Modelling the record trapped field by pulsed field magnetisation of a composite bulk MgB_2 superconducting ring

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***Abstract*—The recent results of Hirano et al. [1] produced a record breaking trapped field of 1.61 T in a composite MgB_2 ring, comprising copper plates and a soft iron yoke. Inspired by these results, a systematic numerical study was conducted to investigate the key parameters leading to the success of Hirano et al. [1]. Leveraging a finite-element method modelling framework in a commercial software package (COMSOL Multiphysics), we accurately replicated their experimental results [1]. Excellent quantitative agreement with the experimental data was achieved by making novel assumptions to the thermal physics, namely to that of the heat flow within the sample. The models are extended to investigate open & remaining questions; such as the influence of the iron yoke and the copper plates, and their interaction with the applied field. The results of the study illustrate how composite MgB_2 rings may be optimised to trap even higher fields, and how the physics of their operation affect the trapped field distribution and magnitude. This submission disseminates the physics and modelling techniques used in detail, illustrating the novel modelling methods adopted to accurately simulate bulk composite MgB_2 rings acting as trapped field magnets.**

***Keywords*—Bulk superconductor, FEM, MgB_2, PFM**

I. INTRODUCTION

Bulk superconductors fabricated from MgB_2 (magnesium diboride) materials show great promise for trapping large magnetic fields, which can be exploited in engineering applications such as magnetic separation, superconducting rotating machines, and advanced NMR/MRI [2]–[5]. MgB_2 can offer a number of advantages over materials more traditionally used for fabricating bulk superconductors, such as (RE)-BCO (RE = Rare Earth, B=Ba, C=Cu, O=oxide). The lightweight, polycrystalline structure is 'rare-earth-free', can trap highly homogenous fields due to the long coherence length below 39 K [6], and may be fabricated using a number of techniques with relative ease [7]. Indeed, whilst the record high trapped field in an MgB_2 disk of 5.4 T at 12 K [8] may be lower than (RE)-BCO [9], the magnetisation potential is still great; at least double the saturation field of ferromagnetic iron. Achieving these records involved using the 'Field-Cooled' (FC) magnetisation technique [10], which ensures full magnetisation of the bulk to characterise its performance. This requires a large, static magnetising field from bulky and expensive magnets, that are usually superconducting. Pulsed-field magnetisation (PFM) meanwhile, has no such constraints, and has greater commercial and practical applications due to its portable and inexpensive setup, despite an often lower trapped field [11]. Adopting favourable magnetising coil fixtures, and optimising the magnetisation technique with multiple pulses has yielded promising results for PFM [12]–[16].

Hirano et al. [1] achieved the PFM record high trapped field, by embedding bulk MgB_2 superconducting rings between layers of copper and inserting a soft-iron yoke. When pulsed with a magnetic field, the copper plates induce eddy-currents, which in turn increase the effective pulse rise time. This should reduce the heat generated in the bulk; thought to be beneficial to trapping higher fields using the PFM technique [15]. Further, the high thermal conductivity and heat capacity of copper may be favourable in transferring heat from the bulk generated during the PFM process. Meanwhile, the iron yoke inserted into the bore of the sample acts to retain flux during the pulse, and concentrate the trapped field. We therefore have a large number of variables which may be controlled; from the number of copper layers adopted and their thickness, to the effect of a soft iron yoke insert compared to no insert. This high variable number heeds well for finite-element modelling [17] [18], where parameters such as these can be readily and simply altered. This is the impetus behind the presented work; to leverage the advantage of numerical modelling for this large variable space problem. In this submission we illustrate the key outcomes of this modelling based investigation, and disseminate the novel modelling methods adopted to achieve a successful and accurate replication of the experiment of Hirano et al. [1]

II. Modelling Details

Figure 1 illustrates the geometry of the 2D axisymmetric models implemented with COMSOL Multiphysics version 5.4. As per the experiment, three sample configurations were modelled [1]. These included; a 'Single Bulk' consisting of MgB_2 only, a 'Composite w/o Yoke' bulk, consisting of three copper layers sandwiching two MgB_2 bulks, and finally a 'Composite w. Yoke' bulk: which is the 'Composite w/o Yoke' configuration but with an iron yoke inserted to the bore of the ring.

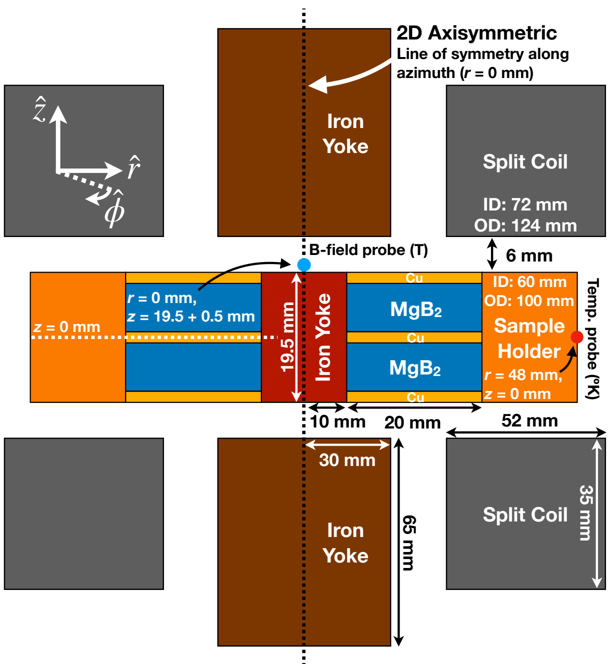

Fig. 1: Geometry of the 2D axisymmetric model implemented in COMSOL Multiphysics; complete with split coil magnetisation fixture with iron yokes.

Utilising the **H**-formulation of Maxwell's equations, we are able to capture the electrodynamics of the experiment. The *E*-*J* Power law was applied to the MgB_2 domains to model the highly non-linear *I*-*V* relationship this material exhibits in the superconducting state. The magnetic field-dependence of the critical current density, $J_c(\mathbf{B})$, was interpolated using reference data [19]. Meanwhile, the thermal transient equation was adopted to model the thermal physics of the bulk and sample holder; allowing heat to flow towards a cold-stage, as per the experiment [1].

Figure 2 illustrates the validation of the model by the experimental data; comparing the magnitudes of the applied pulses and the maximum temperature observed in the experiments. Excellent quantitative agreement is obtained, which gives us confidence in the accuracy of the later explored 'extension studies'.

III. Results

Whilst above we present results illustrating the validation of the model, the full results will be presented at the HTS Modelling Workshop. Here, we will present in full the 'extension studies' of this investigation. This involved investigating the influence of the copper plates, and the iron yoke in magnetising the composite MgB_2 bulks. We first investigated how varying the number of copper layers affects the pulse magnitude, duration, and magnetisation potential of the composite bulks. We also investigated the influence of the iron yoke in concentrating flux during magnetisation, and how this action affects the heating of the bulks.

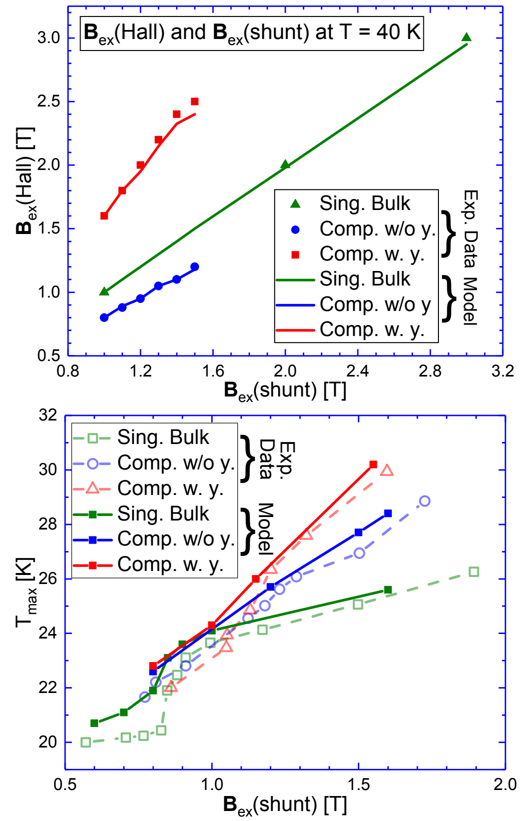

Fig. 2: TOP: Applied field ($\mathbf{B}_{ex}$(shunt)) vs the measured field at the centre of the top surface of the sample ($\mathbf{B}_{ex}$(Hall)), at 40 K. BOTTOM: Experimental data compared to the modelled results, for the maximum temperature recorded at the temperature probe (r = 48 mm, z = 0). Prior to pulse; samples at 20 K.

IV. Conclusion

In conclusion, we have successfully validated our numerical modelling framework by replicating the experimental data presented by Hirano et al. [1]. We present an accurate modelling of the pulsed-field magnetisation of a superconducting composite MgB_2 bulk, which led Hirano et al. to achieve a record-high trapped field. We extend our studies to investigate elements of the experiment which are difficult or impractical to investigate experimentally, and shall present these results in full at the HTS Modelling Workshop.

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