RHIC OPERATIONAL STATUS*

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Abstract

As the first hadron accelerator and collider consisting of two independent superconducting rings RHIC has operated with a wide range of beam energies and particle species. Machine operation and performance will be reviewed that includes high luminosity gold-on-gold and copper-on-copper collisions at design beam energy (100 GeV/u), asymmetric deuteron-on-gold collisions as well as high energy polarized proton-proton collisions (100 GeV on 100 GeV). Plans for future upgrades of RHIC will also be discussed.

THE RHIC FACILITY

With its two independent rings RHIC is a highly flexible collider of hadron beams ranging from colliding intense beams of polarized protons to colliding fully stripped gold ions. The collision of 100 GeV/nucleon gold ions probes the conditions of the early universe by producing extreme conditions where quarks and gluons are predicted to form a new state of matter. Several runs of high luminosity gold-gold collusion as well as comparison runs using proton, deuteron and copper beams have demonstrated that indeed a new state of matter with extreme density is formed in the RHIC gold-gold collisions.

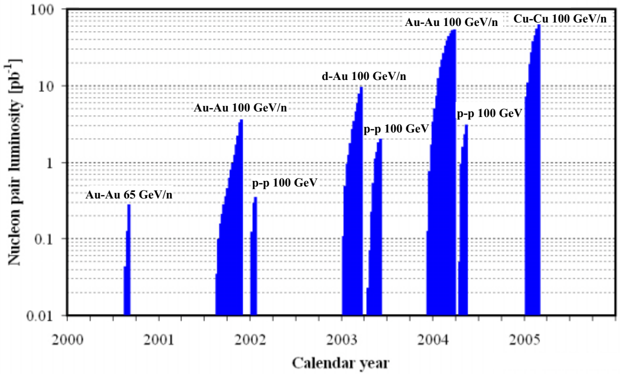

Figure 1: Integrated nucleon-pair luminosity for all the RHIC running modes since start of operation for the experiment PHENIX.

The RHIC polarized proton collider has opened up the completely unique physics opportunities of studying spin effects in hadronic reactions at high-luminosity high-energy proton-proton collisions. It allows study of the spin structure of the proton, in particular the degree of polarization of the gluons and anti-quarks, and also verification of the many well-documented expectations of spin effects in perturbative QCD and parity violation in W and Z production. The RHIC center-of-mass energy range of 200 to 500 GeV is ideal in the sense that it is high enough for perturbative QCD to be applicable and low enough so that the typical momentum fraction of the valence quarks is about 0.1 or larger. This guarantees significant levels of parton polarization.

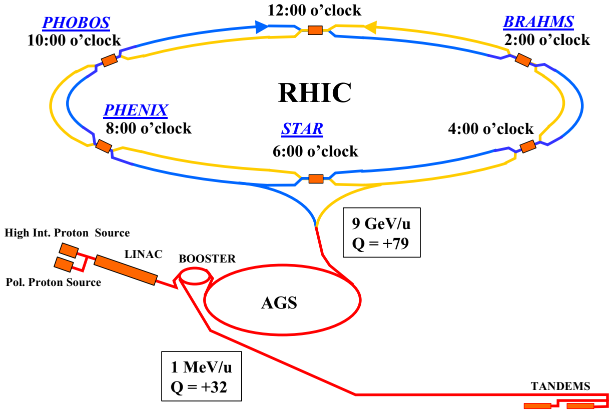

Figure 2: Layout of RHIC and the injector accelerators. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy.

During its first five years of operation RHIC has already exceeded the design parameters for gold-gold collisions, has successfully operated in a asymmetric mode of colliding deuteron on gold with both beams at the same energy per nucleon but, of course, different rigidity, and very successfully completed an additional comparison run of colliding copper beams with record luminosities. In addition, three very successful commissioning periods with polarized protons demonstrated the performance of RHIC as a high luminosity polarized collider. A first data run with polarized proton collisions is presently underway. For the main part of all these runs RHIC was operating with beam energies of 100 GeV/nucleon - the gold beam design energy. Additional running at lower beam energy was also accomplished during these same running periods again demonstrating the high flexibility of RHIC. Fig. 1 shows, in semi-logarithmic scale the achieved integrated nucleon-pair luminosity for the many modes of operation of RHIC since its start of operation in 2000. Using nucleon-pair luminosity allows the comparison of the different modes properly reflecting the relative statistical relevance of the data samples and also the degree of difficulty in achieving high luminosity.

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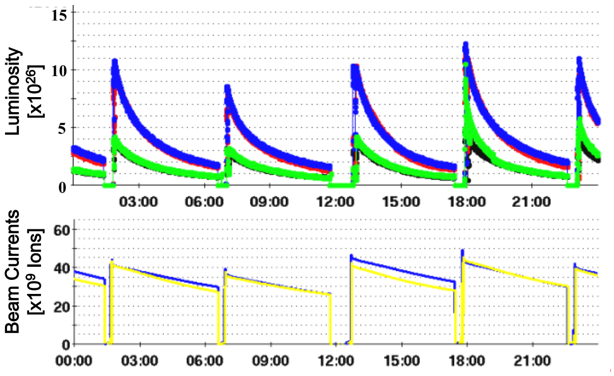

Figure 3: Evolution of the collision rate at the four RHIC detectors and beam currents in the blue and yellow ring during typical stores.

HEAVY ION OPERATION

Gold-Gold Operation Fig. 2 shows the layout of RHIC and the four injector accelerators Tandem, Linac, Booster and AGS. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy, at which point they are fully ionized. The performance of the injector[1] is summarized in Table 1. The Tandem Van de Graaff accelerates Au^{-1} from a sputter source to about 1 MeV/nucleon. The 530 ms long beam pulse is stripped to Au^{+32} and injected into the Booster using horizontal and vertical phase space painting. After acceleration to about 100 MeV/nucleon the beam is stripped to Au^{+77} and transferred to the AGS where it is accelerated to the RHIC injection kinetic energy of 8.6 GeV/nucleon. In the AGS the beam bunches from the Booster are merged to reach the required intensity of about 1×10^9 Au ion per bunch at a longitudinal emittance of 0.3 eVs/nucleon. The final stripping to bare Au^{+79} occurs on the way to RHIC.

RHIC is the first super-conducting, slow ramping accelerator that crosses transition energy during acceleration. At transition energy the spreads of the particle revolution frequency stemming from the spread in velocity and spread in path length cancel exactly and all particles maintain their relative position for a long time. Interaction between particles can then cause instabilities. With pulsed quadrupole power supplies the transition energy is changed quickly during acceleration to effectively jump across it. The dispersion distortion required to change the transition energy is local and the betatron tune shift is corrected in a zero-dispersion region. This scheme allows for up to 1 GeV change in transition energy with very little lattice distortion.

Table 1: RHIC injector performance

Location	RHIC bunch intensity	Efficiency
Tandem	5.4×10^9	
Booster Injection	2.9×10^9	54%
Booster Extraction	2.4×10^9	83%
AGS Injection	1.2×10^9	50%
AGS Extraction	1.1×10^9	92%
Total		20%

The two RHIC rings, labelled blue and yellow, are intersecting at six interaction regions (IR), four of which are occupied by the collider experiments BRAHMS, STAR, PHENIX and PHOBOS. All IRs can operate at a betastar between 2 and 10 m. In two interaction regions (STAR and PHENIX) the quality of the triplet quadrupoles allows further reduction of betastar to 1 m. Typically betastar is 10 m at injection energy for all IRs and is then squeezed during the acceleration cycle first to 5 m at the transition energy, which minimizes its momentum dependence, and then to 1 m for PHENIX and STAR and 3 m for the other experiments at store energy. A typical acceleration cycle consists of filling the blue ring with 56 bunches in groups of 4 bunches, filling the yellow ring in the same way and then simultaneous acceleration of both beams to storage energy. During acceleration the beams are separated vertically by up to 10 mm in the interaction regions to avoid beam losses from the two beams colliding.

Typical stores last about 5 hours. Fig. 3 shows the evolution of the collision rate in the four experiments. The collision rate was measured using identical Zero Degree Calorimeters (ZDC)[2] at all four interaction regions. The ZDC counters detect at least one neutron on each side from mutual Coulomb and nuclear dissociation with a total cross section of about 10 barns. After optimizing longitudinal and transverse steering the peak luminosity at PHENIX and STAR is up to $14 \times 10^{26}\ cm^{-2}\ s^{-1}$ ($5.8 \times 10^{31}\ cm^{-2}\ s^{-1}$ nucleon-pair luminosity) with an average luminosity over the 5 hour store of $4 \times 10^{26}\ cm^{-2}\ s^{-1}$, which is twice the design average luminosity . This corresponds to an initial normalized 95% beam emittance of about $15\pi\ \mu m$ growing to about $30\pi\ \mu m$ at the end of the store. The beam loss and transverse emittance growth during the store is mainly caused by intra-beam scattering, which is particularly important for the fully stripped, highly charged gold beams[3].

The total gold beam intensity was limited mainly by vacuum break-downs in the room temperature sections of the RHIC rings[4]. This pressure rise is associated with the formation of electron clouds, which in turn appear when the bunch peak intensity is high around transition and after bunch compression and when the bunch spacing is small. This situation was greatly improved by installing vacuum pipes with internal coating of non-evaporative getter (NEG) that is properly activated. The resulting residual pressure is 10^{-11} Torr or less. The NEG coating acts as a very effective distributed pump and also suppresses electron cloud formation due to its low secondary electron yield.

The bunch intensity was also limited by a very fast single bunch transverse instability that develops near transition where the chromaticity needs to cross zero. It can be stabilized using octupoles. This instability has a growth rate

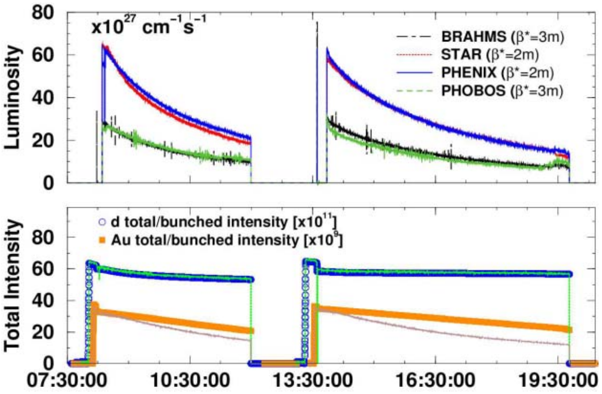

Figure 4: Evolution of the luminosity and beam intensities at the four RHIC detectors during two typical deuteron-gold stores.

faster than the synchrotron period and is similar to a beam break-up instability. Recently it was observed that this instability is enhanced by the presence of electron clouds.

Deuteron-Gold Operation During Run-3 RHIC was operating for the first time with asymmetric collisions[5]. Colliding 100 GeV/nucleon deuteron beam with 100 GeV/nucleon gold beam will not produce the required temperature to create a new state of matter and therefore serves as an important comparison measurement to the gold-gold collisions. The rigidity of the two beams is different by about 20%, which results in different deflection angles in the beam-combining dipoles on either side of the interaction region. This requires a non-zero angle at the collision point, which slightly reduces the available aperture.

The injection energy into RHIC was also the same for both beams requiring the injector to produce beams with different rigidity. With same energy beams throughout the acceleration cycle in RHIC the effect of beam collisions could be minimized. Typical bunch intensity of the deuteron beam was about 1.2×10^{11} with emittances of about 12 $\pi \mu m$ [norm., 95%] and 0.3 eVs/nucleon. The gold beam parameters were similar to the gold-gold operation described above. The high intensity deuteron beams required careful adjustment of the chromaticity, especially around transition, to avoid transverse instabilities. A peak luminosity of $6.2 \times 10^{28}\ cm^{-2}\ s^{-1}$ ($2.4 \times 10^{31}\ cm^{-2}\ s^{-1}$ nucleon-pair luminosity)and store-averaged luminosity of $2.8 \times 10^{28}\ cm^{-2}\ s^{-1}$ was reached at the IRs with the 2 m betastar. Fig. 4 shows luminosities and beam currents for d-Au collisions. The much shorter beam lifetime of the gold beam clearly demonstrates the stronger effect of intra-beam scattering (IBS) for gold than deuteron beam.

Copper-Copper Operation The collision of copper ions[6], an intermediate size nucleus, served as an additional comparison measurement to determine the minimum energy density needed to create the strongly-coupled quark gluon plasma. The copper beams are expected to be less affected by intra-beam scattering due to the lower charge but this was compensated by a significantly higher bunch intensity of 4.5×10^9 ions/bunch available from the Tandem. The higher beam intensity tested new limits for both the fast instability at transition crossing and pressure rise in the warm sections in RHIC. For the latter case the newly installed NEG coated vacuum pipes proved to greatly improve the intensity limits. As a result a new record peak and average nucleon-pair luminosity of $7.9 \times 10^{31}\ cm^{-2}\ s^{-1}$ and $3.2 \times 10^{31}\ cm^{-2}\ s^{-1}$, respectively, was achieved. The integrated luminosity delivered to the four RHIC experiments is shown in Fig. 5. A total of 15 nb^{-1} (or 60 pb^{-1} integrated nucleon-pair luminosity) was delivered to STAR and PHENIX each.

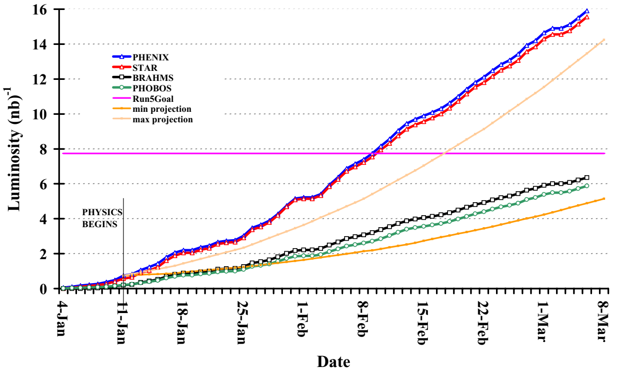

Figure 5: Integrated luminosity of the Cu-Cu run delivered to the four RHIC experiments.

POLARIZED PROTON COLLISIONS

Fig. 6 shows the lay-out of the Brookhaven accelerator complex highlighting the components required for polarized beam acceleration. The new 'Optically Pumped Polarized Ion Source'[7] is producing 10^{12} polarized protons per pulse. A single source pulse is captured into a single bunch, which is ample beam intensity to reach the nominal RHIC bunch intensity of 2×10^{11} polarized protons.

In the AGS a new 6% helical dipole partial Siberian snake[8] that rotates the spin by $11°$ is sufficient to avoid depolarization from imperfection resonances up to the required RHIC transfer energy of about 25 GeV. Full spin flip at the four strong intrinsic resonances can be achieved with a strong artificial rf spin resonance excited coherently for the whole beam by driving large coherent vertical betatron oscillations. With a 80% polarization from the source 50% polarization was reached at AGS extraction. The remaining polarization loss in the AGS is caused by weak intrinsic resonances. A recently installed, much stronger super-conducting helical dipole partial snake should eliminate all depolarization in the AGS[9].

The full Siberian snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC each consist of four 2.4 m long, 4 T helical dipole magnet mod-

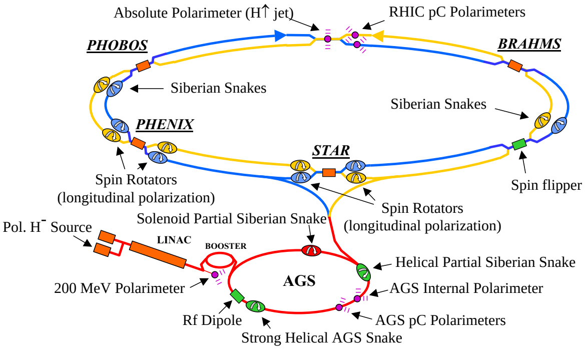

Figure 6: The RHIC accelerator complex with the elements required for the acceleration and collision of polarized protons highlighted.

ules each having a full 360° helical twist. The 9 cm diameter bore of the helical magnets can accommodate 3 cm orbit excursions at injection. Fig. 7 shows the orbit and spin trajectory through a RHIC snake. The super-conducting helical dipoles for both the RHIC snakes and spin-rotators and the new AGS partial snake were constructed at BNL using thin cable placed into helical grooves that have been milled into a thick-walled aluminum cylinder[10].

In addition to maintaining polarization, the accurate measurement of the beam polarization is of great importance. Very small angle elastic scattering in the Coulomb-Nuclear interference region offers the possibility for an analyzing reaction with a high figure-of-merit which is not expected to be strongly energy dependent[11]. For polarized beam commissioning in RHIC an ultra-thin carbon ribbon is used as an internal target, and the recoil carbon nuclei are detected to measure both vertical and radial polarization components. The detection of the recoil carbon with silicon detectors using both energy and time-of-flight information shows excellent particle identification. It was demonstrated that this polarimeter can be used to monitor polarization of high energy proton beams in an almost non-destructive manner and that the carbon fiber target could be scanned through the circulating beam to measure polarization profiles. A polarized atomic hydrogen jet was installed as an internal target for small angle proton-proton scattering which allows the absolute calibration of the beam polarization to better than 5 %.

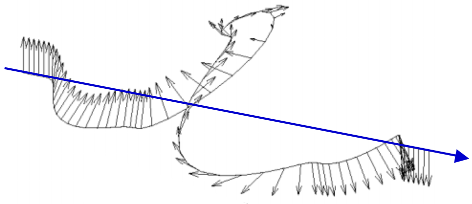

Figure 7: Orbit and spin tracking through the four helical magnets of a Siberian Snake at $\gamma = 25$. The spin tracking shows the reversal of the vertical polarization.

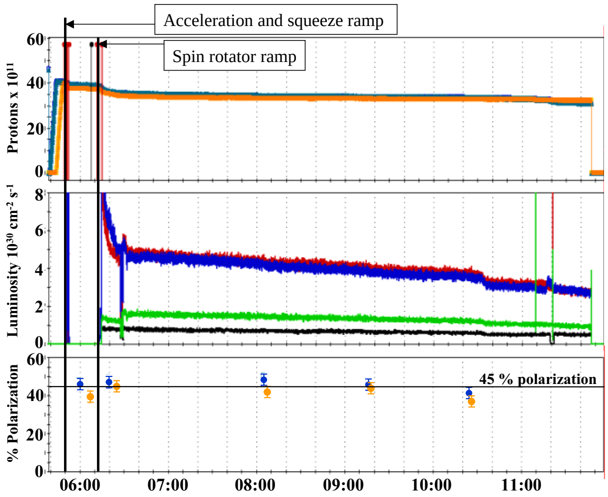

Figure 8: Circulating beam, luminosity at PHENIX (blue), STAR (red), PHOBOS (green), and BRAHMS (black), as well as the measured circulating beam polarization in the blue and yellow RHIC ring (blue(dark) and yellow(light) lines and symbols, respectively) for one typical store.

Fig. 8 shows circulating beam current, luminosity and measured circulating beam polarization of a typical store during last year's run[12]. A peak luminosity of about about 5×10^{30} cm^{-2} s^{-1} was reached. The beam polarization of 45 % was calibrated at 100 GeV with the absolute polarimeter mentioned above. To preserve beam polarization in RHIC during acceleration and storage the vertical betatron tune had to be controlled to better than 0.005 and the orbit had to be corrected to better than 1 mm rms to avoid depolarizing "snake" resonances[13].

More than 20 years after Y. Derbenev and A. Kodratenko[14] made their proposal to use local spin rotators to stabilize polarized beams in high energy rings, it has now been demonstrated that their concept is working flawlessly even in the presence of strong spin resonances at high energy.

Operation at full collision energy of $\sqrt{s} = 500$ GeV is planned for the future with a luminosity of up to $1.5 \times 10^{32}\ cm^{-2}\ s^{-1}$.

RHIC UPGRADE PLANS

An initial upgrade of the RHIC luminosity for heavy ion operation by a factor of four beyond design ($2 \times 10^{26}\ cm^{-2}\ s^{-1}$) can be achieved by doubling the number of bunches to 110 (100 ns bunch spacing) and reducing betastar from 2 m to 1 m. As described above this has already partially been achieved although further progress is required in controlling vacuum break-downs before routine operation with 100 ns bunch spacing is possible.

Further upgrade of the luminosity requires that the emittance growth from intra-beam scattering is reduced or eliminated. The growth of the beam size due to intra-beam scattering can be overcome by cooling the beams with a high intensity cold electron beam[15]. To cool the 100 GeV/n gold beam with 10^9 ions per bunch in RHIC a 54 MeV electron beam with an average current of 100 - 200 mA is required. In this case the charge of each electron bunch is about equal to the charge of the ion bunch. The high beam power of 5 - 10 MW of the electron beam makes it necessary to recover the beam energy by decelerating it in a super-conducting linac. Operation of an energy-recovering linac has been successfully demonstrated at JLab with a 160 MeV, 9 mA electron beam.

Table 2 shows the parameters for future RHIC luminosity upgrades for the first stage without electron cooling and then with electron cooling. Electron cooling has the most dramatic effect on the luminosity of gold collisions. However, it also improves operation with polarized protons due to the lower beam emittance.

Electron cooling of the high energy, heavy ion beams in RHIC extends beyond presently operating electron cooling facilities in several regards: the use of bunched electron beam accelerated by a linear accelerator, beam cooling during collider operation, and the use of a highly magnetized, angular momentum-dominated electron beam to avoid recombination of e^- and Au^{79+}.

An R&D program has started to develop the critical items of the RHIC electron cooling system. A super-conducting rf photo-cathode gun operating at 703.8 MHz will be developed to provide the intense and ultra-bright electron beam. A 703.8 MHz super-conducting cavity for the energy-recovering linac is being built that is capable of accelerating the high intensity electron beam without causing beam-breakup. A long, highly uniform super-conducting solenoid for the electron cooling section will be designed and possibly demonstrated with a prototype.

Table 2: RHIC luminosity upgrade with electron cooling.

Gold-gold	w/o e-cool.	with e-cool.
Beam energy [GeV/n]	100	100
Emittance (95%) [$\pi \mu m$]	15 → 40	15 → 3
Beta function at IR [m]	1.0	1.0 → 0.5
Number of bunches	112	112
Bunch population [10^9]	1	1 → 0.3
Beam-beam param. per IR	0.0016	0.004
Ave. lum. [$10^{26} cm^{-2} s^{-1}$]	8	70
Proton-proton:		
Beam energy [GeV]	250	250
Emittance (95%) [$\pi \mu m$]	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^{11}]	2	2
Beam-beam param. per IR	0.007	0.012
Ave. lum. [$10^{32} cm^{-2} s^{-1}$]	1.5	5.0

A low emittance cooled gold beam in RHIC will also be essential for a future electron ion collider at RHIC. A high current 10 GeV polarized electron beam would be collided with the 100 GeV/n cooled gold beam or the 250 GeV polarized proton beam at a RHIC interaction region with luminosities of $5 \times 10^{30}\ cm^{-2}\ s^{-1}$ (eAu) and about $1 \times 10^{33}\ cm^{-2}\ s^{-1}$ (ep)[16][17].

ACKNOWLEDGMENT

The highly successful operation of RHIC was made possible by the excellent and dedicated RHIC design, construction, commissioning, and operations teams.

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