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EXPERIENCE AND CHALLENGES WITH ELECTRON COOLING OF COLLIDING ION BEAMS IN RHIC*

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Abstract

Electron cooling of ion beams employing rf-accelerated electron bunches was successfully used for the RHIC physics program in 2020 and 2021 and was essential in achieving the required luminosity goals. This presentation will summarize experience with electron cooling of colliding ion beams in RHIC, including various challenges. We also outline ongoing studies using rf-based electron cooler LEReC.

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 a lower temperature electron distribution.

Electron cooling of ion beams employing a high-energy approach with RF-accelerated electron bunches was recently successfully implemented at BNL [2-6]. During the 2019 RHIC run with Au ions, electron cooling was commissioned for 3.85 GeV/nucleon 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. 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 phys-ics program in search of the QCD critical point on the phase diagram and was essential in achieving the required luminosity goals [7, 8].

THE LEReC ACCELERATOR

LEReC is based on state-of-the-art accelerator physics and technology: reproducibly high quantum efficiency photocathodes with a sophisticated delivery systems which can hold up to 12 cathodes simultaneously (specifically designed to support long-term operation); 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 CsK_2Sb photocathode, inserted into a DC gun with an operating voltage around 400 kV. A 704 MHz fiber laser is modulated to produce optical macro-bunches (~30 pulses per bunch) at 9 MHz frequency, which matches the repetition rate of ion bunches in RHIC. The resulting macro-bunch of electrons consisting of 30 individual electron bunches is synchronized with each individual ion bunch, as illustrated in Fig. 1.

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.

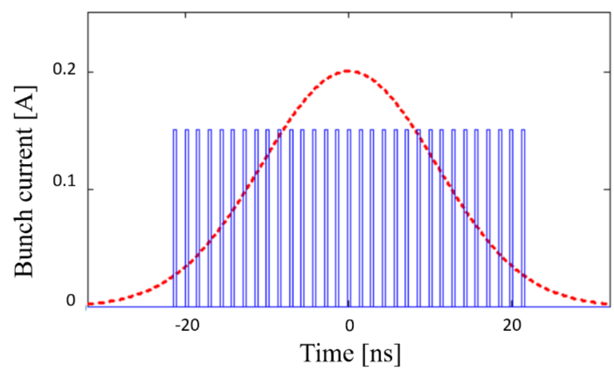

Figure 1: The LEReC beam structure. Thirty electron bunches (blue) spaced by 1.4 ns placed on a single ion bunch (red), with ion bunch repetition frequency of 9 MHz.

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 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. Figure 2 shows layout of the LEReC accelerator.

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.

One more feature of LEReC 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 of crucial importance in the context of using electron cooling in future high-energy colliders.

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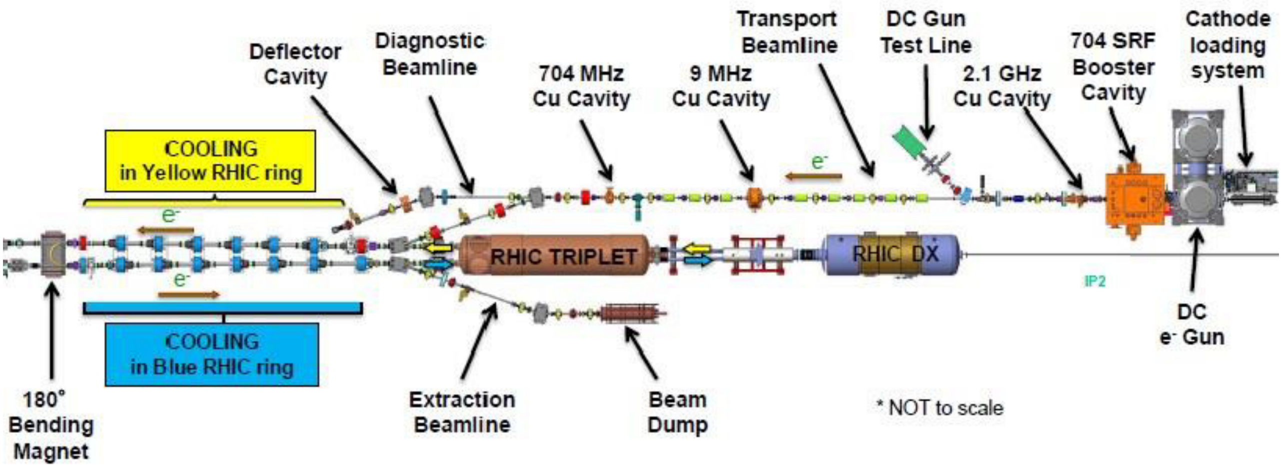

Figure 2: Layout of the LEReC accelerator.

OPERATIONAL EXPERIENCE

Stable 24/7 running of high-current electron accelerator and robust cooling was provided over many weeks of collider operation during 2020 and 2021 RHIC physics runs. Reliable long-term operation was ensured by implementation of laser position feedbacks [9, 10], intensity feedback, energy feedback, automatic cooling section orbit correction and orbit feedback. Robust cathode production and transporter (which allows to hold up to 12 cathodes simultaneously) systems were fully operational, delivering high quality CsK_2Sb cathodes [11]. The initial cathode quantum efficiency was routinely around 8% with a lifetime, driven by vacuum conditions inside the gun, of about 10 days. This allowed for stable long-term operation with only a short access to the RHIC tunnel 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 relative rms energy spread of electron bunches $< 4\times10^{-4}$. Matching of average longitudinal velocities between electrons and ions was maintained at $< 1\times10^{-4}$ (using longitudinal cooling process), with energy regulation at the 1×10^{-4} level. Cooling performance during typical physics stores at 4.6 GeV/nucleon is shown in Figure 3.

As designed, electron cooling effectively counteracted emittance and bunch length growth due to the intrabeam scattering. In addition, transverse cooling was optimized to further reduce the ion beam sizes. Once the transverse beam sizes were cooled to smaller values, the dynamic squeeze of ion beta-function at the collision point was established.

Luminosity optimization with cooling included 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. The positive effect of cooling on the event rate is reported in [7, 8].

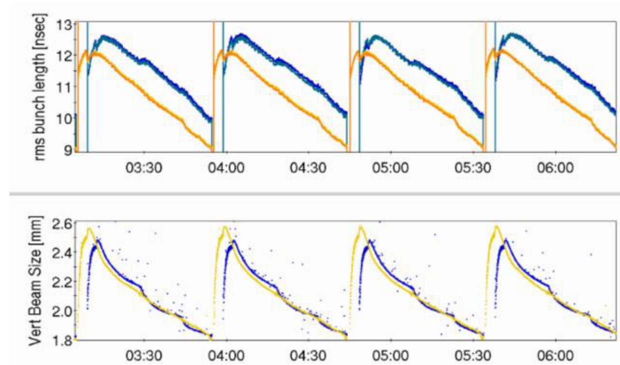

Figure 3: RHIC physics stores with Au ions at 4.6 GeV/nucleon using 2 MeV electrons. Top plot – rms bunch length of ion bunches in the Yellow and Blue RHIC rings; Bottom plot - rms vertical size of ion bunches.

CHALLENGES

Application of electron cooling directly at the collision energy of the hadron beams brings several challenges which requires special optimizations. Of special concern is control of the ion beam distribution under cooling in order not to overcool the beam core. LEReC design choice of non-magnetized cooling allowed us to choose rms velocity spreads of the electrons close to those of the ion beam. As a result, most of the ions experienced linear part of the friction force without overcooling of ion beam distribution.

Providing transverse cooling appeared to be more beneficial for collider operations compared to the longitudinal cooling. This is because longitudinal cooling led to higher peak currents of ions, affecting the ion beam's lifetime due to the space-charge effects.

Several challenges which required special consideration are summarized below.

Overfocusing by Ion Beam

LEReC was designed without continuous longitudinal magnetic field in the cooling section, making it technically simple. However, without magnetic field, electron bunches were subject to the space-charge focusing from ions, resulting in larger electron angles which led to reduced cooling.

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The effect was further amplified because different electron bunches experienced different focusing along the longitudinal profile of the ion bunch. In addition, because intensities of ion bunches were increased in operations beyond those anticipated during the cooler design stage, the overfocusing was especially strong at the start of a physics store, with cooling becoming beneficial only after some intensity drop.

Multiple Use of Electron Beam for Cooling

One of the special features of LEReC is that the same electron beam, after cooling ions in one RHIC ring, is used again to cool ions in the other RHIC ring. To provide effective cooling in the second collider ring, electron beam optics had to account for focusing from the ions on the electrons in the first cooling section.

Diffusion and Heating

Using bunched electron beam for cooling at 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. [12] and references therein). Subsequently, more models were developed to get better agreement with experimental observations. Systematic measurements of emittance growth rates and their dependences on various parameters were conducted [13]. During operation at the lowest energy when space-charge effects from the electrons were most important, the second harmonic 1.4 GHz RF cavity was successfully used to lengthen electron bunches which helped to reduce the heating effect. It is important to note that this additional diffusion mechanism (heating) was easily counteracted by cooling and was not a limiting factor for collider operation with cooling.

Losses on Recombination

During cooling process, 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 [14]. However, such suppression was not implemented in LEReC because the losses predicted were relatively low. In operations, losses due to the recombination were partially reduced by introducing small velocity offset between electrons and ions.

Lifetime in the Presence of Electron Beam

Even with good 6D cooling, lifetime of ions was impacted by the electrons. The mechanism behind this effect is under study. Possibly, this is because ions experienced significant non-linear beam-beam force from the electrons.

The higher the electron current the stronger the lifetime of the ions was impacted. As a result, increasing electron beam current, with resulting stronger longitudinal and transverse cooling, was not necessarily the best way to increase the luminosity. This effect also depended on the collider rings working points in the tune space. For example, for the working point just below the quarter-integer tunes, the effect on ion beams lifetime from electrons was less pronounced allowing for a higher optimum electron current of around 20 mA. However, with large space-charge tune spreads of the ion beam this working point was less favourable for the ions due to the crossing of several resonances. On the other hand, for a working point closer to an integer, which worked best for the ion beams in the absence of the electrons, the effect on the ion's lifetime from the electrons was stronger which required reduction of electron current to around 10-15 mA, with reduced cooling performance.

Overall, in operational conditions, the non-linear resonances and the lifetime of colliding ion beams were the main limitations in finding optimum operational settings for three beams simultaneously: two colliding ion beams plus an electron beam, with an additional beam-beam effect from the electrons.

Despite many challenges of cooling optimization for ion beams in collisions, cooling was beneficial for collider operations and helped to achieve required physics goals [8]. This experience with electron cooling of colliding beams allows us to explore various challenges and limitations.

ONGOING COOLING STUDIES

Rf-based electron cooler LEReC offers a unique opportunity to study various aspects of cooling using short electron bunches. The following dedicated studies started in 2021 using Accelerator Physics Experiments (APEX) program at RHIC: 1) emittance growth of ion beam due to interaction with electrons [13]; 2) coherent excitations and circular attractors in cooled ion bunches [15, 16]; 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 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 [17, 18] proposed for the Electron Ion Collider (EIC).

SUMMARY

Electron cooling of gold ion beams employing RF-accelerated electron bunches was successfully used to cool ion beams in both collider rings during RHIC operation in 2020 and 2021. Despite many challenges of cooling optimization for colliding ion beams, cooling was beneficial for collider operations.

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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