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Viewpoint

Realization of compact hybrid trapped field magnet above 10 T with 7 T applied field

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Abstract
In this paper, Takahashi *et al* reported a successful case to reach this goal with a hybrid trapped field magnet (i.e. inner lens and outer cylinder trapped field magnet). The inner lens were cooled from room temperature to about 20 K in zero field cooling followed by applied field (e.g. 7 T) that the flux density will be concentrated to above 10 T. And in the same time the outer trapped field magnet will be field cooled from room temperature to about 20 K in this above 10 T field.

This is a viewpoint on the letter by Keita Takahashi *et al* (2021 *Supercond. Sci. Technol.* 34 05LT02).

Following the discovery of Y–Ba–Cu–O high temperature superconductor (HTS) in 1987 by Wu and Chu with superconducting transition temperature Tc higher than that of liquid nitrogen boiling temperature (77 K) [1], many studies have tried to use this Y–Ba–Cu–O HTS for high magnetic field applications. Soon, it was discovered that most of the rare earth elements can replace Y in the Y–Ba–Cu–O compound, and have similar Tc near 90 K [2]. This family of compounds are known as rare-earth barium copper oxides, or REBCO. Other series of cooper-oxides HTS compounds, i.e. Bi–Sr–Ca–Cu–O and Tl–Ba–Ca–Cu–O with even higher Tc were also discovered later. Nevertheless, two basic intrinsic materials problems related to the critical current density Jc(H,T) of HTS limited the progress of HTS high-field applications. First, the weak magnetic flux pinning force associated with Bi–Sr–Ca–Cu–O HTS limits the operating temperature of high magnetic field applications to below 30 K [3]. Secondly, the weak link effect of the grain boundary limits the Y (or RE)–Ba–Cu–O HTS material to be in the form of an epitaxial film or single-grained monolith [4]. Single-grained monoliths are typically referred to simply as bulks and are fabricated using a seeded melt-growth process to obtain the required texture. The requirement of biaxial texture has driven the development of so-called second generation (2G) or coated conductor REBCO tapes to achieve the required Jc performance in long lengths of conductor'. Using this 2G HTS tape, prototype hybrid magnets running at 4 K with a magnetic field exceeding 30 T have been demonstrated in recent years [5]. This hybrid magnet consists of a 15 T low-temperature superconductor (made of NbTi and Nb_3Sn) outer coil and 17 T inner coil (made of 2G-HTS), both of which are operated at 4 K, weigh close to 2 tons [6].

On the other hand, single-grained monoliths have also shown significant progress. Two RE–Ba–Cu–O monoliths, each with a diameter of 2.65 cm and a thickness of 1.5 cm, cooled in the field of an 18 T magnet demonstrated the capability to trap magnetic flux density exceeds 17 T at 29 K. In two reports [7, 8], a trapped field close to 10 T can be achieved at 45 K–50 K. In the report by Tomita and Murakami [7], RE–Ba–Cu–O was impregnated with Wood's metal together with resin reinforced carbon fiber. And in the other report by Durrell *et al* [8], the monoliths were reinforced with shrink-fit steel. REBCO monoliths can perform either magnetic flux concentration/shielding by zero field cooling (ZFC) or flux trapping by field cooling (FC), and Durrell and Cardwell have shown that different types of portable strong field sources can be realized [9].

The paper by Takahashi *et al* [10] described the detailed experimental procedures and results of a hybrid trapped field magnet with four pieces of RE–Ba–Cu–O bulks. A compact quasi-permanent magnetic field source near 10 T can be realized through a 7 T external applied field together with a 20 K cryostat. The paper by Takahashi *et al* is the third in a series of reports to validate the concept of hybrid trapped field magnet lens (HTFML) in which a trapped field above 10 T can be achieved using an externally applied field less than 10 T (7 T in this report). In previous papers [11, 12], the experiment of RE–Ba–Cu–O monoliths at 77 K and a hybrid magnet with MgB_2 lens at ∼20 K and RE–Ba–Cu–O cylinder at 50 K were reported. This article also summarizes these developments.

In this latest work, Takahashi *et al* have successfully reached this goal with a hybrid trapped field magnet consisting of an inner lens and outer cylinder trapped field magnet. The inner lens was cooled from room temperature to about 20 K in ZFC followed by application of a 7 T field, resulting in a flux density concentrated to above 10 T. At the same time, the outer trapped field magnet was FC from room temperature to about 20 K in this >10 T field.

Since a RE–Ba–Cu–O monolith can be used as either a magnetic flux concentration/shield by ZFC or as a flux trap by FC, the inner part of this device acts as a lens to amplify the magnetic flux strength, and the outer part acts as an externally applied magnetic flux source. Therefore, it is possible to realize the internal total magnetic flux density greater than the externally applied magnetic flux density. By appropriately controlling the cooling temperature of the RE–Ba–Cu–O inner lens to be lower than the temperature of the outer cylinder, Takahashi's team have realized the concept of HTFML above 10 T. This differential cooling speeds between inner and outer pieces is achieved by a special experimental setup to have different thermal conduction between the cryostat and the working pieces.

The authors also conducted an experiment in attempt to trap magnetic field higher than 10 T, but failed due to RE–Ba–Cu–O monolith fracture caused by flux quench at about 12 T. Detailed procedures and failure analysis were also reported, indicating the need for further improvements in structural strengthening and cooling procedures.

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References

[1] Wu M K, Ashburn J R, Torng C J, Hor P H, Meng R L, Gao L, Huang Z J, Wang Y Q and Chu C W 1987 Superconductivity at 93 K in a new mixed-phase Y-Ba-Cu-O compound system at ambient pressure *Phys. Rev. Lett.* **58** 908

[2] Hor P H, Meng R L, Wang Y Q, Gao L, Huang Z J, Bechtold J, Forster K and Chu C W 1987 Superconductivity above 90 K in the square-planar compound system *A*Ba2Cu3O6+x with *A* = *Y*, La, Nd, Sm, Eu, Gd, Ho, Er and Lu *Phys. Rev. Lett.* **58** 1891

[3] Larbalestier D, Gurevich A, Feldmann D M and Polyanskii A 2001 High transition temperature superconducting materials for electric power applications *Nature* **414** 368–77

[4] Dimos D, Chaudhari P, Mannhart J and LeGoues F K 1988 Orientation dependence of grain-boundary critical currents in YBa2Cu3O7−δ bicrystals *Phys. Rev. Lett.* **61** 219
[5] Weijers H W *et al* 2016 Progress in the development and construction of a 32 T superconducting magnet *IEEE Trans. Appl. Supercond.* **26** 4300807
[6] Weijers H W National MagLab, Oxford Instrument, SuperPower Inc. 2017 (available at: https://nationalmaglab.org/news-events/news/new-world-record-magnet-fulfills-superconducting-promise)
[7] Tomita M and Murakami M 2003 High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K *Nature* **421** 517
[8] Durrell J H *et al* 2014 A trapped field of 17.6 T in melt-processed, bulk Gd-Ba-Cu-O reinforced with shrink-fit steel *Supercond. Sci. Technol.* **27** 082001
[9] Durrell J H, Ainslie M D, Zhou D, Vanderbemden P, Bradshaw T, Speller S, Filipenko M and Cardwell D A 2018 Bulk superconductors: a roadmap to applications *Supercond. Sci. Technol.* **31** 103501
[10] Takahashi K, Fujishiro H, Namba S and Ainslie M D 2021 Experimental realization of an all-(RE)BaCuO hybrid trapped field magnet lens generating a 9.8 T concentrated magnetic field from a 7 T external field *Supercond. Sci. Technol.* **34** 05LT02
[11] Takahashi K, Fujishiro H and Ainslie M D 2018 A new concept of a hybrid trapped field magnet lens *Supercond. Sci. Technol.* **31** 044005
[12] Namba S, Fujishiro H, Naito T, Ainslie M D and Takahashi K 2019 Experimental realization of a hybrid trapped field magnet lens using a GdBaCuO magnetic lens and MgB2 bulk cylinder *Supercond. Sci. Technol.* **32** 12LT03