Superconductors 101

Facts, demos, tips and tricks

The basics

Superconductors are materials that have no electrical resistance, so you can pass an electric current through them with no loss of energy and no heating.

Superconductors need to be cold in order to superconduct. The ones we use for the demos need to be cooled with liquid nitrogen. Superconductors have a 'critical temperature' that depends on the material of the superconductor

Superconductors are not really magnets. If you pass a current through a superconductor, it will produce a magnetic field – in the same way that if you pass a current through a wire it will produce a magnetic field. But in the same way you wouldn't normally describe a wire as a magnet, you wouldn't normally describe a superconductor as a magnet. However, a superconductor can produce a magnetic field if you induce a current in it using a magnetic field.

For more info, see this 5 min video https://www.youtube.com/watch?v=RFFx7R7r7J4 or see 'What's going on' sections below.

The demos

There are two different effects that you can demonstrate: the Meissner effect and flux pinning (aka 'quantum locking').

The usual kit

- Superconductor
    - Might be called a "puck" because of the shape – usually cylindrical, about an inch across and a few mm tall.
    - The ones we have are either YBCO (said "Y B C O") – yttrium barium copper oxide – or GdBCO (gadolinium barium copper oxide) – or BSSCO (said "bis-co") – bismuth strontium calcium copper oxide. The large dense pucks are YBCO.
- Liquid nitrogen
    - Usually in a bucket
- Oxygen monitor
- Gloves
    - Enough for the presenter and for both hands of anyone who might be helping

- Goggles
    - For the presenter and any helpers
    - Also supposed to have a face shield if pouring nitrogen from one container to another
- Magnets
    - This could be the long track (on a table) or a short track (which can be hand-held)
    - The magnets are made from neodymium, iron and boron. They are more than 10 times stronger than a typical fridge magnet.
    - Sometimes useful to have a spare bar magnet too, to show the orientation of the magnets on the track
- Pyrex jug
    - Easy to scoop nitrogen out of the big white bucket with this
    - Also easy to pour nitrogen
    - Also looks impressive
    - Alternative: large plastic ladle
- Ladle for pucks
    - This is a 3D printed device that is like a ladle. You can use it to cool the pucks down in the nitrogen and easily scoop them out.
- Superconductor in a pot
    - This is for flux pinning / train demo
- Spacers
    - Also for flux pinning / train demo

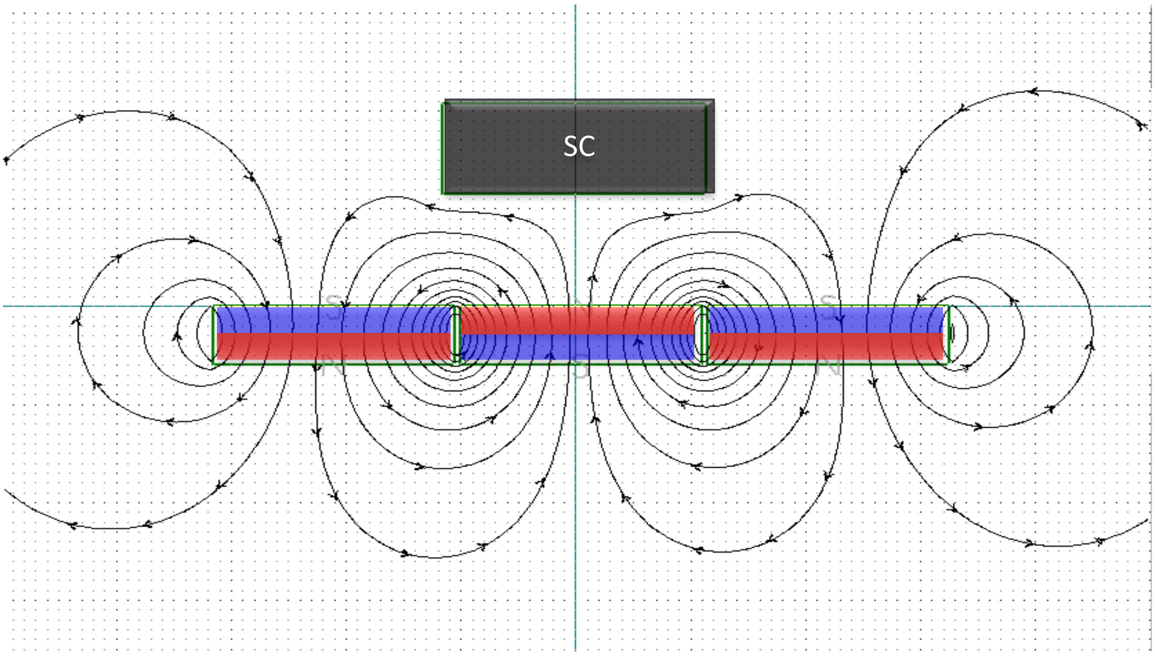
The Meissner effect

How to

1. Take a jug of nitrogen
2. Put your puck in the ladle and put the ladle in the nitrogen to cool. The superconductor will take a while to be cold enough, so be patient. You can tell when its pretty much done because the nitrogen will no longer be boiling (i.e. showing bubbles) on the surface of the superconductor.
3. Use the ladle to move the superconductor out of the nitrogen and over the top of the magnets. The superconductor will float a couple of cm above the magnets.
4. Once the superconductor warms up (maybe 30s, depending on conditions) it will drop onto the magnets. You need to cool it again to show the effect again.
5. It doesn't take much for it to fall off sideways, so take care if holding the magnets.

What's going on?

The superconductor does not want to have external magnetic field lines (i.e. the field from the permanent magnet) going through it – this is a property of superconductors. So to keep the external magnetic field outside, it generates its own magnetic field to perfectly match the field it sees. If you put the superconductor near a north pole, it will produce its own north pole, which will repel the magnet, keeping the superconductor away from the magnet and thereby making it float. In this way, superconductors are sometimes described as “magnetic mirrors”. It can be thought of as sitting in an



armchair of magnetic field lines (or flux). It will sit fairly happily in the middle, but doesn’t take much to go over the arm of the chair and end up on the floor.

Flux pinning

How to – the easy way

1. Place two spacers on top of the track of magnets and put the superconductor in a pot on top of them
2. Pour nitrogen into the pot to cool it. You will have to keep topping it up bit by bit until you can see that the nitrogen sitting on top of the superconductor is no longer boiling.
3. Put the lid on for extra insulation if you like, ideally while there’s a bit of nitrogen in there to cool it.
4. Remove the spacers from under the pot. You can do this with tweezers or the top of one of the ladles works too. Remember everything is cold though so don’t use fingers.
5. The pot will now be floating above the track. It will move back and forth along the track, but will be hard to push off sideways. If you’re using a shorter track, you can pick the track up and hold it sideways or upside down, but beware that it is going to slide along the track unless you keep it level. It isn’t a problem, but something to be careful of. Best to keep a hand underneath in case the superconductor warms up and drops off, though this takes a while (maybe a minute?) with the superconductor in a pot.

How to – the trickier way – small track only

1. Cool a superconductor in nitrogen using the jug and ladle as before. Make sure it is really definitely cold.
2. In one deft movement (!), take the superconductor out of the nitrogen, hover it over the magnets and press it down towards the magnets.
    a. You want to touch it as little as possible, as you want it to stay as cold as possible
    b. One trick is to hold the bar of magnets across the palm of your hand, with your thumb on top. When you take the superconductor out of the nitrogen, use the ladle to put it under your thumb, and use your thumb to press it down onto the track
3. You should then be able to turn the track sideways and upside down, but be careful as the superconductor will quickly warm up and fall off, so be ready to catch it

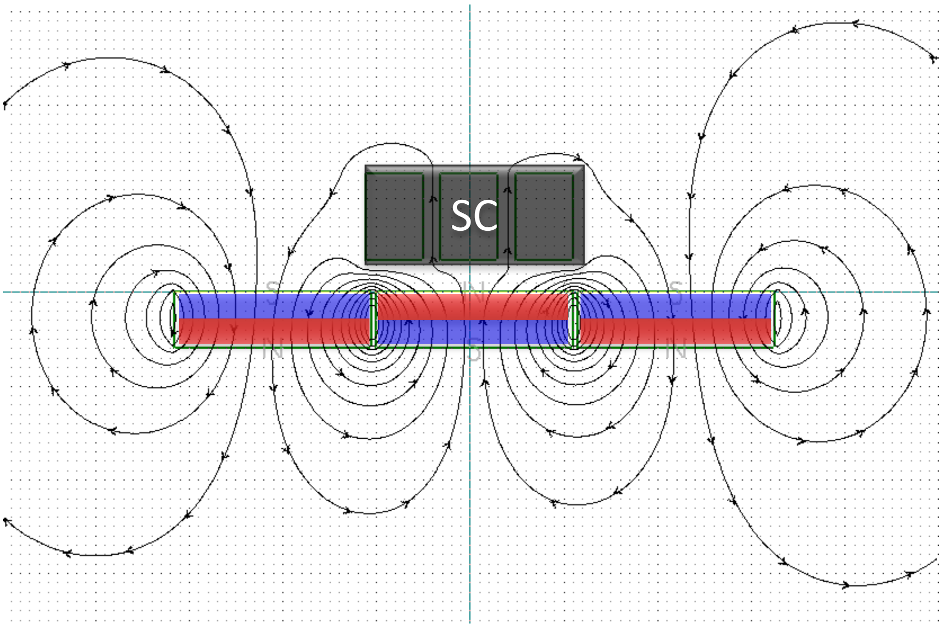
What's going on – the easy way

When the superconductor is warm, it isn't really a superconductor – or at least, it isn't superconducting yet. This means it has no problem being in a magnetic field, and the field lines pass straight through it. As you cool it, the field lines stay there and the superconductor stays there. In fact, the field lines will find little imperfections in the superconductor and will go through those. The magnetic field is then "pinned" or "locked" in place. The superconductor will not tolerate a change in field. This means the superconductor will happily travel along the track, as the field is the same all along the track. However it will not move sideways off the track, or nearer to or further from the track, as all of these would involve a change of field. This is why you can tip it upside down.

What's going on – the trickier way

When you first hover the superconductor above the magnets, this is the same as the Meissner effect above, and the superconductor is expelling all of the external field (assuming it is an ideal superconductor – in fact you will probably see a little bit of pinning). However, you then force the superconductor closer to the magnets, which means you are forcing it into a higher magnetic field. It can no longer keep all of this field out, so the field finds a way through the superconductor – it will find the imperfections and the field lines (flux) will go through those. The superconductor will then be pinned in place in the magnetic field, and will behave as though you had cooled it down in that field, as explored above.

The complete (Meissner) flux exclusion only works up to a threshold flux density called the lower critical field, B_{c1}. For YBCO, B_{c1} is around 0.01 to 0.1 Tesla. If you apply $B > B_{c1}$ then magnetic flux can penetrate in the form of narrow threads called flux lines or fluxoids. When we do this demo we are probably creating fluxoids, which are pinned inside the superconductor and prevent lateral motion.



Other things to remember

- Dry the superconductors before you put them away or they will degrade
- Look out for little droplets of nitrogen skittering around on the table top when you pour the nitrogen – this is the Leidenfrost effect
- Safety is important
    - Anything that has had nitrogen in or poured on may be cold, even if it doesn't look it
    - Use an oxygen monitor
        - If you have the oxygen monitor on the same surface as you are pouring nitrogen, it is likely to go off. Put it somewhere sensible but on a different surface.
    - Wear gloves and goggles and closed-toe shoes and make sure any helpers or volunteers do the same
    - Don't let people stand too near or put their hands on the table with the nitrogen on in case you spill some
    - The Nd-Fe-B magnets are very strong, and can affect card readers, wrist watches etc. so keep those things away from the magnets. Also, if you bring two of the magnets near to one another they can fly together very quickly, so watch your fingers!
- The superconductors are brittle so try not to drop them