SUPERCONDUCTING MAGNETS IN HIGH ENERGY PHYSICS

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ABSTRACT

The applications of superconducting magnets in high energy physics in the last ten years have made feasible developments which are vital to high energy research. These developments include high magnetic field, large volume detectors, such as bubble chambers, required for effective resolution of high energy particle trajectories, particle beam transport magnets, and superconducting focusing and bending magnets for the very high energy accelerators and storage rings needed to pursue the study of interactions between elementary particles. The acceptance of superconductivity as a proven technology in high energy physics was reinforced by the recognition that the existing large accelerators using copper-iron magnets had reached practical limits in terms of magnetic field intensity, cost, space, and energy usage, and that large-volume, high-field, copper-iron magnets were not economically feasible. This paper will describe some of the superconducting magnets and associated systems being used in and being developed for high energy physics.

INTRODUCTION

Although the first superconductor, mercury, was discovered in 1911, and so-called type II or "hard" or "high-field" superconductors were tested as early as 1925, it was not until the 1950's that a few small superconducting magnets were built which generated only modest magnetic field intensities. These magnets served as the prelude for the major efforts which were quickly mounted following the decisive breakthrough made by Kunsler et al, with the development in 1961 of the very high-field high-current-carrying intermetallic compound Nb$_3$Sn. Recognizing the potentials of this compound, within a few days after the announcement of the discovery, scientists and engineers in the high energy physics community at the various laboratories began avid pursuit of people working to develop superconductors, seeking information and encouraging further developments. Within a short time, Nb$_2$Ti alloys were produced in long lengths of wire, and these alloys were soon supplanted by the more ductile alloys of NbTi, which also had superior superconducting properties, and which are still used in most magnet applications today.

Most early superconducting magnets exhibited an unsable parameter characterized by "degradation" or failure to reach the current or field intensity expected from tests on short samples of the conductor and "training" or an improved performance after each transition of the superconducting magnet to the normal state. "Degradation", or premature quenching, is usually attributed to the process of "flux-jumping" which is a sudden discontinuous field change accompanied by rapid heating as flux penetrates the conductor. The phenomenon depends on the intrinsic properties of the hard type II superconductors. "Training" is in a large measure attributed to conductor motion resulting from electromagnetic forces, but there may also be other causes.

Stabilization against flux jumping was first achieved about 1964 with the development of "fully stabilized" or "cryostatically stable" conductors. Such conductors consist of superconducting filaments in close thermal, electrical, and mechanical contact with sufficient normal metal of high electrical conductivity so that during a transient instability the current may transfer to and be carried by the normal metal without the temperature of the conductor rising above the level at which the superconductors may return to the superconducting state. Early conductors of this type were multistrand cables of twisted superconducting and copper wires impregnated with indium or solder. Later, fully stabilized composite conductors in the form of NbTi strands or rods co-drawn in a round or rectangular copper matrix became available.

The fully stabilized composite conductors are appropriate for very large devices with large amounts of stored energy such as bubble chamber magnets but their low overall current density...

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makes them unsuitable in compact high-field magnets such as those used as bending and focusing magnets in accelerators. The need for stable, high current density conductors led to the development of other stability criteria. "Adiabatic" or "enthalpy" stabilization is achieved by subdividing the superconductor into many fine filaments, each of small enough cross section that the energy dissipated during an adiabatic flux jump can be absorbed by the material itself without its temperature rising to the level which would cause a transition from the superconducting to the normal state.

In "dynamic" stabilization, a balance must be established between the generation of heat caused by the movement of magnetic flux in the superconductor and the rate of removal of this heat. This is achieved by combining the superconductor with a small amount of normal metal to slow down the flux motion and increase the time for the heat being generated to escape.

More recently, "intrinsically" stable multifilamentary conductors have been developed which consist of a twisted composite wire containing many fine superconducting filaments metallurgically bonded in a high conductivity normal metal matrix. The diameter of the filaments is chosen not only for stabilization against flux jumps, but also to minimize power losses in the conductor under ac or pulsed conditions. The filaments are twisted in the metal matrix to effectively decouple each filament electrically from the others. This type of conductor is commercially available in many forms and has seen increasing use in many applications.

There are many examples of different types of superconducting magnets that have been developed for high energy physics at laboratories in the United States and elsewhere in the world. However, in order to describe several applications of magnets for high energy physics in some detail, the discussion shall deal primarily with magnets that have been and are being constructed at Brookhaven National Laboratory (BNL) and will mention only briefly several magnets at other laboratories.

**LARGE DETECTOR MAGNETS**

One of the early applications of cryostatically stable NbTi conductor was for the superconducting magnet for the Brookhaven 7-foot Bubble Chamber. This magnet, which is shown in Fig. 1, was the largest split-pair, air-core superconducting magnet anywhere when it was initially energized in 1968. It was constructed of double-layer pancake coils of 2.4 m i.d. and 2.75 m o.d. and weighs 18,600 kg assembled.

The magnet was designed to produce a central field intensity of about 3.0 T with a current of 6000 A in the conductor and there is at that current a stored energy of 51 MJ in the field. It has been operated routinely with the bubble chamber for the high energy physics program at BNL for well over 2000 hours, usually generating a magnetic field intensity of about 2.5 T.

The design of the superconducting magnet was begun at a time when stabilized superconducting cables were being used to wind many magnets. Because of the irregular cross-sectional geometry of the cables it was considered difficult to support them against large electromagnetic forces, and, consequently, stabilized strip conductors were investigated. Copper was selected as the stabilizing material and a winding configuration was designed which allowed a large percentage of the face area of the strip conductor to be cooled by direct contact with liquid helium.

Figure 2 is a schematic view of a section of a coil layer of the superconducting magnet. Each turn of a coil layer is wound with four components which are, in order radially outward: the stabilized superconductor, an adhesive-backed Mylar insulating strip, a stainless steel reinforcement member or reinforcing strip, and a copper cooling channel spacer strip which allows liquid helium to contact 90 percent of the face of the conductor.

The stabilized superconductor consists of six parallel Nb-46% (by volume) Ti filaments metallurgically bonded within a 30.8 X 2.0 mm OFHC copper substrate. Each NbTi filament has a cross-sectional area of approximately 2.4 mm². The copper to superconductor ratio is about 6:1. This conductor is an early version of stabilized strip conductor, and, because the NbTi filaments are not twisted around each other, long time-constant eddy currents are generated in loops consisting of the filaments and the copper between them when the magnetic field is changed. The maximum perturbation on the main field of these eddy currents varies from about 0.018 T at the center of the magnet to approximately 0.115 T near the magnet windings.

A dominating concern in the design of large, high-field magnets is the problem of support for the thermal and electromagnetic stresses. The 0.3 mm thick stainless steel strip wound in with the conductor in this magnet aids in supporting the stresses in the magnet windings. A design parameter for this magnet was to limit the stress in the copper to a value less than
about 12.0 kG/mm² because at higher values of stress the electrical resistance of the copper begins to increase. The stress could be limited by increasing the amount of copper beyond that required for stabilization, but a less expensive technique, in this case, was to use a separate support strip whose strength properties are superior to copper. The maximum stresses in the copper and the stainless steel at 6000 A and 3.0 T central field would be 10.8 and 28.0 kG/mm², respectively. The contribution of differential thermal contraction to the stress in the copper is about 0.9 kG/mm² (tensile) while that to the stress in the stainless steel, is 4.7 kG/mm² (compressive). It should be noted that the stainless steel in this configuration does not support the major portion of the hoop forces, but does tend to restrain any possible "creep" in the copper.

As shown in Fig. 1, the magnet consists of two halves which are separated by an I-section bridge structure to allow for the entry of particle beams to the bubble chamber inside the magnet. The layers of the magnet are separated by Micarta insulating spacers which are slotted to permit radial and axial flow of liquid helium. At 3.0 T the attractive force between the coil halves is 1150 tons or slightly greater than 10⁶ kG. This force, in turn, bearing on the edges of the conductors at the phenolic spacers, produces a maximum compressive stress in the copper of the conductors of about 7 kG/mm². The pitch of the spacers is, therefore, a compromise between the open space necessary for the helium coolant and a reasonable stress level in the copper.

The overall current density in each half of the magnet at 3.0 T, including all mechanical structure, is 2.6 X 10⁶ A/cm². The superconducting magnet system requires approximately 300 kW of power, the major part of which is for refrigeration. Only about 6 kW are needed to maintain the field of which only a small fraction is dissipated in the cold magnet, the remainder being dissipated in room temperature cables and connections. A conventional copper-iron magnet generating the same magnetic field over a comparable volume would require around 20 MW of power.

The superconducting magnet for the 7-foot Bubble Chamber has been described in some detail to illustrate some of the considerations involved in the design of such large magnets and to give a perspective for the parameters of these magnets.

Figure 3 shows a larger later generation superconducting magnet being assembled, the air core magnet for the 15-foot Bubble Chamber at Fermi National Accelerator Laboratory. This magnet has an inner winding diameter of 4.25 m and an outer winding diameter of 5.1 m, and with an overall current density of 1885 A/cm², generates a central field intensity of 3.0 T. At this field, the stored energy is 396 MJ. Figure 4 shows the vacuum tank for the magnet which contains the magnet and its helium vessel. The vacuum tank has a 4.0 m clear bore for the bubble chamber.

Figure 5 shows a more modern version of a strip conductor used for the 15-foot Bubble Chamber magnet. The conductor consists of four components: the center strip contains NbTi filaments which are twisted to minimize eddy current and embedded in copper, two outside copper strips which are grooved to allow flow of helium, and a copper backing strip. These four components are soldered together.

The Fermi Lab magnet is one of the largest magnets constructed thus far.

BEAM TRANSPORT MAGNETS

One of the more extensive applications of superconducting magnets in High Energy Physics is as dipole bending magnets in beam transport systems which direct particle beams from the accelerators to detectors. Two examples of such magnets will be described, the 80° bending magnet (3) and the bending magnets for the High Energy Unseparated Beam at Brookhaven. (4)

The 80° bending magnet system was the first superconducting primary beam transport system placed in routine operation in an "on-line" application where its successful operation was critical to the entire high energy physics program scheduled for the accelerator for discrete periods of time. The system has been operated "on-line" for approximately one-third of the total AGS physics running time since October 1973, deflecting the primary proton beam from the accelerator to the 7-foot Bubble Chamber and several other experimental setups. Failure of the superconducting magnet system would result in these experiments being turned off. Since October 1973, the magnet system has been opened only once to replace a defective gas-cooled lead which had overheated.

The magnet system consists of two magnets, each 2 m long, which at fields up to 1.7 T, deflect protons with a maximum momentum of 30 GeV/c by 80°. The two identical magnets are of the rectangular aperture "window-frame" type as shown schematically in Fig. 6 with an iron core surrounding the rectangular cross section coil package except at the ends where the conductor is bent up to permit passage of the beam pipe. The magnet cross section, shown in Fig. 6, is 37.8 cm high by 43.5 cm wide and the aperture or inner diameter of the warm
The iron core which is closely coupled around the coil, reduces the ampere turns required for magnetic fields below iron saturation by a factor greater than 2. Above 2.0 T systematic aberrations due to saturation require an auxiliary correcting coil which is approximately an air core sextupole. The excitation required of this correcting coil commences at approximately 2.0T and increases linearly to several percent of the dipole ampere turns at 4.0 T. By using the single auxiliary correcting coil with the dipole coil in a predetermined way, magnetic fields comparable in precision and predictability to those of conventional magnets can be obtained at all levels of excitation. Figure 7 shows one of the magnets being wound and illustrates how the conductor is bent at the ends to permit passage of the beam pipe.

The dipole coil is wound with 340 turns of a commercial NbTi superconducting composite with a rectangular cross section of 1.4 mm by 1.9 mm. This conductor contains 361 NbTi filaments, each approximately 75 microns in diameter, embedded in copper with the entire matrix twisted one turn per inch. The copper to superconductor ratio is 1.25 to 1.0. At 4.0 T the current density in the dipole conductor is 3.03 X 10^4 A/cm^2. The correcting coil conductor was formed by further reducing the dipole conductor to one-fourth its cross section. The current density in this conductor is also about 3 X 10^4 A/cm^2. The conductors are insulated with a thin layer of Formvar.

Figure 8 shows sections of the main dipole coil and the auxiliary correcting coil. In this figure can be seen the sheets of anodized high purity aluminum which are placed between the vertical layers of the coils. These aluminum sheets are grooved to provide helium coolant channels over 50% of one face of the conductor layer and the anodized surface of the aluminum provides additional interlayer insulation in the coil. Excellent thermal and dynamic stability are provided by the high thermal conductivity and diffusivity of the aluminum which cause locally produced heat to be dissipated rapidly into helium over a large area. Since helium is the only significant heat sink at magnet operating temperatures, this mechanism inhibits quenching. If a quench is initiated, however, it is propagated rapidly transversely and longitudinally so that high voltages and temperatures are not generated in the coils of the magnet.

The coils are wound on a stainless steel bore tube without bonding agents and are free to move longitudinally during thermal cycles. The use of the aluminum interlayer spacers provides a coil structure such that the coil turns are constrained to move outwards against the supporting iron under magnetic pressure as coherent vertical layers. Such coherent coil movement changes the aspect ratio of the rectangular aperture very slightly and has a completely negligible effect on the magnetic field. A completed magnet module is shown in Fig. 9.

The two magnets showed very little training, both reaching a maximum field of about 4.4 T after only a few quenches. The field measurements indicated that the magnetic field distributions in the two magnets are identical and agreed with computations to better than one part in 10^4 over their useful aperture and over the entire range of field. Measurements have also shown a field uniformity \( B/B_0 \) of 10^{-4} over essentially the full aperture at low fields and over about 60% of the aperture at 3.8 T.

The magnets cryostats are connected to a CTI Model 1400 helium refrigerator by about 37 m of transfer line in a closed cycle. A 1000-liter helium storage dewar is connected in parallel as backup. Figure 10 shows the magnet-refrigerator system during tests. Refrigeration performance is monitored remotely by observation of magnet dewar transducer readouts. Magnet charging, control and monitoring are also done remotely. Figure 11 shows the two magnet dewars installed in a tunnel in the proton beam line.

The 80° bending magnet system has also been used to study the effects of radiation heating on superconducting magnets, since such magnets for accelerators and primary beam lines can be accidentally quenched by beam heating.

A beam of \( 8 \times 10^{12} \) protons at 28.5 GeV/c passing through the 80° magnets in a curved trajectory with the beam center only 2 cm from the beam pipe at various locations has an energy of about 40 kJ in a 3 µsec pulse. The 80° magnets have been quenched well over 50 times by accidental missteering of this beam and during radiation studies.

In these studies the magnets have demonstrated great thermal stability, surviving 3 µsec thermal pulses delivering up to 1 kJ into the cold magnet at repetition periods as short as 1.3 sec, and absorbing thermal transients before quenching with almost an order of magnitude greater heat input than expected from considerations of the enthalpy of the conductor.

The radiation heating studies are important for the very large superconducting accelerators being planned for the future.

bore vacuum pipe is 7.2 cm. The iron core which is closely coupled around the coil, reduces
The High Energy Unseparated Beam line at Brookhaven contains four large superconducting dipoles which bend a secondary beam by 20°. These magnets are of the cosine 2 type and are of similar but not identical design to the prototype magnets being developed for the very large colliding beam accelerator at Brookhaven called "ISABELLE". The HEUB dipoles and the "ISABELLE" magnets consist of a single layer of wide braided conductor distributed around the circular aperture of each magnet in discrete groups and graded into a current distribution varying azimuthally as the cosine of the angle from the median plane as shown in Fig. 12. The discrete groups are separated by insulating spacers of filled epoxy and the grading within each group is done by interleaving a spacer braid of copper wires. The spacer braid is made of copper wires to reduce the thermal barrier between turns and thereby aid azimuthal propagation of normal zones during a quench. The increased azimuthal propagation in addition to longitudinal propagation along the conductor braid helps to distribute the heat from a normal zone more rapidly through the coil windings and decreases the possibility that excessive temperatures may be generated in local sections of the coil.

The HEUB dipoles have laminated cylindrical iron shields which are constructed in two halves with the split on the median plane. The two halves are keyed and held together by 1.3 X 5.1 cm stainless steel girth bands on 25 cm centers. The magnet coil assembly is inserted in the shield by a shrink fitting technique after the two shield halves have been welded together and integrally honed. After the coil-shield assembly reaches a uniform temperature of 300°K throughout, the girth bands are stressed at approximately 130 N/mm², still well below the elastic limit. Sextupole and decapole field correction coils are incorporated in the design as shown in Fig. 12, in the form of l-block approximations to cos 3 φ and cos 5 φ distributions, located internal to the main winding and wound from series connected strands cabled from the same basic composite wires as in the main conductor.

The HEUB dipoles have a warm bore of 20 cm, a winding i.d. of 25 cm, and a winding thickness of 2.03 cm. The iron laminations have an i.d. of 29.8 cm and an o.d. of 81.2 cm. The lamination stacks are 2.5 m long. Each magnet weighs about 10⁶ kg. A magnetic field intensity of 4.0 T is generated with a current of 2650 A in the conductor. At this current the overall current density in the coil is 1.9 X 10⁴ A/cm² and the energy stored in the field is about 1 MJ.

The conductor for the HEUB dipoles consists of a flat braid of 95 wires, each 0.305 mm in diameter, with 1.2 twists/cm and with a 10 μm layer of Cu-10 wt% Ni on the outside to reduce eddy currents. Each wire contains 517.9 μm NbTi filaments embedded in OFHC copper, with a nominal Cu/Sc ratio of 1.25:1. The braid is partially impregnated with a soft alloy, In-7 wt % Pb, chosen for its heat capacity which improves conductor stability. The metallic braid impregnant causes considerable "coupling" owing to the reduced electrical resistance between touching wires. The effect of this coupling is to introduce a charge-rate dependent magnetization superimposed on the d.c. magnetization of the superconductor. The use of the copper-nickel jacket decreases the time constant of this magnetization to less than one minute and minimizes the field distortion caused by this effect.

Figure 13 shows a HEUB magnet assembled in the center section of the cryostat, and Fig. 14 shows the cryostat after assembly has been completed and installed in the beam line. All four of the HEUB magnets reached or exceeded the design field of 4.0 T after a number of "training" quenches. In actual operation, the integral sextupole component of the field can be reduced to less than 4 X 10⁻⁴/cm² at all field levels by using the sextupole trim coil.

The refrigerator for the HEUB beam line is a large model 4000 CTT unit which has a capacity of 1500 W at 4.5 K with liquid nitrogen precooling. Without precooling, the capacity is reduced to 900 W. The refrigerator has redundant sets of expansion engines and requires about 500 kW of compressor power to achieve rated capacity. The refrigerator liquefies helium in a 4000 liter capacity storage vessel from which liquid is supplied to the four magnet cryostats through a single line 83 m long. The system operates in closed cycle.

The first two magnets were installed and first operated in September 1976, and the second pair were installed and first energized in the beam line in December 1976. Since that time, the four-magnet system has been operated routinely for the High Energy Physics Program.

ACCELERATOR RING MAGNETS

The application of superconducting magnet technology to high energy physics has focused at Brookhaven on the magnet system for the Intersecting Storage Accelerator, ISABELLE. This accelerator facility will consist of two interlaced magnet rings which provide the bending and focusing fields for protons circulating in opposite directions at energies up to 400 GeV. The configuration shown schematically in Fig. 15 will be essentially a circle broken by six symmetrically placed long straight segments where the counter-rotating beams will cross and collide, making available interactions energies up to 800 GeV. The ISABELLE project will
The ISABELLE magnet system will be superconducting because of the enhanced performance capability and reduced electric power consumption made possible by this approach. There will be a total of 1096 superconducting magnets in the two storage rings whose circumference will be 3834 m. The design field for the bending magnets is 5.0 T. The electric power required for the superconducting magnets is estimated at 6 MW and that for the cryogenic system at 15 MW. The use of conventional iron magnets with copper or aluminum windings would require that the circumference of the rings be 2.5 to 3 times as large and the electric power demand for operation about 3 times as great.

ISABELLE will operate in conjunction with the Alternating Gradient Synchrotron (AGS) at Brookhaven. A number of pulses of protons from the AGS will first be stored in the magnet rings, then accelerated from 30 GeV to 400 GeV and then stored again prior to colliding the counter rotating protons in the intersecting interaction regions. The operation is complex and requires high performance magnets with large warm bore apertures and very precise magnetic field profiles and control.

The program at Brookhaven for the last several years has been directed toward developing superconductor dipoles and quadrupoles on which the design of the magnet storage rings for ISABELLE could be based. One meter long models were first constructed and more recently a full-sized quadrupole and a number of full-sized dipoles have been constructed, both in-house and by outside companies, and tested.

The ISA dipole magnets are of the cosine φ type, wound from a single layer of wide braided superconductor. The maximum field that can be generated from this design for a given current density depends on the aspect ratio of the conductor. The larger the aspect ratio (width/thickness) of the conductor in the magnets the higher the peak field obtainable from a layer of the magnet. The conductor is similar to that for the HEUB dipoles and consists of ninety-seven 0.305 mm wires which have been transposed in a braid. The braid is impregnated with a metallic filler, compacted, and insulated with a barber-pole wrap of fiber glass and epoxy. Each wire contains many fine filaments of NbTi embedded in copper and twisted, and is sheathed with a thin layer of Cu-Ni. Figure 16 shows photomicrographs of the individual wires and the braid, and shows photographs of the braid and a cross section of a quadrant of the magnet winding. The spaces in each of the coil blocks of the magnet not occupied by conductor, contains copper braid to aid in the azimuthal distribution of heat during a quench. The wedges between coil blocks are molded from a filled epoxy which has shrinkage properties similar to the blocks.

Each coil half of the magnet is wound and then pressure molded at an elevated temperature to form a monolithic structure. The halves are mounted on a circular bore tube containing field shaping windings and held by epoxy fiber glass bands which have been precisely machined to provide a predetermined fit in the cylindrical iron core as shown in the isometric drawing in Fig. 17. The fiber glass epoxy bands and the inner tube around which the coil halves are mounted are grooved to allow the flow of helium.

In the assembly process, the cylindrical laminations comprising the iron core are stacked and then, by a thermal shrink fit, slid into the stainless steel support tube. The bore of the laminations are carefully honed. The coil assembly, held together by the epoxy fiber glass bands, is then cooled by the liquid nitrogen and inserted in the laminations. When temperature equilibrium is reached between the coil assembly and iron laminations, a predetermined preload is achieved which helps to restrain mechanical motion during subsequent magnet operation and reduces "training" of the magnet.

The prototype superconducting dipole magnets tested thus far were designed for an earlier, lower energy storage accelerator. These magnets have a coil inner diameter of 12 cm, are 4.25 m long, and weigh approximately 5000 kg. The tests were conducted in both pool boiling helium and with forced convection using helium gas at 15 atm. The design field of approximately 4.0 T was attained with most magnets after several quenches and a field of approximately 3.0 T in two cases with forced convection at slightly reduced temperatures.

A prototype magnet for the 400 X 400 GeV storage accelerator has been assembled and will be tested in the near future. This magnet differs from previous models in that it is longer, 4.75 m, has more turns in its windings, and is designed to generate a field of 5.0 T. This magnet and the magnets in the ISABELLE storage rings will be cooled by forced convection of helium gas at 15 atm passing through the grooves at the inner and outer surfaces of the magnet coils. The return gas from the magnet is used to cool a heat shield surrounding the magnet in its cryostat.
Figure 18 is a schematic of two magnets as they would appear side-by-side in the ISABELLE rings. Figure 19 shows two cryostats containing ISABELLE model dipoles connected in series for a half-cell test.

Figure 20 is an artist's rendering of the ISABELLE ring and the associated buildings and the relationship of the new accelerator to the existing AGS which will serve as the injector.

A second major effort in superconducting accelerator magnets is presently underway at Fermilab and is directed toward the construction of the Fermilab Energy Saver/Doubler. The Energy Saver/Doubler is a superconducting magnet synchrotron to be installed in the Main Ring tunnel of the Fermilab 500 GeV accelerator. This superconducting synchrotron should be capable of accelerating protons injected from the present Main Magnet Ring to energies up to a maximum of 1000 GeV. Approximately 800 22-foot long superconducting dipoles operating at a peak field of 4.3 T together with 240 quadrupole magnets will be required for the Energy Saver/Doubler.

Figure 21 shows a schematic of a Fermilab double layer dipole magnet (6) which approximates a cosine $\frac{x}{a}$ distribution. Figure 22 shows several dipoles of an initial group of 20 which are being installed in series under the present Main Ring magnets.

The thrust of high energy physics toward ever higher energies that are available and will be available at colliding beam accelerators at CERN in Europe, at SLAC, and at ISABELLE has led to the very active consideration of larger and more complex superconducting magnets for detector arrays. Magnets producing toroidal, solenoidal, and dipole fields are being discussed and evaluated. Although some of these magnets may have a diameter of 5 to 6 m, a length of 10 m, and weigh with an iron flux return as much as 4000 tons, the accumulated experience in superconducting magnet construction over the past 20 years brings to these considerations a large degree of confidence.

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REFERENCES


6. Private communication from FR Huson, Fermi National Accelerator Laboratory.
FIGURE 1. THE 7-FOOT BUBBLE CHAMBER SUPERCONDUCTING MAGNET
FIGURE 2. A SCHEMATIC VIEW OF A SECTION OF A COIL LAYER OF THE 7-FOOT BUBBLE CHAMBER SUPERCONDUCTING MAGNET
Figure 3. Assembly of the superconducting magnet for the FNAL 15-foot bubble chamber
FIGURE 4. THE VACUUM VESSEL FOR THE FINAL 15-FOOT BUBBLE CHAMBER SUPERCONDUCTING MAGNET.
FIGURE 5. THE CONDUCTOR FOR THE FNAL 15-FOOT BUBBLE CHAMBER MAGNET
Fig. 6 Crossover-section of the superconducting transport magnet

Figure 6. Cross-section of the 8° superconducting bending magnet.
FIGURE 7. A VIEW OF THE 8° SUPERCONDUCTING MAGNET BEING WOUND SHOWING THE END CONFIGURATION
FIGURE 9. A COMPLETED 8° MAGNET MODULE
FIGURE 10. THE MAGNET-TRANSFER LINE-REFRIGERATOR SYSTEM FOR THE 8° SUPERCONDUCTING MAGNETS
FIGURE 11. THE $8^\circ$ SUPERCONDUCTING MAGNETS INSTALLED IN THE PRIMARY PROTON BEAM LINE
FIGURE 12. A SCHEMATIC OF HEUB DIPOLE CROSS-SECTION
FIGURE 13. HEUB MAGNET ASSEMBLED IN CENTER SECTION OF CRYOSTAT
FIGURE 14. HEUB MAGNETS INSTALLED IN BEAM LINE
FIGURE 15. A SCHEMATIC OF THE BROOKHAVEN INTERSECTING STORAGE ACCELERATOR, "ISABELLE"
Figure 16. "Isabelle" Conductor and Coil Winding
FIGURE 17. ISOMETRIC DRAWING OF AN "ISABELLE" DIPOLe MAGNET
FIGURE 18. SCHEMATIC OF TWO MAGNETS IN THE "ISABELLE" RINGS
FIGURE 19. TWO "ISABELLE" MAGNETS IN A HALF-CELL TEST
FIGURE 20. ARTIST'S RENDERING OF THE "ISABELLE" ACCELERATOR
FIGURE 21. SCHEMATIC OF A FERMILAB DOUBLE-LAYER SUPERCONDUCTING DIPOLE ACCELERATOR MAGNET
FIGURE 22. INSTALLATION OF SUPERCONDUCTING MAGNETS FOR THE FERMILAB ENERGY SAVER/DOUBLER UNDER THE MAIN RING