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THE CULHAM SUPERCONDUCTING LEVITRON

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ABSTRACT

This paper describes the mechanical construction of the central section of the Culham Superconducting Levitron with particular regard to the cryogenic aspects of the machine. A short circuited superconducting coil carrying a current of up to 0。5 MA turns is arranged to be levitated magnetically so that a plasma may be formed around it without any structural components invading the plasma. The levitating and plasma trapping fields are also largely provided by superconducting coils. The construction of the superconducting coils and their He gas cooling system is described with a particular note of the cold thermal contact device used for cooling the levitated ring。 The requirements of the cryogenic support structure, which has to provide strength and rigidity yet allow thermal contraction together with low thermal conduction, are discussed and the resulting design to achieve these requirements is described.

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INTRODUCTION

In the field of research which is directed at eventual generation of energy from the nuclear fusion reactions between hydrogen isotopes, worldwide interest in the study of hydrogen plasma physics has been pursued for the last two decades. Many devices for forming and trapping high temperature plasmas have been built and considerable advances have been made towards understanding and controlling plasmas.

There are a number of types of these machines and all of them depend on forming a high energy plasma in a high vacuum chamber and confining it in a limited volume, isolated from the vacuum chamber walls, for as long as stable conditions can be maintained. Since the plasma consists of charged particles moving at high velocity a magnetic field is generally used as the mechanism for confining it. The various geometries of magnetic fields employed give rise to a number of families of confinement systems. One of these families requires a toroidal winding with other windings situated on a vertical axis as shown in Fig.1. A plasma formed within or injected into such a configuration will be trapped in a region surrounding the conductor 'a', the charged particles being forced to follow magnetic field lines which follow a helical path around this conductor. The practical disadvantages of this layout are that in order to supply current to the core conductor and to hold it physically in position, current supply leads and mechanical supports have to pass through the plasma thereby causing the plasma energy to be dissipated and creating poor conditions for plasma observation. One way of overcoming this disadvantage is to pulse the windings 'b' thereby inducing the required current in the core conductor. Meanwhile the supports are withdrawn from the core for a short time during which diagnostic observation of the plasma is carried out. This naturally limits observation to times in the order of several milliseconds whereas for many experiments times of many seconds are necessary. It so happens that the required direction of the current in the core conductor and the direction of the surrounding magnetic field are such that the core conductor is in equilibrium when in the centre of the system and the currents involved are sufficiently high to levitate it to the median plane of the system. Electro-mechanical stabilisation is required however to prevent sideways and angular displacement. If now it were possible to dispense with the supply conductors to the core the system would offer an excellent experimental arrangement for plasma physics studies. This latter condition can be achieved by making the core winding as a short-circuited superconducting coil and inducing a persistent current in it. This type of machine is known as a Superconducting Levitron and one has recently been built by the U.K.A.E.A. at Culham Laboratory for Plasma Physics and Nuclear Fusion Research.

THE CULHAM MACHINE

Fig. 2 shows a pictorial view of the main parts of the plasma trapping chamber. This stainless steel vacuum chamber is 1.7m diameter by 0.9m high in the Culham machine. In this machine the vertical field coils (BV coils) are built as four units which are fed with current in pairs so that the field shape can be trimmed to optimise for various types of physics experiments. There are several methods of creating a plasma, the usual method in this machine is by injecting a beam of high energy neutral particles into the neighbourhood of the core conductor. This conductor is generally known as the "ring" in the Levitron. In this region the particles are ionised and are trapped by being forced to gyrate at their ion cyclotron radius around the field lines while at the same time following the helical path of the field lines around the ring. Hence a toroidal volume of plasma is formed around the ring. For physics reasons it is necessary to have a vacuum of 10^{-9} torr in the plasma region so the whole chamber is pumped by turbo molecular pumps and the critical regions at the centre are further pumped by surfaces cooled to 4.5 K and 3.2 K. The general vacuum environment serves also as the thermal insulation for the cryogenic components within.

As was explained earlier, the whole advantage of this machine lies in making the levitated ring as a superconductor. Since the BV coils are in close proximity to the ring and contained within the same cryogenic and vacuum envelope it was found economic to build these as superconductors as well.

The toroidal field coils ($B\phi$ coils) which surround the chamber are of more conventional water cooled copper design. The maximum currents required in the various coils are: ring 500×10^3 amp. turns, outer BV 550×10^3 amp.turns/coil, inner BV 990×10^3 amp.turns/coil, $B\phi$ 900×10^3 amp.turns. These currents result in considerable attractive forces between the BV coils, e.g. 300 kN between the outers and 100 kN between the inners, so that the support structure between them has to be quite massive. Considerable mechanical forces can also occur, under some fault conditions, between the BV coil system and the $B\phi$ system. These large forces must be supported through the mechanical structure which links the cryogenic components to the vacuum chamber shell which is at room temperature.

The BV coils, being secured to the internal structure of the machine, are cooled by circulating helium gas at 4.5K and a pressure of 1.2 atm. through them in a closed cycle from an external refrigerator. The ring cooling however poses a unique problem since it must float freely in the centre of the plasma region and it is not possible to provide a continuously piped supply of coolant to it. A number of pairs of indium faced copper blocks cooled to 3.5K are driven in hydraulically and clamped to the ring to cool it to the required temperature. When the ring is sufficiently cool and has been energised these cold clamps are withdrawn so that the experiment can commence. The thermal capacity of the ring is made sufficiently high for it to remain below the critical temperature for many minutes. A typical experiment requires the ring to levitate for half a minute and the cold clamps are re-introduced between experiments.

Stability of Ring

The ring, though stable vertically, is in unstable equilibrium horizontally and in some modes of operation unstable against "flip over". Its position is sensed optically and error signals are fed to servo amplifiers which control the current in a system of twelve stabilising coils positioned around the ring and which provide local magnetic fields to oppose ring movement. These coils are wound from copper strip housed in stainless steel cases and are kept at liquid nitrogen temperature by a piped supply. When the ring occupies its proper position in the true centre of the magnetic system there are of course no de-centring forces induced in it and no current flows in the stabilising coils. With slight displacements the de-centring force increases alarmingly, typically at the rate of 30 kN per cm. It is impracticable to provide sufficient power in the stabilising coils to cope with more than 1 mm displacement and even at this the servo-amplifiers are generating 30 kW in the liquid nitrogen cooled stabilising coils. It is therefore necessary to provide a means of catching the ring should it escape from the stable position. A strong aluminium alloy catcher cage surrounds the plasma region so that the kinetic energy of the escaping ring will be prevented from damaging the comparatively delicate components of the machine. The catcher cage is supported from the vacuum chamber wall through an energy absorbing system in order to limit the force of the impact on the ring itself. Since the catcher cage is run at liquid nitrogen temperature its electrical resistance is reduced to a low value and it provides a degree of dynamic stabilisation to the ring due to induced eddy current braking. In practice the positional fluctuations of the ring when floating are smaller than 10^{-2} mm.

A detailed account of the ring stability problems and the design of the stabilising system is given in ref. /1/.

Ring Handling

It is necessary to pick up the ring from the bottom of the cage, where it rests when the machine is not in use, and manoeuvre it into its central working position before the stabilising system can be arranged to take over. Part of this action takes place when the ring is above its critical temperature or for other reasons has no current circulating in it. During the stages immediately prior to switching over to the stabilising coils the ring will have a large current flowing and unless it is very close to its working position will exert very high forces which will have to be overcome by the ring handling device. To carry out this handling operation twelve positioning jacks have been fitted, four horizontally mounted acting radially inwards and equi-spaced around the periphery, four acting vertically downwards from above and four acting vertically upwards from below. These positioning jacks are hydraulically operated from outside the vacuum chamber, the outer ends being connected to double acting hydraulic cylinders which operate at room temperature. The inner ends of the jacks which handle the ring must present a very low thermal load on the ring. To avoid the complications of cooling the jacks to 4 K, they are cooled by liquid nitrogen at a point about 30 cms back from the tip and the construction between the cooled point and the tip is made from thin walled stainless steel tube (25 mm. dia.). The heat leak to the ring is then kept to an acceptable level but the strength of the jack is by no means sufficient to withstand the high forces which would be imposed on it when the ring is significantly off centre and full current is present in all coils. The action of picking up the ring and manoeuvring it into the central position is therefore carried out before energising the coil systems, the current in the coils then being built up slowly and the ring position adjusted according to the force re-acting on the jacks as the ring approaches its working position. The jacks are controlled with a high degree of positional accuracy over the innermost 10 mm of their travel and a load cell incorporated in the mechanism gives a reading of the force the ring imposes on the jack. When the ring is properly centred and the stabilising coils are allowed to take control the positioning jacks are withdrawn rapidly to a position outside the plasma region.

Ring

The ring winding itself consists of 3,461 turns of 0.75 mm. dia. wire containing 121 twisted filaments of Nb - Ti wire in a copper matrix, wound into a circular cross section of 70 mm diameter, the mean turn diameter being 600 mm. It is overwound with 1 mm thickness of glass tape and vacuum impregnated with epoxy resin. This winding is fitted into a 5 mm thick stainless steel case designed to withstand a working pressure of 150 atmospheres. The case is electron beam welded around the winding under carefully controlled conditions which ensure full penetration in order to achieve the maximum strength at the joint whilst avoiding too deep penetration of the beam which would burn into the winding. The weld also has to be vacuum tight. The winding is located centrally in the case by P.T.F.E. spacers which leave an annular space of 2.5 mm around the winding. The space is filled with helium at a pressure of 150 atmospheres at room temperature and the filling orifice is sealed off by welding. The outer surface of the stainless steel case is highly polished and copper plated to a thickness of 0.25 mm and a final gold finish has been added to keep the emissivity as low as possible. The copper plating has the effect of conducting the heat to the cold clamp pressure points from the rest of the surface. The complete ring weighs 70 kg. Fig.3 shows the short sample characteristics of the superconductor at a number of temperatures. The load line for the winding has been drawn in to indicate the position of the maximum operating point.

Helium was chosen as the filling medium in order to provide high thermal capacity and to ensure good thermal conductivity between the case and the winding. At the working temperature the helium pressure is between 1 and 2 atmospheres and the 1 litre contained within the ring case accounts for a very large part of the total thermal capacity of the assembly. In practice this has proved sufficient for the ring to remain superconducting for 20 minutes after the cold clamps have been removed. The winding was tested in gas prior to being welded into the shell by feeding it with a current giving a total of 0.5 MA turns and the temperature was allowed to rise until the coil quenched at 5.5 K indicating a performance very close to the short sample value.

A photograph of a cross section through a dummy ring using copper wire is shown in Fig.4. The electron beam welds at the equatorial joint can be seen and the P.T.F.E. cord spacers are also visible.

BV Coils

In the early design conceptual stage the BV windings were envisaged as liquid helium cooled coils wound in a porous support following the conventional superconducting coil construction. However the experiments carried out when developing the gas cooled epoxy encapsulated ring winding were so successful that it was decided to use a similar construction for the BV coils. They are wound from multi-strand twisted Ni - Ti filaments in a copper matrix. The outer coils use a conductor 1.45 mm diameter having 163 filaments and a 4 : 1 copper to superconductor ratio while the inner coils use a 1.45 mm diameter conductor having 361 filaments and a 2 : 1 copper to superconductor ratio. The magnetic centres were measured and carefully related to reference pads fixed to the outside of their cases. When the four BV coils were mounted in the framework they were lined up to ensure parallel and axial location by using these reference pads. Helium gas at 4.4 K and a pressure of 1.2 atmospheres is flowed continuously through the cases from a closed circuit refrigerator plant. The electrical connecting leads are cooled by the return gas passing along their entry conduits. In practice it has been found that this rigidly encapsulated type of winding will operate immediately at its full working current without having to be "trained". The stainless steel cases are of all welded construction and in order to ensure that the winding is firmly held within the case and cannot move under the magnetic forces a large "wavy washer" type spring of phosphor bronze is compressed between the winding and the case.

Further details of the design manufacture and testing of the superconducting windings will be found in refs. /2/ , /3/ .

Cryogenic Support Structure

The requirements of the BV coil support structure are that it shall

(a) withstand the forces generated between the BV coils with a minimum of deflection

(b) withstand possible accidental torque of 2×10^4 Newton metres with respect to the Bϕ winding about a horizontal axis

(c) allow the BV coils to contract 4 mm across their diameter while keeping them concentric to the whole room temperature system

(d) provide as low a thermally conductive path as possible between the cryogenic and room temperature components.

The strength and rigidity required by (a) and (b) calls for a massive structure, but (d) requires that the structure be of low cross sectional area. To satisfy (c) the structure must be able to accept a uniform expansion about the axis without sacrificing rigidity. It is important then that in satisfying any of these requirements none of the others is made to suffer. The main elements of the support structure are shown in Fig.5.

Four box section beams fabricated from 1 cm thick stainless steel are bolted to the four BV coils to form a rigid assembly which operates at 4.5 K. The beams are cooled by conduction from the coil cases and in order to aid rapid heat transfer from the mass of the beams they are copper plated to a thickness of 0.75 mm. The assembly of the four BV coils and the cryogenic support structure weighs 1054 kg.

This 4.5 K assembly is mounted on a liquid nitrogen cooled strong ring through a triangulated tubular structure. This choice of structure allows the expansion differences between the 4.5 K and 77 K components to be accommodated within the elastic deflection of the tubes while maintaining concentricity. The tubes are 45 mm diameter 1.6 mm thick in order to provide high load bearing struts with low cross sectional area. The liquid nitrogen cooled strong ring is made from 76 mm diameter x 6.3 mm thick stainless steel tube and is anchored to the base plate of the main vacuum chamber through six mounting pads. The contraction across the major diameter of the strong ring is 4.3 mm and this is accommodated by arranging the fixing between the ring and pad as a pin sliding in a bush and allowing the ring radial movement only at each of the support points. The bush is lined with glass loaded P.T.F.E. to provide a good sliding bearing and at the same time to reduce thermal transmission losses. With this construction the total heat conducted to the helium cooled surfaces is 2 watts and the total heat input through the support pads to the liquid nitrogen system is 24 watts.

A stainless steel framework is welded to the strong ring so that the assembly forms a cylindrical skeleton of liquid nitrogen filled tubes which support and cool a sheet copper radiation shield which completely envelops the cryogenic components. Screens at 77 K are also fitted between the BV coils and the plasma region to avoid direct bombardment of these cold surfaces by the high energy plasma particles with consequent evolution of loosely bound hydrogen. These BV screens could suffer high induced forces under some operating conditions so they are built from heavily copper plated stainless steel instead of plain copper.

The Refrigerator System

The 3.2 K and 4.5 K components are cooled by circulating helium gas from a B.O.C. refrigerator. The system employs a standard refrigerator which uses liquid nitrogen precooling at 10 atmospheres followed by expansion through a turbine and several stages of heat exchange between flow and return gas. The output of the refrigerator at 5 K, 9.5 atm. is fed to an "auxiliary cryostat" where it is expanded through a Joule Thompson valve to form a liquid sump at 4.4 K. The gas boil-off from this sump is circulated through the superconducting coils at 1.2 atms. A second sump in which the pressure is further reduced by pumping provides a temperature of 2.9 K. Heat exchange from these sumps to the circulating gas provides outputs of supercritical helium at 3.0 K 2.5 atms. for the cold clamp and cryopump supplies.

Fig.6, which is reproduced here by kind permission of B.O.C., shows a simplified flow diagram of the system. The auxiliary cryostat and cold box are mounted immediately beneath the Levitron vacuum chamber in order to keep the vacuum insulated transfer lines compact. The compressor which is a two-stage 500 c.f.m. machine driven at 300 r.p.m. by a 125 H.P. motor is installed in a separate building 50 metres away. The vacuum pump associated with the 2.9 K sump is a two-stage non-lubricated rotary piston machine driven by a 30 H.P. motor.

The calculated machine loads are:

1. BV coils, 8 watts at 4.5 K
2. BV current leads, 0.15 g/s helium at 4.5 K, 1.2 atm.
3. Cold clamps, 10 watts at 3.5 K
4. Cryopumps, 1.5 watts at 3.2 K
5. Heat inleaks along relief valve lines 2 watts at 4.5 K.

The refrigerator was designed for loads 50% higher than these calculated figures. A fuller description of this system is given in /4/ .

The Liquid Nitrogen Circulating System

An extensive liquid nitrogen supply system is provided to supply the many 77 K internal components. The strong ring and radiation shield tubular framework are fed at the bottom through a magnetic valve which is controlled by a vapour pressure operated level sensor. Four vacuum insulated header tanks are fitted above the vacuum chamber and are filled automatically with liquid nitrogen. Outlets from these tanks are taken through the top plate of the vacuum chamber to feed the stabilising coils. This static immersion arrangement satisfies the widely varying demands of these coils which under equilibrium conditions consume minimal liquid but under some conditions could suddenly evolve 30 kW for several seconds.

The cold clamps, positioning jacks and catcher cage supports are all fed with a continuous throughput of liquid nitrogen from a 1.5 atm. pressurised supply line. Many of these components need to have considerable movement at the point where the supply pipes are attached, and it is necessary to provide much of this plumbing in a flexible form. Over fifty pieces of flexible tubing of lengths between 0.5 metres and 2 metres have been made from 10 mm. dia. and 30 mm. dia. stainless steel bellows tubing fitted together concentrically with the interspace evacuated and permanently sealed. In addition to these flexible supply lines a further sixty liquid nitrogen distribution pipes are required to connect to a large number of components mounted on the vacuum chamber. In order to avoid the difficulty of accurately tailoring each of these pipes as rigid double walled items a simple design of "semi-flexible" vacuum insulated line has been standardised. These lines are basically 10 mm. diameter soft copper tubing with standard cone couplings for connecting. They are sleeved with 30 mm. diameter stainless steel bellows which is also evacuated and permanently sealed. These lines could be manufactured remotely from the machine without need for high dimensional tolerances and formed to convenient runs in situ. The couplings were individually insulated on assembly by moulding a self-foaming polyurethane block over them. Many of these continuously fed components are plumbed in parallel and to avoid the unstable flow conditions usually met in liquid nitrogen flow systems of this type the "exhaust" pipes from each of these components are fed into a common phase separating chamber where the gas is allowed to vent freely. The overspill liquid is drained from the separating chamber and returned to a main storage vessel.

Mechanical Design Philosophy

The large number of components installed inside the vacuum chamber, the interconnecting piping and the radiation shielding has led to an assembly where access to the internal components is severely limited. When the rest of the experimental installation is considered it is seen that any dismantling of the vacuum chamber would be a major job. It was necessary therefore to place reliability very high on the list of design requirements. All of the coil cases, whether for nitrogen or helium cooled coils, were designed to be permanently welded around the windings and as the assembly was built up the inter-coil plumbing was fitted by welded joints. This philosophy of an all-welded system instead of a demountable joint system has been followed wherever it is felt that the highest vacuum integrity is more important than serviceability even to the extent of using a welded joint as the vacuum chamber cover plate seal. There are, however, a large number of port holes fitted with detachable cover plates on the surface of the vacuum chamber for the facility of fitting various diagnostic devices. In these instances gold wire seals are used. In order to satisfy the requirement for vacuum integrity, good weldability, high strength and low magnetic permability, A.I.S.I. 316 type stainless steel was used throughout. Before being accepted every piece of the material was checked to ensure freedom from magnetism.

Vacuum System

The vacuum chamber is roughed down by a carbon bladed rotary pump and Zeolite adsorbers to a pressure of 10^{-2} torr and below this point by two 250 litre/sec. turbo-molecular pumps. The large surface area of coil cases and cryo structure at 4.5 K automatically provides cryopumping but there are also eight purpose-made cryopumping surfaces made from copper plates each of 0.1 m^2 area which are cooled to 3.2 K by helium circulating from the refrigerator. In practice a pressure of 10^{-6} torr can be achieved at atmospheric temperature and when the full crogenic system is operated the pressure falls to 10^{-9} torr at which point the chamber may be valved closed, and the turbo-molecular pumps stopped.

Operation of the Machine

Careful control is exercised over the rates of cooling in order to avoid unacceptable temperature differences with consequent mechanical stresses across the machine. It is usual to allow 72 hours to cool to 77 K and a further 48 hours before the BV coils are energised. The procedure for inducing current in the ring is as follows: the ring is held above its critical temperature while a reverse current is passed through the BV coils. The cold clamps are then applied to the ring until its temperature falls below the critical point. The BV current is now reduced to zero and increased to its final value in the forward direction thereby inducing the required current in the ring. The initial reverse currents in the pairs of BV coils must be programmed according to the required final currents in the individual BV coils and ring. During this operation the de-centring forces on the ring are continuously measured and the positioning jacks are adjusted to set the ring in the true magnetic centre. When properly adjusted the stabilising coils will now have zero current. The cold clamps and positioning jacks may be withdrawn and the ring will float. Plasma is now formed in the machine by the injection of high energy neutral particles or by resistive heating from induced currents.

The machine first went operational in February, 1973, using a temporary $B\phi$ winding in order to carry out a first stage in commissioning. After several months of experimental programme during which the handling techniques were mastered and plasma physics performance was verified at low levels, the machine was taken out of service for nine months while the permanent water-cooled $B\phi$ winding was installed. The machine became fully operational again in October 1974 and the maximum currents which have been used so far under operational conditions are: ring 325×10^3 amp. turns, inner BV coils 550×10^3 amp.turns (per coil), outer BV coils 450×10^3 amp.turns (per coil), $B\phi$ winding 700×10^3 amp.turns.

In most of these experiments the plasma has been formed by 50 Hz resistive heating induced from a part of the $B\phi$ winding. Further density build up is expected when a high energy beam of neutral particles is injected from a neutral injector which is fitted to the machine and should be working shortly. A report of the plasma physics studies was presented at the International Conference on Plasma Physics at Tokyo, November, 1974 /5/ .

During the operational period the cryogenic system, superconducting coils and the B.O.C. refrigerator have given reliable performance under continuous cooled down conditions interrupted only for the release of gas from the cold surfaces or for planned maintenance of the helium compressor at 3000 hour intervals.

Acknowledgments:

The author wishes to acknowledge the contribution of his many colleagues in the Levitron group led by Dr. D.R. Sweetman and in the Superconducting coil group led by Mr. D.N. Cornish. Thanks are also particularly due to members of the Engineering project team: to Messrs. J.R. Last and T.R. Pedley for their contributions to aspects of the magnetic field system, to Mr. R.E. Bradford for his contribution to the vacuum system design and to Messrs. C.E. Brookes, B.S. Ingram and F. O'Neill for assistance in mechanical design and installation problems.

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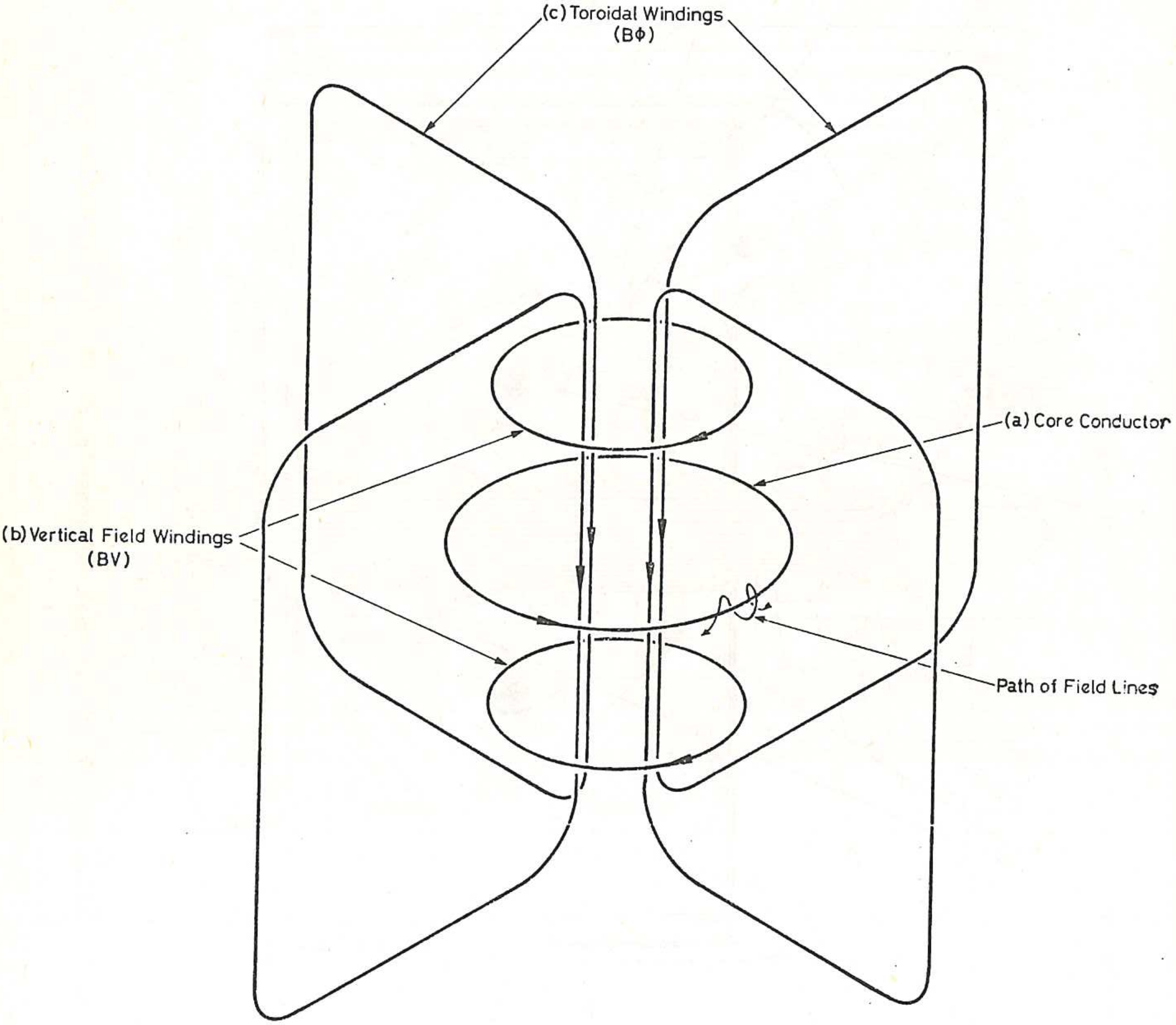


Fig. 1 Arrangement of conductors to create a plasma confinement system

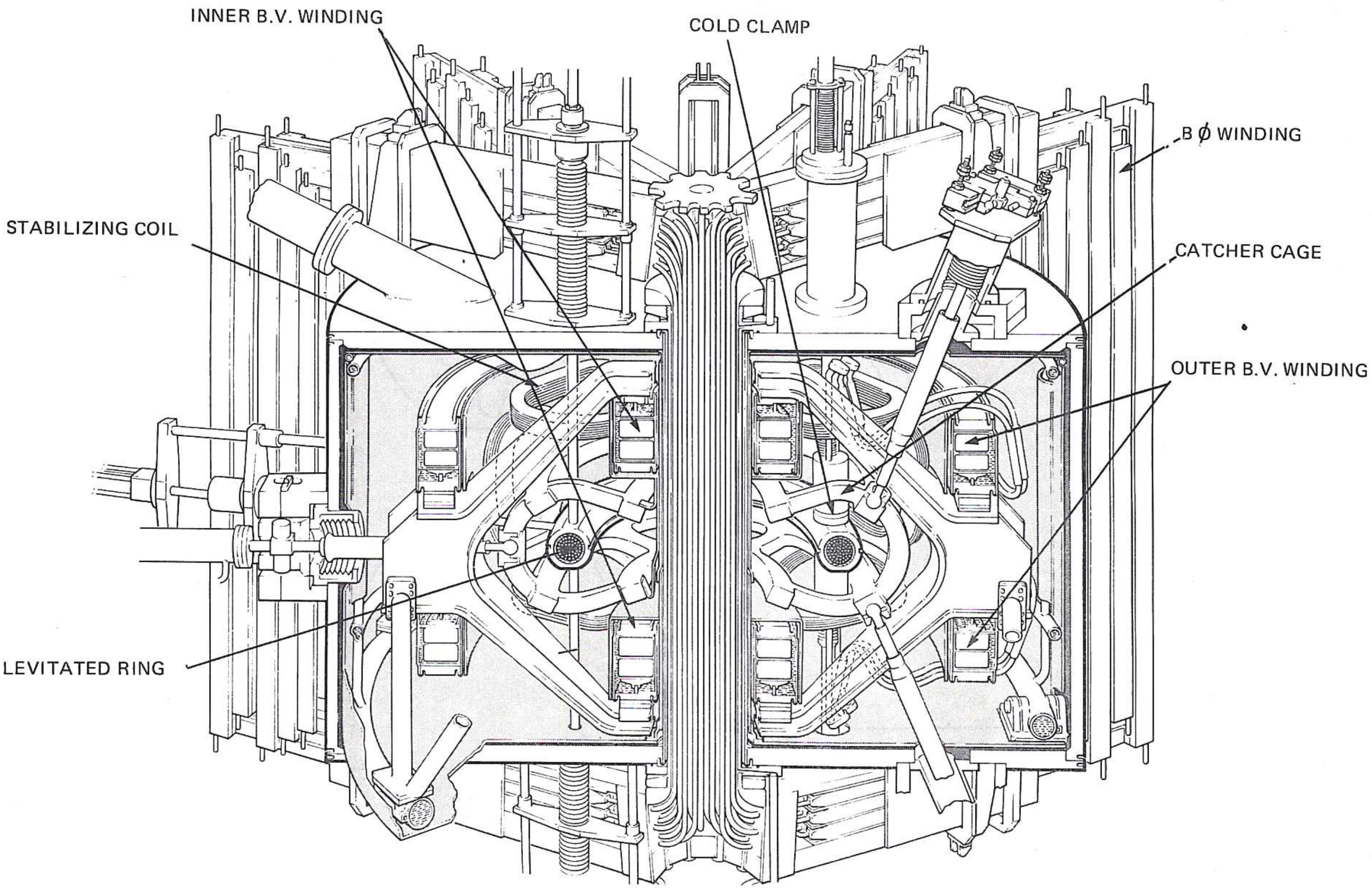


Fig. 2 Illustration of the main components within the vacuum chamber

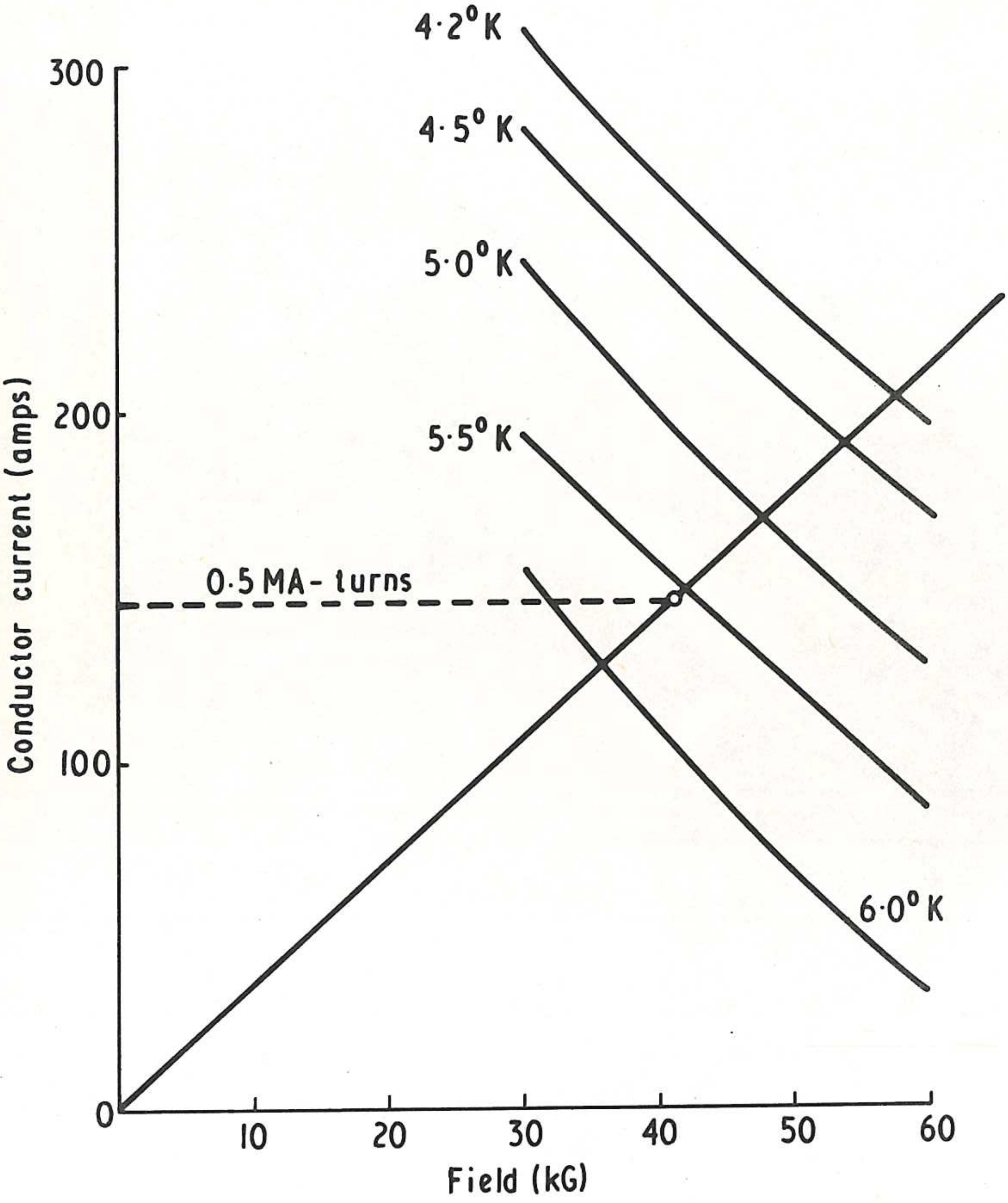


Fig. 3 Short sample characteristics of superconducting wire for ring showing load line

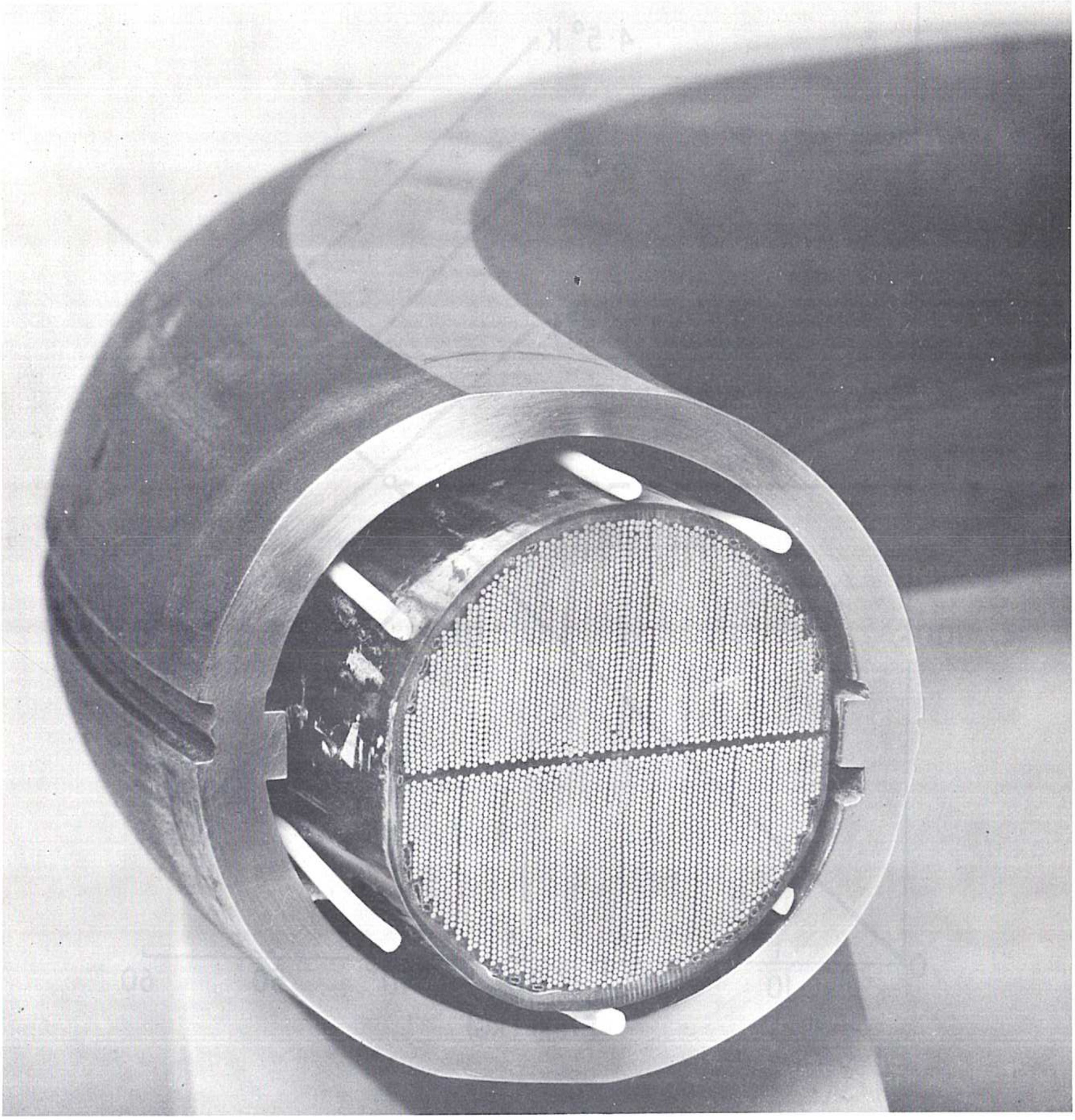


Fig. 4 Cross section through dummy levitated ring

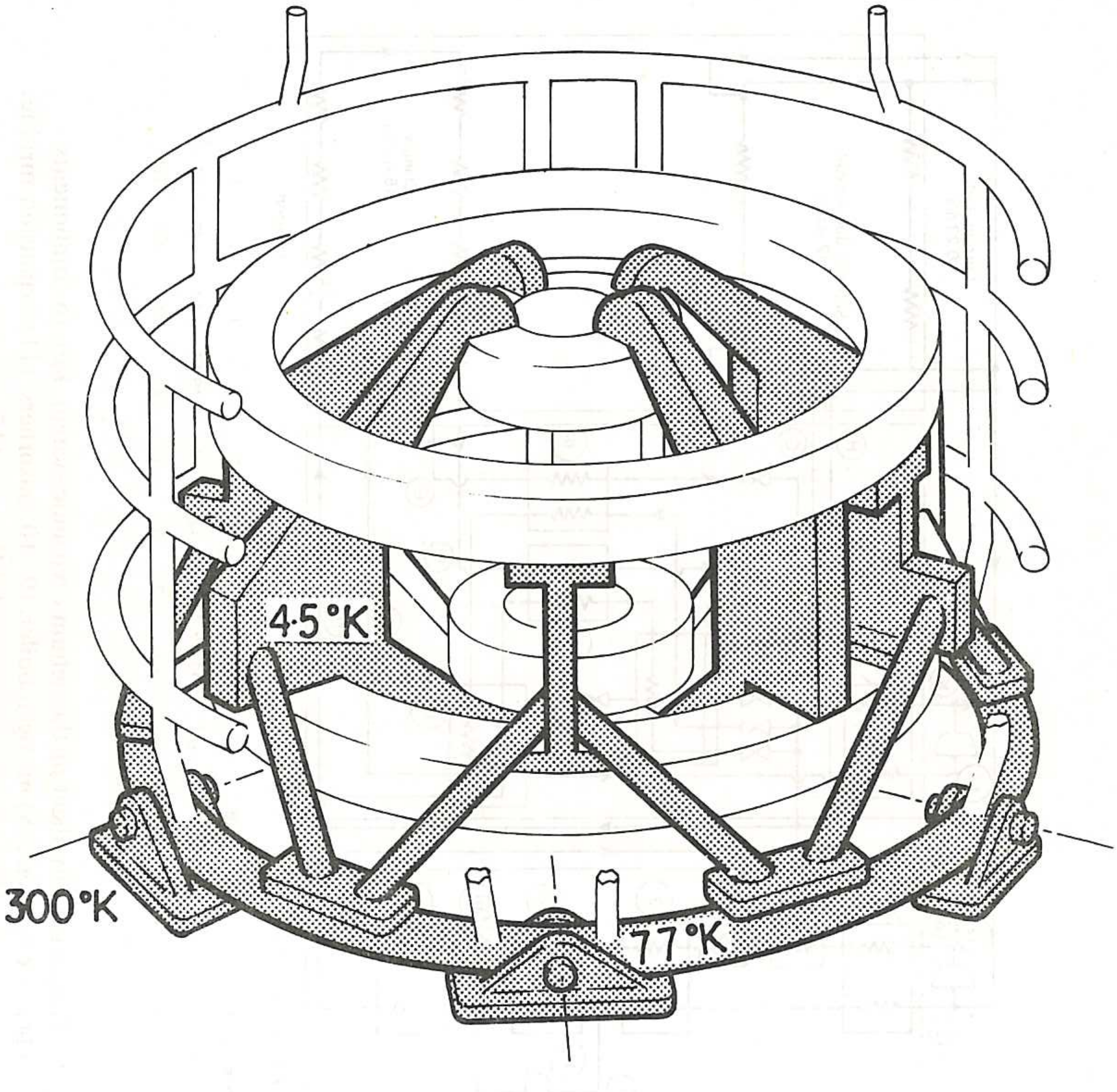
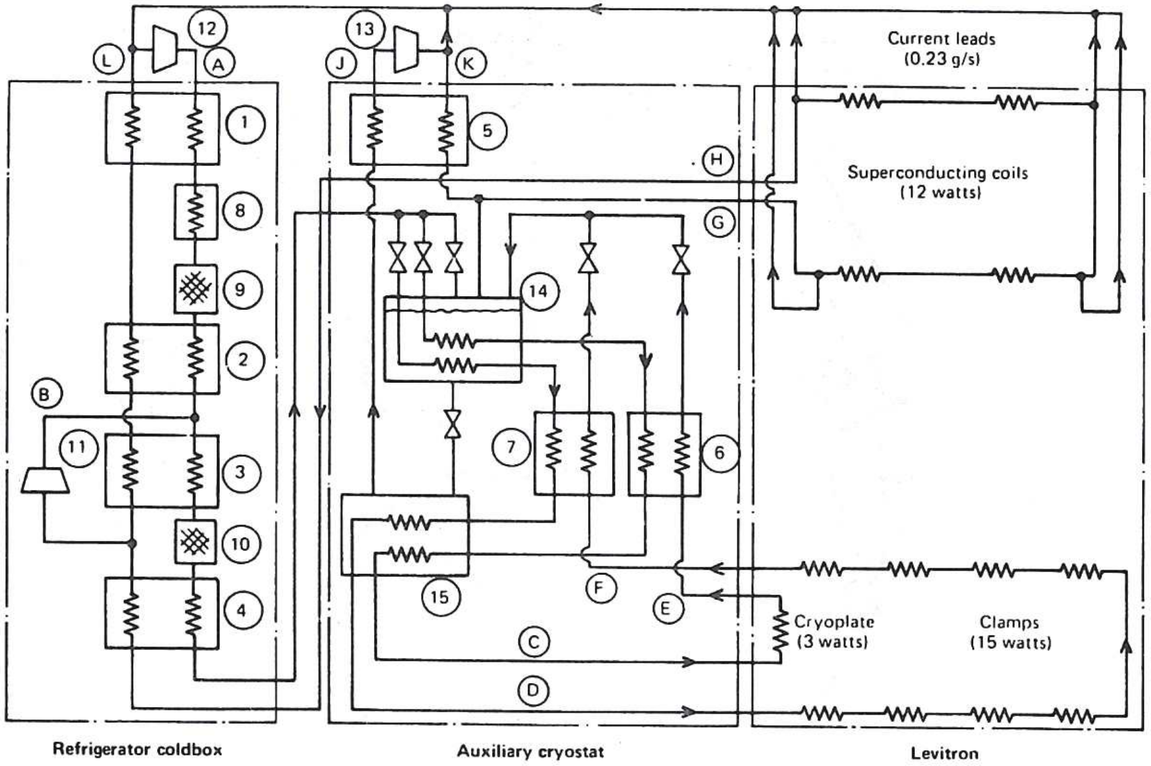


Fig. 5 Cryogenic support structure



Reference point	A	B	C	D	E	F	G	H	J	K	L
Flow (g/s)	37.4	18	6.7	12.7	6.7	12.7	19.4	19.17	2.12	1.90	36.95
Temperature (K)	300	18	3.0	3.0	3.2	3.5	4.4	4.5	295	300	295
Pressure (atma)	10	9.5	2.5	2.5	2.5	2.5	1.2	1.2	0.13	1.23	1.02

Fig. 6 Simplified flowsheet of the helium cryogenic system. Key to components: (1–7) heat exchangers; (8) nitrogen boiler; (9–10) adsorbers; (11) expansion turbine; (12) compressor; (13) vacuum pump; (14) 4.4 K sump; (15) K sump.