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MAGNETIZATION, CRITICAL CURRENT, AND INJECTION FIELD HARMONICS IN SUPERCONDUCTING ACCELERATOR MAGNETS*

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Abstract

The very large energy ratio of machines such as the SSC dictates rather low injection field (for 6T, 20 TeV it is approximately 0.3T). Since the harmonic content at such low fields is largely determined by magnetization currents in the superconductor, the random errors depend on the uniformity of the superconducting wire. In principle the magnitude of the residual fields can be reduced indefinitely by using finer filaments, but in practice there is a lower limit of a few microns. We have compared the injection field harmonics for a number of accelerator dipoles with magnetization measurements made on samples of the conductor used to wind the coils. In addition both the magnetization and harmonics have been compared with short sample critical current measurements made at 5T. The results indicated that an accurate estimate of the variation in injection field harmonics can only be obtained from direct measurements of the magnetization of the cable. It appears feasible to use such measurements to "shuffle" magnets for a large accelerator by predicting the low field properties of a magnet before actually winding the coils.

Introduction

It is well known that the magnetic fields generated by persistent currents in the superconductor of accelerator dipoles is quite significant at low fields, especially for the higher multipoles. These magnetization harmonic fields, which have been measured in several different types of magnets,[1-5] are of concern to accelerator physicists since they determine the field quality at injection. The large energy range (1-20 TeV) envisioned for the Superconducting Super Collider (SSC) makes this injection field so low (for a 6T maximum field it is nominally 0.3T), that the random variation of the superconductor magnetization may limit the effective aperture.

We report here magnetization measurements at low fields on seventeen CBA/Tevatron type cable conductors. These are a small sampling of the 200 cables that were manufactured for the CBA R&D program and were primarily investigated to obtain an estimate of the random variation in the magnetization of the conductor and to correlate the magnetization with critical current data[6] at 5T, and with the magnetization sextupole measurements of CBA magnets.[3] Also these measurements are needed to provide a quantitative basis for the understanding of magnetization multipoles in dipole magnets.

In addition, the magnetization and critical currents were measured on some recent NbTi conductors with filament diameters ranging from 23 to 3 microns. These data provided the basis for testing the scaling of magnetization with current density and filament diameter.

Experiments

The average magnetization (M) of the conductors was measured as a function of transverse applied field (H) and magnetic history at 4.3K. The details of the apparatus and the measurement technique are given elsewhere.[7] The test samples were in the form of a stack of three 30 cm long pieces of cable. The CBA cables were made from 23 strands of 0.68 mm wire with Cu/Sc ratio of 1.7 and filament diameter of 9.0 μm. These wires were produced by three different manufacturers, OST (formerly known as AIRCO), IGC, and MCA.

To compare cables, the width of the hysteresis loop defined as $2\mu_0 M$ was determined at the field of interest, 0.3T.

$$2\mu_0 M \equiv \mu_0 \left(M^{\text{up ramp}} - M^{\text{down ramp}}\right)_{0.3T} .$$

This quantity is related to the critical current density, J_c, as described by the critical state model[8]

$$2\mu_0 M(H) = 2\mu_0 \frac{2}{3\pi} \lambda J_c(H) d \qquad (1)$$

where λ is the volume fraction of superconductor, d is the nominal filament diameter and J_c is the current density in the NbTi.

Results

Table I lists the different conductors measured along with the manufacturer of the wires in the cable. In column three the critical current, I_c (5T,4.2K) is given. The critical currents of cables were measured previously[6] as part of the quality control of CBA conductor, and are for applied field perpendicular to the wide face of the cable. Column four lists the ratio of the critical current inferred from magnetization and the measured I_c at 5T.

Table I
Critical Current and Magnetization Data of CBA Cables

Cable No.	Wire Manufacturer	I_c (5T, 4.2K) A	$2\mu_0 M$ (0.3T) mT	I_c^m (0.3T)/ I_c (5T)
CBA-73	IGC	5108	16.6	5.66
CBA-74	IGC	5051	16.5	5.69
CBA-75	IGC	4815	17.0	6.15
CBA-92	OST	4985	16.2	5.66
CBA-95	OST	4942	17.0	5.99
CBA-96	OST	5030	15.9	5.51
CBA-97	OST	4872	17.2	6.15
CBA-98	MCA	4820	18.0	6.71
CBA-99	MCA	4728	18.2	6.71
CBA-100	MCA	4730	17.7	6.52
CBA-101	MCA	4710	18.6	6.88
CBA-102	MCA	4647	18.0	6.75
CBA-103	MCA	4724	17.7	6.53
CBA-105	MCA-OST	4702	17.7	6.56
CBA-106	MCA-OST	4785	17.3	6.30
CBA-108	MCA	4831	18.9	6.82
CBA-111	MCA	4918	17.4	6.16
Mean		4855	17.41	
σ		±135	±.82	
σ/mean		0.028	0.047	

Correlation of I_c (5T) with M (0.3T)

Data for this set of 17 samples show that whereas the rms variation of the I_c (5T) is 2.8% of the mean, that of the magnetization at 0.3T is much larger, 4.7%. The rms variation in M is expected to be even bigger for a larger set since the I_c (5T) variation of all 200 cables was 4.4%.[6] Figure 1(a)

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shows a histogram of the $2\mu_0M$ values which have been separated in terms of the manufacturer of the wire in the cable. It is evident from this figure that the batch to batch variation in M of any single manufacturer is significantly lower than the overall variation. Figure 1(b) depicts the same for the I_c (5T) data. It should be mentioned that the wires for the cable were "shuffled" in an attempt to reduce the variation in I_c (5T). This selection procedure was successful in lowering the I_c variation in cables to 4.4% as compared to the wire rms variation of 6.5%.[6]

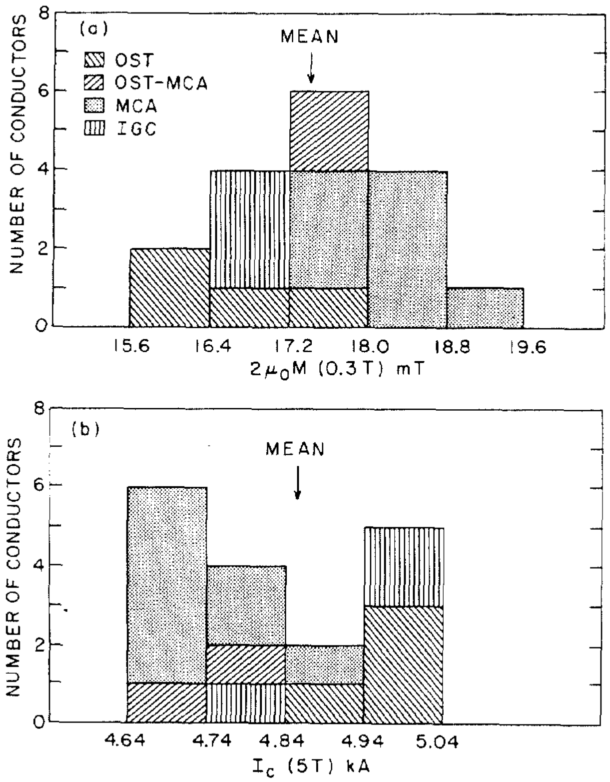

Fig 1. Histogram of (a) $2\mu_0M$ (0.3T) and (b) I_c (5T) for the CBA cables.

The ratio of I_c^m (0.3T)/I_c (5T) given in Table 1 and a comparison of Figs. 1(a) and (b) show that conductors which have a high I_c at 5T do not necessarily have a high M at 0.3T. In fact, for the conductors measured the opposite trend was observed. This just points to the fact that the J_c versus H behavior for conductors from different sources varies significantly at low fields. This behavior was also seen in critical current measurements over the field range 2-8T for wires from different sources.

Random Variation in M and Δb_2

The measurement of magnetization effects in magnets built as part of the CBA R&D program have been reported by Bleser et al.[3] In the harmonic decomposition of the field, b_2, the sextupole term is given as parts per 10^4 of the dipole field component at 4.4 cm. We can define a "magnetization sextupole" $\Delta b_2 \equiv b_2^{up\ ramp} - b_2^{down\ ramp}$ which can be used to compare with magnetization data. Figure 2 shows a histogram of Δb_2 for 18 magnets at 0.31T dipole field. The data show a mean of 35.2 with a rms variation of 2.5 units (7.1% of mean). Although these data reflect the variation in M of $\sim$ 51 cable spools, the correlation of Δb_2 with the measured M (Fig. 3) in terms of the wire source is evident.

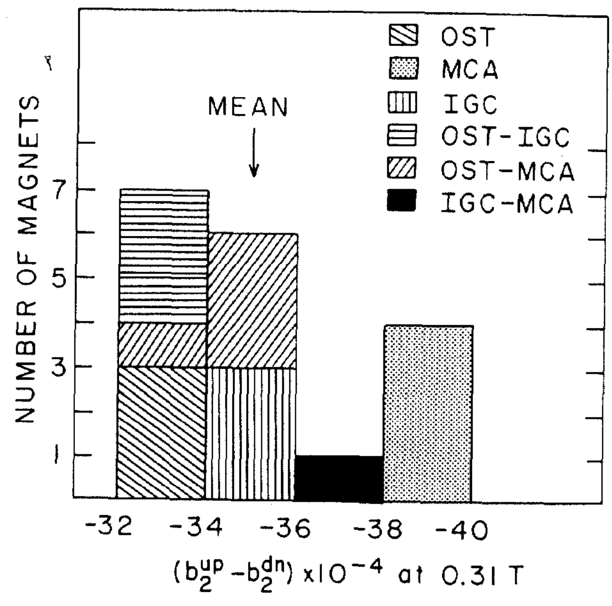

Fig 2. Histogram of Δb_2 for CBA R&D dipoles.

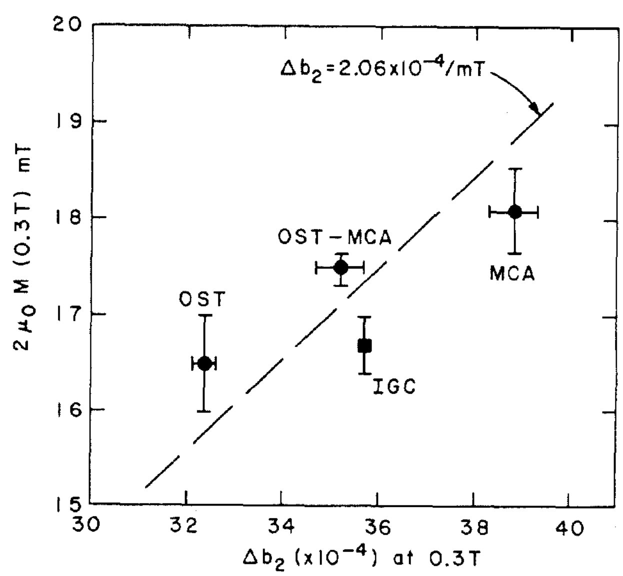

Fig 3. Plot of $2\mu_0M$ vs. Δb_2. The dashed line drawn passes through the origin.

Scaling of $2\mu_0M$ with Filament Diameter

The critical state model predicts that $M \propto J_c d$. So in principle the magnitude of Δb_2 can be reduced indefinitely by using finer filaments. In an earlier report[7] this scaling of M was found to be true for d values ranging from 9 to 200 μm. Recently conductors have been available with high J_c at 5T and some of these have filament sizes $\sim$ 3 μm. Table 2 lists the conductors and the measured J_c at 5T. LBL-280 wire was made from the so-called high homogeneity NbTi and T22 was wire drawn from the LBL-280 strand. "CBA" reflects the standard CBA/Tevatron wire. The FURUKAWA and MCA conductors are experimental wires that have been recently manufactured. Figure 4 shows the behavior of magnetization at 0.3T as a function of d.

Table 2

Conductor Parameters and Magnetization Data @ 0.3T

Conductor Designation	Wire Diameter (mm)	Cu/Sc	Filament Diameter (μm)	J_c (5T, 4.2K) (A/mm^2)	$2\mu_0 M_s$ (mT)	J_c^m (0.3T) (A/mm^2)	J_c^m (0.3T)/ J_c (5T)
LBL-280	0.808	1.3	23.0	2250	108	8793	3.91
T22	0.68	1.3	19.5	2250	85	8163	3.63
"CBA"	0.68	1.7	9.0	1840(6)	47	9779	5.31
FURUKAWA	0.226	1.09	2.85	2380	19	12178	5.12
MCA-004	0.114	1.1	4.0	2497	24	11236	4.50

$2\mu_0 M_s$ is the hysteretic magnetization over the volume of NbTi only and is used to facilitate direct comparison. Table 2 lists the M at 0.3T and the ratio of J_c^m (0.3T) to J_c (5T). This ratio is found to be different for the various conductors which again reiterates the point that extrapolating the behavior of M to low fields from higher field J_c measurements is not suitable.

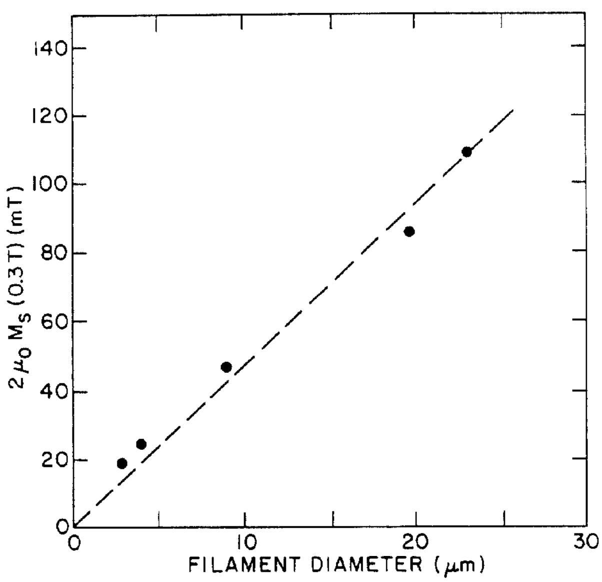

Fig 4. Plot of $2\mu_0 M_s$ versus filament diameter.

For the FURUKAWA conductor, the value of $2\mu_0 M$ of 4.7 mT at 1.2T predicts a I_c of 121 amps. This can be compared with a short sample transport current of 117 amps at the same effective field.[9] The result clearly indicates that down to d values of 2.9 μm, the traditional critical state model is adequate in describing the magnetization.

Also, the data in Table 2 can be used to test the correlation of Δb_2 and M as d is varied. Recently, measurements of Δb_2 and Δb_4 (magnetization decapole) were made on three 4.5 m long, 3.2 cm 2 in 1 SSC model dipoles.[10] The first two were made from conductors similar to "CBA" cable, and the third was made from T22 cable with 19 μm filaments. The measured ratio of Δb_2 in the third magnet to Δb_2 in the first two magnets was 2.1 ± 0.1. The same value is obtained for the ratio of Δb_4. The data in Table 2 predict this ratio to be

$$\frac{2\mu_0 M_s(T22)}{2\mu_0 M_s(CBA)} * \frac{(Cu/Sc+1)_{CBA}}{(Cu/Sc+1)_{T22}} = \frac{85}{47} \times \frac{2.7}{2.3} = 2.1$$

which is in excellent agreement with the magnet measurements. Extrapolating from these measurements the estimated random variation in the sextupole due to magnetization at injection would be 2×10^{-5} cm^{-2} for the SSC high field magnet design using conductor with 3 micron filaments.

Conclusions

In summary, we emphasize the following points: (1) an accurate estimate of the variation in injection field harmonics can only be obtained from direct measurements of the magnetization of the cables, and it appears feasible to use such measurements to "shuffle" coil windings to reduce the random variation in magnets for large accelerators. (2) To filament diameters ∿ 2.9 μm, the critical state model is adequate in describing the scaling of magnetization with $J_c d$. Work is in progress to clarify this scaling down to d values of 1 μm.

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