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# Pulsed Field Magnetization of Superconducting Tape Stacks for Motor Applications

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***Abstract*— The potential of (RE)BCO superconducting bulks in rotating machine designs has been explored through numerous experimental prototypes with the bulks being magnetized to act as field poles. However stacks of superconducting tapes have emerged as a promising alternative for trapped field magnets partly because of their suitability for the pulsed field method of magnetization which is considered the most practical method of trapping flux. The benefits of using a stack of tapes as rotor field poles suitable for motors is reported. The ability to have a long rectangular stack allows for motor designs with more efficient field poles in terms of flux produced per unit area of the pole as well as easy scalability. Such a rectangular stack was magnetized experimentally for the first time using a race-track shaped pulsed field coil giving a highly uniform and well defined trapped field. The unique self-supporting 120 mm by 12 mm stack was produced by compressing HTS tape coated with a thin layer of solder. Shorter rectangular stacks were pulse magnetized over a temperature range of 10 – 77 K using a fully automated pulsed magnetization system.**

***Index Terms*—Superconducting tape, trapped field magnet, pulsed field magnetization, superconducting motor**

## I. Introduction

Stacks of superconducting tape acting as composite bulks have been proven to have excellent field trapping ability making them a promising choice for high field permanent magnets in applications such as motors and generators. A surface trapped field of 2 T has previously been achieved for a 12 mm square stack using the practical pulsed field method of magnetization [1] and over 7 T between two stacks using the field cooling method [2]. In both cases standard commercially available 2G HTS tape was used.

Various geometries of stacks of tape can be used depending on the application. 40 mm tape squares with round holes have been previously been stacked and magnetized for an NMR prototype [3] and similar sized stacks have been explored as permanent magnets [4]. The uniformity of $J_c$ for stacks of tape, their thermal stability at low temperatures and falling cost, give them a number of advantages over conventional bulk superconductors for trapping field. There is also greater flexibility in geometry. For many applications, trapped flux is as important as trapped field and therefore the greater the surface area of a trapped field magnet, the more practical it is for applications. For tape stacks, the two options for increasing trapped flux are to use larger width tape, e.g. 40 mm, or to use rectangular stacks of more commonly produced 12 mm wide tape which is the focus of the present study.

### *A. Motor concept using rectangular field poles*

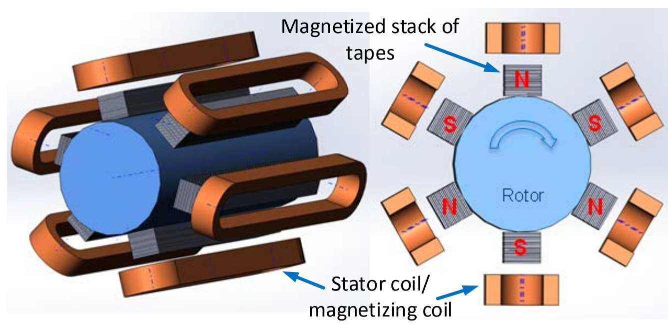


Fig. 1. Conceptual drawing of a motor using rectangular stacks of tapes as field poles on the rotor, magnetized by race-track copper coils on the stator which also act as the motor's stator coils during operation.

Superconducting coils and bulks have been used in numerous motor and generator prototypes [5] in order to increase power and torque density. A prototype machine has been previously created showing that trapped field magnets have the potential to be used as field poles on the rotor of a motor/generator [6]. This prototype of an axial gap-type synchronous motor/generator used GdBCO bulks on the rotor, magnetized by copper stator coils. The radial gap-type concept proposed in this paper follows a similar theme and is illustrated in Fig. 1. Rectangular stacks or tape are arranged on the rotor and magnetized by copper race-track shaped pulsed field coils, which also act as stator coils during normal operation. Rectangular stacks are more efficient in terms of trapped flux than an array of circular bulks for radial gap-type machines and allow scalability by increasing the rotor length. They also do not suffer as much from cross-field demagnetization experienced by bulks in rotating machines [7]. The exact arrangement of the components, and the performance expected for the new concept, will form the basis of a future study.

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### *B. Superconducting tape specifications*

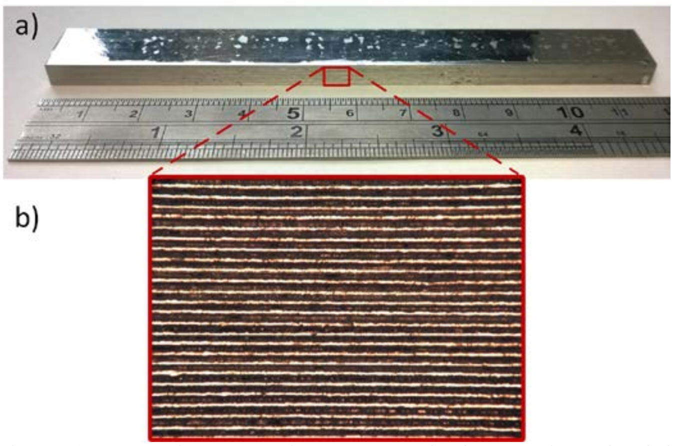


Fig. 2. (a) 12 mm by 120 mm by 5.2 mm stack of 60 tape layers bonded together by heating and compressing the stack whose layers have been pre-coated solder. (b) Zoomed image showing uniformity of layers from the side of the stack.

The 12 mm wide tape used for all the stacks in this paper was produced by SuperOx and had a nominal $I_c$ rating of 400 A at self-field and 77 K. The tape produced by IBAD consisted of a 65 µm Hastelloy substrate, and a top and bottom stabilizing layer of 1 µm of silver. SuperOx solder plated tape, produced by passing the tape through a bath of molten solder, was also used for the 120 mm long stacks. This tape had an additional 5 µm of copper on the top and bottom and a 10 µm PbSn solder layer also on both the top and bottom giving a total tape thickness of approximately 95 µm. The stacks made from the soldered tape were compressed and then heat treated at 210 ˚C for 45 minutes resulting in bonding of the layers and expulsion of approximately 30% of the solder without degradation of the superconducting properties. Fig. 2 shows the finished soldered stack which has high geometric tolerance. More details of the method for creating these soldered self-supporting stacks can be found in [8]. The stacks using unsoldered tape were simply stacked in a sample holder and lightly compressed for measurements.

## II. Field Cooling Magnetization of Rectangular Stacks

### *A. Trapped field profiles*

The first step in charactering the potential of any stack of tapes is to perform field cooling magnetization of a single layer or a few layers as this is a simplest method of saturating tape layers and observing their trapped field profile. Field cooling was performed on a single layer and a 15 layer stack, both cut from unsoldered tape with an aspect ratio of two. The samples were cooled with liquid nitrogen, in the presence of a strong permanent magnet. The magnet was then removed slowly, inducing currents in the tape layers, following by scanning Hall probe microscopy. The trapped field profiles shown in Fig. 3 show that the current paths follow the rectangular geometry giving rise to a pyramidal shaped trapped field with a peak of 163 mT for 15 layers. It is also clear to see that a stack of even just 15 layers is enough to smooth out non-uniformities and random variations present in individual layers. This is an important point as it is a very attractive property for engineering applications for the trapped field to be predictable and uniform which is the case for a stack of many tapes.

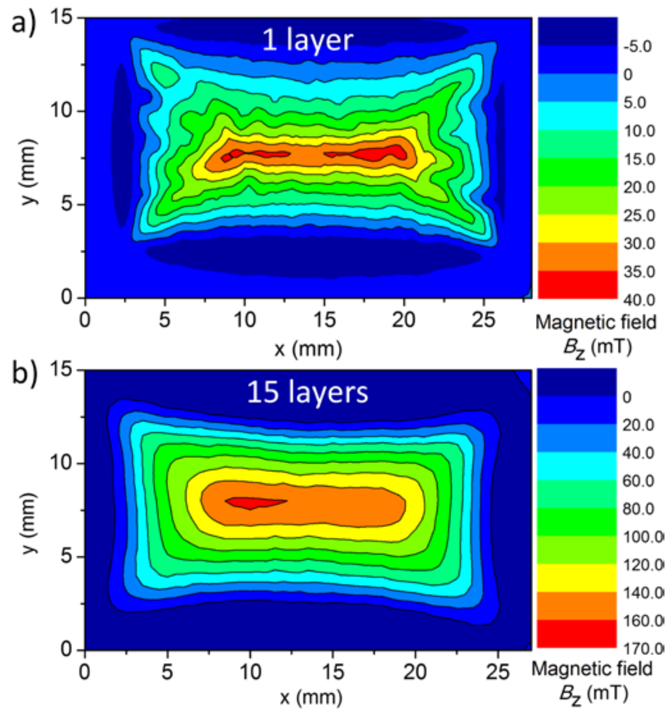


Fig. 3. (a) Trapped field for a single layer and (b) 15 layer stack, composed of 12 mm by 24 mm tape rectangles. Magnetized using field cooling at 77.4 K showing a relatively symmetric profile. The field was measured 0.8 mm above the sample surface in both cases.

### *B. Flux creep for a 5 layer stack at 77 K*

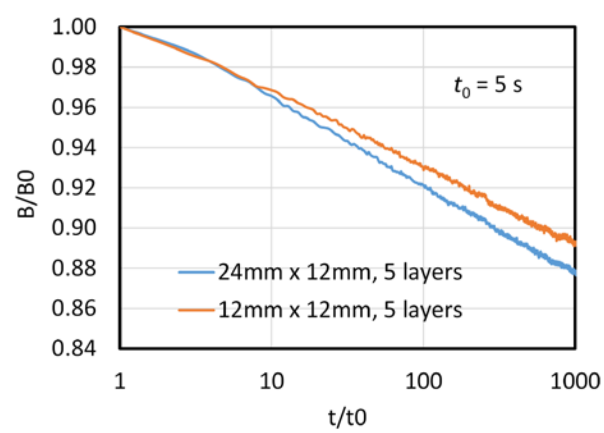


Fig. 4. Flux creep data for a square and rectangular stack of tapes magnetized by field cooling at 77.4 K. The initial trapped field $B_0$ is 74 mT and 64 mT for the rectangular and square stack respectively.

A simple flux creep measurement was performed to confirm that the creep rate for a rectangular stack was acceptable. Following field cooling magnetization at 77.4 K achieved with a permanent magnet, the decay in the trapped field for a 5 layer rectangular and square stack was recorded. Fig. 4 shows the central trapped field decaying logarithmically as expected with only a marginal increase in the magnitude of the creep

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rate for the rectangle. Defining creep rate $S$ by $B(t)/B_0 = 1 + S\ln(t/t_0)$, $S$ = -0.019 for the rectangular stack which is on the lower end of the values expected for a bulk and so is acceptable. It has been shown that this creep rate is dramatically reduced for temperatures lower than 77.4 K [2] which in addition to increased $J_c$, is another reason to operate a machine below 77.4 K.

## III. Pulsed Field Magnetization of Rectangular Stacks

The pulsed field magnetization method was applied on the stacks as this is the most practical method of magnetization and is particularly suited to stack of tapes due to their high thermal stability originating from metallic components. The IMRA method was used by applying a series of pulses with reducing amplitude [9]. The pulse duration was 28 ms.

### *A. 12 mm by 24 mm stacks in a solenoid coil*

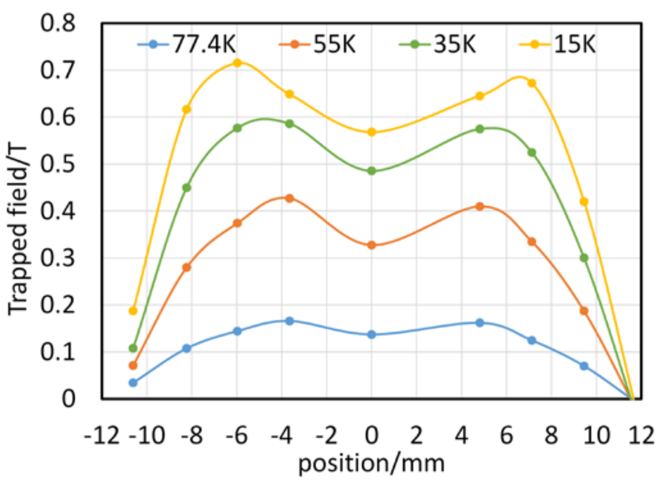


Fig. 5. Trapped field profiles for 15 layer stack composed of 12 mm by 24 mm tape layers. Pulsed field magnetization was used with a sequence of pulses applied at each temperature stage followed by cooling to the next temperature stage, allowing the maximum possible trapped field for pulsed magnetization to be established.

The same 15 layer stack made from unsoldered tape as field cooled in Fig. 3, was pulse magnetized using a solenoid pulsed field coil connected to a capacitor bank. A fully automated pulse sequence was then delivered to the stack which was cooled indirectly with helium gas to a range of temperatures in a Variox Oxford Instruments cryostat. The software automation of the pulsed magnetization process is an important step towards using this method in real applications. The complete system was the same as that used for the original 2 T trapped field study [1] with the full details of the system given elsewhere [10]. After magnetizing at a certain temperature, the sample was cooled down to the next temperature stage for further pulses to be delivered. The starting fields for the sequence of pulses applied for the temperature stages 77.4 K, 55 K, 35 K and 15 K were 1.3 T, 2.9 T, 3.4 T and 3.5 T respectively. This represents an MPSC sequence [9]. These fields were chosen to try and fully penetrate the sample and the resulting trapped fields at the end of each temperature stage are shown in Fig. 5. The reduction in temperature allowed the stack, which is only 0.95 mm thick, to trap an impressive field of 0.72 T at 15 K. It should be noted that a separate test on15 square layers of the same tape, using the applied field, gave a peak trapped field of 0.75 T at 15 K. This is very similar to the rectangular stack but the field profile for the square stack was a standard triangular/pyramidal shape.

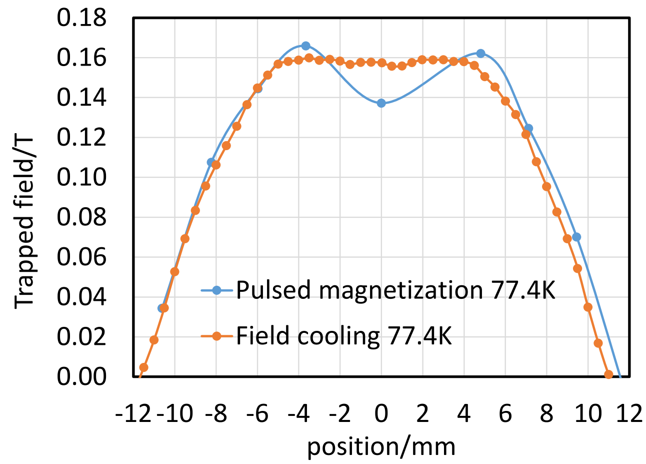


Fig. 6. Comparison of the trapped field profiles for the 15 layer, 24 mm by 12 mm stack, resulting from field cooling and pulsed field magnetization at 77.4 K. Although pulsed magnetization gives a similar peak trapped field, it gives rise to a dip in the central field.

The most interesting feature of Fig. 5 is the dip in the central field seen for all temperatures. This is not because the applied pulsed fields were too low, as separate tests using high applied fields confirmed that the profiles shown are the maximum fields you can trap in the sample using pulsed magnetization. Comparing the data for the 77.4 K stage to a cut of the field cooling data in Fig. 3 (b), shows in Fig. 6 that at this temperature, the peak trapped field is the same but noticeably lower in the sample center for pulsed magnetization. There are clearly some unwanted dynamics associated with rapidly applying a symmetric field of a cylindrical solenoid coil to an asymmetric rectangular sample. The next section shows that this effect is not present if applying the pulsed field with a racetrack shaped coil which is more naturally suited to the geometry of a rectangular sample.

### *B. 12 mm by 120 mm stacks in race-track pulsed field coil*

In order to determine whether rectangular stacks could be magnetized using a pulsed field resulting in a fully saturated profile like that shown in Fig. 3 (b), a stack with an extreme aspect ratio of 10 was created from the solder plated tape as shown in Fig. 2. In order to magnetize this stack, a race-track shaped pulsed field coil was wound as shown in Fig. 7, using 1.4 mm diameter copper wire, with 7 layers and having an inductance of 0.72 mH. S2 glass fiber cloth was used between the coil layers and externally to reinforce the coil together with Stycast resin impregnation. This allows the coil to pulse field more than 2 T. A six pulse IMRA sequence was applied to the 120 mm long stack starting with 1.3 T and ending in 0.7 T to ensure that the optimum field had been applied to saturate the sample.

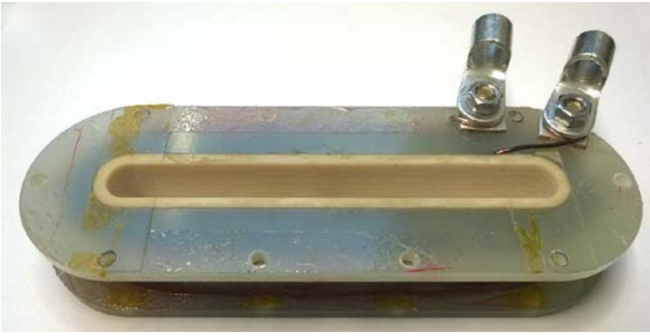

Fig. 7. Race track shaped pulsed field coil used to magnetize the long rectangular stacks of tape. Made from copper wire with internal glass fiber reinforcement. Pulses delivered had a duration of 29 ms.

After the pulsed field sequence had been applied, the stack was carefully removed and placed outside the coil for scanning by a Hall probe array. If *x* represents the transport axis of the tapes, the central peak field along the *x* direction is shown in Fig. 8, with the inset showing the cross-section of the field profile at three points along the 120 mm long stack. It is clear that a very constant and flat field has been trapped along the center of the stack as the minor fluctuations seen are a result of height position error of the scanning Hall probe. The field profile along the center almost resembles that of a permanent magnet. The profiles along the *y* direction, perpendicular to the *x* axis, show that the stack has an expected pyramidal shape that is *constant* along the whole length of the stack, ignoring the edge effects at ± 60 mm. Therefore the trapped field profiles prove that it is possible to magnetize long rectangular stacks with a uniform and well defined trapped field and scalable trapped flux, if using a race-track pulsed field coil. Fig. 5 suggests much greater trapped field and flux could be achieved if using lower temperatures, particularly because the 120 mm long stack had 60 rather than 15 layers.

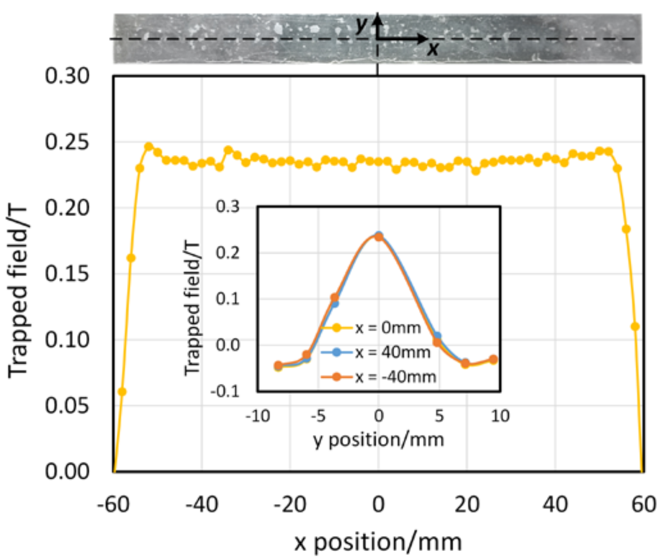


Fig. 8. Trapped field profile for a 60 layer self-supporting stack, with layers soldered together. Magnetized using a pulsed field at 77.4 K. The average center field 0.8 mm above surface is 0.235T.

## IV. Conclusion

Rectangular stacks of superconducting tape have been successfully magnetized proving their potential to act as high field permanent magnets with a high trapped flux. A rectangular geometry for a trapped field magnet is suited well to a radial gap-type synchronous motor forming the basis of a new superconducting motor concept reported. 0.72 T was trapped in a 24 mm by 12 mm stack made of just 15 layers at 15 K, although a cylindrical solenoid coil is believed to cause a double peak effect which may be understood by future modelling. Applicability of the stacks of tape for motor applications was demonstrated by magnetizing a 120 mm long, 60 layer, rectangular stack with an aspect ratio of 10. This unique self-supporting stack was created using new solder plating techniques, resulting in a solid composite superconducting bulk with a high geometric tolerance required for engineering applications. When magnetized by a custom made race-track shaped pulsed field coil, the long stack proved to have highly uniform and well-defined field trapping ability, giving such stacks great potential to be used as rotor field poles in motor applications. In future, the experiments may be scaled up to rectangular stacks with a larger width than 12 mm. Also, to fully exploit the high thermal stability offered by the tape stabilizer and substrate, the soldered tape stack will be soldered onto a heat sink. The enhanced thermal connectivity the solder would provide should allow for significant improvements in trapped field and flux below 77.4 K.

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