CRYOGENIC SUB-SYSTEM FOR THE 56 MHZ SRF STORAGE CAVITY FOR RHIC*

Y. Huang[#], Y. Than, P. Orfin, D. Lederle, T. Tallerico, L. Masi, P. Talty, Y. Zhang
Collider Accelerator Department, BNL, Upton, NY 11973, U.S.A.

Abstract

A 56 MHz Superconducting RF Storage Cavity is being constructed for the RHIC collider. This cavity is a quarter wave resonator that will be operated in a liquid helium bath at 4.4 K. The cavity requires an extremely quiet environment to maintain its operating frequency. The cavity, besides being engineered for a mechanically quiet system, also requires a quiet cryogenic system. The helium is taken from RHIC's main helium supply header at 3.5 atm, 5.3K at a phase separator tank. The boil-off is sent back to the RHIC refrigeration system to recover the cooling. To acoustically separate the RHIC helium supply and return lines, a condenser/boiler heat exchanger condenses the helium vapor generated in the RF cavity bath. A system description and operating parameters are given about the cryogen delivery system.

INTRODUCTION

A 56 MHz superconducting RF storage cavity is planned to be installed in the RHIC IP4 area to provide a large longitudinal bucket for stored bunches of ion beams and hence increase the luminosity of the RHIC machine. The RF cavity is cooled in a helium bath at 4.4 K. Two vacuum jacketed lines, one to the helium supply line (S) and another to the cold vapour return line (R), have been completed in summer 2009. The helium supply from S line always observes pressure fluctuations during normal operations due to changes in the cryogenic load requirements. The cold vapour return line is connected to the re-coolers around the two RHIC rings and the cold-box cold end. Its pressure also varies during normal operations. A warm helium gas return line (WR line) is for current lead flows and is connected to the main helium compressor skids. Its pressure also changes as the compressor loads change.

The cryogenic system designed specifically for the 56 MHz RF cavity is described and the major component design and purchase schedule is also included. The pressures and temperatures in the RHIC distribution lines during normal operation are listed in Table 1.

Table 1: RHIC Cryogenic System Parameters

Lines	**P (atm)**	**Temperature (K)**
S	3.5	5.3
R	1.2	4.6
WR	1.2	300

CRYOGENIC SYSTEM

Superconducting RF Cavity

A computer model showing the niobium cavity and the titanium helium vessel is shown in Figure 1. A chimney pipe centered at the top of helium vessel is for the liquid helium refill and the vapor helium out. The pipe connects to the heat exchanger condenser side. The helium vapor rising enters the condenser at the top and condensed liquid flows back at the condenser bottom to refill the cavity bath. The cavity helium vessel and heat exchanger condenser space is a closed space after initial cool down completes.

The RF cavity design has considered the helium bath pressure changes during the normal operation caused by helium boiling and flow within the helium bath. The reinforcement on the RF cavity reduces its sensitivity to the helium bath pressure changes [1]. However, one of the cryogenic system design requirements is that helium bath pressure fluctuates as small as possible and at lower frequencies to give RF tuners more time to respond

The budgeted heat loads for each 56 MHz RF cavity are listed in Table 2. The thermal shield is estimated to be in the range of 60 W and cooled by vaporized helium cold vapor from the heat exchanger boiler side.

Table 2: Heat Load for Cavity

Dynamic Heat Load to 4.4 K bath	40 W
Static Heat Load to 4.4 K bath	20 W
Heat Load to Thermal Shield	60 W

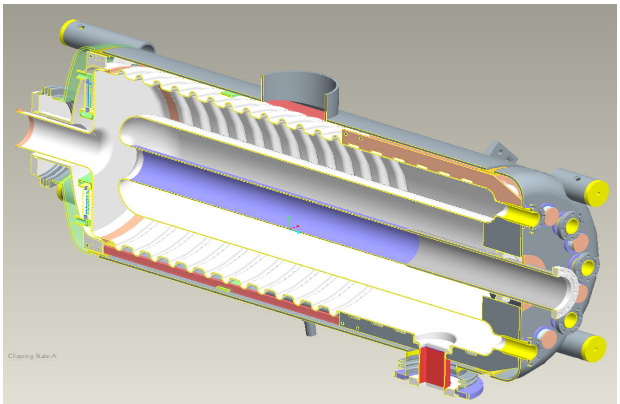

Figure 1: 56 MHz RF cavity and helium vessel model.

Cryogenic System Description

To mitigate the pressure fluctuations originated from the RHIC refrigerator cold-box, compressor skids, and distribution systems, a cryogenic system configuration is

---

*Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy

[#] yhuang@bnl.gov

carefully planned and designed for the cavity cooling. The first phase separator (T1) receives the helium from the existing RHIC helium distribution S line. The helium vapor generated in T1 is sent back to the RHIC distribution system via a cold vapor return R line. The capacity of T1 is sized to hold 50 L liquid and 25 L for vapor space. The helium pressure is reduced from 3.5 atm to 1.4 atm. The vapor pressure in T1 is regulated by a control valve V2 and should be much more stable and hopefully more quiet.

To further isolate the RF cavity cooling system from the RHIC warm helium return line, which is connected to the main helium compressor suction, a boiler/condenser heat exchanger is planned. The helium vapor generated in the boiler tank (T2) is warmed up by an electrical heater to near room temperature before sending it to a dedicated helium compressor to raise its pressure above the warm returnline pressure. This compressor is designed to operate with a suction pressure as low as 0.9 atm so that the temperature in T2 can be regulated slightly on the boiler side. The compressor discharge is connected to the WR line.

The cavity cryogenic system can be operated in two modes. One is to test the effectiveness of condenser/boiler for isolating the RHIC refrigerator and helium distribution systems. The cryogenic system setup also allows an operator to bypass the condenser/boiler. In this operation mode, liquid helium from T1 refills the cavity bath, and the vaporized helium is heated up, compressed, and sent back to the RHIC refrigerator system via the WR line. Vaporized helium from T2 cools both the cavity cryostats and feed box thermal shields. The cryogenic system configuration is shown in Figure 2.

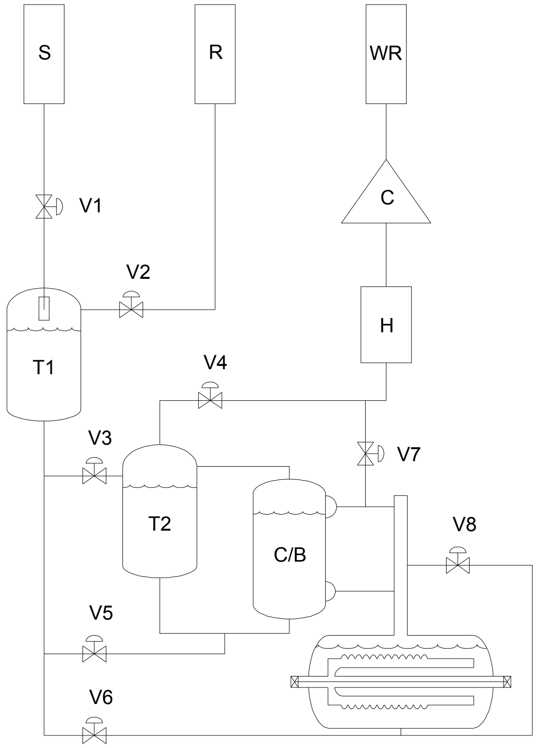

Figure 2: 56 MHz RF cavity cryogenic configuration.

Heat Exchanger Design Requirements

The key component in the cavity cryogenic system is a plate-and-fin type heat exchanger which provides cooling for two 56 MHz storage cavities. There are two functions for this heat exchanger to perform. First, it isolates the cavity helium bath from the RHIC refrigeration and helium distribution systems to reduce both mechanical and thermal acoustic oscillation levels. Second, the heat loads to the cavity helium bath need to be removed efficiently to boiler side. Liquid helium enters the heat exchanger boiler bottom and absorbs heat along its way and vapor fraction is accumulated in T2. Part of the vapor from T2 will be used to cool the thermal shield of the cryostat and the rest will be heated up and sent to the compressor suction. The heat exchanger condenser re-liquefies vapor generated from the cavity helium bath and refills it to maintain its helium level. The heat exchanger main parameters are listed in Table 3.

Table 3: Heat Exchanger Main Parameters

Heat Exchanger Capacity	200 W
Heat Transfer Surface Area	40 m^2
Averaged Heat Flux across Surface	5 W/m^2
Condenser Side Temperature	4.4 K
Boiler Side Temperature	4.3 K

The cavity helium bath temperature depends on the heat load to the system, heat exchanger performance, and boiler-side helium pressure. The boiler side pressure can be regulated by varying the compressor suction pressure. The main heat exchanger parameters are listed in Table 4.

Table 4: Heat Exchanger Main Parameters [2]

Heat Exchanger Material	Al3003F
Parting Sheet Thickness	1.05 mm
Perforated fin sheet	0.2 mm
Thermal Conductivity at 4.4 K	12 W/m-K
Fin Channel Height	4.67 mm
Fin Channel Width	0.77 mm
Flow Area	3.62 mm^2
Wetted Perimeter	10.89 mm

Condenser Thermal Analysis

The parting sheet serves as a primary heat transfer surface and the perforated fin brazed between the parting sheets plays as a secondary heat transfer surface. The helium vapor could be re-distributed within each layer formed by the perforated fin sheet between the parting sheet.

The thermal resistance on the condenser side is due to condensed helium film thickness on the heat transfer surfaces. The helium that enters the condenser is considered to be saturated vapor and almost stagnant. The condensed helium film thickness is estimated [3] from Eq. (1)

$$\delta^4 = \frac{4\mu_L \lambda_L (T_{sat} - T_w) z}{\rho_L (\rho_L - \rho_V) g h_L} \qquad (1)$$

where z is the distance from condenser top edge and δ is the film thickness. The calculated film thickness is 0.03 mm if the heat exchanger height is 0.3 m. The heat transfer coefficient on the condenser side is 623 W/m^{2}K. All helium properties in Eq. (1) are evaluated at 4.35 K.

Conduction Thermal Resistance

The thermal resistance across the heat exchanger primary heat transfer surface is negligible. However, for the secondary heat transfer surface, the temperature difference from the condenser to the boiler is calculated to be 0.006 K for each side.

Boiler Thermal Analysis

For the nucleate boiling regime, the temperature difference between wall and liquid helium is estimated by the empirical fit [4] in Eq. (2)

$$q = 1.0 \Delta T^{2.5} \qquad (2)$$

where q is the heat flux in W/cm^2 and ΔT is the temperature difference in K. With the heat flux at 5 W/m^2, the ΔT is 0.048 K. However, all experiment data for nucleate boiling are above 10 W/m^2 in the literature.

The temperature difference on the boiler side needs to be estimated for the natural convection heat transfer regime. The calculated heat transfer coefficient on the boiler side is in that range of 90 W/m^{2}K. The temperature difference ΔT is about 0.055 K.

Boiler Helium Column Effect

The helium column height in the boiler side is about 300 mm. If we assume that helium is in a saturated state for both liquid and vapor, there is thermal stratification. If the liquid helium at the phase line is 4.3 K, then the liquid helium at the boiler bottom is estimated to be 4.304 K.

Condenser Side Vapor Space Volume

Since the condenser side is a closed volume system, any energy imbalance to the cavity helium bath will vaporize the liquid helium and cause the system pressure and the temperature to rise. To mitigate the cavity helium bath pressure change, a certain vapor space volume is required.

We assumed that all energy is dumped into the liquid helium bath and a certain amount of liquid helium is converted into vapor and no cooling is provided. Another assumption is that helium vapor is in a saturated state. Figure 3 shows the system pressure responses for various vapor space volume when 1 kJ is dumped into the helium bath.

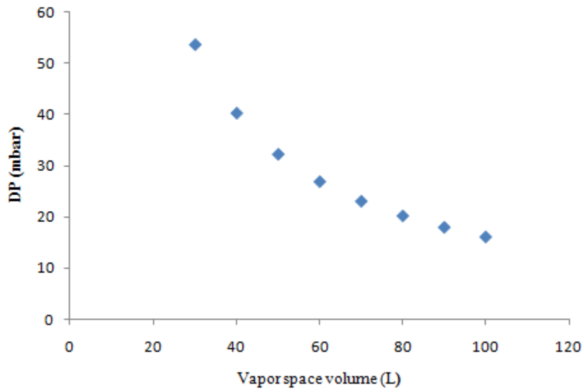

Figure 3: Cavity bath pressure rise for various vapor space volume when 1 kJ is dumped into the cavity bath.

Summary of Condenser/Boiler Design

The temperature difference between the cavity helium bath and the boiler tank (T2) is only 0.1 K. Table 5 lists temperature from boiler to condenser.

Table 5: Temperature Value at Key Points

Boiler Tank Temperature	4.3 K
Helium Temperature at Boiler Bottom	4.304 K
Boiler Side at Fin Center	4.359 K
Boiler Side at Fin Base	4.365 K
Condenser Side at Fin Base	4.365 K
Condenser Side at Fin Center	4.371 K
Condenser Side Vapour Temperature	4.379 K
Cavity Helium Bath Temperature	4.379 < 4.4 K

SUMMARY

The 56 MHz superconducting storage RF cavity project is making progress. The cryogenic system design is in its final stage. The helium supply lines have been tapped into the RHIC helium distribution lines. The plate-and-fin heat exchanger design is near completion and specification will be sent out for bid soon. The cold helium vapor heating system design will start soon as well. A booster compressor specification is underway. The first phase separator and transfer line design work is near completion and will be sent out for bid soon.

REFERENCES

[1] C. Pai et al. “Mechanical Design of 56 MHz Superconducting RF cavity for RHIC Collider,” PAC’11, New York, NY, March 28 to April 2, 2011.
[2] Naoki Kashi, Private Communication, Sumitomo Precision Products Co., Ltd.
[3] G.E. Hewitt, “Process Heat Transfer”, p. 576.
[4] S.W. Van Sciver, “Helium Cryogenics”, p. 213.