A Classroom Demonstration of Levitation and Suspension of a Superconductor over a Magnetic Track

Charles P. Strehlow and M. C. Sullivan*
Department of Physics, Ithaca College, Ithaca NY 14850

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The suspension and levitation of superconductors by permanent magnets is one of the most fascinating consequences of superconductivity, and a wonderful instrument for generating interest in low temperature physics and electrodynamics. We present a novel classroom demonstration of the levitation/suspension of a superconductor over a magnetic track that maximizes levitation/suspension time, separation distance between the magnetic track and superconductor and also insulator aesthetics. The demonstration as described is both inexpensive and easy to construct.

I. INTRODUCTION

Observing first hand the phenomenon of stable suspension and levitation of type II superconductors over permanent magnets is an inspiring and thought provoking experience of great general interest.[1] In the 1930's Meissner first observed the expulsion of magnetic field lines from the bulk of Type I superconductors, which produced unstable levitations of magnets over flat superconductors [2]. To produce stable levitations, Meissner cooled a concave lead slab with liquid helium and placed a small permanent magnet over it.[3] The concavity of the lead slab allowed the magnet to stably levitate within the potential well.

Stable levitation is also possible with type II superconductors. Type II superconductors allow magnetic flux line penetration through their bulk when the applied field H is between $H_{c1} < H < H_{c2}$, where H_{c1} and H_{c2} are called the superconducting critical fields. The penetration of flux lines produces normal-conducting cores inside the flux vortices, and as the superconductor moves, the motion of the normal cores causes dissipation, providing a frictional force and leading to stability. Until the discovery of high-temperature superconductors by Bednorz and Müller in 1986, the phenomenon of stable levitation was reserved only for those working with liquid Helium. Today, with superconductor critical temperatures above 77 K, it has become possible to bring this experience into the classroom using liquid nitrogen.

High temperature superconductors can be used to demonstrate many different levitation phenomena. Magnets can be levitated over superconducting plates, or superconductors can be levitated over permanent magnets. When superconductors with high flux pinning capabilities are used, both levitation above permanent magnets and vertical suspension below magnets are possible. Ref. 3 provides a description of the pinning forces that create levitation and suspension, and Refs. 4 and 5 have detailed explanations provided within the context of intermediate electrodynamics. Much of the stability in this demonstration comes from placing a superconductor in a magnetic field gradient. If there is a strong magnetic field gradient in one direction and no gradient in the other dimension, you can create a magnetic track that both levitates and suspends - the principle behind a superconductively levitated "MagLev" train.[6] The demonstration begins with a superconductor levitating above a track, free to move back and forth along the track. You can then lift the track and turn it upside down, such that the superconductor is suspended below the track, yet still free to move back and forth along the track – but now below the track instead of above it.[7]

We present modifications to a magnetic track classroom demonstration first presented to us by Gregory S. Boebinger of Florida State University with design suggestions from Martin Simon of UCLA. Our rendition of the demonstration utilizes lightweight and sleek insulation materials to maximize the superconductor's levitation height and time (while maintaining an aesthetically pleasing appearance). This demonstration is inexpensive and easy to build.

II. DEMONSTRATION APPARATUS

The demonstration apparatus is a simple combination of a type II bulk superconductor, neodymium-iron-boron magnets and sheet steel. The superconductor used is a hexagonal $YBa_2Cu_3O_7$ (YBCO) bulk superconductor wrapped in insulation to prolong time spent below the superconducting phase transition. Sheet steel forms the base of the track with thinner sheets used for flux trapping shims underneath the track. The neodymium magnets are magnetized through their thickness and arranged on the track base to maximize the cross-sectional gradient of the track's magnetic field.

The aforementioned YBCO superconductor is a hexagonal bulk YBCO designed to enhance flux pinning. We bought our superconductor from SCI Engineered Materials Inc. ($125). It is roughly 3 cm in diameter, and weighs 19 grams. We have measured the maximum trapped field to be roughly 250 mT. Tests conducted with the uninsulated superconductor above our magnets produced levitations of 2.5 cm and levitation times between 7 and 15 seconds. On its own, this is a somewhat short and

TABLE I: Table of insulation materials, time below the superconducting transition temperature, and height above the track. This list represents only a subset of the materials we tested. The final design, three layers of tissues, mylar, and teflon tape, did not have the longest time below the critical temperature, but had the highest levitation height of the two-minute-plus levitation time designs.

Insulation	Levitation time (s)	Levitation height (cm)
Al foil and floral foam	249	0.762
Al foil and styrofoam	203	0.63
Layered tissues, mylar, and teflon tape (three layers)	118	1.8
Layered tissues, mylar, and teflon tape (two layers)	85	1.9
Packaging foam, mylar tissues, and teflon tape	45	0.89
uninsulated	13	2.0

unsatisfactory demonstration.

In order to increase time before the superconductor warms back up to the transition temperature, a multitude of insulation materials and combinations were investigated, a subset of which is listed in Table I. We decided to use a combination of 0.051 mm thick aluminized mylar, teflon tape and tissues (Kimwipes). We cut three geometrically similar patterns out of Mylar, each successive pattern slightly larger than the previous (to compensate for the inner layers). Then we wrapped the naked superconductor in a tissue followed by the smallest mylar pattern, and sealed it using the teflon tape. The pattern was repeated twice, with the final layer leaving silvery Mylar exposed to the viewer on the hexagonal faces. We also tied a long strand of fishing line around the superconductor, which provides a leash to lift the superconductor from the nitrogen to the track. Although our final design did not produce the longest levitation/suspension time, this insulation model is compact and lightweight, providing a large enough fraction of the naked superconductor's levitation height to still be impressive while increasing the levitation time by a factor of nine. The largest downfall of with this model is the time it takes to cool the superconductor from room temperature to liquid nitrogen temperatures, on the order of 20 to 25 minutes. Fig. 1 shows the insulated superconductor both levitating above and suspended below the magnetic track.

The base of the track is a 305 mm × 610 mm × 7.6 mm sheet of 410 grade stainless steel ($50). Type 410 steel is magnetic, easy to work, and relatively inexpensive. We bent the sheet into a U-shape to serve as a stand, as shown in Fig. 2(a). We also purchased 0.31 mm thick shim stock of types 410 and 430. The shims are attached on the underside of the base directly under the magnets and should be wide and long enough to cover the entire

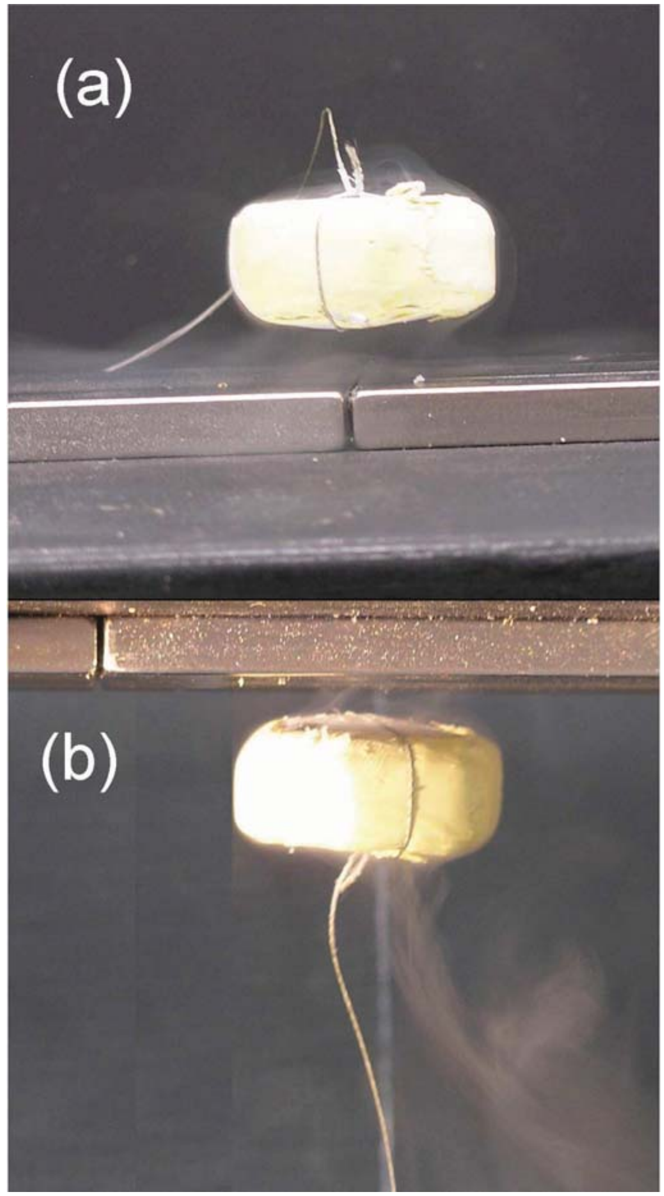

FIG. 1: (Color online) Photographs of the insulated superconductor and the magnetic track. Inset (a) shows the superconductor levitating above the track, inset (b) shows the superconductor suspended below the track. The string tied to the superconductor is to make it easy to take it in and out of liquid nitrogen. Note the cold air falls down in both pictures.

area of the track. The shims capture and direct the magnetic field existing on the underside of the track. The shims also help to bind the track together and overcome repulsion between track sections due to fringing fields. To build the track, we used Nd-Fe-B ceramic permanent magnets, grade N42 ($4 each). The magnets are 76 mm × 13 mm × 6.4 mm and magnetized through their thickness. The magnets are aligned along the track three wide and seven long, in the following fashion:
S - N - S

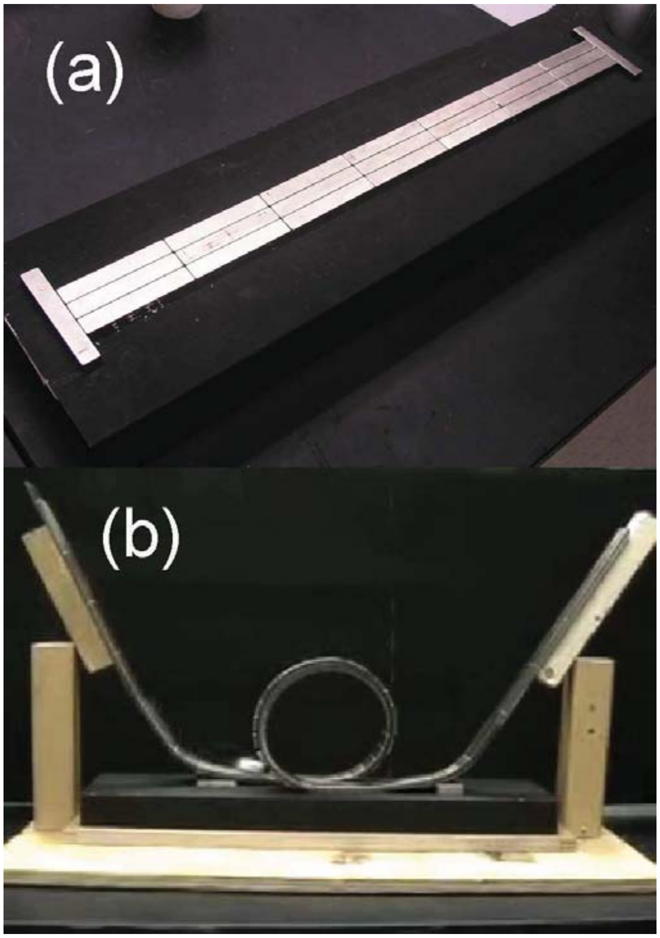

FIG. 2: (Color online) Pictures of magnetic tracks. Inset (a) shows the simplest demonstration track. The magnets are magnetized through the thickness, and are aligned S-N-S. The brakes at the end are aligned with N up. The track is 410 grade steel with thinner shims underneath the track. Inset (b) shows a roller-coaster track that can demonstrate levitation and suspension simultaneously as the superconductor goes through the loop. The superconductor is in motion at the bottom of the loop.

S - N - S
S - N - S
This schematic is shown in Fig. 3. This arrangement of polarities produces a magnetic field gradient in the x-direction above the track and acts to confine the superconductor in the x while allowing motion in the y-direction. At each end of the track there is one magnet placed perpendicular to the others whose polarity is parallel to the innermost magnet. These magnets act as brakes for the track and reflect the superconductor with no energy loss.

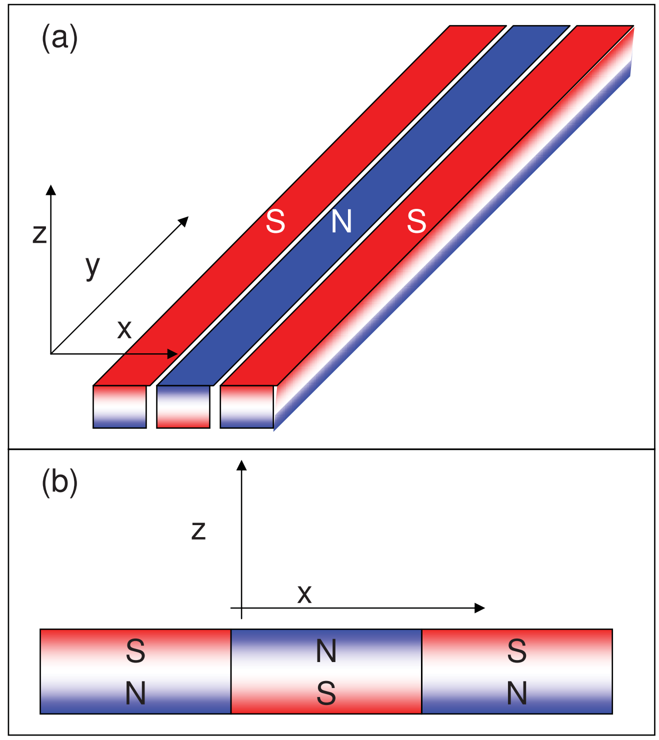

FIG. 3: (Color online) A schematic of the magnetic track. Inset (a) shows the magnets magnetized through their thicknesses and oriented S-N-S on the track. This produces a large gradient in the x-direction to confine the superconductor while allowing free motion in the y-direction. Inset (b) shows a cross-section of the track.

III. THEORY

The theoretical phenomenon that this demonstration is centered around is known as the Meissner effect; or the expulsion of magnetic flux by superconductors.[2] A superconductor will expel magnetic flux by creating a magnetic field in the opposite direction as the external field, in this way becoming a perfect diamagnet. This diamagnetism provides a force of repulsion, and the superconductor levitates above the source of the external field. Most any diamagnetic or ferromagnetic material can levitate in an external magnetic field, although the levitation is an unstable equilibrium except in certain configurations, such as a magnet levitating above a concave lead bowl,[3] or by other more complicated arrangements.[8]

Type I superconductors such as lead, tin, and mercury act as diamagnets, and expel all magnetic flux from their bulk and create maximum repulsion. Type II superconductors, such as Nb_3Sn or the more recently discovered high-temperature superconductors (like YBCO), on the other hand allow certain amounts of flux to penetrate through their bulk. These flux lines penetrate the superconductor and have a circulating supercurrent around a normal core: this entire collection is called a vortex. In

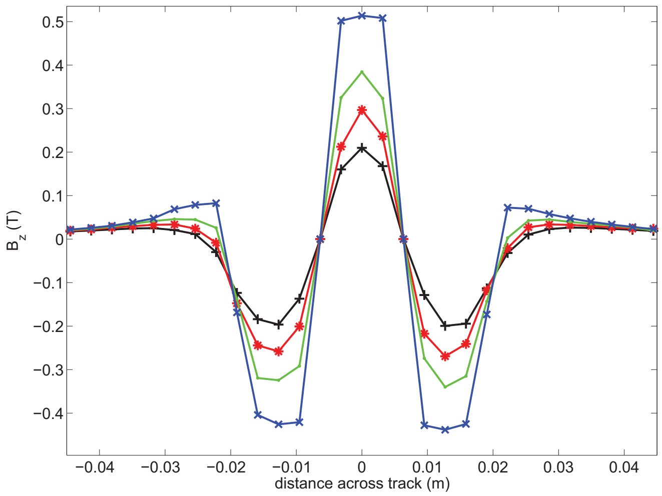

FIG. 4: (Color online) The z-component of the magnetic field above the track at various heights: blue x, 3.2 mm above; green dot, 6.4 mm above, red star, 9.5 mm above, and black cross, 12.7 mm above. Even 12.7 mm above the track, the gradient is still very strong.

general, these vortices are free to move in the superconductor, and moving the normal cores creates dissipation in these materials. In practice, grain boundaries or impurities often trap the vortices in one place, "pinning" them to one spot in the superconductor. This keeps them from moving and allows dissipation-free current flow in type II superconductors. This flux pinning can be enhanced by growing the superconductor with additional impurities. Regular type II flux line pinning produces a frictional force that provides drag as vortices move from one pinning site to another, and creates stable levitations. Enhanced flux line pinning is so strong that both levitations as well as inverted suspensions are possible.[9]

The final crucial aspect of this demonstration is the design of the track. Along the length of the track, in the y-direction, there is no variance in the field, which allows the superconductor to move back and fourth with no energy loss. Perpendicular to the length of the track, the bar magnet's poles are aligned anti-parallel to each other, (S-N-S). This alignment produces a considerably strong gradient in the x-direction, as shown in Fig. 4. The variance of magnetic field strength from one side of the track to the other is so great and the pinning so strong in this superconductor that there is not only drag but also a restoring force. If the superconductor is given a small push in attempt to force it from the track, it will oscillate slightly and quickly return to its original position.

IV. CONCLUSIONS AND FUTURE WORK

We have constructed a demonstration that illustrates simultaneously levitation and suspension of superconductors above or below a magnet as well as the principles behind magnetically-levitated trains. The simplicity of this demonstration also provides the researcher with a wealth of possible project refinements and new project opportunities.

The gaps between the magnets along the length of the track create small magnetic gradients and also create drag and reduce the speed of the superconductor as it moves along the track. By measuring the energy loss, a quantitative value for that drag could be obtained. Another possible area of interest is to measure the magnetic force between the superconductor and the track.[10]

The insulation for the superconductor is the most flexible aspect of the demo, having only the constraints of weight and size. The extent of the insulation investigation done for our project was limited by our budget and the arts and crafts stores in our town. Students may expand their search and find other insulation models that work better than our final design – though some suggested insulation materials (such as aerogels) may remain outside of most budgets. Another insulation option is a container that has a liquid nitrogen reservoir that can keep the superconductor cold for much longer times – the drawback of this system is that it is very difficult to invert.

Another area of expansion is in the track design. Although a straight track is by far the most simple demonstration to build, you can build circular tracks [6] or other more exotic designs. Based on student suggestions, we have built a superconducting roller-coaster: an inclined plane leading into a vertical loop as a way of demonstrating the energy conservation properties of the demonstration, as shown in Fig. 2(b). Other possibilities include a hanging roller-coaster or a helical track.

V. ACKNOWLEDGEMENTS

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* Electronic address: mcsullivan@ithaca.edu

[1] As an example, the popular website `wikipedia.org` contains a listing for "physics." As of this writing, the picture posted on that site is a magnet levitating above a superconductor.

[2] M. Tinkham, *Introduction to Superconductivity*, 2nd ed., (Dover, Mineola New York, 1996).

[3] E. H. Brandt, "Rigid levitation and suspension of high-temperature superconductors by magnets," Am. J. Phys. **58**, 43 (1990).

[4] A. Badia-Majos, "Understanding stable levitation of superconductors from intermediate electromagnetics," Am. J. Phys. **74**, 1136 (2006).

[5] A. A. Kordyuk, "Magnetic levitation for hard superconductors." J. Appl. Phys. **83**, 610 (1998).

[6] W M Yang, L. Zhou, Feng Yong, P.X. Zhang, X.X. Chao, X. B. Bian, S.H. Zhu, X. L. Wu and P. Liu, "A small Maglev car model using YBCO bulk superconductors," Supercond. Sci. Technol. **19**, 537 (2006), and a quick internet search will reveal several short videos of other superconductively levitated model trains.

[7] Videos of the demonstration can be seen at `http://www.ithaca.edu/hs/depts/physics/facstaff/mcsullivan`.

[8] M. D. Simon, L.O. Heflinger, and A.K. Geim, "Diamagnetically stabilized magnet levitation," Am. J. Phys. **69**, 702 (2001.)

[9] For a more complete discussion of this phenomenon, see Refs. 2, 3, or 4

[10] S. O. Valenzuela, G. A. Jorge, and E.Rodriguez, "Measuring the interaction force between a high temperature superconductor and a permanent magnet," Am. J. Phys. **67**, 1001 (1999).