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CRYOGENICS FOR THE MUON g-2 SUPERCONDUCTING MAGNET SYSTEM

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The g-2 muon storage ring magnet system consists of four large superconducting solenoids that are up to 15.1 m in diameter[1,2]. In addition there is a 1.8 meter long actively shielded inflector dipole that is to guide the beam into the storage ring. The g-2 superconducting magnets will be cooled using forced two-phase helium in tubes that is provided from the J-T circuit of a 625 W refrigerator. The two-phase helium flows from the refrigerator J-T circuit through a heat exchanger in a storage dewar that acts as a phase separator and a buffer for helium returning from the magnets. The g-2 magnet cooling system consists of three parallel two-phase helium flow circuits that provide cooling to; the four large superconducting solenoids, the current interconnects between the solenoids with the 5300 A solenoid gas cooled electrical leads, and the inflector dipole with its 2850 A gas cooled electrical leads.

INTRODUCTION

The g-2 cryogenic system provides cooling power for the g-2 superconducting magnets so that their operating temperature is less than the critical temperature of the superconductor with some safety margin. The cryogenic system is designed for various modes of operation that include: cool down from 300 K to 4.5 K, operation of the solenoids alone at 4.5 K, and warm up of the cryogenic system to 300 K. In addition, the cryogenic system is designed to handle solenoid and inflector quenches and other transient conditions, such as charging and discharging the magnets.

The g-2 cryogenic system is divided into two parts, which are: 1) the helium refrigerator and helium compressor system (including the helium make up and recovery system) that is located in building about 50 meters from the g-2 hall, and 2) the control dewar and cryogenic distribution system for the g-2 storage ring superconducting magnet system that is located within the g-2 experimental hall. The two parts of the g-2 system are connected by low temperature supply and return lines to and from the refrigerator and 300 K helium supply and return line form the compressor system. The cryogenic flow system in the g-2 hall is shown in Figure 1.

CRYOGENIC SYSTEM HEAT LOADS AND REFRIGERATION REQUIREMENTS

Table 1 presents that the estimated heat load for liquid helium in the g-2 magnet system is approximately 350 watts. If one provides a 20 percent contingency allowance (about 70 watts), the g-2 magnet system requires 420 watts for cryogenic operation (including the gas to the leads). A refrigerator acceptance test was run in November of 1993. This test showed that 400 W refrigeration and 1 gram per second of helium liquefaction were achieved simultaneously at 4.5 K when the input flow form the compressor was 83 grams per second. This machine will deliver 625 watts of refrigeration when it is operated off two compressors that will each deliver a pure helium mass flow of 50 grams per second. The ratio of available refrigeration to the refrigeration required is about 1.5.

The cool down of 6200 kg of solenoid cold mass and the cryogenic distribution system will take about 50 hours. An additional 12 hours is required to fill the 1000 liter control dewar with the refrigerator. Once the solenoids and the control dewar are at their normal operating temperature of 4.5K, the inflector can be cooled to 4.5 K in less than one hour. The rate of cool down is limited by the frictional stagnation pressure drop in the cooling tubes, the size of the cooling tubes and the available pressure from the refrigerator. In general, the limiting system mass flow is less than the choked flow condition of 41 grams per second (at 300 K). The cool down rate is further limited by the temperature difference between the inlet and outlet of the solenoids that is imposed by thermal stresses in the magnets.

Table 1. Estimates of the heat leak for the g-2 magnet system.

	4.5 K Load	80 K Load
Magnet System Heat Load (W)		
Outer Coil Cryostat	52.1	71.6
Upper Inner Coil Cryostat	54.0	38.4
Lower Inner Coil Cryostat	54.0	38.4
Inflector Cryostat	7.5	5.1
Cryostat Interconnect System	11.3	46.0
Magnet System Sub Total	178.9	199.5
Distribution System Heat Load (W)		
Refrigerator to Control Dewar Piping	11.6	---
Control Dewar	5.0	---
Control Dewar to Ring Piping	7.7	---
Control Dewar to Inflector Piping	11.3	---
Valves and Joints	22.0	32.0
80 K Dewar to Ring Piping	---	34.0
Distribution System Sub Total	56.6	66.0
1.14 g s^{-1} Lead Gas Equivalent Refrigeration (W)*	114.0	---
Total Refrigeration (W)	350.5	265.5
Contingency Allowance 20 percent (W)	70.1	51.3
Cryogenic System Design Operating Point (W)	420.6	307.8

* Refrigeration liquefaction Coefficient = 100 J g^{-1}.

TWO-PHASE HELIUM COOLING CRYOGEN DELIVERY AND ITS CONTROL

The two-phase helium flow will be supplied by the helium compressor through refrigerator heat exchangers and the J-T circuit. Two-phase cooling avoids the increase in temperature along the flow circuit found in supercritical or single phase gas cooling circuits. The operating temperature of the magnets is close to the temperature of the helium in the control dewar (0.1 to 0.2 K difference)[3]. The advantage of a two-phase helium cooling in tubes for the g-2 magnets are as follows: 1) The cool-down of the magnet is well controlled because the helium in the tube flows along a well-defined path. 2) The total helium mass in the cooling system is less than the mass of helium in a bath cooled cryostat. 3) The amount of helium in direct contact with the magnet coil is limited to the helium within the g-2 coil cooling tube. This has positive safety implications for the magnets and their cryogenic vacuum vessels. 4) The location of the helium input and output to the magnet cryostat and the location of the gas cooled electrical leads is not impacted by this type of cooling system. The helium for the gas cooled leads can be drawn off as a mixture of gas and liquid from any part of the flow circuit.

The cryogenic system employs a control dewar with a built-in heat exchanger to sub-cool the helium from refrigerator J-T flow circuit before it goes into magnet cooling tubes. This approach provides low quality (defined as quality in the steam tables) liquid helium with higher pressure and lower temperature than the J-T circuit that has no after-J-T isobaric cooling. This is important for long cooling channels like that in the g-2 solenoid cooling circuit, because the pressure drop along the channel is high and the transport capacity of the system is limited by excessive pressure drop (estimated as 4 psia). The heat exchanger in the control dewar shifts the phase of the helium from the gas side of the two-phase dome to the liquid side. The liquid pressure in the control dewar is lower than that in the heat exchanger and while liquid temperature in the heat exchanger is the saturation temperature at control dewar pressure. Therefore, the outgoing helium from the heat exchanger will be the subcooled. The control dewar and heat exchanger also have the effect of damping out the oscillations due to two-phase flow. The control dewar also acts as suffer vessel that can provide additional cooling by using the liquid stored in the dewar during times when the thermal load exceeds the capacity of the refrigerator.

THE THREE PARALLEL COOLING CIRCUITS

The g-2 magnets will be cooled through three parallel forced two-phase helium cooling circuits. During normal operation at 4.5 K the refrigerator J-t circuit will deliver 30 to 40 grams per second of two-phase helium to the g-2 cryogenic system. About 70 percent of this mass flow will be directed to the four solenoids. The remainder of the flow will be split between the solenoid superconducting leads and the inflector magnet.

The four solenoids are cooled in series by two-phase helium that flows in a rectangular channel with inside dimensions of 11.1 by 30.1 millimeters. The total length of this channel in the four solenoids is about 182 meters. There is an additional 32 meters of piping in the circuit that has an inside diameter of 15.9 mm. The average density of the helium in the solenoid cooling circuit is about 60 kg per cubic meter so there is only about 4.0 kg of helium in this circuit. This is helium that sees about 2.1 MJ of stored energy from the solenoids during a quench. Two quench recovery lines have been added into the cooling circuit. This will reduce the peak pressure of the flow circuit during a quench by a factor of two. In the worst case pressure rises in the cooling circuit, during a solenoid magnet quench will be less than 0.7 MPa. This also eliminates the over-pressure problem of the in line electrical insulators.

The superconducting leads between the superconducting solenoids are separately cooled. The cooling tube for the leads is a finned extruded tube that is welded to the high purity aluminum matrix of the g-2 solenoid superconductor. The inside diameter of the lead cooling system tube is 9.53 mm. The length of this circuit is about 32 meters. The mass flow in the lead circuit can be bout 15 percent of the mass flow needed to keep the solenoid magnets cold at 4.5 K. Since this circuit cools the superconducting leads in and out of the four solenoid coils, five or six in-line cold electrical insulators are required in this flow circuit, depending on the electrical ground location. The solenoid 5300 A gas cooled electrical leads draw their cold helium off this flow circuit.

The inflector magnet must be cooled separately from the solenoids and their leads. The inflector magnet must be kept at a temperature of 12 to 15 K while the solenoid magnets are being charged to their full design current. Thus the inflector flow circuit is in parallel with the solenoid and lead cooling circuits. The cooling of the inflector dipole is through an in-out cooling tube that has an inside diameter of 8 mm and a length of 3.4 meters. The tubes that connect the inflector magnet to the outside world have an inside diameter of 9.53 mm and total length of 14 meters. The required flow in this circuit during normal 4.5 K operation is about 15 percent of the main solenoid magnet cooling circuit flow.

GAS COOLED ELECTRICAL LEADS

The four g-2 solenoid coils will be hooked in series electrically. They are powered through a single pair of 5300 A gas cooled electrical leads that are cooled by gas drawn from the solenoid lead two-phase flow circuit. The solenoid leads will be located in the cryostat insulation vacuum chamber. The inflector dipole is powered through a pair of 2850 A gas cooled leads that are supplied with helium from the inflector two-phase flow circuit. These gas cooled leads will be in the insulating vacuum space of the inflector magnet cryostat.

Each of the 53200 ampere solenoid gas cooled leads will consist of a bundle of five multi-tube leads. Each of the multi-tube leads is made of nested phosphorous deoxidized copper tubes with annual flow passages between the tubes.[4] (Each of the 2850 A inflector leads is constructed in a same fashion except there are fewer tubes in the bundle) Multiple current carrying tubes will increase the current capacity of each tube in the bundle. Multiple flow passages will increase the lead efficiency for enhanced heat transfer and low flow pressure drop. These leads can be operated at any physical orientation including upside down (the cold end is up; the warm end is down). A pair of the 5300 A solenoid leads can be made to fit in a space that is 110 mm in diameter by about 750 mm long. The inflector leads are also quite compact.

THE REFRIGERATOR AND ITS CONTROL

The refrigerator operates on a modified liquid-nitrogen-precooled Claude cycle, based on the combination of three elementary cooking process: quasi-isobaric cooling in six heat exchangers, adiabatic expansion in dual reciprocating expanders, and isoenthalipic J-T expansion in a valve nozzle. These components are integrated in a vacuum-insulated and liquid nitrogen shield-cooled cold box, fed with high pressure gaseous helium from two 50 gram per second screw compressors.

The refrigeration delivered by the g-2 refrigerator is controlled by a stable control system that takes advantage of the fact that the compressor flow is a function of the compressor inlet and outlet pressures. When heat load goes down, less gas is delivered to the control dewar and its pressure is decreased. This causes the compressor suction pressure to decrease, which decreases the flow through the compressors and the refrigeration delivered to the load. A further reduction of the heat load causes the reducing regulators to open and liquefaction to start. Conversely when the need for refrigeration increases, the control dewar and compressor suction pressure rises causing the compressor to deliver more helium flow the refrigerator cold box at an increased outlet pressure. This raises the refrigerator output. If the heat load is greater than the refrigerator capacity, a back pressure regulator will open causing boil off helium to be recovered automatically. The system is self regulating and it will maintain a constant liquid level in the control dewar unless there is a gas loss from the system.

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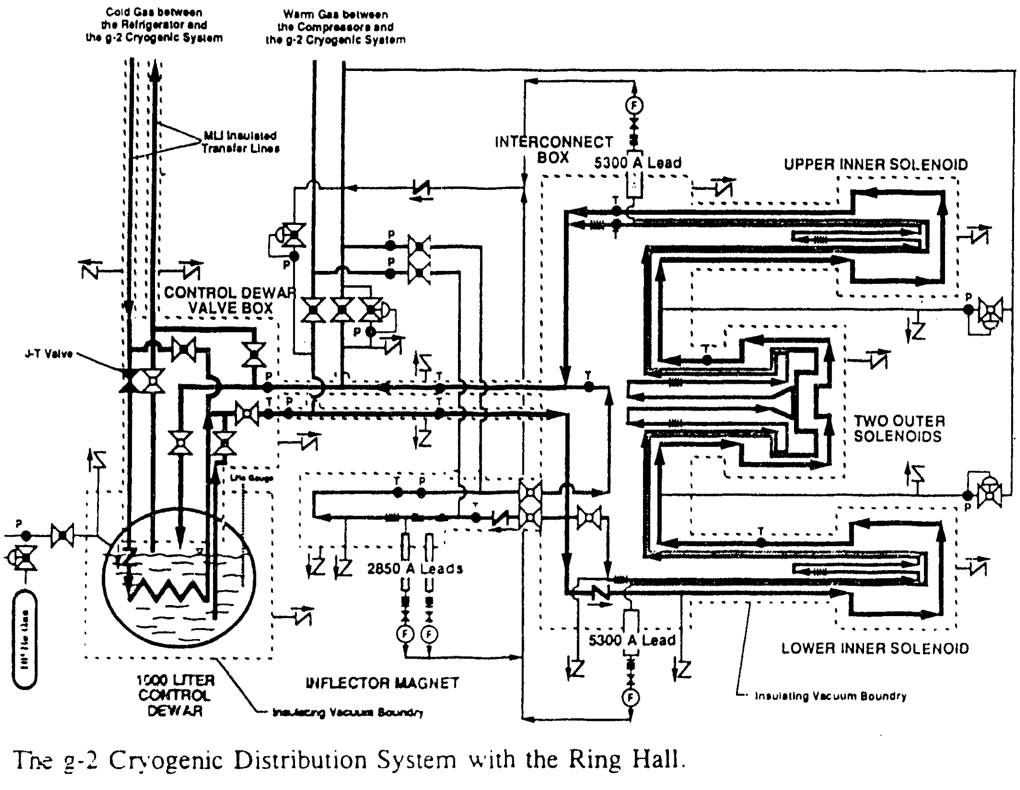

Fig. 1 The g-2 Cryogenic Distribution System with the Ring Hall.

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