



Palm-size miniature superconducting bulk magnet

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ABSTRACT

The development of a small, light, powerful and energy-efficient superconducting magnet has been desired in order to realize better efficiency and manipulability in guiding magnetic nano-particles, magnetic organic cells and other items to the right place. This study focuses on the development of a high-temperature superconducting (HTS) bulk magnet characterized by comparatively low leak magnetism despite a relatively high magnetic field. On this basis, the authors developed a palm-sized superconducting bulk magnet, which is the world's smallest, lightest, and lowest power consuming, as well as a new technology to effectively magnetize such a bulk magnet in a compact Stirling-cycle cryocooler (magnet C) with a pre-magnetized HTS bulk magnet (magnet B) in a compact cryocooler. This technology is demonstrated in two steps. In the first step, magnet B is magnetized using a superconducting solenoid magnet with a high magnetic field (magnet A) via the field cooling method. In the second step, magnet C is magnetized in the high magnetic field of magnet B. The prototype magnet C weighs 1.8 kg, and measures $235 \times 65 \times 115$ mm ($L \times W \times H$). Magnet B was magnetized to 4.9 T using a 5 T magnet, and the target, magnet C, was magnetized using magnet B so that its maximum trapped magnetic flux density reached the value of 3.15 T. The net power consumption in a steady cooling state was 23 W, which is very low and comparable to that of a laptop computer.

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1. Introduction

Recently, high-temperature superconducting bulk magnets (hereafter: 'superconducting bulk magnet') capable of generating high magnetic flux density in a small space have been widely used, and there has been much research and development of technologies that use this strong magnetic force. Examples include wastewater purification equipment [1–3], desktop NMR (nuclear magnetic resonance) systems [4], desktop MRI (magnetic resonance imaging) systems for small animals [5,6], magnetic stem cell delivery systems, MDDS (magnetic drug delivery systems) [7] and X-ray studies using synchrotron radiation [8]. We have previously developed a hand-held, high-temperature superconducting bulk magnet system [9] that can be used in MDDS and magnetic stem cell delivery systems and that weighs less than 10 kg. Users of these magnet systems desire an energy-efficient superconducting magnet that is lighter, smaller, and of a size that facilitates easy operation.

One reason superconducting bulk magnets tend to be avoided is that, once magnetized, the bulk superconductor must constantly be kept at low temperature. Superconducting bulk magnets in which a high-temperature bulk superconductor (hereafter: 'bulk superconductor') is continuously cooled by a cryocooler result in high electrical costs for the user. To reduce electrical costs as much

as possible, we need to lower the amount of heat that penetrates the bulk superconductor, use a highly efficient cryocooler with the minimum cooling capacity required, and keep the amount of power consumed by the cryocooler low.

We have developed a miniature superconducting bulk magnet that greatly reduces power consumption and fits in the palm of one's hand. A Stirling-cycle cryocooler with an integrated compressor was selected to ensure that the cryocooler was small and light enough to be portable. Our new magnetization method [10], magnetizing a superconducting bulk magnet with another one, can be used to miniaturize the magnet. We report the magnetization properties trapped from using the field cooling method (hereafter: 'FC Method') on our prototype of a miniature superconducting bulk magnet.

2. New magnetization method and optimized magnetization

2.1. New magnetization method

This magnetization method consists of two steps. First, a superconducting bulk magnet with an integrated cryocooler and built-in ring bulk superconductor (hereafter, 'Magnet B') is magnetized by a pre-excited superconducting solenoid magnet with a high magnetic field (hereafter, 'Magnet A') using the FC Method. Second, a miniature superconducting bulk magnet with an integrated cryocooler (hereafter: 'Magnet C') is magnetized using the FC Method in the magnetic field of Magnet B.

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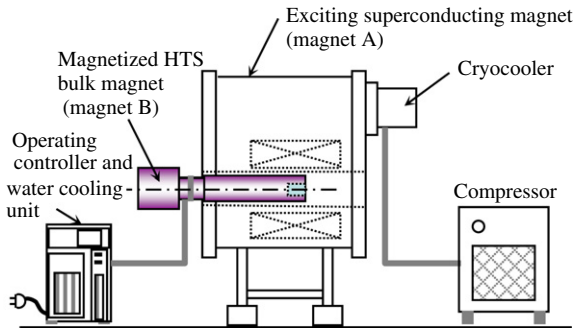


Fig. 1. First magnetization system where a superconducting bulk Magnet B is magnetized by solenoid Magnet A.

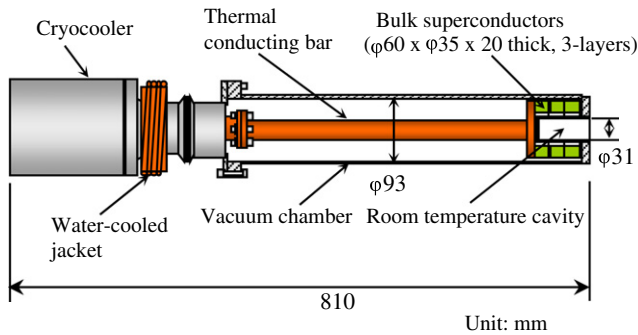


Fig. 2. Schematic overview of the HTS bulk Magnet B for a two-step magnetization system, with three laminated high- T_c bulk superconductors in the vacuum chamber.

As shown in Fig. 1, when Magnet B is magnetized by Magnet A in the first step, the cryocooler of Magnet B must be positioned outside the leakage magnetic field of Magnet A, because it has a built-in electric motor that cannot operate in the presence of the magnetic field. Therefore, the bulk superconductor of Magnet B, placed in the center of the magnetic field of Magnet A, must be positioned away from the cryocooler, and the two must be thermally connected via a copper or aluminum thermal conductor. This means that the surface of Magnet B that needs to be cooled to low temperature increases, which increases the amount of heat penetration, and therefore a high-performance cryocooler must be used. This makes the miniaturization of Magnet B difficult, and the operating power consumption cannot be reduced.

However, the scope of the leakage magnetic field of the magnetized Magnet B is much smaller compared to that of Magnet A, meaning that the cryocooler used in Magnet C can be placed close to Magnet B. Thus, Magnet C can be miniaturized.

2.2. Optimizing size of bulk superconductor

We used a ring bulk superconductor with an outer diameter of 60 mm for Magnet B. This size was selected, because the inner diameter of the bore of Magnet A was 100 mm at normal temperature, and the size of the vacuum chamber of Magnet B also had to be taken into account. The larger the exciting magnetic field of Magnet B and the diameter D_c of the bulk superconductor of Magnet C, the more the magnetic flux density trapped in Magnet C increases. As the exciting magnetic field of Magnet B, that is, the trapped magnetic field in the room temperature cavity of the ring bulk superconductor of Magnet B, becomes stronger, the inner diameter D_b of the bulk superconductor of Magnet B will have to be smaller. However, if the outer diameter of the bulk superconductor of Magnet C inserted in the cavity becomes smaller, the magnetic flux density obtainable also decreases. After considering



Fig. 3. One of the $\text{GdBa}_2\text{Cu}_3\text{O}_7$ ring bulk superconductors used in Magnet B.

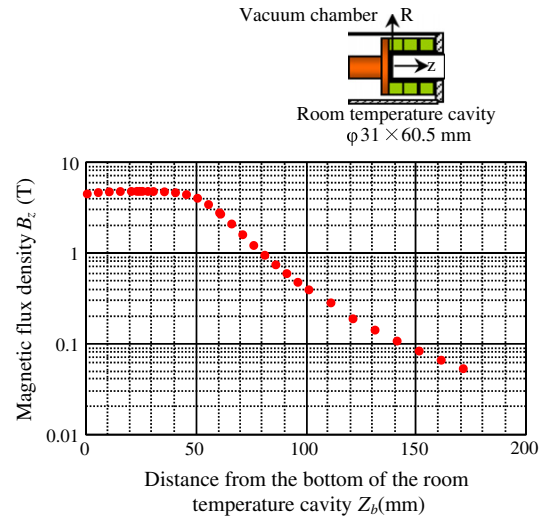


Fig. 4. Measured magnetic flux density B_z distribution at the bottom center of the magnet B room-temperature cavity under magnetization in the 5 T field of magnet A.

a variety of combinations for D_b and D_c , and conducting a numerical analysis using Bean's model [11] method to compare the trapped magnetic fields of Magnet B and C, we selected a D_b and D_c of 35-mm and 20-mm, respectively.

3. Results of magnetization experiment

3.1. Structure of Magnet B and trapped magnetization properties

The structure of Magnet B is shown in Fig. 2. The material of the ring bulk superconductor used is one of the Gd-series (Gd–Ba–Cu–O) and, as shown in Fig. 3, an aluminum alloy ring is fixed to its outer circumference. Three layers of ring bulk superconductors were used, and each had an outer and inner diameter of respectively 60-mm and 35-mm, and a thickness of 20 mm. The inner room temperature cavity has an inner diameter and depth of 31-mm and 60.5-mm respectively. The center of the second ring bulk superconductor placed in the center of the magnetic field of Magnet A and the tip of the cryocooler were placed 610 mm apart in order to ensure stable operation of the cryocooler. A Stirling-cycle cryocooler with an integrated compressor was used.

After the room-temperature ring bulk superconductors of Magnet B had been inserted into the bore of Magnet A, which was excited to 5 T, the ring bulk superconductors were cooled to about 38 K by the cryocooler. Magnet A was then demagnetized, causing Magnet B to be magnetized. The magnetization properties trapped in the room temperature cavity of Magnet B are shown in Fig. 4.

We let Z_b be the axial distance from the bottom of the cavity, and B_z the magnetic flux density in this direction. As can be seen

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