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SIMULATIONS OF COHERENT ELECTRON COOLING WITH VARIED BEAM PARAMETERS*

J. Ma†, Y. Jing, G. Wang, Brookhaven National Laboratory, Upton, New York, USA
V. N. Litvinenko, Stony Brook University, Stony Brook, New York, USA

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 performance of PCA based CeC has been predicted in 3D start-to-end CeC simulations using code SPACE. The dependence of the cooling rate on the electron beam parameters has been explored in the simulation studies.

INTRODUCTION

Strong hadron cooling (SHC) is essential to attain the luminosity required by the future Electron-Ion Collider (EIC) design [1-6]. SHC based on the cooling scheme known as CeC [7-9] has been investigated as a promising technique.

Several CeC schemes have been proposed with different implementations of the CeC amplifier. While micro bunched electron cooling (MBEC) is now being used to design the CeC for the EIC [6,10], the PCA-based CeC (Fig. 1) can be tested in an ongoing experiment at BNL's RHIC (Fig. 2).

In this paper, we present simulation studies of the PCA-based CeC [11]. Working principle of PCA is the plasma cascade instability (PCI) [12,13].

Our simulation tool is the SPACE code [14], a parallel, relativistic, three-dimensional (3D), electromagnetic (EM) Particle-in-Cell (PIC) code, which is capable of simulating interactions between relativistic particle beams. SPACE has been applied to the simulation studies for the mitigation effect by beam induced plasma [15], the modulation process in CeC [16-19], CeC with free electron laser (FEL) amplifier [20-23] and the CeC with PCA [24-26]

DESIGNED BEAM PARAMETERS

The setup of the CeC system in the simulation study is based on the CeC experiment at BNL's RHIC, which includes a 2.88-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. Table 1 lists the designed electron beam parameters in simulations. The peak current and emittance are carefully chosen to excite the PCI in PCA. 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 root-mean-square (RMS) emittance.

Table 1: Electron Beam Parameters

Beam energy, γ	28.5
Peak current, A	50
Normalized KV emittance, μm	6
RMS energy spread	2e-4

Figure 3 shows the electron beam size evolution in the PCA-based CeC system using designed beam parameters listed in Table 1, and the energy kick to hadrons in the kicker section. The energy kick from the electrons corrects the hadrons' energy towards the nominal value, which results in the cooling. The simulation results demonstrate sufficient energy kick to hadrons which results in reasonable local cooling time. More simulations of the modulator and the PCA can be found in [16-26].

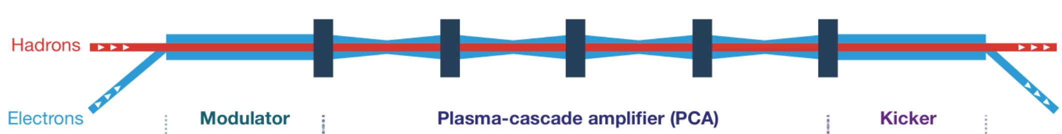

Figure 1: Schematic of a CeC system with the PCA at BNL's RHIC.

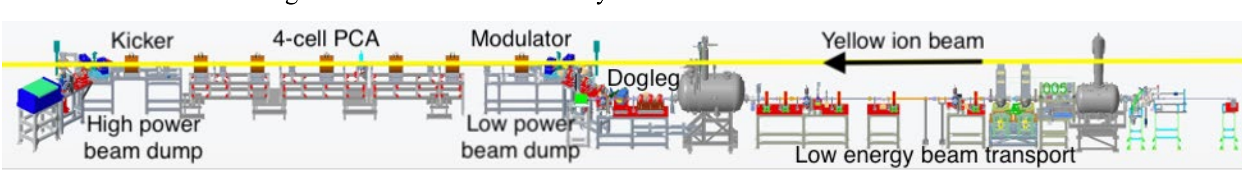

Figure 2: PCA-based CeC system installed at RHIC. The electron beam is generated in a 1.25 MV superconducting radio frequency (SRF) photo-electron gun, accelerated to 14.56 million electronvolts (MeV), and merged to co-propagate with the 26.5 GeV/u ion beam circulating in RHIC's yellow ring.

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† jma1@bnl.gov

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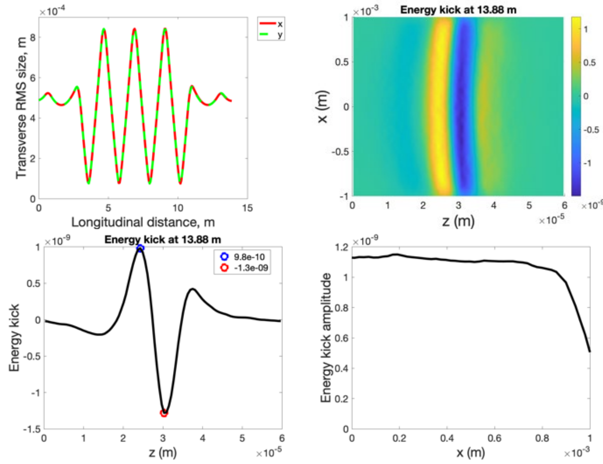

Figure 3: Evolution of the transverse RMS beam size in the PCA-based CeC system (top left), the energy kick for ions with various longitudinal and horizontal positions (top right) and for ions with zero offset in horizontal position (bottom left), and amplitude of the energy kick along the horizontal direction (bottom right).

VARIED BEAM PARAMETERS

In more accurate cooling simulations, the beam distribution at the entrance of the CeC section is obtained from realistic beam dynamics simulations starting from the gun – the generation of the electron beam (refer to Figure 2). In this multi-slice simulation, the beam dynamics has been simulated in another code Impact-T [27], and the beam distribution at the modulator's entrance is imported to SPACE for CeC simulations.

The setup in the beam dynamics simulation is adjusted to approach the designed beam parameters (refer to Table 1) at the modulator's entrance. Figure 4 shows the variations of the beam parameters from slice to slice.

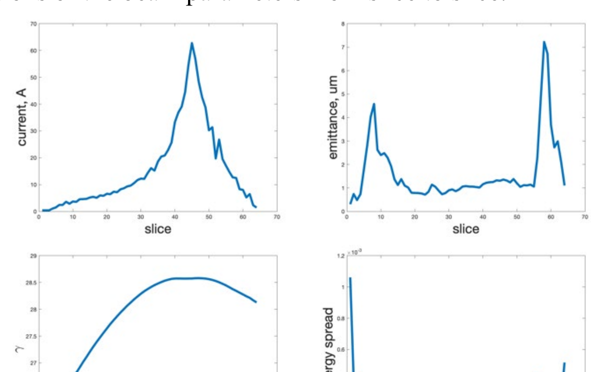

Figure 4: Peak current (top left), normalized RMS emittance (top right), average energy γ (bottom left), and RMS energy spread (bottom right) of slices in the electron beam at the entrance of the modulator, which are obtained from realistic beam dynamics simulations starting from the gun of the CeC system at BNL's RHIC. Duration of each slice is 1 picosecond.

A matched lattice for all the slices is not practical because of the varied beam parameters between slices. The solenoid strength is adjusted to match the transverse beam size of slice 45, while other slices are mismatched (Fig. 5).

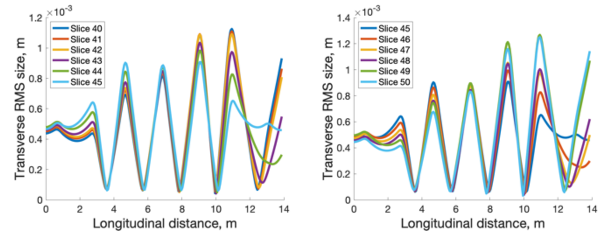

Figure 5: Evolution of the transverse RMS beam size in the PCA-based CeC system for different slices in the electron beam. Solenoids are tuned to match the beam size of slice 45.

Figure 6 shows the energy kick from slice 45, and Figure 7 displays the energy kick introduced by different slices. While slice 45 provides reasonable energy kick at different transverse offsets, the energy kick by other slices decays rapidly along the transverse direction, which is caused by the mismatched beam envelope and nonuniformity in the current profile.

The weighted sum of the energy kick amplitude with the probability density function of Gaussian distribution is used for fair comparison. The expected ion beam size in the CeC experiment has been used for the Gaussian distribution to predict overall cooling performance.

Figure 7 shows that only a few slices provide sufficient overall cooling performance. This imposes a requirement on the uniformity of the electron beam between slices.

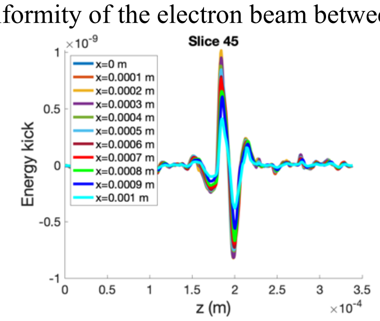

Figure 6: Energy kick to ions at various horizontal positions for slice 45.

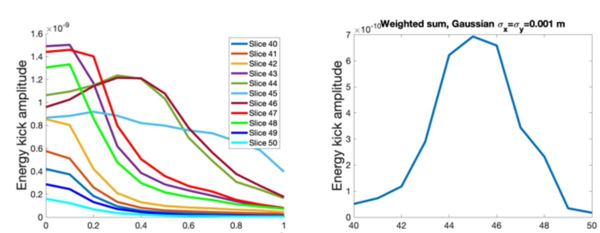

Figure 7: Amplitude of the energy kick for slices in the electron beam (left), and weighted sum of the energy kick amplitude with the probability density function of Gaussian distribution (right). The RMS of the Gaussian distribution is set at 1e-3 m, which is the expected ion beam size in the CeC experiment.

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SCANNED BEAM PARAMETERS

A range of beam parameters has been scanned around the designed beam parameters listed in Table 1, and the corresponding cooling performance is assessed.

According to PCI theory [12], peak current and emittance are two important factors that affect PCA gain. Therefore, the electron beam's current and emittance are varied from the designed beam parameters, and the resulting energy kick is displayed in Figure 8. Moreover, a 2D map (peak current and emittance) scan has been completed and is presented in Figure 9.

Figures 8 and 9 indicate that the strong energy kick requires low emittance and high peak current, which imposes requirements on the electron beam parameter for the realistic beam dynamics simulations starting from the gun of the CeC system at BNL's RHIC.

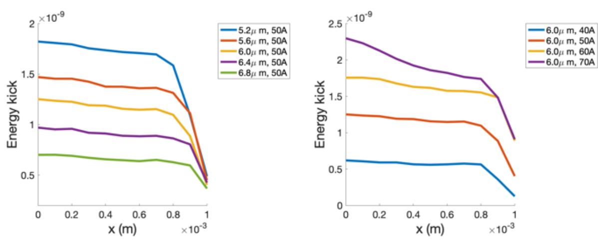

Figure 8: Amplitude of the energy kick for an electron beam with peak current 50 A and various emittances (left), and normalized KV emittance 6e-6 m and various peak currents (right).

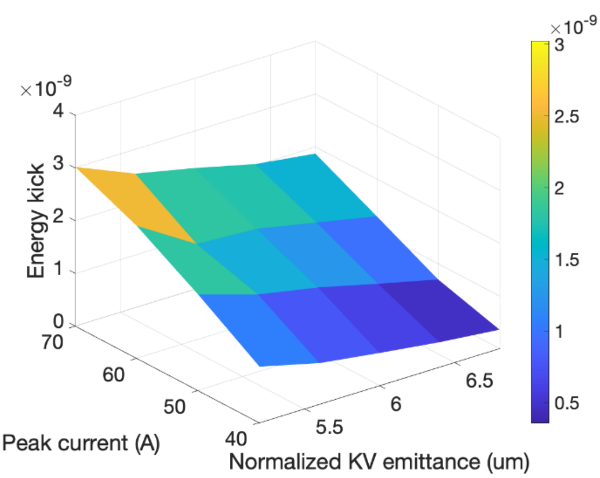

Figure 9: Amplitude of the energy kick for an electron beam with peak current 40 A to 70 A, and normalized KV emittance 5.2e-6 m to 6.8e-6 m.

CONCLUSION

We have simulated properly designed electron beam parameters which will provide good cooling performance in the PCA-based CeC system. Beam parameter variations from realistic beam dynamics simulation has been included to predict cooling performance. A scan of beam parameters has been performed to provide requirements on the electron beam parameter for the realistic beam dynamics simulations starting from the gun of the CeC system at BNL's RHIC.

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