

COIL EXTENSION, DEFORMATION AND COMPRESSION DURING EXCITATION
IN SUPERCONDUCTING ACCELERATOR DIPOLE MAGNETS

A.V. Tollestrup, R.E. Peters, K. Koepke and R.H. Flora
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

Summary

The measurement of conductor motion, caused by exciting a superconducting dipole magnet, is compared to the measured field quality.

Introduction

Strict limits on the magnetic field harmonics are required in synchrotron bending magnets. In the case of the Fermilab Doubler synchrotron, a calculation of the lattice shows that the superconducting dipoles require a sextupole component on the order of $3 \times 10^{-4}/\text{in}^2$ to correct for chromaticity.¹ Higher harmonics are generally required to be smaller and independent of current.

In order to realize higher field harmonics smaller than the chromaticity correction, the conductor placement in the superconducting coils of the Fermilab Doubler dipole magnet must be accurate to .001 inch. As the magnet is energized, the Lorentz force on the conductors rises quadratically with current and deforms not only the coil but also the external stainless steel collar that supports the coil. The conductor motions related to these deformations produce non-linear field terms which if too large will have to be compensated with separate correction elements. The field perturbations attributable to the magnet yoke are expected to be small as it is sufficiently spaced from the coil to ensure minimal saturation.

The cross section of the dipole is shown in Fig. 1.

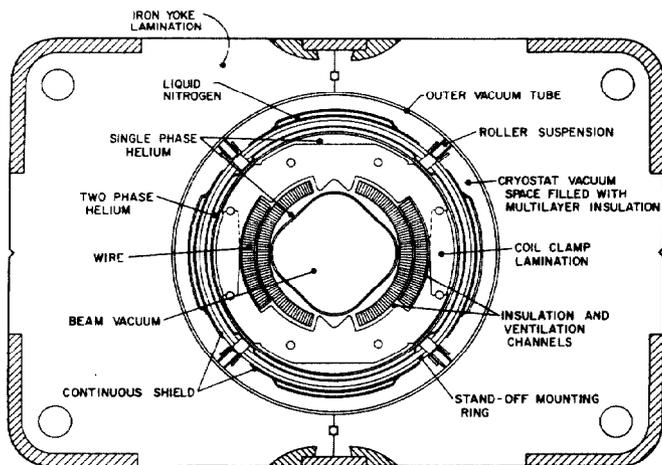


Fig. 1 Energy Doubler dipole cross section.

The coil consists of two concentric cylindrical layers of superconductor, azimuthally segmented to optimize the bore field homogeneity. The inner shell has an inner diameter of 3.000 inches and contains 68 turns. The outer shell has an outer diameter of 4.298 inches and contains 42 turns. The wall thickness of the stainless steel collar in the median plane of the magnet was .375 inches. It has since been increased to .571 inches. The force on the conductors can be expressed in terms of its azimuthal and radial components. At 4.5T bore field, the inner coil turns,

*Operated By Universities Research Association, Inc. under contract with the United States Energy Research & Development Administration.

farthest from the median plane, experience a force of 123#/inch in a direction that tends to compact the coils azimuthally.² At the parting line the force is purely radial and elliptically deforms the collar. The conductor motions related to these deformations were measured and compared to the measured resultant field perturbations.

Coil Motions

An extensometer was constructed to measure the axial strain in a superconducting dipole during excitation. Two struts, each held in place by spring tension, were placed in its bore, one at each end of a five-foot magnet. Two concentric stainless steel tubes, each fixed to one of the two struts, were used to transmit the axial position of the struts out of the cold dewar environment. The relative axial motion of the two tubes was then measured with a dial indicator. A typical measurement is shown in Fig. 2. The permanent strain left after each cycle is due to friction between the magnet collars and the coil.

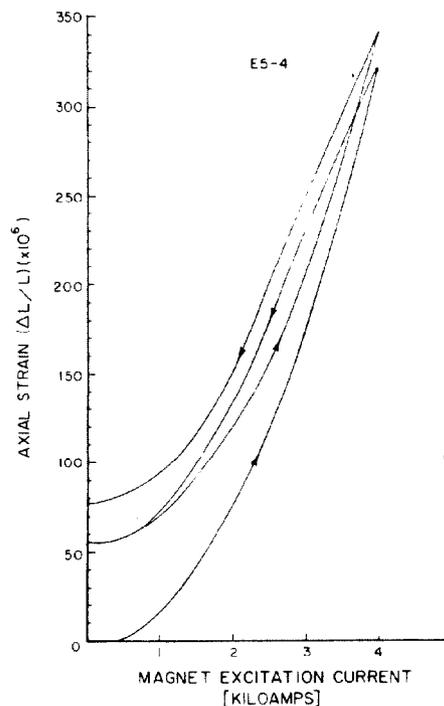


Fig. 2 Axial strain during excitation

The median plane radii of the coil and the collar (Type I) were measured as a function of excitation current. The data was collected by noting the deformation of calibrated hoops mounted in the bore of the magnet and on the o.d. of the supporting collar. The hoop deformation was measured with four strain gauges mounted 90° apart along the hoop's circumference and at the maximum strain points. All strain gauges were separately monitored in the 1/4 bridge configuration. The B² correction term associated with this strain gauge cancels automatically if the ring is calibrated in terms

of the sum of the four absolute strains.

The measured change of the collar radius has an I^2 dependence as expected for elastic deformations (Fig. 3). The difference between the inner and outer radii, the coil compaction, was less than .001 inch, the accuracy of the measurement.

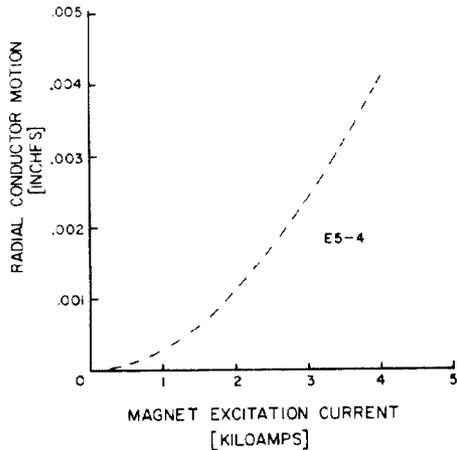


Fig. 3 Radial Motion During Excitation

A "Scissometer" was constructed to measure the azimuthal conductor motion in the dipoles during excitation (Fig 4). Two G10 struts, each held in place by spring tension, were placed along two different diameters of the transverse coil cross section. As in the case of the extensometer, two concentric tubes were used to transmit the angular position of the struts out of the dewar. The relative angular motion of the tubes was measured with a dial indicator.

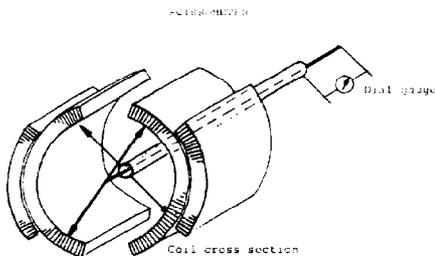


Fig. 4 Scissometer schematic

Figure 5 illustrates the azimuthal conductor motion of three different coil construction techniques. The coil with aramid insulation had a great deal of azimuthal motion. Impregnating the superconducting cable with epoxy prior to application of insulation brings the motion under control.

Field Perturbations

The results of a harmonic analysis of two experimental five-foot, E-series dipole magnets are shown in Figs. 6-9. Since our emphasis here is on excitation dependent changes, the data have, with the exception of the sextupole component, been averaged such that the contribution from the superconductor magnetization is not shown and translated such that each harmonic has a zero average value at 0.4 kA. The first of these magnets E5-2 (solid curve), was the last five-foot magnet whose

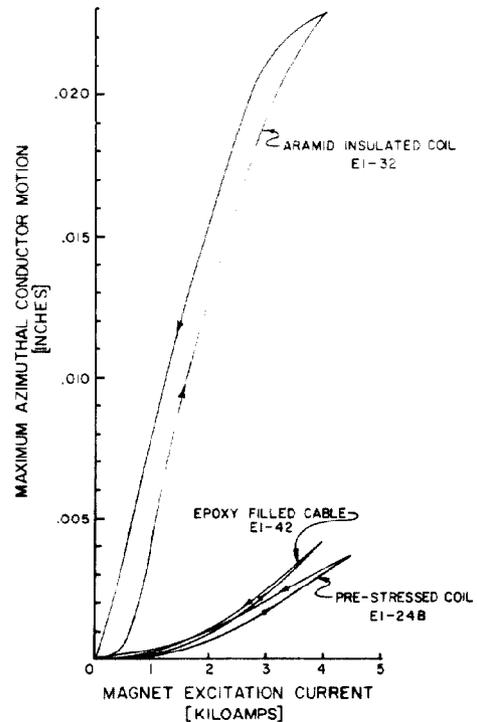


Fig. 5 Azimuthal motion during excitation

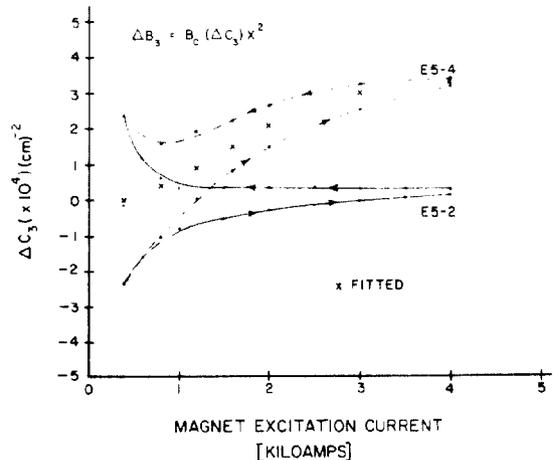


Fig. 6 Normalized sextupole amplitude for two experimental iron-free E5-series dipole magnets.

coils were wound with rectangular cable. This coil appears to be very stable in that none of the field components varies by an amount sufficient to change the field homogeneity at 2.0 cm radius by more than 3×10^{-5} . The second set of curves was obtained from E5-4 (broken curve), which was the first E5-series dipole to be constructed with keystoneed cable. Each of the field components exhibits a pronounced dependence on the excitation current. This behavior is not representative of the experimental dipoles which have been produced. The effect is primarily due to an inadequate azimuthal preload on the coil which arose during the transition from the use of rectangular to keystoneed conductor in the E5-series. We shall now propose a simple model which accounts for these changing harmonics.

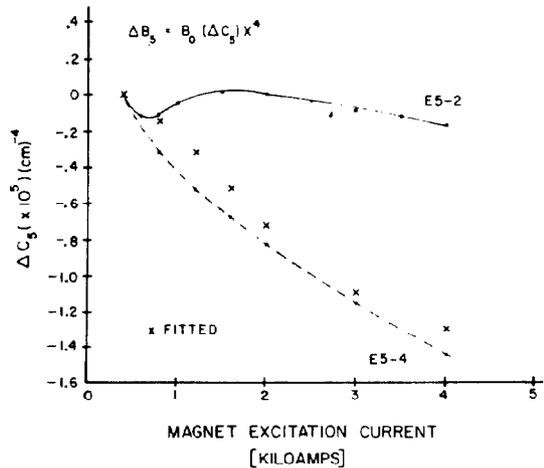


Fig. 7 Normalized decapole amplitude for two experimental iron-free E5-series dipole magnets.

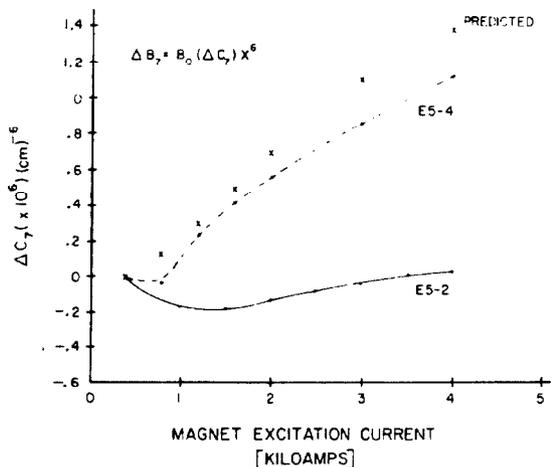


Fig. 8. Normalized 14-pole amplitude for two experimental iron-free E5-series dipole magnets.

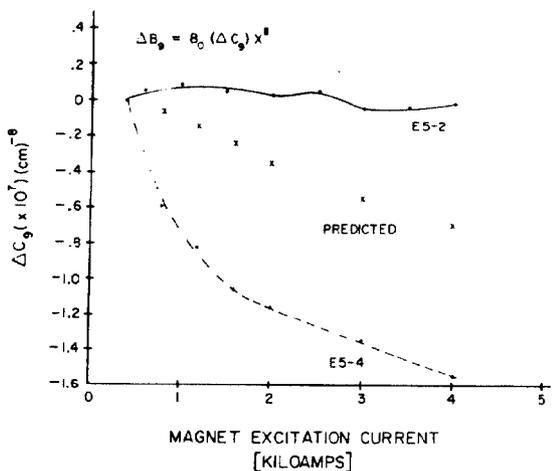


Fig. 9 Normalized 18-pole amplitude for two experimental iron-free E5-series dipole magnets.

The internal coil surface and external collar surface undergo equal radius changes which vary quadratically with the excitation current (Fig. 3). The shape of the perturbed cross section is closely approximated by an ellipse whose semi-major axis differs from the nominal coil radius by $e_r = .00026 \text{ inch/kA}^2$. The corresponding radial and azimuthal motion of a conductor initially located at polar coordinates (R, θ) are (elliptic approximation):

$$\Delta R = e_r \cos(2\theta)$$

$$\Delta\theta = -(e_r/2R) \sin(2\theta)$$

The effects of this motion on the harmonic coefficients have been included.

The azimuthal compression curve, while not shown here for E5-4, was measured and has nearly the same shape but half the amplitude of E1-32 (Fig. 5). For the purpose of this calculation, we have averaged over the mechanical hysteresis loop, subtracted the azimuthal contribution of the elliptic deformation, and normalized the curve to unity at 4 kA. The amplitude of the motion is the first unknown variable, with the relative motion constrained to follow the shape of the experimentally determined compression. Since we do not have physical access to the outer conductor shell, we have assumed the shape determined for the inner shell also describes the azimuthal motion of the outer shell. The amplitude of the outer shell conductor motion is the second free parameter.

The two constants were determined from a linear least-squares fit to the sextupole and decapole data, since these are the dominant multipoles. The fitted sextupole and decapole terms are represented by an "x" in the figures. The corresponding points for the 14- and 18-pole components are predictions based upon no a priori reference to the magnetic measurements. The partial justification for this simple model is the excellent agreement between the fitted and measured sextupole and decapole. There are, however, two additional factors: 1) the agreement between the measured and predicted 14-pole and the correct qualitative prediction of the 18-pole (which is quite small to begin with) and, more importantly, 2) the fitted azimuthal amplitude for the inner shell is within 10% of the measured value. (The predicted motion for the outer coil corresponds to a change in arc length, over 42 conductors, of .034 inches.)

Conclusion

Two effective means have been developed which increase the modulus of elasticity of the coil. The first consists of molding the coils slightly oversized and then forcing them to size inside the collar; i.e., prestressing the coil. The second method consists of impregnating the superconducting cable with several epoxy or alumina loaded epoxy systems prior to insulating the cable. Both methods have been successful in limiting the measured azimuthal conductor motion.

The magnet field perturbations were also measured in two five-foot dipoles. In the case of E5-4 where the azimuthal motion was relatively large, the measured change in field harmonics agreed with the field perturbations calculated from the measured coil motions. In E5-2, a rigid magnet, the magnetic field was seen to be insensitive to current except for the persistent current effect. These measurements lead us to the conclusion that non-linear field terms arising from coil motions are correctible to a level required for a synchrotron.

Acknowledgements

The following people designed and built the experimental apparatus and helped make the measurements: E. Ioriatti, P. Hamilton, H. Warren, W. Habrylewicz, and L. Harris.

References

- ¹T.L. Collins, Fermilab TM-678
- ²S.C. Snowdon, "A Progress Report For The Energy Doubler/Saver, Collider Project", Fermilab Report, June 1976.