MAGNETIZATION CURVES OF SUPERCONDUCTORS--TYPE I, TYPE II AND TYPE III

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The building of superconducting accelerators has become an extremely intricate and increasingly complex technology. Though I am almost totally ignorant about accelerators, let me, nevertheless, try to show where and when I think the use of superconductivity may be an ideal technique and compare this to other arrangements where the use of superconductors may eventually precipitate disaster.

A perfect superconductor has two distinct features, one electric in nature while the other is magnetic. The first involves the total disappearance of any electric resistance in the material for dc currents below certain critical values. The second, the magnetic feature, is the Meissner effect which is the total expulsion of any magnetic field below a certain critical field strength. In other words, the superconducting metal behaves like a perfect diamagnet.

The Meissner effect was discovered 22 years after the first detection of the infinite conductivity by Kamerlingh Onnes. This delay was due, in part, to the fact that infinite conductivity does not require a priori a complete diamagnetism whereas the inverse is true, since complete diamagnetism does require infinite electric conductance. And, as a consequence of this infinite electric conductance, the Meissner effect can be measured only with static fields or dc fields. From an experimental point of view, this is by far more difficult than the electric measurements of conductivity, and yet, there is just no substitute for it. Also, from a materials standpoint, the problems of obtaining a 100% Meissner effect in a metal are almost insurmountable while the infinite conductance can easily be achieved and measured by any graduate student. Part of the difficulty in the measurement of the Meissner effect lies in the requirement that one has to have a singly connected body in order to obtain total flux expulsion. In principle, this means that a perfect single crystal is necessary, without faults, voids or holes. Therefore, the Meissner effect is hardly ever measured and yet is always assumed to be a 100%--as if the metal were perfect from a crystallographic point of view. Unfortunately, this is a situation that never exists. For applications of superconductivity in a static electric or magnetic field, these distinctions are entirely unimportant and it does not matter if the material shows no Meissner effect whatsoever--a condition too easily achieved through poor metallurgy.

In an alternating magnetic field, however, just the opposite is true. Since most applications of superconductivity require ac fields, there will be cases where an incomplete Meissner effect will transform superconducting technology from a cure to a curse. The only protection against this is to preliminarily measure the actual Meissner effect, something which is hardly ever done these days. After all, it is so very difficult to do accurately. If the Meissner effect for a singly connected superconductor is not complete, then field penetration will occur, and an ac field thus creates hysteresis losses and local heating.

There are usually two kinds of superconductors known, those of the first kind (Type I) and those of the second (Type II). The superconductors of the first kind have one critical magnetic field only, H_0. Below this field they are supposed to have a complete Meissner effect and above it no trace of superconductivity remains. Superconductors of the second kind have a lower critical magnetic field for the existence of a complete Meissner effect, H_{c_1}, which is below H_0. Now, when H_{c_1} is reached, superconductivity no longer vanishes suddenly with increasing magnetic field but instead gradually disappears until H_{c_2} is reached, which is usually far above H_0 -- in the order of several 100 kgauss for high temperature superconductors. This is the range where superconducting magnets now operate in spite of

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the fact that only a small amount of the whole sample remains superconducting in these fields. Usually, the higher H_{c_2} is the lower H_{c_1} will be.

This again is a comparatively easy experiment to determine this fact. Since one straight line has disappeared entirely it seems reasonable from an intuitive point of view to question the linearity of -M with fields below H_{c_1}, the last remaining straight line in the diagram. In view of the fact that through poor metallurgy, it is easy to have singly connected samples without any Meissner effect whatsoever, the perfection required for a 100% Meissner effect may never be attainable. Any deviation from a straight line will then be tantamount to hysteresis, dissipation and local heating. This then is what we are dealing with today, a "Type III" superconductor, or in other words a metallurgically realistic Type II superconductor with all those imperfections that tend to make an ac technology based on a 100% Meissner effect destined for unpleasant surprises.

A dc technology based on a few percent of superconductivity left at high fields is safe and reliable. An ac technology requiring a complete Meissner effect up to H_{c_1}, in my opinion, demands a materials perfection which we do not have at the present time. And, it is really not quite clear--at least to me--that it will ever be possible. Undoubtedly, the lower the applied magnetic fields, the better the approximation to a straight line will be.

In a superconductor, all critical fields are functions of the transition temperature. If materials could be found with much higher critical temperatures, materials which at the same time approach crystallographic perfection, then the problem of the incomplete Meissner effect might eventually vanish.

Therefore, if organic superconductors at room temperature are just around the corner, it might be advisable to wait until then with the construction of superconducting cavities for accelerators. In the meantime, if magnetic fields are required in accelerator technology, no great difficulties should arise as the use of superconducting magnets has been shown time and again to be a reliable technology.

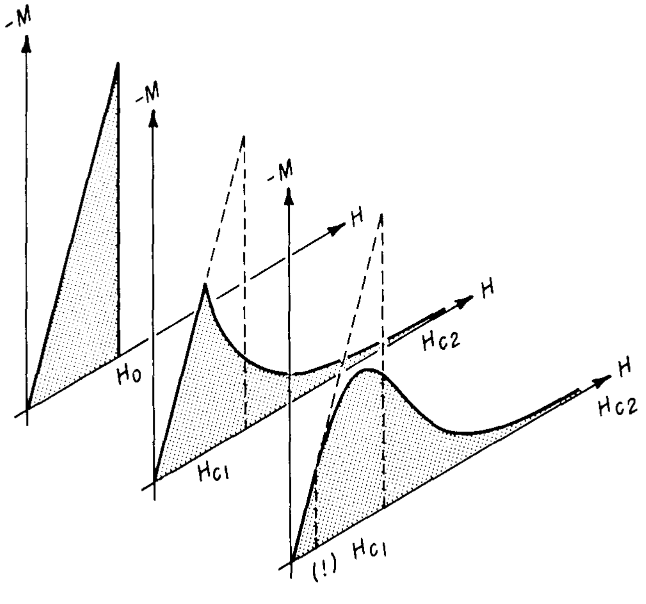

Fig. 1. Magnetization curves for Type I, Type II, and Type III superconductors.

DISCUSSION

Schwettman, Stanford: If you don't mind, I'll take the chair to respond just briefly to a couple of comments you made. First of all, I would like to say that you've stated very beautifully the distinction between those applications such as magnets, which basically depend on the resistance being zero and require only the partial existence of a superconducting state in a real sample, and the contrasted situation in the superconducting accelerator or any rf application of superconductivity where you really depend on the Meissner effect. You're quite correct that it is a qualitatively different problem, and it is a very difficult problem. The second comment that I would like to make is that despite all its difficulties. that is to say the difficulties in achieving high magnetic fields in superconducting cavities. one can nonetheless even with these difficulties operate at energy gradients that are, in fact, as large -- in fact, they're larger than what is possible to achieve using conventional techniques in high duty cycle applications. If you look at the existing accelerators, for instance, the high duty cycle electron linac at MIT operates at 0.8 MeV per foot. The high duty cycle machine here at LAMPF is somewhat lower in gradient partly because protons are accelerated. Even with all their shortcomings, superconducting cavities have been operated at 1 MeV per foot and 2 MeV per foot, not in test cavities, but in practical structures so that although we might not achieve the very high gradients that we hoped to achieve before, they are in fact of great practical interest at the present state of development. The third fact that I'd like to point out is that most likely the problem of greater practical importance, even more than the problem of the Meissner effect, is that of electron loading following field emission. So, if you think we're in bad shape from the Meissner effect, we, in fact, have other problems that are probably more severe than that. And as to coupling room temperature superconductivity and the superconducting accelerator, that's beyond me, I won't comment on that at all. Thank you. Let me open to the floor.

Matthias: Do you mind if I answer you just quickly? (laughter)

Schwettman: I'd be happy for you to answer. (laughter)

Matthias: Thanks first that you agree with me. Thank you also when you point out that I don't know anything about accelerators; but, of course, you see I said that right in the beginning. I know nothing about accelerators, so if you tell me what the gradients are I'm full of admiration; and if you can do it only with superconductors, well, so much the better. But there I have two things to say.

If you want to do it with superconductors, and I'm strictly an experimentalist, I personally have an eerie feeling that if you have equipment, which, the moment you ever open it to air, this is the end of it. So, it is my feeling maybe you could make superconnecting cavities in a better way with different materials, and I understand, of course, your reluctance to go next door and get the room temperature superconductors. But, apart from this, there are many materials today the world hasn't looked at, and if they do, undoubtedly, they will be better in my opinion than lead, which oxidizes overnight, niobium which intrinsically seems to be a type-two superconductor, and things of this kind. I mean, the world today has a larger number of superconnectors all of which are better, some of them, of course, may be a little bit exotic, but it's better than having to anneal the whole accelerator every time the vacuum goes to pieces. I mean, that's my personal feeling.

Schwettman: Putting the humor apart, I'd like to point out one more fact, which is that we have done the experiment that you just referred to and that is, measure the sensitivity of superconducting accelerator structures to such problems as vacuum failures. We, quite frankly, didn't do that experiment on purpose, nonetheless, it turned out to be a very important observation.

Unfortunately, during the installation of a 20-foot long superconducting structure, which consisted of 55 cells, just as we began to cool down this structure to helium temperature, the valve to the accelerator structure was opened in the process of installing the beam-line equipment. It was an accident on the part of a technician. Unfortunately, the accelerator structure was already below ice temperature, and here we opened it up to the atmosphere. Well, fortunately someone heard the pump starting to gurgle, so they recognized within a minute or so that they had to close that valve. But in that time, of course, there was a great deal of gas that had condensed on this cold surface. In fact, all of the water vapor in the air had condensed on the cold surface. We didn't know quite what to do, but being experimentalists, it was clear that there was only one alternative, we simply warmed up the structure, pumped it out and started cooling down again. The simple fact of the matter is that the Q of that structure was then measured to be 4 x 10^9, which is more than sufficient for our application; and the energy gradient of that structure was then measured to be 3.8 million volts per meter, which is again in the ball park that I just described to you.

So it helps as an experimentalist to know some of the facts. If you'd like to comment?

Matthias: Oh, I think that's wonderful that it works so well, but you see, we are thinking -- I mean we the other kind of experimentalists -- we are thinking about superconducting magnets and cables and we don't think overnight, we think for the next 20 years. I mean if the power transmission of the country would rely on superconducting cables, we have to be sure these things last, so I'm delighted that it worked so well.

Citron, Karlsruhe: I missed one point: you said somewhere that the Q of a cavity was very sensitive to this small deviation from linearity. A little later, talking of quality control, you said that you couldn't do anything with ac measurements, and that the only way was to do the difficult experiment of measuring the Meisner effect. Now, if you are very sensitive to an effect, then can't you do this quality control also by Q measurements?

Matthias: You are, of course, quite right. That is, measurement in an indirect way of the Meissner effect. But yet it is not a measurement of the Meissner effect, because at these frequencies what you see is the infinite conductivity. And this is what I was trying to say: maybe the Q is an indirect way of measuring the Meissner effect, but I don't really know this until this has been corroborated by different experiments; and I am completely honest, I don't know how to do those.

Allen, SLAC: Even with a complete Meissner effect there is another component that comes in, in that, the conductivity is not infinite in ac fields. And even if you do come up with a superconductor that has a long linear region, it might have to be rejected, because the surface conductivity is too high for ac.

Matthias: That is the reason why I said an almost complete Meissner effect. You're perfectly right, you have to consider the penetration depth and that you cannot cope with. That's the reason why I said an almost perfect Meissner effect.