Assessment of critical factors affecting the performance of trapped field magnets using thin film superconductor tapes

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Abstract. Trapped field magnets have been investigated using Zr-added (Gd,Y)Ba-Cu-O thin film superconductor tapes. Trapped field profiles were examined both experimentally and by simulation over a temperature range of 30 to 77 K. A good match is found between experimental and simulation trapped field data at 77 K and 65 K, but higher trapped field values were obtained experimentally at lower temperatures. Trapped field values up to 1.55 T were measured in an 11 mm thick stack of 55 μm thick superconductor tapes arranged in a crisscross fashion with three tapes per layer. A substantial increase in the trapped field values was found by simulation, in tape stacks made with 20 μm thick tapes. Using such thin tapes, trapped field values of nearly 2 T is predicted in ~ 13 mm thick tape stacks at 77 K.

1. Introduction
High power wind turbines with ratings of 5 MW or more are preferred to maximize the capture of wind energy. For such high power wind turbines, the use of permanent magnet-based direct drive generators provides significant advantages in terms of cost and reliability. The most powerful, conventional permanent magnets contain a significant amount of neodymium, a rare-earth that is limited in supply which affects the development of high power wind turbines [1, 2]. Additionally, the permanent magnet-based generators are heavy which restricts the feasibility of wind turbines in power range of 10 MW. For this reason, there is a strong incentive to develop new types of magnets that have a lower content of rare-earth materials and that can enable lighter-weight, powerful wind turbines [2]. Thin film superconductor tapes or coated conductors contain only a small amount of superconducting material and hence only a miniscule amount of rare-earth materials while exhibiting very high critical current densities [3]. Trapped magnetic fields up to 7 T have been demonstrated at 4.2 K in single stacks of square 12 × 12 mm superconductor tapes [4 - 6].

It is important to achieve high and uniform trapped magnetic fields in superconductor tapes so that they could replace permanent magnets. Previously, trapped magnetic field profiles in arrays of crisscross- and straight-arranged stacks of (Gd,Y)-Ba-Cu-O (GdYBCO) superconducting tapes were investigated [7] since large arrays would be needed if these tapes are to be used as trapped-field magnets in practical applications. It was found that a crisscross arrangement of arrays of stacked
superconductor tapes yielded more uniform trapped magnetic field profiles and a lower decay rate of the trapped magnetic field as a function of distance from the tape stack surface, compared to a straight arrangement [7].

The influence of density of nanoscale defects incorporated in the superconductor film on the magnitude and decay of magnetic fields trapped by the tapes has also been investigated [8]. It was found that tapes with 7.5% zirconium addition which resulted in BaZrO₃ nanocolumns in the superconductor film exhibited the highest trapped field and the least time dependent decay of the field at 77 K [8]. Hence in this work, crisscross-arranged superconductor tapes made with 7.5% Zr addition were used. The purpose of this work was to determine how the magnitude of the magnetic field trapped by a stacked array of superconductor tapes is influenced by number of tapes in the stacked array, thickness of individual tapes and the operating temperature.

2. Experimental and Simulation
0.055 mm thick, 12 mm wide thin film GdYBCO tapes with 7.5% zirconium addition were used in this study. The tapes consisted of 0.05 mm thick substrate, 1.5 μm thick superconductor film and no copper stabilizer. The tapes exhibited a nominal critical current density of 2.5 MA/cm² at 77 K, 0 T. For the trapped field measurements, first, the superconductor tapes were cut into 36 mm long segments and stacked in a crisscross arrangement with three tape segments per layer [7]. A maximum tape stack thickness of 12.98 mm was tested. The superconductor tape stack was cooled in a magnetic field of 1.5 T to 77 K. After turning off the external magnetic field, the trapped field profile was measured over the surface of the tape stack. Details of the trapped field measurements are provided in [8]. The trapped field measurement system consisted of a three- axis linear motion table on which a cryogenic hall probe (Arepoc, model Axis-3, three-axis hall sensor) was mounted. The trapped magnetic field was measured at the center of the superconductor tape stack, 3 mm from the surface of the stack, as a function of time for up to 3 hours, initially at one minute intervals and later in longer intervals. After 16 minutes, the trapped field was measured at increasing distance from the surface of the center of tape stack. Thirty minutes into the measurement, the Hall probe was scanned over a 50 mm × 40 mm area over the sample holder in 1 mm steps to measure and map the trapped magnetic field at 3 mm from the tape stack surface.

Trapped field measurements were also conducted in a second system, over a temperature range of 30 K to 77 K. In these measurements, the superconductor tape stack was cooled in a field of 5 T to 20 K. After the external field was turned off, the trapped field was measured at the center of the tape stack, 1 mm from its surface. Measurements were conducted at 30, 40, 50, 65 and 77 K.

Simulation of the trapped field profiles was conducted by finite element analysis using COMSOL software. When an external magnetic field is applied to a tape, the magnetic flux penetrates from the sides towards the center of the tape. When the external field is removed, the flux in the tape decreases from the sides of tape. The slope of the magnetic field profile is determined by the critical current density of the tape [9]. Figure 1a is a schematic of the full penetration current flow that is established in the tapes to maintain the trapped field. The figure shows two layers of tape each with three tapes are arranged next to each other – in a horizontal orientation in the first layer and in a vertical orientation in the second layer. The net current density direction is distribution is determined through vector addition resulting in a profile shown in Figure 1b. Since the trapped magnetic field depends on the critical current density ($J_c$) and because $J_c$ of a tape depends on the trapped field in the adjacent tape it is exposed to, the simulation model uses the engineering current density, $J_e$, as a function of magnetic field as its primary input; In the current 3D model, the peak field is assumed the same for all the tapes and no flux creep is considered. Since the temperature is an important parameter evaluated in this study, $J_e$ characteristics as a functional of magnetic field at different temperatures from 30 to 77 K were used. The critical current data of 7.5%Zr-added GdYBCO tapes of SuperPower were used [10].
3. Results and Discussion
A trapped field profile measured 3 mm above the surface of a stack of 236 layers of crisscross-arranged tapes, at 77 K is shown in Figure 2. It can be seen that a crisscross arrangement of superconductor tapes results in nine peaks in the trapped field profile corresponding to the nine overlapping regions formed by crisscrossing of three tapes in each layer. The intensities of the nine peaks are similar, suggesting that a relatively uniform trapped field profile can be obtained over a large area using the crisscross configuration. The valleys in the trapped-field profile correspond to the regions with overlapping edges of each tape. The maximum trapped magnetic field is 0.26 T, 3 mm above the center of the tape stack.

Figure 1. (a) Current density distribution in two layers of crisscross-arranged tapes. Solid arrows and hatched arrows indicate current flow direction in the three vertically-arranged tapes and the three horizontally-arranged tapes (b) Net current density direction from COMSOL model of two layers of crisscross-arranged tapes (because of symmetry, only $\frac{1}{3}$ of the stack, shown within the square with dashed lines in (a) is modeled)

Figure 2. Trapped magnetic field profile at a distance of 3 mm above a stack of 236 layers of crisscross-arranged superconductor tapes made with 7.5% zirconium addition.
Trapped field profile results from the simulation of a stack of 128 layers of crisscross-arranged tapes are shown in Figure 3a. It can be seen that the simulated profile qualitatively matches very well with experimentally-obtained trapped field profile shown in Figure 3b.

Figure 3. (a) Trapped field profile from simulation of a stack of 128 layers of crisscross-arranged tapes (because of symmetry, only ¼ of the stack is modeled). (b) Trapped field profile from experimental measurements on a stack of 128 layers of crisscross-arranged tapes.

A quantitative comparison of the trapped field values of a 12.98 mm thick stack of 0.055 mm thick tapes (236 layers) obtained from simulation and experiments is shown in Figure 4. A good match is found between the simulation and experimental data. Discrepancy between the trapped field values between those obtained from simulation and experiment may be due to the following reasons: i) experimental data is affected by flux creep. We had reported previously that that flux creep is higher (and trapped field values decay more rapidly with time) in tape stacks with fewer layers [8]; ii) variability in critical current density of tapes used in experiment. A constant critical current density value was used for all tapes in simulation in relation to the peak c-axis field in the stack; iii) difference in the magnetic field dependence of critical current density used in simulation with that of actual tapes used in the experiments.

Figure 4. Maximum trapped magnetic field values in stacks of crisscross-arranged 55 µm thick superconductor tapes, obtained from simulation. Experimental data is included for comparison.
Figure 4 also includes simulation data from a thicker (19.25 mm) stack of tapes. No significant increase is seen in the trapped field which indicates that there is no benefit in adding more layers of tapes beyond about 13 mm, using 0.055 mm thick tapes.

Next, the effect of temperature on trapped field profiles with increasing number of layers of 0.055 mm thick tapes was examined by simulation and the results are shown in Figure 5. It is seen in Figure 5 that the maximum trapped field values increase with decreasing temperature from 77 K to 30 K. It is also observed that all temperatures, the trapped field values increase with increasing number of layers of 0.055 mm thick tapes in the stack. Unlike the experimental data that had revealed a linear increase in trapped field values with increasing number of layers [8], the simulation data shows a non-linear (logarithmic) increase in trapped field values with increasing number of layers of tapes in the stack. A trapped field value of nearly 1.4 T was obtained at 30 K which is about six times higher than the value at 77 K.

![Figure 5](image_url)

**Figure 5.** Maximum trapped magnetic field values in stacks of increasing thickness of crisscross-arranged 0.055 mm thick superconductor tapes at different temperatures, obtained from simulation. Dashed lines are logarithmic fit to the data points.

Results from trapped field measurements over a temperature range of 30 to 77 K are shown in Figure 6. As shown in the figure, the experimental trapped field values at 65 K and 77 K match well with simulation data. However, with decreasing temperature, the experimental trapped field values tend to increase linearly whereas a reduced rate of increase is seen in trapped field values from simulation. This finding is similar to the non-linear increase in trapped field values with increasing tape stack thickness in simulation data as seen in Figure 5 compared to the linear increase observed in experimental data [8]. It is seen from Figure 6 that the experimentally-obtained trapped field value reaches 1.55 T at 30 K.
Figure 6. Comparison of maximum trapped fields at different temperatures of 11 mm thick stacks of 0.055 mm thick tapes obtained by simulation and experiments.

Maintaining the temperature at 30 K, the effect of individual thickness of tapes in the stack was investigated. The individual tape thickness was varied from 0.055 mm to 0.035 mm to 0.020 mm. Results are shown in Figure 7. It is found from the figure that at 30 K, the maximum trapped field values increase with decreasing tape thickness from 0.055 mm to 0.020 mm i.e. with increasing number density of tapes in the stack (number of layers of tapes in a given stack thickness). Also, in tapes of all thickness, the maximum trapped field values increase with increasing number of layers of tapes. A trapped field value of nearly 3 Tesla is reached at 30 K.

Figure 7. Maximum trapped magnetic field values in increasing thickness of stacks of crisscross-arranged 55 µm, 35 µm and 20 µm thick superconductor tapes at 30 K, obtained from simulation.
A comparison of the maximum trapped magnetic field at 77 K in a 12.98 mm thick tape stack made with 55 and 20 \( \mu \text{m} \) thick tapes, obtained from simulation, is shown in Figure 8. It is seen from the figure that the trapped magnetic field increases sharply with decreasing distance from the tape stack surface using the thinner tapes, reaching nearly 2 Tesla, 1 mm from the stack surface. This result clearly shows the benefit of using thinner tapes for maximizing trapped magnetic field.

**Figure 8.** Maximum trapped magnetic field values in stacks of crisscross-arranged 55 \( \mu \text{m} \) and 20 \( \mu \text{m} \) thick superconductor tapes, obtained from simulation.

**Conclusions**

The influence of operating temperature, thickness of individual tapes and thickness of tape stacks on the magnitude of magnetic field trapped by crisscross-arranged superconductor tapes have been investigated by simulation. Experimental verification was also conducted with 11 mm thick tape stacks over a temperature range of 30 to 77 K. The results show increased trapped fields with increasing tape stack thickness at all temperatures with 55 \( \mu \text{m} \) thick tapes. The trapped fields were found to increase linearly with decreasing temperature in experiments and nonlinearly in simulation. The difference could be due non uniformity in the magnetic field dependence of \( J_c \) of long tapes (even though the measured \( J_c \) at 77 K, 0 T is uniform) which is not considered in simulation. Additionally, a higher fidelity model that takes flux creep into account needs to be developed. Simulation results showed a drastic improvement in trapped fields when the individual tape thickness is decreased from 55 to 20 \( \mu \text{m} \).

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