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PRECISE BEAM VELOCITY MATCHING FOR THE EXPERIMENTAL DEMONSTRATION OF ION COOLING WITH A BUNCHED ELECTRON BEAM *

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Abstract

The first ever electron cooling based on the RF acceleration of electron bunches was experimentally demonstrated on April 5, 2019 at the Low Energy RHIC Electron Cooler (LEReC) at BNL. The critical step in obtaining successful cooling of the Au ion bunches in the RHIC cooling sections was the accurate matching of average longitudinal velocities of electron and ion beams corresponding to a relative error of less than 5e-4 in the e-beam momentum. Since the electron beam kinetic energy is just 1.6 MeV, measuring the absolute e-beam energy with sufficient accuracy and eventually achieving the electron-ion velocity matching was a nontrivial task. In this paper we describe our experience with measuring and setting the e-beam energy at LEReC.

LEREC DESCRIPTION

LEReC [1, 2] is the world's first electron cooler utilizing RF based acceleration of electron bunches. It is the first cooler applied directly to the ions in the collider at top energy and it is the first cooler that utilizes the same electron beam to cool ion bunches in two collider rings.

The LEReC accelerator consists of a 400 keV photo-gun followed by the SRF Booster, which accelerates the beam to 1.6-2.6 MeV, the transport beamline, the merger that brings the beam to the two cooling sections (in the Yellow and in the Blue RHIC rings), the cooling sections (CSs) separated by the 180° bending magnet and the extraction to the beam dump. The LEReC also includes two dedicated diagnostic beamlines: the DC gun test line and the RF diagnostic beamline. The LEReC layout is schematically shown in Fig. 1.

The friction force acting on the ion in the cooling section is given by [3, 4]:

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m_e} L_C \int \frac{\vec{v_i}-\vec{v_e}}{|\vec{v_i}-\vec{v_e}|^3} f(v_e) d^3 v_e \qquad (1)$$

where e and m_e are electron charge and mass, n_e is electron bunch density in the beam frame, Z is ion charge number, L_C is Coulomb logarithm, which for LEReC is ~10, v_e and v_i are respectively electron and ion velocities in the beam frame and $f(v_e)$ is the electron bunch velocity distribution.

LEReC design parameters are chosen so that electron bunch transverse and longitudinal root mean square (rms) velocity spread is equal to respective ion velocity spread. For such a choice, ions on average experience linear cooling force in both transverse and longitudinal dimensions.

Requirements to electron bunch relative momentum spread and angular spread in the laboratory frame are [1]:

$$\sigma_\delta = 5 \cdot 10^{-4}; \quad \sigma_\theta = 130\,\mu\text{rad} \qquad (2)$$

It is also important to match electron relativistic γ-factor relative to ion γ with accuracy better than 5e-4 to observe and optimize the cooling of ion bunches.

Electron bunches satisfying conditions (2) were obtained during LEReC accelerator commissioning in 2018 [5].

Longitudinal component of force (1) has a relatively weak dependence on electron angular spread, which is affected by the presence of the ion beam in the CS. Since the electron bunch momentum spread is satisfying (2) regardless of ions presence, it was enough to match the electron and ion beam γ-factors to observe the longitudinal cooling.

The lowest e-beam energy required for LEReC operation is 1.6 MeV, which means that electron beam absolute energy must be measured and set with an accuracy of 0.8 keV.

We had planned and implemented a three-step process for electron beam γ-matching to the ion beam.

First, to set the absolute energy of the electron beam with an accuracy better than 5·10-3 we utilized the 180° bending magnet as a spectrometer.

Second, to check and fine-tune γ-matching we used the recombination monitor and e-beam energy scan performed with small steps.

Finally, we performed the energy scan with even finer steps to obtain and optimize the longitudinal beam cooling.

LOW ENERGY HIGH ACCURACY SPECTROMETER

The 180° bend is located between the first and the second LEReC cooling sections.

It is designed to have a bending radius $\rho_0 = 0.35$ m. The entrance to the magnet is equipped with two beam position monitors (BPMs) and its exit is equipped with one BPM.

The field of the U-turn bending magnet was mapped in +/-20 mm range around the design beam trajectory at 200 G, 240 G and 300 G flat-top fields corresponding respectively to 1.6 MeV, 2 MeV and 2.6 MeV electron beam energies [6]. The field was measured with a probe combining Hall sensor and a customized high-accuracy NMR probe capable of measuring fields as low as 140 G [7]. The resulting field map had a required accuracy of 0.02 G.

In the final U-turn bend setup at its destination in the RHIC tunnel the same probe was installed at a known, and well-mapped, fixed location in the uniform region of the

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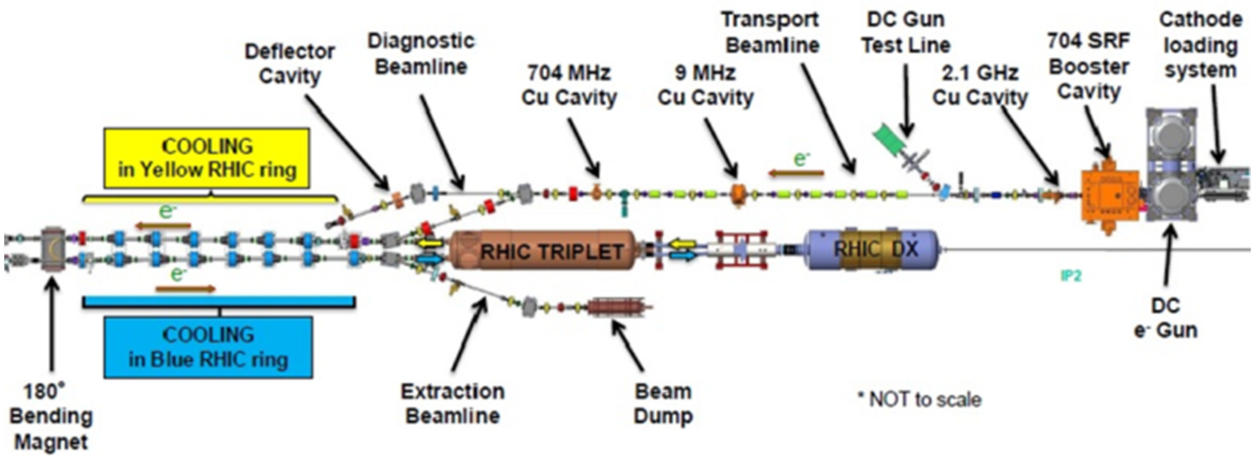

Figure 1: LEReC layout.

bending field. The continuous readings of the probe were used to properly scale the field map during energy measurements.

The 180° bend setup is schematically shown in Fig. 2.

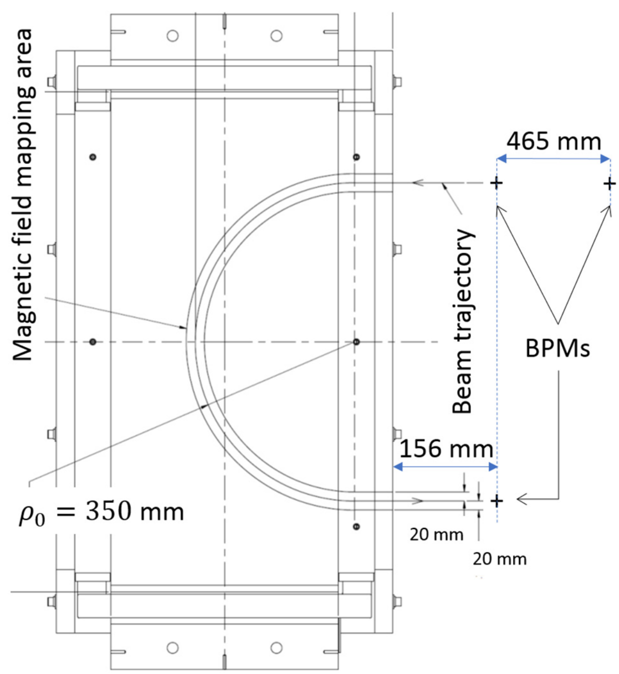

Figure 2: Schematics of 180° bend.

In the hard-edge approximation the horizontal e-beam displacement (x_{out}) at the exit of 180° bend is given by:

$$x_{out} = -x_{in} + 2\rho_0 - 2\rho\cos\theta_{in} \quad (3)$$

where x_{in} is the trajectory displacement at the entrance of the bend, θ_{in} is the trajectory angle at the entrance to the bend and ρ is the radius of off-energy trajectory through the bend.

To measure beam energy (E) in the 1.6-2.6 MeV range with the accuracy required for LEReC one must perform proper Taylor expansion of the exact expression for magnetic rigidity [8]:

$$B\rho = \frac{mc}{e}\sqrt{\left(\frac{E_0(1+\delta)}{mc^2}+1\right)^2 - 1} \approx B_0\rho_0\left(1+\frac{E_0+mc^2}{E_0+2mc^2}\delta\right) \quad (4)$$

where c is the speed of light and $\delta = E/E_0 - 1$.

Defining the fractional error in setting the dipole field as $\Delta \equiv B/B_0 - 1$, from (3) and (4) we get:

$$x_{out} = -x_{in} - 2\rho_0\frac{E_0+mc^2}{E_0+2mc^2}\delta + 2\rho_0\Delta \quad (5)$$

were x_{in} and x_{out} correspond to BPM readings (x_1, x_2, x_3) as:

$$x_{in} = x_2 + S_b\frac{x_2-x_1}{S_{12}} \quad (6)$$

$$x_{out} = x_3 + S_b\frac{x_2-x_1}{S_{12}} \quad (7)$$

Here S_{12} is the distance between the first and the second entrance BPMs, S_b is the distance from the second BPM to the hard edge dipole entrance and from the dipole exit to the exit BPM, x_1 and x_2 are the horizontal readings of two entrance BPMs and x_3 is the exit BPM reading.

Proper B_0 for hard edge approximation is found from field mapping data, S_{12} is measured in mechanical survey and S_b is found from survey and from magnetic map data.

Equations (5-7) solve the problem of obtaining an accurate energy measurement from spectrometer readings.

The results of hard-edge approximation were also compared to the beam tracking in the measured magnetic field [8] and were found to be in a perfect agreement.

The spectrometer measurements showed that the initial LEReC settings based on calibration of RF cavities provided a 100 keV higher e-beam energy than the design 1.6 MeV energy.

RECOMBINATION MONITOR

Some of Au^{79+} ions recombine with electrons via radiation recombination process in the CS, become Au^{78+} and

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get lost in the high dispersion RHIC region [9]. The recombination rate is the highest when the electron and ion γ-factors are matched.

A special lattice was developed with a high dispersion region in the RHIC arc downstream of the cooling section. The losses due to recombination were registered in this region with a dedicated plastic scintillation detector (PSD).

To match electron and ion γ-factors we scanned electron energy with ~1 keV steps around the energy found by the spectrometer while monitoring the PSD signal.

Due to high background counts the recombination monitor was not particularly precise. Yet, the increase in registered recombination rate was observable and well repeatable.

Figure 3 shows that the matched energy was at about 1.589 MeV (as measured by the spectrometer). That is, the spectrometer error at the time of the scan was about 11 keV.

Later we discovered the problem with calibration of our spectrometer BPMs. After fixing it, the error of spectrometer readings was reduced to 6 keV. Therefore, the accuracy of 4e-3 was achieved for the spectrometer-based energy measurements.

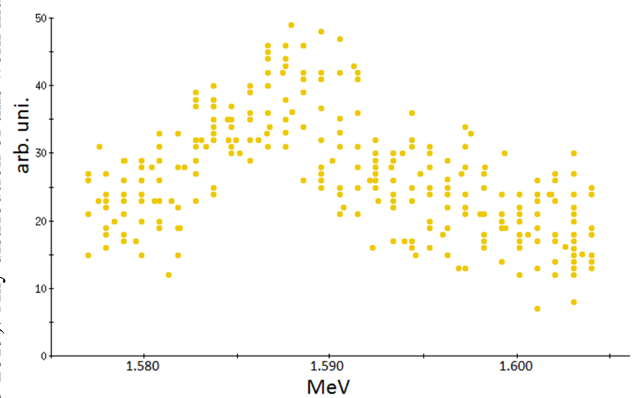

Figure 3: Recombination rate during the energy scan. PSD readings are given on y-axis and spectrometer readings on x-axis.

OBTAINING FIRST COOLING

After rough matching of electron and ion γ-factors based on recombination rate maximization, we engaged in an electron energy scan with sub-keV steps trying to observe bunched beam cooling.

In the absence of electrons, the ion bunch length increases due to intra-beam scattering (IBS) until ions fill the whole RF bucket. On the other hand, electron cooling must keep ion bunch length at a smaller constant value determined by the balance of the IBS diffusion and the cooling friction forces.

The shape, length and peak current of the ion bunches are continuously read by the RHIC wall current monitor (WCM).

Hence, to obtain cooling, we had a few (six in our case) ion bunches stored in the Yellow RHIC ring. All of them but one were overlapped with electron bunches. We scanned electron bunches energy while comparing the rms length and peak current of ion bunches interacting with the electrons with the length and peak current of the non-interacting (test) ion bunch.

The signature of the cooling was very clear. The cooled bunch length was reduced and its peak current increased in comparison to respectively the length and the peak current of the test ion bunch.

Figure 4 illustrates a typical bunched electron cooling.

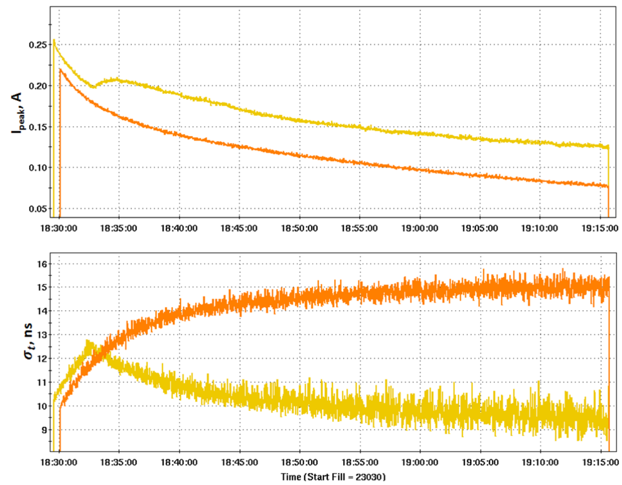

Figure 4: Typical observation of bunched electron cooling. The upper plot shows evolution of peak current of cooled (yellow trace) and test (orange trace) ion bunches. The lower plot shows evolution of the rms bunch length of the cooled and the test ion bunches during RHIC store.

Since our spectrometer was providing a good energy measurement accuracy and the longitudinal cooling was easily detectable during the energy scan, we decided to skip the recombination scan for 2 MeV energy settings. Instead, we set LEReC RF based on the spectrometer readings and scanned electron energy monitoring ion bunch length and peak current. The whole process of precise γ-matching at 2 MeV took us just a few hours.

CONCLUSION

LEReC is the world's first electron cooler utilizing RF based acceleration of electron bunches.

The critical step in obtaining first bunched beam cooling was matching the average longitudinal velocities of electron and ion beam so that γ-factor of two beams coincide with precision better than 5e-4.

In this paper we describe our experience with electron and ion beam γ-matching and with obtaining the electron cooling of RHIC ions.

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