SMB DESIGN BASED ON ADVANCED CALCULATION METHODS VALIDATED BY PRACTICAL EXPERIENCE

Wolf R. Canders, Jan Hoffmann, Hardo May, Richard Palka
Technical University of Braunschweig, Institute of Electrical Machines, Traction and Drives
Hans Sommer-Str. 66, 38106 Braunschweig, Germany
w.canders@tu-bs.de

ABSTRACT

The paper presents advanced three-dimensional calculation methods for the determination of the force and stiffness properties of contact-less, inherently stable superconducting magnetic bearings (SMBs). Based on these methods the magnetic bearings design has been optimized to achieve an utmost reduced amount of HTSC-material for a given force and stiffness.

Based on the condition that iron free field excitation systems are applied (no iron poles), three dimensional analytical calculation methods are compared with numerical ones. 3D numerical field calculation programs have been extended to consider even any complex iron structures associated with SMBs exhibiting high force densities.

Exemplary different optimized designs of SMBs are presented, capable to suspend the rotor-weight of a turbo compressor or a carbon fiber ring of an inertial energy storage system. Another layout enables a fully 3-dimensional contact-less levitation of a LH_2-tank with no degree of freedom in motion. Beside the mere supporting functions the SMBs have to withstand the internal and external dynamic forces which occur during the operation.

INTRODUCTION

SMBs are one of the most promising applications of high-T_c superconductors (HTSC) [1], [2], [4]. They are based on the force interaction of a field excitation unit – permanent magnets (PMs) e.g. – and HTSC-bulks [6]. The special merits of these bearings are: Contact free and inherently stable operation from stand still up to highest speeds and thus offer no wear out, no need for control- and sensor-units, high reliability and no EMC-problems.

Of outstanding interest is their use for high speed machines e.g. turbo machinery [7] or rotating energy storage systems [8] and for linear and two dimensional planar transport systems [1], [5]. SMBs are very convenient for applications with extreme requirements operating under clean room or vacuum environment.

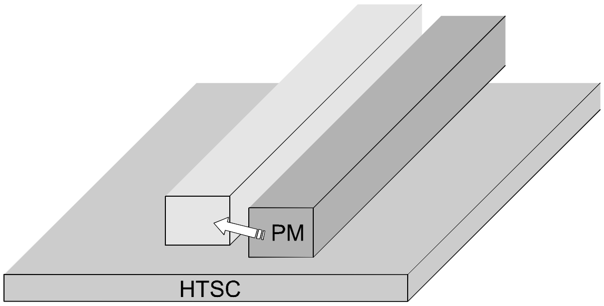


FIGURE 1 Illustration of the force interaction of a PM above an infinite expanded HTSC.

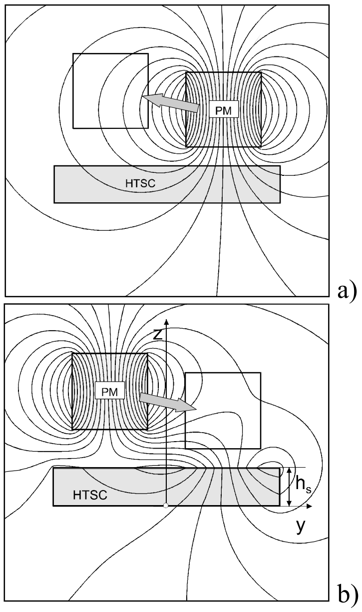


FIGURE 2 Arrangement with a finite width but infinite long HTSC
a) Field distribution of the permanent magnet in the position, where the HTSC is activated and displaced by external forces (arrow) into the framed position.
b) Field distribution in the displaced position of the PM as a superposition of the field generated by the PM and additionally by surface currents within the HTSC.

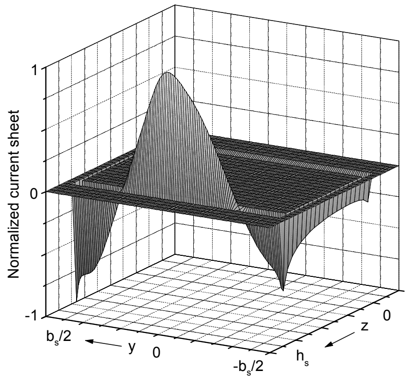


FIGURE 3 Current sheet distribution within the cross section area of the HTSC shown in FIGURE 2 b.

Due to their robustness and reliability they represent in many cases an advanced alternative to active magnetic bearings (AMBs).

The force generation between a HTSC and a field excitation system is illustrated in FIGURE 1 and 2 in principle. As indicated by the arrow, after cooling of the HTSC below the critical temperature (FIGURE 2 a) the PM (dark gray) is shifted sideward and simultaneously lifted by external forces. In this displaced position (bright gray) the PM is exposed to restoring forces (FIGURE 2 b). This force generation is based on a physical phenomenon, which is inherently associated with superconductivity. As it is known from eddy current phenomenon in conventional conductors, also superconductors react with eddy currents to flux variations of the flux penetrating them in the superconducting cooled state. The current density distribution in the cross section area of the HTSC, which is shown in FIGURE 3, exhibits that these eddy currents form a current sheet on the surface of the superconductor (skin effect). They shield the internal region perfectly from any field variations. As a result of the Lorentz law these currents create together with the local field the restoring forces. The mode of operation of the various SMBs is based on this principle. An analytical calculation model for the forces of this basic iron less arrangement is shown in FIGURE 1 with an infinite expanded HTSC and is presented in [3]. This configuration offers reduced flux densities and small field gradients only. But for the design of machines and magnetic bearings with high force densities, new calculation models capable to take the full magnet and iron structure into account have been developed [10], [5]. They can be applied for ideal superconductors (critical current density $j_c \rightarrow \infty$) and furthermore, with the codes described in [6], to finite j_c-values which are closer to the practice. Even oscillations of the levitation system can be taken into account.

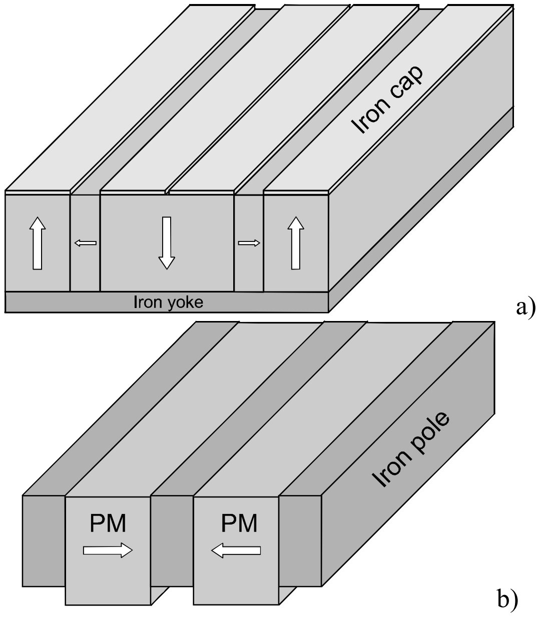


FIGURE 4 Linear field excitation systems consisting of high energy PMs and flux guiding iron parts.

Nearly all excitation systems for high speed SMBs consist of high energy PMs, whose flux is homogenized (FIGURE 4 a) and concentrated (FIGURE 4 b) by iron poles. By a circular bending of these linear excitation systems those for radial bearings (FIGURE 5) can be derived. Apparently circular shaped excitation systems for axial SMBs (FIGURE 6) can be derived from a horizontal bending of the linear systems shown in FIGURE 4.

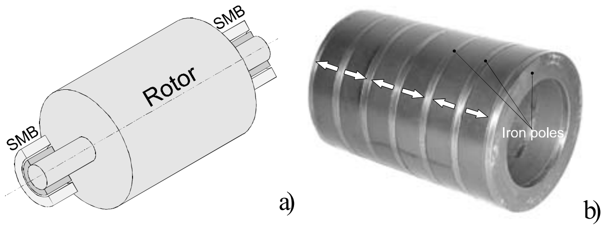


FIGURE 5 a) Design of a rotor which is magnetically supported by radial SMBs.
b) Cylindrically shaped excitation system for radial SMBs composed of alternating axially magnetized PMs located between cylindrical iron poles.

Based on these basic topologies, within several research projects (funded by the German federal government) SMBs for a contactless transport system (FIGURE 7) and turbo machines (FIGURE 8) have been calculated designed and tested. The demonstrator shown in FIGURE 7 was built within the frame of a Chinese-German research project and operated while the M^2S-HTSC-V conference in Beijing 1997 [9].

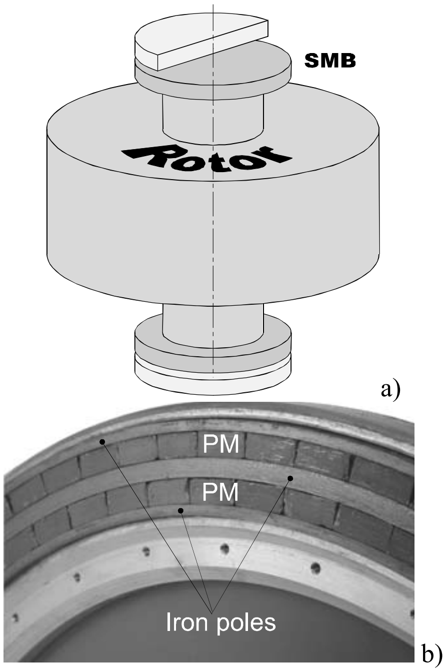


FIGURE 6 a) Rotor magnetically supported by axial SMBs
b) Circular shaped excitation system for axial SMBs composed of PMs inserted between cylindrical iron poles

The photo shows the body of the vehicle and the disassembled Dewar for simple LN_2 cooling of the HTSC-bulks. This vehicle was supported by an excitation rail similar to that shown in FIGURE 6 b but with a diameter of 3 m. The vehicle was not only contactless supported and guided by the linear SMBs but furthermore driven by an electric linear motor.

FIGURE 7 Demonstrator of linear transport system with SMBs of the joint Chinese German research project [9]).

Within a further research project first approaches for the design of high speed, lubricant free SMBs for Turbo-machines have been investigated and a model arrangement was built and tested. FIGURE 8 a) depicts the design and b) the assembly of an appropriate test bench. The shaft of the demonstrator could be driven up to 10,000 rpm and disturbed and loaded by inverse AMBs as magnetic actuators. The cylindrical SMB shown in c) consists of a Dewar in which a cold head embraces the HTSC-cylinder. Separated by a thermal insulation, the cylindrical excitation system shown in FIGURE 5 a) is radially supported together with the shaft in the warm bore of the Dewars.

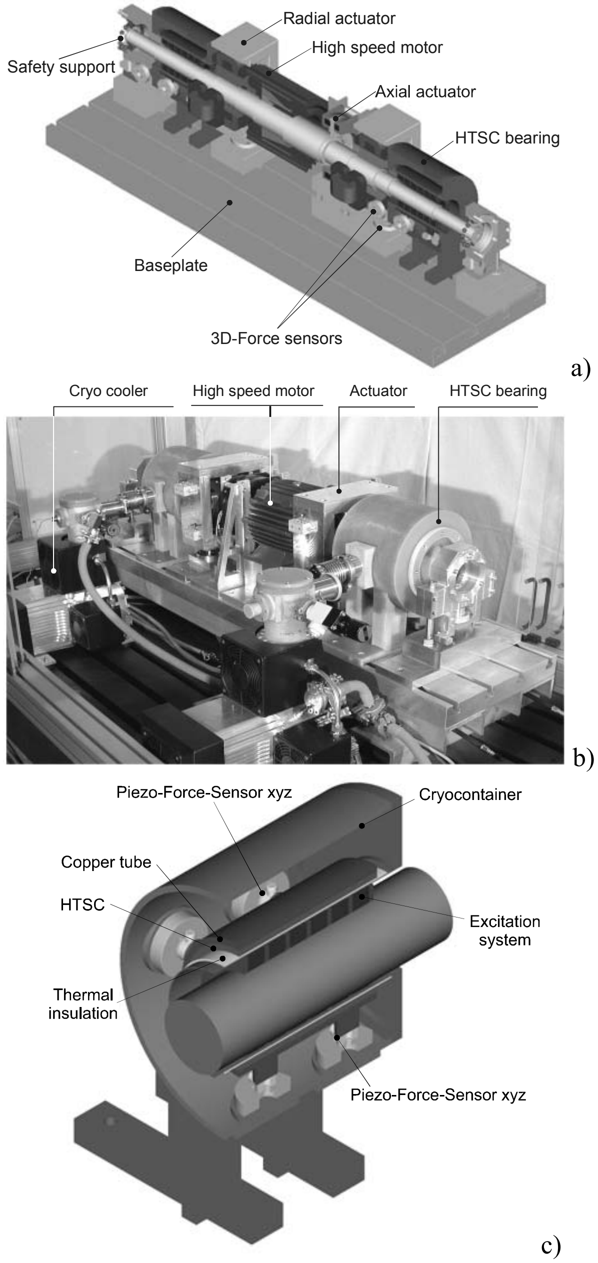
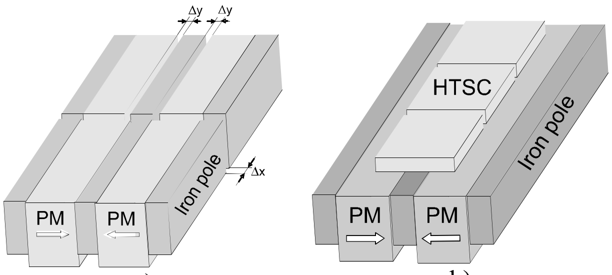


FIGURE 8 One of two SMBs for the support of the high speed shaft.
a) and b) Design and photo of the test bench for the SMBs;
c) Design of the SMB consisting of a cylindrical copper cold head with HTSC bulks in a Dewar and an excitation system similar to FIGURE 5 b in the warm bore.

MATHEMATICAL MODEL FOR THE 3-D FIELD-SC INTERACTION

As both the excitation systems according to FIGURE 4 and FIGURE 5 b) and the HTSC cylinders according to FIGURE 8 c) have been treated so far as perfect homogeneous in the direction of motion (x- respectively φ-coordinates), all force calculations could be carried out in a two-dimensional plane orthogonal to the direction of movement (FIGURE 2). If however those simplified 2-D force calculations under the consideration of infinite j_c-values have been compared with measurements [11], major differences could be observed. Even under the consideration of finite and even flux depending j_c-values [6], the differences between measured and calculated forces are larger than some 10%. For further improvements of the force predictions the calculation models had to be extended to the tree dimensional ones. As can be deduced from the photographs of FIGURE 6 b and FIGURE 7, neither the magnets of the excitation system nor the cluster of superconductor bulks are perfectly arranged as one uninterrupted unit. The extended calculation model, which has been developed, is able to consider imperfect excitation systems with not matching PMs and even interrupted iron structures FIGURE 9 a). Furthermore HTSC-clusters composed of individual, electrically insulated HTSC-bulks (FIGURE 9 b), can be considered fore more sophisticated force determinations.



a) b)

FIGURE 9 Linear field excitation system in a flux collection arrangement consisting of iron poles and PMs.
a) Arrangement with not matching PMs and interrupted iron structure.
b) SMB with individual HTSC-bulks.

CALCULATION RESULTS

To determine the influence of the finite dimensions of both the excitation system and the HTSC-bulks, in a first step the HTSC was treated as finite wide but still infinite long (FIGURE 2). In a second step the HTSC and the excitation system was treated with finite dimensions in all three directions (FIGURE 10). As a first result, for the infinite expanded model the numerical force determinations based on Finite Elements showed fairly small differences in a sub per-mille region to the analytical obtained values according to [3]. If the finite width was taken into account (FIGURE 2), the forces, which cannot be calculated analytically anymore, dropped down by ≈16% and furthermore, with the assumption of finite width and length of the HTSC (FIGURE 10), the force is further reduced to 75%. As a result of these basic examinations it can be stated that, depending on the dimensions of the excitation system and the individual HTSC-bulks, advanced calculation codes have to be applied for more improved force predictions.

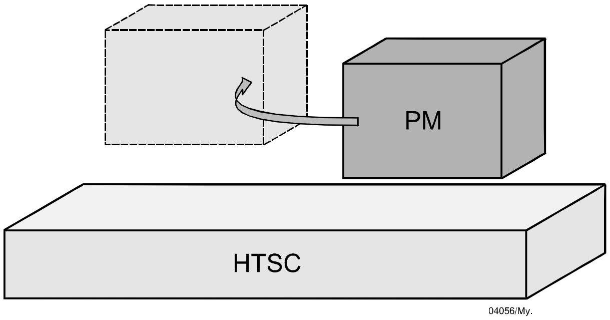


FIGURE 10 Illustration of the HTSC-PM force interaction in the case of a finite expanded HTSC.

If the HTSC body is built from a cluster of individual HTSC-bulks placed above the excitation system and electrically insulated from each other (FIGURE 9), the spreading of the magnetic field cannot perfectly be suppressed anymore. As indicated in FIGURE 11, the magnetic field penetrates the HTSC plane between the adjacent HTSC bulks. These parasitic field portions can be observed particularly if the j_c-values of the HTSC bulks are small. Intensive efforts have been made to suppress of these phenomena by enhancing either the j_c-values or welding the individual HTSC-bulks together [12] to perform a coherent superconducting plate. The influences of differently arranged HTSC-bulks on the normal and lateral forces have been determined for the arrangement mentioned in FIGURE 12 with the following particularities. The PMs of the excitation system offer clearances similar to that of FIGURE 6 b) and FIGURE 9 a). After the cooling of the HTSCs, they have been approached to the excitation system from a distance of 9 mm to 4 mm and simultaneously 1.5 mm shifted sideward (FIGURE 12). At all three different bearing arrangements with reaction rails composed of one, two and three (FIGURE 12) bulks have been investigated. They develop related normal forces of 100%, 95% and 90% and related lateral forces of 100%, 97% and 36%. These results shall give only an impression give the influence of individual HTSC bulks on the performances of SMBs.

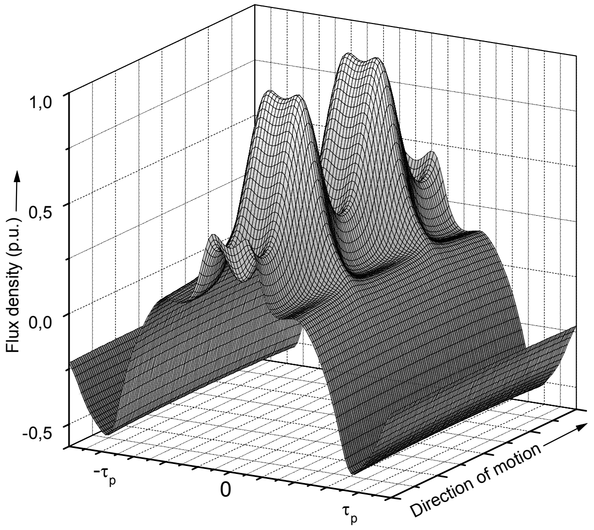


FIGURE 11 Field distribution of a flux collecting excitation system (3 poles) in the plane underneath the HTSC-bulks according to FIGURE 9 b. The HTSC plane is composed of three individual bulks.

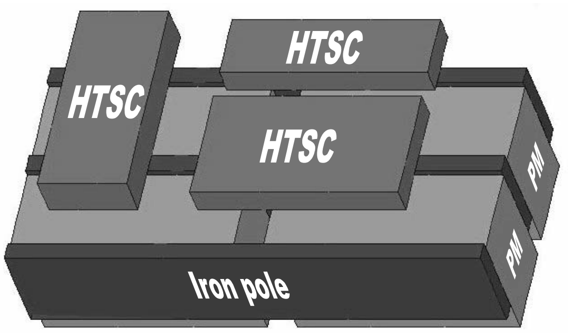
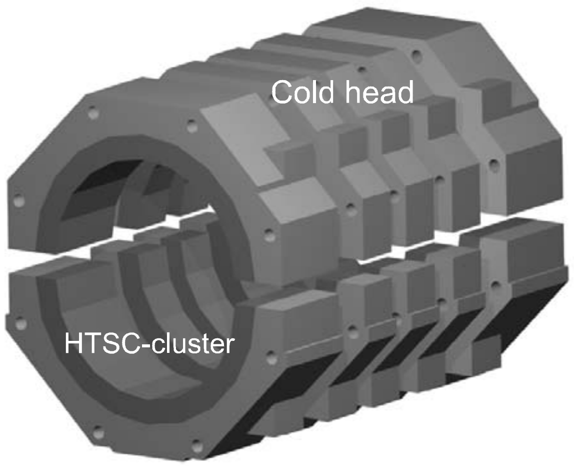
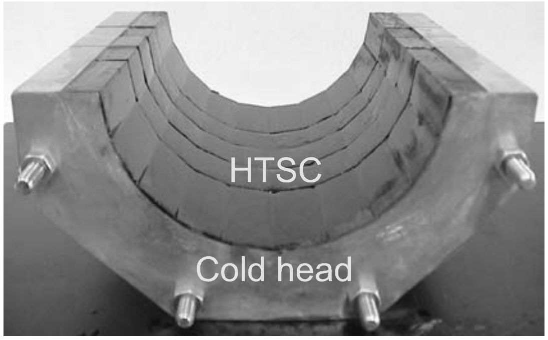


FIGURE 12 Model SMB with differently arranged HTSC-bulks. The PM structure is interrupted by a space of 4mm. The reaction rail is composed from three HTSC bulks.



a)



b)

FIGURE 13 a) Advanced double shell arrangement of the copper cold head with integrated HTSC-bulks for the SMB shown in FIGURE 8
b) Photo of the lower copper half shell with the HTSC-reaction rail composed of individual bulks.

As till now all expanded HTSC-rails have to be composed from individual bulks, many arrangements similar to FIGURE 12 have been built up, calculated and validated by measurements. However it has to be considered, that for monetary reasons the HTSC-bulks of the SMB shown in FIGURE 13 b have been manufactured as a batch process from more than 50 pieces at once offering an unfavorable range of quality dispersion (forces) of almost 25%. Thus the 3D calculations showed deviations from the measurements in the same range and had to be adjusted to this imperfectness. Afterwards the program has been used to arrange the individual bulks on the cold head of FIGURE 13 b in such a way that the resulting radial and axial stiffnesses were almost uniform distributed across the whole bore of the SMB (FIGURE 14).

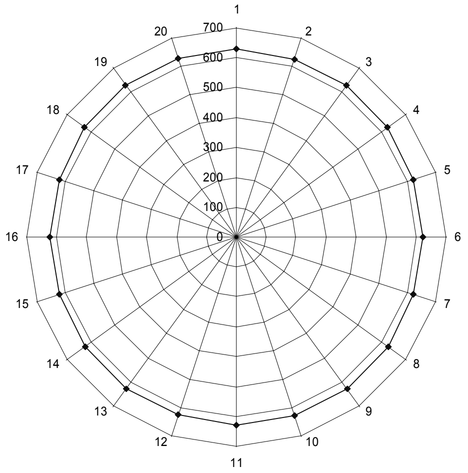


FIGURE 14 Circular distribution of the radial stiffness after arranging the individual HTSC-bulks according to the optimized magnetic balancing.

Within a further joint research project the inner tank of a double walled container for liquid LH_2 for automotive applications was contact-free supported and thus the thermal path from the ambient into the inner

LH_2 container was interrupted (FIGURE 15 a). Two competing SMB configurations have been analyzed and their thermal insulation capability was evaluated. Beside a concentric cylindrical SMB similar to FIGURE 5 (the inner tank replaces the rotor) a planar SMB with a chess board formed magnet arrangements according to FIGURE 15 b) have been built. For both designs the application of the three dimensional calculation code resulted in satisfying values with respect to the predictability of the force values.

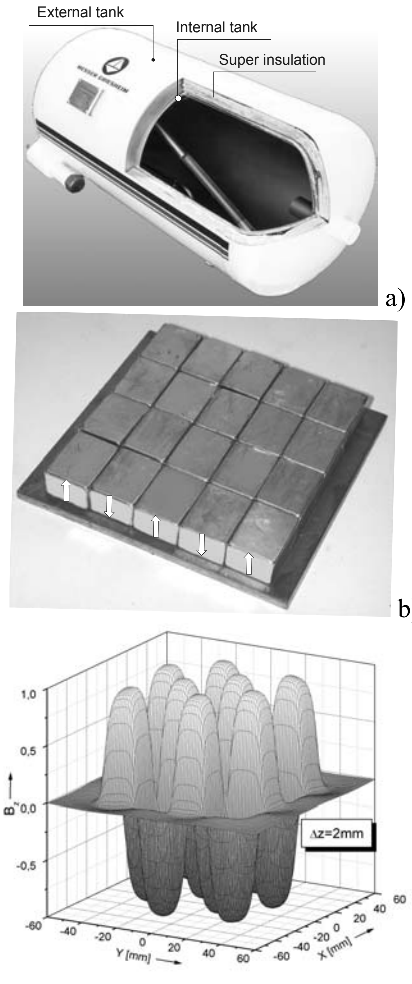


FIGURE 15 a) Double walled LH_2 cryocontainer for automotive applications. Partially sliced open to illustrate the double walled construction.
b) Chess board formed planar excitation system
c) 3D field distribution with an extremely increased field gradient to achieve enhanced force densities.

ACKNOWLEDGEMENTS

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