Next generation of HTS magnetic application: HTS bulk and coil interaction

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Abstract
The next generation of HTS magnetic bearings (SMB) will operate at magnetic field excitation higher than permanent magnets (> 1.0 T). The new bearing type is capable to support heavy -load rotors of more than one ton mass. Using FEM we calculate the interaction of HTS bulk and 2G coil to achieve higher magnetic flux excitation and flux gradients of HTS bearings at temperatures of 50 – 60 K. The new total HTS bearing type multiplies the present 10 -15 N/cm² force density obtained with PM’s by a factor of 5 and passes the force properties of active magnetic bearings (AMB). HTS coil excitation is capable to increases the levitation forces to more than the present 10 kN level and reduces relative cooling and material effort per load. We design a magnetic bearing for HTS bulk -coil excitation.

1. Introduction

What is the future SMB development? Physically it is clear that the magnetic excitation due to PM’s is basically limited by the available coercitive force of the PM material. This limitation is tried to overcome by the use LTS/HTS coils for excitation in magnetic bearing. Several groups in advanced laboratories are concentrated on HTS coil interaction with increased magnetic flux excitation. First success is reported by RTRI in Tokyo e. g. for a 10 kWh railway flywheel [1]. A promising load capacity of 20 kN has been demonstrated at cusp fields of 5 T (NbTi coil) and 2.8 T (Bi2223 coil) against 60 mm GdBCO bulks, respectively. The disadvantage of the NbTi coil excitation is necessity of Helium temperature and about 15 K for BSCCO coil, here provided by cryo-cooling.

For rotating application we favored in the past the journal–type superconducting magnetic bearing (SMB) interaction by using permanent magnet (PM) rings and bulk REBCO superconductors [2]. Subdivision of the PM rings in multi-pole arrangement increases the bearing stiffness. Because of the limited magnetization of PM material NdFeB and the strong flux decay in air the achievable magnetic force density is limited to 5-10 N/cm². An increase of the magnetic excitation flux $B_{exc}$ in the air gap would enhance the forces by a square factor $B_{exc}^2$. Therefore, with $B_{exc} = 1T$ instead of now 0.5 T e. g., the force density would approach the 30 – 40 N/cm² level of active magnetic bearings (AMB).

We investigate magnet field generators, calculate the optimum coil design und propose the achievable force density under coil bulk excitation.

2. Magnetic field generators

For preparing a magnetic field of a certain level one has in general some technical options: Conventional or superconducting wired coil, permanent magnet PM, or superconducting bulk magnet. The physical basis for generating magnetic forces is the ability to produce a magnetic field of a certain value and distribution. Magnetic fields may have different physical and technical origins. The conditions and constraints range from atomic scale collective electron spin behavior (PM), magnetic flux trapping in bulk superconductors, and magnetic coil circuits in solenoids. Between

![a.png](attachment:image.png)  ![b.png](attachment:image.png)  ![c.png](attachment:image.png)

Figure 1. Magnetic flux generators: 120 mm PM rotor , 4 kg, 30 mm YBCO bulk, T =77 K, 120 g, and 140 mm YBCO tape double pancake coil; T= 45 K, 2.5 kg.
technical and economical constraints the question arises: How can we provide a magnetic field as a universal tool at a minimum effort and cost? In Fig. 1 we exhibit and compare three field generators providing similar magnetic flux. A 120 mm PM rotor consisting of 6 NdFeB PM rings separated by 5 Fe flux collectors (a). A melt-textured YBCO bulk superconductor of 30 mm diameter, 15 mm thick (b), and a 140 mm experimental 2G pancake coil delivering homogeneous central field of 0.5 T at 77 K and 48 A (c). For comparison the magnetic devices one has to consider the different technical environment and conditions, like the cryogenics in b and c, the power supply (c) or the mechanical structure for magnetic biasing (a).

Next, we will analyze and compare the properties of the field generating device and discuss the possibility of magnetic bearing improvement.

3. Magnetic design and performance

In Fig. 2 the magnetic circuits obey the conservation equation of magneto-statics. The provided magnetic flux and magnetomotive force of coils is considered rigorously in B and H units per volume.

Permanent Magnet PM (a)    YBCO bulk superconductor (b)         REBCO coil (c)

Permanent Magnet PM (Fig. 2a)

The magnetostatic field concepts are based on the existence of magnetic dipole, the equivalent torque, and on the phenomenon of magnetization. For a PM with the area A and the height $h_{PM}$ under the condition of a constant flux density we can assume a simple expression with the magnet height and area:

Magnetomotive force mmf follows:

$$\text{mmf} = \int \mathbf{H} \cdot d\mathbf{l} = h \frac{B}{\mu_0} \rightarrow H_{PM} h_{PM}$$

The H- field arises from the free ends of the dipole chains and is conservative. In contrast the B-field has no sources, but consists of closed induction lines. $\nabla \cdot \mathbf{B} = 0$ expresses the observation that no true magnetic mono-poles can exist in which the B-field could terminate. Magnetic flux $\Phi$ is,

$$\Phi = \int \mathbf{B} \cdot dA = \mu_0 A n I / h$$

$B_{PM} A_{PM}$

The equation express the experience in the work with permanent magnets. The magnetic performance is simply correlated with the cross section area $A_{PM}$ and the height $H_{PM}$. Both geometrical parameters give the magnetic volume, and together with the coercitiv ity force parameter ($kA/m$) the magnetic performance of a PM.

The maximum energy product of a PM $(B \cdot H)_{max}$ is about half of the coercitivity force $H_c$, giving the parameters $H_{PM} \approx H_c/2$, $B_{PM} \approx B_c/2$. Practically, the best PM material (NdFeB) shows flux densities on the surface between 0.4 – 0.6 T. According to the above formulas higher flux density is directly coupled with an increase of the volume respective the mass of PM.

Using available 200 mm PM ring biasing in a high- gradient magnet design at sub-cooled LN$_2$ (72 K) axial forces up to 10 kN are achieved (Fig. 3). The performance of magnetic bearings with PM’s can be improved.
by lowering the HTS temperature, as it is demonstrated in Fig. 3. The maximum obtainable force is always limited by the excitation field.

**Bulk superconductor (Fig. 2b)**

Bulk superconductors can be considered in a rough scale as analogous magnets to PM’s. Following the Maxwell equation, the rotation of the internal magnetic flux density determines the maximum trapped field flux density in z direction \( B_z \). For an infinite long cylindrical sample with a diameter of 2R the flux is given by the relation,

\[
R \int_0^R J dr \quad \Rightarrow \quad B_z^{\text{max}} = \mu_0 J_c R
\]

After this equation, the maximum trapped field depends on the critical current density \( J_c \) and the diameter \( D = 2R \) of the superconducting domain.

In practice, the value is reduced by geometrical and demagnetization effects by about 20% relative to applied magnetic flux density \( B_{\text{exc}} \). Bulk superconductors can trap routinely 1.2 – 1.5 T at 77 K, and may provide at least a two times higher \( B \) values compared to PM’s. At reduced temperatures much higher trapped magnetic flux can be deposited into the HTS bulk material. In Fig. 4 the increased trapped flux maximum in large multi-seed YBCO bulks is demonstrated. At 50 K and 5 T excitation the material is capable to trap almost 3.5 T which is about four times higher compared to the 77 K value.

**Solenoid - circular coil (Fig. 2c)**

A circular (thin) coil with a diameter \( D = 2R \), height \( h \), wound with \( n \) turns in a length \( l = n \pi D \) follows,

\[
B = \mu_0 n l
\]

As a magnetic performance factor the flux density \( B \) and the volume \( V \) needed for a corresponding force interaction, can hold for a normalization and comparison,

\[
B V = \mu_0 D h / 4 * (I \bullet I)
\]

The coil performance is proportional to the geometrical parameters \((D \bullet h)\) and to electrical Ampere-meters \((I \bullet l)\). The above equation gives advices to the necessary material and power costs of a coil circuit producing a improved flux density \( B \).

**4. FEM calculation of optimum magnet configuration**

Finite element model calculations are performed in an axi-symmetric model. Table 1 shows the chosen parameters for the FEM model. More than 60 different electric and magnetic configurations have been calculated. For a given maximum conductor length of 1000 m the number of pancakes and double pancakes (DP) are optimized. As parameters the DP iron collector stacking distance, the driving pancake current \( 40, 60 \) and \( 80 \) Amperes, the Fe collector shape, and Fe magnetic back circuit are varied.

Table 1 gives the FEM parameters used in the calculation by the geometrical position of rotor and stator. Fig. 5 displays a FEM result of an optimum gradient coil configuration consisting of 3 pairs of DP with 2 pairs of Fe collectors sandwiched by 2 mm thick Cu plates for efficient cooling.

An optimum set of parameters could be obtained according to the performed calculations:
- Double pancakes should be stacked in pairs.
- At 80 A the magnetic flux is 1.3 T within 2 mm of the rotor surface.
- At the inner part of the YBCO bulk rotor the flux is still 0.3 - 0.7 T.
- Magnetic flux gradients are \( dB_r / dr = 83 \) T/m, \( dB_z / dz = 33 \) T/m.
- The optimum distance DP - Fe collector is 20 mm.
- At 80 A the D-pancakes see a background flux density of 2.0 T; 50 K cooling is required.
Table 1: FEM Model Parameter

| Material Parameter | Density [g/cm³] | Magnetic Property |
|--------------------|----------------|-------------------|
| YBCO, melt textured| 6.0            |                   |
| 2G coated conductor + polyimide | 7.25         |                   |
| Fe, collector + magnetic circuit | 7.8          |                   |
| Glass fiber        | 2.05           |                   |
| Insulation, resin, epoxy |             |                   |
| Fe, max. magn. flux density | 2 T          |                   |
| Other materials    | μ_r = 1        |                   |

Figure 5. FEM calculation of coil magnetic flux distribution (3x DP, 2x 20 mm Fe, 6 x Cu plate, 80 A)

5. High-gradient magnetic flux concept

Due to the availability of 2G wires a promising possibility to increase the force density of SMB is given. The electromagnetic force is now generated by a magnetic field of stacked coils (Fig. 6). In contrast to most of the magnetic coil applications, where a great homogeneity of the magnetic field is gained, we follow our concept of a high-magnetic flux gradient by assembling Fe collectors between the coils after Fig. 5. The FEM calculations in Fig. 5 give the optimum coil design together with the Fe collectors. The essential features are taken from Fig. 5; at 80 A coil current about 1.3 T is the generating flux in the gap between bearing stator and cryostat rotor. The 1.3 T flux density is about 3 times higher than equivalent parameters with PM’s. From this and the experiments in Figs. 3 and 4 we calculate the expected force density in Fig. 7. The Fe collectors are almost field saturated by 1.9 T which influences the coil J_c operation. To maintain the high flux excitation the coils have to operate at about 50 K because of the strong J_c(B) dependency. With a force density of 40 N/cm² at 50 K and 1.3 T gap excitation the HTS coil and bulk interaction opens a substantial improvement of HTS magnetic bearing. The performance approach or pass the values of active magnetic bearings AMB.

Conclusions

HTS coil bulk magnetic interaction has been analyzed to get a proof for the next generation of total HTS magnetic bearings. Magnetic flux generators are compared in the parameters and conditions. Higher flux is achieved by more PM volume only. FEM calculations give the optimum Double Pancake coil configuration assembled in pairs with Fe collectors. For an excitation of 1.3 T in the gap the estimated force density at 50 K is more than 40 N/cm² and passes the active magnetic bearing AMB parameters.

References

[1] H Seino, K Nagashima, Y Tanaka, M Nakauchi, Study of Superconducting Magnetic Bearing Application to the Flywheel Energy Storage System that consist of HTS bulk and Superconducting coils, J. Phys. C Conf. Series, p. 1076
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