The physics of superconducting magnets

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A review of those aspects of superconductivity that are relevant to its use in the generation of high magnetic fields. The differences between the so-called hard and soft superconductors are outlined and the behaviour of hard superconductors in high magnetic fields is explained in terms of the formation of a mixed state. The filamentary and negative surface energy models that lead to such a mixed state are described. The use of hard superconductors in the form of wire or strip for the winding of solenoids is discussed. Attention is also given to the magnetization of superconducting rings by inductive methods. The future prospects for superconducting magnets are summarized.

1 Introduction

One of the tools that has been particularly important to the advancement of physics in recent years is the high-field magnet, that is a magnet capable of producing a field of, at least, several tens of kilo-oersteds. Now, although power must be used in creating such a magnetic field, none should be needed in maintaining it once it has been created. Indeed, this is manifest at low field strengths from the behaviour of permanent magnets. However, the fields that can be reached using permanent magnets do not fall within the defined high-field range. In order to maintain higher field strengths it has, until very recently, been necessary to expend energy, sometimes at a considerable rate. Fields of up to the order of 50 kilo-oersteds have been achieved using iron-cored electromagnets, but little help can be obtained from the use of an iron core beyond this region. For the highest steady fields, air-cored solenoids, such as those used by Bitter and his colleagues at Massachusetts Institute of Technology, have been employed. Such solenoids are wonderful examples of precision engineering but they require exceptional direct-current power supplies for their operation. For example, a solenoid with a 1 in. bore capable of generating 100 kilo-oersteds used 1·7 megawatts of power, and 800 gallons of water per minute were needed to keep it cool! Such large currents are employed in high-field solenoids, that, even with the best electrical conductors, the Joule heating effect is really formidable.

Many workers, despairing of ever obtaining the facilities for producing high steady fields, have resorted to pulse techniques, discharging large banks of condensers through coils to produce

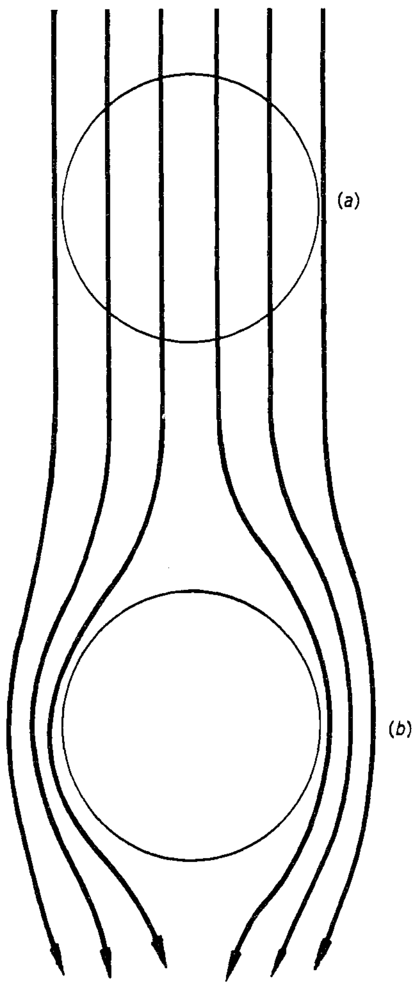

Figure 1 Flux distribution (*a*) that would result from the disappearance of resistance of a normal metal *after* placing it in a magnetic field, and (*b*) that is actually observed for an ideal superconductor cooled from above its transition temperature in the same field (the Meissner effect).

transient fields which have been, in some cases, considerably greater than the highest recorded steady fields. However, most experiments can be performed only with steady fields and it is likely that pulsed fields will be useless for nearly all technological applications. An example of such an application is to be found in the direct generation of electricity from heat by the so-called magneto-hydrodynamic (MHD) method; a very hot (and, therefore, highly conducting) gas is passed through a transverse magnetic field, thereby causing the flow of a transverse electric current. Calculations have shown that magnetic fields of up to 50 kilo-oersteds, extending over volumes having linear dimensions measured in metres, will be needed in effective magneto-hydrodynamic energy convertors. It would be ironic if the engineers who are developing magneto-hydrodynamic generators should succeed in solving all the problems associated with the high temperature of operation, only to find that all the electricity generated must be used in maintaining the magnetic field across the device!

One way of reducing the electrical resistance of the windings of a solenoid, and thereby decreasing the power consumption, is by lowering its temperature. It is well known that the electrical resistivity of a pure metal becomes much smaller at very low temperatures, as the atomic vibrations are then less effective in scattering the electrons. In fact, liquid-hydrogen-cooled magnets have been described, but the advangtaes to be gained by refrigeration are not obvious since, although the power consumed by the magnet becomes less, a considerable amount of power must be used in producing the refrigerant. What is really needed, of course, is a conductor of zero electrical resistance.

As long ago as 1911, Kamerlingh Onnes discovered a conductor with no resistance when he cooled a sample of mercury below a temperature of about 4° K. Since then, many other metals have been found to have zero resistance at very low temperatures, when they are known as superconductors. The transition temperature T_c from the normal to the superconducting state ranges from nearly 20 °K downwards according to the metal or alloy (liquid helium boils under atmospheric pressure at 4·2 °K). It is natural to ask why superconductors have only recently been used in the generation of magnetic fields, in view of the fact that the phenomenon of superconductivity has been known for such a long time. It is the object of this article to answer this question, and to show how it is that specific superconductors can be used in high-field magnets.

2 Behaviour of superconductors in magnetic fields

2.1 *Ideal superconductors*

Most of the early work on superconductivity (like that of Kamerlingh Onnes on mercury) was carried out using pure elemental metals and it is instructive to consider their behaviour first, although they are, in fact, of no use in generating high magnetic fields. Such materials are known as ideal superconductors. Their most obvious characteristic is, of course, their absence of electrical resistivity: a current has been observed to persist without loss in a superconducting ring for more than two years. The persistent current can be quenched by raising the temperature above T_c and it is also found that the material returns to the normal resistive state if the magnetic field rises above a critical value H_c. This critical field is itself a function of temperature, rising from zero at T_c to its highest value at 0 °K, but, even at the absolute zero of temperature, it is never more than about 2 kilo-oersteds for any ideal superconductor.

The quenching of superconductivity in fields greater than H_c itself sets a limit to the current that can be carried by a superconducting wire. Silsbee showed that such a wire becomes normal when the current that it carries is just sufficient to produce a magnetic field H_c at the surface (Silsbee's rule).

The vanishing electrical resistivity of a superconductor is by no means its only characteristic. Another independent feature is the absence of magnetic flux inside a superconductor. Of course, the zero electrical resistance implies that any change in the external magnetic field should produce eddy currents in the superconductor so as to prevent any resultant change in the internal field. However, Meissner and Ochsenfeld, in 1933, showed that any magnetic flux inside a specimen in the normal state is driven out when it is cooled below the superconducting transition temperature (see figure 1). This exclusion of magnetic flux from a superconductor is known as the Meissner effect; put another way, it can be said that an ideal superconductor is a perfect diamagnetic material. It is, in fact, not quite true to say that flux exclusion is complete since it does penetrate into a surface layer of the order of 10^{-6} to 10^{-5} cm thick (the so-called penetration depth). This flux penetration is of great importance in explaining the behaviour of those superconductors that are actually used in producing high fields.

2.2 *Hard superconductors*

A large number of superconducting materials fail to show the ideal behaviour described above. These non-ideal materials are either alloys, intermetallic compounds or highly strained metals and are known as hard superconductors since they are generally hard in the metallurgical sense (ideal superconductors are, conversely, sometimes known as soft superconductors). One of the most important features of hard superconductors is that they do not exclude magnetic flux in the same way as the ideal materials; in other words, the Meissner effect is incomplete. The technological importance of hard superconductors lies in the fact that they remain superconducting up to much greater field strengths than do soft superconductors. They also often have appreciably higher transition temperatures.

As long ago as 1930, de Haas and Voogd observed that lead–bismuth alloys remain superconducting in fields of up to about 20 kilo-oersteds. Silsbee's rule suggests that the current-carrying capacity should rise with the critical field value but, unfortunately, it is found that this rule merely gives an upper limit to the current that can be carried by a hard superconducting wire. Most hard superconductors become normal at much smaller currents than those indicated by Silsbee's rule, another difference between hard and soft superconductors. It is primarily for this reason that the application of superconductors to high-field generation was so long delayed.

The turning point came in 1961 when Kunzler and his team at Bell Telephone Laboratories discovered that short wires of the compound niobium–tin, Nb_3Sn, which has a transition temperature of about 18 °K, remained superconducting in liquid helium when carrying a current of density exceeding 10^5 A cm^{-2} in a field of 88 kilo-oersteds. Shortly afterwards, other materials, such as the niobium–zirconium alloys, with comparable superconducting properties, were also prepared and, in the few years that have followed, compact superconducting solenoids for producing high fields have become commonplace in the research laboratories of the world.

3 Theory of hard superconductivity

3.1 *The filamentary model*

The key to the behaviour of hard superconductors is to be found in the concept of the penetration depth. This concept was first introduced by F. and H. London when they extended Maxwell's equations of electromagnetism so that they were consistent with both the zero resistance and flux exclusion aspects of ideal superconductivity. Although more recent theories lead to values for the penetration depth that are somewhat different from those deduced by the Londons, they confirm its existence, as do a number of experiments (e.g. on the absorption of high-frequency electromagnetic radiation by superconductors).

It is obvious that the exclusion of magnetic flux from a soft superconductor implies an increase in the energy of the superconducting state, which must become greater as the external magnetic field rises. In zero magnetic field, the energy of the superconducting state must, of course, be less than that of the normal state (otherwise the metal would become normal) but, at fields exceeding H_c, the additional energy associated with flux exclusion causes the superconducting state to have the higher energy, and the metal becomes normal. Suppose, however, that we consider a volume enclosed by a superconducting sheet that is thinner than the penetration depth. Some magnetic flux can then penetrate into the volume and, in consequence, less energy is involved in flux exclusion than would be the case if the superconducting sheet were thicker. We can infer that very thin sheets of soft superconductor can remain superconducting in higher magnetic fields than the critical field for the bulk material. Thus, one can account for the high critical field of a hard superconductor if one assumes that it consists, not of homogeneous superconducting material, but rather of thin sheets (or filaments) of superconductor separated by normal regions. Such a mixed-state model accounts satisfactorily for the observed flux penetration (the incomplete Meissner effect) and for the breakdown of Silsbee's rule. It is worth noting that, as a consequence of Silsbee's rule, the critical current of a soft superconducting wire is proportional to its diameter, whereas that of a hard superconducting wire is expected to be proportional to its cross sectional area.

A mesh of superconducting material separated by normal material could arise if some parts of the material were physically different from other parts. Then, even if all the material were superconducting in zero field, one would expect some parts to return to the normal state on raising the magnetic field to a certain value. If the remaining superconducting parts consisted of regions thinner than the penetration depth they would remain superconducting at fields higher than the critical field for homogeneous material. A beautiful demonstration of the so-called filamentary model of a hard superconductor has been described by Bean and his co-workers of the General Electric Laboratories in Schenectady. They compressed mercury into the interconnected pores of unfired Vycor glass, thus producing a network of mercury filaments of about 4×10^{-7} cm diameter. Figure 2 shows the magnetization curve for the mercury-in-Vycor filaments compared with that for bulk mercury at a temperature of 2·16 °K. The curves show that the filaments remain superconducting up to a field about 20 times greater than the bulk critical field.

It is well known that the hardness of metals and alloys can be attributed to the presence of linear defects in the crystal structure that are known as dislocations. The lattice immediately surrounding a dislocation is subjected to highly localized strain and we would expect it to have a

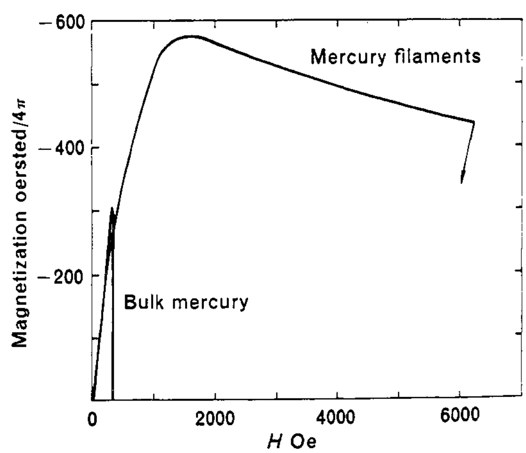

Figure 2 Magnetization curves at 2·16 °K for bulk mercury and for filaments of mercury in unfired Vycor glass (from Bean, Doyle and Pincus).

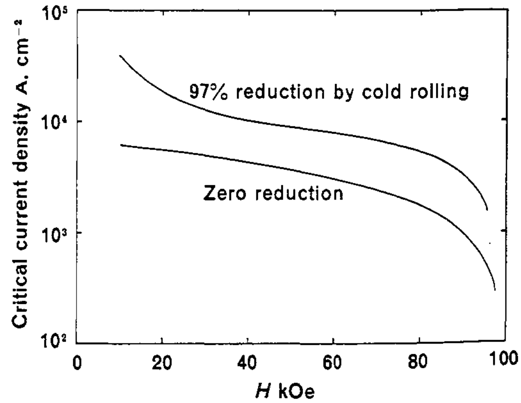

Figure 3 Effect of cold rolling on the critical current density of a niobium–zirconium alloy in liquid helium (from Kunzler).

range of critical field values differing slightly from that of the unstrained material. In particular, regions close to dislocations which have slightly higher than average critical fields might be expected to act as superconducting filaments when the rest of the material goes normal. This idea is very attractive since it accounts for the increase in critical current which usually results from metallurgical working (and, hence, an increased density of dislocations). Figure 3 shows the effect of cold-rolling on the critical current density of a niobium–zirconium alloy. It is, in fact, believed that current-carrying filaments associated with dislocations are responsible for the behaviour of some of the hard superconductors. However, the role of dislocations as flux-pinning agents, as will be described in § 3.2, is probably of much greater significance.

3.2 *Negative surface energy*

The mechanism described above does not provide the only explanation for the formation of a mixed state. In a pure metal, the surface energy at the boundary between normal and superconducting regions is always positive; this tends to inhibit the formation of a mixed state. However, according to the phenomenological theory of Ginzburg and Landau, it is possible for the surface energy between the normal and superconducting states to become negative in a high enough magnetic field. If the surface energy becomes negative a break-up of the material into superconducting regions separated by normal regions is favoured. Then, if the superconducting regions are thin enough, the critical field must rise. The Ginzburg–Landau theory shows that one of the conditions for negative surface energy is that the mean free path of the electrons in the normal state should be small. Thus, negative surface energy is expected for impure metals and alloys or for strained materials, in which the electron free path length is reduced by scattering on foreign atoms or other defects.

The validity of the negative-surface-energy theory for alloys of lead and indium has been demonstrated by Livingston. Pure lead is a soft superconductor with a magnetization curve as shown in figure 4; the critical field is rather less

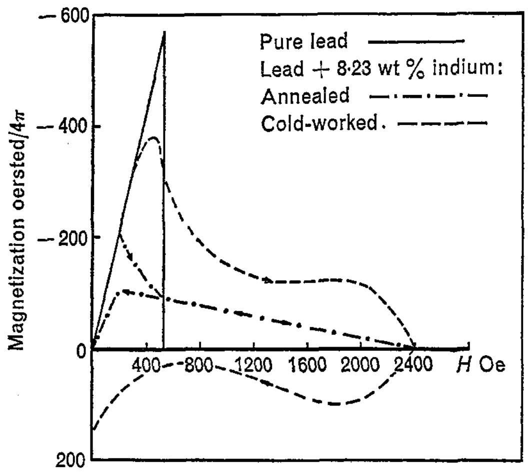

Figure 4 Magnetization curves for pure lead and for a lead–indium alloy at 4·2° K (from Livingston)

than 600 oersteds. On the other hand, an alloy of lead with 8·23% indium shows a much higher critical field of 2400 oersteds even when it is annealed so that it is soft from the metallurgical viewpoint. Actually, one usually refers to two critical fields for such a material, which is known as a type II superconductor (another term for an ideal superconductor being type I). The field at which the behaviour departs from that of an ideal superconductor is called the lower critical field H_{c1}, while the field at which superconductivity disappears altogether is called the upper critical field H_{c2}. At fields below H_{c1} the surface energy is positive and the material behaves as an ideal superconductor, but at fields between H_{c1} and H_{c2} the surface energy is negative and flux penetration occurs. The broken line in figure 4 shows the

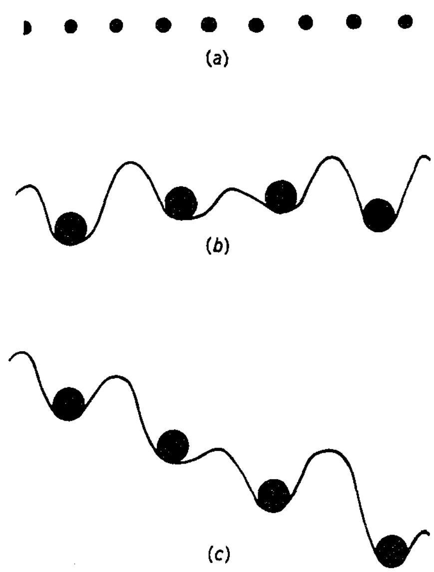

Figure 5 Barriers to flux motion in a type II superconductor with defects. (*a*) shows schematically the regular distribution of flux lines in a defect-free material. The defects in a real material lead to a variation of energy represented by the curve in (*b*), bundles of flux lying at the energy minima. The energy diagram is altered to that of (*c*) when current flows perpendicular to the flux lines but motion of the flux bundles requires thermal activation.

magnetization curve for the alloy when cold-worked. This curve differs from that for the annealed material in exhibiting considerable hysteresis (there is very little hysteresis for the annealed alloy) but the upper critical field is the same.

The formation of a mixed state due to the negative-surface-energy effect does not of itself permit the superconductor to carry large currents in high fields. Abrikosov showed that there is a regular arrangement of quantized flux lines in a negative-surface-energy superconductor when it carries no current. However, if a current is passed with a component perpendicular to these flux lines, it leads to an increased concentration of flux lines on one side of the sample and a decreased concentration on the other. If the force that drives the current is removed, the flux lines will tend to rearrange themselves once more in a uniform pattern, thus quenching the current. This effect would undoubtedly occur immediately in a defect-free type II superconductor, which would therefore have a negligibly small critical current, but in any real material there are defects which tend to pin the flux lines and prevent them moving. Figure 5 illustrates this flux-pinning effect schematically.

At any temperature above the absolute zero, it is possible for the flux lines to be released from their pinning points by the atomic vibrations so, strictly speaking, the currents in a hard superconductor are not persistent in the same sense that they are for a soft superconductor. However, at the low temperatures at which superconductivity occurs, thermal activation is a very slow process, and, in a typical example, Kim of Bell Telephone Laboratories has estimated that the field in a hard superconducting ring should decay by no more than 10% in 300 years! Thus, even in hard superconductors, the resistance can be regarded as being zero for most practical purposes.

Quite clearly, the current-carrying capacity of a negative-surface-energy superconductor depends on its ability to pin the magnetic flux lines. It is understood that dislocations are particularly effective pinning agents. Thus, high dislocation densities lead to high current-carrying ability both for the filamentary model and for the negative-surface-energy model.

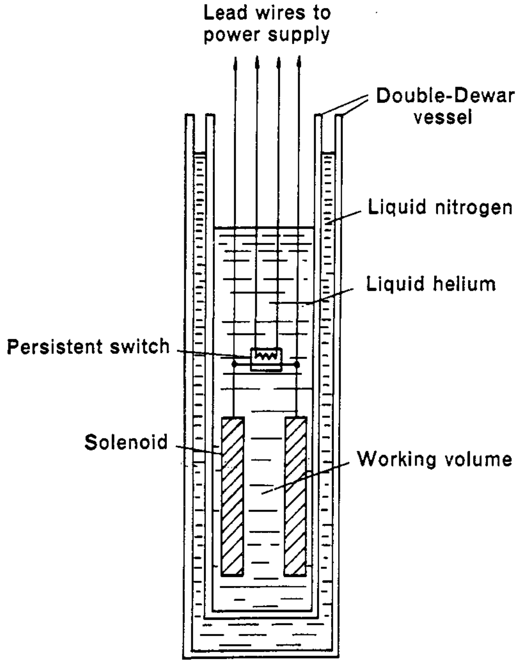

Figure 6 Schematic diagram showing section through a superconducting magnet system.

4 Superconducting solenoids

In making a high-field superconducting solenoid, the choice of material is the first consideration. The most important hard superconductors at the present time are niobium–tin, niobium–zirconium and niobium–titanium. Niobium–tin has a critical field of over 200 kilo-oersteds and an extremely high current-carrying capacity at lower fields but is very brittle. Niobium–titanium and niobium–zirconium, on the other hand, have critical fields of only 145 and 130 kilo-oersteds respectively, but both are ductile. Niobium–zirconium can carry higher currents than niobium–titanium in moderately high magnetic fields and is consequently the material commonly employed in most superconducting magnets. The table summarizes the properties of the three materials mentioned above, together with the compound vanadium–gallium, V_3Ga, which has a still higher critical field than niobium–tin, but is similarly brittle and has not been used much yet.

The actual winding of a niobium–zirconium or niobium–titanium solenoid presents no unusual problems but niobium–tin solenoids have called for novel techniques. For example, in one method a composite wire of elemental niobium and tin is first wound into a solenoid and then heat treated so as to form the intermetallic compound. Alternatively, thin layers of niobium–tin are deposited on to a ductile substrate (preferably in strip form) after which the solenoid can be wound conventionally. However, either method leads to a rather high proportion of the space being filled by material that is not the required compound, so that the high critical-current density of niobium–tin has never been fully exploited.

One problem that the designer of a superconducting magnet has to face is that the current-carrying capacity of long wire, when wound into solenoidal form, rarely attains the value that one measures on short specimens. This degradation effect is believed to be associated with the generation of heat accompanying flux-creep (the term used to describe the movement of flux past pinning points). This heating effect is highly localized and, provided that it remains so, does little harm. However, catastrophic growth of hot spots, leading to a complete transition into the normal state, in assisted by the poor thermal conductivity of most hard superconductors. Thus, it is important that the rate of change of current in a superconducting solenoid should be kept low, and the power supply invariably incorporates a mechanism for increasing the current slowly and steadily. Otherwise, the power supply is a simple affair, only a few amperes at a very low voltage normally being required.

A typical superconducting magnet system for low-temperature experiments is illustrated in figure 6. A common feature of such systems is the so-called persistent switch which consists of a piece of superconducting wire that short-circuits the solenoid. This wire is heated, and therefore driven normal, when it is necessary to change the current through the magnet, but otherwise the persistent switch allows a constant magnetic field to be maintained after the power supply has been removed. The importance of this feature lies in the elimination of Joule heating in the lead wires, thereby minimizing the consumption of liquid helium. For measurements at other than liquid helium temperature, it is necessary that the Dewar vessels should be of re-entrant shape, so some of the working space is then lost. On the other hand, working space is lost in a conventional magnet when it is used for low-temperature experiments.

5 Inductive methods for the magnetization of superconductors

Mention has been made of the difficulty experienced in making a solenoid from one of the brittle superconductors. The situation would be eased if the magnet coil could be machined from the bulk material but this implies a very small number of turns and a very large current. In the limit, of course, the magnet would consist of a single turn, i.e. a ring. It is not yet known whether superconducting rings can be used in practical applications, but a study of their behaviour is, at least, highly instructive.

Consider the magnetization curve of a thick-walled hard-superconducting tube, as shown in figure 7. The diagram shows the internal field H_i plotted against the external magnetizing field H_e. Along the line OA, the increasing external field induces loss-less currents which successfully prevent any flux reaching the interior, though gradual penetration of flux into the wall of the cylinder does occur. At point A the whole wall is carrying its maximum current and, thereafter, the internal and external fields differ by an amount which depends on the integrated current-carrying capacity of the superconductor. After the external field reaches that at point B (less than the critical field) it is lowered, but along the line BC the internal field remains constant; this constancy of the internal field is brought about by a change in the direction of flow of the circulating currents. At point C, the sample is once again carrying its maximum current (in the reverse direction to that at point A) and, as the external field is reduced to zero at point D, the internal field falls to some value H_s (which is, incidentally, equal to the value of the external field at point A). In effect, the superconducting cylinder has become a kind of permanent magnet, since the field H_s will remain steady so long as the material is surrounded by liquid helium.

The cylinder can be magnetized in an alternative manner by cooling it through its transition temperature T_c in an external magnetic field which is subsequently removed. However, the internal field is then limited to more or less the value of the maximum available magnetizing field. If higher fields are to be achieved one must resort to the methods of flux-compression or flux-pumping. A typical flux-compressor is shown in figure 8. It consists of a cylinder with two interconnected holes. After magnetization by cooling from the normal state in an external field, a superconducting plunger is inserted in the larger of the holes. This tends to drive the flux

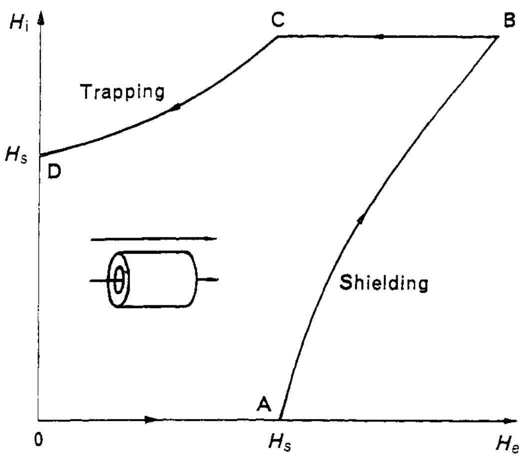

Figure 7 Magnetization curve for a hard-superconducting ring. The field in the ring is plotted against the external field.

into the smaller of the holes, though it must be remembered that hard superconductors are not perfect diamagnetic materials, so that flux penetration of the walls does occur. Experiments by the author and his colleagues at the Hirst Research Centre in Wembley showed that a field of 50 kilo-oersteds should be reached in a niobium–tin flux-compressor, with walls considerably thinner than a centimetre, from a magnetizing field of, say, 10 kilo-oersteds, provided that the plunger is inserted sufficiently slowly. A field of nearly 25 kilo-oersteds was actually achieved by flux compression, this being in accordance with theory for the particular configuration used.

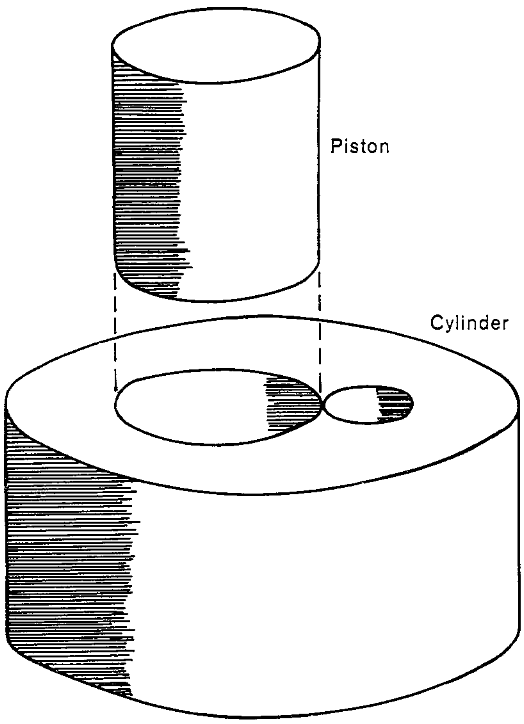

Figure 8 A simple flux-compressor (as described by Swartz and Rosner).

There is, of course, an intermediate stage between the thin wire solenoid with its more or less conventional power supply and the single-turn flux-compressor. This is the solenoid with windings of large cross section area, which therefore needs a large current to produce a high magnetic field. The introduction of a large current, through what must be leads of normal metal, into the liquid helium bath presents considerable problems. It would be much more convenient if the lead wires carried a much smaller current, which might then be increased through the solenoid itself by inductive methods. This is the idea behind the flux-pump shown in figure 9. All the wires shown in this diagram, other than the primary winding of the toroidal transformer and its leads, are superconducting. S_1 and S_2 are persistent switches, as described previously, that can be driven normal, and therefore effectively opened, by heat from an adjacent coil. At first S_1 is closed and S_2 is open. The current in the n-turn primary winding of the transformer is

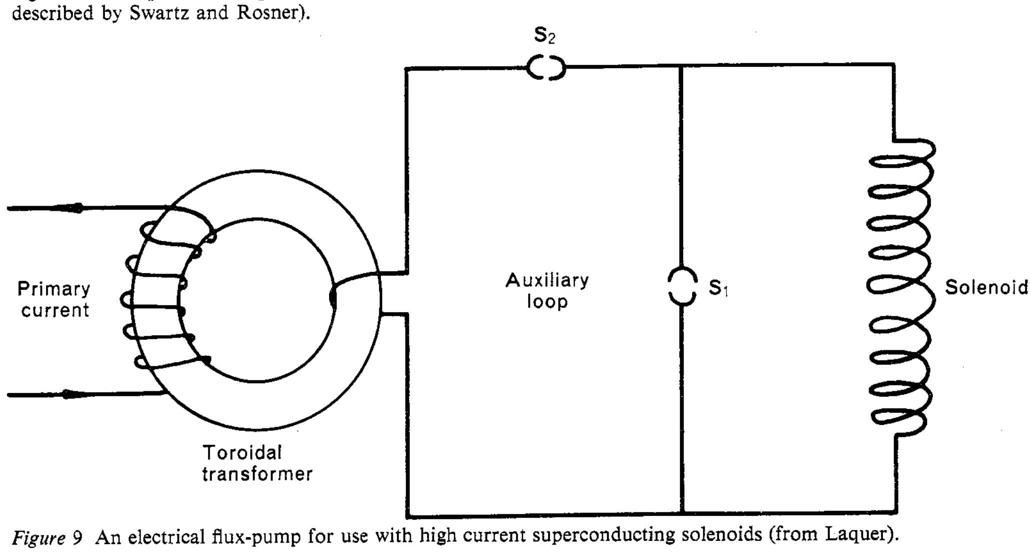

Figure 9 An electrical flux-pump for use with high current superconducting solenoids (from Laquer).

raised from zero to a value I_0. Then, when switch S_2 is closed and the primary current is reduced to zero, a current nI_0 is induced in the secondary winding of the transformer. Switch S_1 is successively opened and closed, whereupon a persistent current equal to $nI_0L_2/(L_1+L_2)$ flows through the solenoid of inductance L_1, the inductance of the auxiliary loop being L_2. Continued operation of this cycle of events leads to a current nI_0 through the solenoid, so that, if n is made large enough, any desired magnet current can be achieved.

A most ingenious device, for inducing current flow in a superconducting coil without external current leads, has been described by Volger and Admiraal. This device, which is called a superconducting unipolar dynamo, is illustrated in figure 10. It makes use of the fact that the magnetic flux through a hole in a soft superconductor must remain constant. A normal 'hole' containing a specific quantity of flux is obtained by cooling the superconducting disk from above its critical temperature, with a permanent magnet held in the position shown. The magnet is then rotated about the axis of the disk, causing the normal hole to rotate with it. It will be seen that each rotation of the magnet leads to an increase in the flux through the superconducting loop composed of the coil, its leads and part of the disk. The flux contained in this loop, and consequently the current through the coil, can, in principle, be raised to any required level (provided that the circuit is not driven into the normal state). In a practical demonstration of the device, Volger and Admiraal raised the current through a niobium–zirconium coil from zero to 50 A, using a lead disk as the soft superconductor.

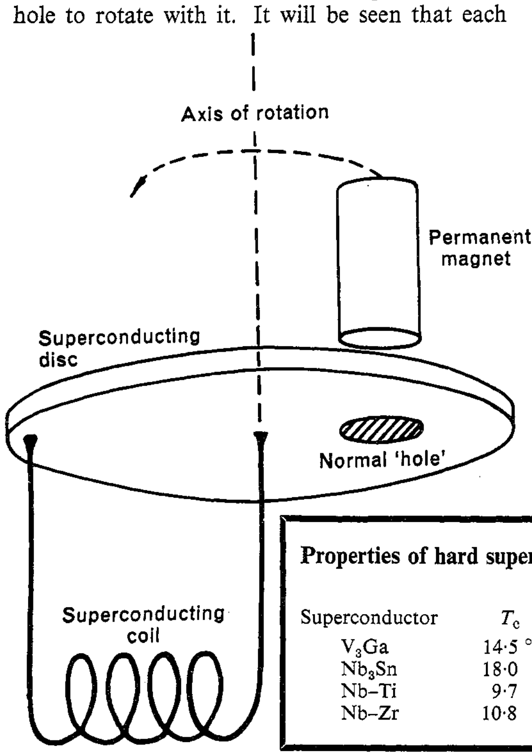

Figure 10 A unipolar dynamo for inducing current in a superconducting solenoid (from Volger and Admiraal).

6 Future prospects

At present, superconducting solenoids producing more than 50 kilo-oersteds are commercially available from several manufacturers and experimental magnets giving more than 100 kilo-oersteds have been made. Developments in the immediate future are likely to lead to larger working volumes within the magnets rather than higher fields, but there is no doubt that superconducting solenoids capable of generating fields well in excess of 100 kilo-oersteds would be welcomed by research scientists. The measurements on niobium–tin and vanadium–gallium suggest that a 200 kilo-oersteds magnet is already a possibility, though the low critical-current densities at very high fields imply that it would need a very large solenoid with a very small working space. There would obviously be more chance of producing such high fields if materials with still larger values of H_c were to be discovered, but an argument by Clogston suggests that these larger critical fields might never be found. In explaining hard-superconducting behaviour, no account was taken of the magnetization of the material in the normal state. However, since a normal metal is paramagnetic, its free energy is lowered on applying a magnetic

Properties of hard superconductors (Berlincourt)

Superconductor	T_c	H_c (at 0 °K)	Critical current density (at 4·2 °K, 80 kOe)	Mechanical characteristics
V_3Ga	14·5 °K	270 kOe	10^5 A cm^{-2}	brittle
Nb_3Sn	18·0	210	$>2\times10^5$	brittle
Nb–Ti	9·7	145	2×10^4	ductile
Nb–Zr	10·8	130	5×10^4	ductile

field. Thus, the energy in the normal state will always fall below that in the superconducting state in a high enough magnetic field, quite apart from the effect of flux exclusion which tends to raise the superconducting energy. The limiting field deduced by Clogston is dependent on the difference between the free energies in the normal and superconducting states at zero field, which in turn depends on the transition temperature; it is found, thus, that H_c cannot exceed about 18·4 T_c kilo-oersteds (T_c being in °K). Unless new superconductors with transition temperatures appreciably greater than 20 °K are discovered, it seems that critical fields above 400 kilo-oersteds are out of the question. Nevertheless, even if the so-called Clogston limit proves to be insuperable, superconducting magnets will continue to make their mark on science and technology.

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Forthcoming conferences and courses

1966	Subject	Venue	Further details from
27 June	The integration of physics and chemistry in schools	Manchester	Dr. J. A. Clegg, Dept. of Physics, Imperial College, London, S.W.7
4–8 July	Radioactivity work in school science	Dundee	Dundee College of Education
4–8 July	The alternative physics syllabus	Dundee	Dundee College of Education
4–11 July	Nuffield O-level physics	Stratford	Mr. G. Wright, Physics Dept., Westham College of Technology
6–14 July	Applied physics	Cardiff	Your L.E.A. (form 106 RCS)
9 July	New apparatus	Southampton	Dept. of Education, Southampton University
10–15 July	Nuffield O-level physics	Newcastle upon Tyne	Mr. J. W. Brinbridge, Institute of Education, University of Newcastle
11–15 July	Atomic physics in the school curriculum	Sheffield	The Secretary, Institute of Education, Sheffield University
11–15 July	Nuffield physics workshop	Southampton	Dept. of Education, Southampton University
11–15 July	Electronics for beginners	Dundee	Dundee College of Education
11–15 July	Elementary a.c. theory	Dundee	Dundee College of Education
11–15 July	The alternative physics syllabus	Glasgow	Jordanhill College of Education, Glasgow
11–15 July	The alternative physics syllabus	Edinburgh	Moray House College of Education, Edinburgh

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