PROGRESS OF HIGH-ENERGY ELECTRON COOLING FOR RHIC*

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Abstract

The fundamental questions about QCD which can be directly answered at Relativistic Heavy Ion Collider (RHIC) call for large integrated luminosities. The major goal of RHIC-II upgrade is to achieve a 10 fold increase in luminosity of Au ions at the top energy of 100 GeV/nucleon. Such a boost in luminosity for RHIC-II is achievable with implementation of high-energy electron cooling. The design of the higher-energy cooler for RHIC [1] recently adopted a non-magnetized approach which requires a low temperature electron beam. Such electron beams will be produced with a superconducting Energy Recovery Linac (ERL). Detailed simulations of the electron cooling process and numerical simulations of the electron beam transport including the cooling section were performed. An intensive R&D of various elements of the design is presently underway. Here, we summarize progress in these electron cooling efforts.

ELECTRON COOLING FOR RHIC-II

Research towards high-energy electron cooling of RHIC includes simulations and benchmarking experiments to establish with some precision the performance of the cooler and development of hardware for cost and risk reduction. Recent progress in intensive R&D program was described in detail in numerous contributions to the 2007 Particle Accelerator Conference. An overview of these contributions is reported in Ref. [2].

The present performance of the RHIC collider with heavy ions is limited by the process of Intra-Beam Scattering (IBS) [3]. To achieve the required luminosities for the future upgrade [4] of the RHIC complex (known as RHIC-II) an electron cooling system was proposed [5].

The baseline of the heavy-ion program for RHIC-II is operation with Au ions at total energy per beam of 100 GeV/nucleon. For such an operation, the electron cooling should compensate IBS and provide an increase by about factor of 10 in an average luminosity per store.

For RHIC-II operation with the polarized protons, the electron cooling should assist in obtaining required initial transverse and longitudinal emittances or prevent their significant increase due to IBS. Although IBS is not as severe for protons as for heavy ions, a proposed increase in proton intensity for RHIC-II upgrade makes IBS an important effect as well.

Although extensive studies of the magnetized cooling approach for RHIC showed that such approach is feasible [1], the baseline was recently changed to the non-magnetized one [6, 7].

Electron cooling at RHIC using the non-magnetized electron beam significantly simplifies the cooler design. The generation and acceleration of the electron bunch without longitudinal magnetic field allows us to reach a low value of the emittance for the electron beam in the cooling section. The cooling rate required for suppression of the Intra-Beam Scattering (IBS) can be achieved with a relatively small charge of the electron bunch ~ 5 nC.

Since non-magnetized cooling requires a low temperature of the electrons, a possible problem which one can encounter in cooling of heavy ions is a high recombination rate of ions with the electrons. In the present design, suppression of the ion recombination is based on employing fields of a helical undulator in the cooling section [8]. In the presence of undulator field, electron trajectories have coherent azimuthal angle which helps to suppress recombination.

To make sure that our representation of the friction force is accurate, an undulator field was implemented in the VORPAL code [9], and numerical simulations were performed for different strength of the magnetic field B and pitch period λ [10]. In all simulated cases, it was found that the friction force scales close to predictions based on a modified logarithm [8, 11]. This confirmed our expectations that with a modest reduction of the friction force values one can introduce relatively large azimuthal coherent velocity of electrons to suppress recombination [12]. Details on VORPAL simulations about undulator effects on the friction force can be found in Ref. [13].

In its 2006-2007 baseline (which presently undergoes some changes) the proposed electron cooler uses a double pass, superconducting ERL to generate the electron beam with maximum energy of 54.3 MeV [14]. 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 R&D ERL is presently under construction at BNL with commissioning being planned in early 2009 [15].

The electron cooler will be located at the 2 o'clock IR of RHIC. There are various RHIC lattice modifications, which result in sufficiently large space available for cooling (up to 100 meters) [16]. 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 [12].

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HARDWARE DEVELOPMENT

Electron beam needed for cooling will be delivered by superconducting ERL [14]. The superconducting RF (SRF) gun produces 5 nC electron beam with the exit energy of 4.7 MeV. The beam then goes through injection channel comes to SC RF Linac to be accelerated to 54.3 MeV. The 54.3 MeV beam is transported to RHIC for cooling of ion beams in both rings, and then is returned back to the ERL.

SRF ERL Cavity

A 5-cell ERL accelerating cavity at 703.75 MHz was developed. The cavity and cryostat were fabricated by Advanced Energy Systems (AES) [17]. It was processed and tested at Jefferson Laboratory. The process yielded a good performance with the cavity reaching 20 MV/m acceleration, with a Q of 1×10^{10} at a field of 19 MV/m (starting from a low field Q of 4×10^{10}) [18]. This “single mode” cavity has strong damping of all HOM through the 24 cm diameter beam pipe and 1 V/pC loss factor, thus it is ideal for multi-ampere current ERLs.

SRF Gun

The production of a high bunch charge with low emittance requires a high RF electric field at the cathode. For CW operation, a SRF gun is most advantageous. One and a half cell 4.7 MeV gun for RHIC-II high-energy cooler is being designed. A half cell 2.5 MeV SRF gun is under construction for the R&D ERL by BNL and AES [15].

Diamond Amplified Photocathode

RHIC-II electron cooler requires 50-100mA of electron beam current. For other future projects, currents more than 100mA will be needed. The production of CW 100 mA to 1 ampere current with a long lifetime and low thermal emittance is a challenge. The scheme used combines a high Quantum Efficiency (QE) photocathode with a diamond window, which also offers protection of the gun and cathode from each other. The amplification gain in the diamond results from the generation of a large number of electron-hole pairs. In measurements, gains of two orders of magnitude were achieved reproducibly, as well as good theoretical understanding of the gain dependence on the field using a plasma separation model [19].

The thermal emittance is a very important characteristic of cathodes. A lower thermal emittance cathode can lead to a lower beam emittance. A diamond amplified photocathode, being a negative electron affinity (NEA) cathode, promises to deliver a very small thermal emittance.

R&D ERL

A 20 MeV ERL is presently under construction at BNL. It will serve as a test-bed for future RHIC projects, including high-energy electron cooling [13]. The facility is based on a half cell superconducting 2.5 MeV RF gun, superconducting 5-cell RF accelerating cavity and about 20m long return loop. The ERL is scheduled for commissioning in early 2009 and will address many outstanding questions relevant for high current, high brightness ERLs.

COOLER DESIGN AND PARAMETERS

Design of the cooler, discussed in this paper, employs large beta-functions (400 meters for ions and 500 meters for electrons), the density of electron bunch was reduced compared to initial estimates, which in turn reduced the recombination rate. The parameters of undulator were set for magnetic field of 10 G and a period of 8 cm, corresponding to an effective temperature of 30 eV and recombination lifetime of 166 hours.

To ensure good cooling performance a quality of the electron beam should not suffer significantly as a result of the electron beam transport in the ERL, merging of the electron and ion beam, transport through the cooling section and interactions with the ion beam.

A lattice of the ERL was designed using PARMELA to provide electron beam parameters satisfying the RHIC electron cooling requirements [20]. In addition, a multi-parameter program was used for optimizing the injector and the emittance of electron bunch [21].

Table 1: 2006-2007 design parameters of electron cooler for RHIC-II.

Parameters	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}
rms bunch length	cm	0.8
rms beam radius in cooling section	cm	0.4
cooling section length	m	80

With the non-magnetized cooling approach, electron angles in the cooling section should be comparable to the angular spread of the ion beam being cooled. With ion beam 95% normalized emittance of 15 μm and beta-function in the cooling section of 400 m, the rms angular spread of ion beam is 7.6 μrad.

In the baseline cooling simulations with 5nC electron beam we assumed “effective” rms angular spread of the electrons of 8.6 μrad, which, for example, corresponds to the electron beam rms normalized emittance (thermal contribution) of 4 μm if no other contributions to electron angular spread are present. An emittance of 3 μm (demonstrated in simulations [20, 21]) corresponds to rms angular spread of 7.5 μrad and allows to accommodate additional contributions from other sources. To have a minimum impact on cooling performance, the goal is to constrain total contribution to the rms angular spread of the electrons to about 10 μrad.

Beam current dependent effects such as space charge, wake fields, CSR and trapped ions may reduce electron beam quality. The defocusing effect of space charge at the cooling section led to implementation of compensating weak solenoids in the cooling section design. Summary of these effects and their impact on cooler design are given in Ref. [22].

The stability of the circulating ion beam in the presence of electrons due to two stream instabilities of various modes or due to the reduction of the Landau damping due to longitudinal cooling of the momentum spread of ions was studied. Simulations and theoretical estimates were performed to calculate the thresholds of the instabilities caused by these effects [23]. No problems were found given the present baseline parameters of the cooler.

Parameters of electron cooler which were used in simulations reported in this paper are given in Table 1.

COOLING PERFORMANCE

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.

For protons, the goal of electron cooling is to produce required initial 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. In addition, electron cooling can provide effective cooling for higher intensities of Au ions as well as for other ion species.

Table 2: Baseline RHIC-II parameters and luminosities.

Parameters	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}

An accurate estimate of the cooling times for high-energy cooling requires detailed calculation of the cooling process, which takes place simultaneously with various diffusive mechanisms. This task becomes even more challenging when cooling is performed directly at a collision energy which puts special demands on the description of the beam distribution function under cooling [7].

Cooling dynamics simulations for RHIC-II presented in this paper were performed using the BETACOOL code [24]. The effects typically included in the simulations are electron cooling, IBS, particle loss in collisions (burn-up), loss from the rf bucket and recombination. An example of such a simulation with all effects being included is shown in Fig. 1.

The simulated luminosity performance in Fig. 1 is based on an electron bunch with 5nC charge and 4 μm “effective” emittance. 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 (2007)” document [1].

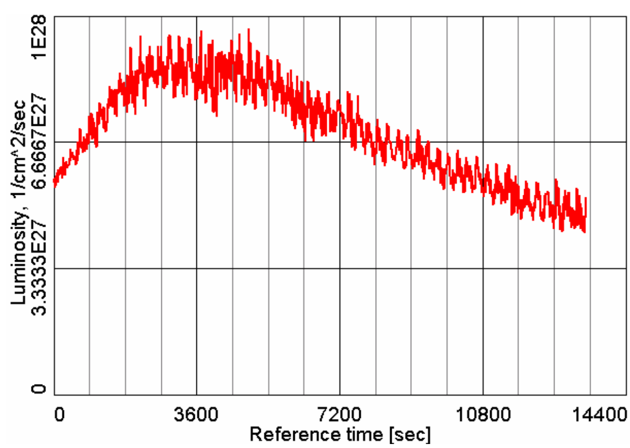

Figure 1: Electron cooling simulation of Au-Au luminosity: ion bunch intensity 1×10^9, 111 bunches; using single electron bunch per ion bunch. Average luminosity in 4 hour store is 7×10^{27} $cm^{-2}s^{-1}$.

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 apply shaping of the longitudinal distribution of the ions, thus avoiding long tails which are detrimental to the detector’s operation. In addition, with 2 electron bunches (5nC charge each), 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. 2 an average simulated luminosity of Au ions in 3 hour store is 2×10^{28} cm^{-2} s^{-1}.

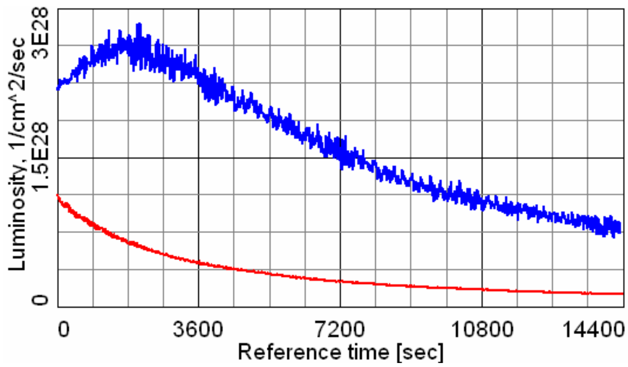

Figure 2: Simulation of Au-Au luminosity for ion bunch intensity 2×10^9 and 111 bunches using two 5nC electron bunches per single ion bunch with (blue top curve) and without (red bottom curve) electron cooling, taking β*=0.5 m and 1 m, respectively.

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. 3). Also, it maximizes the useful interaction region in the detector.

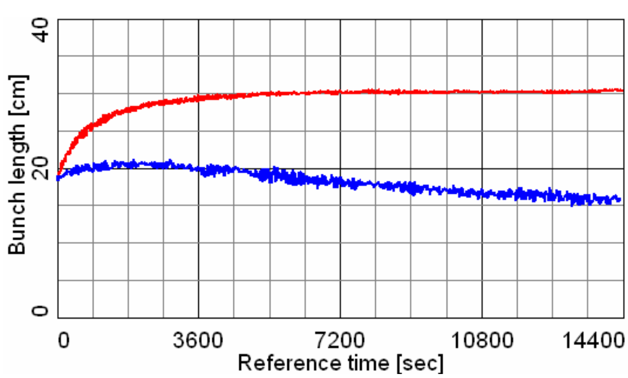

Figure 3: Simulated bunch length for ion bunch intensity 2×10^9 using two 5nC electron bunches with (blue bottom curve) and without (red upper curve) electron cooling.

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. 4 shows the luminosity performance for Cu-Cu collisions.

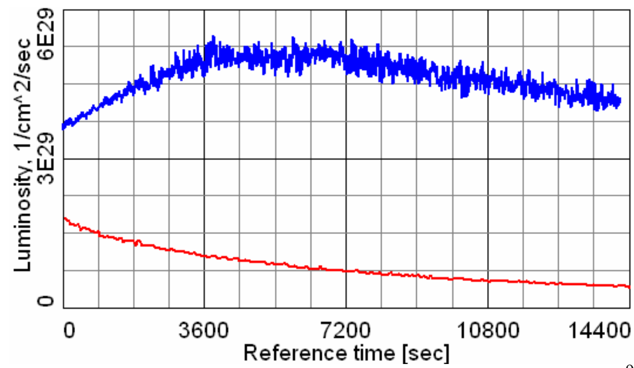

Figure 4: Cu-Cu luminosity for ion bunch intensity 8×10^9 and 111 bunches. Average luminosity in 4 hour store 4.6×10^{29} and 0.8×10^{29} $cm^{-2}s^{-1}$ with (upper blue curve) and without (low red curve) electron cooling, respectively.

For protons, in addition to pre-cooling at low energy, the present cooling system can be effectively applied to proton collisions at 100 GeV (see Fig. 5). At 100 GeV electron cooling can maintain the transverse emittance of protons, as well as keep rms bunch length to about 20 cm.

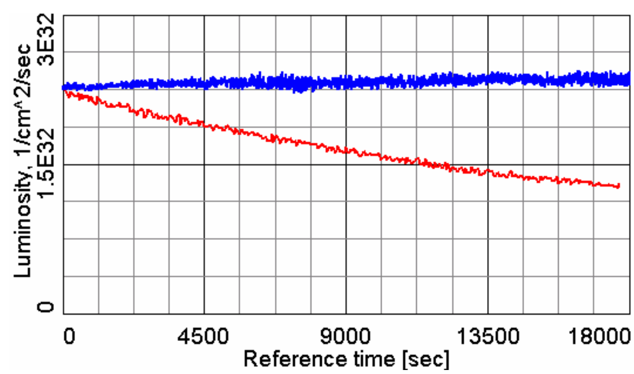

Figure 5: p-p luminosity at 100 GeV for ion bunch intensity 2×10^{11} and 111 bunches, using two 5nC electron bunches. With (upper blue curve) and without (low red curve) electron cooling, respectively.

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 [25] 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 [25]. Such pre-cooling was studied at 25 GeV/n, and cooling performance found was satisfactory.

PRESENT DEVELOPMENTS

The electron cooler for RHIC-II with parameters in Table 1 was carefully studied over the last two years. A detailed cost estimate of such a cooler was also performed. Presently, work is underway on various modifications of the cooler, such as relocation of ERL inside the RHIC tunnel and employing existing straight section in RHIC without its modification. Such changes promise significant reduction in the cost of the RHIC-II cooler. Preliminary evaluation of the new design parameters show that cooler can deliver the same performance as the one presented in this report.

In addition, the work has been started on a feasibility study of coherent electron cooling [26] for RHIC. This approach promises very good cooling performance at high energies [27].

SUMMARY

A significant progress has been made in the R&D towards high energy electron cooling of RHIC. Much of recent progress was reported in the proceedings of 2007 Particle Accelerator Conference. The feasibility of electron cooling of RHIC for a significant luminosity increase has been established and extensive R&D is being carried out on accelerator components and techniques.

ACKNOWLEDGMENTS

We would like to thank members of electron cooling team at BNL as well as many collaborators from other laboratories (FNAL, JLAB, JINR, BINP) and industry (AES, Tech-X) whose work is summarized in this progress report. The author is grateful to I. Ben-Zvi for help with preparation of this report.

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