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PERSISTENT CURENT IN COILS MADE OUT OF SECOND GENERATION HIGH TEMPERATURE SUPERCONDUCTOR WIRE (POSTPRINT)

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Power Generation Branch
Power Division

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14. ABSTRACT
We report the results of an experimental study of a persistent coil made out of $YBa_2Cu_3O_{7-\delta}$-coated conductors. The magnitude of the persistent current and the rate of decay were investigated. Two distinct modes of relaxation are evident—one is flux creep and the other, which is much faster, is of less obvious origin. Our conclusion is that the persistent current in such a coil can be large enough and decay slowly enough so that coated conductors can be used to make persistent coils for variety of applications.

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Persistent current in coils made out of second generation high temperature superconductor wire.

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We report the results of an experimental study of a persistent coil made out of $YBa_2Cu_3O_{7-\delta}$ coated conductors. The magnitude of the persistent current and the rate of decay were investigated. Two distinct modes of relaxation are evident—one is flux creep and the other, which is much faster, is of less obvious origin. Our conclusion is that the persistent current in such a coil can be large enough and decay slowly enough so that coated conductors can be used to make persistent coils for variety of applications. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2969798]

In recent years there has been remarkable progress in manufacturing $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated superconductors.[1] It is important to find innovative ways to incorporate them in variety of applications. Several publications have outlined approaches to accomplish twist,[2] transposition,[3] and persistent current flow[4] in devices based on coated conductors. Here, we present the results of an experimental investigation of persistent current flow in a "coil," which consists of independent persistent loops (no joints) made out of coated conductors and nested together. We have determined the amount of current flowing through this coil and its relaxation rate. The relaxation rate is sufficiently low for the coated conductors to potentially be used to form large persistent coils operating at or near liquid nitrogen temperature for a range of applications: from persistent magnets for magnetic resonance imaging machines to electric motors and superconducting bearings,[5,6] where they can replace bulk YBCO, to more exotic applications such as magnetic shields needed to protect the crew from radiation on long-duration missions to Mars and on a lunar base.[7]

Several individual 12×150 mm^2 sections of coated conductors with a nominal critical current 170 A, produced by SuperPower Inc.,[8] were used in this study. There was no copper stabilizer attached; only a 1–3 μm thick silver coating covered YBCO film deposited on 100 μm thick Hastelloy substrate. In each of the sections, a slit—1 mm wide and 124 mm long—was milled so that the superconducting film formed a closed path for supercurrent. Up to seven sections with no insulation between them were stacked on top of each other and unfolded, forming a coil shown in Fig. 1. There are two important properties of such coils. First, each section (a loop) is effectively twisted[2] in a sense that the superconducting film is on the outer side of the coil in one-half of the loop (in the foreground) and is inside the coil in the second half. Thus, the twist pitch is equal to the length of the loop. Second, the sections are transposed: section (1) in Fig. 1 forms the outermost layer in one-half of the coil and the innermost layer in the second half. The order in which sections are placed in the coil with respect to its center is reversed in its two-halves. This is somewhat similar to the transpositions in a Roebel bar arrangement.[3]

The persistent current was induced by a transformer arrangement, as shown in Fig. 1. The superconducting loops served as its secondary winding. A small slit in the core of the transformer was used to insert the individual sections of coated conductors inside the rectangle core. The magnetic flux density in the center of the coil was measured at 1 s intervals by a cryogenic sensor and computer controlled LakeShore 450 Gaussmeter.

The persistent current in the coil is induced as the result of the conservation[9] of the fluxoid Φ',

$$\Phi' = \Phi_{tr} + \Phi_s + \mu_0 \oint \lambda^2 \vec{j}_s \, d\vec{s}. \qquad (1)$$

Here, Φ_{tr} is the variable magnetic flux produced by the transformer and Φ_s is the magnetic flux inside a given loop produced by the current circulating in the entire coil, $\mu_0=4\pi\times10^{-7}$ N/A^2. The integration of the supercurrent density $\boldsymbol{J}_s$ is carried out over the superconducting contour of an individual loop. One can show that for coated conductors the integral term is smaller than the flux Φ_s by a factor $\lambda^2/Wd \ll 1$, where $\lambda \sim 150-200$ nm is the magnetic penetration depth, $W=5.5$ mm is the width of the conductor, and $d\approx1$ μm is the thickness of the superconducting film. Thus, Eq. (1) simply reduces to a condition of magnetic flux conservation. The current I_s circulating within the coil can be estimated from the value of the magnetic flux density measured in the geometric center of the coil. The vertical component of magnetic field B_z in the center of the coil is given by

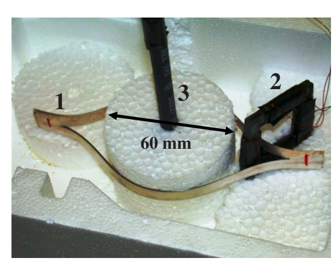

FIG. 1. (Color online) The persistent coil and the setup. (1) Seven identical sections of coated conductor stack together and unfolded forming a coil placed on 6 cm diameter cylindrical coil former. (2) A transformer used to induce current in persistent coil. (3) A tube through which a magnetic field sensor is inserted in the middle of the coil. The coil was immersed in liquid nitrogen.

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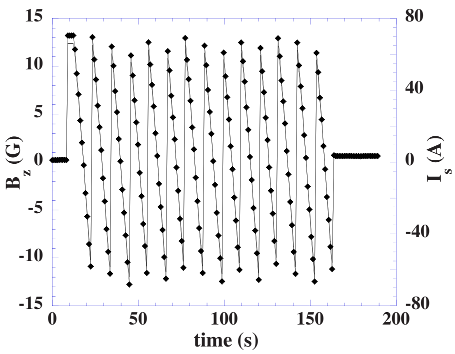

FIG. 2. (Color online) The coil was cooled under zero flux conditions and then the sawtooth current was fed into the primary windings. The response shows sawtooth variations in the measured magnetic field in the center of the superconducting coil. The scale on the right shows the corresponding values of the circulating current obtained from Eq. (2) with $dB_z/dI_s = 0.2$ G/A.

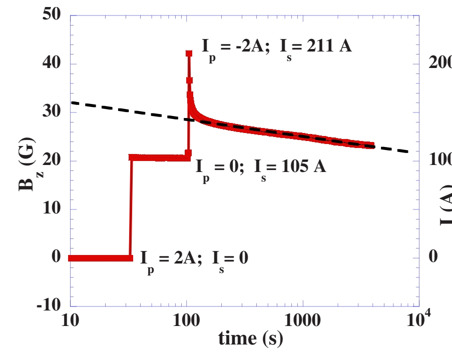

FIG. 3. (Color online) Shown are three steps of charging the coil. It was cooled with the current running through the primary winding of the transformer. Then the current was turned off and then turned on again with the opposite polarity. The dashed line is a guide to the eyes, which indicates the logarithmic decay due to the flux creep.

$$B_z|_{\rm ctr} \approx \frac{\mu_0 I_s K}{2R}. \quad (2)$$

Here K is a numerical coefficient that depends on the coil geometry ($K=1$ corresponds to a thin circular loop). The length of the sections and the radius of the coil former $R=3$ cm (Fig. 1) were chosen so that the curvature radii of both concave and convex parts of the coil are approximately the same, equal to 3 cm. For this shape and without corrections for the finite width of the conductor and the presence of the transformer, we get $K\approx 0.96$. The finite width of the conductor leads to small negative corrections to K of the order of $W^2/R^2 \sim 3\times 10^{-2}$; the small core of the transformer with the cross-section 4.4×6.7 mm^2 slightly distorts the distribution of the flux density and also reduces the value of K. Thus, using $K=0.96$ in Eq. (2) we will slightly underestimate the current by approximately 10%. Hereafter in order to deduce the value of the current in the superconducting coil, we will use $dB_z/dI_s = \mu_0 K/2R = 0.2$ G/A.

Figure 2 shows the response of the superconducting coil under zero fluxoid conditions ($\Phi'=0$). The coil consisting of seven nested sections was immersed in liquid nitrogen with no current running through the transformer. After its temperature stabilized, the sawtooth current I_p was fed into the primary windings. The primary current varied in the range of ± 1 A at constant rate of 0.2 A/s. At $|I_p|=1$ A the flux through the transformer core is well below the saturation level, as determined by a dc magnetization measurement, so that $\Phi_{\rm tr}(t)$ reproduces the sawtooth shape of the primary current. Since $\Phi_s(t) = -\Phi_{\rm tr}(t)$, see Eq. (1), the current induced in the superconducting loops and the magnetic field in the center of the coil also exhibit the sawtooth shape with the maximum current I_s through the entire coil close to 70 A. Note that in a closed resistive secondary winding, the induced current under sawtooth excitation of the primary would be constant and proportional to $\partial\Phi_{\rm tr}(t)/\partial t$.

This is an illustration that the supercurrent is proportional to the vector potential $\mathbf{A}$ rather than the electric field $\mathbf{E} = -\partial\mathbf{A}/\partial t$. At this rather high ramping rate a certain modulation of the induced current is evident due to the nonlinearity of the current-field interaction.

In Fig. 3 the response of the coil to a finite frozen in flux is shown. The coil was cooled while the dc $I_p=2$ A was running through the primary winding. Then the current was turned off. This induced $I_s \approx 105$ A persistent current in the multiloop superconducting coil. Then, the dc of the opposite polarity was fed into the primary. This doubled the induced current, exceeding the capacity of the coil to carry it without loss. The relaxation was monitored for more than an hour with the current running through the primary. The dc power supply had stability margins of 0.02%. The slow logarithmic relaxation $I_s \approx a\text{-}b \ln(t)$ indicated by the straight line is characteristic of the magnetic flux creep—thermally activated jumps of vortices between pinning sites.[9] The half life of the persistent current provides a measure of the relaxation rate. By extrapolating the data we obtain that it would take about 840 h for the current to decay from 140 to 70 A. The half life increases exponentially with the reduction in the temperature.[10]

An interesting feature of the relaxation shown in Fig. 3 is that over the first 40–50 s, immediately after the peak current was reached and before the relaxation settled into the flux creep mode, the decay of the induced current is much faster than the thermally activated creep. Most experiments in which the flux creep in YBCO crystals has been investigated cannot monitor the relaxation over such short periods of time for technical reasons, e.g., Ref. 10. The results of numerical simulations[11] and their interpretations[12] suggest that "off-equilibrium" configurations of vortices created, in our case, by the sudden change in induced current can relax without the need for thermal activation. Therefore, the relaxation rate of such configurations can be much faster than that of the flux creep. What is intriguing here is that the relaxation that takes place over about a *minute* of time seems to be *too slow* to be understood as a rapid dispersal of a supercritical assembly of vortices[12] or as the result of unpinned flux flow. This leaves a possibility that the initial phase of the relaxation evident in Fig. 3 is due to an entirely different mechanism specific to the coated conductors and the topology of our coil. One can see, Fig. 1, that the induced current makes four 90° turns over the length of the loop. In Ref. 13 it was shown that any sharp changes of the direction of current in a superconducting film induces electric field and, therefore, leads to energy dissipation. Microcracks, grain boundaries, etc. have the same effect. This dissipation caused by the strong nonlinearity of the current–electric field characteristic is weak and is difficult to detect in transport measurements. Under the persistent current conditions this mode of relaxation can be studied. More work is needed, however, to clarify this issue.

In summary, we have demonstrated the possibility of making persistent coils of a practically unlimited size using coated conductors. Unlike the coil proposed in Ref. 4, where the same current flows through the total length of the conductor, the coil assembled from individual sections is more robust. A weak section or a small weak spot does not limit the performance of the whole assembly. Therefore, coated conductors for such a coil would likely not need a stabilizer. If an individual section fails, the magnetic energy associated with it will be distributed among other sections and the heating of the conductor minimized. This not only reduces the cost of manufacturing for the conductor but increases substantially the engineering current density. At a critical current of $J_c = 200-300$ A/cm width[8,14] and a substrate with a thickness of $D = 50$ μm, the engineering current density can reach $J_E = J_c/D = 40-60$ kA/cm^2. Thus, the coated conductors can be superior to the bulk YBCO option in many potential applications, providing a comparable engineering current density with superior uniformity and consistency, especially for large size pieces. Even more elaborate, multiply connected superconducting pieces can be assembled from currently manufactured coated conductors in the form of tapes and 4 cm wide sheets.[14]

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