RHIC HEAVY ION OPERATIONS PERFORMANCE*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) completed its fifth year of operation in 2005, colliding copper ion beams with $\sqrt{s}$=200 GeV/u and 62.4 GeV/u[1]. Previous heavy ion runs have collided gold ions at $\sqrt{s}$=130 GeV/u, 200 GeV/u, and 62.4 GeV/u[2], and deuterons and gold ions at $\sqrt{s}$=200 GeV/u[3]. This paper discusses operational performance statistics of this facility, including Cu-Cu delivered luminosity, availability, calendar time spent in physics stores, and time between physics stores. We summarize the major factors affecting operations efficiency, and characterize machine activities between physics stores.

1. INTRODUCTION

RHIC consists of two independent superconducting 3.8 km rings (the “blue” and “yellow” rings), intersecting at six interaction points (IPs) and providing luminosity to 2–4 concurrent experiments. RHIC has completed five successful physics runs since commissioning in 1999, including both heavy-ion and polarized proton spin physics programs. Table 1 shows design, achieved, and upgrade machine parameters for RHIC as an ion collider.

Figure 1 summarizes RHIC performance in the 2005 Cu-Cu $\sqrt{s}$=200 GeV/u run. Measured luminosity at four experiments is compared to minimum and maximum luminosity projections from run planning documents[4], with minimum projections based on previous RHIC heavy-ion. RHIC as a Cu-Cu collider exceeded the maximum projection, achieving 15 nb^{-1} of integrated luminosity at the low-$\beta^\star$ experiments, more than twice the $7\mathrm{nb}^{-1}$goal. The initial physics production store of 28 bunches of 4.5×10^9evolved into the final configuration of 37 bunches with 5×10^9Cu ions/bunch.

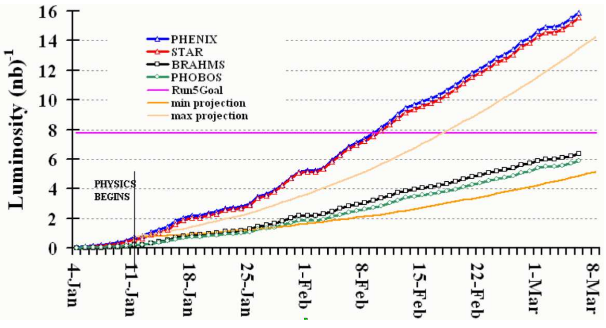

Figure 1: Delivered Cu-Cu $\sqrt{s}$=200 GeV/u luminosity in RHIC Run-5.

With ions, injection is performed with $\beta^\star$=10 m at all IPs, and acceleration ramps squeeze to $\beta^\star$=5 m at all IPs to optimize for transition jump optics. $\beta^\star$ is then squeezed to final collision optics during the remainder of the acceleration ramp to minimize ramping time to reach collision optics. Collision optics are typically set to $\beta^\star$=5 m at non-experimental IPs, and $\beta^\star$=0.85–3 m at experimental IPs. These settings are based on experiment background issues and presence of nonlinear correctors. The beams are vertically separated with ±5 mm bumps through the acceleration ramp, and RF-locked in an “anti-cogged” position to avoid detrimental beam-beam effects.

A change of species for a RHIC run typically requires about 1–3 weeks of setup period to establish ramping and collisions. This is followed by 1–2 weeks of ramp-up to set up detectors and maximize luminosity production. This is a substantial portion of the typical 27–31 weeks of annual RHIC operations. Setup and ramp-up periods are shorter during planned mid-run species changes, as injector development can often occur during RHIC physics stores.

2. THE RHIC CYCLE

Fig. 2 shows activity in RHIC between two Cu-Cu physics stores in 2005. The details shown are typical for the periods between same-species heavy-ion physics stores at RHIC, and can be divided into four periods: beam dump and magnet ramping, preparing beam for injection, accelerating beam to collision energy, and preparing collisions for physics. The period from dumping beams to the start of physics data collection is defined as turn-around time, and is discussed in the next section. All times in the following paragraphs refer to Fig. 2.

From 18:12:30 to 18:18:00, beams are dumped, and RHIC magnets are ramped down to a parking current and back to injection to maintain proper hysteresis. This time is dominated by limits set by superconducting magnet quench detection. The beam dump time was originally determined by a voting consensus among participating experiments; physics stores are now a fixed length, optimized to maximize usable luminosity delivered to experiments.

From 8:18:00 to 8:33:00, beams are prepared for injection. This period is highly variable, depending on the injector readiness and the amount of injection tuning required. Injector readiness also benefits from fixed physics store lengths, as dump times are more predictable for operations when running multiple injector physics programs and saving energy costs. Pulsed injector element drift and persistent current chromatic effects (drifting about 2 units over 15 minutes after returning to injection[5]) are the main

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Table 1: RHIC 200 GeV/u heavy c.m. energy ion performance evolution. Run-# parameters shown provided the highest experiment luminosities. Enhanced luminosity numbers are facility goals c. 2008, before electron cooling.

Species [Run]	No of bunches	Ions/bunch $[10^9]$	$\beta^\star$ [m]	Emittance [$\pi\mu$rad]	$\mathcal{L}_{peak}$	$\mathcal{L}_{store,ave}$	L_{week}
					$[\times 10^{26}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	
Au-Au (Design)	56	1.0	2	15-40	9	2	50 $\mu\mathrm{b}^{-1}$
d-Au (Run-3)	55/110	120d/0.7Au	2	15	700	200	4.5 nb^{-1}
Au-Au (Run-4)	45	1.1	1	15-40	15	4	160 $\mu\mathrm{b}^{-1}$
Cu-Cu (Run-5)	36	4.5	0.85	10–30	198	80	2.3 nb^{-1}
Au-Au (Enhanced)	112	1.1	1	15-40	36	9	350 $\mu\mathrm{b}^{-1}$

items requiring further injection tuning in this period. At the end of this period, both rings are filled with fresh beam and ready for acceleration. The bottom plot of Fig. 2 shows

From 8:33:00 to 8:38:00, beams are accelerated to collision energy. The top plot shows the main magnets ramping back up to storage energy, while the bottom plot shows a group of vertical red lines marking tuning points through the acceleration ramp. RHIC is the only superconducting accelerator to cross transition, and beam intensity losses are seen before and through transition. The heavy ion acceleration ramp time of about five minutes is dominated by limits set by superconducting magnet quench detection.

From 8:38:00 to 8:40:00 collisions are prepared for physics. This includes longitudinal RF cogging, rebucketing into 198 MHz RF storage cavities, collision steering, and collimation setup. The preparation time for physics collisions can be as long as tens of minutes with collision optimization at all four IPs, and collimation optimization to minimize backgrounds. This is often necessary when pushing machine parameters to maximize delivered luminosity. Upon completion of these items, an event (ev-physics) is generated to notify all experiments that machine setup for that physics store is complete.

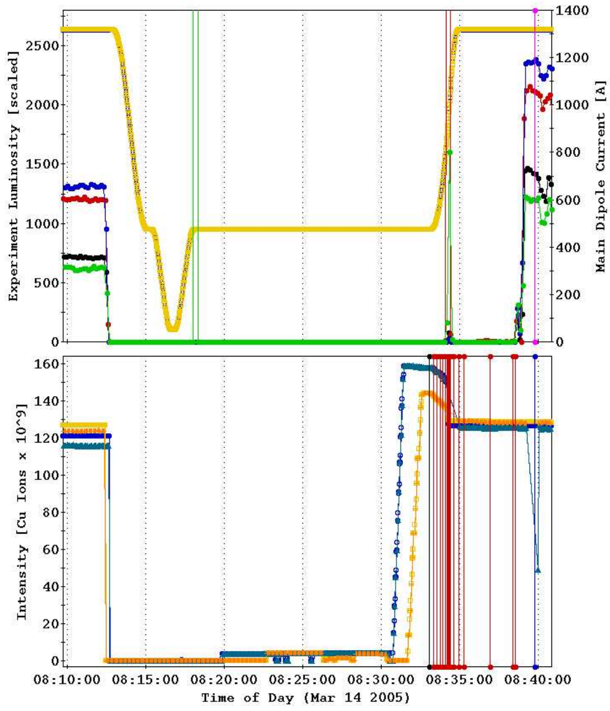

Figure 2: Activity in RHIC between two Cu-Cu stores. The bottom plot shows beam current. The top plot shows measured experiment luminosity and main dipole current. See Section 2 for further details.

With the exception of injection tuning and some aspects of physics setup (collision steering, collimation), all activities between stores are controlled by a software sequencer. This program ensures store-to-store reproducibility of machine activities, and automatically checks for error conditions such as premature abort kicker slow discharge or unexpected beam loss.

3. TIME BETWEEN STORES

The time between dumping beams and the next physics data collection start is defined as turn-around time. Heavy ion luminosity degradation during a physics store is dominated by intrabeam scattering, naturally leading to a short store lengths and more turn-around times. Therefore, it is crucial to charaterize every step in the turn-around time process and minimize it, since heavy ion luminosity degradation during physics stores due to intrabeam scattering naturally leads to shorter store lengths and more frequent store turn-around. Fig. 3 shows the turn-around time for all stores during the RHIC Cu-Cu $\sqrt{s}$=200 GeV/u run. The average time between stores in this pariod was 75 minutes without including extremely long failure times of greater than ten hours.

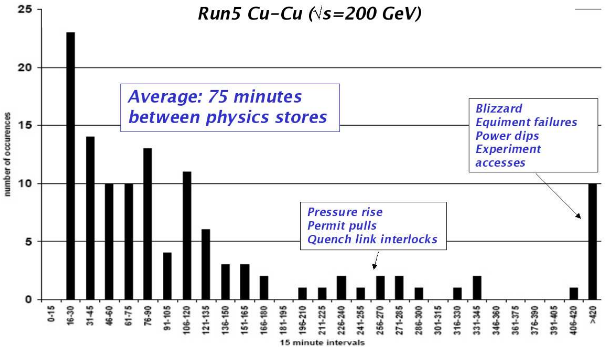

Figure 3: Histogram of turn-around time for the RHIC Cu-Cu $\sqrt{s}$=200 GeV/u run.

The turn-around times in Fig. 3 fall into three categories: routine, excessive, and failure. 80% of turn-around times shown were routine, 10% were excessive, and 10% were failure. Section 2 shows described one example of a routinely achieved turn-around time of about 25 minutes. Integrated luminosity gains of 5–10% can be achieved by reducing the average turn-around time to 25 minutes. Turn-around times of less than 120–130 minutes are considered routine, and are usually longer than the optimal turn-around time because of injector readiness problems, or experiment access between stores for minor equipment repair.

Moderately long turn-around times (120–300 minutes) can be attributed to aggressive machine development, superconducting magnet quench link interlocks, or significant equipment repair, such as power supply replacement. With only eight weeks available for high-energy Cu-Cu physics operation, incremental luminosity development was necessary, including gradual increase in beam intensity and number of bunches. This development occasionally resulted in a store abort from pressure rise or beam losses.

Excessively long turn-around times (longer than 300 minutes) were all associated with facility failures. These failures include two blizzards, experiment or accelerator failures that were spontaneously converted into maintenance days, and power dips.

4. RELIABILITY AND UPTIME

Fig. 4 shows the percentage of calendar time spent in store conditions for over the past four years. The time in store for the past two years has been about 52-53%. The overall goal is 60% calendar time in store (101 hours/week). The time in store is measured from the each ev-physics on event to the corresponding beam dump event. Calendar time, including scheduled maintenance and accelerator physics experiments, is used to calculate the fractional time in store. Each experiment uses this time differently depending on detector readiness and turn-on time.

Time in collisions at store for the Cu-Cu $\sqrt{s}$=200 GeV/u run was 52% of calendar time, and increased to 74% of calendar time for the $\sqrt{s}$=62.4 GeV/u run. The significant difference in uptime for the two operational modes can be attributed to an increased quench margin and to the more relaxed beam parameters used for the low energy run, including 30% lower bunch intensity and a larger $\beta^\star$ at the low-$\beta^\star$ interactions. The facility availability of the machine for all uses including physics stores, setup, ramping, and beam experiments is shown in Fig. 5. The average availability was near the target value of 80%.

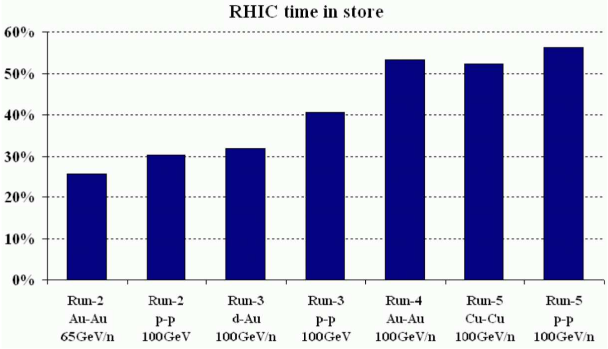

Figure 4: RHIC calendar time spent at storage energy for each run.

Figure 5: RHIC 2005 Cu-Cu run availability by week.

Future RHIC luminosity upgrades involve electron cooling of the ion beams. R&D of a 54 MeV electron cooler is underway, with expected completion in 2008. A weekly integrated Au-Au luminosity of 350 μbarns is planned before the cooling upgrade, as shown Table 1. Injectors are providing design intensity. Efforts are concentrating on increasing the number of bunches colliding per physics fill, currently limited by electron cloud and pressure rise effects. Facility physics time of 60% and availability of 80% will be maintained with efforts to automate and speed up collimation, collision steering, and other factors affecting turn-around time.

ACKNOWLEDGEMENTS

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REFERENCES

[1] F. Pilat et al., "Operations and Performance of RHIC as a Cu-Cu Collider", PAC'05, Knoxville, Tennessee (2005).

[2] W. Fischer et al., "Luminosity Increases in Gold-Gold Operation in RHIC", proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland (2004).

[3] T. Satogata et al., "Commissioning of RHIC Deuteron-Gold Collisions", proceedings of the 2003 Particle Accelerator Conference, Portland, Oregon (2003).

[4] T. Roser, W. Fischer, M. Bai, and F. Pilat, "RHIC collider projections: FY2005-2008", available online at http://www.rhichome.bnl.gov/RHIC/Runs/RhicProjections .

[5] W. Fischer, A. Jain, and S. Tepikian, "Beam-based measurements of persistent current decay in the Relativistic Heavy Ion Collider", Phys. Rev. ST Accel. Beams **4**, 041002 (2001).