BUNCHED BEAM 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 should be able to deliver an electron beam of adequate quality in a wide range of electron beam energies (0.9-5 MeV). An attractive option is to use electron bunches produced with the superconducting RF (SRF) injector. Such a scheme of cooling with bunched electron beam is also a natural approach for high-energy electron cooling which requires RF acceleration. In this paper, we describe the requirements and design aspects of such an approach.

INTRODUCTION

Mapping the Quantum-Chromo-Dynamics (QCD) phase diagram is one of the fundamental goals in the heavy-ion collision experiments. The QCD critical point is a distinct feature of the phase diagram, the existence of which is predicted by various QCD models. The beam energy scan phase-I (BES-I) runs for physics, motivated by the search of the QCD critical point, were successfully conducted at RHIC in 2010-11. During BES-I physics runs data sets were collected for Au+Au (center of mass) energies of 7.7, 11.5, 19.6 and 39 GeV. Driven by physics and the BES-I results, the future physics program called BES-II is proposed for Au+Au energies below 20 GeV (γ=10.7). However, required event statistics is much higher than previously achieved and relies on significant luminosity improvement in RHIC at energies below γ=10.7. Electron cooling was proposed to increase luminosity of the RHIC collider for heavy ion beams at these low energies [1-2].

In a collider, the maximum achievable luminosity is typically limited by the beam-beam effects. For heavy ion beams significant luminosity degradation via the bunch length and the transverse emittance growth comes from the intra-beam scattering (IBS). For low-energy RHIC such IBS growth can be counteracted with electron cooling. If IBS were the only limitation, one could achieve a small hadron beam emittance and bunch length with the help of cooling, resulting in a dramatic luminosity increase. However, as a result of low energies, the direct space-charge force from the beam itself is expected to become the dominant limitation [3-4]. The main role of electron cooling for the lowest energy points is thus 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 additional cooling of the transverse or longitudinal emittances of the hadron beams. This, in turn, allows us to reduce the β*, providing larger luminosity gain. Recently, operation with long ion bunches and a new low-frequency RHIC RF system was suggested which should help to mitigate some observed limitations of beam lifetime at low energies offering a better path towards luminosity improvement [5-6].

This electron cooling technique requires electron beam to co-propagate with the same velocity as the ion beam in a localized portion of circular collider called the cooling section. An electron beam up to 5 MeV kinetic energy is needed to cover the full energy range of interest.

Such Low Energy RHIC electron Cooler (LEReC) based on the SRF linac is presently under design at BNL.

COOLING CONSIDERATIONS

The energies of electron beam needed for low-energy RHIC are sufficiently high (0.9-5 MeV), which allows us to consider cooling using bunched electron beam. One of the challenges for bunched beam cooling is providing beam transport of electron bunches without significant degradation of beam emittance and energy spread. A low-frequency 84.5 MHz RF gun can provide relatively long electron bunches. As a result, even for high bunch charges, space-charge effects remain under control. One can then deliver an electron beam of the necessary quality to the cooling section. In addition, the use of long ion bunches [5-6] allows us place several electrons bunches on a single ion bunch, which in turn relaxes requirements on charge in individual electron bunch and should allow us to achieve good beam quality needed for cooling.

Since non-magnetized cooling significantly simplifies electron beam transport and reduces the cost of the cooler, it was chosen as our baseline approach. Due to a relatively low beam current required for our cooler (Table 1), an approach with zero magnetic field on the cathode and thus no magnetic field in the cooling section is feasible. Short solenoids will be placed every 2 m to correct the angular spread accumulated due to the electron beam space-charge self field in the cooling section.

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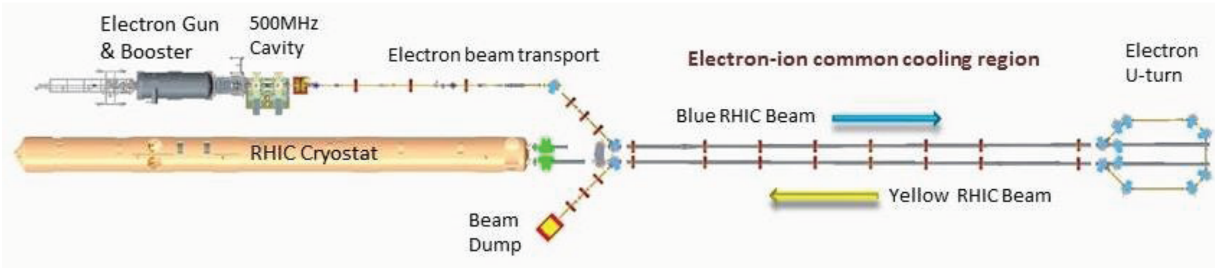

Figure 1: LEReC beam line layout. The cooling sections will be located in a RHIC warm region.

The use of undulators for recombination suppression in the cooling section is compatible with approach chosen. However, the use of undulators would require significant engineering additions to the cooling section while, in our case, the expected benefit for luminosity with recombination suppression seems rather modest. Thus, the recombination suppression with undulators is presently not included in the LEReC baseline.

ELECTRON ACCELERATOR

Beams for LEReC will be provided by a short SRF linac [7], which comprises a quarter wave resonator (QWR) photoemission electron gun, a QW SRF booster cavity and a normal conducting harmonic cavity to correct RF-induced energy spread. The two SRF structures will be housed in the same cryomodule with a superconducting solenoid in between the cavities. Preliminary optimization of the cavity shape is performed in collaboration with Argonne National Laboratory. Electron beam will be accelerated to the required energy and then transported from the SRF accelerator to the first cooling section in the Blue RHIC ring, cool ions in the first cooling section, turned around between Blue and Yellow RHIC rings (U-turn), cool ions in the Yellow ring and transported to the beam dump, as shown in Fig. 1.

Electron beam will be generated by illuminating a multi-alkali (CsK_2Sb or NaK_2Sb) photocathode with green (532 nm) light from a laser. The photocathode is inserted into a 84.5 MHz quarter-wave SRF cavity thus forming an SRF photoemission electron gun. The photocathode is located in a high electric field. Immediate acceleration of the electrons to a high energy reduces emittance degradation caused by a strong non-linear space-charge force. The low RF frequency of the gun reduces the effect of RF curvature on the beam.

The SRF gun will produce bunch trains (several bunches) with relatively long electron bunches, about 1 ns, at 84.5 MHz bunch repetition frequency. The bunch train repetition rate will be the same as the repetition rate of ion bunches in RHIC. The optical system will allow creating dedicated bunch patterns for different RHIC energies and ion bunch lengths with several bunches at 84.5 MHz frequency followed by a long gap corresponding to the frequency of ion bunches. For example, for very long ion bunches at lowest energies with new 4.5 MHz RHIC RF we can place up to 9 electrons bunches on a single ion bunch (see Fig. 2).

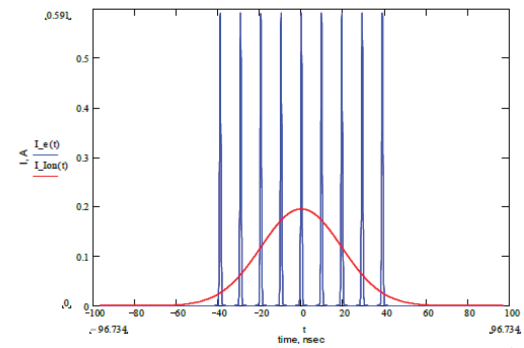

Figure 2: Nine electron bunches (blue) placed on a single ion bunch (red). Example for long ion bunches with proposed 4.5 MHz RHIC RF at $\gamma = 4$, time is in ns.

COOLER PARAMETERS

The requirement on the transverse angles of electron beam in the cooling section is given by the angular spread of the ion beam. For example, for the rms normalized emittance of 2.5 mm-mrad at γ=4.1, and 30 m beta function in the cooling section, the ion beam rms angular spread in the lab frame is 0.14 mrad. The ion beam will have rms longitudinal momentum spread in the range of σ_p=4-5×10^{-4}. This sets requirement on the rms momentum spread of electron beam of < 5×10^{-4}.

To keep the transverse angles of electron beam at an acceptable level (< 0.15 mrad) an integral of residual transverse magnetic field in the space used for cooling should be kept below 1 Gauss·cm (at γ=4). Shielding of residual magnetic field to such a level could be provided by several concentric cylindrical layers of high permeability alloy or by the correction coils.

Some cooling section space is taken up by very short (10 cm) weak (200 G) solenoids (to control angular spread due to the space charge), steering dipoles and beam position monitors to keep the electron and ion beam in close relative alignment. Diagnostics details for the LEReC project can be found in Ref. [8].

Since the electron beam does not have any magnetization, space used by the solenoids will be lost from the cooling process. Longitudinal field of 1 G produces rotational angles of 75 μrad at γ=4. Presently, design of these solenoids, placed every 2 m, is being optimized to maximize the space between them which satisfies requirement on B_z < 1 G. To allow for about 12 meters of effective cooling the full length of the cooling section, including solenoids, is presently 14 m. Basic parameters of electron beam are shown in Table 1 (see [9] for details). The charge per bunch needed depends on the energy at which cooling is applied and which RF system is being used in RHIC. For example, for γ=4 and 4.5 MHz RHIC RF the use of a bunch train allows us to split the total charge of 4 nC required for cooling, into 9 bunches with 0.44 nC per bunch. Although electron bunch occupies a small portion of the ion bunch, all ions could be cooled as a result of the synchrotron oscillations. To provide effective cooling of ions with different amplitudes a slow motion of the electron bunch through the ion bunch ("painting") is desired. With the present scenario of many electron bunches spread through the ion bunch such a painting maybe not necessary.

Table 1: Electron Beam Parameters

Electron Beam Energy	0.9-5 MeV
Charge per Bunch	0.4 –2 nC
Electron Beam Current	20-40 mA
RMS Norm Emittance	< 2.5 mm mrad
Transverse Angles	< 0.15 mrad
RMS Energy Spread	$< 5 \times 10^{-4}$
Bunch Length	750 ps

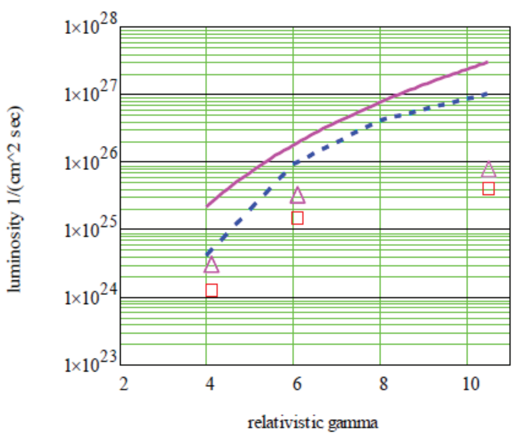

Figure 3: Luminosity in RHIC with and without the electron cooling upgrade. Red squares: measured average per store luminosity in BES-I; magenta triangles: measured maximum luminosity; blue dash line: luminosity with cooling (present RHIC RF); magenta top line: with cooling and long ion bunches (new RF system).

PERFORMANCE WITH COOLING

Projection of potential luminosity improvement as a function of energy is shown in Fig. 3. One can see that close to 10-fold improvement from cooling may be expected only at highest energies if one uses existing 28 MHz RHIC RF system (blue dash line in Fig. 3). At the lowest energies expected luminosity improvement could be rather modest (see [10] for details). A proposed low-frequency RHIC RF system (4.5 or 9 MHz) would allow for longer ion bunches and significant transverse cooling at low energies; the projected performance with this system is shown by the magenta curve in Fig 3. Performance in either scenario may be lower than indicated, due to remaining uncertainties in the beam lifetime improvement from cooling.

CHALLENGES

Successful operation of LEReC cooler requires stable and reliable CW operation of the SRF gun with electron beam current up to 40 mA. A long lifetime of the photocathode inside such a gun with a charge per bunch up to 2 nC is also required. Demonstration of some of the unique and challenging features is being planned with the existing 704 and 112 MHz SRF guns at BNL.

The achievement of very low transverse angular spread for the electron beam is challenging and is being addressed by a proper beam transport and engineering design [9]. The attainment of required low energy spread in the electron bunch relies on shielding of the longitudinal space-charge force with the vacuum chamber, use of long electron bunches and minimization of the length of beam transport. The repeatability of low energy electron transport is challenging due to remnant fields in the optics and hardware. Electron beam with small emittance and energy spread should be provided for several energies of interest. Quality of the beam should be preserved through the entire beam transport since the same beam will be used for cooling in both RHIC rings.

Besides many technical issues, this will be the first electron cooler to cool beams under collisions. This puts special requirements on the control of the ion beam profile under cooling. Careful optimizations between electron cooling and ion beam lifetime will determine how close one can actually get to the projected luminosity improvement.

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