Hall Probe Magnetometer for SSC Magnet Cables: Effect of Transport Current on Magnetization and Flux Creep

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Abstract

We constructed a Hall probe magnetometer to measure the magnetization hysteresis loops of Superconducting Super Collider magnet cables. The instrument uses two Hall-effect field sensors to measure the applied field H and the magnetic induction B. Magnetization M is calculated from the difference of the two quantities. The Hall probes are centered coaxially in the bore of a superconducting solenoid with the B probe against the sample's broad surface. An alternative probe arrangement, in which M is measured directly, aligns the sample probe parallel to the field. We measured M as a function of H and field cycle rate both with and without a dc transport current. Flux creep as a function of current was measured from the dependence of ac loss on the cycling rate and from the decay of magnetization with time. Transport currents up to 20% of the critical current have minimal effect on magnetization and flux creep.

Introduction

A consideration in the design of Superconducting Super Collider (SSC) magnet cables is ac losses in the superconductor. These ac losses may be either time-dependent or time-independent [1]. Normally, ac loss measurements are made on open-circuited samples. In actual use, however, the superconductor carries a transport current which can influence the ac loss of the sample [2–4]. Another concern in SSC cable design is magnetic relaxation in the filaments. Measurements of large field decays in accelerator magnets, attributed to flux creep, have been reported [5–8]. However, the observed field decay in the magnets is much larger than the relaxation measured in small open-circuited samples.

The objective of this study was to examine the effect of transport current on the magnetization and the magnetic relaxation in an SSC cable carrying transport current. We describe a Hall probe magnetometer that can measure magnetization, ac losses, and flux creep, with and without transport current [9]. The magnetometer uses two Hall-effect field sensors. One measures the applied field H and the other measures the magnetic induction B or the magnetization M. Hall probe magnetometers have been used to study ferromagnetic materials, ferrites, anisotropy fields, superconducting tubes, and field profiles [10–13].

Experiment

A schematic diagram of the Hall probe magnetometer is shown in Fig. 1. The applied field is supplied by a superconducting solenoid, 21 cm in length, 7.6 cm bore, with a maximum field of 7 T. Two cryogenic Hall-effect field sensors are used; one measures the applied field H and the other measures the magnetic induction B. Both probes are aligned perpendicular to the applied field and centered coaxially in the bore of the solenoid. Their vertical separation is 4 cm. The sample is mounted so that its broad face is perpendicular to the field with the B probe mounted firmly against it. The self field from the transport current is parallel to the B probe and, ideally, is not detected. Any self field actually sensed by the B probe appears simply as a dc offset in the hysteresis loops.

The fields H and B are measured with two commercial gaussmeters. Their analog outputs are low-pass filtered and input to a differential amplifier, which subtracts the signals, and sent to a computer, which calculates M. Magnetization can be calculated using the expression $M = (B/\mu_0 - H)/(1-D)$, where D is the demagnetizing factor, approximately equal to 0.5 for the transverse field orientation.

A U-shaped sample is used so that the current contacts can be soldered to the cable far enough from the Hall probe sensing area to not affect the measurement. To obtain repeatable results, the sample must be positioned accurately, with the face of the sample firmly against probe B and properly centered. This is achieved with three guide tubes and a Be-Cu-spring-loaded mount for probe B. The insert is shown in Fig. 2. (Only two guide tubes are shown for clarity.) Samples are mounted to the sample plate using clamps at both ends of the sample. The sample plate is 6.1 cm in diameter, which allows for samples approximately 5.3 cm in length to be mounted. The guide tubes are used for support and for sample positioning. The tubes are symmetrically spaced so that the circular sample plate can slide firmly between them. The sample rod can easily be removed and loaded while the probes and the solenoid remain immersed in liquid helium.

The instrument may be calibrated with a Ni standard the same size as the sample or with a superconductor transfer standard which has been measured on a conventional magneto-

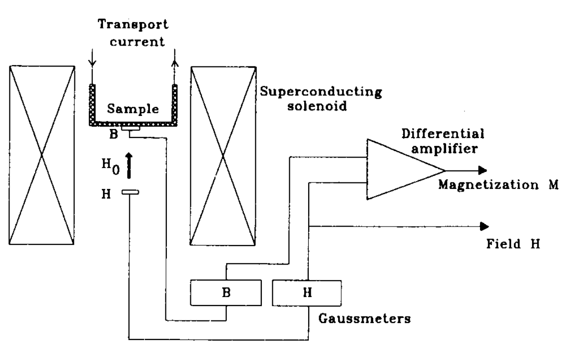

Figure 1. Schematic diagram of the Hall probe magnetometer. The magnetic field H_0 is supplied by a superconducting solenoid. The sample is bent into a U-shape so that the solder contacts can be made away from the Hall probe sensing area.

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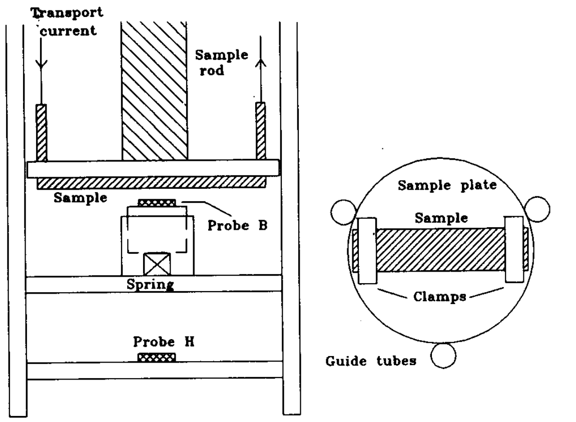

Figure 2. Mechanical diagram of the Hall probe magnetometer showing the sample mounting assembly. Probe *B* is in a spring-loaded holder which assures contact to the sample. The guide tubes support the probes and direct the sample plate to probe *B*.

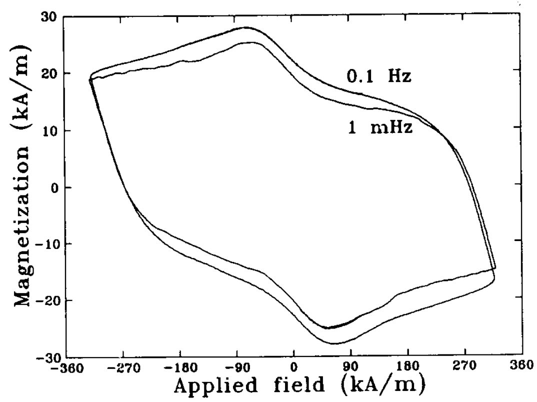

Figure 3. Plot of magnetization versus field at 0.1 Hz and 1 mHz. The difference in loss between the two curves is the result of eddy current coupling of the filaments at the higher frequency.

meter. The Hall-effect sensors must be calibrated before the measurements. This is done by removing the sample, setting the field to a known value, and adjusting the gain of the meters until each gaussmeter displays the correct field value. A disadvantage of Hall effect field sensors is their nonlinearity above 3 T, typically 0.2%. For small values of *M* in large fields, the nonlinearity can lead to distortion in *M*. The problem can be mitigated if values of the background signal as a function of field are subtracted from the sample data during data processing.

An alternative Hall probe arrangement increases the sensitivity of the *M* measurement. In this arrangement, the sample probe is aligned so that its sensing plane is *parallel* rather than perpendicular to the applied field and *M* is measured directly. We call this the "*M* configuration," as distinct from the usual "*B* configuration." A disadvantage of this technique is that the alignment of the *M* probe must be precise to avoid sensing the applied field.

The sample used for the measurements was a Nb−Ti multifilamentary SSC magnet cable with 23 strands. Each strand had approximately several thousand filaments, 4.2 μm in diameter. Only three of the 23 strands were used in the transport current measurements so that the applied current, limited by the power supply, would be closer to the critical current of the sample. All measurements were made at 4.0 K.

Results

Magnetization versus Field

A direct measure of magnetic hysteresis loss can be obtained from magnetization-versus-field loops. Time dependent losses, such as flux creep and eddy current coupling, can be measured if the applied field is swept at different cycling rates [1]. Figure 3 shows a typical plot of magnetization versus field for two field cycle rates. The sample was a short section of cable with no applied transport current. The response of the Hall probes is fast enough to measure the higher frequencies with excellent resolution. As seen in Fig. 3, the area of the hysteresis loop is greater for the 0.1 Hz field cycle rate than for 1 mHz. At 0.1 Hz, the eddy currents generated in the copper matrix have not yet decayed and still couple the filaments, which leads to larger ac loss. At very low frequencies, other time-dependent effects, such as flux creep, can be measured as a small decrease in hysteresis as the field cycle rate decreases. For example, we observed an average 2.5% reduction in magnetization on comparing curves at 5 and 0.5 mHz (not shown).

The effect of transport current on the magnetization curves is presented in Fig. 4. The sample consisted of three strands of wire. Curves are shown for 0 and 200 A of transport current. The critical current for the three strands is estimated to be 1 kA at zero field. The effect of the applied current is seen as a small decrease in magnetization at high fields as the critical current is reduced. This effect would be more pronounced at higher fields or currents [14].

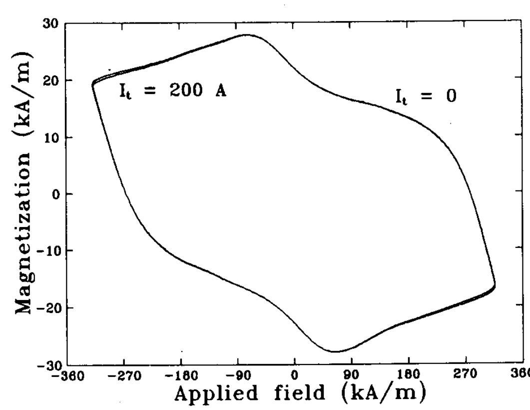

Figure 4. Plot of magnetization versus field for 0 and 200 A of transport current. The effect of the applied current is small, showing a decrease in hysteresis only at the higher field values due to the reduction in critical current.

Flux Creep and Transport Current Effects

There should be an effect of transport current on flux creep, considering the increase of the Lorentz force acting on the pinned flux vortices. The Hall probe magnetometer is well suited for flux creep measurements with and without transport current because it does not require sample motion for signal detection. Unexpected variations in field in other dc methods can give erroneous results in hysteretic materials. For example, VSM and SQUID magnets might have enough field inhomogeneity to cause minor hysteresis loops to be traversed during sample motion.

The decay in magnetization as a function of time for 0 and 200 A of transport current are shown in Fig. 5. The measurements were made on three strands in the *M* configuration at a field of 0.3 T, after a field cycle of 0 to 6 T, 6 to 0 T, and 0 to 0.3 T. The dc current was applied at the start of the field cycle. After switching the magnet into persistent mode, magnetization was measured as a function of time. The field decay of the solenoid during the measurement was negligible as monitored at the *H* probe.

The data in Fig. 5 include the fast decay resulting from the dissipation of eddy currents. The fast decay is large and nearly complete in less than 100 sec. After that, there is a slow decay of only a few percent of the initial magnetization that continues beyond our measuring time. As seen from the graph, the effect of transport current is minimal. Field-decay effects observed in accelerator magnets occur at low current levels, usually less than 20% of the critical current. From these results, it seems that the effect of transport current on flux creep is not large enough to explain the field decay in SSC magnets.

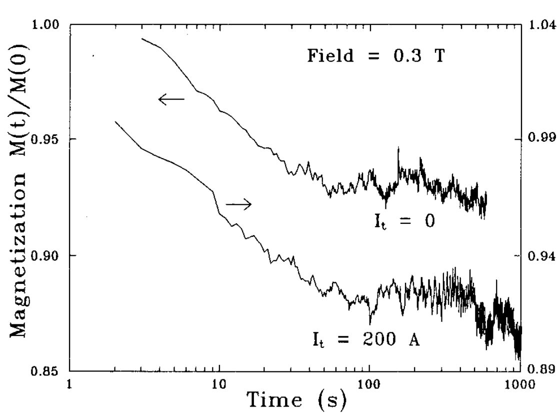

Figure 5. Plot of magnetization versus time at 0.3 T for 0 and 200 A of transport current I_t. The left scale is for zero transport current; the right scale is for 200 A. There is slight increase in decay rate with transport current.

Conclusion

A Hall probe magnetometer was constructed to measure the effect of transport current on magnetization and flux creep in SSC magnet cables. The Hall probe measurement is static; it does not require sample motion or field change to induce a signal. The speed at which the field can be cycled is limited only by the magnet inductance and the power supply compliance voltage. However, the calibration of *M* is not direct. The instrument sensitivity in the *B* configuration is less than that of other magnetometers and very small samples cannot be measured.

Transport current causes a decrease in magnetization at high fields and current. The current has a small effect on flux creep, although not enough to explain the large decay observed in SSC magnets. In the case of actual SSC dipole magnets, however, the different current levels, field cycles, and field gradients to which the cable is exposed is more complicated than in our experiments.

Acknowledgment

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