HTS Bulk Magnetic Application in Flywheel Energy Storage Systems FESS and MAGLEV Transportation

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Abstract

With High Temperature Superconducting (HTS) magnet technology a great potential of application in superconducting magnetic bearing (SMB) and linear magnetic levitation (MAGLEV) technology becomes attractive. Besides the superconductor each application sets specific technical requirements. We present our study and work contributions on improvements of rotational and linear magnetic bearings to stabilize heavy flywheel fiber rotors and mobile vehicles in three different larger MAGLEV train concepts. We discuss the design and fabrication of an Flywheel energy storage system FESS with an 1-ton load SMB on top. The SMB force density approaches 10 – 15 N/cm² in axial direction at 2-3 millimeter magnet gap interaction for journal-type bearings and a density of 5 - 7 N/cm² for linear MAGLEV vehicles at centimeter-sized gap distances. We describe the attempts to increase the force beyond the present 10 kN bearing load performance and to control sensitive bearing issues as damping, cooling and rotor dynamics. Magnetic levitation tests trained on linear and circular guideways from 40 to 150 m length attract great interest for future extension of mobility in urban and local transportation. Compact and robust vacuum cryostats’s containing YBCO bulk HTS with LN₂ cooling enable improved mobility and operation of larger MAGLEV trains for transporting people and goods. Three different larger MAGLEV train demonstrator concepts using YBCO bulk cryostats in Brazil, China and Germany are compared in their present status.

1 Introduction

The continuous development of high- Tc material, both in bulks and wires improves the possible application that is in most cases a magnetic one. Magnetic levitation is a fascinating effect demonstrated by the man – loading magnetic levitation platform in Fig. 1. Correspondingly, technical magnetic bearings use the interaction between magnetic fields and bulk superconductors governed by the relations of magneto-motoric forces according to Maxwell and Faraday. The availability of these bearings opens new possibilities for their applications. SMB have specific properties that differentiate them from mechanical bearings. The principle advantages are related to the absence of any physical contact with a number of benefits as no lubrication and abrasion, ideal for clean- room application and the ability to operate under complicate conditions like vacuum, cold, steam, heat and aggressive chemical environment. The greatest obvious practical advantage is the exclusion of any solid friction allowing a high-speed, low- noise and smart operation. The small loss that is still present being cause by the not perfect homogeneously magnetized rotor or magnetic guideway configurations.

The use of extremely low-loss high-temperature superconducting (HTS) bearings is deemed necessary to meet the long idle time requirements of flywheel energy storage systems (FESS). High specific stored energy in a level of 10 kWh will require corresponding rotational speeds of perhaps 10000 rpm and rotor weights up to several hundred kilograms. At the beginning of the HTS era flywheels have been
demonstrated with superconducting magnetic bearings. When up-scaled, designing and construction of a complete superconducting flywheel except the high – speed bearings require more attention and technological skills however, as efficient cryogenics coupled with thermal insulation, motor/generator construction, containment, power management and understanding of rotor dynamics. Many of the parameters have been reported in between [1-3]. The controllability of the rotor dynamics seems to be an especial critical parameter. Most rotor crashes in the past have their origin in this field.

Boeing Corp. has successfully developed a 5 kWh /3 kW flywheel energy storage systems [1]. The cfpr rotor is stabilized by a bottom HTS thrust bearing with YBCO hexagonal arranged bulks. A zero-stiffness Evershed – PM bearing on top gives radial stability but is axially unstable. A Japanese NEDO consortium performed tests on a 10 kWh/ 100 kW flywheel [2], and in a German joint project ATZ /Magnet-Motor (MM) built a compact 5 kW/250 kW flywheel system and tested especially the rotor properties [3]. While the first project (Boeing) uses the suspension of an axial HTS magnet bearing, the two other mentioned larger FESS are equipped each with strong journal HTS bearings of 175 mm and 200 mm diameter, respectively, to stabilize the rotors. The Japanese flywheel possesses in addition an upper and lower radial active magnetic bearing AMB (Koyo Seiko) to confine the radial rotor movement within the limited 0.6 mm magnetic gap of the HTS bearing and to stabilize the 380 kg rotor safely. The ATZ / MM flywheel rotor is stabilized at the bottom using a strong PM bearing, being radially stable but pushes the rotor against its gravity with a stiffness of 1.2 kN/mm.

Similar technical challenges of designing and construction of mobile thermally insulated light-weight and robust cryostats for magnetic levitation (MAGLEV) trains with long-time operation are discussed in the second part of applications [4-7]. Engineering properties, advanced magnetic excitation systems and thermal and mechanical stability of robust high - load YBCO MAGLEV cryostats are presented. From the electromagnetic interaction against the linear guideway each cryostat produces high axial forces of 2.5 kN levitate the train 10 – 20 mm above the permanent magnetic track.

2 Materials

2.1 Magnetic Excitation Engineering

From the viewpoint of force functionality a bulk superconductor basically acts as a passive element. We assume the existence of an external magnetic field either generated from permanent magnets (PM) or coil will interact with the HTS. The magnetic field is screened perfectly by surface currents (Meissner effect) or the magnetic flux is trapped by pinning forces within the bulk. Meissner screening effect is usually ignored by PM- HTS force consideration because of its weakness (a few per mill of pinning force). Curiously, public levitation experiments and levitation pictures especially in www with bulk HTS are still described erroneously as Meissner effect. It’s nearly one hundred percent pinning force that levitates a PM several centimeter stably above a bulk HTS, however.

For an efficient application start to estimate the magnitude of forces one can determine the necessary material and design. Magnetic circuits obey the basic laws of electricity and magnetism, in
special the rules for conversation of magneto-motoric force. The performance PMs in Fig. 2 depend on the energy product \((BH)_{\text{max}}\) with an operating point at half of the coercitvity force \(H_{\text{PM}} \sim H_c/2\) and a magnetic flux density about half of the remanence force \(B_{\text{PM}} \sim B_r/2\). To achieve higher magnetic forces and larger magnetic flux density excitation a larger volume and mass input of the magnet material is required. Parallel, magnetic engineering or sometimes called magnetic biasing can generate higher flux densities and allows a motion of the vector of magnetization as it shown in Fig. 2. Thereby either the magnets are pressed repulsively together or an iron sheet is positioned between the magnets to collect and turn the flux.

In a first try of any levitation system the so-called mirror image concept is useful. It can give the relation between the expected force density as a function of the magnet dimension and gap distance. The calculation in Fig. 3 assumes an ideal diamagnetic superconductor response to an external magnetic excitation. The magnetic interaction is thereby considered a one-to-one reaction. In this model both the field magnitude of the response as well as regarding the position of the diamagnetic image follow perfectly the origin. In Figure 3 the distance force density FEM calculation of permanent magnets in a principle 2D mirror image is shown. The distance is a simple ratio of the diameter of the PM giving three curve parameters with increased PM height ranging from half, equal and double the distance to the superconductor. The results on the ordinate are given as pressure related magnet performance \(P_d/(\mu_0H_c^2/2)\). Curves and calculation give a first approach about the expected force density for given PM parameters.

For HTS bulk interaction two basic magnetic sources are becoming practical, permanent magnets and magnetic coils. Practically easy to realize is the interaction with PMs because no current supply becomes necessary relative to coil excitation. However, having a magnet and a superconductor wouldn’t automatically give a good magnetic configuration or bearing. PMs need often configured and combined in opposite directions and generate a substantial flux enhancement as it is shown in Figure 2. Dependent on the distance to the HTS an iron flux collector between the magnets improves the flux confinement and orientation. Further optimization is possible by a Halbach configuration whereby the iron as flux collector is replaced by a PM driving the total generated magnetic flux to one side of the PM assembly. In Fig. 4 2D FEM calculation compares two PMs with \(D \times h\) to be 30 x 35 on left and 50 x 40, respectively. The field line distributions and the determined integral flux at 10 mm distance demonstrate the improvement. A double PM cross section (right) increases the integral flux density by about 25 % only, however.

Our technical experience collected over years with PM rings indicates some other critical issues. PM rings under rotation posses a sensitive material specific tensile strength equivalent to about 120 m/s rim speed. To overcome this limitation, high-strength composite banding structure winded around needs to be used to protect the PM rings from cracking. The banding structure pre-stresses the PM ring under compression so that high tensile stress will not be developed during

![Figure 3: FEM 2D calculation of the expected magnetic pressure relative to the magnet performance based on the mirror image concept](image)

![Figure 4: FEM 2D calculation of generated flux of different PM geometry; left \(D \times h = 30 \times 35\), right \(50 \times 40\); distance 10 mm](image)
bearing rotation. If the PM ring is larger than a diameter of 200 mm (D > 200 mm) the ring needs to be assembled from corresponding segments with probable introduction of magnetic field inhomogeneity. Practically, a careful balance and compromise in the design between attaining higher speed and maintaining a low-loss bearing has to be considered in each case.

Magnetic coil application as an alternative to PMs is mentioned briefly in the flywheel section.

2.2 REBCO Bulk Superconductors

In the following we will review briefly large-scale HTS bulk production in an engineering level serving the increased HTS bulk demand for magnetic applications. Top seeded melt growth (TSMG) is a well understand melt texturing process studied and improved in the last decade in many HTS groups [8-10]. In addition, Light Rare Earth (LRE=Sm, Gd, Nd)) materials are attracting the interest, partly by using generic thin film seeds (Sm123, Nd123) and processing in reduced and normal oxygen atmosphere [11,12]. Especially GdBCO bulk samples prepared by cold-seeding seem to have higher Jc values at 77 K compared to YBCO. Bulk YBCO and GdBCO with large domain size up to 150 mm diameter and high intra-domain critical current density has been developed by Quench Melt Growth (QMG) method under reduced oxygen atmosphere by Nippon Steel Corporation. REBCO single grain bulks with extreme dimensions above 80 – 100 mm diameter require a material-controlled peritectic temperature gradient to prevent parasitic nucleation and unwanted grain growth.

Fig. 5 displays typical top seeded melt growth (TSMG) YBCO growing procedure applied by ATZ for single grain fabrication [3]. The melt texture process follows a characteristic temperature route: heating up to about 1050°C, 0.5 – 1 hour dwell time, fast cooling to 1015°C – 990°C and re-crystallization with a ramp-down of 0.5 – 1 K/h to 940°C, cooling with 50 K/h or furnace cooling to room temperature. In last step oxygen annealing the samples at 500°C to 350°C for 200 h is performed. With the top seeding technique displayed in Figure 5 high quality superconducting magnetic material in blocks of circular or rectangular shapes up to 60 mm can be fabricated. Larger samples or superconductor bulks with circular shape (rings, tubes, and segments) could not be easily grown as single crystalline material. Therefore, the bulks must be mechanically machined into the desired shape, than assembled to the component design, glued together and fine-machined up to the precise shape.

Using seeding technique single crystal superconducting bulks can be fabricated in large batches (Figure 6). 30 mm bulk cylinders in Figure 6 exhibit peak values of the trapped field of about 0.8 - 1.0 T at 77 K. However, by assembling the individual grains the resulting magnetic pressure of the assembly is limited due to the existence of (non-superconducting) joints between bulks. For larger applications, the average magnetization determined over the total assembly is more important than the peak values.

To raise the material quality for larger magnetic applications we fabricate large-sized high performance melt textured bulks with multi-seed domain structure to increase the average trapped
field value. In Figure 7 high-Tc TSAG YBCO bulks of 3-seed multiple-grain structure are shown. The multiple-seeded samples reduce the machining and assembling effort and the production costs of larger superconducting magnetic stator planes, rings or tubes. Helpful is the addition of Ag$_2$O which decreases the formation temperature substantially (10 wt % Ag drops $T_p$ by nearly 8°C) without influencing the material composition. In general, the fabrication effort and time for large bulks is substantial causing high material costs. In addition, under machining and cutting procedure the probability of damage of such large samples is always evident. In most cases such large bulk samples carry an external bandage to achieve a better mechanical stability. A careful post-growing treatment is recommended. ATZ’s fabrication strategy is therefore the corresponding assembling of 2:1 sized rectangular YBCO bulks (66 mm x 33 x 14 mm) in Fig. 7 allowing the fabrication of both larger magnetic journal bearing HTS stators as well as plane-like areas of assembled and glued bulks e. g. for MAGLEV cryostats.

2.3 Application Relevant Properties of HTS Bulks

2.3.1 Critical Current Density

High Tc- superconductors are capable to trap magnetic fields permanently and are becoming to superconducting magnets. The principle schematics about trapped flux density in a bulk superconductor are shown in Fig. 8. The trapping performance is proportional to the critical current density $J_c$ of the material. $J_c$ is the most important parameter of all superconductors. In the successfully applied BEAN model one assumes a simplified model for the current distribution.

In the critical state model, the sum of the quantized vortex currents is substituted by a macroscopic screening current density that the sample is capable to carry. In this way, the material can be assumed to have the magnetic permeability of free space ($\mu_0$), and a macroscopic screening current density $J_c$ with a non-linear relation of the induced electric field in the material. The BEAN model considers that this macroscopic current density has a constant value equal to $J_c$. Inside the superconductor the electromagnetic properties can be represented by a non-linear $E$-$J$ relation.

Measurements of the critical current density are performed inductively using corresponding magnetometers. Thereby, the induced magnetic moment loops were measured on small specimens cut from the parent grains using a Superconducting Quantum Design SQUID magnetometer.
The $J_c$ value parallel to the sample $c$ axis was calculated for these specimens using the following equation derived from the BEAN model:

$$J_c = 20(\Delta M)/a(1 - a/3b),$$

whereby $\Delta M$ is the hysteresis in the volume magnetization, $a$ and $b$ are the cross-sectional dimensions of the sample perpendicular to the applied field and $a < b$.

Following the Maxwell equations the internal magnetic flux density rotation determines the critical current by

$$\nabla \times B = \mu_0 J_c$$

In one dimension, the above equation is reduced to:

$$dB_x/dx = \mu_0 J_c$$ in rectangular coordinates,

$$dB_z/dr = \mu_0 J_c$$ in cylindrical coordinates, respectively

The maximum trapped field flux density in the $z$ direction $B_{z\text{, max}}$ of an infinite long cylindrical sample with a diameter of $2R$ is given by the following relation:

$$B_{z\text{, max}} = \mu_0 J_c R$$

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 $B_a$.

As an example, in case of a cylinder geometry one has to consider $dB/dr = \mu J_c$, integrated in the Bean model gives $B^* = \mu_0 J_c R$ for the maximum trapped magnetic flux $B^*$. Assuming a critical current $J_c = 10^4 A/cm^2$ and a grain diameter $2R = 40$ mm, it gives a trapped field value $B^* = 1.2$ Tesla.

After above equations a better bulk performance is given by increasing the critical current density $J_c$ as well as by the length scale over which the currents flow, i.e. the grain size. Both factors determine the field trapping ability that is improved in the last decade routinely to maximum values of 1.2 T at 77 K for YBCO.

A geometrical condition for generating high currents and high trapped field values is an optimum geometry of the magnetic field component which should be orthogonal to the crystallographic $a$, $b$ plane of YBCO single grain bulk. Figure 9 displays measurements of different YBCO cylinders with an orientation parallel and perpendicular to the radial magnetic flux distribution. Surprisingly, the axial force seems to be less sensitive to the crystal orientation of the YBCO stator for displacement values up to 4 mm. In contrast, the polycrystalline stator exhibits lower magnetic forces as expected.

Very recently the Cambridge group reported about a trapped field of 17.6 T between a pair of melts processed GdBCO bulks reinforced with a shrink-fit steel bandage [13]. Using a simple Bean approach the critical persistent current has to be $1.12 \times 10^5 A/cm^2$. At this field the Lorentz force $J \times B$ is increased to about 80 MPa, a factor three higher than the maximum tensile strength of ReBCO bulk material. From the maximum trapped field of 17.6 T a repulsive magnetic pressure of 12.3 GPa would appear when two such magnetized samples are pressed together.
### 2.3.2 Mechanical and Thermal Properties

For application it is important to increase the mechanical strength of the REBCO material. The tensile strength of YBCO at 77 K is between 20 – 30 MPa. REBCO bulks above 60 mm cylinder size show sensitive mechanical properties and tend to broke under high forces and stresses. The improvement of mechanical properties is therefore highly desirable. The addition of Ag₂O improves the microscopic stability and tensile strength of REBCO bulks. Resin impregnation of the bulks and reinforcement by a surrounding bandage either from metal (Al - alloy, stainless steel, and titanium) or of glass and carbon fiber give further stability and with applying pre- tension it compensates the tensile stress acting on the bulk during the magnetization process.

The magnetization and cool-down process is an extremely sensitive procedure for REBCO bulks. It generates great Lorentz forces which can cause distortions in the crystalline and domain structure. Rigorously spoken, the maximum trapped field is not limited by the magnetic properties of the material rather than by the produced internal magnetic force. This force passes the maximum tensile strength of 30 – 35 MPa already at about 3 Tesla. The resulting stress is a Lorentz force between the trapped field \( B_0 \) and circulating current loop \( A_c = B_0/\mu_0 \) in the magnitude \( \sigma \) \[N/cm²\] = \( A_c \times B_0 \).

To prevent mechanical damage the samples are armed under pre- pressure by a steel or carbon fiber bandage. Further on, the tensile strength of bulk YBCO superconductors can be improved by epoxy resin impregnation and wrapping with a carbon fiber fabrics [14]. The epoxy is able to penetrate from the surface along microcracks and can fill micro-structural defects up to a few millimeter depths. Due to the stabilizing technology the internal stress during magnetization from 7 to 0 T at 65 K were reduced from 150 MPa to 40 MPa. Epoxy resin impregnation enhances the mechanical strength of YBCO by a factor of 2.5 and with 60 - 80 MPa at 77 K the material strength approaches the properties required for most industrial applications. The same effect of surface stabilization can be obtained by copper surface plating and additional heat treatment as it is demonstrated in Figure 10. The averaged crack stress level processes on more than a dozen YBCO melt textured samples showed an increase by about 50%. In a mechanism Copper as a small atom diffuses at elevated temperatures into the sample surface and is filling the micro-holes and cracks with a beneficial stabilizing effect.

In connection with the formation of crystal defects during oxygenation Diko [15] has investigated the cracking behavior of YBCO bulk and has shown post-growth treatments to influence weak links and modify the effectiveness of pinning centers. By eliminating oxygenation-caused cracks with high –pressure \( O_2 \) treatment up to three times increased critical current density has been demonstrated.

The heat transfer mechanism is basic for the cryogenic conditions of bulk HTS. In most application the bulk stator is hold stationary and the magnetic component is in motion. For this the heat transfer process has to be studied carefully to achieve a high enthalpy of the cold mass and a safe operation. In case of losses due to eddy currents, e. g. a fast and continuous transfer of heat in the bulk is desirable. For this we measured the coefficient of heat transfer of polycrystalline YBCO to \( \lambda_{YBCO} = 4.5 \) W/mK in Fig. 11 between RT and 45 K.
2.3.3 Doping Strategy

Besides the mechanical properties the material applicability is determined by pinning performance of the magnetic flux in magnetic vortices (Shubnikov phase). Pinning is a process step displayed in Fig. 12 of microstructure engineering. The non-superconducting RE211 phase preferred in a nanoscale size provides the basic pinning background. Compared to LTS the new HTS possess a relatively weak intrinsic pinning. This observation has led to wide spectrum of doping concepts, ranging from columnar defects generated by irradiation (in a thickness of a few nm), substitution of ions in the HTS atomic structure, and specifically doping by addition of secondary phases.

A doping content of 0.3 wt% PrO₂ and/or 0.6 wt% CeO₂ is effective to influence the microstructure to refine the Y211 particles. Because of increasing costs PrO₂ doping is gradual eliminated to refine RE₂BaCuO₅ precursor powder. It is replaced by CeO₂ doping which seems to have an equivalent beneficial effect on the particle size.

The strong effect of refinement of second non-superconducting phases RE211 or RE422 on the critical current density has been shown in by Muralidhar [16]. Extremely fine 211 powders in nanometer scale are produced by ball milling treatment technique. By adding Gd211 of 70 nm size and 10 nm NbO₃ particles on a mixed NEG (Nd, Eu, Gd)–Ba–Cu–O matrix system Jc values of 925 kA/cm²@65 K and 640 kA/cm²@77 K could be obtained. Even for 90 K the critical current density was in a level of 100 kA/cm².

2.4 HTS Bulk Characterization-Trapped Magnetic Flux

The trapped magnetic flux measurement for HTS bulk characterization has a long tradition. The method was simply and easy to perform but displays their limitation as the HTS bulk material was becoming better electric and magnetic properties. Today, the measurement of the trapped field distribution after field cooled excitation seems a more adequate and reliable parameter of the magnetic bulk performance.

In Fig. 13 we demonstrate a magnetic flux density distribution of a 46 mm YBCO bulk specimen. The measured distribution is instructive in multiple regards. Although the maximum excitation flux was 1.45 Tesla using conventional Weiss magnet the measured trapped flux density in the center of the sample is approximately 1.2 T at 0.5 mm distance. The gradient of the field distribution changes from the center to boundary indicating different Jc values. This behavior displays higher critical current density values Jc near the bulk center and reduced critical supercurrents in the distance. Larger Jc at higher fields correspond to the often observed peak effect at mixed valence RE₁₋ₓREₓBaCuO superconductors.

High resolution trapped field measurements can explain the grain boundary behavior in multi-seed samples too. Fig. 13 in the center exhibits the flux distribution of a 3-seed YBCO bulk after melt textured processing, preparation (flat surface) and a surface scan. The as-grown sample with the...
SmBCO seeds on top show a non-vanishing trapped field distribution between the three peaks. The scanning Hall results of multigrain bulks give evidence of components of the super-current across the grain boundaries in the multi-seed bulk. While the intra-grain current determines the three individual magnetic peaks, an additional inter-grain current can pass the GBs and contribute a substantial part to the total trapped magnetic flux density integrated over the bulk. The latter is especially beneficial for large-scale applications.

Larger bulk fabrication is demonstrated in Fig.13 bottom. YBCO blocks of the size 90mm x 60 mm 20 mm are tested for trapped flux motor application. The scanning Hall distribution displays 8 individual crystals corresponding to the 8-seed structure. At an excitation field of 0.75 T the trapped flux peak values scatter between 600 and 650 mT. While in the length direction the grain boundaries show a certain flux overlap of 200 - 300 mT, in the perpendicular direction the neighboring 4-crystal rows indicate almost no trapped flux overlapping distribution. The latter behavior gives some evidence that between the two 4-crystal rows super-current is flowing rarely.

3 Flywheel with Superconducting Magnetic Bearing

For rotating application we favor the journal –type magnetic bearing interaction. Fig. 14 shows the principal design and the rules for an optimized magnet excitation of a radial and axial high gradient HTS bearing. The corresponding magnetic distribution of the B vectors (Br and Bz) can be calculated. After that the field decays with the exponential function along the radius vector r and relative to the axial distance of the magnet poles L (pole pitch). The obtained by flux field gradient generated by the PM / Fe configuration determines the radial force Fr and stiffness dFr/dr. Along z direction a sin / cos function covers the periodic field variation in axial direction and determines the axial force and stiffness of the magnetic bearing.

It has been shown that subdivision of the magnets in a multi-pole arrangement with the pole pitch L in Fig.14 increases the bearing stiffness provided the air gap can be kept small. On the other hand, in superconducting bearings force generation needs a displacement. Small magnetic air gaps < 2 mm improve the flux density in the gap but limit the possible displacement of the rotor. For larger distances > 2 mm the enhancement of the electromagnetic force due to Fe collectors is caused by the steeper flux gradient generated by the Fe collectors. In addition, larger gaps are useful to prevent any dangerous rotor stator contact in fast rotating machines, like flywheels or high-speed motors. The thermal insulation between the cold HTS stator and the warm rotor (or vice versa) is becoming easier in assembling at larger gap distances.

In the next chapter we compare the different FESS demonstrator concepts with superconducting magnetic stabilization and the critical concepts.

A self–stabilizing magnetic bearing is definitely a most fascinating and promising technology. Due to its physical properties it needs no electronic control and operates completely passively. Basically, the HTS bearing (SMB) is inherently fail-safe in contrast to active controlled bearing AMB after power loss. Using liquid nitrogen as a cooling fluid the HTS superconductor is operated at fairly low temperature, far below critical operation points and is therefore safe and reliable.

Because of the mechanical bearing friction a conventional flywheel loses about 2% of its stored energy per hour lowering the round-trip efficiency for diurnal, load leveling to half of the daytime energy. A magnetic bearing can reduce these losses by one order of magnitude. We therefore look first to the bearing concepts. An operating temperature of liquid nitrogen (T=77 K) is considered as satisfactory and sufficient far below the critical superconducting temperature Tc = 92 K, and therefore safe and reliable. Better electromagnetic force density values up 13 N/cm² axial and 6.5 N/cm² and especially higher
stiffness parameters up to 4 kN/mm are obtained at temperatures of 60–70 K [3] with the HTS magnetic bearing in Fig. 15. A moderate lowering of the temperature by 10-20 K relative to LN$_2$ reduces the hysteresis effects. Nevertheless, the practical force densities seem to be leveling off to 10 N/cm$^2$@77 K and about 17 N/cm$^2$@67 K [2]. Evidently, the maximum flux excitation with PM is practically not more than 0.5 T at the superconductor surface because of geometrical and constructive constrains in bearing designs. Larger bearing forces need an increase of the active magnetic area. A corresponding concept for a 20 kN radial force is shown in Fig. 16. The concept is based on the test results in Fig. 17 of the flywheel bearing in Fig. 15. The high-gradient concept of Fig. 14 displays two further issues: The bearing temperature and the correct pole pitch. The pole pitch distance is a result of the iron collector thickness, which is in case of the flywheel bearing at best for 18 – 20 mm.

It should mentioned, a substantial increase of the force performance of SMB is expected by a combination of bulk superconductors with superconducting coils. First calculations and experiments of the RTRI (Railway Technical Research Institute) in Tokyo were performed in a demonstrator NbTi coil configuration consisting of two coils in vertical forward and reverse field direction. The magnetic design generates a cusp field on a 60 mm x 20 mm GdBCO bulk superconductor between. A force density of about 100 N/cm$^2$ and a load capacity close to 20 kN axially could be obtained at about 1.6 T [17]. However, due to the physical character of the cusp field the axial and radial stiffness parameters are relatively low (< 1 kN/mm). With this configuration, safe rotor stabilization will be difficult.

The magnetic forces are increased with lower temperature. The force – displacement curves in Fig. 18 are measured at sub-cooled LN$_2$. At an optimal magnet configuration the 72 K curves shown in Fig. 17 are almost linear with displacement and approaches a force of 10 kN at 3 mm displacement. The PM – Fe geometry for the given air gap of 3 mm is optimized by variation of the PM/Fe thickness changing the pole pitch parameter. The compact 10 kWh/250 kW flywheel with the principal components is shown in Fig.18. The flywheel details are described in detail elsewhere [3]. The 600 kg glass/carbon fiber rotor is magnetically stabilized by the HTS bearing on top and radially confined by a (axially unstable) PM bearing at the bottom.

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**Figure 16:** Concept of a 20 kN journal bearing to stabilize the rotor of a turbo machine.

**Figure 17:** Displacement force curves of the ATZ / MM flywheel magnetic bearing for different PM-Fe stacks (pole pitch).

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**Figure 18:** Top side view of the 1 ton HTS bearing without rotor used in the 5 kWh /250 kW flywheel [3].
In the following we briefly scan flywheel technical key and operational issues to gain the desired flywheel high-speed operation.

### 3.1 Practical Rotor Damping

Rotor dynamics is the most challenging task of FESS operation under higher rotational speeds. By speeding up the rotor is passing several eigenfrequencies. Especially critical is the situation by approaching the rigid body frequencies which are accompanied by sudden increase of the rotor amplitude.

Further on, the rotor as a solid body is fixed elastically in one or two points on magnetic bearings which can cause additional motion effects. In Fig. 19 we studied on a test bearing the influence of the superconductor temperature on the first fundamental frequency of the system in radial and axial direction.

The frequency ratio axial/ radial two-to-one is related to the corresponding stiffness values. The curves show only a weak dependency on the temperature in agreement with the stiffness behavior.

One typical effect is the situation where the magnetic and inertia axes are parallel but separated
by a distance. The structure of this resonance caused losses whereby rotor’s center of mass moves around circles. If the geometric and magnetic axes of the rotor are not parallel, the dynamics of rotor is even more complex.

We investigated the damping possibilities of our 5 kWh/250 kW flywheel with respect to HTS and PM bearing. It followed a decision to provide our one-ton HTS bearing with an auxiliary damping system shown in Fig. 15. The dampers are self-constructed and connect and stabilize the superconducting stator with the housing. The four dampers have two functions: They operate by a pressurized viscous liquid and fix the stator after cooling and thermal shrinking. Under rotation they damp the HTS bearing. With the external HTS bearing dampers we calculated the effect of damping on the amplitude s of the PM bearing in Fig. 20. The HTS bearing damping was constant $c_{\text{damp}}(\text{HTS}) = 65 \text{ N/ (m/s)}$. With a damping of 1000 N/(m/s) on the PM bearing the rotor amplitude is safely confined to an amplitude of 0.5 mm.

3.2 Carbon Fiber Rotor

Carbon or glass-fiber (cf, gf) rotor winding is a special engineering skill which belongs to the fiber fabricating field, well known in modern airplanes for the wings or the body. In Fig. 21 we show a photograph of the 600 kg gf-cf rotor of our 5 kWh/250 kW demonstrator flywheel [3]. The rotor is a hollow cylinder and is made primarily of carbon fiber compound. To get the system compact, the motor/generator (M/G) unit is integrated concentrically in the cylindrical rotor. Winding the rotor was performed after calculations and tests about the maximum rim speed and the resultant centrifugal forces. The centrifugal force ($f$) acting on a thin rim with the thickness $t$ is obtained to be

$$f = 2\pi \rho r^2 t \omega^2$$

In Fig. 21 the photo shows the carbon fiber (cf) rotor of the ATZ/MM FESS together with equilibrium conditions of the stress and shear parameters under rotation with an angular speed $\omega$. The condition of equilibrium for the rotor stress distribution follows the equations. Under simplified conditions (thin axisymmetric disk) the stress distribution depends only on the radius $r$, and not on the thickness. The equilibrium condition for the corresponding strain is then $\varepsilon_\perp = \frac{\sigma_\perp}{E}$. In the practical winding process of the rotor a circumferential preload to the composite is applied. This technique enables an engineering-controlled optimization of the stress/strain distribution within the cf-winded composite rotor. Using a pretension applied during the winding fiber ribbon an elastic tension of he ribbon is obtained. The pretension winding keeps the inner layers under a resulting stress and increases the possible maximum speed limit of the rotor.

It should be mentioned that a thermal load or condition can influence the stress-strain distribution of a rotor in two opposite directions. The curing temperature can be used to cause stresses in the composite, if the composite has been cured at elevated temperature. Negatively, under rotation a possible temperature load reduces the maximum speed limit of the composite rotor.

Our rotor was substantially heavier than the rotors in the Boeing and NEDO flywheels. We could shift the critical rigid body frequency of the rotor to lower values of about 8 Hz (~500 rpm) still the vibration amplitudes were considered too large (0.8 – 1.4 mm). The ATZ/MM team decided to damp and confine the critical amplitudes by a dynamical operation where the rotor at lower frequencies up 20 Hz runs in the mechanical emergency bearings at both ends of the shaft. After passing the critical rpm the mechanical bearings were retracted giving the rotor free to run in the magnetic bearings.
3.3 Cryogenics

An important parameter for the bearing function is the temperature of the superconductor. For cooling the HTS bearing a one-stage 40/35 Watt/1.8 kW Gifford McMahon (GM) cryo – cooler was adapted by a flexible copper braid. A complete test program with 20 cold-warm cycles was performed to gain reliable experiences with thermodynamics. At zero thermal loads the cold head goes to a temperature of about 35 K. Within the assembled bearing the lowest measured temperature on the YBCO surface was 45 K generating high Jc values with excellent magnetic properties of the superconducting bulk ring. The low temperature causes less hysteresis and relaxation effects of the levitation forces and stiffnesses (Fig. 17). Between the GM cold head and YBCO ring at largest distance the temperature gradient was less than 1 K. Following Fig. 22 the cooling procedure serves a safe operation of the bearing after about 10 hours. After switching – off the cryo-cooler at 45 K the HTS temperature due to heat losses increases rather slowly and pass the 77 K level in about 90 minutes. In an emergency case this large time window allows a safe switch-off procedure of the electric and dynamic rotor system.

The necessary energy for cooling down the HTS magnetic bearing can be calculated by

\[ Q_{\text{HTS}} = [M_{\text{Cu}} C_{\text{Cu}}, M_{\text{HTS}} C_{\text{HTS}}] \Delta T, \]

with \( M_{\text{Cu}}, M_{\text{HTS}}, \) the mass of copper and YBCO superconductor, respectively. \( C_{\text{Cu}}, C_{\text{HTS}}, \) are the corresponding coefficients of the specific heat of both materials. The total cold mass was about 21 kg. The following parameters are used:

- \( M_{\text{Cu}} = 16500 \) g
- \( C_{\text{Cu}} = 0.383 \) Ws/g K
- \( M_{\text{HTS}} = 4800 \) g
- \( C_{\text{HTS}} = 0.25 \) Ws/g K

The coefficient of heat transfer of bulk YBCO is experimentally determined in Fig. 11 to \( \lambda_{\text{YBCO}} = 4.5 \) W/m K in the temperature region 293 K to 77 K. The total energy required to cool- down the HTS bearing (297 K – 77 K / LN\(_2\)) can be calculated to \( Q_{\text{HTS}} + Cu = 1650 \) kJ equivalent to about 10.4 l LN\(_2\). This calculated value is in agreement with the practically measured consumption of 11.2 l LN\(_2\).

The temperature of the cold bearing is measured directly at the cold head and on the other side of the 200 mm ring. Under thermal equilibrium conditions the temperature difference is measured to \( \Delta T = 0.5 \) K.

4 Linear Maglev Trains

Many of the technical parameters and issues of the rotational bearings can be transferred to linear maglev systems. The use of HTS magnetic levitation concepts have been proposed very earlier for transportation systems. The advantages of MAGLEV trains are similar to bearings and result from the lack of mechanical contact known over 100 years from conventional wheeled transport. Thereby MAGLEV technology can have a quite different physical mechanism including electromagnetic suspension (EMS) and electrodynamic suspension (EDS). While EMS technique (German Transrapid) is governed by attractive forces between electromagnets and the steel rail EDS (Japanese Yamanashi
MAGLEV trains) depend on repulsive forces. High-T_c superconducting MAGLEV trains in demonstrator versions go back to the developments after the HTS discovery. Improved versions with transport of persons have been designed and fabricated in the last 15 years [4-7]. A number of experiments have demonstrated the feasibility of magnetic levitation technology. The first experiments were performed by cooling the HTS in open vessels or container thermally separated by Styrofoam. Because of the worse thermal insulation the HTS container often became covered with frozen layers of moisture. The corresponding loss of cooling power enhances the cooling effort, which was compensated by periodic refilling LN_2 into the HTS container. The situation with HTS MAGLEV was about 10 years ago far from the expected performance regarding high forces and to operate service-free for hours or days. In addition, the MAGLEV procedures were determined by more scientific and technical limitation than by successful options:

- According to the individual magnet design developed first a priori and later by FEM calculations the force was generated by fc processes at axial distances of 30 – 20 mm with load decreasing the gap to 10 – 5 mm above the PM guideway.
- Although the total loads were approaching high levels too (Jiaotong, China - 8000 N, IFW Dresden, Germany - 3500 N; Moscow, Russia 3500 N) the force density values with 2 - 4 N/cm² were still limited.
- The magnetic guideway designs generated axial stabilization of the vehicles with lower stiffnesses and hence low guidance forces.
- The lack of mobile HTS cryostats leads to compromises, simple open cooling systems with LN_2 in Styrofoam container, resulting in short operation times and moisture frozen containers.

To overcome these problems, ATZ proposed a number of improvements: (i) high quality melt textured YBCO material of rectangular shape (higher Jc, better assembling), (ii) nearly invisible cooling of the Maglev HTS bulks by means of vacuum cryostats, (iii) together with former targets a better magnetic guideway design. The concept and target for solving the demands on MAGLEV side is shown in Fig. 23

The present MAGLEV status is characterized by utilizing well-constructed vacuum cryostats containing 24 YBCO bulks in a plane of almost 500 cm². More than 30 cryostats have been fabricated for MAGLEV application in China, Germany and Brazil. Due to perfect thermal insulation each cryostat can operate more than 24 hours having a thermal loss of about 2 Watt only. Each cryostat shown in Fig. 23 and Fig. 24 consists of a top G-10 plate and a stainless steel (ss) body. The 2 mm magnetic distance between the YBCO surface and the cryostat bottom is a technical highlighted feature. Together with an appropriate magnetic guideway it enables large levitation forces up to 3000 N@10 mm levitation height per cryostat.

Up to now has ATZ developed and fabricated 38 compact MAGLEV vacuum...
cryostats. Four HTS cryostats can carry almost 1 ton at 10 - 12 mm magnetic gap above a magnetic guideway with a force density of about 5 - 6 N/cm². In addition for Maglev operation ATZ has performed FEM calculations to optimize the guideway PM configuration shown in Fig. 23. Fig. 23 exhibits a basic configuration rule for the geometrical size of the PM and Fe collectors dependent of the chosen magnetic gap distance g. Most of the used algorithm to calculate the interaction with the superconductor follows the critical state model. Improvements are expected by using Halbach or semi – Halbach magnet configurations. The optimum magnetic configuration depends always on the actual gap distance between superconductor and magnetic surface, mostly selected to 10 mm distance. The principle design the high- gradient guideway concept considers the magnetic distribution of the principal vectors \( B_y \) and \( B_z \) following the rotational bearing concept of Fig. 14.

Inside of each cryostat 24 multi-seeded YBCO bulks of the dimension 64 mm x 32 mm x 12 mm are located in a copper holder. The total HTS area is about 490 cm² per cryostat. The superconductors are cooled using LN₂ by conduction cooling.

As noticed the 2 mm magnetic distance between the YBCO surface and the cryostat bottom is a technical challenge but successfully solved in a robust construction. It enables large levitation forces respective a high load capacity. Cooling-down to superconductivity is effective in about 30 minutes. Due to a cryogenic storage capacity of 2.5 liter LN₂ a long operation is ensured. Our measurements of the LN₂ consumption under static conditions indicate a 25 – 30 hours operation without refilling liquid Nitrogen.

The levitation forces depend strongly on the optimum magnetic track configuration. Fig. 26 gives a picture of the measured levitation of a YBCO cryostat on a semi-Halbach PM configuration of the University of Rio de Janeiro [6].

After the first Maglev operation about 15 years ago in Chengdu now an 80 m long oval PM Germany (Fig. 27). The maglev is now more than 3 years active without any degradation effects. Except the superconductor part the Maglev demonstrator in Dresden possesses a contactless current transformation and a linear motor between the two efficient PM tracks for acceleration and velocities up to 20 km/h. The total costs of the MAGLEV train were about 2.2 million EURO.

A similar Maglev system with ATZ’s superconductor vacuum cryostats is designed, tested, and built - up at the University of Rio de Janeiro, Brazil (Fig. 27, left photograph). The MAGLEV train, named Maglev COBRA, is proposed to operate on 150 m long magnetic guideway transporting up to 15 persons.
The COBRA train is in the final stage magnetically levitated by 24 cryostats with a calculated total load of 5 tons.

In order to realize the possible high-speed potential of MAGLEV transport the ASC Lab/Southwest Jiaotong University in Chengdu has built a new 45 m circular PM track and investigate several potentially commercial issues of MAGLEV transport systems including the influence of the air friction and possible scaling up and miniaturization of MAGLEV technique (Fig. 27, right).

References


