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ELECTRON COOLING OF COLLIDING ION BEAMS IN RHIC: STATUS AND PERSPECTIVES*

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Abstract

Electron cooling of ion beams employing a high-energy approach with rf-accelerated electron bunches was recently implemented at BNL using the LEReC accelerator. Following the successful cooling commissioning in 2019, it was used to cool ion beams in both collider rings with ion beams in collision. The electron cooler LEReC successfully operated for the RHIC physics program in 2020 and 2021 and was essential in achieving the required luminosity goals. Apart from its use in RHIC operations, LEReC is used to study various aspects of electron cooling physics using short electron bunches. This report summarizes experience with electron cooling of colliding ion beams in RHIC, as well as ongoing studies.

INTRODUCTION

Electron cooling is a well-established technique for obtaining low-emittance 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 electrons which have lower transverse and longitudinal temperatures.

Electron cooling of ion beams employing a high-energy approach with RF-accelerated electron bunches was recently successfully implemented at BNL [2-6]. Such a scheme of cooling with a bunched electron beam is a natural approach for the extension of electron cooling to high beam energies. As such, the successful demonstration of Low Energy RHIC electron Cooling (LEReC) serves as a prototype for future high-energy electron coolers, both in physics and technology.

The high-current high-brightness electron accelerator was commissioned in 2018 with all required electron beam parameters achieved [3]. During the 2019 RHIC run with Au ions, electron cooling was commissioned for 3.85 GeV/nucleon total energy gold beams using electrons with a kinetic energy of 1.6 MeV and then for 4.6 GeV/nucleon gold beams using 2 MeV electrons. At the same time, the first electron cooling of hadron beams in collisions was also successfully demonstrated [2]. Electron cooling of colliding gold beams became fully operational during the 2020 RHIC physics run. It successfully operated in 2020 and 2021 for the RHIC Beam Energy Scan II physics program in search of a QCD critical point on the phase diagram and was essential in achieving the required luminosity goals [7].

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THE LEReC ACCELERATOR

LEReC is based on state-of-the-art accelerator physics and technology: reproducibly high quantum efficiency photocathodes with a sophisticated delivery system which can hold up to 12 cathodes simultaneously (specifically designed to support long-term operation with up to one cathode exchange per day); 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 (see, for example, Ref. [3] and references therein).

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 matches the repetition rate of ion bunches in RHIC. For RHIC operations, 30-36 electron bunches per bunch train were used.

Once electron bunches of the 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 the ions in that ring, 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. Figure 1 shows layout of the LEReC accelerator.

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

A series of normal conducting RF cavities are used to reduce the energy spread within electron bunches to the required level. A warm 2.1 GHz cavity (3rd harmonic of the 704 MHz) is used to remove the non-linear energy spread introduced by the RF curvature. For operation with longer electron bunches in 2021, an additional 1.4 GHz cavity (2nd harmonic of the 704 MHz) was successfully employed. After the 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 variations within the bunch train (macro-bunch) caused by beam loading in the RF cavities.

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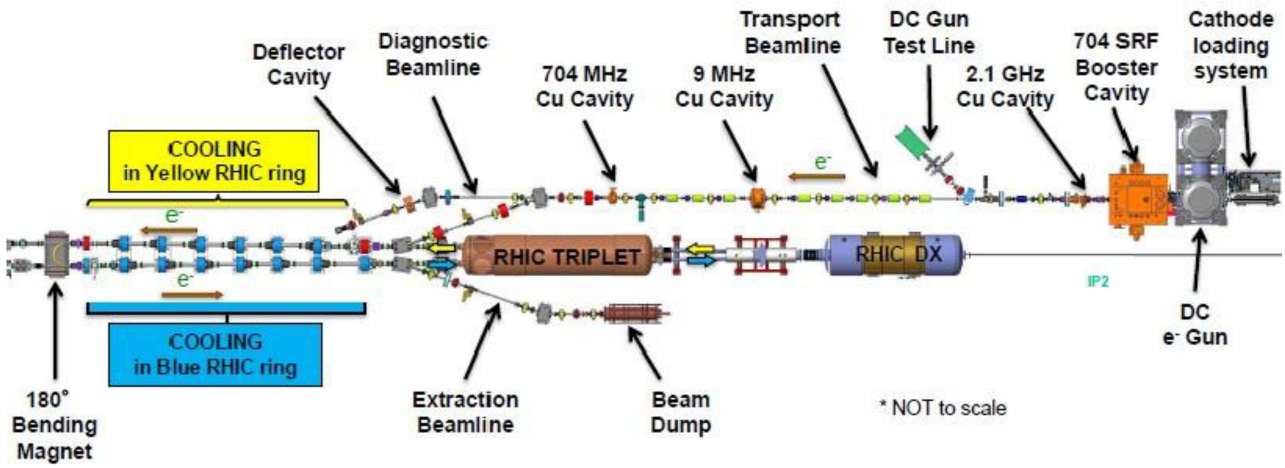

Figure 1: Layout of the LEReC accelerator.

SPECIAL DESIGN FEATURES

Unlike in any previous coolers, the LEReC cathode is not immersed in a magnetic field and no continuous magnetic field with precise solenoids is required in the cooling regions. This significantly simplifies the technical design. However, the requirements for the electron beam quality become more demanding since one needs to have tight control of the transverse electron velocities.

The space-charge beam dynamics during the acceleration of the bunches inside the gun determines the temperature of the electron beam, which is very different from the electron beam temperatures typically obtained during electrostatic acceleration of dc beams in standard coolers. For LEReC, a CsK_2Sb photocathode and laser pulse shaping are used to generate "cold" electron beams with small longitudinal and transverse temperatures.

The low transverse angular spread for the electron beam was achieved by a proper design of the space-charge dominated beam transport and the engineering design of the cooling sections, shown in Fig. 2.

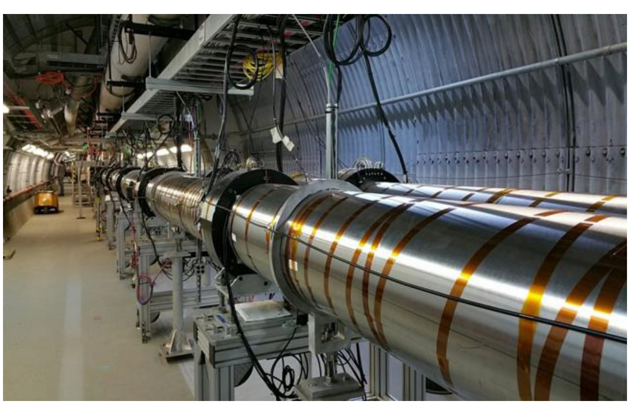

Figure 2: LEReC cooling sections in the Yellow and Blue RHIC Rings.

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. Measurements made using a transverse mode deflecting cavity showed that a relative energy spread of less than 2×10^{-4} corresponding to an absolute energy spread of 400 eV was achieved for the 2 MeV electron beam.

In the LEReC approach an individual electron bunch occupies only a small portion of the ion bunch and only selected ions experience the friction force during a passage through the cooling section. However, as a result of the synchrotron motion of ions, on successive passages all ions experience interactions with electrons and are cooled with characteristic times larger than the synchrotron period.

One more innovation is that the electron beam, after cooling ions in one RHIC ring, is used again to cool the ions in the other RHIC ring. This is also the first implementation of electron cooling for colliding ion beams. The latter is also of importance in the context of using electron cooling in future high-energy colliders.

ROADMAP TO COOLING IN A COLLIDER

The matching of electron and ion beam average longitudinal velocities was achieved by employing a well-calibrated 180-degree dipole spectrometer magnet between the two cooling sections and by observing losses caused by a radiative recombination of heavy ions with electrons [4]. Once the electron and ion beam velocities were matched, longitudinal cooling of Au ion beam was observed on April 5, 2019.

Shortly after the demonstration of cooling in the longitudinal plane, the electron-ion trajectories in the cooling sections were carefully matched transversely. This led to the first observation of transverse cooling, seen as a reduction of the transverse beam sizes.

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

Following the cooling demonstration of all ion bunches in both RHIC rings using the 9 MHz CW electron beam,

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the focus shifted next towards operational aspects of cooling in RHIC, thus commissioning first electron cooling in a collider.

Cooling was successfully commissioned at 3.85 and 4.6 GeV/nucleon ion beam energies using electrons with kinetic energies of 1.6 and 2 MeV, respectively. An example of cooled ion bunches in two RHIC rings undergoing collisions during normal physics operation is shown in Fig. 3. In the absence of cooling both the transverse and longitudinal beam sizes are increasing due to a diffusion process called intrabeam scattering.

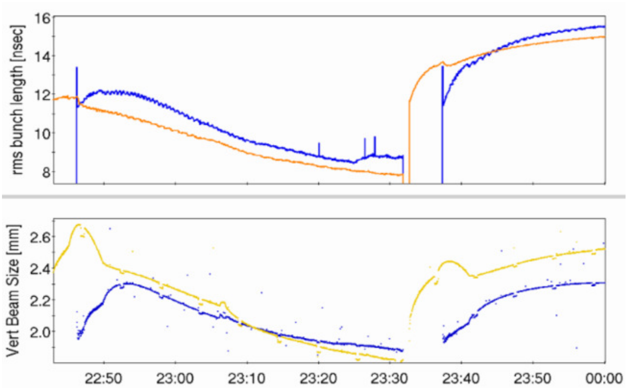

Figure 3: RHIC physics stores with Au ions at 4.6 GeV/nucleon using 2 MeV electrons. First store: with cooling, second store: without cooling. Top plot – rms bunch length of ion bunches in the Yellow and Blue RHIC rings; Bottom plot - rms vertical size of ion bunches.

OPERATIONAL EXPERIENCE

During the 2020 RHIC physics run electron cooling became fully operational; stable 24/7 running of high-current electron accelerator and robust cooling was provided over many months. Reliable long-term operation was ensured by implementation of laser position feedbacks [8, 9], intensity feedback, energy feedback, automatic cooling section orbit correction and orbit feedback. Robust cathode production and a transporter system (holding up to 12 cathodes) were fully operational, and delivered high quality cathodes [10]. The initial cathode quantum efficiency was routinely around 8% with a lifetime of about 10 days (determined by the gun vacuum pressure). This allowed for stable long-term operation with only a short access to the RHIC tunnel (on scheduled maintenance days) once every few weeks to exchange cathodes.

The electron current, which was selected based on optimization between cooling and effects on luminosity, was 15-20 mA (for operation with Au at 4.6 GeV/nucleon in 2020) and 8-20 mA (for operation with Au at 3.85 GeV/nucleon in 2021). Typical electron beam emittances used in operations were < 2 µm (rms, normalized) and the relative rms energy spread of electron bunches < 4x10^{-4}. Matching of average longitudinal velocities between electrons and ions was maintained at < 1x10^{-4} (using longitudinal cooling process), with energy regulation at the 1x10^{-4} level. The cooling performance during typical physics stores at 4.6 GeV/nucleon is shown in Fig. 4.

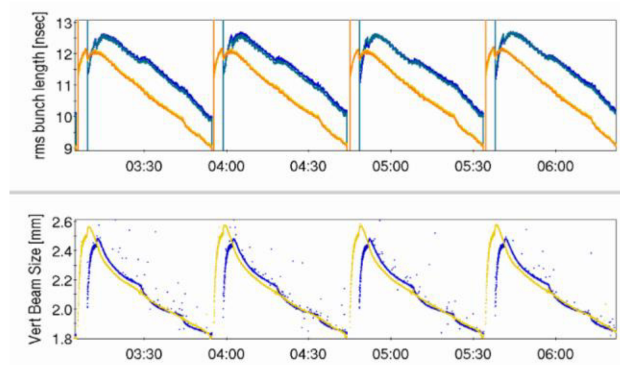

Figure 4: RHIC physics stores with Au ions at 4.6 GeV/nucleon using 2 MeV electrons. Top plot – rms bunch length of ion bunches in the Yellow and Blue RHIC rings; Bottom plot - rms vertical size of ion bunches.

The positive effect of cooling on the event rate, illustrated in Fig. 5 (typical physics stores from the 2020 physics run with Au ions at 4.6 GeV/nucleon), is a part of multi-parametric optimization of RHIC operations. Among other aspects, this includes the fine-tuning of the RHIC rings working point, the lengthened cooled stores due to a slower decay in the event rate, an ability to perform a beta-squeeze of the cooled stores (in the shown example it takes place at 900 s into the cooled store), and a reduced detector background due to the longitudinal cooling eliminating the ion debunching. For details of RHIC operation with cooling see Ref. [7].

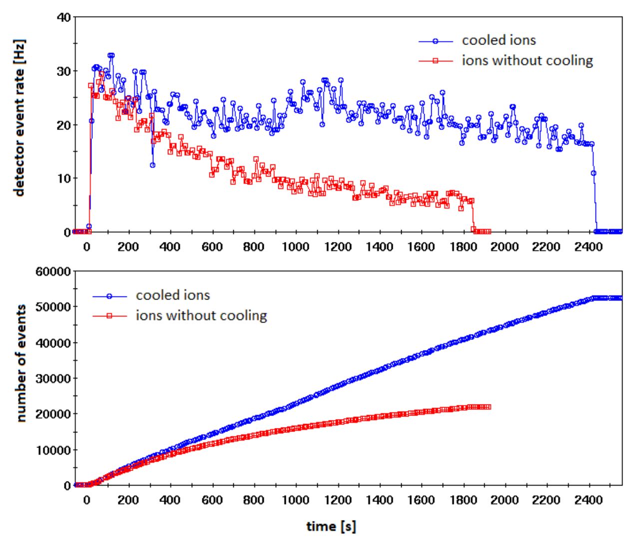

Figure 5: RHIC STAR detector event rate (top plot) and number of accumulated events per physics store (bottom plot) for cooled (blue line) and not cooled (red line) stores.

Cooling performance in 2021, during typical physics stores with Au ions at 3.85 GeV/nucleon, is shown in Figure 6. The jumps in the bunch length during physics stores reflect an additional RF manipulation for ion beams during the beta-squeeze to alleviate space-charge effects.

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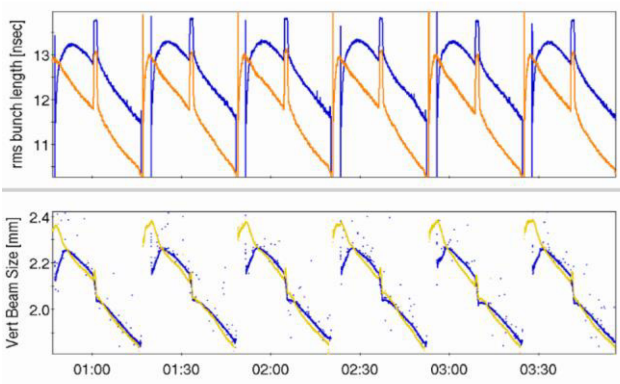

Figure 6: RHIC physics stores with Au ions at 3.85 GeV/nucleon using 1.6 MeV electrons. Top plot – rms bunch length of ion bunches in the Yellow and Blue RHIC rings; Bottom plot - rms vertical size of ion bunches.

LUMINOSITY OPTIMIZATION WITH COOLING AND CHALLENGES

Application of electron cooling directly at the collision energy of the hadron beams brings several challenges and requires special optimizations. For example, control of the ion beam distribution under cooling to not overcool the beam core and control of the ion bunch peak current, especially when ion beam space charge is significant. The interplay of ion beam space-charge and beam-beam effects requires finding the best collider settings, including working point on the tune diagram, which then has to be reconciled with the presence of the electron beam. The dominant effect for collider performance becomes luminosity lifetime in the presence of the electron beam. The final optimization of cooling has to be performed during operational conditions for physics, optimizing various effects with a goal to maximize the integrated luminosity, rather than maximizing the cooling process by itself.

During physics operation in 2020 and 2021 electron cooling effectively counteracted emittance and bunch length growth due to the intrabeam scattering. In addition, the electron beam angles in the cooling section were optimized to provide transverse cooling thus reducing the ion beam sizes. Once the transverse beam sizes were cooled to small values, the dynamic squeeze of ion beta-function at the collision point was established. Providing transverse cooling appeared to be more beneficial for collider operations compared to the longitudinal cooling, which led to higher peak currents of ions, affecting the ion beam's lifetime due to the space-charge effects of ion beams.

An increase of the ion bunch intensity allowed to boost the initial luminosity significantly. However, high ion beam intensities resulted in stronger focusing of the electrons, and resulted in reduced cooling during the initial part of the physics store.

Using many short electron bunches to cool a long ion bunch at such a low energy can lead to emittance growth of ions, which we called "heating". Several models were developed which predicted such emittance growth (see for example Ref. [11] and references therein) caused by the space-charge interactions with electron bunches. Subsequently, more models were developed to reconcile theory with observations. Systematic measurements of heating rates were reported in [12], while an exact mechanism behind the observed emittance growth is still being explored. During operation in 2021, the newly implemented 1.4 GHz RF cavity was successfully used to lengthen electron bunches which helped reducing the heating effect. It is important to note that this additional diffusion mechanism (heating) was counteracted by cooling and was not a limiting factor for collider operation with cooling. However, in addition to this heating mechanism, the presence of the electron beam affected the lifetime of the ions. The mechanism behind the latter effect is presently under study. The stronger the electron current the stronger the lifetime of the ions was impacted. As a result, an increase in the electron beam current, with resulting stronger longitudinal and transverse cooling, was not necessarily the best way to increase the luminosity. Scans of the electron beam current were regularly conducted, and, depending on the collider working point in the tune space and other settings, optimized electron current values were chosen to maximize the luminosity. For example, for a working point just below the ¼ tunes, the effect on ion beams lifetime was less pronounced allowing for a higher optimum electron current of around 20 mA. On the other hand, for a working point closer to 0.1, the effect on the ion beam lifetime from the electrons was stronger requiring a reduction of the electron current, at the expense of cooling performance.

In addition, with average velocities of the electrons and ions well matched, losses of the ions due to radiative recombination were noticeable. Suppression of losses on recombination in electron coolers without continuous longitudinal magnetic field was considered in the past [13]. However, such suppression was not implemented in LEReC since the predicted losses were relatively low. In operations, losses due to recombination were partially reduced by introducing a small velocity offset between electrons and ions.

Despite some challenges of cooling optimization for ion beams in collisions, cooling was beneficial for collider operations and helped to achieve the physics goals [7]. This experience with first application of electron cooling for colliding beams allows us to explore various effects and limitations. Some of these observations were already explored using computer simulations [14]. Dedicated study of other effects, found during operations, are presently underway, and the knowledge gained will be applicable to the design of high-energy coolers.

ONGOING COOLING STUDIES

Apart from its use in RHIC operations, LEReC offers a unique opportunity to study various aspects of electron cooling using short electron bunches, as well as effects relevant to the ion beam lifetime in a collider in the presence of electron cooling. The following dedicated studies started in 2021 using Accelerator Physics Experiments (APEX) program at RHIC: 1) emittance growth of ion beam due to

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interaction with electrons [12]; 2) coherent excitations and circular attractors in cooled ion bunches [15]; 3) recombination of ions due to interactions with electrons in the cooling section without continuous magnetic field; 4) cooling of ion bunches with electrons overlapping only small portion of an ion bunch; 5) dispersive cooling (redistribution of cooling decrements) to provide stronger transverse cooling at the expense of the longitudinal cooling; 6) effects of the presence of an electron beam on ion beam lifetime.

A detailed experimental exploration of the effects above is critical for a proper design of high-energy coolers, including those proposed for the Electron Ion Collider (EIC).

HIGH-ENERGY COOLING APPLICATIONS

A successful demonstration of cooling using LEReC approach allows us to consider similar technique for higher energies. This was done, for example, in a recent feasibility study of electron cooling applications for the EIC.

To obtain a small vertical emittance of protons, cooling can be performed at the relatively low proton energy of 24 GeV using 13 MeV electrons. The same electron accelerator can be used to cool protons at 41 GeV using 22 MeV electrons. A feasibility study of such an electron cooler is reported in [16].

Extending the LEReC approach to even higher electrons energy of 150 MeV, which is needed to cool protons at 275 GeV in the EIC, is not practical due to the high current requirement for such an electron accelerator. Instead, for a 150 MeV electron cooler, one can use electron storage ring approach. With such a ring-based electron cooler, electrons would cool protons, while the electron beam parameters required for cooling could be maintained via radiation damping provided by wigglers installed in one of the sections of an electron ring. A feasibility study of ring-based electron cooler, which employs non-magnetized cooling (similarly to LEReC) and uses the ions and electrons dispersion in the cooling section to redistribute cooling decrements, is reported in Ref. [17].

Ongoing experimental studies of various cooling effects using LEReC are aimed to assist with high-energy cooler designs described above.

SUMMARY

Electron cooling of ion beams employing a high-energy approach with RF-accelerated electron bunches was recently implemented at BNL. It was successfully used to cool ion beams in both collider rings with ion beams in collision during RHIC operation in 2020 and 2021. Robust and stable cooling was maintained over many months of collider operation.

LEReC operations for RHIC physics program concluded in 2021. The focus now is shifted towards studies of various aspects of cooling process using short electron bunches and high-current electron accelerator R&D.

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