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THE RELATIVISTIC HEAVY ION COLLIDER (RHIC) REFRIGERATOR SYSTEM AT BROOKHAVEN NATIONAL LABORATORY: SYSTEM PERFORMACE AND OPERATIONS UPGRADES FOR 2003*

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ABSTRACT

The main function of the RHIC cryogenic system is to maintain the superconducting magnets in the two rings of the new collider-accelerator at Brookhaven National Laboratory at or below 4.5K. The main feature in the RHIC cryogenic system is the helium refrigerator. A new process control philosophy was implemented that allows this system to track the actual load from the accelerator rings and lets it respond accordingly. The refrigerator capacity decreases as the load decreases and increases as the load increases. This has resulted in the following improvements in the operation of the system:

- Higher reliability because the rotating equipment does not have to run at full load continuously.
- Greater stability because the system tracks the load continuously and responds quickly to any transients such as a quench.
- Reduced power consumption because the discharge pressure of the system is adjusted continuously to match the load; therefore, the compressors draw less power when the load from the accelerator rings decreases.

This paper also addresses other modifications introduced that added to the efficiency, stability, and reliability of the system. As a result of this upgrade the Carnot efficiency of the refrigerator system has increased to 15% from around 10%.

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INTRODUCTION

The basic function of the RHIC cryogenic system is to maintain the superconducting magnets in the two rings of the collider at or below 4.5K. The main feature of the cryogenic system (shown schematically in Fig.1) is the helium refrigerator. It was designed to match the load of the CBA project with a primary capacity of 25 kW at about 3.8K and a secondary, higher temperature capacity of 55 kW at about 55K. It is essentially a Claude cycle that incorporates 10 heat exchangers, 6 expanders, and 2 cold compressors. It works as a refrigerator/liquefier built around oil flooded screw type compressors and expanders with oil lubricated bearings.
This system was adapted to meet present RHIC refrigeration requirements, i.e. about 11 kW at 4.5K and 25kW at about 55K.
A new process control philosophy was implemented which allows the system to track the actual load from the accelerator rings and responds accordingly. This process control philosophy has been used by helium refrigerators at Thomas Jefferson Laboratory for over 10 years and was adapted to the RHIC refrigerator. The implementation of the new control philosophy has resulted in the following improvements:

a. Reduction in input power required to run the system.
b. Added reliability to the system.
c. Provided more stability in allowing the system to track continuously the load and quickly responds to any transients such as a quench.

PROCESS CONTROL IMPROVEMENTS

A new process control philosophy was implemented that allows the system to track the actual load from the accelerator rings and responds accordingly. It allows the discharge pressure of the second stage compressors to increase or decrease in response to the refrigerator's need. If the load increases, the low pressure return flow increases leading to an increase in the flow rate through the 2nd stage compressors and an increase in the high side discharge pressure resulting in an increase of the refrigerator's capacity.
If the load decreases, the low-pressure return flow decreases resulting in a decrease of the high side discharge pressure and a decrease in power required to meet the actual refrigeration load. The new process control involved changes in the compressors gas management and implementation of new control schemes for liquid pots, turbines, the heat exchangers balance valves, and quench recovery.

1.Compressor gas management

Table 1.1 below shows the comparison between the old and the new schemes on the compressor gas management. With the old process control system, the 2nd stage discharge pressure was fixed and independent of the actual refrigeration load from the magnets. The compressors ran full capacity regardless of the refrigerator's need; and the power input required for the cold box was always fixed and did not change when the load changed. The excess flow from the compressors was bypassed (dumped) from mid-pressure to low pressure to control the rate of refrigeration. With the new process control system, the control loops are established in a way to prevent the process from approaching too closely the safety limits of the rotating machinery (i.e. over-speed and lack of bearing capacity for turbines and motor over-load for compressors, etc.) during upset conditions, and to facilitate the system in recovering from such transients. The second stage discharge pressure is maintained to the cold box, regardless of the supply flow and return flow, until compressor bypass ceases or the mass-in demand exceeds the control valve capacity. This is in contrast to the old scheme, where nothing directly maintains the 2nd stage discharge pressure. This helps to maintain the high cold box capacity required to recover from these transients. The major advantage in this case is system stability.

Another feature in the new scheme is that make up gas can be injected at the mid pressure stage whenever the storage tank pressure is higher than the inter-stage pressure. The advantage here is the power savings, i.e., not having to compress the make up mass flow from 1st stage to the inter-stage pressure. In addition, this reduces the pressure transient on the load (rings magnets), and adds to the system stability by reducing the load on the 1st stage compressors during make-up. The minimum suction pressure set point was decreased from 1.2 atm to 1.05 atm for the 1st stage compressors and the inter-stage pressure is allowed to float. The minimum set point for the mid pressure has been limited to 2.5 atm to avoid any oil issues in the compressors. This has added more flexibility to the system and more capacity to handle the gas in cases of transients, such as a quench.

Table 1. 1 Comparison of control schemes

	Old	New
Mass In	Based on low 1st stage suction pressure; mass comes into 1st stage suction.	Based on low 2nd stage discharge pressure; mass comes into inter-stage [1].
Mass Out	Based on high 1st stage suction pressure; mass comes out of 2nd stage discharge.	Based on high 2nd stage discharge pressure; mass comes out of 2nd stage discharge.
1st Stage Suction Pressure	Constrained by mass in and mass out functions.	Minimum low pressure is regulated by 1st stage by pass [2].
Inter-stage pressure	High end regulated by 1st stage bypass.	Minimum inter stage pressure is regulated by 2nd stage bypass [2].
2nd Stage Discharge Pressure	Regulated by adjusting inter-pressure set point.	Constrained by mass in and mass out functions.

Notes:

[1] If storage tank pressure is less than inter-stage pressure, mass comes into 1st stage suction.

[2] On the high end, the system will regulate itself, to some degree, due to the compressors being volumetric devices; i.e. if suction pressure increases, mass flow rate increases, and visa- versa.

Table 1.2 below describes the gas management primary control loops.

Table 1.2 Gas Management Primary Control Loops

Process Variable (PV)	Control Device (CD)	Set-Point (SP)/Action
Suction pressure to 1st stage compressor	By-pass valve 1st stage	1.05 atm/ Open CD if PV less than SP
Suction pressure to 2nd stage compressor	By-pass valve 2nd stage	2.5 atm/Open CD if PV less than PV
2nd stage discharge pressure	Pump-back (Mass out) valve	0.2 atm above pump-back SP/Open CD if PV greater than SP.
2nd stage discharge pressure	Inter-stage mass in valve (if tank farm pressure minus mid-pressure is greater than 1atm)	SP= required discharge pressure for a given load/ Open CD if PV less than SP.
2nd stage discharge pressure	1st stage mass-in valve (if tank farm pressure minus mid-pressure is less than 1 atm)	SP= required discharge pressure for a given load/ Open CD if PV less than SP.

2. Additional gas management control

To compensate for a given load, the discharge pressure is varied by changing the mass in set point with respect to the liquid pot shown in Fig.2. As the level in the liquid pot (i.e. PV) decreases the discharge pressure will increase. The set point is determined as follow:
A maximum discharge pressure corresponds to a minimum level in the liquid pot, and a minimum discharge pressure corresponds to a maximum level in the liquid pot. A linear interpolation between the maximum and the minimum pot level is made to obtain the required discharge pressure.

If the flow returning from the ring is large due to an upset condition (similar to a quench), which can cause a compressor trip or the loss of a first stage compressor, we take the following actions:

a. Reduce the return flow from the ring by closing a valve that control the flow back from the rings to the low pressure side of the cold box.
b. Reduce the flow to the lowest turbine train (T5& T6) by closing its inlet valve (guide vanes) no more than 15% in steps. This reduces the 1st stage compressor suction pressure.

In case of a loss of a 2nd stage compressor the mid pressure is expected to rise. To prevent the mid pressure from rising above a maximum value that can trip the compressors, several controls are implemented in the following order:

a. Restrict the shield flow until the mid pressure decreases below the maximum.
b. Reduce the flow through the cold turbines no more than 15% in a way not to trip the turbine.

The RHIC rings helium return control valve process variable was originally set to control the temperature in the ring pots by controlling the back pressure. It is now changed to prevent the 1st stage compressor suction pressure from exceeding 1.3 atmospheres. During a quench, this valve will contain the pressure in the rings, and feed it to the compressors as they can handle the flow. This has reduced the time to recover from a quench because the refrigeration of the return helium is now utilized.

The turbine process control was changed to a cascade control. The inlet valve to the 1srt turbine is kept wide open with the rest of the turbines in the same temperature step trying to match its speed.

3. Refrigerator cold end piping changes

The piping from the lowest turbine (T6) and the cold compressor discharge to the coldest heat exchanger was reversed. This anomaly existed in the system from the 1st day when the system was assembled. This contributed to a considerable irreversibility and increase in the input power requirement.

4. Reconfiguration to eliminate the cold compressor

For a supply temperature 4.5 K operation the cold compressor is not required. A new bypass line and a control valve between the rings return (upstream of the cold compressor suction) and the liquid pot return to the coldest heat exchanger (HX-9) was added.

PERFORMANCE OF THE REFRIGERATOR AFTER THE CHANGES

The approximate loads for RHIC refrigerator from both rings, before the changes were made, were as follow.

Table 3. RHIC Refrigerator Loads Before the Changes

4.5K Refrigeration Loads	7.5 to 8.0 KW
4.5 K Liquefaction load (Lead Flow)	35 gm/sec
55K Shield load	25 KW

The power consumption in this case was approximately 9 MW.

The refrigerator loads this year are summarized in the following table.

Table 4. Present RHIC Refrigerator Loads

4.5K Refrigeration Loads	7.5 to 8.42 KW
4.5 K Liquefaction load (Lead Flow)	31 gm/sec
55K Shield load	24 KW

The input power required to meet the above refrigerator loads is about 7.2 MW.

CONCLUSION

A new process control was implemented for RHIC cryogenic system, which is allowing the system to track the actual load from the accelerator rings and responds accordingly. The machine slows down as the load decreases and speeds up as the load increases. This has resulted in the following improvement:

a. A power reduction of about 1.8 MW. The required power to run RHIC cryogenic refrigerator in the past was around 9 MW. The system is presently operating with an input power of around 7.1 MW. As a result, the refrigerator efficiency is around 15% Of Carnot.
b. Higher reliability. The rotating equipment does not have to run full load continuously all the time.
c. A more stable system. As the system tracks continuously the load, it responds quickly to any transients such as a quench.

Going forward, our goal is to continue this project to further reduce the input power required to run the system and, at the same time, further improve its reliability and flexibility.

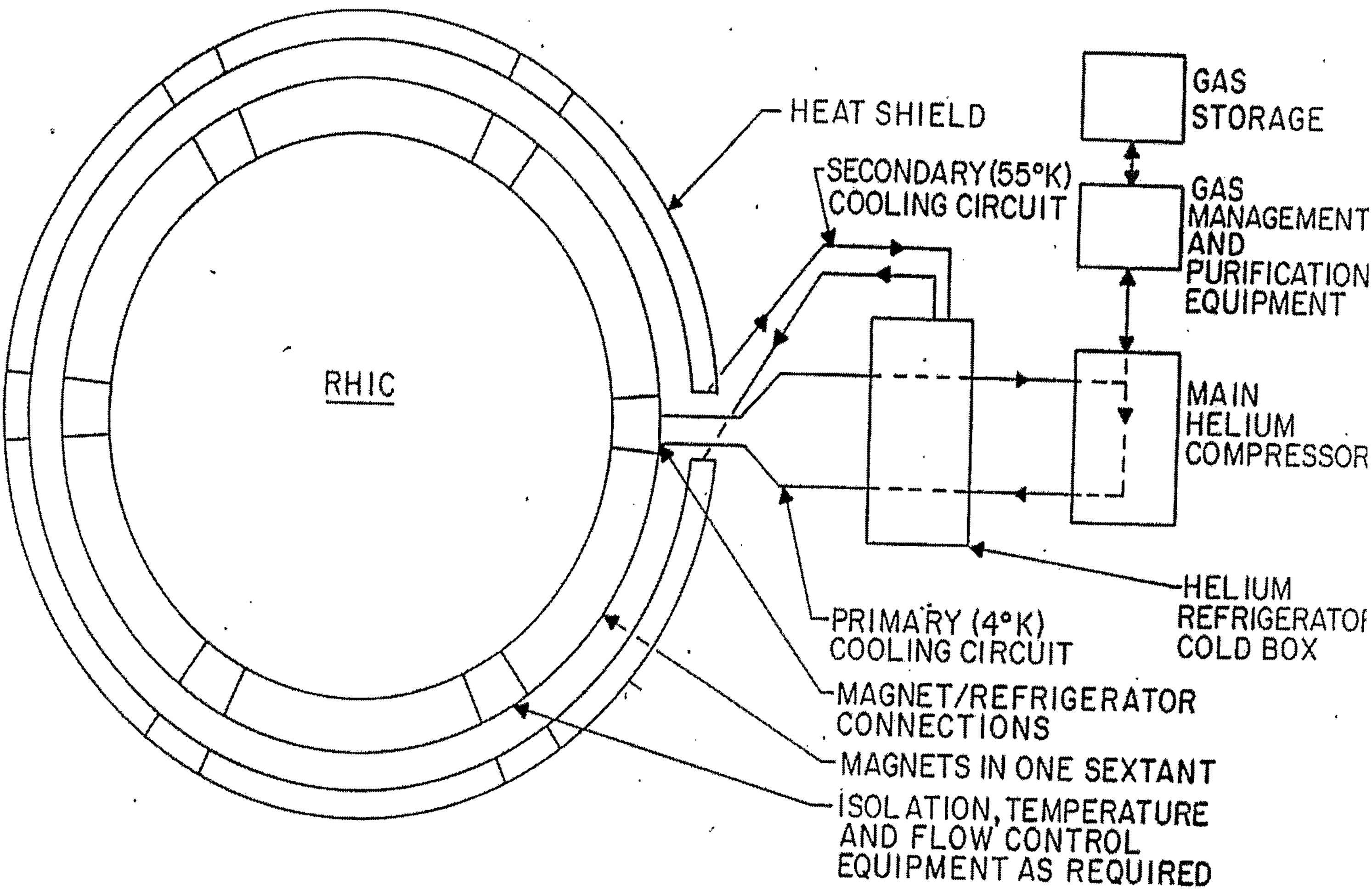

Fig.1 Schematic drawing of RHIC helium cryogenic system.

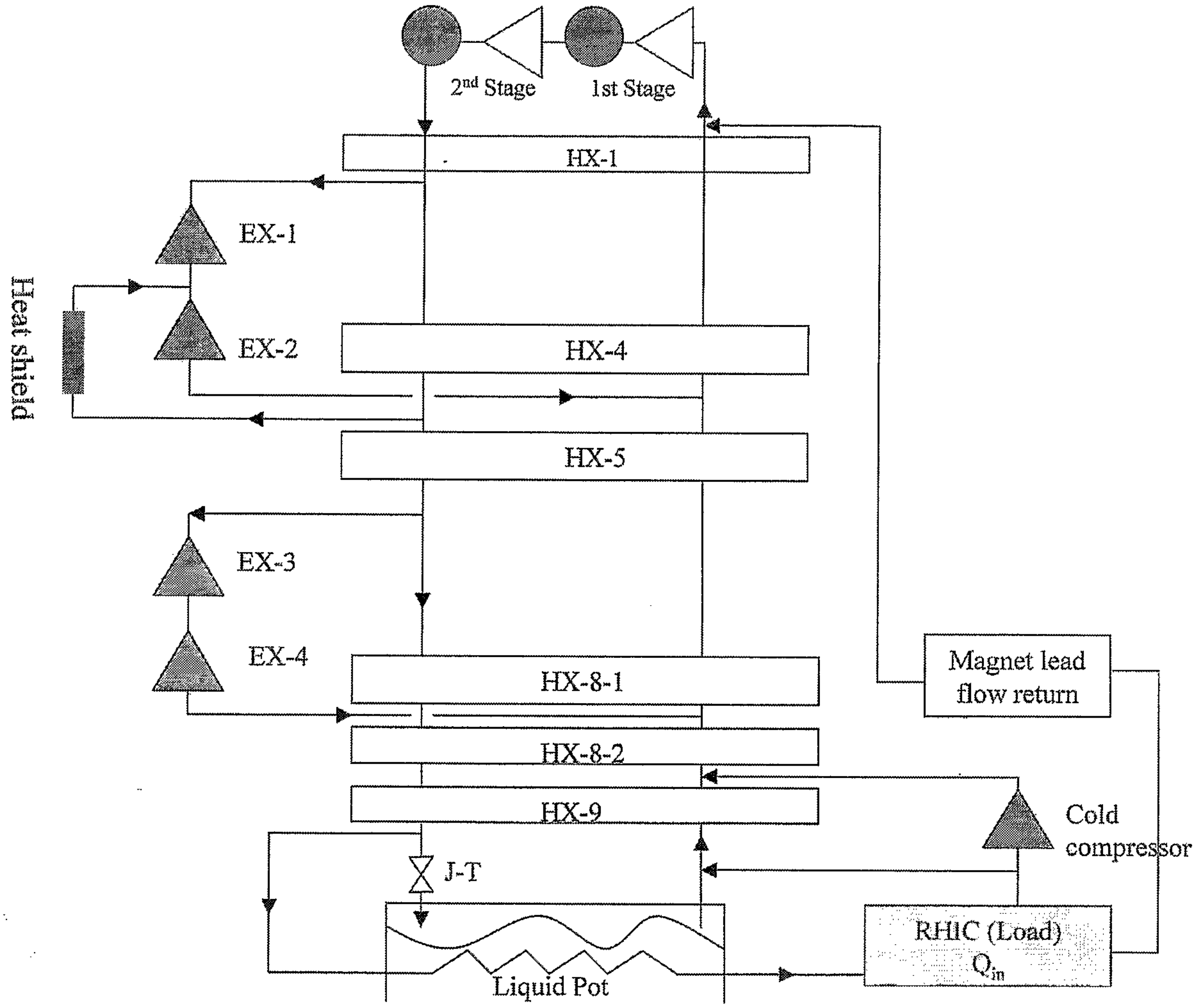

Fig. 2 Schematic diagram of RHIC Refrigeration System.

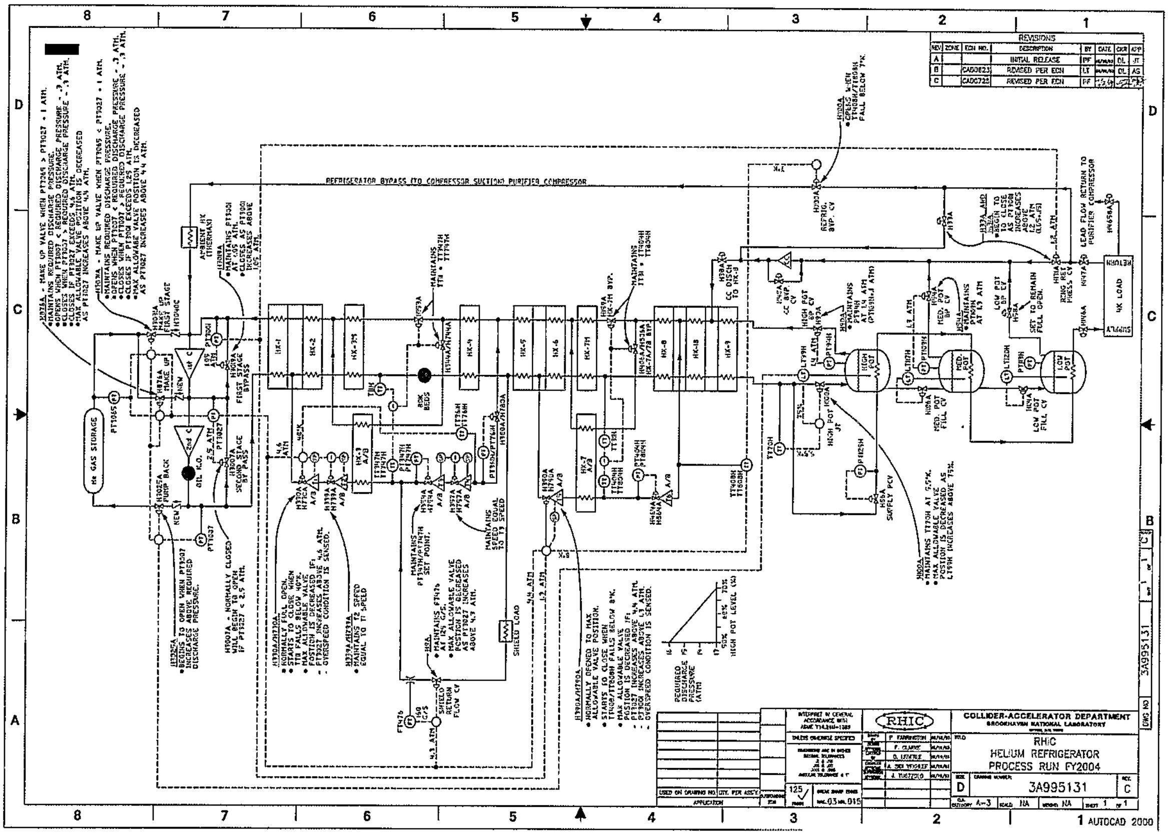

Fig.3 RHIC Refrigerator System