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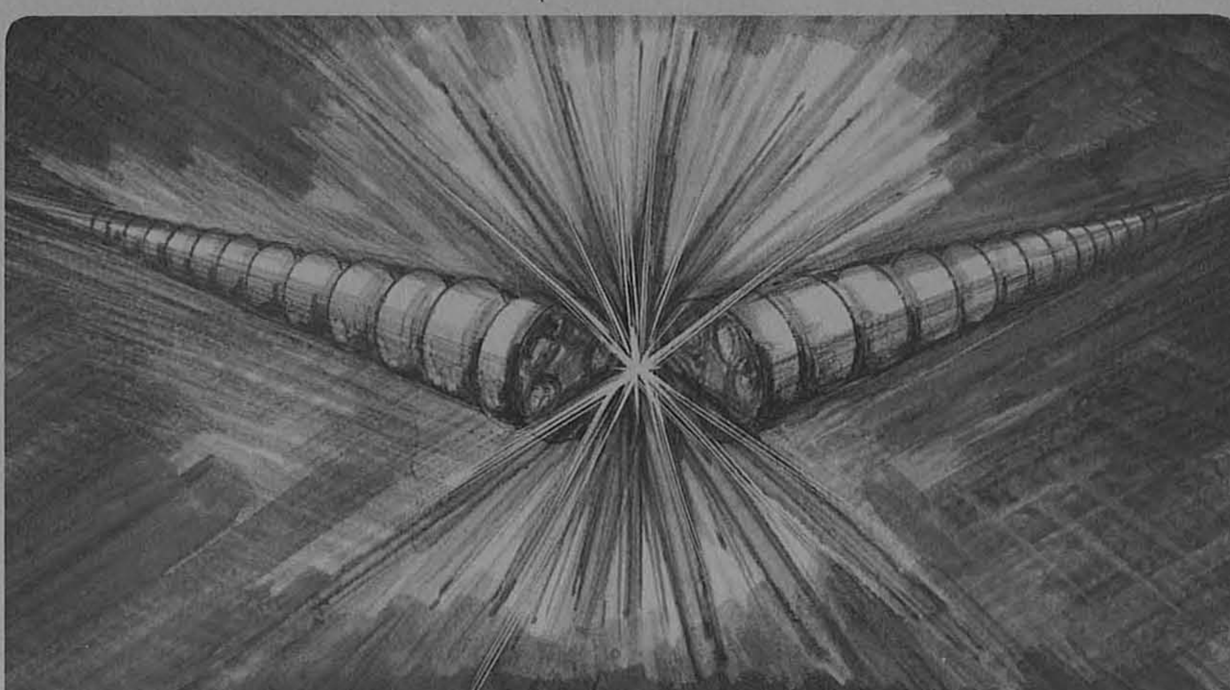

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Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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W. Gilbert, A. Borden, W. Hassenzahl, G. Moritz, C. Taylor
Lawrence Berkeley Laboratory
University of California

Abstract

Error fields in a dipole due to superconductor magnetization and conductor misplacements add unwanted multipole, mainly sextupole and decapole, terms to the desired dipole field. Two persistent mode sextupole correction coils inside the bore of model SSC dipoles have been built and tested. A shorted superconducting sextupole coil has a current induced in it by the error sextupole field such that no sextupole field can penetrate into the proton beam region. The correction sextupole coils are one layer thick and are wound from a single length of insulated composite Nb-Ti and copper wire 0.60 mm in diameter. Each of the six poles has ten turns and is mounted on a 1.75 cm radius stainless steel bore tube. Details of testing and trimming of the correction coils are described. Test results of the measured magnetic field within the model SSC dipoles with the correction coils in and out of persistent mode operation are presented. An electrical heater is used to drive the coil out of the persistent mode. Measurements of joint resistance and coil decay time constants are also given.

Introduction

The required uniformity of the magnetic field in the superconducting bending magnets (dipoles) of the proposed very large Superconducting Super Collider accelerator is determined by the requirement that the particle beam remain within the beam aperture and not be lost. The allowable field nonuniformity is only about 10^{-4} of the guide dipole field. Error fields are generated by errors in conductor placement, saturation of surrounding iron, and "magnetization" circulating currents flowing in the filaments of the superconductor. These fields are large enough to require correction coils to achieve this field uniformity level.

For a magnet with dipole symmetry, the only field errors from the above causes allowed are higher odd multipoles, viz., sextupole, decapole, etc. If there are conductor placement errors that are not symmetric, even multipoles can also be present. For the "magnetization" effect, the error multipoles decrease rapidly with increasing number and we need only concern ourself with the sextupole and decapole induced fields.

Several small aperture dipole magnets have been built and tested at the Lawrence Berkeley Laboratory as part of the SSC Research and Development program. The systematic "magnetization" fields have been measured and agree well with present theory. Superconducting sextupole correction coils have been operated with two of the dipoles.

These correction coils are placed inside the dipole aperture to produce a sextupole free dipole field at the particle beam location. These correction coils can be powered by an external current supply. They can also be self-powered by shorting their leads so as to form a persistent superconducting circuit.

Model SSC Magnets - Sextupole Error Fields

The small aperture dipole magnets that we have been developing and testing are approximations and variations of the SSC Reference Design A dipole (see Ref. 1). These two layer magnets with a close-in, cold-iron return is shown in cross section in Fig. 1 and is described in more detail in Ref. 2. The superconducting Nb-Ti filaments are some 22 microns diameter in the inside layer and some 17 microns diameter in the outside layer. Circulating currents, which are set up in each superconducting filament as the dipole field is ramped up and down, result in persistent-current generated higher multipole error fields. Figure 2 shows the sextupole moment, at 1 cm radius, for magnet D-12A-1, caused by this effect. The constant offset is due to construction errors. There are similar, but reduced, field errors for the higher multipoles. From accelerator theory considerations, the sextupole should be less than one unit (1/10,000 the dipole field) over the entire field swing of the magnet - as compared with the 30 units at an injection field of 0.3 tesla as shown in Fig. 2.

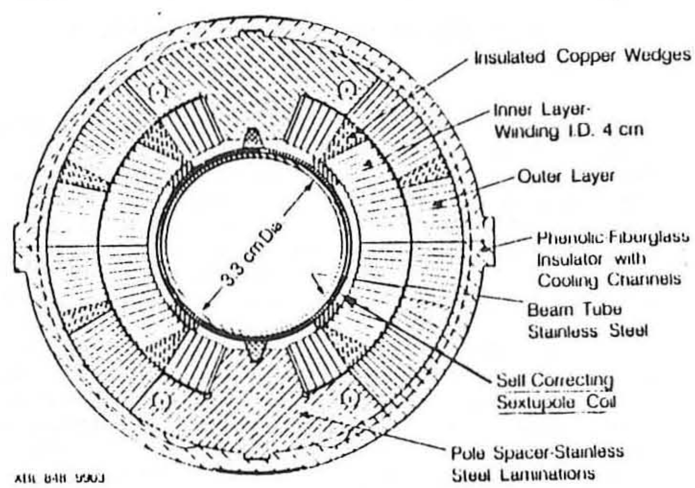

Figure 1. A cross section of the model SSC main ring dipole coils showing sextupole correction coil. Iron yoke not shown.

A satisfactory theory of the magnetization of the Nb-Ti filaments through the generation of persistent-current doublets from changes in the dipole field has been developed by M. Green[3] and the calculated fields are in good agreement with measurement.

Flux Blocking via Self-Correcting Harmonic Coil

The sextupole field generated in the dipole coil is opposed by the field generated in a sextupole correction coil placed between the particle beam region and the dipole coil. The first practical demonstration of this technique was at SACLAY.[4] If the correcting coil is superconducting, and put in the persistent mode by soldering the leads

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together, the coil will have zero or very small resistance. Then according to Lenz's law, the total flux through the circuit is constant. If the total flux is initially zero, the induced current I in the circuit is given by:

$$LI + \phi_{ext} = 0, \text{ where L is the circuit inductance}$$

This current is continually opposed to the variations of the applied flux and consequently corrects the unwanted harmonic.

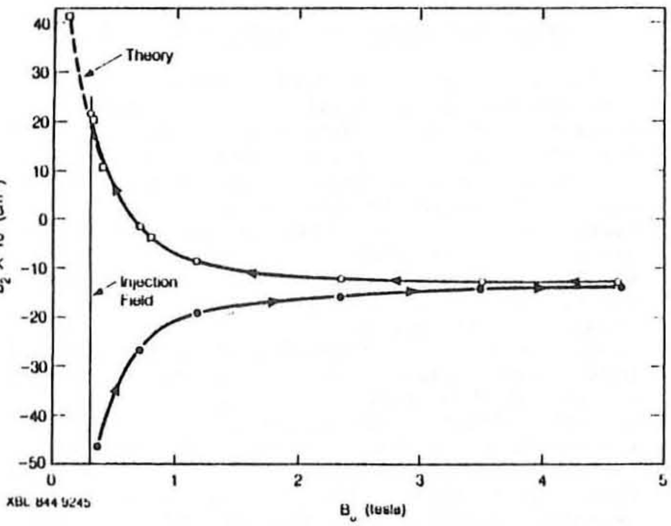

Figure 2. The sextupole moment measured at 1 cm radius in magnet D-12A-1 as the current is increased and then decreased.

Design and Construction of the Sextupole Correction Coil

Three correction coils have been constructed using somewhat different fabrication techniques. The composite multifilament Nb-Ti in copper round wire is 0.50 mm in diameter, has organic insulation, and an overall diameter of 0.60 mm. A single length of conductor is used for the entire winding so the only resistive joint is at the soldered end. The first coil was wound as six identical flat pancakes, 12 turns per pole, epoxied together and then transferred to the outer surface of a stainless steel bore tube. Coil testing, for dipole field to sextupole coil coupling, was performed in a large uniform beam handling dipole. It was found that variations in the effective pancake areas resulted in dipole field coupling of the order of 1-2 percent and a special dipole cancellation loop had to be added to the sextupole coil to reduce this.

The second and third coils were wound as cylindrical shells on spiders over stainless steel bore tubes and then moved radially inward onto the bore tubes. The second and third correction coils were constructed using more precise conductor alignment techniques. Only 10 (rather than 12) turns were used in each of the 6 coils. A reference line along the length of the coil form was established optically to 0.05 mm. This same tolerance was maintained for the positioning of the other conductors/coils relative to the reference line. The dipole to sextupole coupling was reduced as above and, after the dipole cancellation loop was added, the final coupling was very small. The outer radius of the bore tube is 1.75 cm; the coils are 1.1 meter and 1.3 meter long. An electrical heater over the conductor in the region of the shorted end leads is used to drive the circuit out of the persistent mode. A 10 cm long solder joint was used in coil 2 and a 26 cm long joint in coil 3.

The second and third coils were tested using the same equipment (supplied by the magnet measurements group) as was used for the first coil. However, a new mounting fixture was made that allowed the coil to be rotated smoothly. The effective dipole area of the coil, as constructed, was 26.7 cm^2. The effective sextupole area of the coil is some 3000 cm^2. A dipole compensating winding was made from one of the two coil leads and was placed on the correction coil in the appropriate circumferential position in the central field region (rather than the end field region) The final dipole linkage was reduced to 0.25 cm^2, which is about 1/10,000 of the sextupole coil area, and is small enough for the coil to be used as a self-correcting element.

Tests of Self-Powered Sextupole Coils In Model Dipoles

Magnet D-12A-2

Figure 3 shows the sextupole reduction in dipole D-12A-2 with the self-powered coil up to the maximum dipole field of 6.5 T. Integrated field values are shown and the large negative offset in the uncorrected magnet is caused by very large sextupole fields in the initial version of the newly developed flared out ends. Another, possibly better, way of presenting the data is to display the sextupole, at the beam radius of 1 cm, in gauss as is done in Fig. 4 for the low field region and in Fig. 5 for

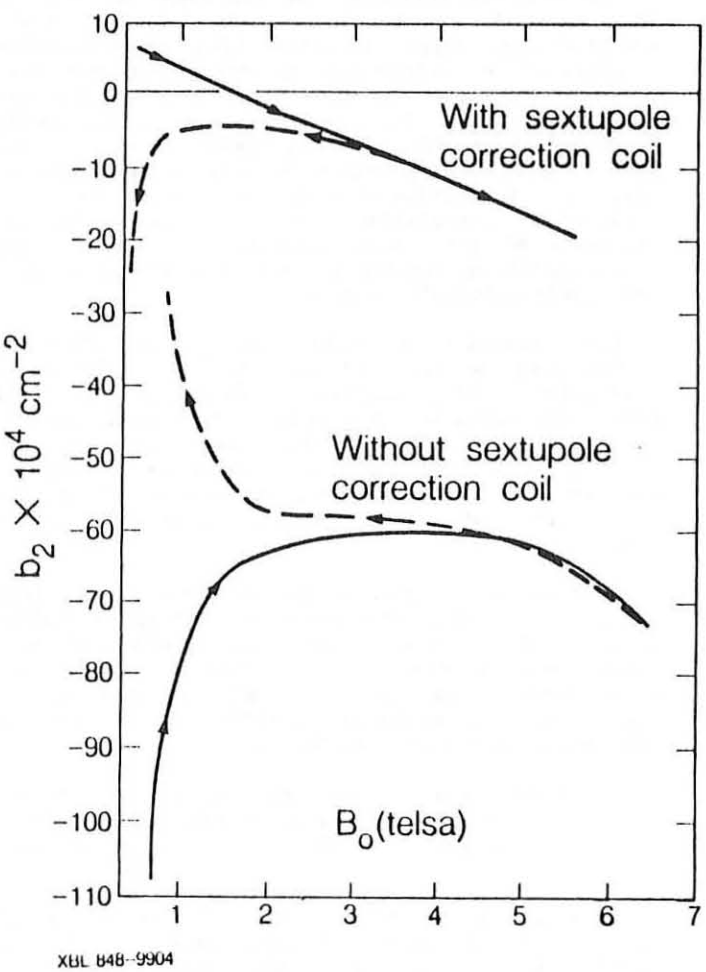

Figure 3. Sextupole moment for magnet D-12A-2 with and without operating sextupole correction coil.

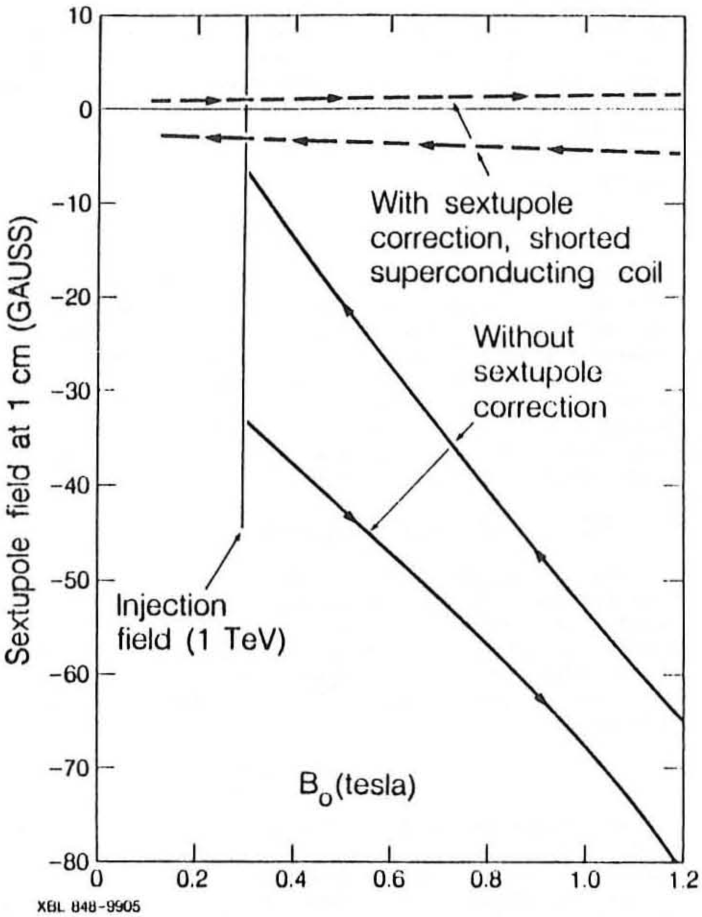

Figure 4. Sextupole field for magnet D-12A-2 with and without correction coil over low field region.

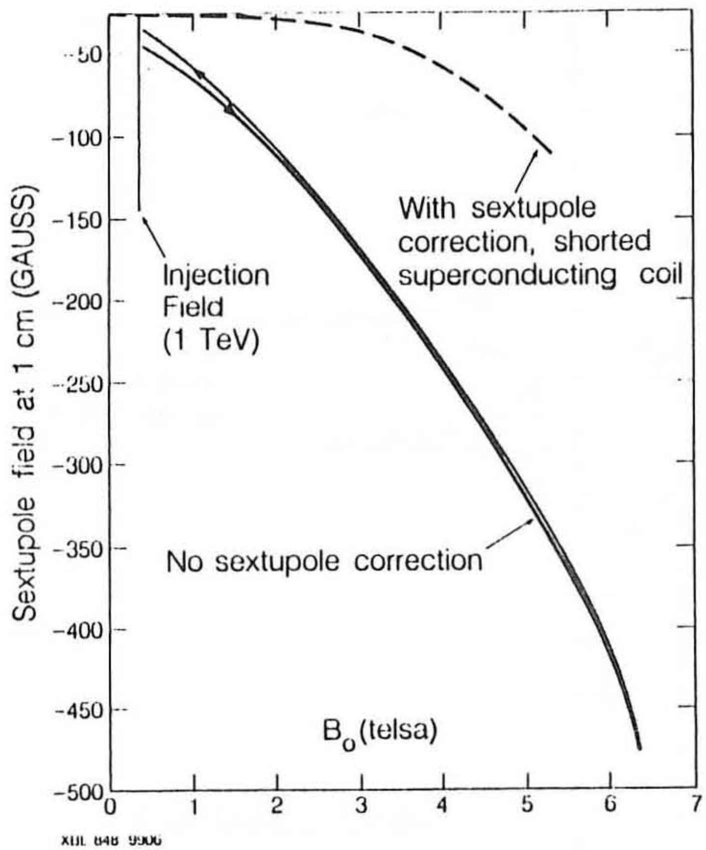

Figure 5. Sextupole field for magnet D-12A-2 with and without correction coil over entire field region.

the entire field range. At low field, the correction is excellent but a quadratic departure is observed at higher fields and is apparently due to mechanical deformation.

The effective resistance of the persistent mode sextupole coil is determined by measuring the decay rate of the trapped sextupole field when the current in the dipole magnet is reduced to zero. A large sextupole field is trapped by energizing the heater on the sextupole coil when the dipole is at high field. The heater is then turned off and the dipole current is also turned off. The mean decay time was 48.6 hours, the coil inductance is calculated to be 6.47×10^{-4} henry, leading to an effective circuit resistance of 3.7×10^{-9} ohm. This resistance is higher than that expected for a 10 cm long solder joint, but there was some question as to whether the correct solder was used since this solder contained some silver.

Magnet D-12B-1

A third SSC model magnet, with improved ends, is D-12B-1. The third correction coil was longer than the one discussed above (1.27 meters vs 1.08 meters) and the solder used for the end joint was 50 percent lead-50 percent tin, which is presumed to be superconducting in the low field region. Also the end joint was lengthened to 26 cm (from 10 cm).

The test data are shown in sextupole moment units in Fig. 6 and one can see that the integrated sextupole component for the uncorrected magnet is much better than the previous magnet, Fig. 3. The improvement with the sextupole coil operating can also be seen. A false magnet trip signal when the magnet was being ramped from 1 to 2 kA allowed 8 to 10 G of sextupole to enter the beam aperture region. The cause of this flux penetration is unknown; fast current rundown (0.1 sec) may have quenched the sextupole coil. As a result of this perturbation the corrected curve is not centered about zero field and the run could not be repeated as the experiment was ended for other reasons.

The mean decay time for this coil was 781 hours. The calculated inductance of 7.59×10^{-4} H results in an effective circuit resistance of 2.7×10^{-10} ohms.

Discussion of Results

a. Success of Self-Correcting Sextupole Coil

The persistent mode sextupole correcting coil operated as expected and reduced the error sextupole field from the dipole by a factor ranging from five to fifteen. This shielding factor may already be enough to allow for this type of field correction in a major accelerator. Some reasons for the lack of perfect shielding are discussed below.

b. Sextupole due to sextupole coil deflection

A quadratic dependence of the corrected sextupole field on central dipole field can be observed in Fig. 5. This is due to a current induced in the coil by a dipole coupling, which is caused by the Lorentz force on the sextupole coil. This force, and the subsequent dipole moment and deflection are proportional to the product of the dipole field and

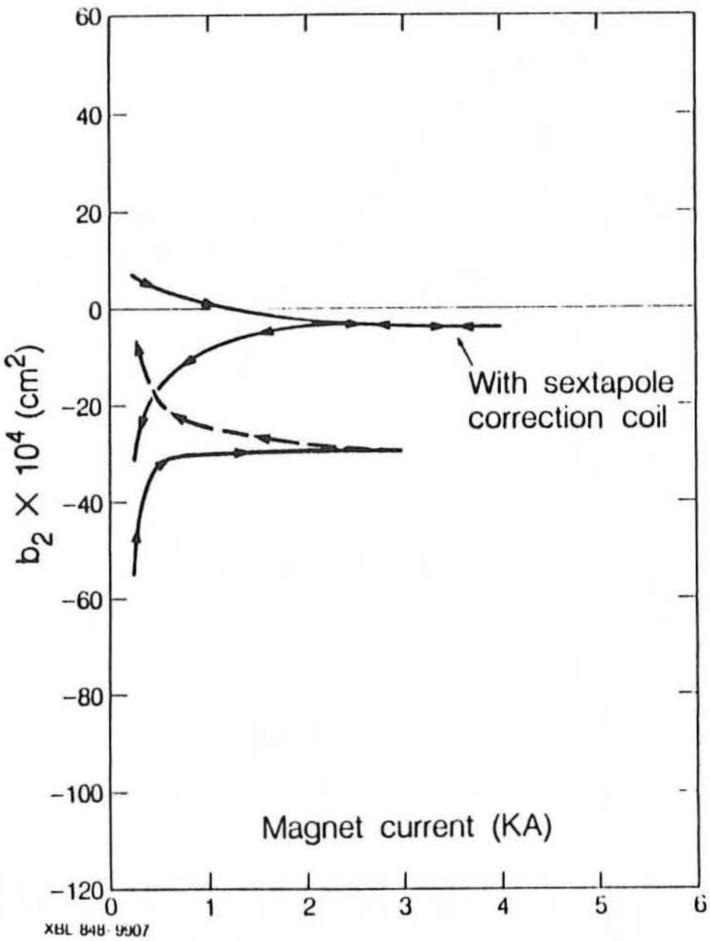

Figure 6. Sextupole moment for magnet D-12B-1

the uncorrected sextupole field, which is approximately proportional to the field squared. A complete discussion is given in an LBL internal note[5]. The deflection could obviously be reduced by using a thicker construction tube for the coil. Since the final dipole magnet will have a much smaller sextupole component than these early models, the sextupole correction current and the subsequent Lorentz force will also be much reduced.

c. Residual sextupole due to misalignment of dipole and sextupole coils

An auxiliary experiment was done with the D-12B-1 magnet in which the sextupole coil operated as an externally powered correction element. Current was fed into the correction coil through two special current leads with the heater energized. At a dipole current of 1000 A, the sextupole current was varied to yield the minimum net sextupole field. The minimum, which occurred at 8.0 A, was 5 percent of the original field, and at an angle almost 90 degrees out of phase with the original error field. This is consistent with the dipole and sextupole coils being oriented some 3 degrees with respect to each other. Upon disassembly, measurements confirmed that the misalignment was in the 2 to 3 degree range. Future assemblies will be aligned more precisely.

d. Other causes for lack of complete cancellation

The sextupole coil is in the form of a uniform current density block but with a relatively small number of turns per pole (10) . The calculated coupling, or overlap integral, for this geometry is about 98 percent.[6] Higher multipole fields are generated by the small number of current carrying wires - this effect has been estimated to be some 2 to 3 percent. These two effects alone could reduce the correction efficiency to some 96 percent. We are analyzing other possible reduction sources, i.e. end effects.

e. Time Constants

(i) Joints

The joint resistances quoted, 3.7×10^{-9} and 2.7×10^{-10} ohm, are somewhat higher than we expected from previous experiments carried out on shorter joints.[7] However, the lower value of 2.7×10^{-10} ohms is satisfactory for a full length correction element some 17 meters long since it would result in a mean decay time of greater than one year. Research is continuing on reducing the joint resistance still further.

(ii) Flux penetration at high B-dot

The one magnet trip in which the dipole magnet did not go normal but flux was pumped into the beam region was either a case of the sextupole coil's going normal for a short time or represents some B-dot limit that was exceeded. Future tests on the flux rate capabilities of these correction coils are planned.

Acknowledgements

The Magnetic Measurements Group of M.I. Green, D.H. Nelson, and D.A. Van Dyke, provided all the magnetic field measurements for the three dipoles discussed above. Additionally they were heavily involved in the measurements of the sextupole correction coils and the trimming involved in reducing the dipole-sextupole coupling to acceptable levels.

Thanks are also extended to the magnet testing team of J.B. Rechen, R.F. Althaus, and C.D. Kemp.

F.L. Perry successfully struggled with the problem of accurately winding and fabricating the correction coil.

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