Impact of Cryogenics and Superconducting Components for HTS Magnetic Levitation Devices

F. N. Werfel, U. Floegel - Delor, R. Rothfeld, T. Riedel, P. Schirrmeister, R. Koenig, and V. Kantarbar

***Abstract* -- Practical REBCO bulk superconductor-based components and devices as rotational and linear magnetic bearings are well understood. A high-stiffness HTS magnetic bearing with 0.1 mm low hysteresis is demonstrated for narrow-gap operation. Linear magnetic bearings up to 10 ton load has been successfully implemented in linear Maglev trains under real outside conditions. The REBCO bulk –based magnetic levitated (Maglev) trains are proposed for urban and low-speed transport concepts. Contrary, high-mobile, lightweight and flexible HTS bulk components are developed under the extreme and safe conditions of manned spaceflight for astronomy and space application. YBCO bulk proton irradiation tests for space application are presented. In the International Space Station (ISS) the interaction of the earth magnetic field with a perfect fast moving diamagnet within a project called Magvector/MFX is measured and investigated. We compare an anticipated model with space experiments performed in the last two years in the ISS. The paper will summarize recent progress in this field, and present how cryogenic and HTS component design can positively impact levitation and screening performance. Properties of cryogenic systems and devices of mobile applications in their complexity and required robustness will be compared to stationary HTS systems, and the effect of different cooling options have to been considered.**

***Index Terms* - HTS bulk, magnetic bearing, linear Maglev, mobile HTS, space application, earth magnetic field.**

I. INTRODUCTION

IN THE shadow of HTS 2G wires bulk superconductors go a separate way in fabrication and application. The material base is safe and reliable, and fortunately processing single and multi-seed high – temperature bulk superconductors for large- scale application has been extensively reported [1]-[5]. The arising question is the technical and technological degree of conversion into robust and well–designed engineering solutions. The difference between wire and bulk is not restricted to fabrication process alone. Moreover, the universal tool is the high magnetic field provided by both, but in different structure and origin. Magnitude seems not the criterion after the recent obtained high – field values of HTS coils with 8.5 T at 40 K [6] and bulks in the 17 T level at 29 K [7], [8].

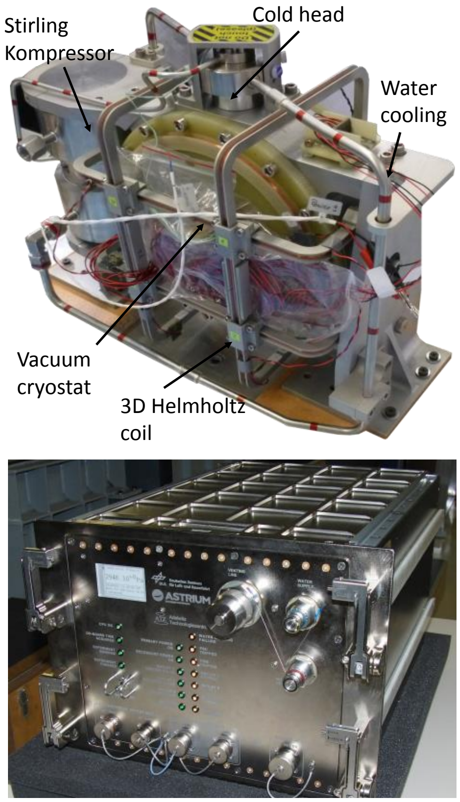

Fig. 1. Space ISS experiment MFX/MagVector device consisting of highly variable and mobile vacuum cryostat with cryo-cooler, 3D –Helmholtz coil, temperature and magnetic field sensors (top). European Drawer Rack (EDR) containing MFX device and operating in the ISS from 2014 by the German mission "Blue Dot" (bottom).

Geometrical field constraints are more severe: Coils as solenoids produce current induced high magnetic field in a small bore while bulks after trapping open the field in a free space with a great variability and without additional powering. The previously reported achievements and applications are evident advances toward these universal magnetic properties. The present challenge is the growing complexity of the HTS devices.

The HTS bulks are widely used for axial magnet bearing, magnetic coupling up to mobile magnetic train in linear configuration. As a key issue the magnetic force density is a stringent and challenging function of the magnet superconductor distance and design. The physical behavior contrasts and put all performed attempts of high magnetic levitation forces with a minimum of material effort into perspective.

One objective of the presentation here is the latest status of magnetic bearings in rotational and linear design suspending

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technical wheels under high-speed conditions and Maglev vehicles levitated for smart and fast transportation tasks.

Finally, ATZ has constructed and fabricated a transportable experiment with a conductor of variable conductivity in a moving magnet field. The experiment shown in Fig. 1 was specified for space application with the last German Mission of the Astronaut Alexander Gerst on the International Space Station (ISS). The experiment called MFX/Magvector is still measuring and collecting data about the interaction between a fast moving high temperature bulk superconductor switching between normal conductivity and superconductivity and observing the interaction with the surrounding earth magnetic field. Experiments are planned up to 2017 [9], [10].

The special target of this article is to highlight achieved engineering applicable features of the HTS bulk technology, the cryogenics, and the requirements and conditions when systems designed and transferred into mobile HTS devices.

II. ADVANCED REBCO BULK IN MAGLEV APPLICATION

A. High – stiffness low hysteretic HTS bearing

Great efforts have been made to apply HTS-PM levitation elements to study design, dynamics and damping, and force stiffness optimization. Ring or tube shape HTS and PM are extensively used and the levitation characteristics is investigated analytically and experimentally [4], [5].

A small HTS magnetic bearing of 20 mm diameter for high – speed application up to 50000 rpm has been developed in Fig. 2. The YBCO stator rings are grown with fourfold radially seeded bulks as hollow cylinders (Fig. 2). This gives an optimum magnetic geometry of the rotor and the radially oriented YBCO c axes B||c. When the rotor is field – cooled and displaced in vertical direction a high axial stiffness of 80 N/mm ensures a vertical rotor stability. The magnetic configuration of the rotor consists of 20 mm PM rings interspaced by 4 mm thick Fe collectors giving an axial pole distance of 14 mm (pole pitch) and an extremely low hysteresis behavior of 0.1 mm under periodic axial forces.

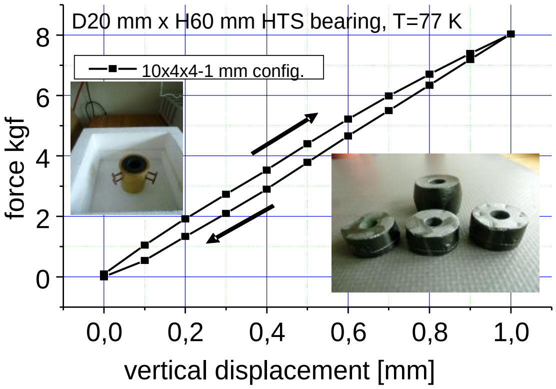

Fig. 2. High stiffness low hysteresis 20 mm HTS magnetic bearing for 50 000 rpm with optimum B||c geometry with radially seeded YBCO rings.

B. Linear magnetic bearing: Maglev demonstrator

Other issues, such as thermal contraction, insulation, vacuum seal, and temperature monitoring are common to conventional systems. An engineering key point is the design of mechanical support structure of the cold part. All metal, plastics and ceramic parts have to follow the thermal contraction and expansion by cooling and warming up (temperature cycling). Since testing verification of the thermal performance is among the scope of this study, test instrumentations and interfaces need to incorporate in the full prototype Maglev platform development.

Since the first technical solutions almost 15 years ago linear magnetic levitation attracts great interest in the extension of mobility in urban and local transportation [11]-[13]. Soon it became clear that vacuum cryostats containing YBCO bulk opens the independence and enables the mobile character of Maglev trains with longer – time operation. The challenges of using the various thermally insulated light-weight, but high-load construction for cryostat achieving long-time operation have been discussed and measured in Ref [5]. The present MAGLEV status is characterized by use well-constructed vacuum-tight housing with intrinsic cryo-pump. Each cryostats contains 24 selected YBCO bulks in a plane of almost 500 cm².

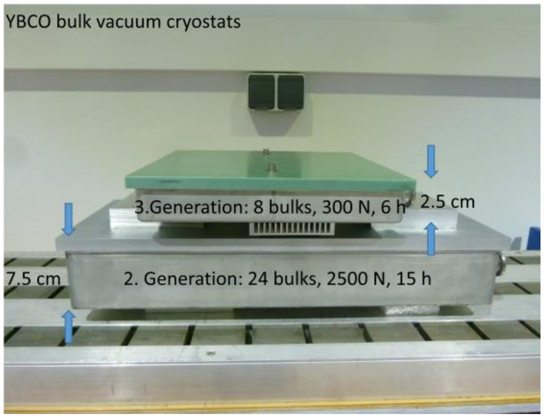

Fig. 3 Compact MAGLEV Stainless Steel vacuum cryostat containing 8 and 24 three-seed YBCO bulks for loads of 30 kg and 250 kg at 15 mm, respectively.

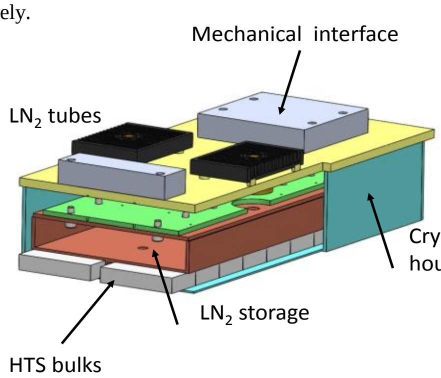

Fig. 4. New generation of 7.5 cm flat LN$_2$ vacuum cryostat containing 24 three-seed YBCO bulks super-insulated in stainless steel housing.

More than 40 cryostats have been fabricated for Maglev application in China, Germany and Brazil. Due to perfect thermal insulation each cryostat of the first generation can operate more than 24 hours having an extremely low thermal loss of about 2.5 Watt. Each cryostat shown in the structure in Fig. 4 consists of a top G-10 plate and a Stainless Steel (ss) body. The 1.5 mm magnetic distance between the YBCO surface and the cryostat bottom is a great advantage and a technical highlighted feature.

Additional effort is being now made in the development of mobile handling and down- sizing the HTS Maglev devices with LN_2 in- situ cooling. Based on the already produced 40 cm long vacuum cryostats and the operational experiences of three larger demonstrator laboratories we continued in the technical development and fabrication of a new generation of Maglev devices presented in Fig. 3 and Fig. 4. Due to the more flat geometry the center of gravity is lower at the guideway and improves guidance and tilt stiffness.

Together with an appropriate magnetic guideway it enables large levitation forces above 3500 N@10 mm levitation height. Clearly, the future magnetic systems will be selected and specified coils. Our preliminary study revealed that the mass of a REBCO coil at an operational temperature of 40 K is lighter than that of a current LTS coil for Maglev [1]. At such high temperatures, cooling system only consumes a relatively small amount of energy, compared to that with LTS magnets. The overall magnet weight is minimized already at around 50 K [2]. Operational temperature in the region of 40–50 K also enables cryo-cooler cooling without liquid helium. Also, a simplified magnet structure will improve its reliability.

Issues and factors of the superconducting devices are summarized:

- mobile cooling system, closed –cycle refrigeration, machine cooling, position–independent function
- light-weight, robust construction, replaceable HTS
- perfect thermal (vacuum) insulation, super-insulation
- external function control (temperature, signal transmission)

III. REBCO BULK IN SPACE APPLICATION

A. *YBCO bulk proton irradiation tests for space application*

Future manned satellites have to be protected against the powerful mix of high-energetic charged particles envisaged during long- duration missions. The present shielding system consists of aluminum and ceramic materials interspaced by Kevlar – Aramid fibers and similar combinations. Magnetic fields generated or screened by superconductors would be the alternative. For this we report bulk tests in the structure: (i) irradiation on earth, (ii) screening on earth, (iii) irradiation and screening in space. .

First, superconductors for their possible applications in long-duration missions need to be investigated for particle interaction. High energy protons in a dose of 10 kRAD generated in a cyclotron were hitting and penetrating YBCO bulk superconductors and the possible damage or degradation of electromagnetic performance was investigated.

Less information is known from the proton irradiation and the effect on the YBCO bulk superconductor. Protons interact with thin surface of the material only but may generate secondary effects like radiation.

Four single grain YBCO samples (2 x D 30 mm, 2 x D 42 mm) and two 3-seed samples are selected for the investigation. All samples were measured by a Hall scanning procedure with constant activation field of 1.1 Tesla and a waiting time of 20 minutes. In Fig. 5 the YBCO samples were measured in the original state without any treatment, and after two times irradiation procedure with a typical medical dose of 10 kRAD for human application. 10 kRAD corresponds to 100 GRAY (GY) and is equivalent to an energy density of 100 Joule/kg. After 10 kRAD proton irradiation, no changes in the trapped field measurements could be detected. The moderate reduced trapped flux values in maximum and averaged values after irradiation are within the similar behavior for untreated samples. Hence, it is assumed that the performance of HTS bulk devices in space application due to proton impact shows no degradation in the critical current density and the structure of the magnetic domains even under longer mission duration.

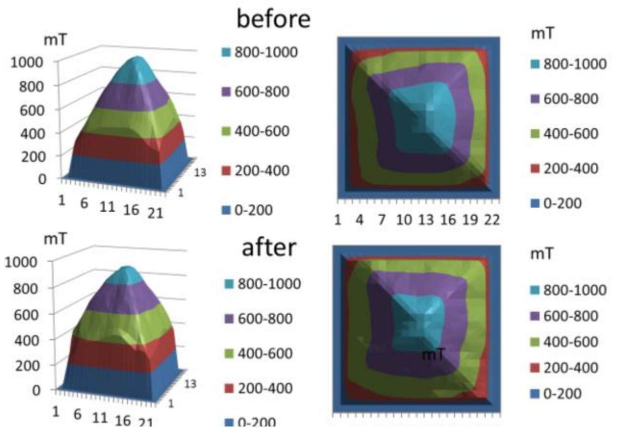

Fig. 5. Trapped flux measurements of proton irradiated YBCO bulk.

However, we can assume that irradiation with moderate doses of high energy neutrons and charged particles can result in a significant interaction with thin film superconductors as it used in the 2nd generation of REBCO wires and coils made of it.

In parallel connection with the German space mission of Alexander Gerst in 2014 another material test procedure was performed. Two small probes of bulk HTS (30 grams) were lunched and uploaded in a Ziploc bag, stored for 6 months in Columbus space lab of the ISS for Magvector experiments and recovered to Earth. The material properties before and after the space mission showed similar to Fig. 5 no changes as it should be expected.

B. *Magnetic screening of the earth magnetic field*

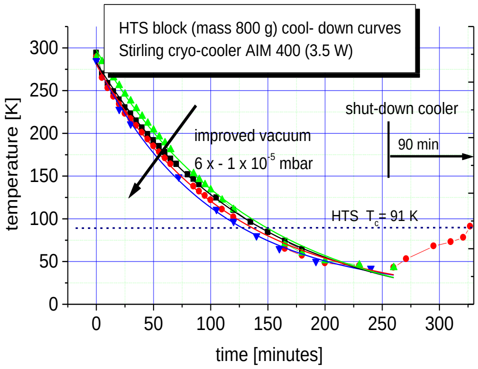

Fig. 6 Cool-down measurement using a compact Stirling cryo-cooler of a large YBCO block (0.8 kg) in a vacuum cryostat similar to Fig. 1.

To control the temperature of bulk superconductors during magnet field shielding experiments we developed compact high-efficient vacuum cryostat in aluminum /G-10 housing.

The time for reaching the critical temperature depends on the mass of the superconductor, the cooling power of the machine applied and the thermal losses with the surrounding at ambient temperature. The different colored thermal scans of a 120 mm circular YBCO plate, 13 mm thick under insulation vacuum conditions of 6 – 1 x10^{-5} mbar are displayed in Fig. 6. The blue curve /triangles are for 1 x 10^{-5} mbar while the green triangles gives the values of a half decade lower vacuum (6x10^{-5} mbar). The superconductive state is obtained in about 2 hours. The lowest temperature was T= 45 K. Switching off the cooling machine (Stirling type) leave the bulk (melt textured YBCO) for about 90 minutes in the sc state and allows an undisturbed measurement of the interaction between earth magnet field and conductor.

A superconductor showing Meissner effect has a magnetic moment that is diamagnetic, i. e. the current loops are of such a polarity to create a magnetic field that is opposing and cancelling the applied external field.

This passive shielding experiment is given in Fig. 7. The melt textured YBCO plate in Fig. 7 has a diameter of d=120 mm and a thickness of t =12 mm. It consists of 8 single crystals growth by multi-seeding with SmBCO. The experiment is performed inside a vacuum cryostat with G-10 top plate. An AIM 3.5 W@80 K Stirling cryo-cooler serves for the low temperature management as demonstrated in Fig. 6. During the measurement the cryo-cooler was switched off. Measurements with a magnetic sensor FCL 100 started 20 mm central above the YBCO surface. The high sensitive flux gate sensor measures +/- 100 µT, DC to 100 kHz. The YBCO plate shields the earth magnetic flux dependent on the z position of the flux gate magnetometer. The magnetic flux starts with 23 µT at 20 mm, shows at a distance z twice of the disk diameter (240 mm) in central position a levelling off and approaches the unscreened level of B_E = 48 µT for z > 4 d .

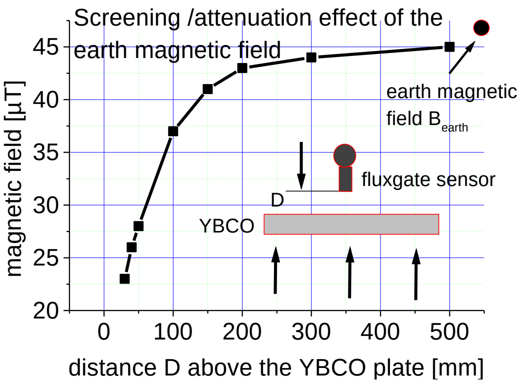

Fig. 7. Static measurement of earth magnetic screening achieved by a 120 mm YBCO plate. During cooling the plate magnetic field is compensated by 3d- Helmholtz coil.

C. ISS Experiment MagVector / MFX

In 2014 the German Astronaut A. Gerst flew with Sojus TMA 13 M to the ISS for a six-month stay during which he installed the Maglev/ MFX experiment. The key device is shown in Fig. 1. MFX is an abbreviation for an experiment aboard the International Space Station which qualitatively investigates the interaction between a moving magnetic field (of earth origin) and a variable electrical conductor. The expected changes in the magnetic field structure on the Ram and Wake side is analogous approached to Fig. 7 and picturized in Fig. 8. The data of the electrical conductor are of interest for technical applications as well as for astrophysical research. Magvector investigates how Earth's magnetic field interacts with an electrical conductor and modifies the magnetic distribution around the conductor. The principal interaction will follow Fig. 8. and table I. The experiments are separated in (i) warm reference measurements with fair conductivity, and (ii) cold measurements having a perfect conductor of electricity that cannot tolerate any electric field E. The temperature is changed and controlled by a modified Stirling cryo-cooler comparable to that in Figs. 1 and 6. It operates during the last two years periodically reliable between room temperature and 60 K onboard.

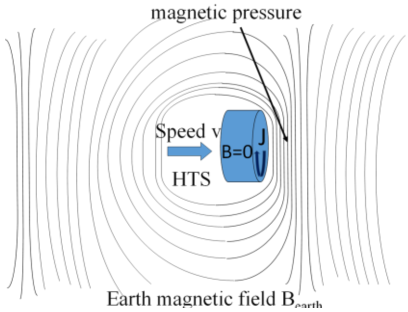

Fig. 8. Schematics of fast moving conductor in Earth magnet field B_{earth}.

For the experiments a superconductor is positioned insight a vacuum cryostat embedded with temperature and magnetic flux gate sensors. Outside the cryostat (Fig. 1) a 3d- Helmholtz coil can be powered to compensate any external magnetic component. MFX is installed inside a European Drawer Rack (EDR, Fig. 1) which itself is installed inside of a larger ISIS drawer. The experiments are still on-going, and so far the measurement runs have been successful. All received data show excellent values for the evaluation which is still under process. There are efforts on the way to keep the experiment running until 2017/18.

TABLE I:
MAGVECTOR / MFX PARAMETERS

Signal	Range	Sample Frequency	Measurement Device	Comments
magnetic field	± 1 mV	1Hz	magnetic sensor	Mini FCL 100
pressure	0-100 mPa	1Hz	pressure transducer	MKS Dualtr.
temperature	± 1 mV	1Hz	thermocouple	Typ K(Ni-NiCr)
video	Columbus System Camera			HD – Mode

IV. CONCLUSION

Bulk HTS are integrated increasingly into complex magnet and screening devices. Insulation and cooling has been perfected which allows the fabrication of mobile sc machines. Maglev demonstrator trains operate reliable now since nearly a decade and the function of HTS elements under space conditions is established. The ISS MFX / Magvector experiment is going on.

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