POSSIBILITY OF A SUPERCONDUCTING BULK MAGNET FOR THE MAGLEV TRAIN

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ABSTRACT

Superconducting magnets which use high critical temperature, T_c, oxide superconductors are promising for industrial applications including the magnetically levitated (Maglev) train. Since the discovery of high T_c superconductors in 1986, much effort has been devoted to developing materials with a high critical current density, J_c. Recent development shows that rare-earth $REBa_2Cu_30_{7-x}$ and light rare-earth $LREBa_2Cu_3O_{7-x}$ superconductors prepared by melt processes have a high J_c at 77 K in high magnetic fields. A wide variety of applications of (RE)-Ba-Cu-O superconductors have been proposed. Further, (LRE)-Ba-Cu-O bulk superconductors melt-processed in a reduced oxygen atmosphere, named oxygen-controlled-melt-growth (OCMG) process are very promising for high field application as a superconducting permanent magnet with liquid nitrogen refrigeration. Compared to a good quality melt-grown REBCO bulk, LREBCO bulks exhibit larger J_c in high magnetic fields and much improved irreversibility field, H_{irr}, at 77 K, implying that more effective flux pinning can be realized in a commercially feasible way. In this paper, we discuss the possibility of a superconducting bulk magnet for the Maglev train in the aspect of a preliminary design of the bulk magnet and also melt processing for REBCO and LREBCO bulk superconductors and their characteristic superconducting properties.

INTRODUCTION

Magnetization of $REBa_2Cu_3O_{7-x}$ (RE: Rare Earth, REBCO) superconductors [1] with a high critical current density (J_c) results in a strong bulk magnet. Therefore, the superconducting bulk magnet or the superconducting quasi-permanent magnet for the magnetically levitated (Maglev) train [2-3] with liquid nitrogen refrigeration could be realized, instead of Nb-Ti coils which require liquid helium as a coolant. Further a large $LREBa_2Cu_3O_{7-x}$ (LRE: Light Rare Earth, e.g. Nd, Sm, Eu, Gd, LREBCO) bulk superconducting magnet is believed to trap very high magnetic fields - over 5 T at 77 K. If that happens, it will have a great impact on future transport systems.

It has been expected to apply the REBCO bulk to a superconducting magnetic bearing, a flywheel, a motor, high field magnetic shielding, and a superconducting bulk magnet. [4] The trapped magnetic field of the superconducting bulk magnet with a large single domain has been reported to be superior to that of a conventional permanent magnet. It is known that the superconducting bulk magnet can generate a higher magnetic field with increasing critical current density and volume of the bulk superconductor. Activation processes by using a pulsed magnetic field in zero field cooling, or a static magnetic field in a zero field or field cooling are prospective methods [4-5].

Many of the high critical temperature (T_c) superconductors show superconductivity at temperatures higher than liquid nitrogen, 77 K. In sintered YBaCuO, J_c is low because of the existence of weak links such as grain boundaries, and defect structures. However, recent development shows that melt-processed REBCO [6-9] and LREBCO [10-12] superconductors have a high J_c at 77 K in high magnetic fields. Solidification processes for producing REBCO and LREBCO superconductors are effective for obtaining a high J_c. Although some superconducting compounds from the Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O systems exhibit higher T_c in comparison with the RE-Ba-Cu-O system (e.g. Y-system), they are considered inadequate for bulk-type applications at 77 K because their irreversibility lines are drastically depressed over a wide temperature range [13-14].

In the present paper, important points in melt processing of the RE-system and the LRE-system are described. Properties of oxygen-controlled-melt-growth (OCMG)-processed LREBCO superconductors [10-12] and their characteristic flux pinning are also presented. Further, the possibility of a superconducting bulk magnet for the magnetically levitated (Maglev) train, or magnetic levitation system is discussed [15].

BULK SUPERCONDUCTORS AND MELT PROCESSES

In this section, melt processing for the LRE-systems and characteristic superconducting properties of melt-grown LREBCO bulk superconductors, mainly for NdBCO, are briefly described. Melt processing has been a key processing route for the fabrication of bulk high-temperature superconductors required for practical applications. A solidification technique for the Y-Ba-Cu-O system (Y-system) has been developed [4], known as the melt-textured growth (MTG) process [6] with a large J_c value $\geq 10^4$ A/cm^2 at 77 K and 0 T, the quench and melt growth (QMG) [7-8], the melt-powder-melt-growth (MPMG) [9] process with a large J_c value $\geq 3\times10^4$ A/cm^2 at 77 K and 1 T. The melt process opened the possibility of various monolithic bulk applications operative with liquid nitrogen refrigeration.

While reported J_c values of melt-processed YBCO superconductors have already surpassed the lower limit for practical applications, J_c enhancement over the order of 10^5 A/cm^2 and its less severe degradation in high fields at 77 K are still required for both better performance and a safety margin. As a promising process, an oxygen-controlled-melt-growth (OCMG) process for the $LREBa_2Cu_3O_{7-x}$ systems (LRE-systems, LRE: Nd, Sm, Eu) was developed [10-12]. In comparison with optimally melt-processed YBCO superconductors, OCMG-processed LREBCO superconductors exhibit larger J_c in high magnetic fields and much improved irreversibility field (H_{irr}) at 77 K for the applied field (H) parallel to the c-axis of the crystal (H//c), implying that stronger flux pinning can be realized in a commercially feasible way.

The OCMG process was developed to solve the fundamental problem of a depressed T_c with a broad superconducting transition of LREBCO superconductors when they were melt-processed in air. The OCMG process was also found to be effective in achieving high T_c phase in other LRE-systems. Significant effects of the oxygen partial pressure, $p(O_2)$, controlled during melt processing, on T_c and the superconducting transition behaviors are displayed for the Nd-Ba-Cu-O system. Reduced oxygen atmospheres are obviously effective in fabricating NdBCO superconductors with high T_c and the sharp transition. After melt processing in a flowing mixed gas of 1% O_2 in Ar ($p(O_2)= 10^{-2}$ atm) and subsequent oxygen annealing, a high T_c phase with sharp transition could be reproduced. The highest onset T_c of 96K with sharp transition was achieved [10-12]. The same effect was also observed for other LREBCO superconductors, particularly for Sm and Eu. Since $p(O_2)$ must be controlled during the process in the OCMG process, melt processing in air has been favored. For this point, we have just recently succeeded in fabricating fairly good quality NdBCO bulks with the melt process in air [16].

For practical applications, the improvement in the mechanical properties is also essential. The strength and the fracture toughness of YBCO are considered to be improved by Ag addition in the melt growth of the crystal from the partial molten state [17]. The size and the distribution of Ag particles in the crystal can be determined by controlling the growth rate or undercooling.

PROPERTIES OF BULK SUPERCONDUCTORS

Trapped Magnetic Field of REBCO

A significant magnetic field can be trapped by a superconductor when it exhibits large flux pinning forces. Figure 1 shows the field distribution of an MPMG-processed YBCO sample at 77 K, after being field-cooled in an external magnetic field of 3 T which was subsequently removed. The trapped field distribution was measured using a Hall probe. At the center of the sample, a magnetic field of 1.4 T is trapped, showing that the material becomes a quasi-permanent magnet [4].

At the present stage, YBCO bulk superconductors have a relatively low H_{irr} at 77 K which limits the maximum achievable trapped field. However, LREBCO bulk superconductors show much higher H_{irr}, which should make these superconductors applicable for this purpose [10-12].

Critical Current Density, J_c of REBCO and LREBCO

High J_c has been a major issue for high-temperature superconductors for practical applications. The critical current is an extrinsic superconducting property which can be controlled by defect type, amount and distribution. Figure 2 shows a typical J_c–B curve for OCMG-processed NdBCO superconductors at 77 K. We followed the usual MPMG processing procedure except for the $p(O_2)$ control. For a comparison, the J_c–B curve of a good quality MPMG-processed YBCO sample is also displayed [18-19]. The J_c–B curve was obtained from the dc magnetization hysteresis (M-H) loops measured by a SQUID magnetometer. It is shown that while J_c of the NdBCO is lower in low fields compared to the MPMG-processed YBCO, it becomes higher in high fields.

This behavior is also common to other OCMG-processed LREBCO (LRE: Sm, Eu) samples and is closely related to the existence of the anomalous secondary peak effect in the M-H loops for H//c. In other words, much stronger pinning in high field regions is realized.

We believe that there exists a slight chemical variation and thus Nd-substituted Ba regions of low T_c are distributed in the high T_c matrix of OCMG-processed NdBCO superconductors, and that these regions will be driven normal in high fields and turn into effective flux pinning sites. The field necessary for these regions to be driven normal depends on chemical composition. This is the origin for the anomalous second peaks, the field-induced pinning.

For further enhancement of J_c, we have approached with two different methods; one is by microstructure control and the other by thermal processing control. The control method for the $Nd_4Ba_2Cu_2O_{10}$ (Nd422) second phase particles in the Nd123 matrix is important, since it is known that the Y211 refinement is effective in J_c improvement. The control of thermal processing conditions in a given $p(O_2)$ is important primarily for the achievement of sample homogeneity in large grains and also closely related to the secondary peak position.

Trapped Magnetic Field of YBCO and SmBCO

A significant amount of magnetic field can be trapped by a LREBCO bulk superconductor when it exhibits large flux pinning forces as mentioned above. Figure 3 shows the field distributions trapped by an MPMG-processed YBCO and an OCMG-processed SmBCO sample for a comparison [20]. A single mountain-like distribution of trapped fields evidences that both samples are single textured domain without weak links. Samples were first field-cooled in the liquid nitrogen with an external field of 3.5 T. Subsequently, the applied field was decreased to 3 T and held for measuring the trapped field, and finally removed to 0 T again for the measurement. The trapped field distribution was measured using a Hall probe.

From Fig. 3, we can see a very interesting difference in the trapped fields between two samples at 3 T, although there is no apparent difference at 0 T. That is, in the external field of 3 T, while YBCO can trap only a negligible field, SmBCO can trap a significant amount of magnetic flux (about one third of the maximum trapped field at 0 T). The reason is ascribed to higher J_c in high fields for SmBCO in comparison with YBCO. This result obviously represents that OCMG-processed LREBCO bulks can trap much higher field than YBCO at 77 K in the case that the sample dimension is similar. It is estimated that fields greater than 5 T can be trapped at 77 K, if optimally-processed large bulks are produced from these materials, because LREBCO bulk superconductors show much higher H_{irr}.

Pulsed Magnetization of YBCO

Pulsed Magnetization is one of the prospective methods for having a sample with large trapped fields. An electromagnet made of copper wire can generate a high magnetic field by pulsed current without liquid helium and superconductors. Figure 4 shows one example of the two-dimensional distribution of the trapped magnetic field over the YBaCuO sample surface, in a pulsed magnetic field of 1.2 T [5]. A pulsed magnetic field was applied perpendicular to the YBaCuO superconductor prepared by the Melt-Powder-Melt-Growth (MPMG) process at 77 K. A period of the pulsed current of zero to peak and peak to zero was 340 µsec. The sample size is 10 mm × 10 mm × 1 mm. After the sample was magnetized, the two-dimensional distribution of the trapped magnetic field over the YBaCuO sample surface was measured by a scanning microsize Hall sensor with an active area of 50 µm × 50 µm at an interval of 0.5 mm. The distance between the Hall sensor and the sample surface was 2.5 mm.

At 1.2 T, it is seen that the whole sample is magnetized, and the distribution has a 4-fold symmetry which indicates the homogeneous superconducting properties of the sample. A maximum remnant magnetic field of 0.15 T was obtained at the center of the sample surface. The maximum trapped magnetic field by a static magnetic field also reached approximately the same value. Therefore, the pulsed magnetization was shown to be effective. The maximum trapped magnetic field increased with an increasing applied magnetic field, and showed a peak. Then the trapped field decreased with a further increase of pulsed magnetic field [5].

SUPERCONDUCTING BULK MAGNET

Maglev is a super high-speed non-contact transport system with a combination of superconducting magnets (SCM) and linear motor technology. The Maglev system is levitated, guided, and propelled by magnetic forces acting between the superconducting magnets and the ground coils such as the levitation/guidance coils and the propulsion coils. The SCM is one of the most basic elements of the Maglev, and the enhancement of reliability and durability of the SCM is a major research and development issue. Two SCMs with on-board refrigerators are mounted on each bogie of the train, and each SCM consists of four superconducting coils with a pole pitch of 1.35 m. The pole size is 1 × 0.5 m, and each pole is composed of a race-track coil made of NbTi superconducting wires in a persistent current mode at 4.2 K. The magnetomotive force is 700 kA [2-3].

One of the prospective designs is a racetrack coil made of high T_c superconducting wires similar to the NbTi coil. Another one is a superconducting bulk magnet, or a superconducting quasi-permanent magnet. Magnetization of REBCO superconductors with a high J_c would result in a strong bulk magnet, e.g. a superconducting bulk magnet for the Maglev train. In the case of the superconducting bulk magnet, each pole will be composed of small bulk superconductors, because the size of the bulk at present is reported to be up to 100 mm in diameter.

Figure 5 shows a model of a superconducting bulk magnet, when the diameter (d) of a bulk is 100 mm, and the thickness (t) is 20 mm. Each pole consists of 8 × 4 bulks. The distribution and the magnitude of magnetic fields are then calculated for the bulk magnet composed of bulk superconductors. Magnetic fields for.the conventional SCM composed of race-track coils are also calculated for a comparison. The effects of the size and the current density of the bulk superconductor on generated magnetic fields are studied. A perpendicular component of the magnetic field generated by the bulk magnet through the ground coils on the guideway is calculated by the Biot-Savart law. A constant current density without magnetic field dependence is assumed by the Bean model. The gap between the surface of the bulk and the center of the ground coil takes 150 mm for the levitation/guidance coil, and 222 mm for the propulsion coil.

Figure 6 shows the distribution of calculated magnetic fields, B_y at the center of the levitation/guidance coil for the case of 8 × 4 bulks, when the current density of the bulk is 1 A/mm^2. The distribution of the magnetic field of the bulk magnet was almost the same as that of the conventional race-track magnet. Figure 7 shows the distribution of calculated magnetic fields, B_y at the center of the levitation/guidance coil when each pole consists of 4 × 2 bulks, 200 mm in diameter, and the current density of the bulk is 1 A/mm^2. When the diameter of the bulk becomes large and the number of the bulks per pole is reduced, the magnitude of magnetic fields, B_y increases. However, the fluctuations in the magnetic fields also increase within each pole as shown in Fig. 7 [15].

As a result, the current density necessary for the SCM of the Maglev train is estimated to be larger than 10^5 A/cm^2 for $d = 100 - 200$ mm and $t = 20$ mm. The generating magnetic field depends on the diameter and the thickness of a bulk, and the required current density decreases with increasing thickness and size of a bulk. Currents flowing through the outer region of the bulk contribute much more to generating magnetic fields than those through the inner region. It should be noted that mechanical properties limit the trapped magnetic field, that is J_c, due to the electromagnetic force.

Therefore, for designing the SCM of the Maglev train, increasing the critical current density and the size and thickness of bulk superconductors is a key issue. The strength of a bulk superconductor is also important together with increasing J_c.

In addition to the material properties, the magnetization method of a bulk is a basic issue for the bulk magnet. One of the methods is a pulsed magnetization. Trapped field properties by the pulsed magnetic field are briefly described above in YBCO superconductors prepared by the MPMG process. Another method is the magnetization of superconductors in a static magnetic field by a SCM. Furthermore, a cooling temperature for operation and an arrangement of bulks are also important for planning an outline of a SCM. An arrangement of hollow cylindrical bulks are one of the outline plans of a SCM, because the current flowing through the outer region of a bulk contributes more to generating magnetic field.

CONCLUSIONS

Up to date, major applications of high-temperature superconductors have been confined to products in the form of wires and thin films. However, recent development of melt-processed REBCO and LREBCO bulk superconductors with a high J_c at 77 K and high magnetic fields has initiated the possibility of various applications in the bulk monolithic form, such as magnetic bearings, flywheels and superconducting bulk permanent magnets. In this paper, we discussed the possibility of the superconducting bulk magnet in the Maglev train.

(LRE)-Ba-Cu-O bulk superconductors melt-processed in a reduced oxygen atmosphere (OCMG process) are very promising for high field applications. LREBCO bulks exhibit higher J_c in high magnetic fields and much improved irreversibility field, H_{irr}, at 77 K. The control of microstructure by altering the amount, size, and shape of the second phase (Nd422 for Nd, LRE211 for Sm, Eu) would lead to reduction of cracks, improvement of mechanical properties, further enhancement in J_c, and so forth. The addition of Ag to REBCO and LREBCO superconductors is considered to be effective for improving the strength of the bulk. Through the optimization of processing, further improvements in T_c, J_c and H_{irr} as well as mechanical properties such as the flexural strength and the fracture toughness would be realized. The homogeneity and size of the bulk superconductor is also a key issue to be overcome.

Summarizing the results of calculation for the bulk magnet, a magnetic field is generated by the bulk magnet composed of small oxide-superconducting bulks, and the distribution of the magnetic field is almost the same as that of the conventional race-track magnet. The magnitude of the magnetic field generated by the bulk magnet depends on the size and the critical current density of the bulk superconductor. Therefore, it is significant to improve the critical current density and to increase the size of bulk superconductors. The strength of a bulk superconductor is also important together with increasing J_c. Furthermore, magnetization methods, cooling temperatures for operation, and arrangements of bulks are major issues for designing a SCM.

Since a large LREBCO bulk superconducting magnet is believed to trap very high magnetic fields - over 5 T at 77 K, LREBCO and REBCO superconductors will surely promote the application of bulk high-temperature superconductors in high magnetic fields. The superconducting bulk magnet for the Maglev train is expected to be one of the most important prospective applications.

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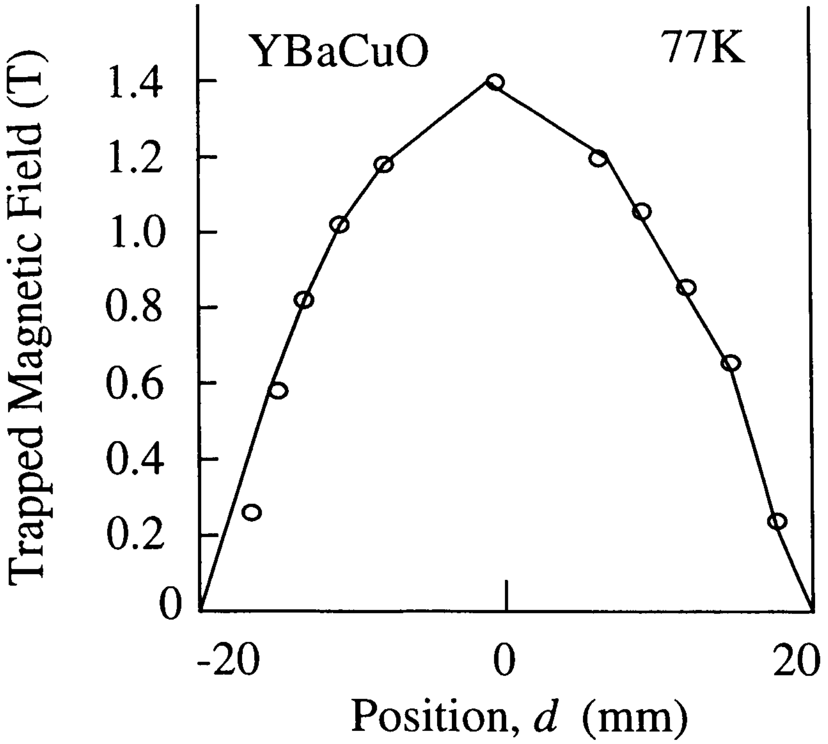

Figure 1. Trapped field distribution of an MPMG-processed YBCO superconductor at 77 K.

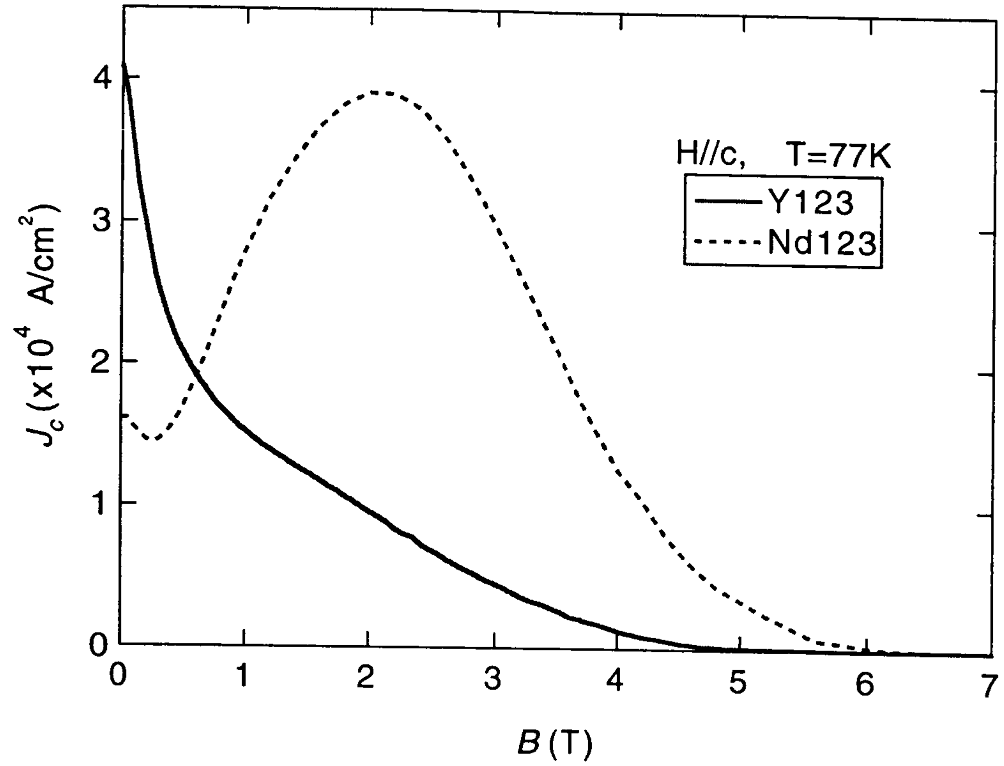

Figure 2. Typical J_c-B curve for OCMG-processed NdBCO superconductors at 77 K. For a comparison, the J_c-B curve of a good quality MPMG-processed YBCO sample is also displayed.

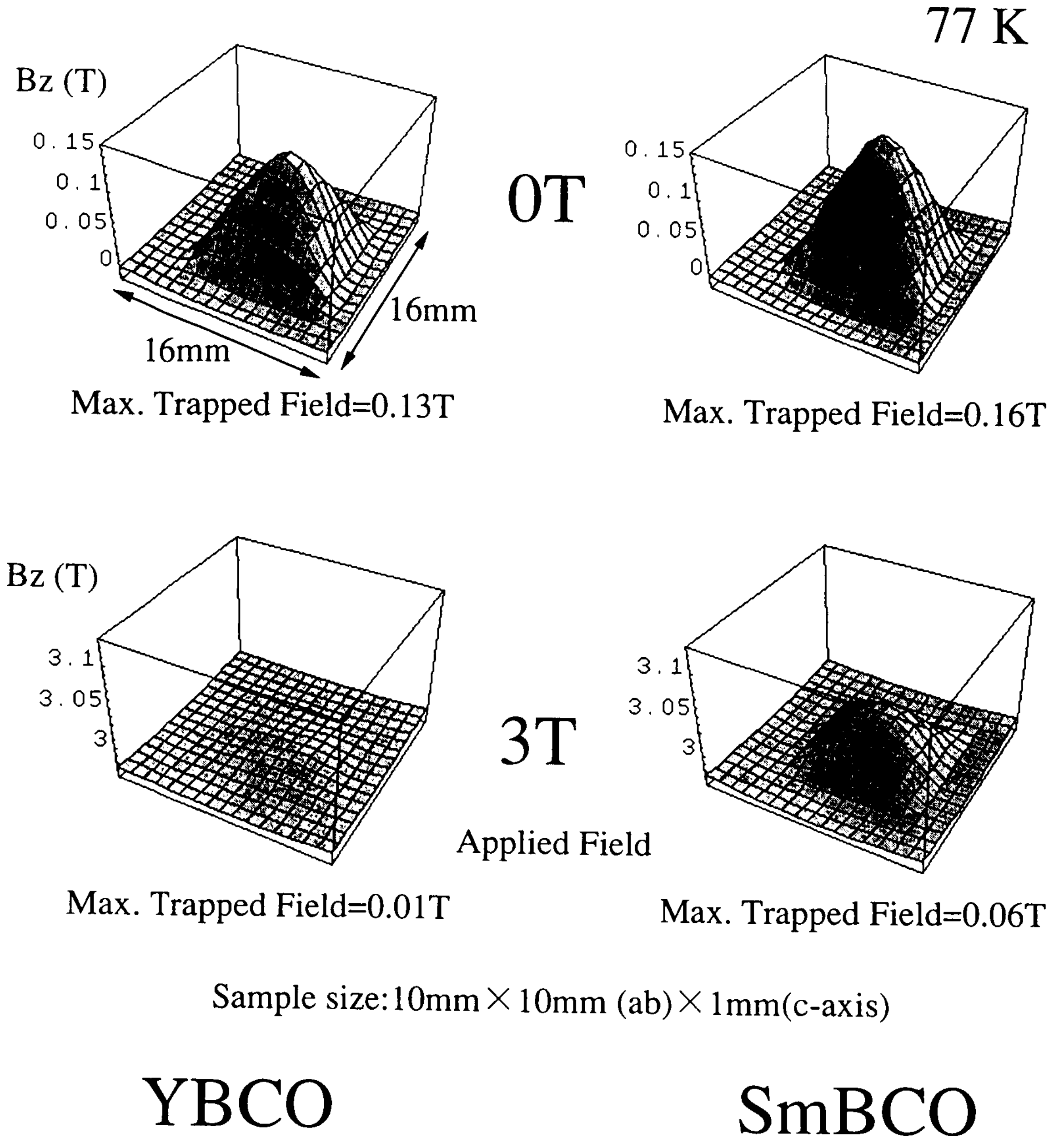

Figure 3. Field distributions trapped by an MPMG-processed YBCO and an OCMG-processed SmBCO sample for a comparison at 77 K.

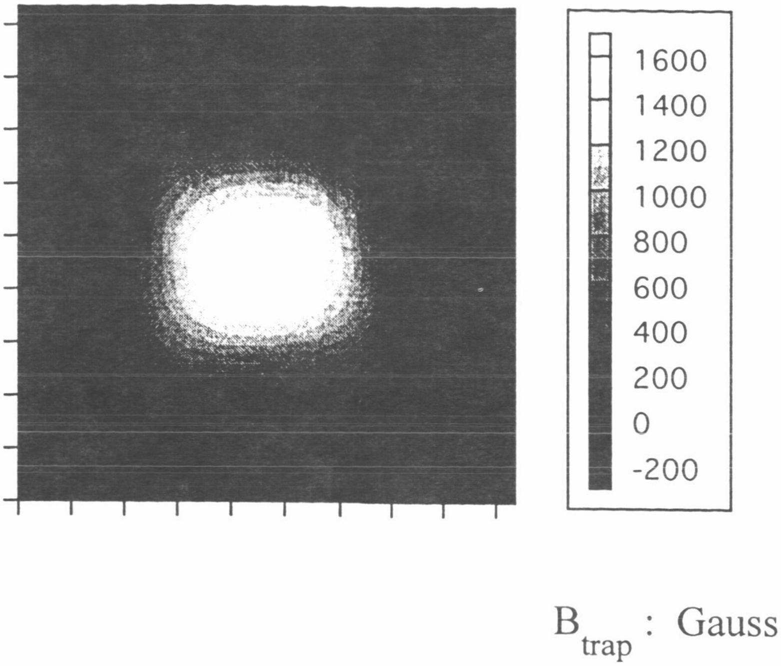

Figure 4 Two-dimensional distribution of the trapped magnetic field over the YBaCuO sample surface at a pulsed magnetic field of 1.2 T.

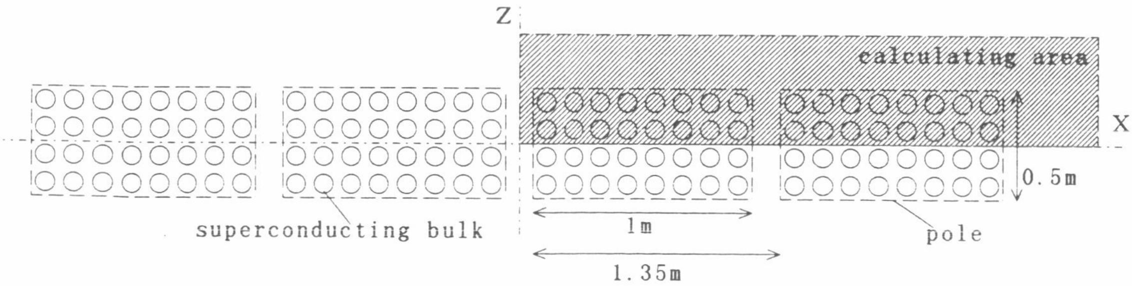

Figure 5. Model of bulk magnets, when the diameter of a bulks is 100 mm, each pole is composed of 8 × 4 bulks, and the bulk magnet is composed of 4 poles with a pitch of 1.35 m.

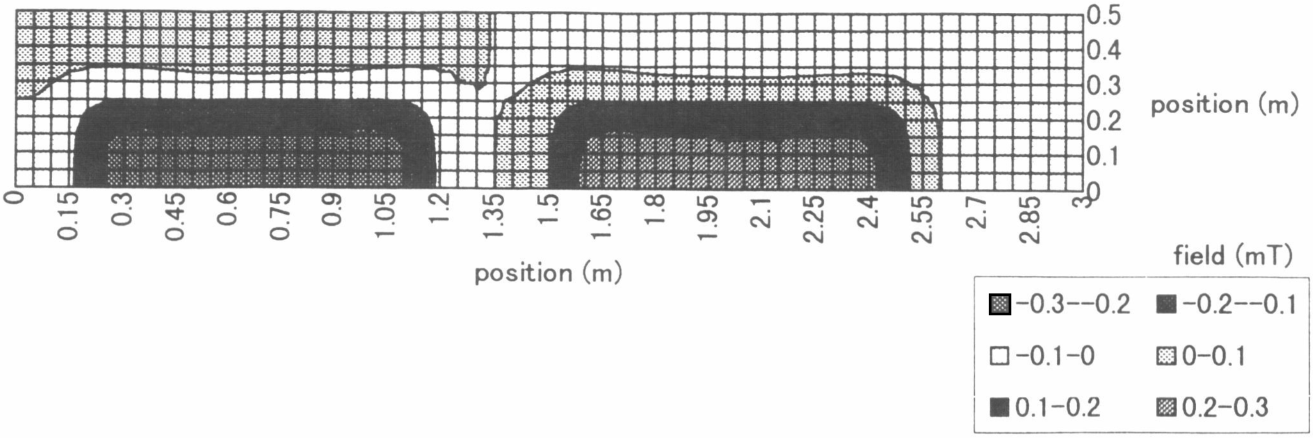

Figure 6. Distribution of calculated magnetic fields, **B_y** at the levitation/guidance coils. Each pole is composed of 8 × 4 bulks, 100mm in diameter and 20mm in thickness, and a current density of 1 A/mm^2 in the bulk is used.

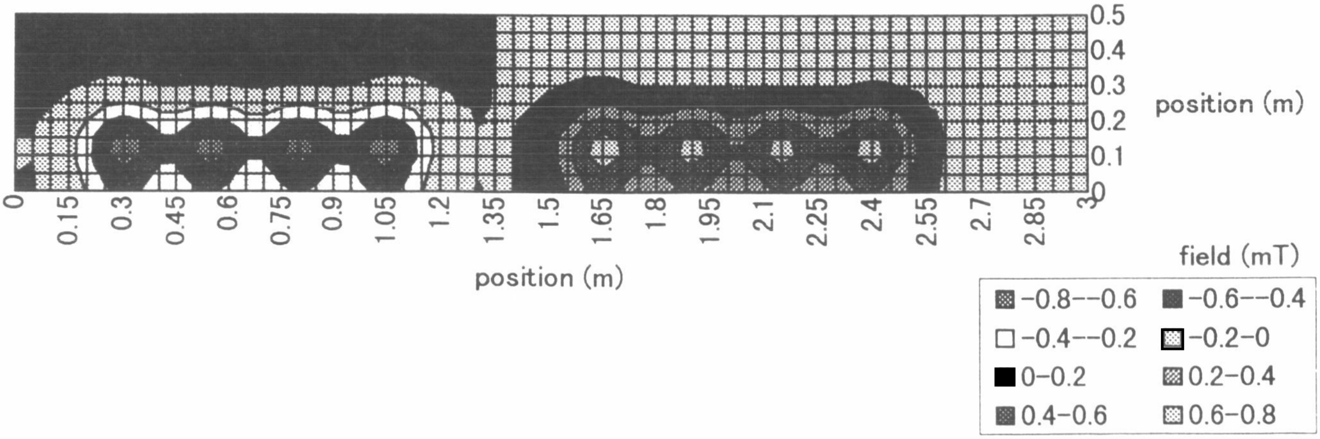

Figure 7. Distribution of magnetic fields, **B_y** calculated at the levitation/guidance coils. When each pole is composed of 4 × 2 bulks which are 200 mm in diameter and 20 mm in thickness, and the current density of the bulk is 1 A/mm^2.