Composite superconducting bulks for efficient heat dissipation during pulse magnetization

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Abstract. Pulsed field magnetization is the most practical method of magnetizing a (RE)BCO bulk, however large heat generation limits the trapped field to significantly less than possible using field cooling. Modelling has been used to show that effective heat removal from the bulk interior, using embedded metallic structures, can enhance trapped field by increasing thermal stability. The reported results are for experimental pulsed magnetization of a thin walled YBCO sample with 55 vertical holes embedded with high thermal conductivity wires. A specially designed copper coldhead was used to increase the trapped field and flux of the perforated YBCO by about 12% at 35 K using a multi-pulse magnetization. Moreover, by filling the perforations with copper, the central trapped field was enhanced by 15% after a single-pulse at 35 K. 3D FEM computer model of a perforated YBCO bulk was also developed showing localised heating effects around the perforations during pulse magnetisation.

1. Introduction

Superconducting bulks can act as very compact sources of magnetic field, which makes them attractive for a variety of different applications, such as motors [1] and contactless bearings [2]. However, pulse magnetisation causes rapid heating of the bulk superconductor. Modelling has been used to show that effective heat removal from the bulk using embedded metallic components can enhance the trapped field by increasing the effective thermal conductivity [3]. To implement such structure a composite bulk, comprising of a perforated bulk with embedded copper wires, was assembled and tested. To efficiently sink the heat, extracted from the bulk, a specially designed copper thermal mass was used, which minimises eddy current heating. Furthermore, a 3D critical state magneto-thermal model was developed to study the thermal and magnetic flux dynamics in the composite during pulse magnetization.

2. Experimental pulse magnetization

The sample used in this study had a diameter of 16 mm and a height of 19.5 mm. The sample had a total of 55 perforations in a hexagonal lattice with seven largest holes around the perimeter and the centre having an average diameter of 0.58 mm, the rest 0.42 mm. To improve thermal contact between the copper wires and YBCO, the YBCO bulk was impregnated with Apiezon N thermal grease at 50°C

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and any trapped air was removed under vacuum. Copper (RRR=30) wires with diameters 0.4 and 0.5 mm were inserted into the bulk. Then, the vacuum treatment was repeated. The assembled composite bulk is shown in figure 1c. To effectively sink the heat extracted from YBCO, a copper thermal mass (referred to as coldhead) was made, the design of which inhibits eddy current formation. The coldhead comprises of 1 mm sheets of copper glued with Stycast resin, compatible with vacuum and low temperatures. Finally, thermal grease was applied on the interface between coldhead and the YBCO sample.

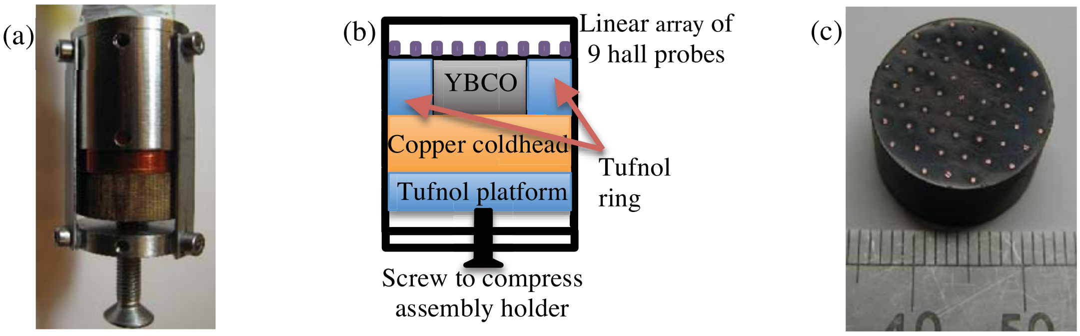

Figure 1. a) Picture of the sample holder with the sample inside; b) schematic diagram of the sample arrangement; c) YBCO sample with copper wires inserted into the perforations.

The sample was magnetized using the MPSC and IMRA techniques [4]. The pulsed field was reduced in steps of 0.2 T until there was no significant improvement in the trapped field or flux observed. Then, the temperature was reduced and the process repeated. The starting and ending fields of each sequence at temperatures tested are indicated in table 1. The pulse magnetisation was performed using the experimental setup developed at the Applied Superconductivity and Cryoscience Group, University of Cambridge [2]. The Hall probes (figure 1b) measured the magnetic flux density 0.5 mm above the sample surface.

Table 1. Sequence of pulses applied to the samples starting at “Start field” and then pulsing with incrementally smaller (by 0.2 T) field until “End field” is reached.

Temp. [K]	Start field [T]	End field [T]
77.4	3.6	1.6
55	5.0	2.6
35	5.8	3.4
15	4.8	1.8
10	4.6	1.8

3. Results and discussion

Figure 2a shows the central trapped field and figure 2b shows the trapped flux above the YBCO sample. It is worth noting that the trapped flux continued to increase even after the central field has saturated, since the trapped field profile has widened. If we take a “bare bulk” (supported only by tufnol) as a baseline we see that the most significant increase in the trapped field is seen after adding a coldhead to the sample assembly; at 35 K the trapped field and flux was increased by 12.4% and 11.9% respectively. By further adding copper into the YBCO perforations there was only a marginal 1.6% improvement in the trapped flux at 35 K. This is likely because the multi-pulse magnetisation techniques already address the heating problem. However, there is marked improvement when comparing the trapped flux and field after the *first* pulse at intermediate temperatures (see figure 3). By inserting wires into the perforations, the central trapped field at 35 K increases by 15%. Hence, the amount of pulses and time needed to fully magnetise the sample can be reduced. Furthermore, filling the perforations does not increase the volume of the sample and the perforations themselves are made for a completely different purpose – to reduce oxygenation time, porosity and cracking [5,6] during bulk YBCO manufacture.

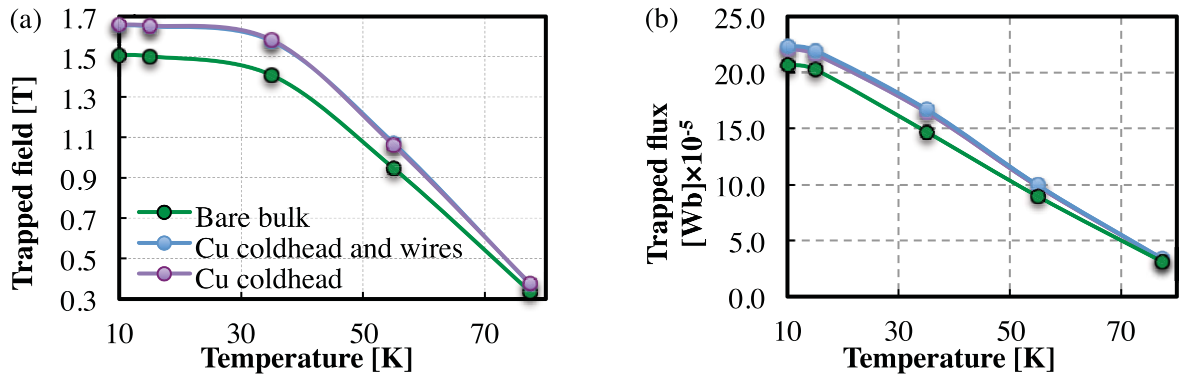

Figure 2. Trapped central field a) and flux b) after multi-pulse magnetization.

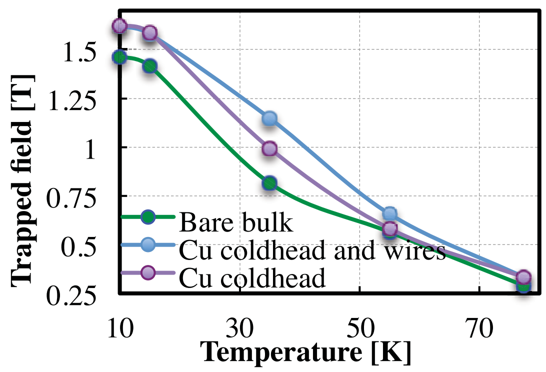

Figure 3. Trapped field after the first pulse at each temperature.

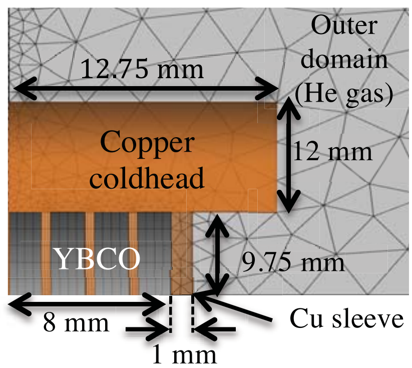

Figure 4. Dimensions of the modelled geometry. Cu sleeve was used in some of the tests.

4. FEM model of the composite bulk

A magneto-thermal FEM model of the perforated YBCO geometry was developed using COMSOL Multiphysics 4.3a. The basis of the model was a 3D critical state model (H - formulation, no thermal effects) developed by Zhang *et al* [7]. Complexity of the geometry modelled, combined with added thermal effects, makes the model very computationally demanding. To minimize element count in the model, symmetries were exploited by modelling only 1/6 of the sample. Furthermore, another symmetry plane along the middle of the sample in the x-y plane (see figure 4) was introduced to reduce the computation time to a manageable 55 h. A 5 T and 31 ms duration pulse was applied to model single pulse magnetization. The equilibrium temperature was set to 40 K and the cooling by He gas was simulated by a cooling source around the periphery of the sample assembly. The source has power, which is proportional to the difference between current and equilibrium temperature and saturates at 30 W when this difference reaches 15 K.

The dynamics of pulse magnetization of the bulk with holes (filled with copper) is illustrated in figure 5. The main difference, compared to the dynamics expected for a normal bulk, is that the current is forced to meander around the perforations where local current density increases, resulting in 'hotspots'. This shows that the copper in the perforations provides cooling where it is needed most. The simulation results also show that by filling perforations with copper, the maximum temperature reached during magnetisation is lower and the equilibrium temperature is reached faster. The final trapped field inside the bulk has no indications of holes present in the sample. However, little difference in the trapped field was seen when modelling the bulk with and without copper filling the holes. This may be due to the cold head geometry not matching the experiments and a relatively low exponent (n = 9) in the *E-J* power law, used in order to stabilize the simulation and reduce the computation time. As a result, the main purpose of the model developed is to give an insight into flux dynamics for a bulk with 3D anisotropy, and only a qualitative link to the experiments. A general point arising from both the model and experiment is that certain forms of symmetrical J_c anisotropy such as an array of holes of zero J_c, does not necessarily prevent large trapped fields.

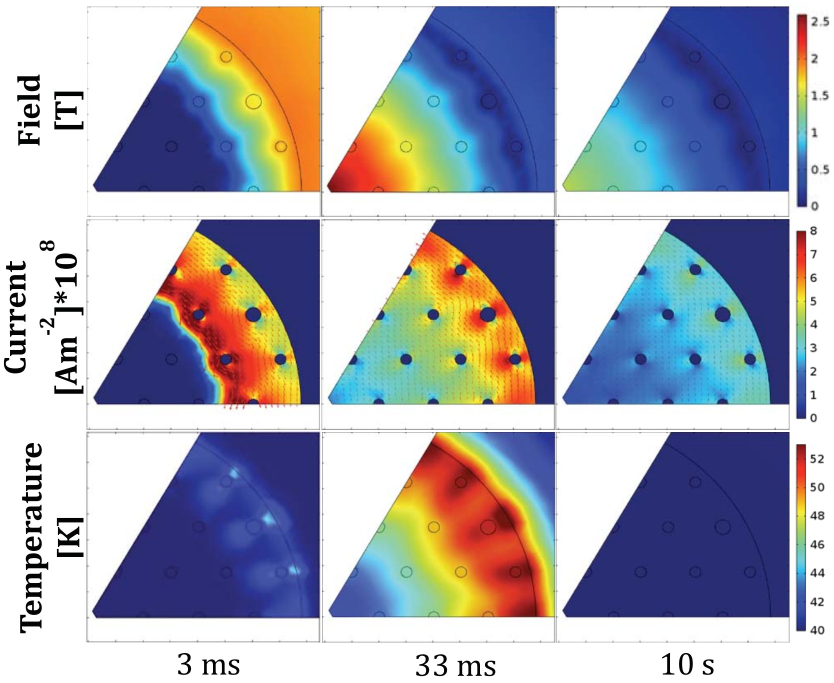

Figure 5. Flux density, current density and temperature in plane through the centre of sample at 3 ms, 33 ms and 10 s after the start of a pulse in YBCO with Cu coldhead and wires in the perforations.

5. Conclusions

A composite YBCO bulk with copper embedded in the perforations was magnetized using pulsed magnetization and the performance of the sample was evaluated. Using the MPSC magnetization technique and filling the perforations with copper, resulted in a modest 1.6% increase in trapped flux (compared to a bulk and coldhead alone). Nevertheless, the performance is substantially increased when considering the trapped field after the first pulse. A 15% increase in trapped field was observed after the first pulse at 35 K, which suggests that such composite samples can be fully magnetized faster and with a lower number of pulses. A 3D critical state FEM model that considers thermal effects was constructed. The model showed localized heating effects around perforations and confirmed that the heat removal was significantly improved by using composite structures.

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