Possible RHIC upgrades with superbunches*

W. Fischer†, M. Blaskiewicz, and J. Wei
Brookhaven National Laboratory, Upton, NY 11793, USA

Abstract

Over the next years it is planned to upgrade RHIC in a number of ways, leading to RHIC II, a hadron collider with electron cooling in store, and eRHIC, an electron-ion collider. We explore upgrade possibilities with superbunches in RHIC. Superbunches can potentially increase the luminosity in three ways. First, the ion bunch intensity is limited by instabilities during transition. This can be ameliorated with a reduced peak current in long bunches. Second, with electron cooling for heavy ions, the dominant beam loss is from burn-off. To increase the luminosity further, one can increase the number of bunches, or use superbunches. Third, in polarized proton operation the dominant luminosity limit is the beam-beam interaction, and a luminosity increase of an order of magnitude or more may be possible.

INTRODUCTION

The Relativistic Hadron Collider (RHIC) at Brookhaven National Laboratory is in operation since 2000. It has 2 physics programs, one based on colliding ion beams, the other based on polarized protons collisions. The collider has operated with 4 ion combinations (Au-Au, d-Au, Cu-Cu, and polarized p-p) at 7 energies. In polarized proton operation, the average store polarization reached 57%. Luminosity was delivered to 5 experiments (BRAHMS, PHENIX, PHOBOS, STAR, and PP2PP), 2 of which (PHENIX and STAR) are large and designed for high luminosity. Since 2000 the luminosity delivered per run has increased by approximately 2 orders of magnitude (Fig. 1). Over the next years upgrades are planned to increase the luminosity and polarization even further, and add the possibility of high-luminosity electron-ion collisions. We look even beyond these upgrades and explore possibilities for the use of superbunches in RHIC.

PLANNED RHIC UPGRADES

By now the RHIC design parameters have been exceeded (see Tab. 1). Four major upgrades of the RHIC complex are currently planned: the evolution towards the Enhanced Design goals, the new Electron Beam Ion Source (EBIS), RHIC II with electron cooling of colliding beams, and the electron-ion collider eRHIC.

The Enhanced Design goals call for a four-fold increase of the heavy ion luminosity over the design value, by reduction of β^* and an increase in the number of bunches. While the β^*-reduction from 2 m to 1 m has been achieved, the doubling of the number of bunches from 56 to 111 has not yet been demonstrated. The number of bunches is limited by dynamic pressure rises caused by electron clouds [1]. An extensive vacuum upgrade program was executed over the last few years. The main elements of this program are the bakeout of all bakeable elements, the large-scale installation of NEG coated beam pipes in the warm regions, and improvements to the cold-bore vacuum system that allow for an average vacuum of 10^{-6} Torr before the cool-down begins. The vacuum upgrade is largely complete, and it is expected that the Enhanced Design parameters for ions can be achieved in the next ion running period. The most fundamental heavy ion luminosity limit is then intrabeam scattering, which leads to luminosity lifetimes of only 2.5 h.

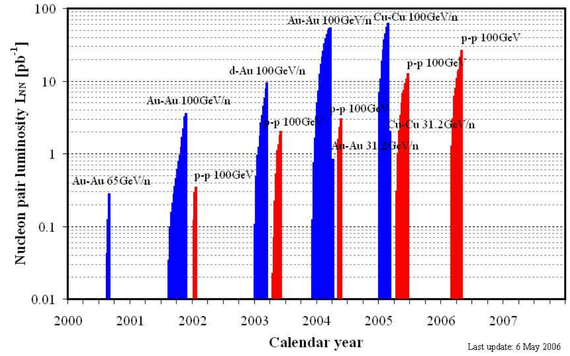

Figure 1: Integrated nucleon-pair luminosity $L_{NN} = A_1 A_2 L$, delivered to PHENIX, one of the high-luminosity RHIC experiments. A_1 and A_2 denote the number of nucleons in the colliding ions, and L the integrated luminosity. The polarized proton run in 2006 is still under way at the time of paper submission.

RHIC is the only machine that can collide polarized protons [2]. The acceleration and storage of polarized protons requires special care, and years of development. Depolarizing resonances in the AGS injector, and RHIC, are overcome by special magnets, so-called Siberian snakes. RHIC has collided polarized protons up to a beam energy of 205 GeV [3]. The Enhanced Design luminosity for polarized protons is larger than the current proton luminosity record, held by the Tevatron. The polarized proton luminosity is also limited by electron cloud effects, and in addition by beam-beam effects.

Currently only species for which high intensity negative ion sources exist can be used. 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 Tandems with an Electron Beam Ion Source (EBIS) [4] followed by a Radio Frequency Quadrupole

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† Wolfram.Fischer@bnl.gov

Table 1: Main RHIC 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 population, 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 population, initial	10^{11}	1.0	1.3	— 2.0 —	
β-function at IP	m	2.0	1.0	1.0	0.5
Peak luminosity	10^{30}cm^{-2}s^{-1}	15	30	220	750
Average store luminosity	10^{30}cm^{-2}s^{-1}	10	20	150	500
Average store polarization	%	–	57	70	70

† The first long polarized proton run at 250 GeV is currently planned for 2009. A long run is needed to achieve the goals at 250 GeV.

(RFQ) and short Linac. 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. It is planned to commission EBIS in 2009.

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 beam size during stores. The effects of intrabeam scattering can only be overcome through active cooling. To cool heavy ion beams at store, an electron beam of 54 MeV with a charge of 5 nC per bunch is required [5]. A high intensity, high brightness superconducting rf electron gun is being developed, which will injected into a superconducting energy recovery linac (ERL). 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. Technically constrained, electron cooling could be commissioned in RHIC in 2012.

With the addition of an electron machine, either a ring or an ERL, an electron-ion collider can be realized. The proposed electron-ion collider eRHIC [6] has a center-of-mass energy range of 30-100 GeV with a luminosity of 10^{32}-10^{34} for e-p and 10^{30}-10^{32} e-Au collisions. An essential design requirement 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 gun, the interaction region optimization, and the mitigation of limiting beam dynamic effects such as the beam-beam interaction, and electron clouds for the hadron beam. Technically constrained, eRHIC construction could start in 2012, and last for approximately 3 years.

RHIC UPGRADES WITH SUPERBUNCHES

We now explore RHIC luminosity upgrade possibilities with superbunches, beyond the upgrade path laid out in the previous section. Superbunches can potentially increase the luminosity in three ways. First, the ion bunch intensity is limited by instabilities during transition. This can be ameliorated with a reduced peak current in long bunches. Second, with electron cooling for heavy ions, the dominant beam loss is from burn-off. To increase the luminosity further, one can only increase the number of bunches, or use superbunches. Third, in polarized proton operation the dominant luminosity limit is the beam-beam interaction, and a luminosity increase is also possible with superbunches. Superbunch hadron collider were proposed in Ref. [9], and luminosity increases with long bunches were considered in Refs. [7, 8, 10, 11]. In the following we will refer to RHIC with superbunches as “SuperRHIC”.

Transition crossing

In RHIC, all ions except protons cross the transition energy. The short bunches at transition can lead to single bunch instabilities and limit the bunch intensity [12]. In Fig. 2 the 3 strongest principal components of a BPM signal are shown. Instabilities were observed with 2 growth times, about 15 ms and about 150 ms. Up to a certain intensity, the instabilities can be suppressed with chromaticity settings, and octupoles.

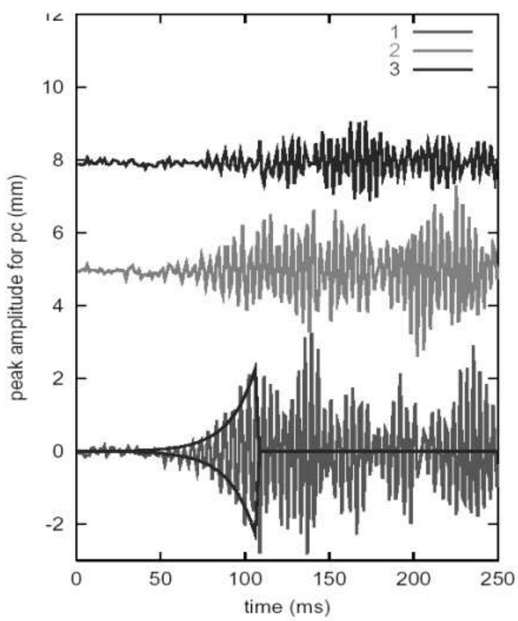

Figure 2: Time series of the 3 strongest principal components of a BPM signal. The traces are vertically offset to improve clarity [12].

The shorter bunches also lead to denser electron clouds, which lead to an increase in the electron-impact desorption rate (Fig. 3). The pressure rises in some locations when the beam energy approaches the transition energy, and falls again when the transition energy has been crossed. The increase in the electron cloud density can further lower the stability threshold and lead to beam losses, more pronounced near the end of the bunch train (Fig. 4) [13]. All these effects can be mitigated with a reduced peak current.

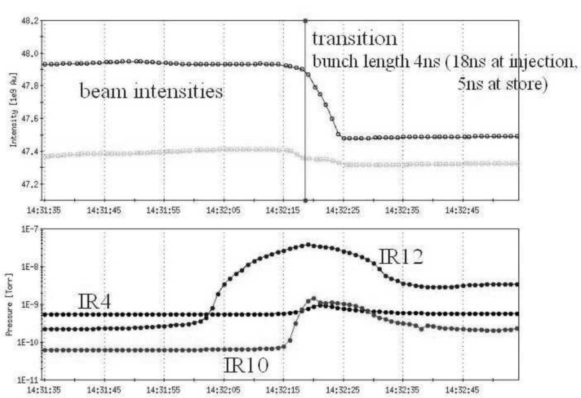

Figure 3: Beam intensities, and 3 pressure readings around transition crossing.

Focusing-free transition crossing (FFTC) has been proposed for RHIC, using induction acceleration [14]. In this scenario, the rf voltage is ramped down when approaching transition, and the bunches are accelerated through transition with an induction acceleration device, after which the

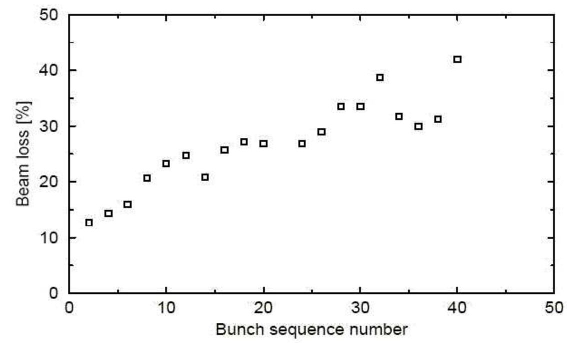

Figure 4: Beam loss at transition as a function of the bunch sequence number [13].

rf voltage is increased again. For the nominal RHIC ramp rate 48kV/turn are required, which is now technically feasible [15]. To reduce the required voltage, the ramp rate can be reduced. If the induction acceleration is only needed ± 12 ms around transition, barrier cavities can be avoided. Fig. 3 shows, however, that a reduction in the peak current is desirable for a few seconds around transition. In this case the bunches need to be contained by barrier buckets. With FFTC, it may be possible to approximately double the intensity of ion bunches.

Superbunches for heavy ion operation

With electron cooling in RHIC II the dominant beam loss in collision will come from burn-ff, the beam loss due to the particle interactions studied by the experiments. With particle losses from burn-off only, and no emittance growth the time-dependent bunch intensity $N_b(t)$ and luminosity $\mathcal{L}(t)$ can be written as

$$N_b(t) = \frac{N_b(0)}{1+t/\tau} \quad \text{and} \quad \mathcal{L}(t) = \frac{\mathcal{L}(0)}{(1+t/\tau)^2} \qquad (1)$$

where the lifetime τ given by

$$\tau = \frac{N N_b(0)}{n_{IP}\mathcal{L}(0)\sigma_{tot}} = \frac{2\pi}{3(\beta\gamma)} \frac{\epsilon_n \beta^*}{n_{IP} f_{rev} N_b(0) \sigma_{tot}}. \qquad (2)$$

N is the number of bunches, n_{IP} the number of interaction points, $(\beta\gamma)$ the relativistic factors, ϵ_n the normalized 95% emittance, f_{rev} the revolution frequency, and σ_{tot} the total cross section for the particle interaction. The luminosity lifetime is

$$\tau_{\mathcal{L}} \approx \tau/2. \qquad (3)$$

In operation a lifetime as low as $\tau_{\mathcal{L}} \approx 2-5$ h is acceptable, although effects other than the luminosity will reduce $\tau_{\mathcal{L}}$ further. Tab. 2 shows the calculated luminosity lifetimes for various RHIC and LHC parameters. Ion operation in RHIC II (with electron cooled beams in store), and an upgraded LHC (with the same bunch intensity and number of bunches) would operate close to the burn-off limit.

With such a low $\tau_{\mathcal{L}}$ a further increase of the transverse beam density at the interaction point, through more cooling

Table 2: Calculated luminosity lifetimes $\tau_{\mathcal{L}}$ for various RHIC and LHC parameters. The LHC case with $5\times$ the design luminosity assumes the same bunch intensity and number of bunches as the LHC design case.

		RHIC I Enhanced ~2008		RHIC II (e-cooling) ≥2012		LHC design >2007	LHC $5\times$ design ?
		Au-Au	p-p	Au-Au	p-p	p-p	p-p
energy	GeV/n	100	250	100	250	7000	7000
peak luminosity $\mathcal{L}(0)$/IP	10^{30}cm^{-2}s^{-1}	0.003	220	0.009	710	10000	50000
number of IPs n_{IP}	...	2	2	2	2	2	2
luminosity lifetime $\tau_{\mathcal{L}}$ (Eq. (3))	h	7	116	2	36	22	4

or β^*-reduction, will not yield more integrated luminosity. With these measures the burn-off rate is increased and the store length becomes even shorter. Most of the collider operation time is then spent with refilling. One can, however, increase the luminosity at the burn-off limit further, by filling more beam of the same density. Two such possibilities exist:

1. An increase of the bunch intensity N_b and the emittance ϵ_n at the same rate (N_b/ϵ_n =const). In this case the luminosity increases as $\mathcal{L} \sim N_b$, and the beam-beam parameter ξ is held constant. The bunch intensity N_b is likely to be limited by either the injector chain or the beam size in the final focus quadrupoles.

2. An increase in the number of bunches N, which leads in the extreme case $N \to \infty$ to superbunches. The number of bunches is likely limited by electron cloud effects, or the stored energy. However, electron cloud effects for superbunches are less severe.

In a superbunch collider, the long bunches are used to partially compensate the head-on induced beam-beam tune shift with long-range interactions [8, 9]. With 2 crossings in orthogonal planes (horizontal and vertical, or 2 skew planes), the same beam-beam induced tune spread can be achieved in both planes.

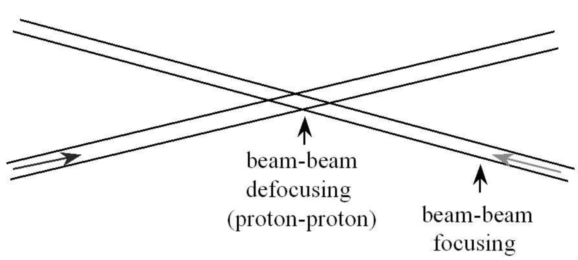

Figure 5: Schematic of partial compensation of the beam-beam induced tune shift from head-on collisions with long-range interactions. The change of the beam size in the interaction region is not shown.

We consider a scheme for the RHIC heavy ion operation with three long bunches in each ring, that fill approximately half of the circumference (Fig. 5). With these bunches luminosity can be delivered to any experiment, and enough space is provided for the abort gap. Tab. 3 shows the calculated peak luminosities and luminosity lifetimes for the RHIC II and SuperRHIC conditions. We assume that the peak current, limited at transition, is the same in both cases, without giving credit to possible improvements from FFTC. The parameters are arranged so that the luminosity lifetime $\tau_{\mathcal{L}}$ remains constant. Note that the electron cooler would require an upgrade to cool a much larger fraction of the RHIC circumference. In this scenario the heavy ion luminosity would increase by a factor 16.

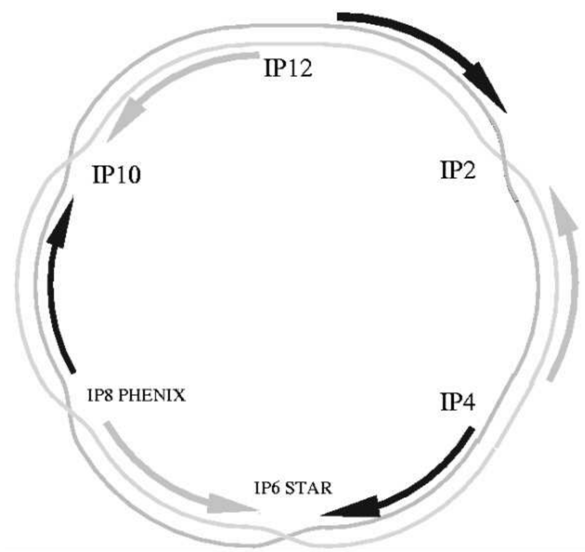

Figure 6: Schematic of three long superbunches in each of the RHIC rings. The number of bunches must be a multiple of three to deliver the same luminosity to the experiments in IP6 and IP8. Two of the six interaction regions are shown uncrossed to create very long strait section that could accommodate the electron cooling section and the eRHIC detector.

Superbunches for polarized proton operation

In polarized proton operation, RHIC is primarily limited by the beam-beam effect. Hadron colliders (Sp$\bar{\text{p}}$S, Tevatron) have achieved total beam-beam induced tune spreads

Table 3: Parameters for heavy ion superbunch operation in RHIC.

		RHIC II	SuperRHIC	comment
energy	GeV/n	100	100	
number of bunches N	...	111	3	observe 6-fold RHIC symmetry
bunch intensity N_b	10^9	1.0	800	same peak current for both cases, no credit for FFTC
bunch length l_b	m	0.3	600	rms (RHIC II), full (SuperRHIC)
average beam current I_b	A	0.11	2.4	
full crossing angle	mrad	0.0	0.5	possible with existing correctors
peak luminosity $\mathcal{L}(0)$/IP	$10^{26}\text{cm}^{-2}\text{s}^{-1}$	70	1100	
number of IPs n_{IP}	...	2	2	
luminosity lifetime $\tau_{\mathcal{L}}$ (Eq. (3))	h	5	5	

of $Q_{bb,tot} \approx 0.025$. Compensating beam-beam effects in hadron colliders, both head-on and long-range, is still an unsolved problem, but progress has been made in recent years, giving new hope to a larger total achievable beam-beam tune spread. We will assume a SuperRHIC scenario with $Q_{bb,tot} = 0.025$, and one with $Q_{bb,tot} = 0.05$.

In Fig. 7 a schematic is shown of four superbunches in each of the RHIC rings. The number of bunches must be a multiple of four to allow for all spin combinations at the single interaction point. We again assume that half of the circumference is filled with beam. Tab. 4 shows the main parameters for RHIC II with electron cooling, and Super-RHIC with $Q_{bb,tot} = 0.025$ and $Q_{bb,tot} = 0.05$. The luminosity lifetime in all cases is 3 h. In the SuperRHIC case with $Q_{bb,tot} = 0.025$ the luminosity increases by a factor 30. Note that here too, the cooling system needs an upgrade. Currently it is not clear if cooling under these conditions can be made sufficiently strong. For the SuperRHIC case with $Q_{bb,tot} = 0.05$ both a cooling system upgrade and beam-beam compensating is required. If this can be accomplished, a more than 2 orders of magnitude increase in the luminosity over the RHIC II parameters is calculated.

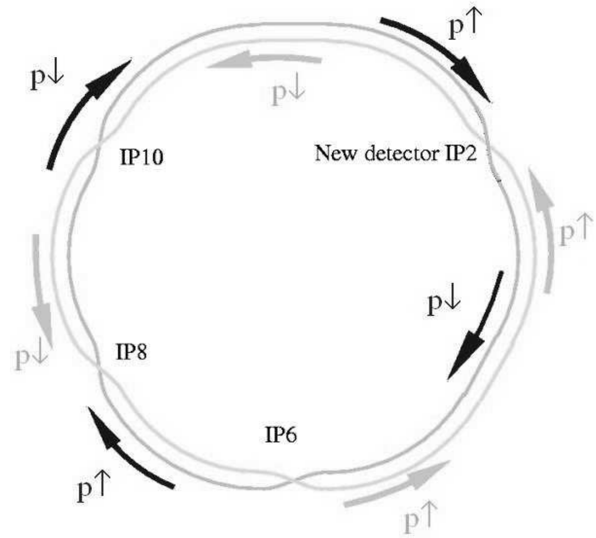

Figure 7: Schematic of 4 superbunches in each of the RHIC rings. The number of bunches must be a multiple of 4 to allow for all spin combinations at the single interaction point.

SUMMARY

Since 2000 RHIC has increased both the heavy ion and the polarized proton luminosity by about 2 orders of magnitude. Planned upgrades of the machine include the evolution towards the Enhanced Design goals, a pre-injector based on an Electron Beam Ion Source (EBIS), RHIC II with electron cooling of colliding beams, and a high-luminosity electron-ion collider. We reviewed further upgrade possibilities with superbunches, which could be beneficial for transition crossing, as well as heavy ion and polarized proton luminosity increases. Such a luminosity upgrade must be accompanied by a detector upgrade.We have not reviewed the details of the implementation, but rather outlined the potential gains if superbunches can be implemented in RHIC. Some of the technical problems are addressed in detail in these proceedings, in particular in the articles of the successful superbunch acceleration at KEK.

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Table 4: Parameters for polarized proton superbunch operation in RHIC.

		RHIC II	SuperRHIC		comment
energy	GeV	250	250	250	
number of bunches N	...	112	4	4	for all spin combinations
bunch intensity N_b	10^9	2.0	1500	3000	limited by $\Delta Q_{bb,tot}$
bunch length l_b	m	0.15	480	480	
average beam current I_b	A	0.28	7.5	15	
full crossing angle	mrad	0.0	0.5	0.5	
beam-beam parameter ξ/IP	...	0.012	0.012	0.025	last column requires beam-beam compensation
peak luminosity $\mathcal{L}(0)$/IP	10^{34}cm^{-2}s^{-1}	0.07	2.2	8.8	last 2 columns also need cooling
average luminosity $\mathcal{L}(0)$/IP	10^{34}cm^{-2}s^{-1}	0.05	1.6	6.3	last 2 columns also need cooling
luminosity lifetime $\tau_{\mathcal{L}}$ (Eq. (3)	h	3	3	3	

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