ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB265

SIMULATIONS OF COOLING RATE FOR COHERENT ELECTRON COOLING WITH PLASMA CASCADE AMPLIFIER*

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Abstract

Coherent electron cooling (CeC) is a novel technique for rapidly cooling high-energy, high-intensity hadron beam. Plasma cascade amplifier (PCA) has been proposed for the CeC experiment in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Cooling rate of CeC experiment with PCA has been predicted in 3D start-to-end CeC simulations using code SPACE.

INTRODUCTION

The Department of Energy (DOE) has selected BNL as the site for the future Electron-Ion Collider (EIC). Strong hadron cooling is essential to attain the luminosity required by the EIC design. CeC [1-3] is the most promising technique for the rapid cooling of high-energy high-intensity hadron beams in the EIC.

A general CeC scheme consists of three main sections, the modulator, the amplifier, and the kicker. In the modulator, hadrons co-propagate with the electrons and induce density modulation by attracting surrounding electrons. The density modulation is then amplified in the second section of CeC, the amplifier. In the kicker, the electron beam interacts with the hadrons, correcting their energies towards the nominal value, which results in cooling of the hadron beam.

Several CeC schemes have been proposed with different implementations of the CeC amplifier, including the high-gain free electron laser (FEL) amplifier [3], the microbunching instability (MBI) amplifier [4], and the PCA [5]. In this paper, we present simulation studies of the PCA-based CeC. Working principle of PCA is the new plasma cascade instability (PCI) [6-7] occurring in electron beams propagating along a straight trajectory.

Figure 1 shows the layout of a PCA-based CeC system, where solenoids are used to modulate the transverse size of the electron beam and to excite the PCI amplifying the density modulation induced by hadrons in the modulator.

Our simulation tool is the SPACE code [8], a parallel, relativistic, three-dimensional (3D), electromagnetic (EM) Particle-in-Cell (PIC) code, which has been used in the simulation studies for the mitigation effect by beam induced plasma [9], the modulation process in CeC [10-13], the cooling performance of CeC with FEL amplifier [14-17] and the sensitivity study of PCA [18].

SIMULATION SETUP

The setup in the simulation study is based on the CeC experiment at BNL RHIC. Figure 2 shows the layout of the CeC system installed at BNL RHIC. The CeC section includes a 3-meter modulator, an 8-meter 4-cell PCA and a 3-meter kicker. The lengths of the PCA cells are 1.8 m, 2.2 m, 2.2 m, and 1.8 m. Figure 3 presents the simulated evolution of transverse root mean square (RMS) size of the electron beam in the modulator, the PCA and the kicker. The electron beam parameters used in the simulations are listed in Table 1 and are relevant to the CeC experiment at BNL RHIC. A transverse Kapchinsky-Vladimirsky (KV) distribution has been applied to the electron beam in the simulations. Note that the KV emittance is 4 times of the traditionally defined RMS emittance.

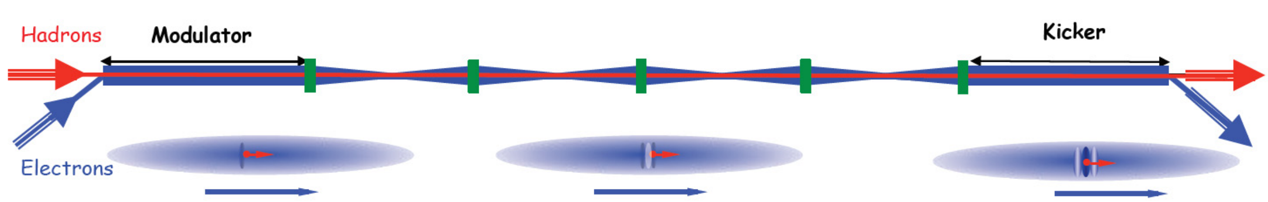

Figure 1: Schematic of a CeC system with the PCA.

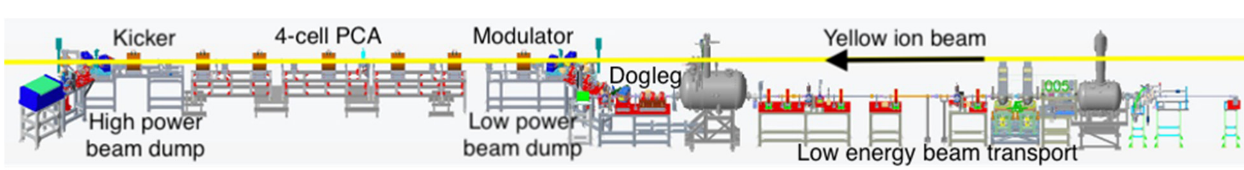

Figure 2: PCA-based CeC system installed at BNL RHIC. The electron beam is generated in a 1.25 MV superconducting radio frequency (SRF) photo-electron gun, accelerated to 14.56 MeV, and merged to co-propagate with the 26.5 GeV/u ion beam circulating in RHIC's yellow ring.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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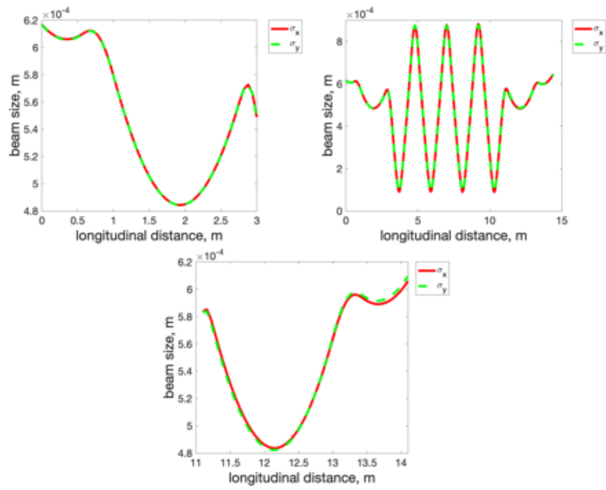

Figure 3: Evolution of transverse RMS beam size in the CeC section (top right) and the zoom-in plot for the modulator (top left) and the kicker (bottom).

Table 1: Electron Beam Parameters

Beam energy, γ	28.5
Peak current, A	75
Normalized KV emittance, mm mrad	7
RMS energy spread	2e-4

MODULATOR

Analytical solution to the modulation problem exists for a moving ion co-propagating with a uniform electron beam [19]. Our simulation results have achieved a good agreement with theory in both density modulation and velocity modulation [10]. In this study, we have simulated a realistic modulator and co-propagated the electron beam with a single gold ion Au^{+79}, and the resulting density modulation at the exit of the modulator is displayed in Fig. 4. While the single ion stays at the center of the computational domain in the co-moving frame, the density modulation in the electron beam is slightly before the ion, because the electron beam has 0.1% higher energy than the ion to compensate the delay in the PCA. In the PCA section, the strong solenoid fields delay the electron beam in longitudinal direction, making it fall behind the ion in the kicker section. We have increased the electron beam energy by 0.1% to compensate the delay.

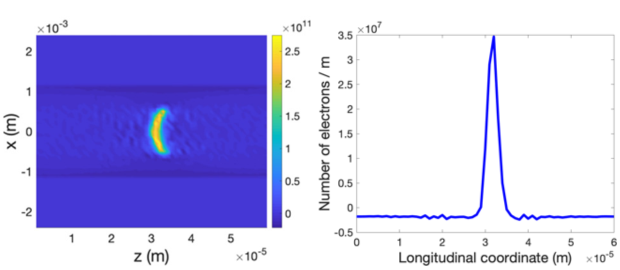

Figure 4: 2D (left) and 1D (right) plot of the density modulation in the electron beam induced by a single ion at the exit of the modulator section.

We have performed the simulation study about how the density modulation is affected by the energy difference between the electrons and the ions. The ion with the reference energy has co-propagated with the electrons with different energies. The resulting density modulation is quantified using the bunching factor, which is defined as

$$b \equiv \frac{1}{N_\lambda}\sum_{k=1}^{N_\lambda} e^{i\frac{2\pi}{\lambda_{opt}}z_k}, \; -\frac{\lambda_{opt}}{2} \leq z_k \leq \frac{\lambda_{opt}}{2}, \quad (1)$$

where λ_{opt} is the optical wavelength, the summation is over a slice of λ_{opt} wide, centered at the ion's location, and N_λ is the total number of electrons within that slice.

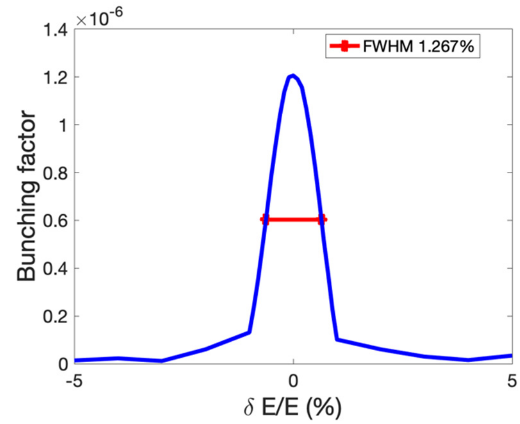

Figure 5: Bunching factor amplitude of the density modulation induced by a single ion for various energy differences between the electron beam and the ion.

Figure 5 shows the dependence of the bunching factor on the energy difference between electrons and the ions. The peak density modulation is achieved when the electrons and the ions have the same energy. The density modulation decreases when the energy difference increases, with the full width at half maximum (FWHM) 1.267%. The 0.1% energy difference used to compensate the delay in PCA will not affect the modulation process significantly.

PLASMA CASCADE AMPLIFIER

In the PCA section, the PCI is excited to amplify the density modulation in the electron beam. Figure 6 displays the density modulation at different locations through the PCA. The signal of the density modulation flips the sign in each PCA cell, which is consistent with the PCI theory [6] and requires even number of PCA cells.

We have tracked the evolution of density modulation at different frequencies through the PCA section to characterize the gain spectrum, as is shown in Fig. 7. Figure 8 presents the evolution of the density modulation in the 4-cell PCA.

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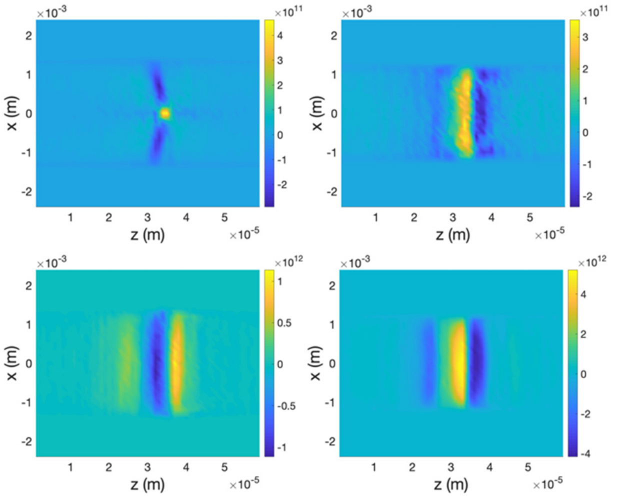

Figure 6: 2D plot of density modulation in the 1st cell (top left), 2nd cell (top right), 3rd cell (bottom left) and 4th cell (bottom right) in the PCA section.

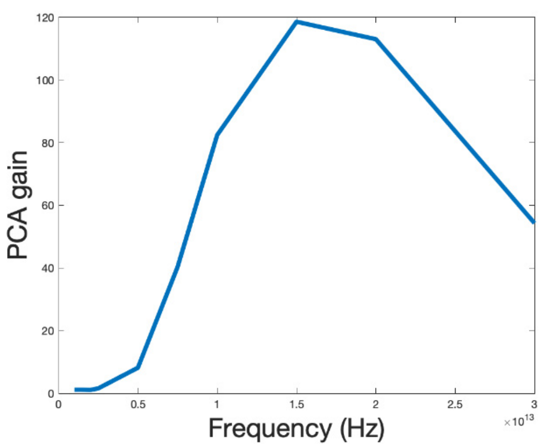

Figure 7: PCA amplification for density modulation at different frequencies.

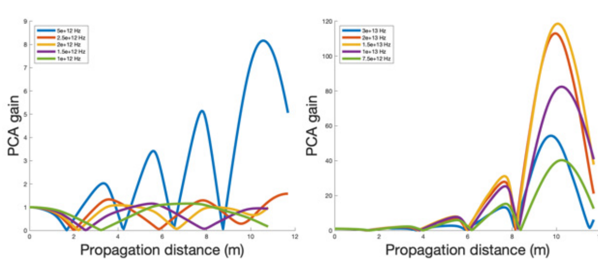

Figure 8: Evolution of PCA gain for initial density modulation at various frequencies through the PCA section.

KICKER

In the kicker, the electron beam with amplified modulation gives energy kick to ions towards the reference energy, which leads to the cooling of the ion beam. Figure 9 shows the evolution of the amplified density modulation in the kicker section.

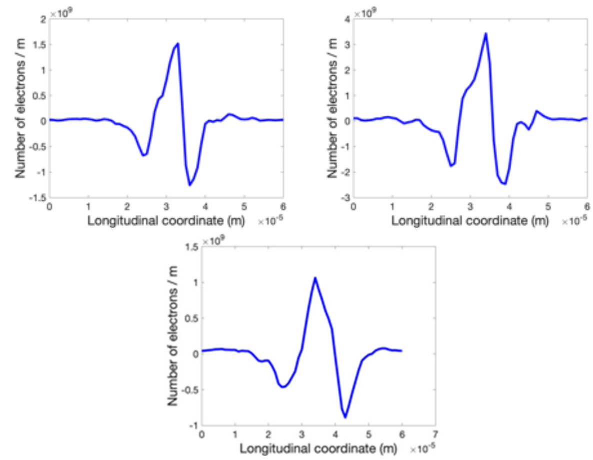

Figure 9: 1D plot of the density modulation at the entrance (top left), in the middle (top right), at the exit (bottom) of the kicker section.

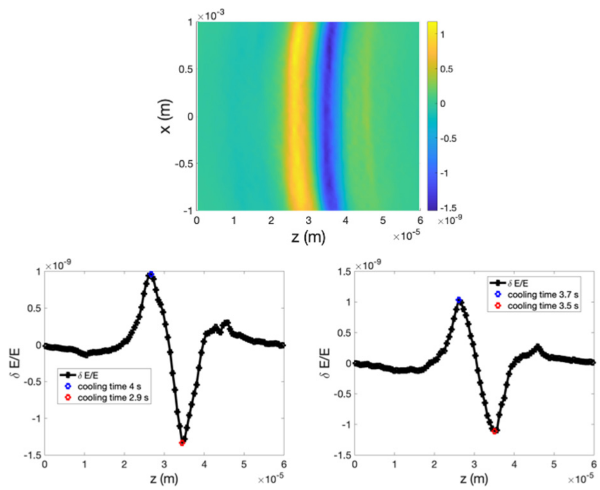

Figure 10: The energy kick to ions in the kicker section within a single pass through the PCA-based CeC system, for ions with various longitudinal and horizontal positions (top), for ions with zero horizontal position (bottom left), and for ions with horizontal offset 0.4 mm (bottom right).

We have tracked the energy kick received by ions at different locations in the kicker section, and demonstrated sufficiently short local cooling time, as is shown in Fig. 10. A more realistic estimation of cooling time should include random kicks from surrounding ions and electrons.

CONCLUSION

We have presented the simulation studies of the PCA-based CeC system, including the modulator, the PCA, and the kicker.

The modulation process has been simulated for various energy differences between the electrons and the ions in the modulator. The amplification of density modulation at different frequencies has been obtained in the simulations of PCA. The local cooling time for ions has been predicted from the kicker simulations.

We will continue the simulation study to support the CeC experiment at BNL RHIC and the design of the future EIC at BNL.

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