Enhanced flux creep in Nb-Ti superconductors after an increase in temperature

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The magnetic fields of Superconducting Super Collider (SSC) dipole magnets change with time when the magnets are operated at constant current. The decay of the field is thought to be a consequence of flux creep in the Nb-Ti filaments in the superconducting cables. However, measured magnetic relaxation of small samples of SSC cable as a function of time is unlike the large decays that are observed in the fields of the actual magnets. We have made relaxation measurements on sample SSC conductors at 3.5 and 4.0 K after field cycling. The decay at both temperatures was 2.8% in 50 min. However, the relaxation measured after a temperature increase from 3.5 to 4.0 K was 4.8% in 50 min. A likely reason for the greater magnetization decay is that, after an increase in temperature, the Nb-Ti is in a supercritical state, with shielding currents flowing at a density greater than the new critical current density. This causes enhanced flux creep. We suggest that a small temperature rise during the operation of SSC magnets may contribute to the unexpectedly large magnetic field decay.

Synchrotron accelerators, such as the Tevatron and the proposed Superconducting Super Collider (SSC), use magnets made of cables of multifilamentary Nb-Ti superconductor wires. The magnetization of the Nb-Ti filaments contributes to the magnetic field of the accelerator magnets. Flux creep, that is, thermally activated jumps of bundles of flux vortices, produces a decay in the magnetization of superconductors with time,[1,2] and flux creep has been presumed to cause a troublesome slow decay in the field, often measured as a multipole field, of accelerator dipole magnets over a period of hours.[3–6] Magnetometer measurements of flux creep on samples of multifilamentary superconductor wire and cable used in the construction of these magnets show some flux creep.[7,8] However, after an initial rapid decay of magnetization, the flux creep is about one order of magnitude smaller than the field decay in the actual superconductor magnets.

Recently, Sun *et al.*[9] showed that flux creep in superconductors could be reduced or even eliminated by operating in a subcritical state achieved by lowering the conductor's temperature after the critical state is achieved. Clem has suggested that such a scheme, applied to accelerator magnets, might lessen the field-decay problem.[10] In this letter, we consider the inverse theorem that the enhanced flux creep seen in accelerator magnets may be a consequence of an increase in operating temperature, which forces the conductor into a supercritical state. We find that an increase in sample temperature of 0.5 K, after a typical SSC field cycle, almost doubles the rate of magnetization decay.

The sextupole fields of model SSC dipole magnets change with time when the magnets are operated at constant current under conditions similar to SSC accelerator use. Large field decays have been observed,[6,11] and such decays can result in beam loss during the SSC injection period of several hours. The logarithmic time dependence of field decay and the temperature dependence of relaxation in different dipole magnets suggest a flux creep mechanism. For example, the reported rate at 1.8 K was less than at 4.2 K.[6] However, the measured relaxation of samples of cable is generally less than the field relaxation reported for the magnets.

To examine the magnetic decay process, we made a series of three relaxation measurements at 3.5 and 4.0 K. The measurements were made with a superconducting quantum interference device magnetometer using a scan length of 2 cm, which corresponds to a field variation of $<0.01\%$. The field from a superconducting solenoid was applied perpendicular to the flat side of a 0.7 cm sample of multifilamentary Nb-Ti superconductor cable. The sample had 23 strands, each with approximately 10 000 4.2-μm-diam filaments. To simulate the original SSC field cycle, for comparison with existing field-decay data, all measurements were made after the following field cycle: 0–5 T, 2 min pause; 5–0 T, 2 min pause; 0–0.3 T, 2 min pause. The final 2 min pause was included to avoid the fast decay resulting from eddy-current coupling and to establish a reproducible initial starting time, $t = 0$. The pauses ensured field stability before the measurements were taken and were in addition to the time required to ramp to each field and to switch into persistent mode.

Curves (a) and (b) in Fig. 1 for 3.5 and 4.0 K show magnetization $M(t)$ as a function of time scaled by the magnetization $M(0)$ at $t = 0$. The decay rates due to thermal activation are nearly the same, about 2.8% after 3000 s, but the value of $M(0)$ is approximately 10% less at 4.0 K. The rate of decay, $R \equiv [\Delta M(t)/M(0)]/\Delta \ln t$, for the decade of time 300–3000 s, is 0.008, in good agreement with measurements by Ghosh on SSC wires.[8] It is about one-third to one-tenth the sextupole-field decay rate observed in SSC model magnets after a similar field cycle.[8]

Magnetization decay was then measured after a temperature step from 3.5 to 4.0 K. The field cycle was the same, but after stabilizing at 0.3 T at 3.5 K, the tempera-

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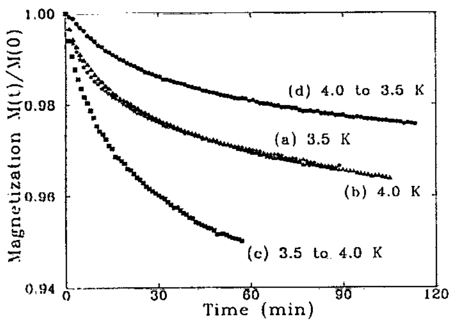

FIG. 1. Decay of magnetization as a function of time measured with a SQUID magnetometer at (a) 3.5 K, (b) 4.0 K, (c) 4.0 K after an increase in temperature from 3.5 K, and (d) 3.5 K after a decrease in temperature from 4.0 K.

ture was increased to 4.0 K. During the temperature stabilization, which took 2 min, the magnetization decayed by about 10%. After temperature stabilization, magnetization versus time was measured using the same routine as before, beginning at $t = 0$. The results are shown as curve (c) in Fig. 1. The decay is 4.8% in 3000 s, $R = 0.014$, significantly greater than for curves (a) and (b). The decay rate was also measured after a *decrease* in temperature from 4.0 to 3.5 K using the same protocol. As expected, the decay rate was less, 1.8% in 3000 s, $R = 0.006$, shown as curve (d). Similar measurements were made for smaller temperature steps. After a 0.1 K increase from 3.9 K, the magnetization decayed by 3.2% in 3000 s, $R = 0.010$. Measurements on samples from other SSC cables showed similar trends.

The enhancement in magnetic relaxation after an increase in temperature may be related to the temperature dependence of the critical current density J_c. Sun *et al.*[9] showed that flux creep in high-temperature superconductors could be reduced by a decrease in temperature. A sample initially in the critical state has magnetic shielding currents equal to the critical current density. Upon decreasing the temperature, J_c increases and the sample is in what we call a subcritical state, with shielding currents less than the critical current density. This reduces flux creep.

We expect that an increase in temperature would increase flux creep. After the magnetic field is cycled, the sample is initially in the critical state. When the sample is warmed, J_c decreases and the sample is in what we call a supercritical state, with shielding currents greater than the critical current density. To restore equilibrium, the shielding currents and associated pinned flux must redistribute, leading to enhanced flux creep. Considering the operating conditions for SSC magnets, we suggest that a temperature increase may contribute to the measured sextupole-field decay with time.

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