

# Measurements of the magnetic field distribution in the high $T_c$ superconducting bulk magnet during the magnetization process

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## INTRODUCTION

A high critical temperature ( $T_c$ ) superconducting bulk magnet is a novel magnet for magnetic resonance imaging [1]. The bulk magnet acts like a permanent magnet by trapping an external magnetic field and can produce a stable magnetic field like a conventional superconducting magnet (SCM) without a large installation space, because the cryostat structure is very simple. However, it is a still challenging problem to achieve a homogeneous magnetic field sufficient for MRI because of the complicated magnetization process of the bulk magnet. In this study, we clarified the magnetization process by measuring the magnetic field distribution of the bulk magnet.

## MATERIALS AND METHOD

The MRI system we used consists of a superconducting bulk magnet, a 3-axis gradient coil set, an 8 mm diameter saddle shaped RF coil, and an MRI console. The bulk magnet comprised six annular superconductors (60 mm OD, 28 mm ID, 20 mm high,  $T_c = 93\text{K}$ ) made of c-axis oriented single-domain  $\text{EuBa}_2\text{Cu}_3\text{O}_y$  crystals. The bulk magnet was installed in a cryostat of which room temperature bore has 23 mm diameter.

The bulk magnet was magnetized by a field cooling method as follows. Firstly, the bulk magnets were cooled down to 50 K using a pulse tube refrigerator in a constant external magnetic field  $B_e$  (field strength = 4.74 T) produced by an conventional SCM (JASTEC JRTC-300/89) as shown in Fig. 1. After temperature stabilization of the bulk magnet,  $B_e$  was reduced from 4.74 to 0.0 T.

$B_0$  distribution was measured using  $\text{CuSO}_4$  doped water in an 8 mm diameter NMR sample tube and a phase shift method based on 3D spin echo sequences (TR/TE=100/20 ms, FOV = 12.8 mm<sup>3</sup>, matrix size = 64<sup>3</sup>) both during the field cooling process and during the field decreasing process at the  $B_e$  of 4.74, 4.0, 3.0, 2.0, 1.0, and 0.0 T. The  $B_0$  inhomogeneity was evaluated in the central cylindrical area (diameter = 6 mm, height = 6 mm).

## RESULTS AND DISCUSSION

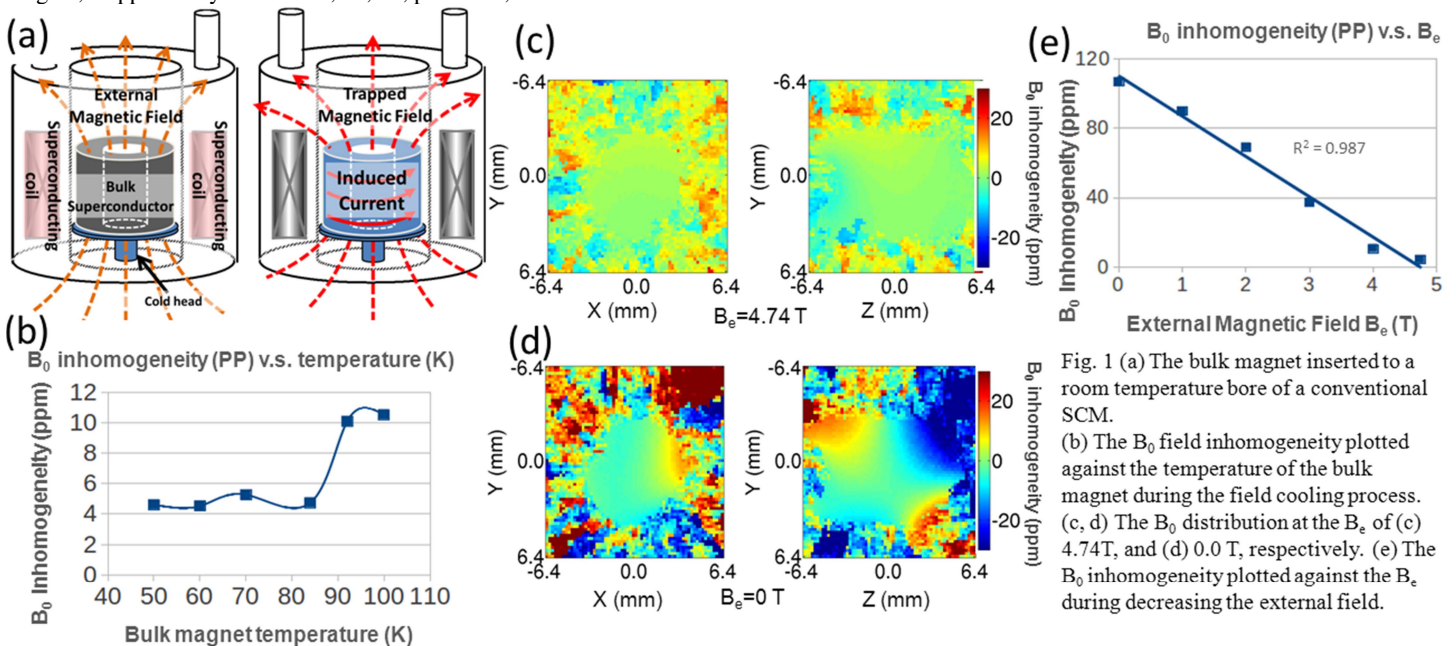
Figure 2 shows the  $B_0$  inhomogeneity (peak-To-peak: PP) plotted against the temperature of the bulk magnet during the cooling process. The inhomogeneity of the bulk magnet varied steeply around the temperature of  $T_c$  which may be caused by the superconducting transition. Figure 3(a-c) show  $B_0$  distribution at the  $B_e$  of 4.74, 3.0, 0.0 T, respectively. As the  $B_e$  was reduced, the  $B_0$  inhomogeneity increase linearly with  $B_e$  as shown in Fig. 3(d). Table 1 shows magnitudes of the spherical harmonic terms up to second-order of  $B_0$  distribution at the  $B_e$  of 4.74 T, and 0.0 T. This table clearly shows that the magnitude of  $T_{2,2}$ , and  $T_{2,-2}$  terms drastically increased which suggests asymmetric superconducting current distribution in the bulk magnet possibly caused by inhomogeneity of the bulk crystal.

## CONCLUSION

In this study, we measured  $B_0$  distribution in the bulk magnet both during the field cooling process in the constant external magnetic field (4.74 T) and in the reducing external field in the constant temperature (50 K). As a result, we successfully observed how the magnetic flux was trapped by the bulk magnet or the superconducting current was induced in the bulk magnet. Our experimental results and a computer simulation for the bulk magnet will develop a new magnetization protocol or a new bulk magnet design to achieve more homogeneous magnetic field for MRI.

## REFERENCE

[1]K. Ogawa, et al., "Development of a magnetic resonance microscope using a high  $T_c$  bulk superconducting magnet," Applied Physics Letters, 98, 23, p.234101, 2011.



Tab. 1 The magnitude of the spherical harmonic terms up to second-order for the  $B_0$  inhomogeneity at the  $B_e$  of 4.74 T and 0.0 T.

$B_e$ (T)	4.74	0
$T_{1-1}$ (ppm)	0.18	12.81
$T_{10}$	-0.10	15.88
$T_{11}$	3.27	2.66
$T_{2-2}$	-0.12	0.92
$T_{2-1}$	<b>0.25</b>	<b>54.29</b>
$T_{20}$	2.80	4.31
$T_{21}$	<b>2.28</b>	<b>34.86</b>
$T_{22}$	0.18	7.43