Simulation of the Ion Bunch in the Presence of the CeC for the New Energy Scheme

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Outline

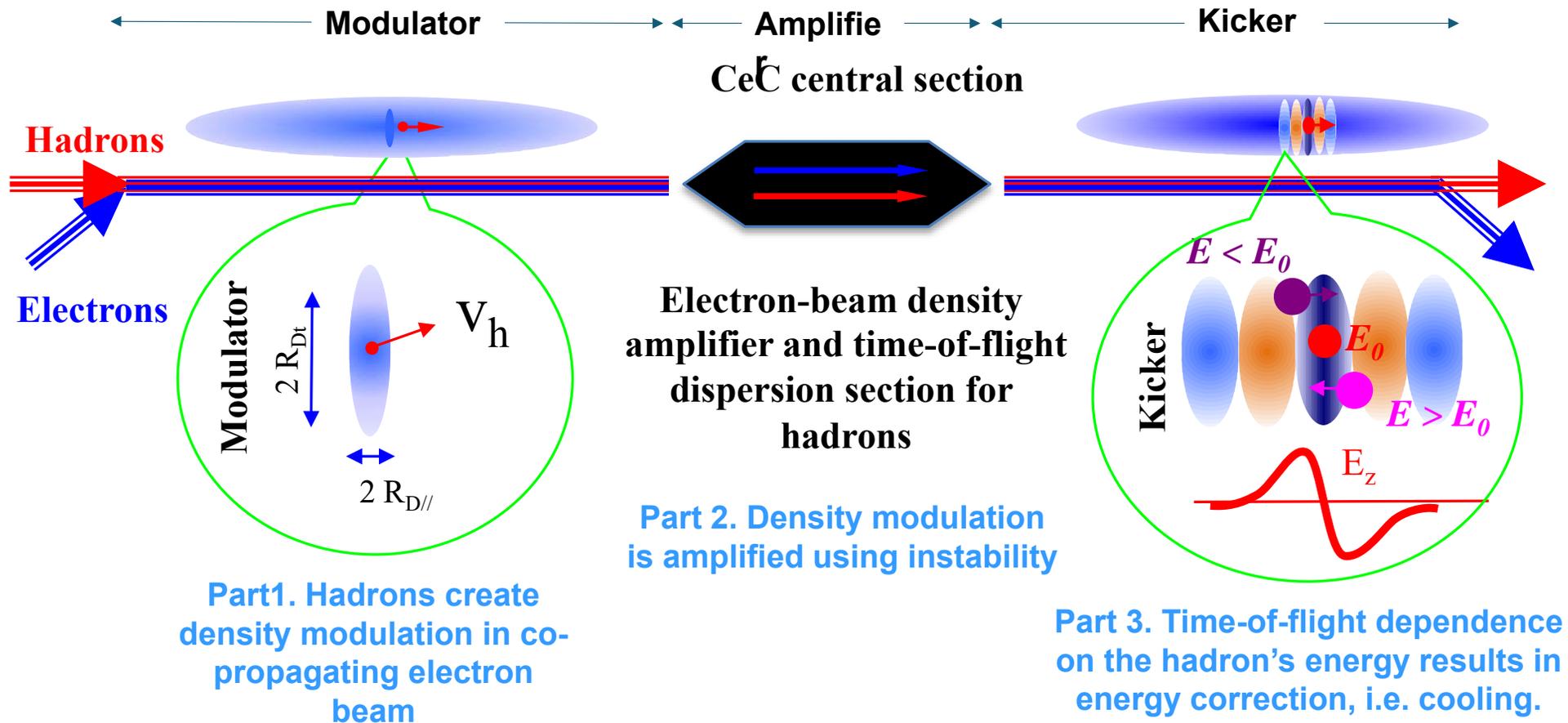Brookhaven
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Coherent electron Cooling

Modulator   **Amplifie**   **Kicker**

CeC central section

Hadrons

Electrons

V_h

$2\,R_{Dt}$

$2\,R_{D//}$

Electron-beam density amplifier and time-of-flight dispersion section for hadrons

$E < E_0$

E_0

$E > E_0$

E_z

Part1. Hadrons create density modulation in co-propagating electron beam

Part 2. Density modulation is amplified using instability

Part 3. Time-of-flight dependence on the hadron's energy results in energy correction, i.e. cooling.

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Plasma-Cascade Instability

$$\tilde{n}'' + \omega_p^2 \tilde{n} = 0$$

Longitudinal plasma oscillation with periodically varying plasma frequency

$$\frac{d^2 \tilde{n}}{dt^2} + \omega_p^2(t) \tilde{n} = 0;$$

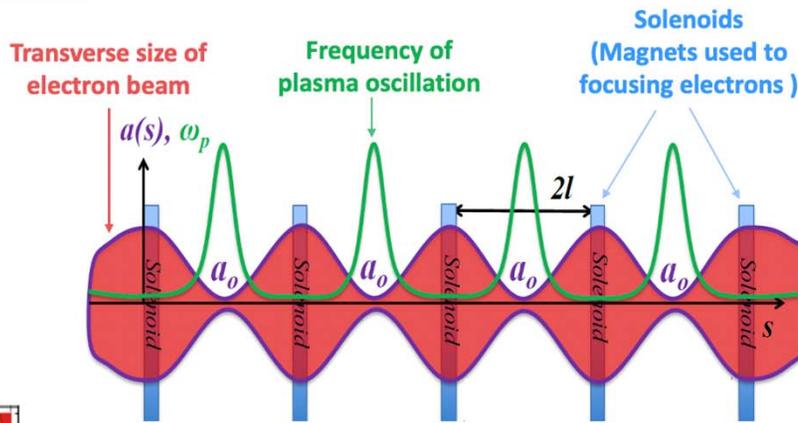Betatron motion in a FODO cell

$$y'' + K_y(s) y = 0,$$

FODO CELL

$$\hat{n}'' + 2k_{sc}^2 \hat{a}(\hat{s})^{-2} \hat{n} = 0$$

$$\hat{a}'' = k_{sc}^2 \hat{a}^{-1} + k_\beta^2 \hat{a}^{-3}$$
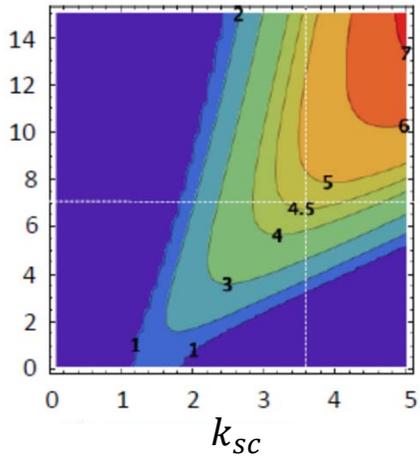
$$\begin{pmatrix} \hat{n} \\ \hat{n}' \end{pmatrix}_{s=-l} = M_{total} \begin{pmatrix} \hat{n} \\ \hat{n}' \end{pmatrix}_{s=l}$$

Transverse size of electron beam

Frequency of plasma oscillation

Solenoids (Magnets used to focusing electrons)

$a(s), \omega_p$

$2l$

a_o a_o a_o a_o

Solenoid

s

k_β

k_{sc}

Stability condition

$$|\lambda| = \left| (M_{total})_{1,1} \pm \sqrt{(M_{total})_{1,1}^2 - 1} \right| \leq 1$$
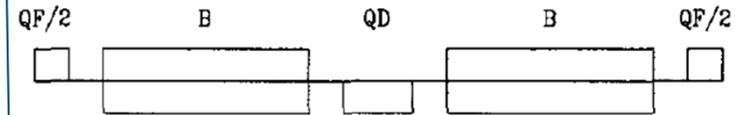
$$k_{sc} = \sqrt{\frac{2}{\beta_o^3 \gamma_o^3} \frac{I_o}{I_A} \frac{l^2}{a_o^2}}$$

$$k_\beta = \frac{\varepsilon l}{a_o^2}$$

QF/2   B   QD   B   QF/2
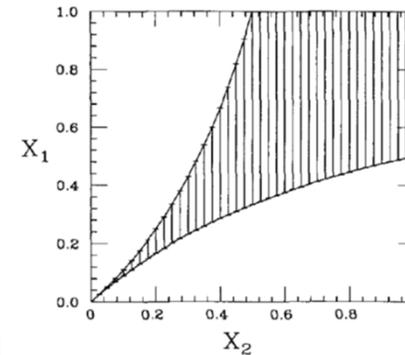
$$M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f_1} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f_1} & 1 \end{pmatrix}$$
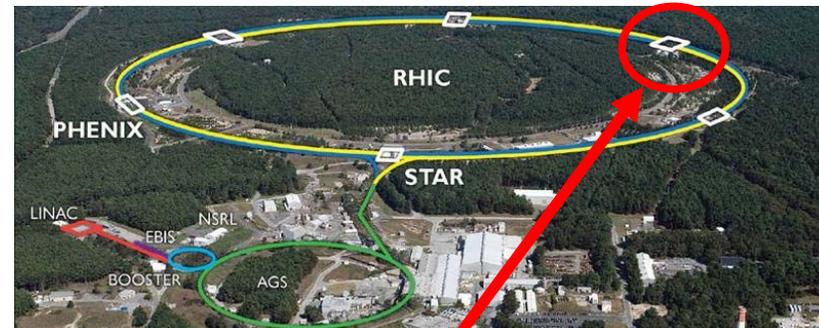
$$= \begin{pmatrix} 1 + \frac{L_1}{f_2} - \frac{L_1}{f_1} - \frac{L_1^2}{2f_1 f_2} & 2L_1(1 + \frac{L_1}{2f_2}) \\ \frac{1}{f_2} - \frac{1}{f_1} - \frac{L_1}{f_1 f_2} + \frac{L_1}{2f_1^2} + \frac{L_1^2}{4f_1^2 f_2} & 1 + \frac{L_1}{f_2} - \frac{L_1}{f_1} - \frac{L_1^2}{2f_2^2} \end{pmatrix},$$
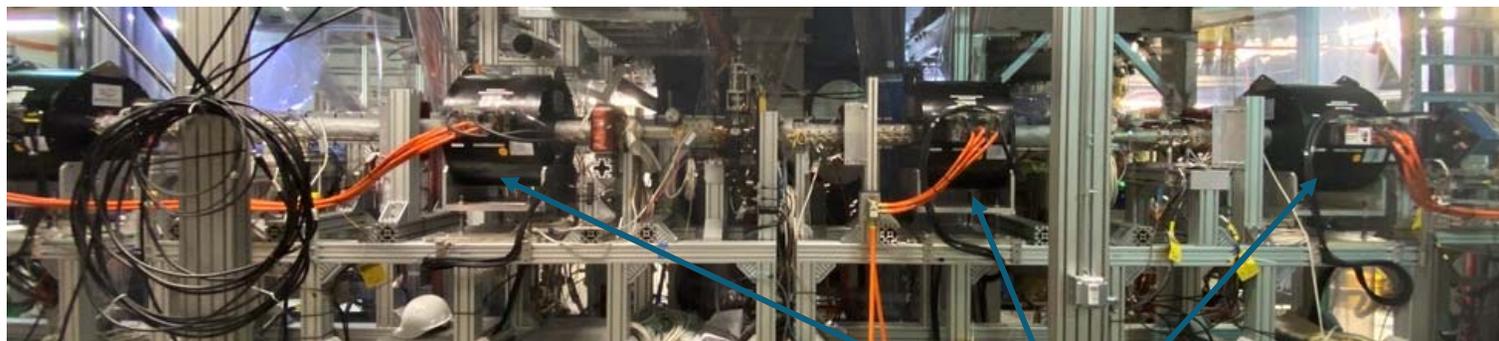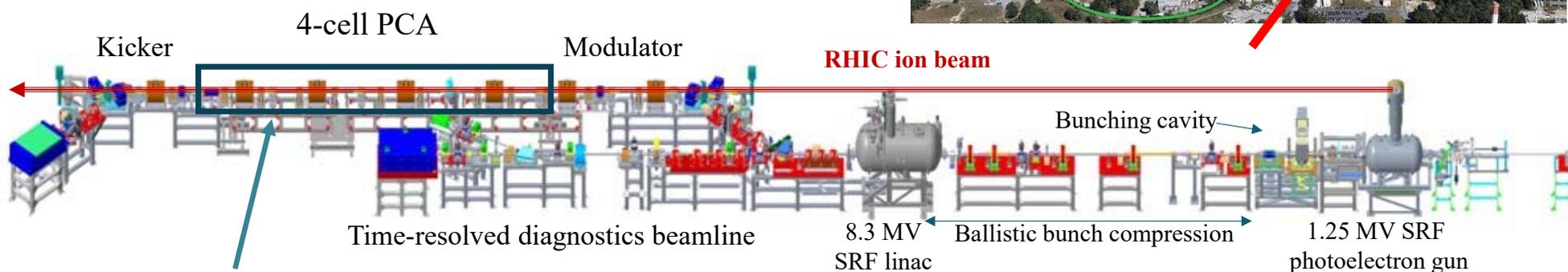
$$X_1 = L_1 / 2f_1$$
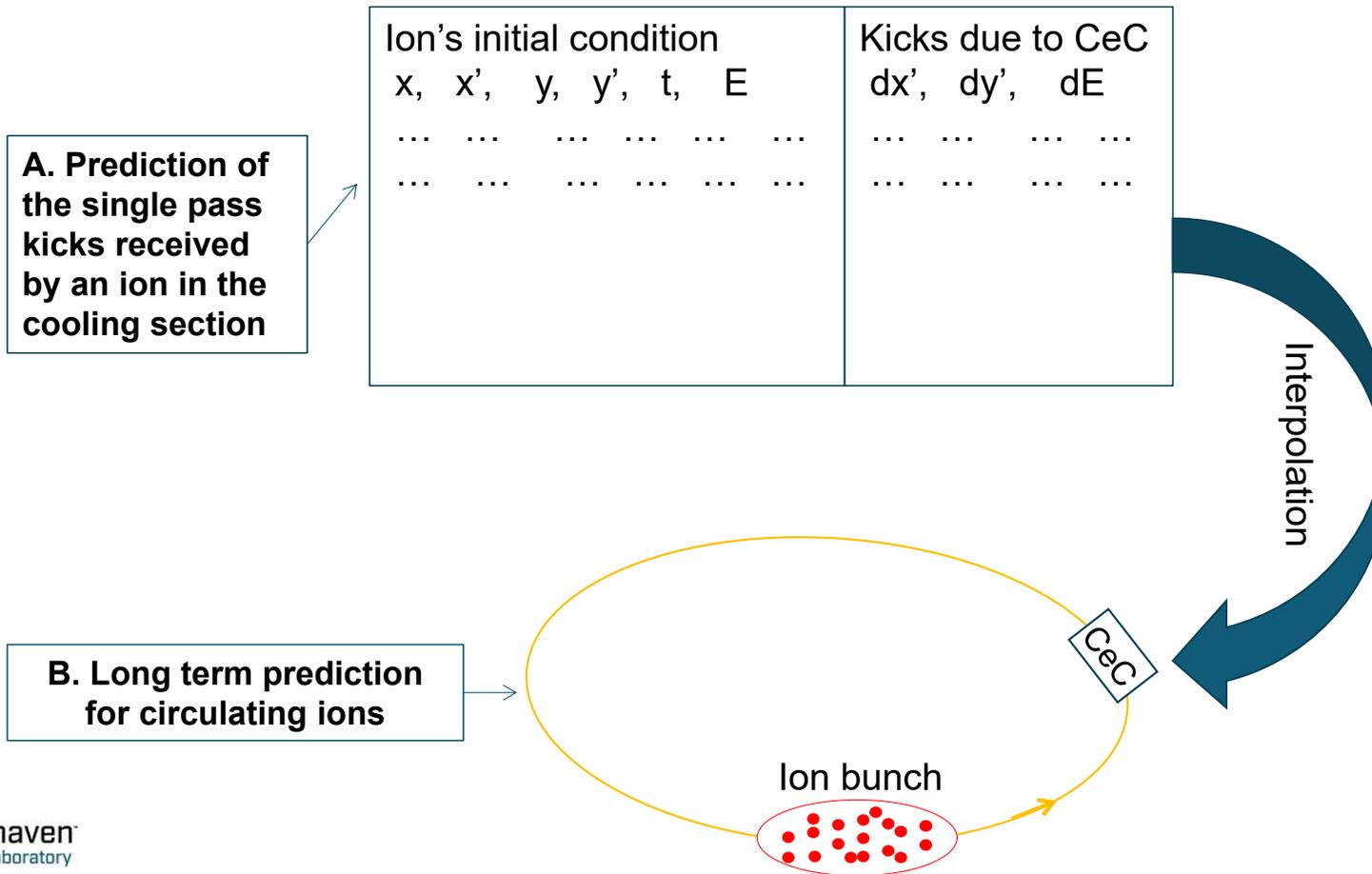
$$X_2 = L_1 / 2f_2$$

CeC experiment at RHIC

Kicker 4-cell PCA Modulator RHIC ion beam

Bunching cavity

Time-resolved diagnostics beamline 8.3 MV SRF linac Ballistic bunch compression 1.25 MV SRF photoelectron gun

Solenoids for Plasma-Cascade Amplifier

Overall Structure of CeC Prediction

Ion's initial condition						Kicks due to CeC			
x,	x',	y,	y',	t,	E	dx',	dy',	dE	
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…

A. Prediction of the single pass kicks received by an ion in the cooling section

Interpolation

CeC

B. Long term prediction for circulating ions

Ion bunch

The ion tracking codes

Create Macro-ion (2e5~6e6) → RF update → Transverse motion update → IBS update → CeC update

The code was benchmarked with numerical solution of the Fokker-Planck equation for a linear cooling force.

RF update
$$\begin{cases} \bar{\varepsilon} = \varepsilon + \dfrac{q}{mc^2} V_{rf}(\tau), \\[2mm] \bar{\tau} = \tau + \dfrac{T_{\text{rev}}\eta}{\beta^2 \gamma_0} \bar{\varepsilon}, \end{cases}$$

Transverse betatron motion update

$$\begin{pmatrix} \bar{x} \\ \bar{p}_x \\ \bar{y} \\ \bar{p}_y \end{pmatrix} = \begin{pmatrix} \cos\psi_x & \sin\psi_x & 0 & 0 \\ -\sin\psi_x & \cos\psi_x & 0 & 0 \\ 0 & 0 & \cos\psi_y & \sin\psi_y \\ 0 & 0 & -\sin\psi_y & \cos\psi_y \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{p}_x \\ \bar{y} \\ \bar{p}_y \end{pmatrix}$$

CeC update
$$\Delta\delta\gamma_{j,n} = \Delta\delta\gamma_{cool}\left(x_{j,n}, y_{j,n}, z_{j,n}, \delta\gamma_{j,n}\right) + d_{ion} \cdot X_{j,n} + d_e \cdot Y_{j,n}$$
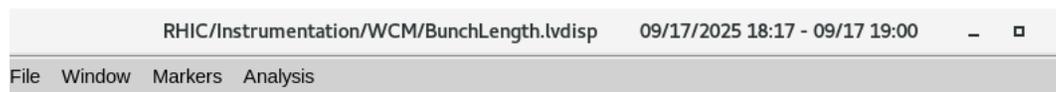
IBS update
$$\Delta x'_{j,n} = d_{IBS,x}\left(z_{j,n}\right) \cdot X_{j,n}, \ \Delta y'_{j,n} = d_{IBS,y}\left(z_{j,n}\right) \cdot Y_{j,n}, \Delta\delta_{j,n} = d_{IBS,z}\left(z_{j,n}\right) \cdot Z_{j,n}$$

Ion beam parameters

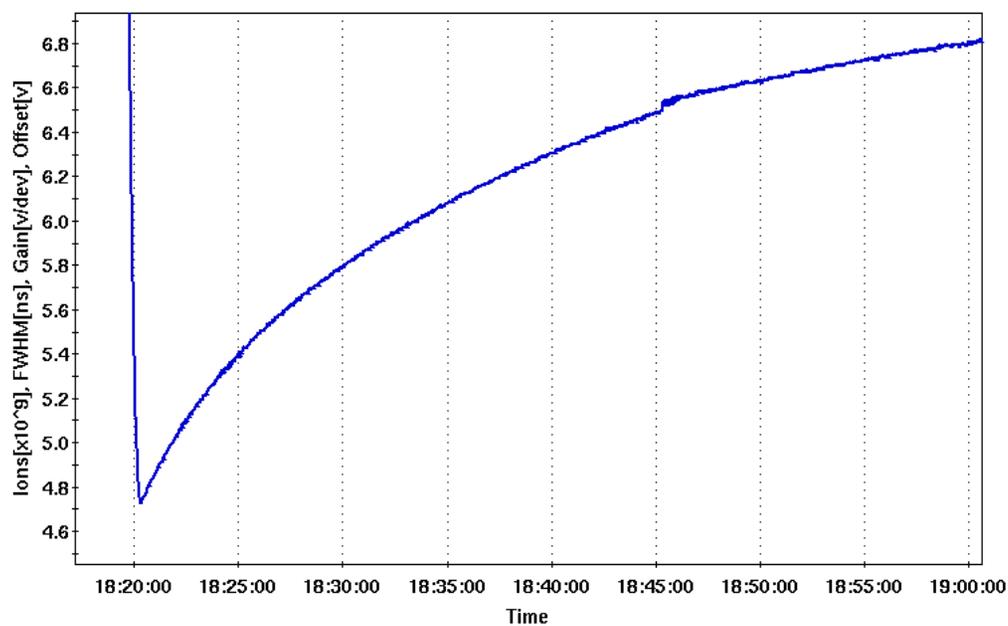- We have developed the RHIC ramp for the CeC experiment with γ=19.5 on 9/17/2025.
- During the CeC store, the ion bunches have intensity of 1e9.
- To make the cooling easier, we plan to cool an ion bunch with intensity of 2e8.

Ion beam parameters	
Energy, γ	19.5
Bunch intensity	2e8
RMS bunch length	2 ns
Norm. RMS emittance	2.5 mm.mrad
RF frequency	28 MHz
RF voltage	4.3 MV
Average beta function at IR2	11 m
Average RMS beam size	1.2 mm

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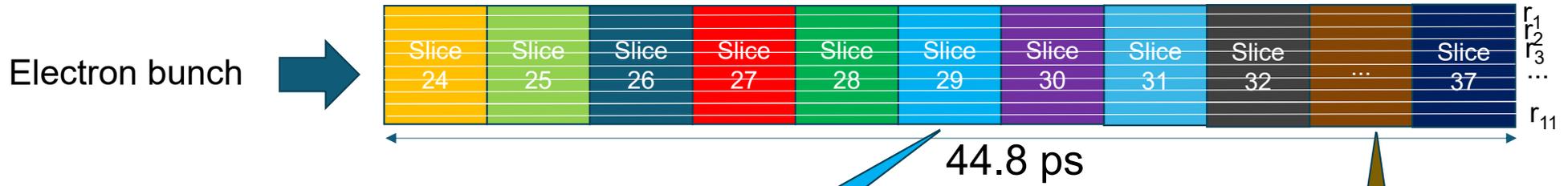# Benchmarking IBS algorithm with experiment

Electron beam parameters

- The table shows what is needed to have sufficient PCA gain for cooling. In reality, the parameters such as peak current, slice emittance and local energy spread will not be uniform across the whole bunch.
  - ➤ Hence, it is crucial to have a significant portion of the electron bunch satisfy these requirement.
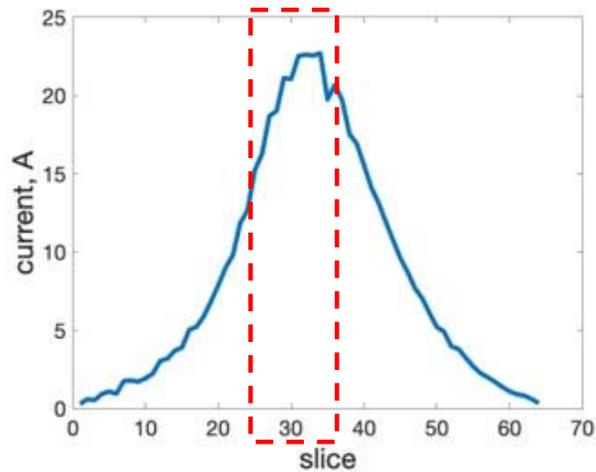 - ➤ The ion tracking algorithm needs to apply different cooling force for ions at different location within the electron bunch.

Electron beam Parameter	
Charge per bunch, nC	0.8
Peak current, A	20
Normalized emittance, RMS, μm	1.25
Beam energy (inj), MeV	1.71
Final beam energy, MeV	10
Energy spread, RMS	$< 2 \times 10^{-4}$
Bunch rep-rate, kHz	78

Dependance of the cooling force on the location of the ion

Electron bunch

| Slice 24 | Slice 25 | Slice 26 | Slice 27 | Slice 28 | Slice 29 | Slice 30 | Slice 31 | Slice 32 | ... | Slice 37 |

r_1
r_2
r_3
...
r_{11}

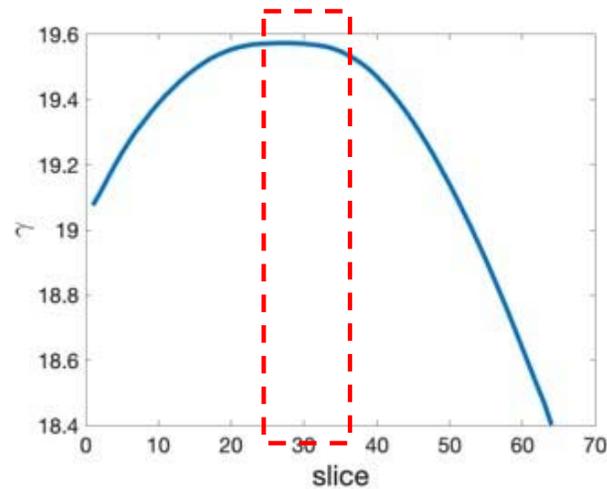44.8 ps

Energy kick at 13.88 m
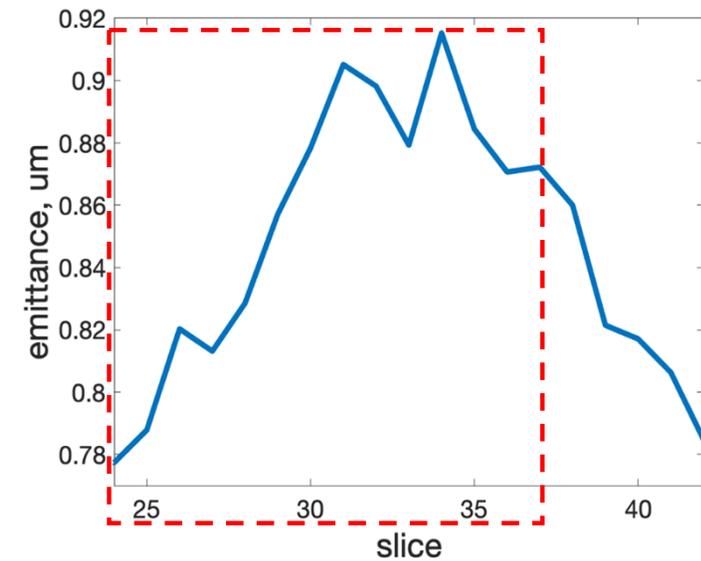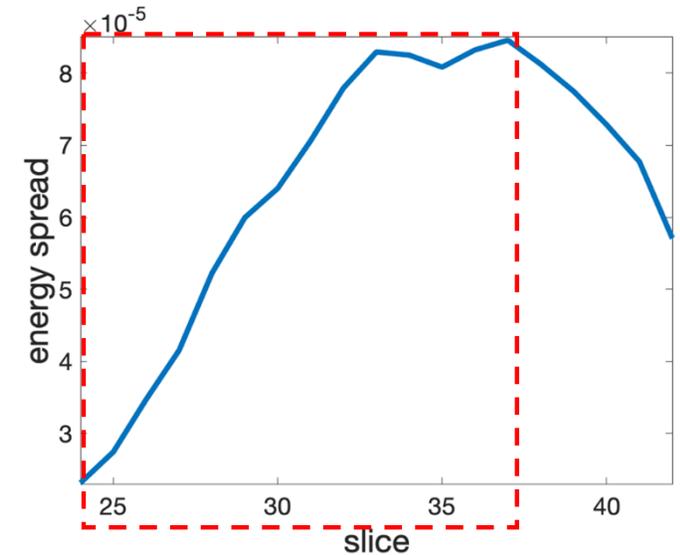

Energy kick at 13.88 m

Courtesy to J. Ma

Electron beam parameters from simulation

(a)

(b)

- The average energy starts to decrease after slice #31 which leads to slippage of the cooling wave-packet w.r.t. the ion to be cooled.
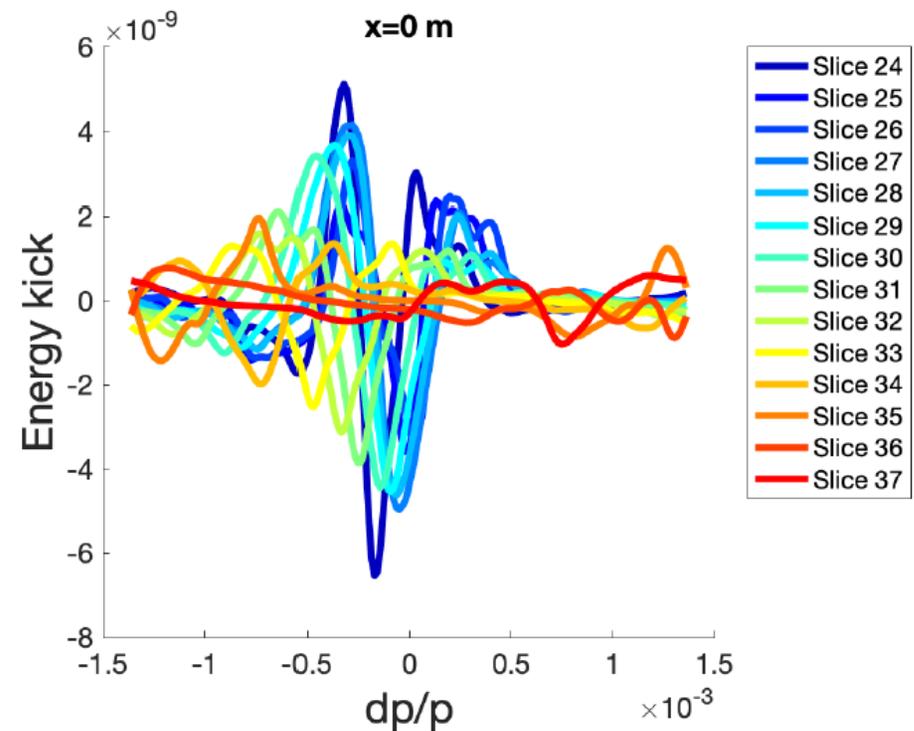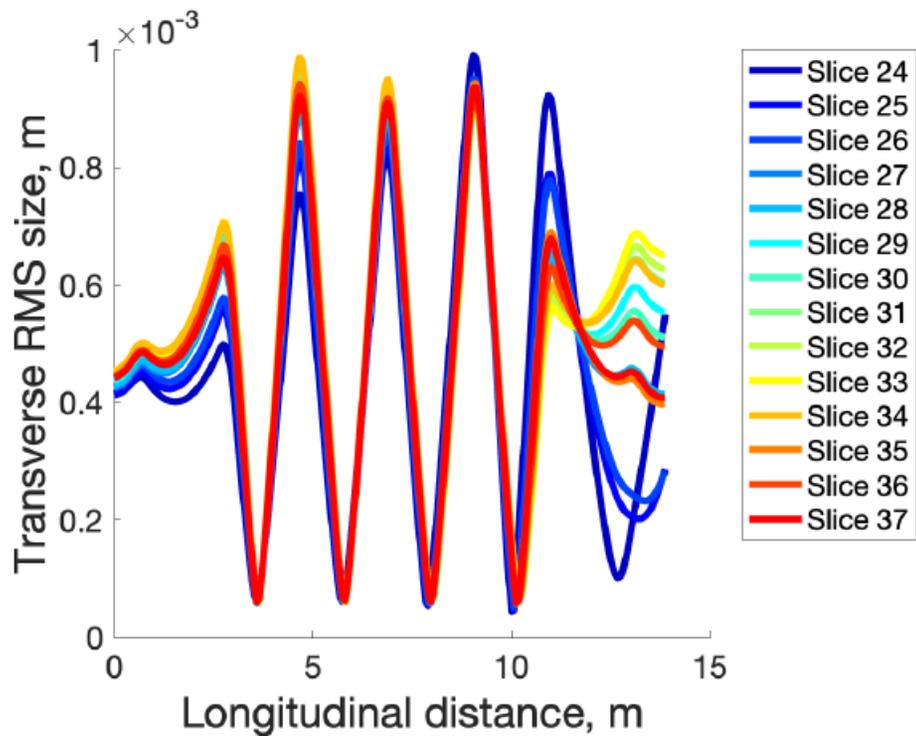
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Three setups of the PCA

40.51 A	-80.68 A	84.6 A	-84.6 A	84.6 A	-80.68 A	40.51 A
40.51 A	-80.68 A	83.8 A	-83.8 A	83.8 A	-80.68 A	40.51 A
50 A	-82 A	86.9 A	-86.9 A	86.9 A	-82 A	50 A

- There are seven solenoids in the cooling section. Solenoid 1 controls the beam size at the CeC modulator. Solenoid 2 to solenoid 6 are key components for the plasma-cascade amplifier (PCA). Solenoid 7 controls the beam size exiting the common section.
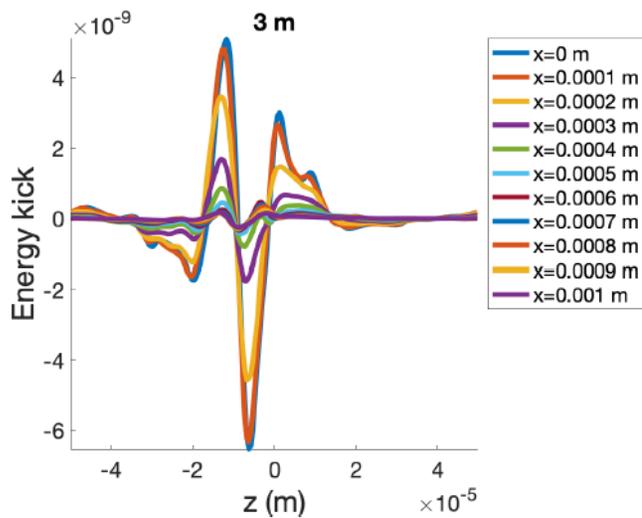
Setup 1: Dependance of cooling force on the longitudinal location of the ion

The cooling wakes from slice 31-37 have significant delay w.r.t. other slices and their amplitudes are significant. Setup 2 and setup 3 are attempts to reduce the amplitudes of these 'anti-cooling' slices.
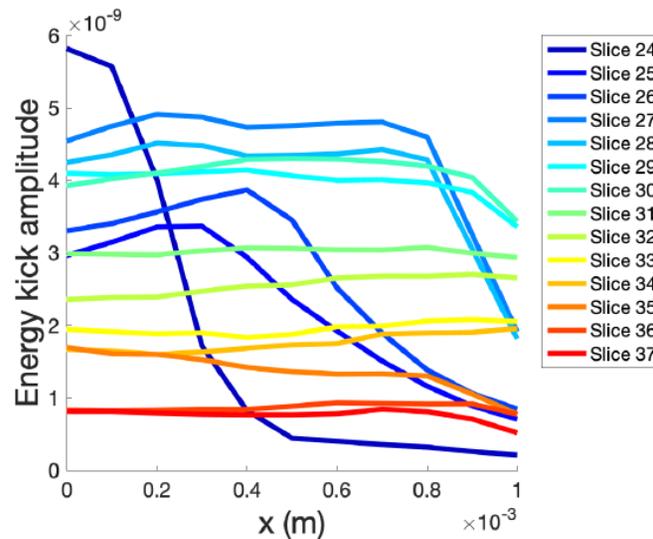
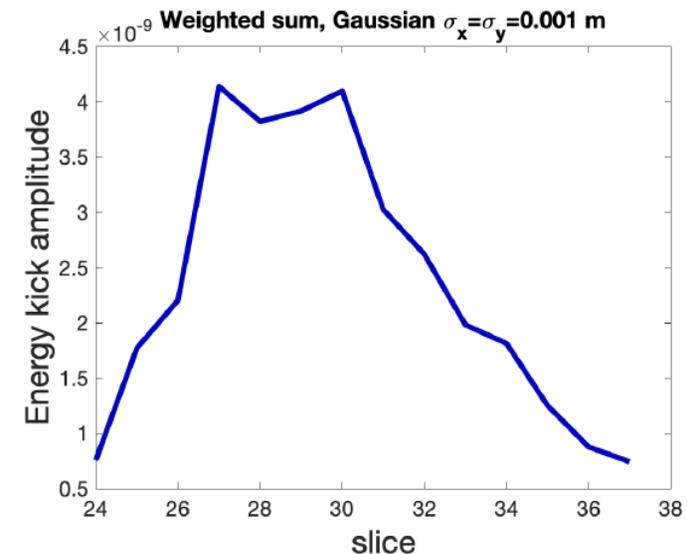# Setup 1: Dependance of the cooling force on the transverse location of the ion

Cooling wakes at different transverse location for slice #24

Amplitude of the cooling wakes as a function of the transverse location
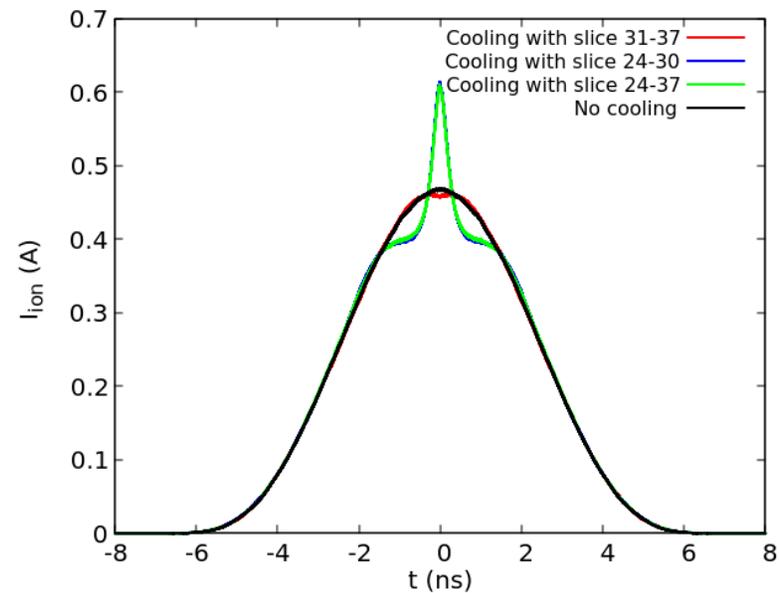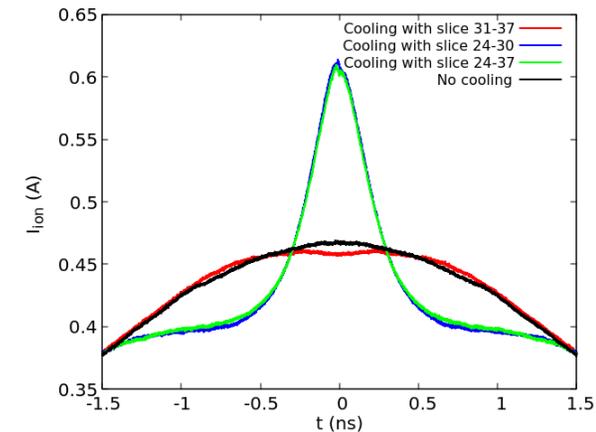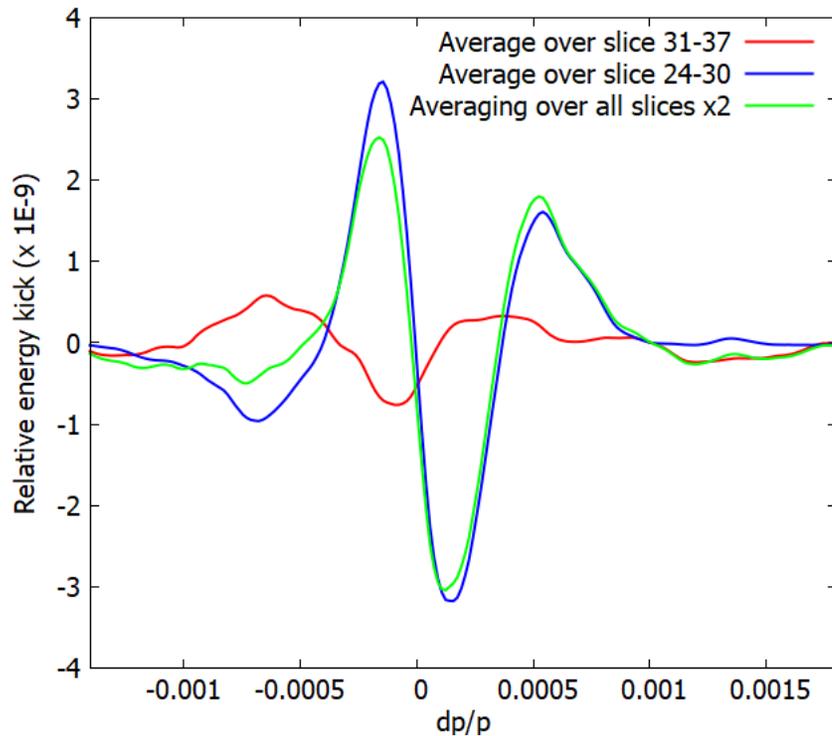
Amplitude of the cooling wakes averaged over the transverse distribution of the ion beam

Ion beam Evolution for setup 1

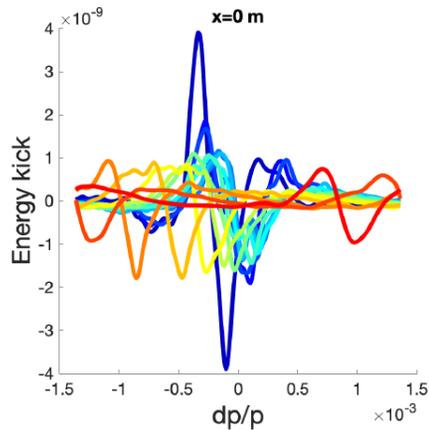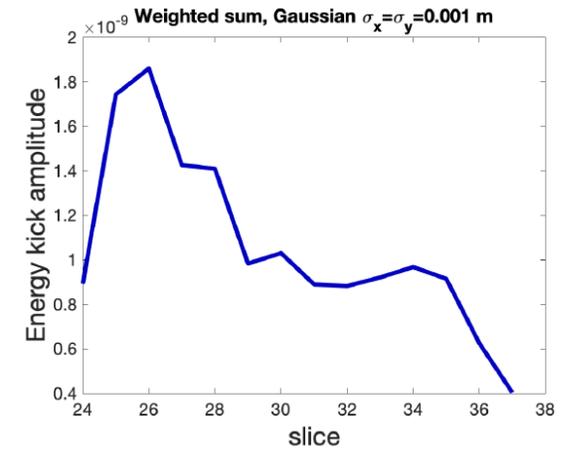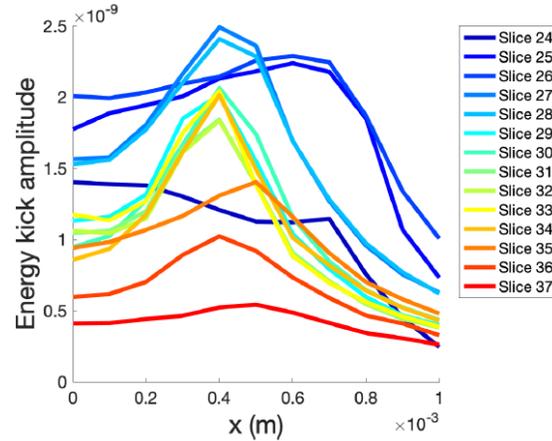While the amplitudes of the cooling wake for slice31-37 are not small, their average contribution to cooling tends to cancel each other and consequently, anti-cooling effects from these slices are insignificant.

Setup 2 & setup 3

- While trying to reduce amplitudes of the cooling force from 'anti-cooling' slices, setup 2&3 also reduced the cooling force for cooling slices.
- In addition, for setup 3, the cooling force decays quickly with transverse offset.

Comparison of three PCA schemes

- Setup 1 looks most promising out of the three setups;
- Cooling performance from setup 3 become much worse since not only the amplitude of the cooling force become smaller, the cooling force also decays quicker with the transverse offset of the ion.

Tolerance on noise in electrons

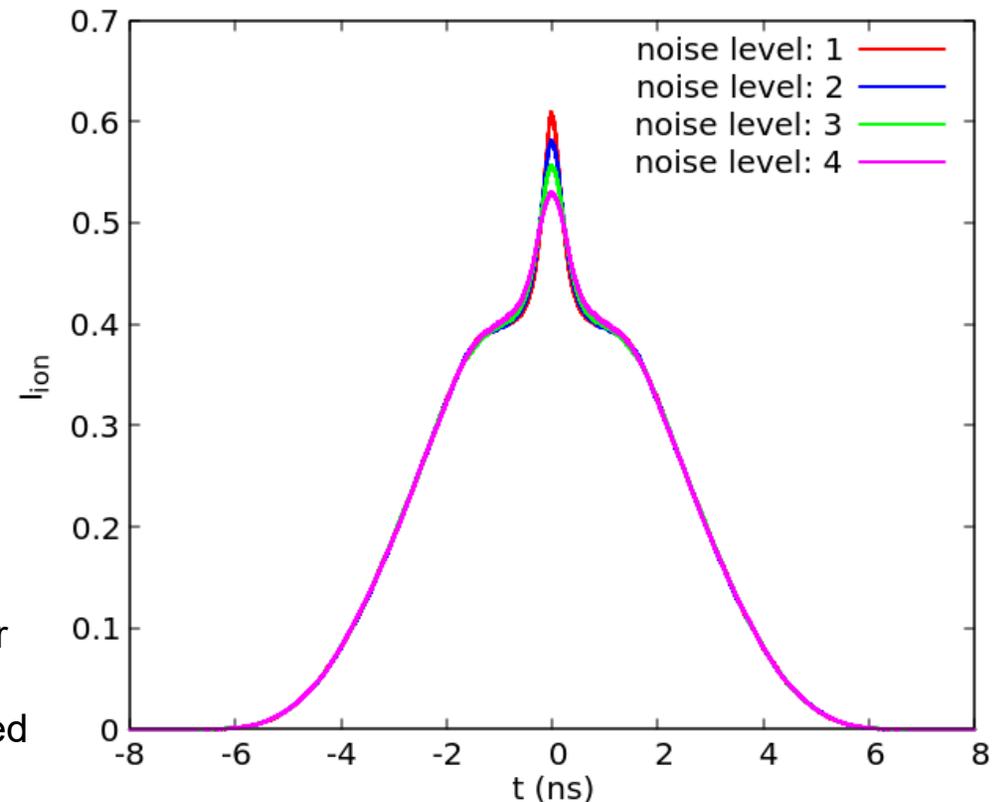- In the presence of excess noise in the electron beam, the diffusive kicks due to the neighbour electrons become larger.

- To implement this effects into the ion tracking, a factor R is introduced into the CeC updates algorithm

$$\Delta\delta\gamma_{j,n} = \Delta\delta\gamma_{cool}\left(x_{j,n}, y_{j,n}, z_{j,n}, \delta\gamma_{j,n}\right) + d_{ion} \cdot X_{j,n}$$
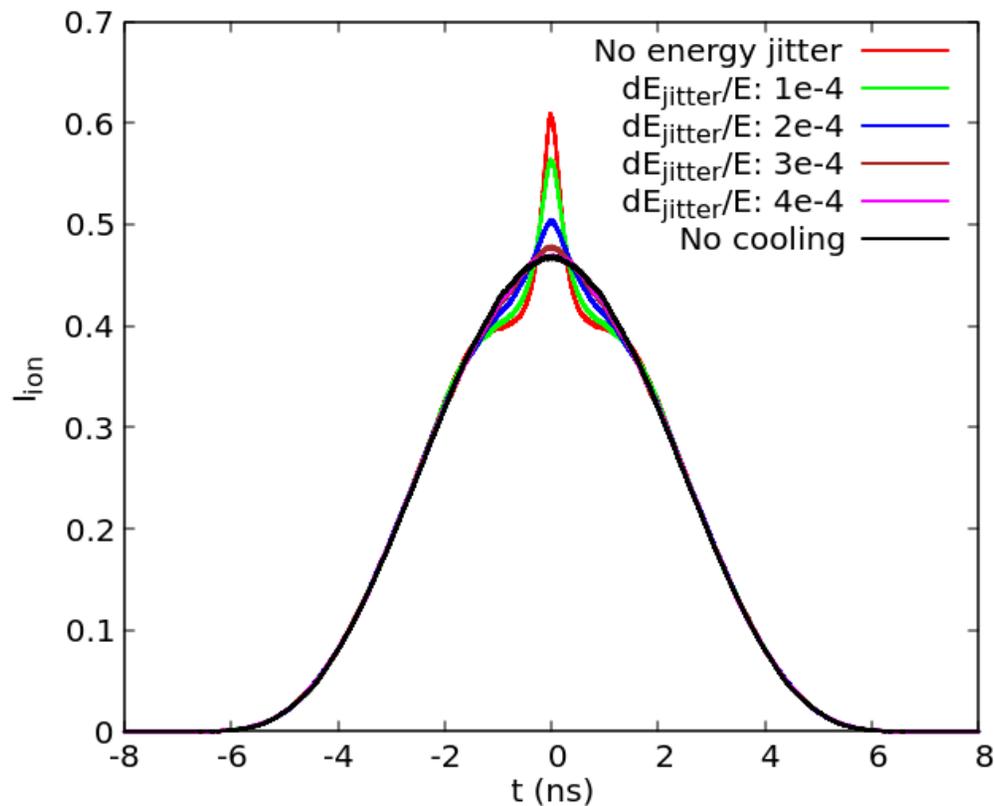$$+ R \cdot d_e \cdot Y_{j,n}$$

Poisson Noise: $R = 1$

Noise level 2: $R = 2$

- The effects from the noises in the electrons are weaker than what they were for the FEL-based CeC, since the coherent length is significantly shorter in the PCA-based CeC. (0.5 mm in FEL-based CeC and ~0.02 mm in PCA-based CeC)

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Tolerance on the energy jitter

If the presence of the energy jitter in the electron bunches, the relative position of the cooling wake will shift around w.r.t the ion to be cooled and hence reduce the cooling efficiency.

Summary

- According to simulations with SPACE, the cooling force for the new energy scheme (gamma=19.6) have been increased by a factor of 4, compared with what was simulated for the previous energy scheme (gamma=28.6). In addition, the portion of the electron bunch contributing to cooling has also been increased from 10-15 ps to 22.4 ps.
- With the significantly increased cooling force and increased portion of electrons participating in cooling, the modification of the profile of the ion bunch due to cooling should be observable after 4 minutes of cooling.
- The preliminary studies show that the cooling performance in this scheme should not be significantly affected if the noise level in the electrons stays below four times of the Poisson noise.
- The energy jitter of the electron beam has to stay below 1e-4 to avoid substantial reduction in the cooling performance.