RHIC AND ITS UPGRADE PROGRAMS*

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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. After a brief review of the achieved performance the presentation will give an overview of the plans, challenges and status of machine upgrades, that range from a new heavy ion pre-injector and beam cooling at 100 GeV to a high luminosity electron-ion collider.

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 layout of the RHIC accelerator complex is shown in Fig. 1. 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 collisions 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.

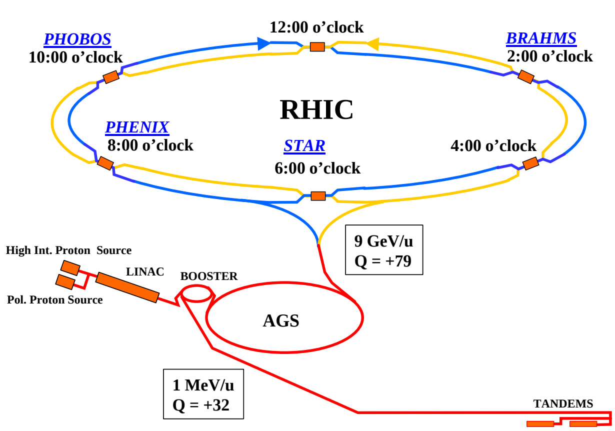

Figure 1: Layout of RHIC and the injector accelerators. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy.

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 the 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.

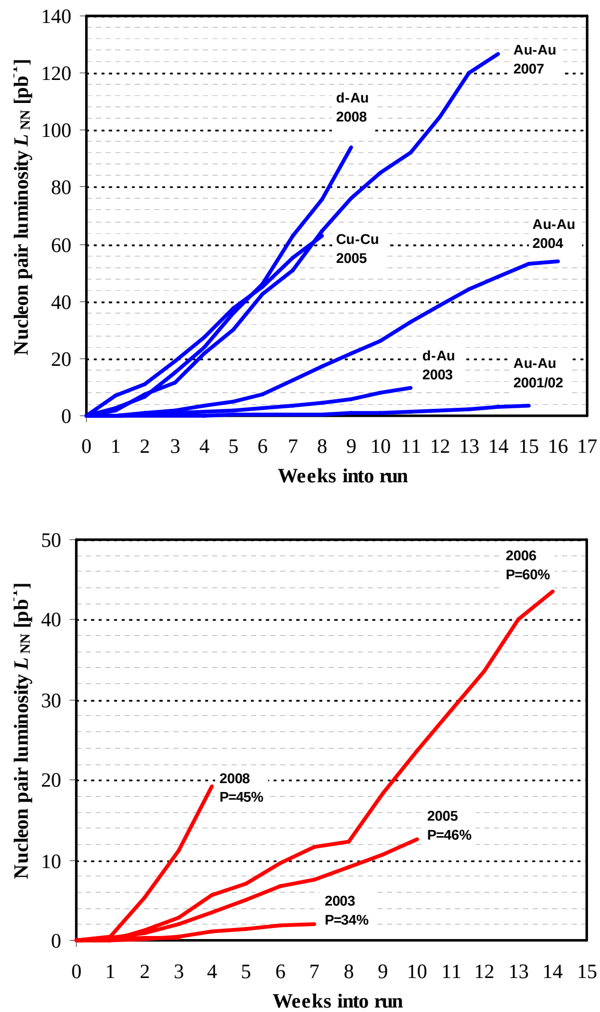

Figure 2: Integrated nucleon-pair luminosity for the heavy ion run (top) and the polarized proton run (bottom) running modes since the start of RHIC operation.

During its first six years of operation RHIC has already exceeded the design parameters for gold-gold collisions, has successfully operated in an asymmetric mode of colliding deuteron on gold with both beams at the same en-

* Work performed under contract No. DE-AC02-98CH10886 with the auspices of the DoE of United States, and support of RIKEN(Japan).)

ergy per nucleon but, of course, different rigidities, and very successfully completed an additional comparison run of colliding copper beams with record luminosities. In addition, four very successful commissioning and running periods with polarized protons demonstrated the performance of RHIC as a high luminosity polarized collider. 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. 2 shows the achieved integrated nucleon-pair luminosities 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.

COLLIDER OPERATION

Gold-Gold Operation Starting with Au^{-1} from a sputter source the gold ions are stepwise ionized as they are accelerated in the Tandem Van de Graaff, the AGS Booster and the AGS to RHIC injection energy. The electrostatic acceleration in the Tandem Van de Graff provides an extremely bright gold beam that can be captured and bunch-merged to provide the necessary bright bunches of 1×10^9 Au ions with a transverse emittance of less than $15\pi\ \mu m$ and a longitudinal emittance of less than 0.3 eVs/nucleon. The final stripping to bare Au^{+79} occurs on the way to RHIC.

The two RHIC rings, labeled 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 less than 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 111 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 long-range beam-beam interaction.

Typical stores last about 4 - 5 hours. The collision rate was measured using identical Zero Degree Calorimeters (ZDC) at all detectors. 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 a peak luminosity at PHENIX and STAR of up to $30\times10^{26}\ cm^{-2}\ s^{-1}$ ($120\times10^{30}\ cm^{-2}\ s^{-1}$ nucleon-pair luminosity) with an average luminosity over the 5 hour store of $12 \times 10^{26}\ cm^{-2}\ s^{-1}$, which is six times the original RHIC design average luminosity . This corresponds to an initial normalized 95% beam emittance of about $17\pi\ \mu m$ growing to about $35\pi\ \mu m$ 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.

The total gold beam intensity in RHIC used to be limited by vacuum break-downs in the room temperature sections of the RHIC rings[1]. 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 about 10^{-11} Torr. 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 is still 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 and the instability threshold can be reduced by lowering the peak current during transition crossing. This instability has a growth rate 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[2].

The high charge state of the gold ion makes it possible to contemplate stochastic cooling of the 100 GeV/n bunched beam. A 5-8 GHz longitudinal stochastic cooling system was installed using novel high power multi-cavity kickers and high energy bunched beam stochastic cooling was successfully demonstrated[3]. Fig. 3 shows the vertex distribution at the end of the store with and without stochastic cooling. It clearly shows a significant increase in luminosity in the central region. The full stochastic cooling system in all planes is now under construction and is the center piece of the next major luminosity upgrade of RHIC.

Deuteron-Gold Operation For two runs RHIC was operating with unequal beams[4]. Colliding 100 GeV/n 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

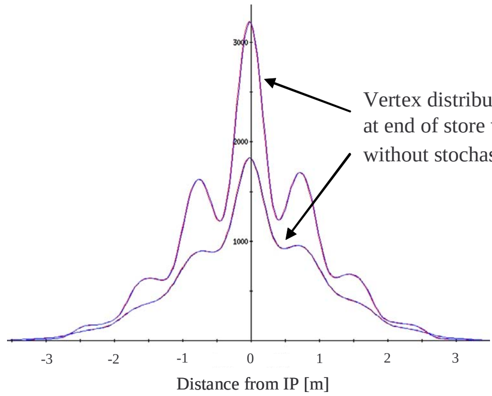

Figure 3: Vertex distribution at the end of a 100 GeV/n Au-Au store with and wihtout logitudinal stochastic cooling.

the acceleration cycle in RHIC the effect of long-range beam-beam interaction in the IRs could be minimized. The 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. During the last run the RHIC ring with the gold beam was operated with increased focusing to reduce the effect of intra-beam scattering on the transverse emittance. As a beneficial side effect the two beams crossed transition at different times, which reduced the development of the fast transverse instability. A peak luminosity of $25 \times 10^{28}\ cm^{-2}\ s^{-1}$ ($100 \times 10^{30}\ cm^{-2}\ s^{-1}$ nucleon-pair luminosity)and store-averaged luminosity of $13 \times 10^{28}\ cm^{-2}\ s^{-1}$ was reached at the IRs with a 0.85 m betastar.

Polarized Proton Operation Fig. 4 shows the lay-out of the RHIC accelerator complex highlighting the components required for polarized beam acceleration. The ‘Optically Pumped Polarized Ion Source’[5] 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 two partial Siberian snakes are installed, an iron-based helical dipole that rotates the spin by 11° and a superconducting helical dipole that can reach a 3 Tesla field and a spin rotation of up to 45°. A view down the magnet gap is shown in Fig. 5. With the two partial snakes placed with one third of the AGS ring between them all vertical spin resonances are avoided up to the required RHIC transfer energy of about 25 GeV as long as the vertical betatron tune is placed at 8.98, very close to an integer. With a 80% polarization from the source 65% polarization was reached at AGS extraction. The remaining polarization loss in the AGS come from weak spin resonances driven by the horizontal motion of the beam[6]. It is planned to overcome them by quickly shifting the betatron tune during resonance

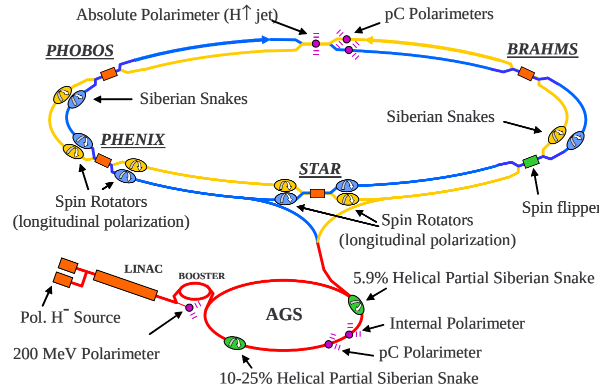

Figure 4: The RHIC accelerator complex with the elements required for the acceleration and collision of polarized protons highlighted.

Figure 5: View down the magnet gap of the warm, iron-based helical partial Siberian snake of the AGS.

crossing.

The full Siberian snakes[7] (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 superconducting helical dipole magnet modules each having a full 360° helical twist. Fig. 6 shows the orbit and spin trajectory through a RHIC snake.

The accurate measurement of the beam polarization is required for set-up and operation of the polarized pro-

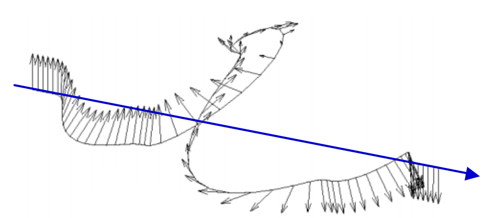

Figure 6: Orbit and spin tracking through the four helical magnets of a Siberian Snake. The spin tracking shows the reversal of the vertical polarization.

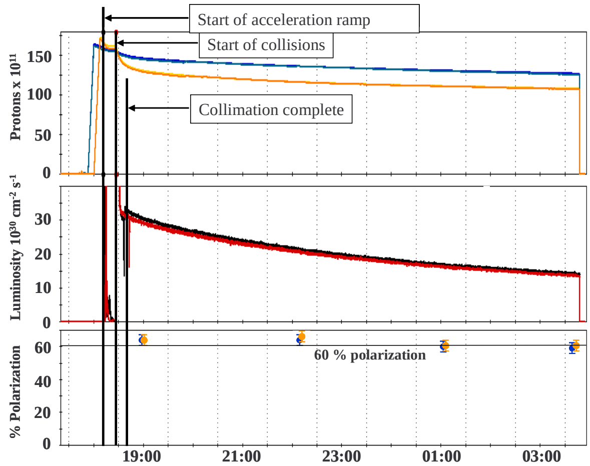

Figure 7: Circulating beam in the blue and yellow ring, luminosity at PHENIX (black) and STAR (red), as well as the measured circulating beam polarization in the blue and yellow RHIC ring (blue(dark) and yellow(light) lines and symbols, respectively) for one typical store.

ton collider. 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[8]. 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 the 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 beam and polarization profiles. A polarized atomic hydrogen jet was also installed as an internal target for small angle proton-proton scattering which allows the absolute calibration of the beam polarization to better than 5 %.

Fig. 7 shows circulating beam current, luminosity and measured circulating beam polarization of a typical store. During the most recent run a peak luminosity of about about 35×10^{30} cm^{-2} s^{-1} was reached[9]. The beam polarization of about 60% 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[10] and the orbit had to be corrected to better than 1 mm rms to avoid depolarizing “snake” resonances.

A first successful test of polarization survival during acceleration to 250 GeV crossing three very strong spin resonances was performed[11]. A polarization of 45% was measured at 250 GeV using the pC polarimeter calibrated at 100 GeV. This preliminary result bodes well for a successful operation of RHIC with polarized 250 GeV proton beams producing collisions at $\sqrt{s} = 500$ GeV with a planned luminosity of up to $200 \times 10^{30}\ cm^{-2}\ s^{-1}$.

RHIC UPGRADE PLANS

An initial increase of the RHIC luminosity for heavy ion operation by a factor of six beyond the RHIC design luminosity was achieved by approximately doubling the number of bunches to 111 (100 ns bunch spacing) and reducing betastar from 2 m to about 0.8 m. An additional reduction of betastar is not possible since, due to intra-beam scattering, the beam size at the end of a four-hour store would exceed the aperture in the final focus triplets. Further upgrade of the luminosity, therefore, requires that the emittance growth from intra-beam scattering is reduced or eliminated at the full store energy of 100 GeV/n.

With the success of longitudinal stochastic cooling of the 100 GeV/n RHIC gold beams full stochastic cooling in all planes is planned[12]. The bandwidth of the system is 5 - 8 GHz. Initially only one transverse plane in each ring will be installed since simulations indicate that due to x-y coupling both transverse planes will be effectively cooled. If this is not the case the second plane will also be installed.

Table 1 shows the parameters that were achieved in RHIC as well as the expectations with full high energy stochastic cooling installed in RHIC. Beam cooling only affects the luminosity of gold collisions. The proton-proton luminosity will be improved by reducing betastar and increasing the bunch intensity since intra-beam scattering is negligible for proton beams.

Alternatively cooling of the RHIC beams with a high intensity, cold electron beam is being explored. To cool the 100 GeV/n gold beam with 10^9 ions per bunch in RHIC a 54 MeV electron beam with a 5 nC bunch charge (50 mA average current) and a 4 μm rms transverse emittance is required. Only an energy recovering linac (ERL) can provide such high quality, intense electron beams. A 20 MeV

Table 1: RHIC achieved and upgrade parameters

Gold-gold:	achieved	luminosity upgrade
Beam energy [GeV/n]	100	100
Beta function at IR [m]	0.8	0.5
Number of bunches	111	111
Bunch population [10^9]	1.1	1.0
Ave. lum. [$10^{26} cm^{-2} s^{-1}$]	12	40
Proton-proton:		
Beam energy [GeV]	100	100 (250)
Beta function at IR [m]	1.0	0.5
Number of bunches	111	111
Bunch population [10^{11}]	1.5	2.0
Ave. lum. [$10^{30} cm^{-2} s^{-1}$]	23	80 (200)
Polarization [%]	60	70

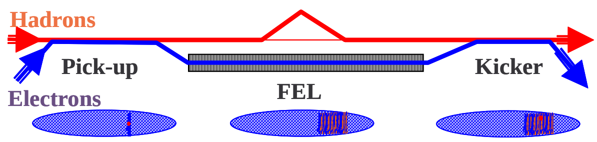

Figure 8: Layout for Coherent Electron Cooling. A short bright electron bunch overlaps with a hadron bunch.

test ERL[13] is presently under construction, which includes a high intensity (0.5 A) super-conducting rf photocathode gun operating at 703.8 MHz, a 703.8 MHz superconducting cavity for the energy-recovering linac and a highly flexible recirculating beam line. The accelerating cavity was specifically designed to accelerate and decelerate the high intensity electron beam with minimal higher order modes and without causing a beam-breakup instability.

Recently an even more powerful cooling technique for high energy hadron beams was proposed[14]. Called 'Coherent Electron Cooling' (CEC) it would use the same high brightness electron beam co-moving with the hadron beam. After a short distance it would be imprinted with the charge distribution of the hadron beam. A Free Electron Laser (FEL) with a gain of 100 - 1000 would then amplify the density variations of the electron beam, which then would act back on the properly delayed hadron beam to correct its energy deviations (Fig. 8). This cooling technique is essentially stochastic cooling with a very high frequency bandwidth. The expected cooling time for 250 GeV protons would be less than 20 minutes and much less for heavy ion beams. The 20 MeV test ERL mentioned above can be used for a proof-of-principle test of CEC of 40 GeV/n heavy ion beams in RHIC.

The very bright electron beams available from ERLs also allow for the design of a high luminosity polarized electron-ion collider at RHIC[15]. Fig. 9 shows a layout for adding a 10 - 20 GeV electron ERL to the RHIC complex. The energy of the main linac would be 2 GeV, expandable to 4 GeV. The full beam energy would be reached with 5 recirculation passes. With an ERL the electron beam would collide with the hadron beam only once allowing for a much larger beam disruption parameter for the electron beam. In this way an average luminosity of more than $1 \times 10^{33}\ cm^{-2}\ s^{-1}$ can be reached.

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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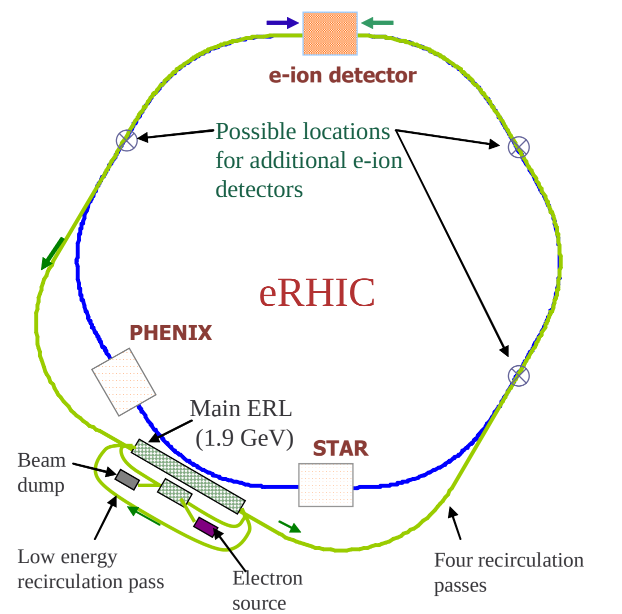

Figure 9: Layout of a polarized electron-ion collider at RHIC (eRHIC)

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