DESIGN ASPECTS OF AN ELECTROSTATIC ELECTRON COOLER FOR LOW-ENERGY RHIC OPERATION*

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Abstract

Electron cooling was proposed to increase the luminosity of the Relativistic Heavy Ion Collider (RHIC) operation for heavy ion beam energies below 10 GeV/nucleon. The electron cooling system needed should be able to deliver an electron beam of adequate quality in a wide range of electron beam energies (0.9-5MeV). An option of using an electrostatic accelerator to produce electrons for cooling heavy ions in RHIC was evaluated in detail. In this paper, we describe the requirements and options which were considered in the design of such a cooler for RHIC, as well as the associated challenges. The expected luminosity improvement and limitations with such an electron cooling system are also discussed.

INTRODUCTION

In Brookhaven National Laboratory (BNL), a physics program, motivated by the search of the QCD phase transition critical point, requires operation of RHIC with heavy ions at very low energies corresponding to γ=2.7-10 [1]. The Intrabeam Scattering (IBS) process 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 [2].

The required electron beam (0.9-5MeV) can be produced either using electrostatic or RF beam accelerators [2-3]. Both approaches were considered in the past. The present cooler design is based on the existing FNAL Recycler's 6MeV Pelletron, which is operating at 4.36MeV [4-6]. It should be able to provide cooling of ions all the way up to the standard RHIC injection energy. This would require Pelletron operation up to 4.9MeV, which seems feasible since high-current operation is not required. 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 the strong dependence of electron cooling times on energy, operation at lower energies results in much faster cooling times as well.

COOLER CONSIDERATIONS

At low energies, RHIC ion bunches are very long with the full bunch length up to 10m. A DC electron beam is ideally suited for cooling such long ion bunches. To counteract IBS at the lowest energy points only 0.1A of DC current is required. To also provide additional cooling of the beam emittance for higher energies points requires an electron beam current of about 0.2A.

The DC electron beam will be generated by a thermionic cathode gun located in the high-voltage (HV) terminal of the electrostatic accelerator called Pelletron [4]. After the beam is accelerated to the required energy it is bent into the beam transport line and transported to the cooling sections in RHIC. After the two cooling sections (one in the Yellow and one in the Blue rings), the electron beam is turned around and brought back to the Pelletron.

Depending on beam energy and longitudinal emittance, the ion beam will have relative rms longitudinal momentum spread in the range of σ_p=4-6×10^{-4}. This sets a limit on the rms momentum spread of the electron beam to < 5×10^{-4}. Presently, for the Recycler's electron beam, it is about 1×10^{-4} which satisfies this requirement.

The requirement on the transverse angles of the electron beam in the cooling section is given by the angular spread of the ion beam. For example, for a rms normalized emittance of 2.5 mm-mrad at γ=2.7, and 30m 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 a transverse angular spread of the electrons in the cooling section < 0.2 mrad. Since the ion bunch angular spread decreases with energy increase, a stricter control of the electron angular spread will be needed at higher energies to maintain the cooling performance.

In the cooling section, the interaction of the ion and electron beams results in ion beam loss due to recombination. Using a strong magnetic field in the cooling section allows one to incorporate a large transverse temperature of the electron beam for recombination suppression, as it is typically done in low-energy coolers. On the other hand, a novel idea of suppressing ion recombination based on the use of an undulator field in the cooling section was proposed for RHIC [7]. Using an undulator to suppress recombination allows one to use a non-magnetized electron beam with relatively small temperatures for cooling [8, 9]. To explore this concept an undulator field was implemented in the VORPAL code [10], and systematic numerical studies of the friction force were performed [11-12].

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Cooling Section

As required for low-energy coolers, a design with continuous magnetic field transport and strong magnetic field in the cooling section ("magnetized cooling") may be possible for our energies of interest (see, for example, [13]) However, its implementation becomes very challenging technically and requires extensive R&D. Such R&D is being pursued, for instance for the NICA project [14]. Another potential problem which is more pronounced with the magnetized cooling approach is over-cooling of the core of the beam distribution, which becomes very important for beams under collisions [15]. On the other hand, for energies above 0.9MeV needed for our project, continuous magnetic field transport is no longer required. Thus, non-magnetized cooling is preferred.

The most straightforward approach is to use the Recycler's cooling section "as is", where control of the angular spread is accomplished by 2m-long weak (100G) solenoids. This is different from low-energy coolers where a strong magnetic field changes the transverse beam dynamics and affects cooling significantly. Here cooling dynamics is essentially "non-magnetized" with a weak magnetic field needed just to keep the angular spread at the required level. With a magnetic field in the cooling section, a small magnetization at the cathode is also needed.

An alternate approach with zero magnetic field on the cathode, thus no magnetic field in the cooling section, was also considered. In this case, to compensate the space-charge effect from the electron beam, only short corrector solenoids every 2m are needed to keep the electron beam angular spread in the cooling section at the required level. Such an approach corresponds to a pure case of non-magnetized cooling. This was the baseline for a high-energy RHIC cooler with bunched electron beams. Unfortunately, a similar approach to low-energy RHIC cooling using a DC electron beam faces several problems. First is the problem of accumulating secondary ions in the electron beam potential which affects its angular spread, although this can be alleviated by providing small gaps in the electron beam with sufficient frequency [16]. The second issue is that focusing from the beam of positively charged gold ions itself was found to be too strong to preserve the angular spread of the electron beam without a continuous magnetic field in the cooling section. We therefore adopted an approach with weak (50-100G) continuous magnetic field in the cooling section, as in the case of FNAL Recycler's cooler.

With a magnetic field in the cooling section, a significant contribution to the electron angular spread comes from the drift velocity in cross magnetic (solenoidal) and electric (radial space-charge) fields, especially at the lowest energy of interest. Since the resulting angular spread is inversely proportional to the strength of the magnetic field, the effect is minimized with larger magnetic field values in the cooling section. On the other hand, to have effective cooling one would like to have the radius of the electron beam in the cooling section larger than the radius of the ion beam. Here, on the contrary, it is more beneficial to have a smaller solenoidal field in the cooling section for a given magnetic field strength and beam radius at the cathode. The mechanical design implications of these effects were evaluated taking into account the minimum allowable size of the vacuum chamber, which would not create a limiting aperture in RHIC, and its maximum, which should fit into the Recycler's cooler solenoids bores. As a result, 3-inch OD beam pipes were chosen for the RHIC cooling sections. Concurrently, two locations in the RHIC tunnel with sufficient space for the cooling sections were identified and the required RHIC optics was developed.

In addition, experimental studies were conducted at FNAL with the Pelletron in order to determine the range of magnetization possible as well as other relevant parameters [17]. A good range of magnetization (field on the cathode 80-255G), thus of electron beam size in the cooling section, was established. However, for the lowest energies of interest for RHIC, the radius of the electron beam will still be either comparable or smaller than the radius of the ion beam. Thus some painting with the electron beam will be needed to control the ion beam distribution under cooling and the beam lifetime. Operation at 1.6MV with DC current up to 0.4A was also demonstrated, which is well above the current values expected to be needed for cooling (see Table 1).

Table 1: Basic Parameters of Electron Beam.

Electron kinetic energies, MeV	0.9-4.9
DC current, mA	100-200
Length of cooling section per ring, m	6-10
RMS momentum spread	<0.0005
RMS transverse angles, mrad	<0.2
Undulator magnetic field, G	3
Undulator period, cm	8

As for the case of the high-energy RHIC-II cooler [18], 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. A careful cost-benefit analysis will be necessary before including undulators in the baseline design.

PERFORMANCE WITH COOLING

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, the space-charge effect on the hadron beam becomes smaller which permits cooling of the transverse or longitudinal emittances of the hadron beams as well. This, in turn, allows us to reduce β*. Thus electron cooling provides a larger luminosity gain for higher energy [2-3].

In 2010 successful RHIC operation for physics was established at γ=4.1 and γ=6.1, which is significantly below the typical RHIC injection γ=10.5. At γ=6.1, the dominant limitation was IBS, so that applying electron cooling for this energy would compensate both transverse and longitudinal emittance growth, minimize beam losses from the RF bucket and on the transverse acceptance, and significantly increase the integrated luminosity.

Figure 1 shows results of a BETACOOL [19] simulation of possible luminosity evolutions with and without electron cooling for γ=4.1, assuming that beam lifetime is limited only by IBS. Simulations were done for an ion bunch intensity $N_i=1\bullet10^9$, initial 95% normalized emittance of 15 mm-mrad, rms momentum spread $\sigma_p=5\bullet10^{-4}$ and 112 bunches. Only 60mA of DC electron current was sufficient to counteract IBS, which led to small recombination beam loss. If needed, cooling times can be further decreased to about 1-2 minutes by increasing the electron beam current to 200mA.

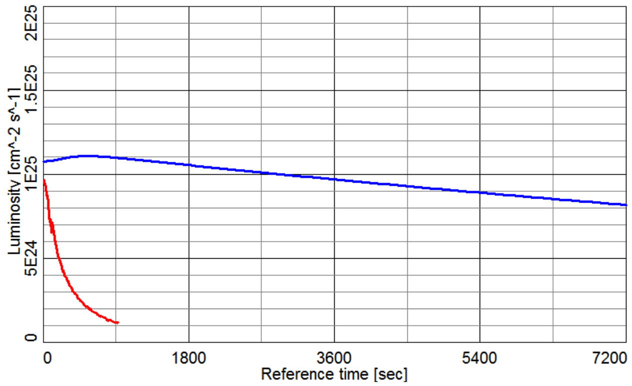

Figure 1: Simulation of luminosity with (blue upper curve, no suppression of loss from recombination) and without (lower red curve) electron cooling at γ=4.1.

As can be seen in Fig. 1, electron cooling could provide long store times with relatively constant luminosity. The overall expected gain in average luminosity with electron cooling, taking into account the time needed for refill between short stores without cooling, could be up to a factor of six below γ=6.1, and a factor of six or more at γ=6.1 and higher energies.

Note that during RHIC operation at γ=4.1 in 2010 the measured fast time component of the beam lifetime decay was much shorter than expected from IBS and was attributed to other effects [20]. As a result, beam lifetime at γ=4.1 has to be significantly improved first in order to expect substantial luminosity gains from electron cooling at this energy. Otherwise, with the performance achieved in 2010, only a modest improvement of about a factor of two should be expected from cooling. At the lowest energy of interest, γ=2.7, a beam lifetime satisfactory for physics production has not been achieved yet, but more test runs are being planned.

In principle, using FNAL Recycler's Pelletron can provide cooling all the way up to c.m. energies of 20 GeV/nucleon. Since this energy also corresponds to the present RHIC injection energy of gold ions for the high-energy RHIC program, the use of such a cooler could be beneficial for the RHIC high-energy program as well.

SUMMARY

As a result of a feasibility study, including experimental operation of FNAL Recycler's Pelletron at 1.6MeV, it was shown that FNAL's electron cooler is well suited for the low-energy RHIC program. Such an electron cooling system can significantly increase RHIC luminosities at low-energy operation as well as provide pre-cooling of either transverse or longitudinal ion beam emittance for the high-energy RHIC program. This will require an electron cooler operating in the kinetic energy range of 0.9-4.9MeV. Presently, no decision has been made to proceed with the engineering stage of the project.

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