RHIC OPERATIONAL STATUS AND UPGRADE PLANS*

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Abstract

Since 2000 RHIC has collided, at 8 energies, 4 combinations of ion species, ranging from gold ions to polarized protons, and including the collisions of deuterons with gold ions. During that time the heavy ion and polarized proton peak luminosities increased by two orders and one order of magnitude respectively. The average proton polarization in store reached 65%. Planned upgrades include the evolution to the Enhanced Design parameters by about 2008, the construction of an Electron Beam Ion Source (EBIS) by 2009, the installation of electron cooling for RHIC II, and the implementation of the electron-ion collider eRHIC. We review the current performance, and the expected performance with these upgrades.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was commissioned in 2000. It is currently the only collider of heavy ions, and the only collider of polarized protons. The machine has delivered luminosity to 2 high-luminosity experiments (PHENIX and STAR), and three more experiments (BRAHMS, PHOBOS, and PP2PP). BRAHMS and PHOBOS have now finished data taking, PP2PP will be integrated into STAR.

RHIC was built to study the interactions of quarks and gluons, and to test the theory describing these interactions, Quantum-Chromo-Dynamics (QCD). With the collisions of heavy ions, a hot dense matter was discovered that existed only microseconds after the Big Bang. In RHIC this new form of matter was found to behave like a perfect liquid and is often referred to as the strongly interacting quark-gluon plasma or sQGP [1]. Collisions of spin-polarized protons aim to reveal the structure of the proton, in particular the source of the proton polarization [2]. Only 20% of the proton spin can be explained by the spin of quarks within it. The missing understanding of the proton spin has been called the ”proton spin crisis”. The fundamental questions about QCD that the RHIC program addresses are [3]:

- What are the phases of QCD matter?
- What is the wave function of the proton?
- What is the wave function of a heavy nucleus?
- What is the nature of non-equilibrium processes in a fundamental theory?

* Work performed under U.S. DOE contract No DE-AC02-98CH1-886, and with support from RIKEN (Japan) and Renaissance Technology Corp. (USA).

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To answer these questions large integrated luminosities are requested by the experiments, as well as high polarization of proton beams. Equally important is the ability to collide various ion species, including different species in the two rings, at the full range of available energies.

The planned RHIC upgrades target higher luminosity and proton polarization, as well as increased operational flexibility and reliability. The main upgrades are the evolution towards the Enhanced Design parameters; the new Electron Beam Ion Source (EBIS); RHIC II, a luminosity upgrade based on electron cooling; and eRHIC, a high-luminosity electron-ion collider.

A number of other upgrades are planned or under investigation. These include reliability replacements in the more than 40-year old injector complex, emittance reduction measures in the injector chain, the extension of the energy range to higher [4] and lower values [5], an upgrade of the polarized source, a second cold snake in the AGS, a further reduction of the beam size at the interaction point, and the use of electron lenses and superbunches [6].

To compare the luminosities for different ion species the nucleon-pair luminosity

$$\mathcal{L}_{NN}(t) = A_1 A_2 \mathcal{L}(t) \tag{1}$$

can be used, where A_1 and A_1 are the number of nuclei in the ions of the colliding beams respectively, and $\mathcal{L}$ the is usual luminosity. For the calculation of the nucleon-pair luminosity one assumes that the beams are made out of nuclei, not ions. The integrated nucleon-pair luminosity is then

$$L_{NN} = \int \mathcal{L}(t)dt. \tag{2}$$

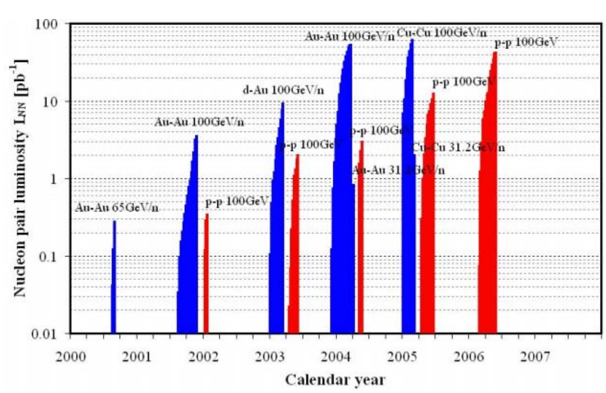

Figure 1: Integrated nucleon-pair luminosity L_{NN} delivered to PHENIX, one of the two high-luminosity experiments. Note that the area is not indicative of the delivered luminosity. The display shows, however, the time in physics operation.

Table 1: Operating energies, achieved beam parameters and luminosities for Au-Au (Run-4, 2004), Cu-Cu (Run-5, 2005), d-Au (Run-3, 2003), and polarized p-p (Run-6, 2006). The achieved beam parameters and luminosities are given for operation at a beam energy of 100GeV/n.

species	energies [GeV/u]	no of bunches	ions/bunch $[10^9]$	β^* [m]	emittance [mm mrad]	$\mathcal{L}_{peak}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\mathcal{L}_{store,avg}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	L_{week}
Au-Au	9.8, 27.9, 31.2, 65.2, 100	45	1.1	1	15-40	15×10^{26}	5×10^{26}	160 μb^{-1}
Cu-Cu	11.2, 31.2, 100	37	4.5	0.9	15-30	2×10^{28}	0.8×10^{28}	2.4 nb^{-1}
d-Au	100	55	110d/0.7Au	2	15-25	7×10^{28}	2×10^{28}	4.5 nb^{-1}
p$\uparrow$-p$\uparrow^*$	11.25, 31.2, 100, 204.9	111	135	1	18-25	35×10^{30}	20×10^{30}	7.0 pb^{-1}

*Blue and Yellow ring average store polarization of 65%, in stores at 100 GeV. Both STAR and PHENIX elected to have 9 non-colliding bunches.

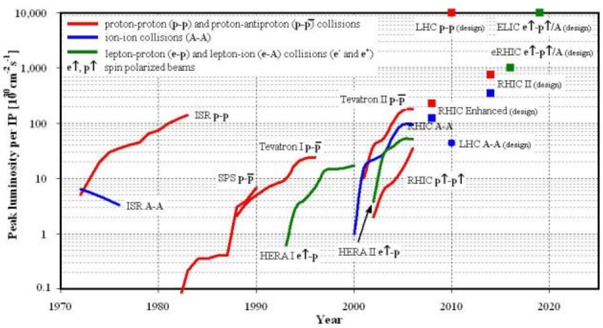

Figure 2: Peak luminosity evolution of hadron colliders. Shown is the nucleon-pair luminosity $\mathcal{L}$ as a function of the calendar year.

OPERATIONAL STATUS

Achieved Performance

Since 2000 RHIC has operated under various conditions [7]. Four different ion combinations collided, including one asymmetric combination (Au^{79+} on Au^{79+}, d^+ on Au^{79+}, Cu^{29+} on Cu^{29+}, and polarized p^+ on polarized p^+), at a total of 8 different energies, from 9.8 GeV/n to 204.9 GeV (see Fig. 1 and Tab. 1). The polarized proton program currently runs at a beam energy of 100 GeV. The average polarization of stored proton beams at this energy reached 65%. Proton beams were delivered with horizontal, vertical, and longitudinal polarization to the large experiments PHENIX and STAR. Only vertically polarized beams can be delivered to the other experiments. Polarized beams were accelerated up to 204 GeV [8] and development to 250 GeV beam energy is under way. The first physics run at 250 GeV is currently scheduled for 2009 [2].

Over the last 6 years the heavy ion and polarized proton peak luminosities increased by 2 orders and one order of magnitude respectively (Fig. 2), and now exceed the design values (Tab. 2). For comparison, Fig. 2 shows the peak luminosity evolution of all hadron colliders, including the design values for the RHIC upgrades, and other machines planned or under construction.

In a typical year, about 30 weeks of cryo operation are scheduled, and 2 pairs of ion species collide at several energies. 1.5 week is needed to cool the rings down to 4 K, and 0.5 week for controlled warm-up at the end of a run. After both rings are cold, 2.5 weeks are needed for set-up before physics operation begins. Set-up for a second ion combination is somewhat shorter. The energy can be changed in 2-3 days, and the spin rotator configurations in 1-2 days. Recently a combined tune and chromaticity feedback system was commissioned [9]. A further reduction of these setup times is expected when this system becomes fully operational. During the last three years, the calendar time in physics stores varied between 46% and 56% (Fig. 3). Note that the calendar time in the calculation includes all interruptions such as ramping, set-up, machine maintenance, machine development, and accelerator physics experiments. While the reliability of a number of systems improved over the last few years, the failure rate of other systems increased [10].

Performance Limitations

A number of effects limit the machine performance. For Au ions, the luminosity lifetime is about 2.5 h due to intrabeam scattering (IBS) [11]. IBS drives particles out of the rf buckets, and increases the transverse beam size. It is planned to arrest the debunching in store with longitudinal stochastic cooling [12]. Recently, cooling could be demonstrated in a bunch with 2×10^9 protons, an intensity comparable to those of heavy ion bunches, with a cooling time of about 1 h [13]. To reduce the beam-size in all three dimensions, and increase both the peak and average luminosity, electron cooling is needed (see RHIC II below).

The bunch intensity of heavy ion beams is limited by the injectors, and instabilities at transition crossing [14]. The observed instabilities are fast, transverse, and single bunch only. However, electron clouds can lower the stability threshold for these instabilities [15].

The number of bunches is limited by dynamic pressure

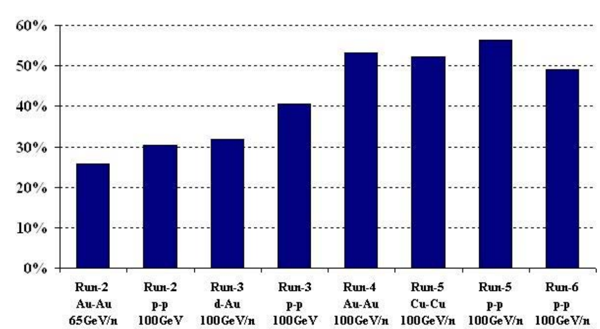

Figure 3: Fraction of calendar time spent in physics stores.

Table 2: RHIC design, achieved, enhanced design, and RHIC II parameters for gold ions and polarized protons.

quantity	unit	design 1999	achieved 2006	enhanced design ∼2008	RHIC II ≥2012
Au^{79+} on Au^{79+}					
beam energy	GeV/n		— 100 —		
number of bunches	...	60	45	— 112 —	
bunch intensity, initial	10^9	1.0	1.1	— 1.0 —	
β-function at IP	m	2.0	1.0	1.0	0.5
peak luminosity	$10^{26}cm^{-2}s^{-1}$	12	15	32	90
average store luminosity	$10^{26}cm^{-2}s^{-1}$	2	5	8	70
polarized p^+ on polarized p^+					
beam energy	GeV	250	100	— 250 —	
number of bunches	...	60	111	— 112 —	
bunch intensity, initial	10^{11}	1.0	1.4	— 2.0 —	
β-function at IP	m	2.0	1.0	1.0	0.5
peak luminosity	$10^{30}cm^{-2}s^{-1}$	15	35	220	750
average store luminosity	$10^{30}cm^{-2}s^{-1}$	10	20	150	500
average store polarization	%	–	65	70	70

rises caused by electron clouds. In the last heavy ion runs the machine was operating with 45 Au and 37 Cu bunches respectively, instead of the possible 111 bunches. Over the last few years both the cold and warm vacuum systems were upgraded [16]. A large part of the warm beam pipes were replaced with NEG coated ones. In the cold sections, more pumps were installed to reduce the average pressure before cooldown to 10^{-7} Torr, resulting in less than one monolayer of H_2 on the beam pipe walls after cooldown.

The proton polarization is limited by the source, and the AGS polarization transmission. In the AGS a warm and a cold Siberian snake were installed to overcome spin depolarizing resonances for bunches of the required intensity [17]. The AGS cold snake was used for the first time operationally in the most recent run, leading to new polarization records in RHIC (Tab. 1) [18]. There is little polarization loss in RHIC up to energies of 100 GeV. Polarization development to 250 GeV is still under way.

The proton luminosity in RHIC was limited by the available bunch intensity of polarized beams from the AGS. With the AGS cold snake this limit is overcome. The main luminosity limit is now the beam-beam effect together with other nonlinear and modulational effects. Polarized proton beams were also limited by dynamic pressure rises. After the vacuum upgrades operation with 111 bunches became possible and dynamic pressure rises do not limit the performance any more. However, a possible slow emittance growth due to electron clouds is a concern [16].

Table 3: Parameters for RHIC EBIS, and parameters achieved in a Test EBIS of half the required length. [19].

quantity	unit	RHIC EBIS	Test EBIS achieved
e-beam current	A	10	10
e-beam energy	keV	20	20
ion trap length	m	1.5	0.7
trap charge capacity	10^{11}	11	5.1
charge yield (Au)	10^{11}	5.5 (10 A)	3.4 (8 A)
pulse length	μs	≤40	20
yield Au^{32+}	10	3.4	> 1.5

UPGRADE PLANS

Enhanced Design Parameters

The Enhanced Design parameters call for an increase in the heavy ion luminosity by a factor 2 over the achieved value, and an increase in the polarized proton luminosity by a factor 7.5, after an energy increase from 100 GeV to 250 GeV (Tab. 2). In addition, the average proton polarization in RHIC stores is to increase from 65% to 70%. For this, the performance limitations mentioned above must be overcome. The goals are expected to be reached about 2008[1]. It is also planned to further reduce the setup time, and to increase the time in store to 60% of calendar time, or 100 h/week.

[1] A long polarized proton run at 250 GeV is needed to demonstrate the luminosity goals at this energy. The first such run is currently scheduled for 2009.

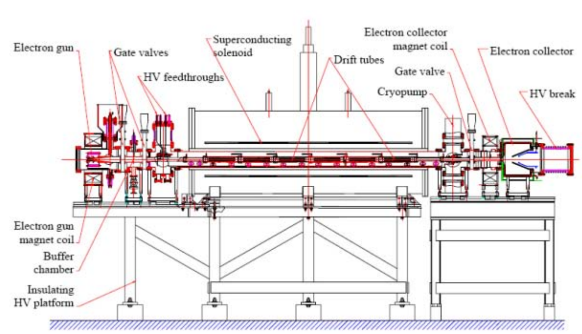

Figure 4: Schematic of the proposed EBIS for RHIC.

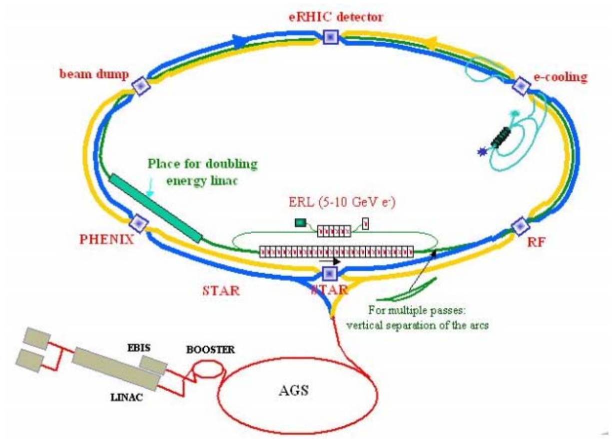

Figure 5: Layout of the RHIC accelerator complex with EBIS, electron cooling, and an ERL for eRHIC.

EBIS

Currently only species for which high intensity negative ion sources exist can be prepared for RHIC. These negative ions are accelerated in the electrostatic Tandem accelerator, and then injected into the AGS Booster. It is planned to replace the pair of upgraded Tandems with an Electron Beam Ion Source (EBIS) followed by a Radio Frequency Quadrupole (RFQ) and short Linac (see Tab. 3, Fig. 4 and Fig. 5) [19]. With the construction of EBIS a further upgrade of the Tandems can be avoided, needed to maintain their reliability, and new ion species can be prepared for RHIC, including uranium and polarized ^{3}He. The overall system reliability is expected to be improved at reduced operating costs, with beam intensity and brightness comparable to the existing scheme. A Test EBIS of half length was built and successfully tested (Tab. 3). It is planned to commission EBIS in 2009.

RHIC II

Due to their high charge state the luminosity lifetime of heavy ion beams is dominated by intrabeam scattering effects. These lead to particle loss out of the radio frequency buckets, and to an increase in the transverse beam size during stores. However, the high charge state of heavy ions also makes electron cooling more efficient than for protons. R&D work is pursued to implement electron cooling for colliding beams in RHIC [20].

Unlike in machines with much lower beam energy, electron cooling in RHIC does not aim to shrink the emittances by a large amount. The transverse emittances of heavy ion beams are to be reduced by about a factor 3, and then the luminosity is to be held constant. With this the average store luminosity of heavy ions is increased by an order of magnitude (Tab. 2 and Fig. 6), and the store length is limited by burn-off, the particle loss due to luminosity. Recent calculations showed that luminosity improvements can also be expected for protons.

To cool Au ions at store, an electron beam of 54 MeV is needed (Tab. 4). With non-magnetized beam, recently

Table 4: ERL parameters for electron cooling in RHIC.

quantity	unit	value
energy after gun	MeV	4.7
final energy, 100 GeV/n Au	MeV	54.3
final energy, 250 GeV p	MeV	136.2
rf frequency	MHz	703.75
bunch frequency	MHz	9.8
bunch charge	nC	5
rms emittance	μm	≤ 4

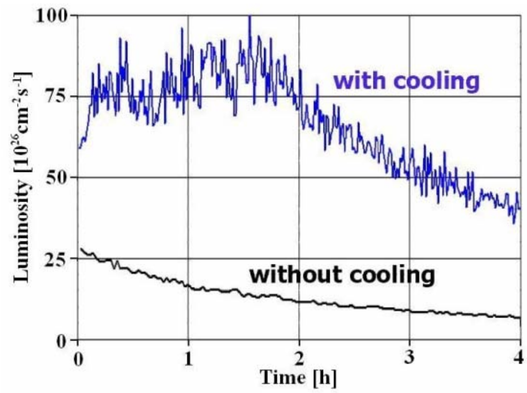

Figure 6: Simulation of the Au-Au luminosity evolution with and without cooled beams [21].

demonstrated to cool 8.9 GeV antiprotons at Fermilab [23], an electron bunch charge of 5 nC gives the required performance. Such a beam has a power of 2.7 MW. A high intensity, high brightness superconducting rf electron gun is being developed, which will inject beam into a superconducting energy recovery linac (ERL) (Fig. 7) [20]. In the gun a diamond window is considered for electron amplification [24]. To advance the technology, a R&D ERL is being constructed, in which the electron beam will reach about half the energy required in the electron cooler. Lattice modification in one of RHIC's interaction region are studied to accommodate the cooling section (Fig. 5) [25]. Technically constrained, electron cooling could be commissioned in RHIC in 2012.

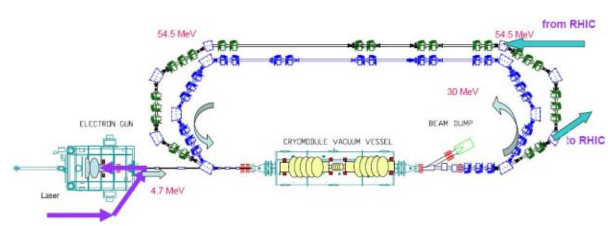

Figure 7: ERL layout with 2 turns for electron cooling of RHIC beams [22].

eRHIC

The proposed electron-ion collider eRHIC has a center-of-mass energy range of 30-100 GeV with a luminosity of approximately $10^{32} - 10^{34}\text{cm}^{-2}\text{s}^{-1}$ for e-p collisions, and $10^{30} - 10^{32}\text{cm}^{-2}\text{s}^{-1}$ for e-Au collisions (Figs. 2 and 5, Tab. 5). Although the center-of-mass energy is lower

Table 5: eRHIC parameters for the highest beam energies in the ring-ring and linac-ring version [26, 27].

quantity	unit	ring-ring			linac-ring		
		e	p	Au	e	p	Au
beam energy E	GeV, GeV/n	10	250	100	10	250	100
bunch intensity N_b	10^{11}	1	1	0.01	1	2	0.01
bunch spacing t_b	ns	— 36 —			— 36 —		
beam size aspect ratio at IP σ_y/σ_x	...	— 0.5 —			— 1 —		
free space from IP L^*	m	— 3 —			— 5 —		
peak luminosity $\mathcal{L}$	10^{30}cm^{-2}s^{-1}		200	2		1800	18

than HERA's, eRHIC's design luminosity is larger by more than an order of magnitude. An essential design element is the availability of longitudinally polarized electron, proton, and possibly light ion beams at the interaction point. The eRHIC design work concentrates on the electron beam preparation, the high-intensity polarized electron gun, the interaction region optimization, and the mitigation of limiting beam dynamics effects such as the beam-beam interaction, and electron clouds for the hadron beam. The eRHIC accelerator R&D has the goal of construction start in 2012.

A ring-ring and a linac-ring version are under consideration (see Tab. 5). The electron ring design in the ring-ring version is close to the electron ring design in a B-factory. It would also allow to accelerate and store positrons. The linac-ring version with an ERL for the electron beam preparation has a potentially higher luminosity reach, an can be easier upgraded to a higher electron energy by adding more cavities (Fig. 5). If positrons are needed, a separate small positron ring can be added.

SUMMARY

Over its 6-year operational life, the Relativistic Heavy Ion Collider has collided 4 ion species at 8 different energies. During that time, the heavy ion and polarized proton peak luminosity increased by 2 orders and one order of magnitude respectively. The average store polarization reached 65%. The main upgrades include the evolution to the Enhanced Design parameter, the new Electron Beam Ion Source (EBIS), the luminosity upgrade RHIC II, based on electron cooling in store, and the high-luminosity electron-ion collider eRHIC.

ACKNOWLEDGMENTS

The author is thankful to the members of Brookhaven's Collider-Accelerator Department whose work is summarized in this article. A special than for help with the preparation of this article to J. Alessi, I. Ben-Zvi, V. Litvinenko, V. Ptitsyn, T. Roser, and D. Trbojevic.

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