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SIMULATIONS OF COOLING RATE AND DIFFUSION FOR COHERENT ELECTRON COOLING EXPERIMENT

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Abstract

Start-to-end numerical simulations have been performed using the code SPACE and GENESIS for the single pass of gold ions through the coherent electron cooling (CeC) device installed in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Cooling rate of CeC experiment has been predicted using off-reference energy ions in a finite Gaussian electron beam through a realistic beam-line, in which settings of quadrupoles and free-electron laser (FEL) device are relevant to BNL RHIC.

INTRODUCTION

Coherent electron cooling (CeC) [1, 2], a novel technique for rapidly cooling high-energy, high-intensity hadron beams, consists of three sections: a modulator, where the ion beam imprints a density wake on the electron distribution, an amplifier, where the signal induced by the ions is amplified, and a kicker, where the electron beam carrying the amplified signal interacts with the ions, resulting in dynamical friction for the ion. A general schematic of CeC is illustrated in Fig. 1.

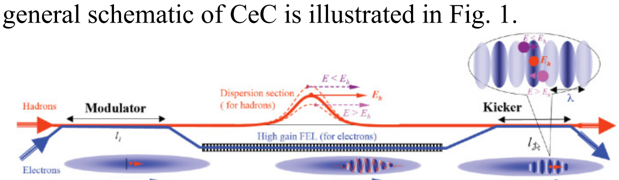

Figure 1: Schematic of coherent electron cooling concept.

Table 1 lists the Beam parameters used for CeC numerical simulations, which are relevant to BNL RHIC.

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	5 π mm mrad	2 π mm mrad
R.M.S. energy spread	1e-3	3e-4

Our Simulation tools are SPACE [3] and GENESIS [4]. SPACE is a parallel, relativistic, 3D electromagnetic Particle-in-Cell (PIC) code and has been used for the study of plasma dynamics in a dense gas filled RF cavity [5], the study of mitigation effect by beam induced plasma [6], and the study of plasma-cascade micro-bunching amplifier [7]. SPACE contains electrostatic module using AP-Cloud method [8], which is used in this study to calculate the space charge forces in beam frame. GENESIS is a three dimensional, time dependent code, developed for high gain FEL simulations.

Simulation studies of modulator, the first section of CeC, have been performed using a single ion with code SPACE [9, 10, 11, 12]. The particle distribution at the end of modulator simulation is put into GENESIS for FEL simulation, which act as amplifier, the second section of CeC device at BNL RHIC. The output from FEL simulation is brought back into SPACE for simulations of kicker, the third section of CeC.

MODULATOR

Figure 2 shows the evolution of β function of electron beam in the modulator section and the resulting density modulation induced by a single gold ion with reference energy located at the center of the Gaussian electron beam. More simulation results of modulation process using ions with various off-reference energies and off-axis locations can be found in [9, 10, 11, 12].

Quadrupoles are used to focus the electron beam in modulator and to match beam size in horizontal and vertical directions at the exit of modulator, which gives maximum gain in the following FEL section.

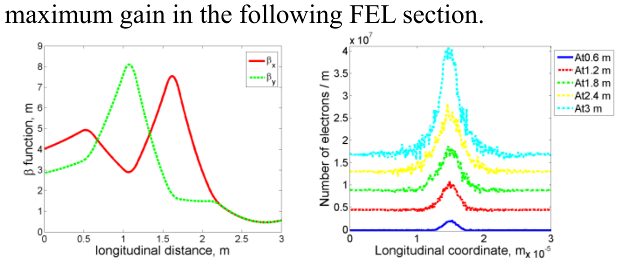

Figure 2: Evolution of β function (left) and longitudinal density modulation (right) in modulator section.

AMPLIFIER

The amplifier is used to strengthen the modulation signal carried by the electron beam, and has various implementations, such as the plasma-cascade micro-bunching amplifier [7]. High gain FEL is used as the amplifier in the CeC proof-of-principle experiment at BNL, and we have used code GENESIS for FEL simulations.

6-D particle distribution at the exit of modulator has been saved into a binary file, which is the input to FEL simulations. We also specify the wiggler settings according to the FEL device at BNL RHIC, which

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consists of three separate wigglers with drift space in between. Achieving matched beam β function over all three wigglers is impossible because of the drift space, so we have designed an oscillating beam envelope with minimum variation over the whole FEL section. Fig. 3 shows the locations of the three wigglers and the optimal β function evolution.

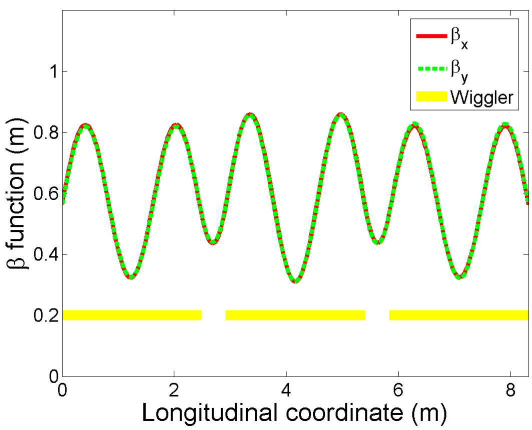

Figure 3: Location of three wigglers in FEL device and β function evolution with minimum overall variation.

Bunching factor is an important parameter in GENESIS, which is defined as [4] in Eq. (1),

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

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 modulator simulations, it is sufficient to use one slice of electron beam with length λ_{opt}, as λ_{opt} is 30 times larger than longitudinal Debye length. In FEL, we need much larger scale in longitudinal direction because of the widening of the wave packet. Typically we have used 400 slices in FEL simulations using GENESIS. Figure 4 shows the initial and final bunching factor amplitudes in FEL. We clearly observe the widening of the signal and an approximate gain of 210 in bunching factor amplitude.

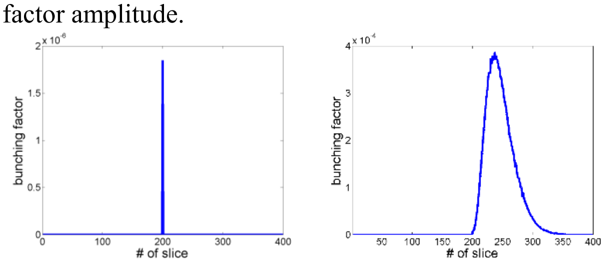

Figure 4: Amplitudes of bunching factor at the entrance (left) and exit (right) of FEL section.

Electron beam is delayed by wigglers, resulting in a slippage between ions and electrons, and the slippage is 37 slices with λ_{opt} as the slice length. Ion beam should appear at the location where the maximum amplitude of amplified signal occurs at the exit of FEL, to achieve maximum cooling. We have selected the optimal peak current and emittance of electron beam, given in Table 1, to make the maximum gain of bunching factor amplitude at 237th slice at the exit of FEL, as is shown in Fig. 4.

The diffusion of the ion's energy is associated with two processes: intra-beam scattering (which we do not discuss here) and random kick associated with longitudinal electric fields induced by surrounding ions:

$$D_{CeC} = \frac{\langle(\sum_k \Delta E_k)^2\rangle}{T} = \frac{\langle\sum_k \Delta E_k^2\rangle}{T} \quad (2)$$

where T is the revolution time of the ions in the rings and ΔE_k is energy change of a sample ion caused by k^{th} ion in the beam. We naturally assumed that there is full mixing at optical wavelength scale and their energy kicks are random. The kick from k^{th} ion on the one we sampled can be presented in a form of wave-packet:

$$\Delta E_k = -\varepsilon(z - z_k)\, sin(k(z - z_k) + \varphi) \quad (3)$$

where k is the FEL wavenumber, $z - z_k$ is the distance between ions, φ is the phase for the self-action of the ion, and $\varepsilon(z - z_k)$ is the energy kick envelope which is a smooth function of the FEL wavelength. In this case we can rewrite expression for diffusion as

$$D_{CeC} = \frac{N_i'}{2T}\int_{-\infty}^{+\infty} \varepsilon^2\, dz \equiv \frac{\varepsilon_0^2}{2T} N_i' l_c \quad (4)$$

where $\varepsilon_0 = \varepsilon(0)$ is energy kick by self-correction peak field, $N_i' = N_i/\sqrt{2\pi}\sigma_z$ is linear density of the ions in the beam and $l_c \equiv \int_{-\infty}^{+\infty} \varepsilon(z)^2 dz/\varepsilon_0^2$ is the electric field correlation length.

ε_0/E_0=1.73e-9 is calculated from simulation results where E_0 is ions' reference energy, N_i'=3.75e+7/m and T=1.28e-5 s are obtained using parameters relevant to BNL RHIC, and l_c=1e-3 m is derived from the wave packet at exit of FEL simulation which is shown in Fig. 4. The diffusion rate for CeC is D_{CeC}/E_0^2=4.53e-9/s.

KICKER

In the kicker, the interaction between ions and the electron beam carrying amplified modulation signal reduces the energy spread of ion beam. The electron beam distribution at the exit of FEL has been put back into code SPACE for kicker simulations. We have used electrons within 4 slices (236th to 239th), where maximum gain occurs, at the final stage of FEL simulations using GENESIS. Figure 5 shows the β function evolution and the amplified modulation signal in kicker section. Quadrupoles are used in the kicker to focus the electron beam and the quadrupole setting is symmetric with that in modulator.

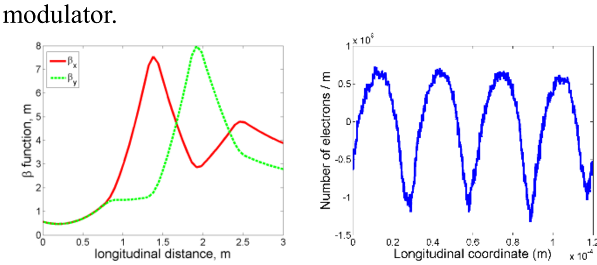

Figure 5: Evolution of β function (left) and final longitudinal density modulation (right) in kicker section.

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Gold ions with reference energy should get zero velocity kick, so we need to phase the kick force to find the correct location for reference energy ions. We have recorded the electric field at various longitudinal positions in the electron beam and made time integral over the whole kicker section to obtain the velocity kick to ions, and the result is shown in Fig. 6 with black dash line.

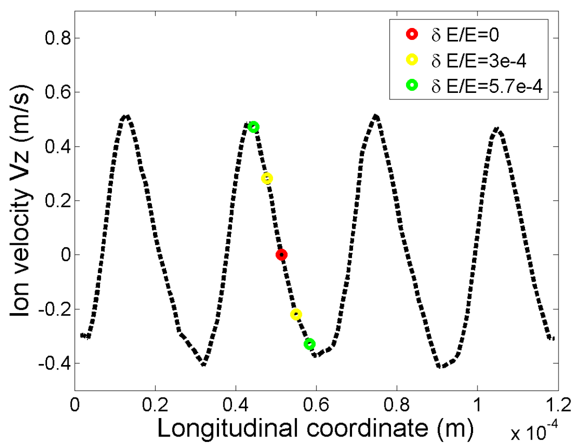

Figure 6: Velocity kick to a single gold ion at various longitudinal locations in a single pass through CeC system. Red dot represents the ion with reference energy, which gets zero velocity kick. Yellow dots show the higher energy ion (right) and lower energy ion (left) with energy spread 3e-4. Green dots indicate the higher energy ion (right) and lower energy ion (left) with energy spread 5.7e-4.

The red dot in Fig. 6 is the location for the gold ion with reference energy, which gets zero velocity kick, and locations of off-reference ions can be calculated from energy spread. The green dots in Fig. 6 tell us that the maximum energy spread we can have in ion beam is 5.7e-4, because ions with larger energy spread could exceed the cooling regime and result in anti-cooling. Red dots in Fig. 6 illustrate the off-reference ions with energy spread 3e-4, which is our parameter in CeC experiment given in Table 1.

Figure 7 shows the velocity kick to an ion with reference energy in kicker. The change in kicker force is due to the slippage of electron beam. Electrons lose energy in FEL section, and therefore slip backwards with respect to ions. The reference energy ion is put slightly behind the peak of wave packet at the entrance of kicker, and passes the peak later because of the slippage of electron beam. Consequently, the kick force pulls the ion forward initially and backward later, and gives overall zero kick.

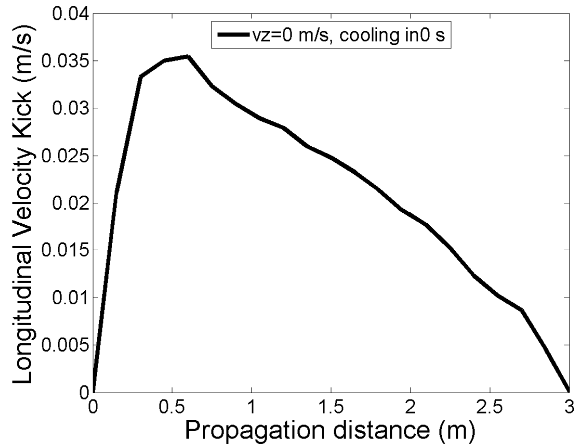

Figure 7: Velocity kick to a single gold ion with reference energy in kicker.

We have tracked the velocity kick to off-reference ions in the kicker section and calculated the cooling time, and the results are given in Fig. 8.

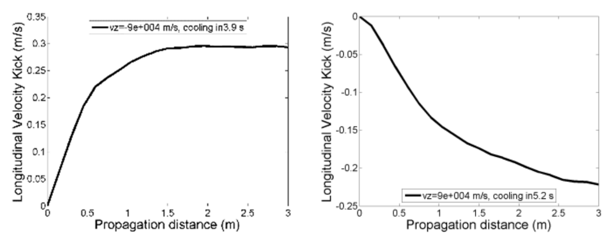

Figure 8: Velocity kick to a single gold ion with lower energy (left) and higher energy (right) with energy spread 3e-4 in kicker and resulting cooling time. Values of velocities are in beam frame.

The ion with lower energy continues slipping backwards while the higher energy ion keeps going forwards, with respect to the reference energy ion. The electron beam, which loses energy in FEL, always moves backwards. The combination of all these movements causes the difference in velocity kick and cooling time between higher energy and low energy ions in Fig. 8.

CONCLUSION

We have used code SPACE and GENESIS performing start-to-end simulations for CeC. A reasonable beam envelope has been obtained in a realistic beam-line, with quadrupoles in modulator and kicker and 3 separate wigglers in amplifier (FEL). Kick force has been phased in the kicker section and velocity kick has been tracked for ions with reference and off-reference energies to predict cooling time, which is a strong support for the CeC experiment at BNL RHIC.

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