A 17.6 T Trapped Field in Ag doped Bulk $GdBa_2Cu_3O_{7-\delta}$

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July 8, 2014 (HP83). We have recently published [1] a paper co-authored with colleagues from Cambridge, the Applied Superconductivity Centre at NHMFL/FSU and the Boeing Corporation describing successful trapping of 17.6 T in a bulk superconductor at 26 K. This is about 0.4 T in excess of the previous record field obtained by Tomita *et al.* [2]. Bulk superconductors offer the prospect of convenient, permanent magnet like, fields but of much larger intensity with the very best rare earth magnets achieving little more than 1 T. The utility of such materials is self-evident in spite of the necessity of cryogenic cooling.

The question that immediately arises is as to why it has taken 10 years to achieve a fairly moderate increase on Tomita *et al.*'s result. To understand this it is important to consider that the limiting factor to the high field performance of such bulks is, unusually in superconductor applications, not the critical current density of the superconductor itself. As one of the previous record holders explains in a recently published viewpoint on our paper [3] it is the tensile strength of the superconductor that limits performance. The strains inside a bulk superconductor during charging to 17 T can reach ~100 MPa with the strain scaling as B^2. As the superconductors in question are brittle ceramics featuring a large number of cracks it is clear that this is a challenging problem. Moreover in materials where fracture toughness is important there is often a wide spread of performance since generally it is the one "worst crack" that determines performance.

Fig. 1. The assembled stack of two GdBCO bulk samples, each of diameter 24.15 mm and height 15 mm. The samples were reinforced with a ring of 3 mm thickness fabricated from 304 Stainless Steel. [Reproduced from [1] under the CC-BY license]

Of lesser importance, but nonetheless a significant consideration, is thermal stability. A low thermal conductivity bulk is susceptible to localised quenching which leads to "flux jumps" and escape of magnetic field from the sample during trapping. Tomita *et al.* addressed this using a combination of an Al heat sink through the centre of the sample and impregnation with Wood's metal. We addressed the problem by adding 15 wt% Ag to our bulk which causes many of the cracks and voids in the sample to become filled with silver. This increases both thermal and normal state electrical conductivity of the sample and ameliorates, to some extent, the flux jumping problem.

To achieve high trapped fields, some sort of mechanical reinforcement of the sample is required. Two classes of techniques have been exploited in the literature, steel banding [4] where due to differential thermal contraction a pre-stress is applied to the bulk, and reinforcement with carbon fibre epoxy [2]. We were interested in a quick and easy method which led to our selecting steel banding. We realised, however, that the pre-stress introduced by differential thermal expansion is relatively modest and looked to improve it. We hit upon the simple, and indeed frequently employed in engineering, solution of "shrink fitting". We carefully machined our bulks to be perfectly cylindrical and prepared slightly under size stainless steel (304L) rings. When heated, these rings expanded and could be slipped over the bulks, as the rings cooled they contracted applying pre-stress to the bulk superconductor. This pre-stress then further increased as the samples were cooled to measurement temperature. In this way we sought to avoid tensile stress sufficient to break them. Stress is arising inside the bulks during the charging process.

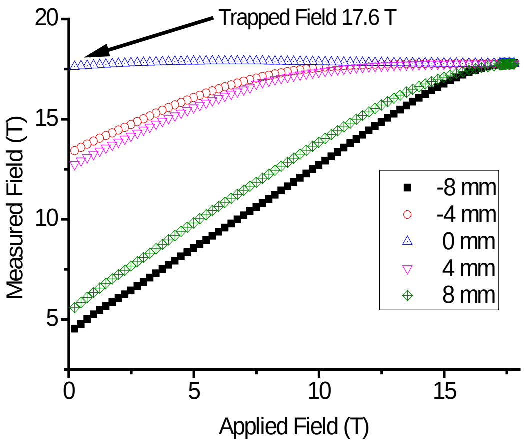

Fig. 2. The field measured at the interface between the two samples in the stack by an array of Hall probes (distances indicated are from the centre of the sample) as the magnetising field was ramped down. [Reproduced from [1] under the CC-BY license]

We suspect that, since the steel we are using is near its yield point, we are near the limit of trapped field performance obtainable with this technique. We are, therefore, currently seeking to improve the performance of our samples by incorporating alternative methods of reinforcement.

References

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[4] Fuchs, G., *et al., Applied Physics Letters* **76** (No. 15) 2107-2109 (2000).