Mobile HTS Bulk Devices as enabling ton-force Technology for Maglev Trains

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

Abstract- **The status of bulk superconductor magnetic levitation (Maglev) train technique is evaluated. Existing industrial magnetic trains (electromagnetic, electrodynamic) point to key performance factors as load, speed, efficiency and environmental protection. On that basis a feasibility analysis of trapped-field train demonstrators should be attained. HTS bulk trapped field experiments at lower temperatures up to 6.8 T were performed and the HTS mass production capability is indicated. For increasing the transport load a new generation of robust and mobile LN_2 vacuum cryostat type is developed. The new device is designed and scaled up according to the technique and practical experience of a smaller cryostat with 250 kg load and 30-40 hours operation time. A test vehicle levitated by four cryostats on a magnetic guideway is presented. It is capable to levitate more than one ton. The new cryostat consists of 30 tiles 3-seed YBCO bulks, it levitates up to 0.5 ton at 10 mm distance, and with 5 l LN_2 stored it achieves an operation time of up to 2 days. We report about the integration of YBCO bulks, thermal insulation, LN_2 re-filling, and mechanical construction. With the new development we obtain evidence to manage higher train forces of several tons.**

Index Terms—Magnetic levitation, Maglev train, bulk superconductor, YBCO, vacuum cryostat

I. Introduction

Superconducting electromagnetic levitation is an area of interest in modern transportation systems. To achieve the mainstream of traveling demands as safety, larger capacity, energy saving and shorter travel time magnetically levitated (Maglev) trains compete with the traditional wheel-rail trains and airplane traffic. The HTS bulk Maglev train application started around two decades ago [1] and was improved stepwise with a number of feasibility demonstrator trains in China, Brazil and Germany [2]-[4]. Additionally, in-tube trains with reduced pressure are considered for fast transportation of goods [5]. With increased discussion about indications of a climate change in our world and the unabated advanced growth of the mass tourism "green" factor efforts, to minimize environmental impact are becoming a dominant role in the acceptance. Advantages for Maglev are observed in the energy consumption and CO_2 emission per passenger compared to present trains and airplanes [6].

Two basic elements influence the Maglev concept significantly, except speed and conformability: The magnetic guideway, which is the most expensive part, and the HTS part including cooling. For mobile HTS devices the biggest worry for most customers is the cooling and refrigeration system.

The magnetic guideway has been extensively investigated by designing and engineering to achieve a magnetic maximum at a minimum material input [7]-[10]. A Halbach configuration which uses permanent magnets (PM) as flux collector instead of Fe shims gives the best results. More complex and sensitive is the engineering construction of the HTS device. It should be portable, mechanically stable, thermally insulated, having low-cooling effort, and economic in investment. ATZ Corporation has been prioritized vacuum cryostat with YBCO bulks in a stainless steel chamber with independent and refillable effective LN_2 cooling.

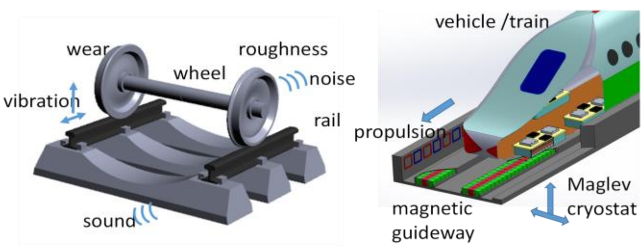

Fig. 1. Comparison of traditional wheel –rail and innovative Maglev transport systems.

The here discussed Maglev train is a ground transportation system that uses magnetic forces to levitate and guide vehicles at a certain distance on a magnetic active guideway. The characteristics are the lack of wheels, axles and bearings, and in the consequence, it has no mechanical contact, no wear, friction, lubrication and noise (Fig.1). Maglev vehicles can move easily faster, with a smart ride quality at higher transport efficiency.

In industrial scale a prominent Maglev train is the electromagnetic (EMS) type German Transrapid technique system, now operating in Shanghai at high speed (max. 430 km/h). A modified version (without guidance coils) is active with the Beijing S1 line at lower speed (80 km/h). In parallel, the Japanese high-speed electrodynamic (EDL) Yamanashi Maglev levitation train has attained a maximum speed of 603 km/h in 2015, limited only by lack of sufficient propulsion power. Between the two Maglev types shown in Fig. 2, a number of technical and transport features exist: EMS operates at a smaller distance (a few centimeters) in contrast to some tens centimeter magnetic distance of the EDL. In the latter, superconducting coils in the vehicle (at present NbTi) generate eddy currents in conductive side tracks when fast moving. The high sophisticated coil structure, sketched in Fig. 2, is integrated in the side walls of the train where levitation and

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guidance coils are arranged alternating with propulsion coils. The so-called “null-flux” coil design with cross-connected coils on both sides of the train is a technical highlight, developed to reduce the magnetic drag (Fig. 2). While the EDL train needs a speed for the levitation function, the EMS Transrapid technique (Fig. 2, left) is able to lift the vehicle at zero speed.

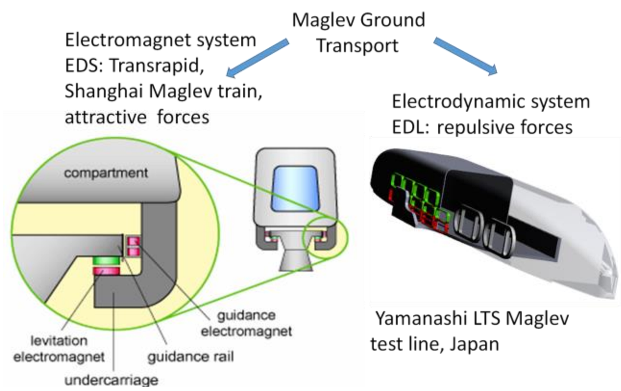

Fig.2. Large-scale electromagnetic (EMS) and electrodynamic levitation (EDL) systems.

II. Large –scale Maglev trains

A. HTS bulk Maglev status

Bulk superconductors have been recommended shortly after the discovery of the HTS. Because of flux pinning a self-stabilizing levitation in linear direction was demonstrated in several R&D stages. In 2000 the first man–loading Maglev test vehicle with LN_2 cooled bulks was constructed in China and operated successfully nearly one decade [1]. Similar Maglev demonstrators are built up in Germany (SupraTrans I and II) and Brazil (Maglev Cobra) [2]-[3]. All of the larger Maglev demonstrator vehicles used a similar designed HTS cryostat technique developed by ATZ. With 24 pieces of YBCO bulk in a 3-seed configuration less than 4 kg YBCO material can levitate magnetically 250 kg load (levitation efficiency factor ~ 60).

B. HTS bulk trapped field experiments

HTS bulk superconductors can easily be used as trapped field magnets. A considerable progress in the trapped field has been obtained above 10 T. To date the thermo-mechanical bulk properties limit the maximum trapped field to about 17 T. Nevertheless, several attempts are going on to demonstrate the capability to trap 20 T in bulk HTS [11]. The success in high-field trapping seems to depend on the critical current J_c, but also on an adequate reinforcement technique by steel or carbon fiber bandage.

Traditional, most of the large-scale applications have a trapped field level up to one Tesla. For present Maglev levitation PM/HTS interaction a maximum pressure p of 15 N/cm² at a few mm distance is obtained. According $p=B^2/2\mu$, that pressure corresponds to a magnetic field interaction of 0.61 T in the gap. Higher specific pressure can be obtained either by smaller distance (which is usually limited) or by higher trapped field. Fig. 3 exhibits a trapped field experiment of a standard

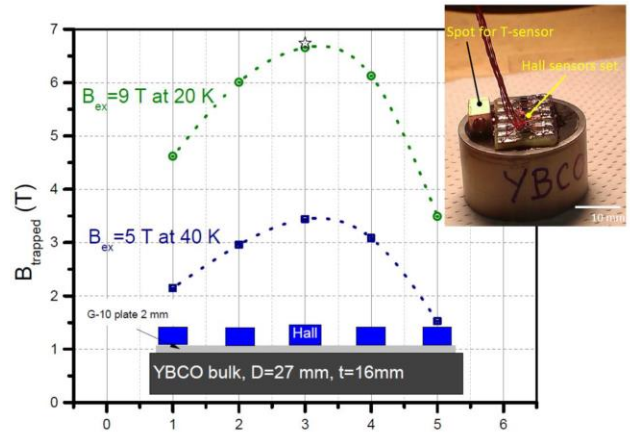

Fig.3. Trapped flux experiments across a 27 mm YBCO bulk sample.

YBCO sample without Ag, as it is used for Maglev purpose. At 40 K an external field of 5 T generates a maximum trapped field of 3.6 T, whereas at 20 K and 9 T external field gives a 6.8 T trapped field value. The five Hall probes across the 27 mm diameter at 2-3 mm distance to surface display a typical field cone structure of the trapped flux (Fig. 3).

Larger bulk superconducting machines and devices require usually the production and preparation of thousands of REBCO bulks. The manufacturer must have the capability to scale-up the HTS production on demand. In addition, the material availability on stock does not mean to have production competence of a perfect superconducting device. A significant percentage of design and construction goes into the so-called system technology: Cryogenics, thermal insulation, mechanical frame and support. The interface connection to the surrounding non-superconducting infrastructure have to take in consideration as well. The latter can be ranged from current leads, terminal devices or vehicle boogies in case of Maglev trains.

C. Mobile Maglev bulk cryostats

Fortunately, in the last years numerical and analytical models have been developed to understand the performance and use bulk superconductors in magnetic devices [11]-[12]. The ultimate technical needs for effective cryogenics parallel to the material fabrication was a long time underestimated. Similarly, the deficient situation with powerful and economic availability of robust cryostats for superconductors has been recognized in the last years. Complete engineering solutions of compact and light-weight cryostats are still distributed rarely. Moreover, for mobile application the design of cryostat determines the technical solution basically. In the following we characterize the development of mobile HTS bulk application for Maglev train, conclude about the technological consequences for the bulk fabrication, and present the performance of a new type cryostat 500 with a magnetic suspension load of 500 kg.

Cooling of HTS has evolved considerably since the earlier open LN_2 bath experiments. While static application uses cryo-cooler, mobile HTS devices require mobile cooling solutions as well. For a Maglev vehicle running on a linear magnetic track the cryostat with the inner architecture is displayed in Fig. 4.

Inside a stainless chamber 24 pieces of 3-seed melt textured YBCO bulks of the size 64 x 32 x 12 mm³ are assembled providing an HTS area of 495 cm². On top a 12 mm thick glass fiber plate provides both the thermal insulation as well as mechanical connection to a bogie or vehicle mechanical interface. The magnetic distance of 2 mm between the lower YBCO cold surface and the warm cryostat outer bottom ensures an optimum distance for high magnetic forces on a corresponding magnet rail.

The thermal insulation is obtained by vacuum evacuation of

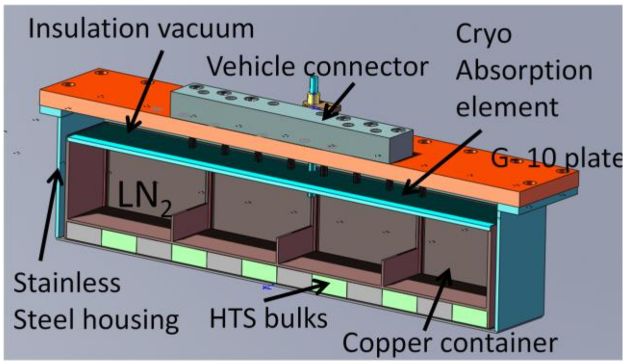

Fig. 4. Cross section of a trapped field HTS bulk vacuum cryostat containing 24 pieces of 3-seed YBCO bulks at the bottom level and a capacity of 2.5 l LN_2.

< 10^{-4} mbar that is additionally improved and stabilized using an intrinsic vacuum cryo-absorption element when LN_2 cooling is active. The cryo-absorption element (active coal particles) is located on the (cold) top wall of the inner copper container. The vacuum insulation between the cold superconductors and the warm stainless steel chamber prevents any outer water condensate from the atmosphere. Additionally, several layers of superinsulation foil reduce radiative heat transfer (thin polypropylene with a 5 nanometer Al layer). The YBCO bulks are fixed in a two-chamber copper frame separated by a thin wall from the LN_2 storage chamber. Cooling the YBCO bulks is therefore performed via conduction and excludes any

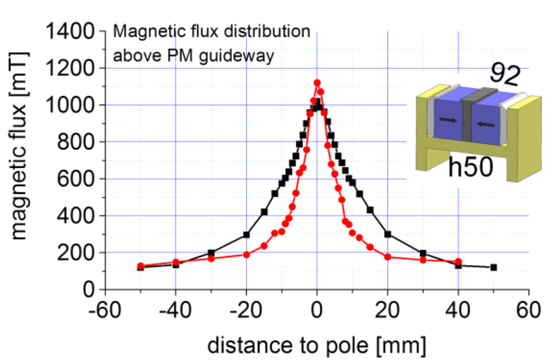

Fig.5. Measurement of the PM/Fe central symmetric magnetic field configuration above the guideway. The maximum field at the surface is above 1 T displaying the high magnetic field gradient on both sides. Two Hall probes with different active surface are used (0.2 x 0.2 mm² red circles, 0.4 x 0.4 mm black rectangles). Due to the size differences and the (invisible) different depths of the active Hall surfaces within the two sensor fingers the curves in Fig. 5 in maximum and widths are not identical.

humidity condensation or frost degradation. The 2.5 l LN_2 capacity allows an operation time of about two days statically

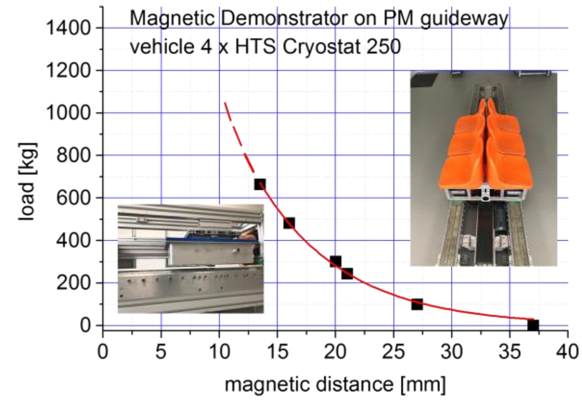

Fig.6. Maglev rider demonstrator: Load-distance curve with four YBCO vacuum cryostats on a permanent magnetic (PM) guideway.

TABLE I
SCIENTIFIC -TECHNICAL PARAMETERS OF MOBILE MAGLEV VACUUM CRYOSTATS FOR LOADS OF 250 AND 500 KGS

	Cryostat 250	**Cryostat 500**
length x width x heights	Material AISI 304 405 x 147 x 100	Material AISI 304 454 x 300 x 137.8
Bottom [mm]	1.5	2.0
Total weight [kg]	17	33
Vacuum [mbar] Mech. construction	~5 x 10 E-5, Super-insulation G-10 frame	~5 x 10E-5 Super-insulation G-10 frame
Magn. dist. [mm]	2.2 mm	2.8 mm
LN2 capacity [l]	2.5	5.2
filling LN2 [min]	~ 35	~ 35
Mechanical adaptor to bogie	1 x Al6061, Tapped screw holes	2 x Al6061, fish-tail Customized, tapped screw holes
YBCO bulk superconductors 3-seed [l x w x h], Weight /pcs [g] Magn. area [cm²]	2 x 12 pcs in two rows: 24 64 x 32 x 12 155 A(total)= 492	3 x 10 pcs in three rows: 30 78 x 39 x 13 260 A(total)= 912
Operation time (filled LN2)	~40 h statically	> 36 h statically
Magnetic force	F = 2500 -3000 N@10 mm Halbach 150 mm	F=5000 N @5-8 mm 3 PM 50 x 50 x 40

and > 30 hours under dynamic conditions. After refilling LN_2 any experiment can be performed without time limit. We estimated a thermal power loss of 2-2.5 W per cryostat by monitoring N_2 flow.

The load capacity depends on the magnet configuration of the guideway. A typical force of 2500 N is obtained at 10 mm distance after field cooling height of about 30-40 mm. Halbach magnetic biasing of the guideway gives higher forces of 3000 N under similar magnetization conditions. Systematic studies and improvements of the YBCO quality (J_c, crystal size, domain overlap in 3-seed bulks) and an optimum and effective PM/ Fe configuration has enabled excellent values of the magnetic levitation.

A levitation test vehicle (Maglev rider) has been constructed shown in Fig. 6. The rider vehicle can levitate 6 persons at a distance of 10 – 15 mm above the magnetic rail. The two parallel monopole magnetic rails consist of a permanent magnet configuration shown in Fig. 5 together with measured field distribution. Between two PMs in the size 50 mm x 50 mm x 40^{m} mm (^{m} is the magnetization geometry) a 12 mm Fe shim as monopole collects the opposing magnetic flux. At the surface the monopole has a maximum field of 1.1 –1.2 Tesla, which is detected by Hall probe measurements in Fig. 5. Due to the size differences and the (invisible) different depths of the active Hall surfaces within the two sensor fingers we measured the flux distribution at different heights above the collector and the curves in Fig. 5 are not identical in maximum and widths. With the lateral distance relative to the pole center the field descend significantly and the flux gradient stabilizes the trapped field HTS bulk laterally.

Four superconducting vacuum cryostats shown in Figs. 4, 6, and 7, each located and assembled in one of the four corners of the bogie, support and levitate the on-top vehicle. The vehicle possess six (2 x 3) sidewise seats for conveying passengers. Four vertical jack sockets between the tracks and driven by a lift motor with gears raise and hold mechanically the vehicle with the cryostats in a position above the PM guideway (distance about 35 mm) when the superconductors are warm.

Each cryostat consists of the structure displayed in Fig. 4. The demonstrator vehicle has a weight of 124 kg including the four cryostats. Field cooling (fc) is made at a distance of about 35 mm. A corresponding distance-load curve is displayed in Fig. 6 together with two insert pictures of the vehicle and the mounted cryostat.

Due to the optimum PM configuration with respect to the geometrical bulk geometry inside the cryostat (2 x 12 pcs YBCO bulks) high levitation forces are obtained. According to Fig. 6 we measured levitated loads of 300 kgs at 20 mm, 550 kgs at 15 mm, and expect more than 1000 kgs at 10 mm levitation height. The levitation characteristics and performance enable the transport of 6 persons. At 10 mm reference distance the force density is 5.3 N/cm^2, which is about 50% higher than the previous HTS Maglev demonstrators [1]-[3].

D. Heavy–load cryostat development

HTS bulk Maglev vehicles are typically characterized by transport capability, energy and cooling consumption, maintenance, modular fabrication and arrangement. With the smaller HTS cryostats described above a load capacity of about one ton per running meter can be obtained. For higher Maglev forces a new type of bulk superconductor and cryostat design is developed recently. The project target was the doubling of the previous load, i.e., each cryostat should levitate 500 kgs.

For this, larger multi-seed superconductors in the size of 80 x 40 x 13 mm³ were selected and melt textured. After scanning tests and evaluation, the fabrication of many hundreds of the new sized bulks was performed. In parallel, the cryostat design has been modified to the necessary larger magnetic area. Careful inspection and calculation of the different thermal expansion coefficients of the cryostat materials (YBCO, copper, stainless steel, and glass fiber) give stringent size limits because of the distinct differences in the thermal expansion coefficients. A warm/cold operating material should not exceed a maximum dimension of 50 cm. The only way to increase the

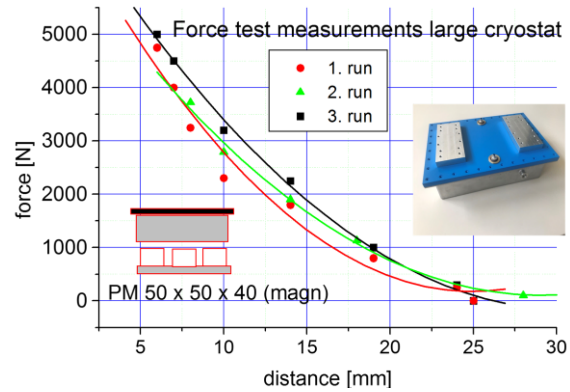

Fig.7. Measured load capability of a new cryostat type 500 against a simple PM rail arrangement (N-S-N configuration).The load curves varies within the first three measuring runs and become stable at further tests.

magnetic performance was therefore given by increasing the cryostat width.

The results of that development procedure are summarized in table I by making a comparison between the previous cryostat 250 and the new one cryostat 500. The number of acting superconductors has been increased moderately, from 24 to 30 YBCO bulks. The latter were arranged now in three rows with 10 tiles per row, precisely machined, fixed and glued into the copper frame. Due to the larger bulk size with the final dimension 78 x 39 x 13 mm³ the total magnetic area of the new cryostat 500, in contrast to the previous cryostat 250, is almost doubled. With the larger magnetic area a step-up of the levitation force to 5000 N is expected.

In a first measurement of the new Maglev cryostat 500 shown in Fig. 7 promising results are obtained. The measured load was about 5000 N at 7-8 mm magnet distance. The PM structure of the guideway, however, was less suited and in no sense technically adapted to the greater widths with the 3 rows YBCO bulks. It is concluded from the measured levitation force in Fig. 7 that with a better PM multipole structure increased forces of 5000 N and above at 10 mm magnetic distance could be attained.

The new Maglev bulk HTS development will provide a specific load capacity of 2 tons per running meter. With that new Maglev load characteristic the construction of vehicles for urban traffic is becoming feasible in a short time.

III. CONCLUSION

Significant progress in the application of bulk HTS superconductors for self-stabilized Maglev vehicles on a PM guideway is demonstrated. Four mobile cryostats support a demonstrator Maglev rider on a monopole magnetic track. The vehicle is capable to transport 6 persons at 10-15 mm magnetic distance. The maximum total load of the rider is above one ton. Trapped flux measurements of the HTS standard YBCO bulk material at lower temperatures give 3.6 T (5 T) at 40 K and 6.8 T (9 T) at 20 K. With a new designed mobile cryostat 500, having 30 pcs 3-seed YBCO bulks on board, magnetic forces of

5000 N per cryostat has been measured. That device progress make it suitable for attaining increased specific Maglev forces, approaching the 2 ton level per running meter, and that meets the target of Maglev tram and small train load requirements.

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