



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

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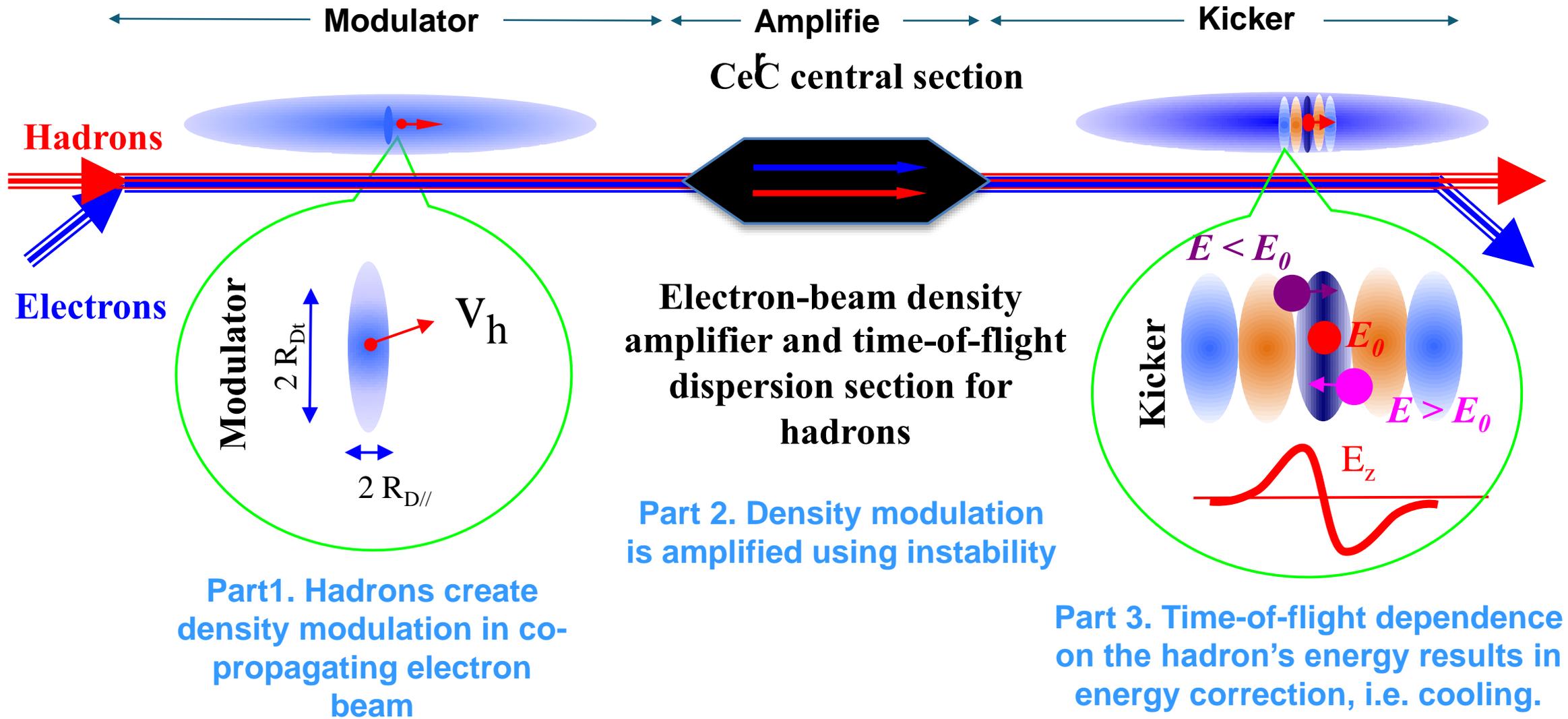


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Outline

- ❑ Introduction
 - Coherent electron cooling (CeC)
 - Plasma cascade amplifier (PCA)
 - CeC experiment at RHIC
- ❑ The simulation of the PCA-based CeC experiment
 - Overall structure
 - Ion tracking procedures
 - Implementing the dependance of the cooling force on the ion's 3D location
- ❑ Results for the PCA-based CeC experiment in the new beam energy
 - Comparing results for the three PCA setups
 - Tolerance on the noises in the electrons
 - Tolerance on the energy jitter of the electron bunches
- ❑ Summary

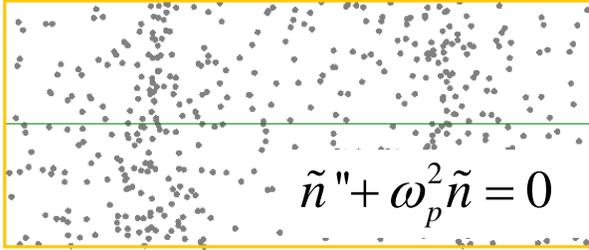
Coherent electron Cooling



Plasma-Cascade Instability

Longitudinal plasma oscillation with periodically varying plasma frequency

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

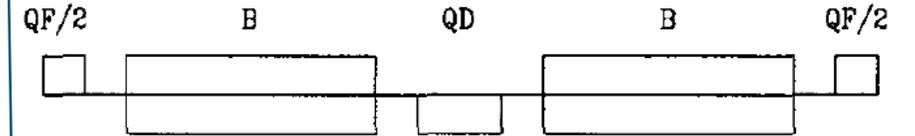


$$\tilde{n}'' + \omega_p^2 \tilde{n} = 0$$

Betatron motion in a FODO cell

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

FODO CELL



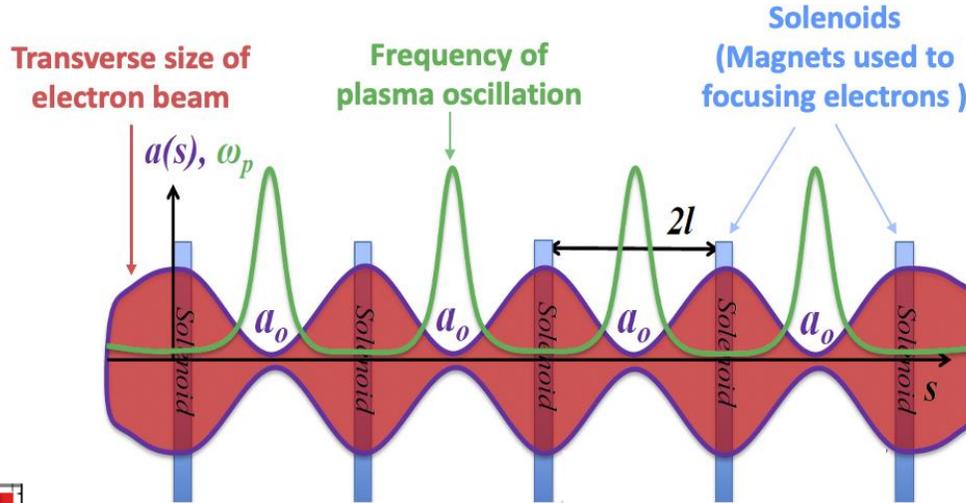
$$M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f_1} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f_1} & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1 + \frac{L_1}{f_2} - \frac{L_1}{f_1} - \frac{L_1^2}{2f_1 f_2} & 2L_1(1 + \frac{L_1}{2f_2}) \\ \frac{1}{f_2} - \frac{1}{f_1} - \frac{L_1}{f_1 f_2} + \frac{L_1}{2f_1^2} + \frac{L_1^2}{4f_1^2 f_2} & 1 + \frac{L_1}{f_2} - \frac{L_1}{f_1} - \frac{L_1^2}{2f_1^2} \end{pmatrix},$$

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

$$\hat{a}'' = k_{sc}^2 \hat{a}^{-1} + k_{\beta}^2 \hat{a}^{-3}$$

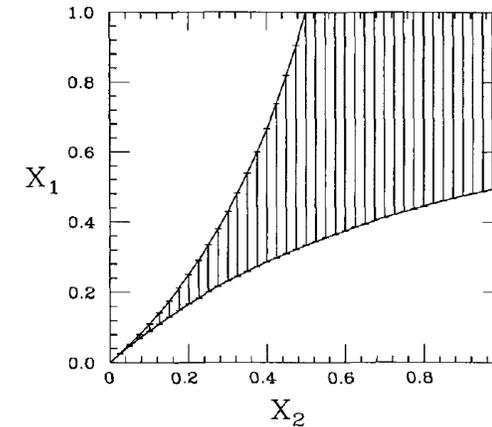
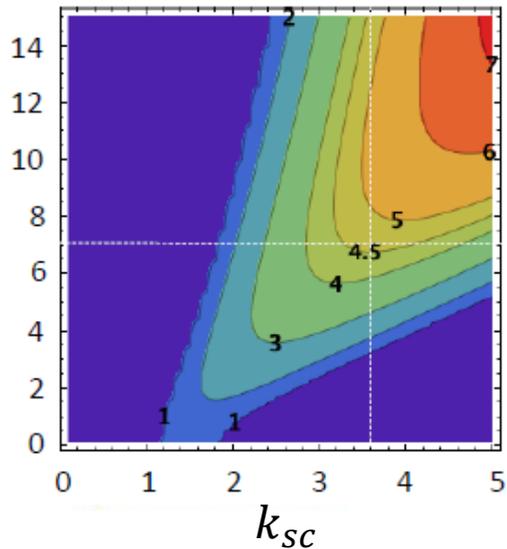
$$\begin{pmatrix} \hat{n} \\ \hat{n}' \end{pmatrix}_{s=-l} = M_{total} \begin{pmatrix} \hat{n} \\ \hat{n}' \end{pmatrix}_{s=l}$$



Stability condition $\rightarrow |\lambda| = \left| (M_{total})_{1,1} \pm \sqrt{(M_{total})_{1,1}^2 - 1} \right| \leq 1$

$$k_{sc} = \sqrt{\frac{2}{\beta_o^3 \gamma_o^3} \frac{I_o l^2}{I_A a_o^2}}$$

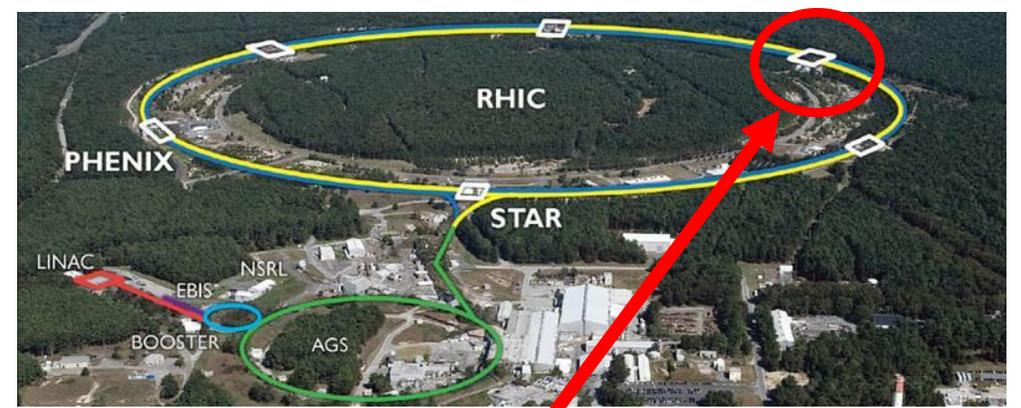
$$k_{\beta} = \frac{\epsilon l}{a_o^2}$$



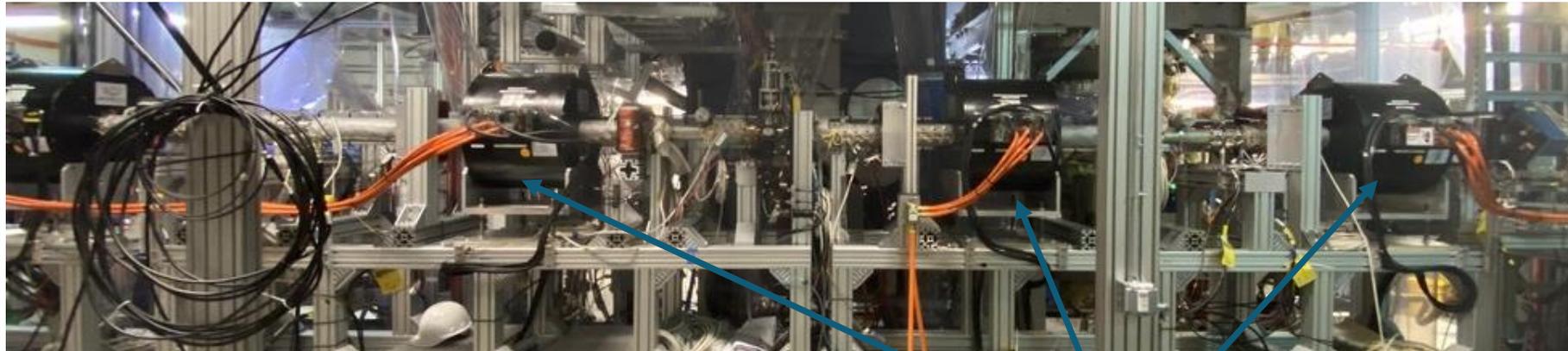
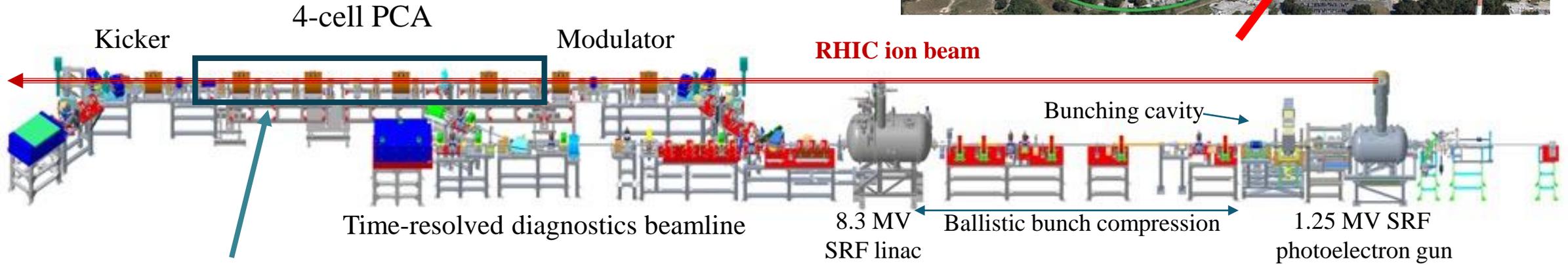
$$X_1 = L_1/2f_1$$

$$X_2 = L_1/2f_2$$

CeC experiment at RHIC



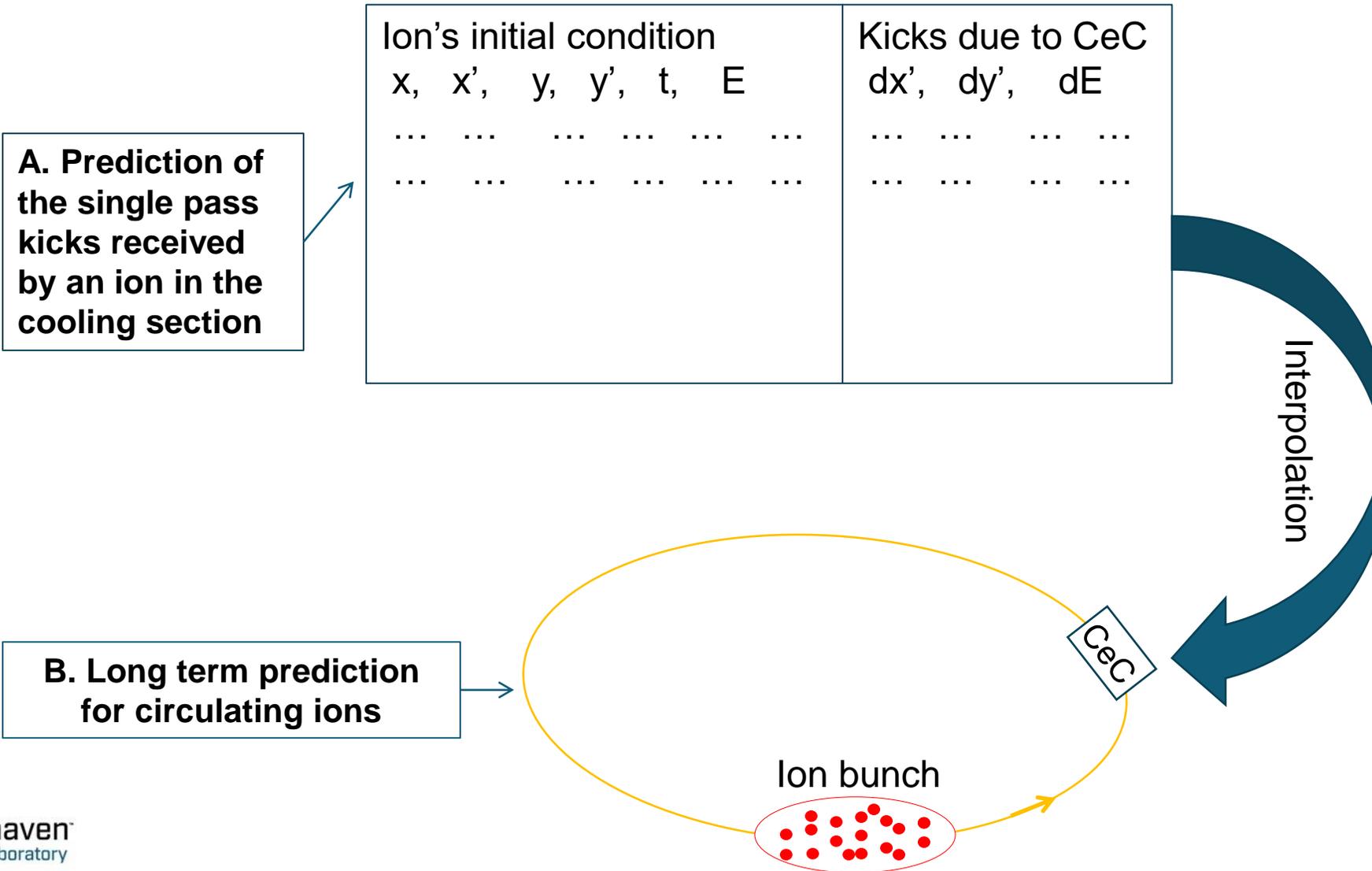
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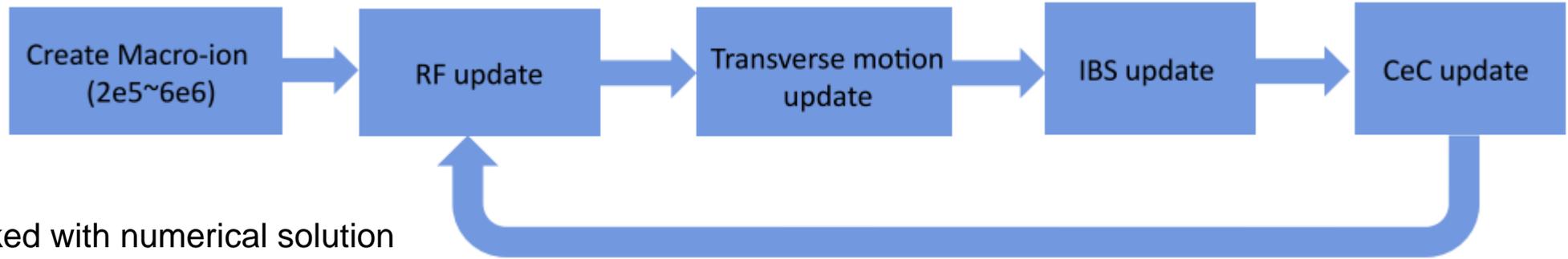
Solenoids for Plasma-Cascade Amplifier

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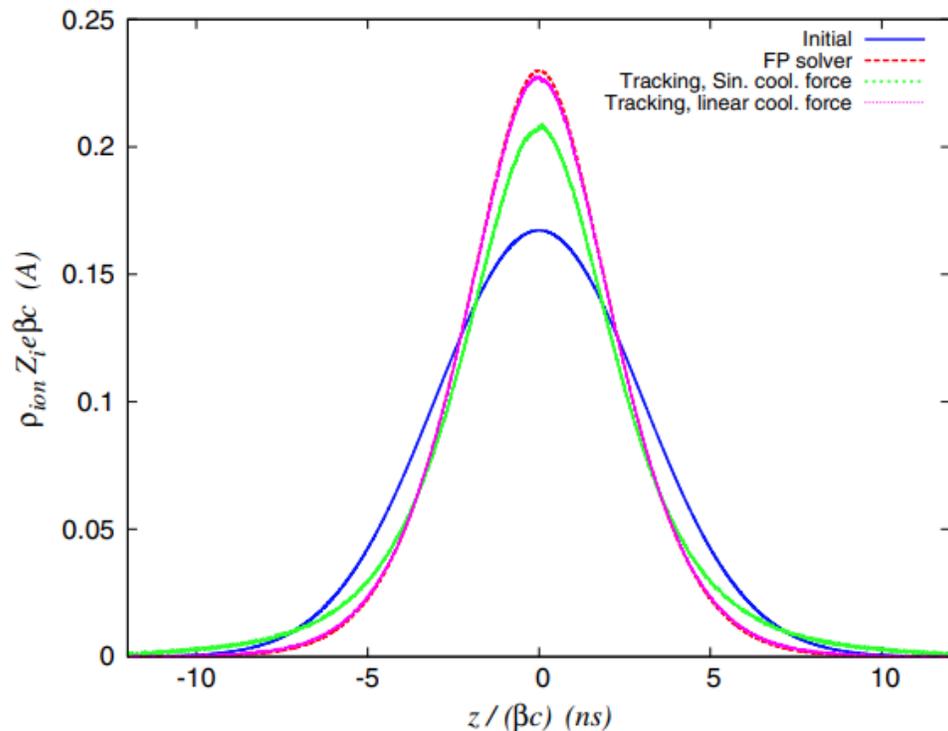
Overall Structure of CeC Prediction



The ion tracking codes



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



RF update

$$\begin{cases} \bar{\varepsilon} = \varepsilon + \frac{q}{mc^2} V_{rf}(\tau), \\ \bar{\tau} = \tau + \frac{T_{rev}\eta}{\beta^2\gamma_0} \bar{\varepsilon}, \end{cases}$$

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

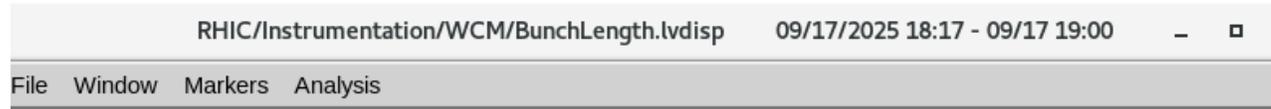
IBS update $\Delta x'_{j,n} = d_{IBS,x}(z_{j,n}) \cdot X_{j,n}, \Delta y'_{j,n} = d_{IBS,y}(z_{j,n}) \cdot Y_{j,n}, \Delta\delta_{j,n} = d_{IBS,z}(z_{j,n}) \cdot Z_{j,n}$

Ion beam parameters

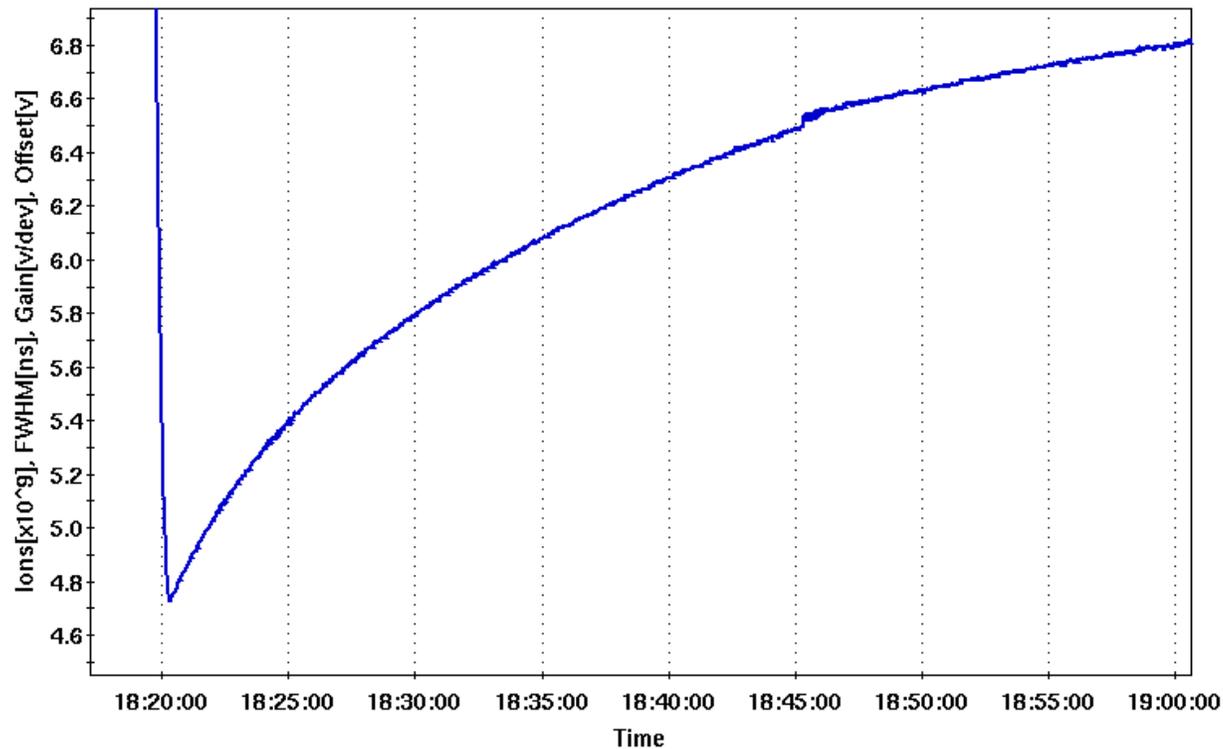
- We have developed the RHIC ramp for the CeC experiment with $\gamma=19.5$ on 9/17/2025.
- During the CeC store, the ion bunches have intensity of $1e9$.
- To make the cooling easier, we plan to cool an ion bunch with intensity of $2e8$.

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

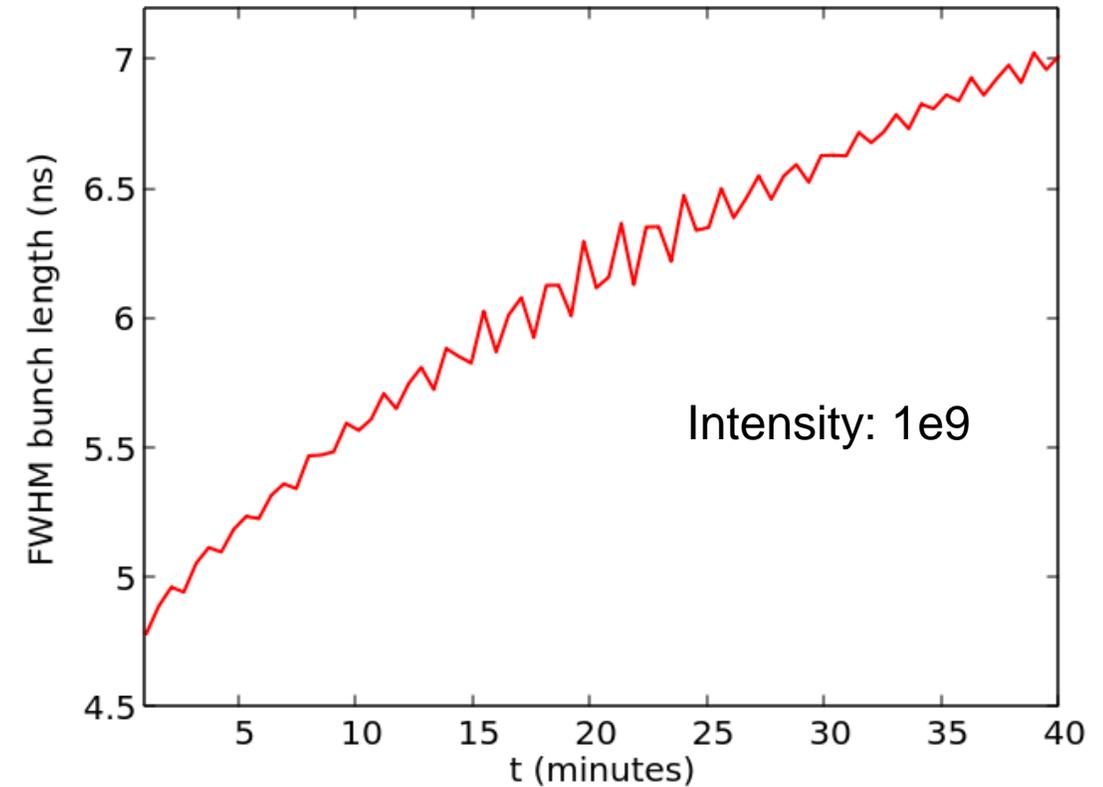
Benchmarking IBS algorithm with experiment



Yellow WCM



ye1_AvgFWHM

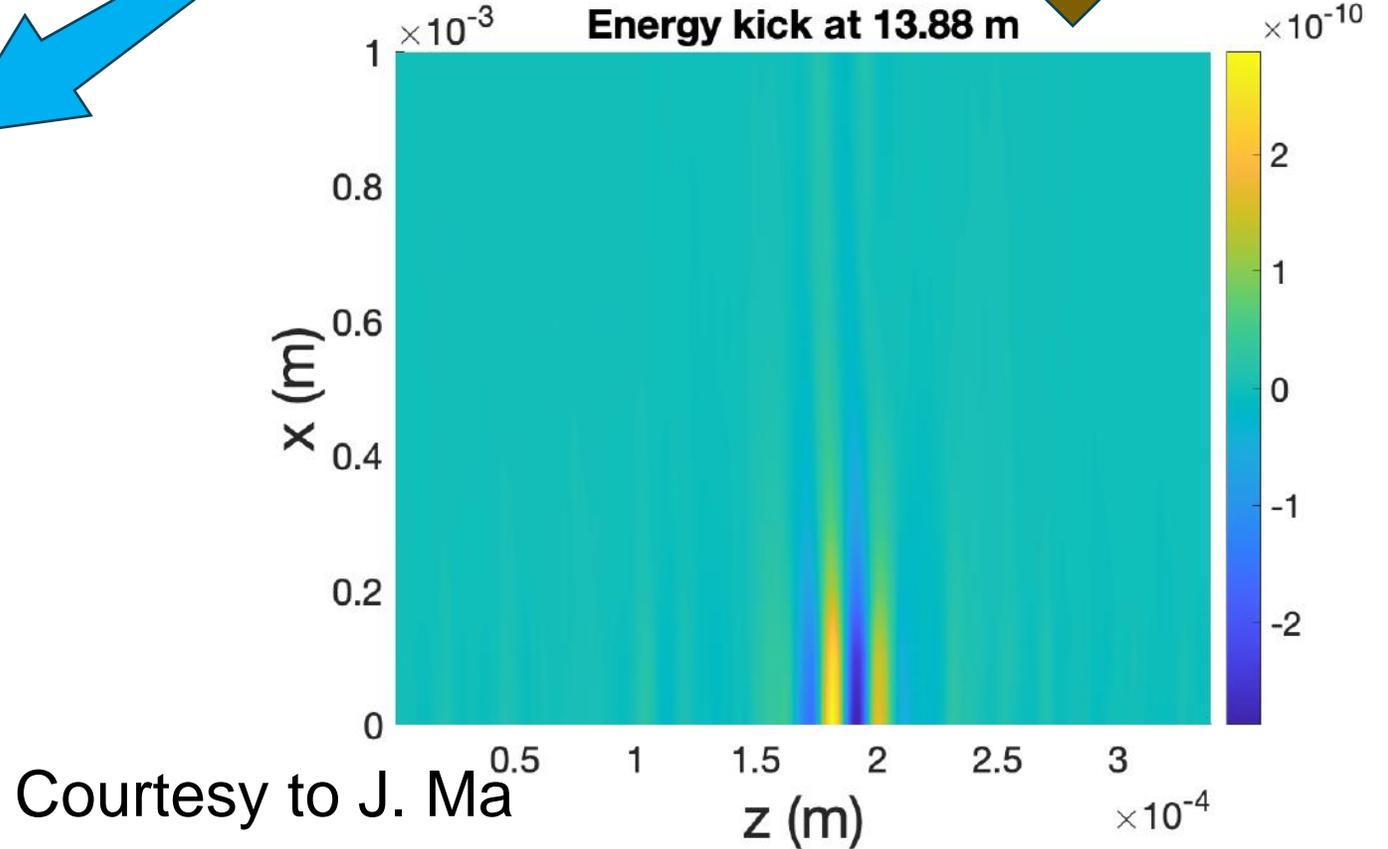
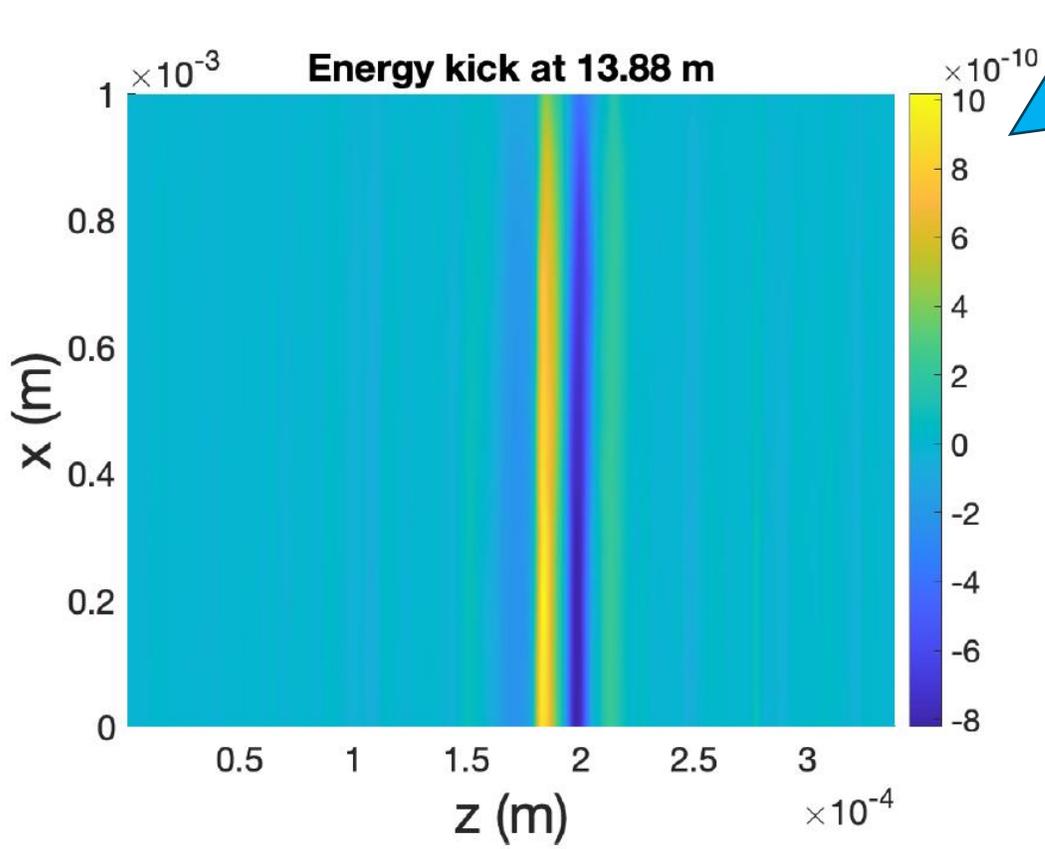
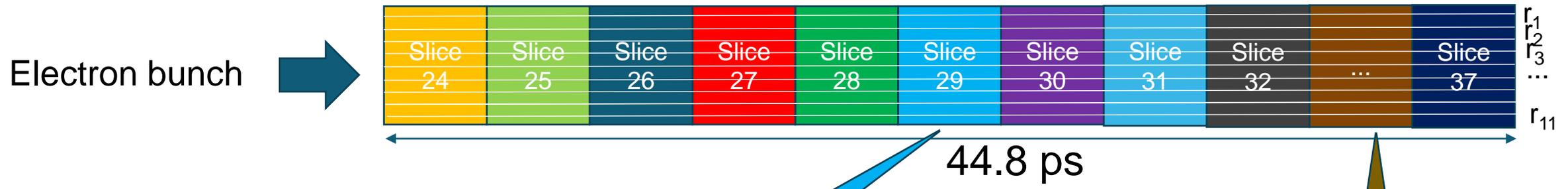


Electron beam parameters

- 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.

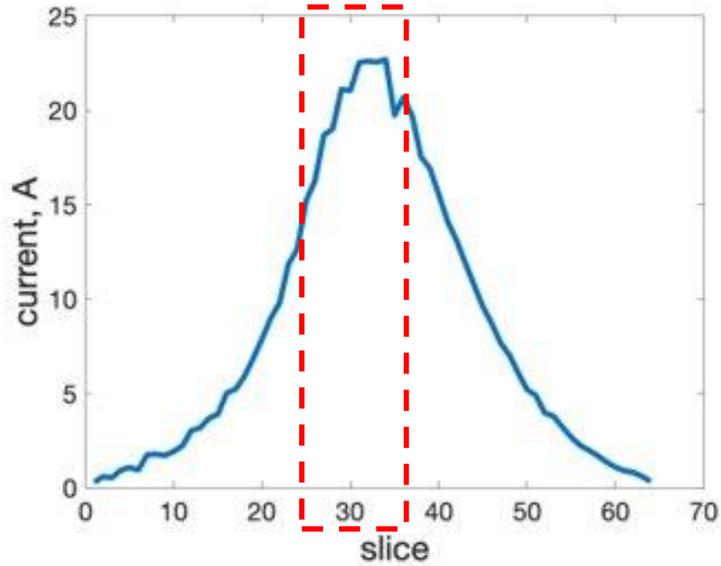
Electron beam Parameter	
Charge per bunch, nC	0.8
Peak current, A	20
Normalized emittance, RMS, μm	1.25
Beam energy (inj), MeV	1.71
Final beam energy, MeV	10
Energy spread, RMS	$< 2 \times 10^{-4}$
Bunch rep-rate, kHz	78

Dependance of the cooling force on the location of the ion

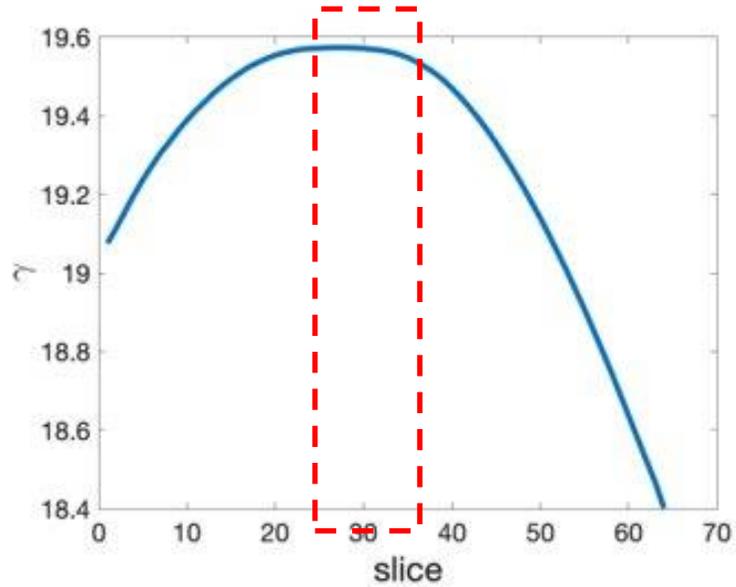


Courtesy to J. Ma

Electron beam parameters from simulation

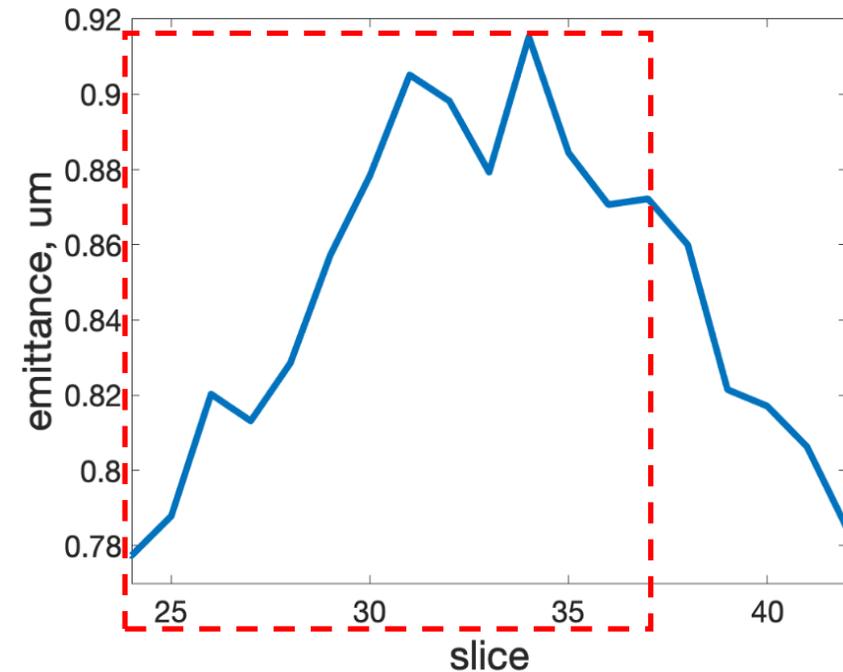
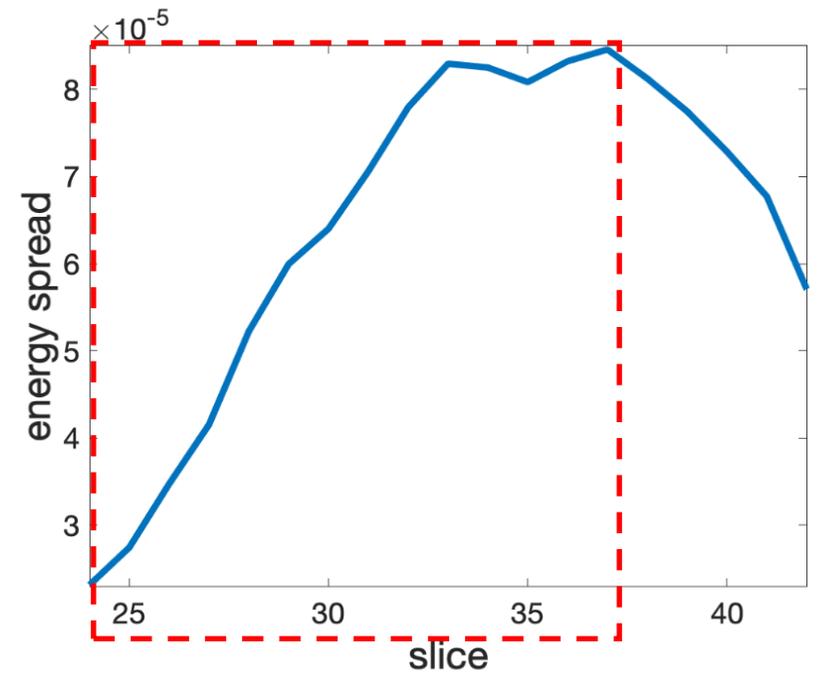


(a)

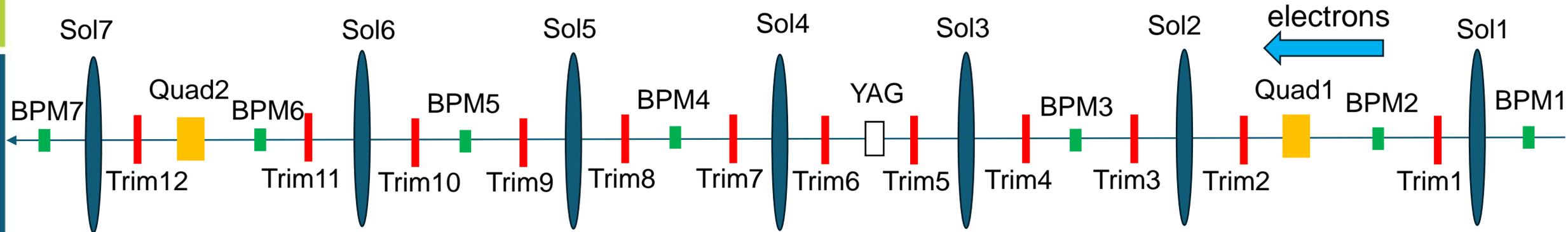


(b)

- 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.



Three setups of the PCA

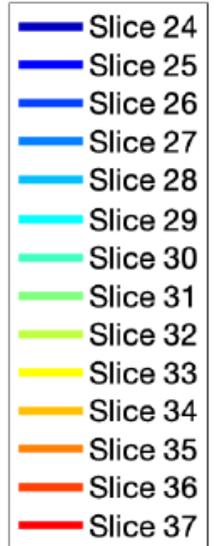
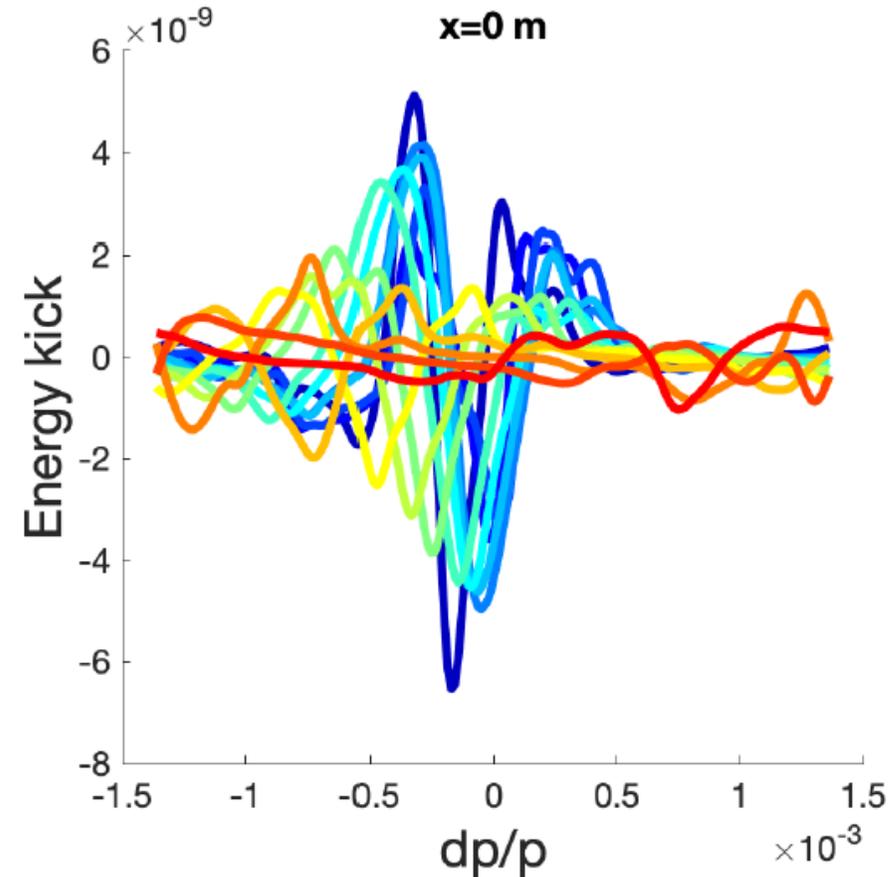
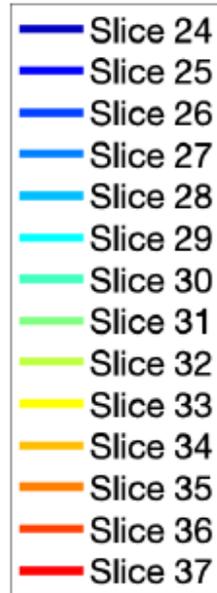
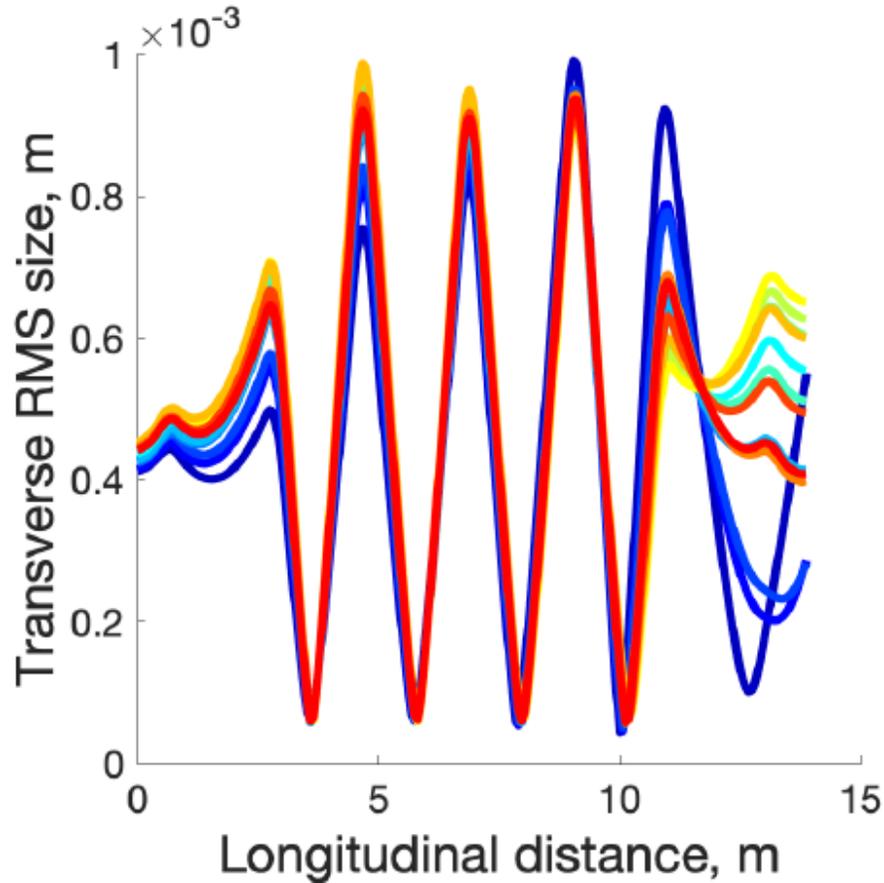


40.51 A	-80.68 A	84.6 A	-84.6 A	84.6 A	-80.68 A	40.51 A
40.51 A	-80.68 A	83.8 A	-83.8 A	83.8 A	-80.68 A	40.51 A
50 A	-82 A	86.9 A	-86.9 A	86.9 A	-82 A	50 A

- 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.

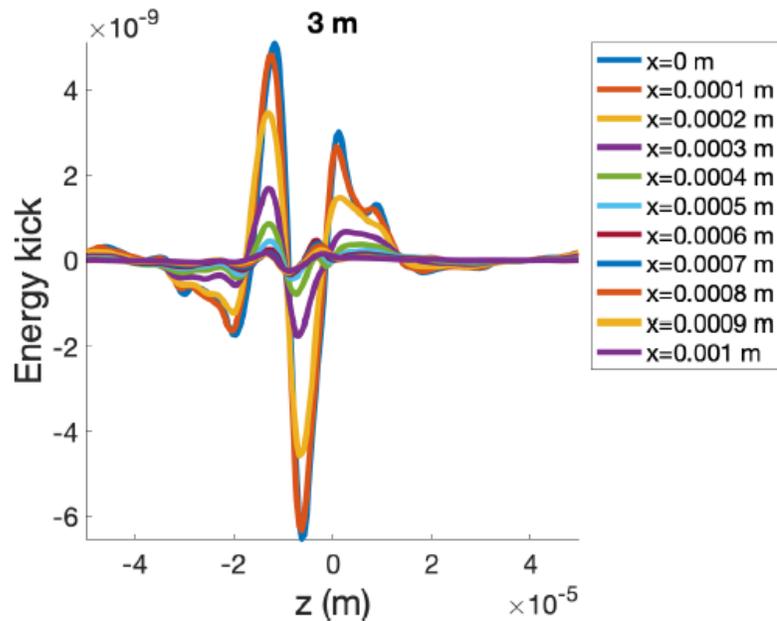
Setup 1: Dependence of cooling force on the longitudinal location of the ion

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.

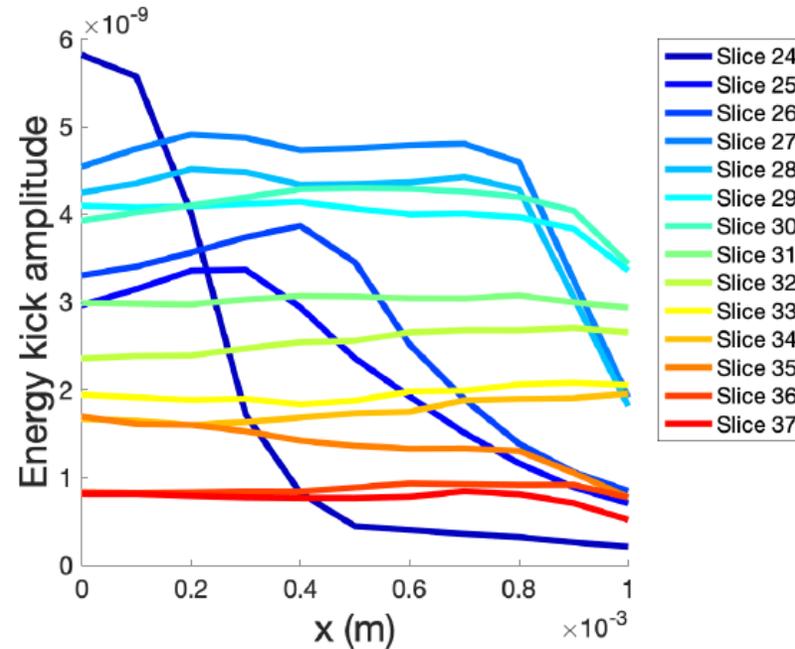


Setup 1: Dependence of the cooling force on the transverse location of the ion

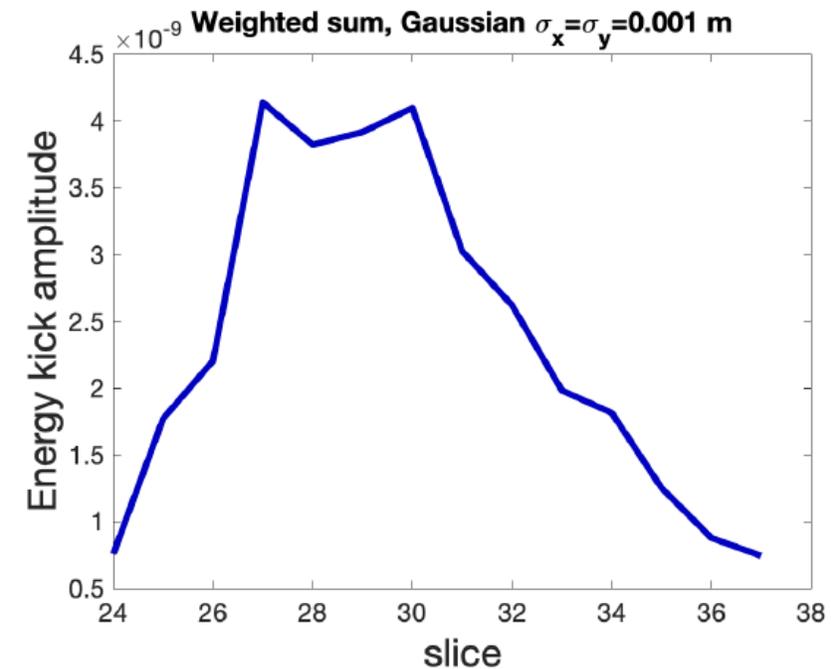
Cooling wakes at different transverse location for slice #24



Amplitude of the cooling wakes as a function of the transverse location

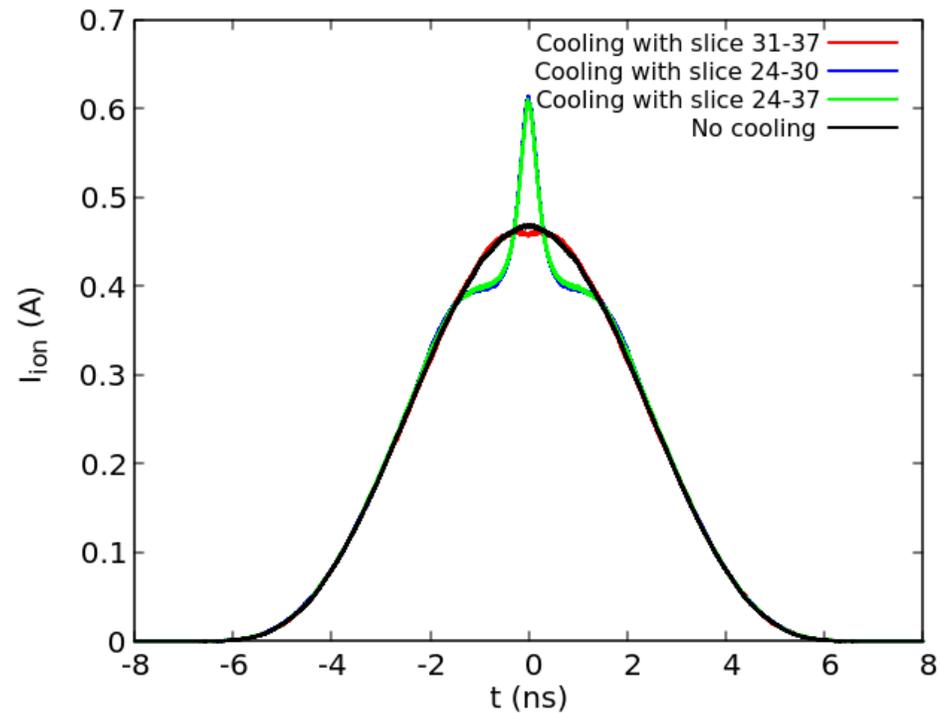
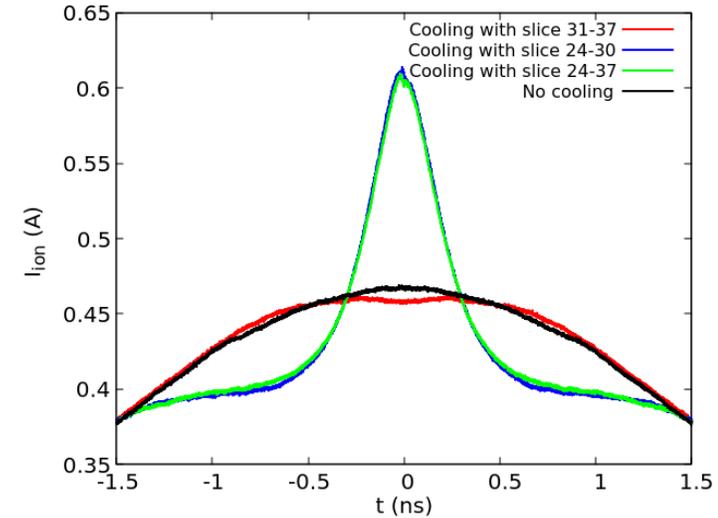
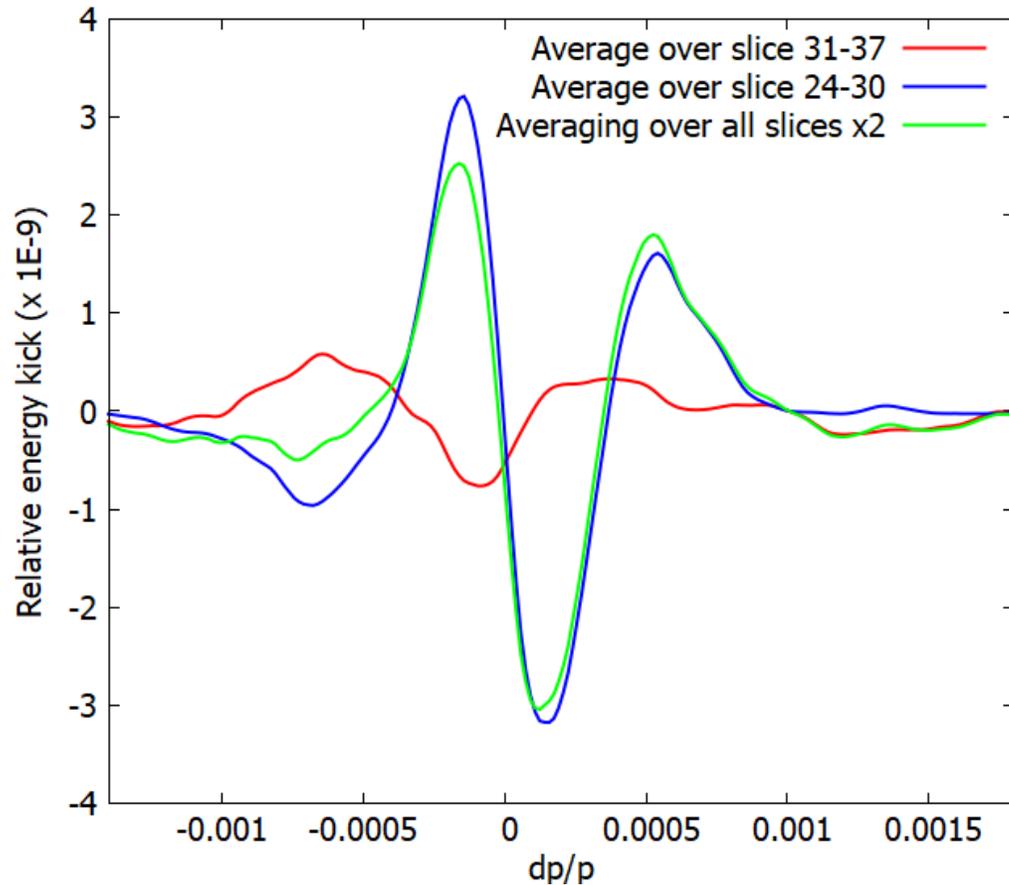


Amplitude of the cooling wakes averaged over the transverse distribution of the ion beam



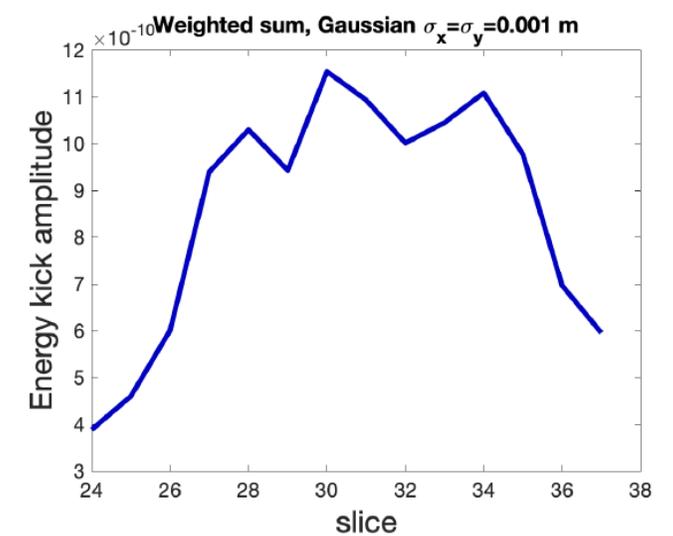
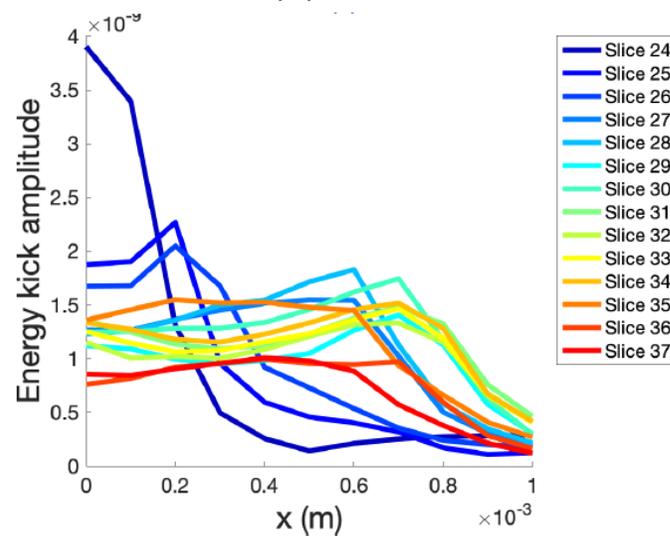
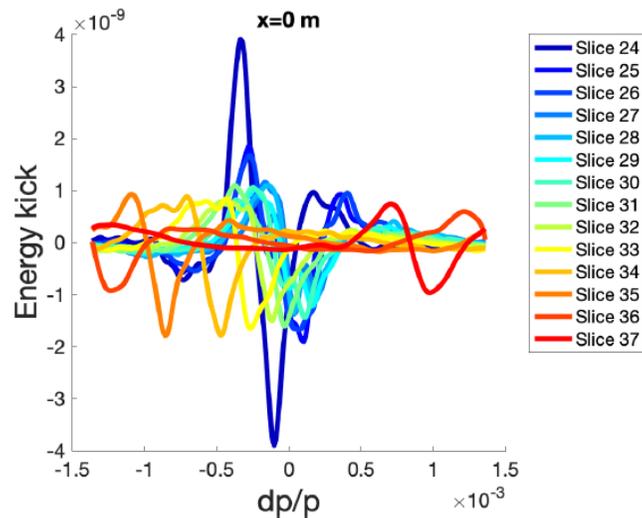
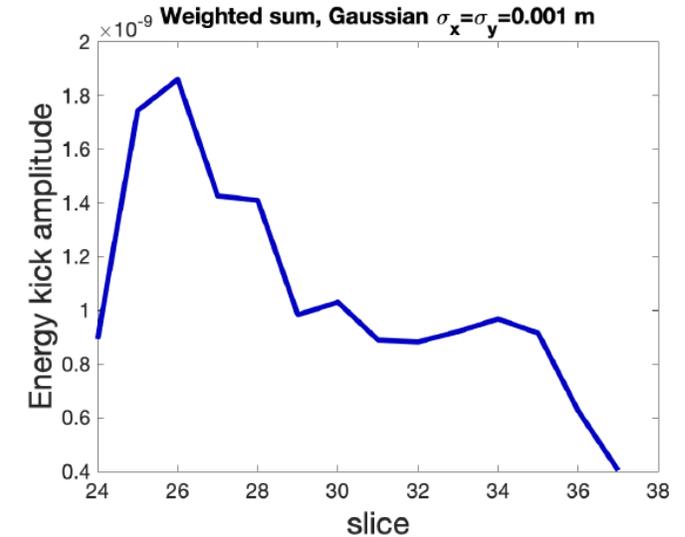
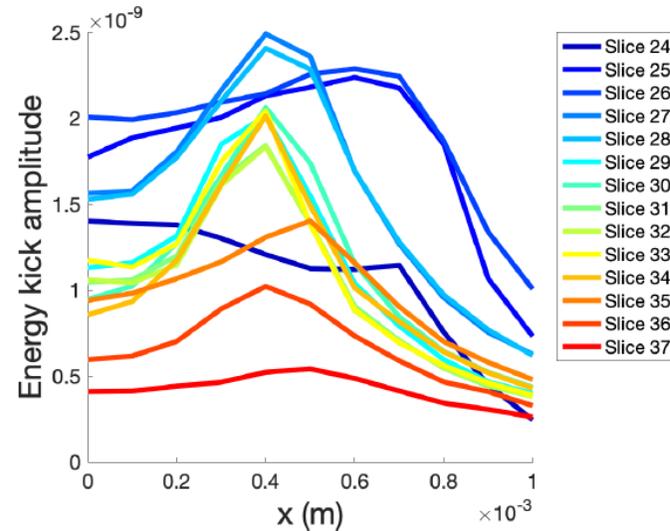
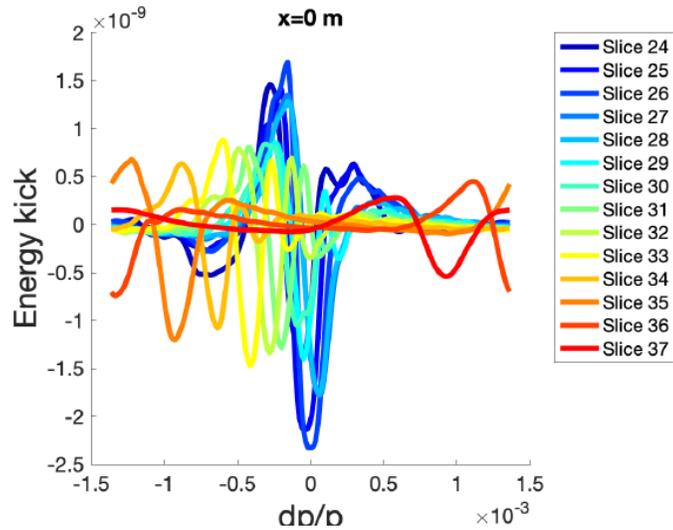
Ion beam Evolution for setup 1

While the amplitudes of the cooling wake for slice 31-37 are not small, their average contribution to cooling tends to cancel each other and consequently, anti-cooling effects from these slices are insignificant.



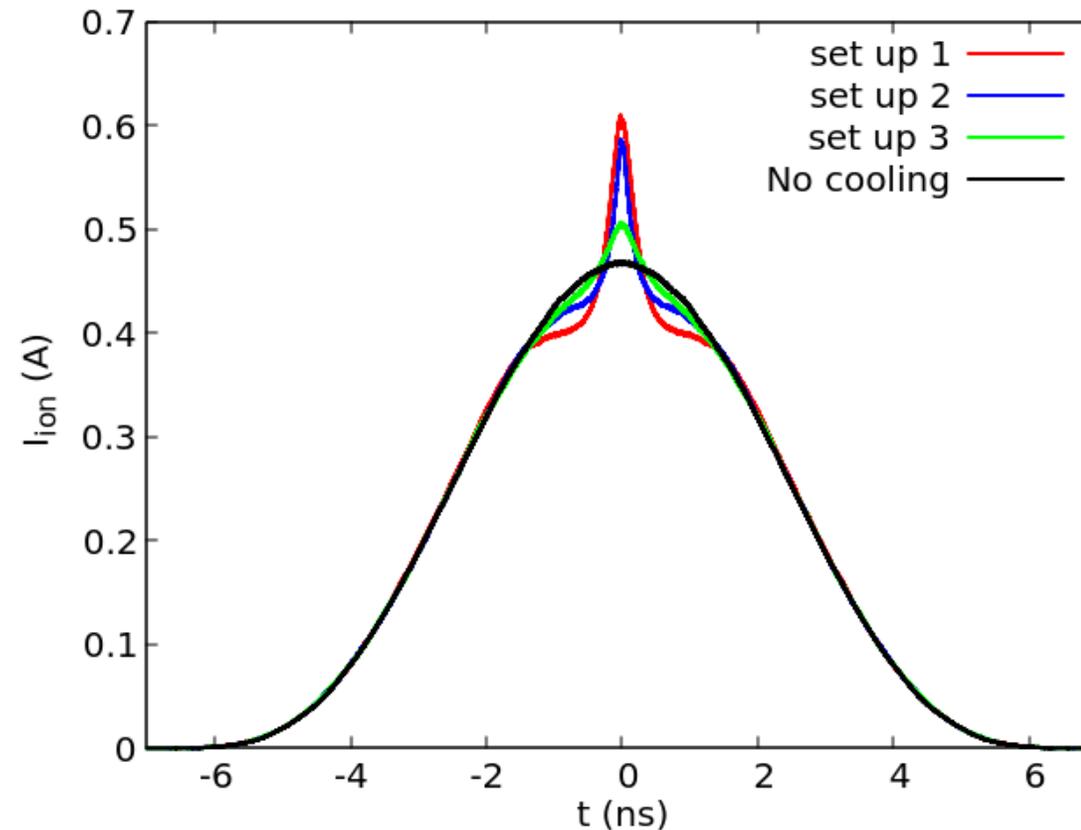
Setup 2 & setup 3

- 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

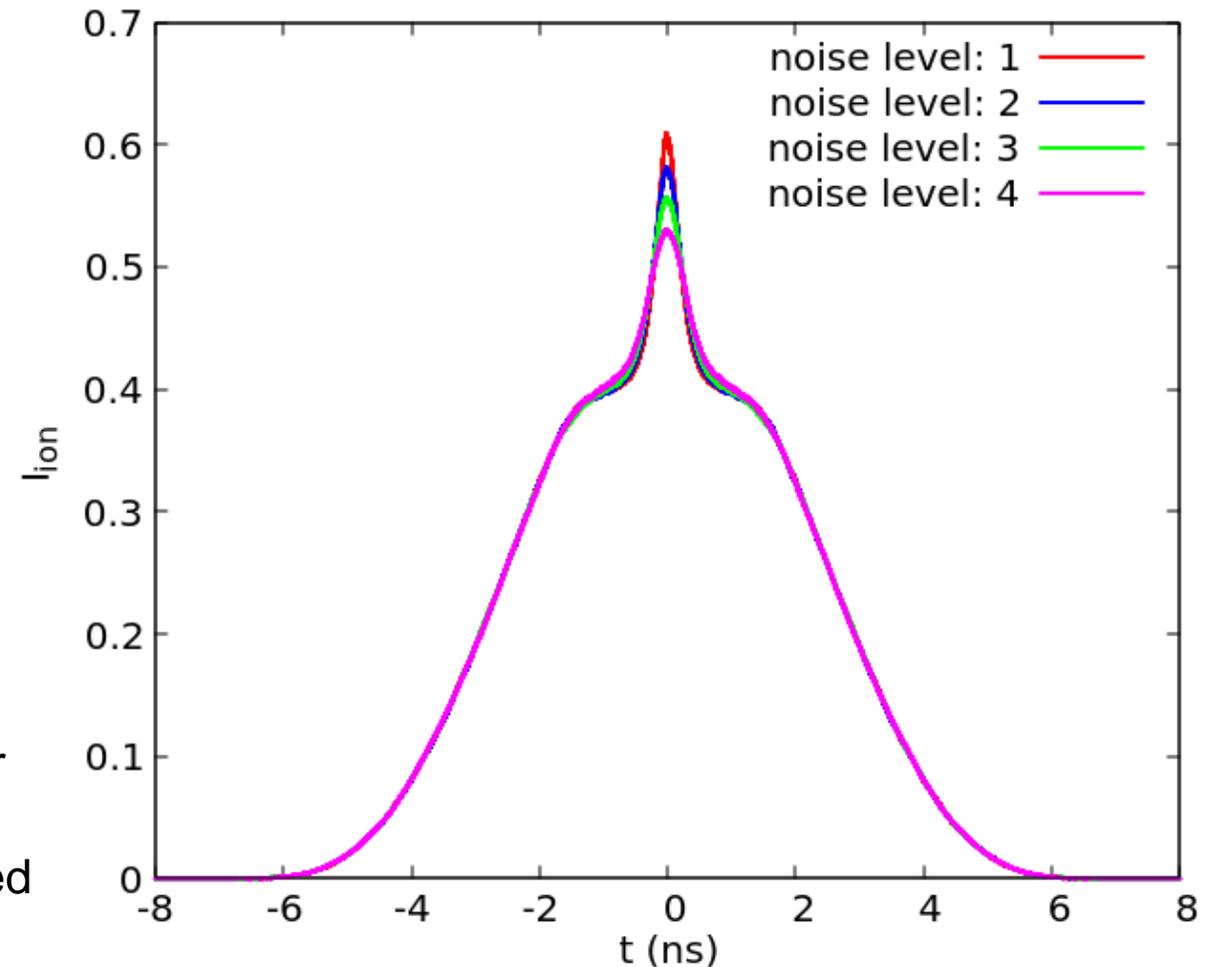
- In the presence of excess noise in the electron beam, the diffusive kicks due to the neighbour electrons become larger.
- To implement this effects into the ion tracking, a factor R is introduced into the CeC updates algorithm

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

Poisson Noise: $R = 1$

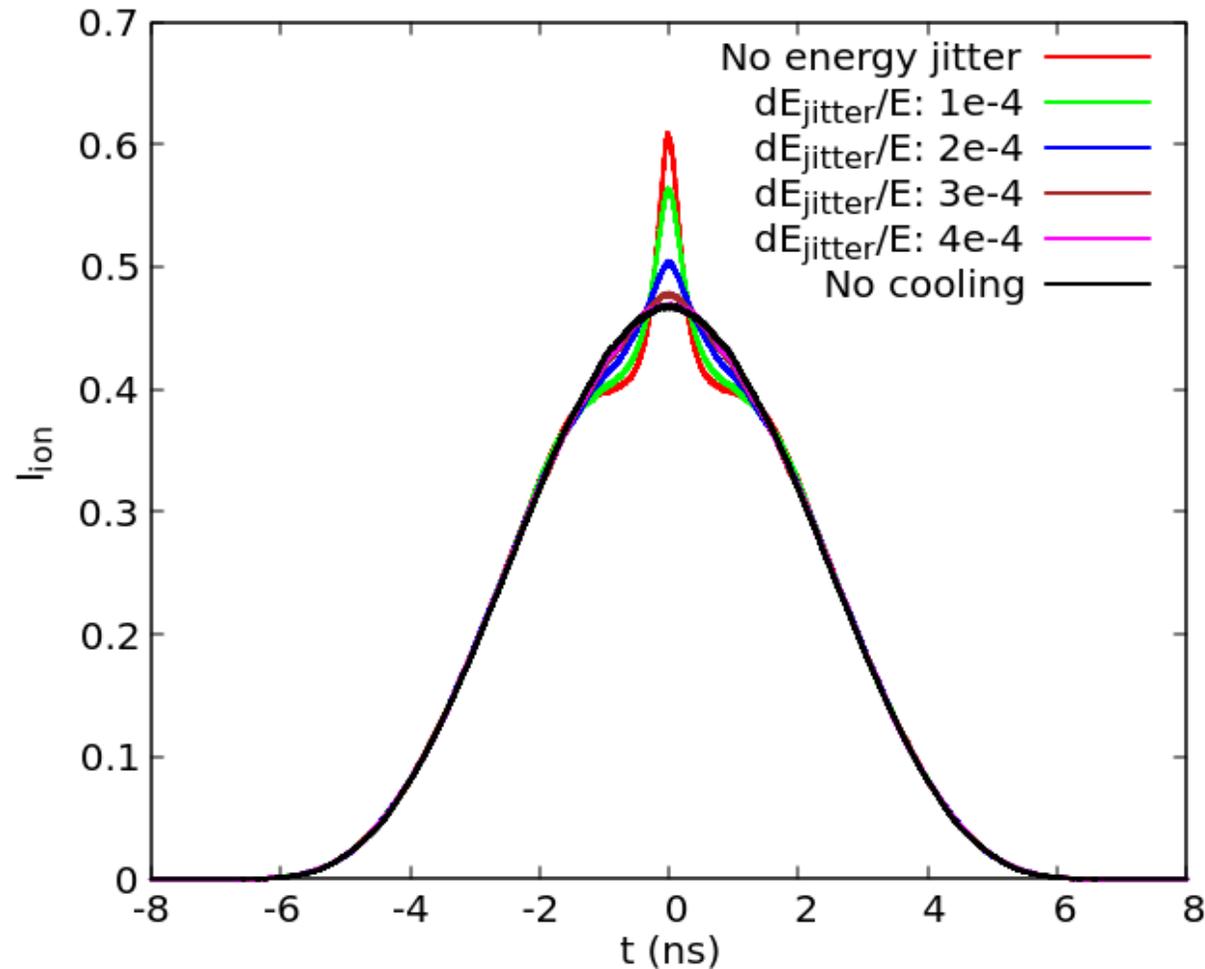
Noise level 2: $R = 2$

- 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)



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.