COMMISSIONING OF RHIC VACUUM SYSTEMS*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) has two concentric rings 3.8km in circumference. There are three vacuum systems in RHIC; the insulating vacuum vessels housing the superconducting magnets, the cold beam tubes surrounded by the superconducting magnets, and the warm beam tube sections at the insertion regions and experimental regions. The vacuum requirements and the design of three vacuum systems are described. The experience gained during the commissioning of these vacuum systems is presented with emphasis on locating helium leaks in the long arc insulating vacuum system.

1 INTRODUCTION

RHIC [1] comprises two interweaving rings that intersect with each other at six experimental regions. RHIC will store and collide two counter-rotating ion beams with masses from proton to gold and energies up to 250 GeV/nucleon for periods greater than ten hours. Over 1700 superconducting magnets of various types and lengths, housed in the magnet cryostats and cooled by superfluid helium (He), are used to bend and focus the particle beams. There are three distinct vacuum systems in RHIC: (1) the room temperature (warm bore) beam vacuum regions which house the injection, acceleration, instrumentation and experimental regions; (2) the cold beam pipes (cold bore) encased by the superconducting magnets; and (3) the insulating vacuum vessels (cryostats).

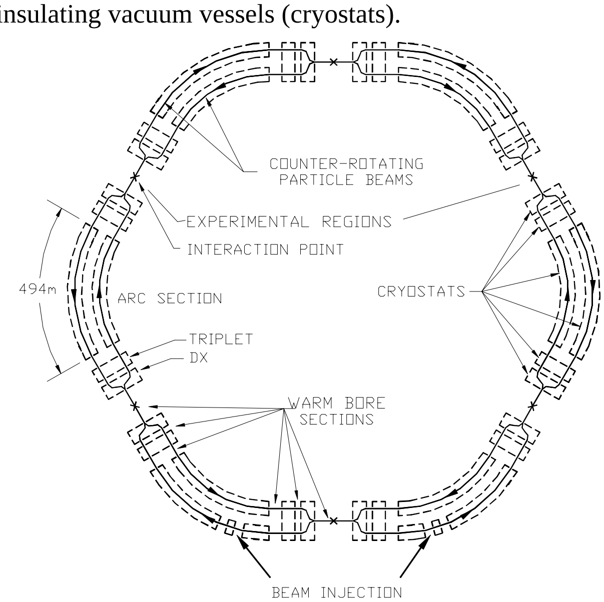

Fig. 1 The Layout of Two RHIC Rings

The total length of cold bore and cryostats in these two rings is ~ 6.4 km, divided into 12 arc sections of 494m each and 24 short insertion sections. A schematic view of the collider is shown in Fig.1. The layout of the vacuum equipment for one-twelfth of the collider is shown in Fig. 2. Each 494m arc section consists of a continuous cryostat, housing 64 superconducting magnets with alternating dipole and corrector-quadrupole-sextupole (CQS). The lengths of the standard dipole and CQS are ~9.5m and ~4.5m, respectively. Major benefits of the long cryostats without vacuum barriers are economics, increased reliability and lower heat load, with increased pump down and leak checking difficulty as the main disadvantage. The 64 interconnected magnets form a continuous cold beam tube. The two adjacent insertion triplet magnet strings (Q3-Q2-Q1-D0) reside within a common cryostat due to their proximity. The large aperture DX magnet that bends and focuses both beams shares the same insulating volume with the triplets but has a warm beam tube connected to the experimental beam pipe and the DX-D0 chamber.

The required beam vacuum levels are derived from beam lifetime and detector background considerations. The warm bore design vacuum is $<5x10^{-10}$ Torr ($\sim1.7x10^{+7}$ molecules/cm^3) consisting of 90% H_2, 5% CO and 5% CH_4. The cold bore design vacuum is $<1x10^{-11}$ Torr ($\sim2x10^{+7}$ molecules/cm^3 after correcting for thermal transpiration) consisting of only H_2 and He since all other gases will condense on the 4K surface. Elastic and inelastic scattering from beam-residual gas interactions were considered when determining the vacuum requirements for the worst case in RHIC, i.e. Au at injection energy of 10 GeV/amu. The elastic scattering (multiple Coulomb scattering) causes the growth of the transverse emittance. Using the Fokker-Planck diffusion equation, the rate of growth is $\sim10^{-4}$ mm.mrad/hr [2] which is insignificant in comparison with the emittance growth due to intra-beam scattering.

The inelastic scattering includes electron capture and nuclear scattering, which cause immediate beam loss. The total electron capture cross section [3] consists of radiative, non-radiative and vacuum captures and is $\sim10^{-25}$ cm^2 for RHIC residual gas composition [2][4]. The energy independent nuclear scattering cross section is proportional to the geometrical cross section and is $\sim10^{-24}$ cm^2 for RHIC residual gas composition. The beam-gas lifetime dominated by the inelastic scattering will be several hundred hours for Au [4]at the design vacuum of $2x10^{+7}$ molecules/cm^3 which is much longer than the overall beam lifetime of ten hours. Background noise to the detector due to beam-residual gas nuclear scattering at and near experimental regions puts the most stringent requirement on RHIC beam vacuum systems.

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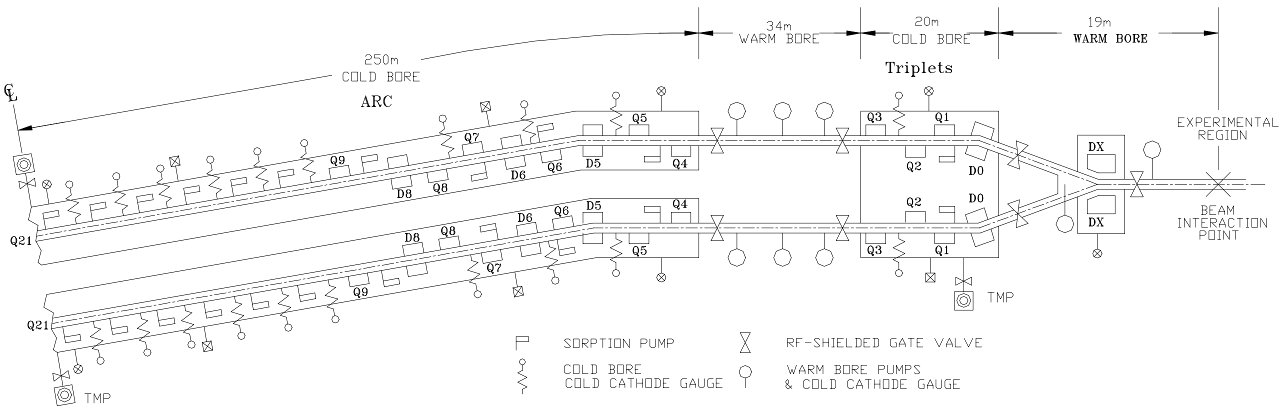

Fig. 2 The layout of Three Vacuum Systems in One-Twelfth of RHIC Rings

The probability of beam-gas interaction ±40m around the collision point will be ~1x10^{-4} interactions per bunch per crossing. The total beam-gas rate will be ~10^{3} Hz which is comparable to the beam-beam rate [5] at the design luminosity of 10^{-26}cm^{-2} s^{-1}. Of course, only a small percentage of the beam-gas events fall into the interaction diamond and overlap with the beam-beam events.

To minimize the heat transfer from the ambient cryostat wall to the magnet cold mass and the He conduits through gas convection, insulating vacuum of 10^{-5} Torr inside the cryostat is necessary.

2 RHIC VACUUM SYSTEMS

2.1 Warm Bore Vacuum System

The warm bore regions occupy ~16% of the ring circumference and are divided into 52 vacuum sections with length ranging from 4m for rf cavities to 34m for a standard Q3-Q4 section. RF-shielded gate valves located at the ends of warm sections are used to isolate them from adjacent warm bore and cold bore sections. Most warm bore pipes are made of 127mm OD stainless steel and utilize conflat flanges. They are joined together with rf-shielded bellows and ion pump tees. The injection, rf cavity, extraction and instrumentation vacuum chambers have more complex geometry and include components with high outgassing materials such as ferrite and graphite. The DX-D0 chambers where both beams merge into DX magnets have long internal perforated shields to minimize beam impedance. The beam pipes inside the experimental detectors are made of 1mm thick beryllium for its transparency to energetic particles. The warm bore sections are pumped with large sputter ion pumps and titanium sublimation pumps. Inverted magnetron cold cathode gauges (CCG) are used to monitor the warm bore vacuum. With the exception of the rf cavities, all warm bore sections including DX beam pipes are in-situ bakeable to 250°C.

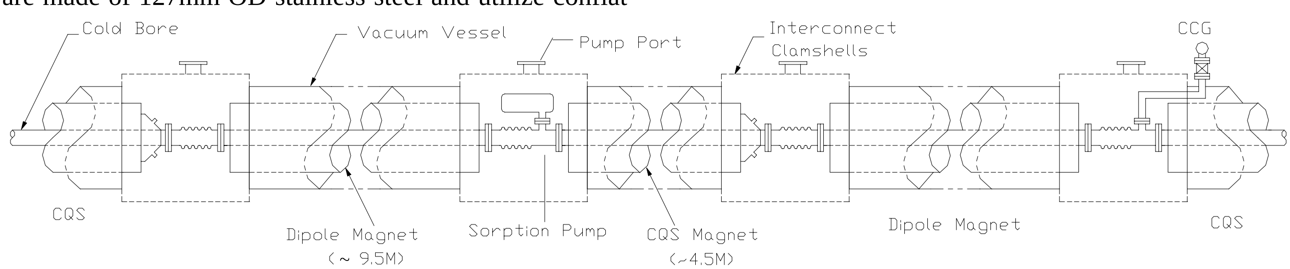

Fig. 3 Vacuum Layout of RHIC Arc Section

2.2 Cold Bore Vacuum System

A series of interconnected magnets forms the RHIC cold bore, as shown in Fig. 3. Each magnet vessel comprises magnet coils and laminations built upon a seamless stainless steel tube that extends beyond the length of the magnet. Each magnet vessel was pressure tested to 20 atm. during manufacturing. The magnet vessel is then assembled along with four He conduits and an aluminum heat shield, insulated with blankets of multi-layer thermal insulation (MLI), and inserted in a carbon steel cryostat. Approximately 10% of the dipole magnets and all the CQS magnets were cold tested before installation. Once installed, the beam tubes with conflat flanges are connected with rf-shielded bellows to form a continuous cold bore.

There are 40 cold bore sections isolable from adjacent warm bore sections with rf-shielded gate valves. The cold bore pressure is expected to be immeasurably low if He leaks are absent. No welded, brazed or bolted vacuum joints serve as barriers between the beam vacuum and the contained superfluid He. Helium can leak into the cold bore from the He filled magnet vessels only through metallurgical flaws in the cold beam pipes. Sorption pumps containing activated charcoal are mounted to the pull through ports of the rf-shielded bellows at every fourth interconnect (~ 30m intervals) to pump He and H_2. The pumping speed of the sorption pump at the cold bore port is ~ 2.5 l/s. CCGs identical to those in the warm bore are used to monitor the cold bore pressure. They are mounted on the ambient cryostat at ~30m intervals. A 1.5m long 1" diameter flexible conduit attached to cold bore port snakes through the MLI and the 55K heat shield, and is then connected to the CCG.

Prior to magnet cool down, the cold bore is usually roughed down to ~10^{-4} Torr with a turbomolecular pump station (TMP). After cooldown, the CCGs read mid-10^{-10} Torr pressure due to the localized outgassing of the gauge conduits. Changes in CCG pressure readings ΔP_w, are assumed to be contributed by He. With no net He flow between the cold bore and the CCG and factoring in thermal transpiration, then

$$\Delta P_w = S_{He} \,x \{T_w / T_c\}^{0.5} \,x\; P_c$$

with S_{He}: the CCG sensitivity correction for He (= 1/7)
P_c: the cold bore He pressure
T_w: the temperature at the CCG (~ 295K)
T_c, the temperature of the cold bore (~ 4.5K)

then P_c = ~0.8 x ΔP_w.

With background reading of 10^{-10} Torr at CCGs, pressure changes of 10^{-11} Torr level in the cold bore should be easily observable by the CCGs.

2.3 Cryostat Insulating Vacuum System

There are 28 insulating vacuum volumes: 12 long arcs, 12 triplets and 4 short cryostats between the ambient injection magnets. The volume of the long arc cryostat is ~150m^3 and that of triplet-DX over 50m^3. The insulating vacuum requirement is 10^{-5} Torr. At 4K, all gases except He will be effectively pumped by the magnet cold masses. Helium may originate from leaks in the magnet vessel welds or in the bellows where the superfluid He and the superconductor cables are piped from one magnet to the next. Helium may also come from the leaks in welds of the four He conduits running the full length of the cryostats. A side view of the cryostat magnets and interconnects is shown in Fig. 4.

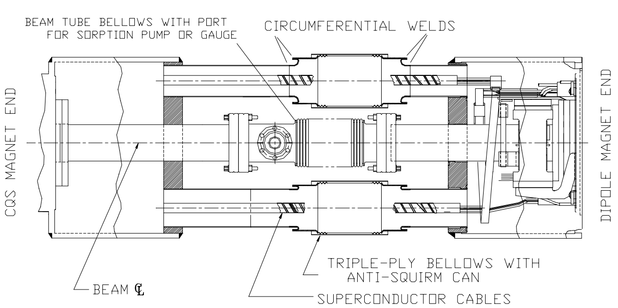

Fig. 4 Magnet and Beam Tube Interconnecting Bellows

After installation and survey of each magnet, the superconductor cables are brazed together, insulated and tested followed by positioning and welding of the triple-ply bellows. The four He conduits are then joined by welding. In all, there are 16 in-situ circumferential welds at each interconnect. Each of these welds must be verified at room temperature with sufficient sensitivity to ensure that it will not spoil insulating vacuum after cool down.

After completing a long string of interconnects, the He conduits are pumped down and the in-situ welded joints leak checked to a sensitivity of ~10^{-8} std.cc/sec He (all the leak rates referred from here on are equivalent leak rate at room temperature in standard cc per sec He). The triple-ply He bellows welds between magnets are leak checked by pressurizing the magnet vessel to ~2 atm He and sniffing around the weld zone. The sensitivity of this approach is ~10^{-4} std.cc/sec at best when sniffing is done carefully and the tunnel He background is low. Some earlier bellows welds were checked with vacuum-jacketed fixtures which gave far better sensitivity, however, they are not used due to the significant effort required to use the fixtures and the high success rate of the automatic welder. The cryostat clamshells surrounding the interconnect are then welded together to form the cryostat. The completed cryostat is roughed down to ~10^{-2} Torr by a mobile roots blower/mechanical pump station, before the pumping is transferred to a TMP.

Two major requirements in the design of the insulating vacuum system are: locating serious He leaks to within one interconnect; and instituting local pumping provisions on these leaks until repairs are made. A pump port and transverse conduit as shown in Fig. 5 are at each interconnect to meet these requirements. Transverse conduits are high conductance path at interconnects linking the three temperature regions (the 4K magnet, the 55K heat shield and the ambient wall). The He conductance of the conduit is 400 l/s, optimized using a voltage analogue to simulate actual conductance [6]. The 100mm pump ports are capped with manual valves allowing the addition of pumps without venting the cryostat. One TMP is mounted on the pump port located at the midpoint of each long cryostat. The combination of the transverse conduit and the

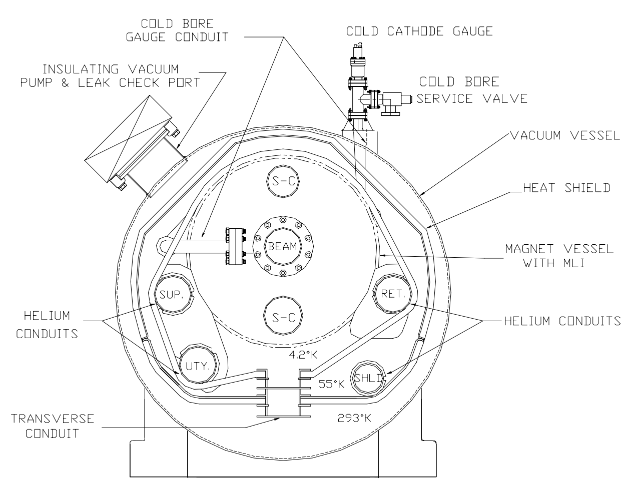

Fig. 5 Cross Sectional View of Arc Interconnect

TMP provides a He pumping speed of ~100 l/s. In the event of an internal helium leak, the TMP generates a He pressure gradient with sufficient resolution to locate the leak to within one interconnect. Additional TMPs are then added to the pump ports nearest the leaks to ensure that leaks of $<10^{-2}$ std.cc/sec can be effectively pumped and adequate insulating vacuum maintained until repairs can be made.

3 COMMISSIONING EFFORT

The first sextant test (FST), the completion and testing of one-sixth of the ring, was carried out in January1997 with vacuum established, magnets cooled down and powered, and beam injected. Modifications were made to the design of some helium flex lines and to the assembly procedures when He leaks resulting from flux corroded flex lines and inappropriate use of ultrasonic welders were identified. The remaining sextants were commissioned in late 1998 and early 1999. This section summarizes the performance of the three vacuum systems during FST and recent commissioning effort, with emphasis on locating and repairing He leaks in the insulating vacuum systems which is by far the most difficult and time consuming efforts.

3.1 Commissioning the Warm Bore

Work on warm bore sections could only begin after the adjacent cryostats/cold bore sections were completed. After installation, alignment and assembly, a TMP backed by a dry mechanical pump was used to rough down the warm bore section. After leak checking, the sputter ion pumps were conditioned and energized. To this date, 44 of the 52 warm bore sections are complete with vacuum reaching 10^{-9} Torr in a few days comprising of mostly H_2, H_2O and CO. The remaining sections will be commissioned after the installation of the four experiment detectors and the termination of the ion pump and gauge cables. Three warm bore sections have been in-situ baked and reached pressure of $\sim 1\times10^{-10}$ Torr, comprising mostly H_2. Other warm sections will be baked and conditioned in the coming year.

3.2 Commissioning the Cold Bore

The cold bore sections were pumped down to pressures of 10^{-4} Torr or better by TMP and valved off. The pressure would slowly creep to mid 10^{-2} Torr over a few months, which is still adequate for cool down. After cool down, the CCGs at cold bore typically read 10^{-10} Torr range when the true pressure in the cold bore is $<10^{-11}$Torr. The usefulness of the CCGs in monitoring the cold bore He pressure, in the unlikely event of He leaks from magnet volume into the cold bore, was studied during FST [7]. Helium from a calibrated leak of 4×10^{-5} std.cc/sec was continuously introduced into the cold bore for 9 days while CCG readings were monitored and recorded. The CCG readings increased sharply when the He fronts reached the particular gauge locations, then leveled off. The cold bore He pressures derived from the changes in the CCG readings were compared and found to be in good agreement with those calculated[7]. This result indicates that the CCGs are useful to detect cold bore pressure increases with sensitivity down to $\sim 10^{-11}$ Torr. The study also validates the need and the effectiveness of the sorption pumps in slowing the He pressure front speed and in reducing the magnitude of the He pressure zone.

3.3 Commissioning the Insulating Vacuum

After the completion of installation and welding, the cryostat volume was pumped down by a mobile roots blower/mechanical pump station with pumping speeds of ~ 140 l/s and 30 l/s, respectively. Typical pump down curves for arc cryostats (with a volume of ~ 150 m^3) are shown in Fig. 6. The pressure decreased rapidly to ~1 Torr within one day then leveled off due to the gradual desorption of ~50 liters of water absorbed in the MLI [8]. Most insulating volumes have to be bled back to atmosphere pressure several times to repair cryostat vessel air leaks or internal He leaks. Without major air leaks, pressure of mid10^{-2} Torr is usually reached in a few days, which is needed to ensure adequate leak checking sensitivity. Once pressure of low 10^{-2} Torr was reached, the TMP was switched on to maintain the insulating vacuum until cool down.

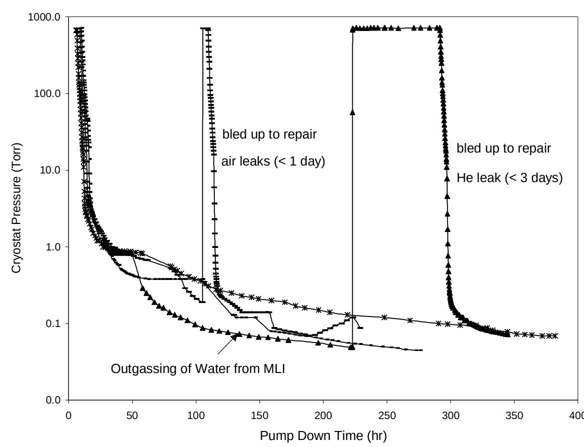

Fig. 6 Pumpdown Curves of RHIC 494m Arc Cryostats with 300CFM roots blower and 60 CFM mechanical pump

During FST, with insulating vacuum established, high He background levels were observed in the cryostats when the magnet vessels and He conduits were pressurized. A

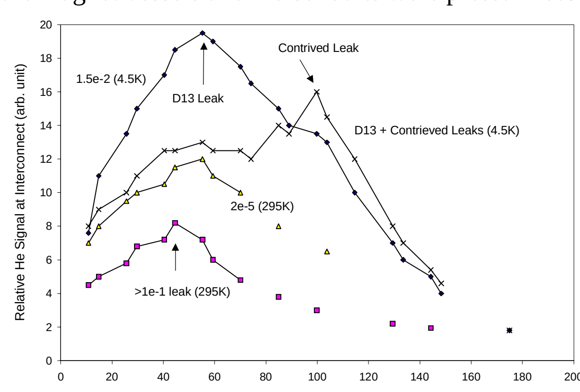

Fig. 7 Helium Pressure Gradients at Interconnects in 494m Arc Cryostats

series of pressure tests were conducted to isolate the leaks to specific conduits by individually pressurizing each to 15 atm He while the others evacuated. After identifying which conduits leaked and quantifying the leak rates, the leak was traced to the offending interconnect by measuring the cryostat He pressure gradient generated by the TMP [9] as shown in Fig.7. The gradients across a typical CQS magnet were ~5% and across a dipole magnet ~10%. Two large leaks were found and repaired at specific interconnects in the arcs using the gradient method. After the repair, an additional 10^{-5} std.cc/sec leak, masked by the large leak, was found 200m away. A mobile TMP was positioned at the interconnect to pump He. After cool down, the leak rate increased to $1.5\text{x}10^{-2}$ std.cc/sec due to the increase in density and decrease in viscosity of superfluid He. The pressure at this interconnect was maintained at $\sim10^{-4}$ Torr range, considered the local upper limit for the insulating vacuum.

After FST, this interconnect was opened and the leak was located by sniffing while pressurizing the He conduit. This approach can only detect 10^{-5} std.cc/sec leaks, when parked on the leak. Bagging and accumulating helps identify 10^{-6} leaks, but provides little benefit for locating smaller leaks. For example, the 10^{-5} std.cc/sec leak was located by leaving the conduit under 5 atm. for overnight with the cryostat at atmospheric pressure. This yielded a slight increase above 5 ppm He background in air using a sniffer probe. A leak of $\sim10^{-6}$ std.cc/sec would require an impractical 10 days of accumulation to be observed with the sniffer probe.

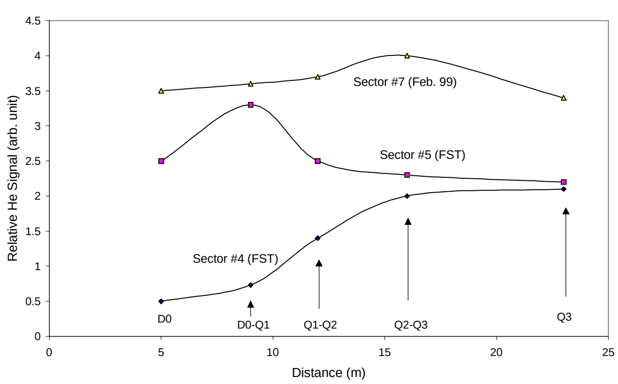

Fig. 8 Helium Pressure Gradients in RHIC Triplet Cryostats

During the most recent commissioning effort, all He volumes were first pressurized to 3 atm. Ten He leaks of various sizes were observed at different insulating volumes. One dozen additional leaks showed up when the He pressure was increased to 15 atm. Leaks at 10^{-7}-10^{-6} std.cc/sec levels were deemed too difficult to locate and vacuum could be safely maintained by mobile TMPs even when the leak rates increase by a few decades after cool down. The large ones ($>10^{-3}$ std.cc/sec) were quickly located and repaired. Leaks of 10^{-5}-10^{-4} std.cc/sec levels in the arcs were also located using He pressure gradient.

Locating 10^{-5}-10^{-4} std.cc/sec range leaks in the triplet cryostats was more challenging due to the larger and more complicated cryostat vessel accommodating both strings of magnets, which reduces the effectiveness of the pressure gradient. Typical He pressure gradients inside the triplet cryostats are shown in Fig. 8. They do not point to the exact interconnect in some cases. Innovative approaches were developed to locate these leaks. Some leaks were located by differentiating the He arriving time at leak detectors mounted at each interconnect while pressurizing the He volumes. Others were located by differentiating the size of He signal when low pressure He was introduced into individual power lead at each interconnect. With the cryostat bled up to atmosphere, each interconnect was then probed with a sniffer through the pump port to confirm the measured He gradient data prior to cutting open the interconnect. With the interconnect open, the sniffer was then used to pin-point the leak location.

4 SUMMARY

The RHIC vacuum systems have been commissioned and are ready for collider operation. All three systems performed as expected. The designed vacuum of $5\text{x}10^{-10}$ Torr in the warm sections can be reached without difficulty after bakeout. 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. In the long arcs, the combination of transverse conduits and pumping ports proved effective to locate He leaks to within one interconnect and to pump on the leaks. In the DX-triplet cryostats, locating leaks has been more challenging due to the complex geometry and the high-conductance space which prevent the formation of He pressure gradients. Innovative approaches have been developed to locate these leaks

Overall, there were less than two dozen leaks found after the installation was complete. This excludes the damaged flex lines and bellows caused by misuse of ultra sonic welders prior to FST; and damaged triple-ply bellows which squirmed due to insufficiently supported interconnect pipes during commissioning. With approximately 25,000 in-situ He line welds and a total welded length of over 5 km, the welding and leak checking of insulating vacuum could be considered rather successful.

5. REFERENCES

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