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A Train Without Wheels: Magnetic Levitation Using High-Temperature Superconductors

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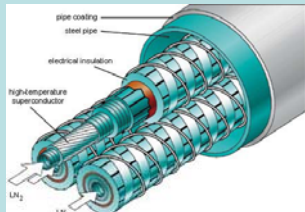


What is a Superconductor?

A superconductor is a material which conduct an electric current without resistance. Superconductivity is observed in a variety of materials such as tin, aluminum, metallic alloys, and even some ceramics. A common property of superconductors, is that the zero resistance state only occur below their so-called critical temperature which varies for different materials. In a properly cooled loop of superconducting material, a current can flow indefinitely.

Practical applications of superconductors have become more common as progress has been made in discovering materials with increased critical temperature and thereby reducing the cost of cooling. Currently, the highest known critical temperature is 138 K (-211 F).

Superconductors can be used to make extremely effective electromagnets, which are commonly used in equipment such as MRI scanners, NMR machines, and mass spectrometers. They are also used to guide the beams in particle accelerators such as the Large Hadron Collider at CERN.



Loss free energy transport in superconducting cable (physicsweb.org).



36.5 MW ship propulsion motor manufactured by American Superconductor.

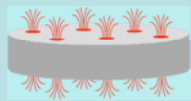
Superconducting Vortices

In addition to their remarkable electric properties, superconductors also behave in a curious fashion when they are exposed to a magnetic field. If the magnetic field is weak it is completely expelled from the superconductor which is known as the Meissner-Ochsenfeld effect.

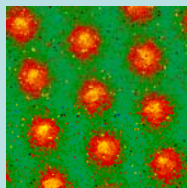
At higher fields the superconductor is unable to expel it, and in stead vortices (or electric tornadoes) appear. The magnetic field is funneled through the vortices, which are surrounded by superconducting electric currents. The vortices each carry one quantum of magnetic flux ($h/2e$) and therefore a change of the field will cause the vortex density to increase or decrease.



Depending on the quality of the superconductor the vortices may either be free to move (clean samples) or they may be strongly pinned to defects (dirty samples). In the latter case the vortices will oppose any attempt to change the magnetic field since it would require them to move in or out of the superconductor.



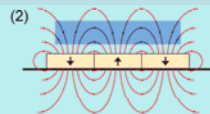
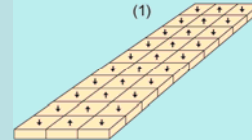
Magnetic field lines confined to vortices as they pass through a superconductor.



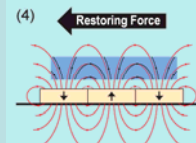
Vortices emerging at the surface of a superconductor, imaged by Scanning Tunneling Spectroscopy.

How Does Levitation Work?

Our magnetic levitation demonstration consists of two parts: A magnetic track and YBCO superconductors with a critical temperature of 93 K (-292 F) cooled by liquid nitrogen. The track (1) is made up of several hundred individual magnets organized in three parallel rows, oriented such that the magnetic field is directed up at the center and down at the edges.



A slight displacement of the superconductor will now lead to a mismatch of the magnetic field and the "frozen in" vortices, and give rise to a restoring force which seeks to realign the two (4). The restoring force acts both perpendicular to the track as well as in the vertical direction. Only along the direction of the track is the magnetic field uniform (1) and the superconductor is free to move.



When the superconductors is cooled below the critical temperature in the presence of the track's magnetic field (red lines), vortices are nucleated in the YBCO (2). Due to the large degree of imperfections in the YBCO material the vortices are strongly pinned, creating a stable imprint of the magnetic field (black lines) at the time of cooling (3).

A slight displacement of the superconductor will now lead to a mismatch of the magnetic field and

History of Superconductivity

The history of superconductivity is rich in discoveries, both of new phenomena, new superconducting materials and breakthroughs in our understanding of the fundamental physics behind it all. Many of these discoveries have earned Nobel prizes. The figure shows a timeline of the history of superconductivity.

Superconductivity was discovered in 1911 by Heike Kamerlingh-Onnes who used liquid helium to cool mercury to 4.19 K (-452° F) and observed a total loss of electrical resistance. In 1912 he showed that a current running in a superconductor does not diminish over time. For his discoveries, Kamerlingh-Onnes was awarded the 1913 Noble Prize in Physics.

In 1933 Walter Meissner and Robert Ochsenfeld found that superconducting materials expelled magnetic fields. Together with zero resistance, this Perfect diamagnetism constitutes the two hallmark properties of a superconductor.

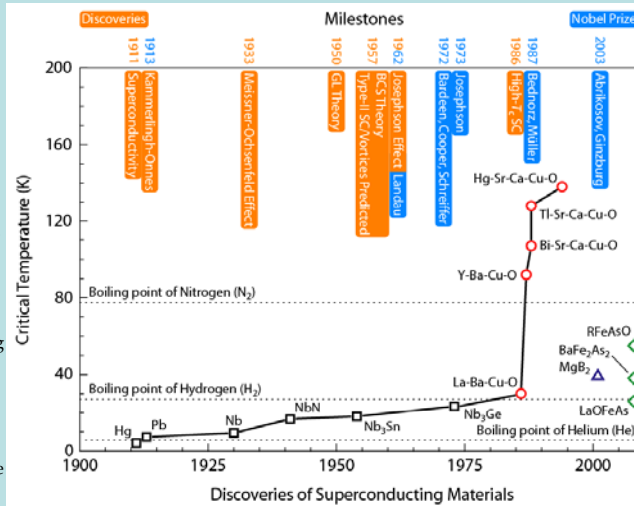
The 1950-ies saw the emergence of the two most successful theoretical models

of superconductivity: The phenomenological Ginzburg-Landau (GL) theory and the microscopic Bardeen-Cooper-Schrieffer (BCS) model. Furthermore, in

1957, Alexei Abrikosov predicted the existence of a second (type-II) class of superconductors and the formation of magnetic vortices in such materials.

In 1986 Johannes Bednorz and K. Alex Müller discovered the first ceramic, high temperature superconductor, with transition temperatures which soon exceeded the boiling point of liquid Nitrogen at 77 K (-321 F). In recent years superconductivity have been found in MgB₂ as well as the iron-arsenic pnictides.

Current research includes both studies of the fundamental properties of superconductors as well as the potential for practical applications. At Notre Dame several groups are involved in such research, including the synthesis of novel superconducting materials, studies of the properties of exotic superconductors and their vortices, and the applications in e.g. single-photon sensors.



Real Levitating Trains

Magnetic levitation (maglev) trains are in use in several places throughout the world. The first levitating passenger train operated in Hamburg, Germany in 1979, although only permanent magnets were used. While wide-spread use is still uncommon, there are plans for levitating trains in place in many countries.

By using superconductors, levitating trains at test tracks in Japan have been able to reach a speed of 360 mph.



Manned MLX01-901 train at the Yamanashi Maglev Test Line in Japan. This train have reached a speed of 360 mph and sustained a two-train crossing test at a relative speed of 637 mph.

Picture from the Railway Technical Research Institute, Japan.

Acknowledgment

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