Towards Uniform Trapped Field Magnets Using a Stack of Roebel Cable Offcuts

Tom B. Mitchell-Williams, Anup Patel, Algirdas Baskys, Simon C. Hopkins, Anna Kario, Wilfried Goldacker and Bartek A. Glowacki

Abstract—**Stacks of high temperature superconducting tape can be magnetized to produce a variety of different trapped field profiles in addition to the most common conical or pyramidal profiles. Stacks of tape using discarded Roebel cable offcuts were created to investigate various stacking arrangements with the aim of creating a stack that can be magnetized to produce a uniform trapped field for potential applications such as NMR. A new angled stacking arrangement proved to produce the flattest, most uniform field of all the overlapping stacking arrangements and has the potential to be scaled up. FEM modeling in COMSOL was also performed to complement the measurements and explain the limitations and advantages of the stacking arrangements tested.**

Index Terms— **Hall probe scans, Roebel cable, stack of HTS tapes, superconducting tapes.**

I. Introduction

Roebel cables have been demonstrated as an effective architecture for reducing AC losses in coated conductors (CC) [1], [2]. Low AC losses are required for applications such as superconducting transformers, motors/ generators and fusion power plant coils. However, manufacturing Roebel cables wastes approximately 50% of the CC material in the form of offcuts. The current work investigates using the offcut material to form trapped field magnets with uniform field profiles.

Uniform trapped fields are required for a new generation of small-scale NMR/MRI devices. Large-grain bulk superconductors can trap high magnetic fields and the profile can be adjusted using soft ferromagnetic materials [3]. The conical trapped fields produced by bulk superconductors, or stacks of tape where there is no misalignment between tape layers, is maximally non-uniform. This is due to the nature of macroscopic current loops circulating around the whole sample, throughout the sample cross-section, unlike the case of a permanent magnet, which can be described by an array of small current loops equivalent to only a *surface* current around the whole sample. Therefore, conventional bulk superconductors and the first stacks of tape created, although good at producing high fields, are fundamentally not suited to producing uniform trapped fields. However, ring shaped bulks and stacks of tape samples have been used to generate uniform fields in a similar manner to a coil. Hahn et al. have investigated the use of stacks of 40 mm square tape annuli with a 25 mm bore for use in a compact NMR device [4], [5] and similar experiments have also been done using bulk YBCO/GdBCO rings [6], [7]. An alternative approach, presented here, seeks to replicate the properties of permanent magnets using trapped field stacks of tape to generate uniform fields. Selva et al. have shown that stacked arrays of tape can yield more uniform trapped field profiles than previous stacks over a larger area [8] but clear undulations in the fields would be a problem for an NMR device. The purpose of the current work was to investigate new arrangements that are fundamentally better suited to producing more uniform trapped fields including a novel angled stack arrangement.

12 mm square stacks of superconducting tape have been established as efficient trapped field magnets with fields of up to 7 T recorded when field cooled due to the persistent currents set up in the tape layers [9]. They have also been shown to be advantageous compared to bulk superconductors when pulse magnetized at low temperature due to their improved thermal stability [10], [11].

II. Stacking Configurations

A. Superconducting Tape

Superconducting tape from SuperPower (12 mm wide, 0.096 mm thick, 325 A $I_{c,\text{self-field}}$) was used to make a Roebel cable. The offcuts stamped out during manufacture were trimmed to enable easy handling as shown in Fig. 1.

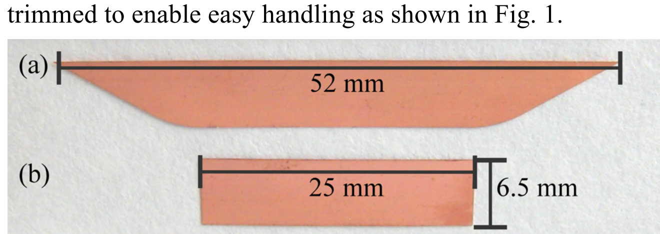

Fig. 1. Roebel cable offcut piece. (a) Before trimming and (b) after trimming.

This work was supported in part by the Engineering and Physical Sciences Research Council, U.K., and in part by SKF S2M, France.

Additional data related to this publication are available at the University of Cambridge data repository (https://www.repository.cam.ac.uk/handle/1810/250510).

T. B. Mitchell-Williams, A. Patel, A. Baskys, and S. C. Hopkins are with the Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB3 0FS, U.K. (e-mail: tbm23@cam.ac.uk).

A. Kario and W. Goldacker are with the Karlsruhe Institute of Technology, Institute for Techinical Physics, D-76344 Eggenstein-Leopoldshafen, Germany.

B. A. Glowacki is with the Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB3 0FS, U.K., with the Department of Physics and Energy, University of Limerick, Plassey, Ireland, and also with the Institute of Power Engineering, 02-981 Warsaw, Poland.

B. Stacking Configurations

The offcut pieces were stacked in 5 different arrangements as shown schematically in Fig. 2. with the new angled arrangement shown in Fig. 2.(e). The cross sections in Fig. 2 are representative for the full length of the tape pieces, i.e. there is no transposition just stacked tape pieces.

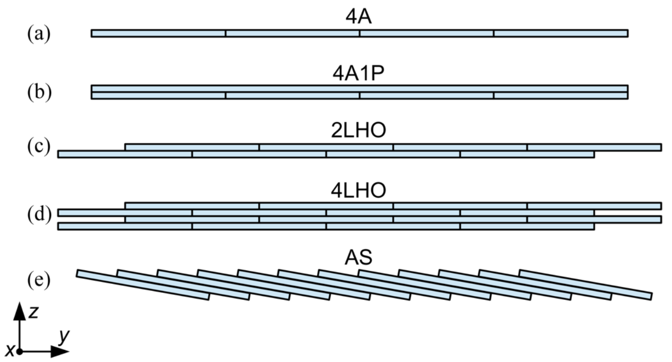

Fig. 2. Schematic of tape stacks in cross section, not to scale. The majority of the tape pieces had their thickness parallel to *z*, their width parallel to *y* and length parallel to *x*. The primary Hall scan direction was parallel to *y*. (a) 4 adjacent pieces, (b) 4 pieces with 1 perpendicular, (c) 2 layers half offset, (d) 4 layers half offset, (e) angled stack. The angled stack was made of 27 tape pieces, each offset by 1 mm relative to adjacent pieces.

The trapped field profile for a rectangular piece of tape is approximately a triangular prism, with good uniformity parallel to the long axis [12]. Therefore, the interest was to find a stacking arrangement that extended the uniformity in the direction parallel to the tape width (in the *y* direction). Hence, configurations using overlapping tape pieces to smooth out the profile were investigated in an attempt to replicate the array of magnetic dipoles responsible for permanent magnet fields.

The flats stacks, Fig. 2(a)-(d), were held in place during cooling, magnetization and measurement using Kapton® tape and vacuum grease. The angled stack, Fig. 2.(e), was made from 27 pieces of tape and constructed using a custom-built aluminum holder. The tape pieces were offset by 1 mm with respect to their neighbors and the pieces were at an angle of 5.7° to the horizontal.

III. Experimental Trapped Field Results

A. Scanning Hall Probe Magnetometry

The tape stacks were zero-field-cooled to 77 K in liquid nitrogen before being magnetized using an applied field of 0.20 T ramped at a rate of 6.25 mT s^{-1}. The trapped field profiles were characterized using scanning Hall probe magnetometry. The Hall probe (Toshiba THS118) was scanned using a bespoke stage controlled by in-house software. The probe control current was nominally 5 mA and the sensitivity 1.18 V T^{-1}. The scan was started 300 s after magnetization to ensure flux creep did not significantly affect measurements. The trapped field was measured 2.15 mm above the sample surface. The scan step size was 0.25 mm in the *y* direction and 0.5 mm in the *x* direction.

B. Trapped Field Profiles

To quantify the uniformity of the trapped magnetic field a 'Profile Roughness' (R_{rms}) metric was developed. This was calculated in an analogous way to root-mean-square surface roughness for materials and gave a measure of the average variation away from the mean trapped field; the mathematical definition of this metric is in the Appendix. The ratio of the roughness to the mean trapped field was used to compare the relative roughness of stacks containing different numbers of tape pieces. The results for each of the stacking configurations are summarized in Table I.

With no overlap between adjacent pieces as for sample 4A, the trapped magnetic field profile had a pseudo-sinusoidal

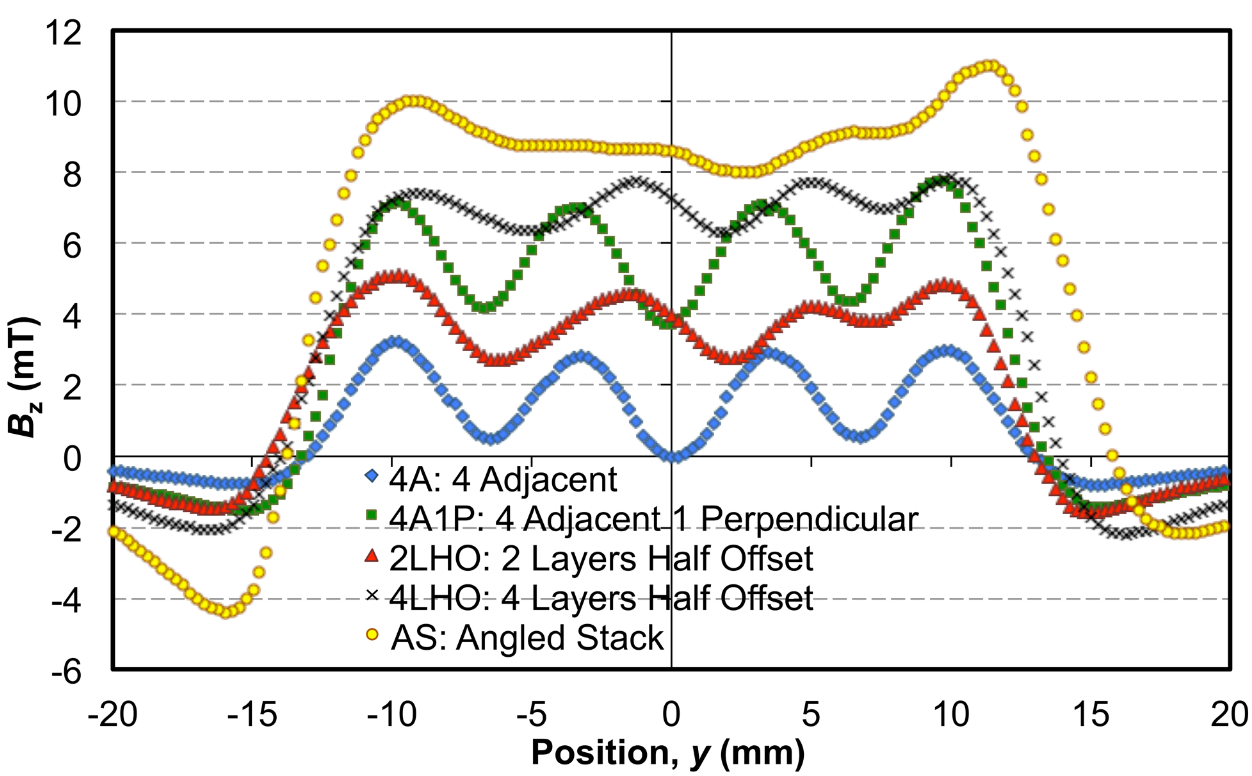

Fig. 3. Trapped magnetic field profiles for each of the stacking configurations. The field was measured 2.15 mm above the top surface of the stacks.

TABLE I
TRAPPED FIELD PROFILE ROUGHNESS DATA

Sample	Mean Trapped Field, B^* (mT)	Profile Roughness, R_{rms} (mT)	Ratio, R_{rms}/B^* (%)
4A	1.73	1.00	57.7
4A1P	5.80	1.14	19.7
2LHO	3.73	0.39	15.8
4LHO	7.04	0.49	7.0
AS	8.52	0.31	3.7

Details of how data were sampled for mean and roughness calculations are in the Appendix.

shape as can be seen in Fig. 3. The peaks corresponded to the center of the tape pieces and the troughs to the edges. When a tape piece was added with the long axis parallel to the scanning direction, as for sample 4A1P, the magnitude of the trapped field increased but the amplitude of the variation across the sample remained similar. In contrast when 2 layers of tape were offset by half a tape width, sample 2LHO, the mean trapped field was not increased as significantly but the profile was smoother. Adding an additional 2 layers to form configuration 4LHO resulted in a similar R_{rms} to 2LHO but an increased trapped field. The angled stack, AS, had the highest trapped field and smoothest profile.

The undulations seen in the 2LHO and 4LHO have 2 primary contributions; the relative height difference of the offset layers and small misalignments and nonuniformities in the tapes. Although the latter contribution has the potential to be eliminated, the former, however, is a fundamental feature of the stacking arrangement and will always lead to some profile undulation as discussed through modeling in the next section.

The dip in the field profile at +3 mm in Fig. 3. for AS is likely to be caused by a local defect in one of the tape pieces. It was found during preliminary tests that some of the individual offcut pieces had defects that reduced the field they were able to trap. It has been found in previous work that the effect of defects in individual layers tend to be averaged out when stacked simply [13]. However, for the stacks reported here, discrepancies between tapes are not as readily smoothed out due to the spatial offset each tape has relative to adjacent pieces.

The field profiles in the x direction (parallel to the tape axis) for a small central region of the stacks were also measured. The size of the scanned region in the x direction was limited to 5 mm. Complete profile mapping will be conducted along with flux creep experiments as part of a future study. Nevertheless, the expected high uniformity of the field profile over the region scanned was seen with a profile roughness of <0.14 mT for the angled stack, corresponding to a relative roughness of <1.6%.

IV. COMPARISON WITH MODELING RESULTS

A. Modeling Framework

Time independent FEM modeling was conducted in COMSOL Multiphysics 5 using the AC/DC module and a stationary study. The simple approximation of uniform surface currents was used to simulate the superconducting surfaces on domains of the same cross-sectional dimensions as the real tape pieces. The models were 2D considering changes only in the yz plane shown in Fig. 2., assuming no variation in the x direction, which is a good approximation for our region of interest. Although uniform surface currents may seem an oversimplification, it is an important first step for investigating the parameters that affect the trapped field profiles. Preliminary models simulating $I_c(B,\theta)$ of the tapes showed 9.6% lower profile roughness compared to the uniform case. More extensive time-dependent critical state modeling as in [10] is currently underway to investigate the effect of J_c anisotropy on field profiles and the evolution of current density during magnetization. However, these models take a long time to solve and are often unstable due to the relatively high number of mesh elements and complex geometry. They will be reported in detail in a future publication.

B. Modeling Results

It was found that the measurement height had a significant effect on the field profile and corresponding roughness as can be seen in Fig. 4.

The modeling showed that the asymmetries and regular undulations present in the 2LHO and 4LHO configurations are inherent to the arrangements rather than purely due to nonuniformities and misalignments. For example, the asymmetry in the peak at +5 mm in sample 2LHO and 4LHO appear in the modeled profile too. The lower relative roughness for 4LHO compared to 2LHO suggested that more layers would lead to a smoother profile. This was confirmed by simulating an 8 layer stack (8LHO), which showed a lower relative roughness than either 4LHO or 2LHO.

However, the undulations are still present due to the difference in height each layer is away from the measurement plane. The undulations only disappear if the layers are infinitesimally thin. When the trapped field was measured above the top surface of the stack the layers closer to the measurement plane contributed more strongly than the layers further away. Hence each pair of layers did not fully cancel out each peak and trough. The advantage of the angled stack configuration is that it avoids this problem because in the central region each of the tapes contribute equally to the field profile. It can be seen that the angled stack arrangement has the advantage of a smoother profile for a similar number of tapes.

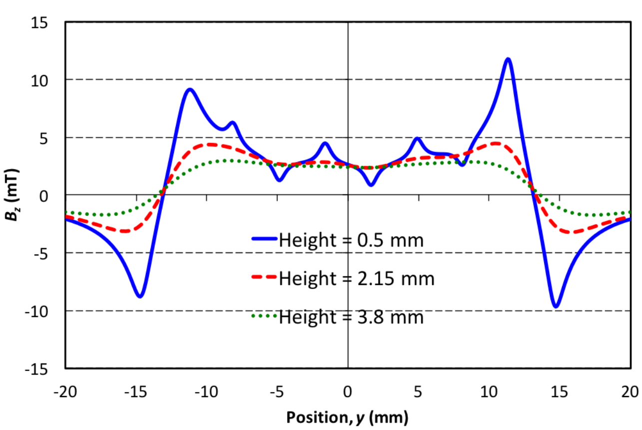

Fig. 4. Simulated field profiles for 2LHO tape stack arrangement at different heights above the sample surface. The roughness is strongly dependent on the measurement height.

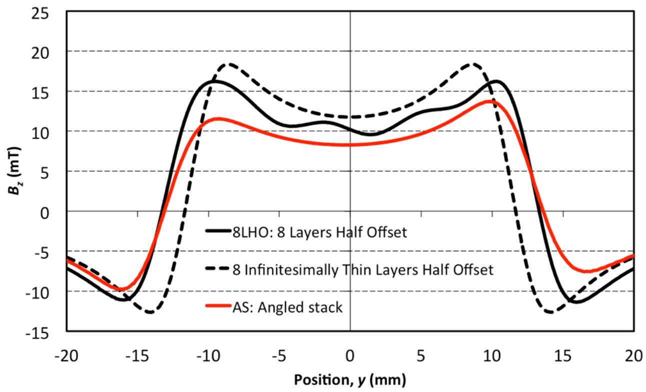

Fig. 5. Simulated trapped field profiles for an 8 layer half offset stack (8LHO) and an angled stack equivalent to AS. Also the profile for a half offset configuration with each of the layers infinitesimally thin. All profiles are for a measurement height of 2.15 mm.

The angled stack field profiles also show height dependence, as can be seen in Fig. 6, but the roughness drops off much more rapidly away from the surface than for LHO stacks. The simulated magnetic field distributions for the angled stack and 8LHO arrangements are shown in Fig. 7.

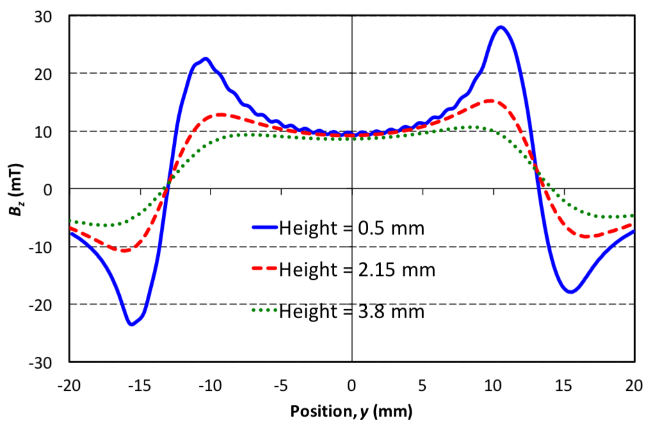

Fig. 6. Simulated trapped field profiles at different measurement heights for an angled stack equivalent to AS.

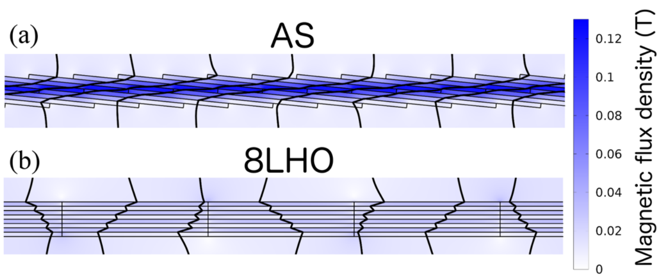

Fig. 7. Simulated magnetic field distribution plots for (a) the angled stack and (b) 8 layers half offset configurations. Only the central region is shown for clarity. The field lines bend significantly within the stacks.

V. Summary

Superconducting tape offcuts from the production of a Roebel cable were stacked in different configurations and magnetized at 77 K. The trapped magnetic field profiles were mapped using Hall probe magnetometry. The uniformity of the field profiles for the new tape stacks were quantified and compared. It was shown that more uniform field profiles could be achieved by adjusting the stacking arrangement, with the most successful being an angled stack. Comparison with finite element modeling results demonstrates the inherent advantages of the angled stack configuration.

Further work will be conducted with 12 mm wide tape pieces to improve the magnitude and uniformity of the trapped field profiles for angled stacks as well as more modeling to explore the performance limits of these stacks. Self-supporting angled stacks will be constructed using solder coated tape and efforts made to significantly reduce the roughness ratio. Also, the effect of layers of soft ferromagnetic material on the shape and magnitude of the field profile will be investigated in addition to flux creep measurements.

Appendix

The profile roughness, R_{rms}, and mean trapped field, B^*, were calculated in the following way. The data were selected from a central region to avoid the end-effect peaks dominating the result. The regions of interest are shown in Fig. 8. The mean trapped field and roughness were calculated using data between Y_s and Y_f in the region marked αL in Fig. 8. In the current work $\alpha = 0.5$. The mean trapped field, B^*, for the n data points between Y_s and Y_f is given by (1).

$$B^* = \frac{\sum_i^n B_i}{n} \tag{1}$$

Where B_i is an individual data point in the sampled region. The profile roughness, R_{rms}, is given by (2).

$$R_{rms} = \sqrt{\frac{\sum_i^n (B_i - B^*)^2}{n}} \tag{2}$$

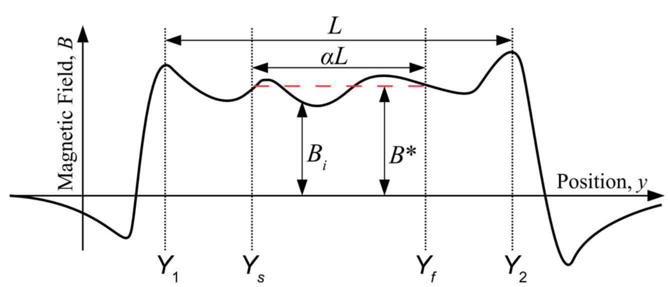

Fig. 8. Schematic magnetic field profile showing the data range sampled. Y_1 and Y_2 correspond to the positions of the end-effect peaks. Data between Y_s and Y_f were used for analysis. The mean trapped field, B^*, is for the data sampled. In the current work alpha = 0.5.

References

[1] W. Goldacker, R. Nast, G. Kotzyba, S. I. Schlachter, A. Frank, B. Ringsdorf, C. Schmidt, and P. Komarek, "High current DyBCO-ROEBEL Assembled Coated Conductor (RACC)," *J. Phys. Conf. Ser.*, vol. 43, pp. 901–904, 2006.

[2] W. Goldacker, F. Grilli, E. Pardo, A. Kario, S. I. Schlachter, and M. Vojenčiak, "Roebel cables from REBCO coated conductors: a one-century-old concept for the superconductivity of the future," *Supercond. Sci. Technol.*, vol. 27, no. 9, p. 093001, 2014.

[3] M. P. Philippe, M. D. Ainslie, L. Wéra, J.-F. Fagnard, A. R. Dennis, Y.-H. Shi, D. A. Cardwell, B. Vanderheyden, and P. Vanderbemden, "Influence of soft ferromagnetic sections on the magnetic flux density profile of a large grain, bulk Y–Ba–Cu–O superconductor," *Supercond. Sci. Technol.*, vol. 28, no. 9, p. 095008, 2015.

[4] S. Hahn, S. B. Kim, M. C. Ahn, J. Voccio, J. Bascunan, and Y. Iwasa, "Trapped field characteristics of stacked YBCO thin plates for compact NMR magnets: Spatial field distribution and temporal stability," *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 1037–1040, 2010.

[5] S. Hahn, Y. Kim, J. P. Voccio, J. Song, J. Bascuñán, M. Tomita, and Y. Iwasa, "Temporal Enhancement of Trapped Field in a Compact NMR Magnet Comprising YBCO Annuli," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 3–7, 2014.

[6] S. Kim, T. Nakano, R. Takano, and S. Y. Hahn, "Study on trapped field characteristics of HTS bulk annuli with iron rings for ferromagnetic shimming of a compact NMR magnet," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 2273–2276, 2009.

[7] T. Nakamura, D. Tamada, Y. Yanagi, Y. Itoh, T. Nemoto, H. Utumi, and K. Kose, "Development of a superconducting bulk magnet for NMR and MRI," *J. Magn. Reson.*, 2015.

[8] K. Selva and G. Majkic, "Trapped magnetic field profiles of arrays of (Gd, Y)$Ba_2Cu_3O_x$ superconductor tape in different stacking configurations," *Supercond. Sci. Technol.*, vol. 26, no. 11, p. 115006, 2013.

[9] A. Patel, K. Filar, V. I. Nizhankovskii, S. C. Hopkins, and B. A. Glowacki, "Trapped fields greater than 7 T in a 12 mm square stack of commercial high-temperature superconducting tape," *Appl. Phys. Lett.*, vol. 102, no. 10, pp. 1–6, 2013.

[10] A. G. Page, A. Patel, A. Baskys, S. C. Hopkins, V. Kalitka, A. Molodyk, and B. A. Glowacki, "The effect of stabilizer on the trapped field of stacks of superconducting tape magnetized by a pulsed field," *Supercond. Sci. Technol.*, vol. 28, no. 8, p. 085009, 2015.

[11] A. Patel, S. C. Hopkins, and B. A. Glowacki, "Trapped fields up to 2 T in a 12 mm square stack of commercial superconducting tape using pulsed field magnetization," *Supercond. Sci. Technol.*, vol. 26, pp. 1–7, 2013.

[12] A. Patel, A. Baskys, S. C. Hopkins, V. Kalitka, A. Molodyk, and B. A. Glowacki, "Pulsed-Field Magnetization of Superconducting Tape Stacks for Motor Applications," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1–5, 2015.

[13] A. Patel, A. Usoskin, A. Baskys, S. C. Hopkins, and B. A. Glowacki, "Trapped Field Profiles for 40-mm Wide Superconducting Tape Pieces," *J. Supercond. Nov. Magn.*, vol. 28, pp. 397–401, 2014.