ELECTRON COOLING SIMULATIONS FOR LOW-ENERGY RHIC OPERATION*

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Abstract

Recently, a strong interest emerged in running the Relativistic Heavy Ion Collider (RHIC) at low beam total energies of 2.5-25 GeV/nucleon, substantially lower than the nominal beam total energy of 100 GeV/nucleon. Collisions in this low energy range are motivated by one of the key questions of quantum chromodynamics (QCD) about the existence and location of critical point on the QCD phase diagram. Applying electron cooling directly at these low energies in RHIC would result in significant luminosity increase and long beam stores for physics. Without direct cooling in RHIC at these low energies, beam lifetime and store times are very short, limited by strong transverse and longitudinal intrabeam scattering (IBS). In addition, for the lowest energies of the proposed energy scan, the longitudinal emittance of ions injected from the AGS into RHIC may be too big to fit into the RHIC RF bucket. An improvement in the longitudinal emittance of the ion beam can be provided by an electron cooling system at the AGS injection energy. Simulations of electron cooling both for direct cooling at low energies in RHIC and for injection energy cooling in the AGS were performed and are summarized in this report.

INTRODUCTION

RHIC has completed seven successful physics runs since commissioning in 1999. RHIC was built to study the interactions of quarks and gluons and test QCD, the theory describing these interactions. At RHIC, nuclear matter at energy densities only seen in the very early universe is 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.

Exploration of the fundamental questions of QCD at RHIC requires 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 are summarized in Ref. [1]. The major upgrade of RHIC calls for 10-fold increase in the luminosity of Au ions at the top energy of 100 GeV/nucleon (termed RHIC-II). Such a boost in luminosity for RHIC-II is achievable with implementation of high-energy electron cooling which is summarized in a separate report [2].

In addition to RHIC-II program at high energies there is a significant interest in low-energy RHIC collisions in the range of 2.5-25 GeV/nucleon total energy of a single beam, motivated by a search for the QCD phase transition critical point [3, 4]. RHIC data will complement existing fixed-target data from AGS and SPS. In this energy range an energy scan will be conducted over about 7 different energies. Although required integrated luminosities needed in this scan are relatively low (5M events minimum per energy), there are several challenges to operate RHIC at such low energies. To evaluate the severity of these challenges and make projections for low-energy operation there have been two one-day test runs during RHIC operations in 2006 and 2007. Results of these test runs are summarized in Ref. [5].

In this report, we present some results of simulations which were performed to evaluate limitations caused by intrabeam scattering (IBS) at these energies, as well as various schemes of electron cooling systems that could be used to counteract IBS growth. All simulations presented in this report were done using the BETACOOL code [6].

PERFORMANCE AND LUMINOSITY LIMITATIONS

For heavy ions at 2.5 GeV/nucleon (total beam energy) the beam size is larger than the nominal injection energy beam size by over a factor of two. As a result, simply fitting low-energy beam into RHIC aperture is challenging. Luminosity lifetime is limited by IBS. An example of emittance growth due to IBS is shown in Fig. 1 for this lowest energy, corresponding to a beam kinetic energy of E_k=1.57 GeV/nucleon. Simulation parameters are given in Table 1, and the corresponding intensity loss due to IBS is shown in Fig. 2. In these simulations it was assumed that the initial longitudinal emittance of the ion bunch is small enough to fit into the bucket acceptance of 0.08 eV-s. To obtain such small emittance, pre-cooling in AGS before injecting into RHIC may be needed; this is discussed later in this paper.

Table 1: Parameters of Au beam for lowest energy scan.

Parameter	Value
Beam total energy E, GeV/nucleon	2.5
Kinetic energy E_k, GeV/nucleon	1.57
Relativistic γ	2.68
Bunch intensity, 10^9	1.0
Rms momentum spread	4×10^{-4}
Rms bunch length, cm	155
Rms emittance (unnormalized), μm	1.04
RF harmonic	387
RF voltage, kV	300

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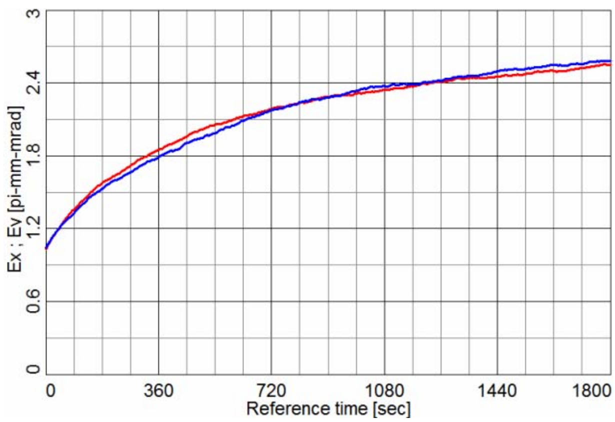

Figure 1: Growth of rms unnormalized emittances (horizontal and vertical) of Au ions in RHIC at kinetic energy of 1.57 GeV/nucleon for parameters of ion bunch given in Table 1.

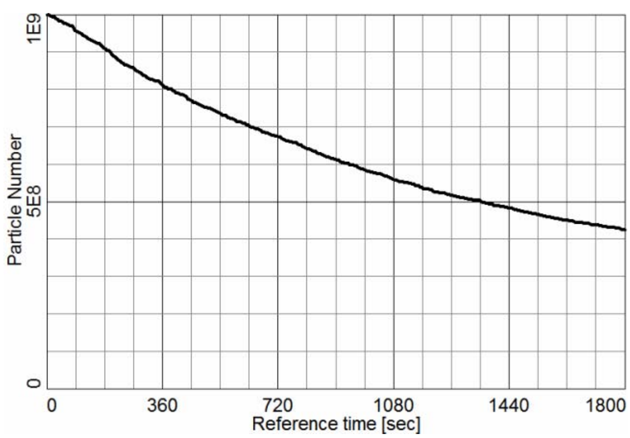

Figure 2: Bunch intensity loss due to IBS at kinetic energy of 1.57 GeV/nucleon for parameters of ion bunch given in Table 1.

For parameters in Table 1 the initial IBS growth times are 250 and 100 sec for transverse and longitudinal emittance, respectively. In IBS simulations shown in Figs. 1-2 no loss on transverse acceptance was assumed. All loss in simulations was purely due to longitudinal IBS resulting in escape of particles from the RF bucket. Slow intensity loss rates of several minutes were observed in the June 2007 test run at E_k=3.66 GeV/nucleon, consistent with predicted transverse IBS growth at that energy [5].

ELECTRON COOLING AT LOW ENERGIES IN RHIC

In Ref. [3] the proposed list of collision energies for the QCD critical point search corresponds to ion beam kinetic energies of E_k=1.6, 2.2, 2.9, 3.45, 5.2, 8.1 and 13.1 GeV/nucleon. An electron beam with a kinetic energy range of 0.87-7.1 MeV is required to cool ions in this energy range. However, for beam energies at and above the present injection energy in RHIC (E_k=10.8 GeV/nucleon), requested luminosities can be easily delivered with only 1-2 days of operations per energy point. As a result, improvements based on electron cooling are not essential for the largest energy points (above E_k=8 GeV/nucleon) in the proposed energy scan. Conversely, the lowest energy points benefit the most from electron cooling; these correspond to electron beam E_k=0.9-2.8 MeV, and are the energies explored here.

Use of electron cooling at low energies in RHIC would counteract IBS and result in small beam emittance and long physics stores. Studies reported in Ref. [7] were based on an electron cooling system developed for RHIC-II [8] which assumed 5nC electron bunches delivered by an Energy Recovery Linac (ERL) and a cooling section up to 80 meters in length. Less demanding cooling scenarios are presented in this paper.

For the lowest energy point, expected peak luminosities are about 5×10^{22} $cm^{-2}s^{-1}$ without electron cooling in RHIC. However, due to a rapid debunching and strong transverse emittance growth, the store length will be just a few minutes with an average luminosity per store about 1×10^{22} $cm^{-2}s^{-1}$. Applying electron cooling directly in RHIC (with parameters of the cooler discussed in this section) will increase average integrated luminosity by at least a factor of 10, and will provide long stores for physics.

ERL based cooler

For proposed high-energy cooling for RHIC-II, the electron beam is delivered by a superconducting ERL with a maximum electron beam energy of 54.3 MeV [9]. To test the hardware and to explore various beam dynamics questions a prototype ERL is presently under construction at BNL with commissioning being planned in early 2009 [10]. This ERL is based on ½ cell superconducting RF gun and a 5-cell superconducting accelerating cavity. It can deliver electron bunches up to energy of 20 MeV. Note that only the gun is needed for electron E_k=0.9-2.8 MeV of interest, and the cooling system can consist of a simple gun to dump setup. In these studies we assume an electron beam charge of 1nC and we limit simulations to the lowest energy of interest. Parameters of electron cooler used in simulations in Figs. 3-4 are given in Table 2. Parameters of the ion beam are given in Table 1. No losses were included in cooling simulations shown, only IBS and electron cooling.

Table 2: Parameters of superconducting gun based electron cooler for low-energy RHIC operation.

Parameter	Value
Kinetic energy, MeV	0.87
Charge per bunch, nC	1
Cooling length L, m	20
Normalized rms emittance, μm	2
Rms momentum spread	3×10^{-4}
Rms beam radius, mm	5
Rms bunch length, mm	8

Figure 3 shows emittance evolution (rms, unnormalized) due to IBS without application of electron cooling (upper black curve) and with electron cooling (lower blue curve). Figure 4 shows evolution of rms bunch length without electron cooling (upper black curve) and with electron cooling (lower blue curve). One can see that ERL-based cooler at this energy could easily counteract transverse and longitudinal IBS, enabling very long physics store and resulting in a significant luminosity increase.

Note that one gets cooling performance shown in Figs. 3-4 if rms normalized emittance of electron beam with charge of 1 nC is about 2 μm. When emittance of 1 nC bunch is increased up to 4 μm, IBS growth is just compensated (no cooling but no growth due transverse and longitudinal IBS either), which could be sufficient.

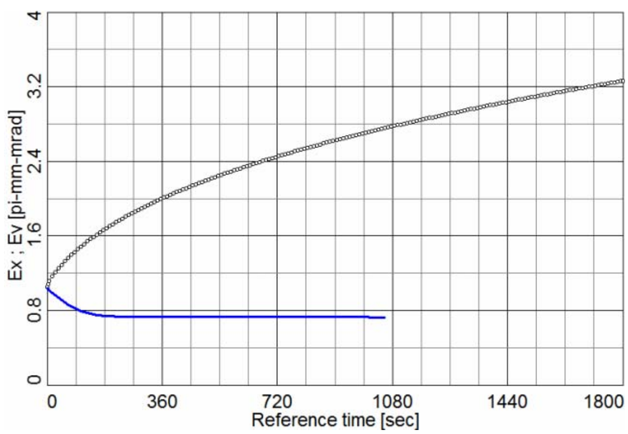

Figure 3: Evolution of transverse emittance (rms, unnormalized) without electron cooling (black upper curve) and with ERL based electron cooling with parameters in Table 2 (blue lower curve).

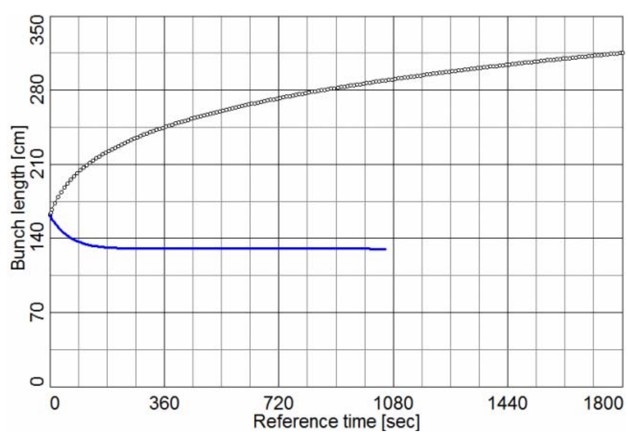

Figure 4: Evolution of rms bunch length without electron cooling (black upper curve) and with ERL based electron cooling with parameters in Table 2 (blue lower curve).

DC Electron Beam Cooler

For completeness, we note that electron cooling with electron beam E_k=0.9-3 MeV can be performed using a DC electron beam, such as from the Recycler cooler at Fermilab [11]. RHIC cooling times would be much smaller than those measured at the Recycler since we need to cool Au ions compared to antiprotons in Recycler. The cooling time is thus reduced by a factor of Z^2/A, where A and Z are the atomic mass and charge of Au ions, respectively.

Figures 5 and 6 show electron cooling simulation for ion beam parameter in Table 1. For simulation based on Recycler cooler, standard parameters of DC electron beam with 0.2A electron beam current were used [12]. One can see comparable performance with both systems. The ERL-based cooling cools at higher energies as well while Recycler cooler is limited to cooling of ions below 9 GeV/nucleon total beam energy.

It should be noted that the present cooling simulations are not optimized, as no specific design of low energy cooling for RHIC exists. However these simulations are promising, and indicate that low energy cooling at RHIC is feasible with realistic electron beam parameters.

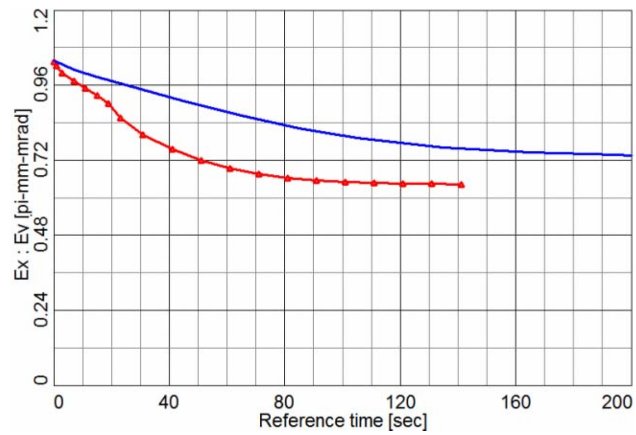

Figure 5: Evolution of transverse emittance (rms, unnormalized) with Recycler-based electron cooling (red lower curve with triangles) and with ERL based electron cooling with parameters in Table 2 (blue upper curve).

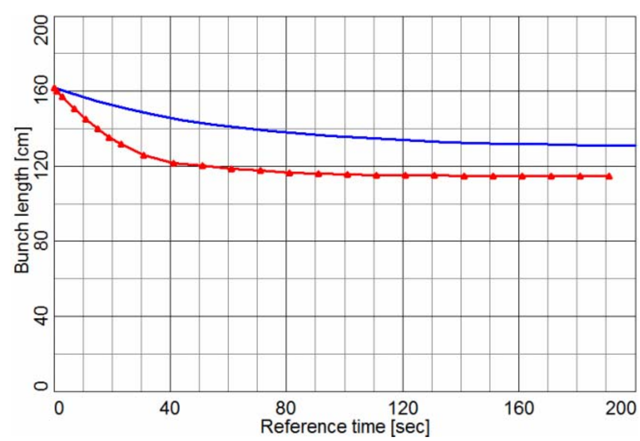

Figure 6: Evolution of rms bunch length with Recycler-based electron cooling (red lower curve with triangles) and with ERL based electron cooling with parameters in Table 2 (blue upper curve).

AGS PRE-COOLING

Although RHIC low-energy electron cooling would provide a significant luminosity increase, very high integrated luminosity is not fully motivated. For the proposed energy scan run, the modest requested luminosities can be delivered without electron cooling in RHIC. 90% longitudinal injection efficiency was achieved during the test run in June 2007 with an ion beam kinetic energy of 3.66 GeV/nucleon [5]. However, for the remaining 3 lowest energy points the present longitudinal emittance of ion beam may be too big to fit into the RHIC RF acceptance. To improve injection efficiency into RHIC pre-cooling of longitudinal emittance of ion beam at AGS injection energy was considered.

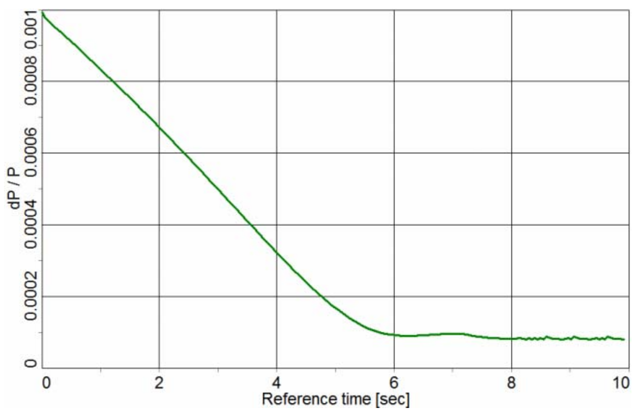

Figure 7: Cooling of rms momentum spread of coasting beam of Au ions at injection energy of AGS.

Table 3: Parameters of AGS cooler and Au ion beam used in simulations of Fig. 7.

Parameter	Value
Electron kinetic energy, keV	53
Relativistic γ	1.1
Relativistic β	0.42
Effective cooling length, m	1.0
Solenoidal magnetic field, T	0.1
Electron beam current, A	1.0
Ion rms momentum spread	1×10^{-3}
Ion rms emittance, unnormalized, μm	3.6
Number of ions	1×10^{9}

The ion beam is injected into AGS with kinetic energy of 97 MeV/nucleon, accelerated and then injected into RHIC. To cool ions at 97 MeV/nucleon one would need standard low-energy DC electron cooler with 53 keV energy. However, in AGS case, one is physically constrained that the full length of the cooler, including toroids, should not exceed 2.6m to fit into the free space available between the magnets, which limits the length of the cooling section increasing the cooling time. On the other hand, cooling time should be fast enough not to impact RHIC injection cycle significantly. In AGS 24 bunches are merged into 4 bunches which are then accelerated and injected into RHIC. To accumulate 100 bunches in a single RHIC ring one then needs 25 AGS cycles (3 seconds each). These constraints were taken into account in simulation studies of electron cooling in AGS. It was found that needed parameters for required cooling are achievable with standard technology. Example of such AGS cooling simulations are shown in Fig. 7. Parameters of AGS cooler used in simulations are given in Table 3.

Simulations in Fig. 7 were done for 1A of electron beam without taken into account well known reduction in cooling rate for high current due to space charge (see for example [13]). A design of the cooler should be carefully done to maximize effective cooling length and to insure good operation at high current to keep cooling times close to the constraints of AGS cycle of about 3 seconds.

FUTURE PLANS

A 14 week low-energy run which should scan 6-7 energies has been proposed for RHIC run 2009-2010. On such a time scale, implementation of electron cooling directly in RHIC is presently not being considered. Commissioning of the ERL is presently scheduled for Spring 2009 [10], and the ERL electron gun may be available in 2010. Feasibility of pre-cooling in AGS is presently under investigation [14]. A test of gold collisions at 1.6 GeV/nucleon kinetic beam energy has been proposed for 2007-2008 RHIC run to determine luminosity lifetime, and to evaluate requirements for potential AGS cooling.

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