ELECTRON COOLING FOR RHIC*

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Abstract

We introduce plans for electron-cooling of the Relativistic Heavy Ion Collider (RHIC). This project has a number of new features as electron coolers go: It will cool 100 GeV/nucleon ions with 50 MeV electrons; it will be the first attempt to cool a collider at storage-energy; and it will be the first cooler to use a bunched beam and a linear accelerator as the electron source. The linac will be superconducting with energy recovery. The electron source will be based on a photocathode gun. The project is carried out by the Collider-Accelerator Department at BNL in collaboration with the Budker Institute of Nuclear Physics.

1 INTRODUCTION

The Collider-Accelerator Department (C-AD) at Brookhaven National Laboratory is operating the Relativistic Heavy Ion Collider (RHIC), which includes the dual-ring, 3.834 km circumference superconducting collider and the venerable AGS as the last part of the RHIC injection chain.

CAD is planning on a luminosity upgrade of the machine under the designation RHIC II. One important component of the RHIC II upgrade is electron cooling of RHIC gold ion beams. For this purpose, BNL and the Budker Institute of Nuclear Physics in Novosibirsk entered into a collaboration aimed initially at the development of the electron cooling conceptual design, resolution of technical issues, and finally extend the collaboration towards the construction and commissioning of the cooler. Many of the results presented in this paper are derived from the Electron Cooling for RHIC Design Report [1], produced by the BINP team within the framework of this collaboration. Electron cooling of RHIC gold ions is a challenging and interesting project, for the following reasons:

1. The RHIC gold beam evolution is dominated by Intra-Beam Scattering (IBS), which leads to emittance growth and beam loss. Cooling has to be done during the storage phase of the machine to keep IBS in check. That means the following unique consequences:
    a. Cooling of a bunched beam.
    b. Cooling of a 100 GeV/u ions, requiring over 50 MeV cooling electron beam.
    c. The electron accelerator cannot be an electrostatic machine.
2. The RHIC cooler will be the first instance of direct cooling of a collider.
3. The two rings would require two coolers operating simultaneously.
4. Electron capture by the fully stripped gold ions is an important factor to consider.
5. Beam disintegration due to the collision process is a significant lifetime limiting effect under cooling.
6. The solenoid of the cooler is a particularly challenging device, a 30 m superconducting solenoid at a field of 1 T, with a required precision of 10^{-5}.

The technical development of the electron accelerator is a challenge for a number of reasons:

1. The accelerator has to transport a magnetized electron beam without the benefit of a continuous solenoidal field.
2. The average current of the accelerator has to be of the order of 100 mA.
3. At the energy of 50 MeV the power is 5 MW, and if dumped at this energy it would lead to complications of the beam dump due to induced radioactivity.
4. The single bunch charge has to be of the order of 10 nC. Yet, this charge has to be compressed to a bunch length of approximately 30 ps to be accelerated by a linear accelerator. This corresponds to a peak current of about 330 A.
5. The electrons have to be debunched before entering the cooling region, to reduce the electrostatic interaction with the ion beam and reduce its energy spread to the required level. Then, following the cooling, the electrons have to be rebunched in order to decelerate them successfully for energy recovery.
6. The electron source is particularly challenging. Two approached are being considered, a DC gun and a photoinjector.

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The unique features of the RHIC cooler mentioned above offer some interesting opportunities in electron cooling R&D:

1. Control of the ion distribution in phase space by special modulation of the electron beam parameters.
2. Cooling of a collider may have interesting implications concerning the beam-beam parameter and collision generated noise.

2 BEAM LOSS ISSUES

The design of an electron cooling system for gold ions at RHIC is greatly affected by two beam lifetime issues: One is the rather well recognized beam recombination, in which ions capture an electron in the cooler section and thus are lost rapidly from the storage ring. The other one is unique to a heavy ion collider, beam loss due to the collision process.

2.1 Electron capture in the cooling section

Ion charge exchange by the electron beam recombination is an additional source of losses.

The value of radiative recombination coefficient α_{req} is given by the equation [2]:

$$\alpha_{rec} = 3.02\times10^{-13}\frac{Z_i^2}{\sqrt{T_e}}\left[\ln\left(\frac{11.32Z_i}{\sqrt{T_e}}\right)+0.14\left(\frac{T_e}{Z_i^2}\right)^{1/3}\right]$$

where Te is the electron beam temperature in eV and Zi is the ion's charge. This equation was found in good agreement with experimental results [3]. The electron temperature should be in the range of 200 to 1000 eV (depending on the store cycle) to avoid significant beam loss. The beam lifetime due to recombination is given by

$$\tau_{rec}=\gamma/(n_e\alpha_{rec}\eta)$$

where η is the fraction of the ring occupied by the cooler with an electron density n_e. Using an electron temperature of 1 keV and fully stripped gold ions (Zi=79) we get a recombination lifetime of 1.9×10^5 seconds, or about 55 hours, well above the 10-hour typical storage time at RHIC.

Naturally, by increasing the electron transverse temperature to nearly 1 keV to reduce recombination, we pay the cost in cooling time. One way to reduce this penalty is to increase the solenoid magnetic field.

For high electron temperature the influence of the magnet field is very significant, and for a temperature in the range of 100-1000 eV it is necessary to use high solenoid magnet field. This will require a 30 meter long superconducting solenoid, with a challenging requirement on precision.

2.2 Beam burn-off

At a high luminosity, gold collisions at 100 GeV/u exhibit beam losses that are dominated by bound electron-positron production and Coulomb dissociation. [4]. The cross section for both effects is 212±10 barns. To lose beam on this mechanism means that the collider reached an optimal luminosity, delivering the maximal rate of data to the experiment. Further increase in the luminosity can be made only by increasing the frequency of injections or number of bunches in the ring.

After reaching an electron bunch intensity $N_e=2\times10^{10}$, an increase in the cooling current does not improve the integrated luminosity over a 10 hours run period. The disintegration cross section $\sigma_{tot}=212$ barns limits the integrated luminosity through:

$$\left(\int Ldt\right)_{\max} = \frac{N_i n_b}{n_{IP}\sigma_{tot}}$$

where $n_b=60$ is the number of bunches in the storage ring, and $n_{IP}=6$ is the number of interaction points delivering this luminosity. From the equation for the integrated luminosity we can see that the maximal integrated luminosity (over time) equals 47 1/mbarn. An integrated luminosity of 38 1/μbarn is reached at a cooling bunch of 2×10^{10} electrons, showing that at this cooling rate 80% of the ions were lost due to IP collisions.

3 TECHNICAL APPROACH

The schematic layout of the RHIC high-energy cooler is shown in Figure 1. The electron beam will be produced with a cw photoinjector (laser photocathode RF gun). The cathode of the gun will be immersed in a magnetic field to produce a 'magnetized' electron beam.

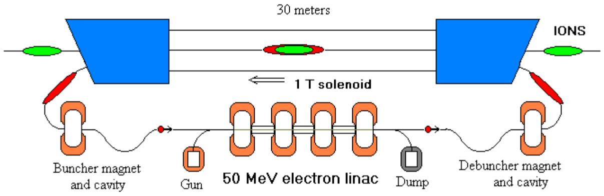

Figure 1. Schematic diagram of the high-energy electron cooler for RHIC.

Following some initial acceleration to about 5 MeV the beam will be injected into a superconducting energy recovery linac. The accelerated beam will be debunched in order to increase it bunch length from about 12 mm to about 50 mm. The purpose of the debunching is twofold: To reduce the space-charge interaction of the electron and ion beams to a safe level and to reduce the energy spread of the beam. The beam transport has to obey certain rules [5] in order to preserve the magnetization of the beam in the transport with discontinuous magnetic field. The magnetized electron beam, which is velocity matched to the ion beam, is then introduced into the 1 T cooling solenoid, overlapping the ion beam. Since the ion beam is much longer than the electron beam, the phase of the electron beam will be modulated in order to cool the required longitudinal extent of the ion beam. Other modulations (in energy and radial coordinates) may be introduced to shape the ion beam in phase-space. Emerging from the 30 m long cooling solenoid, the electron beam will be separated from the ion beam, rebunched (to match the linac acceptance) and decelerated to recover its energy. The beam will be dumped at about 5 MeV.

There are a few straight sections in RHIC where the electron cooler may be introduced. We are considering a placement next to IP4 of RHIC, in the straight section between Q3 and Q4, which can accept the 30 m long solenoids. The electron accelerators will be placed outside the RHIC tunnel.

There are a number of issues to be investigated. The brightness of the electron source is one. We have to produce a high-brightness beam with a high charge-per-bunch in a CW operation. A photoinjector looks promising, but so does a DC gun based system developed at BINP. At this time we are proceeding with both options open. Another one is the high-current energy recovery linac, requiring a current of about 100 mA, or 20 times higher than what has been demonstrated so far. The 1 T, 30 m long ultra-high precision solenoid is another challenge. The required precision is of the order of the ions' angular spread, $\Delta\theta$, given by:

$$\Delta\theta := \sqrt{\frac{\varepsilon ni}{\beta \cdot \gamma \cdot \beta cool}}$$

where ε_{ni} is the ions' normalized emittance and β_{cool} is the beta function in the cooler solenoid. In our case $\Delta\theta$ is about 10^{-5}.

5 ANTICIPATED PERFORMANCE

We assume a 100 GeV/u gold beams in the collider, with either 60 (RHIC) or 120 bunches (RHIC II) stored in each ring. The initial emittance of 15 mm mrad (normalized, 95% emittance) will be cooled to about 6 or less. The bunch population is assumed to be 10^9. The IP beta function is 2 m (RHIC) or 1 m (RHIC II).

The 100 GeV/u gold beam will be cooled only very slightly, to increase its peak luminosity. The beam should not be cooled too far for two reasons. First, the beam-beam parameter may exceed its maximum stable value estimated at 0.004. Second, as discussed in section 2.2, increasing the luminosity too much just leads to a rapid disintegration of the beam in the IP and to a variable luminosity as well as short store times. This can be seen in the figure below, showing the luminosity as a function of time for various cooling rates, using 10^{10}, $3x10^{10}$ and 10^{11} electrons per bunch. The luminosity with no cooling is also plotted, showing how IBS causes a drop in luminosity due to beam loss and emittance increase. Vigorous cooling can lead to a rapid increase, followed by a rapid decline in the instantaneous luminosity. Naturally the cooling can be adjusted to maintain a constant luminosity (at a lower value than the peaks) over the store period to optimize the collider performance.

The luminosity increase that we expect the RHIC II upgrade to deliver is about 40, of which about a factor of 4 is planned from beta function reduction and increase in the number of bunches, a factor of 10 is anticipated to come from the electron cooling.

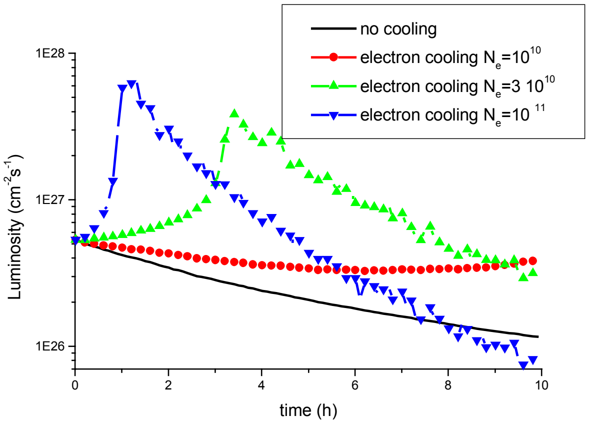

Figure 2. Luminosity as a function of time for a few values of the electron charge per bunch [1].

6 REFERENCES

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