Crossed-magnetic-field experiments on stacked second generation superconducting tapes: Reduction of the demagnetization effects

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The crossed-magnetic-field effect on the demagnetization factor of stacked second generation (2G) high temperature superconducting tapes is presented. The superconducting sample was initially magnetized along the *c-axis* by the field cooling magnetization method. After achieving the magnetic relaxation of the sample, an extensive set of experimental measurements for different amplitudes of an applied ac magnetic field parallel to the *ab-plane* was performed. A striking reduction of the demagnetization factor compared with the reported values for superconducting bulks is reported. The demagnetization factor increases linearly with the amplitude of the ac transverse magnetic field, confirming the universal linear behavior of the magnetic susceptibility which was previously predicted for superconducting bulks in Phys. Rev. B 54, 4246 (1996). The study has been also pursued at different frequencies of the ac transverse magnetic field, in order to determine the influence of this parameter on the demagnetization factor measurements. We report an even lower demagnetization factor as long as the frequency of the transverse magnetic field increases. Thus, the significant reduction on the demagnetization factor we have found by using stacked 2G-superconducting tapes with higher mechanical strength, compared with the one of superconducting bulks, makes to this configuration a highly attractive candidate for the future development of more efficient high-power density rotating machines and strong magnet applications.

The ability of high temperature superconducting (HTS) materials to trap large magnetic fields and maintain them for long periods of time,[1–4] make them highly attractive for their use in a variety of high-field permanent-magnet-like engineering applications, such as magnetic bearings,[5] and high power-density rotating machines.[6,7] However, in practice a major concern arises due to the significant magnetization decay of HTS bulks when the premagnetized sample is subjected to an ac magnetic field orthogonal to the original direction of the magnetization, i.e., when the HTS bulk needs to operate in the so-called crossed magnetic field configuration,[8–10] which indeed is the case for the operation of rotating machinery. The most severe demagnetization effects are found when the ac field perturbations are perpendicular to the direction of the initial magnetization which cause a significant decay of the trapped magnetic field ($\sim 50\%$), even after applying just one cycle of an ac transverse magnetic field with an amplitude similar to the intensity of the trapped magnetic field.[7–12] Therefore, the need for a continuous and stable operation of such devices may be seen dramatically affected as result of a long-term decay of the field produced by any bulk HTS, when its is subjected to more than one cycle of the ac transverse magnetic field. Moreover, despite the fact that the most compact sources for very high trapped field are HTS bulks, these materials are frequently impractical due to their thermal instability at low temperatures and their poor mechanical strength.[13] Thus, for the designing of more efficient and economically attractive superconducting rotary machines, the thermal and mechanical properties of the employed superconducting materials should be significantly improved for those operating regimes requiring high trapped magnetic fields, whilst the detrimental demagnetization effects by cross field configurations are somehow reduced.

By using 2G-HTS tapes, recently Patel *et al.* have reported a series of field cooling magnetization experiments,[3,4] achieving trapped magnetic fields up to $7.34\,T$ at $4.2\,K$ in the middle point between two 12mm square stacks, each made of 120 layers of 2G-HTS tapes. This surprisingly high value for the trapped magnetic field given the small size of the stack together with, the commercial availability of the tapes, almost uniform physical properties in long lengths, and considerably higher mechanical strength compared with the one of superconducting bulks,[4,15] makes the stack configuration of 2G-HTS tapes an ideal candidate for practical applications where strong magnets are required. Thus, in order to validate its practical applicability on high power density rotating machines, first, it is of utter importance observe and understand the performance of a 2G-HTS stack when it is subjected to a cross-magnetic-field experiment. In this sense, and based on our knowledge, any other study about the demagnetization factor of stacked 2G-HTS tapes have been conducted or reported up to date.

Aiming to solve the lack of studies about crossed-magnetic field experiments on stacked 2G-HTS tapes, in this letter we report a remarkable reduction in the demagnetization effects when this configuration is used, by comparison with our previous studies performed on HTS-bulks.[7,14] A comprehensive study on the demagnetization factor of a stack of 2G-HTS tapes has been conducted for different amplitudes and frequencies of the applied trans-

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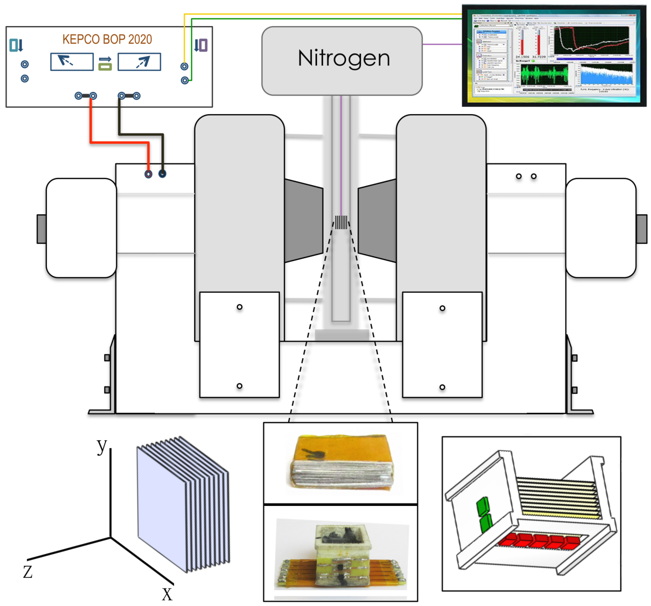

FIG. 1. (Color online) Schematic drawing of the experimental setup described in the manuscript. Pictorial illustrations of the stacked 2G-HTS tapes with the coordinate-system used across this paper (left-bottom corner), and the nylon holder with the sets of Hall probes designed for our measurements (right-bottom corner), are shown. Real pictures of the stack and its holder are shown in the central-bottom of the figure.

verse magnetic field. The sample consists of a stack of sixteen 12 mm square 2G-HTS tape,[15] with the same physical properties summarized by Patel et. al. in Ref. 4. The sample is placed in a nylon holder and two sets of Hall probes are located beneath and besides the sample holder as shown in Fig. 1, and the gap between the sensors and the sample is $0.1mm$. On the one hand, the first Hall probe board is located linearly along the center of the sample in order to measure the trapped magnetic field after the field cooling procedure with magnetic field applied in the z-direction, i.e. perpendicular to the tape surface (see Fig. 1). Sufficient magnetic field was applied for fully penetrating the sample, showing a maximum trapped magnetic field at the center of the outer layer of the stacked tapes (see Fig. 2). Then, by rotating the sample in 90 degrees clockwise, the same Hall probe board allows a straightforward measurement for the decay rate of the trapped magnetic field (or demagnetization factor) when the crossed field along the y-axis is initialized. On the other hand, the second board of Hall probes aims to measure the magnitude of this transverse magnetic field.

The superconducting sample is mechanically secured to the holder by using stycast with a high thermal conductivity, and the holder is then placed inside of a nylon rod capable of withstanding cryogenic temperatures. In our system, the rod is placed into a homemade polycarbonate dewar with an outer diameter of $30mm$. The top section of the rod is connected to a cryogenic reservoir which is capable to provide the enough amount of liquid nitrogen for the operation of the whole experiment (see Fig. 1). Then, in order to apply the external magnetic field to the sample, we have used a dipole magnet with $76\,mm$ diameter, and the superconducting sample is placed exactly in the middle of the poles. In all the experiments, the xy-plane of the superconducting tapes was first aligned parallel to the surface of the magnet poles. Then, the entire sample was initially magnetized parallel to the c-axis by field cooling in liquid nitrogen, with an applied magnetic field intentionally much larger than the full-penetration field calculated by Brandt's analytical approximation,[21] $H_{p\|c} \approx J_c(c/\pi)\ln(2a/c)$, for an analogous $a = 12mm$ square sample of $c = 16\mu m$ thickness and $I_c = 240A$ ($\mu_0 H_{p\|c} = 58.5mT$). Thus, into the Bean's model, for getting a trapped magnetic field of this magnitude at the center of the sample we must apply at least twice this value ($\sim 117mT$), or much higher for field cooling magnetization experiments. In our case, a constant time interval of approximately 600 seconds was allowed for the magnetic relaxation of the stacked tapes due to the thermal activation of vortices over the pinning barriers, following the removal of the applied (c-axis) field until getting a maximum trapped field of $\mu_0 H_{max\|c} = 120mT$, it measured at the center of the bottom tape of the superconducting stack (see Fig. 2). The sample was then carefully rotated in order to apply an ac transverse magnetic field H_{ab}, parallel to the ab plane of the sample. Three sets of experiments were conducted according to the amplitude of H_{ab}, i.e., for $\mu_0 H_{ab}^{peak} = \pm 80mT$ ($\sim 66.6\%$ of $H_{max\|c}$), $\pm 150mT$ (125% of $H_{max\|c}$), and $\pm 300mT$ (250% of $H_{max\|c}$). For each case, two different frequencies were chosen, $0.5Hz$ and $2.5Hz$, and the experimental measurements range is 100 cycles. After this period of time, an additional time interval of approximately 600 seconds was allowed for magnetic relaxation due to the applied transverse field.

Figure 2 shows the renormalized intensity of the trapped field $H_{\|c}/H_{max\|c}$ before and after applying 100 cycles of transverse magnetic field $\mu_0 H_{ab}$ at the different positions where the Hall probes are located (see bottom of Fig. 1). The maximum decrement factor of the trapped field for $|\mu_0 H_{ab}^{peak}| = 80mT$, $150mT$, and $300mT$ operating at a frequency of $0.5Hz$ after 100 cycles is 2.16%, 4.50%, and 10.22%, respectively (Fig. 2-top). On the other hand, for a frequency of $2.5Hz$ the corresponding values for the maximum decrement factor of the trapped field are 0.88%, 3.01%, and 5.99%, respectively (Fig. 2-bottom). From these measurements, a striking decrease in the demagnetization factor of the sample is noticed, in particular when it is compared with similar studies carried on superconducting bulks.[7,11,12] In fact, when a superconducting bulk is subjected to a cross field experiment, even just after the first cycle of the applied ac transverse magnetic field, the original magnetization of the sample can be erased in over a 50% for $|H_{ab}^{peak}/H_{\|c}| \approx 1.5$ in comparable geometries.[7,11] However, in a stack of 2G-HTS tapes we have found that

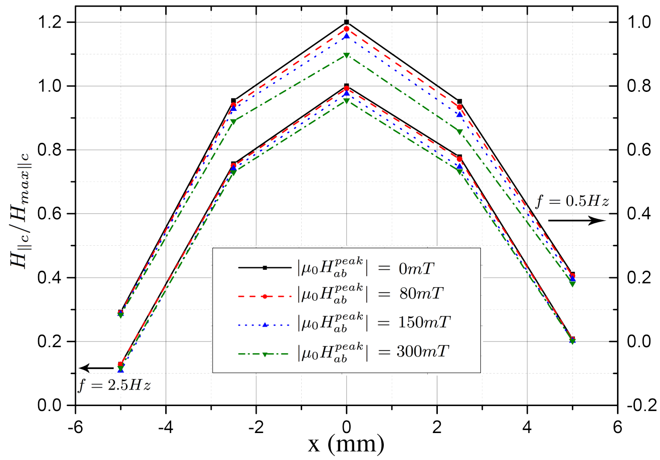

FIG. 2. (Color online)Renormalized intensity of the trapped magnetic field $H_{\parallel c}/H_{max\parallel c}$ at $t = 0$, i.e., before applying the ac transverse magnetic field, i.e., $\mu_0 H_{ab} = 0$ (black solid lines), compared with the renormalized intensity of the trapped magnetic field after 100 cycles of the H_{ab}, for the different Hall probe positions (solid symbols). Three different amplitudes have been considered: $|\mu_0 H_{ab}^{peak}| = 80mT$ (red dashed lines), $|\mu_0 H_{ab}^{peak}| = 150mT$ (blue dotted lines), and $|\mu_0 H_{ab}^{peak}| = 300mT$ (green dash-dotted lines). For each amplitude of H_{ab}, two different operation frequencies have been also considered, i.e., $f = 0.5Hz$ (top set of curves, left scale), and $f = 2.5Hz$ (bottom set of curves, right scale).

the demagnetization factor of the sample is significantly lower ($\sim 5\%$) even after 100 cycles of the ac perturbation, which makes this configuration much more attractive for the development of practical applications.

From the theoretical point of view, several approaches have been made in the literature to attempt to describe the demagnetization of irreversible type-II superconductors subjected to crossed magnetic field, including the two-velocity hydrodynamic model,[16] E-J power law models,[7,11,14] and a wide number of material laws contextualized into our generalized critical state model.[10,17] However, nowadays is well known that the two-velocity hydrodynamic model cannot explain all the experimental facts observed in type-II superconductors, as it is the case of the inversion of the current flow in a longitudinal transport problem (a current is applied parallel to some bias magnetic field), a phenomena which has been successfully explained into the generalized critical state theory.[?] Furthermore, due to the recently reported possibility to extend and compare the E-J power law models with the critical state model,[18] the critical state theory is still the strongest candidate to explain the electromagnetic behavior of type-II superconductors. In this approach, the equilibrium configurations of flux quanta are treated by the macroscopic relation $|\mathbf{J}\times\mathbf{B}| \leq F_p$ between the volume pinning force and the average values of the current density and magnetic flux density, i.e., a maximum value for the pinning force is equivalent to a critical value in the component of the current density perpendicular to the local magnetic induction, $J_\perp \leq J_{c\perp}$.

In our case of study, when the superconducting sample is in the critical state or close beyond this, the magnetization currents are initially circulating in the $ab-$plane of each 2G-HTS layer due to the applied $H_{\parallel c}$ (penetrating the entire sample), and obeying the condition $J_{ab} \leq J_{c\perp}$ with the critical current density $J_{c\perp}$ perpendicular to the local induction $\mathbf{B}$. Then, when applying a transverse field H_{ab} the profiles of current along the entire sample may be redistributed due to the induction of current profiles closing along the $c-$axis, which indeed, are created in order to equilibrate the inhomogeneous distribution of $\mathbf{B}$, by ensuring the charge conservation condition $\nabla \cdot \mathbf{J}(\Omega) = 0$ with Ω defining the sample volume. Thus, as the decremental factor on the magnetization involves the redistribution of the original magnetization currents by those created by the flux penetration of the transverse field H_{ab}, its effect is straightforwardly linked to the aspect ratio between the ab plane and the thickness of the sample, as well as to the physical mechanisms governing the quasi-steady motion of the local profiles of current density. On the one hand, about the mutual orientation of the transverse ac field and the currents circulating in the critical state, any applied field H_{ab} is perpendicular to the circulating current in some regions of the sample, whilst it is parallel to them in some others. When the in-plane field is parallel to the circulating current this event may induce to the redistribution of current profiles due to the flux cutting mechanism,[10] and for the zones where the in-plane field is perpendicular to the circulating current the critical state condition $J_{ab} \leq J_{c\perp}$ is preserved. However, as in general $J_{c\parallel} > J_{c\perp}$,[19] or even $J_{c\parallel} \gg J_{c\perp}$,[20] the decremental on the magnetization due to the flux cutting mechanism can be seen overshadowed when the threshold value for the current density is assumed to satisfy the simple condition $J_c \leq J_\perp$.[17] This fact justify why most of the crossing experiments can be explained with,[9] or without,[8,12] the flux-cutting mechanism with no appreciable quantitative differences, but also states that at least a minimum amount of demagnetization must be observed for any cross-field experiment, unless the measure lacks of enough experimental resolution. However, as the physical mechanisms of flux cutting and flux depinning both may increase the demagnetization factor for any type-II HTS material, it may stated that the strong decremental on the demagnetization factor for stacked 2G-HTS tapes has its origin on the aspect ratio of the sample.

A semi-quantitative explanation of the influence of the aspect ratio on the demagnetization factor for stacked superconducting tapes can be achieved by analyzing the limiting cases for the fully penetration field. In this sense, given the small thickness of the superconducting material in a 2G-HTS tape ($\sim 1\mu m$),[15] and hence in a stack of 2G-HTS tapes, both compared with a superconducting bulk of the same longitudinal dimensions (12mm square), the amount of magnetic field need for achieving the full

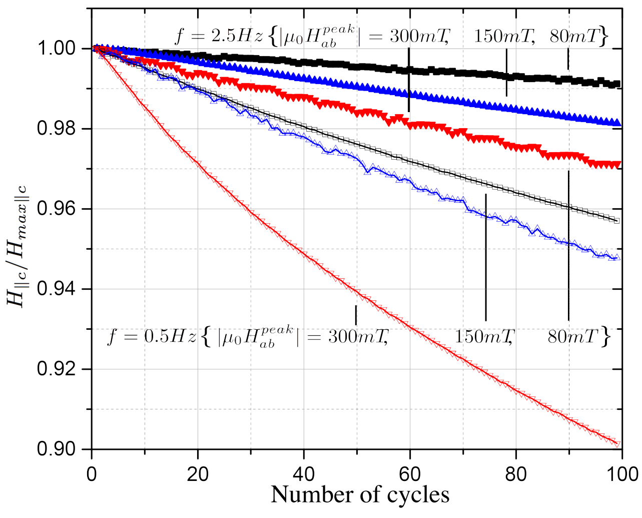

FIG. 3. (Color online) Renormalized intensity of the trapped magnetic field $H_{\|c}/H_{max\|c}$ at the center of the bottom layer of the stack of 2G-HTS tapes, for different amplitudes of the applied ac transverse magnetic field: $|\mu_0 H_{ab}^{peak}| = 80mT$ (black solid squares), $|\mu_0 H_{ab}^{peak}| = 150mT$ (blue solid up triangles), and $|\mu_0 H_{ab}^{peak}| = 300mT$ (red solid down triangles), as a function of the number of cycles. Two different frequencies for the H_{ab} field have been considered: $2.5Hz$ (solid symbols), and $0.5Hz$ (empty symbols).

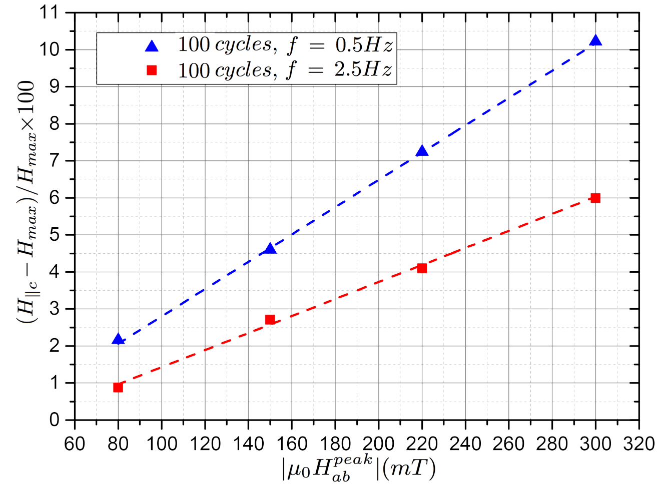

FIG. 4. (Color online) Percentage demagnetization factor for the crossed field experiments.

collapse of the magnetization, by fully penetrating the sample with a transverse magnetic field parallel to the ab plane, $\mu_0 H_{p\perp c} \simeq J_{c\perp} a \approx 9.42T$, is much higher than our previous estimation, $\mu_0 H_{p\|c} = 58.5mT$. In other words, according to the charge conservation principle and the critical state theory, we would need to apply a very strong transverse magnetic field, in order to create current profiles flowing along the c-axis capable to consume (redistribute) the existent current profiles flowing along the ab-plane. This simple fact explains why the demagnetization factor of a stack of 2G-HTS tapes is significantly reduced when it is compared with a superconducting bulk. Besides, we performed an additional experimental verification by trying to magnetize the stack of 2G-HTS tapes (initially demagnetized) in perpendicular direction to the c axis, by using the field cooling magnetization method with the same rate of magnetic field used before for getting a trapped inductive field of $120mT$ parallel to the c-axis, but no magnetization signal was observed and therefore, no appreciable current along the c-axis was induced.

Finally, in Fig. 3 we show the renormalized intensity of the trapped magnetic field $H_{\|c}/H_{max}$ at the center of the bottom layer of the stack of 2G-HTS tapes as a function of the number of cycles and elapsed time (up to 200 sec), when an ac transverse magnetic field of different amplitudes and frequencies is applied. Besides the relevant decreasing on the demagnetization factor found when a stack of 2G-HTS tapes is used as replacement of a HTS bulk, our results can be summarized by analyzing the final values of the trapped field when a certain number of cycles of the transverse magnetic field has been applied. In this sense, the percentage demagnetization factor related with the decremental on the trapped field at the center of the bottom layer of the superconducting stack, after 100 cycles of the ac transverse field is shown in Fig. 4. On the one hand, it can be noticed that the demagnetization factor linearly increases with the amplitude of the transverse magnetic field, $|H_{ab}^{peak}|$. On the other hand, the higher the operating frequency of the transverse field the lower the demagnetization factor. We also call the attention to the reader to the fact that our observations for stacks of 2G-HTS tapes confirm the original statement made for superconducting bulks by E. H. Brandt in Ref. 21, when he affirmed that the ac magnetic susceptibility $\chi(\omega)$ during creep, shows a *universal* linear behavior depending only on the geometry and the creep time, but not on temperature, applied or internal magnetic field, or any material parameter.

In conclusion, we have examined the cross-magnetic-field effect on the demagnetization factor of a stack of 2G-HTS tapes previously magnetized along the c-axis by the field cooling magnetization method. Different frequencies and amplitudes of an ac magnetic field applied parallel to the ab-plane have been considered. Remarkably, a strong reduction of the demagnetization factor has been found even after 100 cycles of the ac perturbation ($\sim 10.2\%$ in the worst of our cases), when in the case of a superconducting bulk the expected demagnetization factor after just one cycle of the ac transverse field can be even much higher than 50%.[7,9,11,12,14] The universal linear behavior of the magnetic susceptibility predicted by Brandt in Ref. 21 for the case of superconducting bulks, is now confirmed for the case of stacks of 2G-HTS tapes by showing the linear dependence of the demagnetization factor as function of the amplitude of the ac transverse magnetic field. Moreover, we report that the demagnetization factor for a stack of 2G-HTS tapes can be lowered even more by applying a higher frequency on the transverse field. Thus, we conclude that with the higher mechanical strength of the commercial 2G-HTS tapes,[15] its capacity for trapping high magnetic fields,[4] and the significant reduction of the detrimental demagnetization effects in cross-magnetic-field experiments, the use of stacks of 2G-HTS tapes would lead to the development of more efficient high-power density rotating machines and strong magnet applications.

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