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3D START-TO-END SIMULATIONS OF THE COHERENT ELECTRON COOLING

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Abstract

Coherent electron cooling (CeC) is a novel technique for rapidly cooling high-energy, high-intensity hadron beam. Two designs of coherent electron cooler, with a free electron laser (FEL) amplifier and a plasma-cascade micro-bunching amplifier, are cost effective and don't require separation of hadrons and electrons. These schemes are used for the demonstration experiment in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). SPACE, a parallel, relativistic 3D electromagnetic Particle-in-Cell (PIC) code, has been used for simulation studies of these two coherent electron cooler systems.

INTRODUCTION

A coherent electron cooling (CeC) [1, 2, 3] system consists of three sections: modulator, amplifier and kicker. In the modulator, the ions induce the modulation signal in the electron beam through Coulomb force. The modulation signal is boosted in the amplifier, and leads to the cooling of the ion beam in the kicker. In this paper, we present the simulation study of two coherent electron cooler systems. Figure 1 [3] shows the schematic of CeC using a free electron laser (FEL) as the amplifier, and Figure 2 [4] illustrates the layout of CeC with a plasma-cascade amplifier (PCA).

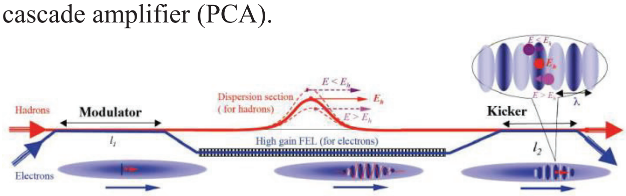

Figure 1: Layout of coherent electron cooler with a high gain free electron laser amplifier.

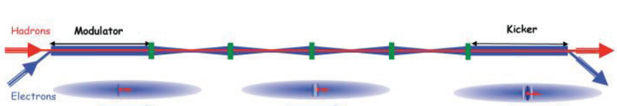

Figure 2: Layout of coherent electron cooler with a plasma-cascade amplifier.

We mainly use code SPACE [5] for numerical simulations. SPACE is a parallel, relativistic, 3D electromagnetic Particle-in-Cell (PIC) code, which has been used for the study of plasma dynamics in a dense gas filled RF cavity [6] and the study of mitigation effect by beam induced plasma [7]. GENESIS [8] has been used in the simulations of FEL amplifier in our study.

SIMULATIONS OF CEC WITH FEL AMPLIFIER

Modulator

In modulator, ions attract surrounding electrons and induce the modulations in electron beam. Analytical solution to the modulation problem exists for a moving ion co-propagating with a uniform electron beam [9]. Our simulation results have achieved a good agreement with theory in both density modulation and velocity modulation [10].

Beam parameters listed in Table 1 are related with the CeC experiment at BNL RHIC, and have been used in simulation studies.

Table 1: Parameters of electron and ion beams

	Electron	Ion, Au^{+79}
Beam energy	γ=28.5	γ=28.5
Peak current	75 A	
Normalized emittance	8 π mm mrad	2 π mm mrad
R.M.S. energy spread	1e-3	3e-4

Figure 3 shows the dynamics of β functions of electron beam and the longitudinal density modulation at several propagation distances in the modulator. We use quadrupoles to match the transverse beam size at the exit of modulator, which is required to obtain the amplification of modulation signal in the FEL amplifier. The dependence of modulation process on various parameters has been explored in detailed simulation studies [11, 12, 13].

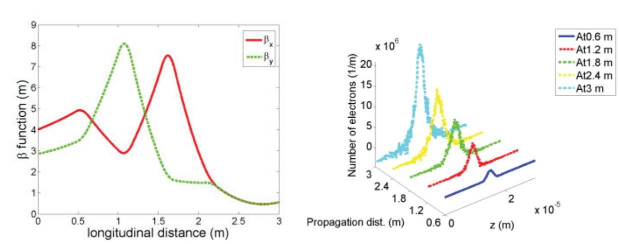

Figure 3: Evolution of electron beam β function (left) and longitudinal density modulation (right) in modulator.

FEL Amplifier

We have transferred the particle distribution at the exit of modulator from code SPACE to code GENESIS for the

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simulations of FEL amplifier. GENESIS uses bunching factor to quantify the longitudinal bunching, which is defined in Eq. (1) [8],

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

where λ_{opt} is the FEL 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.

In the CeC experiment at BNL RHIC, the FEL system has three sections of wigglers separated by drift space. We have designed a lattice with oscillating beam size and minimum overall variation, as is shown in Fig. 4. The growth of the bunching factor amplitude is displayed in Figure 4 for shot noise and in Fig. 5 for the modulation signal. Figure 5 shows that the modulation signal has been amplified by 210 times in FEL section, which is sufficient for the cooling. Diffusion rate for CeC has been calculated using the electron distribution at the exit of FEL amplifier [14].

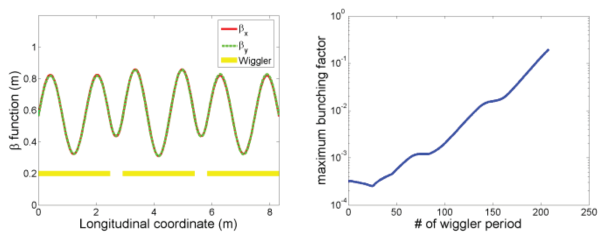

Figure 4: Location of three-section wigglers and β function evolution with minimum overall variation (left) and evolution of bunching factor amplitude of shot noise (right) in FEL amplifier.

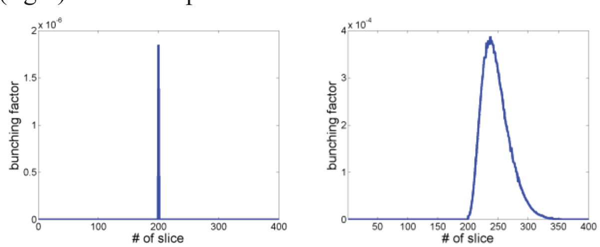

Figure 5: Bunching factor amplitude of modulation signal at the entrance (left) and exit (right) of FEL amplifier.

Kicker

In the kicker, electrons with amplified modulation signal give energy kick to ions towards their reference energy, which leads to the cooling of ion beam. We transfer data from GENESIS to SPACE for kicker simulations. Quadrupole setting in the kicker is symmetric with that in modulator. Figure 6 shows the electron beam envelope and the longitudinal density modulation in the kicker, and the energy kick from electron beam to ions is displayed in Fig. 7.

Green dots in Fig. 7 indicate ions with energy spread 5.7e-4, which is the limit for CeC experiment, as larger energy spread may reduce cooling and even cause heating. Yellow dots represent ions with energy spread 3e-4, which is the working point of CeC experiment.

The electrons lose energy in FEL section, so they have smaller group velocity than the ion in the kicker section. We have adjusted the phase of the electrons to put the ion slightly behind the peak of the density modulation. Therefore, the ion with reference energy in Fig. 7 gets positive velocity kick initially and negative velocity kick later. The overall velocity kick is zero in the kicker. The velocity kick to ions with off-reference energies, shown in Fig. 7, is used to predict the cooling time. A more realistic estimation of cooling time should include random kicks from surrounding ions and electrons.

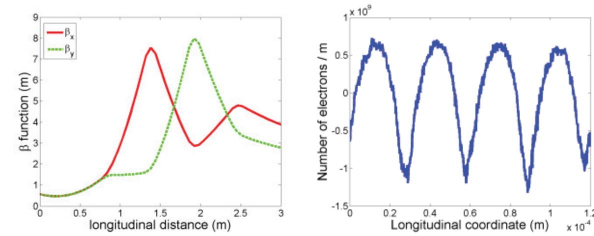

Figure 6: Evolution of electron beam β function (left) and amplified longitudinal density modulation (right) in kicker.

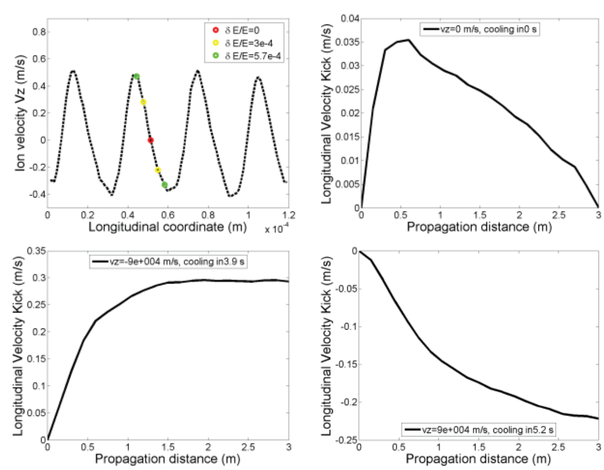

Figure 7: Coherent longitudinal velocity kick to ions with various energy spread (top left), a single ion with reference energy (top right), a single ion with lower energy of energy spread 3e-4 (bottom left) and a single ion with higher energy of energy spread 3e-4 (bottom right) in kicker.

SIMULATIONS OF PLASMA-CASCADE MICRO-BUNCHING AMPLIFIER

In the plasma-cascade micro-bunching amplifier, electron beam is strongly focused to cause the fast-growing plasma instability and to amplify the modulation signal. Our simulations use parameters of PCA designed for BNL RHIC [4].

Figure 8 shows the transverse beam size evolution in a four-cell PCA and the gain of longitudinal density modulation. The maximum gain is 120 at 30 THz, which is suitable for CeC.

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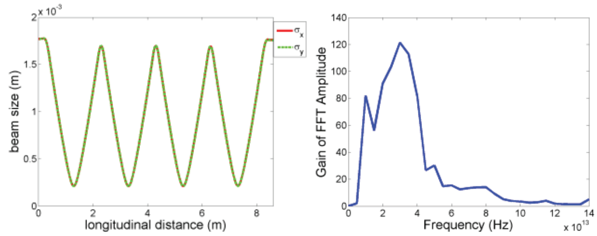

Figure 8: Evolution of transverse beam size (left) and spectrum of gain of density modulation (right) in a four-cell plasma cascade amplifier.

We have added an initial density modulation and tracked the evolution of the signal. Dynamics of the density modulation in PCA are presented in the 2-D plot in Fig. 9. Electrons at the transverse edge fall behind the central electrons, as they experience stronger solenoid field, which is observed in Fig. 9. In the middle right plot of Fig. 9, several transverse modes appear when electron beam passed the waist of the second cell in PCA. The amplification in density modulation in PCA has been demonstrated in the simulation studies. The evolution of the initial velocity modulation has been investigated [15].

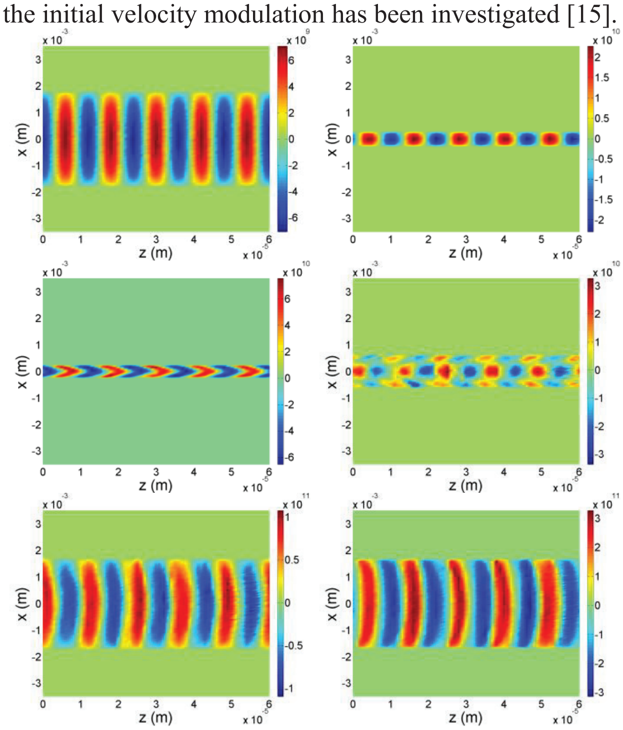

Figure 9: 2-D density modulation in the electron beam at the entrance of PCA (top left), at the waist in first cell (top right), slightly before the waist of second cell (middle left), slightly after the waist of second cell (middle right), end of third cell (bottom left) and exit of fourth cell (bottom right). X-axis is along the horizontal direction and z-axis is along the longitudinal direction.

CONCLUSION

We present the simulation studies of CeC system with two types of amplifiers, the FEL amplifier and the PCA, using code SPACE and GENESIS.

Start-to-end simulations have been performed for ions passing through the coherent electron cooler with FEL amplifier, and the cooling time has been predicted.

The performance of PCA has been explored, and the spectrum of the gain in PCA has been analyzed. Detailed beam dynamics through the PCA have been obtained through numerical simulations.

SPACE will be used in the future study of CeC, and provide strong support to the design and operation of CeC experiment at BNL RHIC.

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