ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUZE5

STUDIES OF ION BEAM HEATING BY ELECTRON BEAM*

S. Seletskiy[†], A.V. Fedotov, D. Kayran
Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Presence of electron beam created by either electron coolers [1] or electron lenses in an ion storage ring is associated with an unwanted emittance growth (heating) of the ion bunches. In this paper we report experimental studies of the electron-ion heating at the Low Energy RHIC electron Cooler (LEReC).

INTRODUCTION

Low energy RHIC electron cooler (LEReC) [2-7] is the first electron cooler based on RF acceleration of electron bunches. LEReC utilizes a non-magnetized electron beam and provides the cooling of colliding ions with the same e-beam in both RHIC rings. LEReC was commissioned in 2019 and was successfully used in RHIC operations in 2020 (at $\gamma = 4.9$) and in 2021 (at $\gamma = 4.1$).

It was noticed that in the presence of the electron beam, and with the transverse cooling suppressed by an offset from the optimal e-beam energy, the transverse emittance of the ions starts growing at a rate, which is higher than the rate of intra-beam scattering (IBS). We call this extra growth of emittance – an electron-ion heating (e-i heating).

In this paper we discuss the status of dedicated measurements of the electron-ion heating.

EXPERIMENTAL SETUP

Electron bunches in LEReC are produced by a 375 keV photo-gun. In operations the CW electron beam consists of 9 MHz macrobunches, each containing 36 704 MHz electron bunches. Each ion bunch passing through the LEReC cooling section (CS) is overlapped with one electron macrobunch (Fig. 1).

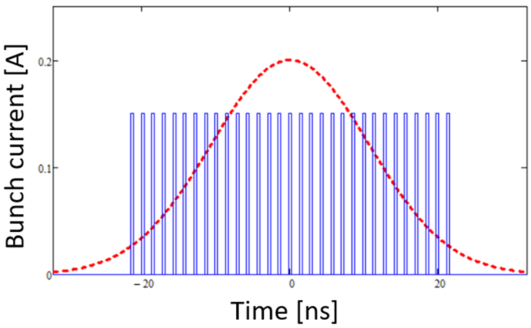

Figure 1: Ion bunch (red) overlapped with electron macrobunch (blue) in the cooling section

The LEReC gun is followed by the SRF Booster, which accelerates the beam to 1.6-2 MeV. The transport beamline and the merger bring the beam to the cooling section in the Yellow RHIC ring, and then through the 180° bending magnet to the CS in the Blue RHIC ring. Finally, the extraction beamline sends electrons to the high-power beam dump. The LEReC layout is schematically shown in Fig. 2.

LEReC cooling section contains 8 short solenoids (not shown in Fig. 2) used for fine-tuning of the e-beam envelope. The distance between solenoid centers is 3 m. Since LEReC is a non-magnetized electron cooler, both the self space charge and the ions' space charge strongly affect transverse beam dynamics of e-bunches [7].

The bunches in the electron macrobunch sample slices of an ion bunch having different charges. Therefore, an electron bunch angular spread and size vary both along the cooling section and from one bunch to another. In this paper we characterize the angular spread and the transverse size of electron beam by values averaged over the CS length and over all the bunches of the macrobunch.

In our experiment we worked with ion bunches of reduced intensity, both to reduce the ion-electron focusing in the CS and to reduce the effect of the IBS-induced growth of the i-bunch emittance. We also used the ion bunches in the Yellow ring only to exclude the beam-beam effects.

All the measurements were performed with 1.6 MeV electrons.

MEASUREMENTS

Description of Measurement Procedure

We base calculation of the rate of i-beam emittance change on the measurements of the vertical size of the ion bunches performed with the H-jet [8].

To measure the electron-ion heating rate we first match γ-factors of electrons and ions [2] to pre-cool the ion bunches to a particular transverse emittance. Next, we offset electron beam energy by about 5 kV, which corresponds to $\approx 6\sigma_{\delta e}$ ($\sigma_{\delta e}$ is the rms relative momentum spread of electrons). Such an offset essentially zeroes the transverse cooling force (Fig. 3 demonstrates this effect). The growth of ions emittance observed under these conditions is driven by both the IBS and the e-i heating.

After that we pre-cool the ions to the same initial emittance and turn off the electron beam completely. For such a set-up the growth of ion emittance is determined only by the IBS.

The difference between the two measured growth rates gives us the rate of the electron-ion heating.

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* Work supported by the US Department of Energy under contract No. DE-SC0012704
[†] seletskiy@bnl.gov

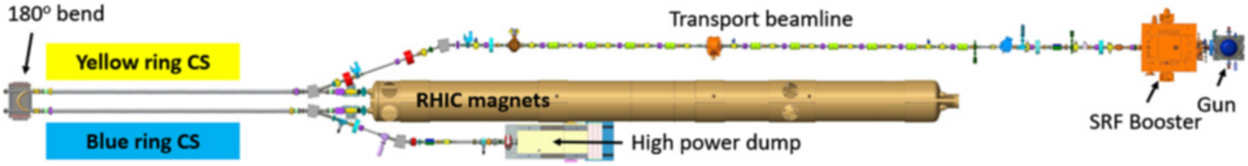

Figure 2: LEReC layout.

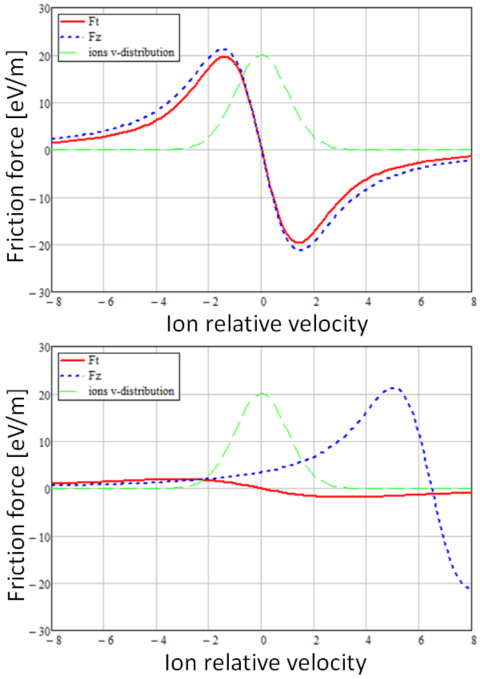

Figure 3: Transverse (solid red line) and longitudinal (dashed blue line) components of the cooling force for an on-energy electron beam (top plot) and the e-beam detuned by 5 keV. Ions' velocity distribution (green) is shown for reference.

Figure 4 demonstrates a typical measurement cycle.

Prior to each set of measurements the 6-D phase space of the electron bunches at the entrance to the cooling section was fully characterized. This information together with the ion bunch charge and its transverse size in the cooling section define evolution of electrons distribution through the CS. A dedicated code [7] was used to calculate the resulting average transverse size and the average density of the electron beam in the cooling section.

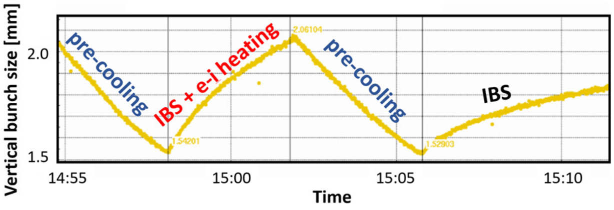

Figure 4: Measurement of e-i heating rate.

The described measurements were performed at various electron beam currents and various settings of the CS solenoids. This allowed us to vary the electron beam's density and transverse size from measurement to measurement.

Results of Measurements

It was noticed early in the experiment that while the instantaneous e-i heating rate ($\lambda_{h(\sigma_y)} = \frac{1}{\sigma_y} \cdot \frac{d\sigma_y}{dt}$) is changing during one measurement, the heating rate multiplied by the fourth power of ions' transverse size (σ_y) is an invariant of the measurement:

$$\lambda_{h(\sigma_y)} \cdot \sigma_y^4 = C \tag{1}$$

Here, C is constant over a single measurement but depends on electron beam parameters.

The relation given by Eq. (1) was repeated in every measurement (see Fig. 5 for an example).

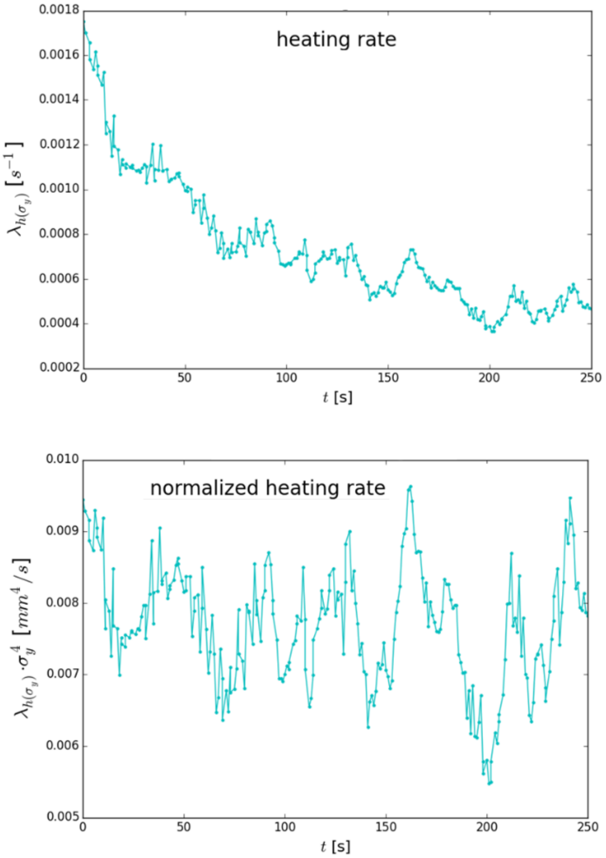

Figure 5: Evolution of the instantaneous e-i heating rate during one measurement

Analysis of the obtained data revealed a clear linear dependence of the normalized heating rate on the average electron beam density (ρ_e), as demonstrated in Fig. 6.

As a result, we can rewrite Eq. (1) as:

$$\lambda_{h(\sigma_y)} \cdot \sigma_y^4 = C_0 \cdot \rho_e \tag{2}$$

where C_0 is a coefficient of proportionality.

It must be also noticed that we did not observe a dependence of heating on the electron beam size (at a fixed beam density).

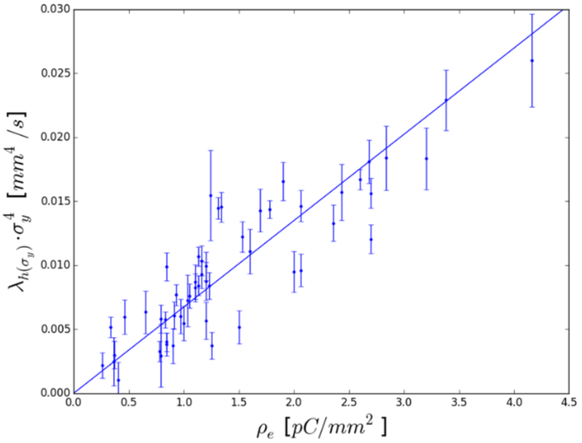

Figure 6: Dependence of heating on e-beam density.

Possible Heating Mechanisms

We applied several conventional models to the measured data.

Neither a simple random walk model with either dipole or focusing kicks, nor a more sophisticated model described in [6] reproduce the experimental dependence (2).

Yet, there is another possible mechanism of transverse heating in the presence of electron beam with the offset energy.

In electron coolers a substantial enough offset in electron energy creates a mechanism of longitudinal heating [9-10]. This heating can be partially redistributed to the transverse direction through the coupling of motion in the longitudinal and the transverse directions. Such a heating can produce the dependence described by Eq. (2).

We performed measurements aimed at checking the connection between the energy offset of the e-beam and the transverse heating of the ions.

To suppress cooling without introduction of an energy offset one can increase the momentum spread of the electrons by chirping the e-bunch energy.

We discovered that while the chirped bunch still provides a noticeable heating, the resulting heating rate is about 1.5 times smaller than the rate measured for electron beam having a comparable energy offset (see Fig 7).

We conclude that while coupling of longitudinal heating to transverse direction does not completely explain the e-i heating, it is a substantial part of the overall heating of ions by an electron beam.

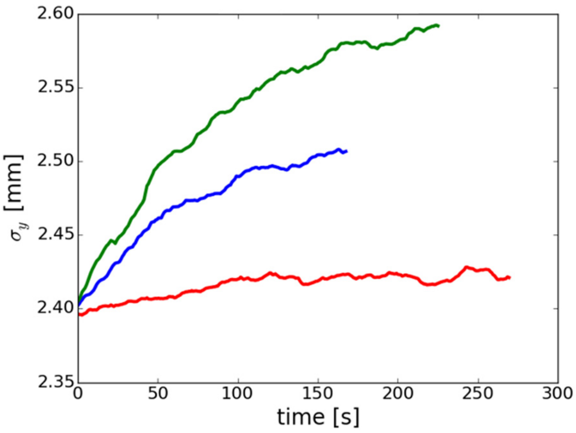

Figure 7: Growth of the transverse size of ion bunches with the same initial conditions in three cases. The red trace shows growth in the absence of electron beam (IBS-driven growth). The blue trace represents heating by chirped e-bunch. The green trace shows heating by an electron bunch with energy offset.

CONCLUSION

We discussed the ongoing studies of the electron-ion heating at LEReC.

It was found that the rate of transverse heating of the ions multiplied by the fourth power of the ion beam size is proportional to the density of the electron beam in the cooling section.

Recent measurements showed that a substantial part of transverse heating can be explained by coupling of longitudinal heating, caused by energy offset of the electron beam, into a transverse direction.

Plans for further studies of the electron-ion heating effects are under development.

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