Superconductively Levitated Transport System—The SupraTrans Project

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***Abstract*—SupraTrans is an innovative transportation concept based on the principle of superconductive magnetic levitation. The aim of the project is to create a fully working prototype, which proves its ability for passenger transport by explicit consideration of the compatibility between systems for propulsion, safety, positioning, power supply, transport logistics and the levitation system itself.**

The SupraTrans technology uses the flux pinning in high temperature superconductors (HTS) to stabilize the lateral and vertical position of the vehicle on the magnetic track. This self-stabilizing system is the main advantage of the superconductive levitation in comparison to all other levitation systems, which need electronic control and power to keep a constant distance between the train and the track.

***Index Terms*—Magnetic levitation, superconductivity, SupraTrans, transporting system.**

I. Introduction

MAGNETIC levitation on the basis of electrostatic or magnetostatic interactions between macroscopic bodies is impossible, according to the sobering conclusion to draw from Samuel Earnshaws theorem published in 1842 [1]. Most of today's solutions for magnetic levitation are, therefore, based on dynamically controlled electromagnets, facing all the problems of sophisticated control systems and considerable power consumption. The more seducing is it to find a system with the simplicity of a fixed arrangement of magnets and iron yokes, which does not violate Earnshaws theorem. The system, which fulfills all these requirements, consists of superconducting materials levitating in the static magnetic field of permanent magnets. Several groups are working on projects to use this simple technique to design new machines with frictionless rotating bearings [2]–[5]. Linear bearings can also be made by superconducting levitation [6]. The idea to set up a superconductive maglev transporting system is then just a small step away. The first man loading maglev system of this kind was presented in Chengdu, China in 2002 [7], [8].

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Fig. 1. The SupraTrans train at its first presentation at the IFW Dresden in September 2004.

The SupraTrans project was started to develop a demonstrator containing all components needed for a transporting system and also taking into account the requirements of a future operator. Therefore SupraTrans is a joint venture of research institutes (IFW Dresden), universities (Dresden University of Technology, Dresden University of Applied Sciences), industrial companies (ELBAS GmbH-railway consulting and engineering, Baumüller Kamenz-linear drives, CIDEON engineering Bautzen-railway conveyer design) and the Dresden Transportation Company (DVB AG) as a potential user. All together, are designing a fully working demonstrator and a test line, which allow to study all the mentioned issues (Fig. 1).

II. Demonstrator

A. Goals

The aim of the SupraTrans project is to prove the concept of a magnetic levitation train based on superconducting levitation and guidance system by the construction of a demonstrator. Its dimensions have been chosen to carry at least one person or a corresponding load. The guideway measures 7 m in length, so it can show the concept of transportation but also fits in the laboratory. The design of the whole system must give flexibility for testing of various additional components, as the propulsion and braking system, speed control, power transport, positioning and passenger safety, individually and together. A first model should work as soon as possible.

Under these preconditions, the first set-up of the demonstrator was determined in the following points:

- Using permanent magnets for the guideway
- Asynchronous linear drive in vertical orientation with two stator segments facing each other and the runner placed in the gap between the stator segments
- Cooling system based on liquid nitrogen
- Power transmission using mechanical contacts and energy storage on the vehicle.

In further steps individual systems will be replaced, if beneficial, step by step by more innovative components like:

- Electromagnetic guideway,
- Asynchronous linear drive in horizontal orientation to enable an absolutely flat track and turnout switches,
- Cryo-cooler (stirling) cooling system,
- Non-contact power transmission via the linear drive

B. Components

1) Levitation and Guidance System: The magnetic guideway is characterized by a magnetic field exhibiting a strong field gradient perpendicular to and a homogeneous characteristic along the driving direction. Forces between the superconductor and the guideway are proportional to both, the maximum field and the field gradient. The field has to penetrate the space above the guideway to enable a considerable levitation gap, but should not affect potential passengers or environment in its close neighborhood. The arrangement of Nd-Fe-B permanent magnets and iron yokes working as flux collectors, as shown in Fig. 2(a), has to be optimized to fulfill all these requirements.

Due to the size of the melt-textured triple-seeded YBCO bulk superconductors of $90\ \mathrm{mm} \times 35\ \mathrm{mm} \times 15\ \mathrm{mm}$ [8], the width of a single track is set to 90 mm. The design of the track has been optimized using two-dimensional finite element methods (QUICKFIELD-software) and three-dimensional finite boundary element simulation (AMPERES-software). The resulting optimized geometry for a single track is shown in Fig. 2(a). Two rows of Nd-Fe-B permanent magnets with a size of $50\ \mathrm{mm} \times 50\ \mathrm{mm} \times 40\ \mathrm{mm}$ are mounted in a soft magnetic steel yoke with head-on magnetization. In this arrangement, the soft magnetic steel in between and beside the permanent magnets acts as a flux concentrator. By this, a magnetic field of more than 1 Tesla at a distance of 0.5 mm above the track has been achieved (Fig. 2(b)). At the working distance of 10 mm above the track, the magnetic field is about 0.5 Tesla, which is a good basis for an appropriate levitation force and sufficient stiffness.

a)

b)

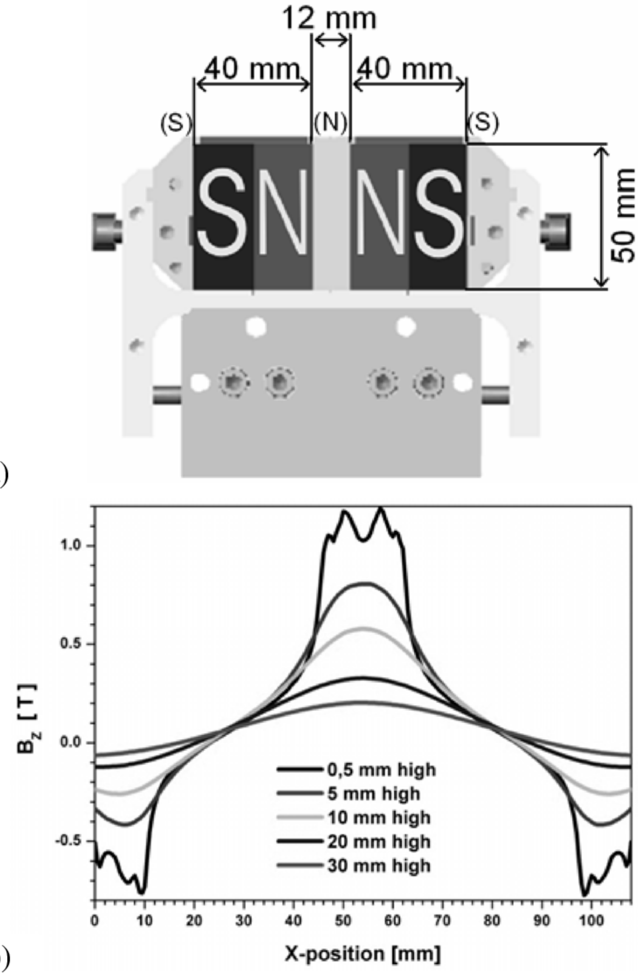

Fig. 2. Cross section of a single magnetic track. a) Nd-Fe-B magnets with opposite magnetization (head-on) are mounted in the soft magnetic steel yoke. b) Horizontal distribution of the vertical field component in different distances above the track.

Levitation and guidance forces were measured using a three-dimensional force measurement device. Fig. 3(a) shows the levitation force as a function of the distance between track and superconductor surface in the case of zero-field-cooling for a $90\ \mathrm{mm} \times 35\ \mathrm{mm} \times 15\ \mathrm{mm}$ YBCO bulk sample at 77 K. With decreasing distance the force increases and reaches a value of 190 N at 8 mm distance by a vertical stiffness of 10 N/mm. Using 40 YBCO bulks of the same kind, as is done in the SupraTrans vehicle, a total weight of up to 800 kg can be carried. However, the curve shows a hysteretic behavior due to flux creep in the superconductor. This results in energy dissipation and lower levitation forces after several cycles. A continuous load change of 240 kg, as seems to be realistic for the SupraTrans vehicle, has been simulated by the measurement shown in Fig. 3(b). Here the superconductor has been moved from its cooling position 40 mm above the track to a working position at a distance of 13 mm. Lowering the force by 60 N (equivalent to 240 kg for 40 bulks), the distance increases to 18 mm. In the following minor loop to 13 mm and back to 18 mm, no hysteretic behavior can be detected. Thus, no flux creep within the superconductors occurs, the system is in an elastic state and the cycles of loading and unloading are

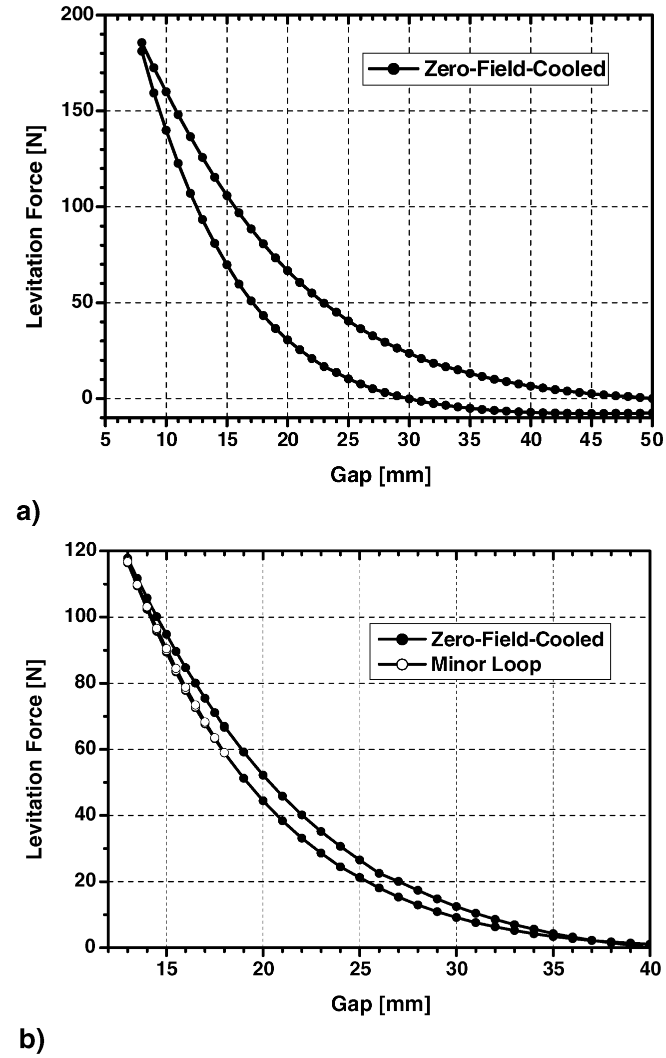

Fig. 3. Levitation force of a triple seeded YBCO bulk ($90\ \mathrm{mm} \times 35\ \mathrm{mm} \times 15\ \mathrm{mm}$). a) Cooled in zero field, the measurement starts at a distance of 50 mm above the track. b) The sample has been cooled at the distance of 40 mm. A minor loop has been taken from 8 mm to 13 mm and back.

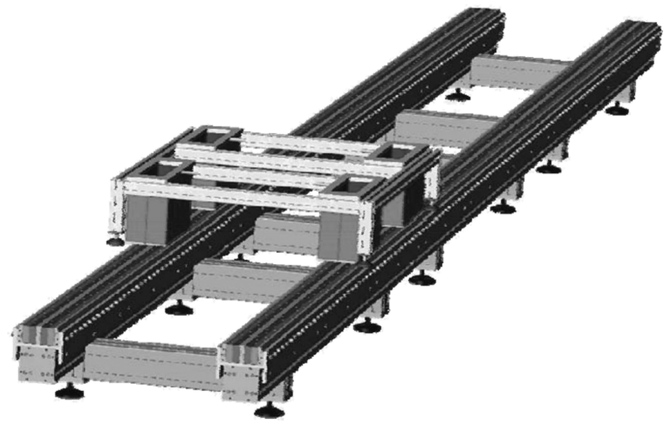

Fig. 4. Sketch of the guideway, consisting of three segments of 2.10 m length, including the vehicle frame with 4 cryostates, but without stator elements of the linear motor and additional components.

reversible. However, experiments with several hundreds of minor loops have to be measured to prove this first result.

For technical applications it is important to search for materials with high pinning forces to enable sufficient levitation and guidance forces, stiffness and to reduce flux creep. The $\mathrm{YBa_2Cu_3O_{7-X}}$-composition shows an extraordinarily strong pinning effect among the available HTSC-materials. It has been shown that fields up to 17 T can be trapped in encapsulated YBCO-bulks at 16 K. Magnetic forces can be generated this way [9]–[11].

The guideway consists of two parallel single tracks, separated into 3 segments of 2.10 m (Fig. 4) and one segment of 0.7 m length for the purpose of easier transport.

Four cryostats, each loaded with 10 YBCO bulks of the dimension of $90\ \mathrm{mm} \times 35\ \mathrm{mm} \times 15\ \mathrm{mm}$, are mounted on the vehicle to keep the superconducting material at the working temperature of 77 K. The cryostats are double-wall containers made of nonmagnetic steel or fiber-plastics. For designing the cryostats it is crucial to achieve a small thickness of the bottom wall, since it directly affects the levitation clearance by a given distance between the superconductor and the guideway. Here, the bottom wall thickness could be limited to 3.5 mm.

2) Propulsion: A long motor will drive the demonstrator with a maximum acceleration of $0.5\ \mathrm{m/s^2}$. The linear drive works in an asynchronous mode, so that both, the stator and the rotor are supplied with a three-phase current. For the stator, the European standard three-phase current of 50 Hz, 400 V is applied, leading to a traveling field of constant amplitude and wave velocity. The wave velocity is given by

$$v = 2\tau_P \bullet f_N = 3.6\ \mathrm{m/s} = 12.96\ \mathrm{km/h} \tag{1}$$

where τ_P, the distance between the magnet poles in the stator, equals 36 mm. The speed of the vehicle is determined by the difference of the wave velocities of the stator and the rotor. It can be adjusted by the speed control on the vehicle, which sets the frequency of the three phase current in the rotor coils. Depending on phase direction and frequency, the vehicle can stop, break or accelerate to a velocity even higher than the fixed wave velocity of the stator field. The information about the phase shift of the traveling field, which is necessary for generating the corresponding rotor current is obtained by Hall sensors mounted on the vehicle and placed in the air gap of the stator.

The stator consists of two rows of vertically oriented stator elements, facing each other with a gap of 20 mm. The rotor board has a thickness of 10 mm floating within the stator gap, resulting in an air gap of 2×5 mm. This geometry is advantageous because of its effective use of magnetic energy to generate an appropriate propulsion force. Because of closed flux paths, the magnetic field between two magnetic poles is much higher compared to an open system of just one stator facing a single rotor element. Further, a changing vertical levitation gap (i.e., because of a changing load) causes the rotor to dive deeper in the stator gap but does not affect the air gap between the stator and the runner. However, for bended tracks and the construction of turnout switches, the vertical geometry exhibits the disadvantage of either a limited bending radius or discontinuities in the propulsion system.

3) Vehicle: The vehicle has been designed in lightweight construction, which still fulfills the requirements of sufficient stiffness, thermal stability, usage of nonmagnetic materials and

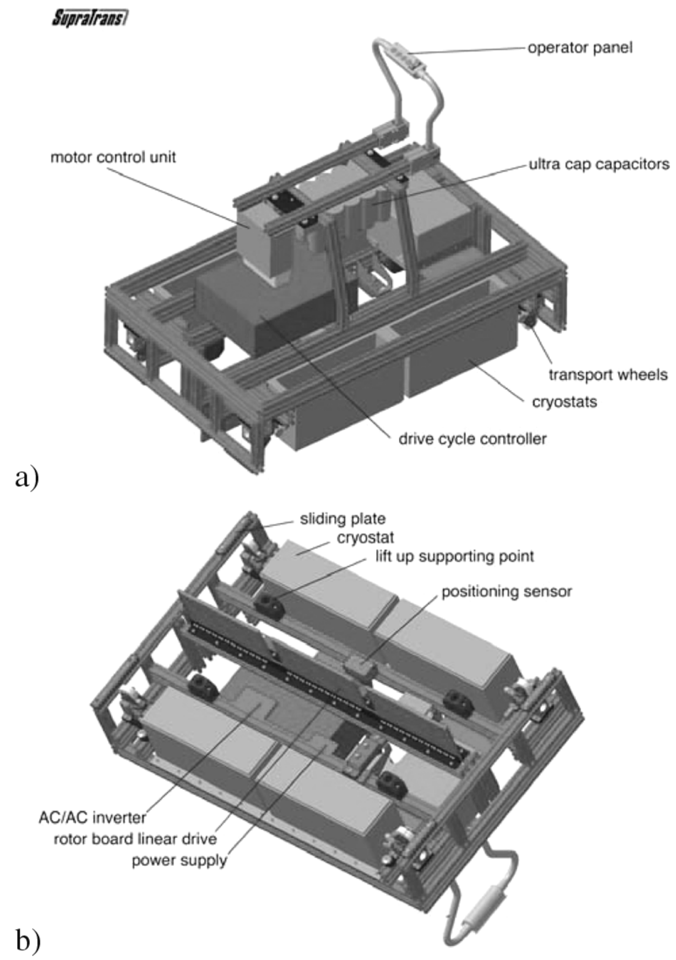

Fig. 5. a) Top view of the uncovered vehicle frame including cryostats and other components. b) Bottom view of the vehicle including the runner board of the linear drive which will extend into the stator gap of the guideway.

flexibility for continuous replacement of components in the ongoing development. Lightweight construction is possible since the levitation and guidance system does not rely on gravitation forces to generate the guiding force. The flux pinning mechanism generates repulsive and attractive forces depending on the deflection of the superconductor from its original position. The vehicle consists of a self-supporting chassis using standard system modules. The equipment is mounted directly on the vehicle or on mounting panels (Fig. 5).

The levitation and guidance system dominates the vehicle design. The four cryostats are mounted in pairs of two in rows under the vehicle with the same track width as for the guideway. The cryostats are comparable to the wheels of a conventional train or car. The rotor boards are placed between the cryostats in the middle of the vehicle. Although the linear drive does work as a breaking system as well, a second redundant brake is useful and compulsory. In the first stage of the development, it is implemented by flexible bumpers at both ends of the guideway to ensure a safe deceleration in case of a total blackout of the propulsion system.

The casing is made up of fiberglass reinforced plastic. It is removable to give access to the technical equipment and has the function of a seat and a protective cover (Table I).

TABLE I
CHARACTERISTICS OF THE SUPRATRANS

guideway	
distance between magnetic rail mid points	575 mm
length of guideway	7 m
flux density at superconductor level	0.6 T
power consumption of drive	3.5 kVA
vehicle	
length	1322 mm
width	800 mm
mass when empty	170 kg
maximum payload	350 kg
energy storage	
voltage	42 V
capacity	67 F
energy content	59 kWs
maximum power consumption	700 W
distance between superconductor and magnetic rail	13…18 mm
constructive air gap between cryostats and magnetic rail	10…15 mm
maximum propulsion	±100 N
maximum acceleration or deceleration at 200 kg total vehicle mass	0.5 m/s^2
demonstration speed	1.0 m/s

4) Operational Concept: Following the aim of the SupraTrans project, to prove the concept of a superconducting magnetic levitation train, the operational concept supports demonstration and testing of the interplay of all technical components. Thereby, the vehicle motion is controlled by the vehicle itself or by an operator sitting on the vehicle. This is in contrast to operational concepts of other modern transport systems (i.e., the Transrapid System) but exhibits the advantage of individually driven cars, which interact by the formation of a network of intelligent autonomous members.

The technical implementation of the demonstrator is based on the demand for a completely wireless vehicle. Two principle operational modes are implemented. In the automatic mode, a predefined operational cycle starts after pressing the start button. Several operational cycles with different parameters for velocity, acceleration and traveling path are available. In the manually controlled mode the vehicle can be driven using a joystick, while the control unit limits the maximum speed, the acceleration and the deceleration and stops the vehicle at the end of the guideway.

III. OUTLOOK

The demonstrator presented in this paper shows the feasibility and advantages of the concept of a maglev train using superconducting levitation. It has been developed under the premise of a first demonstration and as a basis for further testing and improvement of components and their interplay. Further developments are planned to implement the following points:

- Construction of an electromagnetic guideway including a fast electromagnetic turnout switch without mechanically moving parts [12]
- Horizontal orientation of stator segments of the linear drive to enable bended and planar tracks

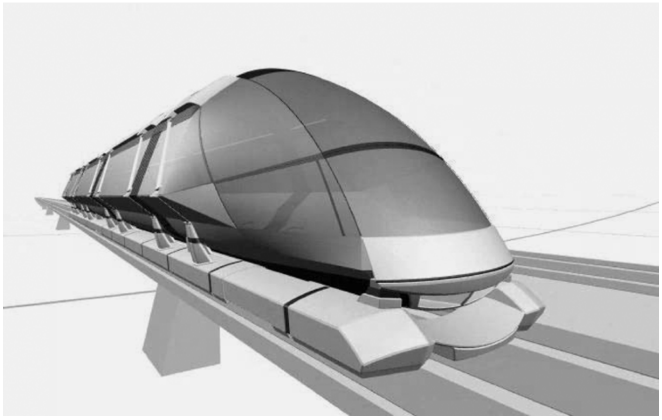

Fig. 6. Design study of a future maglev train [13].

- Electrical cooling system without the need of cryogenic liquids
- Wireless power supply of the vehicle
- Economic studies for different applications

By solving these problems the application of a superconductive maglev train seems to be possible and favorable, especially for short distance transport with a highly branched railroad and velocities below 200 km/h. The features characterizing the SupraTrans technology are a simple levitation and guidance system, new nonmechanic and fast turnouts, much lower power consumption in comparison to conventional systems, extraordinarily high passenger safety due to the physical rational and the possibility of lightweight construction due to repulsive and attractive guidance and frictionless propulsion. This also exhibits the chance to design overhead conveyer or vertically lifted systems, which is of advantage for urban environment. Fig. 6 shows a design study of a future maglev train [13].

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