RHIC PLANS TOWARDS HIGHER LUMINOSITY*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) is designed to provide luminosity over a wide range of beam energies and species, including heavy ions, polarized protons, and asymmetric beam collisions. In the first seven years of operation there has been a rapid increase in the achieved peak and average luminosity, substantially exceeding design values. Work is presently underway to achieve the Enhanced Design parameters. Planned major upgrades include the Electron Beam Ion Source (EBIS), RHIC-II, and construction of an electron-ion collider (eRHIC). We review the expected RHIC upgrade performance. Electron cooling and its impact on the luminosity both for heavy ions and protons are discussed in detail.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has completed seven successful physics runs since commissioning in 1999. RHIC was built to study the interactions of quarks and gluons, and to test the theory describing these interactions, Quantum-Chromo-Dynamics (QCD). At RHIC, nuclear matter at energy densities only seen in the very early universe was created with relativistic heavy-ion collisions.

It was found that at these very large energy densities the matter equilibrates very rapidly, flows as a nearly perfect liquid (small viscosity), has large color fields, collective excitations, and final hadron distributions that reflect the underlying quark structure. The RHIC spin-polarized proton program aims to understand the dynamics of quarks and gluons inside the proton - in particular how they account for the spin of the proton.

The fundamental questions of QCD which can be directly answered at RHIC call for large integrated luminosities, as well as high polarization of proton beams. Equally important is the ability to collide various ion species at the full range of available energies. The planned RHIC upgrades aim towards higher luminosity and proton polarization, as well as increased reliability [1]. The major upgrades include the new Electron Beam Ion Source (EBIS), high-energy electron cooling for RHIC-II, and, a high-luminosity electron-ion collider eRHIC.

Other upgrades which are planned or under investigation include extension of energy range to higher [2] and lower values [3], an upgrade of the polarized proton source, a second cold snake in the AGS, transverse stochastic cooling, further reduction of the beam size at interaction point, and the use of electron lenses and superbunches [4].

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PERFORMANCE AND LUMINOSITY LIMITATIONS

Since 2000 RHIC has successfully operated colliding various species of ions at different energies. For the physics program, the following combinations of ion species and energies were delivered: Au^{79+} on Au^{79+} (9.8, 27.9, 31.2, 65.2, 100 GeV/nucleon), d^+ on Au^{79+} (100 GeV/nucleon), Cu^{29+} on Cu^{29+} (11.2, 31.2, 100 GeV/nucleon), polarized p^+ on p^+ (11.25, 31.2, 100, 204.9). The design and achieved parameters are summarized in Table 1. The average proton polarization of 60% was achieved at store energy of 100 GeV [5]. Operation with polarized protons at 250 GeV is under development [6].

After reaching the design parameters, new Enhanced Design parameters were set both for operation with Au ions and polarized protons [1]. The Enhanced Design parameters already met for Au ions in the 2007 Au-Au run (see Table 1) [7]. For protons, the goal is expected to be met during the first long physics run at 250 GeV.

For heavy ions, the luminosity lifetime is limited by intrabeam scattering (IBS), which drives particles out of the rf buckets and increases the transverse beam size. Stochastic and electron cooling systems are under development in order to counteract beam diffusion due to IBS. Longitudinal stochastic cooling was already successfully commissioned in one of the collider rings and its parameters are being optimized for better luminosity performance [8]. Implementation of longitudinal stochastic cooling in another collider ring is underway, and transverse stochastic cooling is being investigated.

The number of bunches was limited by dynamic pressure rise caused by electron clouds. Electron clouds also lower the stability threshold at transition, and lower the beam intensity [9-11]. Over the last few years both the cold and warm sections were upgraded. A large part of the warm beam pipes were replaced with NEG coated one. These measures allowed to operate with up to 111 bunches during recent RHIC runs. The bunch intensity of heavy ions is also limited by the injectors.

For protons, the luminosity in RHIC was limited by the available bunch intensity of polarized beams from the AGS. In the AGS, a warm and cold Siberian snakes were installed which helped to overcome this limit. The AGS cold snake was used for the first time operationally in 2006 run with polarized protons which lead to new polarization records in RHIC Following the vacuum upgrades, the dynamic pressure rise was overcome, and operation with 111 bunches became possible [5]. The main limitation is presently due to beam-beam effects and other non-linear and modulation driven effects.

Table 1: RHIC Design and Achieved Parameters

Species	No of bunches	Ions/bunch [10^9]	β^* [m]	$L_{store,avg}$ [$cm^{-2}s^{-1}$]	$A_1A_2L_{store,avg}$ [$cm^{-2}s^{-1}$]	$A_1A_2L_{peak}$ [$cm^{-2}s^{-1}$]
Design parameters (1999)						
Au-Au	56	1.0	2	2×10^{26}	8×10^{30}	31×10^{30}
p-p	56	100	2	4×10^{30}	4×10^{30}	5×10^{30}
Enhanced design parameters (by 2009)						
Au-Au	111	1.0	0.9	8×10^{26}	31×10^{30}	140×10^{30}
p↑-p↑	111	200	0.9	60×10^{30}	60×10^{30}	90×10^{30}
Achieved operational values (as of 2007)						
Au-Au	103	1.1	0.8	1.4×10^{27}	54×10^{30}	140×10^{30}
p↑-p↑	111	130	1	20×10^{30}	20×10^{30}	35×10^{30}
d-Au	55	120/0.7	2	2×10^{28}	8×10^{30}	28×10^{30}
Cu-Cu	37	4.5	0.9	80×10^{26}	32×10^{30}	79×10^{30}

*In Table 1, A_1 and A_2 are the number of nuclei in the ions of colliding beams.

UPGRADE PLANS

EBIS

Construction of an Electron Beam Ion Source (EBIS) followed by a Radio Frequency Quadrupole (RFQ) and short Linac is presently underway [12]. With construction of EBIS it is expected that the reliability of injector complex will be improved, and operational cost will be reduced. As a result of this new injector, new ion species can be prepared for RHIC, including polarized ^{3}He and uranium. Presently, commissioning of EBIS is scheduled for 2009.

Stochastic Cooling

Longitudinal stochastic cooling of bunched beams was made operational in one of the collider rings during 2007 run with Au ions [8]. The goal of the system is to stop intensity loss due to particles escaping from the RF bucket, which happens as a result of longitudinal IBS. Parameters of the system are presently being optimized to achieve better luminosity performance. Longitudinal stochastic cooling in second collider ring is being implemented. When both longitudinal systems are operational and, the debunching loss is stopped, about 50% increase in the average luminosity is expected. Transverse stochastic cooling system is also under investigation which will counteract transverse IBS. It will provide an additional luminosity increase.

RHIC-II

Presently, the major goal of this RHIC upgrade is to achieve a 10-fold increase in the luminosity of Au ions at the top energy of 100 GeV/nucleon (termed RHIC-II). A significant increase in luminosity for polarized protons is also planned (see Table 2), as well as for other ion species and for various collision energies. Such a boost in luminosity for RHIC-II is achievable with implementation of high-energy electron cooling [13].

For heavy ions, electron cooling will provide both longitudinal and transverse cooling at the top energy of 100 GeV/nucleon. Electron cooling is more effective for particles in the core of the distribution, while stochastic cooling works best for large-amplitude particles. As a result, when fully implemented, both systems will work together to produce a significant boost in luminosity. The ultimate limitation in peak luminosity comes from the beam-beam limit. The ion intensity is currently also limited by instabilities at transition.

Table 2: Baseline RHIC-II Parameters and Luminosities

Beams	Units	p↑	Au
total beam energy	GeV/n	250	100
95% normalized emittance	μm	15	15
rms bunch length, initial	cm	16	20
ions/bunch	10^9	200	1
no of bunches		111	111
β*	m	0.5	0.5
peak luminosity	$cm^{-2}s^{-1}$	6×10^{32}	10×10^{27}
average luminosity	$cm^{-2}s^{-1}$	4×10^{32}	7×10^{27}

For protons, the goal of electron cooling is to produce required transverse and longitudinal emittances for high-intensity proton beam with 2×10^{11} particles per bunch mostly by pre-cooling at energy of about 30 GeV. Presently, no direct cooling at the top energy of 250 GeV is being planned, although various schemes are under investigation.

Baseline luminosities for the RHIC-II upgrade with electron cooling are summarized in Table 2 for Au ions and polarized protons. Parameters of the cooler are summarized in Table 3. In addition, electron cooling can provide effective cooling for higher intensities of ion beams as well as for other ions. The cooling performance is summarized in next section.

Present electron cooling system for RHIC-II is being designed to cool at the top energy of 100 GeV/nucleon. The same system can be used to cool ions at lower energies down to about 25 GeV/nucleon (staying above transition energy) to provide collision in the range of beam energies of 25-100 GeV/nucleon. Cooling below energy of 25 GeV/nucleon is possible, and was considered [14], but it requires a different dedicated cooling system which is presently not part of the RHIC-II upgrade.

Table 3: Parameters of electron cooler for RHIC-II

	Units	Value
kinetic energy	MeV	54.3
rf frequency	MHz	703.75
bunch frequency	MHz	9.38
bunch charge	nC	5
rms emittance, normalized	μm	< 4
rms momentum spread		3×10^{-4}
cooling section length	m	100

Low-Energy Collisions in RHIC

Recently, a strong interest emerged in running RHIC at low energies in the range of 2.5-25 GeV/nucleon total energy of a single beam [3, 15]. Providing collisions in this energy, which in the RHIC case is termed "low-energy" operation, will help to answer one of the key questions in the field of QCD about the location of a critical point in the QCD phase diagram. Applying electron cooling directly at these low energies in RHIC would result in a dramatic luminosity increase, small vertex distribution and long stores. However, the cost of such electron cooling system will be significant while the need for very high-luminosity is not yet established. On the other hand, a substantial improvement in luminosity can be achieved by decreasing the longitudinal emittance of the ion beam before its injection into RHIC. This will provide good RF capture efficiency. Such an improvement in the longitudinal emittance of the ion beam can be provided at a moderate cost by a simple electron cooling system at the AGS injection energy [14], which is presently under investigation.

eRHIC

The proposed electron-ion collider (eRHIC) is being designed to collide a variety of ions (from 100 GeV/nucleon Au to 50-250 GeV polarized protons) with 10-20 GeV polarized leptons [16]. Two independent designs were developed. The first design called 'ring-ring' option [17] is based on a 10 GeV electron ring added to the RHIC complex. In this scenario, for the high-energy polarized p (250 GeV) - e (10 GeV) collisions, the expected luminosities are $L=0.2\times10^{33}$ and 0.5×10^{33} $cm^{-2}s^{-1}$ for average and peak luminosities, respectively. The other design, called 'linac-ring' option [18, 19] is based on upgrading the RHIC complex with 2-4 GeV recirculating ERL which gives 10-20 GeV in 5 passes (4 passes in the RHIC tunnel). In this case, for the high-energy p (250 GeV) - e (10 GeV) collisions, the expected luminosities are $L=1\times10^{33}$ and 2.6×10^{33} $cm^{-2}s^{-1}$ for average and peak luminosities, respectively. For collisions with heavy ions Au (100 GeV/n) - e (20 GeV), the linac-ring option offers $L\cdot A_1=1\times10^{33}$ and 3×10^{33} $cm^{-2}s^{-1}$ for average and peak luminosities, respectively. Here, A_1 is the number of nuclei in the ion beam. Note, that in the case of linac-ring approach the beam-beam tune shift of the electron beam is not a limiting factor anymore which allows to benefit from electron cooling system by pre-cooling transverse emittances both of protons and heavy ion beams.

Layout of RHIC complex with planned upgrades (EBIS, RHIC-II and eRHIC) is shown in Fig. 1.

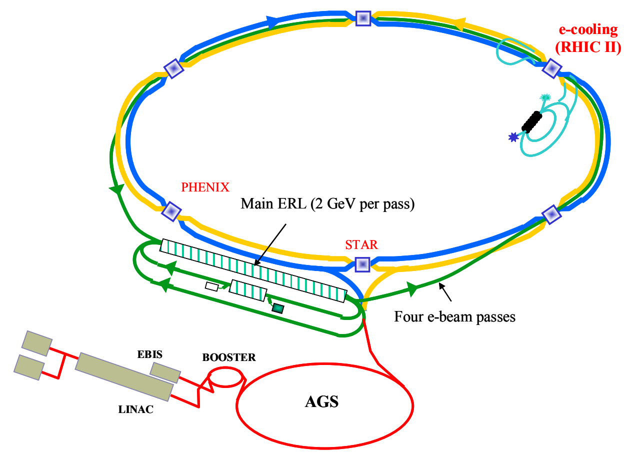

Figure 1: Layout of RHIC complex with proposed upgrades.

RHIC-II PERFORMANCE BASED ON ELECTRON COOLING

In this section we present simulations of RHIC performance with electron cooling. Simulations were performed using the BETACOOL code [20]. The proposed electron cooler uses a double pass, superconducting ERL to generate the electron beam with maximum energy of 54.3 MeV [21]. The cooling power needed requires bunch charge of 5 nC with an emittance smaller than 4 microns (rms, normalized) and a repetition frequency of 9.38 MHz. The necessary transverse and longitudinal electron beam brightness will be generated by a superconducting 703.75 MHz laser photocathode RF gun. To test the hardware and to explore various beam dynamics questions a prototype ERL is presently under construction at BNL with commissioning being planned for 2009 [22].

The electron cooler will be located at the 2 o'clock IR of RHIC, which will be modified to accommodate the cooler. There are various RHIC lattice modifications, which result in sufficiently large space available for cooling (about 100 meters) [23]. The cooling section includes modules of a helical undulator to combat recombination of heavy ions with the electron beam as well as several pairs of solenoids to counteract space-charge defocusing and control the rms angular spread within electron beam to a required level [24].

Cooling at Full Energy

Electron cooling of Au ions at the storage energy of 100 GeV/nucleon allows to increase the luminosity significantly. The baseline goal of RHIC-II is to have a ten fold increase in the average luminosity compared to Enhanced design values of 8×10^{26} cm^{-2}s^{-1}. During the recent 2007 run an average luminosity per store of 1.4×10^{27} cm^{-2}s^{-1} was already achieved.

A careful study of cooling and electron beam dynamics in the ERL was performed [13] which showed that required luminosities in Table 2 are achievable with the cooler parameters summarized in Table 3.

The simulated luminosity performance is based on an electron bunch with 5nC charge and 4 μm "effective" emittance (see [24] for details), shown in Fig. 2. An exact value for the average luminosity during the store may vary depending on the scheme used during the cooling. For example, an rms length of electron bunch is about 1 cm while rms length of an ion bunch is 20 cm. In order not to overcool the core and produce even cooling for particles at various amplitudes the electron bunch is being swept through the length of the ion bunch. An average luminosity per store will depend on how this sweeping is implemented. A detailed description can be found in a "RHIC-II Feasibility Study" document in Ref. [13].

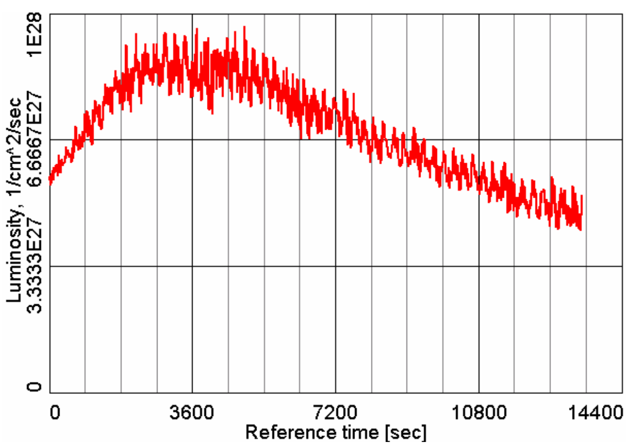

Figure 2: Electron cooling simulation of Au-Au luminosity: ion bunch intensity 1×10^9, 111 bunches; using single electron bunch per ion bunch. Average luminosity in 4 hour store is 7×10^{27} cm^{-2}s^{-1}.

The present design of electron cooling system (703.75 MHz) allows to have 2 electron bunches spaced by 0.4 m to be used simultaneously for the cooling of a single ion bunch. Such an approach allows us to have shaping of the longitudinal distribution of ions avoiding long tails, which is detrimental to the detector operation. In addition, with 2 electron bunches (5nC charge each), the ion bunches of higher intensity, than presently used in operation, can be cooled as well. This will allow future luminosity improvement of the complex. The present limit on bunch intensity comes from an instability at transition limiting an average beam current per ring and resulting in about 1.1×10^9 ions per bunch with 111 bunches. Several measures are being planned which should help to elevate this limit. Figure 3 shows simulations of luminosity with and without electron cooling for bunch intensity of 2×10^9 and 111 bunches (which is a factor of 2 above an average beam current presently achieved in RHIC). The store time is limited by the burn-off of particles in collisions. In Fig. 3 an average simulated luminosity of Au ions in 3 hour store is 2×10^{28} cm^{-2} s^{-1}.

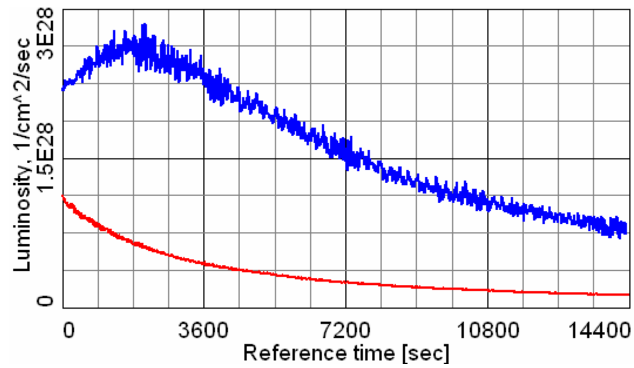

Figure 3: Simulation of Au-Au luminosity for ion bunch intensity 2×10^9 and 111 bunches using two 5nC electron bunches per ion bunch with (blue top curve) and without (red bottom curve) electron cooling, taking β*=0.5 m and 1 m, respectively.

For the present RHIC operation without electron cooling, the β* is limited to about 1 meter (or slightly less) due to the fact that the emittance is increased during the store by a factor of 2 because of the IBS. Further reduction of the β* with such an increase of emittance would lead to a significant angular spread and beam loss. On the other hand, keeping rms emittance constant (by cooling), allows us to start a store cycle with smaller values of the β*.

An additional benefit comes from the longitudinal cooling which prevents bunch length from growing and beam loss from the bucket (as shown in Fig. 4). Also, it maximizes the useful interaction region in the detector.

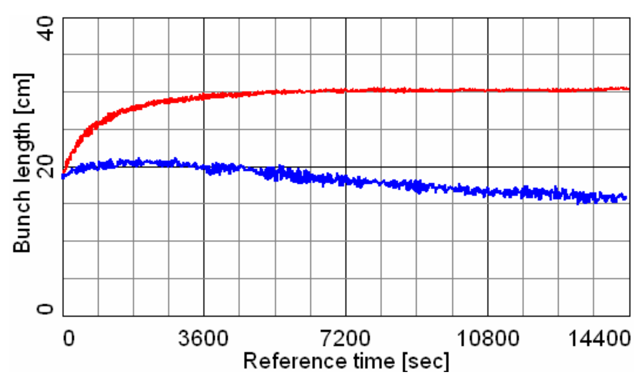

Figure 4: Simulated bunch length for ion bunch intensity 2×10^9 using two 5nC electron bunches with (blue bottom curve) and without (red upper curve) electron cooling.

Cooling of Various Ion Species

For Au-Au collisions at 100 GeV/nucleon with electron cooling, the store time is limited due to a rapid ion "burn-off" in the IP (large cross section from dissociation and bound electron-positron pair production). However, for other ion species, for which the cross section of such a "burn-off" process is small, longer stores can be tolerated. For example, Fig. 5 shows the luminosity performance for Cu-Cu collisions.

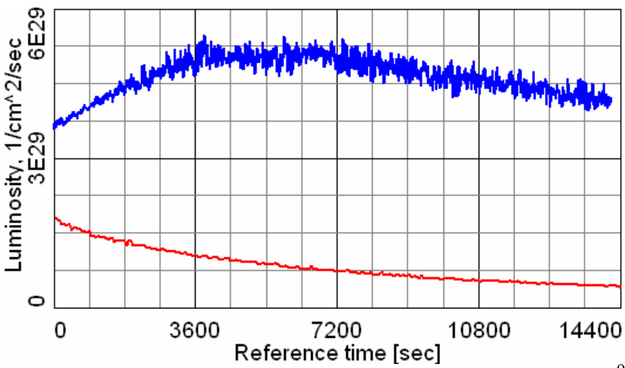

Figure 5: Cu-Cu luminosity for ion bunch intensity 8×10^9 and 111 bunches. Average luminosity in 4 hour store 4.6×10^{29} and 0.8×10^{29} $cm^{-2}s^{-1}$ with (upper blue curve) and without (low red curve) electron cooling, respectively.

For protons, in addition to pre-cooling at low energy, the present cooling system can be applied to proton collisions at 100 GeV. At 100 GeV electron cooling can maintain the transverse emittance of protons, as well as keep rms bunch length to about 20 cm.

Cooling at Various Collision Energies

Fast cooling at low energies also makes such energies attractive for collisions, which is under consideration for RHIC-II and eRHIC. However, rapid cooling of the beam core can lead to problems with a large beam-beam parameter. To keep the beam-beam parameter at an acceptable level, one can vary parameters of the electron beam dynamically during the cooling process.

Pre-Cooling at Low Energy

Pre-cooling at low energy may be very attractive. This is due to the fact that cooling is much faster at lower energy as well as charge of the electron beam needed is smaller. Also, such a pre-cooling at low energy allows effective cooling of protons which is needed to achieve RHIC-II parameters. Pre-cooling at low-energy is required to achieve present design parameters of linac-ring eRHIC collider [16, 19].

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