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REFRIGERATION FOR THE CULHAM SUPERCONDUCTING LEVITRON

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ABSTRACT

Supercritical helium at 3 K is required for cooling the levitated superconducting ring, and gas at 1.2 atmospheres is used for maintaining the main field coils at their operating temperature of 4.5 K. The paper describes the way in which the Levitron and refrigeration plant have been designed together to meet these requirements with the added requirement that all auxiliary equipment must be remote from the Levitron vacuum chamber. The refrigeration plant has been in operation for nearly 7000 hours, initially on dummy load, but in conjunction with the Levitron since November 1972, and details of operating experience are given.

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INTRODUCTION

The Culham Superconducting Levitron has a number of unusual features which we believe will be of interest to those working in the area of cryogenics and superconductivity. It is, as far as we know, the first machine of appreciable size in which the superconducting coils have been specifically designed to operate in gaseous helium. The use of fine filament, twisted niobium titanium conductor, vacuum impregnated in suitable epoxy resin results in coil performances very close to that measured on short samples of the wire.

Separate circuits are required to provide 4.4 K gas at 1.2 atmospheres and 3 K supercritical fluid at 2.5 atmospheres. The design of the Levitron and the refrigeration plant has been co-ordinated so that -

(a) A standard cold box could be used;

(b) The Levitron itself is as simple as possible from the maintenance and operational point of view;

(c) All the non-standard, deep low temperature, equipment is separately housed in an auxiliary cryostat.

DESCRIPTION OF LEVITRON COIL SYSTEM

The main purpose of this paper is to discuss the cooling aspects of the Levitron and the reader is therefore referred to existing literature (ref. 1-5) for further information on this and similar systems.

The heart of the equipment is a room temperature vacuum chamber in which a short-circuited superconducting winding, sealed into a steel case 9 cm minor and 60 cm major diameter, can carry an induced current of up to 0.5 megamp-turns whilst being supported only by magnetic forces. The ring is cooled to its operating temperature by conduction from four pairs of cold clamps which can be brought into contact with it under high pressure and which can then be withdrawn, leaving the ring floating in the vacuum space.

The possibility of cold welding occurring between the clamps and ring, and the rate at which cooling could be obtained between the surfaces in contact in a good vacuum, were investigated on a model. The stainless steel case of the ring is copper plated to a thickness of about 0.015" to improve the thermal conductivity around the ring and it is then gold flashed to prevent oxidation and maintain a good emissivity. The annular space between the case and the winding was filled with helium gas at room temperature and 150 atmospheres to provide good thermal conductivity between the case and winding and added thermal capacity at the normal operating temperature. The top and bottom surfaces of the case are machined flat, as shown in Fig 1, to provide a good bearing face for the cold clamps, which are fabricated from copper and faced with indium pads. The model was built to simulate this arrangement and the effects of clamp pressure, thermal and mechanical cycling, and thermal contact resistance were investigated. The tests showed that a force of 1500 lbs on a 3 in^2 surface was adequate and could be applied many times without the surfaces becoming damaged. Fig. 2 shows the heat transfer rate obtained on the model plotted against ring temperature, the cold clamp being maintained at 3.5 K. Using this data, it was estimated that it would take less than 2 minutes to re-cool the ring from 5 K to 4 K.

In practice, cooling of the ring is close to that predicted. The ring has not yet been energised above 300 kA in the Levitron, although during the proving tests it was run at 550 kA in a separate cryostat. It has been quenched many times at 300 kA when the mean temperature is estimated to rise to 40 K. Re-cooling from this temperature takes about 15 minutes.

With the ring and vertical field coils energised, a high temperature plasma is created in the vacuum space around the ring, and the purpose of the machine is to study the behaviour of the plasma in the presence of the magnetic field surrounding the ring. Heat from the plasma and radiation from the surrounding surfaces will cause the ring temperature to rise and the flight time before re-cooling is necessary, is determined by the thermal capacity of the ring.

The critical temperature of the ring at full rated current is 6 K. To allow some safety margin and a reasonable flight time it was decided to cool the clamps to 3.5 K, using super-cooled helium at 2½ atm. to ensure single phase operation under all conditions. The flight time at full current, during which time the ring temperature will rise from 4 K to 5 K, is estimated to be about 1 hour. This is perfectly acceptable since the ring can be re-cooled in the 2 minutes mentioned above whilst the currents remain unaltered.

The vertical field coils, which are used to induce the ring current and also to provide the levitating field, are shown schematically in Fig.3. For the sake of clarity only the coils and the main low temperature structure have been shown in this diagram. In fact there is very little free space, and that occupied by the coils must be kept to the absolute minimum. A high current density in the winding is vital and space for helium reservoir and expansion volume necessary to limit the pressure in the event of a quench must be minimised. It was considered that the best way of meeting these conditions would be to use windings similar to that in the ring - intrinsically stable Nb-Ti, vacuum impregnated in epoxy resin for strength and to prevent inter-turn movement and cooling with helium gas. The use of gas instead of the more usual liquid has a number of advantages -

(a) No reservoir required in the coil cases;

(b) Instead of liquid level controllers in each coil, only one is required in the main bath in the auxiliary cryostat;

(c) The helium distribution is very simple since the gas flows through all the coils in series;

(d) In the event of a quench the pressure rise in the coil case is very small.

LOW TEMPERATURE SYSTEM

The low temperature system comprises three separate units -

(a) Cold Box This unit houses the standard refrigerator items and produces cold gas which is fed into the auxiliary cryostat through a vacuum insulated transfer line.

(b) Auxiliary Cryostat All the special low temperature items such as liquid sumps, level controllers and low temperature valves are assembled together in this unit. Thus, any item which might require maintenance is removed from the Levitron itself and space is not required in the Levitron for any auxiliary cryogenic equipment. This not only eased the design of the Levitron main chamber but also enabled a relatively simple separate unit to be designed and manufactured completely independent of the Levitron.

(c) Levitron There is a six core vacuum insulated transfer line from the auxiliary cryostat to the Levitron, carrying the coolant to and from the three separately controlled circuits, the vertical field coils, the cold clamps and the cryoplates.

REFRIGERATION REQUIREMENTS

The normal running refrigeration loads were estimated to be:

(a) 8 watts at less than 4.5 K using gas at 1.2 atm. for the vertical field coils;

(b) 0.15 gm/sec of helium gas at less than 4.5 K for current lead cooling at 1.2 atm.;

(c) 10 watts at less than 3.5 K using supercritical fluid at 2.5 atm. for the cold clamps;

(d) 1.5 watts at less than 3.2 K using supercritical fluid at 2.5 atm. for cryopumping in the Levitron chamber;

(e) 2 watts at 4.5 K for heat inleak down blow-off relief valve lines.

To allow for the actual losses being higher than estimated and to ease the operation and control of the cryogenic system the refrigeration plant was designed for loads 50% higher than the above figures. System losses, such as those associated with control valves, transfer lines and liquid sumps comprised an additional load.

The masses to be cooled by the refrigerator were estimated to be:

(a) Field coil and support structure .... 1054 kg

(b) Cold clamps and levitated ring .... 126 kg

(c) Cryoplates .... 5 kg.

CRYOGENIC DESIGN OF COILS

The coil system is arranged so that the gas enters each coil at a point diametrically opposite to the exit point and is thus split into two circumferential paths in parallel. There are cooling channels surrounding each coil and a manifold at the top of the coil case ensures that the gas must flow through these channels from the inner to outer diameter.

The maximum pressure drop through all the coils in series occurs at the commencement of cooling at 300 K when it is estimated to be 0.5 atmosphere with a mass flow of 15 gm/sec. This falls to 0.011 atmosphere under normal running conditions.

Inter-coil forces are taken by a set of four substantial support arms fabricated in stainless steel. Temperature gradients in this structure during cool-down are reduced by copper-plating the arms to a thickness of approximately 0.02"

A number of 0.01" thick washers are required to adjust the total height to the coil assembly inside the case to the required value. They are cut from sheet copper and are positioned at the coil end adjacent to the support structure so that the heat conducted into the coils at these points is spread out and prevents the formation of local hot spots.

The support structure is mounted on a strong ring which also serves as the liquid nitrogen reservoir (Fig.3) for the radiation shields between the coils and the room temperature vacuum tank. There is an independent liquid nitrogen dispensing system for supplying this and other parts of the machine.

REFRIGERATION PROCESS

The refrigeration system employed is essentially a standard machine similar to that used on the Fawley motor project (ref. 6) and is based on a Claude cycle with a single expansion turbine and liquid nitrogen pre-cooling. Referring to the flowsheet (Fig.4) helium is compressed in the two stage dry lubricated compressor to 10 atm. and, after cooling and filtration, passes to the cold-box in which successive cooling occurs in the aluminium plate-fin heat exchangers. The final product, leaving the cold-box at about 5 K and 9.5 atm. is split in the auxiliary cryostat into two streams for the clamps and cryoplate circuits. After partial expansion to 2.5 atm. each stream is further cooled to 3 K by liquid helium baths at 4.4 K and 2.9 K.

These supercritical streams are passed to the Levitron through the six core line and after absorbing heat inside the Levitron return to the auxiliary cryostat. Expansion in the two pressure control valves results in a biphase mixture and the liquid is collected in the 4.4 K bath. The gaseous fraction, together with boil-off from the 4.4 K bath, is returned to the Levitron to cool the magnet coils and current leads.

The cold gas from the 2.9 K bath is heat exchanged against a return stream in an auxiliary exchanger and is pumped by a non-contaminating vacuum pump. Peripheral equipment includes a complete auto recovery system, a small drier for initial system purging and adsorbers at 80 K and 12 K inside the cold-box for long term running. The recovery tank is large enough to contain the helium content of the whole plant thus enabling it to operate as a sealed system. The impurity level should therefore be low and any losses are made up with Grade A helium. If required, the refrigerator is capable of performing the alternative duty of liquifying helium which can be syphoned from the 4.4 K sump where it is produced at the rate of 35 litres per hour.

PLANT LAYOUT

The refrigeration equipment is concentrated in three areas -

(a) The compressor house;

(b) The Levitron area;

(c) The control cubicle.

Due to restrictions in access of personnel to the immediate Levitron area, the control cubicle is sited about 20 metres from the cold-box whilst the compressor is in a separate building 50 metres away.

CONTROL

Plant control is completely automatic after initial cool-down, auto-control loops being provided on the following -

(a) Turbine inlet temperature, achieved by throttling of the inlet valve;

(b) Liquid level control in the two helium baths;

(c) Pressure control on high and low pressure sides of the plant;

(d) Auto recovery/make-up from the recovery tank by means of special helium servo valves.

Turbine stop/start is carried out by push button from this cubicle whilst the main compressor and helium vacuum pump may only be stopped, starting being provided at the machines themselves.

MACHINERY

The compressor is a two-stage V-machine made by Broom Wade and became available as surplus from an earlier project. It operates at the relatively slow speed of 300 rpm which, from the point of view of ring wear, is advantageous. Piston rings and seals are of carbon/PTFE composite. The throughput is 40 g/sec (500 scfm) and the compressor is driven by a 125 hp motor.

The pump used to reduce the pressure of the 2.9 K sump is a two-stage Northey non-lubricated rotary piston machine. Special gas-packed seals are fitted on the shaft to prevent ingress of air. It is capable of pumping 2.5 g/sec of helium with an inlet pressure of 0.13 atm. and it is driven by a 30 hp motor.

The expansion turbine is a BOC helium lubricated machine running at 6000 rps with an isentropic efficiency of over 65%, protected with the standard BOC system.

COMMISSIONING AND OPERATING EXPERIENCE

The refrigerator has now operated for nearly 7000 hours initially against dummy electrical heaters and latterly in conjunction with the Levitron. Some of the more noteworthy experiences may be summarised as follows:

(a) Liquid helium was produced at the first attempt. Similarly the first cool-down of the Levitron was carried right through to 4.4 K although the initial intention was to cool to 80 K only.

(b) No turbine failures have occurred in spite of severe air contamination on two occasions, once due to a pipe coupling on the compressor suction manifold becoming disconnected and secondly due to shortage of feed gas which resulted in subatmospheric suction and air inleakage.

(c) Due to an oversight the plant was left running over a week-end with the turbine inlet valve control coupled to liquid level in the 4.4 K sump via a high gain loop. This gave rise to a short on-off cycle to the turbine - an estimated 3000 start-stops without any damage. This is more than a plant normally performs during its lifetime, and illustrates the reliability of hydrostatic bearings.

(d) The compressor piston rings and sealing glands were examined after about 3000 hours when there was a convenient break in the programme. Wear was not excessive and only the glands on the high pressure piston rod were replaced.

The compressor was due for a full service after 5000 hours but the physics demands on the Levitron have been such that this has not yet been carried out. The machine is due for a shut-down in the near future for additional windings to be fitted, and it is hoped that this service can be delayed until then. The helium leak rate has increased considerably, but this is to be expected under these conditions.

(e) It has been possible to carry out a substantial part of the Levitron commissioning programme without liquid in the 3 K sump. Under these conditions the field coils operate at their normal temperature of 4.5 K but the clamp and cryoplate circuits drift up to 5 K. These conditions are satisfactory for 'floating' the ring at 300 kA and for initial plasma physics experiments to be carried out. The low pressure, 3 K, system has therefore only been in operation for 1000 hours during which time there have been no serious problems.

(f) It was estimated that the refrigerator should be capable of cooling the Levitron from 300 K to 4.5 K in less than 6 hours. The cooling, however, is throttled so that the maximum temperature difference across the coil system does not exceed 30 K which has been rather arbitrarily chosen to prevent damage due to differential contraction. Under these conditions it should be possible to have the plant ready for operation two days after commencement of cool-down. In fact the plant is left un-attended overnight, even during the cool-down stage, and the normal allowance for cooling is three days. However, this is no great hardship since the plant normally remains cold for many weeks at a time.

ACKNOWLEDGEMENTS

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* British Oxygen Company Ltd, London

REFERENCES

1. D.N. Cornish, Proc. International Conf. Magnet Technology, Hamburg, 1970, p. 847.

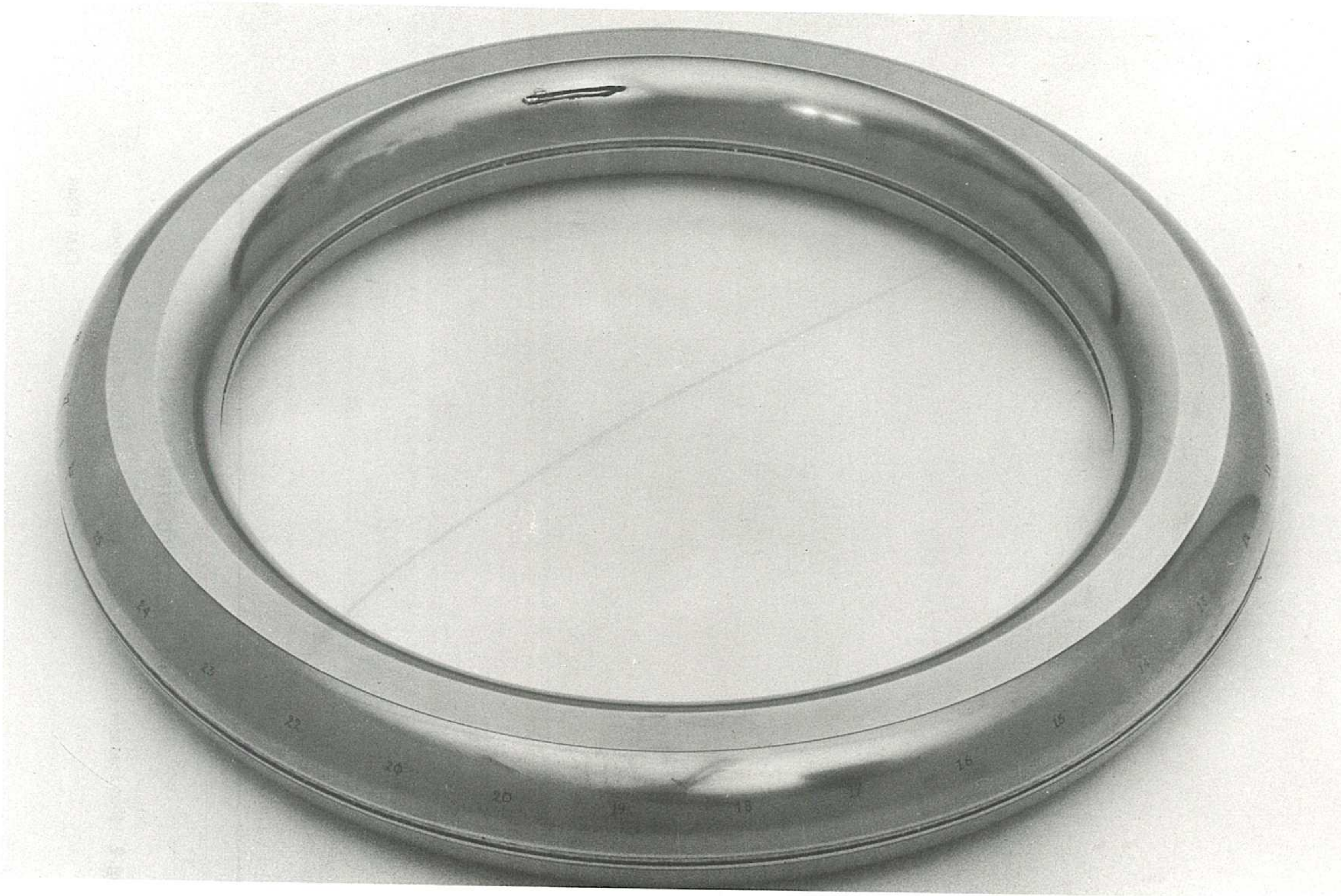
2. C.E. Taylor et al, Lawrence Radiation Lab, Livermore, 1971, UCRL 73076.

3. D.N. Cornish, Proc. Symposium on Electro-magnetic Suspension, Southampton University, 1971.

4. J. File, P. Bonanos, Applied Superconductivity Conf., Annapolis, 1972, p.354.

5. D.N. Cornish, Cryogenics, April 1972, p. 89.

6. F. Tuilin, J.S.H. Ross, Conference on Low Temperatures and Electric Power, London 1969, p.120.



24 inches

Fig.1 Levitron ring ready for assembly in machine

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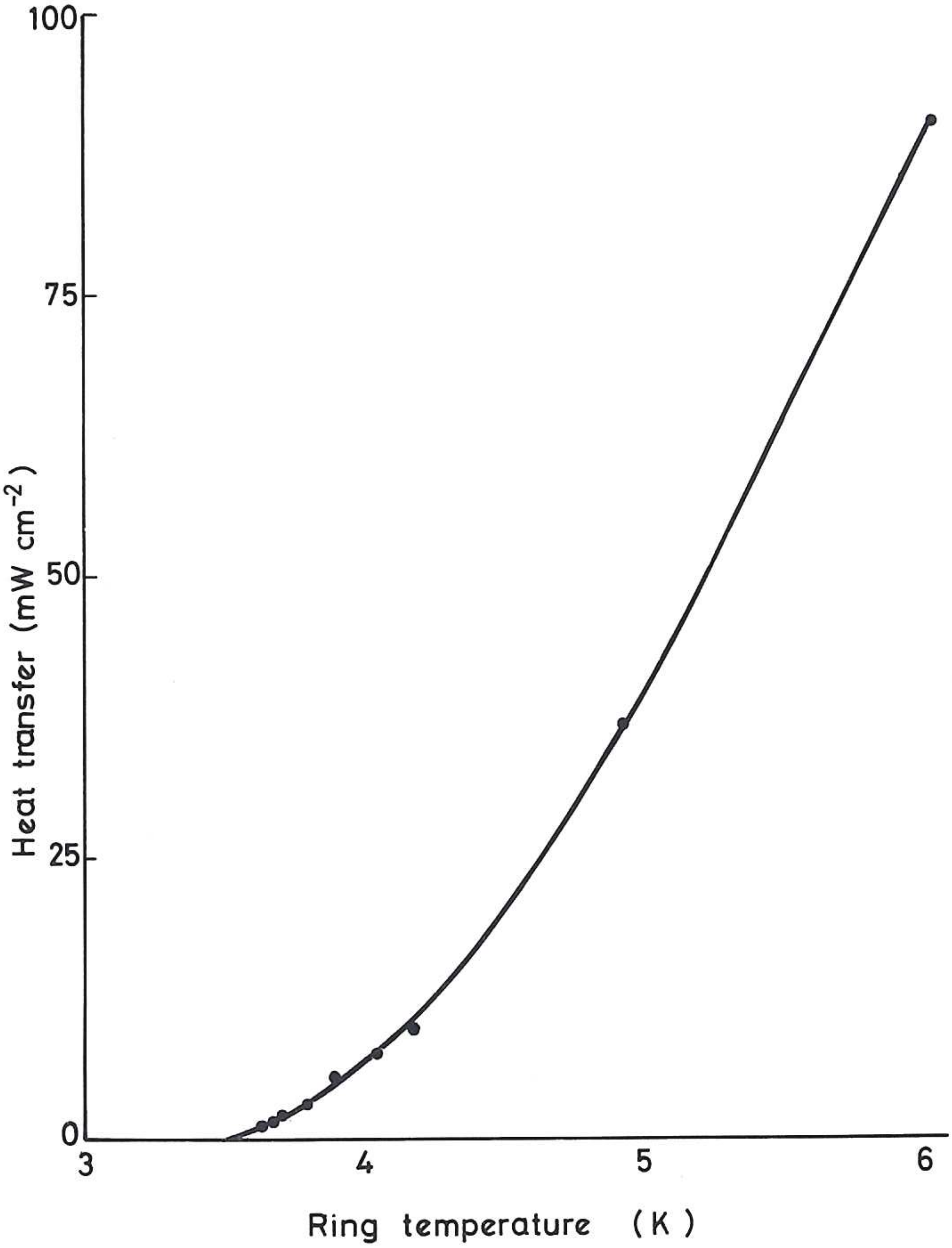

Fig. 2 Heat transfer on model cold clamp. Force = 1500 lb on 20cm^2 surface.

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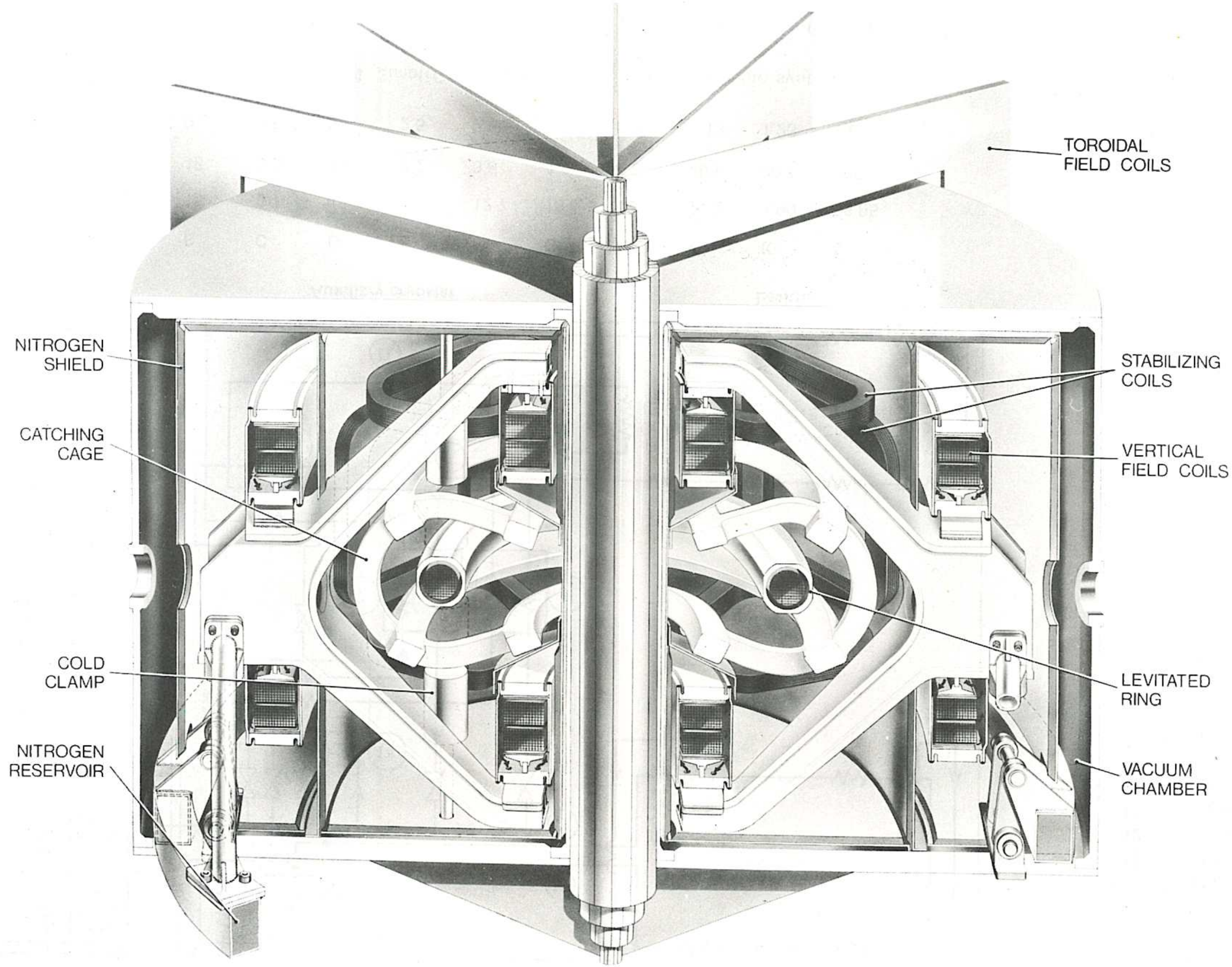
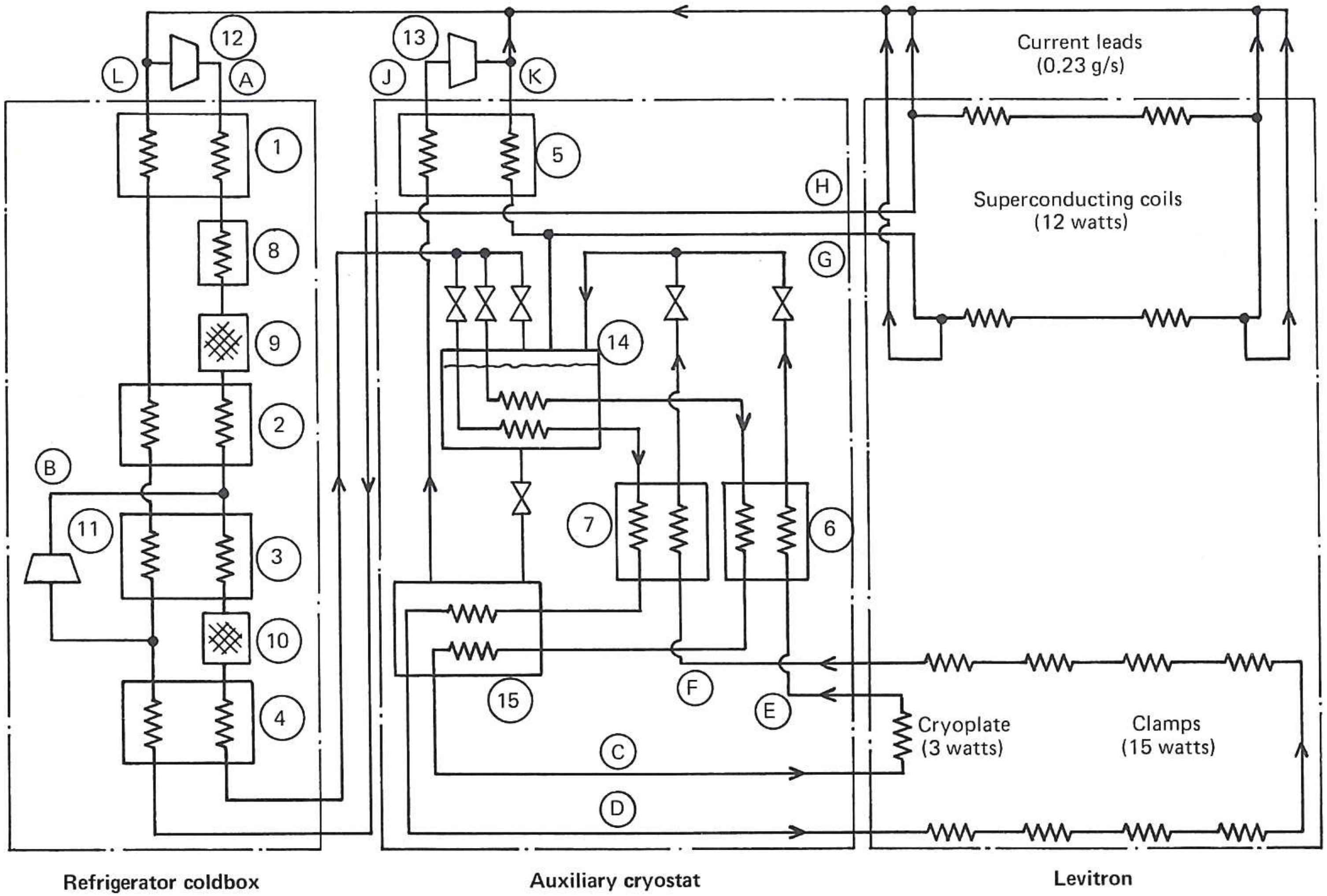


Fig.3 Illustration of central chamber of Superconducting Levitron.



Key to components

1 - 7	Heat exchanger
8	Nitrogen boiler
9 - 10	Adsorbers
11	Expansion turbine
12	Compressor
13	Vacuum pump
14	4.4K sump
15	2.9K sump

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. 4 Simplified flowsheet of the helium cryogenic system.