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Train model levitated on the wall at John von Neumann University in Kecskemet

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Abstract
Using a single magnet row and the ZFC and FC cooling methods, we managed to achieve stable levitation on a vertical wall at 2-3 mm from the wall. In our experiment, we applied a Type-II high-temperature superconductor cooled with liquid nitrogen. The applied superconductor was yttrium barium copper oxide (YBCO) bulk. It was produced at the IPHT Institute in Germany in 2005. The YBCO bulk material, manufactured 21 years ago, has maintained its original geometric and superconducting parameters regarding trapped flux in the material.
The experimental device—which differs from conventional configurations—functioned stably. The superconductor did not fall off the surface, even as it warmed up. The combined ZFC/FC approach applied by us was a unique solution.
In this paper, we present the classic Japanese model compared with our solution. We also present our results of the exchange of bulk YBCO components for superconducting tapes.
Finally, an example is presented: we created a superconducting block of 24 individual tapes, each of 40 mm long and 12 mm wide, for magnetic flux trapping.

1 Introduction

Magnetic levitation above a high-temperature superconductor is a well-known physical phenomenon. In the case of HTS (high-temperature superconductors), two procedures can be applied to prepare the superconducting state in a bulk material. The sample can be cooled in zero magnetic field (this is the ZFC state preparation) or in a magnetic field (this is the FC state preparation). The macroscopic superconducting parameters depend on the preparation procedure, e.g., magnetization and critical current. Vortex lines—a characteristic feature of type-II superconductors—and flux pinning result in fundamentally different physical states and magnetic behaviours depending on the preparation procedure.

In the following, we will briefly describe these magnetization processes and, using diagrams and photographs, explain the physics behind the small train as it travels while levitating along a wall—including why it does not fall off the wall even after the bulk superconductor warms up above its critical temperature.

In our previous work at our university, we developed a levitating train that works with a single row of magnets—a design that differs from the classic Japanese model. The classic Japanese model contains 3 rows of magnets for levitation. Its magnetic field ensures that the magnetic flux is trapped in the pinning centres in the superconducting bulk. This is exclusively achieved by Field-Cooled (FC) preparation (cooling), facilitated by the three rows of magnets. This represents the conventional approach.

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In the case of a single row of magnets (in our solution), an extra magnetic field needs to be applied.

The experiments show that this arrangement works stably.

Besides, a new version of the arrangement was also created. We produced an advanced solution by applying a superconducting block of YBCO tapes. In this version, we applied 11 short pieces of superconducting tapes as a layered superconducting block. The thickness of the superconducting tapes was 0.2 mm. In the superconducting tapes, the thickness of the YBCO layer was 1.6 μm. The width of the applied tape was 12 mm.

2 Basic concepts of the trapped magnetic flux

Zero-field cooling (ZFC) and field cooling (FC) are two different methods for trapping magnetic flux in superconducting materials. By the two methods applied during cooling process can be prepared the material's behaviour in different ways.

2.1 ZFC – Cooling without magnetic field

In the ZFC process, the superconductor is cooled below its critical temperature in zero magnetic field. The external magnetic field is only switched on when the superconducting state is reached [1, 2]. This means that the material becomes superconducting, i.e., the material reaches the desired operating temperature when an external magnetic field is not present. After cooling, the material is superconducting, and it is in the Meissner state. If the external field exceeds a critical value, this is the lower critical magnetic field (H_{c1}), flux lines begin to penetrate into the material [1,2], and a mixed state starts to be formed. (*Figure 1*).

The superconducting state disappears above the higher critical magnetic field (H_{c2}).

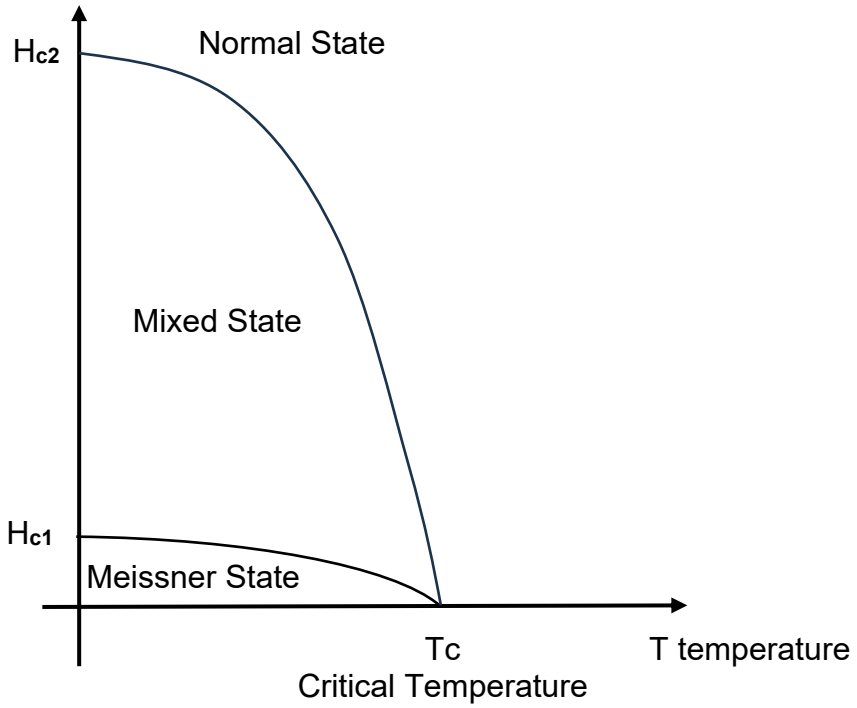

Figure 1. Temperature dependence of the lower and higher critical magnetic fields

2.2 FC – Cooling in a magnetic field

The superconducting material is cooled in a magnetic field. This field is continuously present during cooling [3, 4].

When the temperature is higher than the critical temperature, the sample is in normal state. If the sample is in normal state and it is exposed to an external magnetic field, then it is cooled below

its critical temperature in the external magnetic field; the sample is in the field-cooled state (FC) [3, 4]. This procedure is applied to create strong superconducting magnets ("bulk" magnets), flywheels, etc.

3 Background of the work, previous research projects

We performed several FC magnetization measurements for crack detection in superconducting samples. In Figure 2, based on data measured on a 38 x 38 x 8 mm block, we can check that the material is not cracked. A 3D plot of the experimental result is available. The measurements were carried out by a magnetic scanner. We designed the software specifically for this purpose. Our students developed both the device and software as part of a student research project.

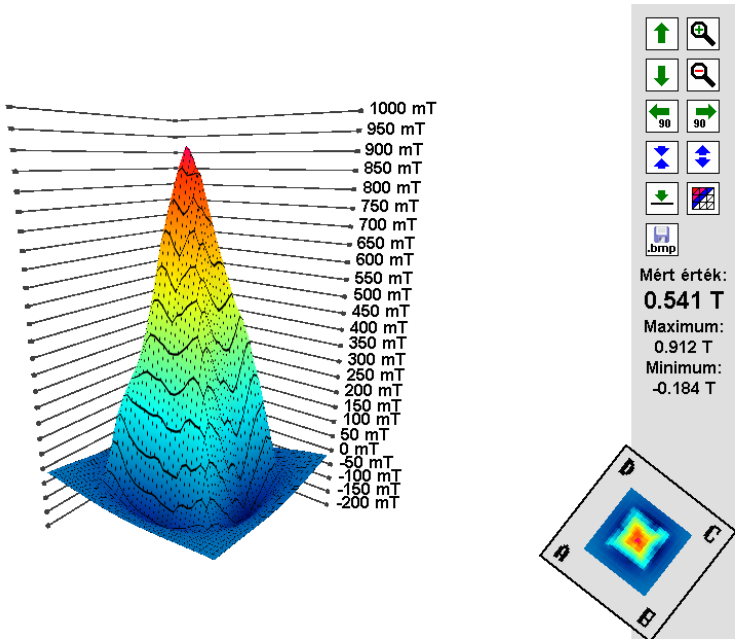

Figure 2. Magnetization measurement for crack detection

Figure 3 shows a faulty piece of superconducting material. The graph depicts a cross-section (dashed line) of a spatial measurement taken at an arbitrary location. The material (YBCO bulk) is cracked.

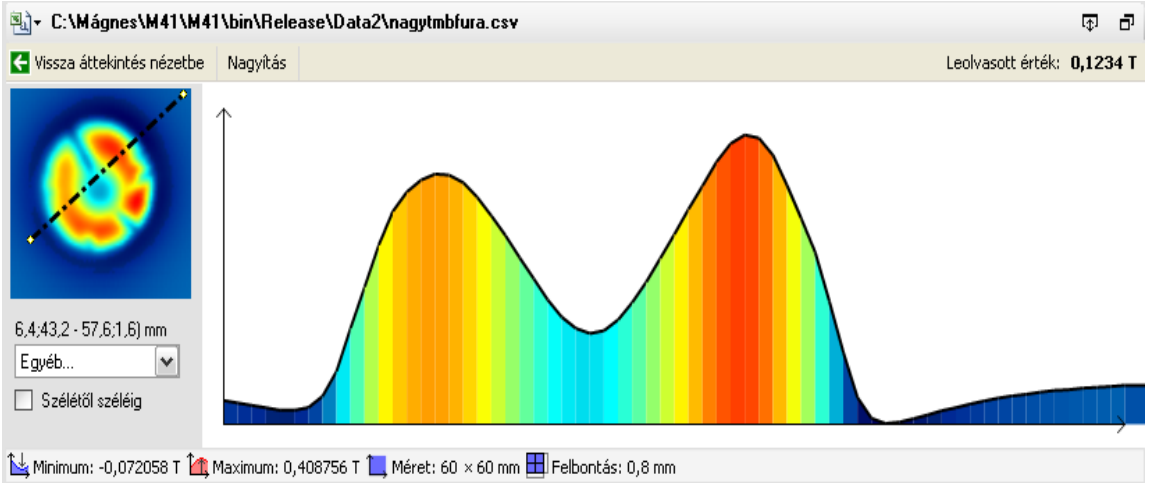

Figure 3. Magnetization for crack detection

Figure 4 shows a comparison of the spatial measurement results for a magnet and a magnetized superconductor.

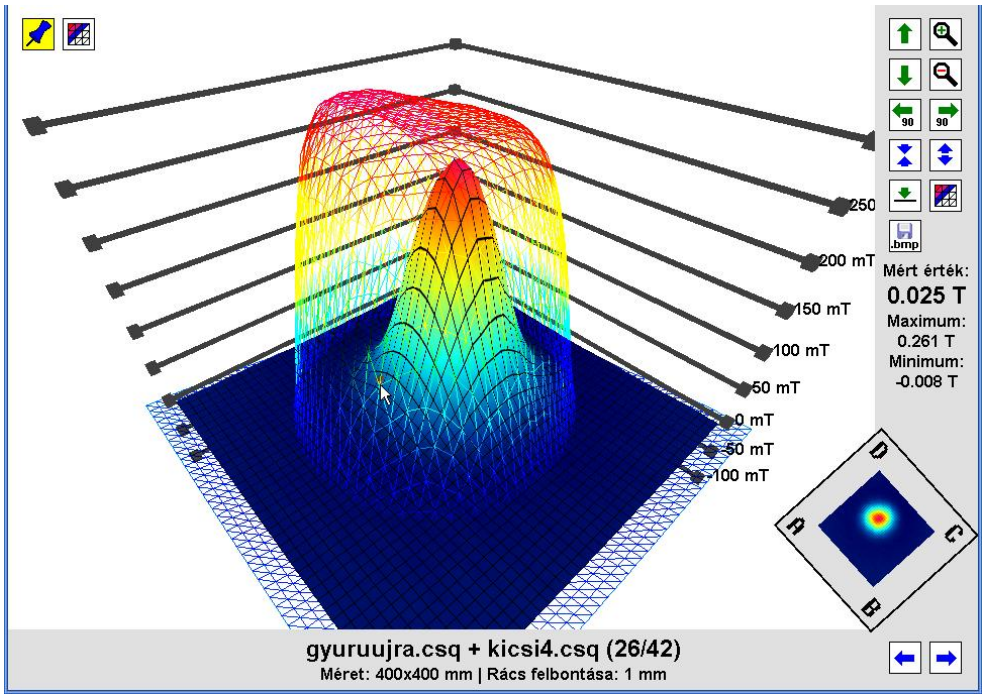

Figure 4. A magnet and a magnetized superconductor together

4 Arrangement of magnets regarding levitation train

4.1 Three-row magnet model (Conventional Japanese train model [5])

An arrangement of permanent magnets and a YBCO bulk is presented in Figure 5. The permanent magnets form a three-line track.

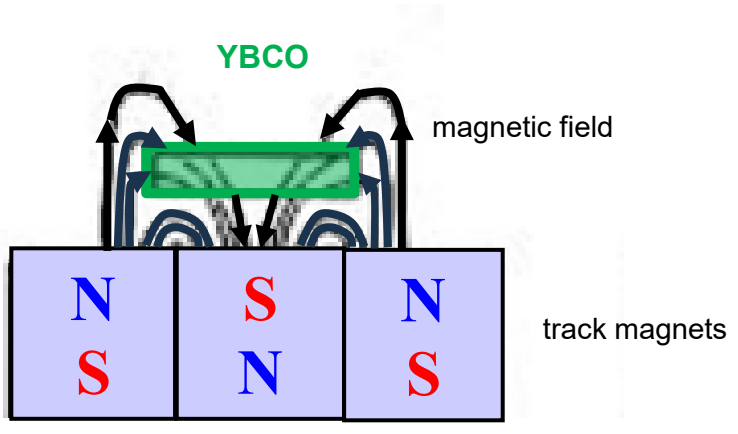

Figure 5. Conventional Japanese model and its magnetic field

The arrangement with the three-line magnets proved to be highly stable. In the case of FC, the magnetic field lines are anchored in the superconducting block, as shown in the diagram (Figure 5).

4.2 Single-row magnet model (Developed at John von Neumann University, Kecskemet)

Figure 6 shows a new solution which was developed at J. von N. University, where a permanent magnet is fixed to the superconducting bulk before cooling (FC).

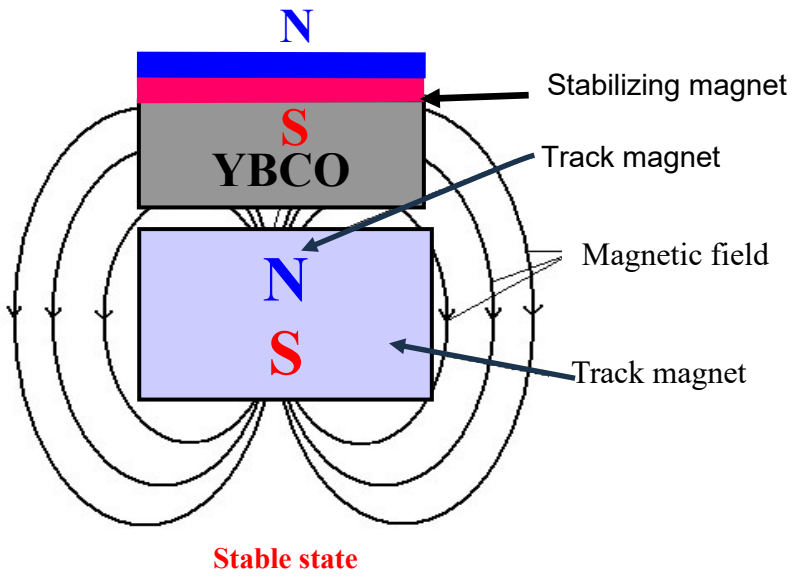

Figure 6. Single-row magnet model

While stability is ensured by the magnet, the levitation is ensured by the superconducting bulk. This development was our previous work. The stabilized state arises because the stabilizing magnet draws the magnetic field lines of the rail (track) into the pinning centres of the superconducting bulk. In the field-cooled (FC) mode, these magnetic field lines become fixed inside the superconductor. Figure 7 shows the model track with a simple railway relay. With this solution, the train can be switched between the tracks.



Figure 7. Prepared for FC cooling

Figure 8 presents the working principle of the railway relay in the top view.

N = North pole, S = South pole.

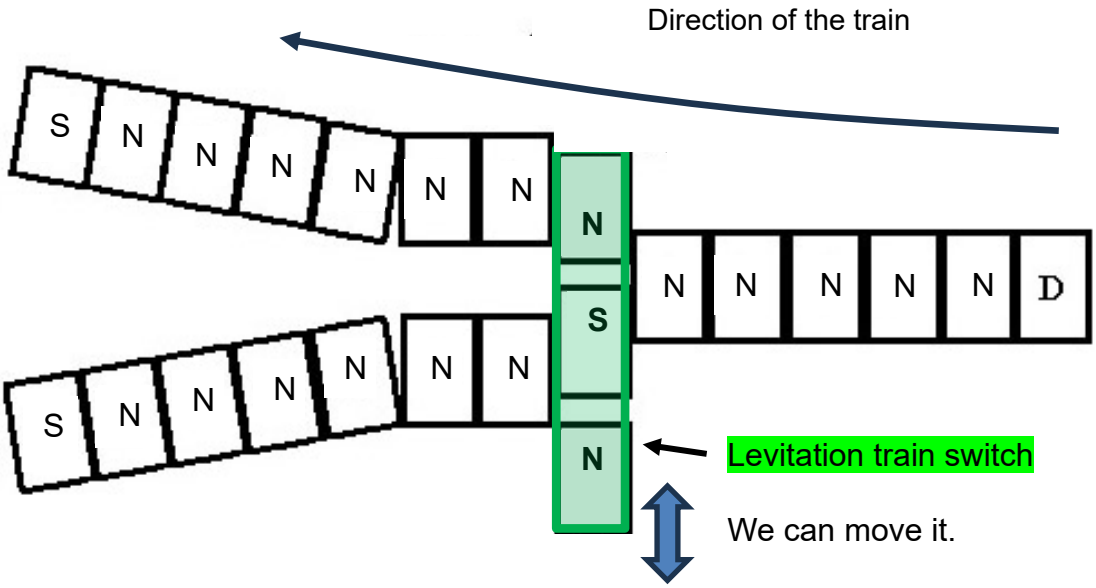

Figure 8. Train track using magnets

Figure 9 shows the magnetic flux density distribution on the surface. Both the software and magnetic field measurement were developed by our students. The computer program is written in C#.

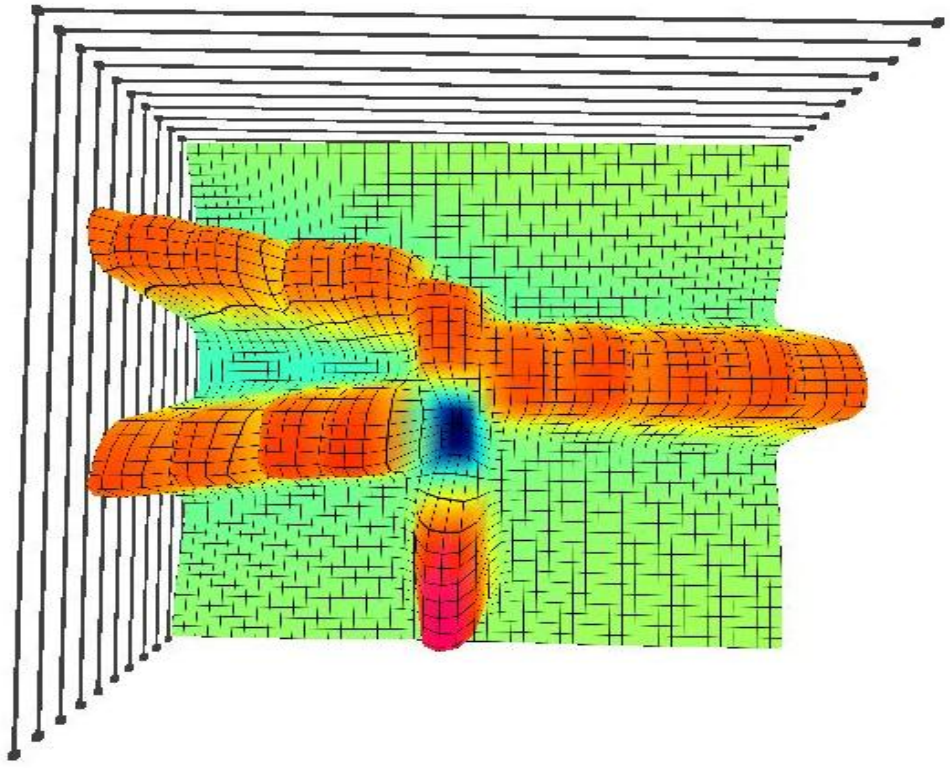

Figure 9. Magnetic flux density distribution on the train track surface.

5 Levitation train on the wall

We implemented our plan by combining FC and ZFC cooling. First, we applied the FC method. In the first step, during the determination of the geometrical position relative to the wall, we applied the flux-pinning characteristic of FC cooling within the superconducting material. In this way, the levitation on the wall could be stabilized (Figures 10, 11).



Figure 10. Side view



Figure 11. Top view

We made a superconducting block from superconducting tapes. It contained 24 pieces of superconducting tape, each 40 mm long and 12 mm wide. Figure 12 shows a levitating block of superconducting tapes. The levitated train is in Figure 13.



Figure 12. Block of tapes levitated under a magnet

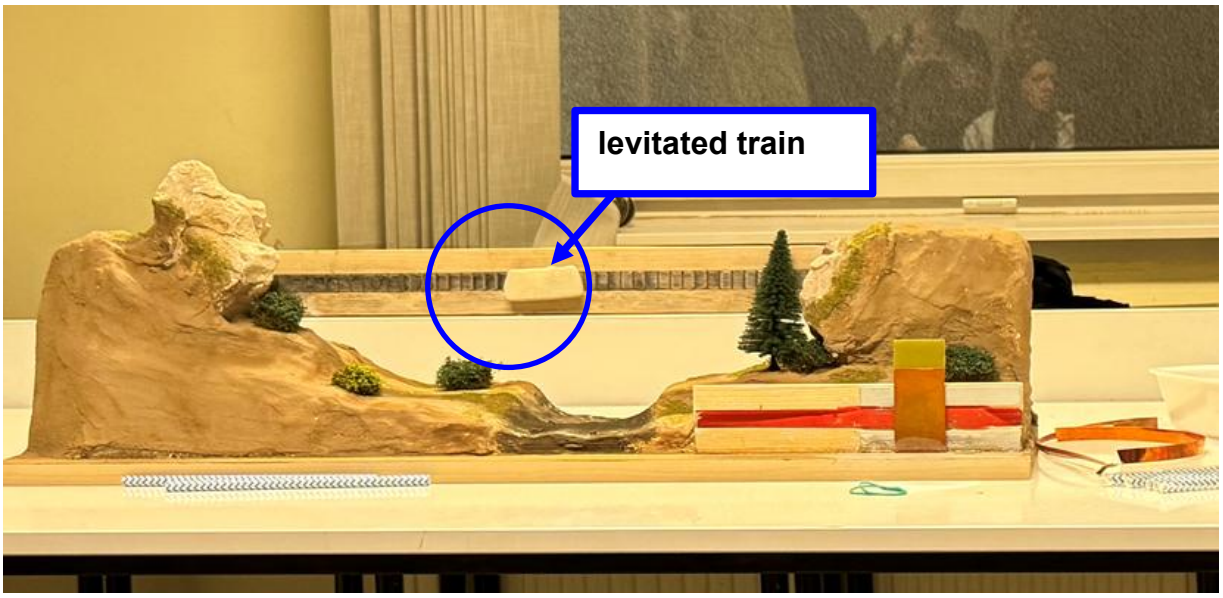

Figure 13. The model railroad layout was built by Laszlo Gocs

6 Summary

The paper describes a solution to produce a superconducting train model. By a combination of FC (field-cooled) and ZFC (zero-field-cooled) modes, stable levitation on a wall has been achieved. The apparatus, originally developed with a YBCO bulk sample, can also be implemented with superconducting tapes.

The tape-based approach offers a simpler implementation process.

Acknowledgment

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