Bulk Superconductor Levitation Devices: Advances in and Prospects for Development

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***Abstract* - Maglev train is a transportation system that uses magnetic interaction and brings many technical, economic and environmental benefits. Here, the progress in designing and manufacturing portable vacuum cryostats containing 24 high-quality threefold seeded YBCO bulks with up to 40 hours LN_2 cooled operation time is reported. PM excitation on a magnetic guideway generates forces on the YBCO cryostats and provide train levitation forces of several tons by assembling the portable cryostats. By means of experiments and systematic improved fabrication we describe the process of material and device scaling-up to gain industrial-near transformation and application. Current PM guideway design with the magnetic flux of 0.5 T at maximum limits the force density to 5-10 N/cm². The conditions for further development, effective fabrication, and design-oriented progress of higher loads, great robustness and better thermal insulation respective longer operation time are outlined.**

***Index Terms* - HTS bulk, Maglev, magnetic train, vacuum cryostat**

I. INTRODUCTION

THE compensation of gravity and the ability to generate a robust unsupported magnetic levitation by engineering applications put the phenomenon even in the 21th century more into the field of magic than science. If one stands on the EARNSHAW [1] level, today existing technical magnetic levitation (Maglev) trains would be a wishfulness without chances of realization. Fortunately, already Kemper, 1938 [2] and Braunbeck, 1939 [3] proposed stably electromagnetic suspension (EMS) with a load of up to 210 kg. That concept used the attractive force between an adjustable magnetic force and a ferromagnetic material. The most prominent and current example of EMS technique is the German Transrapid TR08 connecting Shanghai Longyang Road Station with Pudong International Airport (~30 km) in China since 2000.

Parallel to EMS, the electrodynamic suspension (EDS) of a moving magnet (conventional or superconducting) can produce corresponding forces to suspend vehicles or trains.

Advantageously, EDS developed by the RTRI of the National Japanese Railways in 1970, operates stably without any feedback, but need a certain speed of the magnet to generate the force. Above about 150 km/h the EDS magnet induces in neighbor conducting sheets enough eddy currents to stabilize the train-track configuration. The current EDS magnets consist of NbTi superconducting coils mounted on each bogie of the train and generate alternately north and south poles with a pole pitch of 1.35 m. The race track coils at 4 K have a magnetomotive force of about 700 kA When using superconducting magnets of 5-6 Tesla large operation and levitation distances of about 100 mm are becoming possible in contrast to EMS –type Maglev (8 -10 mm). The Japanese test Maglev train MLX-01 reached a maximum speed of 603 km/h in 2014 on the Yamanashi Maglev test line. However, the Japanese engineers are aware that the small temperature difference between T_c of NbTi (9.6 K) and ^{4}He boiling temperature (4.2 K) and possible magnetic disturbances by ground coils and mechanical vibrations can cause the sudden disappearance of the magnetic force. Therefore, a HTS solution is favored when a broad commercialization of Maglev trains is on the table.

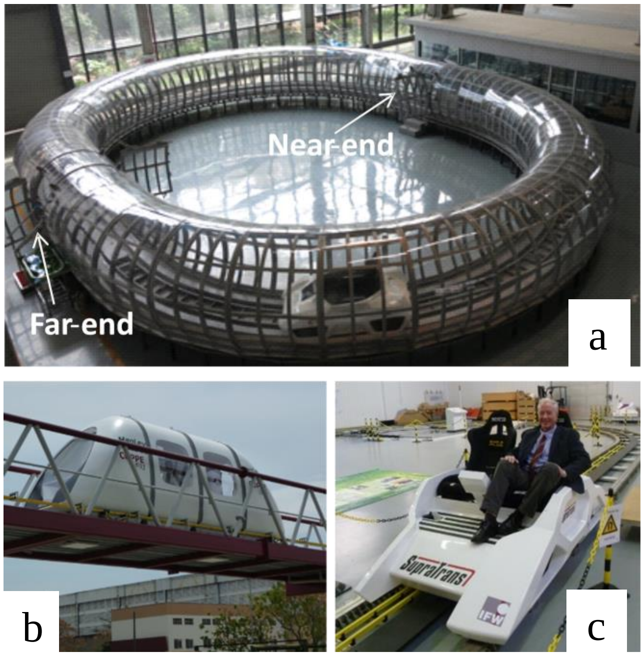

Fig. 1. Superconducting Maglev trains with bulk in vacuum cryostats levitating the vehicle above a PM guideway. a) Evacuated tube train at Southwest Jiaotong University (SWJTU), Chengdu, China [4], b) University of Rio de Janeiro, Brazil, c) IFW Dresden, Germany.

From the physical view the equilibrium and the magneto-mechanical stiffness of the levitation process can be understood as a combination of trapped magnetic field and diamagnetic response of the HTS by means of an image model. When a permanent magnet (PM) approaches the HTS surface (or vice versa), supercurrents in the HTS form a magnetic mirror image of the PM. The trapped and mirrored magnetic field interacts

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with the gradient of the applied magnetic field and generates a stable levitation force. A small living frog has been levitated in a high magnetic field of 16 Tesla in that way. However, a direct levitation of a human (our body consists in 50-60% of water) will be belonging to science fiction. One would need an electrical power of ~ 1000 MW (a typical output of a nuclear power station!) to generate a steady magnetic field of 40 T [4].

Practical HTS Maglev experiences are collected at three larger person-loading test train systems shown in Fig. 1. All three experimental trains operate with bulk HTS and PM guideway. At the Southwest Jiaotong University (SWJTU) Chengdu, China (top) a first tube Maglev train is tested while at the University of Rio de Janeiro (Brazil) and at the IFW Dresden (Germany) double track PM guideways levitate the vehicles with integrated YBCO cryostats [5]-[7].

More than one decade Maglev praxis was obtained in all three demonstration trains where many thousands of people have been levitated and were travelling. The total maximum load at 10 mm distance over the track varies from one to five tons. Contactless linear motors accelerate and speed up the vehicles up to 50 km/h. The Dresden Maglev train has been relocated to the KIT Karlsruhe in 2017.

In the following we review the status and summarize here the development and experience of Maglev bulk cryostats as important and in general intrinsic-deficient devices of superconducting system technique.

II. HTS MAGLEV SYSTEM TECHNIQUE

A. HTS solution toward sustainable

All three Maglev demonstrator trains in Fig. 1 are equipped with HTS bulks in portable cryostats onboard which generate a stable levitation force above the PM tracks.

The application of bulk HTS single or multi-grain type, has been investigated almost since the discovery HTS in 1986. The positive development of bulk YBCO and REBCO (RE = Rare Earth, Gd, Sm) bulk material has been promoted the utilization in Maglev. Maglev is thereby a typical example for importance of superconductor-based module towards commercially stage in the coming years. In trapped field mode the HTS could not only replace the LTS with a temperature advantage, but the bulks could act as powerful PMs with a magnetization bigger than standard NdFeB or SmCo permanent magnets. As a result higher magnetization heights become possible and reduce the effort of mechanical manufacturing precision of the guideway construction. Fig. 2 reviews the steps of integration of bulk superconductors in small and larger vehicles. It presents the scaling and fabrication of vacuum-based YBCO bulk cryostats from the first up to the fourth generation since 2000 by ATZ.

Assembled trapped-flux bulk HTS are typically magnetized by field-cooling (fc) and increasingly popular by pulsed zero-field cooled magnetization (PFM) technique. Especially the latter method is in the focus when compactness, mobility, and relatively inexpensiveness of the technique is discussed. In between, excellent models for bulk superconductor magnetization including flux penetration, material and pulse properties (duration, magnitude, shape) are published [8].

Similarly, the demonstrator Maglev trains in Brazil and China operate in a combination of self-stabilizing levitation and propulsion. Acceleration and actual speed provided by linear motors are separated from the levitation and guidance forces. The final speed of HTS Maglev is, therefore, not limited by the system technology in contrast to EMS and EDS. The only speed limiting factor is the air drag which generates a strong friction above 300 km/h and produces a strong noise.

Maglev trains in evacuated tubes, which are favored by the Elon Musk's group in US (Hyperloop), benefit from the lower air resistance and are an ideal and efficient solution of future fast travelling near Earth vehicles. The highest maximum train speed to date of 603 km/h with the Japanese EDS Maglev on the Yamanashi Maglev test line was, therefore, limited by the available power of the linear synchronous motor (LSM) to overcome the aerodynamic drag.

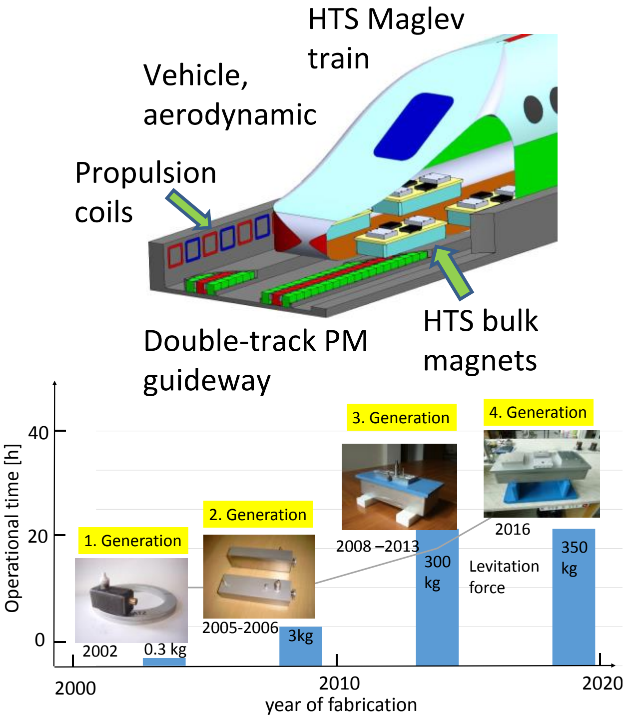

Fig. 2. Superconducting Maglev train with bulk in vacuum cryostats levitating the vehicle above a PM guideway (top). Development of HTS bulk cryostat universal and portable devices along the last two decades by ATZ Corp. (bottom).

An actual experiment [5] with an Evacuated Tube Transport (ETT) system was installed at the Southwest Jiaotong University, China on a 45-m long PM racetrack. In an evacuated –tube with a reduced pressure from ambient 100 kPa to 2.9 kPa the test vehicle showed a largely reduced air friction and allowed a maximum speed of 50 km/h. The reduced pressure is beneficially for LN_2 sub-cooling up to 65 K and provides improvement of the levitation and hysteresis [9]. While the Halbach array concept relative to the standard PM/Fe configuration improves the magnetic field distribution significantly [10], increasing bulk thickness of 12 mm by a bulk double-layer seems to have counter- productive effects in view of economics.

B. *Optimum HTS material design for Maglev*

Large–scale HTS bulk manufacturing has been raised by REBCO bulk production of thousands of tiles with a material input of more than 500 kg. On the way of achieving simple, reliable, portable superconducting devices containing YBCO bulks we investigated standard geometries as single-grain cylindrical and rectangular. Assembling and fitting together many of that bulks to larger functional areas corresponding to higher forces give the requested performance.

After conducting considerable studies in the past years we decided from size, stability, quality, and economy to focus on the production of multi-seeded REBCO bulks receiving beneficial properties by easy assembling. Fig. 3 shows one example of position- sensitive force zfc measurements on a 66 x 33 x 13 3-seed YBCO bulk against a standard SmCo PM 25 mm x 15 mm. The triple-crystal sample is divided into three regions, central crystal (B), right (C, D), and left-hand crystal (E, F) The highest value at 1 mm distance in zfc is 88 N obtained with PM in the center position (B) while above both neighbor crystals (C,D, E,F) the forces are reduced by about one third. In parallel, we measured the trapped magnetic field (insert Fig. 3) which displays clearly the triple flux structure with almost 50% flux density overlap in the grain boundary regions. The magnetic excitation field B_0 =1.5 T was generated by a standard Cu magnet. At 77 K the three flux peaks have comparable maxima of about 0.7 T. At a temperature of 60 K the trapped field peaks increase to 2.5 T @ 5 T excitation.

TABLE I
Force density of single grain and multi-seed YBCO bulks (77 K)

Force density [N/cm²]	Ø 30 mm single	Ø 30 mm assembled	3-seed bulk 66 x 33 x 13
Levitation			
ZFC	12.8	9.75	11.3
FC	10.6	8.7	9.1
Guidance			
FC		0.3	0.4

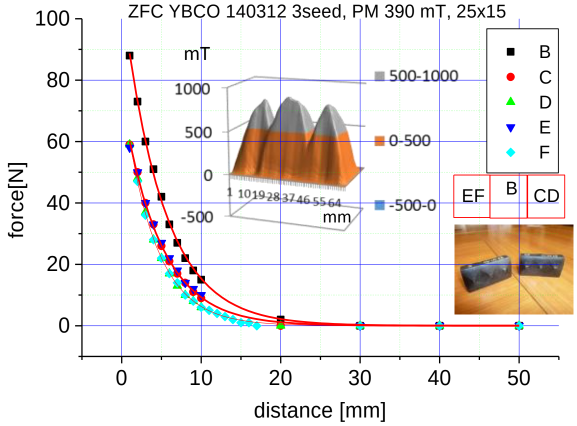

Fig. 3 Position sensitive zfc levitation and trapped field measurement of 3-seed YBCO bulk sample.

For application the as-grown bulks are numerically machined by high- speed diamond cutting, stabilized by metal or resin vacuum infiltration and assembled in planar- or cylinder–like devices. Triple-seeded rectangular bulks of the size 66 mm x 33 mm x 13-15 mm are now ATZ’s standard bulk geometry and applied for most of the magnetic applications.

The 3-seed YBCO bulk possesses several advantages versus cylinder- like geometry. The three crystals grow perfect in the planar (a, b) directions. Measurements of the trapped flux of 3-seed grown bulks show clear advantages compared to assembled individual 3 crystals of the same area. The former averaged trapped magnetic flux is up to 40% higher. We explain it by an additional macroscopic induced supercurrent (except the current of each single grain) passing the two grain boundaries and enclosing all three crystals [11]. Fitting and assembling of the rectangular shape bulks in contrast to cylinder geometry deliver easily a material filling factor >95 % of the active magnetizable area. In table I a comparison of the force density of cylindrical and rectangular YBCO bulks demonstrate the advantage of the latter geometry in case of assembling.

C. *Vacuum cryostats*

High-Tc superconducting magnetically levitated (Maglev) vehicles for future transportation possess substantial advantages, as non-contact movement above a magnetic rail, no wear, no degradation, high-speed operation, no noise, and low energy consumption.

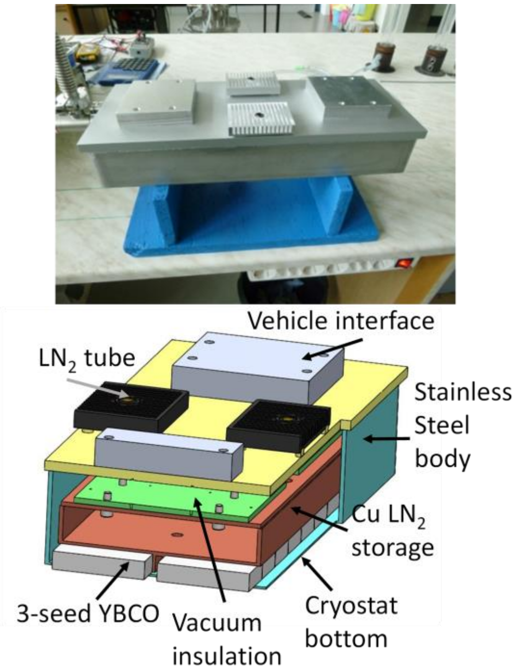

Fig. 4: YBCO superconducting vacuum cryostat (top), explosive design of the new type, flat superconducting vacuum cryostat containing 4.5 kg YBCO melt textured material

A number of experiments have demonstrated the feasibility of that Maglev technology. Cryogenics of the HTS bulks has evolved considerably since most experiments are performed by cooling the HTS in an open vessels or container. Because of the worst thermal insulation an open container is cooled-down with time and becomes covered with frozen layers of moisture. The corresponding thermal loss enhances the cooling effort and need compensation by refilling LN_2 periodically. Cooling is uncomfortable, is the unanimous opinion!

In a new strategy, altogether 45 pieces of superconducting levitation vacuum cryostats are fabricated since 2010. The majority is integrated in test vehicles now in operation in Brazil, China and Germany as shown in Fig.1.

D. Design and technical description of the HTS train device

The vacuum cryostat design together with an explode-view picture is displayed in Fig. 4. The obtainable levitation force is linearly scalable with the magnetic area. The use of trapped field magnets (TFM) safely encapsulated on board of trains, where space is limited, is strong application and selling element. The present HTS Maglev prototypes are designed in a basic configuration consisting of mobile portable HTS bulk cryostats and a stationary magnetic guideway. While for magnetic HTS rotational bearings rotor and stator easily can be exchanged long-length linear Maglev train geometry constrains that flexibility. On has to follow a design of a static magnetic track/guideway and mobile portable superconductor with cryostat.

Cooling the superconductors below the critical temperature T_c is basic. It can be performed in three different ways: Either by (i) liquid cryogen direct cooling, (ii) by cryo-cooler operation and heat transfer with a good thermal contact, and finally (iii) by cooling of a cryogen closed-cycle operation with cryogen gas periodically back-cooled and condensed at a cold head of a cryo-cooler (hybrid-type). While superconductor material properties, as J_c (T, B) or trapped field B_t performance are well investigated and extensively published the necessary system technology including cooling around a HTS device to maintain superconducting function is less carefully studied and technically deficient developed. This situation is caused by several factors, some are connected with a thought as nonscientific procedure, less suited for qualification work or simply the underestimate of the need of sophisticated engineering technology to achieve powerful HTS devices. Effective HTS housings and cryostats belong to that category.

In the following we describe the technical details of a prototype mobile Maglev vacuum cryostat that is applied in the three largest Maglev train test tracks.

Each cryostat in Fig. 4 consists of a stainless steel (ss) body with a G- 10 plate on the top. A mechanical interface on top is provided to fasten the passenger module. The cryostats under the module are moveable in lateral directions / curves.

Inside 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 cm^2 per cryostat. The superconductors are cooled using LN_2 by conduction cooling.

The 2 mm distance between the YBCO surface and the cryostat bottom is a technical highlighted feature and allows large levitation forces respective a high load capacity. Due to the 2.5 liter LN_2 storage capacity long superconducting operation is ensured. Measurements of the LN_2 consumption under static conditions indicate time of up to a two-day operation without refilling liquid Nitrogen. We quantified the corresponding thermal loss of the cryostats be measuring the flow rate of N_2 gas to about 2 Watt.

A great effort was directed to the thermal superinsulation achieving extremely low heat transfer between the cold YBCO part and the outer cryostat housing. Inside, the YBCO bulks and the copper holder are covered by several layers of reflective thin films that reduces radiative heat transport. Simultaneously, a compact and robust cryostat design and construction could be obtained with an advanced and robust thermal insulation as key technology for long time operation of Maglev cryostats.

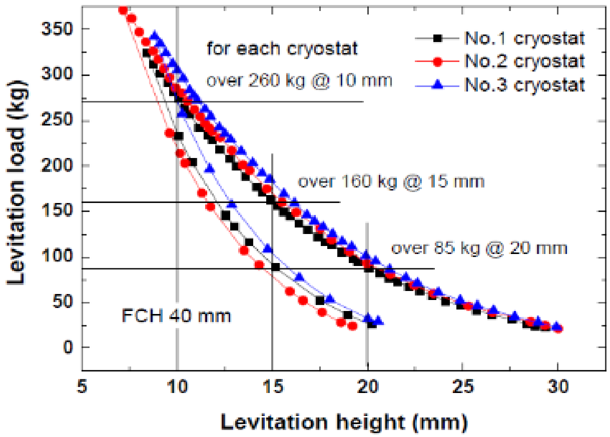

Fig. 5
Experimental force measurement of the magnetic levitation of three YBCO vacuum cryostats on a PM guideway under field-cooled (fc) conditions.

In Fig. 5 the levitation force test results against a standard permanent magnet guideway of three cryostats are given. At a field cooled height (FCH) of 40 mm the force increases with approaching the track in the typical non-linear magnetic behavior. The curves show at 10 mm distance a force/load capability between 280 and 300 kg dependent on the cryostat.

III. CONCLUSION AND OUTLOOK

A small series of superconducting Maglev cryostats for trains in demonstrator versions have been designed and fabricated in the last 10 years. With upgrading more efficient magnet design (Halbach) the force generated by fc increased to about 3000 N at 10 mm distance. Higher forces, lighter and more flat design, and longer operation time of up to two days with 2.6 l LN_2 are achieved. Perfect thermal studies and the technical translation into the cryostat performance by better thermal conduction and radiation insulation reduced the thermal loss to about 2 Watt. The technical conclusions drawing at the extensive experimental studies can be summarized: (1) Within the last ten years a mature cryostat system technique has been obtained: (2) High-quality REBCO material (higher J_c, better pinning) is one important part of the HTS device development, safe housing, cooling and robust operation are the others, not less important for the HTS progress.

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