Ferromagnetic Material in the Superconductor and Its Effect on the Magnetization Sextupole and Decapole in the SSC Dipoles at Injection

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ABSTRACT

It has been shown that the magnetization of a multifilimentary superconductor can be altered by adding nickel to the composite strand. This report presents the results of calculations of the magnetization sextupole and higher multipoles in a five centimeter SSC dipole with and without nickel as part of the strand composite. The relative distribution of the nickel in the inner and outer coil conductors can be used to effectively eliminate sextupole and decapole at the SSC dipole injection field. Calculations of magnetization sextupole in the dipole are presented for strand with substituted nickel filaments and strand with electroplated nickel. the effect of nickel in the strand on the SSC dipole field quality at fields above the injection field is described . The effect of nickel in the strand on magnetization sextupole flux creep decay and the magnetization sextupole temperature dependence is also discussed.

INTRODUCTION

Superconducting dipole and quadrupole magnets exhibit a residual magnetization due to persistent circulating currents in the superconductor. The superconductor magnetization is responsible for the distortions in the symmetrical multipoles found at low fields in a magnet where these multipoles would otherwise be absent.[1] Persistent current magnetization is proportional to the product of the superconductor critical current density J_c and the filament diameter d. This has motivated the production of superconductor with finer and finer filaments. With smaller filaments came smaller interfilamentary spacing and proximity effect coupling. Proximity effect coupling can be eliminated through the use of a dilute Cu-Mn alloy in the interfilamentary space.[2] No matter how small one makes the filaments, one still is faced with their intrinsic magnetization (thermodynamic, reversible) which is diamagnetic. The intrinsic magnetization contributes to the multipole distortion during the field increasing portion of the SSC cycle (injection and acceleration).

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The introduction of suitably placed ferromagnetic piece within the magnet can be used to compensate both the diamagnetic intrinsic magnetizations and the persistent current magnetization. Two approaches have been suggested. The first is to place small pieces of ferromagnetic material within the bore of the magnet or in one of the coil wedges.[3,4] The second approach is to put the ferromagnetic material in the strand itself.[5,6,7]. In an earlier paper, Collings et al[8] reported on the implementation of two in-strand methods of ferromagnetic compensation. These methods are applied to the strand of the five centimeter bore SSC dipole.

DESIGN OF THE CONDUCTOR

When considering the introduction of Ni at the strand (or interfilamentary) level, the question of ferromagnetic size-effect crops up. Thus, it is useful to point out that bulk ferromagnetic properties can be expected in polycrystalline films as thin as ~0.2 μm; but even below this size, Fe and Ni are still ferromagnetic -- albeit single-domain in character.[9] On the other hand, electrolessly (chemically) deposited Ni films, which are amorphous, are not ferromagnetic.

In general, magnetic compensation is achieved when

$$\sigma V_{Ni} = -M_{SC} V_{SC} \tag{1}$$

where σ is the unit-volume (specific) moment of the Ni, M_{SC} is that of the NbTi in the strand, V_{Ni}, and V_{SC}, the volumes of Ni and NbTi, respectively. As indicated above, two modes of compensation are being considered.

If compensation is to be achieved by filament-substitution, Eq. 1 is best rewritten in the form

$$n_{Ni}/n_{SC} = -M_{SC}/\sigma \equiv R \tag{2}$$

where the left-hand quotient is the ratio of the numbers of Ni and NbTi filaments in the group to be compensated.

If Ni-plating is selected as the route, we rewrite Eq. 1 in the form

$$\sigma A_{Ni} = - M_{\ell} \tag{3}$$

where A_{Ni} is the cross-sectional area of the Ni plating of thickness t, and M_{ℓ} is the moment per unit length of the strand of diameter D. This yields the working formula

$$t = -M_{\ell}/\pi D \sigma \quad . \tag{4}$$

THE TWO TYPES OF CONDUCTOR

The principles of strand compensation were demonstrated using two different types of superconductor.[8] In one of the superconductor types, filaments of nickel were substituted for filaments of niobium titanium. In the second types, the superconductor was electroplated with nickel.

The strands with nickel substituted for superconductor were manufactured by Hitachi Cable Ltd.[10] This strand was double stacked conductor with 66 bundles with 85 filaments each. The filament diameter was 3.17 microns. In the uncompensated conductor HCLCU, all 85 filaments per bundle were superconductor. In the compensated conductor HCLNI, two of the 85 filaments per bundle were nickel instead of niobium titanium (see Fig. 1).

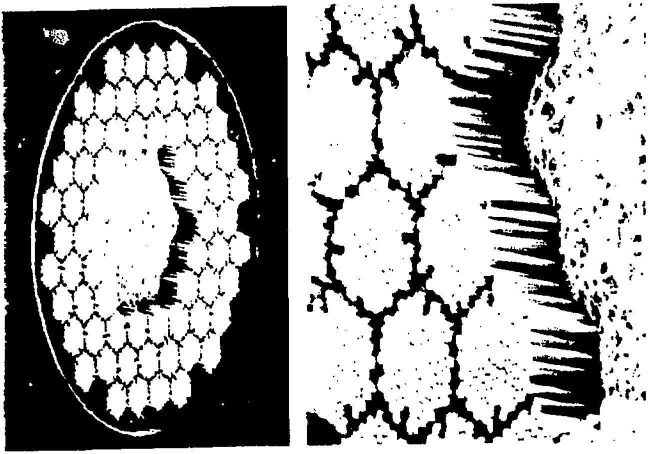

Fig. 1 Scanning electron micrographs of the HCLNI strand etched for Cu plus Ni. (Note the vacancies left by the dissolved Ni filaments.)

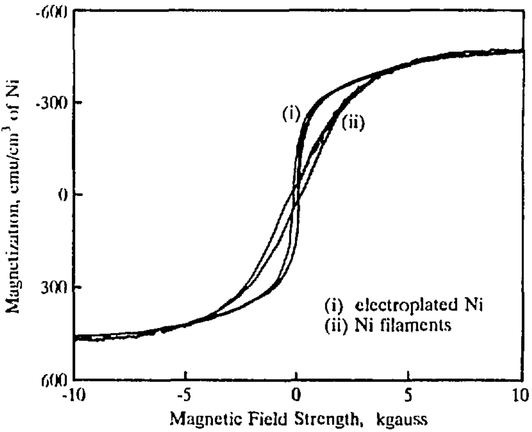

Fig. 2 Superposition of the M(H) loops for strand HCLNI and strand IGCNI at 10K.

The strands which were plated with nickel were manufactured by IGC Advanced Superconductors. This strand is a single stacked conductor with 11,000 filaments, 4.92 microns in diameter. The unplated conductor (designated as IGCCU) was plated with about 1.9 microns of nickel (the plated conductor is designated as IGCNI).

Table 1 compares the two types of superconductor with and without nickel compensation. Figure 2 shows the magnetization loops for the nickel in the Hitachi (HCLNI) strand and the IGC (IGCNI) strand. The shape of the nickel magnetization loops is different but, in both conductors, the saturation magnetization is 497 emu per cubic centimeter (a saturation induction of 0.624 tesla).

Table 1. Comparison of Strand With and Without Nickel Compensation

Hitachi Strands (substitute filaments)[8,10]

	Compensated HCLNI	Uncompensated HCLCU
Number of S/C filaments	5478	5610
Number of Ni filaments	132	---
Filament Diameter (μm)	3.17	3.17
Strand Diameter (mm)	0.385	0.385
Copper to S/C Ratio	1.6928	1.6293
Nickel to S/C Ratio	0.0241	---

IGC Strands (Ni plated)[8]

	Compensated IGCNI	Uncompensated IGCCU
Number of S/C filaments	11000	11000
Filament Diameter (mm)	4.92	4.92
Strand Diameter (mm)	0.827	0.823
Nickel Thickness (μm)	0.88	---
Copper to S/C Ratio	1.5437	1.5437
Nickel to S/C Ratio	0.0232	---

Figure 3 shows the measured hysteresis loop for the compensated HCLNI strand. Figure 4 shows the measured hysteresis loop for the compensated IGCNI strand. At fields strengths near 10 kG (1T), the width of the two magnetization loops is proportional to the product of J_c and d. The two strands have nearly the same J_c (about 3000 A per mm^2 at 5 T and 4.2K) so the width of the IGCNI curve is about 1.55 times larger than the HTCNI curve at a field of 9 kG. At low field, the HTCNI strand exhibits a large amount of additional magnetization probably due to proximity coupling. (The filament spacing within the sub-bundle is less than 0.6 microns.)

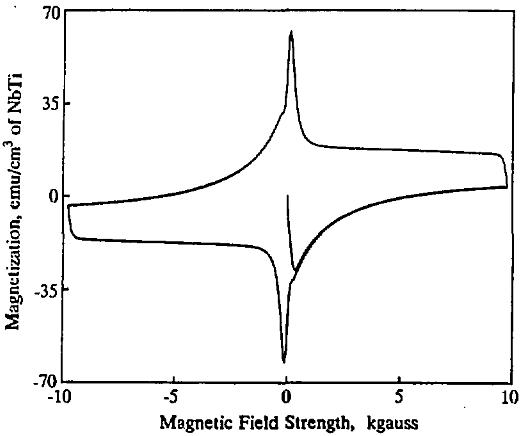

Fig. 3 Magnetic hysteresis loop for strand HCLNI at 4.2K.

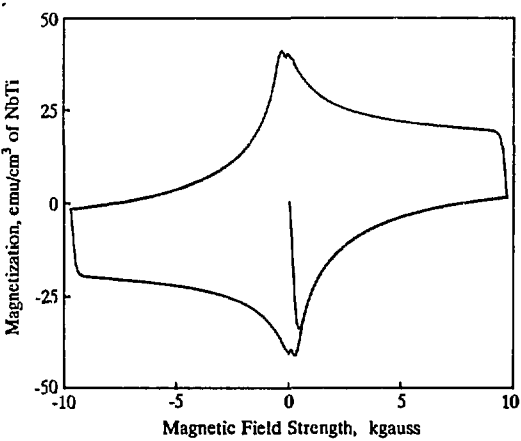

Fig. 4 Magnetic hysteresis loop for strand IGCNI at 4.2K.

CALCULATION OF MAGNETIZATION SEXTUPOLE AND DECAPOLE IN THE SSC DIPOLE

In order to show effect of nickel in the superconductor on magnetization sextupole and decapole, in the SSC dipole, shown in Fig. 5, it was assumed that the entire dipole consisted of conductors wound from HCLCU, HCLNI, IGCCU and IGCNI strands. The packing factor assumed for the two layers was 0.75. Cases which involve the use of conductors HCLNI and IGCNI use the actual magnetization curves shown in Figs. 3 and 4. The magnet cycle for the field going down starts with central induction of 6.6 T and goes down to Bo. The magnet cycle with the field going up starts at 6.6 T, goes down to -6.6 T and goes up to Bo. Cases which involve strands HCLCU and IGCCU use values of J_c derived from the magnetization curves shown in Figs. 3 and 4. As a result, the proximity coupling in strand HCLCU is accounted for in the calculations.

Figure 6 compares the magnetization sextupole ratio at 1 centimeter for SSC dipoles with HCLNI and HCLCU strands. One can see from Fig. 6 that the magnetization sextupole ratio is reduced when the central induction is rising (the sextupole ratio for the central induction falling is increased). The magnetization sextupole becomes zero at a central induction of 0.89 T when the central induction is rising. The magnetization correction can be improved at injection (0.6 T) by increasing the nickel to superconductor ratio from 0.0241 to 0.0275.

Figure 7 compares the magnetization sextupole ratio at 1 centimeter for SSC dipoles with IGCNI and IGCCU strands. As with the HCLNI strands, the nickel plating on the superconductor reduces the magnetization sextupole ratio as the central magnetic induction is rising. The magnetization sextupole becomes zero at a central induction of 1.25 T when the central induction is rising. The magnetization correction at injection can be improved by increasing the thickness of the nickel plating from 1.9 microns to 2.9 microns. (Note: the average field in the coil is 60 percent of the dipole central field.)

The addition of nickel to the superconductor resulted in a reduction of the magnetization sextupole as the field is rising. There was a reduction in the amount of magnetization decapole, but the magnetization decapole is not reduced in the same way as the magnetization sextupole. The ratio of nickel to superconductor in the outer layer must be somewhat larger than it is in the inner layer in order that the magnetization decapole be zero at the same point in the magnet cycle where the magnetization sextupole becomes zero.[11]

SSC dipole magnet compensation with nickel in the superconductor does not change the temperature dependence of the magnetization sextupole in a SSC dipole magnet. (At low fields near injection, the superconductor critical current density changes about 21 percent per degree K.) The addition of nickel to the superconductor does not change the flux creep decay or the related decays of the magnetization sextupole while the SSC dipole magnet central induction is being held at constant value during injection.

CONCLUSIONS

The addition of ferromagnetic material to the superconductor in a SSC dipole superconductor will compensate out the negative magnetization sextupole during injection and acceleration (when the field is rising). Adding nickel filaments to the strand or nickel plating the strand will both shift the whole magnetization sextupole curve in the positive direction. Compensation with nickel in the conductor appears to be a viable method for correcting out the dipole sextupole and decapole due to superconductor magnetization. This correction can be applied to SSC dipole magnets provided the injection energy is not too low (greater than 1.6 TeV). Magnetization compensation with ferromagnetic material does not change the temperature dependence of the magnetization sextupole nor does it change the flux creep decay of the magnetization sextupole in a SSC magnet.

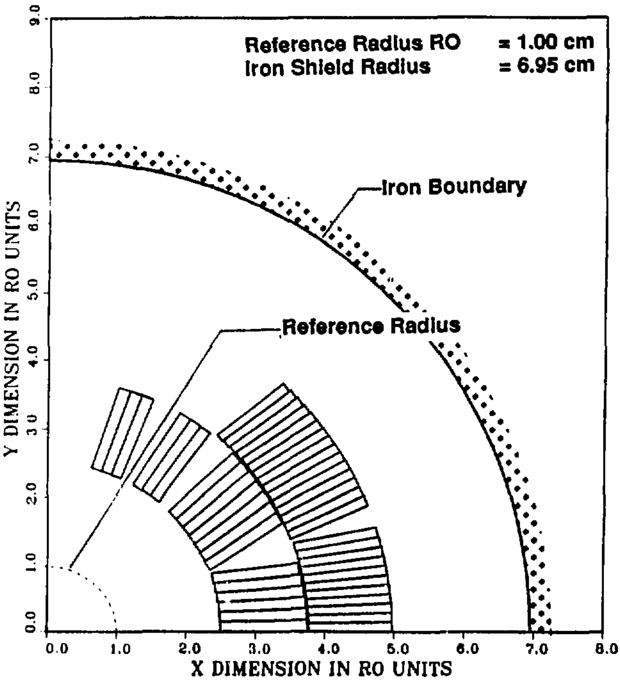

Fig. 5 A quarter section of the SSC DX-201 five centimeter bore dipole magnet.

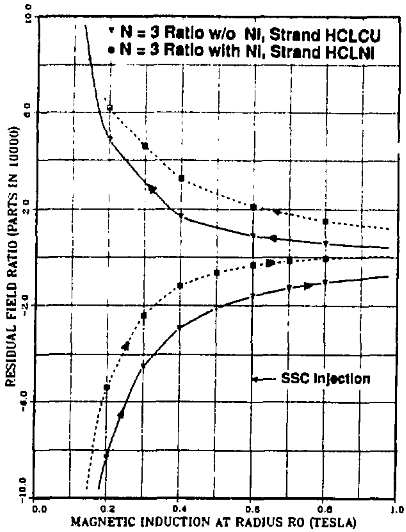

Fig. 6
A comparison of the magnetization sextupole ratio at R=1 cm versus central induction for a SSC dipole with HCLCU and HCLNI strands

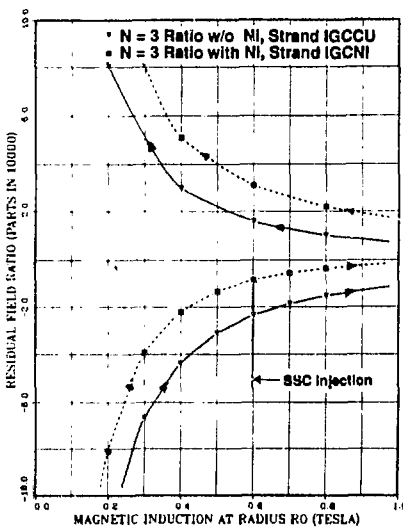

Fig. 7
A comparison of the magnetization sextupole ratio at R=1 cm versus central induction for a SSC dipole with IGCCU and IGCNI strands

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