STATUS REPORTS ON ISABELLE MAGNETS*

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Abstract

The design of the ISABELLE "Palmer" magnets is described. The performance of thirteen such magnets is reported. Average quench fields of 55 kG at 4.5°K have been obtained with essentially no training. The magnets can be shown to be limited only by the short sample characteristics of the cable. Required field quality was achieved in the last four magnets.

Magnet DesignBackground

A brief recapitulation of factors which led to important modifications of the earlier "braid" magnets may be in order, to place the present magnets in perspective. The braid magnets were, as the name indicates, wound from a braided conductor in a one-layer coil, mounted in a non-split laminated iron return yoke by thermal contraction. These magnets proved to have a number of shortcomings. Assembly was complicated, 5 T was attainable only with considerable training, and eddy current effects were difficult to control. In 1981 substantial modifications to the design were introduced in order to cope with these problems, predicated on retraining as many viable features of the original design as possible. A cabled and better insulated conductor, similar to that used at Fermilab, was substituted for the braid, since many of the more serious problems were attributed to inherent properties of the braid. Two layers of this cable could be nicely accommodated in the radial space formerly occupied by the braid. The yoke was split and bolted, for higher prestress and better dimensional control, and other design features, described in a later section, were introduced to better compensate for longitudinal mechanical and thermal effects. The first "cable" magnet was tested with excellent results in the summer of 1981.

Conductor

The conductor is a version of the universally acclaimed superconducting cable pioneered at Rutherford Laboratory; it is nearly identical to the one developed at Fermilab. It is fabricated from an initially round cable twisted from 23 multifilamentary superconducting wires, shaped by compaction into an approximately rectangular and slightly "keystoned" (trapezoidal) cross section, 0.78 cm wide by 0.125 cm mean thickness. Each wire, 0.69 mm in diameter, is itself a twisted composite strand, containing 2100 10 μ m niobium-titanium filaments embedded in high purity copper. The ratio of copper to superconductor is 1.75. The cable is spiral wrapped with two layers of insulation, first with Kapton (this appears to be a prime reason for its success) and then with fiberglass-epoxy tape. The current capacity of the finished conductor is typically 5000 amperes at a field of 5 T and temperature of 4.2°K. A schematic drawing of the conductor is shown in Fig. 1. Each dipole uses 6500 feet of cable.

Fig. 1. Simplified drawing of superconducting cable.

Coil and Iron Yoke

A dipole cross section is shown in Fig. 2. The coil is assembled from four separate long saddle-shaped coils. An "inner" coil is nested within an "outer" coil to form a two-layer subassembly. Two such assemblies, a "top" and a "bottom" coil half, are joined together with an internal electrical splice to make one long cylindrical coil. This coil configuration is quite similar to that of the Fermilab magnets, except for the inclusion of wedges near the poles to help control the two-dimensional field shape. The three-dimensional field profile is controlled by the insertion of spacers in the coil ends, splaying out the turns there. These also help to reduce the tendency of the field to peak near the end of the "saddle" coils.

The coil is clamped in a laminated yoke of low carbon steel, split at the midplane. Being in close proximity to the coil, the yoke contributes about 40% to the field. Of course, it also minimizes the stray field, restrains the coil against the strong outward Lorentz forces, and allows easy extraction of a coil if necessary. The yoke is divided longitudinally into blocks of epoxy-glued laminations (Fig. 3), separated by small gaps and joined by stainless steel rails. As the magnet cools down, the rails and the coil shrink by nearly the same amount (more than the iron), the gaps close up, and longitudinal stresses from differential thermal contraction are minimized. As can be seen from Fig. 3, the coils ends protrude beyond the ends of the lamination stack, thereby further reducing the end field enhancement noted earlier. The coils ends are restrained radially and axially by stainless steel extensions of the yoke and by end restraints.

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Fig. 2. Cross section of dipole magnet mounted in vacuum vessel.

Fig. 3. Schematic drawing of dipole, showing the yoke end configuration and the yoke in the process of being bolted together.

Trim Coils, Vacuum Chamber, and Magnet Vessel

The trim coils are located concentrically within the main dipole coil. Their functions are to correct iron saturation and superconductor magnetization effects (discussed below) and to aid in steering the beam. The trim coil package (see Fig. 4) consists of two concentric superconducting coils, each wound from a 7-strand twisted cable. The inner layer is wound according to a rather novel scheme, consisting of two coils wound in such a way that they produce a pure sextupole or decapole field, depending on the ratio of the currents in the two coil sections. Because of their appearance when initially wound flat, these coils are known as "snow shoe" windings. The turns in each snow shoe coil are interconnected so that their inductive coupling to the main dipole field of the magnet is zero, thereby effectively isolating them from quenches in the main magnet and vice versa. The outer trim coil is a conventional octupole winding,

Fig. 4. Trim coils prior to assembly: At left, a snow shoe (inner) coil; at right, an octupole (outer) coil.

assembled from eight individual coils. (The regular quadrupole magnets contain a combined quadrupole-dodecapole snow shoe trim winding, and a dipole steering coil.) The trim coils are insulated with Kapton and prestressed with high strength Kevlar filamentary wrap. Between the trim coil package and the main coil are longitudinal supports spaced to furnish helium cooling passages. These supports are a combination of fiberglass and elastomer materials which serve to support and center the trim windings in the main coil.

Mounted within the "cold bore tube" (i.e., the inner helium boundary) is the "warm bore tube" or high vacuum chamber (maintained at room temperature). The annular space between these is filled with superinsulation. The magnet yoke fits within a stainless steel support tube — the outer helium boundary. Between this tube and the wall of the outer vacuum vessel are further layers of superinsulation, interrupted by a metal heat shield cooled by helium gas at 55°K.

Winding and Coil-in Yoke Assembly

At the present time each of the four coils is wound separately in a concave mold, and is cured in several stages under high pressure. Layers of Kapton and Teflon are inserted in strategic places, furnishing slip-planes to minimize effects of friction during assembly and operation. G-10 fiberglass-epoxy serves as ground insulation where needed. The coil pole spacers are of laminated braes. The yoke halves are bolted so as to apply a compressive azimuthal prestress of approximately 12 kpsi on the coils at room temperature. When the magnet is cooled, this prestress is reduced to about 9 kpsi — a level calculated to ensure that the coils remain in a state of compression at full field. In the early magnets shims were inserted (at the poles) to realize the proper prestress. In later magnets, to ensure the necessary field quality, these shims are of a fixed dimension and the coils are molded sufficiently close to a fixed size that the prestress remains within a specific "window".

location — essentially a compromise between what is technically realistic and what the accelerator theorists would ideally like.

Our criteria for acceptable magnets are:

- the mean values of the lower allowed harmonics (b_2 , b_4 , and b_6) must be within range of the trim coil capacity, and
- the standard deviations for all harmonics must be less than or equal to one tolerance (for the unallowed harmonics, the deviations are taken from zero).

In addition we require that for each individual magnet, no harmonic may be outside 3 tolerance units.

TABLE I: Measured DC Harmonics (Excluding Ends) in Four Recent Dipoles

$B_0 = 1.87$ T; $I = 1200$ A

Harmonic	Tolerance (10^{-4})	(10 ⁻⁴) Measured Value			
		LM10	LM11	LM12	LM13
b_2	1.6	-24.6	-27.7	-27.8	-28.4
b_4	0.7	2.3	0.6	3.0	3.6
b_6	0.4	0.1	-0.4	0.1	-0.1
b_1	2.9	0	-1.6	0.1	0
b_3	1.0	0.3	-0.3	-0.2	-0.1
b_5	0.5	-0.1	-0.3	-0.5	-0.3
a_1	2.9	2.7	4.8	1.1	-0.4
a_2	1.6	0.1	1.4	0.6	0.4
a_3	1.0	-1.9	-0.7	0.1	-0.1
a_4	0.7	-0.1	0.6	0.1	0.1
a_5	0.5	0.3	0.1	0.6	0.6
a_6	0.4	0	-0.6	-0.1	-0.1

Performance

To date, twelve full-length dipoles (the LM series) have been tested (vertically) in liquid helium. Five of these, LM7, LM8, LM9, LM10, and LM11, have been tested under horizontal forced-flow (super-critical helium) cooling conditions as well. LM9, LM11, LM12, and LM13 included trim coil packages. Six further short dipoles (1.65 m long, the CM series) have also been tested. The latest of the short magnets, CM5, CM6, and CM7, were dedicated to meeting field quality tolerances by fine tuning the winding and assembly process. (LM11 was the first long dipole constructed to achieve field quality.) Three quadrupoles, QM0 (the first demonstration quad), QM1 and QM2 have also been tested vertically.

Magnet Quench Performance

Figure 7 shows the training history of the LM magnets in liquid helium at the nominal temperature of 4.5°K. Within at most two quenches, they attain a quench plateau of 5.4–5.5 T without further signs of training. The downward trend of quench No. 1 from LM7 through LM12 is believed to be due to a softening of coils from a poor batch of epoxy. New epoxy is now being used, and a clear improvement is seen in the training of LM13. The current at which a magnet quenches is virtually independent of the rate at which the current is increased, for ramp rates up to 100 A/sec (the design operating ramp rate is 8 A/sec); i.e., eddy current effects are negligible. Upon lowering the bath temperature below 4°K, varying amounts of training are encountered, with the magnets reaching 5.8 T at 3.8°K and approximately 6 T in the 3°K region, the lowest temperature attainable in these tests. Quench performance in supercritical helium appears to be essentially the same as that observed in liquid helium.

Fig. 7. Training curves in liquid helium for all long dipoles tested to date.

The quadrupole QM0 reached 75 T/m on the first quench in liquid helium at 4.5°K, thus exceeding the design gradient (72 T/m) at once. It reached 78 T/m after three more quenches, with no further evidence of training. The second and third quadrupoles reached approximately the same quench plateau at 4.5°K. QM1, the only quadrupole tested at 3.8°K, reached 80 T/m at this temperature.

Field Quality Status

The Magnetic Measurements Section utilizes both short (30 in.) and long 17.5 ft.) rotating coils for harmonic field analysis. The short coils measure the field integrated over a 30-in. length of the magnet, i.e., essentially the 2-D field, excluding end effects. The long coils measure the field integrated through the entire magnet. Each measuring coil has a number of discrete windings, the voltage output of each being primarily responsive to one component of the multipole field. This allows direct measurement of the various multipoles on a continuous basis, even while ramping a magnet.

We are now able to report on field measurements in the first few long "field quality" dipoles. Figure 8 shows three histograms, summarizing the harmonics for four dipoles: LM10, 11, 12, and 13. (Although the LM10 yoke was not built to field quality specifications, the coil and assembly did meet these specifications.) Three values of current are shown: 264 A (injection current), 1200 A, and 3500 A (essentially full field). The histograms include those harmonics, skew and normal, up to and including terms of 4th order (decapole) which are presently measured with the long harmonics coils, and consequently include the effect of the magnet ends. A normal curve is also fitted to the data. As can be seen, the standard deviation is approximately one tolerance unit over the whole excitation range, with no harmonics falling outside 3 tolerance units. As noted in the next section, the observed harmonics are well within the range of the trim coils. Thus, all four magnets meet our previously stated performance criteria of acceptance with regard to field quality.

The "transfer function" (i.e., the ratio of central field B_0 to current) is measured using a nuclear magnetic resonance probe, with the magnet energized to 1000 A. This parameter averages 15.593 ± 0.006 gauss/ampere in these four magnets. The variation can be attributed to a variation in B_0 along the axis of the magnets, amounting to approximately 5 gauss for $B_0 = 15.600$ gauss. A more consistent determination of B_0/I will require averaging the NMR reading over a longitudinal portion of the magnet axis. Finally, the $|BdI|$ measurements give an average value of $8.2418 \text{ T-m} @ 1200 \text{ A}$, with maximum deviations of $\pm 3 \times 10^{-4}$. This is well within the tolerance on this quantity, 5×10^{-4} . The high accuracy implied by these figures reflects a small magnet-to-magnet variation.

Trim coil packages have been tested in four long magnets to date; LM9, LM11, LM12, and LM13. Those in LM9, 11 and 13 were prototype units made by the R&D Group, whereas the trim coils in LM12 were wound in a new pre-production facility. All future trim coils will be wound in this facility. With the exception of occasional low quenches when initially powered, the R&D trim coils operate at approximately 230 A in all possible configurations with the main coils at 5 T (see Fig. 9), with no evidence of retraining on reversal of polarity. This is comfortably above the maximum design current of 170 A, and thus is ample to compensate all of the observed harmonics.

When a magnet quenches, it is desirable that it be able to absorb its own stored energy without overheating. At low current there is not enough stored energy for concern. At high current the "normal zone" or quench front propagates rapidly, so the energy is widely distributed through the magnet winding. Thus, the chief concern is for quenches initiated (e.g., from beamloss or hot gas) at intermediate current values, ~ 3000 A or 4 T, where maximum localized heating should occur. To establish tolerance limits on heating effects, every development magnet is equipped with small heaters located in strategic spots. Using these to induce quenches, quench propagation velocities and the temperature rise are monitored as a function of magnet current and temperature, with the normal energy extraction circuit removed. One magnet, LM7, was dedicated to quench propagation studies in supercritical helium with temperatures extending down to 2.7°K. Although quench velocities were, somewhat surprisingly, found to be slower than in liquid, LM7 was in fact able to sustain artificially induced quenches under "worst case" provocations without sign of degradation (drop in quench current). Subsequently, short sample tests have established a damage threshold at about 1050°K. The worst case quench in LM7 (with the quench originating on the midplane of the outer coil, at a temperature of 2.7°K)

had $T_{max} \sim 970^{\circ}\text{K}$ for an $\sim 80^{\circ}\text{K}$ margin of safety. It should be noted that this is the most stable point in the magnet, with lower fields, higher critical current and temperature, and is also least likely to be the place where a quench first occurs, since it is shielded from beam losses by the inner coil. An induced quench in the inner coil of LM7, more typical of the quenches expected in an accelerator environment (beam loss-hot gas at 2.7°K) had a safety margin of $\sim 200^{\circ}\text{K}$.

In order to gain an additional margin of safety for possible magnet-to-magnet variations, a quench protection system will be employed. The basic idea is to divert current from neighboring magnets around the one that has quenched. A number of "passive" schemes (i.e., schemes whereby the quenching magnet initiates the protective action, without relying on some form of mediating detector) have been studied. One, known as a "double diode" system, has been selected on the basis of preliminary magnet trials. In this scheme, high current shunting diodes are connected across each half magnet coil, providing two alternate paths, each bypassing half of the total magnet inductance. When a quench occurs, current commutes out of the quenching coil segment, the effective inductance is reduced, and the maximum temperature is also reduced.

Based on both calculations and measurements on LM5, the maximum temperature is reduced by between $\sim 150^{\circ}$ and $\sim 400^{\circ}\text{K}$, depending on the location of the quench. Although some additional testing of this system is necessary, it would appear that magnet protection is well in hand.

Conclusion

We have shown that one can design relatively large aperture superconducting dipole magnets that 1) reach above 5 T with high reliability, 2) show almost no training, 3) have conductor placement with root mean square errors of less than two thousandths of an inch, and 4) are passively self protected in the event of an induced quench. We believe there is good evidence that the required design features to attain these characteristics are 1) the use of a cable which allows helium in intimate contact with the superconducting wires, 2) the avoidance of any bonding directly on a conductor and 3) the use of high precompression provided by a rigid structure.

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