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MAGNETIZATION EFFECTS IN SUPERCONDUCTING DIPOLE MAGNETS

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Summary

Magnetization effect of superconductor on the field quality has been investigated for some of the typical Energy Doubler bending magnets. Calculations were made using the computor program GFUN2D and compared with some measured results. Agreement between them is good. The field quality at low excitation is mainly determined by the magnetization effect. A similar effect due to a stainless collar mechanical support was also calculated, although it is not as big as the first one.

1. Introduction

The homogeneity of the injection field in a superconducting synchrotron is seriously affected by the properties of the superconductor. Superconductor has hysteretic magnetization, which arises from the induced circulating currents flowing in each superconducting filament. This magnetization generates its own field, which disturbs the field quality of the magnet, especially at low field. This problem has been discussed by M.A. Green[1] and G. Parzen[2]. There are several ways to minimize this effect; one somewhat successful method is to reduce the filament diameter. The other way would be to develop a superconducting material with low J_c value at low field. Presently, the effect of magnetization cannot be reduced enough to avoid field distortions. Therefore, it is desirable to use high injection field to reduce the magnetization effect. In the present design, the injection field of the Energy Doubler bending magnet is 4.2 kG, which is bigger than the filament penetration field ($\sim$ 1 kG). There are mainly three magnetization effect. The first one is the transfer function, which is the ratio of magnetic field value and current value; the second is the sextupole field value, especially at low field, and the third is the remanent field.

An additional, though smaller, magnetization field is present. The Energy Doubler/Saver dipole magnet coils are mechanically supported by means of external stainless steel collars. Consequently, the non-zero susceptibility of the stainless steel will slightly modify the field harmonics.

Both of these contributions are included in our analysis. The computations were performed with the computer program GFUN2D[3].

2. Calculations

For this calculation, the program GFUN2D was employed through the IBM Time-Sharing Option (TSO) mode at ANL[4]. In the program, the two-layer conductor region in each quadrant is divided into 32 prisms, and the magnetization within each prism is assumed constant. The magnetic field value at the center of each prism is calculated by the same program. The magnetization curve of the superconducting material NbTi was derived from our hysteresis loss measurement of superconducting wire[5] as shown in Fig. 1. In the actual magnet, the magnetization of NbTi is diluted by copper and some other insulators. A dilution factor of 0.247 was used. Taking into account the dilution factor, a B-H table was separately made, both for increasing field and for decreasing field.

The same kind of calculation can be done for the stainless steel. The measured susceptibility of some stainless steels is given in Table 1. It is not a big effect, especially with Nitronic 33, which is being used for the Energy Doubler magnet cryostat. This effect on field was only calculated at 1,000 A, assuming χ_m = 0.015 of stainless steel 316 and without iron.

3. Results and Discussions

The calculated components of field harmonics are 2, 6 and 10 pole ones. The behavior in these coefficients due to magnetization is shown in Figs. 2 and 3 with the values obtained from E5-2 magnet without an iron yoke.

Transfer Function

The transfer function, which is related to the 2 pole field, is given in Fig. 2 as a function of the exciting field. The measured results are also shown in the same figure. The transfer function was measured using a proton NMR up to 20 kG[6]. The agreement between them is fairly good. The measured value is centered at 8.065. The values during the rise of a ramp are lower than 8.065 and those during the fall of the ramp are somewhat higher. The difference between them at 10 kG is about ± 2 Gauss, which is much smaller than the remanent field value of approximately 10 Gauss. This reflects the reduction of J_c values, which is proportional to $1/(B + B_o)$. If we assume B_o = 2 kG, this expression is in good agreement with the data, even though all of the superconductors in the coil are not in the same field.

Sextupole and Decapole Field Components

The field quality at low field is dominated by the magnetization of the superconductor, which induces high harmonics in the field quality. The normal 6 and 10 pole components in Fig. 3 are those obtained in the harmonic analysis for the 5-foot magnet (E5-2) without iron. The measured data includes a component due to construction errors In all these figures, the calculated values are shifted to compare with the measured ones. In the above calculations, the B-H table does not include the effect of transport current (I_t). This effect gets bigger when the transport current comes closer to quenching current. However, in the low field region, it is negligible. Even without this correction agreement between measured and calculated values is good.

History Effect of Sextupole Coefficient

The 6 pole component was studied under different conditions. The 6 pole component during normal ramping from zero field and also from virgin state are shown in Fig. 4. The effect of field reversal on the 6 pole component was also tested. After exciting the E5-1 magnet (with iron yoke) up to 40 kG, the field was reversed up to -5 kG (at least twice the penetration field). Then, exciting in the normal direction, the 6 pole component was measured at DC current. The results are given also in Fig. 4. The behavior is very similar

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to the magnetization curve. Below 0.5 kG, the sign of the 6 pole component is opposite to that of the normal ramping.

Remanent Field

The remanent field was measured for virgin excitation and the subsequent excitation of the E5-' magnet with iron yoke. As shown in Fig. 5, both remanent components increase until the flux completely penetrates into the filaments, and then level off. They decrease with increasing field, which may be due to the decrease of J_c value and due to increase of transport current. The total remanent field is about 12 Gauss, while the remanent field due to iron yoke is 2.5 Gauss.

The remanent field was also investigated in several ways for the E5-1 magnet with iron yoke and for the E5-2 magnet without iron yoke. The data for the E5-2 magnet was obtained by adjusting the current to the desired value and then either tripping the power supply or gently returning the current to zero. These results are shown in Table 2. The persistent sextupole resulting from a fast trip is systematically smaller than that obtained by slowly lowering the current. The sense of the shift is consistent with the generation of eddy currents in the superconductor during a fast trip. Both 2 pole and 6 pole components of remanent field after tripping were lower than those which had not been tripped.

Magnetization of Stainless Steel

The effect of stainless steel collar causes a constant shift in the field. The increase in the 2 pole field is roughly 0.3% for Stainless Steel 316. The changes of the higher order coefficients are $-1.1 \times 10^{-4}/cm^2$ for the 6 pole and $4 \times 10^{-6}/cm^4$ for the 10 pole component. These shifts do not depend on the excitation field, and can be corrected. The case with Nitronic 33 should be smaller by a factor of 10.

As a conclusion, the magnetization effect is quite serious, especially below the penetration field (~ 1 kG), and injection at any field less than that might be very difficult.

Acknowledgements

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References

[1] M.A. Green: L.B.L. Report, UCID 3508, February 20 (1971). IEEE Trans. Nuclear Science, NS, 664 (1971).

[2] G. Parzen and K. Jellet: BNL Report CRISP 72-73, (1972).

[3] M.J. Newman et al: RHEL/R 244, September, 1972.

[4] R.J. Lari: Proc. 5th Int. Conf. on Magnet Technology, 244 (1975).

[5] M.E. Price and R. Yamada: Fermilab TM 639 (1975).

[6] R. Yamada et al: Application of NMR to Superconducting Magnet using Signal Averager; Contribution to this conference.

TABLE 1

Magnetic Susceptibility of Various Stainless Steel

Alloy/Field	1T	2T	3T	4T	5T
316	0.015	0.016	0.015	0.013	0.012
Nitronic 40	0.0021	0.0020	0.0019	0.0018	0.0018
Nitronic 33	0.0018	0.0017	0.0016	0.0015	0.0015

TABLE 2

Remanent Sextupole Field of E5-2 without Iron Yoke at r = 1.0 cm

I (Amp)	Slow Ramp (Gauss) (0--I--0)	Fast Trip (Gauss)
50	1.42	
100	1.35	
200	1.48	
400	1.57	1.28
600	1.60	1.26
800	1.60	1.23
1000	1.59	1.22
1500	1.59	1.16
2000	1.56	1.13
2500	1.52	1.12
3000	1.48	0.95
3500	1.41	
4000	1.32	
4200	1.19	

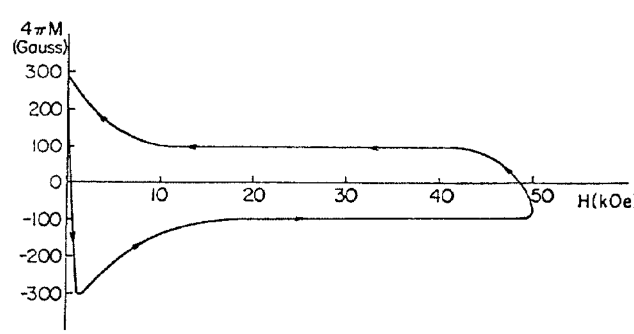

Fig. 1. Magnetization curve of NbTi, calculated from hysteresis data.

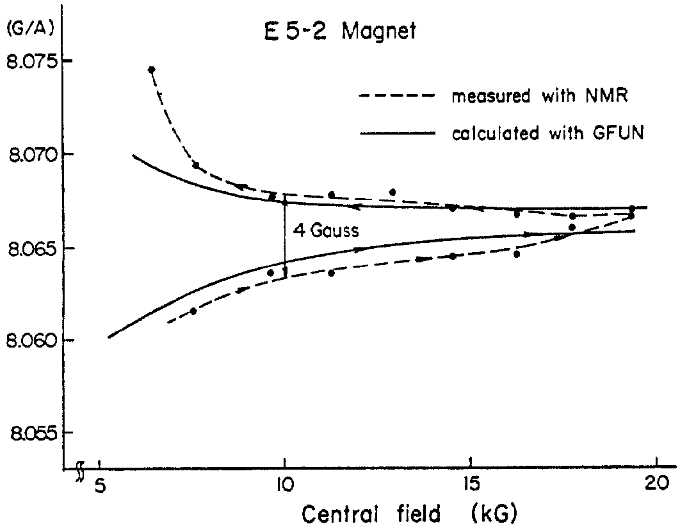

Fig. 2. Transfer function of E5-2 magnet without iron yoke as a function of central field.

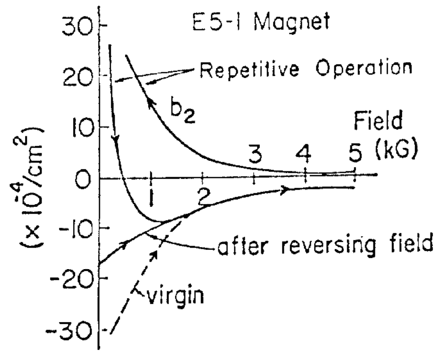

Fig. 4. Effect of history on normal 6 pole coefficient for E5-1 magnet with iron yoke.

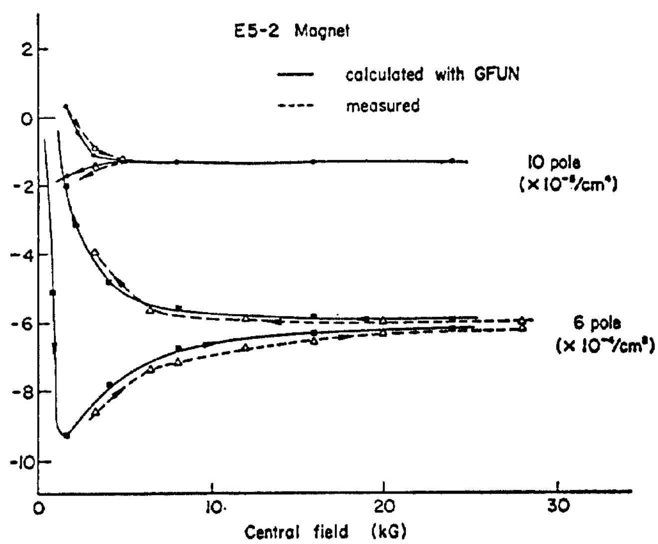

Fig. 3. Normal sextupole and decapole components versus central field.

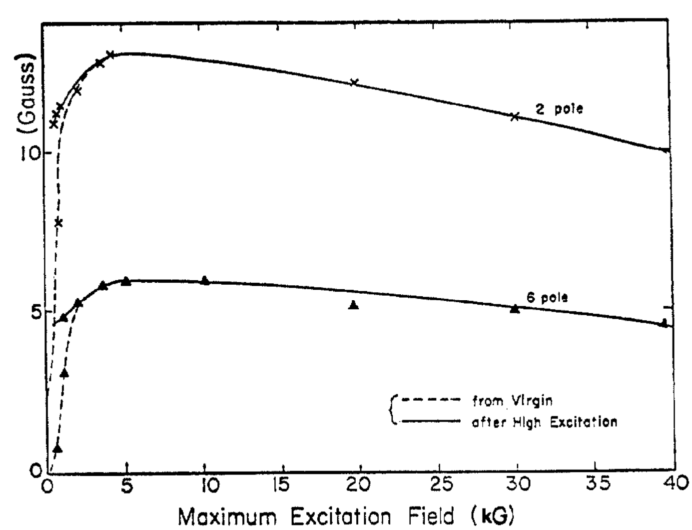

Fig. 5. Remanent field as a function of maximum excitation field for E5-1 with iron yoke measured at r = 1.9 cm.