). Much of the early excitement over the discovery was generated because the upper critical fields of the materials are very high, and hence it seemed likely that magnets of very high field strength could be made. Table 1 summarizes the properties of these particular materials. Research on other superconductors of possible technological importance is going on, but very few others are commercially available.

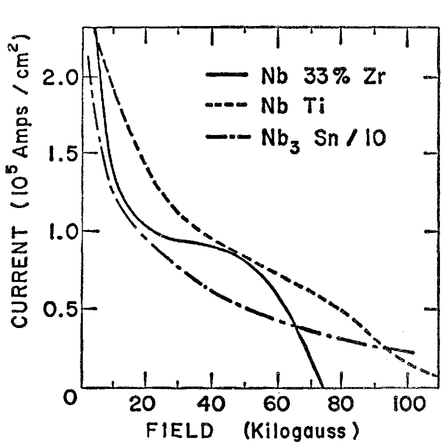

Fig. 1. Limiting curves for current and magnetic field for the three most-used high-field superconductors. Below the curves, the materials are superconducting; above the curves, they revert to normal conductors. Note that a different current scale is used for Nb_3Sn.

As soon as the materials became available, small solenoids with bores of a few millimeters were wound and operated by people in many laboratories. The first niobium-tin magnet was made by a special technique. The solenoid was fabricated of a conductor consisting of a niobium tube containing powdered niobium and powdered tin. After winding, the solenoid was heated for several hours to create the Nb_3Sn. The coil was a one-shot device, for it could not be unwound without destroying the magnet. Niobium-tin ribbon in which a thin layer of the superconductor is vapor-deposited onto a substrate is now available; hence the modern material lacks the defect of the old but is still not robust.

Niobium-zirconium is a much easier material to work with, for it is ductile and easily wound into a coil. Hundreds of solenoids a few centimeters in bore have been made with the use of thin wires of this material to give magnetic fields of volume of a few cubic centimeters and strength up to 50 kilogauss. For some years past, superconducting magnets have provided the simplest and cheapest way of providing magnets of high field and small volume. This has greatly facilitated laboratory work requiring such fields.

Several problems required solution before successful larger magnets could be built. In particular, the current-carrying capacity of the wire was much less than was anticipated on the basis of the results of tests with short samples, such as those shown in Fig. 1. In addition, the problem of dissipating, in a controlled and safe way, the energy stored in the magnetic field needed attention. Neither of these problems was severe for small coils in which both the total cost of materials and the stored energy were low. The great economic gain, however, comes from large magnets which use substantial amounts of superconductors and which store energy in the range of 10^7 to 10^9 joules. Before such large magnets can be built, a complete understanding of the problems involved is essential, including a detailed understanding of coil behavior during quenching.

A superconducting magnet, when cooled below the critical temperature, loses all electrical resistance and then acts as a perfect inductance of value L. If a small voltage, V, is applied to the

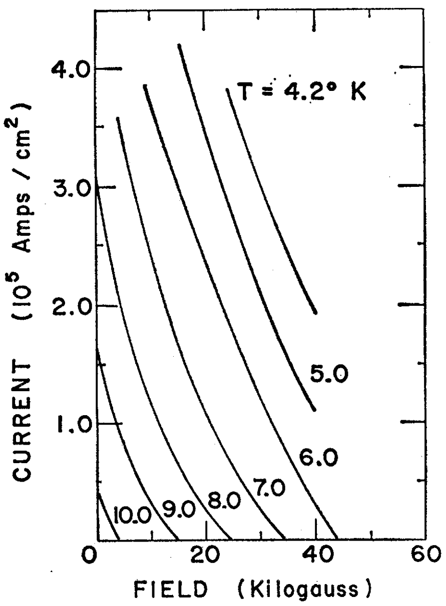

Fig. 2. Variation with temperature of the curve for current and magnetic field for heat-treated niobium-zirconium. The sharp fall of maximum current with increasing temperature, at a fixed magnetic field, is the most important feature.

coil, the current increases so that $L(dI/dt) = V$. Initially, the superconducting wire excludes all flux, but at the lower critical field the flux starts to penetrate the wire and does so in discrete quanta. Soon there are bundles of flux isolated in normal regions of the wire and surrounded by superconducting regions. The flux bundles are thought to be pinned in position by impurities and defects in the material. As the field is strengthened, the Lorentz force on the flux lines increases, finally causing a flux bundle to jump to a new site in the material. Since the magnetic field has different values in different parts of the coil, the jumps occur over a wide range of currents. The distribution of current in the superconductor itself is dependent on the magnetic field. Hence the current redistributes itself during the charging. When the changes in the distribution of current and field occur, a small amount of energy is converted into heat, causing a local but small rise in temperature. As can be seen from the characteristic curves of Fig. 2, as the temperature rises, the maximum current carried by the wire decreases. At some value of coil current, there may occur a flux jump that causes a small part of the coil to exceed the critical temperature for that current. When this happens, a small part of the conductor becomes resistive, and large amounts of heat are generated immediately. The normal resistance of the materials is very high. The big rise in temperature propagates through the coil, both along the conductor and through the body of the coil. This regenerative effect causes the coil to quench, and the energy of the magnetic field is released into the coil and eventually into the liquid helium. At first, the energy is all released in the small region of the coil that first became resistive and, if the time constant of the decay of the field is very short, enough energy can be deposited locally to melt the conductor at that point and destroy the coil. The voltage developed across the normal region is proportional to the rate of fall of current, and it can easily be high enough to cause a turn-to-turn arc and hence melting of the coil.

Flux jumps are not the only triggers that cause a coil to quench. Early experiments showed that the structural integrity of the coil is very important. As the coil is charged, the forces on the conductors change. Unless the coil is designed to withstand the forces, some part of the conductor may move. This movement of a conductor across the flux lines induces eddy currents in the normal regions of the conductor, and the associated joule heating can trigger a quench.

If the coil does not quench, it remains quiescent with the power supply voltage given by the product of the current and resistance of the current leads. If it has a superconducting switch that can be used to short the magnet, the leads can be removed after the magnet is charged; then the field remains at full value as long as the temperature remains constant.

Some Bubble Chamber Magnets

All these effects were known by about 1962. At that time, a group from Carnegie Institute of Technology and Argonne National Laboratory started to design a helium bubble chamber to be equipped with a superconducting magnet. The aim of the project was to build a device large enough to work usefully and competitively in the physics of elementary particles but small enough to have a reasonable chance of success (*6*). The bubble chamber chosen was a cylinder 25 centimeters in diameter and 35 centimeters long with a magnetic field between 40 and 50

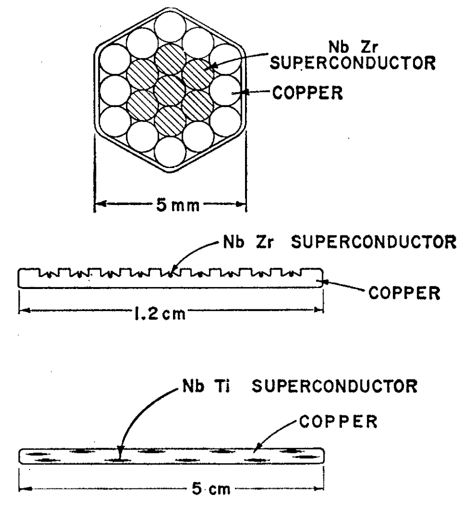

Fig. 3. Some typical stabilized conductors. Cross section of a typical conductor (top) in which copper strands and superconducting strands are cabled together. Two strips of copper in which the superconductor is embedded are shown below. The three conductors are illustrated on different scales.

kilogauss. A bubble chamber that could operate with hydrogen, deuterium, or helium was chosen for reasons important in high-energy physics and because the cryogenic engineering problems posed by the superconducting magnet were simplified by use of a cryogenic bubble chamber. The magnet consisted of six pancakes each 1.25 centimeter thick and 50 centimeters in outside diameter (*7*). Each pancake was layer-wound with copper-coated NbZr wire 0.25 millimeter in diameter. External shunts were placed every other layer. Copper rings were placed between layers. This construction permitted the energy released during a quench to be dissipated safely and reliably. Both the copper rings and the copper coating on the wire provided transformer secondary windings which lengthened the time constant of the system. As the flux collapsed, currents were induced in the copper in such a direction as to oppose the collapse of flux. During a quench, much of the energy was deposited in the shunts which were external to the magnet. The magnet achieved 32.8 kilogauss on a test, but by the time it was completed, obviously superior techniques were available (*8*).

The quality control in some of the early material was not good, so the technique of using a single strand of superconductor as the only path for the current meant that one small bad section could limit a whole pancake.

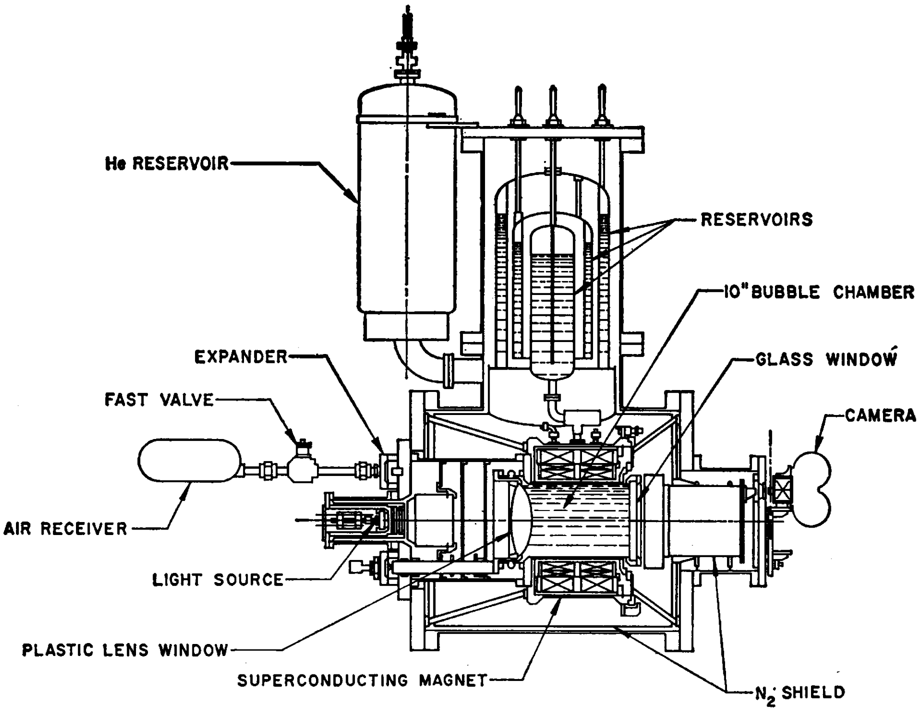

Fig. 4. Assembly comprising helium bubble chamber and superconducting magnet. The chamber, 25 centimeters in diameter, is surrounded by the superconducting magnet in its own cryostat. The maximum magnetic field achieved with this system was 44.4 kilogauss. Expansions are made by moving the plastic lens which is attached to the chamber body by an omega bellows. Two helium reservoirs are used: the small central one operates at atmospheric pressure (4.2°K) for the magnet; the large side reservoir is pumped to a pressure of 250 millimeters of mercury and controls the temperature of the chamber.

Another problem came from the use of epoxy resin to hold the wires. The poor thermal conductivity of this material made it difficult to provide adequate cooling in the middle of the coils. Several people, in different laboratories, realized that the solution to these difficulties was a composite conductor consisting of many parallel superconductors in intimate contact with some normal conductor—usually copper. There are many ways of making a conductor of this type. The simplest technique is to cable strands of superconductor and copper together and to impregnate the resulting conductor with indium. This simple solution allows wide variation in the proportions of normal material and superconductor. The method was originated at Argonne, and a second bubble chamber magnet was wound from such cables (*9*) (Fig. 3). To ensure good cooling of the superconductor, the magnet was wound with stainless steel mesh between layers, allowing the liquid helium to penetrate the structure. The parallel paths of superconductor meant that any bad section in a single strand was shunted by the remaining strands. The copper provided the secondary windings of the transformer and, in addition, could pass the current in case all the strands of superconductor in a section became resistive. The rise in temperature associated with such a condition depends on the degree of cooling; in a well-designed coil it can be small enough to prevent complete discharge of the coil.

A drawing of the bubble chamber assembly is shown in Fig. 4 (*10*). The helium reservoir was pumped to a pressure of 250 millimeters, and the resulting cold helium was circulated in the chamber wall to keep the temperature at 3.2°K. The superheating necessary to make the chamber sensitive was provided by lowering the pressure momentarily by moving the plastic lens window outward. The beam entered the chamber in a direction perpendicular to the page, and the tracks were photographed by three cameras on the right. The superconducting magnet (Fig. 5) was in its own helium container supplied with 4.2°K liquid from the central top reservoir. In a 3-week period during March 1966, 400,000 photographs were taken in a low-momentum K-meson beam at the Argonne ZGS. During the run, the magnet was kept at 40.5 kilogauss with a stability better than 0.1 percent. This field required a current of approximately 500 amperes. In tests preceding the accelerator run, a maximum field of 44.4 kilogauss was attained.

For large magnets it is more convenient to use a strip conductor, a strip of copper with the superconductor embedded in it. Two such composite conductors, that are commercially available, are shown in Fig. 3. The relation between current and voltage of

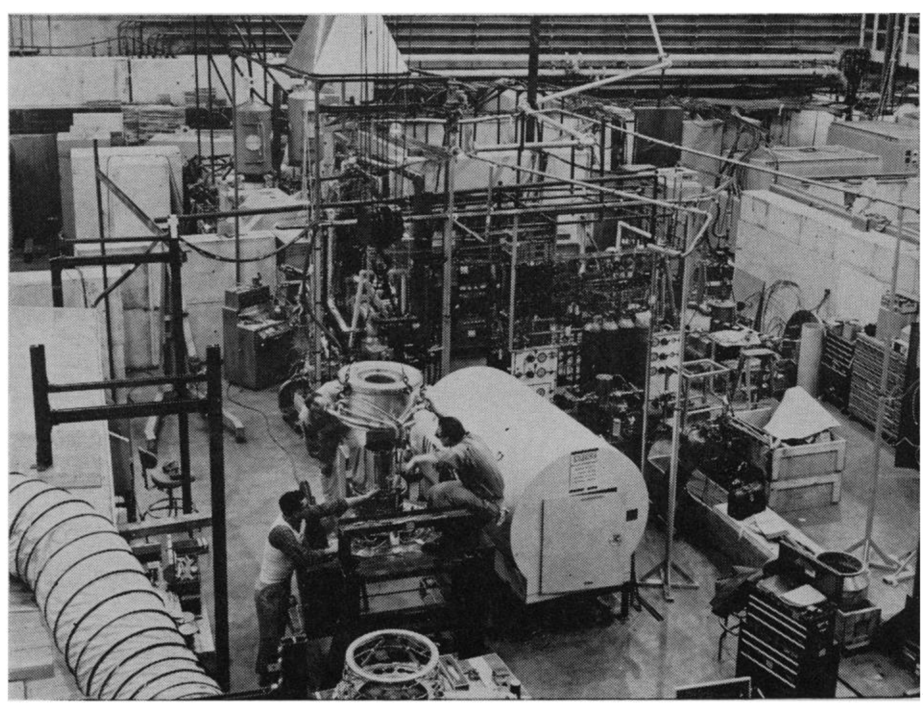

Fig. 5. The ZGS experimental area during assembly of the helium bubble chamber. The superconducting magnet in its cryostat is being lowered over the chamber body.

a magnet wound with the smaller of these two is shown in Fig. 6 (*11*). Up to about 700 amperes the material is completely superconductive, no voltage appearing across the coil. At about this current, the superconductor reaches its limit, and there is excess current in the copper. The slope of the voltage-current line at 800 amperes is given by the resistance of the copper. On reduction of the voltage, the same curve is followed. This remarkable behavior allows large magnets to be designed that need never quench, provided the limits given by the current-voltage curve of the material are not exceeded. Such a coil is said to be fully stabilized. For a sufficiently high voltage, the magnet can be driven normal but the stabilization allows a substantial margin, sufficient to prevent small disturbances, such as flux jumps, from triggering a quench. Many variants of stabilized conductor are commercially available. The exact manufacturing details are proprietory to the individual manufacturer, but for the NbZr or NbTi conductors heat treatment or work hardening is used to enhance the current-carrying capacity of the superconductor. The curves shown in Fig. 2 are for heat-treated NbZr, whereas those shown in Fig. 1 are for untreated material. A large gain in current-carrying capacity is evident. Hence a much smaller amount of superconductor is needed for a given magnet. This is of prime importance only for large magnets, where the cost of materials is a critical factor in design.

For large magnets the space occupied by the winding is small in comparison with the volume of magnetic field, and current density in the material is therefore not a critical parameter. It is in magnets of this type that the stabilized materials are finding their initial application. The first magnet built completely of stabilized material was a model for a magnetohydrodynamic electrical generator (*12*). It provided 40 kilogauss in a cylinder 150 centimeters long and 30 centimeters in diameter.

I now return to applications in high-energy physics. After the success of the small helium chamber magnet, it was decided to construct a superconducting magnet for the large hydrogen bubble chamber being built at Argonne. The magnetic field of 20 kilogauss is to be provided in a cylinder almost 5 meters in diameter and 3.0 meters high. An iron yoke will be used to ensure uniformity of field. The advantages of a

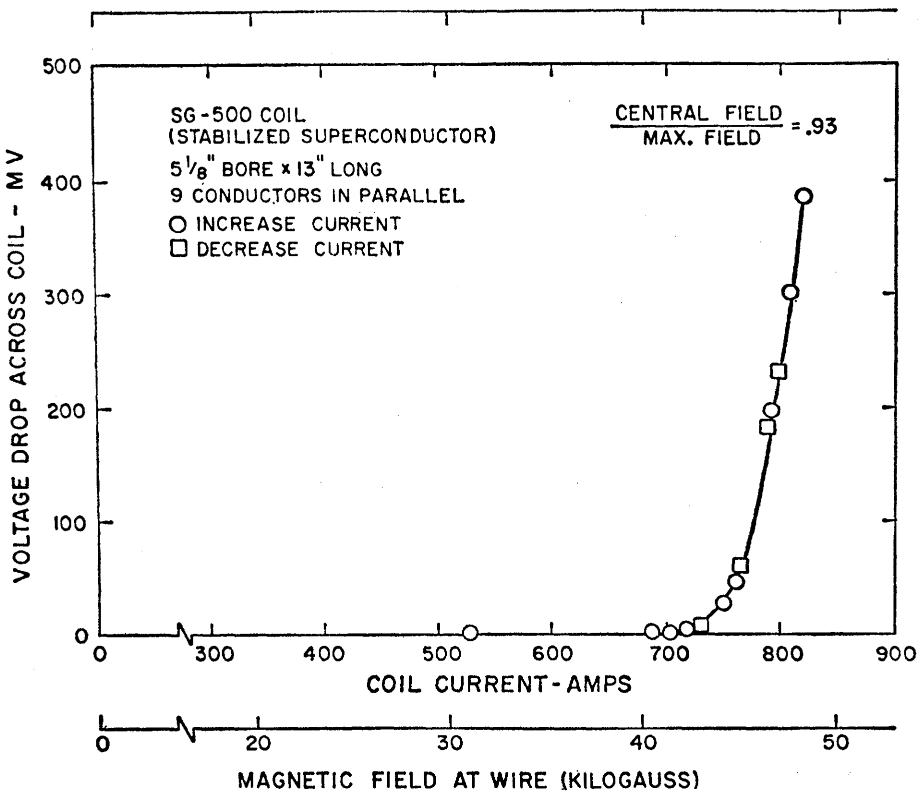

Fig. 6. Current : voltage relation of stabilized superconducting strip. At about 700 amperes, the superconductor has reached its limit; the excess current then flows in the copper substrate. Provided that the cooling is adequate, anywhere on the line is a stable operating point, but a normal operating point is on the zero-voltage part of the curve.

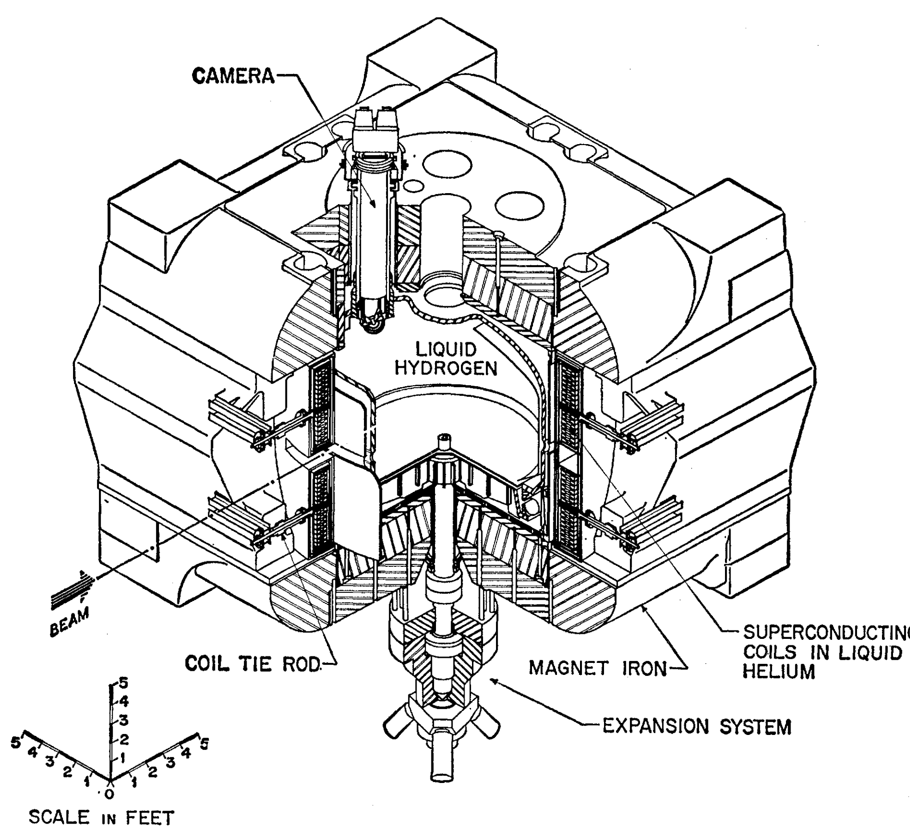

Fig. 7. The 3.7-meter hydrogen bubble chamber under construction at Argonne National Laboratory. The pancake construction of the superconducting magnet can be seen. The magnet is hung from the top iron and constrained horizontally by tie rods.

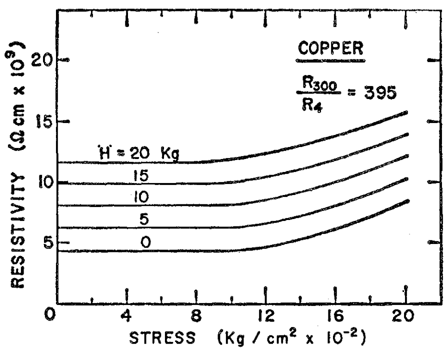

Fig. 8. Resistivity of copper at 4.2°K as a function of magnetic field and stress. The increase in resistance due to the magnetic field and to stressing of the copper is evident.

superconducting magnet in this application are purely economic. The field could have been generated by a conventional magnet using 10 megawatts of power. The capital costs of the two systems were very similar, but the superconducting magnet requires only 300 kilowatts of power to operate the helium refrigerator and the magnet power supply. Hence the savings in operating costs when the chamber comes into operation at the end of 1969 will be substantial. The decision to use a superconducting magnet in this application indicates the degree of confidence in the new technique.

Liquid hydrogen at 28°K fills the chamber, and the refrigeration used for that will also be used as one stage of the helium refrigerator. Only a little more refrigeration will be needed to keep the magnet at 4.2°K. It is not planned to move the chamber, which is expected to operate most of the time. The refrigeration requirements will be quite modest while the magnet is running, but would be much greater if the magnet required frequent chillings from room temperature. The conductor will be wound into pancakes with the use of copper strip (0.254 by 5 centimeters) with the superconductor embedded in it (Fig. 3). The pancakes will be stacked in a closed liquid helium bath such that the helium cools the edge of the strip (*13*). This magnet is very conservatively designed, so much so that it can operate briefly with all the current passing through the copper.

With the iron ensuring a uniform field, the force on the conductor will be a uniform hoop stress contained by the copper and a uniform axial compression taken by spacer blocks between pancakes. The magnet (Fig. 7) will be hung by eight tubes from the iron that will be kept at room temperature. The tubes allow for the contraction of the magnet during cooling. In addition, eight tie rods will be used to carry the stress coming from any possible misalignment of the coils in the iron.

The copper used as the normal conductor in a supermagnet must be selected with care. The important parameters that determine the resistance at the operating field and temperature are the magnetoresistance, the increase in resistance due to the stress, and the decrease in resistance due to temperature (*14*). Figure 8 shows these parameters for some particularly pure copper having a resistance decrease of a factor of 400 between room temperature and 4.2°K. On large samples a value of 200 is more common. Aluminum may also be used in high field magnets, for its magnetoresistance is low (*15*). Knowledge of the rate of heat transfer from copper to liquid helium, the resistance of the copper, and the characteristics of the superconductor permits a stable magnet to be designed with confidence. The specifications of this particular magnet are given in Table 2.

The electrical circuit is shown in Fig. 9. Under normal conditions the 0.001-ohm resistor will be in parallel with the coil, and the time constant will be about 2 hours. Hence the power supply may be disconnected for short periods without discharging the magnet. In an emergency, all the helium will be driven out of the magnet container, the power supply and stabilizing resistor will be disconnected, and 90 percent of the energy will be realeased in the 0.5-ohm energy dump resistor with a time constant of 80 seconds. The helium container surrounding the magnet is made of aluminum and so acts as a low-resistance transformer secondary in case of field collapse. Two to three days will be required to cool the magnet from room temperature to operating temperature. The magnet can be charged in 2 to 3 hours.

Table 2. Specifications of 3.7-meter hydrogen bubble chamber magnet.

Item	Value
Field	20 kgauss
Ampere turns	5×10^6
Current	2000 amp
Conductor dimensions	5×0.254 cm
Inductance of winding	40 henrys
Pancakes, number	30
Energy stored in field	80×10^6 joules
Copper in windings, weight	45,000 kg
Superconductor, weight	300 to 450 kg
Hoop stress on winding	420 kg/cm^2
Coil, axial compressive force	6.8×10^5 kg
Iron, weight	1.45×10^6 kg
Coil, inside diameter	478 cm
Coil, length	304 cm
Power supply, voltage	10 volts
Charging time	2.25 hours
Heat transfer, rate required for complete stability	100 mw/cm^2
Stabilizing copper, resistivity at 20 kgauss field	1.7×10^{-8} ohm • cm

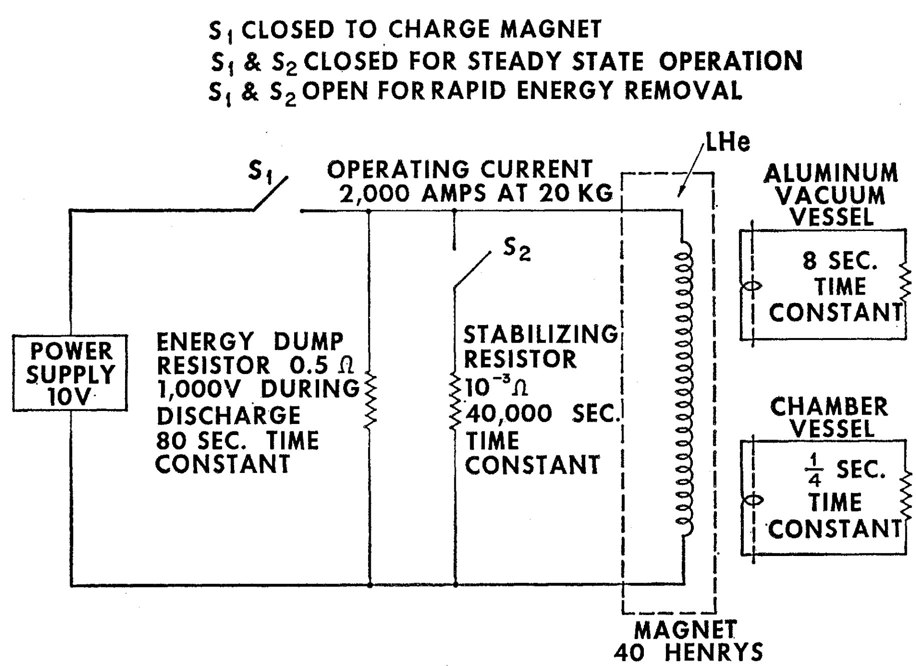

Fig. 9. Circuit of magnet with 3.7-meter hydrogen bubble chamber, showing the protective system.

Similar bubble chambers are under design at Brookhaven National Laboratory (*16*) and CERN in Geneva, except that the fields in these magnets are to be in the range 30 to 35 kilogauss, so that face cooling of the conductor will be required to ensure stability. The magnets of higher field also have a much more severe coil-support problem and may need a reinforced conductor. The magnets are still in the early design stage, although a model of 2-meter diameter is being built at Brookhaven.

Other Supermagnets in High-Energy Physics

In addition to the large magnets just mentioned, superconductors are finding applications in beam-transport magnets and special, small-bore, very high field detector magnets. At Brookhaven, small quadrupoles have been made with Nb_3Sn ribbon (*17*). By exploitation of the very high current density possible with this material, field gradients of 10 kilogauss per centimeter were obtained in a 5-centimeter bore. Such high gradients are very difficult to achieve with copper. For the 200-Gev machine, such high gradients will make possible very substantial cost savings because of the shorter focal lengths of the quadrupole magnets (*18*). In a beam of secondary particles, many individual magnets are spread along a beam line that may be up to 500 meters long. Studies of the problem of distributing the refrigeration over such large experimental areas have shown that various solutions are possible, many allowing substantial cost savings relative to the use of conventional magnets (*19*). Reliability and simplicity of operation remain open questions and will probably be the determining factors that govern the date of routine operation of superconducting magnets in beam-transport systems.

To achieve magnetic fields of 100 kilogauss or above, one must operate with mean current densities in the range 10,000 to 50,000 amperes per square centimeter. In this case, it is not possible to provide enough normal material to stabilize the magnet in the sense mentioned above. Fortunately, at very high fields, the magnetic flux itself seems to stabilize the magnet. Such magnets have obvious problems in routine operation and must be operated below the peak capability. At Brookhaven, a small-bore 120-kilogauss magnet is being used in an experiment to measure the magnetic moment of the negative cascade particle (*20*). Many other laboratories have built magnets (with bores of a few centimeters) with fields over 100 kilogauss with the use of Nb_3Sn ribbon. This article has not emphasized them, because their application in high-energy physics is rather specialized.

In principle, superconducting magnets do not need a power supply, once the equilibrium current is obtained. Some magnets have been operated in this persistent mode, although the small resistance at the junction of different lengths of superconductor does lead to a slow decay of the current for large magnets. An experiment in which particles of the cosmic radiation are used will use a magnet operated in the persistent mode (*21*). The power supply will not be part of the ballon payload since the magnet will be charged on the ground and the power supply will be disconnected before the flight.

Unsolved Problems

Some problems are unique to superconducting magnets. The flux jumps are an indication that the current density in the superconductor is neither uniform nor independent of magnetic field. For ribbon conductors, in particular, different current distributions may lead to small changes in the field shape. In some magnets, when the current is reduced to zero, persistent current loops are induced in the conductor, particularly at the ends of the coil. These currents can give fields of a few kilogauss which cannot be removed, except by warming the coil above the critical temperature. Magnets operated in the persistent mode are also very sensitive to movement of ferromagnetic material in the vicinity. The flux distribution in the magnet changes to assume a minimum-energy configuration so that one must be careful about working near such a magnet.

Superconducting magnets are not usually pulsed because the process of charging and discharging the magnet shows hysteresis and so significant energy losses. Since the energy must finally be dissipated in the liquid helium, refrigeration is very expensive. The guide fields on all the high-energy accelerators are pulsed, so that superconducting magnets do not find an immediate application to the primary accelerator itself.

Summary

The promise of superconductivity making possible large magnets that dissipate no power is now being realized. Most of the early difficulties have been overcome; hence it is now a straightforward engineering problem to design and build a large stable supermagnet. The application of such magnets to research in high-energy physics can be expected to grow rapidly in the next few years.

References and Notes

1. In the physics of elementary particles, particle energies are usually measured in electron volts (ev); 1 Gev = 10^9 ev. The relativistic equation connecting total energy E, momentum p, and rest mass M is $E^2 = p^2c^2 + m^2c^4$, where c is the velocity of light. It is then convenient to measure momentum in energy units divided by the velocity of light c, that is, Gev/c.
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