Rutherford Laboratory

Technical leaflet

C8

SUPERCONDUCTING MAGNETS

1. History and present status

In principle, high magnetic fields in the range 20 to 200 kilogauss can be produced without difficulty by passing a current through a suitably shaped copper coil. As the magnitude and volume of the field increases, however, the power requirements rapidly become excessive, and the range of high field magnets that can be produced is in practice severely restricted by economic considerations. For example, to produce 100 kilogauss over a volume only 8 inches in diameter would require a 10 megawatt power supply.

As long ago as 1911 it was discovered that many substances undergo a transition, at a very low temperature, to a state of zero electrical resistance. Hopes of immediately utilising these effects to construct magnets with zero power dissipation were not fulfilled, however, for it was soon found that the superconducting state was destroyed if the magnetic field exceeded a critical value which was typically only a few hundred gauss, and this has proved to be a general property of almost all of the many hundreds of superconducting alloys and compounds studied during the subsequent 50 years.

Between 1950 and 1960, with improvements in low temperature techniques, superconductivity began to be studied more intensively, and with the help of advances in the theory it began to be realised that there was in fact a class of superconducting materials which should be capable of sustaining high current densities in high magnetic fields. The breakthrough finally came in 1961 when several alloys and compounds were shown to have critical fields in the range 60 to 200 kilogauss, and which, if prepared in a carefully controlled manner, would carry currents in the range 10^4 to 10^6 amps/cm^2 (compared with the 10^3 amps/cm^2 commonly achieved in conventional magnets).

This discovery was of such widespread significance in many branches of science and technology (notably M.H.D. power generation, fusion research, and space research, in addition to high energy physics) that immediate efforts were made to develop the materials on a commercial scale. The performance of the three materials which have received most attention is indicated in Fig. 1. The alloys niobium-zirconium and niobium-titanium are both strong and ductile, and can be produced reliably, and in large quantities, in the form of a .01" diameter wire. In contrast, niobium-tin is brittle and weak, and, although potentially a more useful superconductor, it is much more difficult and expensive to manufacture in a form suitable for magnet construction. So far, the most successful technique has been to produce it as a thin vapour-deposited layer on stainless steel tape, (which reduces the effective current density by a factor 10 or so from the values indicated in Fig. 1). The performances shown are those at the temperature of liquid helium, about 4.2°K; the materials remain superconducting up to higher temperatures (as high as 18°K for niobium-tin), but the current carrying capacity decreases with increasing temperature, and liquid helium temperature will for most applications be the most convenient operating point.

Despite the rapid commercial development of the basic materials, the prospects for superconducting magnets received an immediate and unexpected set-back when it was found that coils of superconducting wire did not perform in accordance with measurements made on short samples of the same wire; the coil would revert to the resistive state at a current perhaps only one half or one third the predicted value, this 'degradation' effect being worse for larger coils. This problem delayed the construction of large reliable superconducting magnets by about three years, and was eventually shown to be due to the evolution to heat within the coil by the discontinuous penetration of magnetic flux into the individual superconducting wires. This has now been overcome by the development, during the past eighteen months, of the principle of "stabilisation", shown in Fig. 2. The superconductor is bonded to a parallel length of low-resistance normal material, such as copper, (Fig. 2a), forming a temporary alternative path for the current in the event of a local resistive region being formed in the superconductor by a thermal disturbance (Fig. 2b). The heat dissipated in the copper is carried away by the liquid helium (for which channels are provided to allow it to penetrate into the coil), allowing the system to recover to its original state. This can be achieved in practice by forming a multistrand cable from copper-coated superconducting wires together with an appropriate number of copper wires, tinning to provide good electrical and thermal contact between the strands, and providing a porous insulation to allow the liquid helium to cool the surface of the copper. Alternatively flat tapes can be formed by bonding the superconductor to copper strip, and many other possibilities are being investigated.

As a result of these developments realistic proposals for large superconducting magnets can now be made with confidence. However, not all types of magnet are yet possible; this is partly due to the fact that the large proportion of normal metal required to achieve stabilisation reduces the effective current density to the region 10^3 to 10^4 amps/cm^2, making it difficult to achieve many of the specialised small-scale coil configurations (e.g. quadrupole focusing magnets) in which the winding space is limited. The other main limitation is the present high cost of the superconducting alloys, making many potentially attractive projects uneconomic, particularly above 100 kilogauss where niobium-tin is the only available material. A very rough indication of the cost of a straightforward superconducting solenoid as a function of size and magnetic field is shown in fig. 3; the full lines show the approximate range of existing magnets, and of magnets being proposed at the present time. This picture may, of course, change rapidly with further developments in the technology.

2. Applications in high energy physics

High energy physics is notable not only for having some of the largest potential applications of superconducting magnets, but also the greatest variety. Unfortunately, the most expensive items, the particle accelerators themselves, utilise pulsed magnets and will not necessarily benefit immediately from the development of superconductors; even in this case, however, calculations suggest that it may eventually prove more economic to use superconductors, because the use of a high magnetic field would allow a large reduction in the circumference of the magnet ring. For storage rings, which will utilise D.C. fields, the advantages are more clear-cut, and reductions in magnet cost by up to a factor 10 are potentially possible. Of more immediate interest is the possibility of superconducting magnets for large bubble chambers, hitherto utilising iron-core magnets and limited to less than 20 kilogauss, which would benefit considerably from the provision of higher fields in the 80 kilogauss region.

At the other end of the scale, many relatively small magnets are required for specialised experimental equipment. Their specification, however, can often be very much more demanding than for the large scale applications. For example, magnetic fields for polarised targets may be required to be uniform to 1 part in 2.10^4 over a region several inches in diameter, and at the same time designed in a way which leaves a substantial aperture free for the incoming and scattered particle beams.

Between the two extremes many types of magnet are utilised for focusing, deflecting, and analysing particle beams. The use of superconducting magnets would considerably extend the capabilities of these devices, allowing, for example, larger deflection angles, shorter beam paths, higher resolution, and the transport of large divergence beams, as well as a number of special applications arising from the smaller physical size of such magnets.

3. Rutherford Laboratory Programme

The Rutherford Laboratory has been studying high field superconductors since their discovery in 1961. The theory of the design and economics of applications in high energy physics has been investigated in considerable detail, and a variety of experimental work has included in particular a study of the behaviour of sintered niobium-tin.

During the past year the research programme has been considerably expanded to include such topics as stabilised cable design and behaviour, heat transfer to liquid helium in narrow channels, design of high current-leads, and the construction of several solenoids for research into the behaviour of coils and coil materials. One of these, due for completion early in 1967, should provide up to 110 kilogauss with an internal diameter of 5". In addition, a number of computer programmes are now being utilised to calculate the magnetic field configurations produced by specified coil systems. More detailed studies of engineering and refrigeration problems have also been initiated.

At the same time, a number of superconducting magnets are being designed and constructed for specific requirements of other groups in the laboratory. Due for completion this year are two corrected solenoids for research into polarised target materials at high fields; one of these will provide 25 kilogauss uniform to 1 part in 10^4 in a region 4 cm in diameter, and the other will give 50 kilogauss with the same uniformity over a region 1 cm in diameter. The cryostat for the 25 kilogauss coil has been designed for operation in either the horizontal or vertical position, and has a re-entrant design allowing a second cryostat, (containing the crystal under investigation and sometimes operating at a lower temperature) to be inserted into the region of uniform field. (Fig. 4).

For operational polarised targets, requiring access for a particle beam, serious consideration is being given to the possibility of utilising a niobium tin conductor, operating at high current density, to surround the target crystal with a very thin-walled coil (perhaps 1 millimetre or less) which would allow the particle beam to pass through with negligible interaction

Two larger-scale magnets are in the design stage; one is the research solenoid referred to above, and the other is a bending magnet, about 7 feet long, with a 30 kilogauss transverse field, homogeneous to $\pm \frac{1}{2}\%$ over a 5 inch horizontal aperture. This will deflect 7 GeV protons through 15° and may be used as a beam switch for a new experimental area. In its simplest form, the magnet would consist of a pair of coils of the form shown in fig. 5, separated vertically to allow passage of the particle beam; in practice the stringent uniformity requirements, and the problem of avoiding regions of high peak field on the windings, will make the final design considerably more complicated.

The largest magnet under consideration is a 75 kilogauss, 6 feet bore, split solenoid for a possible new bubble chamber (Fig. 6). This will require several hundred thousand pounds worth of superconductor, in the form of a stabilised cable carrying several thousand amps. The stored energy in this magnet will be of order 100 megajoules, and provision will be made for rapid extraction of this energy in the event of failure of the low temperature system. The coil will be surrounded by a substantial iron shield, to reduce the stray magnetic fields outside the magnet to an acceptable level. A preliminary design study for this magnet will be completed by the middle of this year.

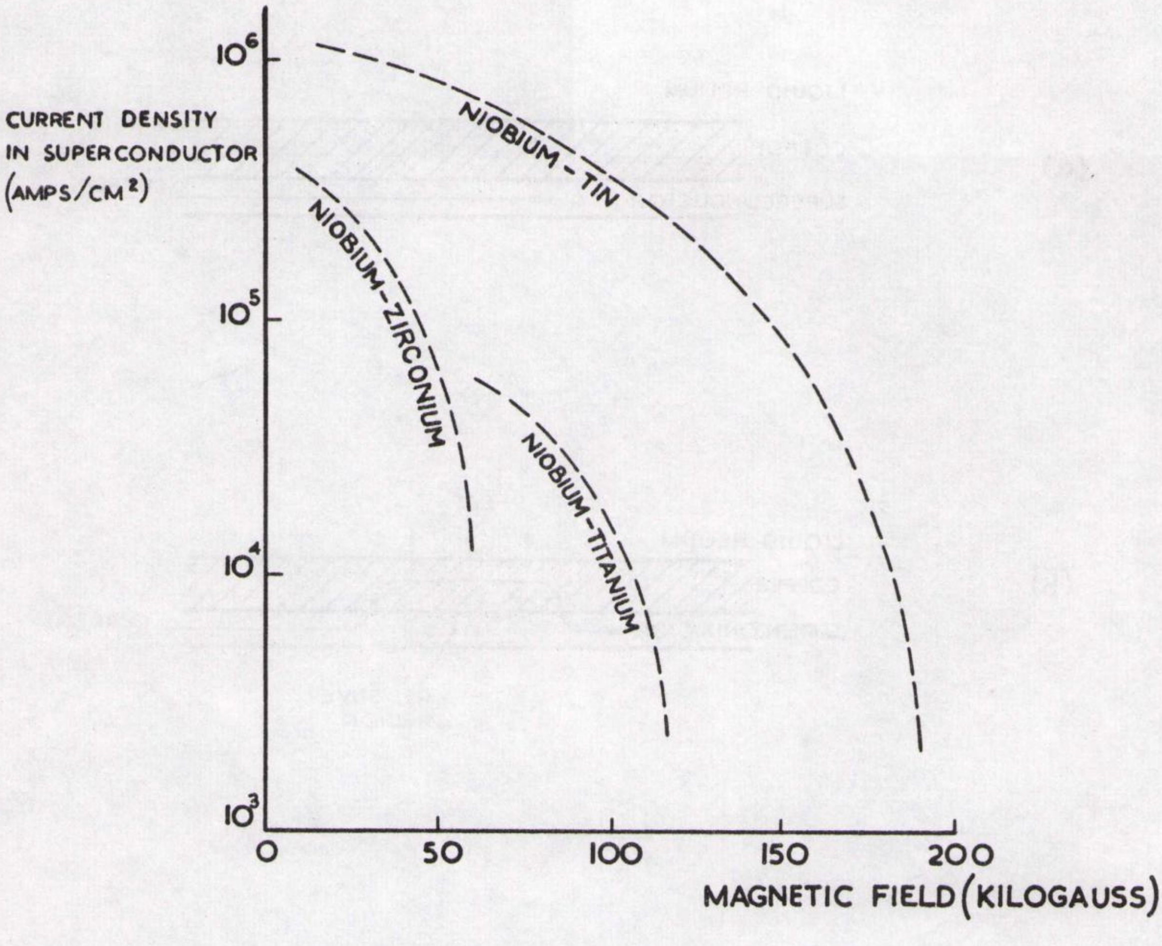

FIG I CHARACTERISTICS OF SOME HIGH-FIELD SUPERCONDUCTORS

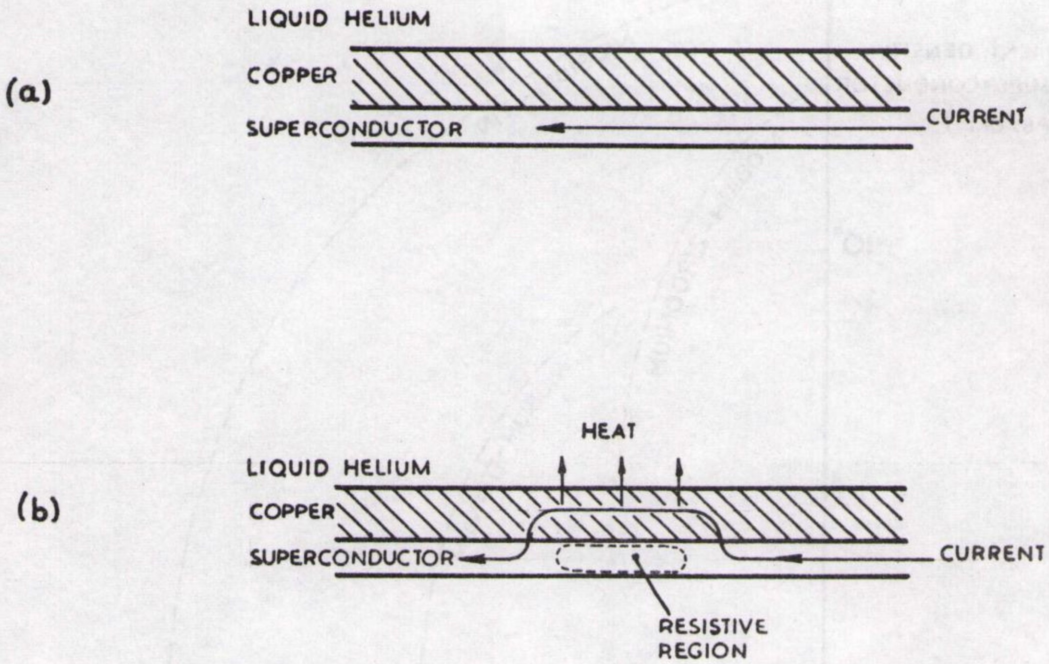

FIG 2 STABILISATION OF SUPERCONDUCTOR

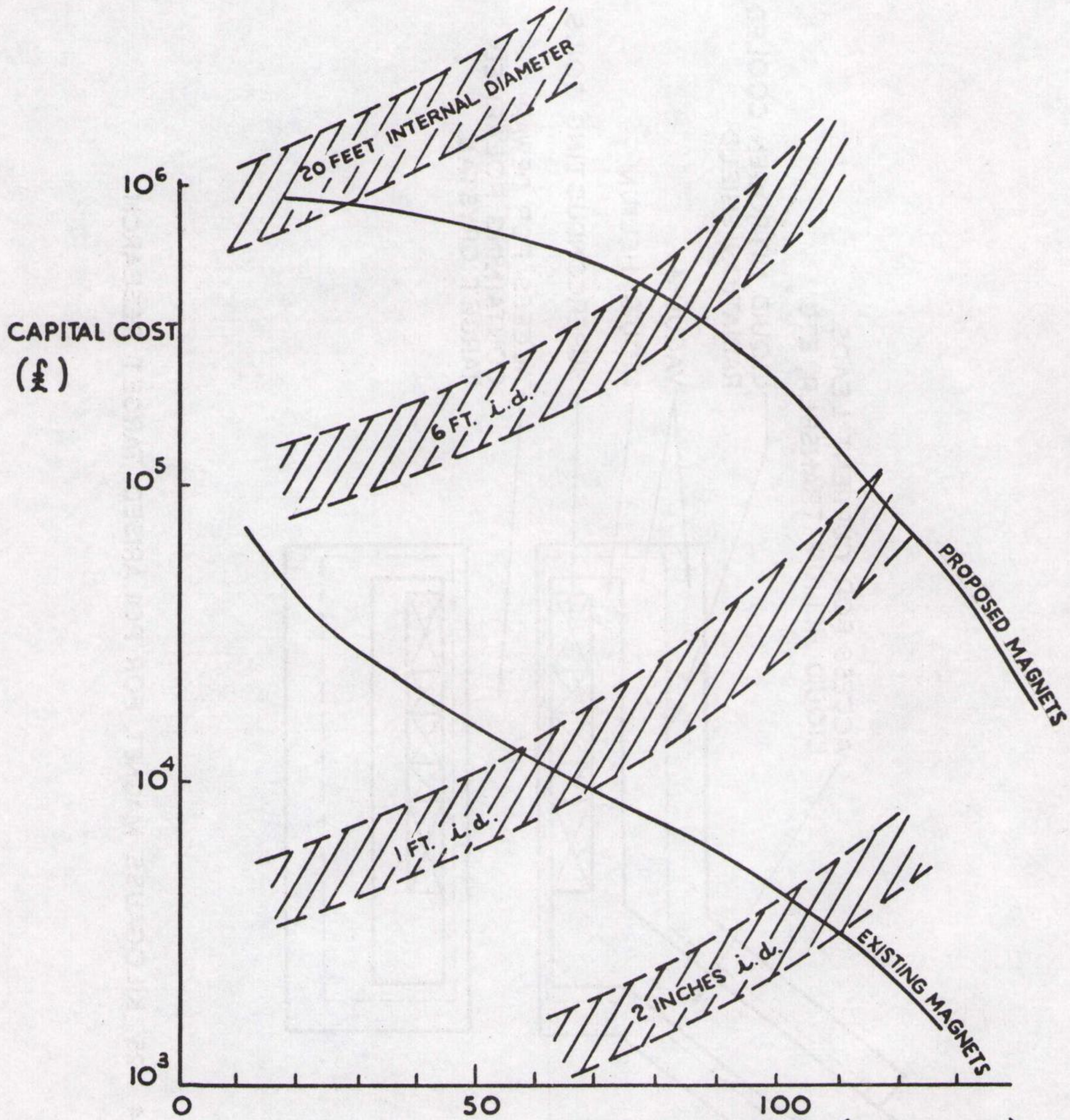

FIG 3. APPROXIMATE COST OF SUPERCONDUCTING SOLENOIDS (APL 1966)

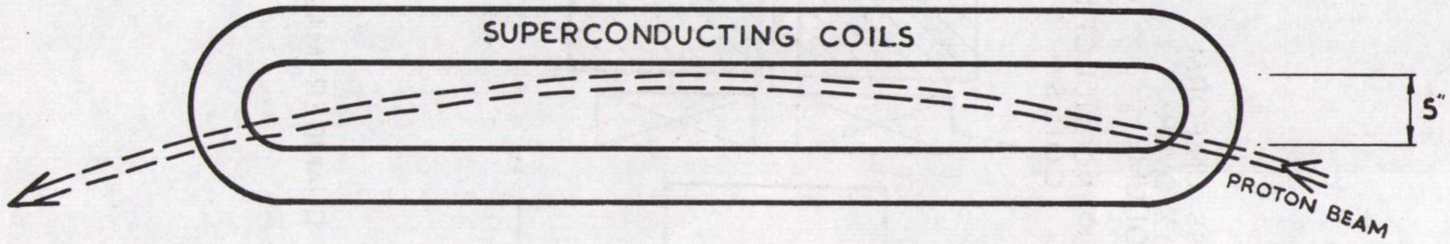

FIG 5 PROPOSED SUPERCONDUCTING BENDING MAGNET.

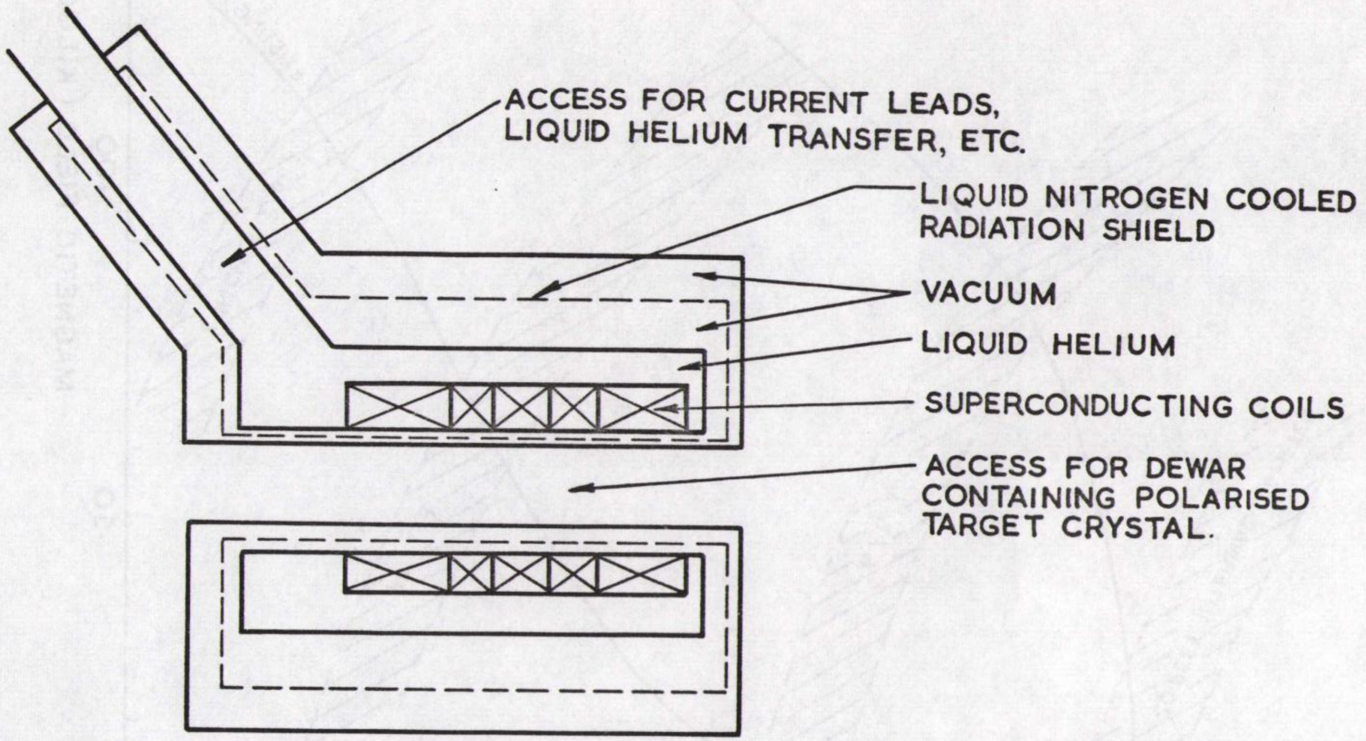

FIG 4 25 KILOGAUSS MAGNET FOR POLARISED TARGET RESEARCH