FIRST ELECTRON COOLING OF HADRON BEAMS USING A BUNCHED ELECTRON BEAM *

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Abstract

The Low Energy RHIC electron Cooler (LEReC) was recently commissioned at BNL. The LEReC is the first electron cooler based on RF acceleration of electron bunches (previous electron coolers all used DC beams). Bunched electron beams are necessary for cooling hadron beams at high energies. The challenges of such an approach include generation of electron beams suitable for cooling, delivery of electron beams of the required quality to the cooling sections without degradation of beam emittances and energy spread, achieving the required small angles between electrons and ions in the cooling sections, precise velocity matching between the two beams, high-current operation of the electron accelerator, as well as several physics effects related to bunched beam cooling. Following successful commissioning of the electron accelerator in 2018, the focus of the LEReC project in 2019 was on establishing electron-ion interactions and demonstration of the cooling process. Here we report on the first demonstration of Au ion cooling in RHIC using this new approach.

INTRODUCTION

Electron cooling is a well-established technique for obtaining high-quality ion beams [1]. In this method, the phase-space density of an ion beam is increased by means of dissipative forces – the dynamic friction on individual ions undergoing Coulomb collisions with a lower temperature electron distribution.

Until now, all electron cooling systems used DC electron beams. LEReC is first electron cooler which employs RF acceleration of electron bunches [2]. Such a scheme of cooling with a bunched electron beam is a natural approach for high-energy electron cooling which requires RF acceleration. As such, LEReC is also a prototype for future high-energy electron coolers, both in physics and technology. With acceleration of electron bunches starting inside the gun, beam dynamics and resulting electron beam temperatures are very different from those typically obtained with electrostatic acceleration of DC beams, which is crucial for the electron cooling process. In addition, LEReC is the first electron cooler to cool hadron beams in collisions.

The high-current high-brightness electron accelerator was successfully commissioned in 2018 with all required electron beam parameters demonstrated [3]. During the 2019 RHIC run with Au ions, electron cooling was successfully commissioned for 3.85 GeV ion beam using 1.6 MeV electrons and then for 4.6 GeV ions using 2 MeV electrons.

THE LEReC ACCELERATOR

LEReC is based on state-of-the-art accelerator physics and technology: photocathodes with sophisticated delivery system; a high-power laser beam with laser shaping and stabilization; a high-voltage high-current DC gun; RF gymnastics using several RF cavities; instrumentation, controls and a machine protection system [4-14].

Electron bunches are generated by illuminating a multi-alkali photocathode, inserted into a DC gun with an operating voltage around 400 kV. The 704 MHz fiber laser produces bunch trains with individual electron bunches of about 40 ps full length at ~9 MHz bunch train frequency, which is the same as the repetition rate of ion bunches in RHIC, as illustrated in Fig. 1.

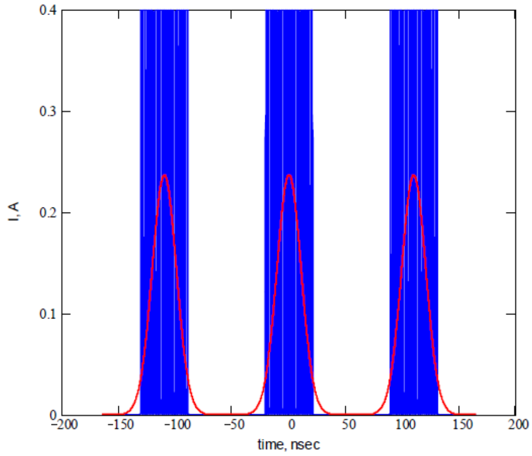

Figure 1: The LEReC beam structure. Thirty electron bunches (blue) spaced by 1.4ns placed on a single ion bunch (red), with ion bunch repetition frequency of 9 MHz.

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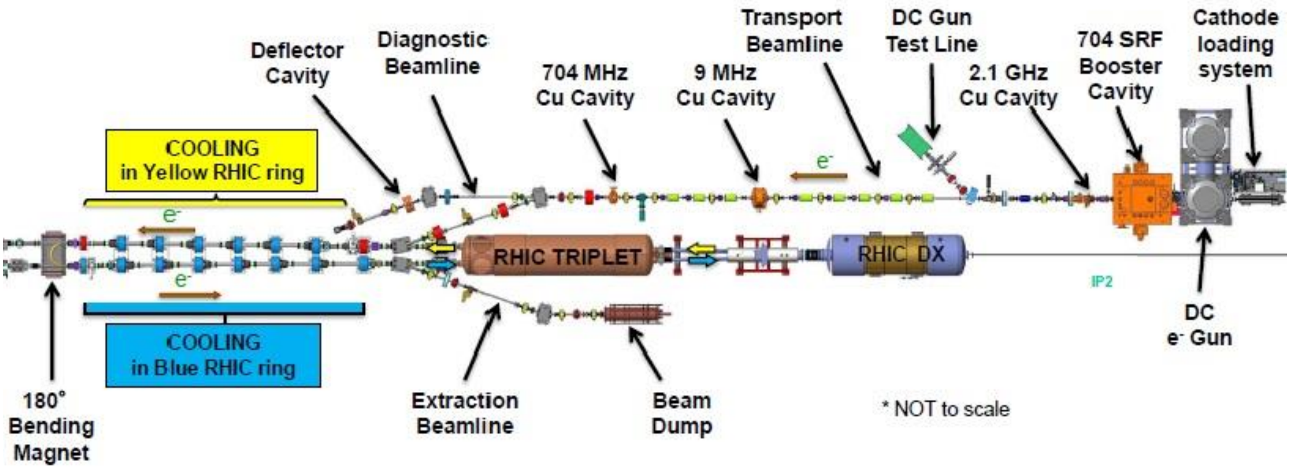

Figure 2: Layout of the LEReC accelerator.

The space-charge beam dynamics during acceleration of bunches inside the gun determines the temperature of the electron beam, which is different from electron beam temperatures obtained during electrostatic acceleration of DC beams in standard coolers. Special care is needed, which in our case was achieved by employing CsK_2Sb photocathodes and laser pulse shaping to generate "cold" electron beams with small longitudinal and transverse temperatures.

Once 375keV electron bunches of desired quality are generated from the gun, they are further accelerated to the required energy by the 704 MHz SRF booster cavity, transported to the first cooling section in the Yellow RHIC ring, used to cool ions, turned around using a 180-degree dipole magnet, used to cool ions in the Blue RHIC ring and transported to the high-power beam dump, as shown in Fig. 2.

To prevent degradation of energy spread due to the longitudinal space charge forces, electron bunches are ballistically stretched by accelerating slightly off-crest in the booster cavity to produce an energy chirp (the correlation between particle position within the bunch and its energy).

Table 1: Design beam parameters in the cooling section.

Electron beam energy, MeV	1.6-2.6
Charge per single bunch, pC	130-200
Number of bunches in macrobunch	30-24
Total charge in macrobunch, nC	3-5
Average current, mA	30-55
RMS normalized emittance, μm	< 2.5
Angular spread, mrad	< 0.15
RMS energy spread	$<5 \times 10^{-4}$
RMS bunch length, cm	3
Length of cooling sections, m	20

A series of normal conducting RF cavities are used to control energy spread within electron bunches at the required level (Table 1). A warm 2.1 GHz cavity (3rd harmonic of the 704 MHz) is used to remove non-linear energy spread introduced by the RF curvature. After bunches are stretched, another 704 MHz warm RF cavity is used to remove the energy chirp. An additional 9 MHz warm RF cavity is employed to remove bunch-by-bunch energy variation within the 30-bunch train (macro-bunch) caused by beam loading in the RF cavities.

ROADMAP TO COOLING

LEReC employs the non-magnetized cooling approach with zero magnetic field on the cathode and in the cooling region [2]. For such a cooling to be effective one needs to have strict control not only of the longitudinal velocity spread of electrons but also of the transverse velocities (both the velocity spread and the average beam velocity).

The low transverse angular spread for the electron beam was achieved by a proper design of the space-charge dominated beam transport and engineering design of the cooling sections [15-16]. The required low energy spread in an electron bunch was obtained by producing a close to uniform longitudinal bunch profile using laser pulse stacking and RF gymnastics. Electron bunches with the required small emittance and energy spread were successfully generated and delivered to the cooling sections [3].

Commissioning of cooling started by operating the electron accelerator at 76 kHz macrobunch frequency, which is the revolution frequency of ions in RHIC at 3.85 GeV. This allowed us to focus on the cooling of a single ion bunch using low average electron current. Also, since the laser beam power in such a mode is low, it was expected that the resulting electron beam parameters should be similar to those measured in the pulsed mode at 1 Hz frequency.

Matching of electron and ion beam average longitudinal velocities was achieved by employing well calibrated 180-degree dipole magnet between the two cooling sections and observing losses caused by a radiative recombination of heavy ions with electrons using a specially developed ion beam lattice with large dispersion at the recombination detector [17-20].

Once the electron and ion beam velocities were matched, longitudinal cooling of Au ion beam in the Yellow RHIC ring was observed on April 5, 2019, as shown in Fig. 3.

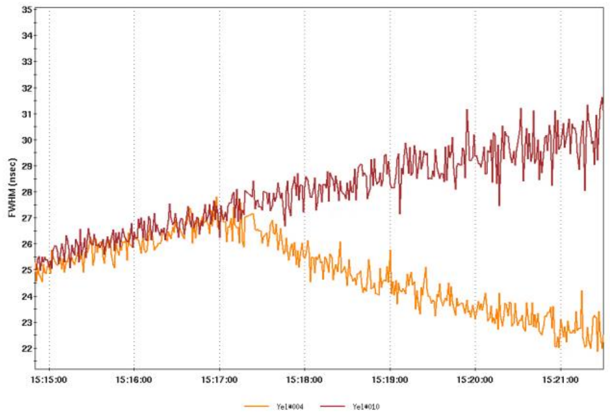

Figure 3: Time evolution of ion bunch length (full-width half maximum, nsec). Uncooled ion bunch – top brown curve (Yel#004). Cooled bunch – low yellow curve (Yel#10). Electron and ion velocities are matched at 15:17.

Shortly after the demonstration of cooling in the longitudinal plane, electron-ion trajectories in the cooling sections were carefully matched which led to the first observation of transverse cooling, measured by a reduction of the transverse emittance. This task is very challenging for the non-magnetized cooling due to strong dependence of the friction force on the transverse angles [2].

After full 6-D cooling of ion bunches was established in the Yellow ring, cooling of ions was also commissioned in the Blue ring, which was quickly followed by simultaneous cooling of ion bunches in both RHIC rings using the same electron beam. The latter task was complicated due to additional focusing of electron beam by ions.

To proceed to cooling of many ion bunches required establishing high-current 9 MHz CW electron beam operation all the way to the high-power beam dump. This task was of special concern since both transverse and longitudinal electron beam parameters were measured only in the pulsed mode bringing a large degree of uncertainty about the beam quality during high-power CW operation. In practice, once high-current CW electron beam was established and energies matched, cooling of several ion bunches simultaneously was observed right away.

Following the cooling demonstration using the 9 MHz CW electron beam, our focus shifted towards operational aspects of cooling in RHIC, which included cooling of full RHIC stores with ion bunches in collisions, thus commissioning first electron cooling in a collider (with beam-beam and other effects impacting ion beam lifetime). An example of such cooling of ion bunches in two RHIC rings undergoing collisions in a detector is shown in Fig. 4.

At the end of the run, cooling was successfully commissioned at 3.85 GeV ion energy using electrons at 1.6 MeV and at 4.6 GeV using 2 MeV electrons.

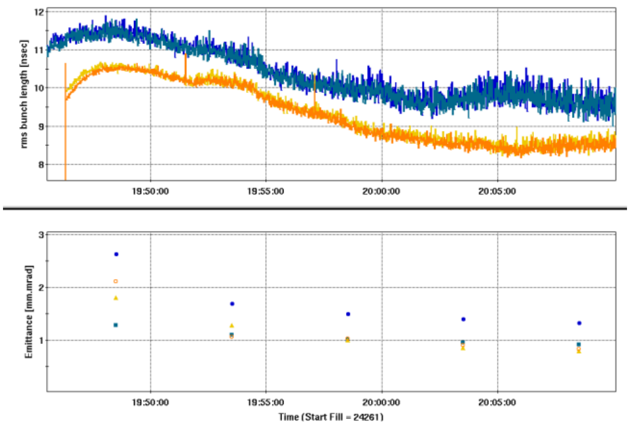

Figure 4: 6-D cooling of a 111x111 bunch RHIC store at 3.85 GeV (1.6 MeV electrons, 15mA 9 MHz CW current). Top plot - reduction of bunch length. Bottom plot - reduction of transverse beam emittances (two rings, two planes).

CHALLENGES

With no magnetic field in the cooling sections, focusing of electrons by ions was significant. Adjusting the electron beam optics to take this into account was challenging.

Using bunched electron beam for cooling at such a low energy led to emittance growth of ions due to modulated focusing from the electrons (called "heating") [21]. Such heating effects were reduced, but not eliminated, by a proper choice of ion beta-function in the cooling section and of a working point. However, to cope with the heating effects, which had strong dependence on electron beam density, we had to operate at electron currents lower than design values. Experimental studies of heating and cooling effects were performed and will be reported elsewhere.

At an energy of 3.85 GeV the ion lifetime in RHIC was limited by several effects besides IBS (which the cooler was designed to counteract) similar to those reported in [22], although with better overall lifetime due to the newly implemented 9 MHz RF system and magnetic hysteresis cycle [23]. Careful optimizations between electron cooling and ion beam lifetime is needed and will determine what luminosity improvement could be achieved for operations.

SUMMARY

The world's first electron cooling based on the RF acceleration of electron bunches was commissioned at BNL. Electron cooling of hadron beams directly in collisions was also demonstrated. Many challenges associated with this new approach were overcome but some remain.

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