THE ISABELLE MAGNETS
A Brief Description

P.F. Dahl

Addendum

In November of 1981, after the first full-size ISABELLE cable-wound dipole was tested, the Magnet Division established a deadline of the end of March, 1982, for the successful testing of six such prototype magnets. This goal was attained on time, but after this booklet had gone to press. Figures (a) and (b) show the combined results for all magnets. From Figure (a) (where the magnets are listed sequentially in the order they were actually tested), it is seen that all dipoles reached the design field of 5.0 T without training. Subsequent training at the bath temperature of 4.5 K, where the initial quench tests are normally performed, was very slight, with an average quench field plateau (for ramp rates up to the ISABELLE ramp rate of 8 A/sec) of approximately 5.5 T. At substantially faster ramp rates a slight increase in field was in fact generally observed.

Each magnet was also tested at lower as well as, in a few cases, higher bath temperatures. The results under these conditions are shown in Figure (b). Here vertically displaced pairs of symbols represent repeated runs yielding training statistics; in these cases the lower symbol represents the first quench field, and the upper symbol the quench field plateau. Judging by the change in slope of temperature vs. field below approximately 3.3 K, and the temperature dependence of measured conductor short sample currents, some training is encountered in this region. In spite of this, quench fields of 6.0 T were routinely reached at the lower temperatures. Although short superconducting dipoles have equaled and even exceeded this field level, this performance is believed to constitute a record for full-size superconducting accelerator magnets.

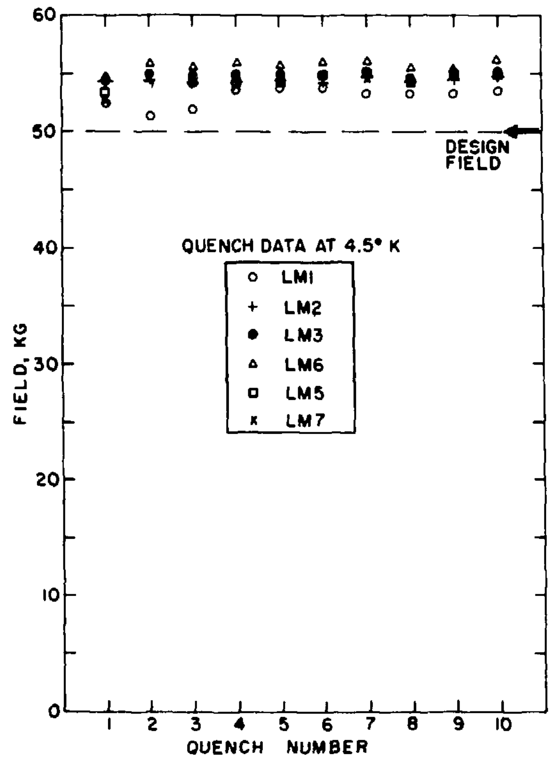

Figure (a) Training curves for dipoles, LM1,2,3,5,6, and 7, for a bath temperature of 4.5°K.

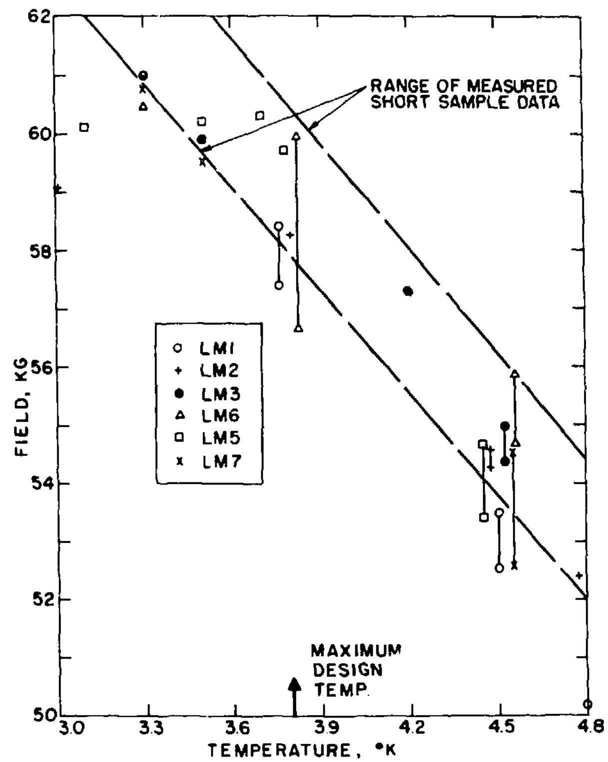

Figure (b) Quench field vs. bath temperature for dipoles LM1,2,3,5,6, and 7.

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A BRIEF DESCRIPTION

P.F. Dahl

January 1982

ACCELERATOR DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

under contract no. DE-AC02-76CH00016 with the
UNITED STATES DEPARTMENT OF ENERGY

ABSTRACT

The modified ISABELLE dipole design, adopted in the fall of 1981, is briefly described, and the assembly procedure and performance of initial prototype magnets summarized. The new magnets incorporate a cabled superconductor wound in a two-layer coil configuration, supported by a laminated split iron yoke. In all cases the prototype magnets reach short sample performance on the first quench, and exhibit virtually no training; eddy current effects are negligible as well.

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January, 1982

ISABELLE, the 400×400 GeV proton-proton colliding beam facility presently under construction at Brookhaven National Laboratory, will utilize superconducting magnets for guiding two beams of high energy protons on adjacent and interlaced circular paths within two 3.8 km long vacuum chambers. The two counter-rotating beams will meet nearly head-on in 800 GeV collisions at six symmetrically placed intersection points. Study of the collision debris will throw new light on the nature of the fundamental constituents of matter.

Approximately 730 dipoles, or bending magnets, are required for the two rings, as well as 350 quadrupoles, or focusing magnets. The maximum dipole field required, for 400 GeV operation, is 5.0T. The corresponding quadrupole field gradient is approximately 60 T/m. Although the earliest full-scale model magnets for ISABELLE date from 1975, the magnets have been the focus of an intense R&D program in the intervening years, primarily to ensure routine operation at full field level with little or no "training", and negligible eddy current effects at the ISABELLE ramp rate. The most significant modifications were implemented in 1981, when the magnet design was basically frozen and a series of prototypes initiated. This booklet contains a brief description of this design and the magnet assembly procedure, with emphasis on the dipole magnets — technically the more demanding of the two types of magnets —, and summarizes the performance of the initial prototype units.

MAGNET DESIGN

A cross section of a dipole magnet is shown in Figure 1. The magnet assembly consists of an inner cylindrical vacuum chamber surrounded by a composite cold bore tube supporting the two-layer main superconducting coil. The coil is clamped firmly under compressive prestress in a laminated split yoke of low carbon steel, which in turn is contained within a heavy-walled stainless steel yoke support tube. The cold bore tube contains helium cooling passages in the form of helical slots, and a set of concentric nested trim coils (also superconducting). Each dipole is 4.75 m long, with an inner main coil diameter of 13.1 cm, and weighs approximately 7 tons. (The quadrupoles have the same radial dimensions, but are approximately 1/3 as long). Cooling is by means of forced circulation of gaseous (supercritical) helium at a maximum temperature of approximately 3.8 degrees Kelvin. The yoke support tube serves as the outer wall of the high pressure helium containment vessel.

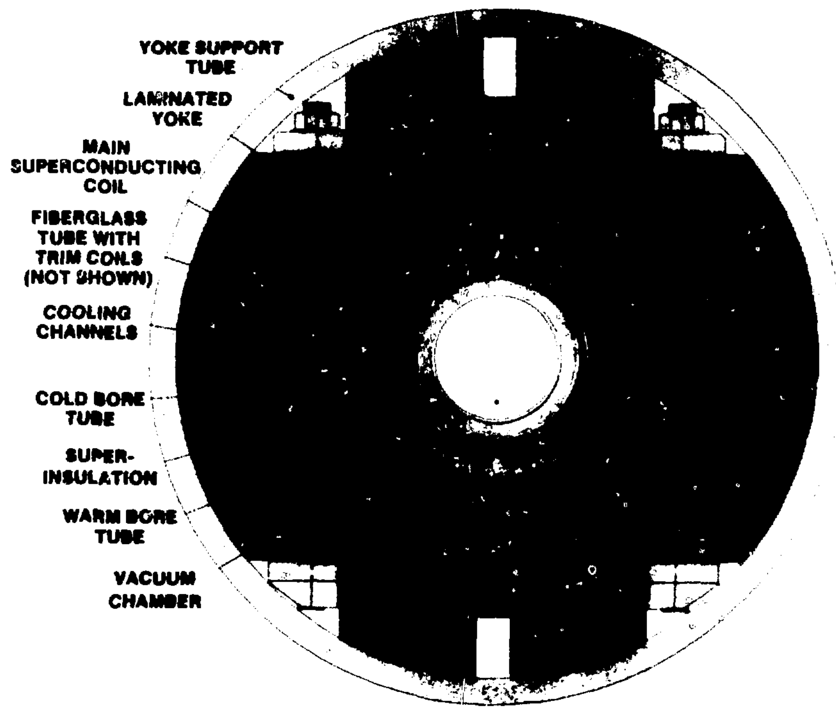

Figure 1. Cross section of ISABELLE dipole magnet. The inner coil diameter is 13.5 cm.

COIL CONFIGURATION

The main coil winding geometry, variously known as a "cosine" or "intersecting ellipse" winding, is a two-layer approximation to the ideal current density distribution required around the periphery of a cylindrical aperture to produce a uniform field within that aperture (or uniform gradient in the case of quadrupoles). It is wound from a cabled conductor, described below. Uniformity of the two-dimensional field distribution is optimized (i.e., higher order field multipoles minimized) by the inclusion of coil spacers or wedges, one per quadrant in each coil layer. In addition, the three-dimensional field shape, or total field integral along the magnet axis, is controlled by inserting spacers in the coil ends; these end spacers also serve to reduce the considerable field enhancement normally experienced near the ends of saddle coils. This enhancement is further reduced by shortening the iron lamination length relative to that of the coil length.

In the absence of iron, this coil configuration has a central field transfer function, B_0/I, of 8.8 Gauss/ampere. With an iron yoke of infinite permeability,

$B_o/I \approx 15.0$ Gauss/ampere. With the yoke geometry in Figure 1, and finite permeability (low carbon steel), saturation at $B_o = 5.0T$ reduces the transfer function by approximately 11%, or $B_o \approx 13.3$ Gauss/ampere.

THE CONDUCTOR

The conductor, shown schematically in Figure 2, is a flat cable fabricated from an initially round helical cable twisted from 23 multifilamentary superconducting wires. This cable is shaped by compaction into an approximately rectangular and keystoned cross section 0.78 cm wide and of 0.125 cm mean thickness. Each wire, 0.69 mm in diameter, is a twisted composite strand, coated

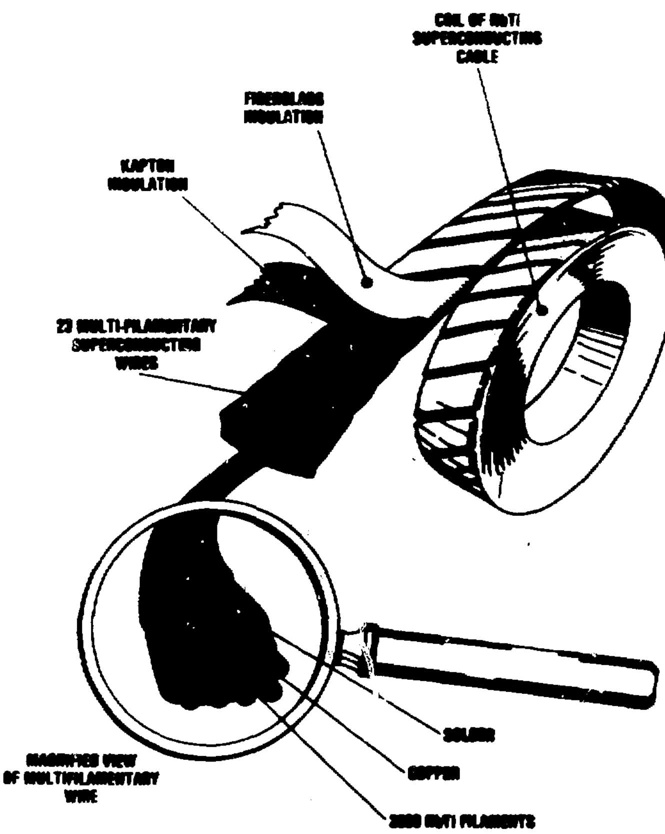

Figure 2. Schematic drawing of 23-strand superconducting cable. The cable is approximately 0.78 cm wide.

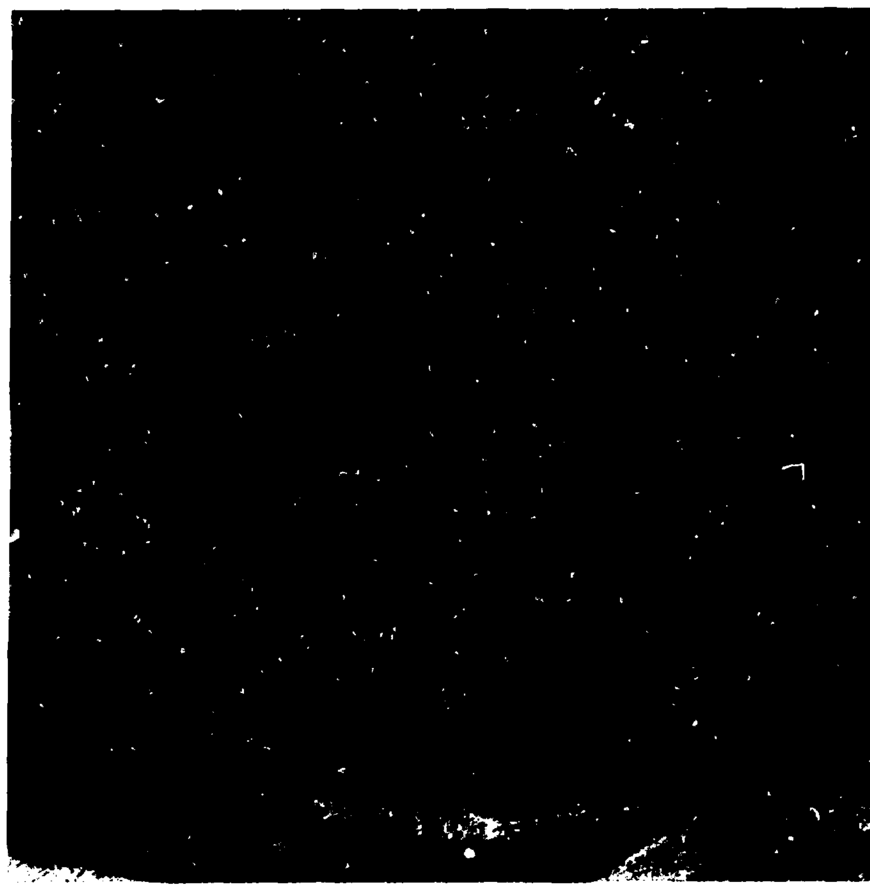

Figure 3. Cross section of superconducting wire, containing 2100 NbTi filaments embedded in a copper matrix. The wire diameter is 0.69 mm.

with silver-tin solder, and contains approximately 2100 superconducting NbTi filaments embedded in a copper matrix (Figure 3). The filament diameter is 10 μm, and the ratio of copper to superconductor is 1.75. The cable is spiral wrapped with two layers of (1 mil) Kapton and one layer of (3 mil) fiberglass tape insulation. This conductor has a current capability of 5000 amperes at 5.0T and 4.2K, well in excess of the magnet design current of approximately 3800 amperes corresponding to the nominal ISABELLE operating field of 5.0T at 400 GeV.

ASSEMBLY

Each half coil is wound separately in a winding/molding fixture, as shown in Figure 4, and is cured in several stages under pressure. The bonding agent is

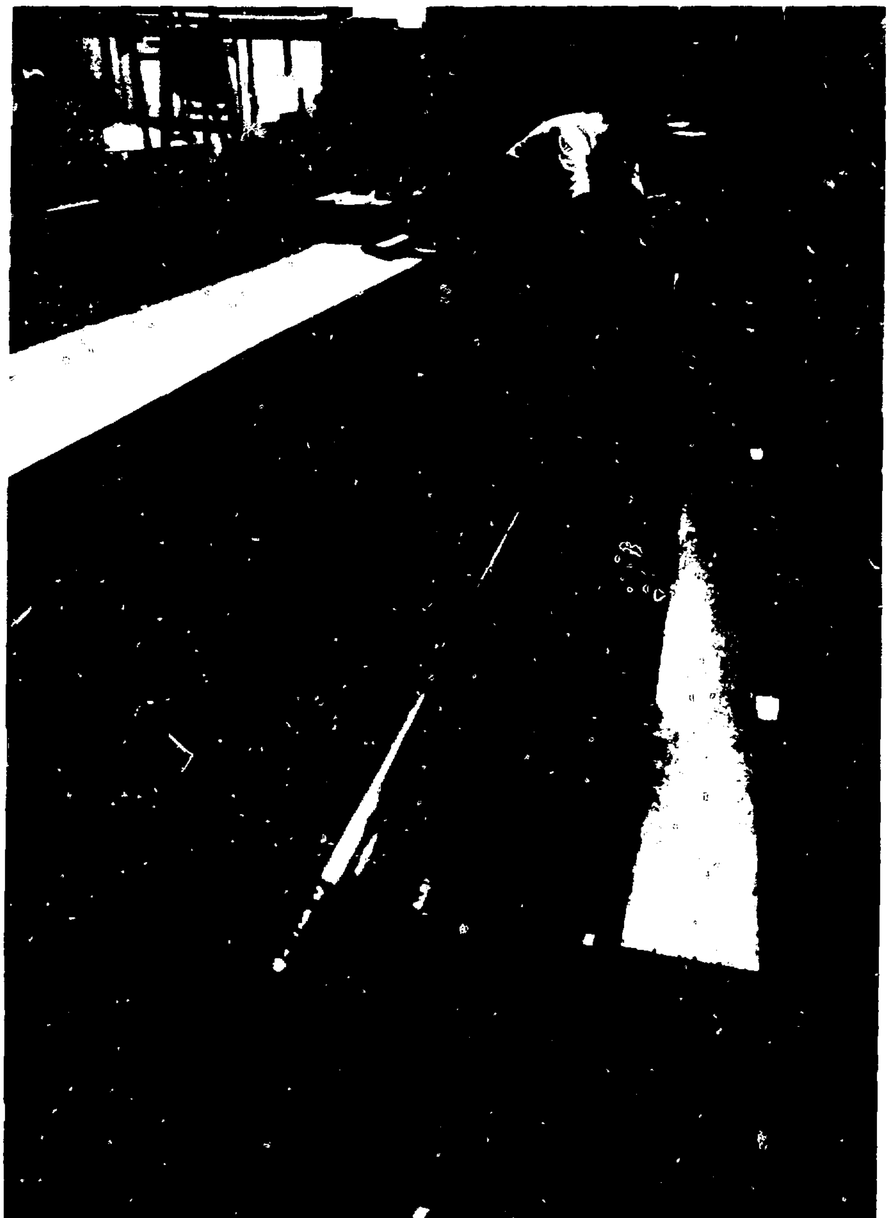

Figure 4. Half of a completed dipole coil in the winding fixture where the coil is cured in several stages under pressure.

epoxy previously applied to the fiberglass insulation between turns. A layer of Kapton and Teflon is inserted between coil layers, these interfaces acting as slip-planes to minimize friction associated with movement of the coils relative to their bearing surfaces. G-10 fiberglass ground insulation is also introduced between coils and pole spacers, between coil layers, and between the coils and the iron yoke (the latter layer being grooved for helium passages). During coil insertion into the iron yoke a temporarily introduced mandrel is expanded, before bolting the two yoke halves, thus applying outward pressure on the coils. At a preliminary stage in closing the yoke this mandrel is removed; prior to final closing the fiberglass bore tube is introduced in its place. This bore tube, also provided with helium cooling grooves, fits snugly only at the ends so that elsewhere there are no forces between it and the coil.

The yoke, cooled by helium, by its close proximity to the coil contributes about 40% to the field and reduces the stray field from the magnet to tolerable levels. The split yoke design, Figure 5, is essential for achieving the necessary coil prestress and allows excellent stress and dimensional control (as well as easy extraction of coils from yoke, if desirable). The yoke halves are bolted to apply a compressive azimuthal prestress of approximately 11 kpsi on the coils at room temperature. When the magnet is cooled to 4° K this prestress is reduced to

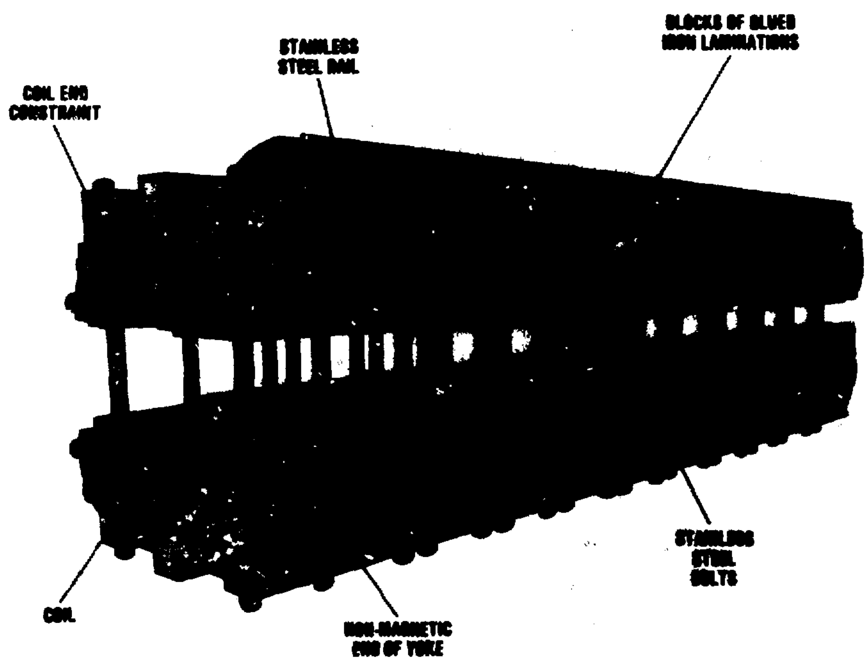

Figure 5. Overall schematic drawing of dipole, showing coil, laminated iron yoke (in the process of being bolted together), and the yoke end configuration.

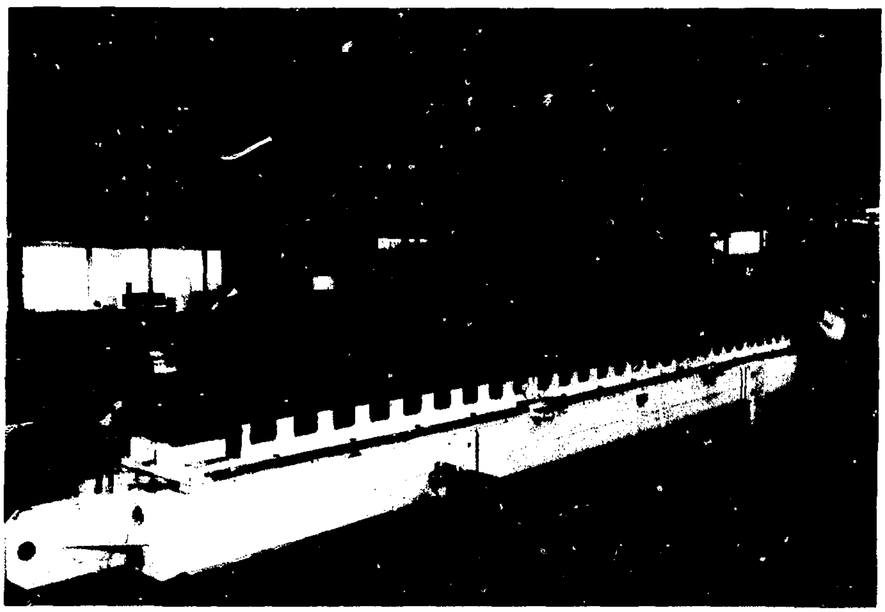

Figure 6. Fully assembled dipole magnet.

about 8 kpsi — a level calculated to ensure that the coils remain in a state of compression up to the maximum coil excitation contemplated, or about 6.5T. The yoke is divided longitudinally into blocks of epoxy-glued laminations, joined by stainless steel rails such that a 1/16" gap separates the blocks at room temperature. As the magnet is cooled the rails shrink more than the iron, the gaps close up, and thus longitudinal stresses from differential thermal contraction between yoke and coils are avoided. As noted earlier, the ends of the coil extend beyond the ends of the lamination stack to reduce the end field enhancement. The coil ends are restrained radially and longitudinally by stainless steel blocks joined to the yoke via the stainless steel rails, and by axial end restraints, as indicated in Figure 4, to minimize motion of coils with respect to the iron at high field. A completed dipole is shown in Figure 6.

INSTALLATION AND OPERATION

Each magnet is contained in its own dewar, as noted, and will be mounted in a separate vacuum vessel for installation in the ISABELLE rings. Figure 7 shows four such vessels, containing three dipoles and one quadrupole (the smallest unit of the regular ring lattice), installed in a prototype section of the machine tunnel. Dipoles and quadrupoles will be connected in series electrically as well as cryogenically, and will be serviced by a single central refrigerator.

The high stored energy of these magnets (1 MJ in the case of a dipole at full field) makes it imperative in case of a quench to protect the quenching magnet

Figure 7. Prototype section of ISABELLE tunnel, including one "cell" of magnets (consisting of three dipoles and one quadrupole).

by diverting the current around it in such an event. For this purpose a solid state shunting diode is connected across the terminals of every magnet. Pressure relief valves are also provided to bleed off the warmed-up helium gas. An external resistive load and associated SCR circuitry will be used to safely discharge the remaining magnets.

PROTOTYPE MAGNET PERFORMANCE

The following discussion is confined mainly to magnet performance aspects relating to "short sample" performance (i.e., field attained compared to that predicted from the conductor characteristics), "training" (the number of quenches, if any, required to reach that field), quench tolerance, and eddy current effects. Performance from the point of view of field quality (uniformity and magnet-to-magnet reproducibility) is not dealt with in any detail here; this must await conductor with better dimensional control than available at the time of writing, the implementation of production assembly techniques, and the accumulation of a meaningful sample of true prototype units.

Tests of the first dipole incorporating the design features outlined here commenced in July of 1981 — approximately six months after this design was adopted — followed by a second one a month later. These two magnets, CM1 and CM2, were short (1.65 m) versions of the 4.75 m long dipoles required for ISABELLE. The first full-length dipole, LM1, underwent tests in October of that year, followed by LM2 in January of 1982. Figure 8 shows the training curve for these four magnets, at a bath temperature of 4.5K. (Overlapping of points necessitated deleting most of the quench points for CM1 and CM2.) The virtually identical performance, with negligible training, indicates that the central field level attained, approximately 5.4T (corresponding to 4150A), is dictated by the short sample limit of the conductor, rather than by mechanical effects. That this is indeed the case is confirmed by subsequent runs of all magnets in which quench fields were measured at 4.8K and 3.7K. Results are shown for the case of dipole CM1 in the insert to Figure 8. Here the dashed lines indicate the range of field-temperature performance predicted from the conductor short sample limit. It should be noted that the conductor utilized in these magnets was a rather old reprocessed conductor furnished by Fermi National Accelerator Laboratory.

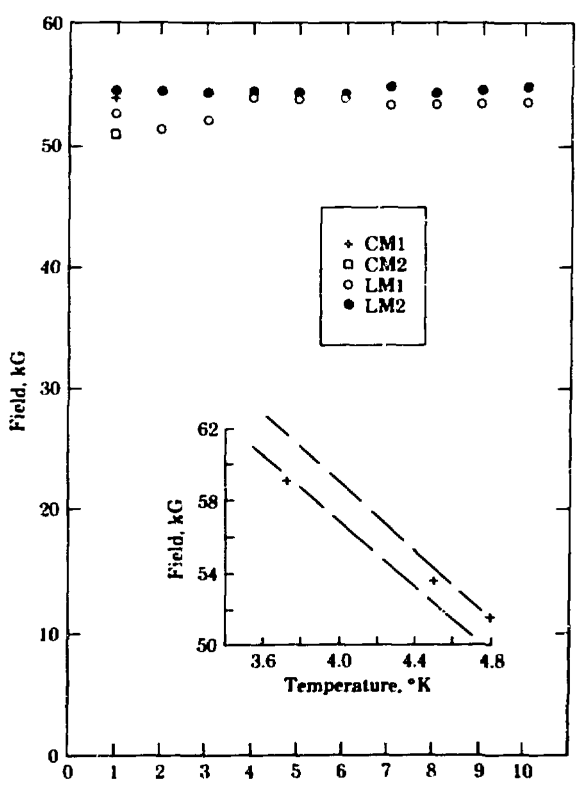

Figure 8. Training curve for four dipoles, at a bath temperature of 4.5K. The insert shows average quench field versus bath temperature for one of the magnets.

Newer conductor intended for use in the ISABELLE magnets is expected to have somewhat better superconducting characteristics. Consequently, at the lower temperature of 3.8K (the maximum operating design temperature for ISABELLE), central fields in excess of 6.0T should be achievable.

Eddy current effects, a serious concern with the braided conductor utilized in earlier ISABELLE magnets, appear to be negligible with the present magnets: their quench current exhibits essentially no ramp rate dependence up to rise times in excess of 100 A/sec (the normal ISABELLE ramp rate is 8 A/sec or 8 minutes from the injection field of 0.37T to full field).

Nor does the attainable dipole current appear to be limited by the powering of a built-in trim coil. Dipole CM2 incorporated such a sextupole trim winding. This winding, whose maximum design operating current is ±80A, was excited to ±200A without inducing a quench in the main coil when the latter was energized to 5.0T. Moreover, at a fixed liquid helium temperature the dipole quench current proved quite insensitive to whether or not the trim winding was energized to a constant value of ±100A.

A critical parameter for a superconducting magnet in an accelerator application is the degree to which it is able to absorb its own stored magnetic energy without excessive local heating during a quench, whether deliberately provoked or induced, for example, by beam loss incidents in the accelerator environment. To establish tolerance limits the present dipoles are routinely subjected to tests in which the temperature rise from "natural" quenches at high field is monitored as the normal protective external resistance is gradually reduced. Quench inducing heaters are also mounted in sensitive regions of the coils. These allow monitoring the temperature rise, without external protection, as a function of quench current level. (It takes longer for the quench zone to propagate through the coil winding at intermediate current than at the higher currents. The slowest propagation, which produces the maximum temperature rise, occurs at about 3000A.) Actually monitored in these tests is the value of the integral $\int I^2 dt$, a quantity related to the maximum coil temperature during a quench. The tests have shown no degradation in magnet performance; indeed, the measurements confirm maximum temperature levels comfortably below that at which degradation would be anticipated based on coil simulation tests and computer modeling studies.

As remarked above, we cannot draw very meaningful conclusions regarding field quality at the time this summary is being written. Factors affecting training performance received priority in the first few magnets; field quality evaluation must await the completion of a series of true prototypes engineered with this as the paramount objective. Nevertheless it may be noted that, expressed in terms of field harmonics or multipoles, measured (non-allowed) terms to date are already within or close to the tolerances required for ISABELLE. Coupled with preliminary trim coil performance data in the ISABELLE ramping mode, it is fully expected that these rather stringent tolerances can be met over the full excitation range.