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High-field flux jump instabilities in cables for accelerator or compact fusion magnets and their effective suppression

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Rare-earth-barium-copper-oxide (ReBCO) superconducting tapes are pivotal for emerging technologies such as fusion reactors and particle accelerators due to their superior performance in high magnetic fields. Despite extensive studies of single tapes, the magnetization behavior of ReBCO tape stack cables at high magnetic fields has been underexplored. Here, we present magnetization measurements of ReBCO tape stack cables at magnetic fields up to 30 T at 4.2 K. Remarkably, flux jump instabilities, typically confined to lower field regimes in single tapes, persisted up to 17 T and higher in tape stacks. Such instabilities could significantly impact the stability and field quality of large-scale superconducting magnets. Crucially, we demonstrate that introducing small intertape spacers substantially mitigates flux jump occurrences, sometimes eliminating them completely. Our findings offer valuable insights for designing stable, high-performance ReBCO cable-based magnets, enhancing their viability for next-generation fusion and accelerator applications.

The pursuit of high-field applications, such as fusion energy and advanced particle accelerators, relies heavily on the development of high-performance superconducting materials[1–4]. One of the most promising candidates is rare-earth-barium-copper-oxide (ReBCO) coated conductors, which combine excellent current-carrying capacity, strong thermal stability, and ease of use in complex magnet designs, eliminating the need for post-winding heat treatment. These characteristics have led to widespread adoption of ReBCO in several flagship high-field magnets, generating up to 45.5 T in test coils[5] and 32 T in operational systems[6].

While the magnetic behavior of individual ReBCO tapes is well documented, their performance in practical configurations such as cables remains significantly underexplored. Cables, whether Roebel, CORC, or tape stacks, are essential in large-scale magnet systems to reduce inductance, improve thermal robustness, and ensure redundancy. However, they also introduce collective electromagnetic behavior not observed in single-tape studies. Accurate magnetization characterization of these larger constructs is limited due to measurement challenges.

Our group has previously demonstrated magnetization measurements of CORC cables using a high-field DC susceptometer approach[7]. In this work, we apply the same methodology to investigate simpler stacked configurations, tape stack cables, used increasingly in prototype accelerator insert magnets and fusion magnets (the latter from companies like Commonwealth Fusion Systems and Tokamak Energy). These cable formats approximate superconducting slabs, leading to significantly increased magnetic penetration fields compared to individual tapes[8–15]. Crucially, we observed flux jump instabilities persisting at unprecedentedly high magnetic fields, up to 17 T. Flux jumps represent a significant issue, potentially destabilizing magnet operation or compromising field uniformity due to thermomagnetic instabilities triggered by intense, localized heat generation.

To address this, we explored the introduction of small copper and G10 (glass fiber reinforced epoxy) intertape spacers. This markedly reduced flux jumping and, in some configurations, eliminated flux jumps entirely. This may be due to the fact that the magnetization is substantially lower for both Cu and G10 interleaved strand samples (i.e., the magnetic coupling between the layers is reduced[16,17]). Adiabatic flux jumps are known to correlate with both lower sample dimensions[18,19], but in particular, lower magnetization[20,21]. The addition of these spacer layers

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may also have facilitated better cooling (which might lead to an enhanced dynamic stabilization[22]) although this was not directly measured.

Given the burgeoning demand for robust superconductors in fusion energy and advanced magnets, our findings have significant implications. Optimizing tape stacking and spacing could enhance the practical reliability of ReBCO cables, accelerating their adoption in fusion reactors and advanced accelerator magnets, where stability and field quality are paramount.

Thus, this work represents a crucial advancement towards not only understanding fundamental instabilities but also optimizing ReBCO cable designs, aligning technological feasibility with scientific innovation.

Methods

Samples

All samples measured in this work were assembled from tape segments cut from a length of SuperPower SCS-4050 HTS tape. The tape was 4 mm wide and had a substrate thickness of 30 μm, a Cu plating thickness of 10 μm (each side), and a tape I_c of 100 A at 77 K and self-field. Three samples were measured; the first consisted of a 2.7 cm long stack of 60-tapes, the second sample was the same except that thin Cu spacers (0.16 mm thick) were placed between each tape and its neighbor, and the third sample, again 2.7 cm long, consisted of a 30-tape stack with G10 spacers (0.38 mm thick) in between each ReBCO tape and its neighbor. We used a diamond saw to cut the samples. In all cases, the field was perpendicular to the tape stack cable width, as shown in Fig. 1. *M-H* Measurements on these samples were made with a field applied perpendicular to the width and length of the tapes within the cable in a LHe environment (4.2 K). The specifications of these tape stack cables are listed in Table 1.

Measurement procedure

The magnetic field was supplied by a 30 T resistive magnet at the National High Magnetic Field Laboratory, Tallahassee, Florida. This magnet not only provided the applied field but also served as the primary coil for a susceptibility approach to magnetization measurement. We used our own custom-made coil set for both the pickup and compensation coils; the same setup was used in our previous work[7].

During the measurement, a voltage was induced in the pick-up coil (which contained the sample) by the ramping of the magnetic field produced by the resistive magnet. The induced voltage, *V*, in the coil was calculated using Faraday's law. We connected a compensation coil (the same size as the pick-up coil but with no sample

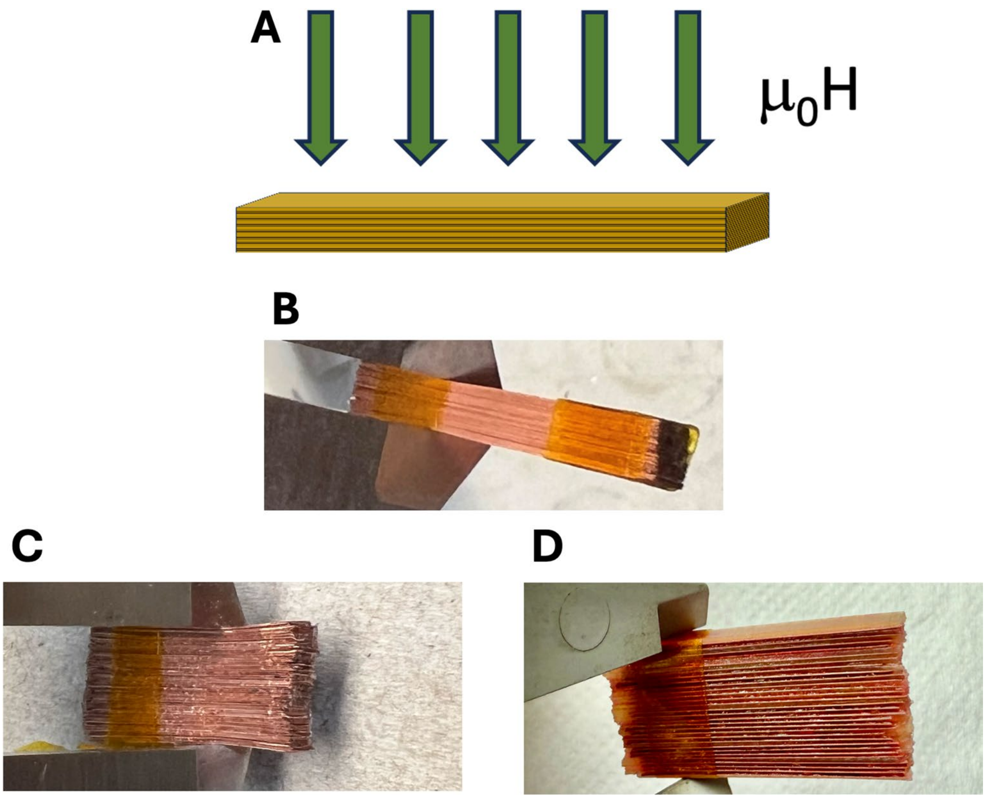

Fig. 1. Tape stack cable configurations and field orientation. (**A**) Schematic showing the applied magnetic field orientation perpendicular to the cable width and longitudinal axis. (**B**) 60-tape stack cable. (**C**) 60-tape stack cable with copper (Cu) spacers inserted between tapes. (**D**) 30-tape stack cable with G10 spacers inserted between tapes. These variations were used to evaluate the impact of inter-tape spacing on magnetization behavior.

Parameter	Value
Tape properties	
Tape thickness	~0.06 mm
Cu stabilizer thickness	10 µm
ReBCO thickness	1 µm
Tape width	4 mm
Substrate thickness (Hastelloy)	30 µm
Sample length	27 mm
Critical Current @77K and self-Field, I_c	100 A
Cable stack configurations	
60 tape stack (cable) sample thickness	3.90 mm
60 tape stack (cable) with Cu-spacers tape sample thickness	13.80 mm
30 tape stack (cable) with G10-spacers tape sample thickness	14.00 mm

Table 1. Physical and structural parameters of ReBCO tapes and tape stack cables.

inside) in anti-series with the pickup coil and measured the resulting voltage. In the absence of a sample inserted in the secondary, this nullifies the induced voltage. When a sample is placed in the pick-up coil, it disrupts the balance, causing a resultant voltage which can be integrated over time to determine the magnetic flux. This flux is then calibrated to obtain the magnetization, M, of the sample.

Calibration was accomplished by determining the demagnetization factor for the stacked tape cables, utilizing a well-established method[23–26].

Results

60-Tape Stack Cable (Sample A)

Magnetization measurements on sample A, the 60-tape stack, were performed at 4.2 K using field sweeps of ± 10 T, ± 20 T, and ± 25 T, with a consistent ramp rate of 10 T/min. Our results are shown in Fig. 2, normalized to cable volume (in this case, the same as the volume of tapes).

The full penetration field, B_p, for sample A (60 tapes, no spacers) was difficult to determine because of substantial flux jumping in the relevant region, although if we translate the initial curve for some of the measurements, we might estimate it as ~ 6 T. Flux jumps are clearly quite strong about the origin, but notably persist up to 17 T. The persistence of flux jumps up to 17 T was unexpected since this is not typically reported for ReBCO tapes, although see[27]. However, it can be remembered that B_p is proportional to sample thickness, rather than width, for thin single (stand-alone) coated conductors, and thus B_p is much lower than it would be expected for superconducting slabs with the same J_c, but much greater for thick ReBCO stacks. For thicker samples, it can be remembered that $B_p \propto J_c w$, where w is the tape width. In this case, then, the magnetization loop height, ΔM, will be much larger for the slabs than for the tapes, and because the tendency to flux jumping is proportional to the energy of flux motion during the thermomagnetic instability, which is $\propto \Delta M$, and thus it has been observed that flux jumping has an onset at a particular value of ΔM.

Several authors have shown that stacks of tapes behave somewhat similarly to thicker slabs of superconductor, and that, in particular, B_p grows with the number of tapes in a stack[2–4,15]. Essentially, when we stack many tapes together, the material acts like a slab conductor (with a J_c reduced by λ), and this tends to lead[28] to $B_{p,\,slab} = \mu_0 \lambda J_c w/2 = \mu_0 I_c/(2t_{tape})$. If we assume a 10 X increase in J_c when reducing to 4.2 K, and a 40% reduction going from 0 to penetration field, this leads to a $B_{p,\,slab} \cong 6.3$ T in the limit of a thick slab, which is much larger than would be found for an isolated tape, given by $B_{p,\,tape} = (5/2\pi)B_d[\mathrm{Ln}(w/t_{YBCO}+1)]$, where $B_d = 0.4\mu_0 I_c/w \cong 0.126$ T, such that $B_{p,\,tape} \cong 0.9$ T at 4.2 K. We might then expect a potential enhancement of flux jumping in stacks of ReBCO tapes for fields below the penetration field of the stack, namely $B_{p,\,slab} \cong 6.3$ T in our case. But in fact, we see flux jumping up to 17 T.

Different field ramp rate studies demonstrate that the flux jumps sustain to higher fields in the case of the slower ramp rates. Figure 3 shows all the different ramp rates, including 2.5, 5, 7.5, and 10 T/min. Slower ramp rates show flux jumps up to ~ 24 T, whereas for 10 T/min, it was up to ~ 17 T.

60-Tape Stack Cable with Cu spacers (Sample B)

A set of magnetization measurements were conducted on Sample B, a 60-tape stack cable incorporating Cu spacers (60 ReBCO tapes, 61 Cu spacers, stacked as Cu/ReBCO/Cu/ReBCO/Cu, etc.). As before, M-H measurements were performed at 4.2 K, employing field sweeps of ± 10 T, ± 15 T, ± 20 T, ± 25 T, and ± 30 T, with a consistent ramp rate of 10 T/min. The resulting magnetization data, normalized to total cable volume (ReBCO tapes + spacers), are presented in Fig. 4.

Sample B shows a markedly lower tendency to flux jump as compared to sample A. Here we can observe a B_p = 2.5 T and a corresponding magnetization, M_p, of 1350 kA/m. Flux jumps are seen only up to an applied field of 5 T, and they are much smaller in size than those of Sample A. We also note that little flux jumping occurs for M less than 1000 kA/m.

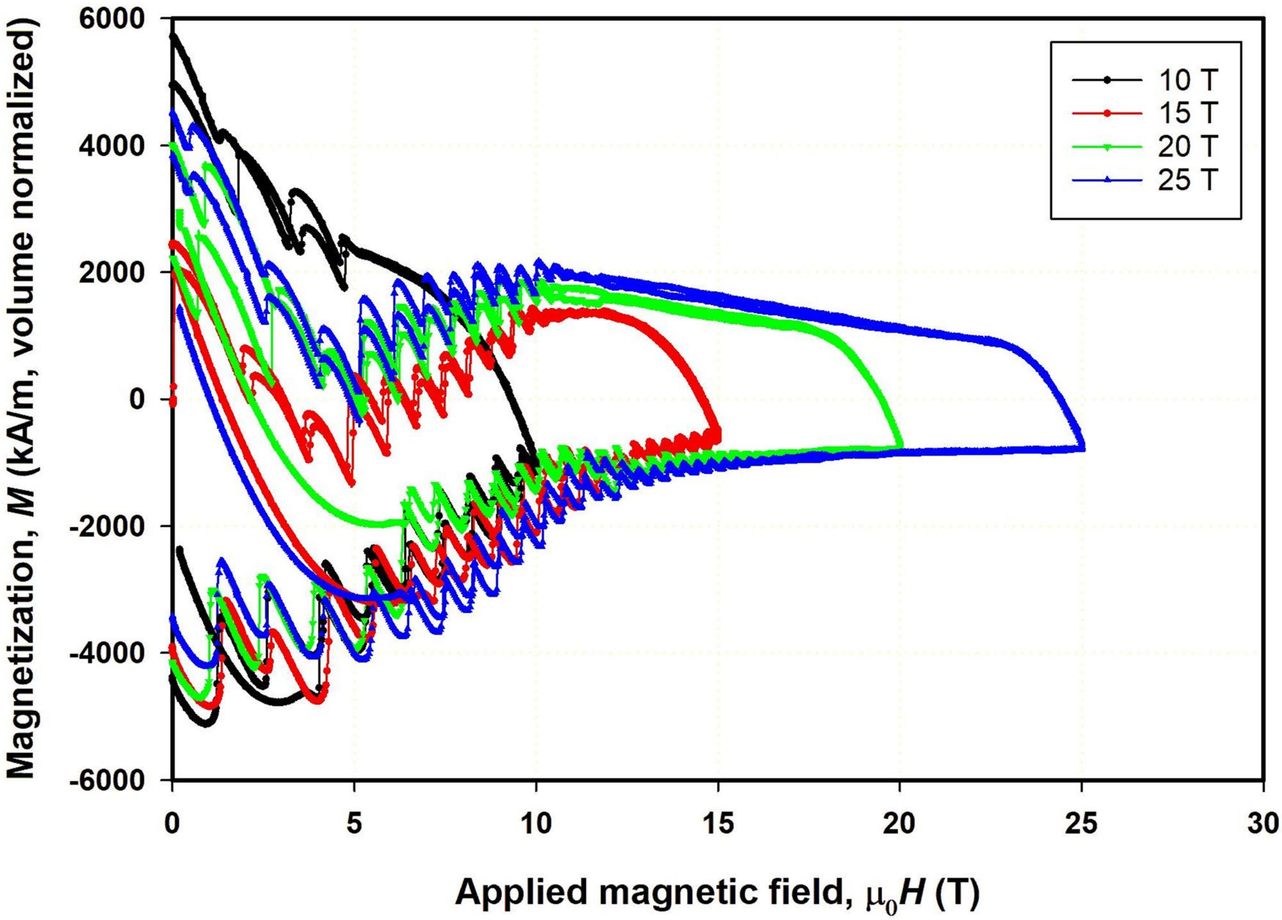

Fig. 2. Persistent flux jumps up to 17 T observed in a 60-tape ReBCO stack cable (Sample A). Magnetization (*M-H*) measured at 4.2 K under a perpendicular field (up to 25 T) reveals repeated instability events. The field was applied perpendicular to the width and length of the tapes within the cable. Magnetization is normalized to the total volume of the cable.

30-Tape Stack Cable with G10 spacers (Sample C)

A set of magnetization measurements were conducted on sample C, a 30-tape stack cable incorporating G10 spacers (30 ReBCO tapes, 31 G10 spacers). As before, *M-H* measurements were performed at 4.2 K, employing field sweeps of ± 10 T, ± 15 T, ± 20 T, ± 25 T, and ± 30 T, with a consistent ramp rate of 10 T/min. The resulting magnetization data, normalized to cable volume, are presented in Fig. 4 for the 30T run only, along with the data from Sample B. The results for lower amplitude sweeps were very similar (omitted for clarity).

Sample C exhibited a full penetration field, B_p = 1.5 T, and a corresponding magnetization, M_p, of 1050 kA/m, indicative of full flux penetration. No flux jumping was observed in this sample.

Discussion

Using the finite thickness superconductor model (see Eq. 65)[29], and "dilute" superconductor approximation[30], the penetration field for sample A was estimated to be $B_{p,\,A}$ = 6.3 T, while that for Sample B can be estimated (including the spacer thickness in the composite volume) as $B_{p,\,B}$ = 2.86 T. Using the same approach for Sample C we find $B_{p,\,C}$ = 1.4 T (no J_c field reduction assumed). The experimentally observed full penetration field is ~ 6 T (extrapolated) for Sample A, and 2.5 T and 1.5 T for Samples B and C, respectively. The maximum magnetization of Sample A, namely 5000 kA/m, is reduced to 2400 kA/m for Sample B and to 1400 kA/m for Sample C once we take the whole composite volume (including spacers) into account. We observe in all samples reduced flux jumping below magnetization values of ~ 1000 kA/m. This threshold was inferred from the analysis of the shielding branch of the *M-H* curves. The values vary in a range of 930 to 1150 kA/m, but the 15 T *M-H* curve is an outlier with a lower value of ~ 700 kA/m. The most significant error component was electronic drift. Once this was corrected for the magnetization reproducibility on repeated segments, it was up to 10%.

It is well established that flux jumps correlate with magnetization[20,21]. Additionally, increasing the separation between tapes tends to decrease the overall magnetization, likely due to reduced coupling within the stack[16,17]. In the case of widely spaced tapes, the magnetization behavior increasingly resembles that of individual tapes[16,17]. Consequently, greater tape separation results in lower magnetization[16,17], which, in turn, should allow for fewer flux jumps, an outcome that is evident experimentally. It is also possible that improved heat diffusion due to tape

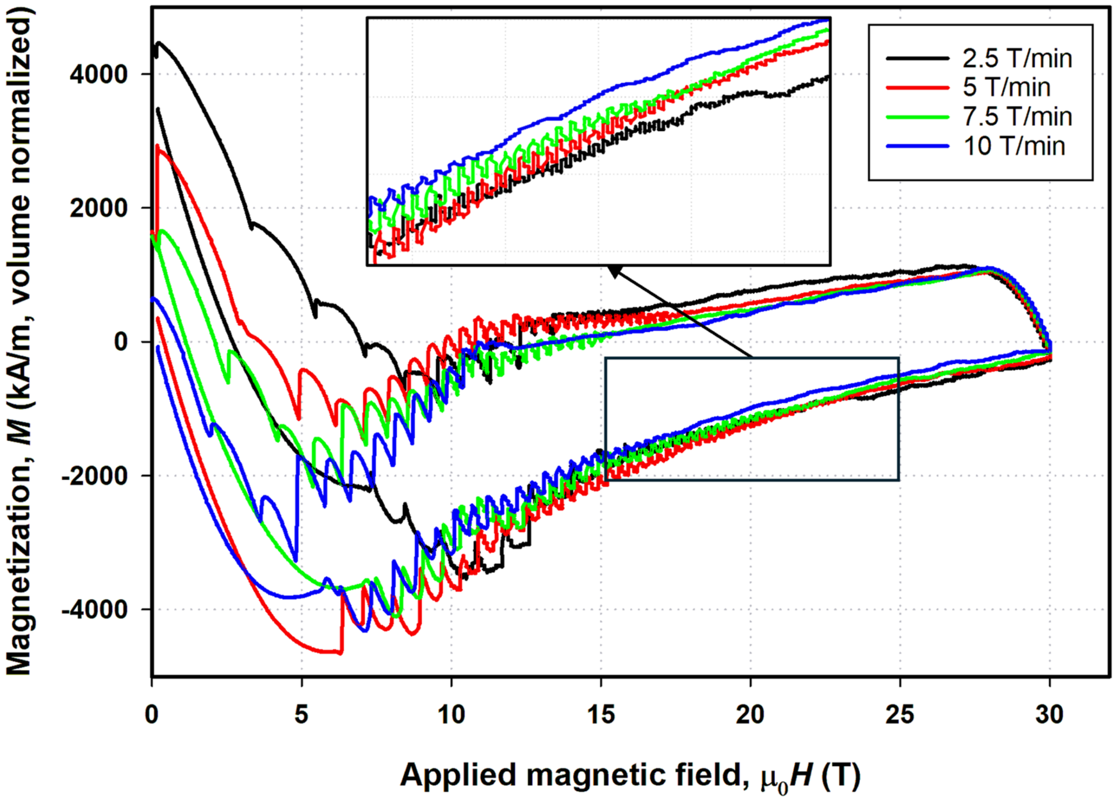

Fig. 3. Ramp rate dependent flux jumps persisting up to 23 T observed in a 60-tape ReBCO stack cable (Sample A). Magnetization (*M-H*) measured at 4.2 K under a perpendicular field (up to 30 T) reveals repeated instability events. The field was applied perpendicular to the width and length of the tapes within the cable. Magnetization is normalized to the total volume of the cable.

separation may be contributing to this reduction in flux jumping (i.e., dynamic stabilization[22]. The observation that both Cu and G10 spacers suppress flux jumping appears to support the idea that the effect is predominantly magnetization-driven rather than thermally driven.

In fact, we chose Cu and G10 as two different spacer materials because we wanted to investigate whether their thermal properties had any influence, but it appears that the tape-to-tape spacing is more critical. It remains true, however, that further modeling would be needed for a more definitive understanding.

Finally, we also note that flux jumping is known to scale with filament width, so here it is relevant for the perpendicular (face-on) orientation but would not be for the edge-on orientation. We performed such measurements on edge-on orientation and confirmed that no flux jump was observed. As noted above, we therefore expect flux jumps to disappear at some angle from perpendicular, and it would be interesting to determine the angle at which they vanish.

Conclusion

This work explores the magnetization of stacks of ReBCO tapes in magnetic fields up to 30 T in the configuration of a tape stack cable. In some samples, flux jumping was observed to persist up to 17 T and higher. Such effects are undesirable and can lead to unwanted signatures in transport properties and in the degradation of magnet field quality. In this work, the applied magnetic fields were perpendicular to the flat face of the tapes, and all measurements were performed at 4.2 K, with a ramp rate of up to 10 T/min. Magnetic fields were applied using a resistive magnet at the NMHFL in Tallahassee, and we employed a DC susceptometer approach with a compensator coil to measure the *M-H* curve of the samples. In our first sample (Sample A), which was a simple stack of 60 tapes, we observed both an increase in the penetration field (compared to the single tape) and the presence of flux jumping up to 17 T. A second sample (Sample B) was made with Cu spacers in between each ReBCO tape, and strong suppression of flux jumping was observed. A third sample (Sample C) was made with further increased inter-tape spacing, in this case with G10 spacers, and flux jumping was removed entirely. These results are directly relevant to the design of stable, high-field magnets, and particularly, those involved with either accelerator or fusion-related HTS magnets.

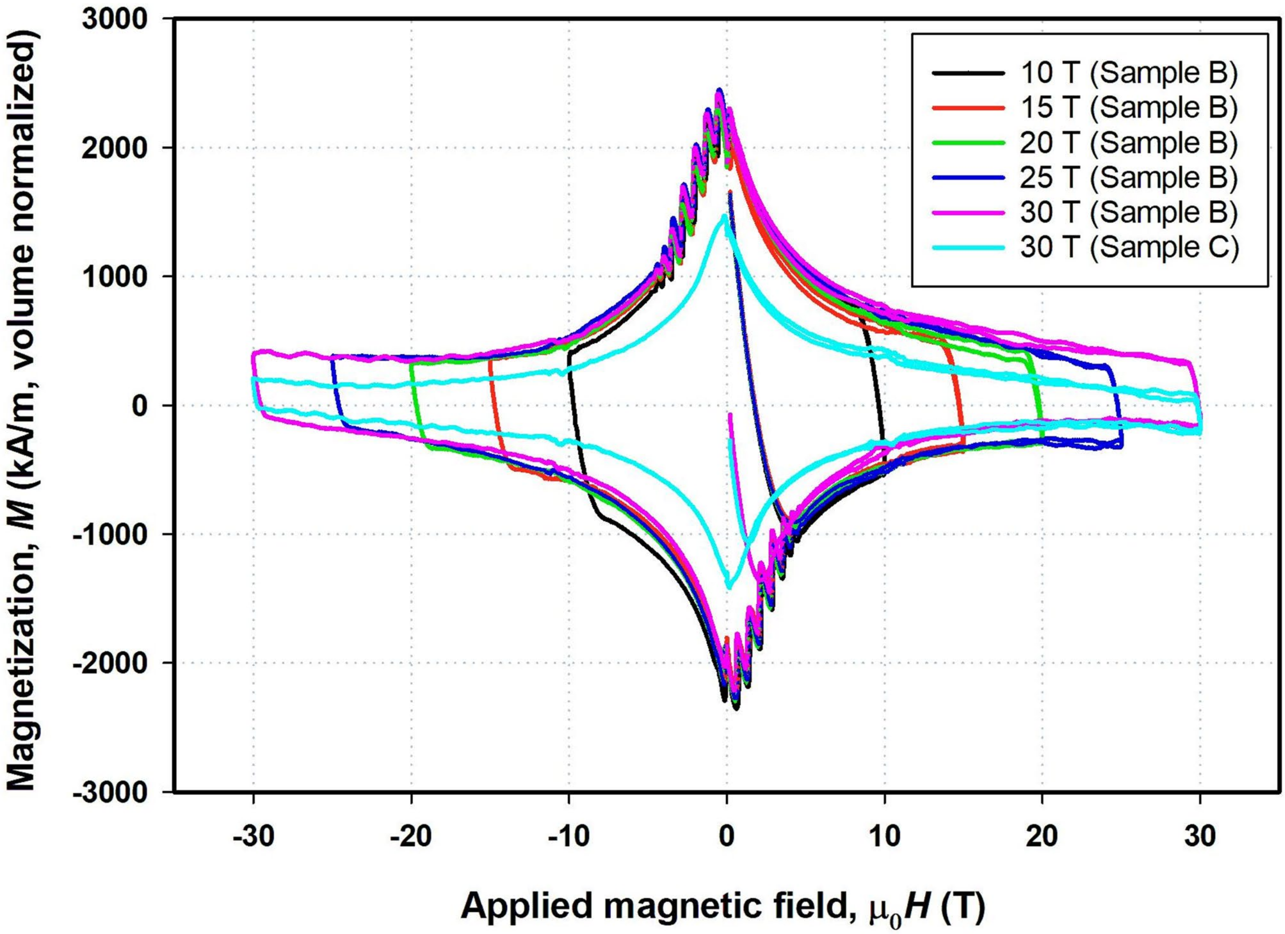

Fig. 4. Suppression of flux jumps in tape stack cables with inter-tape spacers. The *M-H* of sample B, a 60-tape stack cable with Cu spacers (marked as 10 T, 15 T, 20 T, 25 T, 30 T) and Sample C, a 30-tape stack cable with G10 spacers, each measured at 4.2 K, with a maximum applied magnetic field of 30 T perpendicular to the longitudinal axis of the cable and its width. Magnetization is normalized to the total volume of the cable.

Data availability

All data supporting the findings of this study are included within the manuscript.

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References

1. Larbalestier, D., Gurevich, A., Feldmann, D. M. & Polyanskii, A. High-Tc superconducting materials for electric power applications. *Nature* **414**, 368–377 (2001).
2. Mitchell, N. et al. Superconductors for fusion: a roadmap. *Supercond Sci. Technol.* **34**, 103001 (2021).
3. Fusion startup plans reactor with small but powerful superconducting magnets. https://www.science.org/content/article/fusion-startup-plans-reactor-small-powerful-superconducting-magnets
4. Molodyk, A. & Larbalestier, D. C. The prospects of high-temperature superconductors. *Science* **380**, 1220–1222 (2023).
5. Hahn, S. et al. 45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet. *Nature* **570**, 496–499 (2019).
6. Weijers, H. W. et al. Progress in the development and construction of a 32-T superconducting magnet. *IEEE Trans. Appl. Supercond.* **26**, 1–7 (2016).
7. Garg, T. et al. Magnetization in ReBCO-Based CORC cables in magnetic fields up to 30 T for accelerator applications. *IEEE Trans. Appl. Supercond.* **35**, 1–5 (2025).
8. Bykovsky, N., Marzi, G. D., Uglietti, D., Bruzzone, P. & Muzzi, L. Magnetization loss for stacks of ReBCO tapes. *Supercond Sci. Technol.* **30**, 024010 (2016).
9. Mawatari, Y. Critical state of superconducting strip array systems in perpendicular magnetic fields. *IEEE Trans. Appl. Supercond.* **7**, 1216–1219 (1997).
10. Kim, J. H., Kim, C. H., Patil, P., Kvitkovic, J. & Pamidi, S. Electrical characteristics of stacks of YBCO tapes in applied magnetic field. *IEEE Trans. Appl. Supercond.* **21**, 3230–3233 (2011).
11. Zhou, Q. et al. Analysis of AC loss characteristics of stacked High-Temperature superconducting tapes. *J. Electron. Mater.* **52**, 1154–1168 (2023).

12. Kvitkovic, J., Davis, D., Zhang, M. & Pamidi, S. Magnetic shielding characteristics of second generation high temperature superconductors at variable temperatures obtained by cryogenic helium gas circulation. *IEEE Trans. Appl. Supercond.* **25**, 1–4 (2015).
13. Kvitkovic, J., Davis, D., Zhang, M. & Pamidi, S. Influence of interlayer separation on magnetic shielding properties of 2G HTS sheets made of 46 mm wide rabits tape. *IEEE Trans. Appl. Supercond.* **23**, 8200605–8200605 (2013).
14. Ter Harmsel, J., Otten, S., Dhallé, M. & ten Kate, H. Magnetization loss and transport current loss in ReBCO racetrack coils carrying stationary current in time-varying magnetic field at 4.2 K. *Supercond Sci. Technol.* **36**, 015011 (2022).
15. Jiang, Z. et al. The dependence of AC loss characteristics on the space in stacked YBCO conductors. *Supercond Sci. Technol.* **21**, 015020 (2007).
16. Kwon, J., Ebbing, C., Haugan, T., Sumption, M. D. & Collings, E. W. AC loss measurements at high B, dB/dt for ReBCO tape stacks with various values of tape separation and loss in helically wound cables. *IEEE Trans. Appl. Supercond.* **35**, 1–6 (2025).
17. Panasyuk, G. Y. et al. AC loss modeling of Non-Standard arrangements of Y-Ba-Cu-O tapes in a stack. *IEEE Trans. Appl. Supercond.* **35**, 1–5 (2025).
18. Swartz, P. S. & Bean, C. P. A model for magnetic instabilities in hard superconductors: the adiabatic critical state. *J. Appl. Phys.* **39**, 4991–4998 (1968).
19. Wilson, M. N., Walters, C. R., Lewin, J. D., Smith, P. F. & Spurway, A. H. Experimental and theoretical studies of filamentary superconducting composites. *J. Phys. D*. **3**, 1517–1585 (1970).
20. Collings, E. W., Sumption, M. D. & Lee, E. Magnetization as a critical defining parameter for strand in precision dipole applications implications for field error and F-J stability. *IEEE Trans. Appl. Supercond.* **11**, 2567–2570 (2001).
21. Sumption, M. D. & Collings, E. W. Stability and flux jumping of Internal-Sn, Nb_3Sn conductors (and a model system MgB_2). *IEEE Trans. Appl. Supercond.* **13**, 3394–3397 (2003).
22. Wilson, M. N. *Superconducting Magnets. Ch. 7* (Oxford University Press, 1987).
23. Aharoni, A. Demagnetizing factors for rectangular ferromagnetic prisms. *J. Appl. Phys.* **83**, 3432–3434 (1998).
24. Beleggia, M., De Graef, M. & Millev, Y. Demagnetization factors of the general ellipsoid: an alternative to the Maxwell approach. *Phil. Mag.* **86**, 2451–2466 (2006).
25. Osborn, J. A. Demagnetizing factors of the general ellipsoid. *Phys. Rev.* **67**, 351–357 (1945).
26. Kiss, L. F. & Bakonyi, I. An update to the demagnetizing factor dataset calculated for the general ellipsoid by Osborn. *Magnetism* **4**, 173–182 (2024).
27. Jaroszynski, J. et al. Critical Current, lengthwise Fluctuations, and flux jumps in REBCO CC: A torque magnetometry study up to 45 T. (2025). arXiv:2502.02706.
28. Sumption, M. D. et al. AC loss and shielding in stacks of coated conductors: analytic modelling and comparison to experiment. *Cryogenics* **144**, 103963 (2024).
29. Brandt, E. H. Superconductors of finite thickness in a perpendicular magnetic field: strips and slabs. *Phys. Rev. B*. **54**, 4246–4264 (1996).
30. Yuan, W., Campbell, A. M. & Coombs, T. A. A model for calculating the AC losses of second-generation high temperature superconductor pancake coils. *Supercond Sci. Technol.* **22**, 075028 (2009).

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Declarations

Competing interests
The authors declare no competing interests.

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