ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB072

eRHIC IN ELECTRON-ION OPERATION*

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Abstract

As for electron-proton collisions, the EIC science also requires electron-ion collisions over the widest possible energy range at the highest luminosities. Therefore the eRHIC design also provides for electron-nucleon peak luminosities of up to 4.7×10^{33} cm^{-2}s^{-1} with strong hadron cooling, and up to 1.7×10^{33} cm^{-2}s^{-1} with stochastic cooling. Here we discuss the performance issues and design choices for electron-ion collisions that are different from the electron-proton collisions and from the present RHIC ion-ion collisions. These include the ion bunch preparation in the injector chain, acceleration and intrabeam scattering in the hadron ring, path length adjustment with the electron ring, stochastic cooling upgrades, machine protection upgrades, and operation with polarized electron beams colliding with either unpolarized ion beams or polarized He-3.

INTRODUCTION

eRHIC [1] is a proposed Electron-Ion Collider based on RHIC [2] with requirements [3]: (i) highly polarized (~70%) electron and light ion beams; (ii) ion beams from deuteron to the heaviest nuclei (uranium or lead); (iii) variable center of mass energies from ~20 to ~100 GeV, upgradable to ~140 GeV; (iv) high luminosity of $\sim 10^{33-34}$ cm^{-2}s^{-1}, and (v) the possibility of having more than one interaction region. We report on (ii), (iii) and (iv) for e-A collisions. Table 1 shows the main beam parameters for e-Au operation for the energy with the highest luminosity, for the cases with strong hadron cooling and stochastic cooling. The polarization aspects of collider operation with polarized He-3 are covered in detail elsewhere [4–6].

ION OPERATION ITEMS

Ion sources and injectors. The ion sources used for RHIC, are based on a Laser ION source (LION) [7] feeding into an Electron Beam Ion Source (EBIS) [8]. They are extremely flexible and can provide all ions at the required intensities and emittances for eRHIC. Ion beams prepared for RHIC ranged from d to U and were accelerated in the Booster, AGS and RHIC already. The EBIS pre-injector is being upgraded to an Extended EBIS (previously referred to as Tandem EBIS [9]), which provides a longer trap length resulting in up to 40% more intensity, a cell in which He-3 can be polarized in the strong magnetic field of the EBIS solenoid [10], and another cell in which the polarized He-3 and other gases can be ionized. The absolute He-3 polarization will be measured before injection into the Booster [11].

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
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Table 1: Beam parameters for e-Au operation at the energy with the highest luminosity, for the cases with strong hadron cooling and stochastic cooling. The full crossing angle is 25 mrad. Numbers separated by a "/" are for horizontal/vertical. The quoted IBS emittance growth times are for the case without cooling.

	strong hadron cooling		stochastic hadron cooling	
Species	Au	e	Au	e
Energy [GeV]	110	10	110	10
Bunch intensity [10^{10}]	0.05	15.1	0.1	30
No. of bunches	1160		580	
Beam current [A]	0.57	2.2	0.57	2.2
RMS norm. emit. [μm]	5.0/0.36	391/20	2.0/2.0	391/102
RMS emittance, [nm]	42/3	20/1	17/17	20/5.2
β^* [cm]	90/4	193/12	90/14.8	75/48
IP RMS beam size [μm]	195/11.1		123/50	
RMS $\Delta\theta$ [μrad]	217/276	102/92	137/338	163/104
BB parameter/ [10^{-3}]	3/2	43/48	11/4	64/100
Long. bunch area [eV·s]	0.3		1.2	
RMS bunch length [cm]	7	1.9	18	1.9
RMS $\Delta p/p$ [10^{-4}]	6.2	5.5	10	5.5
Max. space charge	0.008	negl.	0.001	negl.
Piwinski angle [rad]	4.5	1.1	18.2	1.5
Long. IBS time [h]	0.36		2.65	
Transv. IBS time [h]	0.89		0.8	
Hourglass and crab	0.85		0.54	
e-N peak lumi. [10^{33}cm^{-2}s^{-1}]	4.2		1.9	

Injection into RHIC and bunch splitting. Presently the accelerating RF system (28 MHz) operates with harmonic $h = 360$, and up to 111 bunches are injected leaving an abort gap of 1 μs. With eRHIC the main harmonic number is changed to $h = 315$ and up to 290 bunches are injected reducing the bunch spacing to approximately 1/3. The bunches are then accelerated, split either once into 580 bunches (using a 56 MHz cavity) or twice into 1160 bunches (using another 112 MHz cavity) and compressed with a storage RF system (using 225 and 563 MHz cavities) [1]. This is the same as for protons. For ions the effective voltage is reduced by a factor A/Z (= 2.5 for Au) compared to protons and the bunch length for the same longitudinal emittance is increased by $\sqrt[4]{2.5} = 1.26$. The injectors have demonstrated the required intensities and emittances taking into account the bunch intensity reduction from the splitting.

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During acceleration all ions except protons have to cross the transition energy. Due to the short bunch length at transition electron clouds have been triggered in the past [12] and led to vacuum pressure rise, instabilities and beam loss. Although electron clouds are no problem in present operation, the transition crossing with the bunch spacing reduced to 1/3 compared to RHIC still needs to be evaluated.

Beam lifetime limits. Without cooling the ion beam lifetimes in eRHIC are primarily limited by intrabeam scattering (IBS), beam-beam interactions, and nonlinear magnetic field errors. Either strong hadron cooling or upgraded stochastic cooling is needed to overcome these limitations.

In present RHIC heavy ion operation IBS and burn-off are the dominant beam loss mechanisms without cooling. While the beam losses from IBS are contained by stochastic cooing, burn-off losses predominantly from Bound-Free Pair Production (BFPP) and Electro-Magnetic Dissociation (EMD) [13, 14] remain. BFPP and EMD create secondary beams ($^{197}Au^{78+}$ and $^{196}Au^{79+}$) that have momentum errors of 0.5% and 1.3% respectively, and losses are distributed around the ring leading to occasional abort kicker pre-fires, single event upsets, and radiation load on the quench protection diodes (see below). In eRHIC burn-off is small and these effects will be greatly reduced, a situation similar to the low-loss Zr+Zr/Ru+Ru operation in 2018 [15].

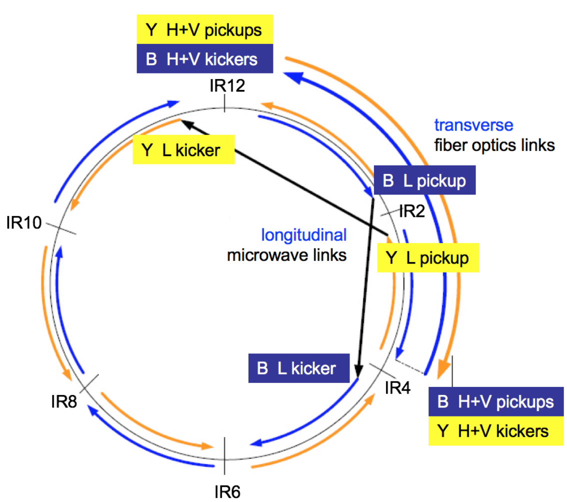

Figure 1: Present layout of the RHIC stochastic cooling systems.

Stochastic cooling. Full 3D stochastic cooling [16–18] for ions has been used in RHIC operation since 2014, and has dramatically improved the luminosity [19, 20]. The present stochastic cooling system (Fig. 1) consists of wide band pickups and cavity kickers. The individual cavities have bandwidths of 10 MHz, which is the current bunching frequency. The cavity resonant frequencies are spaced by 200 MHz, the inverse of the present 5 ns bunch length. The principle of operation employs Fourier decomposition to adjust the phase and amplitude of the individual cavities during the ~80 ns gap between ion bunches to give an optimal kick during the bunch passage.

Without strong hadron cooling, stochastic cooling can be used to maximize the heavy ion luminosities in eRHIC. The existing RHIC stochastic cooling system needs to be upgraded for efficient operation with bunch spacing reduced to 1/6 of the present one. This upgrade predominantly involves reducing the 80 ns voltage risetime to 20 ns. We plan to move the Blue ring cooling system into Yellow and increase all cavity bandwidths to 50 MHz. We expect the existing systems to furnish the necessary voltage, especially the transverse systems. At present we have the longitudinal pickup in IR2, the Yellow longitudinal kicker in IR12, and use a one turn delay filter on the low level signal. The increased momentum spread in the ion bunch will probably require the installation of an additional pickup in IR4 and taking the difference between the two pickup signals instead of employing a one turn delay. Since we are using narrow band systems this difference can be done frequency by frequency, greatly simplifying the low level processing. If necessary more longitudinal kickers can be installed to increase the voltage.

With these stochastic cooling upgrades the expected luminosity is shown in Table 1. With strong hadron cooling [1] the luminosity can be increased further by reducing the vertical and longitudinal emittances and allowing for a reduction in the vertical β^* and the geometrical reduction factor due to the hourglass effect and crab crossing (Table 1).

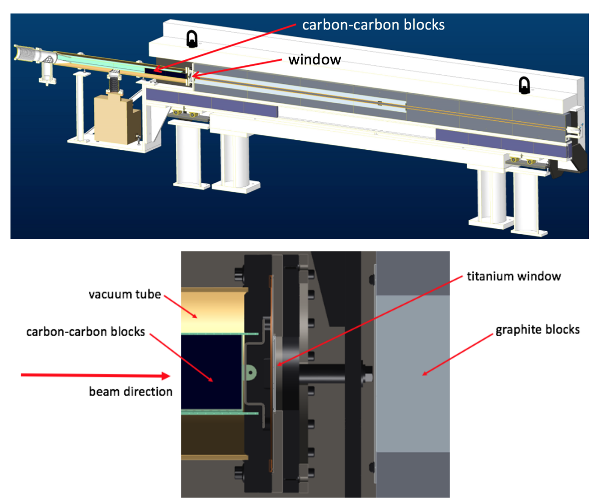

Figure 2: RHIC beam dump (top) and window detail (bottom) after the 2014 upgrade.

Beam abort system and collimation. The RHIC beam dump was last upgraded in 2014 to allow for higher Au intensity with a new Ti alloy vacuum window [21] and new carbon-carbon blocks that disperse the energy of the extracted beam (Fig. 2). A thicker beam pipe was installed to shield the adjacent superconducting Q4 quadrupole from secondary particles. With these upgrades RHIC operated at 100 GeV/nucleon with Au bunch intensities of up to 2.0×10^9

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in 2016. For eRHIC the stored beam energy almost triples requiring another upgrade, possibly including a vertical kicker. Presently the ions are only swept across the window in the horizontal plane.

In 2014 the abort kickers were also upgraded because high intensity proton beams overcame the eddy current reduction design and the ferrites were heating up [22, 23], leading to a reduction in the abort kicker strength. A different ferrite (CMD10 instead of CMD5005) was installed, the eddy current reduction design upgraded, and an active cooling loop installed to prevent the temperature increase. The abort kickers still need to be evaluated for the increased eRHIC beam current.

The RHIC collimation system is primarily for the reduction of unwanted secondary particles in the experimental detectors, created after beam loss in the triplets and other location in the interaction region. These secondary particles create experimental background and may damage detector components. The present collimation system consists of an L-shaped primary and flat secondary collimators in each ring. There is only one primary collimator per ring providing β-collimation, and no dedicated momentum collimation. This setup was sufficient to date although secondary beams created in heavy ion collisions (due to BFPP and EMD) are a concern. In eRHIC, operation is foreseen with radial offsets and the arc locations with local dispersion maxima may become loss locations for particles with large momentum deviations. This also requires further analysis.

Quench protection diodes. In RHIC Run-16 and Run-17 a quench protection diode was damaged due to exposure to beam induced radiation in events with large beam losses. The secondary beams created in heavy ion collisions (see above) also generate radiation to the QP diodes, which are mounted in the horizontal beam plane. The integrated losses from these secondary beams may double over the remaining RHIC operating years. A program of testing a fraction of the RHIC QP diodes has been instituted to monitor their conditions. Figure 3 shows measurements of the bias forward voltage of dipole QP diodes in the Blue ring. Only one diode, at the location of a short dipole, was found to be out of specification and no systematic deterioration has been observed to date.

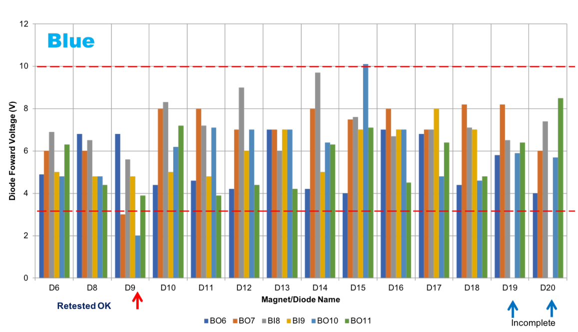

Figure 3: Measured forward bias voltage of Blue dipole quench protection diodes. Only one diode, at the location of a short dipole, was found with out of specification.

Single event upsets. Single event upsets in electronics of equipment in the alcoves is observed in all running modes, and is particularly pronounced with heavy ion collisions at full energy due to the production of secondary beams which are lost around the circumference. Recent operation with lighter Zr and Ru ions [15], for which the secondary beam production is greatly reduced, showed that low loss operation reduces SEU by two orders of magnitude (Fig. 4). A similar performance is expected for eRHIC unless operation with radial offsets also leads to distributed losses.

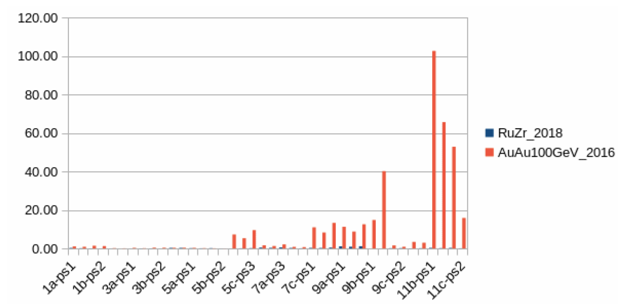

Figure 4: Diagnostic memory upsets per day by alcove for Run-16 (Au+Au) and Run-18 (Ru+Ru/Zr+Zr).

SUMMARY

The primary difference between e-p and e-Au operation in eRHIC is the significantly stronger intrabeam scattering with ions. However, for eRHIC with more bunches than in RHIC the stochastic cooling system can be upgraded to provide the same cooling strength as in RHIC. Strong hadron cooling can increase the luminosity further.

In RHIC, beam losses from burn-off that creates off-momentum secondary beams that are lost around the circumference and lead to occasional abort kicker pre-fires, irradiate the quench protection diodes, and lead to single event upsets in electronics in the alcoves. In eRHIC there are no such secondary beams and these effects will be greatly reduced.

Items that need further study are electron clouds during transition crossing, and upgrades of the beam abort system.

ACKNOWLEDGMENTS

We are thankful to the RHIC operations and eRHIC design teams for discussion and support.

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