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THE ESCAR HELIUM REFRIGERATION SYSTEM*

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SUMMARY

The ESCAR cryogenic system, with its two distribution loops offers many advantages. The system models the kind of system that can and should be used in future accelerators. The refrigerator cold box, with its turbine expanders, and the helium screw compressor system represent a significant step in the development of reliable helium refrigeration systems.

INTRODUCTION

ESCAR, (Experimental SuperConducting Accelerator Ring) requires over 1 kW of refrigeration at 4.5° K,[1,2] which is distributed to the magnets and vacuum panels as liquid. Pool boiling was chosen to cool the 56 ESCAR magnets because, 1) pool boiling results in a small temperature difference between the magnet coil and the fluid, 2) there is no temperature rise along the series string of magnets such as might be found in a single phase fluid system, and 3) pool boiling cryostats are simple and least expensive when the heat input per unit length is large.

A pumped subcooled liquid system, similar to the one proposed by Fermilab,[3] was investigated. We found that the maximum pulse rate of ESCAR would be severely limited because the maximum magnet temperature would exceed 5.0° K as the pulse frequency approaches 0.1 Hz. The most important aspect of the ESCAR system is that all of the magnets are part of series distribution circuit.

The system is divided into three parts: 1) the refrigerator and its compressors 2) the cold helium distribution control box, 3) the magnets, the vacuum cryopumping panels, and their transfer line systems. The ESCAR refrigerator will deliver around 1500 W of refrigeration to the machine and its cryogenic distribution system. The refrigeration system distributes a two phase mixture of liquid and gas from the refrigerator to the magnets and cryopanels. Figure 1 shows a general schematic of the cold helium circuit.

THE 1500-W REFRIGERATOR COLD BOX AND COMRPESSORS

The ESCAR refrigerator is one of two being solicited by Fermi Laboratory and LBL. The specifications:[4] 1) LBL requires 3 gs^{-1} of liquid helium and 1450 W of refrigeration at 4.5° K. 2) Fermi Lab requires 1.7 gs^{-1} of liquid helium plus 950 W of refrigeration at 4.5° K plus 1250 W of refrigeration at temperature ranging between 10 and 20° K. Both machines will have identical cold boxes with turbine expanders. Both laboratories plan to use rotary compressors to maximize reliability.

The compressor has been one of the weak links in cryogenic refrigeration systems because it is the source of much trouble and mechanical breakdown. Historically, the standard cryogenic refrigerator/liquifier has been assembled with reciprocating positive-displacement compressors. The reciprocating compressor has many disadvantages: 1) They have a high capital, installation, and maintenance cost; 2) heavy foundations are required to resist high shaking loads; and 3) lubrication problems cause excessive wear when helium is compressed.

Many people in the cryogenic community feel that rotary compressors have the potential for much greater reliability and lower costs. Rotary screw machines, a rather recent development, have established an excellent record in freon, air and ammonia service. Continuous duty with service intervals in excess of 50,000 hours is common. The LBL refrigerator will use an oil-lubricated rotary screw compressor set. The oil provides lubrication, sealing, cooling and an approach to isothermal compression. Oil removal in the helium process stream presents some design challenges.

ESTIMATED HEAT LOADS IN ESCAR

The ESCAR refrigerator is expected to produce 1450 W of refrigeration at 4.5° K plus 3 gs^{-1} of helium liquifaction. Roughly 800 W of refrigeration is required to overcome static heat loads in the magnets cryo pump panels and the transfer lines (see Table 1). The magnet electrical leads require 2-3 gs^{-1} of gas flow. This leaves 600-700 W of refrigeration available for dynamic heat loads.

Table I. Estimated ESCAR static heat loads (W).

Magnet cryostat heat leak (5 W m^{-1} of magnet):	360
Quadrant termination:	80
Magnet transfer lines (1 W m^{-1})	75
Cryogenic vacuum panels:	150
Cryogenic vacuum panel transter lines (0.5 W m^{-1}):	75
Central cryogenic control box:	50
Total static heat load:	790

Dynamic heat loads stem from two sources, the pulsing magnets when the machine is running as a synchrotron and from bunched beam operation when the machine runs as a storage ring. The two modes of operation do not occur together. Pulsed losses are due primarily to hysteritic losses in the superconductor and eddy currents in the magnet bore tube and cryostat structure. The maximum pulse rate of the system is 0.1 Hz. Bunched beam operation in the later phases of the ESCAR experimental program can be expected to contribute large dynamic loads as the bunched beam length drops below one meter.[5]

THE ESCAR REFRIGERATION DISTRIBUTION SYSTEM CONTROL BOX

The heart of the ESCAR refrigeration system is the refrigeration distribution system control box shown in Fig. 2. The distribution control system consists of 1) a storage dewar with a J-T valve, 2) two heat exchangers within liquid cryostats to supply subcooled liquid to the J-T valves located at the magnets and cryopanels, and 3) a system for distributing cold gas, warm gas, and liquid to the system during various phases of operation. The supply and return to the refrigerator are lines A and B coming into Fig. 2. Line C is a return to the compressor suction. Line D is a high pressure supply of warm gas. Lines E and F supply the ESCAR magnets with refrigeration. Lines G and H supply the vacuum panels with refrigeration. Line J brings back warm helium gas from the magnet leads and gas cooled shields.

The liquid cryostats with heat exchangers are an important part of the distribution system. The helium, which enters the heat exchangers with an enthalpy of 14-16 J g^{-1}, transfers its heat to boiling liquid at 4.4° K. The helium leaving the heat exchanger has an enthalpy of 12 J g^{-1}. The mass flow through the magnets is 80-100 gs^{-1}; the flow rate through the cryopanels is around 20 gs^{-1}. The subcooled liquid or supercritical helium, depending on the pressure, is delivered to the magnets through Line F and to the cryopanels through Line G. At least 30% of the flow to the magnets and the cryopanels is returned as liquid in the heat exchanger cryostat. Excess capacity is trimmed in the control dewar by the use of electrical heaters. The refrigerator can operate continuously at full capacity while the load in ESCAR fluctuates.

The rest of the ESCAR distribution control system consists of circuits to direct the flow of warm gas, cold gas and liquid helium during various phases of the refrigeration cycle. The gas leaves the cold box (line A) at a temperature of about 5° K and returns to the cold box

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(line B) at a temperature of around 4.4° K. The projected design mass flow at A and B is 120 gs^{-1}. Lines C and D are normally warm gas lines. The gas in line D always enters the system at room temperature and provides gas to purge and warm up the magnets and cryopanels. The design flow of this line is 100 gs^{-1} The mass flow rate in line C may be as high as 110 gs^{-1} at temperatures that may vary from 10° K to 300° K. The magnet system transfer lines E and F carry up to 100 gs^{-1} at various temperatures and pressures. This transfer line inside diameter will be 50-60mm. The transfer lines at G and H carry 20 gs^{-1} at various temperatures and have an inside diameter of 25-35 mm. Line J (25 mm I.D.) carries warm gas from the magnet leads.

DISTRIBUTION OF HELIUM TO THE MAGNETS AND THE CRYOGENIC VACUUM PANELS

The distribution system consists of two series cricuits controlled by the two control pots with the distribution box. One series system supplies up to 1300 W of refrigeration to the 56 magnets (which are arranged in series). The magnet circuit, which contains 15 to 20 metric tons of cold mass, has by-pass circuits around each quadrant. The vacuum cryopanels, which form the second series circuit, have no by-pass circuits.

ESCAR has a system of cryogenic roughing pumps in addition to the straight section cryopumping panels. These pumps are separated from the main refrigeration system; and are supplied by small local refrigerators or liquid from a dewar. The cryo-roughing system is independent because 1) the pumps are not required to run continuously, 2) the pumps are required to run at times when the rest of the machine is not running, and 3) the cryogenic roughing pump requires 4.4° K refrigeration during the magnet cooldown, when 4.4° K refrigeration is not available from the main refrigerator.

The distribution system for the magnets, is shown in Fig. 3. The magnets must carry the full flow of refrigeration needed to cool all of the ESCAR magnets. The main transfer lines, which bridge the gap between magnet sections and connect the magnets to the helium distribution control box have a total length of 70 to 80 m and an i.d. of 50-60 mm. The by-pass transfer lines, total length 105 m. may be as small as 25-30 mm i.d. The design pressure drop for the magnet system and its transfer lines is 0.1-0.15 bar (1.5 to 2.2 psi).

The cryogenic vacuum panels are also connected in a simple series loop that carries a flow of 17-20 gs^{-1} of two phase helium. This loop consists of flixible transfer line with an inside diameter of 25-30 mm. The design pressure drop for the vacuum panels and their helium distribution system is 0.3 to 0.4 bar (4.4-5.8 psi).

Recent calculations by W. L. Pope[6,7] using the Martinelli-Nelson technique indicates that a 0.1 bar pressure drop in the magnets and their transfer line system is reasonable. The "weir type" magnet cryostat, which permits reasonable phase separation so that one has a true pool boiling cryostat, does not appear to be the major source of pressure drop in the cryogenic system. The transfer lines and the sections between magnets will have to be carefully selected and designed.

OPERATION OF THE ESCAR HELIUM SYSTEM

The ESCAR cryogenic system must operate in a number of different modes. These include 1) pumping and purging of the system of impurities, 2) cooling the system from room temperature to helium temperature, 3) operating the magnets and cryogenic panels over a range of refrigeration rates, and 4) warming up the magnets and or the cryogenic panels selectively. The key to the process is the refrigeration distribution control box shown in Fig. 2.

A detailed analysis of the various operating modes for ESCAR is given in reference 2. For example, the machine is cooled down by injecting cold gas into the control box through line A. This cold gas goes to the magnets through line F and to the cryogenic vacuum system through Line G. The gas is returned to the control box warmer than it left. Depending on the temperature of the gas returning at E and H, the gas is returned to the refrigerator through line B or returned to the compressor intake through line C. Other basic operation modes can be traced on Fig. 2. The valves in the refrigeration control box will be manually controlled at first; provision for future atuomatic operation is designed into the system.

The ESCAR cryogenic system should permit the machine to be cooled down relatively quickly (in less than 2 days). The warm up of various magnets sections should take less than 1 day. The cryopanel warm up will only require a couple of hours. Better estimates of the system warm up and cooldown times require a better understanding of the behavior of the dipole and quadrupole cryostats. In general, the magnet cooldown and warm up appear to be better controlled than in most cryogenic systems of comparable volume and weight. The ease of cooldown is a major advantage of the simple series cryogenic system.

Preliminary studies indicate that the cryogenic system will respond well to transient and emergency situations. Two systems for magnet quench recovery have been studied. Unfortunately more information is needed before a quench recovery design philosophy can be fully formulated.

LIQUID NITROGEN AND UTILITY REQUIREMENTS FOR THE ESCAR CRYOGENIC SYSTEM

The estimated liquid nitrogen consumption in ESCAR is about 40 gs^{-1} (180 ℓ h^{-1}) of liquid at a pressure of about 2 atm. Half of the nitrogen will be used to precool the helium going into the refrigerator. Liquid nitrogen will be delivered to the magnet quadrants and the vacuum pumps for thermal shielding through a number of parallel circuits, which are controlled by thermostatic demand valves.

The refrigeration system requires 1.1-1.2 MW of installed electrical capacity. Most of the power is needed for the refrigerator compressors. Additional electrical power is needed for the cryogenic control system. An estimated 8 kg s^{-1} (120 GPM) of cooling water is needed to cool the refrigerator compressors.

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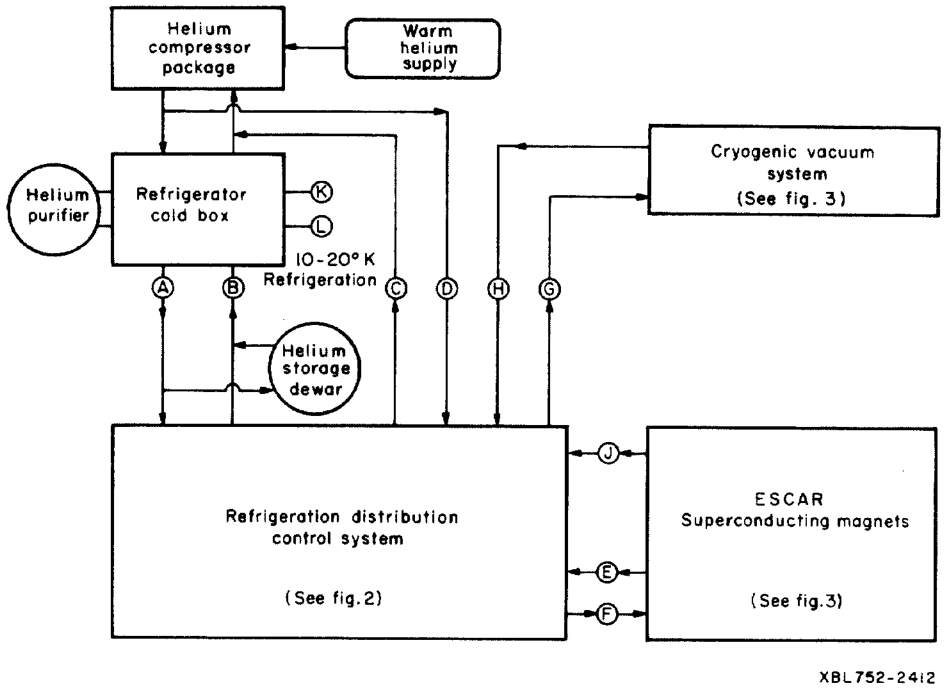

Fig. 1. An overall schematic view of the ESCAR Helium refrigeration system.

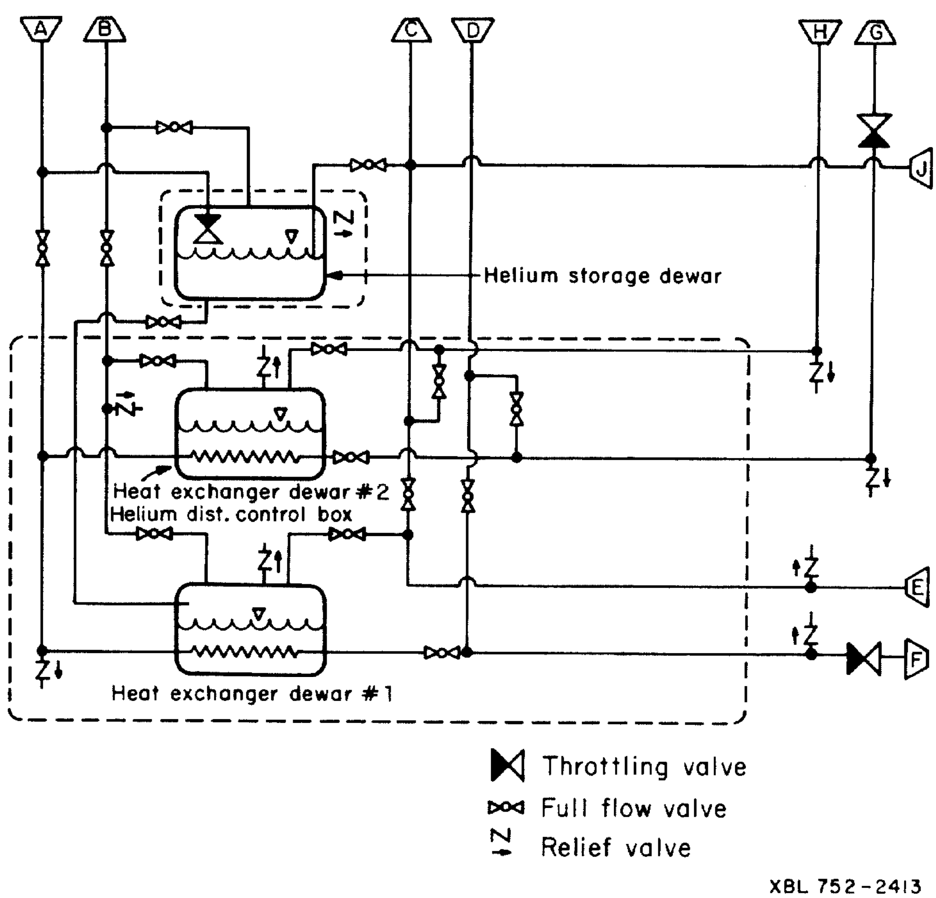

Fig. 2. The refrigeration distribution control system.

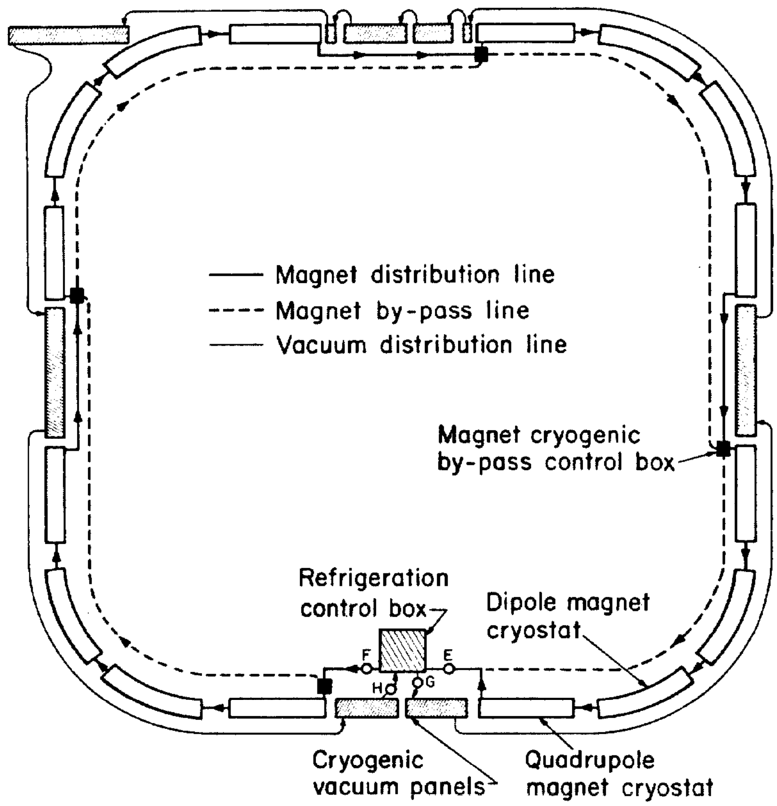

Fig. 3. The liquid Helium transfer line system for the magnets and cryopanels.