Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research B 241 (2005) 281–285
NIM B Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

RHIC performance and future plans ☆

Wolfram Fischer *

Brookhaven National Laboratory, Bldg. 911B, Upton, NY 11973, United States

Available online 7 November 2005

Abstract

The relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory, consisting of two 3.8 km long superconducting rings, was commissioned in 1999. Since then the machine collided fully stripped gold ions at five different energies, up to 100 GeV/n, deuterons with gold ions at 100 GeV/n and protons at 100 GeV with a beam polarizations of up 45%. Over four operating periods the heavy ion luminosity has increased by two orders of magnitude, and now exceeds the design value by a factor of two. Another factor of two is targeted for the next four years, as well as a more than 10-fold increase in the proton luminosity and a 2-fold increase in the polarization. Possible further upgrades include an electron beam ion source (EBIS), stochastic and electron cooling and an electron ring to form an electron–ion collider (eRHIC).

PACS: 29.20.Dh; 29.27.−a

Keywords: Heavy ions; Polarized protons; Collider

1. Introduction

The relativistic heavy ion collider (RHIC) [1] at Brookhaven National Laboratory has two main physics programs, heavy ions and polarized protons. Since 2000, it has delivered luminosity to five experiments, STAR, PHENIX, PHOBOS, BRAHMS and PP2PP (Fig. 1). In heavy ion operation a greater operational flexibility than at other hadron colliders is required. Species and collision energy are changed frequently (Table 1). The heavy ion program has produced a number of striking results, including the discovery of a fascinating new form of matter. Unexpectedly, this extremely hot and dense matter, often referred to as the strongly interacting quark gluon plasma or sQGP, behaves more like a perfect liquid than an ideal gas. In polarized proton operation, both luminosity and polarization are important. The figure of merit for the experiments is either LP^2 or LP^4 where L is the luminosity and P the beam polarization. RHIC can deliver vertically polarized beam to all experiments and longitudinally polarized beam to STAR and

☆ Work supported by the US Department of Energy.
* Tel.: +1 631 344 5452; fax: +1 631 344 5954.
E-mail address: Wolfram.Fischer@bnl.gov

0168-583X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2005.07.125

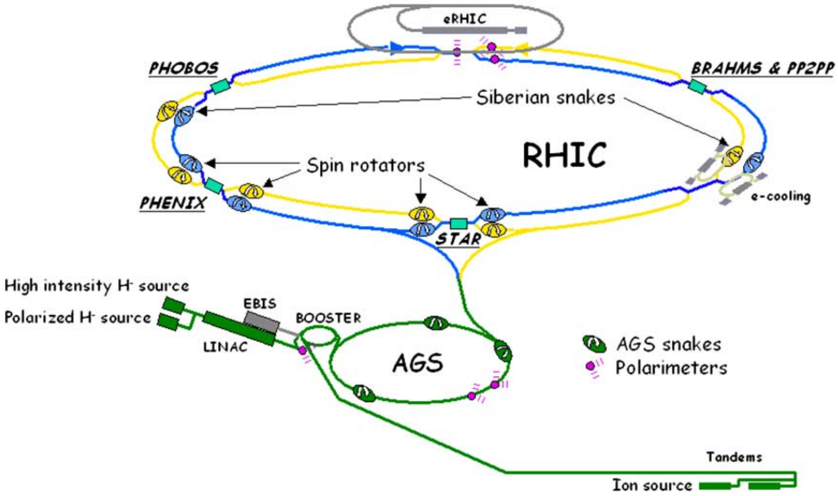

Fig. 1. RHIC overview showing the injectors and possible locations for electron cooling and an additional electron ring.

Table 1
Summary of all RHIC past operating modes (as of 2004)

Mode	Total beam energy [GeV/n]	Total integrated luminosity delivered to five experiments
Run-1: $Au^{79+} + Au^{79+}$	27.9	$<0.001\ \mu b^{-1}$
Run-1: $Au^{79+} + Au^{79+}$	65.2	$20\ \mu b^{-1}$
Run-2: $Au^{79+} + Au^{79+}$	100.0	$258\ \mu b^{-1}$
Run-2: $Au^{79+} + Au^{79+}$	9.8	$0.4\ \mu b^{-1}$
Run-2: $p^{+}\uparrow + p^{+}\uparrow$	100.0	$1.4\ pb^{-1}$
Run-3: $d^{+} + Au^{79+}$	100.7 d/100.0 Au	$73.1\ nb^{-1}$
Run-3: $p^{+}\uparrow + p^{+}\uparrow$	100.0	$5.5\ pb^{-1}$
Run-4: $Au^{79+} + Au^{79+}$	100.0	$3740\ \mu b^{-1}$
Run-4: $Au^{79+} + Au^{79+}$	31.2	$67\ \mu b^{-1}$
Run-4: $p^{+}\uparrow + p^{+}\uparrow$	100.0	$7.1\ pb^{-1}$

PHENIX. The first long polarized proton physics run is planned for 2005.

2. Luminosity and polarization evolution

Since it's commissioning RHIC has collided gold with gold ions, deuterons with gold ions, and polarized protons over a range of energies (Table 1). Another species, copper, will be added in 2005. It was the first machine to collide two beams of heavy ions and the first machine to collide polarized protons. Over the last four years the heavy ion luminosity increased by two orders of magnitude and now exceeds the design value by a factor two (Fig. 2 and Table 2). Another factor of two is expected within a few years. In 2003 the machine also collided for the first time different ion species.

The machine has also reached the design luminosity for proton collisions and has accelerated and stored, at 100 GeV, polarized proton beam with only small losses in polarization. For polarized protons a luminosity increase of more than an order of magnitude is targeted with an almost 2-fold increase in the store polarization (Table 2). Currently the polarization is limited by the AGS injector (Fig. 1).

3. Performance limitations

The deliverable luminosity is limited by a number of effects. Due to the machine complexity, a

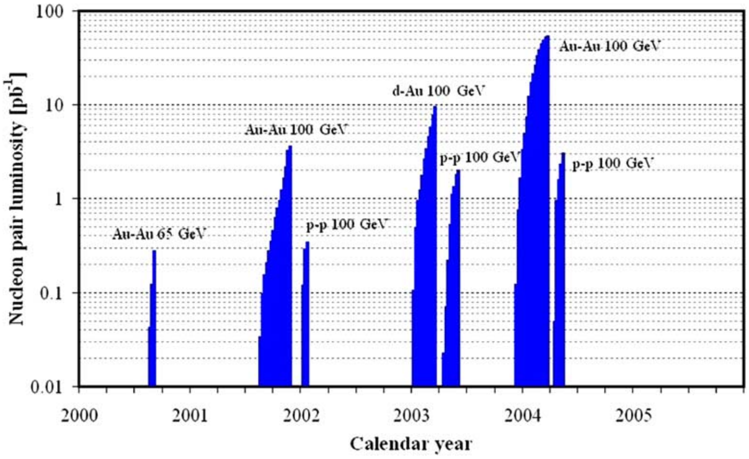

Fig. 2. RHIC nucleon-pair luminosity delivered to the PHENIX experiment. The nucleon-pair luminosity is A_1A_2L, where A_1 and A_2 are the number of nucleons for the species in the two beams respectively and L the luminosity.

Table 2
Design, achieved, enhanced design parameters

Mode	No. of bunches	Ions/bunch [10^9]	β^* [m]	Emittance [μm]	L_{peak} [$cm^{-2}\,s^{-1}$]	$L_{store\ ave}$ [$cm^{-2}\,s^{-1}$]	L_{week}
Design values (1999)							
$Au^{79+} + Au^{79+}$	56	1.0	2	15–40	9×10^{26}	2×10^{26}	50 μb^{-1}
$p^+ + p^+$	56	100	2	20	5×10^{30}	4×10^{30}	1.2 pb^{-1}
Achieved values (2004)							
$Au^{79+} + Au^{79+}$	45	1.1	1	15–40	15×10^{26}	4×10^{26}	160 μb^{-1}
$p^+\uparrow + p^+\uparrow$ [a]	56	70	1	20	6×10^{30}	4×10^{30}	0.9 pb^{-1}
$d^+ + Au^{79+}$	55	110 d/0.7Au	2	15	7×10^{28}	2×10^{28}	4.5 nb^{-1}
Enhanced design values (2008)							
$Au^{79+} + Au^{79+}$	112	1.1	1	15–40	36×10^{26}	8×10^{26}	330 μb^{-1}
$p^+\uparrow + p^+\uparrow$ [b]	112	200	1	20	225×10^{30}	150×10^{30}	55 pb^{-1}

[a] Blue ring polarization of 45%, yellow ring polarization of 40% in RHIC stores at 100 GeV.
[b] Blue and yellow ring polarization of 70% in RHIC stores at 250 GeV.

number of weeks are typically needed to reach peak performance in any given mode. With every mode changes (typically two modes per year), a significant amount of time is spend for set-up and luminosity ramp-up. A change of the collision energy for the same species has been implemented in less than two days during the latest operating period [2].

Heavy ion bunches exhibit significant intra-beam scattering (IBS) effects [3]. For fully stripped gold ions, the luminosity during a 4-hour store drops to 25% of it initial value [2] because particles are leaving the rf buckets and are lost for collisions. In addition, the transverse emittance approximately doubles during a store. Currently the effects of IBS can only be mitigated through fast refills. To overcome IBS, beam cooling at store energies is needed (see below).

With intense beams of all species vacuum pressure rises were observed [4]. These limit the intensity of individual beams and the luminosity since the pressure rises can cause unacceptable experimental background. The pressure rises are predominantly caused by electron clouds. To suppress electron clouds, optimized bunch patterns are used [4]. The warm beam pipes are being replaced by pipes coated with TiVZi, a non-evaporable getter (NEG) material. The NEG material has a low secondary electron yield and also acts as a distributed pump after activation [5]. Recently pressure rises were also seen in some cold parts of the machine. Scrubbing may be needed to increase the intensity threshold.

All species except protons must pass through the transition energy during acceleration. High intensity bunches can experience instabilities during transition crossing since they become short and peak currents large. A fast transverse instability was observed that could be suppressed with octupoles [6]. To avoid head–tail instabilities, the sign of the chromaticity must also be changed at transition. While the transition crossing is done with a γ_t-jump in 30 ms, the chromaticity is changed much slower. In operation it was found that it is favorable to change the chromaticity sign from positive to negative some time before the γ_t-jump.

Protons and light ions are also beam–beam limited. With the enhanced design parameters (Table 2) and two collisions the total tune spread to be accommodated reaches 0.015. This leads to visible emittance growth and thus luminosity reduction. In addition, RHIC is the first hadron collider in which coherent beam–beam effects were seen [7]. These have not yet limited the machine operation.

In proton operation polarization is of critical importance. Horizontal fields can tilt the spin vector from the stable vertical direction and lead to depolarization. Such horizontal dipole fields can be resonantly encountered through the betatron motion (intrinsic resonances), or through vertical orbit errors (imperfection resonances). In RHIC four full helical dipoles are combined into a siberian snake that flips the spin direction. With two snakes per ring a constant spin tune of 1/2 is achieved with which the primary effects of depolarizing resonances can be avoided. Operational experience has shown that the polarization is sensitive to the tunes and the vertical orbit. A higher level of orbit, tune and coupling control is therefore needed. This is especially true when beam is accelerated to 250 GeV since there are numerous strong depolarizing resonances between 100 GeV and 250 GeV [8]. So far the beam polarization in RHIC can be maintained with little loss from injection to 100 GeV. To increase the polarization in RHIC stores, the source is upgraded and a strong helical snake is installed in the AGS. With these changes the average store polarization should reach 70%.

4. Future upgrades

A number of upgrades are under consideration. Beam from an electron beam ion source (EBIS), accelerated through a RFQ and a short linac, can be injected directly into the Booster (Fig. 1). This would replace the existing 35-year old Tandem Van de Graaff electro-static accelerators. With EBIS the injector reliability is expected to increase and the operating cost to decrease. EBIS also has the potential to produce ions currently not available, including uranium and polarized ^{3}He [9].

To overcome the beam size growth from IBS a number of cooling techniques are under investigation. Microwave stochastic cooling is promising because the heavy ion Schottky signals do not exhibit the coherent lines that prevented stochastic cooling at other hadron machines [10]. Electron cooling will be the basis of RHIC II, a luminosity upgrade of the existing machine [11]. It will be the first time that bunched beams are cooled at such high energies. For this a 100 mA electron beam is needed with 54 MeV beam energy. The energy in the electron beam is so large the energy recovery is necessary. A 2–5 T solenoid field of 30 m length will provide the interaction region for electron and ion beam. With electron cooling it is expected to raise the heavy ion luminosity by an order of magnitude. Also under consideration is optical stochastic cooling [12].

An intense and bright ion beam, or polarized proton beam, could also be collided with a polarized electron beam of 5–10 GeV beam energy in a new machine called eRHIC (Fig. 1). Currently ring–ring and linac–ring options are under study, targeting a luminosity in excess of $10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for e–p collisions [11].

5. Summary

RHIC has collided, for the first time, heavy ion beams over a wide energy range and polarized protons. The heavy ion luminosity has increased by two orders of magnitude over the last years. A further increase in the luminosity and polarization are planned for the next four years. Further possible upgrades include an EBIS, stochastic and electron cooling and the addition of an electron ring.

Acknowledgements

I would like to thank the whole RHIC team whose work is reported here. For help in preparing this article I am grateful to J. Alessi, S. Aronson, M. Bai, W. MacKay, T. Roser and T. Satogata.

References

[1] H. Hahn (Ed.), RHIC design manual (October 2000), 2000. Available from: <http://www.rhichome.bnl.gov/NT-share/rhicdm/00_toc1i.htm>.
[2] W. Fischer et al., in: Proceedings of EPAC04, Lucerne, Switzerland, 2004.
[3] W. Fischer et al., in: Proceedings of EPAC02, Paris, France, 2002.
[4] W. Fischer, in: Proceedings of ECLOUD04, Napa, California, 2004.
[5] C. Benvenuti, in: Proceedings of EPAC98, Stockholm, Sweden, 1998.
[6] M. Blaskiewicz, in: Proceedings of PAC03, Portland, Oregon, 2003.
[7] W. Fischer et al., in: Proceedings of PAC03, Portland, Oregon, 2003.
[8] T. Roser et al., in: Workshop on Increasing the AGS Polarization, University of Michigan, 2002.
[9] J. Alessi, Nucl. Instr. and Meth. B, this Conference.
[10] M. Brennan et al., in: Proceedings of EPAC04, Lucerne, Switzerland, 2004.
[11] T. Hallman et al., RHIC II/eRHIC White Paper, submitted to NSAC Future Facilities Subcommittee, 2003.
[12] V. Yakimenko, Nucl. Instr. and Meth. B, this Conference.