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VISUALIZATION OF COUPLING CURRENT PATHS IN STRIATED YBCO-COATED CONDUCTORS AT FREQUENCIES UP TO 400 HZ (POSTPRINT)

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Power Generation Branch
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Visualization of coupling current paths in striated YBCO-coated conductors at frequencies up to 400 Hz

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Abstract

The magnetic flux density component perpendicular to the broad tape face was mapped by miniature Hall probes in the vicinity of a striated YBCO-coated tape at frequencies of external magnetic field from 21 to 400 Hz, applied perpendicularly to the tape surface. For reasons of modelling the coupling current behaviour in tapes with a conductive substrate, we amplified the coupling current–amplitude by soldering 25 μm thick copper foil on the top of the filaments. The aim of this procedure was to decrease the transverse resistivity of the tape. The longitudinal components of the total currents flowing in the tape were calculated by an inverse method from the field map corresponding to the zero phase of the applied field. The diffusion lengths, characterizing the flux penetration into the tape, were determined for the respective frequencies. The experimentally determined diffusion length is in good accordance with theoretical models. While at 21 Hz both weak coupling currents and distinctive hysteretic currents of individual filaments are observed, at 400 Hz the coupling currents are predominant in this YBCO tape.

(Some figures in this article are in colour only in the electronic version)

A significant amount of development has occurred for high-temperature superconducting (HTS) wires and more recently especially for the second-generation (2G) $YBa_2Cu_3O_{7-x}$ (YBCO)-coated conductor. In order to make these HTS tapes suitable for AC applications, a part of this developmental effort has gone toward studies leading to a more AC-tolerant architecture for the conductor [1]. As part of this, a variety of techniques are widely used for characterization of the electromagnetic properties of the HTS tapes, such as AC loss, current density versus electric field (E–J), resistivity versus temperature (R–T) measurements, etc. However, these techniques are typically integral methods describing the tapes as a whole on the scale of several millimetres or more. Much less is known about the behaviour of these tapes on a sub-millimetre scale when exposed to an external AC magnetic field, where local variations of the critical current or the magnetic self-field may occur.

As already determined, the sample length plays an important role in AC loss measurements. While the total hysteresis power loss is proportional to the sample length, the total coupling loss in a twisted multifilament conductor increases as the square of the twist pitch length l_t^2 [2]. A linear, not twisted multifilament tape with the length of L behaves like a twisted one with twist pitch $l_t = 2L$. To reduce the coupling losses in an application, the multifilament HTS tape must be either physically twisted or have a 'twist' of the filaments incorporated into the conductor's architecture [3, 4]. In a rectangular non-twisted multifilament sample, the coupling currents at the end of the tape will flow in a direction perpendicular to the filaments. In the central section of the tape, however, the coupling currents flow in the direction

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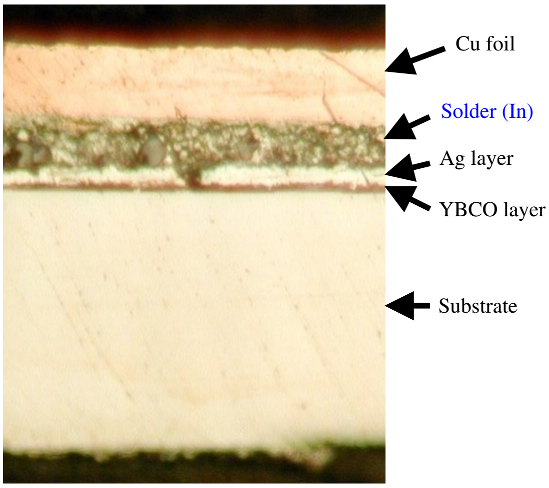

Figure 1. Electron microscope microphotograph of the YBCO-coated conductor tape in lateral cross-section showing the layer structure of the original tape, as well as the additional copper layer soldered with indium solder and reducing thus the transverse resistivity; approximate layer thicknesses are as follows: substrate 50 μm, YBCO 2 μm, silver cap layer 3 μm, Cu foil 25 μm, indium solder 15 μm.

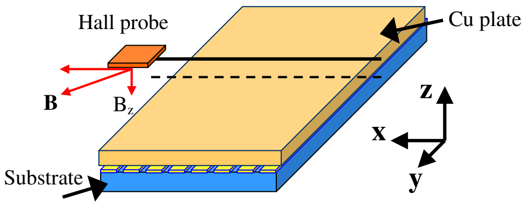

Figure 2. HPM measurement of the z-component of the magnetic self-field due to magnetization currents induced in the tape by AC external magnetic field, perpendicular to the broad tape face.

parallel to the filaments' axis. The measurement techniques, such as the time integration of the pick-up coil voltage [5], the temperature increase of the sample due to the self-heating [6], or a technique based on AC susceptibility measurements [7], provide only the total loss value. Due to the complex current paths in an actual filamentary tape, it is important to verify the simplified theoretical predictions by an appropriate experiment giving information also on the local scale. Magneto-optical imaging (MOI) and Hall probe mapping (HPM) are useful tools in this respect. MOI was already used in experiments focused on the current density distribution in YBCO at frequencies up to 1 kHz [8]. The advantages of HPM compared to MOI are the higher sensitivity of the Hall probe sensors to the magnetic field, higher versatility, and a lower cost of the experimental device. In this work, we focused on the visualization of both the magnetization and the coupling currents in a special filamentary sample of YBCO-coated conductor.

A multifilamentary YBCO-coated conductor sample with the dimensions 4×40 mm^2 was prepared for this investigation from a uniform 12 mm wide coated conductor provided by SuperPower Inc [9]. In this conductor, the $\sim$1 μm thick YBCO layer is deposited on 50 μm thick Ion Beam Assisted Deposition (IBAD) Hastelloy substrate and covered with the silver cap layer about 3 μm thick. The non-superconducting grooves segregating the superconducting stripes were cut by laser ablation as described in [10], and the sample was annealed in flowing oxygen afterwards [11]. The distance between the grooves is 0.5 mm and their width is about 30 μm. Before striation the critical current of the 12 mm wide conductor was about 160 A. The AC loss measurements in the frequency range from 28.5 to 203 Hz indicate that the coupling loss in the sample is quite small, as the loss per cycle at given amplitude of the external magnetic field, B_{ext}, was practically frequency independent. This is the result of post-ablation oxygenation that leads to formation of high-resistivity oxides (NiO, Cr_2O_3, etc) in the grooves [11]. For the purpose of this investigation the coupling currents were amplified to allow their spatial determination by deliberate reduction of the interfilamentary resistance. A 25 μm thick Cu foil was soldered to the surface of the silver cap layer (see figure 1). Thus, the coupling currents were able to flow between the superconducting filaments through the copper overlayer [12].

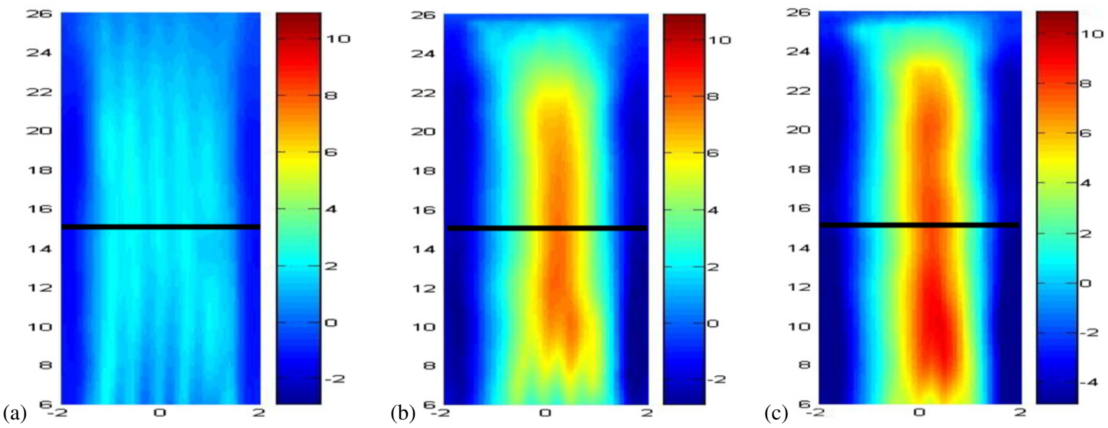

Figure 3. Magnetic self-field map $B_{sf,z}(x, y)$ generated by magnetization currents induced in the tape exposed to external AC field; measurement by Hall probe in the distance $z = 0.35$ mm above the tape. x is the coordinate across the tape (in millimetres), the y-axis (at the left side of the figures) gives the coordinate in the direction along the tape in millimetres, and the colour bar represents the amplitude of the z-component's magnetic flux density B_z (in mT). The phase of the external field $\phi = \omega t = 0$. Lateral self-field profiles along the horizontal lines for $y = 16$ mm are shown in figure 5(a). (a) Frequency 21 Hz, (b) frequency 165 Hz and (c) frequency 400 Hz.

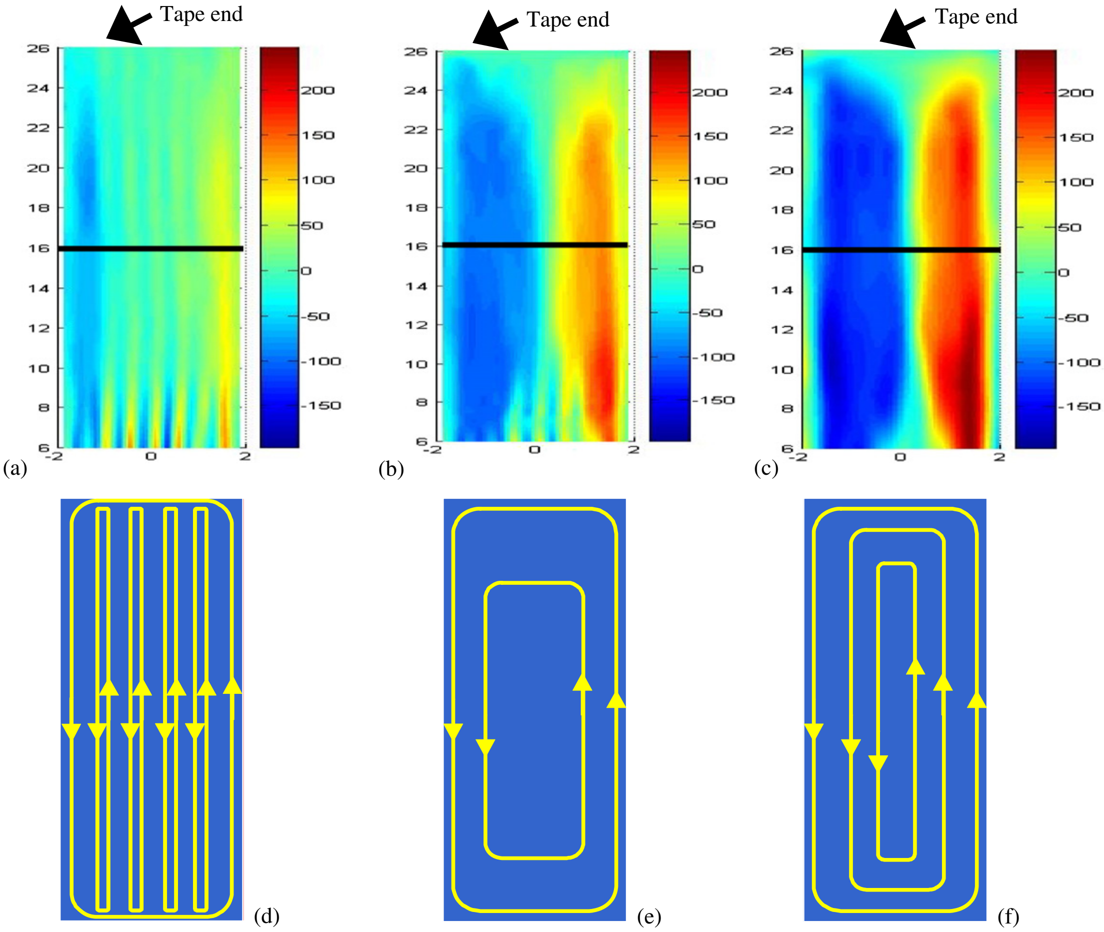

Figure 4. Inversely calculated map showing longitudinal component of coupling currents. The axes x and y are spatial coordinates (in mm), and the colour bar represents the amplitude of the coupling current y-component per unit width I_y in (A cm^{-1}). Note that at the tape ends the longitudinal (I_y)-component decreases to zero; this is due to the increase of the transverse (I_x)-component of the current loops. One can see in (b), (e) and in (c), (f) that at frequencies 165 and 400 Hz, the coupling currents predominate over hysteretic currents, while at 21 Hz, see (a), (d), the coupling currents play only a minor role. Lateral current profiles along the horizontal lines $y = 16$ mm are shown on figures 5(b). (a)–(c) Calculation for frequencies 21, 165 and 400 Hz, respectively, (d)–(f) schematic magnetization currents paths deduced from (a)–(c) calculations.

Miniature Hall probes (developed in our laboratory, HHP-VU) with a sensitivity of ~150 mV T^{-1} and an active area of 50 by 50 μm^2 were used for the field mapping. The experimental system used to perform the HPM measurements is described elsewhere [13]. The system provided a harmonic signal $B_e = B_{\max}\sin(\omega t)$ with $B_{\max} = 33.5$ mT. By using a triggered-signal data acquisition technique for the selected phase of the AC field [13], we measured a series of lateral magnetic self-field profiles $B_{sf,z} = f(x)$, where x is the direction perpendicular to the superconducting stripes. The measurements were repeated by shifting the Hall sensors along the stripes with a spatial step of $\Delta y = 1$ mm from one tape end to the other; see figure 2. At the tape ends, the step Δy was reduced to $\Delta y = 0.5$ mm to track changes of the self-field. The distance of the Hall probe sensor from the tape's surface was $\Delta z = 0.35$ mm. The AC magnetic profiles were measured at the fixed phase of the external field $\phi = \omega t = 0$; they correspond to zero value of the external field, when the coupling current is at its maximum. The maps of $B_{sf,z}(x, y)$ measured at frequencies 21, 165 and 400 Hz are shown in figure 3.

From these results we calculated the lateral distribution of the local sheet current values, $I_{s,y}(x)$, at each position y, by solving the inverse problem. The details of the method used are described in [14]. The number of elements used to calculate $I_{s,y}(x)$ was 85. The paths of the magnetization currents determined by the calculations using the data from figures 3(a)–(c) are shown in figures 4(a)–(c). The magnetization current paths deduced from the calculations in figures 4(a)–(c) are schematically shown in figures 4(d)–(f). The magnetic field profiles $B_{sf,z}(x)$ and the current profiles $I_{s,y}(x)$ at the position $y = 16$ mm are shown in figures 5(a) and (b), respectively. For y-values close to the sample centre $\sum_i I_{s,y}(x_i) = 0$, as no transport current flows in the sample. The mean of lateral sum of absolute values, $1/n\sum_{i=1}^{n}|I_{s,y}(x_i)| = I_y$, equals the total induced sheet current's longitudinal component at longitudinal position y. This value is supposed to be maximum in the centre of the tape and decreasing to the ends in favour of the complementary transverse sheet current component, which is supposed to be maximum at the tape's ends, with amplitude equal to the longitudinal component I_y at the tape's centre.

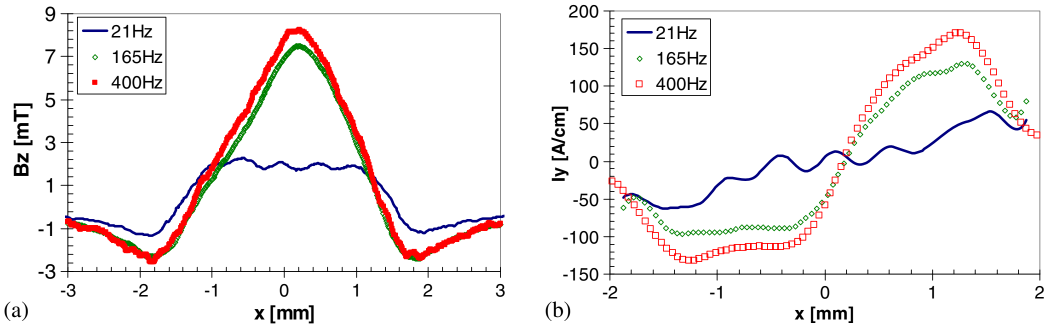

Figure 5. The measured lateral self magnetic field profiles $B_{sf,z}$ (x) and corresponding lateral current profiles I_y (x) along the horizontal line y = 16 mm from figures 3(a)–(c) and figures 4(a)–(c) for the frequencies 21, 165 and 400 Hz, respectively.

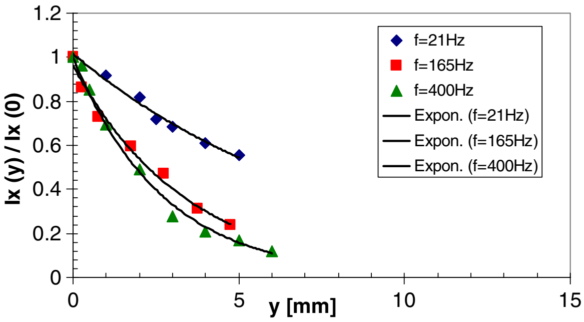

Figure 6. Data normalized and fitted by an exponential curve for each respective frequency, 21, 165 and 400 Hz. On the y-axis are normalized data representing exponential decay of the transverse current component from the tape's end.

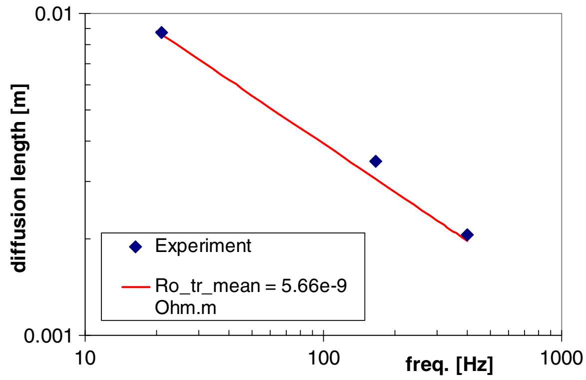

Figure 7. Measured data of frequency dependence of the diffusion length compared to the theory, calculated for the following value of transverse resistivity: $\rho_{tr} = 5.66 \times 10^{-9}$ Ω m.

The magnetic flux penetration into the tape can be quantitatively described by means of the diffusion length which is the length characterizing the exponential decay of the complementary transverse component of coupling current amplitude from the tape ends [15]:

$$l_d = \frac{1}{\sqrt{\mu_0 \omega n_p \ln(1 + 2n_\perp)/2\pi \rho_{tr}}}, \qquad (1)$$

where ω is the angular frequency, $\omega = 2\pi f$; n_p and $n_\perp$ stand for number of filaments parallel or perpendicular to the broad tape side, respectively; and ρ_{tr} is the transverse resistivity. The amplitude of the transverse component of the coupling currents for a given distance from the tape end can be deduced from the decrease in the longitudinal component of the current. While in the tape's central region the longitudinal current component is maximal and essentially equals the net coupling current, it continuously decreases to zero value at the tape ends, ($I_y \to 0$). This decrease is compensated with an increase in the transverse component $I_x = f(y)$ towards the tape ends. The $I_x(y)$-component (complementary to I_y) decays from the tape ends following the exponential function

$$I_x = k \cdot \exp\{-y/l_d\}, \qquad (2)$$

where l_d is the diffusion length.

The diffusion lengths (l_d) were determined from the HPM experiments based on equation (2). Based on curve fitting of the data shown in the figure 6, we determined the diffusion lengths l_d to be 8.7 mm, 3.5 mm and 2.1 mm for 21 Hz, 165 Hz and 400 Hz, respectively. As expected from equation (1), the diffusion length decreases with increasing frequency; see figure 7. Using the expression $R = l_d(f)/l_d$ (21 Hz), the ratios of the diffusion length for each frequency with respect to the diffusion length at the lowest frequency, i.e. 21 Hz, are $R_{165Hz} = 0.40$ and $R_{400Hz} = 0.24$. This is in good agreement with the theoretical square root frequency dependence suggested by equation (1), namely $R_{165Hz} = 0.36$ and $R_{400Hz} = 0.23$.

From the experimentally determined diffusion lengths, we calculated the transverse resistivity using equation (1), taking n_p and $n_\perp$ to be 6 and 1, respectively, for our sample. The mean value of the transverse resistivity determined from the measurements was $\rho_{tr\_mean} = 5.66 \times 10^{-9}$ Ω m. This value compares favourably with the copper foil resistivity measured at LN_2 temperature, $\rho(77\text{ K}) = 2.48 \times 10^{-9}$ Ω m.

In conclusion, we have reconstructed the current paths of the longitudinal (I_y)-component of coupling currents in a striated YBCO conductor with non-striated copper stabilizer. This was accomplished by solving the inverse problem and thus determining the induced coupling currents from the measured magnetic field. The results obtained for three particular frequencies (21, 165 and 400 Hz) confirm the theoretical prediction of the $f^{-1/2}$ frequency dependence of the diffusion length. For the lowest frequency of 21 Hz, we observed weak coupling currents between the filaments with dominant hysteretic currents. At higher frequencies of 165 and 400 Hz the superconducting filaments are almost fully re-coupled by the currents flowing through the copper stabilizer. The resistivity of the coupling medium obtained from the values of the diffusion length by inverting equation (2) is close to that of copper.

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