STUDIES OF LOSSES, DIAMAGNETIC AND PERMANENT MAGNETIC EFFECTS IN SUPERCONDUCTING MAGNETS*

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Abstract

Extensive measurements of superconducting properties of model magnets employing various materials and coil construction techniques have been made. Superconductors of varying properties were used, and loss measurements are given as a function of maximum field and rate of rise. Diamagnetic effects for various coil configurations, strand sizes, Cu/SC ratio, etc., are investigated as well as the effect of magnetic circuit geometry on these properties. The rate dependence of diamagnetic effects and their magnitudes in the aperture of magnets is presented. The other related hysteretic property of superconductors, remanent magnetization, is investigated for various models and SC material parameters. The impact of magnetic circuit geometry on remanence both within coils and within magnet apertures is studied. Amongst these results are the effects of strand size and critical current density, cycle history and geometry. Studies of procedures to minimize remanent magnetization will also be presented.

I. Introduction

High field superconducting dipole magnet designs for possible use in accelerators[1] or beam transport have commonly employed certain current distribution to determine the shape of the field, and iron has played a secondary role in field shaping. For use in fast cycling accelerators, and to minimize distortions of the field due to the magnetic properties of the superconductor twisted composites of very fine superconductor filaments and normal conductor have been developed.[2,3]

In contrast, for slowly cycling magnets employing a traditional magnetic iron circuit of rectangular window-frame design, one can make use of relatively coarse filament composites which have become commercially available.[4] This approach is being followed for[5] a 40kG superconducting 8° bending magnet system to be employed in the transport of the external proton beam at the AGS. The basic ideas used in the 8° bending magnet design have been tested in three small pulsed models and a 20-in. long full aperture model up to fields of 40kG. In companion papers[6,7] the field properties and necessary field corrections are discussed in detail. In this paper we describe the measurements on model magnets of energy losses during pulsing, the dynamic field distortion due to magnetic properties of the superconductor, and the remanent fields in the magnet aperture. The remanent flux trapped in the dipole coil is largely shunted away from the aperture by the closely coupled iron yoke, and is erased in any case as soon as the driving flux has penetrated the filaments below 5kG field. Diamagnetic effects amount to a few gauss in the useful aperture of the small models, and they would scale to become even smaller for larger aperture magnets. The size of the remanent fields and of the diamagnetic field distortion in the aperture depends on the size of the small cooling gaps in the dipole coil package, as well as on the presence of the sextupole correction coils.

II. Pulsed Test Model Descriptions

Three small test models have been built to test the window-frame design. A laminated iron core is common to all three (see Fig. 1). Outside core dimensions are 7 1/2-in. wide, by 3 3/4-in. high, by 7-in. long. The window frame aperture is 1 1/4-in. high, by 3-in. wide. The mean turn length is approximately 20-in. for all models. The coil package for Model #1 consists of 9 layers of 9 turns per layer, of 0.054-in, by 0.108-in. composite superconductor containing 360 filaments of NbTi, 3 mils in diameter, twisted once per inch and with a copper to superconductor ratio of 1.25 to 1. A 1/32-in. thick layer of high purity grooved and anodized aluminum is placed between each layer of conductors. The overall dimensions of the coil package are 0.794-in. wide, by 1.026-in. high.

The coil for Model #2 consists of 9 layers of 8 turns per layer of 0.066-in., by 0.132-in. composite superconductor containing 2133 filaments of NbTi, 1.3 mils in diameter, twisted two times per inch and with a copper to superconductor ratio of 2 to 1. The same thickness aluminum strips were placed between coil layers as in Model #1. The overall dimensions of the coil package are 0.920-in. wide, by 1.088-in. high. There are 5 search coils in the aperture, 3 of which are placed symmetrically in the horizontal mid-plane. Models #1 and #2 contain no correction coils.

Model #3 contains both dipole coils and correcting coils (Fig. 1). The dipole coil package consists of 8 layers of 8 turns per layer of the same conductor as in Model #2. The same thickness aluminum strips were used between coil layers as in the other models. This coil, however, had a 0.086-in. phenolic spacer between the 4th and 5th turn of each layer to provide a 0.086-in. gap along the horizontal centerline of the magnet. This was the simplest expedient to provide good low-field properties within the constraints of the existing core. The overall dimensions of this coil package are 0.785-in. wide, by 1.166-in. high (see Fig. 1). The correcting coil package con-

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sists of 3 layers of 4 turns per layer of 0.040-in. diameter composite superconductor containing 178 filaments of NbTi twisted 4 times per inch and with a copper to superconductor ratio of 2 to 1. A 0.015-in. thick layer of high purity grooved anodized aluminum is placed between each coil layer. The overall dimensions of the correcting coil package are 0.171-in. wide, by 0.168-in. high (see Fig. 1). There are 9 fixed search coils, some of which are shown in Fig. 1. Besides, there are 5 turns of copper wires wound on each side of the back leg, such that the flux through the iron yoke can be measured.

The 20-in. full aperture model of the 8° bending magnet system is described in a companion paper.[5]

III. Losses in Model Magnets

The energy loss per magnet cycle was measured by a standard Hall effect watt meter circuit. A Hall probe is imbedded in a normal air core solenoid which is connected in series with the model magnet. The Hall current source is derived from the voltage on the load. The integral of the Hall voltage over the cycle is then proportional to the energy dissipated in the load.

All models were studied for total energy loss per cycle as a function of rise rate at various fields as shown in Figs. 2, 3 and 4. In both types of superconductor composites, the loss per cycle is constant when the rise time exceeds 7 seconds. When the magnet is pulsed at high fields at low rise rates, the loss in the 2133-strand conductor (Model #2 and #3) is a factor of 1.5 less than in the 360-strand conductor (Model #1). Note that assuming a critical state model and total penetration of the filaments at a constant current density, the losses should be proportional to filament diameter and the volume of the superconductor. For Model #1, this would predict losses which are 2.3 times as large as for Model #2 (ignoring the small iron contribution). In fact, the losses for 20 kG pulsing are nearly identical in the two models, and at 40 kG the losses scale by only a factor of 1.5. For such large filament sizes, surface effects reduce the losses at lower fields. The magnitude of loss in Model #3 is very similar to Model #2 which has the identical primary coil material. While Model #2 has 11% more primary coil conductor, it did not have any auxiliary correcting coil. As a result, the amount of NbTi in the two models is almost the same, and the equal losses are as expected. The losses in Fig. 4 are the same whether the auxiliary sextupole coil is pulsed or not.

IV. Remanence and Diamagnetic Effects

The field measurements are taken with a fixed search coil matrix by pulsing the magnet. Small differences between search coil output and a bucking reference are integrated, and the integral is measured as a function of excitation current. For measurements of relative field changes in the aperture, the center coil of the matrix is used as a reference. For a full magnet cycle (up and down), the hysteresis loop in the field shape which is caused by diamagnetic and remanent field behavior of the superconductor can be displayed on an oscilloscope (see Fig. 5).

Superconductors have "fat" hysteresis loops at low fields due to screening and trapping of flux. In the window frame design, with closely coupled iron, most of the remanent flux is returned through the iron and very little appears in the aperture. This has been confirmed experimentally in the model magnets we have studied. Typically $\sim$ 250G pass vertically through the dipole coil and return through the outer yoke. However, the cooling spaces on the top and bottom of the coil (see Fig. 1) will cause some remanent flux leakage into the aperture. In the case of Model #3, the large midplane gap also increases leakage. Due to the different size of these cooling channels (2.5% to 10% of the aperture height), different remanent fields were obtained for Models 2, 3 and the 20-in. model. The following tables give the general features of the results for the three models. The remanent fields are not sensitive to rise rate.

TABLE I. Remanent Field of Model 2 in Mid Plane

	Left (Gauss)	Center (Gauss)	Right (Gauss)
After 20kG pulse	4.5	1.5	4.3
After 40kG pulse	2.3 ±2	2.5	3.3±2

These small numbers arise from two opposing effects. The iron remanence is in the direction of the driving field and, in the midplane, falls off toward the side with predominantly sextupole behavior. Some of the flux trapped in the superconducting coil, on the other hand, leaks out of the cooling channels at the top and bottom of the coil, opposing the driving field and decreases toward center. One would expect a slightly larger iron remanent contribution at 40kG compared to 20kG.

TABLE II. Remanent Field (Gauss) of Model #3 When Pulsing Dipole Alone

Search Coil Location	Low Field (15kG) Pulsing	High Field Pulsing
#5	25 (dipole)	22 (dipole)
#6	25	22
#2,#8	14	12
#7	14	10
#1,#9	-10	-10

Here the remanent field pattern is further complicated by the presence of the sextupole coil and by the midplane gap in the dipole coil. It should be noted that for a scaled up magnet aperture, the superconducting effects would decrease in the inverse ratio of the scale factor.

The remanence in the aperture due to pulsing the auxiliary coil alone with the primary coil off was also measured (the magnet was demagnetized before measurement). The differences between the output of the various search coils and the center one were taken. The result of these measurements is given in Table III.

TABLE III. Relative Remanence of Model 3 When Pulsing Sextupole Alone

$B_6 - B_5$	0 (Gauss)
B_2-B_5, B_8-B_5	0
$B_7 - B_5$	-7.6
B_1-B_5, B_9-B_5	-10.6

It should be noted that the remanent behavior of the auxiliary coil, due to its self-field alone, will be different from the normal situation where the auxiliary coil superconductor experiences an external predominantly dipole field from the primary coil. Nevertheless, the results of self excitation of the auxiliary coil demonstrate that the remanence due to line dipole magnetization currents in a sextupole array, tend to produce fields of high multipolarities whose effects are observable only very close to the sextupole windings. From Table III it can be seen that search coils #2, #6 and #8, which are a little distance from the auxiliary windings, show no field change with respect to the center coil.

The coherent interaction of the fields and remanence of the primary and auxiliary coils was demonstrated by simultaneous activation of both coils. In fact, a strong control on the remanent field in the aperture was possible. By varying the amplitude and time of fall of the auxiliary coil current during the falling field part of the magnet cycle, a broad smoothly varying change of the total remanent field was achieved. It is possible,for example, to obtain zero remanence at all inner search coil locations at the expense of large remanent fields at the outside locations. In another case illustrating control a uniform remanent field of 8G at all search coils was achieved with no observable aberration multipolarities.

For the 20-in.full aperture model,the remanent field was analyzed with a harmonic coil. The model and the technique is described in another paper.[6] Table IV shows the various multipole terms in gauss at a radius of 1.513-in., the maximum useful aperture of the magnet after the magnet was pulsed to 25 kG. These are the coefficients B_n in the expansion:

$$B_r(r,\theta = \sum_{n=1}^{\infty} B_n \left(\frac{r}{1.513}\right)^{n-1} \cos(n\theta + \varphi_n)$$

TABLE IV. Harmonic Analysis of Remanent Field of 20-in Model (at r = 1.513")

Harmonic Term	B_{rem} (Gauss)	Harmonic Term	B_{rem} (Gauss)
1 θ	+ 12	2 θ	+ 2.3
3 θ	-4.8	4 θ	- 2.9
5 θ	-9.2	6 θ	- 3.4
7 θ	-0.9	8 θ	- 0.8
9 θ	+0.8		

These are preliminary results. There is no satisfactory explanation for the small even terms at this time. Superconducting and iron contributions have not been measured separately. However, the magnetization of the auxiliary coil, which has the fundamental symmetry of a 5 θ term (with some admixture of 3 θ etc.) is quite evident in these data. The sextupole (3 θ) term contains contributions from the iron remanant, from the magnetization leakage out of the cooling gaps on the top and bottom of the dipole coil, and from the auxiliary coil magnetization.

Diamagnetism and remanence are closely related, being due to the screening and trapping of flux by "eddy currents" of infinite duration in the superconductor.

In Model #2, the diamagnetic effect is quite small. For both left and right search coils compared to the center one, the difference, due to diamagnetism, is less than 2G. This number is quite constant for a rise rate >3 sec and a field up to 20 kG (remanent field is also a few gauss).

Due to the presence of the sextupole windings and because of larger mid-plane gaps in the dipole coil, the diamagnetic effect in Model #3 is larger. Figure 5 shows the typical hysteretic behaviour of the magnet Model #3 during the first cycle after a current reversal and on subsequent cycles when pulsing the magnet to 20 kG (3 sec rise time, linear rise and fall). The difference between coil #1 and the center coil is shown, and similar patterns, with smaller distortions, are obtained at the other search coils, as will be described below. On the first pulse after a field reversal (indicated by . on the figure) the remanence of 32G (relative to center) is erased and above ~3 kG, the distortion is the same as on subsequent cycles (indicated by x on the figure).

The following gives the magnitudes of these effects for various locations.

Coil #5 (dipole field) shows 14G diamagnetic field contribution at 5 kG, decreasing slightly to 12G at 12 kG. Note that this effect is of secondary importance, since it only affects the "tracking" relation of B_0 to I.

More important is the relative field change with respect to center coil #5, i.e., the field aberration.

#1 vs #5 (#9 vs #5 gave same results) at 5 kG, #1 is larger by 20G due to diamagnetism. By 15 kG this is down to 16G. (The remanent field difference is 32G.)

#8 vs #5 (#2 vs #5 gave same results) at 15 kG, #8 is larger by 4G due to diamagnetism. By 15 kG this is reduced to 3G. (The remanent field difference is 10G.)

#7 vs #5 at 5 kG, #7 is larger by 4G due to diamagnetism. By 15 kG this is reduced to 3G. (The remanent field difference is 10G.)

#6 vs #5 There is negligible diamagnetic field difference at all levels of excitation ($< 1/3$ G). (The remanent field difference is very small; ~ 0.7G.)

The sextupole coil in Model #3 was pulsed alone (with the dipole coil cycled down to zero remanent field) and the dynamic field shape behaviour was observed. This behaviour would, of course, be modified in the presence of the dipole field. In this experiment the dynamic deviations from the ideal sextupole field shape are dominated by the classical eddy currents induced in the vertical aluminum stabilizer strips, because, in contrast to the dipole field, the sextupole field is not everywhere $\sim$ parallel to these strips. The time constant for the classical eddy currents is of the order of 0.6 sec and, at fast rise rates in the sextupole field, the distortions are quite large in those horizontal planes containing the sextupole racetrack coils.

The sextupole was excited above approximately 140 A which is the correction current needed at about a 34 kG dipole field. Search coils #2 and #8 located in the vertical symmetry plane of the aperture (approx. on the inscribed circle) show very little nonlinear effect. The dynamic distortions amount to less than 1G for rise times as low as 0.5 sec. Search coils #5 and #9 located on the vertical symmetry plane, but in the horizontal planes containing the sextupole racetrack coils, show larger dynamic distortions whose size is inversely proportional to rise times up to 20 sec. But for 20 sec rise times these numbers are $\leq$ 2G.

The distortion is most prominent in search coil #7 because of its close proximity to the eddy currents in the aluminum stabilizing strips of the dipole coil and the sextupole winding (see Fig. 1): at 20 sec rise time these distortions are $\sim$ 8G at 40 A excitation decreasing to about 6G at 140 A.

Thus we find that the dynamic distortion of the sextupole correction field is mainly due to classical eddy currents. The effect becomes small in the useful aperture for rise times exceeding 20 sec. The superconducting diamagnetic effects are not observable (sensitivity $\sim$ few gauss). The classical eddy currents would be reduced further, both in amplitude and time constant, in the presence of a large dipole field because of the increased resistivity of the aluminum in the field. In addition to this, the relative volume of aluminum and superconductor is inversely proportional to the size of the aperture. Such effects will be further reduced for a magnet with an aperture three or four times larger.

V. Discussion of Remanence and Diamagnetism

Remanent field studies are interesting for what they reveal about the magnetization properties of the superconductor. While remanence and diamagnetism are related, remanence is effectively erased at fields less than 5 kG and it is diamagnetism, strictly speaking, which is of direct interest to magnetic field behaviour at higher fields. For example, assume a magnet is used from 5 kG to 40 kG. The most relevant property is the variation in field shape across the aperture as a function of dipole field.

Diamagnetic effects are greatest at 5 kG, the lowest field of interest, for two reasons. Firstly, even for coarse strand superconductors such as used in the present models, screening effects saturate at lower fields than 5 kG and so will only go down as the field increases because of the decreasing critical current characteristic. In the data given on diamagnetism, in all cases by 15 kG the absolute diamagnetic field change ΔB (gauss) is slightly smaller than at 5 kG. Secondly, as the field B_o increases, the relative magnitude of $\Delta B/B_o$ is further reduced.

In spite of the disadvantages of Model #3 which we described, and except for coils #1 and #9 which are extreme in location compared with any reasonable definition of aperture region, the diamagnetic effects are only a few gauss in the small model. There are in addition good reasons to believe that the effects will scale down for larger aperture magnets and that compensation or control can be exercised easily. It is therefore reasonable to state that in the more realistically shaped larger window-frame magnets these effects can be made small even with coarse strand superconductors. Measurements of the diamagnetic effects on the 20-in. long full aperture model are in progress.

References

1. J.H. Coupland and D.E. Baynham, RHEL, "Measurements on Pulsed Superconducting Dipole Magnets," these Proceedings.
2. D.B. Thomas, RHEL, "Filamentary Superconductors for Pulsed Magnets," these Proceedings.
3. P.R. Critchlow et al., Cryogenics (Feb. 1971), p. 3.
4. Kryoconductor Superconducting Wire, Magnetic Corp. of America, 100 Mountain Avenue, Murray Hill, N.J.
5. J. Allinger et al., "A Superconducting 8^o Bending Magnet System," Applied Superconductivity Conference, Annapolis, 1972 (in press).
6. J. Allinger et al., "Performance and Magnetic Measurement of a Full-Scale Cross-Section Model of a Superconducting 8^o Bending Magnet System," these Proceedings.
7. J. Allinger et al., "Magnetic Circuit Consideration for High Field Magnets," these Proceedings.

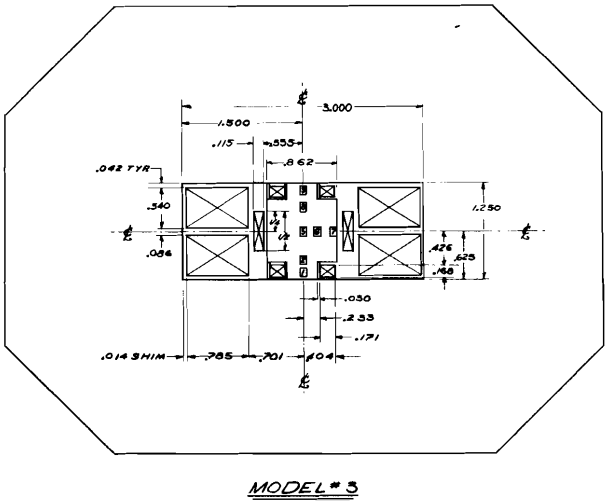

Fig. 1

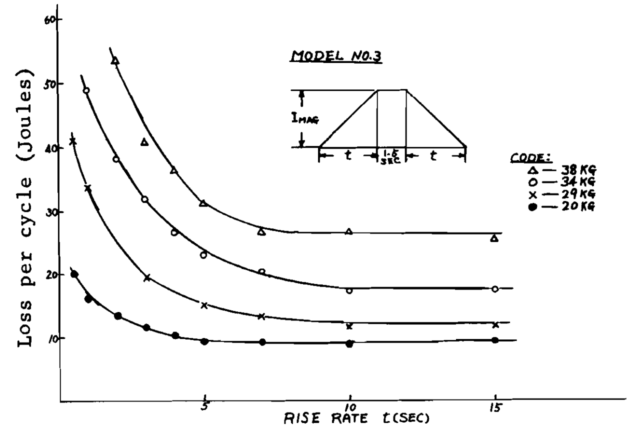

Fig. 4. Energy Loss per Cycle of Model #3.

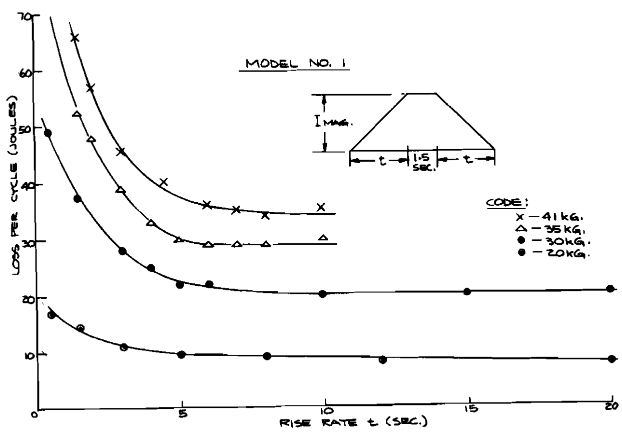

Fig. 2. Energy Loss per Cycle of Model #1.

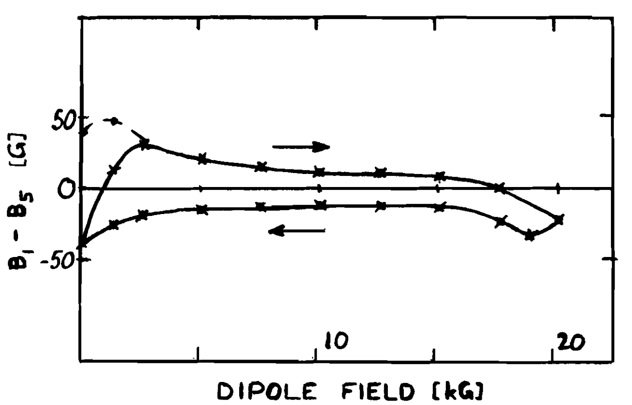

Fig. 5. Remanent Field and Diamagnetism in Model #3 First Cycle after Current Reversal (·) and Subsequent Cycles (x)

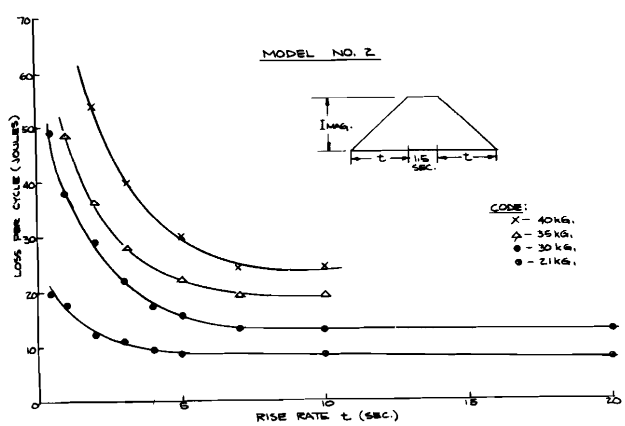

Fig. 3. Energy Loss per Cycle of Model #2.