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MAGNETIZATION MEASUREMENTS ON MULTIFILAMENTARY Nb_3Sn AND NbTi CONDUCTORS

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ABSTRACT

The effective filament size has been determined for a number of high current Nb_3Sn multifilamentary composites. In most cases it is much larger than the nominal filament size. For the smallest filaments (∼ 1 micron) the effective size can be as much as a factor of forty times the nominal size. Samples made by the "internal tin", "bronze route", and "jelly roll" methods have been examined with filaments in the range one to ten microns. Rate dependent magnetization and "flux jumping" have been observed in some cases. NbTi composites ranging in filament size from nine to two hundred microns and with copper to super-conductor ratios between 1.6:1 and 7:1 have been examined in the same apparatus. Low field "flux jumping" was only observed in conductors with very large filaments and relatively little stabilizing copper.

INTRODUCTION

The combination of very small aperture (3-4cm) and large acceleration range (1-20 TeV) envisioned for the Superconducting Super Collider (SSC) makes the magnetic field uniformity at injection a particularly challenging problem. Since the field shape at very low fields is largely determined by magnetization effects in the superconducting windings, there is considerable interest in the low field characteristics and uniformity of conductors; particularly "new and improved" ones.

In this paper, we report the magnetization measurements made on multifilamentary Nb_3Sn and NbTi conductors that were obtained from various sources. Of special interest are the improved Nb_3Sn wires with high critical current density. The effects of the barrier material and the local matrix to niobium ratio on the magnetization were also examined. Critical current measurements were made on most of the conductors to test the scaling of magnetization with current density.

EXPERIMENTS

The average magnetization (M) of several samples of multifilamentary (MF) superconducting samples were determined in these experiments as a function of applied magnetic field (H) and magnetic history at 4.35 K. Measurements of changes of flux through appropriate pickup coils during changes in H were integrated to yield a complete set of values of average specimen magnetization M(H) as a function of H and magnetic history. The field dependence of the critical transport current I_c was determined in a separate experiment.

Procedure

A schematic of the experiment is shown in Fig. 1. The most important part of this apparatus is a large aperture, 5 tesla, dipole magnet which can be ramped at a uniform rate by a programmable 4000 amp power supply. A 1000 A bias supply was sometimes used to obtain data from − 1.5 T to 1.5 T. This magnet provides a large volume of very uniform field, and the pickup coils which are ∼35 cm long are situated near the axis of the dipole to minimize the magnetization effects of the magnet itself. The magnetization was measured by integrating the difference in voltage induced in the two pickup coils.

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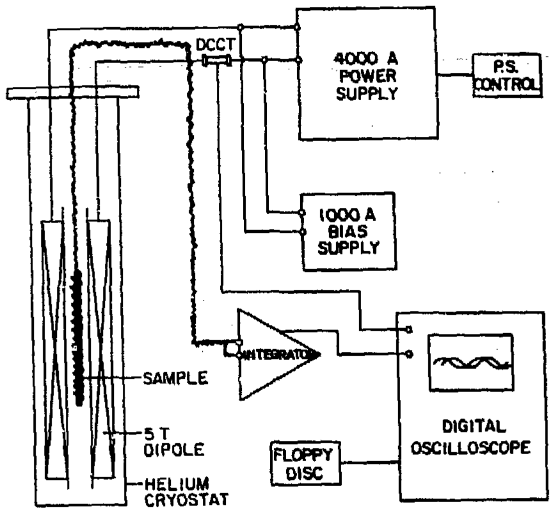

Fig. 1 Schematic - Magnetization Expt.

Typical specimens were in the form of 30 cm lengths of 23 strand cable. In those cases where cables were not available, an equal number of straight wires arranged in two layers was used to simulate a volume of cable. The samples were placed in the pickup coil with the axis of the cable or wires transverse to the applied field.

Analysis of Measurements

The magnetization signal given by the integrator was calibrated by measuring the initial slope dM/dH of 0.254 mm diameter pure niobium wires in a transverse H. Using a demagnetizing factor of 1/2 (appropriate for long thin cylinders in transverse field) one should obtain a value of 2 for the initial slope. The error in this calibration procedure is ∼±5%. However, relative magnetization data are good to ±1%.

As shown by Shen,(1) a typical M-H curve (Fig. 2) can be analyzed in certain sections. For very small external fields, the superconducting filaments should be perfectly diamagnetic. In this region the theory(2) shows that for MF composites the transverse magnetization

$$M = \frac{-2\lambda}{1+\lambda} H \qquad (1)$$

where λ is the fraction of superconductor. In the expression 1 the demagnetization factor of 1/2 for a cylinder is taken into account. Equation (1) serves to check the calibration in those MF conductors where the filaments have independently. In cer-

tain cases λ also represents the maximum area enclosed by multiply connected filaments.

At fields where the filaments are fully penetrated the critical state model[3] can be used to describe the conductor magnetization. If M^- and M^+ indicates the magnetization for the two branches of the hysteretic magnetization curve, with M^- denoting the increasing applied field branch then

$$-2\mu_o M(H) = -\mu_o(M^- - M^+) \qquad (2)$$
$$= 2\mu_o \frac{2}{3\pi} \lambda J_c(H) d_{eff}$$

where d_{eff} defines the independent superconducting dimension. This usually is equal to the filament diameter, d. However, in multiply connected composites this d_{eff} can be much larger than d. Equation (2) can be rewritten in terms of measured quantities

$$-2\mu_o M = 2\mu_o \frac{2}{3\pi} \frac{I_c}{a} d_{eff} \qquad (3)$$

where a is the conductor area of cross-section and I_c is the measured critical current at the appropriate field. I_c, defined for a conductor resistivity of 10^{-14} Ω-m, was measured separately[4] for the various samples using external fields from 0 to 8 T. In using these measurements and Eq. (3) to compare with the magnetization data, one has to taken into account the self field generated during the I_c experiments. Self field estimation for the wires were taken into account using $(\mu_o H)_{SF} = 10^{-4}(2I/R)$ where R is the wire radius.

In the absence of detectable eddy current magnetization the external field was typically ramped at 20 mT/s. However, when eddy current contribution to M was detected, data were taken at ramp rates ranging from 10 mT to 60 mT/s. From these measurements the eddy current effects were separated from those of the persistent currents by plotting M versus $\dot{B}$ (dB/dt), the ramp rate, and extrapolating to $\dot{B} = 0$.

RESULTS

Most of the measurements of magnetization were consistent with the existence of reproducible hysteresis curves after the samples were cycled at least once to high fields. In certain cases magnetic instability evidenced by "flux jumping" were observed for some untwisted MF conductors and those with large filaments.

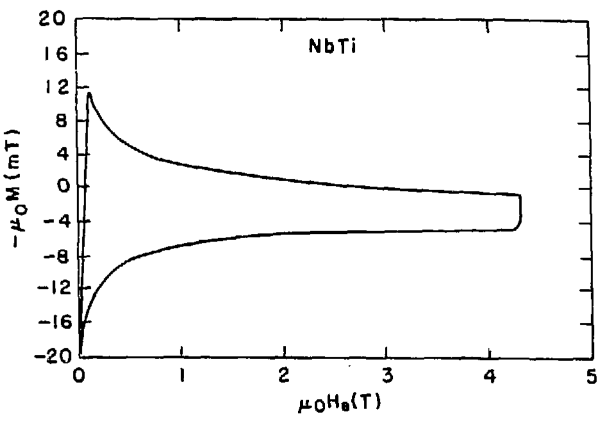

Fig. 2 Magnetization data for NbTi sample #2.

Nb_3Sn

In Table I the relevant parameters of the Nb_3Sn samples that have been studied are listed. The λ given takes into account the volume expansion as Nb_3Sn is formed from Nb. The magnetization data of most samples did not show any rate dependent contribution except the AIRCO[5] conductor, which showed a doubling $\dot{B}_D$ (rate required to double the magnetization due to the filaments) of 16 mT/S. Moreover it was found that inadequately twisted composites exhibited "flux jumping" at fields H < 1 T.

Table I
Nb_3Sn : Sample Parameters

Sample #	Process	Wire Dia. (mm)	Filament Size (μm)	# of Filaments	Barrier Material	λ
IGC-1	Internal-Sn	0.765	1.25	72102	Nb/P	0.19
IGC-2	"	0.681	2.0	22420	Nb/P	0.19
IGC-3	"	0.668	5.0	5900	no barrier	0.33
IGC-4	"	0.681	2.0	22420	Ta	0.19
TWCA-1	MJR/Bronze	0.71	3×12	Expanded Metal	Nb	0.16
TWCA-2	MJR/Sn	0.70	2×8	"	V	0.163
TWCA-3	MJR/Sn	0.305	2×16	"	V	0.27
TWCA-4	MJR/Bronze	0.508	2×10	"	Ta	0.137
MCA	Bronze	0.69	4.1	4675	Ta	0.168
AIRCO	Bronze	1.30	4.5	4807	Nb	0.172
SUMITOMO	Solid-Liquid Diffusion	0.78	45	61	Nb	0.177

The observed magnetization of the conductors at 3.0 T are given in Table II. The measured critical currents are also included. Since the I_c of some conductors is very high at this field the critical current has to be corrected for self field. The IGC[6] "internal tin" conductors were found to have a $d_{eff} >> d$. A significant fraction of the magnetization is due to the niobium (Nb/P) barrier, as has been observed earlier.[7] In Fig. 3 are shown the M-H curves for IGC-2 and IGC-4, one of which has a tantalum barrier. Besides the large niobium tail at low fields, the reacted niobium at the barrier produces a larger magnetization at all fields. Metallographic examination shows a thin ~1 μm layer of Nb_3Sn formed at the barrier. In these Nb_3Sn composites considerable bridging occurs between

Table II
Nb_3Sn : Magnetization Summary

Sample #	$2\mu_o M(3T)$ (mT)	$I_c(3T)$ (A)	$I_{cSF}(3T)$ (A)	d_{eff} (μm)
IGC-1	107	1116	1328	69
IGC-2	56	840	956	45
IGC-3	92	1250*	1524*	40
IGC-4	38.5	1100	1308	20
TWCA-1	55	825	940	44
TWCA-2	58	675	746	56
TWCA-3	122	211	226	73
TWCA-4	11.5	360	380	11.5
MCA	4.2	702	770	3.7
AIRCO	35	1006	1090	79
SUMITOMO	106	950	1030	92

*Extrapolated from higher fields.

the filaments since $d_{eff} \sim 10d$ for IGC-3 and IGC-4. The local matrix to niobium ratio is ~1.2:1 and micrographic studies show that the filaments have grown together which could easily account for the large d_{eff}.

Coupling between filaments is also observed in the "MJR" conductors.(8) TWCA-4, which is an early TWCA conductor made with a Ta barrier and a 4.8:1 bronze to niobium ratio is seen to have a $d_{eff} \sim d$. In comparison TWCA-1 has a bronze to niobium ratio of 2.6:1 and exhibits a much larger magnetization.

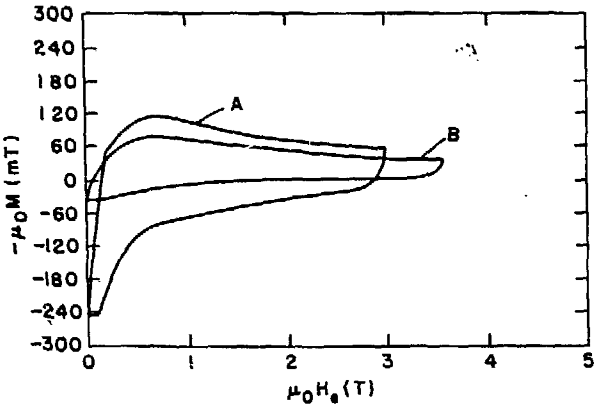

Fig. 3 M-H curve for IGC Nb_3Sn conductor A: IGC-2 with Nb/P barrier; B: IGC-4 with Ta barrier.

The only Nb_3Sn conductor to exhibit the low M effects expected from the very small filament size have been the bronze composites with relatively large filament spacing and tantalum diffusion barriers. The MCA conductor which shows a $d_{eff} \simeq d$ has a local ratio of 1.8:1.

The conductor made by Sumitomo(9) was expected to have large magnetization by virtue of its large filament size. For the particular conductor that was studied $d_{eff} \sim 2d$. Although the final reacted filaments are well separated, random nearest neighbour filaments growing together were observed in micrographs.

NbTi

In a companion study, NbTi conductors with filament sizes ranging from ~9 μm to 200 μm have been measured. Table III lists the conductors measured and the observed magnetization at 3.0 T. Data show that all conductors except #8 were "stable." Clearly, the high copper to superconductor ratio provides the required dynamic stability. Sample #4 with a filament size of 54 μm was found to behave stably, even when all matrix material had been removed and the filaments embedded in epoxy. However, sample #8, which is a single filament conductor, was observed to "flux jump" at fields <1.0 T. As expected the frequency of "flux jumps" increased when the copper stabilizer was removed.

Figure 4 shows the quantity $2\mu_0 M/\lambda \propto J_c d$ as a function of d. The lines A and B are drawn for J_c (3 T) equal to 3.6×10^9 A/m^2 and 2.7×10^9 A/m^2 respectively. This would compare with 2.4×10^9 A/m^2 and 1.8×10^9 A/m^2 at 5.0 T. The J_c of some of these conductors were measured separately and found to agree with that derived from eq. (4) to within a few percent. Also, the low field data for sample #2 (see Fig. 2) showed that the initial slope dM/dH was

Table III
NbTi: Magnetization Summary

Sample #	Wire Diameter (mm)	Filament Diameter (μm)	λ	$2\mu_0 M$ (mT)
1	0.109	8.5	0.279	3.3
2	0.68	9.1	0.37	5.0
3	0.807	22.5	0.435	14.7
4	1.118	54	0.125	12.2
5	1.626	79	0.125	15.7
6	2.05	100	0.125	20.3
7	2.90	141	0.125	24.4
8	0.406	200	0.25	86.2

equal to 0.55. This is in complete agreement with eq. (2) which predicts a value of 0.54 for λ = 0.37.

Also drawn in Fig. 4 are the expected behavior of Nb_3Sn conductors if the filaments behave independently. Lines C and D are drawn for J_c (3 T) equal to 1.63×10^{10} A/m^2 and 1.13×10^{10} A/m^2 respectively. These are typical J_c for Nb_3Sn made by the "internal tin" and the bronze processes. The datum shown by (Δ) is for the MCA bronze processed conductor.

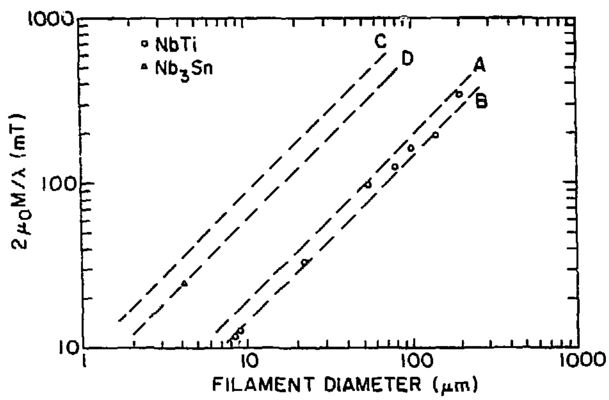

Fig. 4 Plot of $2\mu_0 M$ (3 T)/λ vs. filament diameter d.

Field Dependence of Magnetization and I_c

The critical transport currents were determined for most conductors as a functon of applied field to test the scaling of magnetization with J_c or equivalently with (I_c/a) as given by eq. 3. It was possible to measure I_c down to zero H for the NbTi composites, but in some Nb_3Sn conductors the current is so high below 3 T, that it was difficult to get a proper resistive transition. In Fig. 5 the normalized I_c (i.e. $I_c(H)/I_c$ (3 T)) is given for sample #2. The solid line is the normalized magnetization data, whereas (o) and (x) are the I_c data for a bifilar and an open wound solenoid sample respectively. (x) would reflect data usually taken in the hair-pin configuration. Correcting I_c for self field results in excellent agreement between critical current and magnetization over the range $0.3 < H < 4.0$ T.

Figure 6 shows similar data for the IGC conductors. Except for fields <0.4 T where niobium barrier magnetization predominates, the normalized magnetization as a function of H for all the IGC conductors were similar and are given by the solid line. The low field magnetization behvaior of bronze processed Nb_3Sn were very similar to the "internal tin" wires.

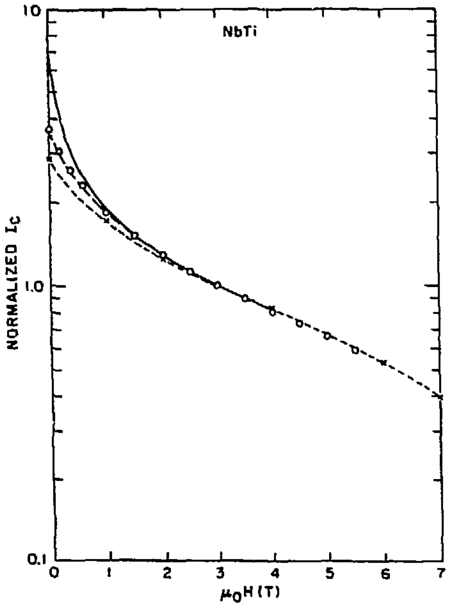

Fig. 5 Normalized I_c vs. field

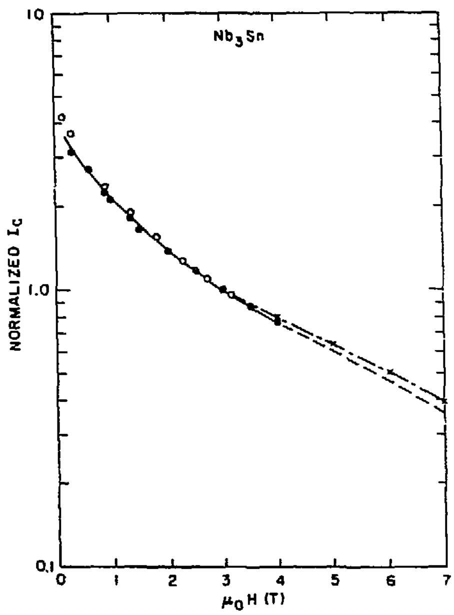

Fig. 6 Normalized I_c vs. field" ___, (•), from magnetization data for IGC-4; (o) data of IGC-2; —·— (x) I_c data, --- I_c data corrected for self field.

CONCLUSIONS

From this study the following conclusions are drawn: (1) where filaments behave independently, M scales with d, (2) besides the bronze type Nb_3Sn with relatively large filament spacing, most of the other Nb_3Sn conductors studied have $d_{eff} > d$, (3) Nb or Nb/P barrier introduces large magnetization at low fields. In applications where such effects are undesirable a tantalum or vanadium barrier must be used. At present work is in progres to study "internal-tin" processed Nb_3Sn with local matrix to niobium ratio > 1.5. At these ratios, filament bridging should be eliminated.

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