PERFORMANCE OF RHIC VACUUM SYSTEMS*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) has been operational since being commissioned in 1999. The three RHIC vacuum systems have performed well and met the design requirements. A brief description of the vacuum systems is given. The experience obtained over the last three years is summarized with emphasis on the management of helium leaks in the insulating vacuum and on the reduction of beam gas events for four major RHIC experiments.

1. INTRODUCTION

RHIC has a circumference of 3.8 km and comprises two interweaving rings that interact with each other at six experimental regions. There are three distinct vacuum systems in RHIC proper [1]. The insulating vacuum vessels house the helium-cooled super-conducting magnets. The 4.5K beam tubes (cold bore) pass through the center of the super-conducting magnets. The room temperature (warm bore) beam vacuum sections house the injection, acceleration, instrumentation and experimental regions. The warm bore design vacuum is $<5x10^{-10}$ Torr ($\sim 1.7x10^{+7}$ molecules /cm^3). The cold bore design vacuum is $<1x10^{-11}$ Torr ($\sim 2x10^{+7}$ molecules/cm^3 at 4.5K) consisting of only H_2 and He. The beam-gas lifetime, dominated by nuclear scattering with cross sections of $\sim 10^{-24}$ cm^2 for Au, will be several hundred hours at the design vacuum levels, much longer than the ten-hour intra-beam scattering lifetime [2]. Background noise to experiment detectors, due to beam-gas events at and near experimental regions puts the most stringent requirement on RHIC beam vacuum systems. At the design vacuum levels, the probability of beam-gas interactions ±40m around the collision point will be $\sim 1x10^{-4}$ interactions per bunch per crossing. The total beam-gas rate will be $\sim 10^3$ Hz which is comparable to the beam-beam rate at the design luminosity of 10^{26}cm^{-2}s^{-1} [3]. The insulating vacuum requirement is $<10^{-5}$ Torr, to minimize the convection heat transfer from the ambient cryostat wall to the cold magnet mass.

2. RHIC VACUUM SYSTEMS

The total length of warm bore is approximately 1.2 km, consisting of the 24 insertion regions, the 12 final focusing regions and the six experimental regions. RF-shielded gate valves are used to isolate adjacent warm bore and cold bore sections. Most warm bore pipes are made of stainless steel and utilize Conflat® flanges, and are joined together with rf-shielded bellows. The experimental region beam pipes are made of 1mm thick beryllium for its transparency to energetic particles.

The total length of cold bore and cryostats is ~ 6.4 km, divided into 12 arc sections and 12 triplet sections. Each 494m arc section consists of a continuous (without vacuum barriers) cryostat, housing 64 super-conducting magnets and has a volume of ~150m^3. The two adjacent triplet magnet strings reside within a common cryostat due to their proximity, which has a volume of ~50m^3. In addition, there are 12 cryogenic valve boxes, each with ~30m^3 volumes; and 113 sections of vacuum-jacketed helium transfer lines of various lengths located inside and outside the RHIC tunnel. The valve boxes and transfer lines, originally the responsibility of cryogenics, were inherited by vacuum following commissioning. The magnet beam tubes in the arcs and triplets are interconnected with rf-shielded bellows to form a continuous cold bore as shown schematically in Figure 1. Cold cathode gauges and sorption pumps are mounted to the pull through ports of the bellows at 30m intervals to monitor the cold bore pressure and to pump He and H_2, respectively.

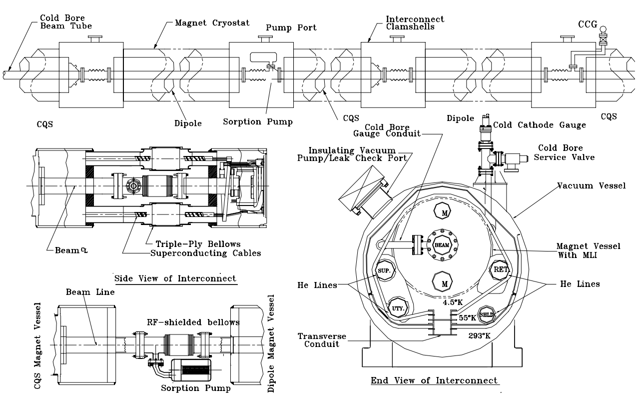

Figure 1. Schematic of arc interconnects with beam line bellows, two magnet lines and four He service lines.

There are six helium lines at the magnet interconnects, two magnet lines and four service lines. Sixteen in-situ circumferential welds join these six helium lines from magnet to magnet at each interconnect. These welds were leak checked at room temperature with sensitivity down to $\sim 10^{-8}$ std.cc/sec He (all leak rates hereafter are of the equivalent leak rate at room temperature in standard cc He per sec) to ensure that they will not spoil insulating vacuum after cool down. After completing a long string of interconnects, the service lines were pumped down and leak checked by spraying He at the welded joints. The triple-ply He bellows welds of the magnet lines were leak

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tested by pressurizing the magnet vessel to ~5 atm He and sniffing around the welds. The sensitivity of sniffing is ~10^{-4} when it is done carefully and the tunnel He background is low. The interconnect clamshells were then welded together to form the completed vacuum vessel. Pump ports on the clamshell and transverse conduits through the cryostat interconnect heat shields allows for He sampling of each interconnect He line weld. After pumping down the insulating vacuum to ~10^{-1} Torr, these welds were leak checked to a much better sensitivity by pressurizing the He line while sampling the cryostat volume at each interconnect through the pump port and transverse conduit with the vacuum pumps and leak detector.

3. PERFORMANCE

3.1 Warm Bore Vacuum

After installation, alignment and assembly, the warm bore sections were roughed down with a turbomolecular pump (TMP) backed by a dry mechanical pump before ion pumps (IP) and titanium sublimation pumps (TSP) were conditioned and energized. A pressure of 10^{-9} Torr was usually reached in a few days, comprising mostly H_2, H_2O and CO. With the exception of the rf cavities and some beam diagnostic components, all warm bore sections are in-situ bakeable to 250°C. Eighteen warm sections at and adjacent to experimental regions have been in-situ baked and reached pressures of ~$1x10^{-10}$ Torr, comprising mostly H_2. Figure 2 shows the changes in pressures ±70m from the collision points of the four major experiments over the last three years. Substantial decreases in pressure were observed, after these warm bore regions were in-situ baked. Further reductions in pressure were achieved when all the TSPs in the incoming beam lines of each experimental region were commissioned. The average pressures at these regions are now several times below the design vacuum levels.

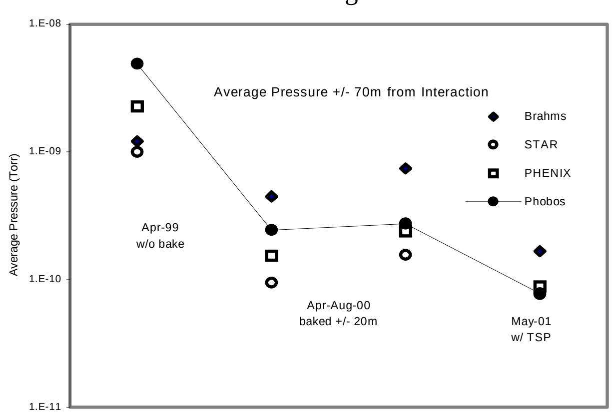

Figure 2. Changes in average pressures at four RHIC major experiments over last three years: Apr-99 Without in-situ bakes; Apr-00 In-situ bake of experimental regions beam pipes; and May-01 Activation of TSPs at incoming beam lines.

3.2 Cold Bore Vacuum System

Prior to magnet cool down, the cold bore was usually roughed down to ~10^{-4} Torr before closing the TMP isolation valve. The pressure slowly increased to mid 10^{-2} Torr over a few months, which is still adequate for cool down. After cool down, the cold cathode gauges (CCG) located outside the cryostats read mid-10^{-10} Torr range when the true pressure in the cold bore is probably <10^{-11} Torr. The high readings are due to the localized outgassing of the gauge conduits. The efficacy of CCGs in monitoring the cold bore He pressure was studied during RHIC first sextant test. The CCGs were found to be useful in detecting cold bore pressure increases with sensitivity down to ~10^{-11} Torr [4]. To date, no internal He leaks have been observed in any RHIC cold bore region, assuring a pressure far below 10^{-11} Torr in the cold bore.

3.3 Cryostat Insulating Vacuum System

A mobile roots blower/mechanical pump station was used to rough the insulating vacuum vessels. Typical pump down curves of the arc vacuum vessels are shown in Figure 3. The pressure decreased rapidly to ~1 Torr within one day then leveled off due to the gradual release of water absorbed in the MLI. Without major air leaks, pressure of mid 10^{-2} Torr was usually reached in a few days. Pumping was then transferred to a TMP to maintain the insulating vacuum.

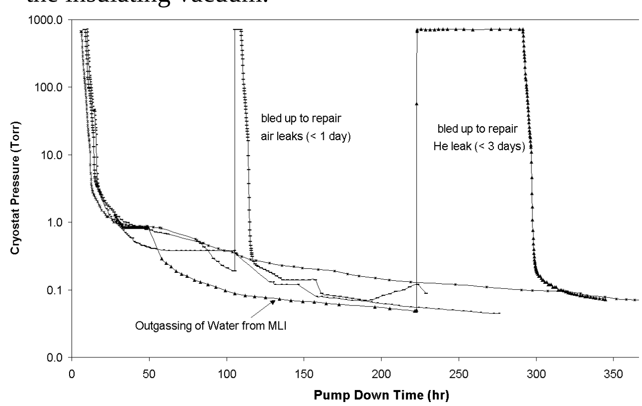

Figure 3. Pump down curves of RHIC arc insulating vacuum volumes with a 300 cfm roots blower pump/mechanical pump.

Before cool down, the magnet vessels and the service lines were individually pressurized with gaseous He up to 15 atm and the He background in the insulating volumes was measured. Leaks larger than 10^{-5} levels have to be located and repaired. After identifying which lines leaked, the leaks were traced to the offending interconnects by measuring the He signal at each pump port with a portable leak detector. Typical He pressure gradients generated by the TMP located at the center of arc were ~5% across a CQS magnet assembly and ~10% across a dipole magnet, which gave clear indication of the locations of the leaks [5]. The large leaks (>10^{-3}) were quickly located and repaired, once the cryostat was cut open. Leaks on the order of 10^{-4} could be pinpointed by sniffing while pressurizing the He conduit. Bagging and accumulating helped identify 10^{-5} leaks, but provided little benefit for locating smaller leaks. Leaks of 10^{-7}-10^{-6} levels could be safely managed by mobile TMPs, even after cool down when the leak rates increase by a few decades (due to the increase in density and pressure, and decrease in viscosity of superfluid He) [6]. Overall, there were about two-dozen leaks of $> 10^{-5}$ level found and repaired among the 25,000 in-situ He line welds in the arcs and triplets. The welding and leak checking of magnet interconnects could be considered rather successful.

Prior to each cool down in the last three years, high He backgrounds were observed in the insulating vacuums of the twelve cryogenics valve boxes. The sources of these leaks were traced to the welds in the housing of the cryogenic process control valves used to regulate He flow in the cryogenic system. The leaks were caused by the gradual corrosion of the welds by the soldering flux residue used in soldering the heat shield grounding straps. Most of the leaks were located and repaired before cool down. However, due to machine schedule, a few smaller leaks were handled with additional pumping. The changes in the leak rates were monitored during the cool down and operation cycles. The leak rates are plotted as a function of He line pressure, temperature and viscosity in Figure 4.

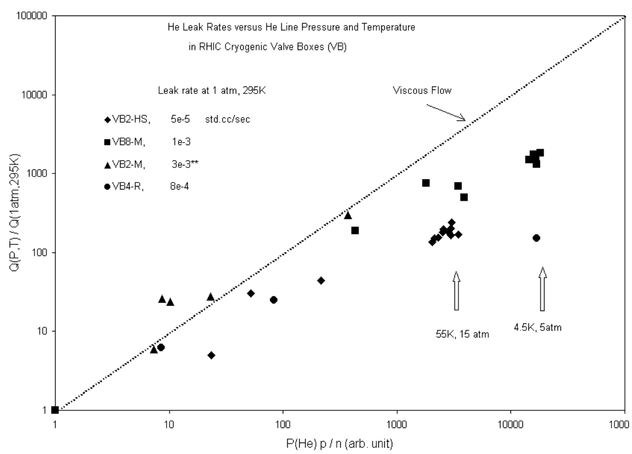

Figure 4. Changes in He leak rates with He line pressure (P), density(p) and viscosity (n) at valve box (VB). HS, M and R represent heat shield, magnet and return lines, respectively. The dotted line represents the calculated leak rates of a viscous flow in the leak passage.

The ultimate leak rates are approximately one decade smaller than those predicted by a viscous flow model [6], which seems to give the worst-case scenario. These measurements allow us to predict the leak rates after cool down based on ambient leak rates, therefore minimizing the risk of committing to operation with leaks that would produce intolerable convection heat loss during machine operation. “Cold leaks,” defined as leaks that present only after cool down, sometimes reported in other cryogenic systems, have not been observed in RHIC.

3.4 Vacuum Instrumentation and Control

There are over fifteen hundred remotely controlled vacuum gauges, pumps and gate valves in the RHIC vacuum instrumentation and control (I&C) system. Eight programmable logic controllers (PLCs) are used to monitor and operate the devices. The PLCs are the link between the intelligent gauge/pump controllers and the Controls' front-end computers (FECs). Gauge and pump controllers are connected to the PLC with RS485 serial networks. Each PLC chassis comprises one processor module, two communication coprocessors and several input and output (I/O) modules. Each coprocessor has six serial communication ports assigned to different types of vacuum devices. The I/O modules have either 32 inputs or outputs, and use 24 Vdc control voltages. Ladder logic programs residing in the PLC processors control the valve solenoids based on input signals from gauges, pumps, and valves. A sector valve can be opened only if the vacuum level satisfies gauge set points on both sides of the valve. Two of three pressure readings must rise above the set points to close a sector valve. A closed valve causes the PLC to remove the beam permit. The vacuum instrumentation and control system has been very reliable during the commissioning and the subsequent physics runs.

4 SUMMARY

The RHIC vacuum systems, though containing numerous welds, flanged joints and special components, have performed extremely well and met or exceeded the requirements of collider operations over the last few years. The design vacuum of $5x10^{-10}$ Torr in the warm sections was reached even without bakes. After in-situ bakes, vacuum around experimental regions reached $\sim 1x10^{-10}$ Torr, thereby decreasing background noise to the detectors. The combination of CCGs and sorption pumps is sufficient to monitor and pump He leaks in the cold bore and to achieve the designed vacuum of $< 10^{-11}$ Torr. The combination of transverse conduits and pumping ports in the insulating vacuum, proved effective for locating He leaks to within one interconnect and to pump on the leaks. A plan to systematically replace all valves in the cryogenic valve boxes is being formulated to mitigate the slow corrosion of the welds in the cryogenic valve boxes, which otherwise would continue to plague the operation and reliability of the cryogenic insulating vacuum. Overall, the implementation of a sound design with adequate quality assurance has yielded the successful performance of the RHIC vacuum systems.

5. ACKNOWLEDGEMENT

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