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DESIGN OF COUPLED OR UNCOUPLED MULTIFILAMENTARY SSC-TYPE STRANDS WITH ALMOST ZERO RETAINED MAGNETIZATION AT FIELDS NEAR 0.3 T

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ABSTRACT

Multifilamentary Cu-matrix strands with interfilamentary spacing as small as 0.2 μm can be almost fully decoupled by the addition of 0.5 wt.% Mn to the interfilamentary Cu. Decoupling in this way seems to be beneficial from a field-stability standpoint. On the other hand, the elimination of coupling does little to reduce residual strand-magnetization at the injection field of about 0.3 T when that field is approached, as usual, along the shielding branch of M(H). This residual diamagnetic magnetization (say M_R) of the winding material is responsible for unwanted distortion (multipole formation) of the dipolar field. It is demonstrated that M_R can be locally cancelled to zero by associating the strand with a small volume-fraction (less than 2%, depending on filament diameter) of pure Ni or any other low-field-saturable ferromagnetic material. The presence of the Ni has little effect on the shape of the M(H) hysteresis loop of the strand, other than to shift its wings uniformly in the +M (when H is positive) and -M directions, respectively. In practice, the Ni could be administered as: (a) additional filaments, (b) interfilamentary barriers, or (c) an electroplated layer on the outside of the strand.

INTRODUCTION

Helmholtz coils, or modifications of them (e.g. saddle-coils) are commonly used for producing dipolar magnetic fields. But if the coils are wound from superconducting strands, residual magnetization, M_R resident in the strand material itself is responsible for multipolar distortions of the desired field. It is well known that the height of the M(H) hysteresis loop -- $\Delta M(H) \equiv (M_{R+} - M_{R-})$, where the signs refer to the trapping (paramagnetic) and shielding (diamagnetic) branches, respectively, of M(H) -- is proportional to the product of filament diameter, w, and critical current density, $J_c(H)$[1]. Thus in an attempt to reduce strand magnetization (in the presence of high J_c) and the attendant field distortion, a strong effort has been under way to produce, on a commercial scale, multifilamentary strands with smaller and smaller filaments. In order to preserve filament quality (i.e. to prevent thickness undulations, or "sausaging") in small filaments, it has been suggested necessary to confine the ratio of filament spacing (s) to filament diameter (d) to $s/d \leq 0.15 \pm 0.02$[2]. The combination of small d with low s/d results in interfilamentary spacings sufficiently close to proximity-effect-couple the filaments. For example, at an s/d of 0.13 Cu-matrix filaments that have been reduced to 5-1/2 μm in diameter are beginning to exhibit coupling; and the coupling becomes worse as d is still further reduced. But if the matrix is alloyed with ~0.5 wt.% Mn, coupling is barely perceptible even with 1 μm diameter filaments[2,3].

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But is this reduction of coupling meaningful within the context of Superconducting Supercollider (SSC) performance? To be sure, the ΔM(H) of closely spaced material has been reduced to its uncoupled value. But what has this achieved from the standpoint of strand magnetization at the beam-injection field of 0.33 tesla? This question can be answered by a glance at Fig. 1, which compares the M(H) loops for "coupled" multi-filamentary strands both with and without the presence of the Cu matrix. Evidently practically all of the coupling magnetization shows up along the trapping segment of the loop. Beam injection takes place after a demagnetization cycle that terminates in a field-increase to 0.33 tesla along the *shielding* segment of M(H).

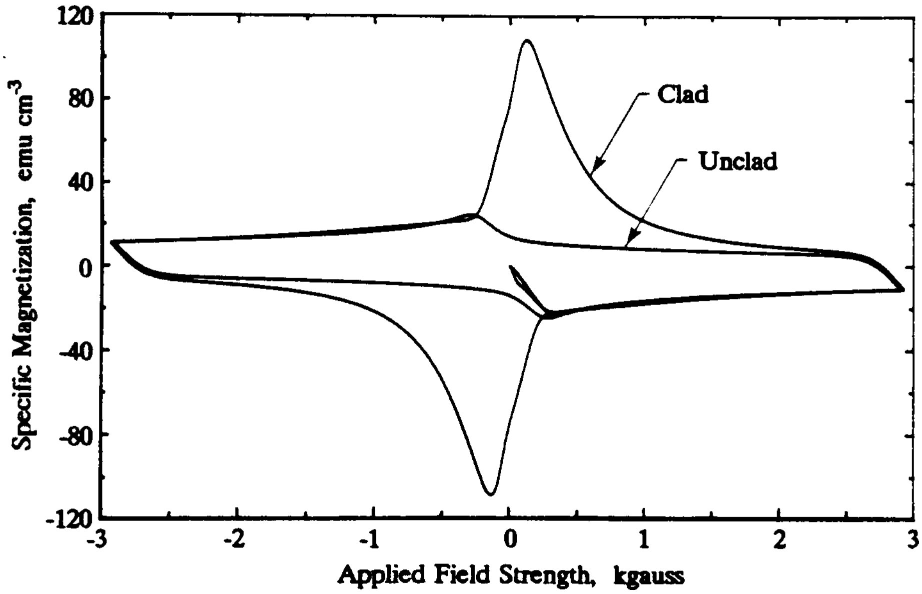

Fig. 1 Specific magnetization (NbTi volume) at 4.2 K of RHIC-009 material both with (clad) and without (unclad) the presence of the Cu matrix. Coupling magnetization is dominant only along the *trapping* branches of the loop.

MAGNETIZATION DECAY IN SSC-TYPE STRANDS

Possibly related to coupling is a second serious problem exhibited by SSC dipole magnets, viz. magnetic field decay following change of field[4]. We are presently investigating this phenomenon with vibrating-sample magnetometry (VSM) using samples that consist of bundles of strand some 6 mm in length (see Ref. 5 for additional magnetometry and sample details). Prior to launching on the drift study proper, an initial test sample was assembled from a length of strand based on RHIC (relativisitic heavy-ion collider) materials. The specifications of it (designated RHIC-009) and related sample materials are given in Table 1.

In order to simulate the magnetic state of the strand just prior to beam injection, magnetization studies were performed along the shielding branch of M(H). Since preliminary experiments indicated that the magnetization drift following field change was very small, the magnetometer was set to one of its high-sensitivity ranges (10^{-2} emu, in this case). Next, to permit full-precision data to be taken on this range, it was necessary to find some way of neutralizing most of the background magnetization (viz. about -0.1 emu). It was decided that background subtraction, free of noise and phase instability, could best be achieved by attaching to the sample holder a weighed amount of fine pure Ni wire. Some M(H) loops for sample RHIC-009 with Ni attached are given in Fig. 2. Note the almost complete diamagnetic moment cancellation in the vicinity of 0.3 tesla.

Table 1 Specifications of Sample Material

Sample Code	Strand Diam.,D, 10^{-2} cm	Fil. Diam.,d*, μm	NbTi area, A_{SC}, 10^{-4} cm^2	Magnetization Test Sample: No. of Strands	Magnetization Test Sample: Length, mm
Cu-Matrix Strands: 6,108 filaments (heat treated)					
RHIC-009	2.51	2.106	2.128	80	6.31
RHIC-013	3.3	2.890	4.007	48	6.31
RHIC-026	6.5	5.490	14.459	14	6.44
Cu-0.5wt.%Mn-Matrix Strands: 22,902 filaments (not heat treated)					
CMN-005	1.27	0.500	0.449	200	5.88
CMN-010	2.75	1.086	2.052	58	5.74
CMN-015	3.85	1.495	4.020	33	5.60

* Obtained by etching-and-weighing using separately measured density of bulk Nb-46.5Ti (= 6.097).

Having proceeded this far, it was recognized that a technique had been developed for fabricating SSC strand with close-to-zero residual magnetization at the injection field. On reflection, it was recognized that Ni barriers had been incorporated into multi-filamentary strands to eliminate proximity-effect interfilamentary coupling[6], but the idea of using Ni to compensate for strand magnetization at injection is new. It may turn out to be convenient to add the Ni as an electroplated layer on the outside of the strand; but should internal Ni be preferred it will be possible to eliminate coupling and compensate for residual shielding magnetization in a single operation.

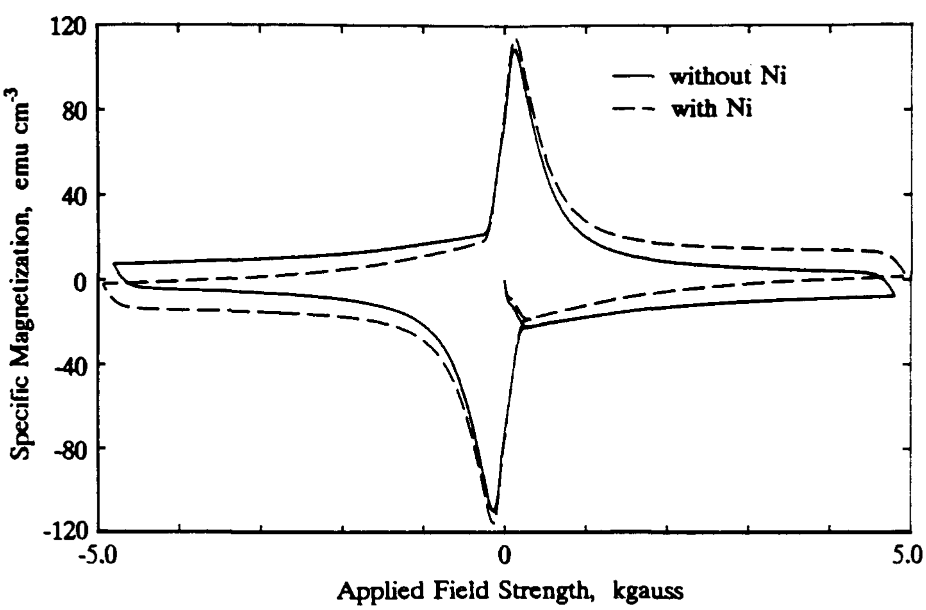

Fig. 2 Specific magnetization (NbTi volume) at 4.2 K of clad RHIC-009, and that of the same sample to which 1.84 mg of pure Ni wire has been attached.

METHODS OF DIAMAGNETIC MOMENT CANCELLATION

In order to cancel the strong diamagnetic moment of a superconductor in the shielding mixed state a large positive moment is needed. Such a moment can be provided by either a paramagnetic or a ferromagnetic material.

Paramagnetic Compensation

Since Cu-Mn alloys have already been recommended as interfilamentary matrices for proximity-effect decoupling, it is natural to enquire into their potential for moment compensation. The 4.2-K hysteresis loop for a Cu-0.93 at.%Mn alloy is depicted in Fig. 3. (The offsets near the origin, the hysteresis, and the slight curvature at higher fields are a consequence of the alloy's mictomagnetism). Since the moment increases monotonically with field it is, in principle, possible to select, for a given superconductor/Cu-Mn volume-ratio, a field strength at which moment cancellation takes place. The disadvantage of a paramagnet is that even if moment-cancellation is practically feasible it would be strongly field-specific.

Ferromagnetic Compensation

Since the superconductor's diamagnetic moment decreases rather slowly with increasing applied field strength, near-compensation over a wide range can be achieved by a field-independent positive moment. An obvious candidate is the saturation moment of a soft ferromagnet (soft, because we would like the moment to drop to zero in zero field). The 10-K hysteresis loop for a sample of pure Ni wire (diameter, 0.1 mm) in what appears to be the as-drawn condition, is depicted in Fig. 4. Since the saturation moment of Ni increases by only 7.7 percent between 20 °C and absolute zero[7,p.5-144] it can be regarded as practically constant throughout the He-temperature range. In Fig. 4, the Ni moment is never fully saturated. The moment of *annealed* Ni saturates in fields less than 1 kgauss; special alloys such as 78 permalloy and deltamax saturate at even lower fields but have larger saturation magnetizations than Ni[8].

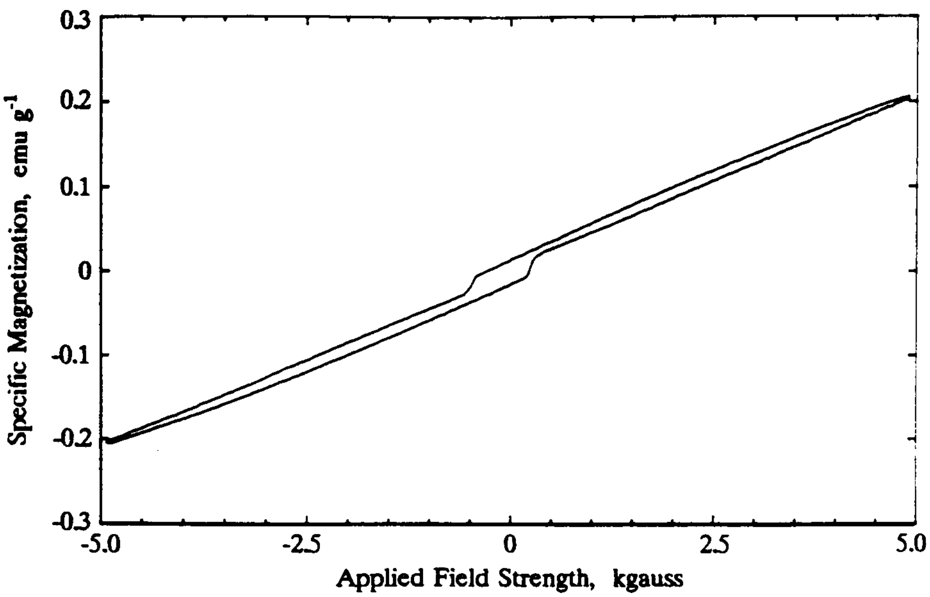

Fig. 3 Specific magnetization of Cu-Mn(0.93 at.%) at 4.2 K

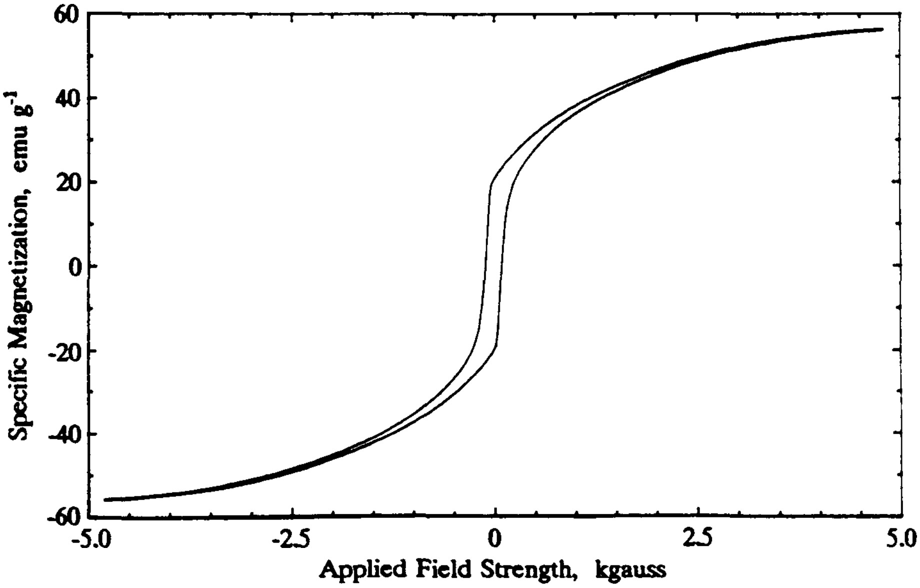

Fig. 4 Specific magnetization of (evidently) unannealed pure Ni wire (0.1 mm diameter) measured at 10 K (the actual sample was RHIC-009 plus Ni measured above the T_c of the NbTi).

DESIGN OF MAGNETIZATION-COMPENSATED STRANDS

The specific magnetizations of six samples of filamentary NbTi in composite-strand form, a sample of Cu-0.93 at.%Mn alloy (both measured at 4.2 K) and a piece of pure Ni wire (0.1 mm diameter; measured at 10 K) at three values of a steadily *increasing* magnetic field (shielding, in the case of the superconductor) are listed in Table 2. For convenience in strand design a per-unit-volume unit of magnetization has been selected.

Table 2 Specific Magnetization of Filamentary NbTi, Cu-Mn (both at 4.2 K) and Ni (at 10 K)

Sample Material	Strength of the Increasing Applied Field		
	0.30 T	0.33 T	0.40 T
Magnetization of NbTi, M_{SC}, emu/cm^3			
RHIC-009	-10.758	-10.176	- 9.124
RHIC-013	-13.073	-12.391	-11.185
RHIC-026	-20.881	-19.917	-18.164
CMN-005	- 6.366	- 6.036	- 5.178
CMN-010	- 6.223	- 5.796	- 5.048
CMN-015	- 6.865	- 6.472	- 5.685
Magnetization of Ni and Cu-Mn, M_{add}, emu/cm^3			
Cu-Mn(0.93 at.%)*	+ 1.136	+ 1.250	+ 1.500
Ni†	+ 467.4	+ 478.1	+ 496.8

* In normalization to unit volume, the density of pure Cu (8.95) was assumed[7,p.2-20].
† In normalization to unit volume, a density of 9.04 was taken[7,p.2-21].

If M represents a material's specific magnetization and A its cross-sectional area, while subscripts "SC" and "add" denote NbTi and the compensating addenda (Cu-Mn or Ni), then the fractional amounts of addenda material required for compensation are simply

$$R_C = A_{add}/A_{SC} = -M_{SC}/M_{add} \quad (1)$$

Compensation with Cu-Mn

For RHIC-type strands (the CMN series already contain Cu-Mn), the results of substituting the Cu-Mn magnetization data into Eqn. (1) are presented in Table 3. Clearly, compensation with the paramagnetic alloy requires an unacceptibly large volume fraction of additional material.

Compensation with Ni

The results of substituting the Ni magnetization data into Eqn. (1) are given in Table 4. Evidently strands with filament diameters between 1/2 and 5-1/2 μm require from 1-1/2 to 4 vol.% of Ni for compensation at fields near the injection field. These levels of Ni (which are based on the NbTi- rather than the total strand volume) can be introduced without significantly increasing the diameter, D, of the strand. Two methods of doing so are indicated in Table 4: (i) an appropriate number of NbTi filaments can be replaced by Ni; (ii) a thin layer of Ni, of thickness $t = (A_{SC}/\pi D)R_C$, can be applied (at any convenient stage of the fabrication process) to the outside of the strand. In addition to these is the possibility of introducing Ni in the form of an interfilamentary barrier.

Table 3 Volume Ratio of Cu-Mn(0.93 at.%) Needed for Compensation at Various Fields

Sample Code	Volume Ratio, $R_C \equiv A_{add}/A_{SC}$ 0.30 T	0.33 T	0.40 T
RHIC-009	9.5	8.1	6.1
RHIC-013	11.5	9.9	7.5
RHIC-026	18.4	15.9	12.1

Table 4 Volume Percentage and Actual Volume of Ni Needed for Compensation at Various Fields

Sample Code	Vol. Pct. Ni, $100R_C \equiv 100A_{add}/A_{SC}$ 0.30 T	0.33 T	0.40 T	No. of Ni Filaments*	Thickness of plating† t, μm
RHIC-009	2.302	2.128	1.837	127	0.6
RHIC-013	2.797	2.592	2.251	154	1.0
RHIC-026	4.468	4.166	3.656	244	3.0
CMN-005	1.362	1.263	1.042	286	0.1
CMN-010	1.331	1.212	1.016	274	0.3
CMN-015	1.469	1.354	1.144	306	0.5

* Number of Ni-replaced NbTi filaments for a total of 6,108 in the case of RHIC and 22,902 in the case of CMN.

† Plated layer applied to the outside of the strand (appropriate to 0.33 T operation) computed from the relationship $t = (A_{SC}/\pi D)R_C$.

CONCLUDING DISCUSSION

A few percent of Ni added to a superconducting strand can offset most of its shielding magnetization over a wide magnetic field range. Pure annealed Ni adds little to the existing magnetic hysteresis. Furthermore, since its magnetization saturates at fields below 0.1 tesla, its only significant effect on the shape of the M(H) loop is to shift the wings uniformly in the +M direction when H is positive and in the -M direction when it is negative.

The addition of Ni to the strand may relieve the SSC magnets' need for fine-filaments, the initial reason for which was to minimize winding magnetization over the operating field range.

We have indicated that the Ni can be introduced as an external coating at some convenient stage during strand processing, or may be incorporated into the strand in the form of replacement filaments. Other possible modes of deployment would be as: (i) a plating applied more-or-less directly onto the individual filaments (cf. Nb "diffusion-barriers"); (ii) an extended interfilamentary web throughout the strand (cf. "mixed-matrix" AC strands).

Diffusion Barrier Technology

In order to suppress intermetallic-compound node formation, it is customary to plate the NbTi elements with a few percent of Nb. In an extension of this procedure, the recommended few percent of Ni could be sandwiched between a pair of Nb layers. It is well known that the height of the magnetization loop, $\Delta M_v(H)$ (emu/cm^3) at any field H is related to the filament's critical current density, J_c (A/cm^2), and diameter, d (cm), by[1]

$$\Delta M_v(H) = (0.4/3\pi)\, J_c\, d \qquad (2)$$

Next, taking $\Delta M_v = -2M_{SC}$, assuming a field of 0.33 tesla, and inserting $M_{add} = 478.1$ emu/cm^3 for Ni, it follows with the help of Eqn. (1) that

$$A_{add}/A_{SC} = (0.2/3\pi)(I_c/A_{SC})(d/478.1) \qquad (3)$$

The thickness, t (cm), of a compensating Ni layer adjacent to a round filament is then given by

$$t = 1.41 \times 10^{-5}\, I_c(A) \qquad (4)$$

Eqn. (4) shows that for a filament critical current at 0.33 tesla of 0.37 A (appropriate for RHIC-026) a Ni layer of thickness 0.052 μm would provide compensation. The corresponding Ni volume would of course be 3.8% of the filament volume. Eqn. (4) also shows that t is independent of filament diameter provided I_c is constant -- as it must be if the strand, whatever its diameter, is to carry a specified current at constant margin.

AC Strand Technology

In order to suppress eddy-current loss in AC applications, it is necessary to increase the transverse resistivity of the strand. One way of accomplishing this (and continuing to visualize the strand in cross-section) is to isolate the individual filaments within the meshes of a Cu-Ni net. To achieve the present goal, the Cu-Ni would be replaced by pure Ni. A step in this direction was taken several years ago by Curtis and MacDonald[9, pp.434-5] in connection with a Tevatron strand production program. NbTi-containing hexagonal-OD Cu tubes (3.05 mm across flats) were electroplated with about 20 μm of Ni prior to billet assembly. During extrusion, a well-preserved and continuous network of Ni barriers was developed. It is interesting to note that in this case, with a NbTi-rod diameter of 2.13 mm) the Ni/NbTi volume ratio was about 5.9%.

Ferromagnetic barriers will of course suppress proximity-effect coupling between the filaments. Accordingly if the Ni-barrier approach is adopted both coupling-elimination (if that still remains a goal) and moment-compensation may be accomplished in a single operation.

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