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Evaluation of Magnetic Force Distribution on A Pair of Superconducting Bulk Magnets

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Abstract

We study on the construction of superconducting permanent magnets by RE123 bulk materials and the investigation of these industrial applications such as a magnetic separation. A bulk magnet can generate strong magnetic fields exceeding 2 T, which is the limit of ordinary iron-cored electromagnets, in a compact device with a low running cost. A magnetic field distribution of the bulk magnet is a cone shape, and it contributes to an increase of magnetic force which is proportional to the product of a magnetic field and its gradient. It is important to evaluate magnetic force when the application of the bulk magnet is discussed. In this paper, two Gd123 bulk materials of 65 mm in diameter were magnetized using a pair of superconducting bulk magnet system and three-axis components of magnetic flux density (B_x, B_y, and B_z) in an open space between the magnetic poles were scanned with pitch of 2 mm in each direction. From these measured data, the axial and radial components of magnetic force factor, $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ and $B_r \cdot \mathrm{d}B_r/\mathrm{d}r$, were calculated. At 10 mm gap, the $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ value reached 180.6 T^2/m for a field of 2.33 T, which is comparable to B_z=6.76 T for a common 10 T-100 mmϕ superconducting magnet.

Keywords: superconducting bulk magnet; magnetic field distribution; magnetic force; pulsed-field magnetization; magnetic separation

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1. Introduction

A superconducting bulk magnet, in which a high-T_c $REBa_2Cu_3O_{7-x}$ bulk superconductor (RE123; RE = Y, Sm, Gd, etc) is magnetized and used like a permanent magnet, is attracting much attention as one of the applications of bulk materials [1]. Since the bulk magnet can generate strong magnetic field exceeding 2 T that is the limit of ordinary iron-cored electromagnets by compact device in a low running cost, various industrial applications such as motor/generator [2], magnetron spattering [3], drug delivery system (DDS) [4] and magnetic separation [5, 6] are considered. To propagate an industrial application of bulk magnet in the feature, it is necessary to enhance a magnetic force, as well as amplitude of magnetic field. A magnetic force F is expressed by

$$F = \frac{\chi}{\mu_0} B \frac{\mathrm{d}B}{\mathrm{d}z}$$

where, χ is the volume susceptibility of the separated substance, μ_0 is the permeability of vacuum, B is the field intensity, and z is the vertical position in the (1) magnetic field [7]. The term of $B \cdot \mathrm{d}B/\mathrm{d}z$ is also designated as a magnetic force factor. In Eq. (1), when the separated material is ferromagnetic, the B and $\mathrm{d}B/\mathrm{d}z$ values do not need to be large due to the values of large χ. To separate the paramagnetic material and the ferromagnetic material with small volume, on the other hand, the large B and $\mathrm{d}B/\mathrm{d}z$ are necessary. Therefore, the reinforcement of magnetic force factor is an important problem in the magnetic separation and DDS for paramagnetic substance.

Although it is known that the bulk magnet has large magnetic gradient in the established theory, the magnetic force factor has not been quantitatively evaluated. In this paper, two Gd123 bulk superconductors of 65 mm in diameter are magnetized by a pulsed-field magnetization method and they are arranged face-to-face with the different pole (*N*-*S*), and then the magnetic field distribution in the open space between the magnetic poles while changing a gap of 50 to 10 mm is measured. Using the experimental data, the axial and radial components of the magnetic force factor are calculated.

2. Experimental

Fig. 1 shows a schematic view of a face-to-face type superconducting bulk magnet system, in which a pair of bulk superconductors is oppositely located. The bulk materials are highly *c*-axis oriented and consist of 75.0 wt.% $GdBa_2Cu_3O_y$ (Gd123), 24.5 wt.% Gd_2BaCuO_5 (Gd211) and 0.5 wt.% Pt powder (Nippon Steel Corporation). The sample size is 65 mm in diameter and 15 mm in thickness, and it is impregnated by epoxy resin reinforced by glass fiber. The epoxy resin on the upper and lower sides of the bulk is removed to reduce a thermal contact resistance to the cold head. The bulk is set on a copper base connected to a cold head of GM refrigerator (GR301; AISIN SEIKI CO., LTD). A Hall sensor (BHT-921; F. W. BELL) and a thermometer are attached to the top surface of the bulk material and under the copper base, respectively. A superinsulation is wound around the bulk superconductor and they are covered with a vacuum vessel. A gap between the top surface of the material and the vessel is 3 mm. The left magnetic pole (pole 1) is settled to the table and the right one (pole 2) is movable along the guide rail to change a gap between a pair of bulk magnets.

The bulk materials are magnetized by the pulsed-field magnetization method. A magnetizing coil, in which a copper wire of 1.2x3 mm^2 is wound 112 turns, is located outside the vacuum vessel as shown in Fig. 1. The coil is cooled at liquid nitrogen temperature and pulsed magnetic field is generated by a condenser bank of 60 mF. The rising time of pulse is about 10 ms and the maximum field is about 7 T.

After the magnetizing coil is removed, the magnetic field distributions are measured by a three-axis type Hall sensor (BH-703; F. W. BELL) in an open space between magnetic poles while changing a gap of 50 to 10 mm. The sensor is scanned with a pitch of 2 mm within the area of 100x100 mm^2 including the magnetic pole of 87 mm in diameter on a parallel plane to the pole surface, where a gap between an initial position of the sensor and the surface of pole 1 is 1 mm.

Using the experimental data above, the magnetic force factors, $B_z \cdot dB_z/dz$ and $B_r \cdot dB_r/dr$, are calculated by Eq. (1).

3. Results and discussion

Table 1 shows the magnetizing results. When five pulsed-fields with the different amplitude are applied the trapped fields of poles 1 and 2 are 2.28 and 2.63 T, respectively.

Fig. 2 shows the axial components of the magnetic field and the magnetic force factor distributions, B_z and $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$, on the surface of pole 1 for a single pole and the gap of 50, 30 and 10 mm. In a single pole, the maximum values of B_z and $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ are 1.09 T and 40.0 T^2/m, respectively. Then, the B_z and $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ values increase when the magnetic poles are arranged face-to-face in 50 mm gap. However, these values of the first quadrant are higher than those of other region, and it is considered that this is because a center axis in the opposed magnetic pole slightly shifts. The peak value of B_z is increased with decreasing a gap, and moreover the distances of a contour line set narrow.

Fig. 3 shows the radial components of the magnetic field and the magnetic force factor distributions, B_r and $B_r \cdot \mathrm{d}B_r/\mathrm{d}r$ on the surface of pole 1 for a single pole and the gap of 50, 30 and 10 mm. In a single pole, the maximum values of B_r and $B_r \cdot \mathrm{d}B_r/\mathrm{d}r$ are 0.50 T and 13.4 T^2/m, which are appropriately one-fifth and one-twentieth than those of the axial components, respectively. In contrast to the results of the axial components, both of B_r and $B_r \cdot \mathrm{d}B_r/\mathrm{d}r$ decrease rapidly with a gap, and reaching almost zero for d=10.

Fig .4 summarizes (a) the axial components and (b) the radial components of the maximum values of magnetic force factor and magnetic field obtained by Figs. 2 and 3, in which the histograms and the solid lines indicate the magnetic force factor, $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ and $B_r \cdot \mathrm{d}B_r/\mathrm{d}r$, and the magnetic field, B_z and B_r, respectively. In Fig. 4(a), the B_z and $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ values of d=50 are about 30% and 60% higher than those of a single pole. These values are greatly enhanced with decreasing a gap, and reaching the values of 180.6 T^2/m and 2.33 T in d=10. It is noted that the B_z and $B_z \cdot \mathrm{d}B_z/\mathrm{d}z$ values are two and three times as large as those of d=50. It is confirmed to improve not only the magnetic field but also the magnetic force factor greatly by opposing a pair of magnetic poles and reducing the gap. In Fig. 4(b), on the other hand, the B_r and $B_r \cdot \mathrm{d}B_r/\mathrm{d}r$ values decrease rapidly with the gap, and reaching the values of 0.11 T and 0.78 T^2/m in d=10, in which they are one-quarter and one-twelfth as small as those of d=50. This is because the magnetic flux is aligned with the axial direction of bulk magnet.

Table 2 compares the B_z and $B_z \cdot dB_z/dz$ values of the bulk magnet and the common superconducting magnet (SCM) with a field of 10 T and a room-temperature bore of 100 mmφ (JMTD-10T100; JASTEC). In SCM, the magnetic force factor is about 21.5 T^2/m for a field of 2.33 T which is the maximum B_z for d=10 obtained by this experiment. To achieve a value of 180 T^2/m which is the maximum $B_z \cdot dB_z/dz$ of bulk magnets, on the other hand, a value of 6.76 T is necessary. These results imply that large magnetic force can be generated even in a weaker magnetic field in the bulk magnet than that of SCM.

4. Conclusions

To propagate an industrial application of bulk magnet, it is important to enhance the magnetic force, as well as strength of magnetic field. In this paper, we evaluated the magnetic force distributions generated by a pair of superconducting bulk magnets with Gd123 bulk materials of ϕ65x15 mm. The bulk magnets trapped the field of 2.82 and 2.63 T by the pulsed-field magnetization, and the magnetic field distributions in an open space between magnetic poles were measured between the gap from 50 to 10 mm. When the magnetic force factor was calculated using the experimental data the axial component achieved a value of 180.6 T^2/m for the trapped field of 2.33 T at 10 mm gap, which was comparable to the $B_z \cdot dB_z/dz$ value for a field of 6.76 T in the common 10 T-100 mmϕ superconducting magnet. Using the obtained data, more detailed investigations are in progress to enlarge the magnetic force.

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Table 1 / BLP-21 / ISS2009

Table 1. Experimental results of magnetization

pole	Polarity	Trapped Field B_T (T)	Temp. T_0 (K)	Applied Field $\mu_0 H$ (T)
1	*N*	2.28	44	5.46, 5.03, 4.65, 4.30, 3.92
2	*S*	2.63	40	5.46, 5.04, 4.65, 4.26, 3.89

Table 2 / BLP-21 / ISS2009

Table 2. Comparison of the magnetic field and the magnetic force factor in the bulk magnet and the common superconducting magnet.

	Magnetic field B_z (T)	Magnetic force factor $B_z \cdot dB_z/dz$ (T^2/m)
Bulk magnet	2.33	180.6
Common superconducting magnet with a field of 10 T and a room-temperature bore of ϕ100 mm	10	395.7
	6.76	180.8
	2.33	21.5

Figure captions

Fig. 1. Schematic view of a face-to-face type superconducting bulk magnet system.

Fig. 2. Magnetic field and magnetic force factor distributions on the surface of magnetic pole 1 for single pole and each gap, *d*. (axial components)

Fig. 3. Magnetic field and magnetic force factor distributions on the surface of magnetic pole 1 for single pole and each gap, *d*. (radial components)

Fig. 4. The gap dependence of magnetic force factors and trapped fields.

Fig.1

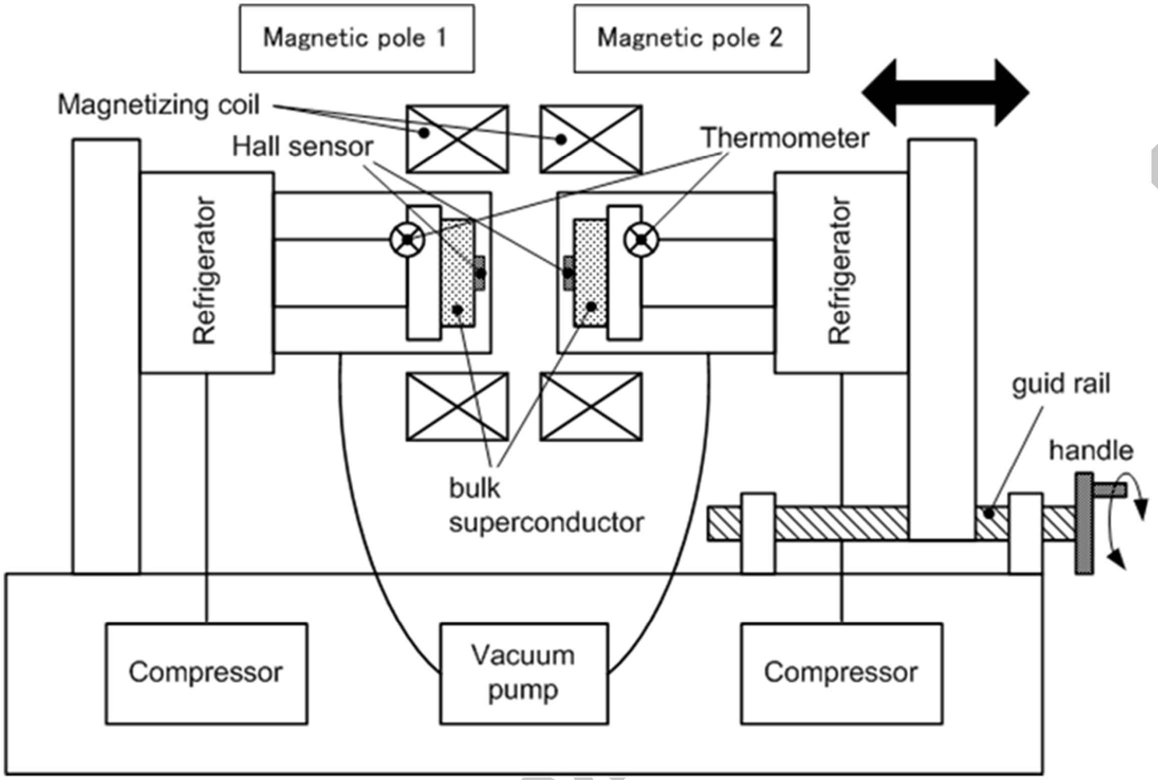

Magnetic pole 1
Magnetic pole 2
Magnetizing coil
Hall sensor
Thermometer
Refrigerator
Refrigerator
guid rail
handle
bulk
superconductor
Compressor
Vacuum
pump
Compressor

Fig.2(a)

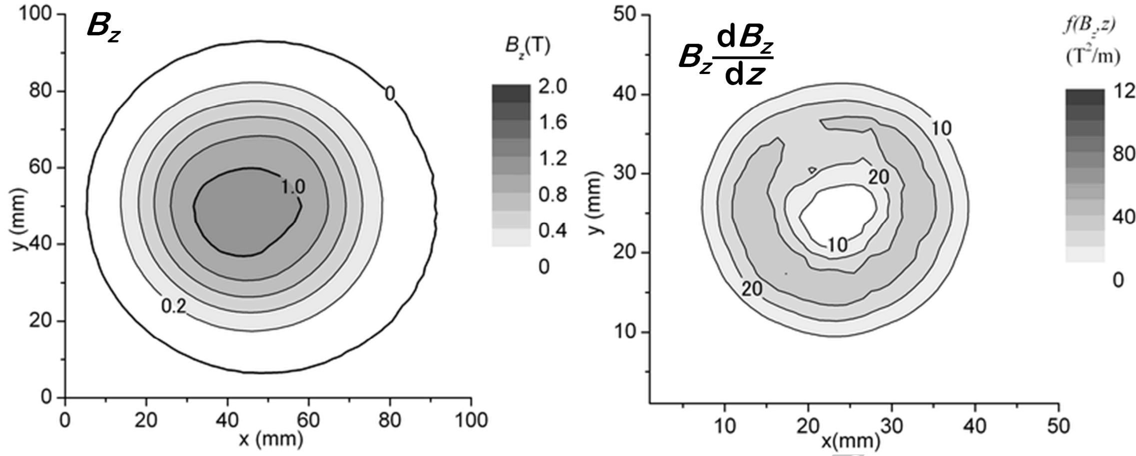

B_z
B_z(T)
2.0
1.6
1.2
0.8
0.4
0
0
1.0
0.2
y (mm)
x (mm)
0
20
40
60
80
100
$B_z \frac{dB_z}{dz}$
$f(B_z,z)$ (T^2/m)
120
80
40
0
10
20
20
10
y (mm)
x(mm)
10
20
30
40
50

Fig.2(b)

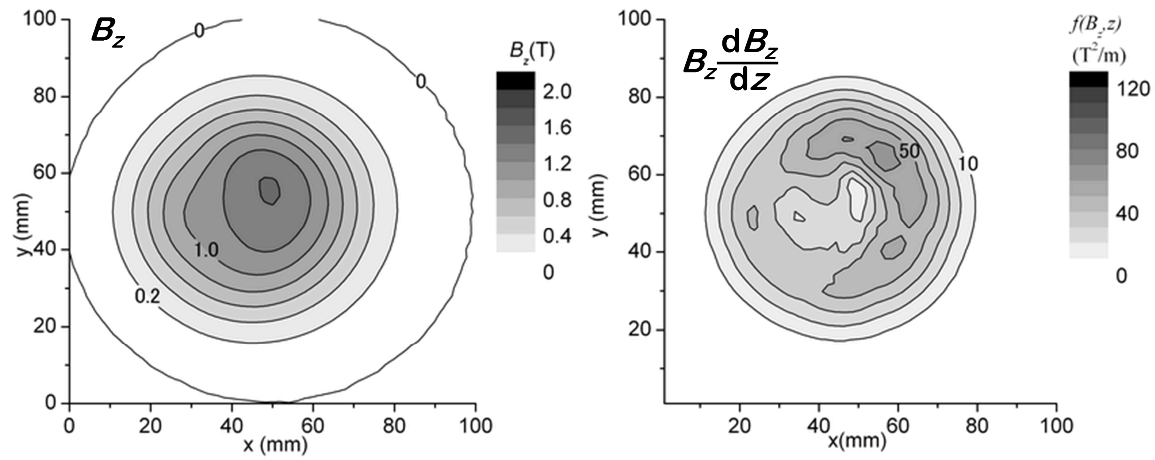

B_z
0
0
0.2
1.0
B_z(T)
2.0
1.6
1.2
0.8
0.4
0
y (mm)
x (mm)
$B_z \frac{dB_z}{dz}$
50
10
$f(B_z,z)$
(T^2/m)
120
80
40
0
y (mm)
x(mm)

Fig.2(c)

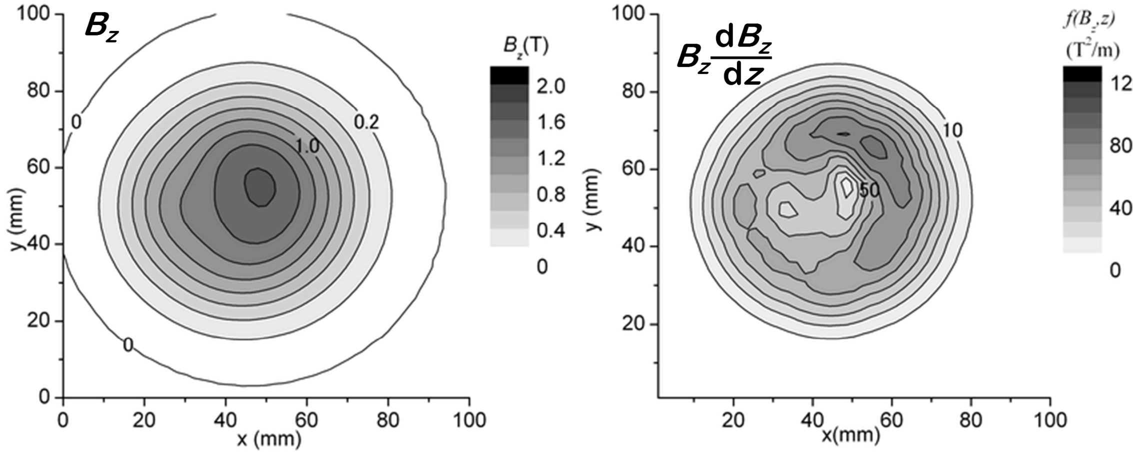

B_z
100
80
60
40
20
0
y (mm)
0
20
40
60
80
100
x (mm)
0
0.2
1.0
0
B_z(T)
2.0
1.6
1.2
0.8
0.4
0
$B_z\frac{dB_z}{dz}$
y (mm)
x(mm)
10
50
$f(B_z,z)$
(T^2/m)
120
80
40
0

Fig.2(d)

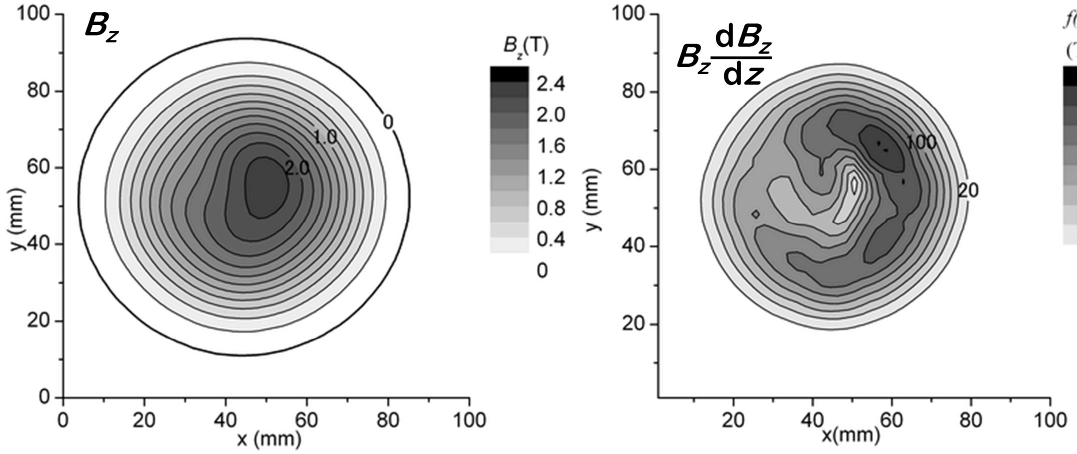

B_z
B_z(T)
2.4
2.0
1.6
1.2
0.8
0.4
0
1.0
2.0
y (mm)
x (mm)
0
20
40
60
80
100
$B_z \frac{dB_z}{dz}$
$f(B_z,z)$
(T^2/m)
180
120
60
0
100
20
y (mm)
x(mm)

Fig.3(a)

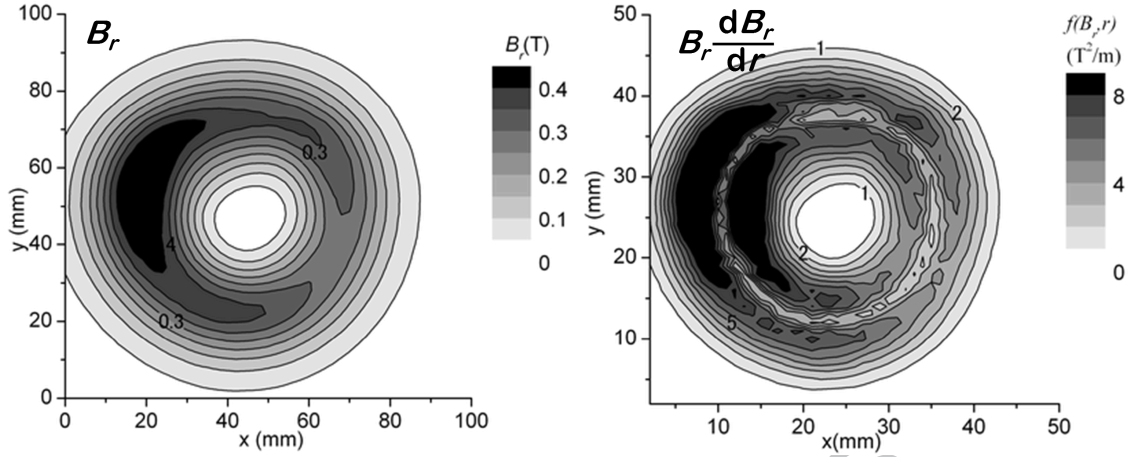

B_r
B_r(T)
0.4
0.3
0.2
0.1
0
0.3
4
0.3
y (mm)
x (mm)
0
20
40
60
80
100
$B_r \frac{dB_r}{dr}$
$f(B_r, r)$
(T^2/m)
8
4
0
1
2
1
2
5
y (mm)
x(mm)
10
20
30
40
50

Fig.3(b)

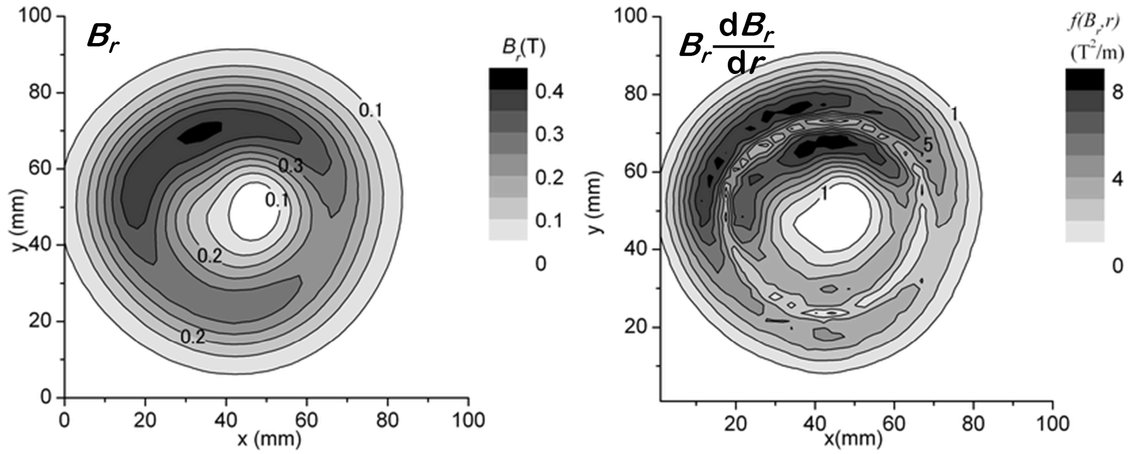

B_r
B_r(T)
0.4
0.3
0.2
0.1
0
0.1
0.3
0.1
0.2
0.2
y (mm)
x (mm)
0
20
40
60
80
100
$B_r\frac{dB_r}{dr}$
$f(B_r,r)$
(T^2/m)
8
4
0
1
5
1
y (mm)
x(mm)
20
40
60
80
100

Fig.3(c)

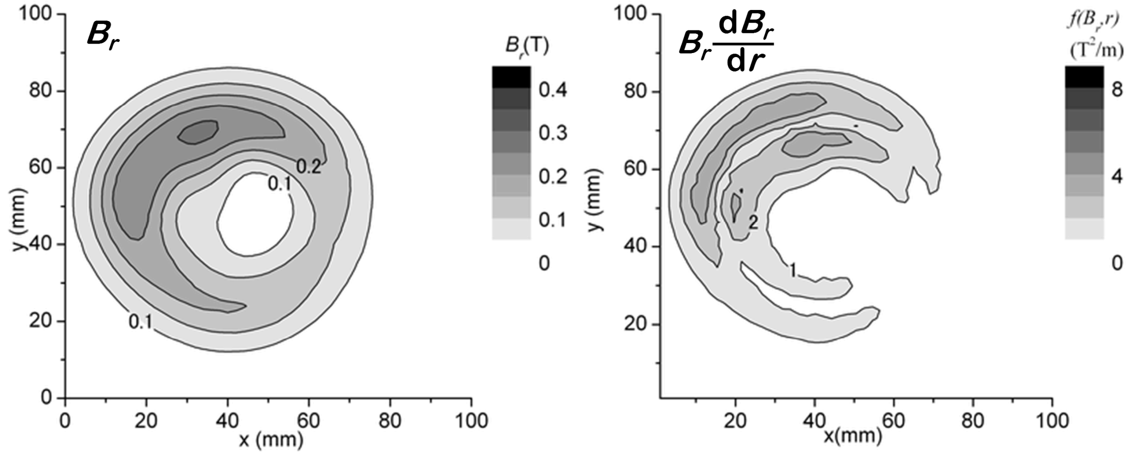

B_r
B_r(T)
0.4
0.3
0.2
0.1
0
0.2
0.1
0.1
y (mm)
x (mm)
0
20
40
60
80
100
$B_r \frac{dB_r}{dr}$
$f(B_r, r)$ (T^2/m)
8
4
0
2
1
y (mm)
x(mm)
20
40
60
80
100

Fig.3(d)

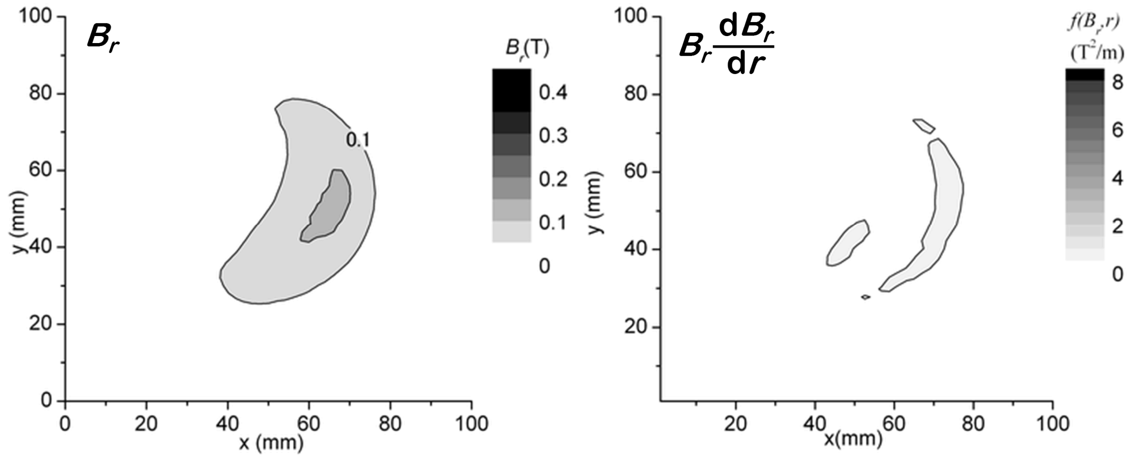
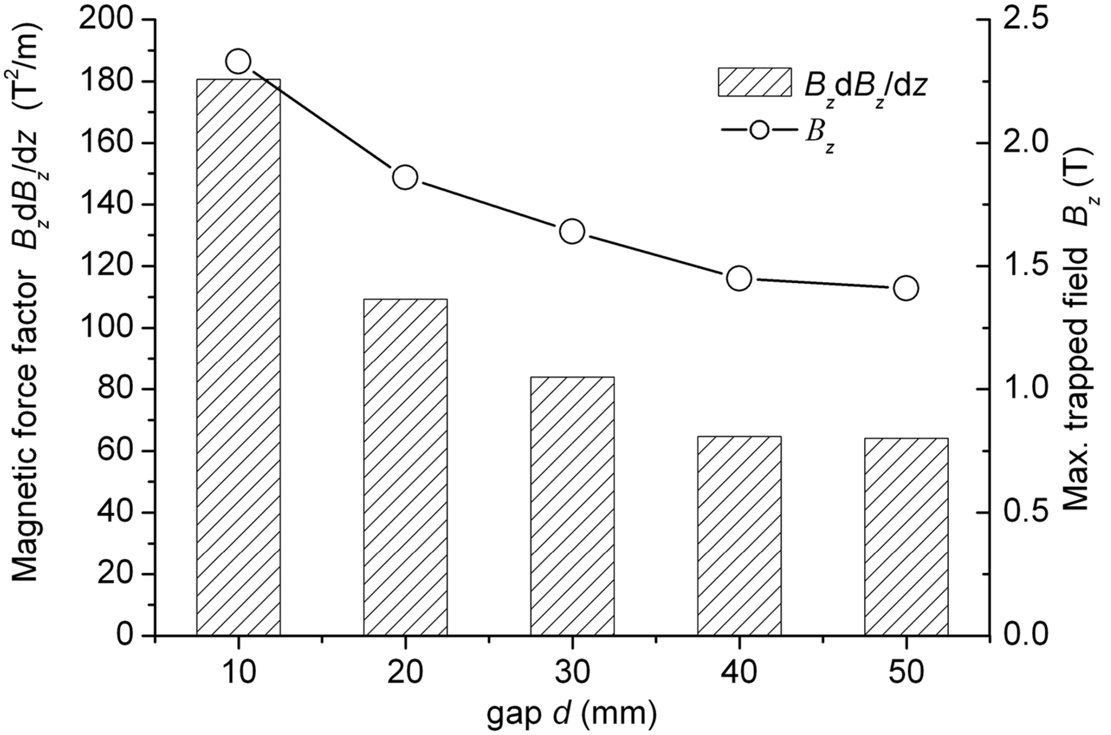
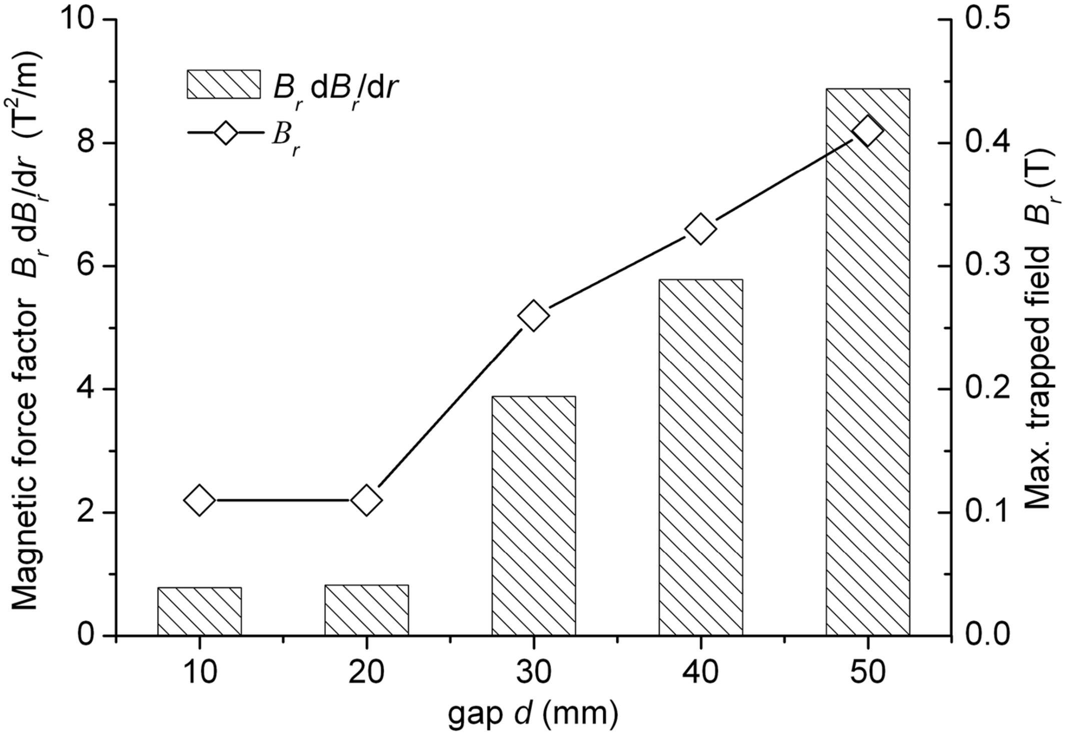

B_r
0.1
B_r(T)
0.4
0.3
0.2
0.1
0
y (mm)
x (mm)
100
80
60
40
20
0
$B_r \frac{dB_r}{dr}$
$f(B_r,r)$
(T^2/m)
8
6
4
2
0
y (mm)
x(mm)

Fig.4(a)



Magnetic force factor $B_z dB_z/dz$ (T^2/m)
Max. trapped field B_z (T)
gap d (mm)
$B_z dB_z/dz$
B_z
0
20
40
60
80
100
120
140
160
180
200
0.0
0.5
1.0
1.5
2.0
2.5
10
20
30
40
50

Fig.4(b)



B_r dB_r/dr
B_r
Magnetic force factor B_r dB_r/dr (T^2/m)
Max. trapped field B_r (T)
gap d (mm)
0
2
4
6
8
10
0.0
0.1
0.2
0.3
0.4
0.5
10
20
30
40
50