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Experimenting with a Superconducting Levitation Train

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Abstract
The construction and operation of a prototype high-Tc superconducting train model is presented. The train is levitated by a melt-processed $GdBa_2Cu_3O_x$ (Gd-123) superconducting material over a magnetic rail (track). The oval shaped track is constructed in S-N-S or PM3N configuration arranged on an iron plate. The train bodies are constructed with FRP sheets forming a vessel to maintain the temperature of liquid nitrogen. The superconductors are field-cooled on the magnetic track, which provides a large stability of the levitation due to strong flux pinning of the melt-processed superconductors. The setup enables to test parameters like stability, speed, and safety, of the superconducting train for various gaps (ranging between 1 mm to 15 mm) between the train and the magnetic track. The experimental results indicate that trains with 1 to 2 mm gaps cannot run properly due to the friction applied to the track. The trains with 10 or 15 mm gaps do not run stable on the track. Our results confirm that a gap of 5 mm is the optimum distance to run the train showing also stability to run fast on the track. The present results clearly demonstrate that the stability of the superconducting trains depends on the gap between the rail and train, which is an important parameter also for the real Maglev trains.
Keywords: Levitation, superconductivity, model train, stability

Introduction

With the upcoming of the high-T_c superconductors (Bednorz and Müller, 1986) liquid nitrogen as coolant became reality, and so the possibility to demonstrate superconductivity in the classroom. Using high-T_c superconducting materials, one may produce superconducting super-magnets (Weinstein *et al*., 1993) which are hundred times more powerful than normal magnets (Tomita and Murakami, 2003). The high performance superconducting super-magnets offer a way to make trains literally "fly" to their destination by using powerful magnets to cause them to float above their track. At present, magnetically levitated trains (Maglev) have attained top speeds in excess of 581 km/h. This new class of transportation could revolutionize in the 21st century in much the same way that airplanes revolutionized the 20th century transport. The currently proposed Maglev trains operate at liquid helium temperature (4.2 K), which is expensive and the required cooling systems are much more complicated. However, the high-T_c superconducting magnets can operate above 77 K, the boiling point of liquid nitrogen, which is much cheaper like Coca Cola. In former contributions, classroom demonstrations of levitating high-T_c superconductors were reported, either levitating above or below simple magnets or above a magnetic track (Strehlow and Sullivan, 2009). These experiments enable to study the basic behavior of stable levitation by type-II superconductors, and were always found to be very inspiring when demonstrating the stable levitation to the public.

Construction and modelling

In our demonstration project, we aimed to put the emphasis on the study of the levitation behavior of a Maglev train. We focused on detailed measurements of the resulting properties of Maglev vehicles when being levitated on a magnetic track. This will enable students to have a longer experience with superconducting levitation as compared to the "simple" levitation experiments which only last several seconds to minutes. Furthermore, there is a fundamental physical difference when cooling the superconducting pellets above the magnetic track (field cooling, FC) as compared to a so-called zero-field cooling (ZFC) process, which is commonly applied. This issue is the central point of this paper and will be discussed in detail. The experimental work described here was carried out as a science fair project. The goal was to construct a prototype high-T_c superconducting train model and to perform measurements concerning the operation parameters of the Maglev train. The levitation demonstration consists of two sub-systems: The magnetic rail and the train model.

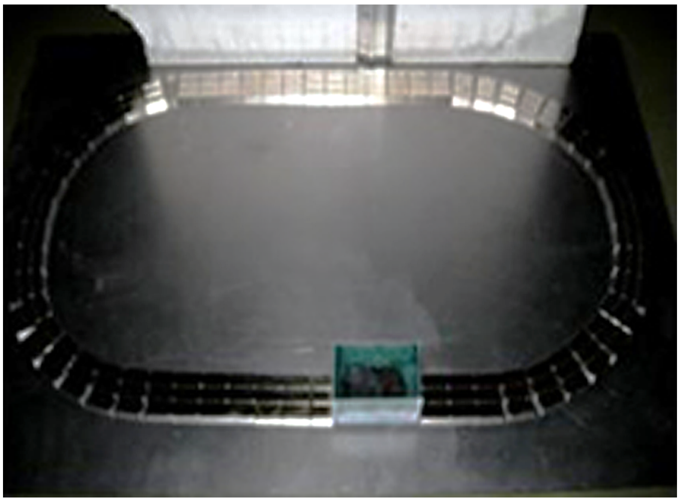

Figure 1. The magnetic rail with the magnets in S-N-S/PM3N configuration

Magnetic rail

The basic construction of the magnetic rail was already discussed by Strehlow and Sullivan (2009), where a rail consisting of three permanent magnets with antiparallel vertical magnetization (named PM3N in the literature) was employed. This configuration was also modeled theoretically (Del-Valle *et al.,* 2008; Del-Valle *et al.,* 2009). We have followed this approach to build a classic oval track, allowing the levitation trains to run several loops with one liquid nitrogen load. The base for the magnetic rail consists of an iron plate which has a size of 60 x 40 x 2 mm^3 (Fig. 1) with the magnets arranged in three rows forming an oval shape with the dimensions of 570 x 300 mm^2. The magnets were arranged in S-N-S configuration (indicating that the magnets arranged in north, south, and north direction– in some publications, this arrangement is called PM3N). For the construction of the rail, in total 189 permanent magnets were employed. Each magnet's magnetic field strength is 0.3 T. It is important to point out that one can arrange the magnets properly if the iron plate has a certain thickness. A 2 mm-thick iron plate was found to work perfectly and the magnets could be arranged without any gaps between them. Thicker iron plates may cause problems as the magnets are strongly attracted to the plate (in this case, the magnets even may break when hitting the base plate) and the proper adjustment of the magnet pieces could be difficult.

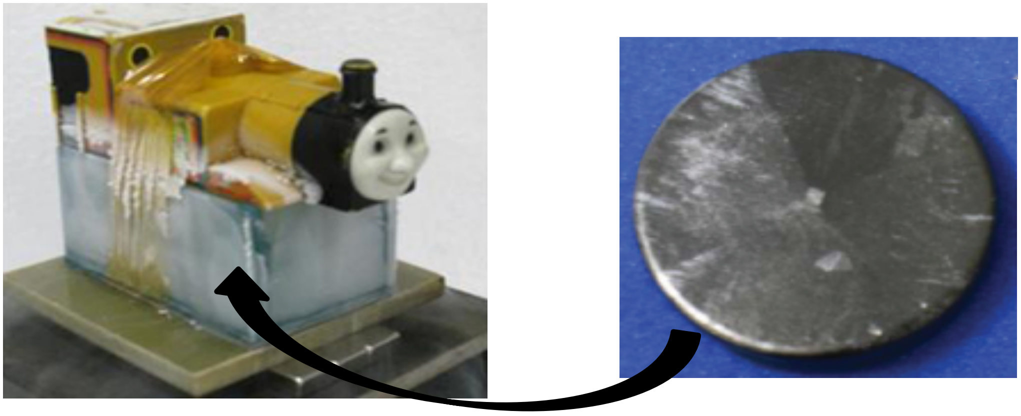

Figure 2: The completed levitation train model with the nitrogen tank, and the toy train model placed above it. The melt-processed superconductor disk is placed in the center of the tank

Train Model and Superconducting Material

The second sub-system is the superconducting material itself. Here, we employed a melt-textured high-T_c superconductor instead of the often used polycrystalline, sintered samples. Such a material cannot be made without special equipment, but has to be bought from suppliers like the RTRI (Railway Technical Research Institute, Tokyo) in Japan or ATZ Superconductors in Germany. The essential difference of such a superconductor to the polycrystalline material is the strong flux pinning, and hence, the high critical current density. The superconducting current loops are here flowing through the entire perimeter of the sample, and not only inside small superconducting grains. The $GdBa_2Cu_3O_y$ (Gd-123) bulk superconductors used in this experiment were prepared by a melt-texturing process and were supplied by RTRI. To improve the flux pinning performance of the Gd-123 material, several state-of-the-art additions were made to the superconductors. Overall, the samples showed a critical current density of 70 kA/cm^2 (magnetic field H oriented parallel to the *c*-axis of the superconductor) at 77 K in self-field, which is considerably larger as compared to the sintered, polycrystalline samples with a current density of only 100...1000 A/cm^2 (Muralidhar *et al*., 2010). The consequence of this difference in the current density is that the material may levitate at a larger height, and can carry even a strong load.

The kernel of the construction is to provide a liquid nitrogen container to maintain the temperature of the superconductor pellet for a much longer time period. Such containers were constructed using Fiber Reinforced Plastic (FRP) sheets and low temperature grease as glue. The dimensions of the boxes are l= 65 mm, b = 40 mm and h = 30 mm. The boxes constructed from the FRP sheets enable the control of the liquid nitrogen losses, as they can hold an amount of liquid nitrogen which enables the train model to perform several loops before the superconductor pellet will warm up above the superconducting transition temperature, T_c. Then, the superconducting pellet (diameter of 32 mm and a thickness of 5 mm) is fixed inside the FRP box by Apiezon grease (see Fig. 2). Finally, the train body (Thomas, and Nozomi Shinkansen) was attached to the FRP body by Captan tapes. The total weight of the train models including the superconductor is 89 g. The weight will rise to 125 g when the model is filled up with liquid nitrogen.

Cooling Schemes for Superconductors

Here, some remarks concerning the FC process for cooling of the superconductors are necessary (Tinkham, 1996; Kobilischka, 2008). A scheme of field-cooling a superconductor pellet is outlined in Fig. 3. A strong, homogeneous magnetic field H will penetrate through the superconducting material (a) when the temperature T is above T_c.

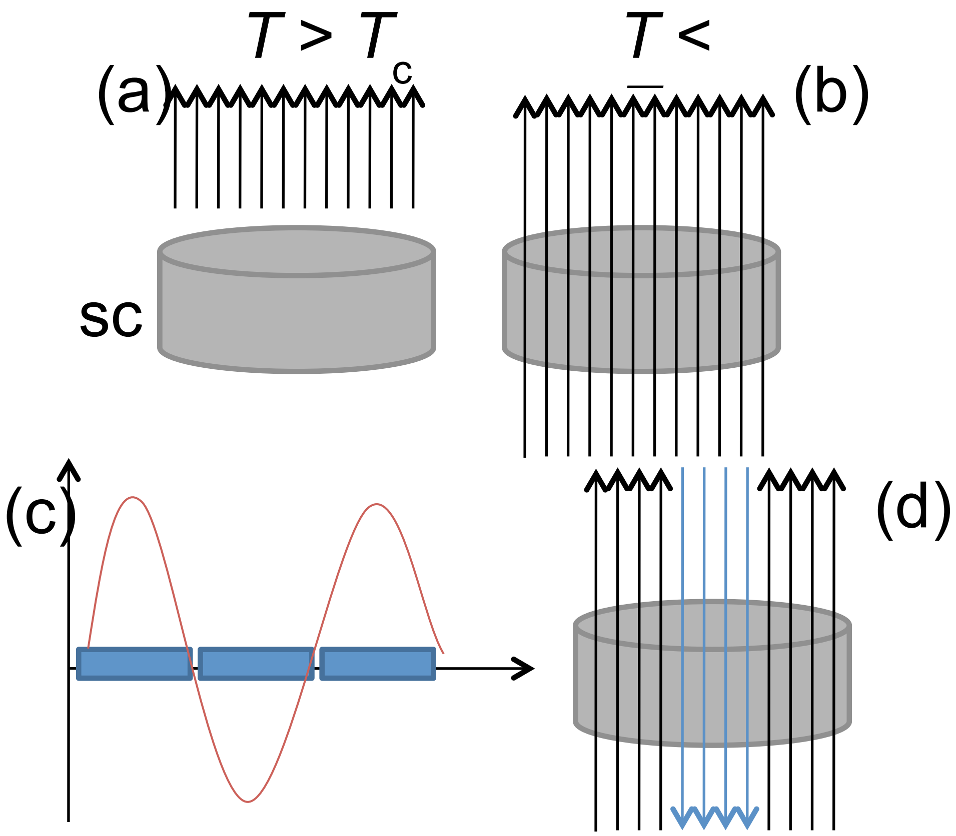

Figure 3. Illustration of the FC process.

Above the superconducting transition temperature, T_c, there is the magnetic field everywhere in and around the sample (a). When cooling the superconductor in the presence of a strong magnetic field below the superconducting transition temperature T_c, flux lines are formed inside the superconductor, and the superconductor is completely filled with flux lines which are anchored at the available flux pinning sites (b). (c) The field distribution above the magnetic rail. As a result, the frozen-in magnetic field as shown in (d) has positive and negative directions.

When cooling the sample below T_c, vortices are generated within the superconductor (b). In case we have a homogeneous, strong-pinning superconducting material like here, the vortices will be anchored at the numerous pinning sites within the material.

Here, it is essential that one uses a bulk, melt-textured superconducting sample which ensures that the shielding currents are running through the entire perimeter. This will not be the case for a polycrystalline material, where the flux can enter via the existing weak-links. As the field distribution above our magnetic track looks like depicted in (c), we will freeze this configuration when field-cooling the sample above the track resulting in a situation like sketched in (d). In general, the FC cooling process leads to a homogeneous field distribution within the superconductor, which is completely different to the commonly applied zero-field cooling, where large flux density gradients arise which are directly linked to the critical current density. In fact, a superconductor piece being cooled lying on a magnet should lift up when the Meissner effect (diamagnetism) sets in.

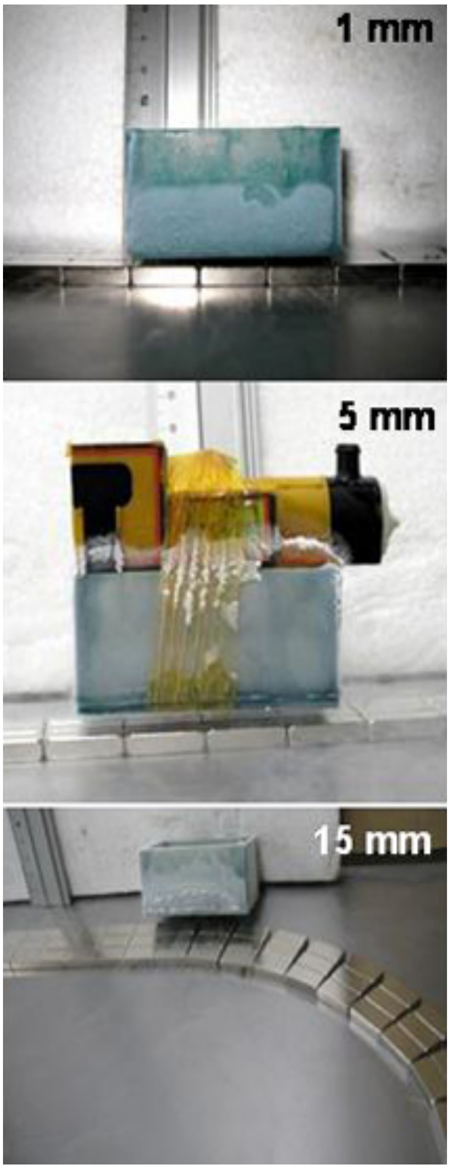

Figure 4. Operation of the Maglev train model.

As the levitation height can be chosen by distance plates, different operation heights are possible. At 1 mm height, the train moves, but there is still friction. 5 mm height was found to be the optimal gap with good performance. A height of 15 mm is still possible, but the levitation is not stable anymore, leading to derailment in the curved sections of the track.

This is often claimed to be the best proof of the Meissner effect as a zero-resistance metal piece would just stay unaffected where it is. However, in contrast to this scenario which is true for most superconductors, our strong pinning samples can be adjusted at any levitation height in the FC process using the FRP sheets, and they do not move off the selected position. This is due to the fact that the flux lines are anchored at their respective flux pinning sites within the superconducting material, so that the any lifting due to the Meissner effect would cost additional energy. In the present situation, the external field provided from the magnets of the track is not homogeneous, but has positive and negative directions due to the S-N-S configuration of the magnets within the track as depicted in (d). This field arrangement is, therefore, also found within the trapped field distribution of the superconducting pellet. The advantage of FC cooling is the fact that all flux pinning sites within the material are occupied by vortices, so the resulting forces to move a vortex around are very large. Such levitation forces can be directly measured by a levitation balance. Therefore, the FC situation provides us with very stable levitation characteristics allowing us to analyze the levitation behavior in detail for various levitation heights.

Experiments to Study the Motion of The Levitated Train Model

Now, the goal was to demonstrate the basic physics of a Maglev train. To optimize the gap between the rail and train model, the levitation height must be adjusted so that the train model runs stable and smoothly. This is an important parameter to construct the real application, so the levitation train model provides here an important insight to the levitation technology. For this purpose, the gap between the rail and train model was varied between 1 mm, 2 mm, 3 mm, 5 mm, 7 mm, 10 mm and 15 mm using FRP plates as appropriate spacers. This represents a cheap and effective means to change the levitation height of the train model.

Table 1. Summary of the experimental results

Gap between the Rail and HTSC Train	Levitation	Speed	Stability & Safety	Comment
1 mm	ok	poor	good	train run slowly and stable
2 mm	ok	poor	good	
3 mm	ok	good	good	
5 mm	ok	very good	very good	train run very fast and stable
7 mm	ok	good	good	
10 mm	ok	poor	not stable	
15 mm	ok	no	no	train not run on the rail and it was moved out of the rail

To achieve a precise control of the levitation gap, the field-cooled (FC) process was adopted in the present experiment. For this, the superconductor inside the train model is cooled down to liquid nitrogen temperature *after* the model train is put on the track. The levitation height is adjusted via the FRP sheets of the respective thickness ranging between 1 mm to 15 mm to establish and optimize the gap between the Maglev and the rail. For this purpose, a set of five FRP plates serves all the needs (1 x 1 mm, 2 x 2 mm, 2 x 5 mm).

In all experiments, the model train could be pushed forward by hand, but a spring-operated system performs better as a constant push is provided. The levitation height, the speed of the vehicles, the stability of levitation, and safety issues were tested, all of which are controlled by flux pinning effect of the high-T_c superconductor. The summary of the experimental observations are presented in Table 1. The results show that levitation gets weaker using a larger levitation gap. Trains with a 1 or 3 mm gap have stability in levitation, but show friction which causes the trains to not run properly (see Fig. 4). The origin of this friction was discussed already by Brandt (1988). The gap was tested with the box-type vehicle, and we found that the stability and speed is perfect for medium-sized gaps. Further, the 5 mm gap was tested using the Thomas train model as well as Nozomi Shinkansen model (Fig. 4). According to our observations, a 5 mm gap train is best suited one because the trains run with good stability and greater speed. It is interesting to note that the 10 or 15 mm gap between the rail and train can levitate properly with larger gap. However, it does not have the proper stability for the train to run, so it falls off the track, especially at the curved sections (Fig. 4). For Maglev trains, the optimum gap between the train and rail is a very important parameter, which will be control the stability and speed. In case of 10 mm gap the train did not run properly. Further, increasing the gap to 15 mm made the train to go off the track, especially in the curved sections. These results demonstrate that around the 5 mm gap is the best optimum for the HTSC train model for high stability and super speed. Using the optimum gap of 5 mm, one could run even both Maglev train models on the single rail. This experiment works very well and the trains run with good stability.

To check the stability during the run, the train was stopped in various locations (for example, in the curved section, along the long sides of the track, and etc). Subsequently, the stability was checked by moving the train in different directions which shows that the levitation train operates in a stable manner. To access the behavior of the trains using different levitation heights, several experimental runs were carried out. To control and unify the pushing force, we utilized a spring to push the train forward. In his way, a similar force could be maintained. The results of these runs are summarized in Table 2.

Table 2. Quantitative analysis of the behavior of the trains using different levitation heights

Gap between rail and HTSC train [mm]	**Time taken for one round course [s]**								**Observations**
	normal				fast				
	T_1	T_2	T_3	av	T_1	T_2	T_3	av	
1	not completed				8	9	8		did not complete the course due to friction
3	5	4	5	4.6	2	2	3		
5	2	2	2	2	1	<1	1	1	good gap from application point of view
7	6	5	5	5.3	no	no	no	no	in case of fast speed: decreased stability
15	no	no	no	no	no	no	no	no	in both cases train derailed

These two experiments enable the students to understand details of the levitation process and to get practical experience with the fascinating piece of physics. In conclusion, a prototype high-T_c superconducting train model was developed and compared to normal train systems. For superconducting train model, a Maglev train and the magnetic rail (track) were constructed. The train models were constructed with FRP sheets forming a tank to maintain the temperature of liquid nitrogen (77 K). This enabled the use of the FC process to cool the superconductors above the magnetic track, which in turn provides very stable levitation characteristics. In the experiment of optimization of stability, speed, and safety, of the superconducting train, several gaps varying from 1 mm to 15 mm between the rail and train were tested out. Our experimental results clarify that small gaps cause the trains not to run properly because some friction to the track appears. Further, large gaps of 10 to 15 mm did not enable the trains to run on the track with the required stability. The best gap to fulfill all demands was determined to be 5 mm. The present results clearly demonstrate that the stability of the superconducting trains depends on the gap between the rail and train, which will be very useful for construction of real applications.

Instructional Issues

The present levitation train model was built as a science fair project by an advanced student. This shows that the basic construction is simple. The most care is required when placing the magnet pieces onto the iron plate to build up the magnetic rail. This step is for itself an important experience as the correct orientation of the magnets must be determined in a simple manner. The superconductor must be bought at a specialized company, because it is not possible to obtain materials with the required quality in an own attempt like it was possible using simple sintered superconductors. The use and the handling of liquid nitrogen in a classroom requires to take care and the proper safety measures. Therefore, it is the best approach to demonstrate the operation first, and then students can be allowed to perform their own experiments with the levitation train. The determination of the stability performance helps to teach the students all the aspects of superconductivity like the concept of field-cooling and the principle of the superconducting vortices.

A similar Maglev model now serves at Saarland University (Federal Ministry of Education and Research, 2014) for demonstration purposes, but also as a hands-on experiment in our school student's training courses. The experiments with the levitation train model proved already several times to be very attractive for the attending pupils as well as their teachers.

Conclusions

In summary, we have presented a construction of a simple superconducting levitation train model. While we are using the now commonly applied type of a magnetic rail, we introduce the field-cooling process employing bulk superconductors. Using this process, it becomes possible to perform a study of the parameters important for the performance, i.e., the levitation height and the stability of operation. In this way, we obtain an useful demonstration experiment, which may serve in a hands-on practical course.

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