Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches

A. V. Fedotov *et al.*

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Experimental demonstration of hadron beam cooling using RF accelerated electron bunches

A.V. Fedotov *, Z. Altinbas, S. Belomestnykh †, I. Ben-Zvi, M. Blaskiewicz, M. Brennan, D. Bruno, C. Brutus, M. Costanzo, A. Drees, W. Fischer, J. Fite, M. Gaowei, D. Gassner, X. Gu, J. Halinski, K. Hamdi, L. Hammons, M. Harvey, T. Hayes, R. Hulsart, P. Inacker, J. Jamilkowski, Y. Jing, J. Kewisch, P. Kankiya, D. Kayran, R. Lehn, C.J. Liaw, V. Litvinenko, C. Liu, J. Ma, G. Mahler, M. Mapes, A. Marusic, K. Mernick, C. Mi, R. Michnoff, T. Miller, M. Minty, G. Narayan, S. Nayak, L. Nguyen, M. Paniccia, I. Pinayev, S. Polizzo, V. Ptitsyn, T. Rao, G. Robert-Demolaize, T. Roser, J. Sandberg, V. Schoefer, C. Schultheiss, S. Seletskiy, F. Severino, T. Shrey, L. Smart, K. Smith, H. Song, A. Sukhanov, R. Than, P. Thieberger, S. Trabocchi, J. Tuozzolo, P. Wanderer, E. Wang, G. Wang, D. Weiss, B. Xiao, T. Xin, W. Xu, A. Zaltsman, H. Zhao, Z. Zhao
Brookhaven National Laboratory, Upton, NY 11973, USA
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Cooling of beams of gold ions using electron bunches accelerated with radio-frequency (RF) systems was recently experimentally demonstrated in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Such an approach is new and opens the possibility of using this technique at higher energies than possible with electrostatic acceleration of electron beams. The challenges of this approach include generation of electron beams suitable for cooling, delivery of electron bunches of the required quality to the cooling sections without degradation of beam angular divergence and energy spread, achieving the required small angles between electron and ion trajectories 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. Here we report on the first demonstration of cooling hadron beams using this new approach.

In the last few decades, advances in accelerator physics provided high-quality beams for various physics experiments and discoveries. For heavy-particle beams where there is no significant radiation damping, several approaches to increasing phase-space density were developed, such as electron [1] and stochastic [2] cooling. The cooling refers to the reduction of the phase-space volume (emittance) of stored beam leading to a beam of smaller momentum spread, low divergence and small cross-sectional area. For electron cooling, invented by Budker [1], an electron beam has to move with the same average velocity as the heavy-particle beam. In the beam comoving frame, with velocity spread of the electrons and heavy-particles of the same order, their temperature (mean kinetic energy) is proportional to their masses. As a result of Coulomb interactions, the heavy-particle beam, which has higher temperature, will be cooled by electrons which have low transverse and longitudinal temperatures.

Until now, all electron cooling systems in operation employed electrostatic acceleration of electrons using direct-current (DC) electron beams [3]. Although such an approach was successfully extended to 4.3 MeV electron energy at FNAL [4], its application to much higher energies becomes less practical. With hadron beam to be cooled and electron beam energies related by the ratio of their masses, to cool protons at 100 GeV would require electrons at 54 MeV energy, for example [5]. A natural approach of accelerating electron bunches to high energies is RF acceleration. The Low Energy RHIC electron Cooler (LEReC) is the first electron cooler based on RF acceleration of electron bunches [6, 7]. With this approach now experimentally demonstrated, one can consider its application to much higher energies opening new possibilities by producing high-quality hadron beams.

For an RF approach, bunches of electrons are produced right at the gun cathode. The resulting beam dynamics and electron beam characteristics are very different from those typically obtained with electrostatic acceleration of DC beams, which is of critical importance for the electron cooling process. It is necessary to generate high-brightness electron beam with small angular divergence and momentum spread and then accelerate it to the required energy preserving beam quality. Production of such an electron beam, its transport and cooling of ion bunches using bunches of electrons included several innovations and proofs-of-principle. Also, for the first time, after cooling ions in one RHIC ring, the same electron beam was successfully used one more time, to cool ions in the other RHIC ring. In addition, while stochastic cooling was successfully implemented in RHIC [8], this is the first implementation of an electron cooling technique to cool ion beams in collision. The latter is of crucial importance with electron cooling being considered for future high-energy colliders [5, 9].

A high-current high-brightness electron accelerator (layout shown in Fig. 1) was successfully commissioned in 2018 [7]. In 2019 cooling of Au ions was commissioned using electron beams with kinetic energy of 1.6 MeV to cool ions at 3.85 GeV/nucleon total energy and then using 2 MeV electron beams to cool ions at 4.6 GeV/nucleon.

*fedotov@bnl.gov
†Presently at Fermi National Laboratory

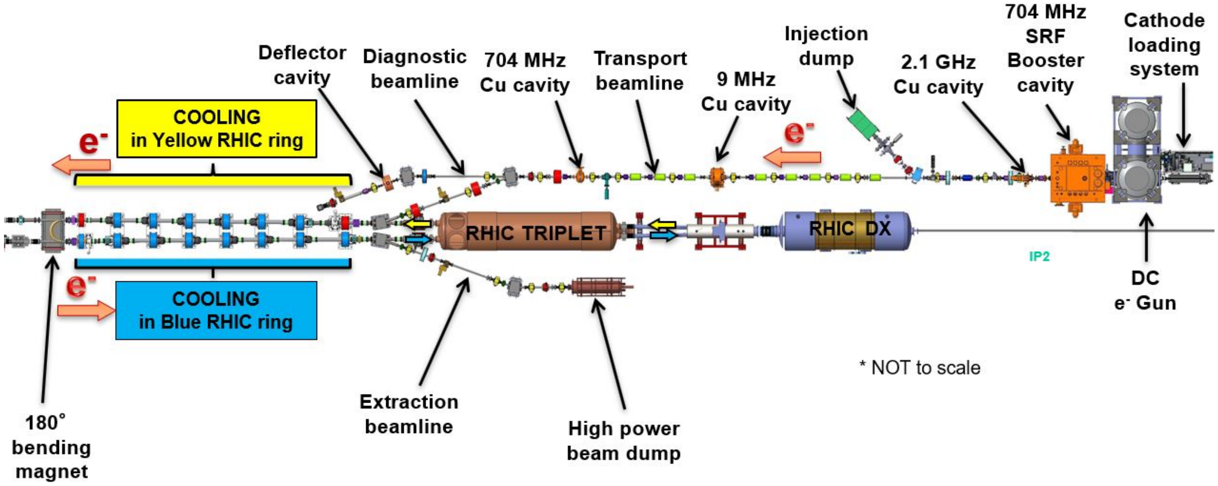

FIG. 1: Layout of the LEReC accelerator (not to scale).

With no magnetic field, the friction force on an ion inside a uniform density electron gas with a velocity distribution function f(v_e) is given by [10, 11]:

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m_e} \int L_c \frac{\vec{V}_i - \vec{v}_e}{|\vec{V}_i - \vec{v}_e|^3} f(v_e) d^3 v_e, \qquad (1)$$

where Z is the charge state of the ion, e the electron charge, n_e the electron density in the beam frame, m_e the electron mass, $\vec{V}_i$ and $\vec{v}_e$ are the ion and electron velocities in the beam frame, and $L_c = \ln(\rho_{max}/\rho_{min})$ is the Coulomb logarithm where ρ_{max} and ρ_{min} are the maximum and minimum impact parameters, respectively.

In typical coolers, the presence of a longitudinal magnetic field in the cooling section changes the collision kinetics, because it limits the transverse motion of electrons, which allows to relax requirements on the transverse velocities of electrons. Unlike in any previous coolers [3, 4], LEReC uses zero magnetic field on the cathode and, as a result, does not require the use of precise solenoids in the cooling regions. This significantly simplifies the technical design. However, requirements on the electron beam quality become more demanding since one needs to have tight control of the transverse electron velocities.

To maximize the cooling power and to preserve transverse ion distribution under cooling [5], important for colliding beams, the electron beam rms velocity spreads are chosen close to those of the ion beam [6]. With a relative longitudinal momentum spread of ions of 5×10^{-4} rms, the requirement for the rms momentum spread of electron beam is also $\approx 5 \times 10^{-4}$. With transverse rms angular spread of ions in the cooling section around 0.15 mrad, the requirement on the electron beam angular spread in the cooling section is $\approx$ 0.15 mrad as well. The design parameters of the required electron beam quality in the cooling sections are summarized in Table I.

TABLE I: Design parameters of electron beam in the cooling sections.

Electron beam energy	1.6-2.6 MeV
Length of cooling sections	20 m
Charge per single bunch	130-200 pC
Total charge in macrobunch	4-6 nC
Average current	36-55 mA
rms normalized emittance	<2.5 μm
Angular spread	<0.15 mrad
rms energy spread	$<5 \times 10^{-4}$
rms bunch length	3 cm

To maintain the transverse angle deviation of the electron beam trajectory < 0.15 mrad, the integral of residual transverse magnetic field in the cooling region must be kept below 1 μT·m. A shielding of the residual magnetic field to such level was achieved using two concentric cylindrical layers of high permeability alloy [12].

Electron bunches are generated by illuminating a multi-alkali photocathode, inserted into a high-voltage gun with an operating voltage around 400 kV. A 704 MHz high-power fiber laser [13] is modulated via an ultrafast electro-optic modulator to produce 9 MHz optical macro-bunches ($\sim$ 30 pulses per bunch). The modulation frequency is the same as the repetition rate of ion bunches in RHIC, and the duration of the optical pulse is increased from 2.1 ps to 40 ps using a pulse stacking technique. The resulting macro-bunch of electrons consisting of 30 individual electron bunches with each bunch stretched to 400 ps is synchronized with each individual ion bunch, as illustrated in Fig. 2. The use of such macro-bunches allows us to split the total charge of 4 nC, for example, into 30 bunches with 0.13 nC per bunch. Although an individual electron bunch occupies a small portion of the ion bunch and only selected ions experience the friction force on a single pass through the electron beam, as a result of the synchrotron motion of ions in an accelerator all ions experience interaction with electrons during their synchrotron period and are being cooled with characteristic times larger than the synchrotron period.

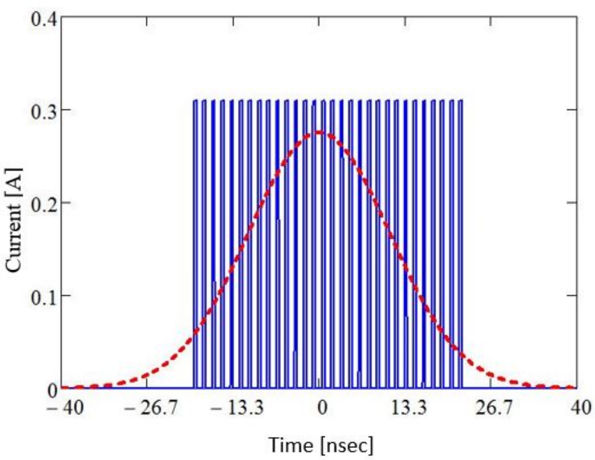

FIG. 2: The LEReC beam structure. Thirty electron bunches (blue) with 0.13 nC charge and 0.4 nsec length each spaced by 1.4 nsec placed on a single Au ion bunch of charge 7.5 nC (red dashed curve), with ion bunch repetition frequency of 9 MHz.

The space-charge dominated beam dynamics during acceleration of the bunches inside the gun determines the momentum spread and divergence of the electron beam, which is different from those obtained during electrostatic acceleration of DC beams in standard coolers. Electron beams with small longitudinal and transverse velocity spreads suitable for cooling were achieved by employing a high-voltage gun, CsK_2Sb photocathodes and laser pulse shaping.

Once electron bunches of the desired quality were generated from the gun, they were further accelerated to the required energy by the 704 MHz superconducting RF 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. 1.

To prevent the degradation of the energy spread due to the longitudinal space-charge forces, electron bunches were ballistically stretched by accelerating slightly off-crest in the booster cavity to produce an energy chirp (which generates a correlation between longitudinal particle position within the bunch and its energy). A series of normal conducting (warm) RF cavities were used to control the energy spread within the electron bunches. A warm 2.1 GHz cavity (3rd harmonic of the 704 MHz) was used to remove the energy spread due to the non-linear part of the RF waveform. After the bunches were stretched, another 704 MHz warm RF cavity was used to remove the energy chirp. An additional 9 MHz warm RF cavity was employed to remove bunch-by-bunch energy variation within the 30-bunch train (macro-bunch) caused by beam loading in the RF cavities.

Commissioning of cooling started by filling RHIC with 6 consecutive ion bunches (instead of the full load of 111 bunches) and generating the corresponding 6 macro-bunches of electrons every 13.2 µs which is the RHIC ion revolution frequency of 76 kHz at 3.85 GeV per nucleon. This allowed us to focus on the cooling of a single ion bunch using low average electron current. In such a mode, only a single ion bunch is cooled effectively because of an energy droop from one electron macro-bunch to another due to beam loading in the RF cavities, thus providing good velocity matching for only a single macro-bunch of electrons. With low laser beam power in such a mode and thus no thermal effects on the laser beam distribution, it was expected that the resulting electron beam parameters should be similar to those measured at 1 Hz, which was the frequency used for electron beam quality characterization [7].

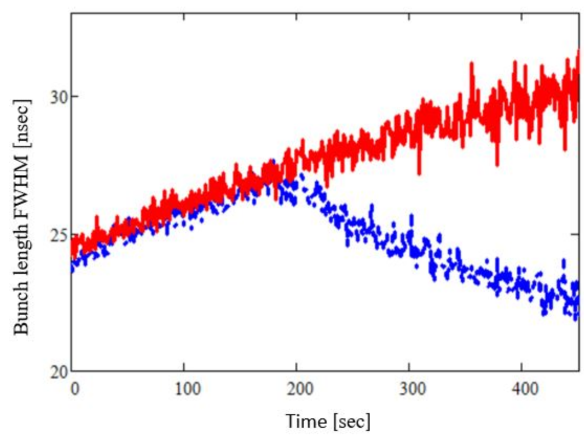

FIG. 3: Measurement of ion bunch length (full-width half maximum) using a wall current monitor. Uncooled ion bunch (top red curve). Cooled bunch (low blue dashed curve), the onset of cooling at t=200 sec starts once electron and ion longitudinal velocities are matched.

Matching of the electron and ion beam average longitudinal velocities was achieved [14] by employing a well calibrated 180-degree dipole magnet between the two cooling sections as a spectrometer 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. First longitudinal cooling of the Au ion beam in the Yellow RHIC ring was observed on April 5, 2019, once the electron and ion beam velocities were matched, at around 200 sec in Fig. 3. In the absence of cooling, the length of the ion bunch is increasing due to a diffusion process called Intrabeam Scattering (IBS) [15], while with cooling IBS growth is fully counteracted and the bunch length starts to decrease increasing phase-space density of the ion beam. Typical longitudinal bunch profiles of ions with and without cooling are shown in Fig. 4.

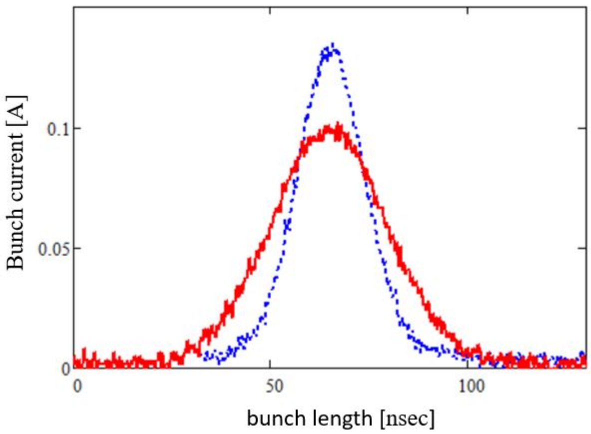

FIG. 4: Longitudinal profiles of an uncooled ion bunch (solid red curve) and a cooled bunch (dashed blue curve) after 20 minutes of cooling.

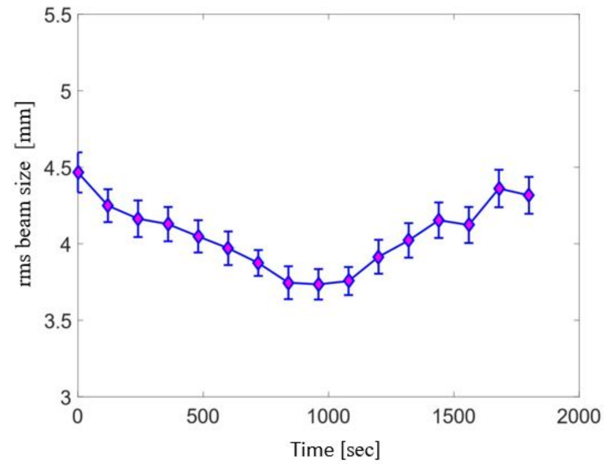

FIG. 5: Time evolution of horizontal rms beam size of a single ion bunch in the Yellow RHIC ring with electron cooling first turned on and then turned off after 1000 sec.

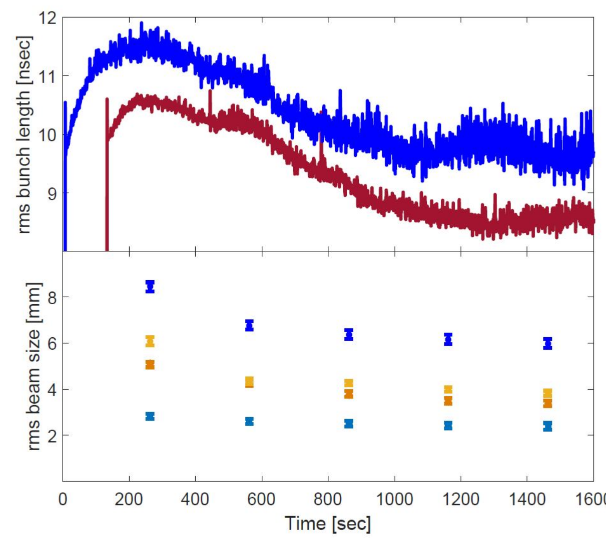

FIG. 6: 6-D cooling of a 111x111 bunch store at 3.85 GeV/nucleon (1.6 MeV electrons, average current of 15 mA at 9 MHz frequency). Top plot - ion bunch length evolution in the Blue and Yellow (brown curve) RHIC rings. Bottom plot - horizontal (circles) and vertical (squares and diamonds) beam sizes in the Yellow and Blue RHIC rings.

With just longitudinal cooling, no improvement of the ions lifetime was observed. In fact, the lifetime of ions interacting with electrons suffered due to additional diffusional growth of ions caused by modulated focusing from the electrons [16]. Such heating effects were more pronounced for operation at the lowest energy of 1.6 MeV due to the strong dependence of the space-charge force from the electrons on the beam energy. This effect was reduced, but not eliminated, by a proper choice of the transverse size of the ion beam in the cooling section. Due to the strong (close to quadratic) dependence of heating rates on electron beam density, and to overcome heating with cooling, the optimum current was found to be roughly half of the value given in Table I. To overcome this additional diffusion mechanism and to improve the lifetime of the ions, it was necessary to establish good transverse cooling in addition to the longitudinal cooling. The task of establishing transverse cooling was more challenging due to the strong dependence of the friction force in Eq. 1 on the transverse angles, especially for the transverse component of the force. After good matching of the electron-ion trajectories in the cooling sections was achieved, transverse cooling of the ion beam was successfully demonstrated. Figure 5 shows measurements of the transverse beam size with electron cooling first turned on and then turned off after 1000 sec.

Once cooling of ion bunches was commissioned in the Yellow RHIC ring, cooling of ions in the Blue ring was also established, which was followed by simultaneous cooling of ion bunches in both RHIC rings using the same electron beam. As a result, this became the first application of electron cooling when an electron beam which already interacted and cooled the ions in one ring was used one more time to cool the ions in another ring.

To proceed from cooling of a single ion bunch using a 76 kHz electron beam repetition rate to cooling of many ion bunches in RHIC required establishing high-current 9 MHz continuous-wave (CW) electron beam operation through both cooling sections all the way to the high-power beam dump. In addition to challenges associated with high-current electron beam operation by itself [17], this task was of special concern for the cooling performance since the electron beam parameters were measured only at 1 Hz repetition rate of electron pulses introducing uncertainties about the beam quality during high-current operation at 9 MHz frequency. Once stable 9 MHz operation of electron beam was established and velocities of the electrons and ions matched, cooling of several ion bunches simultaneously was observed right away.

After cooling of hadron beams using the high-current electron beam was commissioned, our focus shifted towards operational aspects, which included cooling of full RHIC stores with ion bunches in collisions, thus commissioning the 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 both RHIC rings undergoing beam-beam collisions is shown in Fig. 6. Figure 6 shows that both the transverse and longitudinal growth of ion beam sizes is effectively counteracted by electron cooling. The effectiveness of cooling against diffusion depended on the initial intensity of the ions and on cooling optimizations (such as electron trajectory adjustments in the cooling section with respect to the ions). For a typical full physics store with high intensity ions (about $9{\cdot}10^8$ ions per bunch), such as the one shown in Fig. 6, it took a few minutes before cooling started to dominate over diffusion due to IBS. For the cases with lower intensity ion bunches or when the energy spread of ion bunches was already increased due to IBS, reduction of beam sizes typically started right away once the velocities of electrons and ions were matched.

In summary, the world's first electron cooling based on RF acceleration of electron bunches was successfully commissioned, opening the possibility of using this technique at high energies for a variety of applications. Electron cooling of hadron beams in collisions was also demonstrated.

The LEReC project greatly benefited from help of many people from various groups of the Collider-Accelerator and other Departments of BNL, as well as FNAL, ANL, JLAB and Cornell University.

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