Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 67 (2015) 1005 – 1009

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

# Attempt to generate a strong and uniform magnetic field by face-to-face HTS bulk elements in a magnet system

Tetsuo Oka[a,]*, Eri Hirayama[a], Yasuhiro Takahashi[a], Tomoaki Kanai[a], Jun Ogawa[a], Satoshi Fukui[a], Takao Sato[a], Kazuya Yokoyama[b], Takashi Nakamura[c]

*[a]Niigata University, 8050 Ikarashi-Ninocho, Nishi-Ward, Niigata 950-2181, Japan*
*[b]Ashikaga Institute of Technology, 268-1 Omae-cho, Ashikaga 326-8558, Japan*
*[c]RIKEN, 2-1 Hirosawa, Wako 351-0198, Japan*

**Abstract**

A unique experimental attempt aiming to obtain a uniform magnetic field space as required for NMR has been carried out with use of HTS bulk magnets. The magnetic poles were activated as 1.8 T (North) and 1.4 T (South) at 30 K by applying a pulsed magnetic field up to 7 T, and positioned face-to-face with gaps less than 70 mm. The uniformity of the magnetic field required for detecting the NMR signals is less than 1,500 ppm at more than 0.3 T in the cross sectional plane of 2 x 2 $mm^2$. After the preliminary trials which revealed a uniformity of 5,421 ppm at 0.44 T in a 70 mm gap, we attached a ferromagnetic iron plate to a magnetic pole surface to change the magnetic field distribution to be concave. The best uniformity of 358 ppm at 1.11 T was obtained at 9 mm distance from the iron plate surface in a gap of 30 mm. It is stated that the concave magnetic field distribution was compensated by the counter conical-shape field, resulting in the uniform field plane.


Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014

*Keywords:* Bulk magnet; superconductor; pulsed-field magnetization; magnetic field distribution; NMR

## 1. Introduction

Magnetic field generators with various forms, sizes, and magnetic field distributions have been constructed with use of melt-processed HTS bulk magnets (abbreviated as bulk magnet), and examined for practical industrialization

* Corresponding author. Tel.: +81-25-262-7668; fax: +81-25-262-7666.
*E-mail address:* okat@eng.niigata-u.ac.jp


Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.187

of intense magnetic fields (Tomita and Murakami (2003), Oka et al. (2003), Noto et al. (2003)). The industrial features of bulk magnets were evaluated with respect to other magnetic field generators (Oka (2007)). The bulk magnets coupled with refrigerators are characterized by their intense and compact magnetic field. It is known that they exhibit quite peculiar distributions of the trapped magnetic field in comparison with ordinary solenoid magnets or conventional permanent magnets (Oka et al. (2000)). Among the promising applications, an outstanding study has been conducted for NMR magnets. Nakamura et al. (2007) succeeded in detecting the NMR signals in the bore of piled-up bulk magnets for the first time in the world. Furthermore, Ogawa et al. (2011) showed the MRI picture of an embryo of a mouse with use of the same system. Since such homogeneous magnetic fields are possible and to expand the practical application areas of bulk magnets, we aim to investigate the uniformity of the magnetic field in the gap between face-to-face positioned magnetic poles which contain a pair of bulk magnets and cryo-coolers (Oka et al. (2014)). In this paper, we present the magnetic field distributions of the bulk magnets which were activated by the pulsed field magnetization (PFM) technique. The uniformity is discussed from the view point of possible use for the compact NMR devices which have been never realized in the past.

## 2. Experimental

Figure 1 shows the face-to-face type bulk magnet system which was employed in the experiment. In order to install the bulk magnets in the system, we prepared a pair of Gd123 -based bulk magnets which were manufactured by Nippon Steel Co. and Dowa Mining Co. The dimensions are 60 mm in diameter and 15 mm in thickness. A pulsed magnetic field less than 7 T was successively applied to the bulk magnets with use of a couple of pulse coils like in the IMRA method (Oka (2007)). The bulk magnets were activated as 1.8 T (N) and 1.4 T (S) poles, which were measured at each pole surface, and positioned face-to-face with gap less than 70 mm.

As shown in Fig. 2, the trapped field distribution in the space between the magnetic poles was measured after the PFM process by scanning with a Hall sensor (F. W. Bell, BH703). We adopted a three-dimensional Hall sensor which gave us the information along the horizontal $B_x$ and vertical $B_y$ directions as well as the z-axis direction $B_z$ which is along the centre axis of the bulk magnets. The sensors were intermittently scanned with a 2 mm pitch and an interval of 1 s. We measured the field distributions at the centre in the gap and in the region near the left-hand side pole surface, as shown in Fig. 2 and Fig. 5(b). The magnetic field data $B$ were expressed in their vector magnitudes. As shown in Fig. 3, the parameters $A$ and $B_{max}$ were derived from curve fitting for the measured data. The uniformity $U$ of magnetic field was defined by the following equation.

$$U = \frac{A}{B_{\max}} \times 10^6 \,\mathrm{ppm}\cdot$$

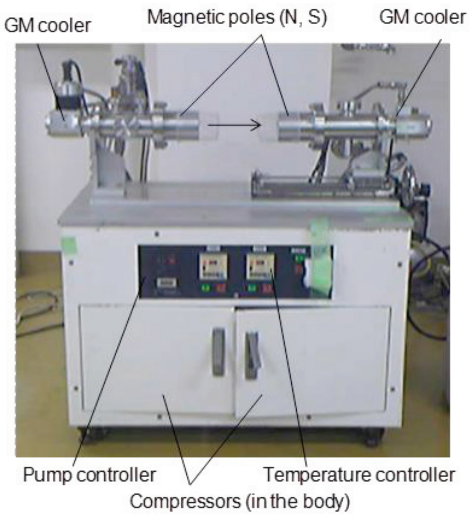


Fig. 1. Photo of the face-to-face HTS bulk magnet system

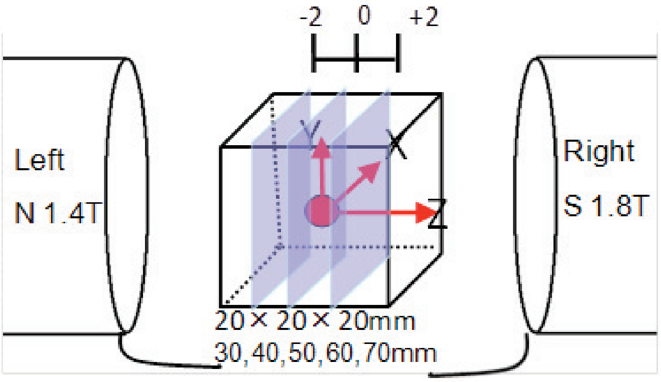


Fig. 2. Schematic view of the space measured between the magnetic poles.

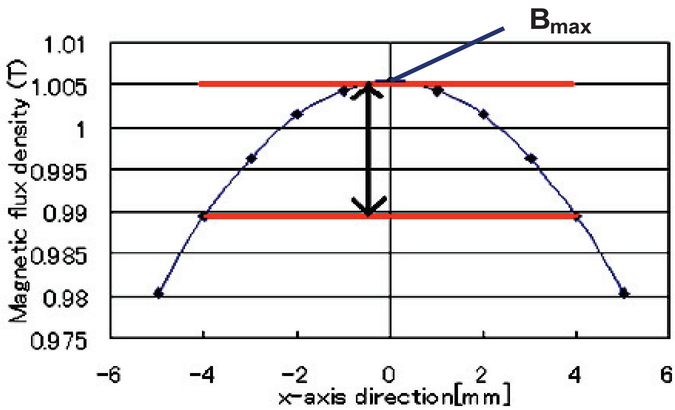


Fig. 3. Definition of uniformity ***U*** of the

## 3. Results and discussion

### *3.1. Distribution uniformity at the centre of the gap*

Since the magnetic field generated by the bulk magnets gives the strongest magnetic flux density just at the centre of the surface, the magnetic flux density at the centre of the space becomes weak and uniform with increasing gap size. The distribution however exhibits a conical shape, and the uniformity reached 5,421 ppm at 0.44 T even at the farthest position with a 70 mm gap between the magnetic poles. Then, in order to make the distribution smooth, we attached an iron plate of 2 mm thickness on the right-side pole surface generating 1.8 T. As shown in Fig. 4, the distribution exhibited concave shape in the region near the pole surface. It gradually changes to be conical with increasing distance from the surface. One can see the flat line at the position of 15 mm, as shown in Fig. 4(d). When a couple of magnetic poles bearing the iron plates were settled face-to-face, we obtained an almost flat distribution with a uniformity of 2,516 ppm at 0.477 T at the centre of a 60 mm gap.

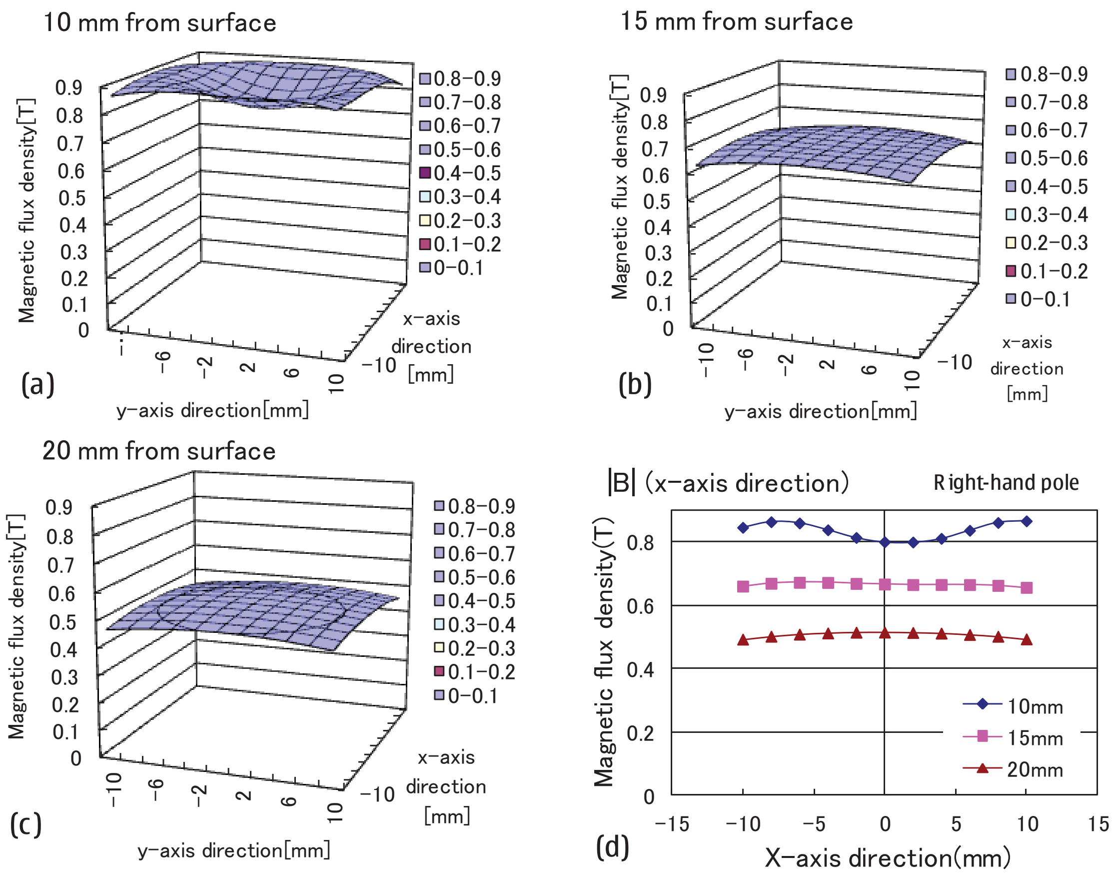


*Fig. 4. Magnetic field distributions (single pole with an iron plate) at 10, 15 and 20 mm from the pole surface with a gap size of 70 mm.*

### *3.2. Coupling the concave and conical distributions*

Figure 5 shows another arrangement of the magnetic poles. The iron plate is attached only on the left-hand side. And the concave and the countering conical shapes were precisely coupled between the gaps of 30 – 70 mm. We estimated the uniformity of the magnetic field distributions as a function of the distance along the z-axis from the pole surface, as shown in Fig. 5(b).

Figure 6 shows the magnetic field uniformity with increasing distance from the left-hand side magnet surface as a function of the gap size between the poles. The data show a similar tendency in the distributions, and the profile in every gap has a minimum point in the valley in the region near the surface. The most uniform distribution of 358 ppm at 1.11 T was obtained at 9 mm from the surface in the 30 mm gap. This performance is significantly above the level of 1,500 ppm, which would enable us to observe NMR signals.

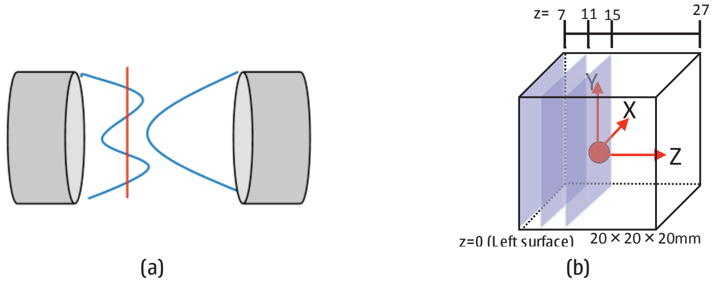


Fig. 5. Schematic illustration of (a) coupled magnetic poles and (b) measured planes between them.

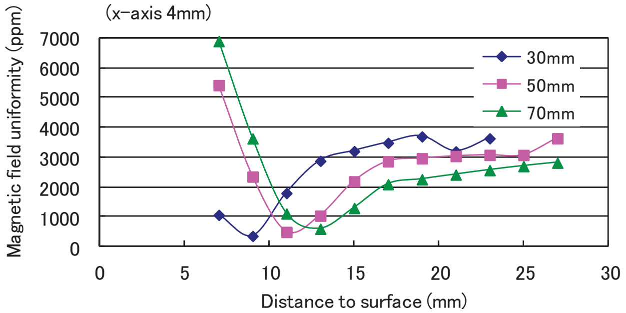


Fig. 6. Magnetic field uniformity measured in the space between various gaps of face-to-face magnetic poles attached an iron plate on one side.

## 4. Conclusion

The uniformity of the magnetic field was improved showing an almost flat distribution in the region near the pole surface when the concave and conical magnetic field distributions were coupled together with use of an iron plate attached to the pole surface. We obtained a best uniform distribution of 358 ppm at 1.11 T at 9 mm distance from the magnetic pole on the left-hand side. The uniformity as a function of various gap sizes exhibited similar profiles. This suggests that the minimum values lies in the valleys in the regions from 9 to 13 mm distance from the pole surface. It is worth noting that the distributions may be improved when we would adjust the peaks more precisely.

## References

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, 517–520.

Oka T., Yokoyama K., Itoh Y., Yanagi Y., Yoshikawa M., Ikuta H., Mizutani U., Okada H., Noto K., 2003. A 3 tesla magnetic field generator using melt-processed bulk superconductors as trapped field magnets and its applications. Physica C 392–396, 709–712.

Noto K., Oka T., Yokoyama K., Katagiri K., Fujishiro H., Nakazawa H., 2003. High $T_c$ bulk magnets and their applications. Physica C 392–396, 677–683.

Oka T., 2007. Processing and applications of bulk HTSC. Physica C 463–465 7–13.

Oka T., Yokoyama K., Itoh Y., Yanagi Y., Yoshikawa M., Ikuta H., Mizutani U., 2000. Construction of a 2–5 T class superconducting magnetic field generator with use of an Sm123 bulk superconductor and its application to high magnetic field demanding devices. Physica C 335, 101–106.

Nakamura T., Itoh Y., Yoshikawa M., Oka T., Uzawa J., 2007. Development of a Superconducting Magnet for Nuclear Magnetic Resonance Using Bulk High-Temperature Superconducting Materials. Concepts in Magnetic Resonance Part B (Magnetic Resonance Engineering) 31B(2), 65-70.

Ogawa K., Nakamura T., Terada Y., Kose K., Haishi T., 2011. Development of a magnetic resonance microscope using a high *Tc* bulk superconducting magnet. Applied Physics Letters 98, 234101-1–234101-3.

Oka T., Hirayama E., Kanai T., Ogawa J., Fukui S., Sato T., Yokoyama K., Nakamura T., 2014. Strong Magnetic Field Generators Containing HTS Bulk magnets and Compact Refrigerators and Their Field-Trapping Performances. IEEE Transactions on Applied Superconductivity 24 doi:10.1109/TASC.2013.2284859.