Highest energy e- cooling in CeC cooling channel

Y. Jing for the collaboration team
V.N. Litvinenko, I. Pinayev, G. Wang (CeC)
A. Fedotov, D. Kayran, S. Seletskiy (LEReC)
and more!
APEX workshop
10.22.2021

70 YEARS OF DISCOVERY
A CENTURY OF SERVICE

U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY

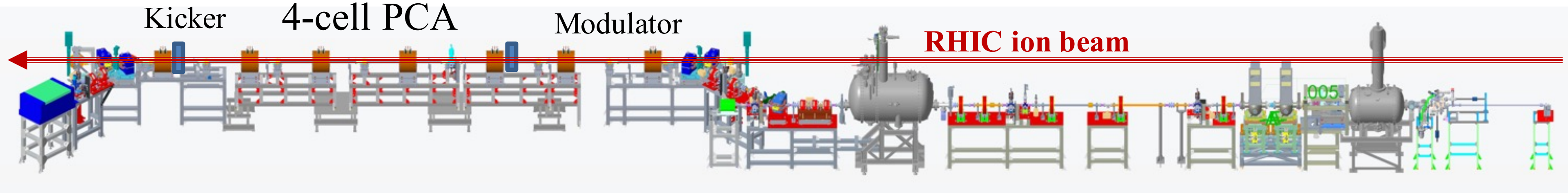
Outline

- Motivation
  - What we observed in CeC run 21
  - Attempts to decipher the e- cooling

- APEX experiment setup and approach

CeC X at RHIC in Run 21

- We discovered microbunching Plasma Cascade Instability - new type of instability in linear accelerators. Developed design of Plasma Cascade Amplifier (PCA) for CeC
- In 2019-2020 a PCA-based CeC with seven solenoids and vacuum pipe with **75 mm** aperture was built and commissioned. During Run 20, we demonstrated high gain Plasma Cascade Amplifier (PCA) and observed presence of ion imprint in the electron beam
- New time-resolved diagnostics beamline was built last year and commissioned during this run. Now we focusing on demonstrating longitudinal cooling.

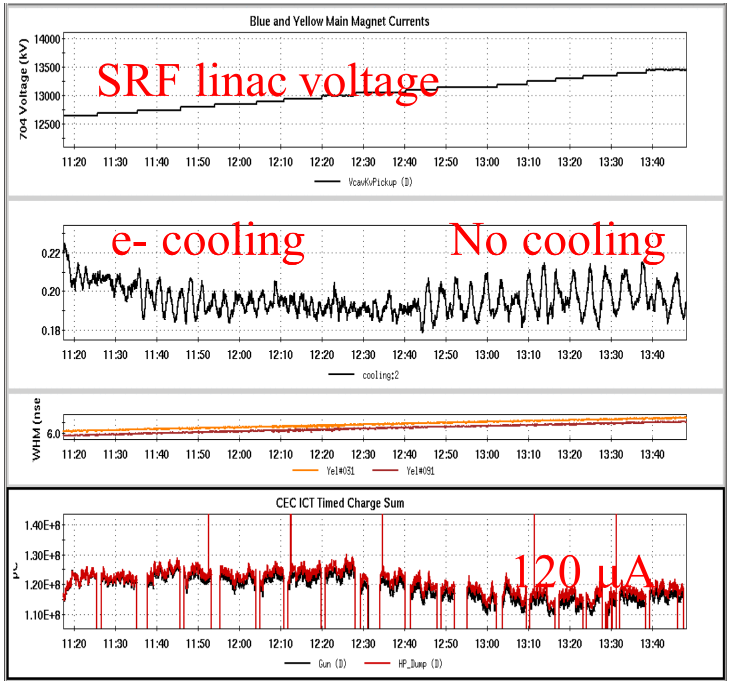


Electron beam KPP

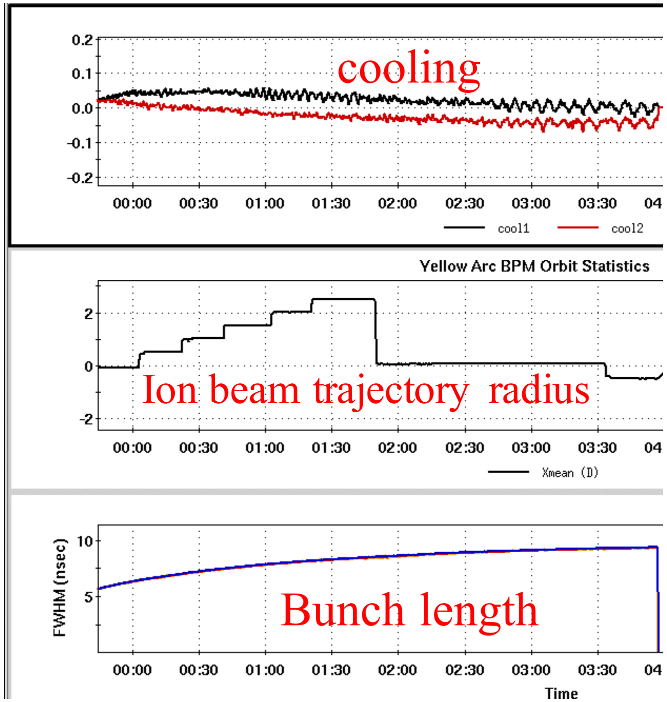
Parameter	Planned	Demonstrated
Lorentz factor	28.5	up to 29
Repetition frequency, kHz	78.2	78.2
Electron beam full energy, MeV	14.56	up to 14.8
Total charge per bunch, nC	1.5	nominal 1.5, up to 20
Average beam current, μA	117	120
Ratio of the noise power in the electron beam to the Poison noise limit	<100	<10 (lattice of Run20)* ***
RMS momentum spread $\sigma_p = \sigma_p/p$, rms	$\leq 1.5\times10^{-3}$	$<5\times10^{-4}$, slice 2×10^{-4}
Normalized rms slice emittance, μm rad	≤ 5	2.5

Details can be found at VL's talk in RHIC retreat

Search for CeC signature and observation of regular bunched electron cooling of 26.5 GeV/u ion beam



Changing e-beam energy requires multiple adjustments



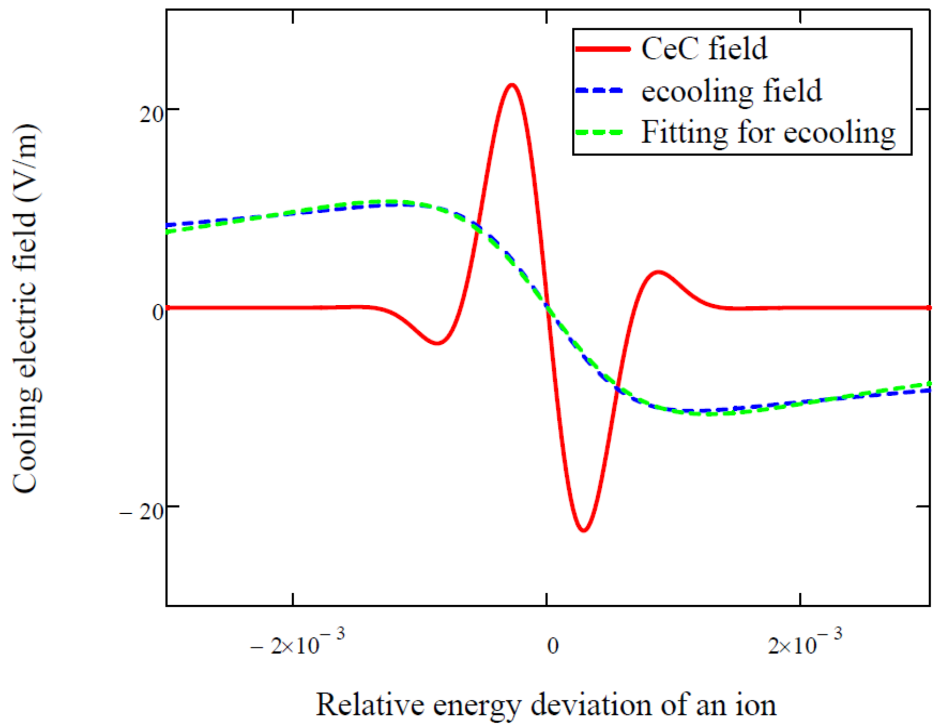
Adjusting ion beam energy – 1 mm x_{mean} corresponds to 0.1% change in the ion beam energy.

- There was no attempt of improving regular non-magnetized electron cooling – we used the lattice optimized for PCA CeC - and the best electron cooling rate was ~ 100 hours. It is consistent with cooling rate estimation made by Dmitry Kayran and > 50 hours cooling rate simulated by Alexei Fedotov (for large angles).

Parameters for CeC PoP experiment

Electron beam parameters		Ion beam parameters	
Energy, γ	28.5	Energy, γ	28.5
Peak current, A	50	Bunch intensity	2e8
Bunch charge, nC	1.5	Bunch length (RMS), ns	3.5
RMS relative energy spread	2e-4 (slice) <5e-4 (projected)	Relative energy spread (RMS)	6E-4
Normalized emittance, RMS, mm.mrad	3e-6	RF voltage (28MHz), KV	100
Beam width at modulator/kicker, RMS, mm	0.485	Normalized transverse emittance, RMS, mm.mrad	2.5
Minimal beam width at amplifier, RMS, mm	0.1	β^* at cooling section, m	5
RMS bunch length, ps	12	Average β function at cooling section, m	10
Cooling section length for e cooling, m	12	Longitudinal emittance, eV.s / u	0.18

Cooling force in CeC and e-cooling



@ Gang Wang

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m_e} \int L_C \frac{\vec{v} - \vec{v}_e}{|\vec{v} - \vec{v}_e|^3} f(v_e) d^3 v_e$$

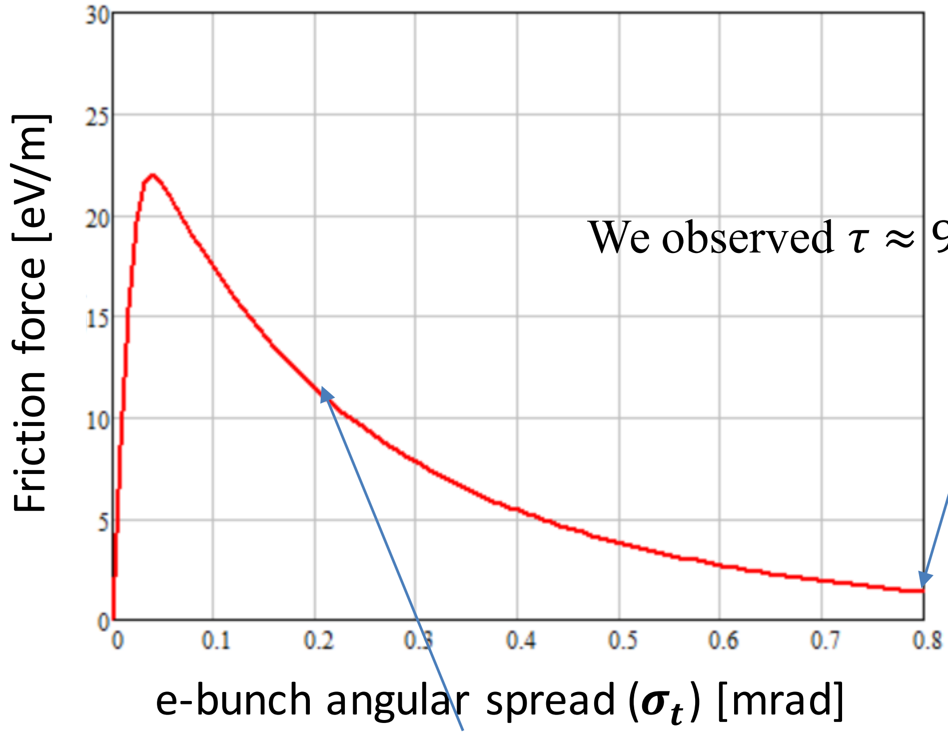
$$f(v_e) = \frac{1}{(2\pi)^{3/2} \Delta_x \Delta_y \Delta_z} \exp\left(-\frac{v_{ex}^2}{2\Delta_x^2} - \frac{v_{ey}^2}{2\Delta_y^2} - \frac{v_{ez}^2}{2\Delta_z^2}\right)$$

Cooling rate in laboratory frame:

$$\lambda_C = \frac{F_z}{\gamma m_i v_{iz}} \eta$$

Tuning of e- cooling rate

The longitudinal friction force strongly depends on e-bunch angular spread:



We observed $\tau \approx 90$ hrs for $\sigma_t \approx 800\ \mu$rad

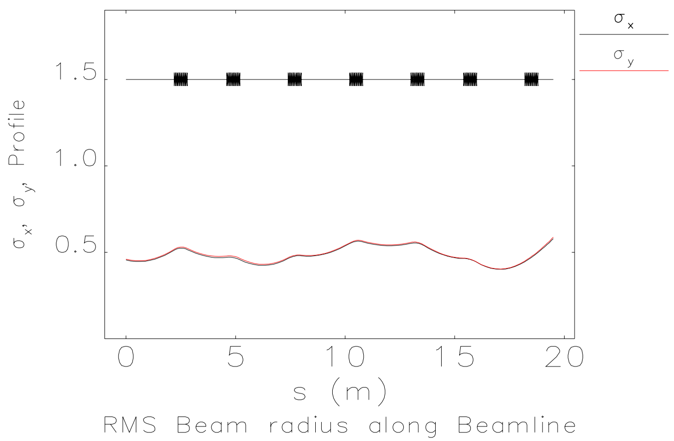
@ Sergei Seletskiy

One can expect $\tau \approx 9$ hrs if $\sigma_t \approx 200\ \mu$rad can be achieved

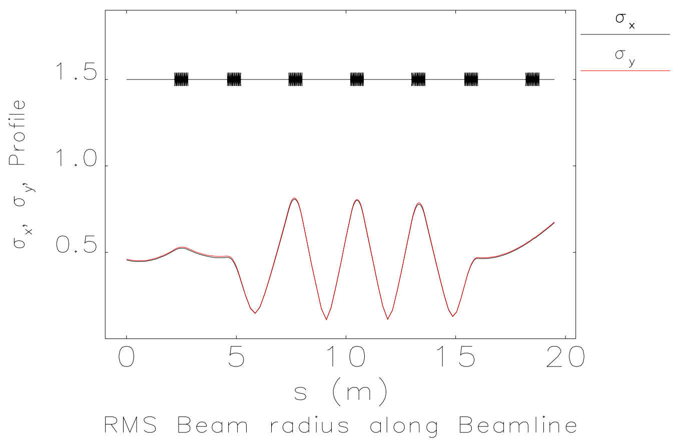
Alexei has independent simulation with proper beam size and 0.2 mrad angular spread showing cooling time ~ 7 hrs

Lattice setup for APEX

The e-bunch angular spread can be easily tuned by changing the common section solenoids



Relaxed setup



PCA setup

Same initial conditions (as well as solenoid 1 strength) were used in both setups and solenoid 7 in the common section was turned off.

We would request half an hour to one hour in each APEX section to:

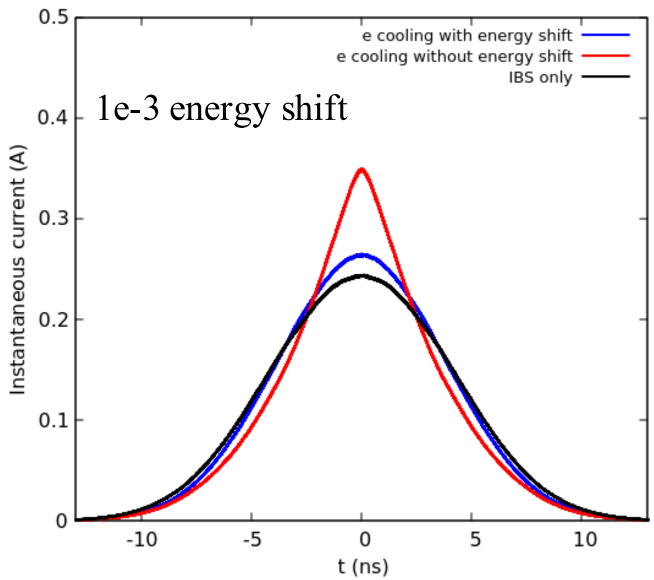
- Setting up the lattice(s) and check machine status
- Confirm matching of e- beam into common section

Characterize the e- cooling

If successful in identifying the e- cooling from using relaxed lattice, we plan to further characterize the cooling and study the dependence of the cooling on:

1. e- energy
2. e- energy spread
3. Energy shift between e- bunch and ion bunch
4. Beam jitters effect in the cooling
5. etc..

Such studies can help broaden our understandings and to verify our theoretical/simulation predictions.



@ Gang Wang

Control the properties of e- beam

We have thorough studies on each machine's parameters effect on the e- beam properties, in simulation and verified in experiments performed in Run 21

Items	requirements	Beam parameter effect	Achieved Run 21	Improvements in Run 22
Laser jitter (ps, rms)	5	2e-4 energy jitter	14-15	5.6
Laser intensity (rms)	1%, transverse uniformity needs improvement	Peak current variation	2%	1%
Trim PS (A, rms)	5e-5	10 um orbit jitter in common section	< 2e-5	
Gun phase (deg, rms)	< 0.1	<0.2 kV/ps energy chirp jitter for core	0.06	
Gun voltage (kV, rms)	< 0.5 kV	< 1 ps separation between peak current and energy	0.04	
buncher phase (deg, rms)	0.2	Energy jitter < 2e-4, chirp jitter < 0.2 kV/ps	0.04	
buncher voltage (kV, rms)	0.14	Chirp jitter < 0.2 kV/ps	0.033	
Linac phase (deg, rms)	< 0.05	Chirp jitter < 0.2 kV/ps	0.05	
Linac voltage (kV, rms)	2.5	Energy jitter < 2e-4	0.52	

We are currently investigating the possibilities of employing machine-learning technique with virtual diagnostics and multi-objective optimization for better controls.

Summary

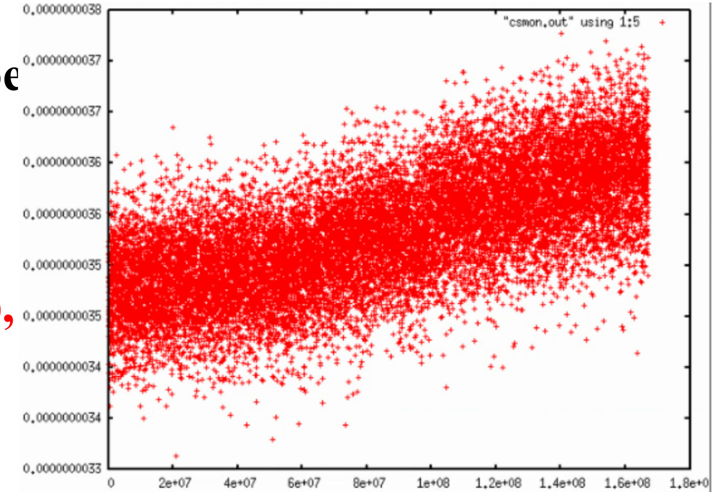
- We observed traditional e- cooling in CeC experiments in Run 21 and the results were confirmed with analytical estimation.
- We want to request APEX time to perform dedicated studies on the e- cooling with the current tools we developed and fully characterize the cooling with e-beam variables.
- The e- cooling we discovered could be the highest in energy so far!

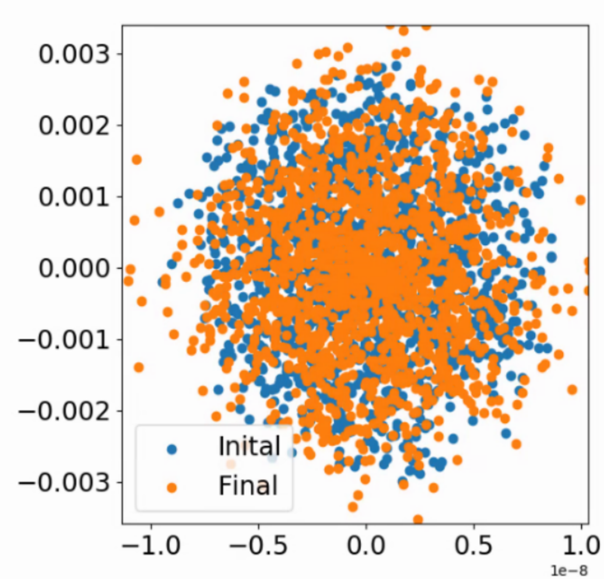
Backup slides

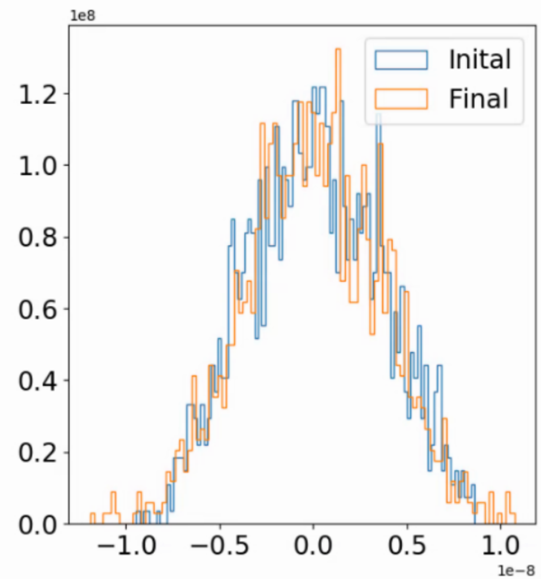
Cooling simulation with simplified CeC parameters (AF), using trackit8az code (heating included)

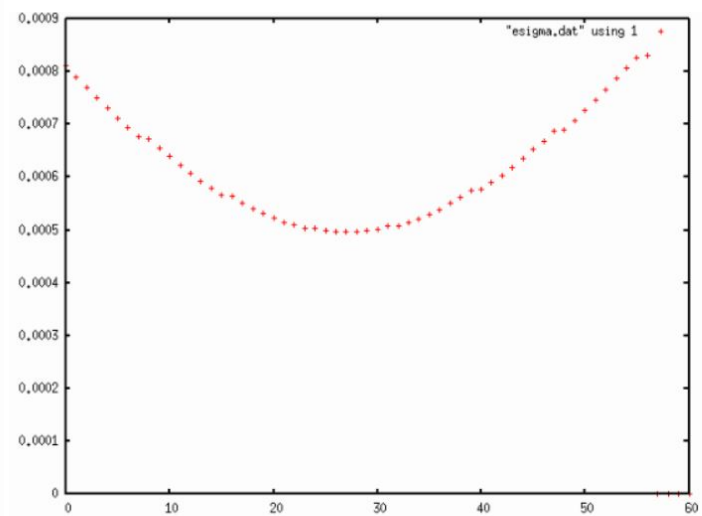
Bunch length with heating
IBS+cooling, without space charge – beam envelope does not expand due to space charge in modulator (space charge is turned off)

additional 0.5mrad angles (as zig-zag every 0.86m), coherent angles would reduce cooling stronger
RMS cooling time: 55 hours

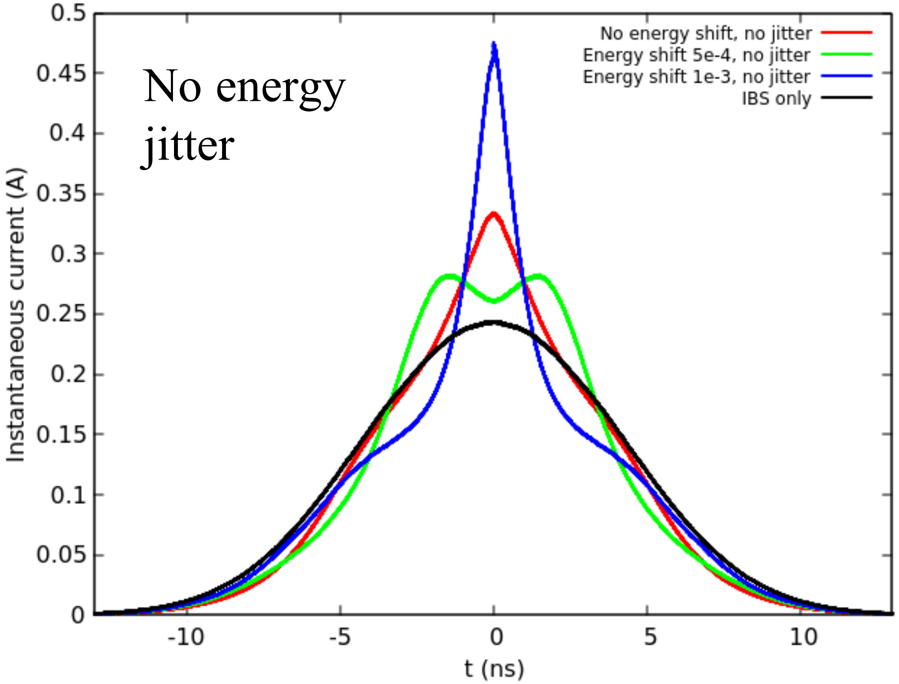


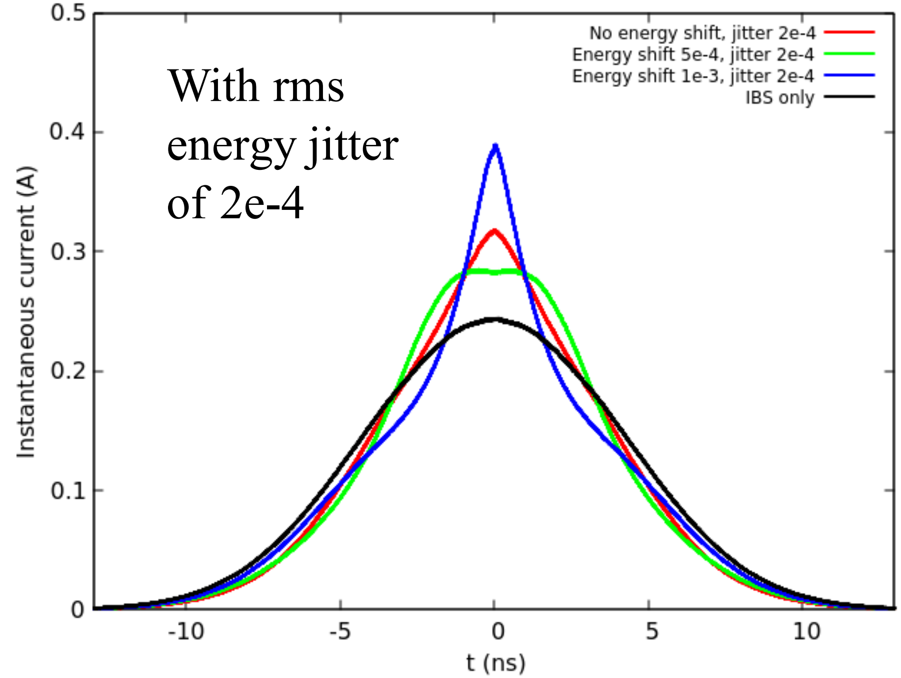






Simulation with both CeC and e cooling working together





Cooling force (Binney's formula)

$$\vec{F} = \frac{4\pi n_e e^4 Z_i^2 L_c\left(\vec{v}_i\right)}{m_e\left(4\pi\varepsilon_0\right)^2}\int dv_x dv_y dv_z \frac{\vec{v}-\vec{v}_i}{\left|\vec{v}-\vec{v}_i\right|^3} f_e\left(\vec{v}\right)$$

$$f_e\left(\vec{v}\right) = \frac{1}{\left(\sqrt{2\pi}\right)^3 \sigma_\perp^2 \sigma_{v_z}} \exp\left(-\frac{v_\perp^2}{2\sigma_\perp^2} - \frac{v_z^2}{2\sigma_{//}^2}\right)$$

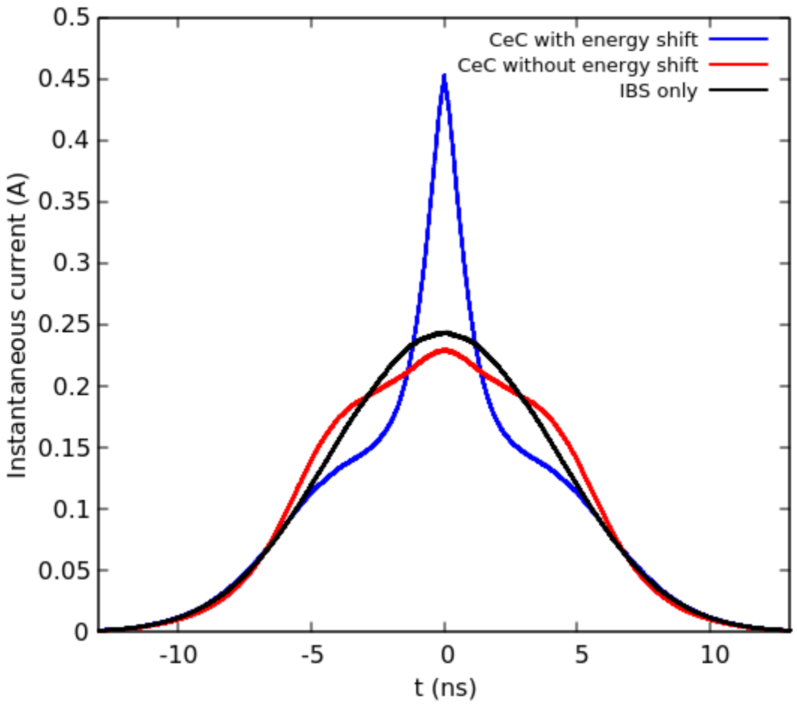
$$\vec{F}_\perp = -\frac{2\sqrt{2\pi} n_e e^4 Z_i^2 L_c}{m_e\left(4\pi\varepsilon_0\right)^2} \frac{\vec{v}_{i,\perp}}{\sigma_\perp^3} B_\perp$$

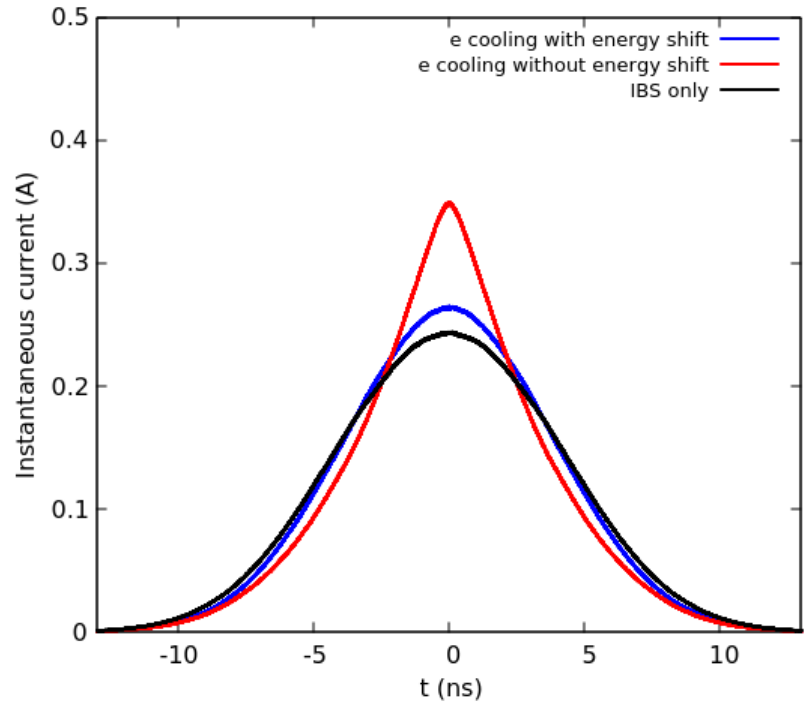
$$B_\perp \equiv \int_0^\infty \frac{\exp\left(-\frac{v_{i,\perp}^2}{2\sigma_\perp^2}\frac{1}{1+\tilde{q}} - \frac{v_{i,//}^2}{2\sigma_\perp^2}\frac{1}{\tilde{q}+\sigma_{//}^2/\sigma_\perp^2}\right)}{\left(1+\tilde{q}\right)^2\sqrt{\tilde{q}+\frac{\sigma_{//}^2}{\sigma_\perp^2}}} d\tilde{q}$$

$$\vec{F}_{//} = -\frac{2\sqrt{2\pi} n_e e^4 Z_i^2 L_c}{m_e\left(4\pi\varepsilon_0\right)^2} \frac{\vec{v}_{i,//}}{\sigma_\perp^3} B_{//}$$

$$B_{//} \equiv \int_0^\infty \frac{\exp\left(-\frac{v_{i,\perp}^2}{2\sigma_\perp^2}\frac{1}{1+\tilde{q}} - \frac{v_{i,//}^2}{2\sigma_\perp^2}\frac{1}{\sigma_{//}^2/\sigma_\perp^2+\tilde{q}}\right)}{\left(1+\tilde{q}\right)\sqrt{\left(\frac{\sigma_{//}^2}{\sigma_\perp^2}+\tilde{q}\right)^3}} d\tilde{q}$$

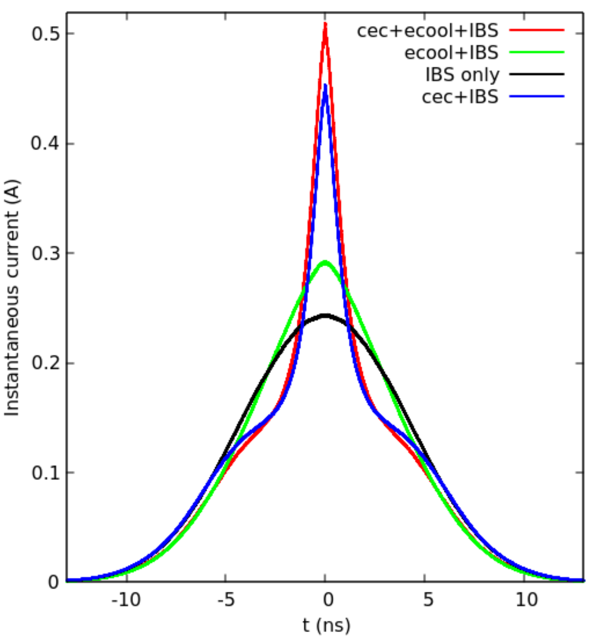
Investigating how energy shift (by 1e-3) affects CeC and e cooling individually

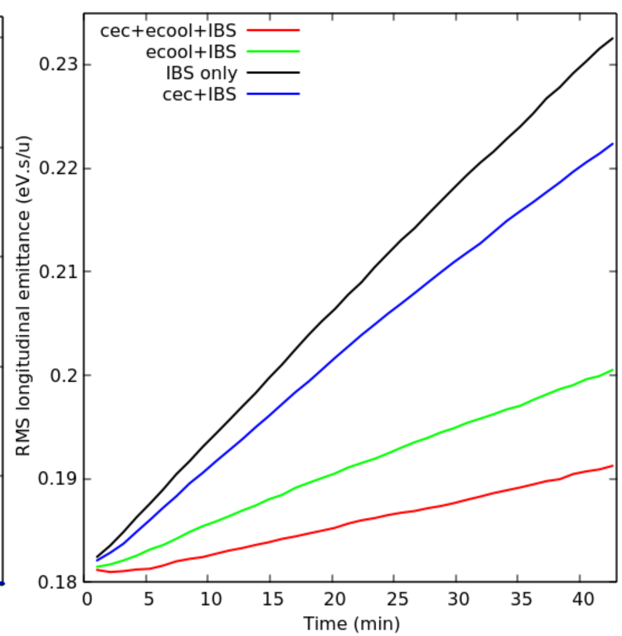


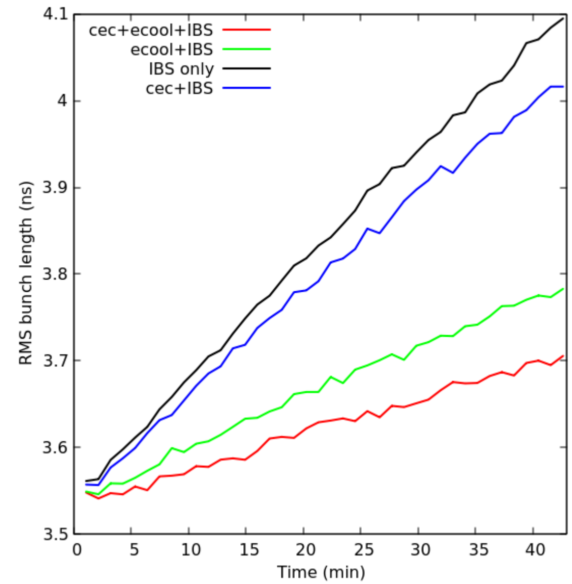


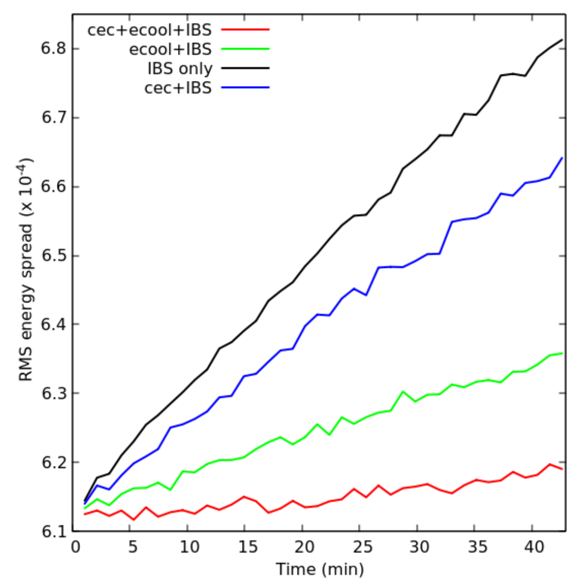
Effects with CeC and e cooling on/off

RHIC 28MHz RF voltage: 0.1 MV
RHIC bunch intensity: 2e8
Relative energy difference between electron bunch and ion bunch (to compensate delay due to solenoid in electron beam line): 1e-3

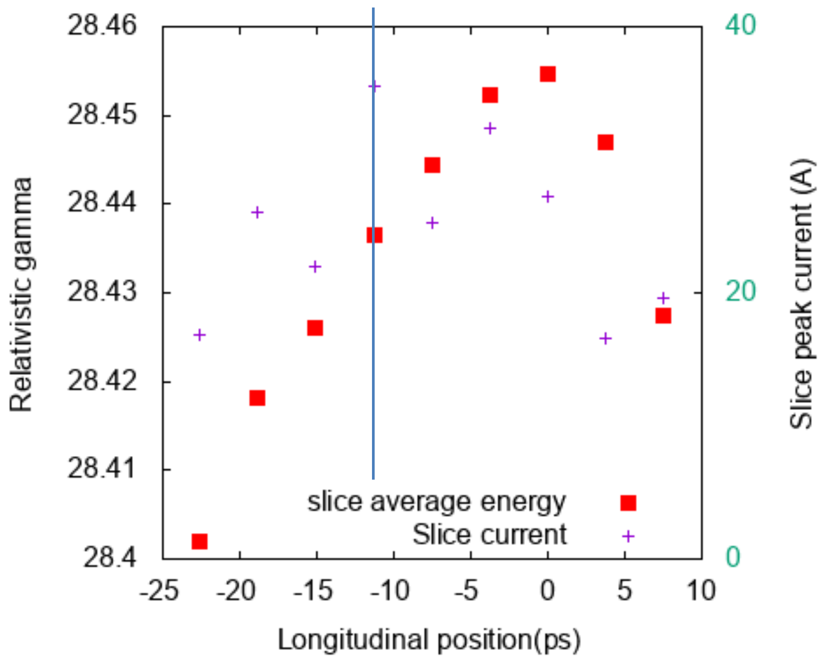




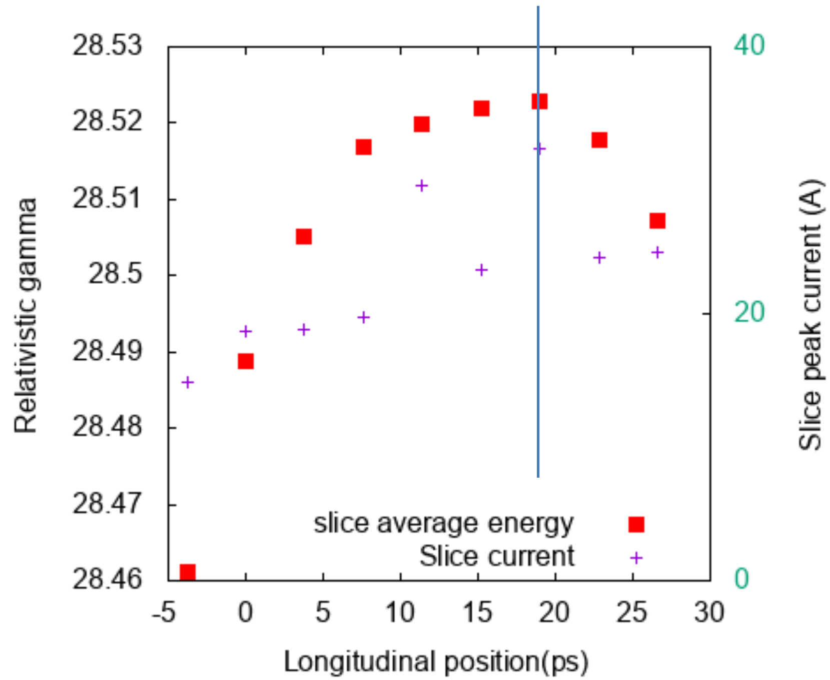




Laser time jitter



- 40 ps



+ 40 ps

- ➢Laser jitter affects the average slice energy significantly.
- ➢A jitter in Laser time (+/- 40 ps) changes slice energy from +0.14%/-0.16% w.r.t. the designed value. Verified in experiments.
- ➢Thus for a rms 2e-4 energy jitter required for cooling, the rms laser jitter needs to be < 5 ps.

Machine Learning for improving CeC operations

- Motivation
  - Tuning of system parameters (i.e. solenoids and trims) are currently done blindly to obtain desirable beam status
  - Optimization is currently done by genetic algorithm (GA), which takes too long
- Goals for ML algorithms
  - Virtual diagnostics: establish mapping between tuning parameters and YAG screen images for image prediction and analysis
  - Multi-objective optimization: optimize peak current, slice emittance, and slice energy spread of the beam at the same time
- Useful techniques
  - Neural network: surrogate model trained with history data to provide direct, accurate mapping between specified input parameters and output results
  - Bayesian optimization: optimize analytically intractable/computationally intensive objective with as few steps as possible, can be used for single-objective and multi-objective problems