ELECTRON COOLING FOR LOW-ENERGY RHIC PROGRAM*

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Abstract

Electron cooling was proposed to increase luminosity of the RHIC collider for heavy ion beam energies below 10 GeV/nucleon. Providing collisions at such energies, termed RHIC "low-energy" operation, will help to answer one of the key questions in the field of QCD about existence and location of critical point on the QCD phase diagram [1-4]. The electron cooling system should deliver electron beam of required good quality over energies of 0.9-5 MeV. Several approaches to provide such cooling were considered. The baseline approach was chosen and design work started. Here we describe the main features of the cooling system and its expected performance.

EXPECTED PERFORMANCE

In a preparation for Low-Energy RHIC physics program, several short test runs were carried out at an intermediate energy point of interest, γ=4.9, for projections of future low-energy RHIC operations [5]. During the first test run with gold ions in June 2007, the beam lifetime was very short and dominated by machine nonlinearities. These nonlinearities were intentionally increased to suppress head-tail instabilities. During the latest test run in March 2008, beam lifetime was improved using a new defocusing sextupole configuration. The store length was extended from 15 minutes in 2007 to 1 hour in 2008 [5].

Some improvements in the useful luminosity are straightforward. For example, doubling the number of bunches (to the nominal 108) will double the event rate. We also expect some improvement in the machine performance with additional tuning. An estimate of run time needed for the proposed low-energy physics program is given in Ref. [6, 7]. Luminosity projections are relatively low for the lowest energy points of interest.

Luminosity decreases as the square of bunch intensity loss due to longitudinal intra beam scattering (IBS) and transverse emittance growth from transverse IBS. Both transverse and longitudinal IBS can be counteracted by electron cooling. This allows one to keep the initial peak luminosity constant throughout the store without beam loss. In addition, the phase-space density of the hadron beams can be further increased by providing stronger electron cooling.

LUMINOSITY LIMITATIONS

Intra-beam Scattering

IBS is one of the major effects contributing to RHIC heavy ion luminosity degradation, driving bunch length and transverse beam emittance growth. IBS-driven bunch length growth causes beam losses from the RF bucket.

At these low energies, strong IBS growth can be counteracted with electron cooling [6, 8]. If IBS were the only limitation, one could achieve small hadron beam emittance and bunch length with the help of electron cooling, resulting in a dramatic luminosity increase. Unfortunately, the defining limitation is expected to be space charge at the lowest energy points in RHIC.

Space-charge Tune Shift

In circular accelerators, the figure of merit for space-charge effects is the shift of incoherent betatron oscillation frequencies. This is called the "space-charge tune shift". When the space-charge tune shift becomes significant, the beam overlaps many machine imperfection resonances, leading to large beam losses and poor lifetime. For machines where beam spends only tens of msec in high space-charge regime, and machines where the resonances are compensated, the tolerable space-charge tune shift can be as big as ΔQ=0.2-0.5. However the acceptable tune shifts are much smaller for long storage times. In some machines, lifetimes of a few minutes were achieved with tune shifts higher than 0.1. For RHIC, we are interested in much longer lifetimes. As a result, we take space-charge tune shift values of about 0.05 as a limit for our present estimate.

For a Gaussian transverse distribution, the maximum incoherent space-charge tune shift can be estimated:

$$\Delta Q = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{F_c}{B_f}, \qquad (1)$$

where F_c is a form factor which includes correction coefficients due to beam pipe image forces (the Laslett coefficients), r_p is the proton classical radius, N_i is the number of ions per bunch, A and Z are the ion atomic and charge numbers, γ, β are relativistic factors, ε is the un-normalized RMS emittance, and B_f is the bunching factor (mean/peak line density). Here we assume $F_c = 1$.

For low-energy RHIC operations, the present RF bucket acceptance is relatively small due to limited RF voltage. The injected ion beam longitudinal emittance is comparable to or larger than the RF bucket acceptance. As a result, the RF bucket is completely filled after injection. For the estimate of the space-charge tune shift ΔQ in this full bucket case, we assume a parabolic ion beam longitudinal profile [9].

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Beam-beam and Luminosity Limits

The linear part of the tune shift due to interaction with a colliding bunch is called the “beam-beam” parameter. If the beam-beam parameter exceeds some limiting value one can have a significant emittance increase due to diffusion processes. In hadron machines, typical limiting values for the beam-beam parameter per single IP are around 0.01. For a round beam, the beam-beam parameter for hadrons is:

$$\xi = \frac{Z^2 r_p}{A}\frac{N_i}{4\pi\beta^2\gamma\varepsilon}\frac{1+\beta^2}{2}. \qquad (2)$$

When the single-bunch luminosity is limited by the beam-beam effect it can be expressed in terms of ξ as:

$$L = \frac{A}{Z^2 r_p}\frac{N_i c}{\beta^* C_r}\frac{2\gamma\beta^2}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi, \qquad (3)$$

where C_r is the ring circumference, β^* is the beta-function at the IP, σ_s is the RMS bunch length, and the factor $f(\sigma_s/\beta^*)$ describes the “hourglass effect”. For low-energy RHIC operations we presently use $\beta^*=10\text{m} \gg \sigma_s$, so we neglect the hourglass effect by approximating $f(\sigma_s/\beta^*)=1$.

When the single-bunch luminosity is limited by the space-charge tune shift ΔQ, it can be expressed as:

$$L = \frac{A}{Z^2 r_p}\frac{N_i c}{\beta^*}\frac{B_f}{C_r}\gamma^3\beta^2 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q. \qquad (4)$$

For typical RHIC beam parameters and fixed $\Delta Q=0.05$, $\xi=0.01$, the maximum achievable single bunch luminosity in RHIC is limited by space charge tune shift for $\gamma<11$, while for $\gamma>11$ the luminosity is limited by beam-beam [9]. In the energies where space charge dominates, luminosity and event rates scale with γ^3.

Beam-beam and Space Charge

An even more interesting and unexplored effect is the interplay of direct space-charge and beam-beam effects, which is the case when one wants to collide beams with significant space-charge tune shift. In such a case, a large beam-beam parameter can excite resonances which will be crossed as a result of space-charge tune spread.

We started to explore these effects in RHIC Accelerator Physics Experiments (APEX) in 2009 with proton beam and conditions where both beam-beam and space-charge tune shifts were large [10]. Some interesting behavior was observed, which was related to strong beam-beam effect. However, observed effects are not directly relevant for lowest energy points from RHIC energy scan. At lowest energies, when RHIC is space-charge limited, the beam-beam parameter is much smaller than the space-charge tune shift. Our plan is to continue this experiment during the next RHIC run with gold ion beams at low energies. Our main goal is to understand whether we can operate with $\Delta Q>0.05$ under collisions, which would provide an additional luminosity improvement with electron cooling, compared to the estimates given in next section.

PERFORMANCE WITH COOLING

Initially we considered electron cooler with a maximum energy of 2.8MeV, this can provide cooling for c.m. ion beam energies of 5-12 GeV/nucleon. At c.m. energies > 12 GeV/nucleon luminosity is sufficiently high so the electron cooling is not really required, although it could significantly increase luminosity even further. However, our most recent cooling approach can provide cooling all the way up to c.m. energies of 20 GeV/nucleon. Since this latter energy also corresponds to the present RHIC injection energy of gold ions for the high-energy RHIC program, the use of such a cooler (with maximum electron energy of 4.9MeV) may be beneficial for the RHIC high-energy program.

In this section some examples of luminosity improvement for the lowest energies of interest are shown. Note that the bunch intensities at lowest energies may need to be reduced to respect the space-charge limit. As a result, the role of electron cooling for the lowest energy points is to counteract IBS: this prevents transverse emittance growth and intensity loss from the RF bucket due to the longitudinal IBS. As the energy is increased, space charge of the hadron beam becomes smaller (see Eq. (1)) which permits cooling of the transverse or longitudinal emittances of the hadron beams. This, in turn, allows us to reduce β^*. Thus electron cooling provides a larger luminosity gain for higher energy points.

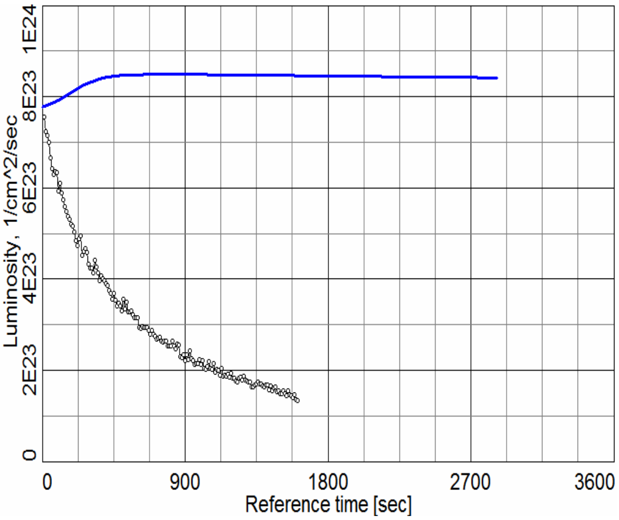

Figure 1: Simulation of luminosity with (blue line, upper curve) and without (black dots) electron cooling at $\gamma=2.7$.

Figure 1 shows results of a BETACOOL [11] simulation of luminosity evolution with and without electron cooling for $\gamma=2.7$. Simulations are done for ion bunch intensity $N_i=0.5\bullet10^9$, initial 95% normalized emittance of 15 mm-mrad, RMS momentum spread $\sigma_p=5\bullet10^{-4}$, RMS bunch length $\sigma_s=1.9$ m, and 56 bunches. There is an intensity loss as a result of the longitudinal IBS and particle loss from the RF bucket. There is also still a significant emittance increase due to transverse IBS even for a reduced bunch intensity of $N_i=0.5\times10^9$ per bunch [9]. This results in the rapid luminosity drop shown in Fig. 1 with black circles. The resulting store length becomes relatively short – one has to refill RHIC every 10-15 minutes. The transverse emittance will be kept constant, and the longitudinal IBS will be counteracted with electron cooling. As a result, electron cooling will provide long store times with relatively constant luminosity. The overall gain in average luminosity with electron cooling, taking into account the time needed for refill between short stores without cooling, will be about a factor of 3. Larger luminosity gains may be possible if we can operate with space-charge tune shifts larger than $\Delta Q=0.05$. Operation with slightly larger tune shifts may be expected with the help of cooling.

Figure 2 shows a simulation of luminosity performance with and without electron cooling for $\gamma=6.6$. Simulations were performed for ion bunch intensity $N_i=1\times10^9$, 95% normalized emittance of 15 mm mrad, and $\sigma_p=5\times10^{-4}$. For these parameters we are not yet space-charge limited. In such a case, in addition to just counteracting IBS, electron cooling allows us to cool the transverse emittance to the space-charge limit, which in turn allows to decrease β^* at the IP: the effect of this can be seen by the luminosity jump in Fig. 2. Thereafter the luminosity remains constant. For the scenario shown in Fig. 2, electron cooling provides a factor of about 6 improvement in average luminosity.

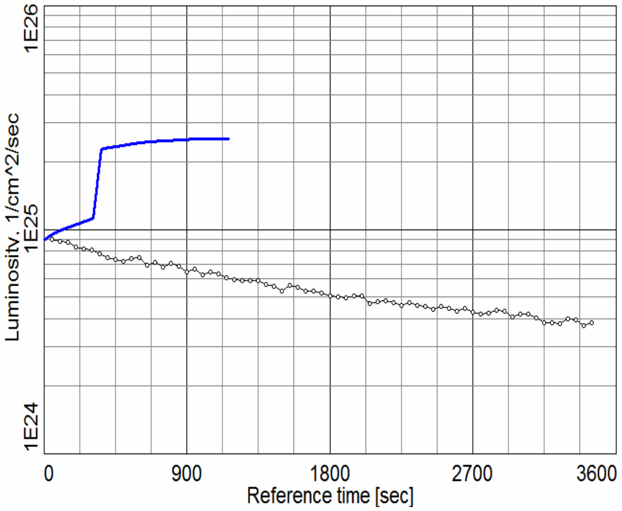

Figure 2: Simulation of luminosity with (blue line, upper curve) and without (black dots) electron cooling at $\gamma=6.6$.

ELECTRON COOLER CONSIDERATIONS

The required electron beam (0.9-5MeV) can be produced either using electrostatic or RF beam accelerators.

RF Based Cooler

The electron beam energies needed for low-energy RHIC are sufficiently high that we can consider cooling using bunched electron beam. The main problem for bunched electron beam is to provide beam transport without significant degradation of beam emittance and energy spread. Two approaches were considered and found feasible [6].

In the first approach a low-frequency RF gun was used to provide long electron bunches. As a result, even for high bunch charges, space-charge effects can be minimized, and one can deliver an electron beam of necessary quality to the cooling section. A prototype of such a 112 MHz SRF gun is presently under construction by Niowave Inc. in Michigan.

In the second approach a 703.75 MHz SRF gun, being built for the R&D ERL at BNL [12], was assumed. The length of electron bunches at this frequency is very short (about 1 cm rms) which would result in quick increase of momentum spread of electron beam due to longitudinal space charge. However, the length of the ion beam is very large with 1.9 meters rms. This allows us to put about 20 electron bunches on a single ion bunch. The charge needed for cooling can thus be divided between 20 electron bunches resulting in 50pC per bunch. With such a low charge the electron beam emittance is very small and is not an issue. The energy spread due to longitudinal space charge is also greatly reduced. The cooling in such a scenario is provided by a pulse/train of bunches with 20 bunches in the train spaced by 42.6 cm apart. More details about results of simulations based on RF approaches can be found in Ref. [6].

DC Approach

Electron cooling with electron beam kinetic energies $E_{k,e}=0.9\text{-}5$MeV can be performed using a DC electron beam, as is being done in the Recycler cooler at Fermilab [13, 14]. RHIC cooling times will be much shorter than those measured at the Recycler since we need to cool Au ions compared to antiprotons in the Recycler. The cooling time is thus reduced by a factor of $Z^2/A=31.7$, where $A=197$ and $Z=79$ are the atomic mass and charge of Au ions, respectively. In addition, due to strong dependence of electron cooling times on energy, operation at smaller energies results in much faster cooling times as well.

Apart from some modifications needed to address electron beam transport at low energies and recombination suppression in the cooling section, it appears that the existing Recycler cooler is ideally suited for low-energy RHIC cooling. As a result, our present baseline approach is based on DC electron beam produced with the FNAL Recycler's Pelletron. An evaluation of modifications to use the Recycler's Pelletron for RHIC is presently in progress.

Non-magnetized vs. Magnetized Approach

In low-energy electron coolers a magnetic field is required to provide transport of the electron beam. For energies of 0.9MeV and higher needed for our project, continuous magnetic field transport is no longer required.

However, in the cooling section, the interaction of the ion and electron beams results in ion beam loss due to recombination. Employment of strong magnetic field in the cooling section allows one to incorporate a large transverse temperature of the electron beam for recombination suppression.

On the other hand, a novel idea of suppression ion recombination based on the use of an undulator field in the cooling section was proposed for RHIC [15]. In the presence of an undulator field, the trajectories of all the electrons have the same coherent azimuthal angle θ, determined by the undulator period λ and field value B at the axis:

$$\theta = \frac{eB\lambda}{2\pi pc}, \tag{5}$$

where p is the electron momentum. Since the recombination cross section is approximately inversely proportional to the electron energy in the ion rest frame, the ion beam lifetime can be sufficiently improved. Using an undulator to suppress recombination allows one to use non-magnetized electron beam with relatively small temperatures for cooling [16, 17]. To make sure that the representation of the friction force in the presence of an undulator field is accurate, an undulator field was implemented in the VORPAL code [18], and systematic numerical simulations were performed for different strength of the magnetic field B and pitch period λ [19]. A comprehensive study of magnetic field errors and their effect on cooling was also conducted [20].

For the low-energy cooler in RHIC both approaches of magnetized and non-magnetized cooling were considered. As for the case of high-energy RHIC-II cooler, it was found that one can use a rather weak undulator with a magnetic field of about 3-5G (8 cm period) to combat recombination in the cooling section, which makes use of the non-magnetized cooling attractive for low-energy RHIC operation as well.

Since non-magnetized cooling significantly simplified electron beam transport and reduced the cost of the cooler, it was chosen as our baseline approach.

COOLER DESIGN AND PARAMETERS

Luminosity improvement is needed mostly for low ion c.m. energies of 5-12 GeV/nucleon. This requires electron beam with a kinetic energy range of 0.86-2.8MeV. It turns out that with a present setup of two RHIC detectors and RF tuning limits, simultaneous operation of both detectors is not possible at some energy points without significant modifications [7]. On the other hand, use of cooling to improve luminosity in the c.m. energy range of 5-8.6 GeV/nucleon, where both detectors can operate simultaneously and where most luminosity improvement is needed, requires only a 0.86-1.8MeV cooler. As a result, the electron cooler should be able to operate at least up to 1.8MeV kinetic energy of electrons and preferably up to 2.8MeV.

Our present baseline cooler design is based on existing FNAL's Recycler Pelletron, which is operating at 4.36MeV. This 6MeV Pelletron in principle should be able to provide cooling of ions all the way up to the present RHIC injection energy. This will require operation of Pelletron up to 4.9MeV, which seems feasible since high-current operation is not required.

At low energy, RHIC ion bunches are very long (rms bunch length 1.5-1.9 m) with the full bunch length up to 30 nsec. DC electron beam is ideally suited for cooling of such long ion bunches. To counteract IBS for lowest energy point only 0.05A of DC current is required. To provide also additional cooling of beam emittance for higher energy points requires electron beam current of about 0.1A.

Depending on beam energy and longitudinal emittance, the ion beam will have rms longitudinal momentum spread in the range of σ_p=4-6×10^{-4}. This sets a limit on the rms momentum spread of electron beam of < 4×10^{-4}. Present relative rms energy spread in Recycler's electron beam is about 1×10^{-4} which satisfies this requirement.

The requirement on transverse angles of electron beam in the cooling section is given by the angular spread of the ion beam. For example, for rms normalized emittance of 2.5 mm-mrad at γ=2.7, and 30 m beta function in the cooling section, the ion beam rms angular spread in the lab frame is 0.18 mrad. This results in a requirement to have transverse angular spread of electrons in cooling section < 0.2 mrad. Since the ion bunch angular spread decreases with energy increase, even stricter control of electron angular spread will be needed at higher energy points to maintain cooling performance. Thus a careful consideration of various effects and estimate of full "angular budget" similar to what was done at FNAL will be needed for the full energy range of interest.

The most straightforward approach is to use the Recycler's cooling section "as is", where control of angular spread is accomplished by 2m long weak solenoids. Here small magnetization at the cathode is required, which is the present Recycler's cooler approach. Due to the relatively small required current, another approach with zero magnetic field on the cathode and thus no magnetic field in the cooling section is also feasible. In the latter case, only short corrector solenoids every 2m will be needed to provide needed focusing in the cooling section. This latter approach would correspond to a pure case of "non-magnetized" cooling. Experimental investigation of this approach is highly desired. Such an experiment can be conducted at existing Recyler's cooler at FNAL. Both approaches to the cooling section will be carefully considered during design.

The use of undulators for recombination suppression in the cooling section is also compatible with both approaches to the cooling section described above. However, the effect of undulators on cooling as well as engineering design should be carefully evaluated. For example, use of undulators together with present Recycler's cooler 2m long solenoids results in additional drift velocities of electrons. For baseline parameters, additional contribution to angular spread due to such drift was found to be within specifications. Regardless of the chosen approach, it appears that use of undulators may require significant engineering modification of the cooling section while the expected benefit in luminosity with recombination suppression seems rather modest. A careful cost-benefit consideration will be done before including undulators in the baseline.

Some basic parameters of the cooler are summarized in Table 1. Electron beam requirements shown in Table 1 are given only for the lowest energy points of interest since cooling requirement at energies above 2.8MeV is not yet fully established. The value in brackets indicates the maximum possible energy of Pelletron-based cooler operation discussed here.

Table 1: Basic Parameters of Electron Beam

Electron kinetic energies, MeV	0.86-2.8 (4.9)
DC current, mA	50-100
Length of cooling section per ring, m	10
RMS momentum spread	<0.0004
RMS transverse angles, mrad	<0.2
Undulator magnetic field, G	3
Undulator period, cm	8

CHALLENGES

Some modification of the Recycler's Pelletron cooler will be needed to address the following issues: operation in a wide range of energies; use of the same electron beam to cool ions in two collider rings; suppression of recombination.

Besides some technical modifications, this will be the first cooler to cool directly beams under collisions. This puts special requirement on control of ion beam profile under cooling [21]. A careful study of interplay of space-charge and beam-beam effects within the hadron beams [10] is needed to understand the limits of cooling applicability.

SUMMARY

We have started design work on a low-energy RHIC electron cooler which will operate with kinetic electron energy range 0.86-2.8 (4.9) MeV. Several approaches to an electron cooling system in this energy range are being investigated. At present, our preferred scheme is to transfer the Fermilab Pelletron to BNL after Tevatron shutdown, and to use it for DC non-magnetized cooling in RHIC. Such electron cooling system can significantly increase RHIC luminosities at low-energy operation.

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