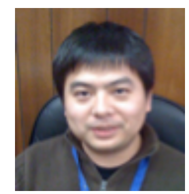

# Coherent electron Cooling (CeC) experiment at RHIC

Vladimir N Litvinenko for CeC group

Yichao Jing, Jun Ma, Irina Petrushina,  Igor Pinayev, Kai Shih, Gang Wang, Yuan Wu

Department of Physics and Astronomy, SBU

Collider-Accelerator Department, BNL

Center for Accelerator Science and Education

CASE Center for Accelerator Science and Education

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

# Why we doing this?

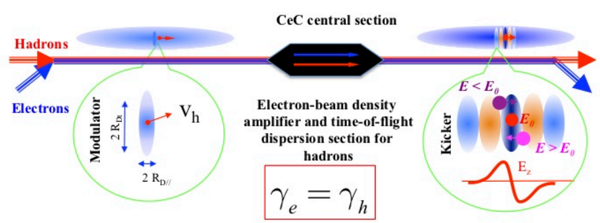
- 2018 NAS Assessment of U.S.-Based Electron-Ion Collider Science: *The accelerator challenges are two fold: a high degree of polarization for both beams, and high luminosity.*
- April 2018 eRHIC pCDR review committee report:

"*The major risk factors are strong hadron cooling of the hadron beams to achieve high luminosity, and the preservation of electron polarization in the electron storage ring*. The Strong Hadron cooling [**Coherent Electron Cooling (CeC)**] is needed to reach $10^{34}/(cm^2 s)$ luminosity. ***Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC***."

Stony Brook University

Center for Frontiers in Nuclear Science

## ICFA mini-workshop CeC 2019




Coherent Electron Cooling –
Theory, Simulations and Experiment

July 24-26, 2019, at the Center for Frontiers in Nuclear Science
Department of Physics and Astronomy, Stony Brook University,
Stony Brook, NY 11794, USA

CASE
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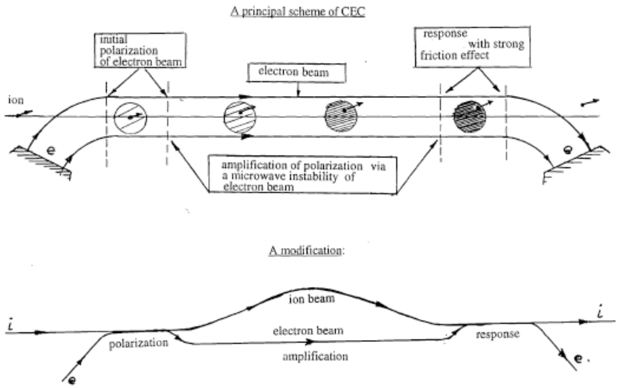
- CeC ICFA mini-workshop has key-note by Ya. Derbenev: how he conceived the idea http://case.physics.stonybrook.edu/index.php/ICFA_workshop_CeC
- In the nut-shell, the idea came from looking at the s "transient term" in the drag-force in 1978 Derbenev's second Doctoral thesis, which differs from the first stationary term

- $$\vec{F}(t) = -\frac{Z^2 e^2}{2\pi^2}\int d^3k \frac{\vec{k}}{k^2}\left\{\frac{\mathrm{Im}\,\varepsilon_{\vec{k}}(\vec{k}\vec{v})}{\left|\varepsilon_{\vec{k}}(\vec{k}\vec{v})\right|^2} + \boxed{i\sum_s\left[\frac{\exp(-i(\omega-\vec{k}\vec{v})t)}{(\omega-\vec{k}\vec{v})\partial\varepsilon_{\vec{k}}(\omega)/\partial\omega}\right]_{\omega=\omega_s}}\right\}$$

*Courtesy of Ya. Derbenev*

- With *Im*($\omega_s$)>0 the term is growing
- Derbenev asked **the question**: can one amplify the micro-bunching induced by hadrons, **Derbenev called the process "Coherent Electron Cooling" or CeC – it includes any type of instability used for amplifying the hadron imprint.**
- ***Coherent elctron Cooler is nothing else that stochastic cooling using electric field induced by micro-bunching in electrob beam. CeC with chicane-based amplified is CeC not MBEC***

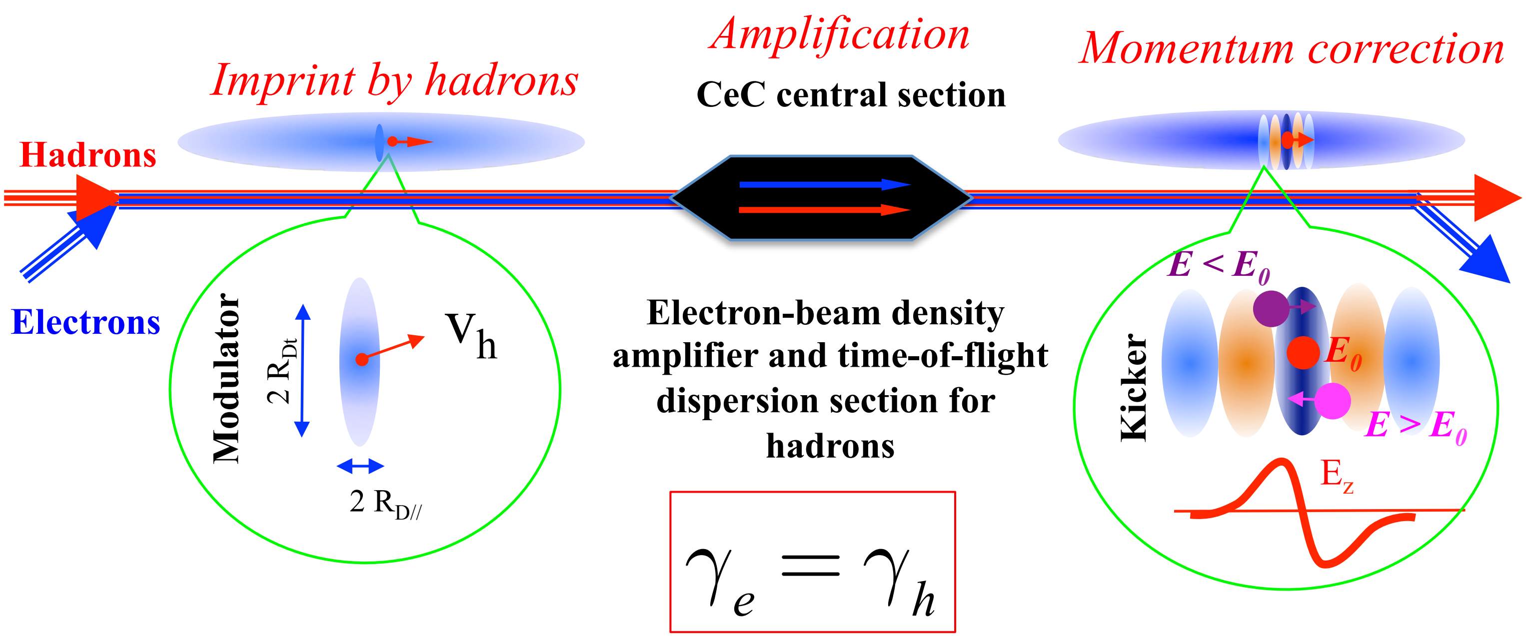




- *Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980)*
- *Coherent electron cooling, Ya. S. Derbenev, Randall Laboratory of Physics, University of Michigan, MI, USA, UM HE 91-28, August 7, 1991*
- *Ya.S.Derbenev, Electron-stochastic cooling, DESY , Hamburg, Germany, 1995 ………*

# What is Coherent electron Cooling

- Short answer – stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz
- Longer answer on next pages




PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

**Coherent Electron Cooling**

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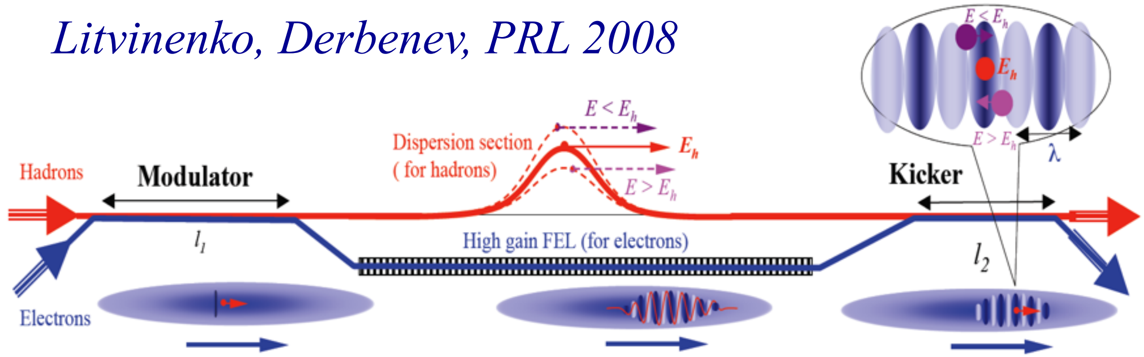
(Received 24 September 2008; published 16 March 2009)

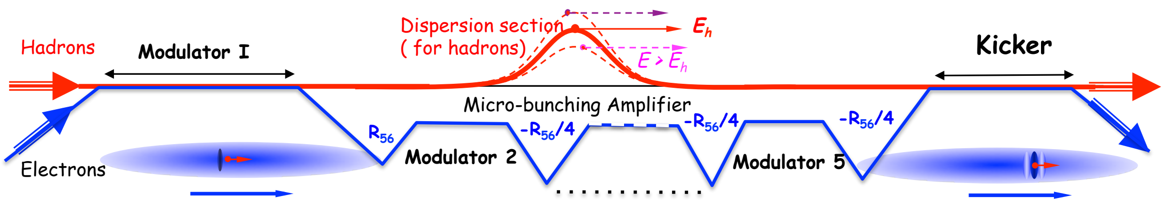
# CeC schemes

*Litvinenko, Derbenev, PRL 2008*



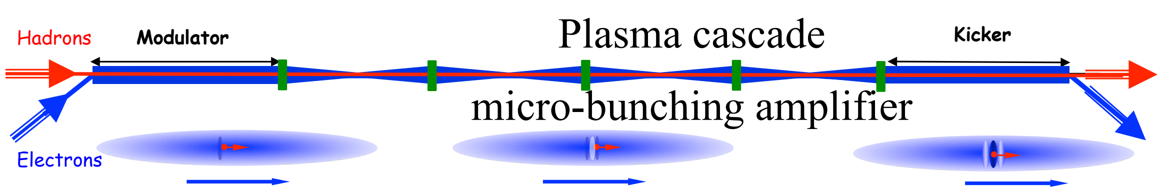

**High gain FEL amplifier**

*Ratner, PRL 2013*



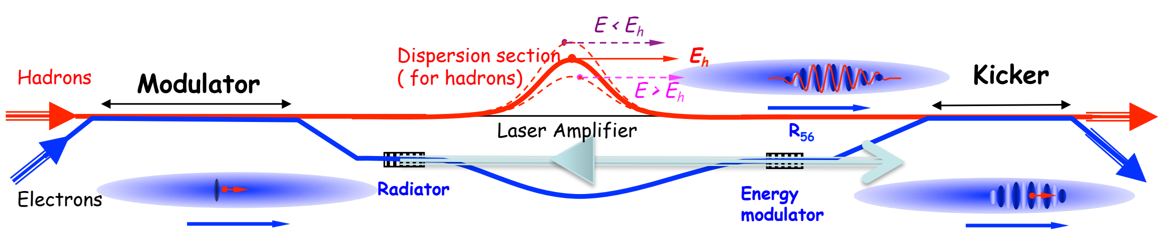

**Multi- Chicane Microbunching amplifier**

*Litvinenko, Wang, Kayran, Jing, Ma, 2017*



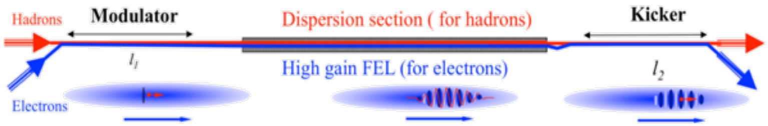

**Plasma-Cascade Microbunching amplifier**

*Litvinenko, Cool 13*

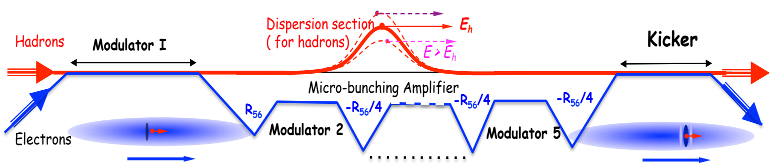



**Hybrid laser-beam amplifier**

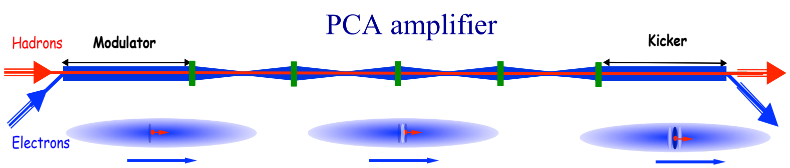
# What can be tested experimentally?



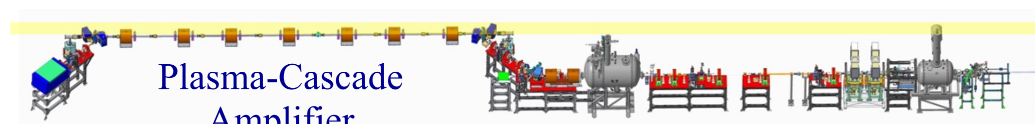

RHIC Run 18

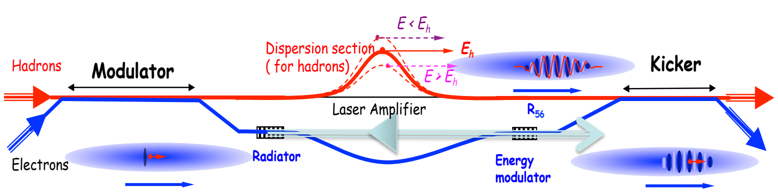




Cooling test would require significant modification of the RHIC lattice & superconducting magnets with cost exceeding $20M.



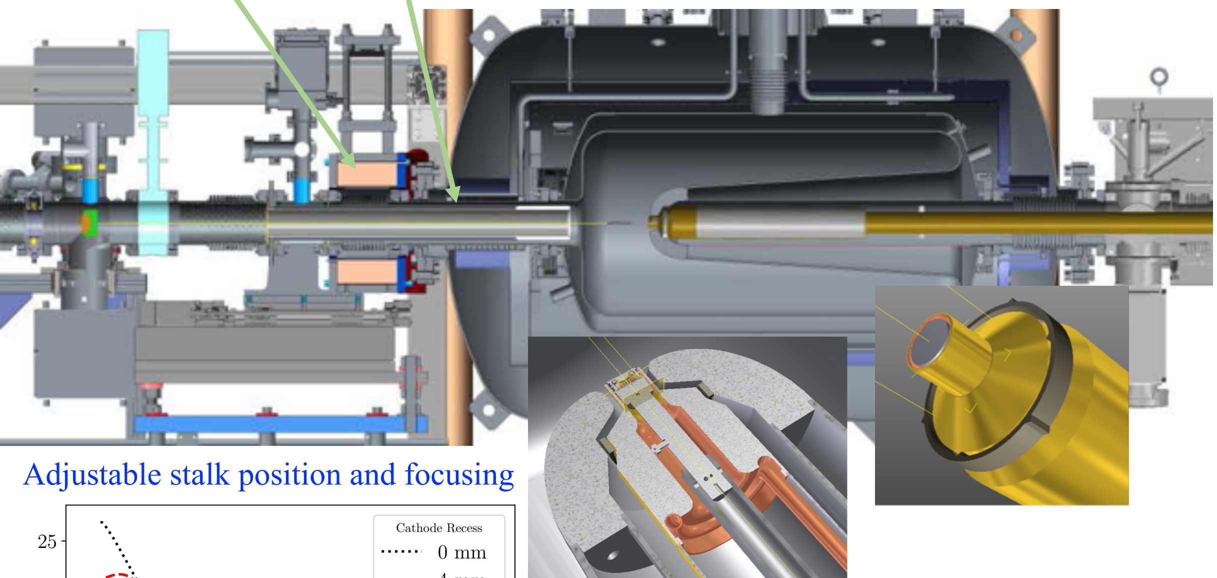

RHIC Runs 20-22



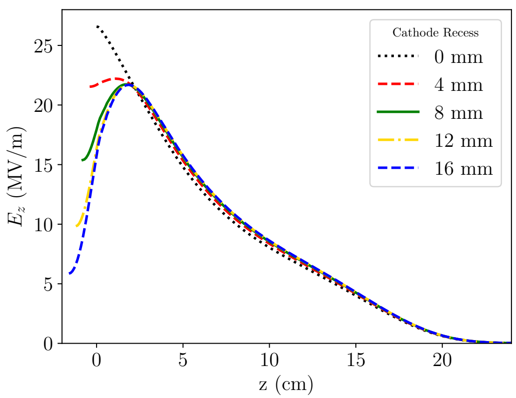




Cooling test would require significant modification of the RHIC lattice & superconducting magnets with cost exceeding $20M

# Record breaking 113 MHz CW SRF Gun

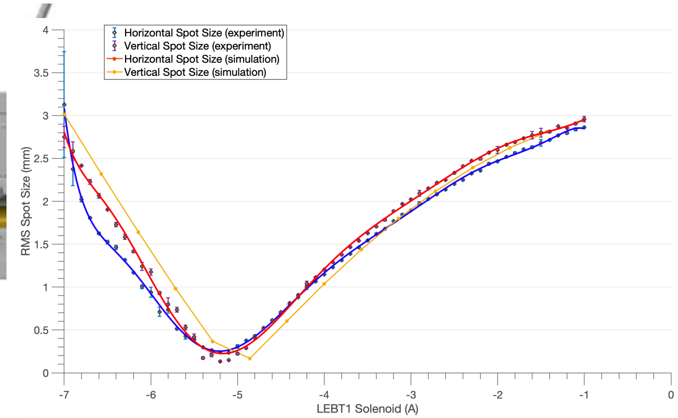



Adjustable stalk position and focusing

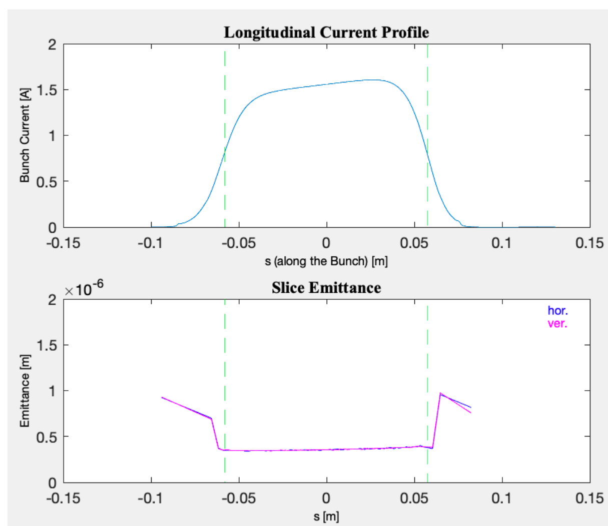



*Gun energy: 1.25 MV*
*Laser spot on cathode r.m.s. size: 0.8mm (3.2 mm diameter)*
*Bunch charge: 600 pC*
*Bunch length: 400 ps*
*Gun solenoid: 8.6 A*

## Simulations vs measurements

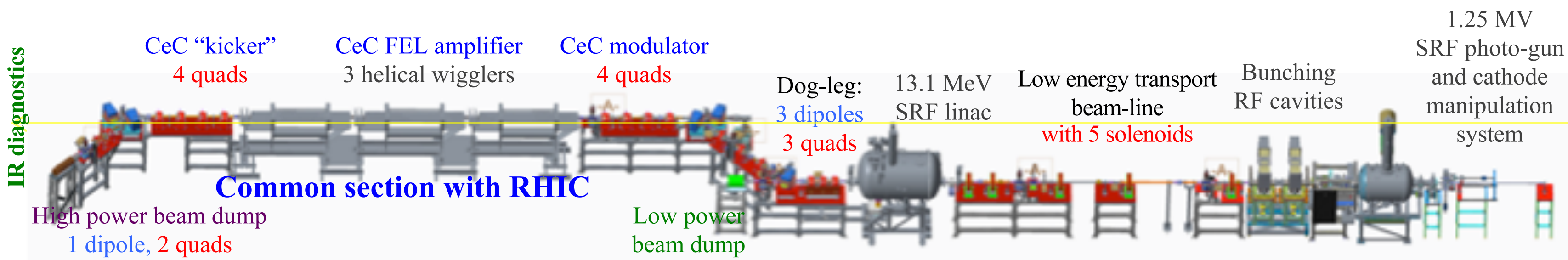



## GPT simulations



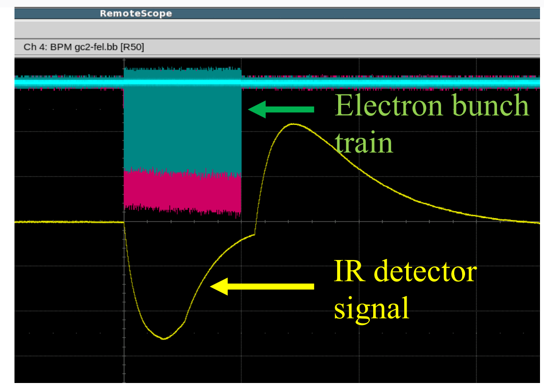

- Quarter wave design
- Operates at 4.2ºK
- $CsK_2SB$ Cathode is at room temperature
- Stalk is RF choke and field pick-up
- Manual coarse tuners
- FPC serves as fine tuner
- Operational CW voltage 1.25 MV
- **Maximum charge 10.7 nC**
- Dark current < 1nA
- **Very low normalized emittance**
    - **0.15 mm mrad at 100 pC**
    - **0.35 mm mrad at 600 pC**

# Attempt to test FEL-based CeC

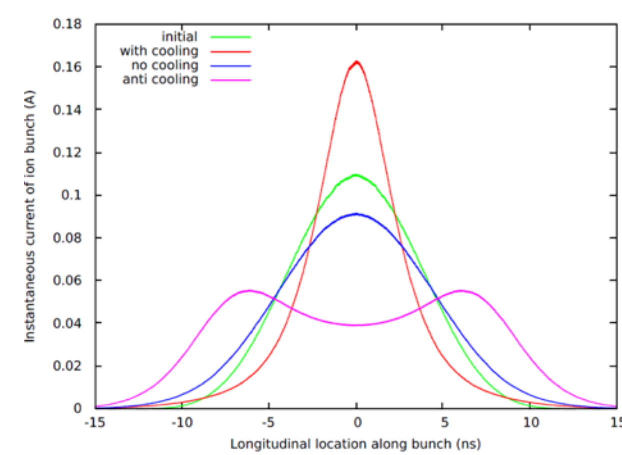



| Parameter | Design | Status | Comment |
|---|---|---|---|
| Species in RHIC | $Au^{+79}$, 40 GeV/u | $Au^{+79}$ 26.5 GeV/u | ✓ to match e-beam |
| Electron energy | 21.95 MeV | 14.56 MeV | Linac's quench limit |
| Charge per electron bunch | 0.5-5 nC | 0.1- 10.7 nC | ✓ |
| Peak current | 100 A | 50 -100A | ✓ |
| Bunch duration, psec | 10-50 | 12 | ✓ |
| Normalized beam emittance | < 5 mm mrad | 0.15 – 5 mm mrad | ✓ |
| Energy spread, RMS | 0.1% | Core <0.1% | ✓ |
| FEL wavelength | 13 μm | 31 μm | ✓ with new IR diagnostics |
| Repetition rate | 78.17 kHz | 78.17 kHz | ✓ |
| CW beam | > 80 μA | 150 μA | ✓ |

FEL lasing pulse at 31 μm: April 2018

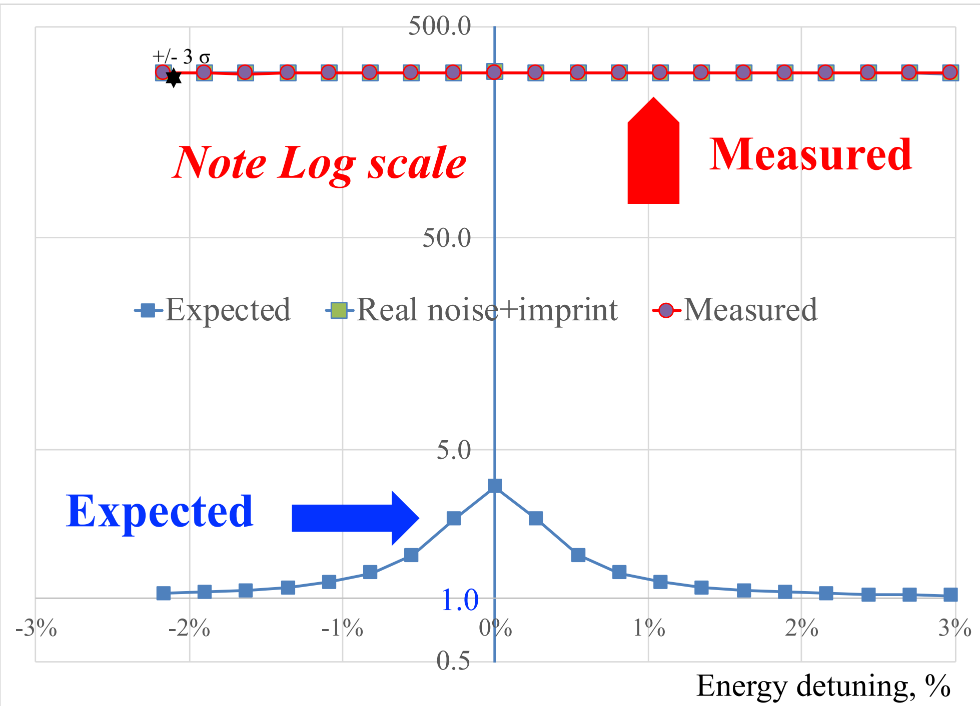



Predicted evolution of ion bunch profile in 40 minutes



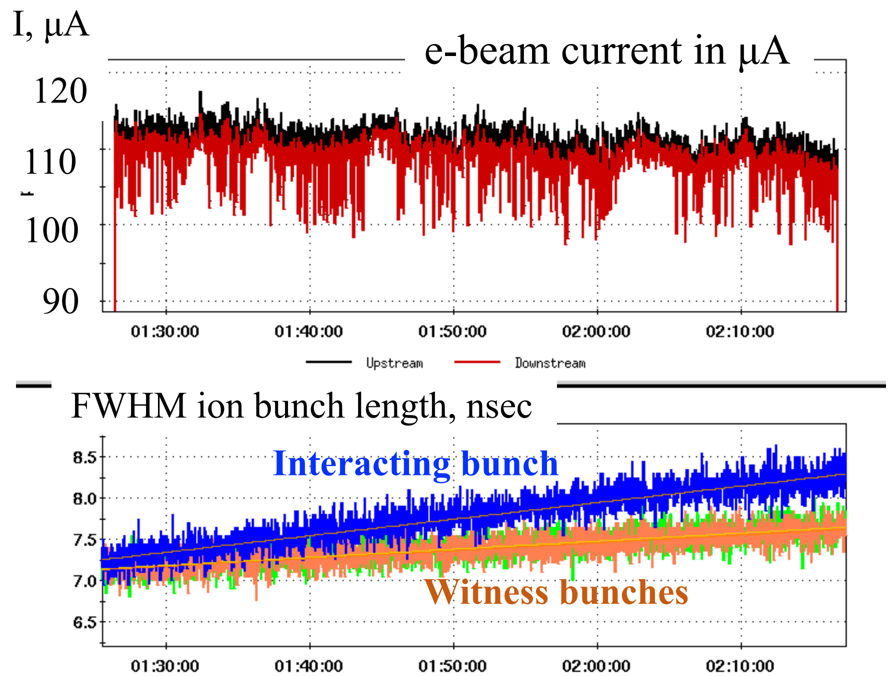
# Puzzle of the CeC Run 18

**Search for ion's imprint in electron beam and matching beam's relativistic factors was the first important step in CeC experiment**




Expected and measured relative change in the FEL signal with overlapping and separated beams. Measurements RMS error is 2%.

**Interaction of ion bunch synchronized is in agreement with the measured FEL-amplified noise level**




Bottom plot: evolution of the bunch lengths for interacting (blue trace) and witness (non-interacting) bunches (orange and green traces)

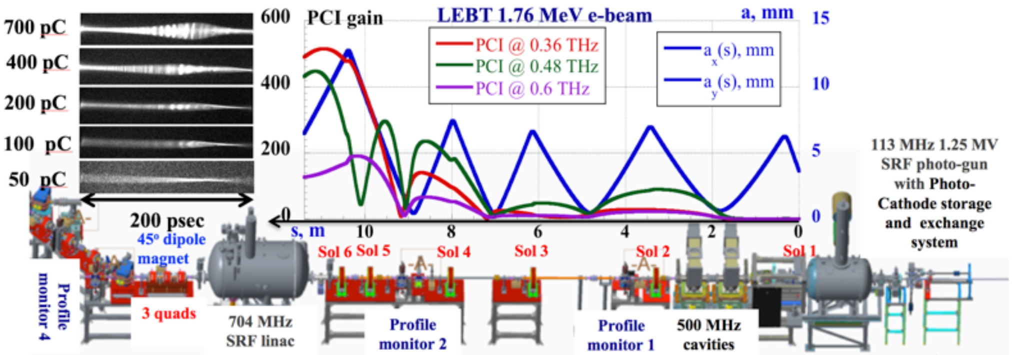
**We ran out of time to demonstrate the FEL-based CeC during Run 18 with RHIC.**

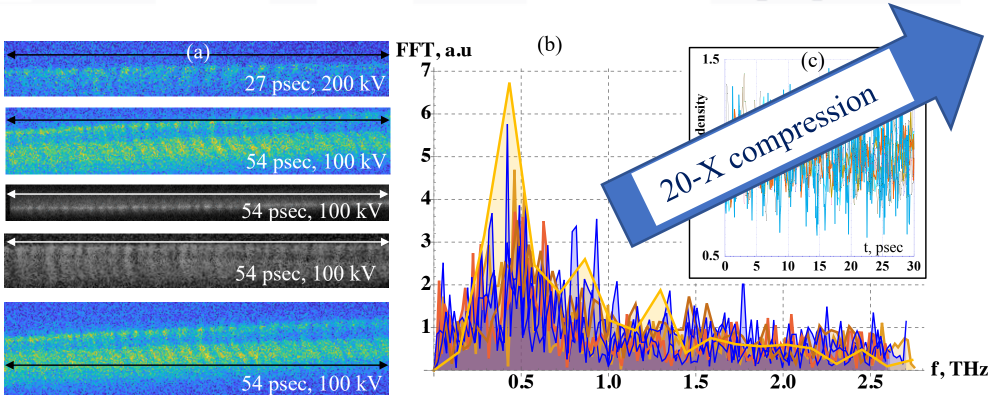
**FEL-based CeC concept remains valid and awaiting for experimental demonstration.**

# Solving the Puzzle

RHIC cryo system extended operation for LEReC mid-September and we used it to find the culprit:
*THz noise in the electron beam (300-fold above the shot noise!) dwarfing the ion beam imprint.*
**This was not a failure of the FEL-based CeC concept, but unexpected excessive noise in the beam**

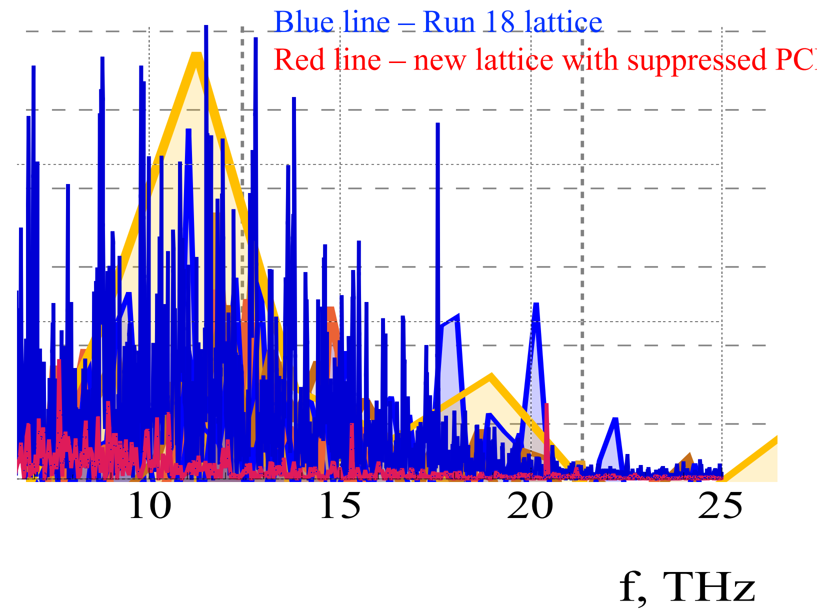
## Uncompressed bunch: simulations and experiment in Sept 2018




(a) Measured time profiles of 1.75 MeV electron bunches with 0.45 nC to 0.7 nC; (b) Seven measured overlapping spectra and PCI spectrum simulated by SPACE (slightly elevated yellow line); (c) Clip shows a 30-psec fragment of seven measured relative density modulations.

## Compressed beam simulation in CeC accelerator using Impact-T code @ NERSC



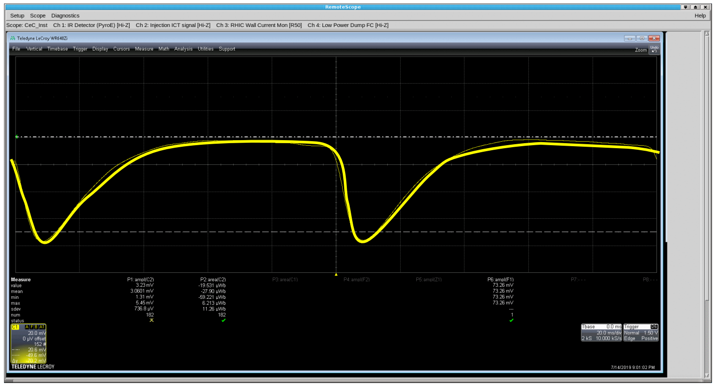

**First we showed it in simulations that we can control noise level in the electron beam and confirmed this in the experiment during a short run in Summer 2019**

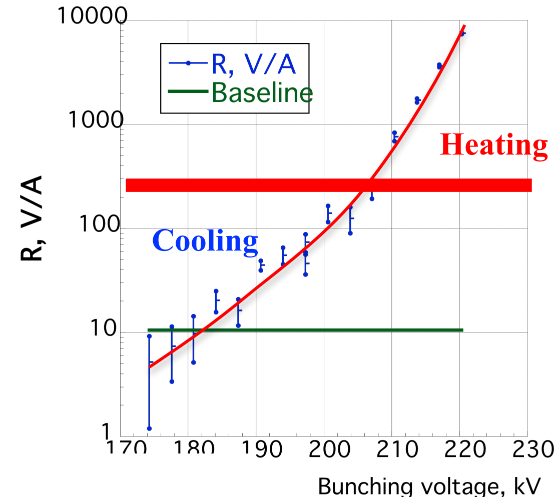
# Control of the noise in electron beam

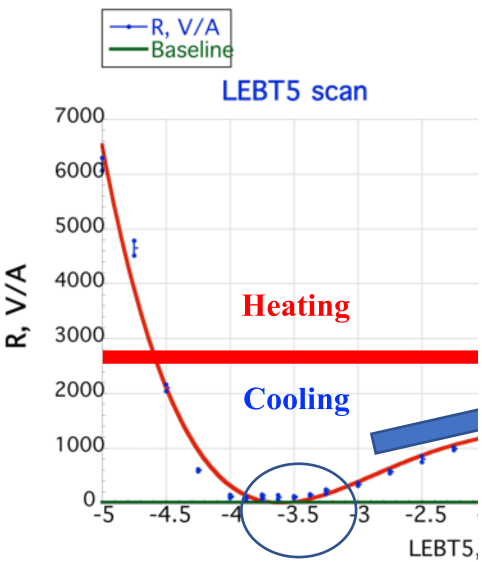
**Run 18 lattice and beam: 0.6 nC per bunch**

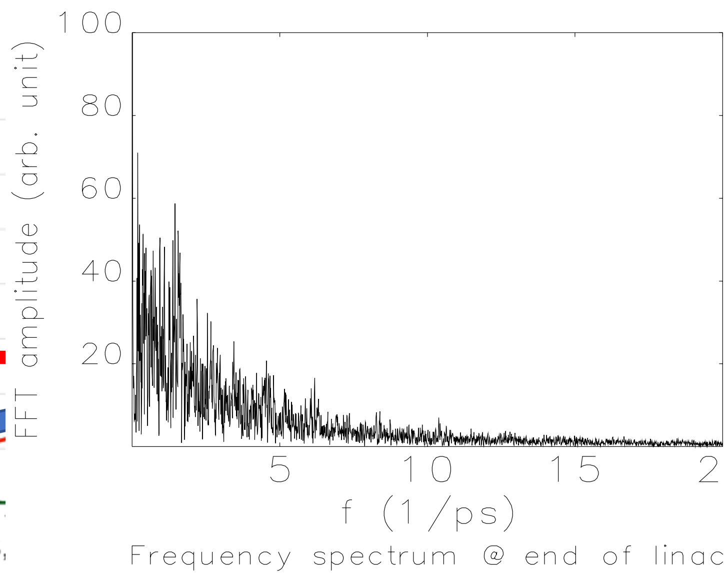
Large signal of 2,500 V/A ~ 250-fold above base line.

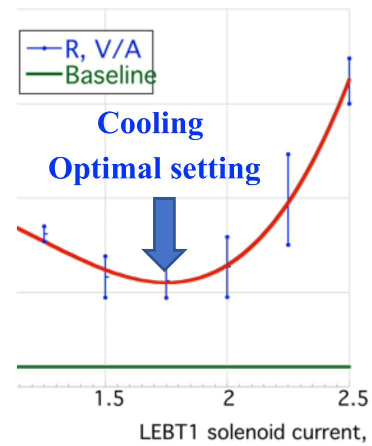
Can be seen both on scope and measured easily





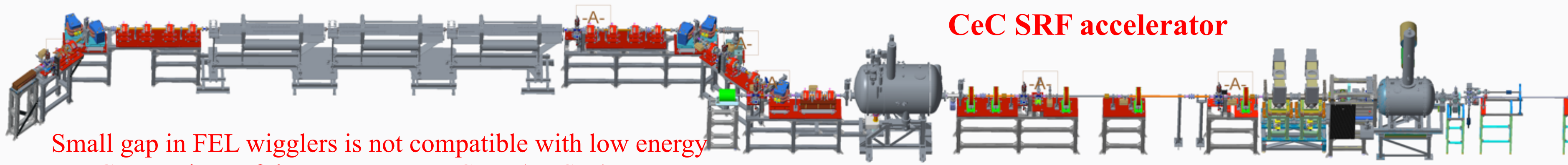




**We demonstrated that with 75 A peak current we can reduce beam noise to acceptable level. It could be as low as 6-10 times above the baseline**

# Changing CeC amplifier from FEL to PCA

**The FEL-based CeC concept is still valid – the system is stored and can be tested in the future**

**CeC SRF accelerator**

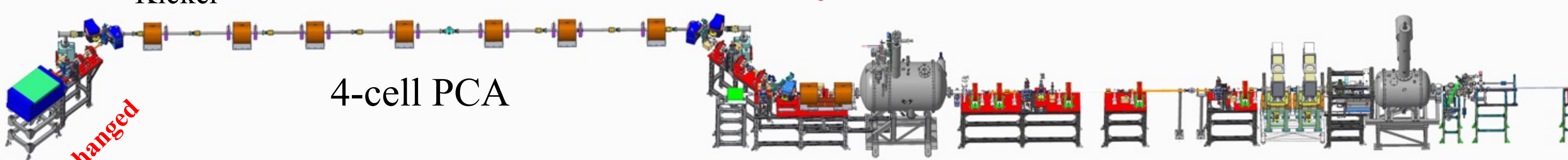


Small gap in FEL wigglers is not compatible with low energy RHIC operations of the Beam Energy Scan (BES-II) program

**Unchanged**

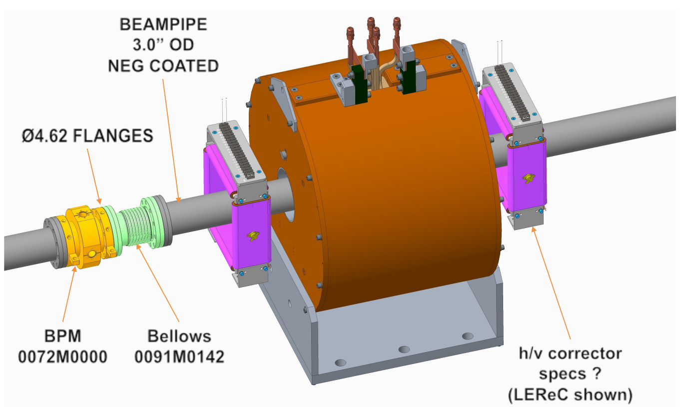
Modulator

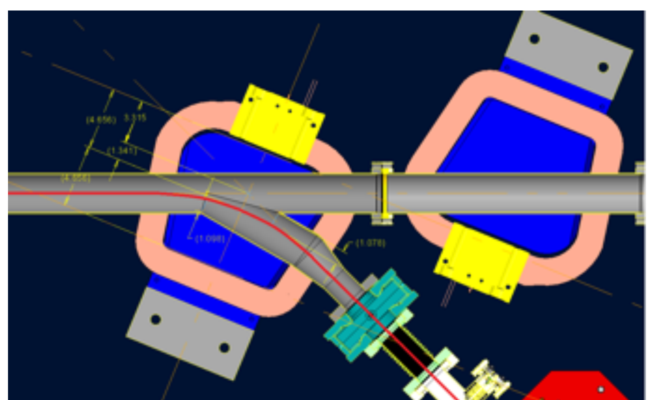
Kicker

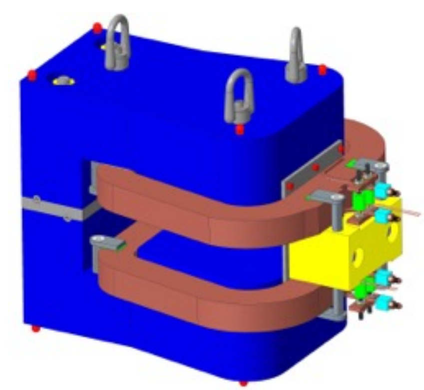


4-cell PCA

**Unchanged**

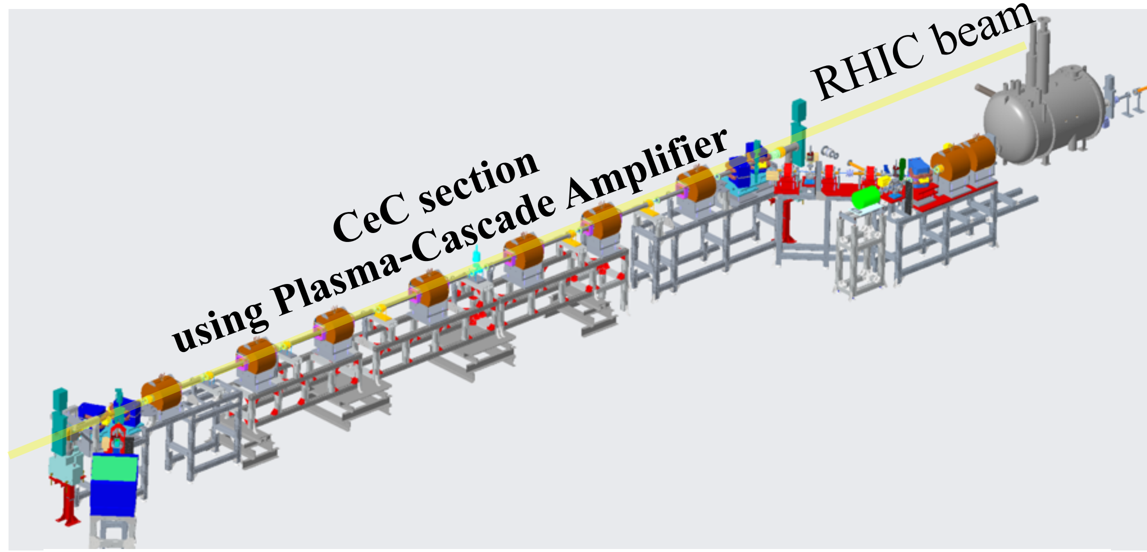




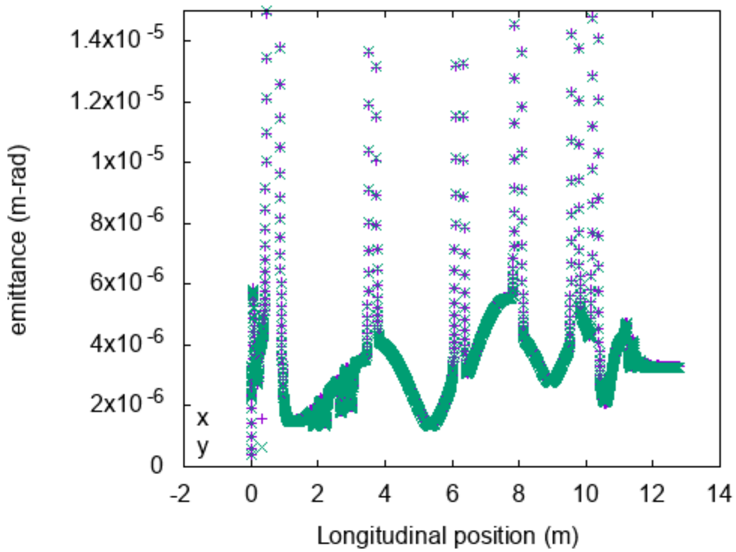
# CeC with PCA: status

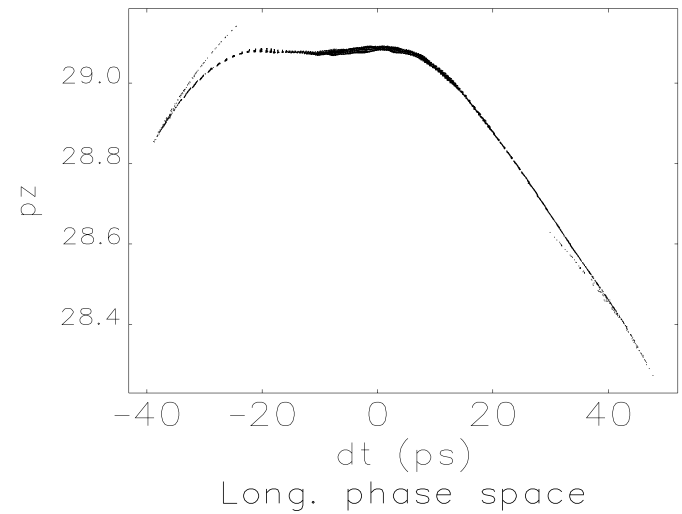
- Mechanical design of the new CeC system is completed
- We commissioned new laser system with controllable pulse shape
- All new vacuum chambers with beam diagnostics are built and installed
- All supports are built and installed
- All solenoids are designed, manufactured, delivered, measured and installed
- Assembly of the plasma-cascade based CeC will be completed this Fall

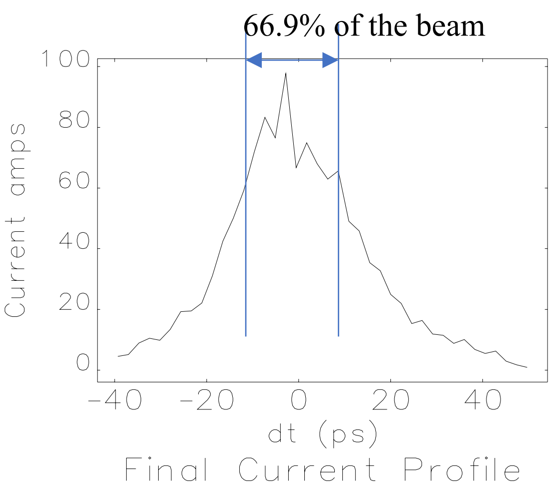


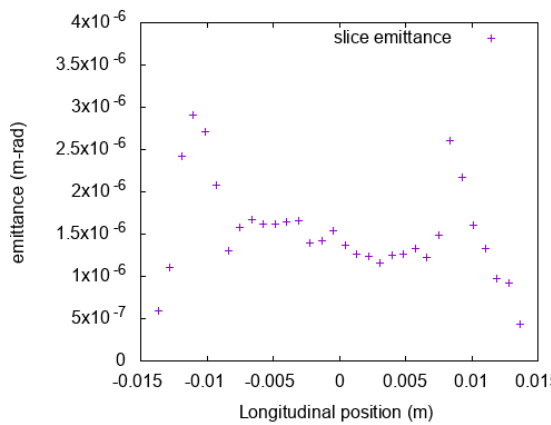

**PCA-based CeC installed at RHIC IP2**

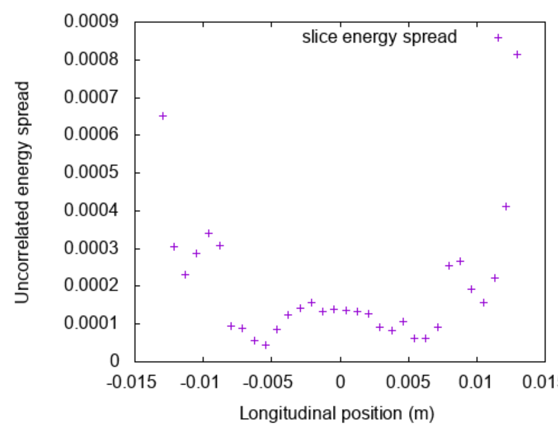
# Optimized electron beam



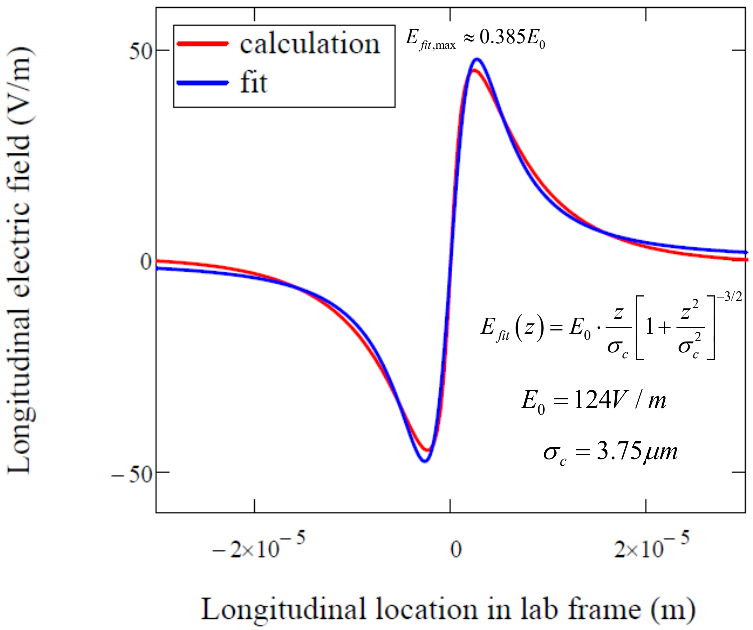

Core part of the beam has < 1.5 um emit., ~ 1e-4 slice energy spread, ~ 70 A peak current, satisfies beam requirement for cooler.

*More in talk by Yichao Jing*

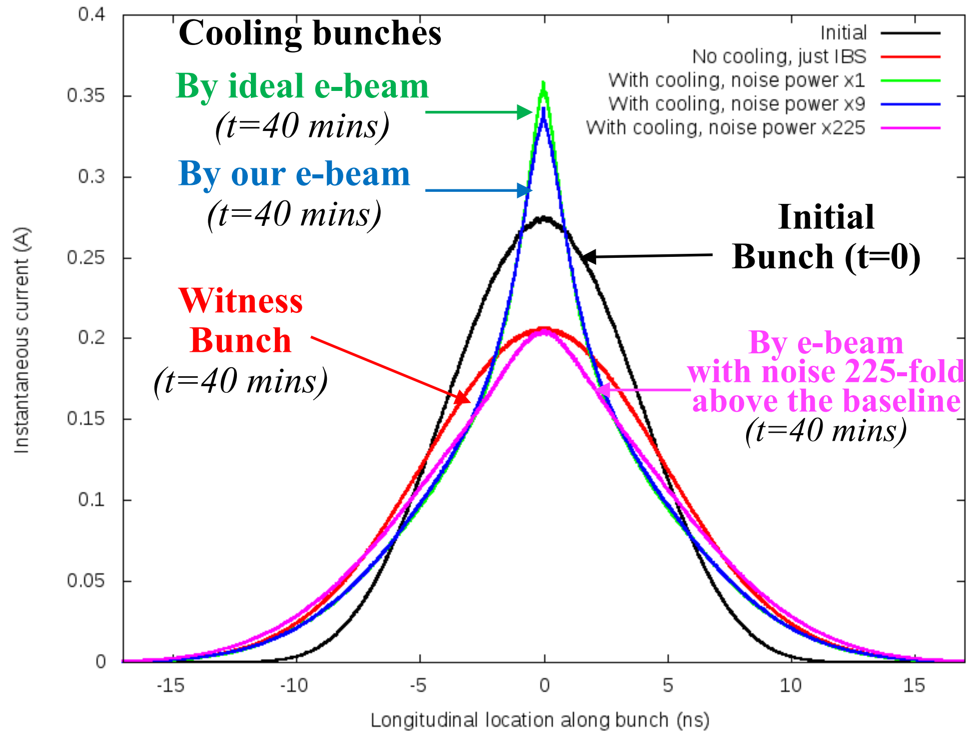
# Simulated performance: full 3D treatment

**CeC theory is important for scaling and for benchmarking of codes – full 3D simulations is the must for any reliable predictions, which have to be tested experimentally**

**Predicted evolution of the 26.5 GeV/u ion bunch profile in RHIC**




Simulated and fitted (used in simulations of the ion beam cooling) energy kick in the PCA-based CeC experiment system




Black – initial profile, red – witness (non-interacting) bunch after 40 minutes. Profiles of interacting bunches after 40-minutes in PCA-based CeC for various levels of <u>white noise amplitude</u> in the electron beam: green– nominal statistical shot noise (baseline), dark blue – 9 fold above the baseline, and green – 225 fold above the baseline

Cooling will occur if electron beam noise is below 225-times the base-line (shot noise)
We demonstrated beams with noise as low as 6-times the baseline

# How to cool transversely : a simple case

Only energy kick

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

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

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

## No x-y coupling

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

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

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

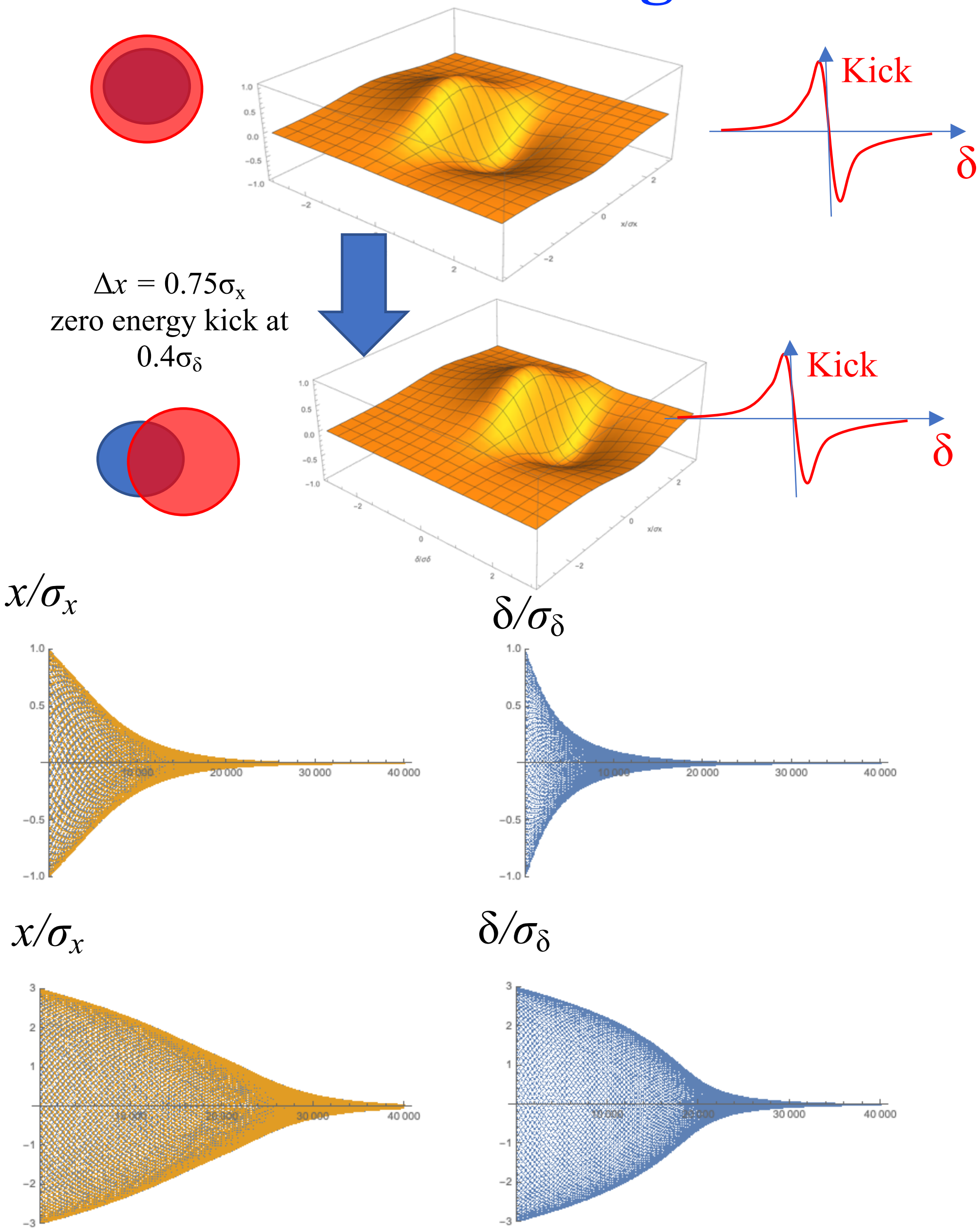
## Qx-Qy resonance

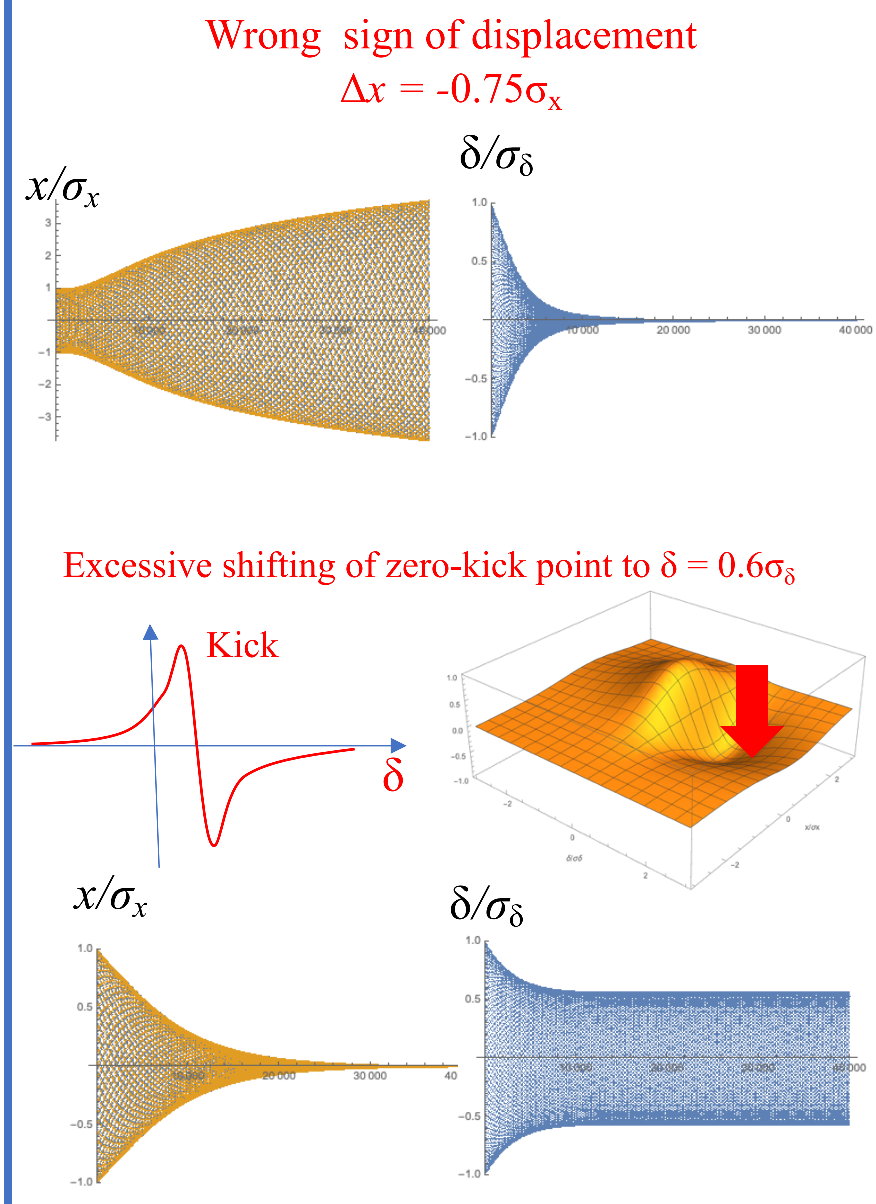
$$Y_1 = \frac{1}{\sqrt{1+|\alpha|^2}}\left(Y_x + \alpha Y_y\right); \; Y_2 = \frac{1}{\sqrt{1+|\alpha|^2}}\left(-\alpha^* Y_x + Y_y\right)$$

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

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

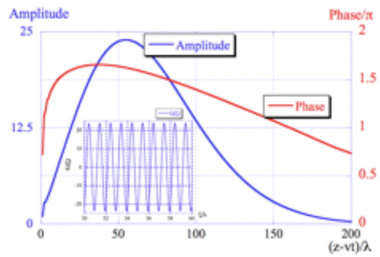
# Distribution of cooling between longitudinal and transverse degrees of freedom – real kick



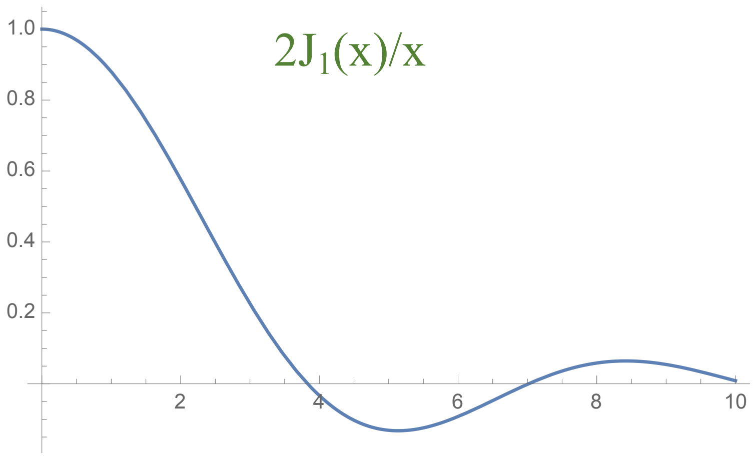
# Answer to Sergei's question: where cooling stops or reverses to anti-cooling

- For periodic or semi-periodic (narrow band amplifier or laser) response - there are periodic band of cooling and anti-cooling

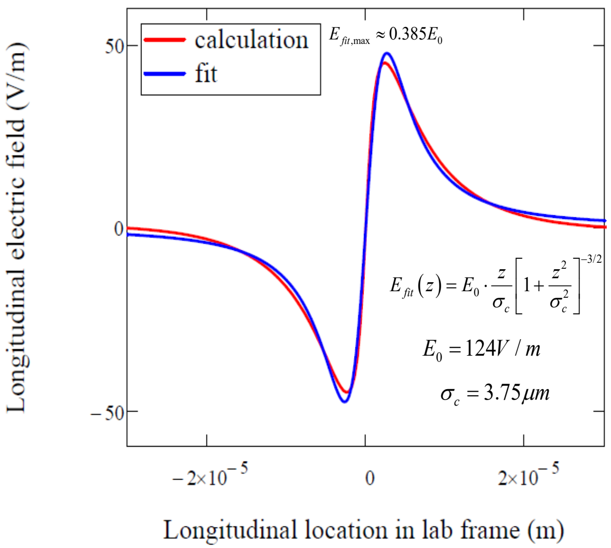



$$\delta = \frac{E - E_o}{E_o} = a \cdot \sin\Omega_s t;\ \Delta\delta = -\xi \sin\left(kR_{56}\delta\right)$$

$$\frac{d}{dn}\left\langle \delta^2 \right\rangle = -2\xi a \left\langle \sin\Omega_s t \cdot \sin\left(kR_{56} a \sin\Omega_s t\right)\right\rangle = -2\xi a \cdot J_1\left(kR_{56} a\right)$$




- Only a broad-band instability – for example plasma-cascade or chicane-based




- Cooling occurs for all amplitudes of oscillations, BUT cooling rate falls at amplitudes exceeding $z_{peak}/R_{56}$ fall ~ 1/a or ~$1/a^2$ (for short e-bunch). The questions is IF IBS/diffusion at large amplitudes overpowers the cooling – depends on the system.
- Clearly, having strong (fast) cooling will allow for tricks such as swiping e-beam about the hadron bunch center and providing for more uniform cooling

# Proposed plan for experimental demonstration of PCA-based CeC

- RHIC Run 20 – requested 8 days of dedicated RHIC time
  - Commission the PCA-based microbunching CeC system
  - Generate low-noise CW electron beam with required parameters
  - Demonstrate plasma-cascade amplification in the CeC section
  - Observe ion imprint in the electron beam and optimize it
- Summer-Fall 2020 – install time-resolved diagnostic beamline
- RHIC Run 21 - requested 14 days of dedicated time
  - Commission time-resolved diagnostic beamline
  - Measure and optimize electron beam parameters
  - Establish interaction of electron and ion beams
  - Demonstrate longitudinal cooling of ion bunch in PCA-based CeC
  - Evaluate longitudinal cooling
- RHIC Run 22 –we plan to ask for 14 days of dedicated time
  - Reestablish operation of CeC system
  - Demonstrate 3D – longitudinal and transverse - cooling of ion bunch in PCA-based CeC
  - Evaluate PCA-based microbunching CeC

# Conclusions

- Unsuccessful attempt of observing imprint during had a very solid explanation – very high level of noise in electron beam dwarfing the ion imprint. This result has nothing to do with validity of FEL-based CeC - it was and still valid. Small aperture was incompatible with low energy RHIC operation during– the FEL-based CeC is removed and stored for future use.
- We learned how to control noise in the beam and to reduce it to the acceptable level
- We developed new design of CeC with plasma-cascade amplifier and completed simulations of the cooling process . It has significant advantages:
  - Very large bandwidth (~ 25 THz for the proposed experiment, ~ 1,000 THz for eRHIC)
  - Cooling of hadrons with all amplitudes of oscillations (e.g. full acceptance)
- The PCA-based CeC system is undergoing installation and will be completed prior to RHIC Run 20.
- We propose three year program to fully evaluate the CeC performance:
  - Year 1 (Run 20) – demonstration of PCA and ion imprint
  - Year 2 (Run 21) – longitudinal cooling of 26.5 GeV/u ion beam
  - Year 3 (Run 22) – simultaneous transverse and longitudinal cooling
- Successful experimental demonstration of PCA-based CeC will serve as a perfect starting point for design of cooler for future Electron-Ion Collider

# The CeC project involved the following:

… never can get all of your photos…