Characterization of pinning stability of HTS Gd123 bulks by using a pulsed-field magnetization

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Abstract. High-temperature superconductor (HTS) Gd-bulks are used for field-pole magnets of rotating machines. We have conducted a study of pulsed-field magnetization (PFM) for the bulks to be magnetized alternatively on the rotor. Performances of HTS bulks have been qualified on the basis of the field-cooling magnetization (FCM). HTS bulks are a kind of crystals containing lots of tiny crystals boundaries. It is difficult to find comparable data between PFM and FCM results, mainly because of the different pinning stability through both processes. We need to assess an effective method of characterization for the flux pinning instability under PFM. We compared two HTS bulks: one shows a flux flow and relatively small trapped flux while the other is magnetized with a little flux instability and a large integrated trapped flux. These Gd123 bulks are 100 mm in diameter and 20 mm in thickness. After applying PFM at the liquid nitrogen temperature, we measured the trapped field density distribution and introduced a new parameter representing the trapped flux instability at each position on the surface of the bulk. We propose a way of visualization of the flux pinning instability of the HTS bulks.

1. Introduction
The diesel-generated electric ship propulsion systems spread fast all over the world. The high-temperature superconductor (HTS) motors have high torque, compact body and high efficiency. We have applied HTS GdBa₂Cu₃O_y-δ (Gd123) bulks (60-mm diameter, 20-mm thickness) as 8 field-pole magnets in a prototype of synchronous rotating machine [1]. When the HTS bulks trap higher magnetic flux as field poles, the rotating machine provides higher torque for the same dimensions. The target key technology is how to get a higher magnetic flux density as a stable trapped flux in HTS bulks.

We try to solve this problem with 100-mm diameter HTS bulks. Recently, a Gd123 bulk superconductor disk with a diameter up to 140 mm was fabricated [2]. Large size bulks have a bigger total trapped field density, making it easier for the armature coils to use this trapped field, compared to
small-size bulks. If we presumably employ 100-140 mm diameter bulks as field poles, we should be able to reduce the dimensions and enhance the torque.

There are two methods to magnetize a HTS bulk: field-cooling magnetization (FCM) and pulsed-field magnetization (PFM). The FCM can lead to uniform trapped flux distributions. Yet, the FCM system is quite heavy and large, which involves difficulties for being built inside a rotating machine and/or its periphery. On the other hand, the PFM makes it possible to magnetize a HTS bulk in narrow space, if we provide pulsed-current magnetization coils. However, the trapped flux distribution with PFM is inhomogeneous because the results of PFM are much influenced by the microstructure of melt-growth bulks’ crystals.

Currently, the HTS bulks we assemble in our motor are qualified by data based on the conventional FCM and then used for PFM. It is however difficult to find the correlation between PFM and FCM results. Considering the limited space of HTS motors, PFM is the most appropriate way of magnetizing the field-pole magnets, hence the need for a new method to discriminate the pinning stability under the PFM. Such qualification must become an indicator of the flux pinning instability occurring inside the HTS bulks.

2. Experimental details

2.1. Samples

We performed the present study with two representative Gd HTS bulks (QMG supplied by Nippon Steel Corporation). The compositions and the dimensions of these samples illustrated in figure 1, Bulk-A and Bulk-B, are shown in table 1.

| Sample | Diameter | Thickness | Gd123 | Gd211 | Pt | Ag |
|--------|----------|-----------|-------|-------|----|----|
| Bulk-A | 100 mm   | 20 mm     | 51.1 wt % | 20.5 wt % | 0.5 wt % | 27.9 wt % |
| Bulk-B | 97 mm    | 20 mm     | 70.9 wt % | 19.2 wt % | 0.5 wt % | 9.4 wt % |

Figure 1. A 100-mm diameter Gd123 bulk sample.

Table 1. The compositions and sizes of sample bulks.

In table 1, one can see Gd123 and Gd211, corresponding to Gd$_{123}$Ba$_2$Cu$_3$O$_{6.9}$ and Gd$_{2}$Ba$_1$Cu$_1$O$_{5.0}$, respectively. Figure 2 and table 2 show the results of trapped magnetic flux density distributions after a FCM performed with a conventional superconducting magnet. Crossing white lines of figure 2 indicate the growth sector boundaries (GSB) of the sample bulks. The four distinct parts are called growth sectors (GS). On the Bulk-A of figure 2, there are two visible valleys with a fall of the trapped flux density within the GS. On the other hand, on the Bulk-B the valley phenomenon is very small and presents a regular conical density distribution profile. On the result of FCM for the
Bulk-A, we can see a clear difference between GS and GSB. The inhomogeneous distribution comes from the biased crystal growth of the HTS bulk.

2.2. **Pulsed-field magnetization**

For the PFM experiment, HTS bulks are first cooled down to liquid nitrogen temperature. After cooling, HTS bulks are magnetized with PFM. These bulks were magnetized by a couple of controlled magnetic density distribution coils (CMDC, figure 3.) [3]. It is made of 2-mm diameter copper wire windings. Each split-type coil is actually an assembly of two vortex-type coils, a 100-mm diameter coil being inserted in a 140-mm diameter coil. Accordingly, the CMDC can be used following two different modes (table 3). In the present study, the coil mode A provides a 140-mm effective diameter by connecting inner and outer coils as shown in figure 3(a). The coil mode B gives an effective 100-mm diameter by using only the inner coil as shown in figure 3(b). The schematic drawing of the PFM apparatus is shown in figure 4.

We measured the trapped flux density distribution by using a Hall sensor (BHT921 F. W. Bell) in a plane 4 mm above the surface of the bulk. The scanning area is 120 mm by 120 mm and the sampling interval is 2 mm.

![Trapped flux density distributions](image)

**Figure 2.** Trapped flux density distributions of magnetized a Gd 123 Bulk-A and Bulk-B with conventional FCM down to liquid nitrogen temperature. The applied static magnetic field was 3T.

| Sample | Bulk-A | Bulk-B |
|---|---|---|
| Maximum trapped field density | 1.93 T | 1.81 T |
| Total magnetic flux | 5.37 mWb | 4.08 mWb |

**Table 2.** The results of FCM for sample bulks.

| Mode | A | B |
|---|---|---|
| Diameter | 140 mm | 100 mm |
| Number of turns | 330 | 230 |
| Thickness | 20 mm | 20 mm |

**Table 3.** Specifications of the controlled magnetic distribution coils (CMDC).

2.3. **Qualification of pinning stability**

To investigate the stability of the trapped field density, the analysis of the data is divided into two steps. The first step is calculating the average of trapped field density values (equation (1)); the second is comparing the average of the trapped field density with each trapped field density distribution as in
equation (2). The data of trapped field density after the first, second and third PFM are defined as $B_1$, $B_2$, and $B_3$, respectively. The average trapped field density is then defined by the following equation.

$$ (B_1 + B_2 + B_3) \div 3 = B_{av} $$

(1)

Thus, we introduce the trapped flux instability $B_{flux}$. It is expressed by the following equation.

$$ \left( |B_1 - B_{av}| + |B_2 - B_{av}| + |B_3 - B_{av}| \right) \div 3 = B_{flux} $$

(2)

The value of $B_{flux}$ is the average deviation of the trapped field density at a single point on the HTS bulk.

Figure 3. Design of the magnetizing coils used for PFM.

Figure 4. A schematic drawing of the experimental geometry of pulsed-field magnetization (PFM).

3. Experimental results and discussion
In this section, we indicate two archetypal results of PFM for HTS bulks: set-1 and set-2. For these bulks, we applied PFM with the three steps described in tables 4 and 6. For the set-1, we applied 3 T with coil mode A at first, next 3 T with coil mode B and finally 3 T with coil mode B (table 4). For the set-2, we applied 2 T with coil mode A at first, then 3 T with coil mode A to finish with 4 T with coil
mode B (table 6). For the set-1 of PFM, the results of the average trapped field density and trapped flux instability distributions are shown in figure 5. From figure 5(a), we can notice an abrupt shape of the distribution and two valleys in the growth sector. In figure 5(b), we can see a criss-cross shape with white areas. These results show us that the area of the growth sector is unstable for trapping flux. It means the bulk-A has a difference of crystal growth at the growth sector. Accordingly, when we applied PFM, flux went in and out the GS. This moving of flux generates heat in the HTS bulk. As a result, it leads to unstable criss-cross shaped distributions. On the other hand, in figure 5(c), we can observe a smooth shape of the trapped field density distribution. In figure 5(d), the distribution’s color is nearly plain. The trapped field appears only at the edge of HTS bulk. This phenomenon is caused by the difference of crystal growth. It caused the instability of the trapped flux at the edge of figure 5(d). These results of bulk-B show the best conditions of crystal growth in its center.

**Table 4. Parameters of PFM set-1.**

| Number of PFM | 1st Coil mode | 2nd Coil mode | 3rd Coil mode |
|---------------|---------------|---------------|---------------|
| Applied magnetic field (T) | Mode A | Mode B | Mode B |
| 3 | 3 | 3 |

![Figure 5](image-url)  
**Figure 5.** The set-1 results of trapped field density distributions and trapped flux instability distributions for both bulks. (a) and (b) are related to the Bulk-A while (c) and (d) concern the Bulk-B.

**Table 5. Result of PFM of set-1.**

| Bulk-A | Bulk-B |
|--------|--------|
|        |        |
Next, with the set-2 of PFM, there is a big valley at the lower right part of figure 6(a). It is caused by an insufficient crystal growth of in the growth sector, leading to differences in the surrounding area and thus to the moving of the field. This displacement generated heat in this part. The figure 6(b) is compatible with this hypothesis. In addition, we can see the difference of color in the middle of this figure. It is an error of measurement, which also slightly occurred in the perpendicular direction. In the figure 6(c), we can observe a smooth shape of the trapped field density distribution, like in figure 5(c), thanks to a good crystal growth of the bulk-B. Yet, we need to apply a bigger magnetic field to break the Meissner effect. Similarly, the figure 5(d) has a distribution of nearly plain color. At the lower right part of figure 5(d), the color is globally black; it is another error of measurement.

Table 6. Magnetizing parameter of set-2.

| Number of PFM | 1st Coils Mode | 2nd Coils Mode | 3rd Coils Mode |
|---------------|----------------|----------------|---------------|
| Coil mode     | Mode A         | Mode A         | Mode B        |
| Applied magnetic field (T) | 2 | 3 | 4 |

Table 7. Result of PFM of set-2.

Figure 6. The set-2 results of trapped field density distributions and trapped flux instability distributions for both bulks. (a) and (b) are for the bulk-A, (c) and (d) are for the bulk-B.
4. Conclusion
We applied the pulsed-field magnetization to two different bulks with different flux instability upon magnetization. The result of field cooling for Bulk-A shows us the clear difference between GS and GSB. On the other hand, bulk-B has a good crystal growth. This fact fits well with the magnetic density distribution appeared after the second PFM. We have introduced the trapped field instability as a specific parameter to visualize the difference with the average deviation obtained after PFM. The trapped field instability shows us the pinning stability properties of the flux. For both bulks A and B, the obtained trapped field instability is higher in the GS than the GSB. A bulk with a large difference in the distribution of the trapped field instability is not suitable for PFM. The insufficient crystal growth generates heat inside the bulk when PFM is applied. This kind of bulks cannot maintain the conical shape of the trapped magnetic field density distribution. A good example is the bulk-A. In contrast with the bulk A, the bulk which shows a small difference in the distribution of the trapped field instability is relatively suitable for PFM. This kind of bulks needs an intense applied magnetic field to get a conically shaped trapped density distribution.

The present results make it possible to discriminate the compatibility for application and provide optimum parameters of PFM to HTS bulks.

5. References
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