MAGNET TECHNOLOGY AT THE MULLARD CRYOMAGNETIC LABORATORY OF THE CLARENDON LABORATORY, OXFORD.

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Abstract

The original high field installation of the Clarendon Laboratory is based on a 2000 kW dc generator. This machine now serves 7 water-cooled solenoids, most of them mobile both vertically and horizontally, giving maximum fields ranging between 4.5 T (102 mm internal diameter) and 12 T (25 mm internal diameter). The installation has been used for a variety of experiments comprising nuclear orientation and nuclear cooling, magneto-optical spectroscopy, research on the properties of semiconductors and semi-metals, measurements on high field superconductors and biochemical applications, and a wealth of technology particularly of the design and construction of resistive solenoids has been accumulated.

With the advent of high-field, high current density superconducting materials, our magnet technology has developed in 2 directions.

1) To relieve the pressure on the single power supply, resistive solenoids are being replaced wherever possible by superconductive coils. These range from simple coils built into the experimental helium cryostat to a coil with a room temperature bore of 51 mm which is to all intents and purposes identical with our standard 51 mm i.d. 9 T resistive solenoids.

2) In order to increase the available fields to about 16 T a hybrid magnet is being constructed. It comprises a 9.3 T, 51 mm bore 2 MW resistive solenoid, surrounded by a 6.7 T superconducting solenoid. In addition a 25 mm bore liquid helium immersed 15 T superconducting coil is being designed.

The High Field Installation

The high field installation of the Clarendon Laboratory which dates from 1948 now occupies the whole of the Mullard Cryomagnetic Laboratory which opened in 1963. The facility is centred on a 2000 kW (4500 A, 450 V) dc motor-generator located in a hall adjacent to the magnet laboratory which has two levels with three and four magnet stations respectively grouped around a central control area. The third level houses purification equipment and pumps for circulating deionised water used as the cooling fluid delivered at 0.7 MPa (100/in.^{2}) with a flow of 2.5 m^3/min. (550 gal/min.). An air to water heat exchanger of the forced draught type is included in the system making possible continuous operation at full power. Each magnet station serves up to four fixed experimental gantries in addition to being available for experiments more of a temporary nature. Mobility is achieved by mounting the solenoid on jacks on a wheeled trolley and making connections to it using flexible reinforced hose and water cooled power cables which allow freedom of movement of about 3 metres horizontally and 1 metre vertically. Figure 1 shows the general arrangement of a magnet station.

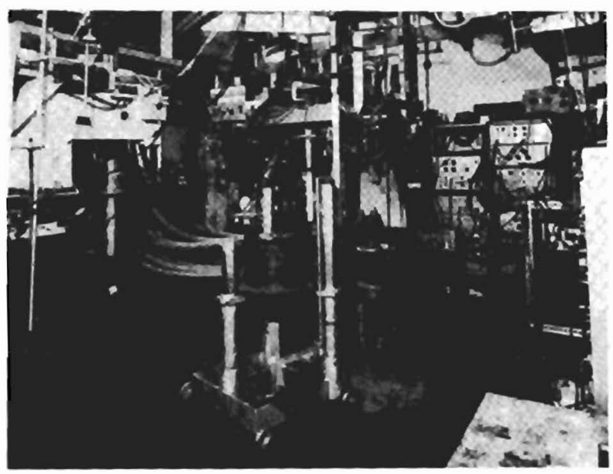

Fig. 1. General arrangement of a magnet station in the cryomagnetic laboratory.

Magnets

Development of magnets designed to match the impedance of the power supply and to meet the needs of expanding research programmes has proceeded along two main lines. In the first largely due to Tsai and described in the literature[1] hard-drawn copper strip is wound under tension into a spiral coil on to a central bush of a chromium copper alloy. Pairs of coils of opposite hand are assembled with a series connection made by a driving fit between the central bushes. During winding the strip is wound with nylon monofilament of usually 0.25 mm diameter and at a pitch of 3 mm to space the turns in a radial direction and provide axial cooling passages. Axial support between coils is provided by spacers of height 2.5 mm machined from a glass-reinforced-plastic laminate and coated with polyurethane. Two coil pairs are connected in series to produce a coil package of simple construction and high reliability. Improvement over the Fabry factor for a rectangular coil of uniform current density is made by grading the thickness of copper strip between coils or sections of coil. Adjustment to the homogeneity of magnetic field over the central region (e.g. by cancellation of the second derivative of the field) is made by alteration to the height of median plane spacer. The coil pairs and axial support spacers are assembled over the bore tube and located on a base plate before being clamped into position in the outer case also fabricated from glass reinforced plastic, see Fig. 2.

Fig. 2. Components of 9.5 T magnet.

TABLE I. Characteristics of some standard "Tsai" Magnets

Useful Bore mm	Coil Geometry $2a_1$ mm	$2a_2$ mm	2b mm	Overall height of magnet mm	Max. working field	Power kW
102	115	285	174	450	4.5 T	1200
51	58	260	126	295	9.5T - 9.9T	2000
25	33	172	100	250	10.5T -10.7T	2000

a_1, a_2 inner and outer radii of solenoid
b half length of solenoid

TABLE II. Characteristics of two "polyhelix" Magnets

Useful Bore mm	Number of sub-coils	Coil Geometry $2a_1$ mm	$2a_2$ mm	2_b mm	Overall height of magnet mm	Max. working field	Power kW
83	7	93	370	205	620 *	7.3	1600
25	10	33	172	trapezoidal winding	250	11.2 - 12.0	2000

a_1, a_2 inner and outer radii of solenoid
b half length of solenoid

*This includes four additional coils for axial profile control of the field in a region 330 mm from the central zone.

The second commonly used design of magnet of which much early development is due to Wood[2] and colleagues at the Clarendon Laboratory and described on several occasions[3] is the "poly-helix", which with concentric sub-coils connected in series is ideally suited to the high voltage power supply of the Cryomagnetic Laboratory. Because of the complicated interdependence of factors influencing the design of such high performance composite coil electromagnets optimisation techniques based on the incremental field per watt concept are adopted but are only possible using a digital computer, the ICL 1906 A of the University Computing Laboratory. Sub-coils are either edge wound from hard drawn copper strip or machined from the solid. Adjacent turns are spaced and bonded with epoxy resin following a phenolic pre-treatment before finish machining to final dimensions. Axial cooling channels usually 0.5 mm in height are formed by bonding strips of glass reinforced plastic to membranes of stainless steel coated with an insulating resin which are inserted in annular gaps between the sub-coils on assembly. Series connections are made with links of copper which are either clamped or soldered to the sub-coil ends.

The installation has been widely used for a variety of experiments including nuclear orientation and nuclear cooling, research on the properties of semiconductors and semi-metals, magneto-optical spectroscopy and biochemical research and also measurements of the properties of high field superconductors.

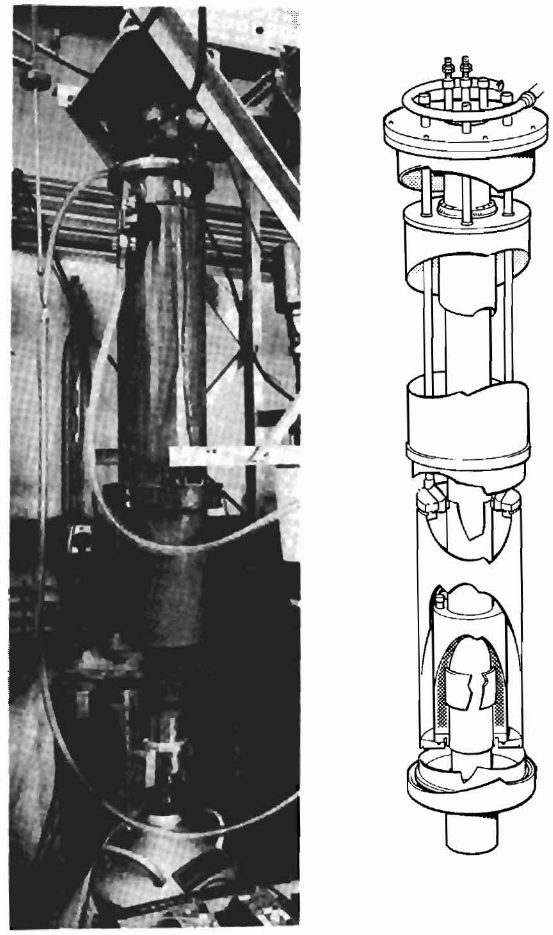

Fig. 3. Cryostat for nuclear orientation studies.

Superconductive Magnets

The successful development of intrinsically stable multifilament conductors of niobium-titanium[4] following early experience with solid core material[5] has resulted in the expansion of a construction programme of superconductive magnets aimed at the relief of some pressure on the 2000 kW power supply and the seven operational solenoids dependent on it.

Many superconductive magnets have been constructed having a wide range of relatively simple geometries and incorporated in experimental helium cryostats for operation at 4.2 K and temperatures below the λ-point to meet the requirements of such applications as nuclear orientation, Raman spectroscopy, Faraday rotation and nuclear magnetic resonance. Typical of such a system is the nuclear orientation cryostat shown in Fig. 3 which includes a 5T coil of 76 mm diameter bore wound from 3 kg of superconducting wire of 0.36 mm overall diameter containing 61 filaments of Nb 44 wt% Ti in a matrix of copper (manufactured by Imperial Metal Industries Ltd.). Sixth order correction for homogeneity is achieved by an inside notch machined from a sleeve cast from filled epoxy resin onto the coil former during construction. Mechanical stability of the windings is ensured by vacuum impregnation with epoxy resin using standard potting techniques and results in reliable operation of the coil on each successive cooldown at a level close to short sample performance of the conductor. The conductor for this particular magnet was supplied in several lengths. The joins made by careful lapping and soft soldering are inside the winding and have a resistance of the order of $10^{-8}\ \Omega$ each. Cryostat design has been largely determined by an existing experimental assembly and is fairly simple. The annular magnet chamber of stainless steel, sealed with demountable indium gaskets has a reservoir of 2.2 litres capacity and is suspended from five thin walled (0.15 mm) german silver tubes 10 mm in diameter and 530 mm long through which the evaporating helium is returned. The current leads made from brass tube run inside these german silver tubes. They were optimised for a total voltage drop of 165 mV and present a surface area of 60 cm^2 per watt dissipated in the lead to the counterflowing gas stream. Brass was chosen as the material for the current leads since overall economies in refrigeration requirements can be made when the leads are to remain connected at the low temperature end yet are used only intermittently to carry the full magnet current.

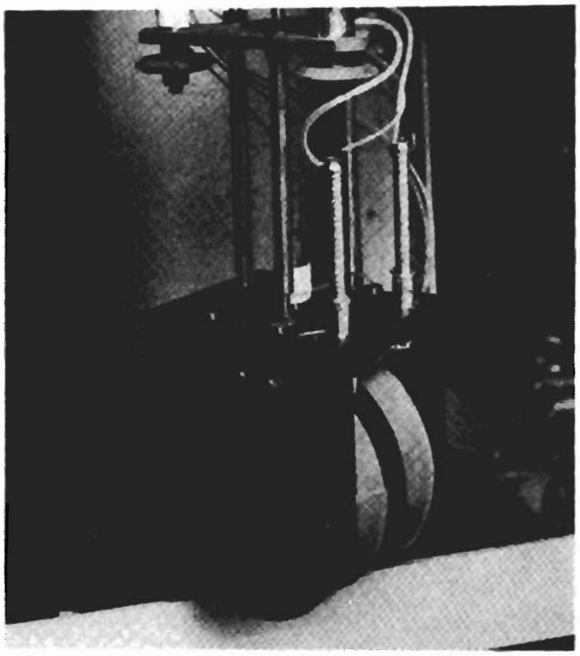

Fig. 4. Split coil for 1.5 K operation.

The split coil shown in Fig. 4 also wound from multifilament conductor of NbTi with an individual filament diameter of less than 30 μ is capable of stable operation at 1.8 K with a corresponding enhancement in performance over operation at 4.2 K[6,7]. This technique is now usefully employed to increase the economic limit of operation of coils made from currently available conductors of niobium titanium to field generation around 10 T.

Currently under construction in our workshops is a superconductive magnet system designed for 10 T operation at 4.2 K with a room temperature aperture of 51 mm diameter (Fig. 5) which can be used as a substitute for one of the resistive solenoids described earlier. The magnet is designed to operate at 150 amperes and consists of a three section outer coil of 105 mm bore wound from intrinsically stable multifilamentary conductor of Nb 44 wt.% Ti graded to suit the local field. The inner coil which contributes 2 T at 4.2 K is constructed with double pancake modules wound from Nb_3Sn ribbon. The design of the cryostat is based on a room temperature aperture system previously constructed in the laboratory which proved highly satisfactory in use. In order to maintain compatibility with the resistive solenoids the overall height of the cryostat was made small. The coil chamber is suspended within the liquid nitrogen shield by means of two 50 mm diameter thin walled (0.25 mm) stainless steel tubes with a length to room temperature of 590 mm. It is thus expected that the liquid helium evaporation rate will be less than 1 litre per hour, the loss rate being accounted for by radiation and the thermal loading of the optimised high current leads. The coil chamber is held in position against sideways movement within the liquid nitrogen shield by six stainless steel wires 0.5 mm in diameter. The liquid nitrogen shield is similarly supported within the outer vacuum case.

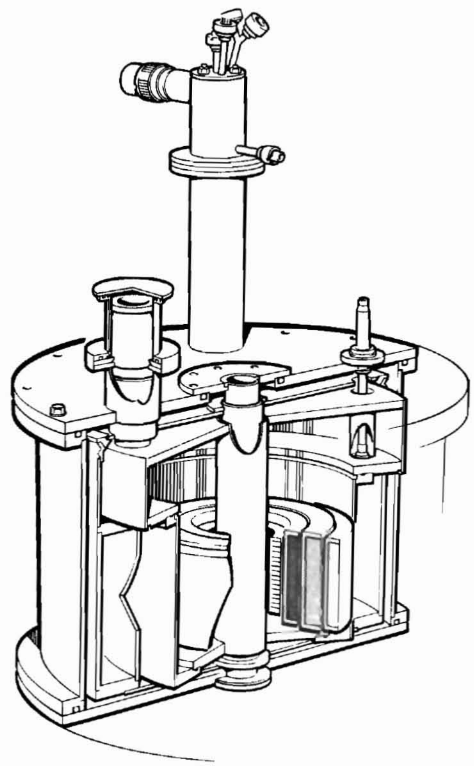

Fig. 5. General scheme of room temperature aperture system.

Higher Field Magnets

There is a growing need in the Cryomagnetic Laboratory for continuously maintained magnetic fields in the range 15 T to 20 T. It is considered impracticable at present to meet this need with an increase in power and an extension to cooling capacity. An additional 5 MW to 7 MW would be required by resistive magnets for the brute-force production of fields in the above range in a bore of 50 mm diameter.

Two other possible ways of producing fields above 15 T are:

1) To construct an all superconductive magnet;

2) To construct a combined superconductive and resistive system or "hybrid" magnet.[8,9,10]

Both methods are being adopted.

For a whole range of experiments a 25 mm bore at 4.2 K is adequate. Furthermore the generation of 15 T in such a bore is within the present capability of the technology of superconductive magnets and can be economically achieved. Thus as a valuable complementary facility a small bore Nb_3Sn solenoid of spiral wound modular design is being constructed* with the above parameters.

As a larger bore facility the hybrid magnet will make efficient use of the 2000 kW installation and be compatible with existing 51 mm bore resistive solenoids in the Cryomagnetic Laboratory such that experimental equipment already developed can be readily accommodated. The design of the combined system[11] is aimed at the generation of 16 T and this will provide a significant increase in large volume field for a minimum of cost. The magnet consists of an inner water cooled solenoid with a working bore of 51 mm diameter generating 9.3 T, surrounded by a superconducting solenoid having a room temperature bore of 250 mm and producing 6.7 T. All water and power connections are located at the bottom end and the inner solenoid can be removed as a unit without disturbing the cryostat and warming up the superconducting solenoid. Thus any other compatible insert can be introduced or the outer superconductive solenoid can be independently used as a large bore facility.

The maximum central field produced by the outer section alone is 0.2 T less than its contribution to the hybrid combination because the stable operating current is reduced by an effectively higher peak field at the superconductor.

A major problem in the design of a hybrid magnet system is the support of forces resulting from the magnetic interaction between the principle sections. Under normal running conditions the axial force is a restoring force and the equilibrium position is stable. However, consideration must be given to an asymmetric failure of the high-power water-cooled solenoid which would result in a relative displacement of magnetic centres and the introduction of a large accelerating force. A small radial displacement gives rise to an unstable situation with an increasing radial force. Because of cryogenic considerations and the need to reduce the refrigeration load, the superconductive solenoid and the resistive solenoid cannot be strongly coupled mechanically. It is therefore desirable to minimise the forces which can potentially act between the two individual sections.

Design of the inner room temperature solenoid is a development, due to Carden[12], of the "polyhelix" scheme described earlier and consists of nine concentric coils connected in six series groups. There are two particular advantages of choosing concentric helical coils for the inner solenoid over the simpler Bitter type of construction. Firstly, by isolating the individual coils both mechanically and electrically the propagation of a local failure is limited to a single coil or pair of coils and the maximum force that can develop under fault conditions is considerably reduced.

Secondly, because the large clamping structure required for axial compression in a disc solenoid is not needed for the coils of the polyhelix, the bore of the superconductive magnet can be made smaller. Axial location of the helical coils is provided by cooling water pressure.

Modular construction of the superconductive outer magnet using rectangular section conductor spiral wound into double pancakes enables best advantage to be taken of variations in critical current between the individual lengths of conductor and also means that damaged sections can be replaced with relative ease should this become necessary. In addition to satisfying the conditions for it to be intrinsically stable, the conductor is also designed to have cryostatic stability. This should thus ensure reliability and predictable operation of the superconducting solenoid even under conditions such as rapid shut-down of the inner solenoid which could result in the adiabatic stability criterion being violated.

Acknowledgements

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