Experimental Cryostat Design for Visible Light Photon Counters

APD Cryogenics Inc.

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1. Abstract

We have designed and are fabricating a liquid helium cryostat that will cool VLPC cassettes to 6.5 $\pm$ 0.2 K. The cryostat meets the VLPC density goals and the space restrictions imposed by the Solenoidal Detector Collaboration (SDC) for the Superconducting Super Collider particle accelerator (SSC). The SSC requires that the cryostat contain 8192 VLPCs in a 20" (50.8 cm) diameter cryostat. The cryostat's height is limited requiring a short, 8.75" (22.3 cm) distance between the ambient top-plate, and the cold VLPCs. Our design uses forced flow of liquid helium to cool copper heat stations, which in turn conductively cool the VLPCs. This configuration allows for non-vertical operation of the cryostat. Control of the flow rate of sub-cooled liquid helium is used to maintain the temperature of the coldest heat station to < 6 K. The detectors are encased in a solid block of copper, which has a weak thermal link to the coldest heat station. The block uses a single temperature sensor and heater to achieve the desired 6.5 K for all the detectors. This control method is reliable, and stable. Our cryostat design is simple, highly reliable, and relatively inexpensive.

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2. Introduction

We have designed a forced-flow liquid helium cryostat to cool Visible Light Photon Counters (VLPCs) as a part of the Solenoidal Detector Collaboration (SDC) for the Superconducting Super Collider particle accelerator (SSC). The goal was to design a cost effective, reliable cryostat that would contain a high density of VLPCs in a limited space at 6.5 K $\pm$ 0.2 K with the ability to be orientated up to 70° off vertical.

The SSC requires a density of 8192 channels in a cryostat with a diameter less than 20" and a height of less than 36." Rockwell International has designed removable cassettes which contain one or more basic 128-channel modules. The SSC design combines four of these modules into a 512-channel cassette. Sixteen of these cassettes are then inserted into the cryostat.

We have designed a brass-board cryostat, as a prototype of the SSC cryostat. The brass-board design meets the required channel density by placing 2048 channels in a 10" diameter cryostat. The removable cassette consists of one 128-channel module, and sixteen of these cassettes are inserted into the cryostat. The height of the cryostat is 13" which allows for the cassette removal within the overall height restriction. This design is easily scaled-up to a 20" cryostat, or four 10" cryostats could be built giving the necessary number of channels.

3. Cryostat Concept

Our concept is to use a vacuum dewar with the cooling provided by the forced flow of liquid helium as shown in Figure 1. Liquid helium is used to cool the cassette just above the detectors to ~ 5.5 K, and the detectors are in thermal contact with a copper bus that is slightly heated to bring the detector temperature to 6.5 K. The cold helium gas is then used to intercept the heat at additional points.

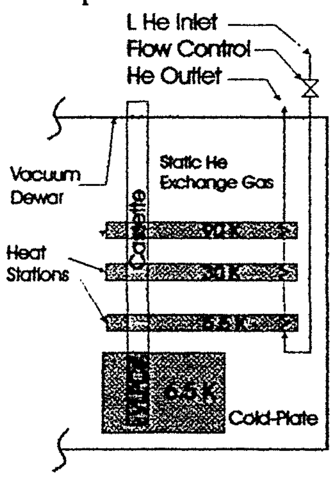

Figure 1. Schematic diagram of the APD Cryogenics cryostat concept.

The temperature of the copper heat stations in the cryostat is controlled by adjusting the flow rate of the liquid helium. The flow is controlled at the entrance to the cryostat, where the helium is a single-phase, sub-cooled liquid. This makes the flow rate constant and the temperature of the heat stations very stable. Since the cassette housing, just above the detectors, is cooled to below the 6.5 K operating temperature, a small amount of heat is added to the cold-plate to achieve the desired temperature. All the cassettes are inserted into a common heat sink which allows the use of only one heater and temperature sensor to control the cold-plate and detector temperature. This simplifies the temperature control scheme and improves system reliability.

The helium used to cool the heat stations is contained inside conduits and does not mix with the static helium in the cryostat that serves as an exchange gas, thus there is no contamination of the helium supply. Non-vertical operation requires only that the void regions in the cryostat be filled with an insulating material to prevent convection.

The brass-board cryostat has 16 cassettes, each containing one 128-channel module, inserted into a 10" diameter dewar as shown below in Figure 2.

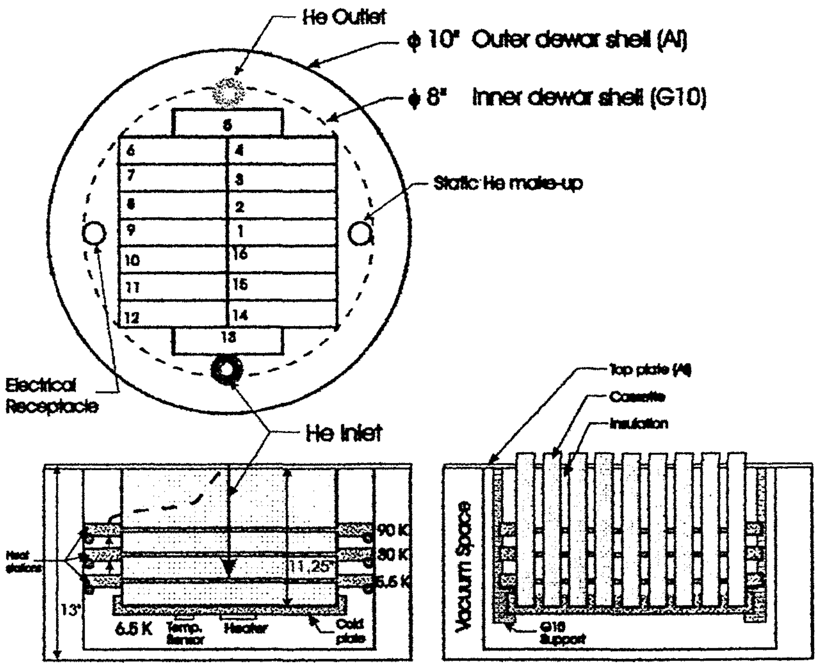

Figure 2. Schematic diagram of the brass-board cryostat.

The sub-cooled liquid helium enters the cryostat through a helium transfer line, and cools the 5.5 K heat station by passing through a coil of copper tubing that is soldered to the copper heat station. The cold helium gas is then circulated around the 30 K and 90 K heat stations prior to exiting the cryostat. The heat stations and cold-plate are supported by G10 columns which are attached to the top plate. The insulation is inserted into the spaces between the cassettes and heat stations as shown, thus eliminating the free space and preventing convection. The cryostat can thus be operated non-vertically without increasing the heat loads or adversely effecting the temperature distribution.

4. Cryostat Analysis

4.1. Mechanical Analysis

The thicknesses of the inner and outer dewar shells were determined using ASME Code, Section VIII. The inner shell is made of a glass-filled epoxy resin, G10, to reduce the heat transfer along the wall. The thickness of the G10 is 3/16" and is based on manufacturing and machine-ability requirements. This thickness gives a factor of safety of 20.

The outer dewar shell is made of aluminum and is 3/8" thick based on manufacturing and machine-ability requirements. This thickness gives a factor of safety of 10.

4.2. Thermal Analysis

4.2.1. Conduction and Radiation

The number of heat stations, their locations and operating temperatures were optimized to reduce the helium consumption. The heat station locations, and operating temperatures are shown below in Figure 3.

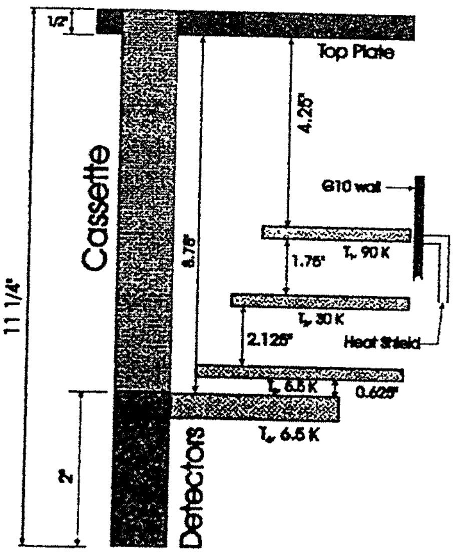

Figure 3. Schematic diagram of heat station location.

The liquid helium enters the cryostat at 4.4 K and cools the #3 heat station at 5.5 K where it is vaporized. The cold gas then intercepts heat at 30 K, and 90 K. Each of the three heat stations cool the cassettes and also remove heat from the inner cryostat wall. The heat station at 90 K also cools a radiation shield.

The cassettes are a significant contributor to the heat load in the cryostat and were carefully analyzed. Data on the internal composition of the cassettes was obtained from Rockwell International, and is listed in Table 1. The cassette shell is made of G10, and contains wires, cables, fibers and the VLPCs. The table gives the component's dimensions, quantity, and cross-sectional area.

Table 1. Cassette composition.

Component	Diameter mm	Width mm	Height mm	Thickness mm	# per Module	Area, mm^2
Polyester Fiber	0.9652				128	93.66
SS Lead Wire	0.0762				304	1.39
Teflon Ribbon		10.80		0.5	16	3.97
G-10 Cover		60.96	15.621	0.7620	1	114.39
Gold on SS Wire				0.00127	304	0.05
Helium		59.44	14.10		1	624.43

The table shows that the interior of the cassette is mostly empty space that is filled with helium, and that the next largest area is from the G-10 shell. The heat transfer, q, down the cassettes was calculated using the one-dimensional heat conduction equation

$$q = \frac{A}{\Delta L} \int_{T_1}^{T_2} k dT \qquad (1)$$

where A is the area, ΔL is the length, k is the thermal conductivity, and T is temperature. Thermal conductivity integrals were used to find the heat loads. Each cassette contributes 422 mW at 90 K, 170 mW at 30 K, and 57 mW at 5.5 K to the total heat load on the cryostat.

The thermal analysis of the cryostat was separated into two major components, a radiation problem and a conduction problem. The radiation takes place between the inner and outer dewar shells, and with the heat shield. The heat load on concentric cylinders due to radiation is found by (Eckert, 1987)

$$q = A_i \sigma \left[\frac{T_i^4 - T_o^4}{\frac{1}{\varepsilon_i} + \frac{D_i^2}{D_o^2}\left(\frac{1}{\varepsilon_o} - 1\right)} \right] \qquad (2)$$

where A_i is the area of the inner cylinder, ε is the emmisivity, σ is the Stefan-Boltzman constant, and D is the diameter. The radiation loads are further reduced by wrapping the inner shell with multi-layer insulation.

The conduction takes place through the cassettes, the inner G10 dewar wall, and the void space or filler material in the cryostat.

4.2.2. Heat Loads and Helium Consumption

The heat station spacing was optimized by varying critical parameters such as wall thickness, materials, lengths and heat station location. The locations of the heat stations were adjusted such that the required helium flow rate through each station was approximately the same. Table 2 shows the heat loads and the liquid helium consumption for various cryostat designs.

Table 2. Heat load and helium consumption.

Cryostat Design	Heat load #1 Station, W	Heat load #2 Station, W	Heat load #3 Station, W	Liquid helium, liter/hour
2 heat stations, short cassettes, SSC design	107	24.4	N/A	23.7
2 heat stations, short cassettes, brassboard design	20.2	4.3	N/A	4.1
3 heat stations, short cassettes, SSC design	106	39.8	12	11.7
3 heat stations, short cassettes, brassboard design, 8 modules	19.9	7.2	1.8	1.8
3 heat stations, short cassettes, brassboard design, 16 modules	26	9.6	2.8	2.7
3 heat stations, long cassettes, brassboard design, 8 modules	10.7	4.2	0.9	**.98**
3 heat stations, long cassettes, brassboard design, 16 modules	15.5	6.2	1.5	**1.5**

The nomenclature for the cryostat design is defined below.

- 2 heat stations: 50 and 5.5 K
- 3 heat stations: 90, 30, and 5.5 K
- SSC design: 20" diameter cryostat with 64 modules with 128 channels each
- brassboard design: 10" diameter cryostat with 16 modules with 128 channels each
- short cassette: insertion length of 8," cold end at 5"
- long cassette: insertion length of 11.25," cold end at 8.75"

The table above shows the effect of adding heat stations and lengthening the cassettes. The addition of a third heat station reduces the helium consumption by 35%. The increase in cassette length reduces the helium consumption by 45%. The number of heat stations is limited by the physical room inside the cryostat, cost for additional stations, and as more stations are added their benefit decreases. The overall cassette length is fixed by the SSC requirements, and the long cassette is at its maximum length.

The cryostat we are fabricating has the long cassettes and three heat stations. The helium consumption for 8 modules is ~ 1 L/hr and for 16 modules is 1.5 L/hr.

4.2.3. Temperature Distribution

It is important that the temperature distribution across the heat station be small in order to insure a uniform temperature across the cassettes and most importantly at the VLPCs. The copper in between the cassettes may be modeled as a conduction bar to find the worst case temperature rise. The temperature distribution in the bar was found by solving the two-dimensional, steady-state heat conduction equation (Ozisik, 1980).

$$\nabla^2 T = 0 \qquad (3)$$

The results are given below in Table 3. The temperature difference is between the end of the bar and the middle.

Table 3. Conduction bar temperature variation.

	#1 Heat Station	#2 Heat Station	#3 Heat Station
Maximum ΔT	2.2 K	0.33 K	0.36 K

The first heat station has the largest ΔT, since it has the highest heat load. This temperature difference will be moderated by conduction with the helium gas between the first and second heat stations. The second and third heat stations have quite small ΔT's, which should not effect the cold-plate's temperature distribution.

5. Cryostat Design

5.1. Dewar

The top plate has 16 cassettes inserted through slots as shown in Figure 2. The actual size of the cassettes is shown below in Figure 4. These dimensions were used to arrange the number of cassettes in a 10" diameter cryostat. Each cassette has a flange which compresses a soft gasket. This makes a very simple seal, that is capable of minimizing the leakage of helium out and air in.

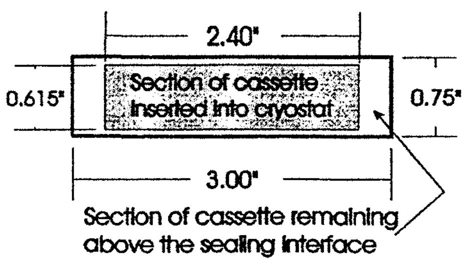

Figure 4. Cassette dimensions.

A close-up view of the dewar construction is shown below in Figure 5. An aluminum outer shell is used for ease of fabrication. The G-10 inner shell was chosen to minimize heat conduction down the wall of the dewar. The top plate is made of aluminum to better distribute the heat and prevent moisture from forming on the top plate. The inner and outer shells are joined together by epoxy. An O-ring is used to seal the helium gas inside the cryostat. A thin copper heat shield is attached to the inner dewar wall to serve as a radiation shield. The vacuum space between the inner and outer shells will be filled with a MLI wrap to further reduce radiation losses.

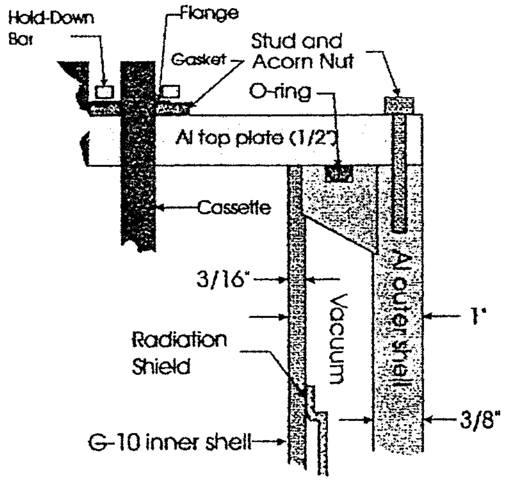

Figure 5. Details of the dewar wall construction.

5.2. Heat Stations

The G-10 support columns and the heat stations form a basket-like structure into which the cassettes are placed. A conceptual sketch of the inner basket is shown below in Figure 6. The heat stations are extended out to contact the inner dewar shell to intercept heat leakage down the wall. The G-10 inserts occupy the void volumes in the cryostat to prevent convection when operating in a non-vertical orientation. These inserts may be made of some other type of insulating material such as rock wool, G10, or foam.

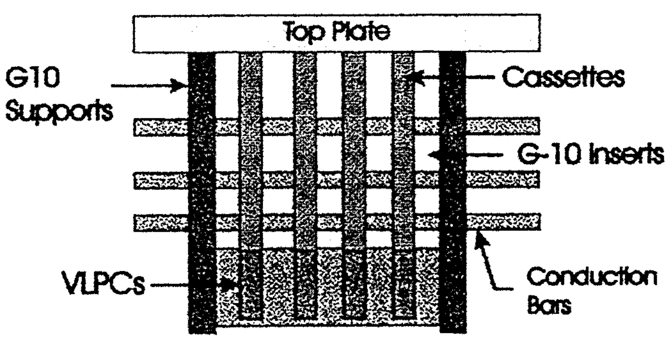

Figure 6. Conceptual sketch of the G-10 support basket, and the copper heat stations.

The three heat stations are identical, and are shown below in Figure 7. They are made of 3/8" thick OFHC copper for good thermal conductivity and strength. The copper tubing in which the helium refrigerant flows is soldered into a groove on the bottom of the heat station. The cold-plate is the same as the heat station except it is 2" thick, and does not extend all the way out to the dewar wall, and does not have any tubing attached. The cold-plate is thicker because it must be thick enough to encase all the VLPCs in the cassette. The dimensions of the slots for the cassettes have been designed such that a warm cassette may be inserted into a cold cryostat. As this is the most restricted case, the design allows for all combinations of insertion and removal.

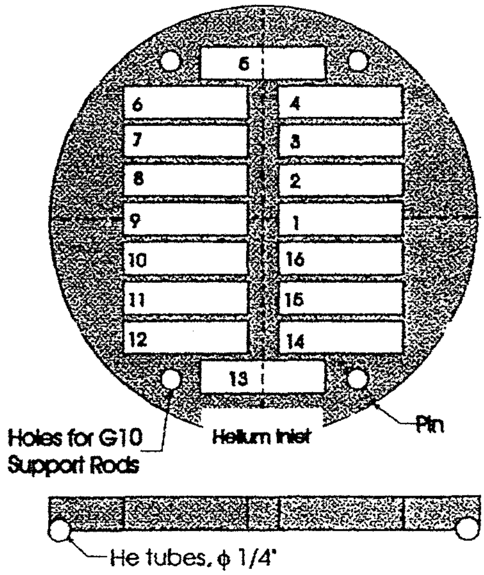

Figure 7. Schematic diagram of heat station construction.

5.3. Controls

The cryostat has three control systems associated with it. Proper temperature control is critical to the operation of VLPCs. The VLPCs are encased in a large thermal mass of copper. The temperature of the cold-plate is sensed with a silicon diode whose output is used to control two cartridge heaters inserted into the cold-plate. Since the temperature of the cassette just above the detectors is 5.5 K, only small amounts of heat need to be added to bring the temperature up to 6.5 K.

The flow rate of the sub-cooled liquid helium is controlled by manually adjusting the valve in the helium transfer line. The flow rate should be adjusted to minimize the amount of heat put into the cold-plate by the heaters. This also minimizes the amount of liquid helium consumed. The valve can also be designed to automatically control the flow rate.

To keep the top plate warm and prevent moisture build-up, a heating system is needed. Two 25 W cartridge heaters that are controlled by a simple on/off thermostat are inserted into the top plate of the cryostat.

6. Summary

We have designed a forced-flow liquid helium cryostat for cooling VLPCs to 6.5 $\pm$ 0.2 K. The cryostat has been designed to meet the high density, orientation, and space requirements of the SSC. There are 2048 channels in a 10" diameter and 13" high cryostat that is capable of operating non-vertically. The cryostat is applicable to any Charged Particle Tracking application that uses VLPCs. The salient features of the cryostat design are:

- The helium flow rate is controlled where the liquid helium is sub-cooled, resulting in a constant flow rate, and stable heat station temperatures.
- The cassettes are inserted into a static helium exchange gas, and sealed with a gasket, thus eliminating the need for a complicated vacuum system.
- The temperature of all the VLPCs in the cryostat is maintained by one sensor and heater adding small amounts of heat, which results in a reliable and stable system.
- Warm/cold cassettes are able to be inserted and removed from a warm/cold cryostat.
- The cryostat may be operated non-vertically.

The test unit that is being fabricated should demonstrate that the design is simple, robust, relatively inexpensive and highly reliable.

7. References

ASME Boiler and Pressure Code, Section VIII, Unfired Pressure Vessels, American Society of Mechanical Engineers, New York, 1983.

Eckert, E.R.G., and Drake, R.M., ***Analysis of Heat and Mass Transfer***, McGraw-Hill, New York, 1987.

Ozisik, M.N., ***Heat Conduction***, John Wiley & Sons, New York, 1980.

8. Acknowledgments

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