

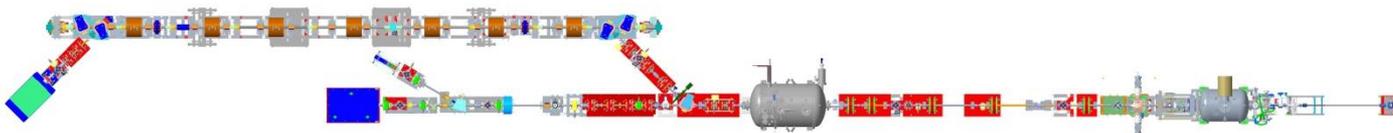


Results of the Coherent electron Cooling experiment at RHIC

Vladimir N Litvinenko, for CeC project team:

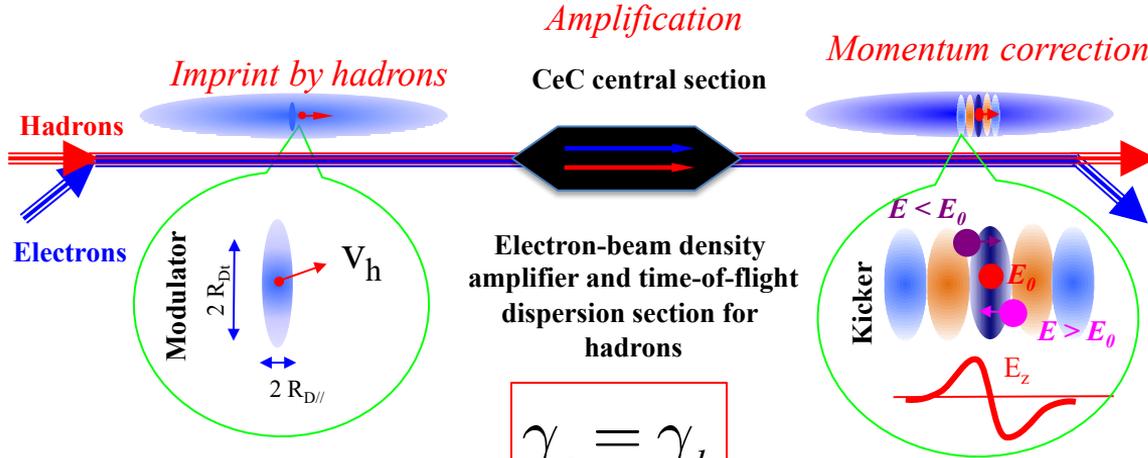
Nikhil Bachhawat, Jean Clifford Brutus, Yichao Jing, Dmitry Kayran, Jun Ma, Igor Pinayev, and Gang Wang

Stony Brook University and Brookhaven National Laboratory



What is Coherent electron Cooling (CeC)

- It is stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz. All CeC systems are based on the identical principles:
 - Hadrons create density modulation in co-propagating electron beam
 - Density modulation is amplified using broad-band (microbunching) instability
 - Time-of-flight dependence on the hadron's energy results in energy correction and in the longitudinal cooling.
 - Transverse cooling is enforced by coupling to longitudinal degrees of freedom.



UM HE 91-28
August 7, 1991

COHERENT ELECTRON COOLING
1. Physics of the method in general

Ya. S. Derbenev
Randall Laboratory of Physics, University of Michigan
Ann Arbor, Michigan 48109-1120 USA

ABSTRACT

A microwave instability of an electron beam can be used for a multiple increase in the collective response to the perturbation caused by a heavy particle, i.e. for enhancement of a friction effect in electron cooling method. The low-scale instabilities of a few kind can be

PRL 102, 114801 (2009)

PHYSICAL REVIEW LETTERS

Coherent Electron Cooling

Vladimir N. Litvinenko^{1,*} and Yaroslav S. Derbenev²
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²Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

PRL 111, 084802 (2013)

PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

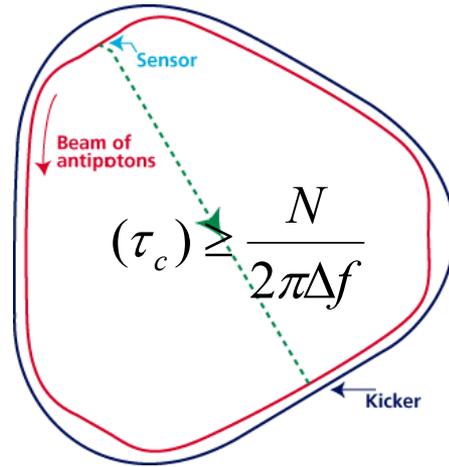
D. Ratner^{*}
SLAC, Menlo Park, California 94025, USA
(Received 11 April 2013; published 20 August 2013)

Critical conditions for the stochastic cooler



S. van der Meer
1984 Nobel physics
prize

RF stochastic cooling
is reaching its limits at
~ 10 GHz bandwidth



$$\langle x \rangle = \frac{1}{N_s} \sum_i x_i = \frac{1}{N_s} x_k + \frac{1}{N_s} \sum_{i \neq k} x_i$$

$$\tau_c = - \left(f_{rev} \frac{1}{\varepsilon} \frac{d\varepsilon}{dn} \right)^{-1} = \frac{N_s}{f_{rev}} \propto \frac{I_{peak}}{Z} \cdot \frac{1}{\Delta f}$$

$$N_s = \frac{\dot{N}}{\Delta f} = \frac{I_{peak}}{Ze} \cdot \frac{1}{\Delta f}$$

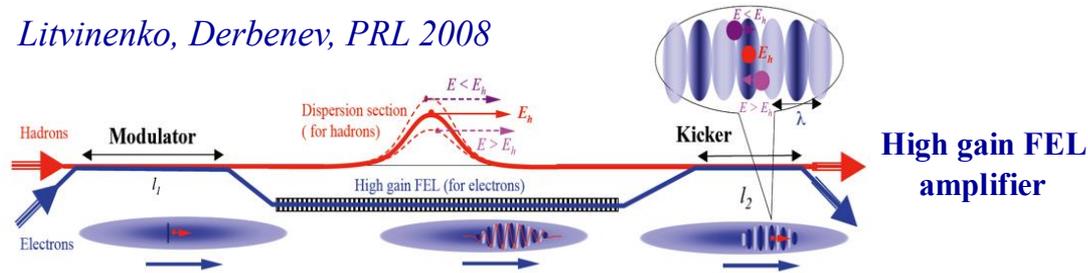
- ✓ **Linearity:** Amplifier must be linear (no saturation) and low noise
- ✓ **Overlapping:** Amplified signal induced by individual particle in the modulator (pick-up, sensor) must overlap with the particle in the kicker
- ✓ **Bandwidth:** Cooling decrement per turn can not exceed $1/N_s$, where N_s is number of the particles fitting inside the response time of the system: $\tau \sim 1/\Delta f$
- ✓ **Noise:** noise in the system should not significantly exceed system signal introduced by shot noise in the hadron beam

S. van der Meer, Rev. Mod.Phys. 57, (1985) p.689

S. van der Meer, 1972, Stochastic cooling of betatron oscillations in ISR, CERN/ISR-PO/72-31

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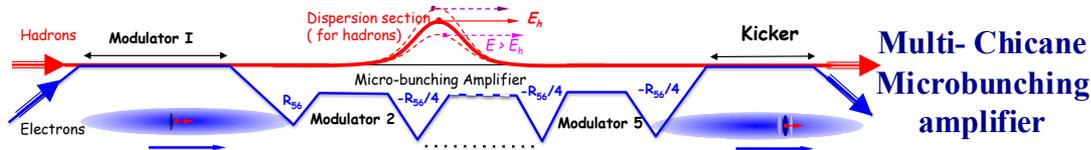
Litvinenko, Derbenev, PRL 2008



Can be tested experimentally at RHIC

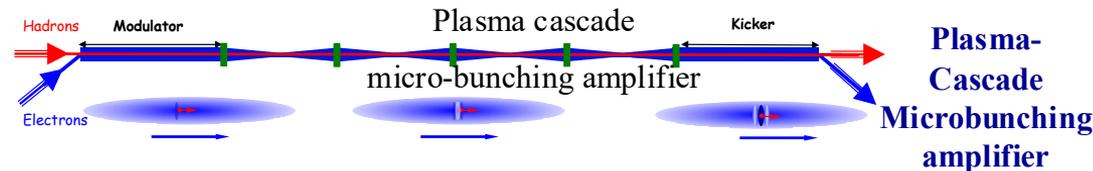


Ratner, PRL 2013



Cooling test would require significant modification of the RHIC lattice & superconducting magnets

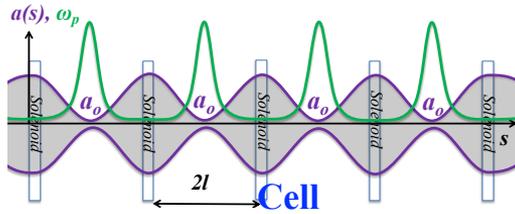
Litvinenko, Wang, Kayran, Jing, Ma, 2017



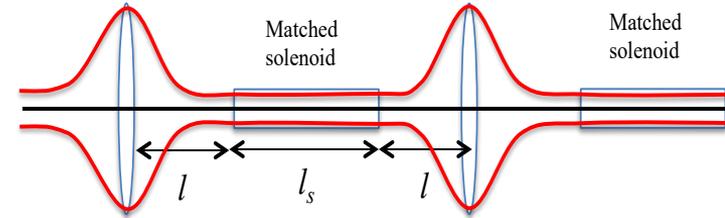
CeC schemes

What is PCA? : Parametric instability caused by strong transverse focusing

“Standard” 4-cell PCA

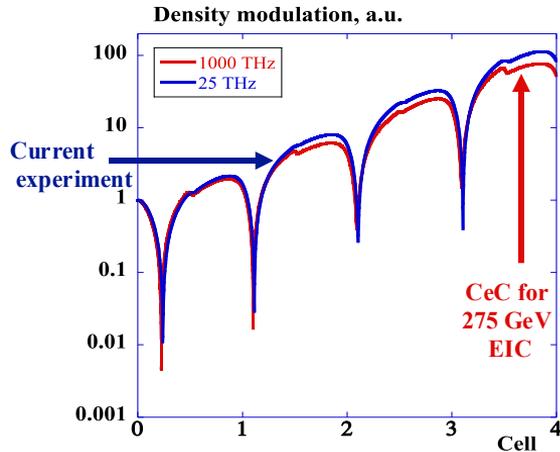
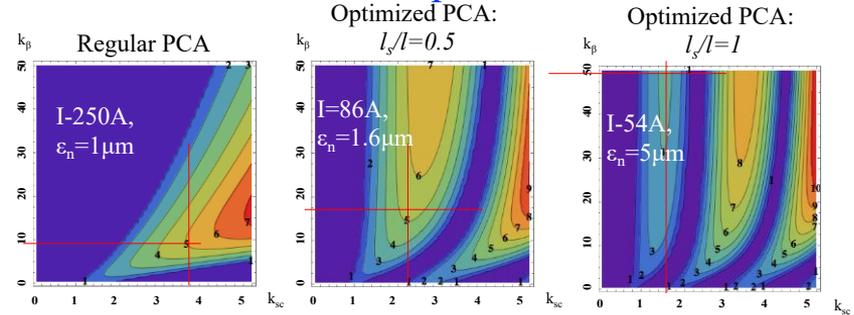


Optimized PCA cell



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

PCA Gain per cell



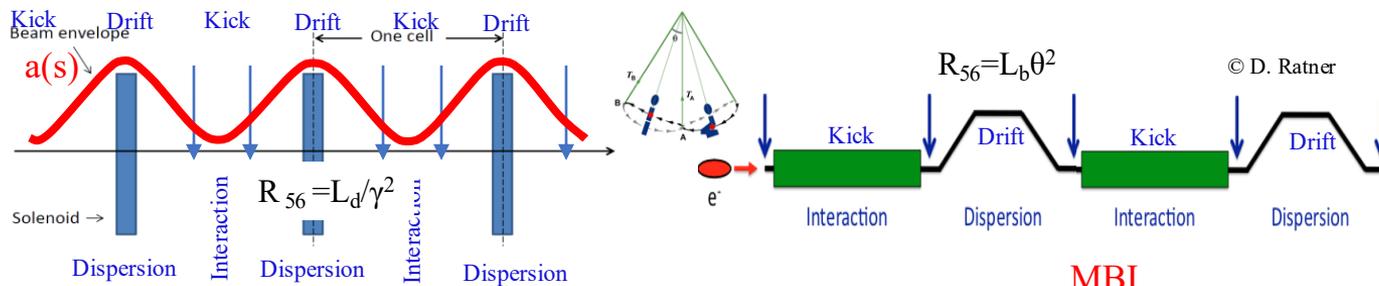
Results of 3D simulations with code SPACE

Simulations of Coherent Electron Cooling with Two Types of Amplifiers, Jun Ma, Gang Wang, Vladimir Litvinenko, International Journal of Modern Physics A (IJMPA), Vol. 34 (2019) 1942029 (

Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams, V.N. Litvinenko, G. Wang, D. Kayran, Y. Jing, J. Ma, I. Pinayev, arXiv preprint arXiv:1802.08677, 2018

What is Plasma-Cascade Instability (PCI)?

How is it different from the previously known micro-bunching instability (MBI)?



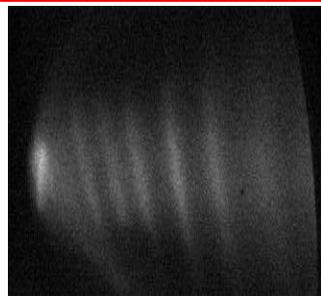
PCI

MBI

Modulate beam density by changing beam radius

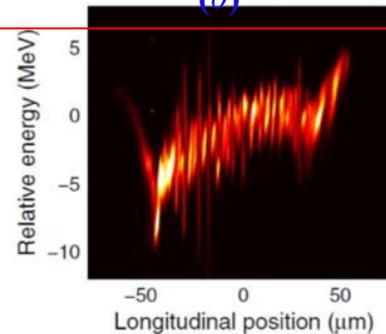
MBI: modulate effective mass (*s-mobility*) by bending beam trajectory (θ)

CeC
accelerator
PCI
experiment



5 0 5
Longitudinal position, psec

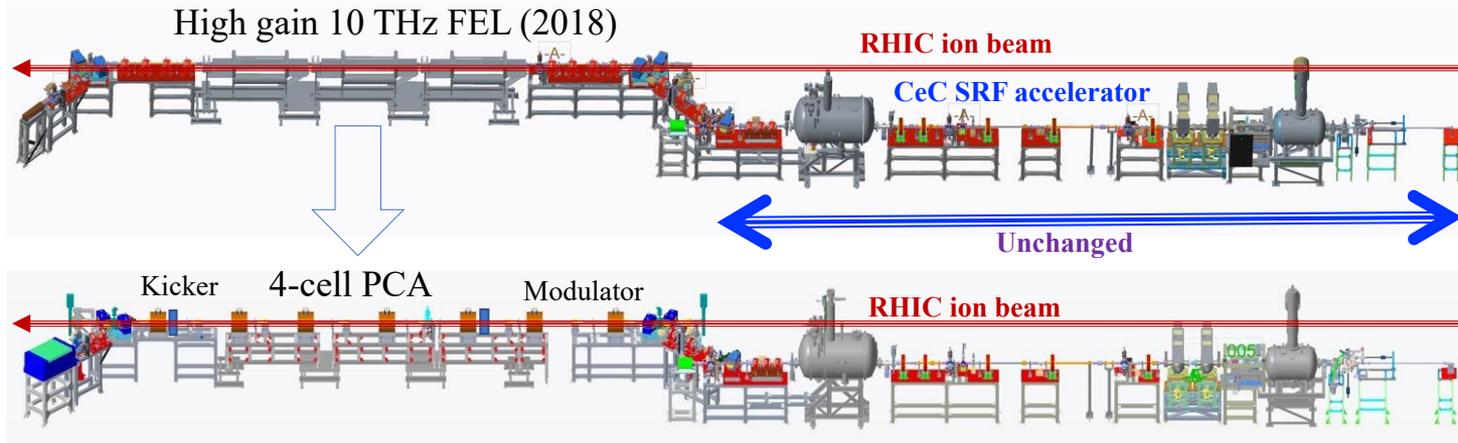
LCLS



Both instabilities can be used a broad-band amplifier in CeC

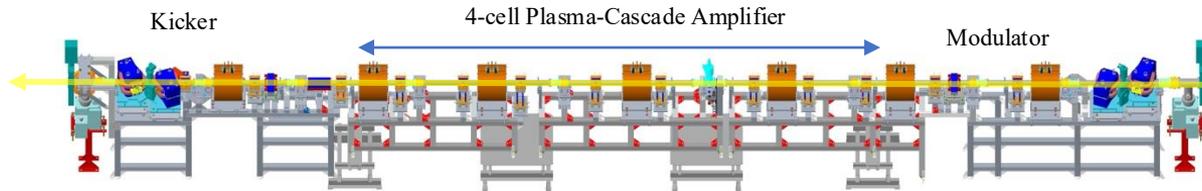
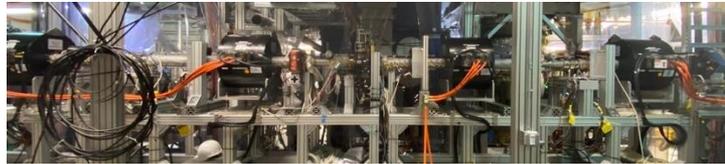
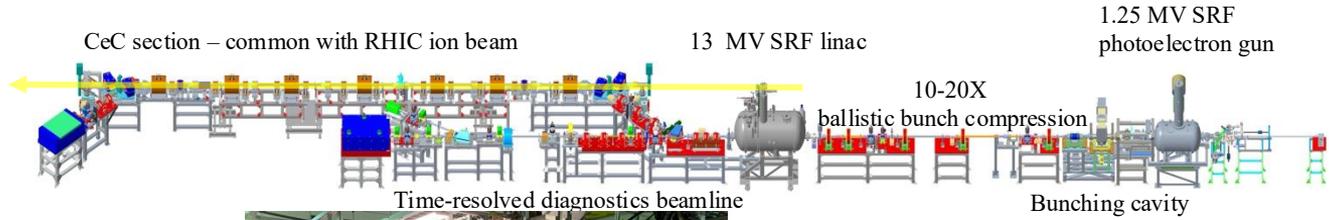
CeC X at RHIC

- ❑ 2014-2017: built cryogenic system, SRF accelerator and FEL for CeC experiment
- ❑ 2018: started experiment with the FEL-based CeC. It was not completed: **28 mm** aperture of the helical wigglers was insufficient for RHIC program with low energy 3.85 GeV/u Au ion beams
- ❑ 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
- ❑ We observed regular e-cooling in Run 21, but CeC cooling was washed out by large timing jitter of the seed laser and resulting 0.35% RMS e-beam energy jitter



The CeC Plasma Cascade Amplifier has a bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

Unique SRF accelerator and CeC amplifier

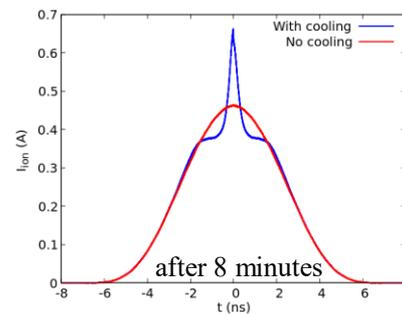
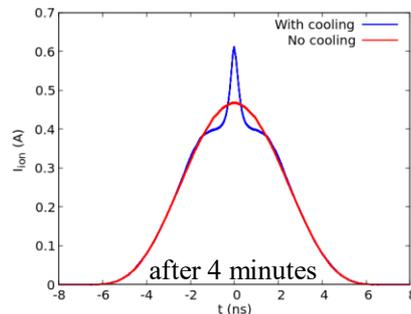


New mode of operation for Run 25

- ❑ To maximize chances for success, we developed new mode of operation below the RHIC transition energy.
- ❑ Lower energy of operation would provide for better quality of ion beam, easier choice for electron beam parameters and better stability
- ❑ This mode of operation would also provide for significantly faster cooling
- ❑ We plan to cool low intensity ion bunches to speed-up the studies

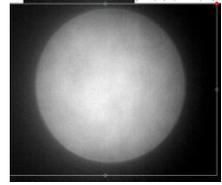
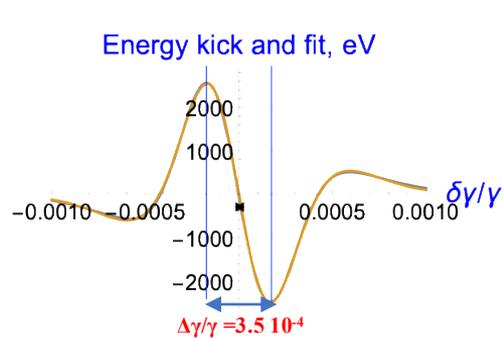
Parameter	Run 25	Previous
γ , relativistic factors of the beams	19.57	28.5
Au ion beam energy, GeV/u	18.2	26.5
Electron beam energy, MeV	10	14.56
Peak current, A (core, 50% of the beam)	≥ 20	≥ 45
Normalized emittance (core, > 50% of the beam), $\mu\text{m rad}$	≤ 1.5	≤ 1.5
RMS relative energy spread (core, > 50% of the beam), 10^{-4}	≤ 2	≤ 2
Energy flat top (core, > 50% of the beam), $ 10^4 \delta\gamma/\gamma $	< 1.5	< 1.5

Simulation of cooling on the bunch with 2×10^8 ions



Simulations are good but experimental data is more important: *CeC operates with electron beam parameters equal to better than the requirements: sample from September 18, 2025*

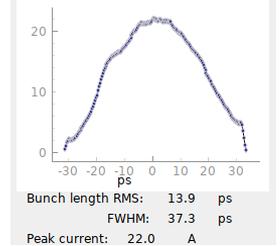
Required: $\epsilon_{\text{norm}} < 1.25 \mu\text{m}$



Peak current: $>20 \text{ A}$

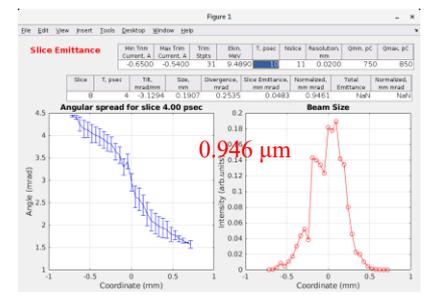
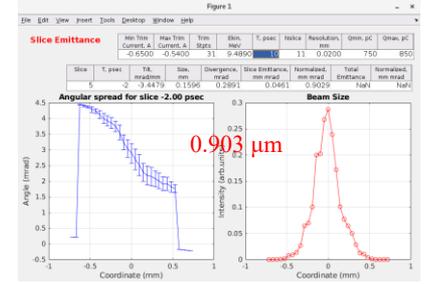
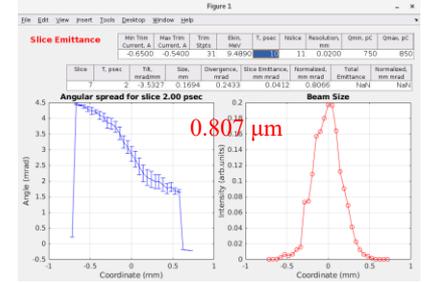
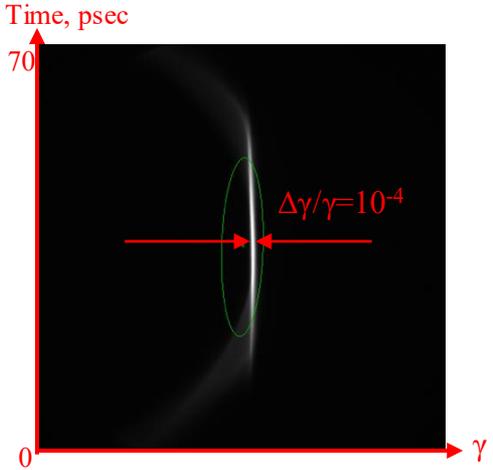
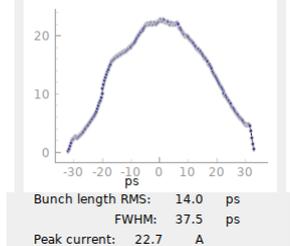
Cavity voltage: Actual \downarrow 75.0 kV
 Kin: 9.5 MeV RF: 1.3 GHz
 Total charge: Actual \downarrow 0.818 nC

Peak Current (A)

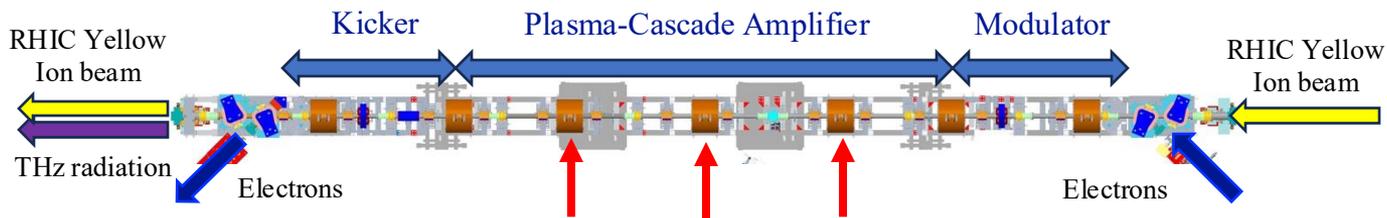


Cavity voltage: Actual \downarrow 75.0 kV
 EKin: 9.5 MeV RF: 1.3 GHz
 Total charge: Actual \downarrow 0.847 nC

Peak Current (A)



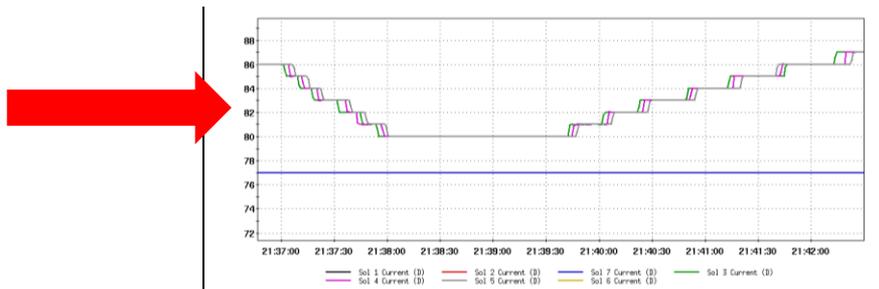
CeC guts: Plasma-Cascade Amplifier (PCA)



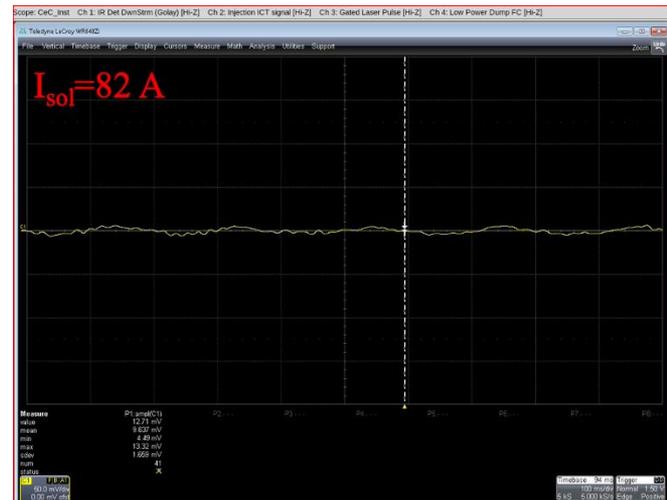
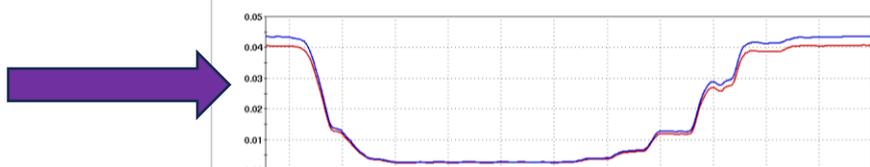
Plasma-Cascade Amplifier is a parametric amplifier: strong focusing solenoids caused periodic modulation of the beam radius and corresponding modulation of plasma frequency. It results in exponential growth of density modulation induced by ions in the modulator.

Classical PCA: changing strength of PCA solenoids result in dramatic increase of the THz radiation: September 22, 2025

Current in PCA solenoids



Measured THz power a.u.



Conclusions

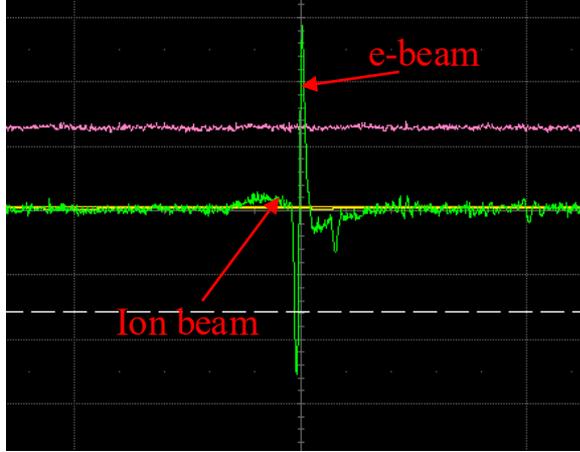
- Demonstration of Coherent electron Cooling remains a very challenging endeavor
- All main components of the CeC process were successfully demonstrated:
 - Ion's imprint into the e-beam density modulation
 - High gain Plasma-Cascade Amplification of the e-beam noise (and ion imprint)
 - Recombination of ions and electrons with matched relativistic factors
- All beam parameters necessary for CeC demonstration are demonstrated
 - More details are in THA1, THA2 and THA3 talk on Thursday morning by Yichao Jing, Jun Ma and Gang Wang
- The CeC accelerator performance is sufficiently stable
- We are ready for CeC demonstration
- The main challenge is allocation of dedicated time with ion beam for CeC project
 - In last 3 years CeC has 3.5 hours of time with ion beam at CeC energy
 - This is the last RHIC run and CeC system will be taken apart after the run ends
 - Two detectors are completing their physics program and ego to use every hour of RHIC operation
 - We are not giving up hope and exploring every possibility for a limited number of shifts for CeC demonstration
- I want to thank everybody who participated and participating in CeC project: RHIC operators, colleagues from Accelerator Physics, RF, Vacuum, Instrumentation, Cryogenics, Control, Mechanical systems and ES&F division, cathode team from Instrumentation Department, as well as the CeC operation team, for their dedicated and steadfast support of our attempt to demonstrate this stubbornly resisting phenomenon

Thanks to all involved in the CeC project

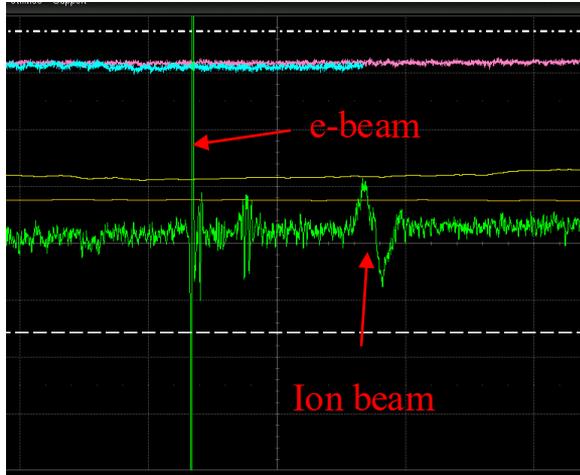


... never can get all of your photos...

Back-ups



Overlap (20 ns, 10 mV per division)



No overlap (50 ns, 2 mV per division)

Synchronization was achieved by observation of the signal from the BPM pick-up electrode in the FEL section.

The Ion Imprint studies: Run 2020

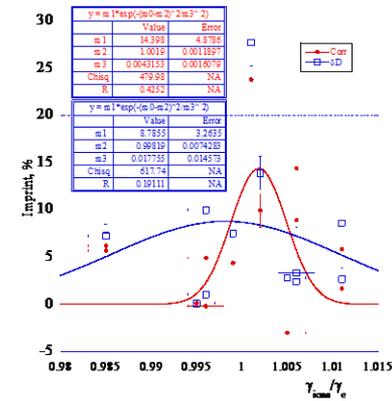
- We observed clear presence of the ion imprint in the electron beam resulting in increase of the e-beam radiation at 35 μm with average imprint of

$$\langle \text{imprint} \rangle = 4.7\% \pm 0.4\%(\text{systematic}) \pm 0.3(\text{random})\%$$

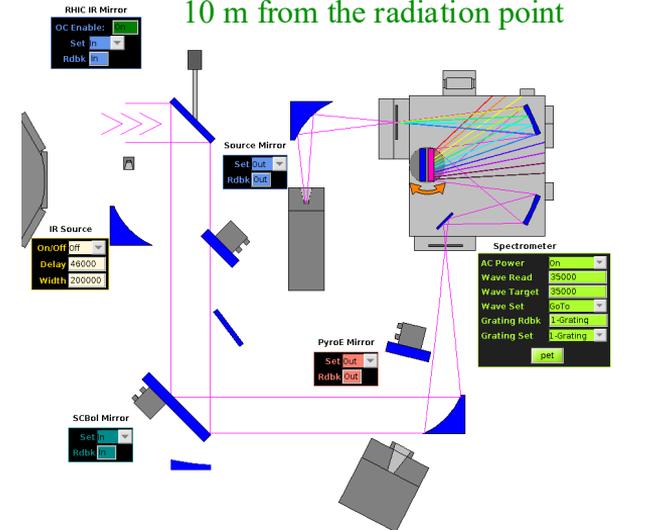
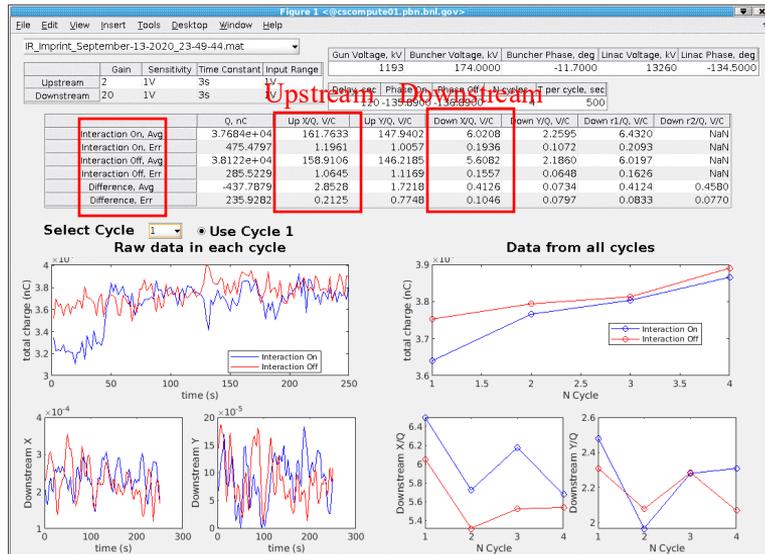
- We applied PCA to boost radiation at 35 μm at the level detectable by current IR detectors after the spectrometer

Typical “good” measurement:

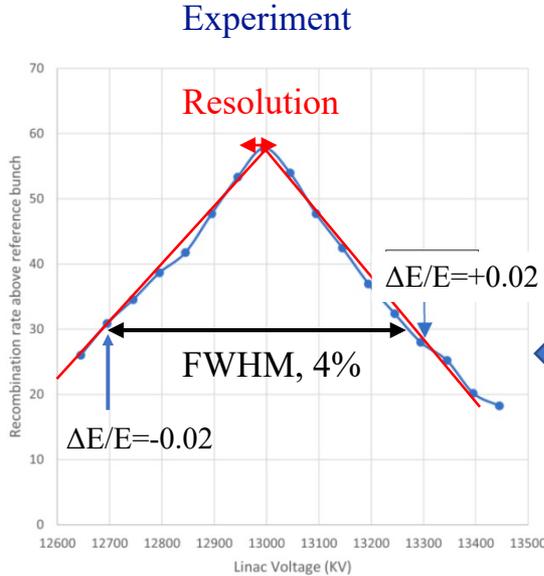
4 cycles with 500 measurements each



Downstream IR diagnostics
10 m from the radiation point

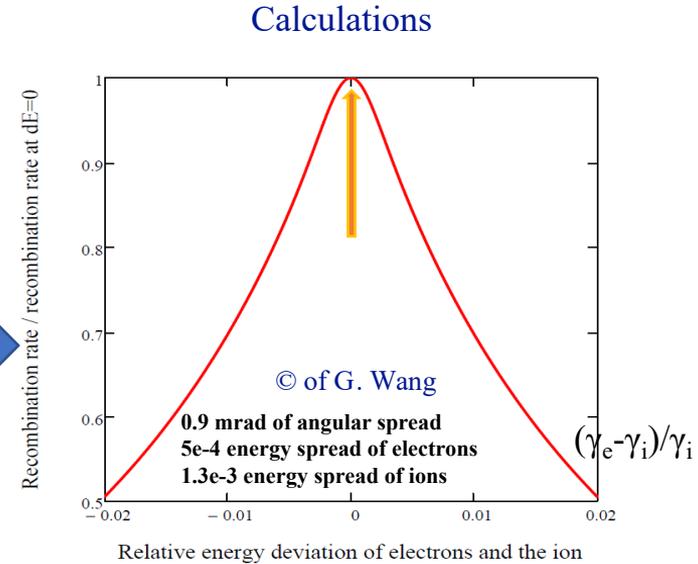


Recombination of electrons with Au ions: Run 2021



Triangular shape of the measured dependence allows to define matching of the relativistic factors with accuracy $\sim 0.2\%$, which is significantly smaller than 4% FWHM.

This finding will reduce the range where we need to search for the CeC signature by 5-to-10 fold.



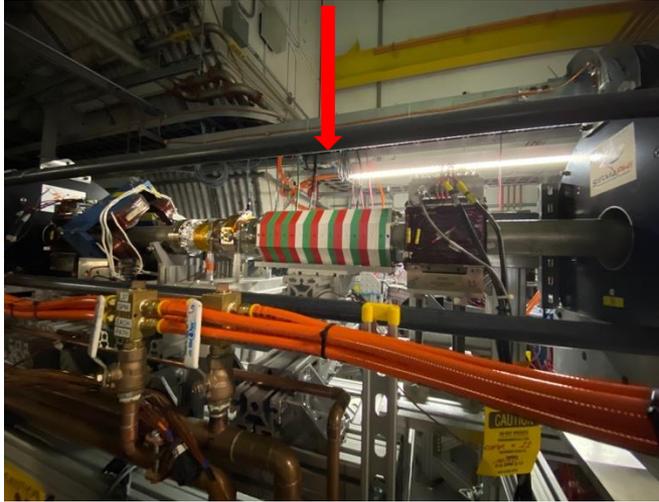
$$\sigma(v_x, v_y, v_z) = A \frac{2m_0}{m_e (v_x^2 + v_y^2 + v_z^2)} \left[\ln \left(\frac{2m_0}{m_e (v_x^2 + v_y^2 + v_z^2)} \right) + \gamma_1 + \gamma_2 \left(\frac{m_e (v_x^2 + v_y^2 + v_z^2)}{2m_0} \right)^{1/3} \right]$$

$$f_e(v_e) = \frac{1}{(2\pi)^{3/2} \beta_{e,x}^2 \beta_{e,z}} \exp\left(-\frac{v_{e,x}^2 + v_{e,y}^2}{2\beta_{e,\perp}^2}\right) \exp\left(-\frac{(v_{e,z} - v_{z0})^2}{2\beta_{e,z}^2}\right)$$

$$f_i(v_i) = \frac{1}{(2\pi)^{3/2} \beta_{i,x}^2 \beta_{i,z}} \exp\left(-\frac{v_{i,x}^2 + v_{i,y}^2}{2\beta_{i,\perp}^2}\right) \exp\left(-\frac{v_{i,z}^2}{2\beta_{i,z}^2}\right)$$

This results include convolution of the exact formula recombination cross-section (in the commoving frame) with distributions of two beams

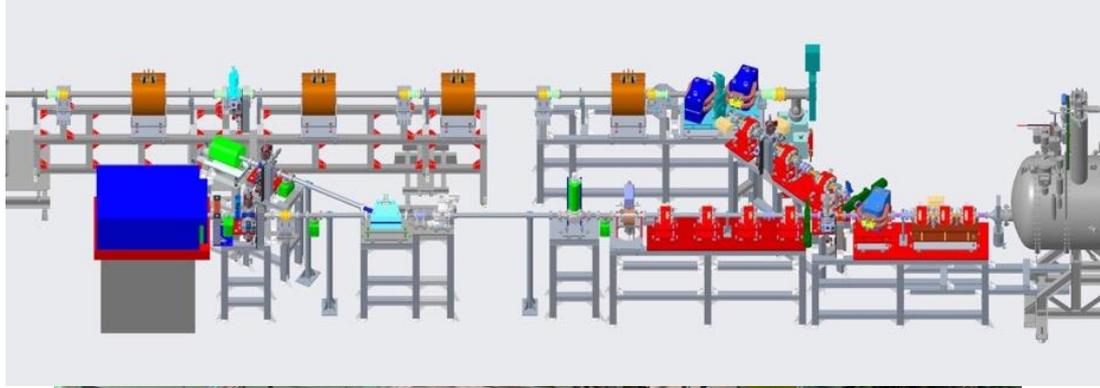
Diagnostics undulator and cryo-cooled IR detector



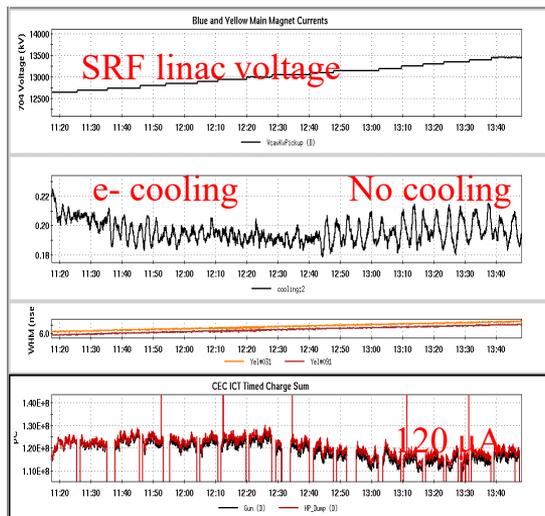
Parameter	Value	Units
Period	8	cm
Gap	7.9	cm
Peak field	0.6	kGs
Radiated power at 50% beam current	4	nW
Fundamental wavelength @ $\gamma=19.57$	115	μm
Central frequency @ $\gamma=19.57$	2.6	THz
Third harmonic	7.8	THz
F_3/F_1	0.04	

- ✓ Cryo-cooled and Golay IR detectors
- ✓ Undulator generates radiation at 7.8 THz harmonic frequency, which is within the bandwidth of the Plasma-Cascade Amplifier (PCA)
- ✓ This system allow us to optimize the PCA gain

Time-resolve diagnostics beam-line: the key for accurate measurements of beam parameters

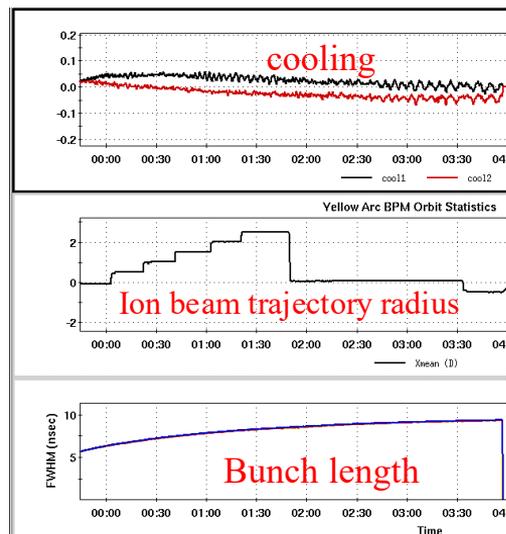


Search for CeC signature and observation of regular bunched electron cooling of 26.5 GeV/u Au ion beam



Changing e-beam energy requires multiple adjustments

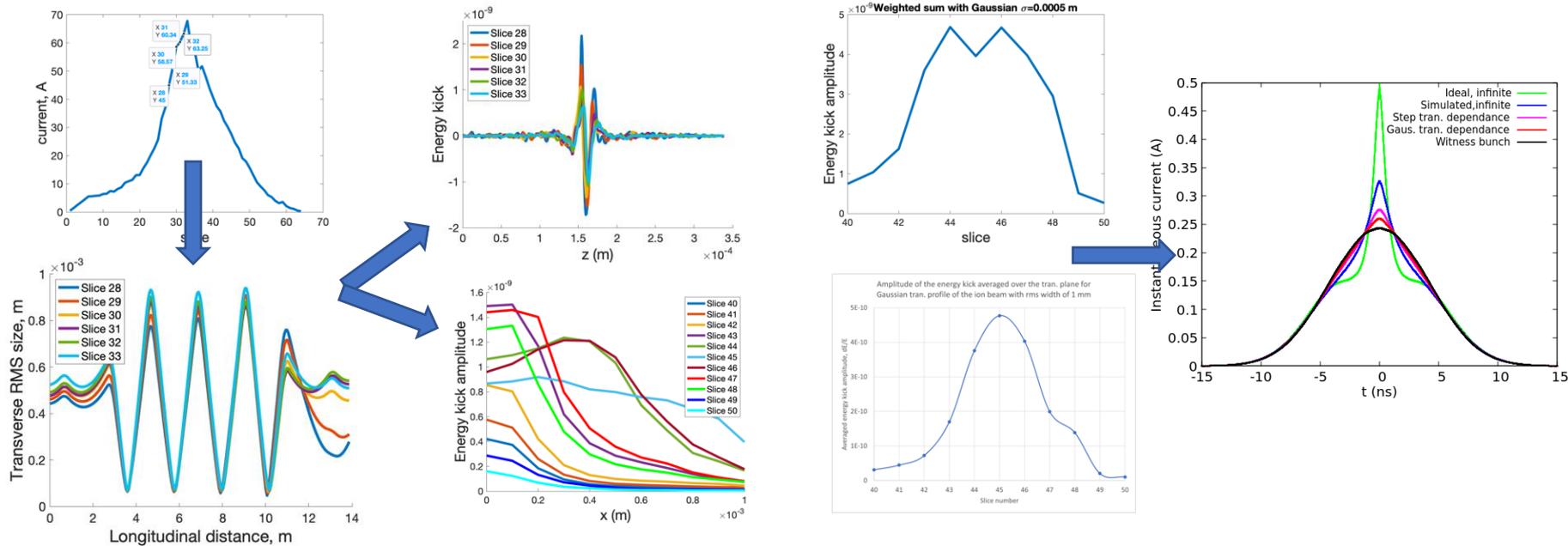
- There was no attempt of improving regular non-magnetized electron cooling – we used the lattice optimized for PCA CeC - and the best electron cooling rate was ~ 100 hours. It is consistent with cooling rate estimation made by Dmitry Kayran and 90 hours cooling rate simulated by He Zhao
- There is one exception – on the 4th of July CeC evening shift we observed cooling rate of 16 hours: this event is possibly a first indication of the CeC cooling, but it is not conclusive



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

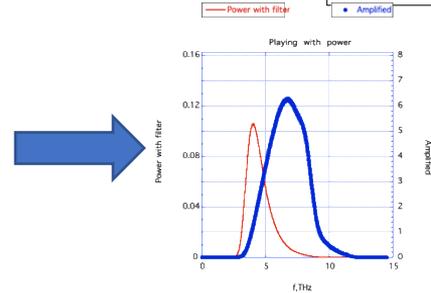
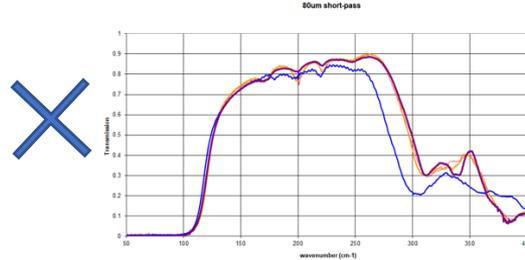
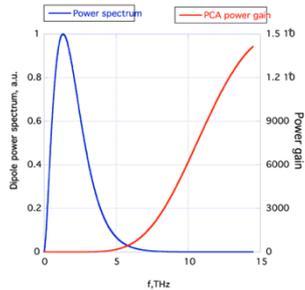
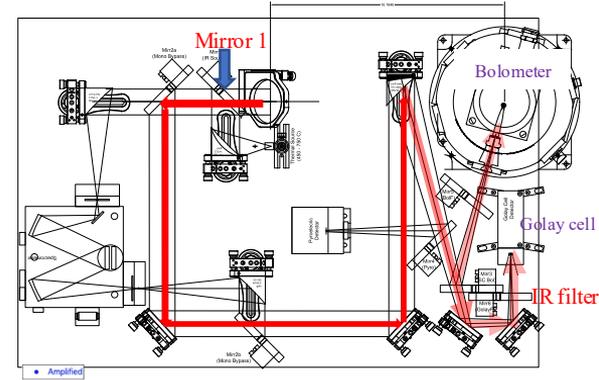
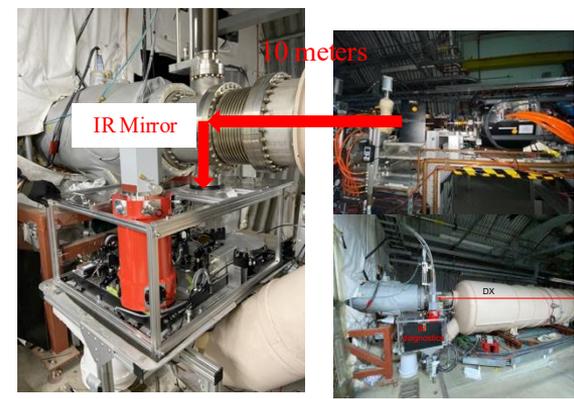
PCA CeC simulations: slice by slice, ion by ion

- Simulations of electron beam are done using Impact T/Z code (Y. Jing, K. Shih) provide distribution of electron beam at the entrance of the CeC section
- This information is used to simulate interaction of ions with individual slices: PCA gain and kick to ions is calculated as function arrival time and transverse position of ion (SPACE code, J. Ma)
- This information is used to simulate evolution of cooled ion bunch (G. Wang and his code) and compare it with reference (non-interacting) bunch
- This is work in progress and preliminary findings will be reported at C-AD MAC next week by Dr. Gang Wang

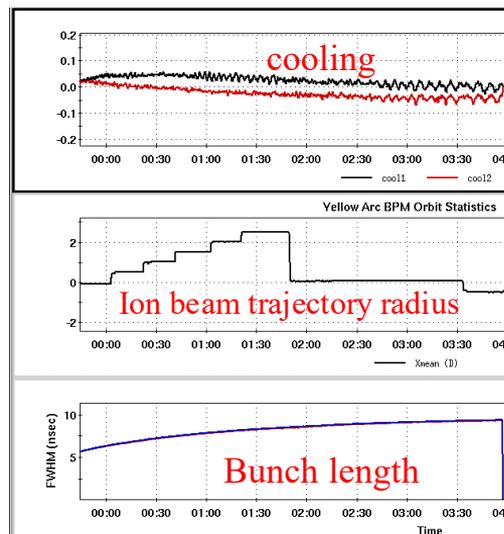
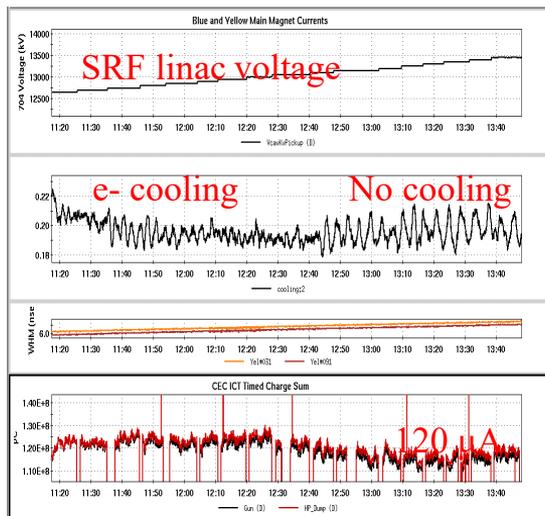


How PCA gain is measured?

- We used IR radiation from the bending magnet at the exit of the CeC section. Critical frequency of synchrotron radiation from the bending magnet is 0.4 THz
- PCA gain peaks at 12THz and there is no gain below 3 THz
- IR radiation is intercepted by 2" mirror 10 meters downstream
- For these measurements, the radiation was delivered to two most sensitive IR detectors: broad-band Golay cell or cryo-cooled Bolometer.
- IR filter with passband of 3.5-10 THz was used in front of the Golay cell to improve sensitivity at high frequencies (see next slide)
- Signal from Golay cell was detected by lock-in amplifier synched with the electron bunch pattern (typically 5 Hz, five 100 msec bunch trains per second). We used 3rd order modulation-demodulation (MDM) technique to remove background unrelated to IR radiation, by periodically blocking IR using Mirror 1.
- Signal from Bolometer was delivered in unsynchronous mode (140 kilo-samples per second) with respect to electron beam pattern. Analog signal was not available. We developed MatLab application for asynchronous detection of this digital pattern.
- PCA gain was evaluated by comparing radiated power in the PCA lattice (strong solenoids) with relaxed lattice (weak solenoids) using the same setting of the CeC accelerator and the electron beam



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

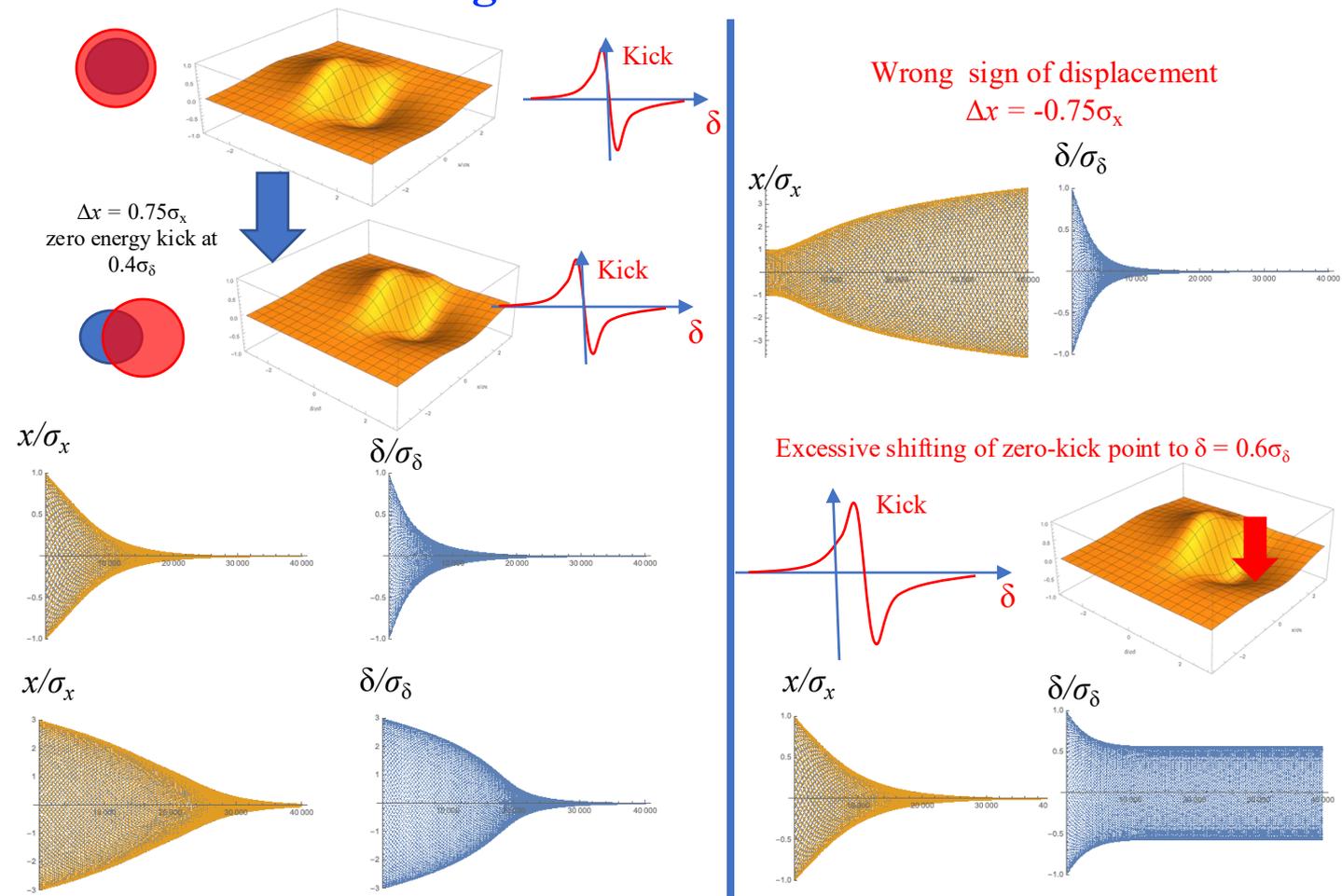


Changing e-beam energy requires multiple adjustments

- 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 90 hours cooling rate simulated by He Zhao
- There is one exception – on the 4th of July CeC evening shift we observed cooling rate of 16 hours: this event is possibly a first indication of the CeC cooling, but it is not conclusive

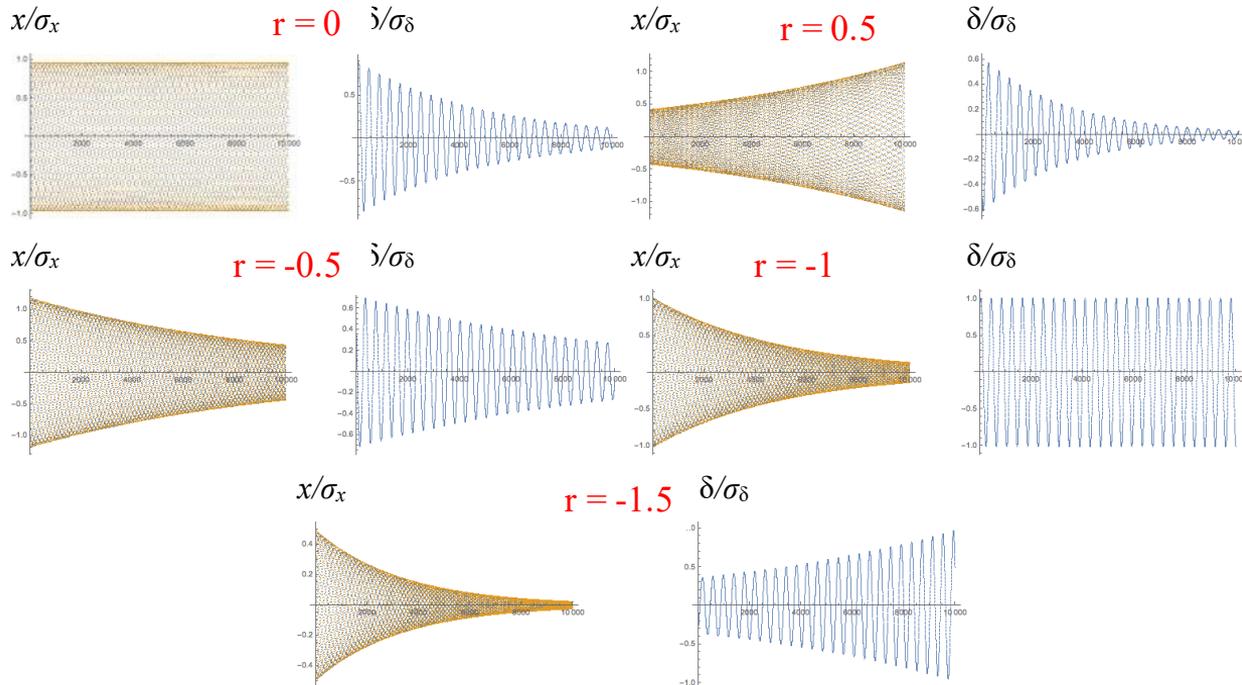
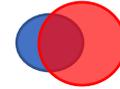
Adjusting ion beam energy – 1 mm x_{mean} corresponds to 0.1% change in the ion beam energy

Distribution of cooling between longitudinal and transverse degrees of freedom – real kick



Distribution of cooling between longitudinal and transverse degrees of freedom – linearized kick

$$\frac{\delta E_h}{E_o} = \text{const} - \zeta_1 x - \zeta_6 \frac{E_h - E_o}{E_o}; \quad r = D\zeta_1 / \zeta_6$$



Linearized case: cooling decrements

We will neglect transverse kicks, which are very weak in CeC

Sorry for repeating trivial formulae from my AP class

Only energy kick

$$\Delta x_6 = \frac{\delta E_h}{E_o} = \text{const} - \sum_{i=1}^6 \zeta_i \cdot x_i$$

$$X = \frac{1}{2} \sum_{k=1}^3 (a_k Y_k(s) e^{i\nu_k s} + c.c.); \mathbf{Y}_{k=1,2} = \begin{pmatrix} Y_{k\beta} \\ -Y_{k\beta}^T SD \\ 0 \end{pmatrix}; \mathbf{Y}_3 \cong \frac{1}{\sqrt{\Omega}} \begin{pmatrix} D \\ -i\Omega \\ 1 \end{pmatrix}; Y_{k\beta} = \begin{bmatrix} y_{k1} \\ y_{k1} \\ y_{k2} \\ y_{k4} \end{bmatrix}; D = \begin{bmatrix} D_x \\ D'_x \\ D_y \\ D'_y \end{bmatrix};$$

$$\langle \Delta a_k \rangle = -\xi_k a_k \rightarrow a_k = a_{k0} e^{-n\xi_k} \quad \text{Re}\xi_{(1,2)} = -\frac{i}{2} (Y_{(1,2)\beta}^T SD)^* \sum_{i=1}^4 y_{(1,2)i} \cdot \zeta_i; \xi_s = \text{Re}\xi_3 = \frac{1}{2} \left(\zeta_6 + \sum_{i=1}^4 D_i \cdot \zeta_i \right),$$

No x-y coupling

$$Y_{1\beta} \equiv Y_x = \begin{bmatrix} w_x \\ w'_x + \frac{i}{w_x} \\ 0 \\ 0 \end{bmatrix}; Y_{2\beta} \equiv Y_y = \begin{bmatrix} 0 \\ 0 \\ w_y \\ w'_y + \frac{i}{w_y} \end{bmatrix}; D = \begin{bmatrix} D \\ D' \\ 0 \\ 0 \end{bmatrix};$$

$$\beta_{x,y} = w_{x,y}^2; \alpha_{x,y} = -w'_{x,y} w_{x,y}$$

$$\xi_x = \text{Re}\xi_1 = -(D\zeta_1 + D'\zeta_2); \xi_s = \xi_6 - \xi_x.$$

Qx-Qy resonance

$$Y_1 = \frac{1}{\sqrt{1+|\alpha|^2}} (Y_x + \alpha Y_y); Y_2 = \frac{1}{\sqrt{1+|\alpha|^2}} (-\alpha^* Y_x + Y_y)$$

$$\text{Re}\xi_1 = -\frac{D\zeta_1 + D'\zeta_2}{1+|\alpha|^2}; \text{Re}\xi_2 = -|\alpha|^2 \frac{D\zeta_1 + D'\zeta_2}{1+|\alpha|^2}.$$

*Can use a non-achromatic transport (time of flight dependence)
or transverse beam separation to couple longitudinal and transverse cooling*

Encountered challenges

- In Run 2018, while operating with FEL amplifier, we discovered that electron beam in the low energy (ballistic compression) section was developing very strong longitudinal instability. Detailed studies showed that this was Plasma-Cascade Instability caused by strong transverse focusing. We developed lattice of the CeC accelerator suppressing this instability and providing quiet electron beam with noise comparable with that of the shot-noise.
- In Run 2021, we attempted to demonstrate CeC, but 5×10^{-4} relative beam energy jitter - caused by 15 psec RMS time jitter of the seed laser pulses - prevented us from observing CeC. It simply was washed away.
- Two additional challenges are coming from 113 MHz SRF gun axis offset from the CeC accelerator beam-line and from presence of transverse field components in 500 MHz bunching cavity. Time-dependent variation of beam centroid create additional complications in beam diagnostics as well as in creating compact e-beam
- In Run 2022, a new seed laser with 3 psec RMS time jitter was incorporated, and we achieved beam parameters sufficient for observation of the CeC cooling. Unfortunately, two major failures, both caused by human errors, consumed 71% of the run time and we were unable to complete the experiment – we simply run out of time
- Run 2023 had additional challenges: it was in the Summer and systems suffered from overheating and AC failures. It also was cut short by an accident with LiHe system in late June.
- Main remaining challenge is large (5% RMS) jitter in the energy of the laser pulses and corresponding variations of the electron bunch charge. This jitter causes significant variation in space-charge dominated dynamics of the electron beam and should be eliminated for reliable measurements and demonstration of CeC