Electromaglev System of a YBCO Bulk Superconductor

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SUMMARY

This paper describes an "Electromaglev" system, in which a HTS sample, that is, a YBCO disk or ring, is stably levitated in a DC magnetic field generated by electromagnets placed under the levitated object. The most versatile and useful features of this system are: (1) easily adjustable levitation height - it is made possible by varying the electromagnet coil current, (2) large levitation height - it is feasible by sufficiently large electromagnets. This levitation system is theoretically and experimentally discussed from the view of levitation stability. Consequently, for stable levitation, specifically pitch stability, magnetic flux is required to be trapped in the YBCO disk as the disk is initially cooled from the normal state to the superconducting state in the presence of an external magnetic field. Further, the levitation height can be controlled by the coil current. The range of the maximum levitation height achieved by a 40mm diameter (with a 30mm diameter hole) YBCO ring was 100mm.

1. INTRODUCTION

The magnetic levitation of high-temperature superconducting (HTS) materials is applied, for example, to magnetic bearings. A permanent magnet disk levitated stably above a superconducting disk, generally of $YBa_2Cu_3O_{7-\delta}$ (YBCO), is a familiar phenomenon of HTS [1-3]. The levitation is achieved by a repulsive force created between the magnetic field of the permanent magnet disk and that induced in the YBCO disk. Levitation is stable. With a system in which both disks are permanent magnets, however, levitation is unstable, because such a system violates requirements set forth by a corollary of Lenz's law. The corollary may be stated as follows: for stable levitation, spatial current flow in at least one of the two disks must have more than one degree of freedom. Note that the amperian current in each of the two permanent magnet disks has only one degree of freedom - in the azimuthal direction. If one of the permanent magnet disks is replaced with a superconducting disk, on the other hand, because induced supercurrents in the disk can flow, both in the azimuthal and radial directions, the currents have two degrees of freedom, making it possible for the other permanent magnet disk to be levitated stably above the superconductor. In the "electromaglev" system, first investigated by Krasnyuk and Mitrofanov in 1990 [4] and studied comprehensively here, the levitated object is an HTS bulk sample rather than a permanent magnet disk. Also, a magnetic field is generated by electromagnets rather than by a permanent magnet. Figure 1 shows a schematic drawing of an "electromaglev" system, in which a superconducting YBCO disk, $2R_d$ diameter and S_d thick, is levitated above a magnet system comprised of two electromagnets referred to as the Outside Coil and Inside Coil. A steel plate on which the two coils are placed enhances the field in the top half of the space. In constrast to this electromaglev system, we may refer to the more common system in which a permanent magnet disk is levitated above a bulk HTS disk as a passive system.

The most versatile and useful features of the "electromaglev" system, as opposed to the passive system, are: 1) readily adjustable levitation height, made possible by varying currents in the electromagnets; and 2) "large" levitation heights, made feasible by using sufficiently large electromagnets. In this paper the condition of stable levitation is theoretically and experimentally discussed for two types of YBCO bulk, 40mm diameter ring (30mm diameter hole) and 100mm diameter disk. For stable levitation a proper amount of magnetic flux is required to be trapped in the YBCO objects by the field cooling. We have succeeded in achieving a maximum levitation height of 100mm with the ring.

2. "ELECTROMAGLEV" SYSTEM

The system used in the experiment is basically equivalent to that shown in Figure 1. For a new system, a large double pancake structure coil has been used as the Outside Coil with its companion Inside Coil to achieve greater levitation height. Figure 2 shows the cross section of the new Outside Coil placed on steel plates. It also shows the detail of the winding, whose conductor is of copper, 1mm thick and 8.25mm high. Turns are separated by insulating spaces, each 3mm wide, placed every 10mm along the conductor.

A 40mm diameter ring and two 100mm diameter disks, both of YBCO, are used as the floating objects. Since the levitation stability is greatly affected by the homogeneity of YBCO bulk crystal, a magnetic flux is trapped in the YBCO bulk and the flux distribution is measured by a Hall probe. Figures 3 and 4 show the results. Figure 3 shows the flux distribution of the ring, which is axially symmetric. Figure 4 shows that of the 100mm diameter disks. Figure 4a shows the flux distribution of a permanent magnet used to apply a flux to the disks; its distribution is very uniform both in the radial and azimuthal directions. Figures 4b and 4c show the flux distributions due to the trapped flux, respectively, for Disks 1 and 2. Although both distributions are not uniform, Disk 1 may be somewhat better than Disk 2.

3. BASIC IDEA FOR STABILITY

The stable levitation is achieved by a repulsive force created between the field induced in the YBCO disk and that of electromagnets [5-6]. For stable levitation, spatial current flow in the disk must have more than one degree of freedom. In this system, though the disk provides two degrees of freedom for its supercurrent, that is not sufficient. To achieve lateral and pitch stability for the levitating disk, the magnetic field created by the electromagnets must satisfy the following spatial requirements, which are derived from consideration of Lorentz force acting on the supercurrent, Id, induced in the disk (see Figure 5):

$$\left[\left(\frac{\partial B_z}{\partial r}\right)_{(R_d,z)} > 0\right]_{Lateral\ Stability} \qquad (1)$$

$$\left[\left(\frac{\partial B_r B_z}{\partial z}\right)_{(R_d,z)} < 0\right]_{Pitch\ Stability} \qquad (2)$$

4. EXPERIMENTAL RESULTS

As stated in section 3, stable levitation needs to achieve lateral and pitch stability. Exciting currents are obtained to generate flux distributions satisfying equations (1) and (2). Figure 6 shows the flux distributions generated by the coil currents I_1 and I_2. From Figure 6a the B_z distribution at current I_2 less than 40A is found to satisfy the lateral stability of equation (1). However, Figure 6b shows the pitch stability to be difficult to realize, especially at lower height z. The higher the current I_2 becomes, the more easily the pitch stability can be realized. From these results we choose 40A as the optimal current I_2. The levitation tests were tried under the condition of I_2=40A,but stable levitation, especially pitch stability, could not be achieved. In all tests, the ring tilted, finally levitating vertically (Figure 7) as the Outside Coil current was increased.

The experiment has demonstrated that in addition to field requirements of equations (1) and (2), the presence of a trapped flux in a disk (or a ring) is another necessary condition for stable levitation. Experimentally, this trapped flux may be induced in the disk through what we call a field-cooling (FC) process, in which a flux may be trapped in the disk when it is cooled from the normal state to the superconducting state in the presence of a magnetic field generated by the electromagnets. Table 1 presents levitation data for the ring. The 1st and 2nd columns give, respectively, currents, I_1 for Outside Coil and I_2 for Inside Coil used to generate an external field during FC; 3rd column gives I_2, held constant, as I_1 was raised to achieve levitation: 4th column gives I_1 when the ring begins levitation, but it also gives I_1 at that time if the ring starts tilting before levitation: 5th column gives the ring's approximate tilt angle at maximum levitation height: Note that to achieve tilt-free levitation the ring must be field-cooled with I_1 above 210A when I_2 is 40A. Figure 8 shows the variation of levitation starting current and maximum levitation height with FC current. The maximum levitation height is shown to decrease with FC current.

The levitation experiment was conducted with two 100mm diameter YBCO disks, each 20mm thick. Table 2 presents a summary of data for the disks. It was not possible to achieve stable levitation for Disk 2 even with I_1=200A, a level sufficient for stable levitation for Disk 1. This inferior behavior of Disk 2 in companion with Disk 1 behavior may be a reflection of Disk 2's homogeneity of field distribution that is poorer than Disk 1's as mentioned in Section 2. Data presented in each table clearly indicate that a trapped flux is essential for stable levitation: with no field cooling, i.e., I_1=0, the first row in each table shows a right-angle tilted levitation.

5. DISCUSSION

For stable levitation, especially tilt-free levitation, field cooling is indispensable. Here, it is elucidated how the trapped flux by the field cooling works for stable levitation. Assuming an axially long HTS bulk the Bean model is used for the superconducting current distribution.

Figure 9 presents the supercurrent distribution in the HTS bulk in an external magnetic field H_d with zero field cooling. The bulk is levitated by Lorentz forces generated between the supercurrent I_d and external magnetic field H_d. Equations (1) and (2) are spatial requirements for stable levitation. As stated above, actually, both requirements are not sufficient to achieve tilt free levitation.

For a HTS bulk with a trapped flux induced through the field cooling process, Figure 10 shows its supercurrent distribution in an external magnetic field H_d. The outside supercurrent penetrates a thickness δ_j into the bulk to eliminate the external magnetic field, and the trapped supercurrent remains inside. Certainly an external field becomes so large that the trapped supercurrent will be cancelled ($H_d \geqq 2H_{d0}$). At the presence of an external field the existence of the inside supercurrent is very different from the bulk with zero field cooling. This will be related to pitch stability.

Now, the disk is assumed to be tilted by $\Delta\theta$ about $-y$ axis as shown in Figure 11. As stated in the section 3 if $(\partial B_r B_z/\partial z)\ r=r_1 < 0$, a restoring force will be generated in the outside supercurrent I_d. On the other hand, since the inside supercurrent has an opposite direction of moment, its restoring force decreases if $(\partial B_r B_z/\partial z)\ r=r_0 < 0$. However, $(\partial B_r B_z/\partial z)$ generally becomes positive at small radial distance r as shown in Figure 12. In that case the inside suppercurrent can contribute to enhance the restoring force.

From the above consideration the radial distribution of the supercurrent is an important factor for pitch stability. In this discussion the Bean model is used as the supercurrent distribution. But the floating object is a thin ring or disk, where the Bean model is not effective. More comprehensive two-parameter models such as Chen and Kim's are needed to better estimate the supercurrent distribution[7].

6. CONCLUSIONS

We have proposed an "Electromaglev" system in which levitation height is controlled by electromagnets. In this paper, levitation behaviors including stability and maximum levitation height were investigated in a system comprised of new large electromagnets and two types of YBCO samples, 40mmΦ ring (I.D. 30mm) and 100mmΦ disks.

For stable and tilt-free levitation, the trapped flux induced through a field cooling process is found to be indispensable. Furthermore, pitch stability requires a supercurrent flow both in the azimuthal and radial directions.

It has been demonstrated that new electromaglev systems can levitate YBCO samples stably and tilt-free. Levitation height may be easily controlled by means of the magnetic field generated by the system's electromagnets. A maximum stable, tilt-free levitation height of ~100mmΦ and 17-mm thick (0.85kg disks) has been demonstrated.

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[7] J H P Watson and I Younas, "Current and field distribution within short cylindrical superconductors," *Supercond.Sci.Technol.*8 (1995) 799-805

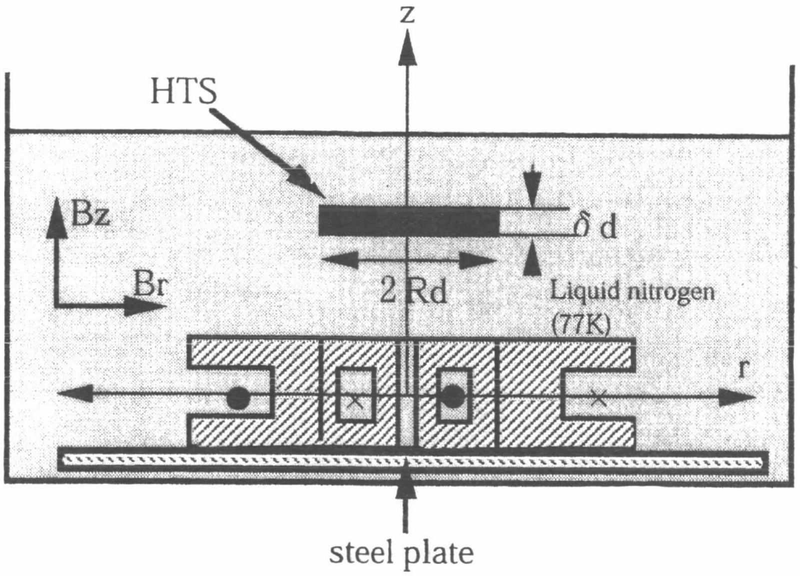


Fig.1 Experimental setup

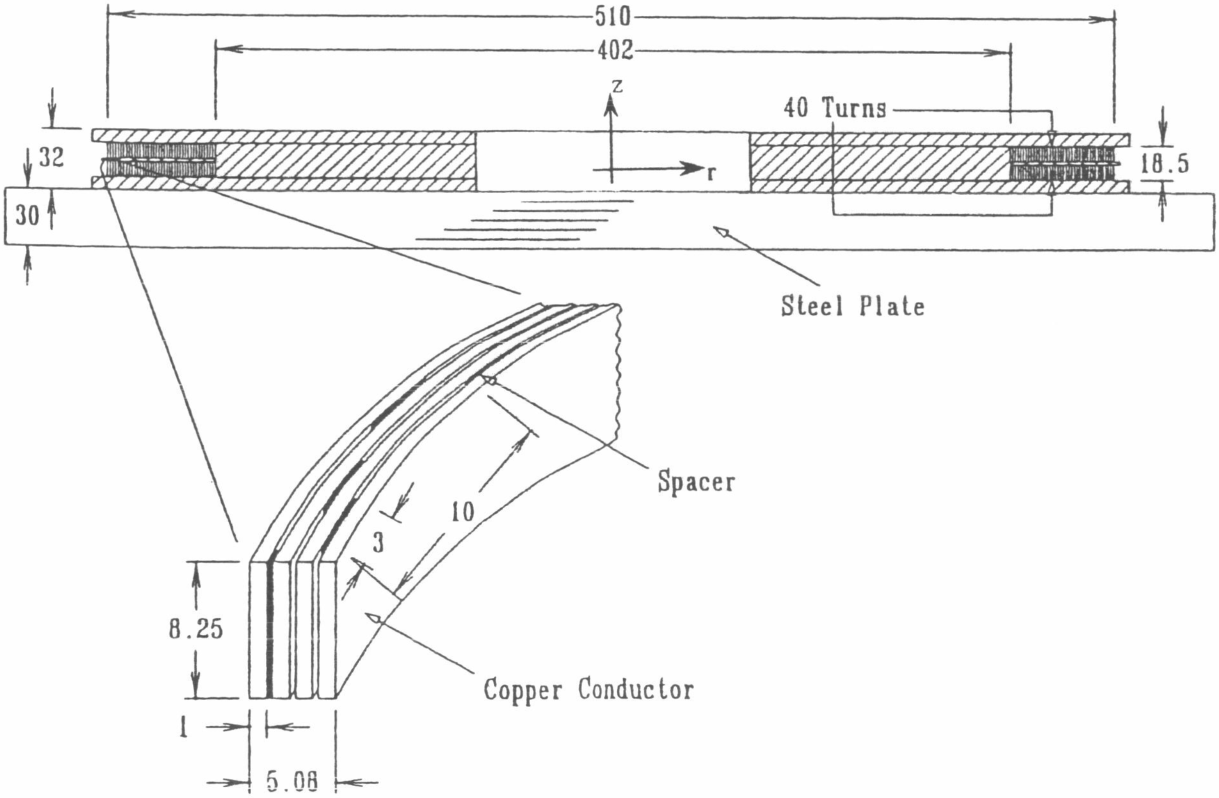
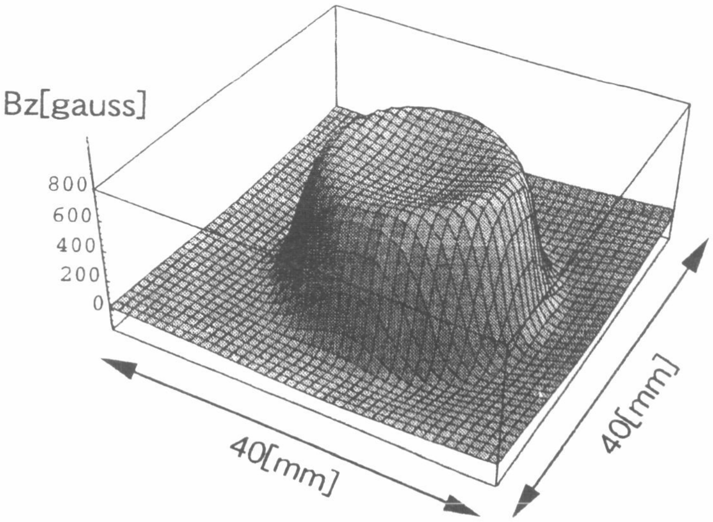
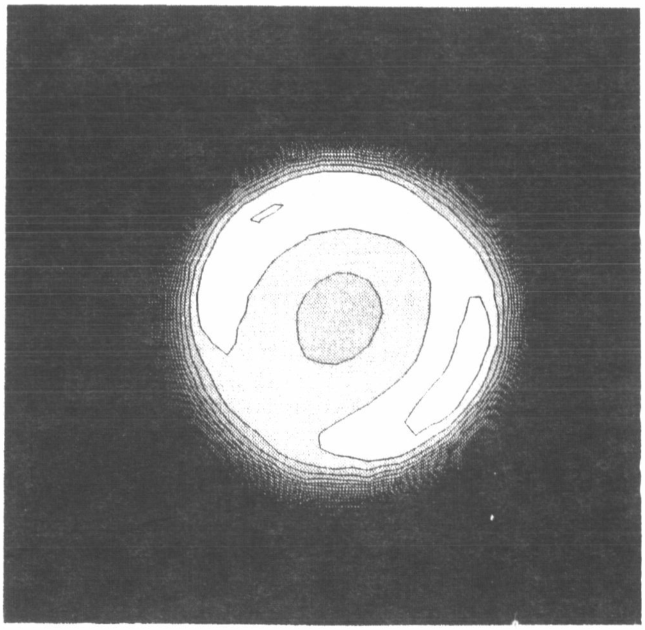


Fig.2 Cross sectional view and winding details of a double pancake coil placed on a steel plate. Dimensions are in mm

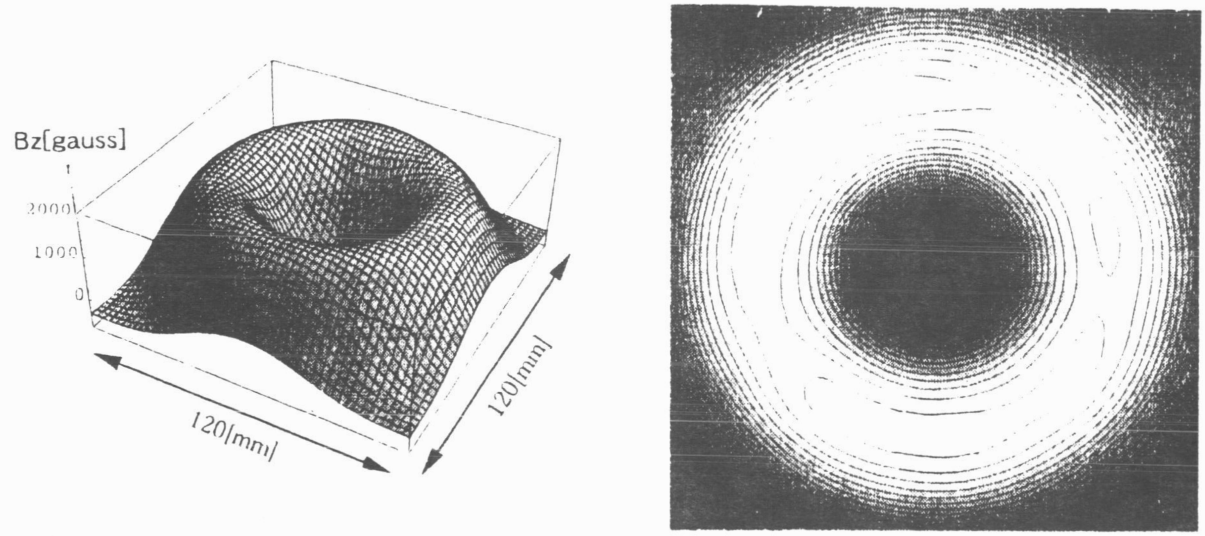


(a) 3D representation

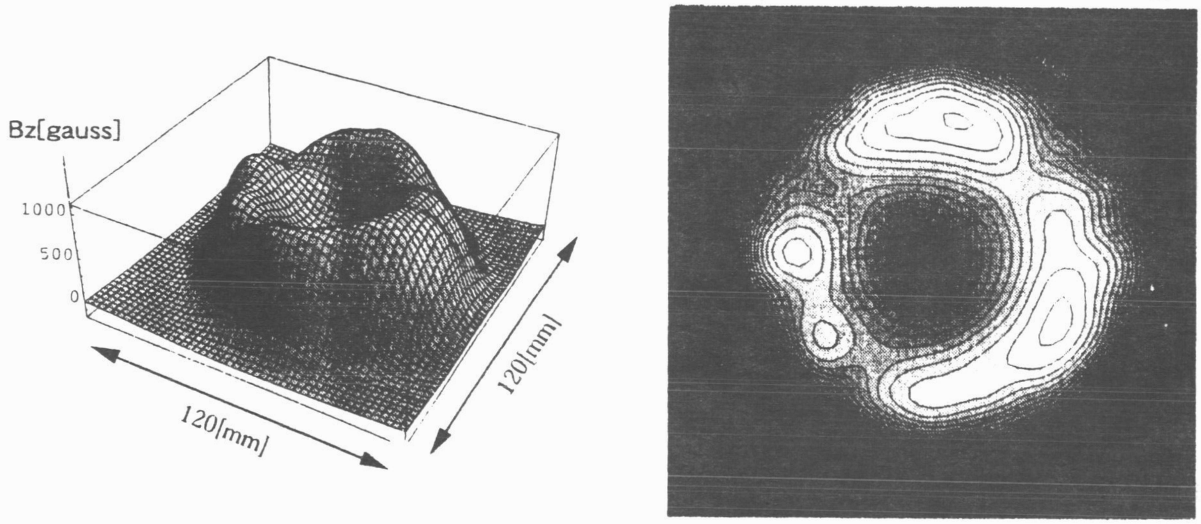


(b) Contour line representation

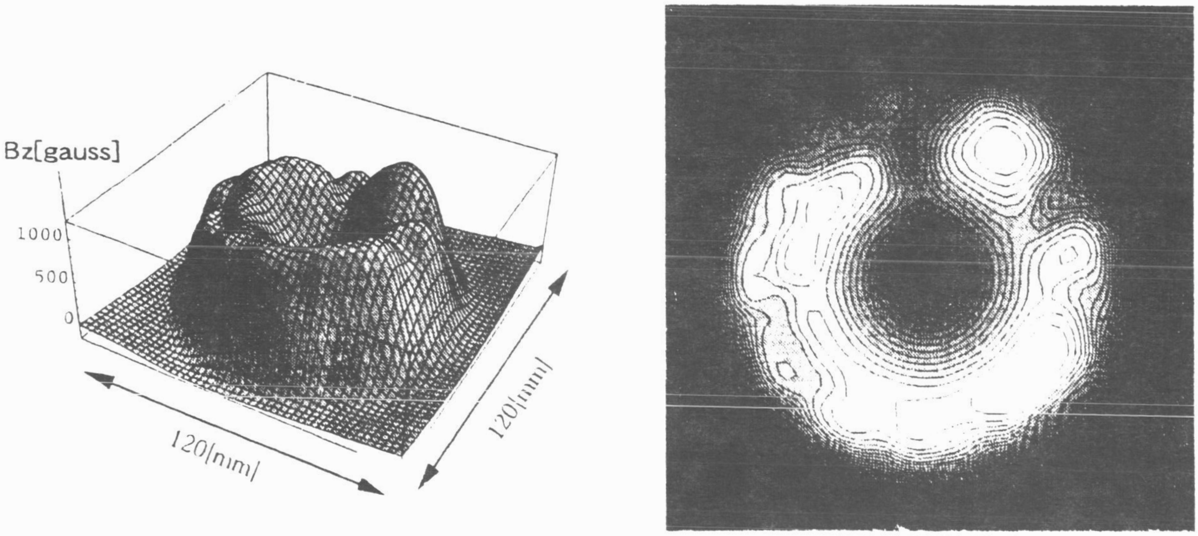
Fig.3 Magnetic flux density distribution of trapped flux in the ring



(a) Bz distribution of the permanent magnet used in the field cooling

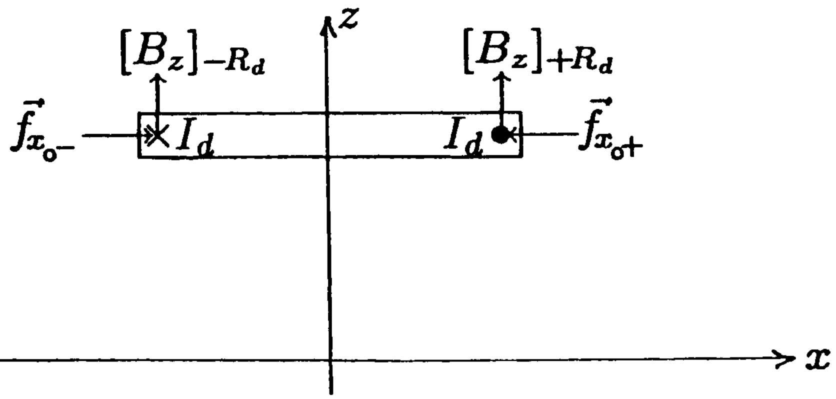


(b) Bz distribution of Disk 1

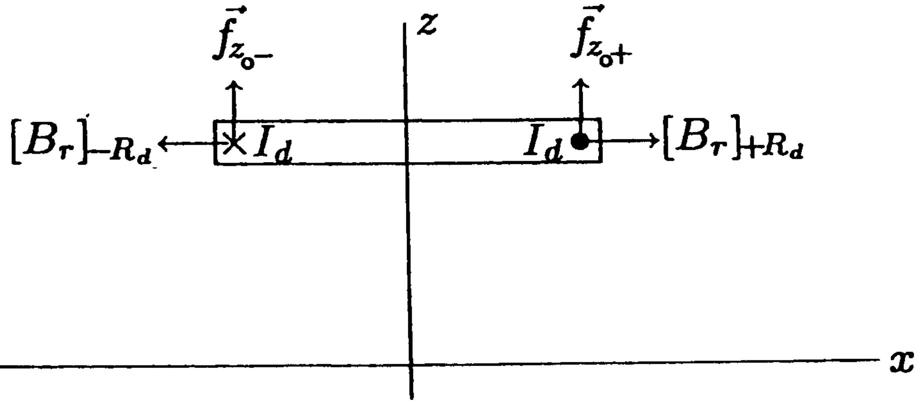


(c) Bz distribution of Disk 2

Fig.4 Magnetic flux density distribution of trapped flux in Disks

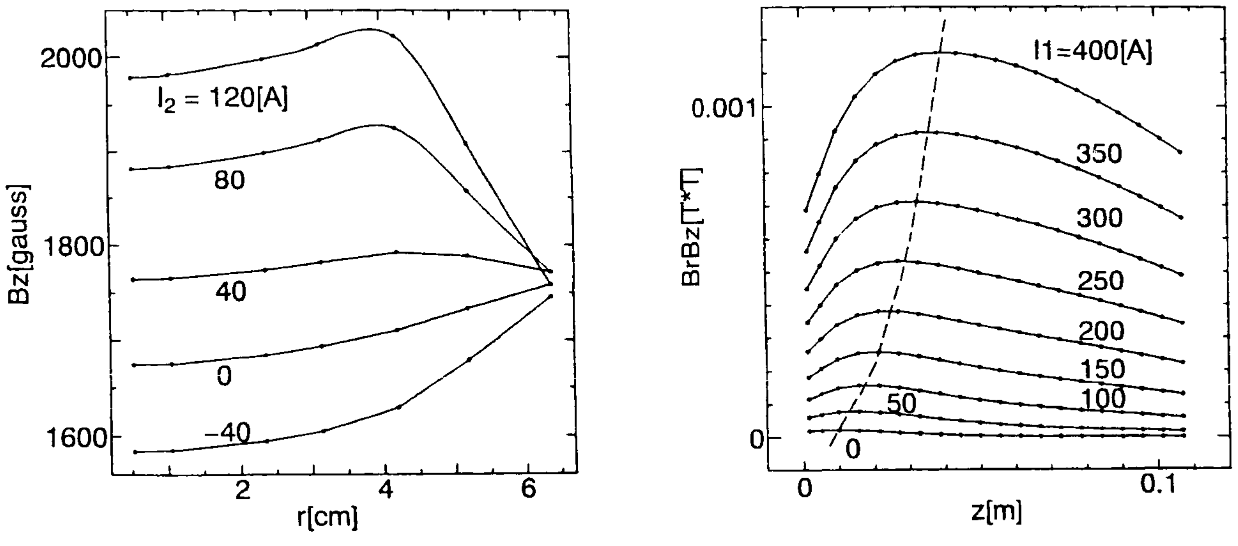


(a) Lateral-direction force



(b) Pitch-direction force

Fig.5 Schematic drawings of a levitated disk subjected to lateral and pitch-direction force



(a) r - Bz (z=2.06[cm],I1=400[A])　(b) z - BrBz (r=2.1[cm],I2=40[A])

Fig.6 Magnetic flux density distribution for levitation stability

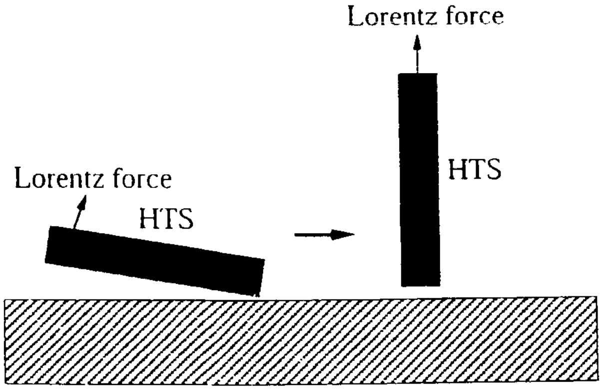


Fig.7 Schematic view of unstable levitation

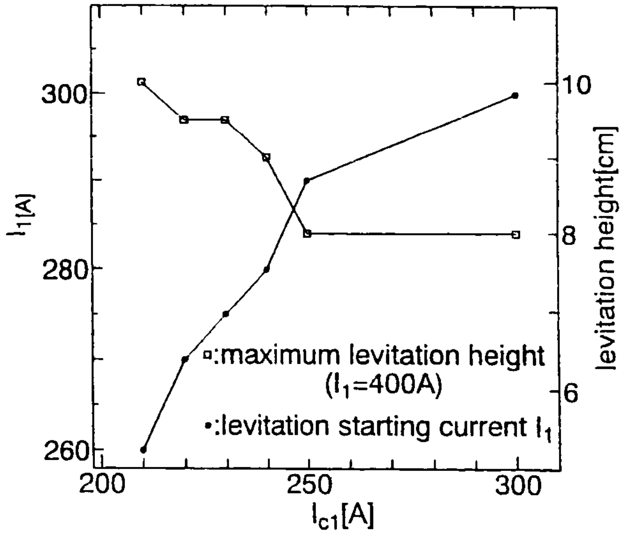
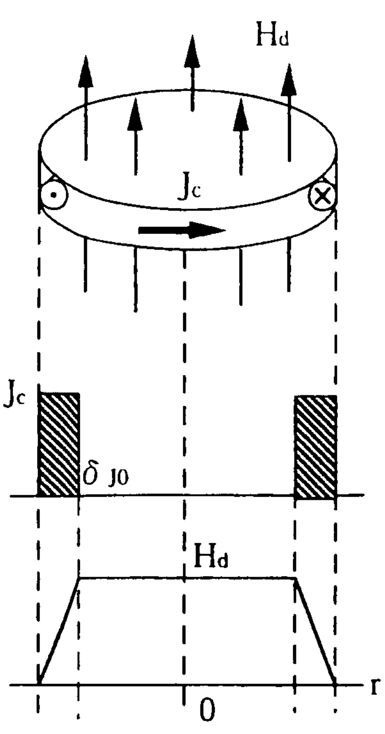


Fig.8 Levitation starting current and levitation height (I_{c2}=40[A])



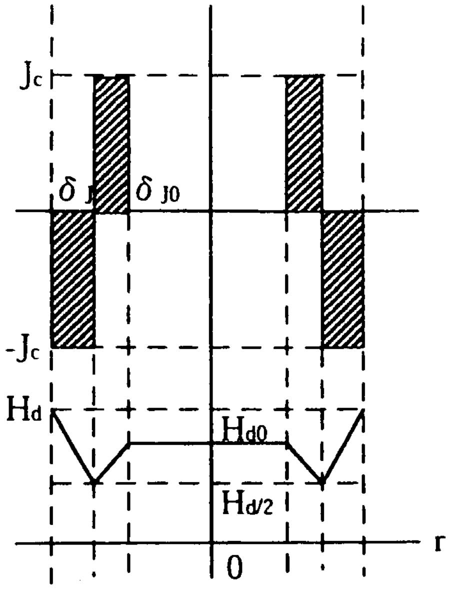
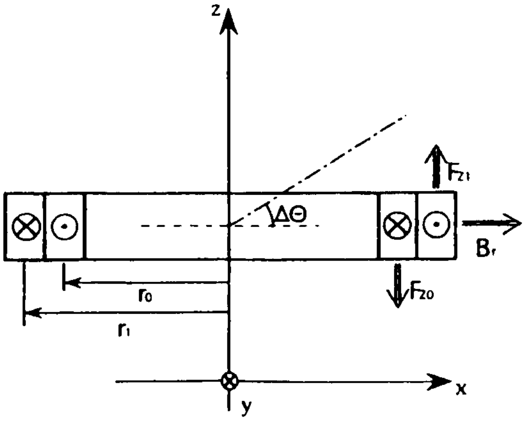


Fig.9 Supercurrent and magnetic field of a disk with a flux trapped by F.C.

Fig.10 Supercurrent and magnetic field of a F.C. disk in an external field Hd



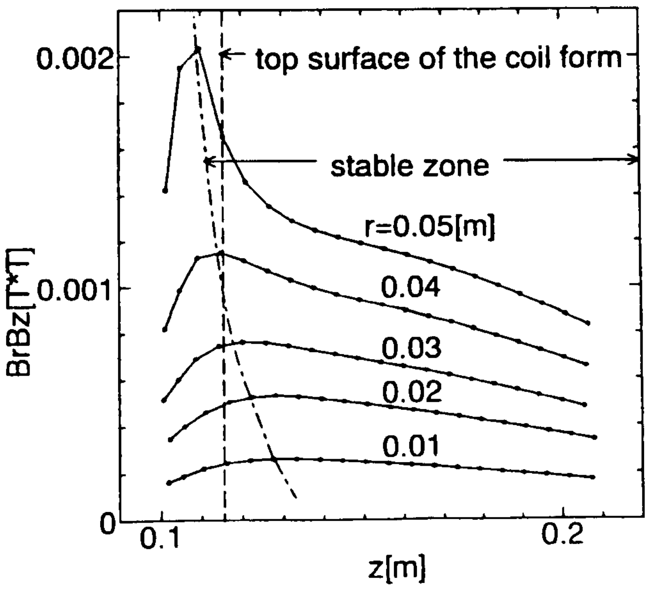


Fig.11 z-direction forces acting on each current layer

Fig.12 z - BrBz relation with a parameter of radial distance r (I_1=250[A], I_2=40[A])

Table 1 Levitation data for the ring

<table>
<tr><th colspan="2">field cooling current</th><th rowspan="2">I_2[A]</th><th>tilting starting current</th><th>levitation starting current</th><th>tilting angle</th></tr>
<tr><th>I_1[A]</th><th>I_2[A]</th><th>I_1[A]</th><th>I_1[A]</th><th>[°]</th></tr>
<tr><td>0</td><td>40</td><td>40</td><td>60</td><td>275</td><td>90</td></tr>
<tr><td>50</td><td>40</td><td>40</td><td>120</td><td>360</td><td>90</td></tr>
<tr><td>100</td><td>40</td><td>40</td><td>150</td><td>310</td><td>45</td></tr>
<tr><td>150</td><td>40</td><td>40</td><td>190</td><td>310</td><td>45</td></tr>
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<tr><td>210</td><td>40</td><td>40</td><td colspan="2">260</td><td>0</td></tr>
<tr><td>220</td><td>40</td><td>40</td><td colspan="2">270</td><td>0</td></tr>
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<tr><td>300</td><td>40</td><td>40</td><td colspan="2">300</td><td>0</td></tr>
</table>

Table 2 Levitation data for disks

<table>
<tr><th colspan="6">DISK 1</th></tr>
<tr><th colspan="2">field cooling current</th><th rowspan="2">I_2[A]</th><th>levitation starting current</th><th>tilting angle</th><th>levitation height</th></tr>
<tr><th>I_1[A]</th><th>I_2[A]</th><th>I_1[A]</th><th>[°]</th><th>h[cm] (I_1[A])</th></tr>
<tr><td>0</td><td>0</td><td>-40</td><td>255</td><td>90</td><td>4 (425)</td></tr>
<tr><td>200</td><td>40</td><td>40</td><td>300</td><td>0</td><td>8 (425)</td></tr>
<tr><td>250</td><td>40</td><td>40</td><td>375</td><td>0</td><td>6～7 (450)</td></tr>
<tr><td>200</td><td>-40</td><td>-40</td><td>350</td><td>20</td><td>7～8 (425)</td></tr>
<tr><td>255</td><td>-40</td><td>-40</td><td>375</td><td>5</td><td>7～8 (450)</td></tr>
<tr><th colspan="6">DISK 2</th></tr>
<tr><td>200</td><td>40</td><td>40</td><td>340</td><td>30</td><td>5～6 (425)</td></tr>
</table>