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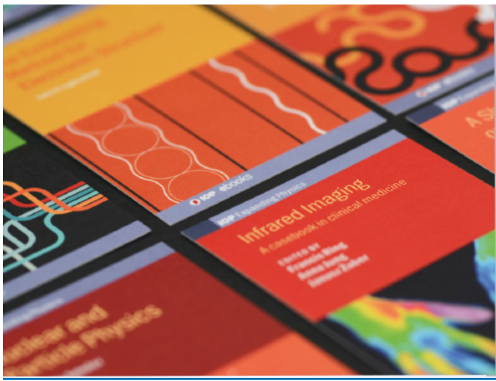

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## Viewpoint

# New type of hybrid magnetic lens for practical applications of HTS bulk superconductors

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This is a viewpoint on the letter by S Namba *et al* 2019 (*Supercond. Sci. Technol.* **32** 12LT03).

High-$T_c$ bulk superconductors such as RE-Ba-Cu-O (RE: a rare earth element) and $MgB_2$ can trap high magnetic fields at low temperatures. The magnetized bulk superconductors can be used as a compact, high strength trapped field magnet (TFM) for many practical applications.

However, the trapped field is limited experimentally by the poor mechanical strength of the brittle ceramic material. A large Lorentz force is developed in the bulk during the magnetization process, which sometimes results in crack formation and propagation, leading to eventual mechanical failure. Remarkable progress has been made in increasing trapped fields with mechanical reinforcement using epoxy resin or shrink-fit stainless steel. Up to now, trapped magnetic fields over 17 T are achieved in RE-Ba-Cu-O disk pairs through field-cooling magnetization (FCM) [1, 2]. The group of Iwate University and University of Cambridge has been working on the magnetization techniques of bulk superconductors. Recently, Fujishiro *et al* [3] suggested the possibility to achieve a trapped field over 20 T in the RE-Ba-Cu-O disk pair by FCM method using numerical simulation. However, FCM requires a high applied field generated by a superconducting magnet, which has limitations for practical applications. Pulsed-field magnetization (PFM) is the most practical method to magnetize bulk superconductors since it is a faster magnetizing process than FCM and is an inexpensive and mobile experimental setup using a copper pulsed magnet. A trapped field of 5.2 T by PFM is reported in an HTS bulk [4]. A flux jump assisted multi-pulse magnetization has recently been reported led to a trapped field of 5.3 T in Gd-Ba-Cu-O bulk [5]. However, the maximum trapped field by PFM is still significantly lower than that achieved by FCM.

The magnetic lens was reported by Matsumoto *et al* for the first time in 2003 [6]. In this device, magnetic flux concentration was carried out by using hollow cylinders made of low- and high-temperatures superconductors. It is important to develop compact high magnetic field systems. A magnetic lens made of a Gd-Ba-Cu-O bulk was placed in a superconducting magnet. An external field of 2 T was amplified to 5.65 T at the center of the lens, demonstrating magnetic flux concentration by a Gd-Ba-Cu-O magnetic lens [7]. A concentrated field of $B_c = 12.42$ T has been obtained at 20 K for a background field of 8 T using a Gd-Ba-Cu-O bulk magnetic lens, and $B_c = 30.35$ T at 4.2 K achieved for a background field of 28.3 T [8].



 

Since the magnetic lens effect vanishes after the applied field decreased to zero, the external magnet must be operated continuously, which consumes energy and is not environmentally friendly. In 2018, the new concept of a hybrid trapped field magnet lens (HTFML) was reported [9]. This consists of a TFM cylinder exploiting the 'vortex pinning effect', combined with a bulk magnetic lens exploiting the 'diamagnetic shielding effect'. The HTFML can reliably generate a concentrated magnetic field in the central bore of the magnetic lens that is higher than both the trapped field in the single cylindrical bulk TFM and the external magnetizing field, even after the externally applied field decreases to zero. In this letter, the first experimental realization using HTFML device was presented. In the HTFML consisting of a Gd-Ba-Cu-O bulk lens and a $MgB_2$ bulk TMF cylinder, a maximum concentrated magnetic field of $B_c = 3.55$ T was achieved at the central bore after removing the applied field of 2.0 T at 20 K. Although, the experimental value of $B_c = 3.55$ T is lower than the value predicted from numerical simulation, the concentrated field will be enhanced with the design optimization of HTFML.

A ring-shaped RE-Ba-Cu-O bulk superconductor is a strong candidate for NMR and MRI systems [10]. An Eu-Ba-Cu-O bulk is suitable for a compact NMR magnet because of its low relative magnetic permeability. The HTFML using a RE-Ba-Cu-O bulk TFM cylinder and a RE-Ba-Cu-O lens pair can be expected to achieve higher HTFM effect compared to that using a $MgB_2$ bulk TFM cylinder [9, 11, 12]. Most recently, the performance of HTFML consisting of an Eu-Ba-Cu-O bulk TFM cylinder and a Gd-Ba-Cu-O lens was reported [13]. At 77 K, a concentrated magnetic field of $B_c = 0.8$ T was experimentally confirmed after removing an applied magnetic field of 0.5 T. The concentrated magnetic field will be enhanced with lowering the operating temperature. In this letter, the authors mentioned that the goal of a concentrated magnetic field is over 10 T (e.g. $B_c = 13.5$ T) when an applied field is 10 T. It is extremely effective for an improvement in the resolution of a compact NMR. The realization of the magnetic field over 10 T in an open space using the HTML system will accelerate practical applications of bulk superconductors.

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## References

[1] 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** 517–20
[2] 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
[3] Fujishiro H, Naito T and Awaji S 2019 Proposal of an effective mechanical reinforcement structure for a REBaCuO disk bulk pair by full metal encapsulation to achieve a higher trapped field over 20 T *Supercond. Sci. Technol.* **32** 045005
[4] Fujishiro H, Tateiwa T, Fujiwara A, Oka T and Hayashi H 2006 Higher trapped field over 5 T on HTSC bulk by modified pulse field magnetizing *Physica* C **334–8** 445–8
[5] Zhou D, Ainslie M D, Srpčič J, Huang K, Shi Y, Dennis A R, Cardwell D A, Durrell J H, Boll M and Filipenko M 2018 Exploiting flux jumps for pulsed field magnetization *Supercond. Sci. Technol.* **31** 105005
[6] Matsumoto S, Kiyoshi T, Asano T, Ozaki O, Koyanagi K, Fujihira J and Wada H 2003 Magnetic flux concentration and magnetic force enhancement using YBCO cylinders *IEEE Trans. Appl. Supercond.* **13** 1652–5
[7] Kiyoshi T, Choi S, Matsumoto S, Asano T and Uglietti D 2009 Magnetic flux concentrator using Gd-Ba-Cu-O bulk superconductors *IEEE Trans. Appl. Supercond.* **19** 2174–7
[8] Choi S, Yoon J-H, Lee B-S, Won M-S, Ok J-W, Zhang Z-Y, Kiyoshi T, Matsumoto S and Lee S-H 2012 Magnetic lens effect using Gd-Ba-Cu-O bulk superconductor in very high magnetic field *J. Appl. Phys.* **111** 07E728

[9] Takahashi K, Fujishiro H and Ainslie M D 2018 A new concept of a hybrid trapped field magnet lens *Supercond. Sci. Technol.* **31** 044005

[10] Nakamura T, Tamada D, Yanagi Y, Itoh Y, Nemoto T, Utumi H and Kose K 2015 Development of a superconducting bulk magnet for NMR and MRI *J. Magn. Reson.* **259** 68–75

[11] Namba S, Fujishiro H, Ainslie M D, Takahashi K, Namburi D K, Zhou D and Naito T 2019 Design optimization of a hybrid trapped field magnet lens (HTFML) *IEEE Trans. Appl. Supercond.* **29** 6801605

[12] Shinden M, Namba S, Hirano T, Fujishiro H, Naito T and Ainslie M D 2000 Numerical simulation of a hybrid trapped field magnet lens (HTFML) magnetized by pulsed fields *J. Phys.: Conf. Ser.* **1590** 012048

[13] Namba S, Fujishiro H, Naito T, Ainslie M D and Zhou D 2000 Realisation of hybrid trapped field magnetic lens (HTFML) consisting of REBCO bulk lens and REBCO bulk cylinder at 77 K *J. Phys.: Conf. Ser.* **1559** 012079