An update on the the Coherent Electron Cooling (CeC) PoP 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

Accelerator R&D PI Exchange Meeting on Nov 7, 2019

CASE Center for Accelerator Science and Education

Stony Brook University

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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***."

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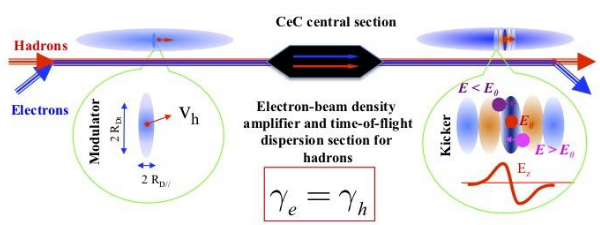
ICFA mini-workshop CeC 2019



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

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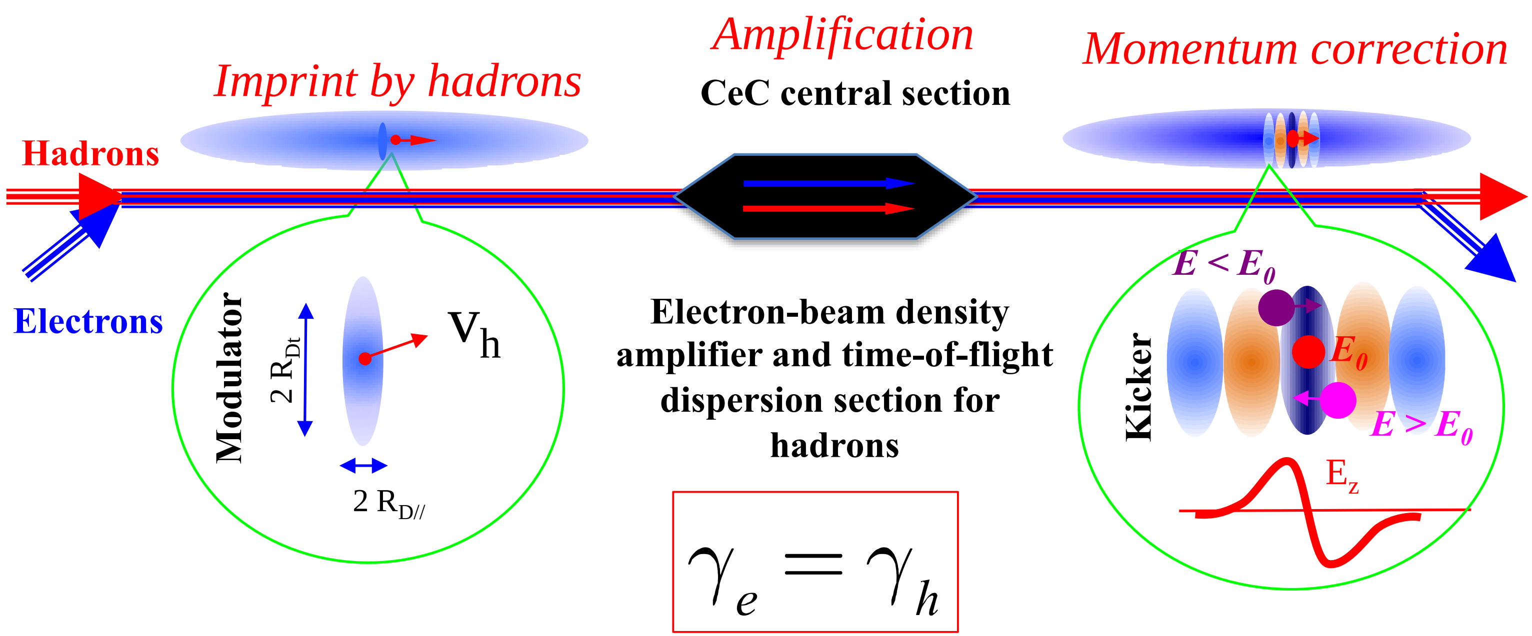
What is Coherent electron Cooling

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



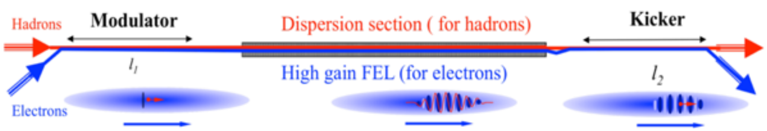
PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]
[1]*Brookhaven National Laboratory, Upton, Long Island, New York, USA*
[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA*
(Received 24 September 2008; published 16 March 2009)

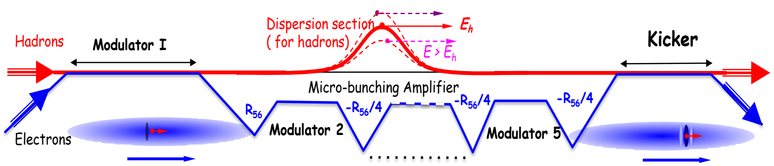
What can be tested experimentally?

Litvinenko, Derbenev, PRL 2008



RHIC Run 18

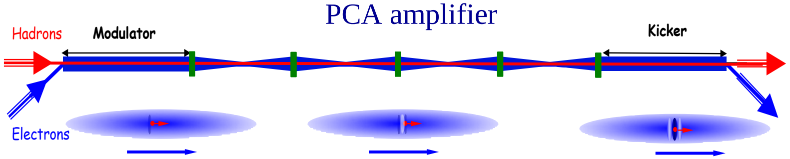
Ratner, PRL 2013



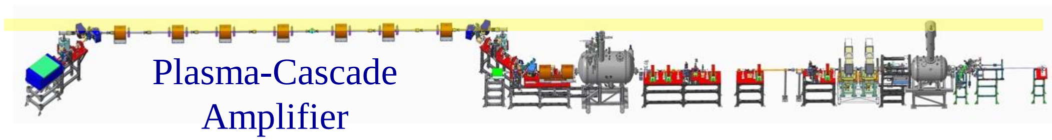
Cooling test would require significant modification of the RHIC lattice & superconducting magnets with cost exceeding $20M.

Litvinenko, Wang, Kayran, Jing, Ma, 2017

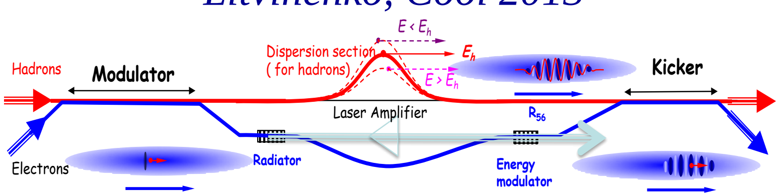
PCA amplifier



RHIC Runs 20-22

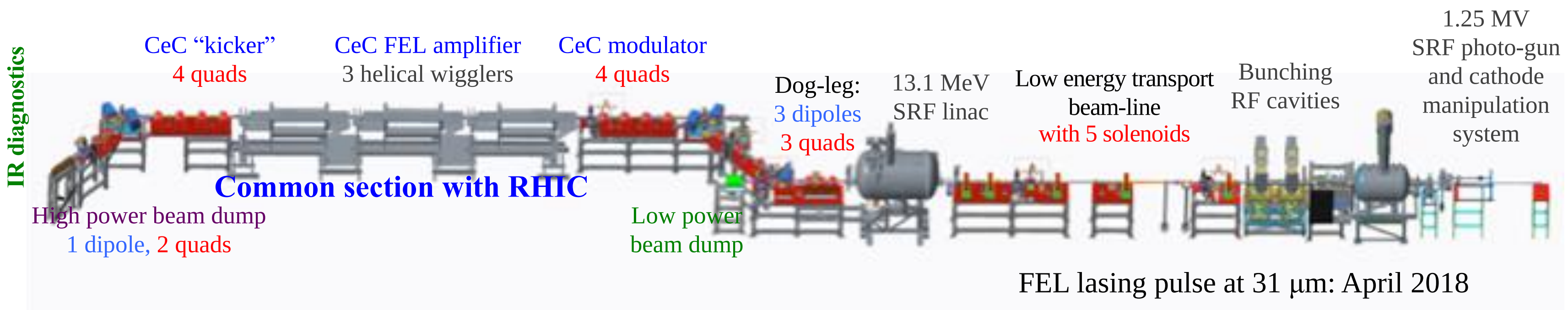


Litvinenko, Cool 2013



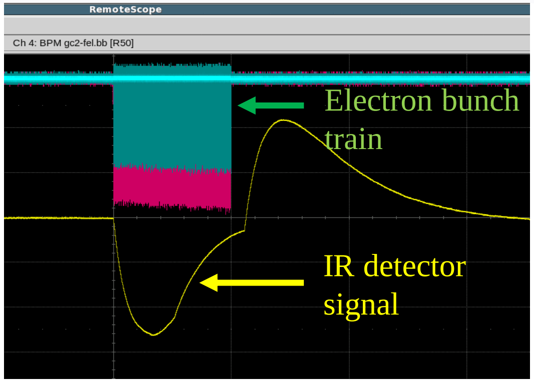
Cooling test would require significant modification of the RHIC lattice & superconducting magnets with cost exceeding $20M

Attempt to test FEL-based CeC

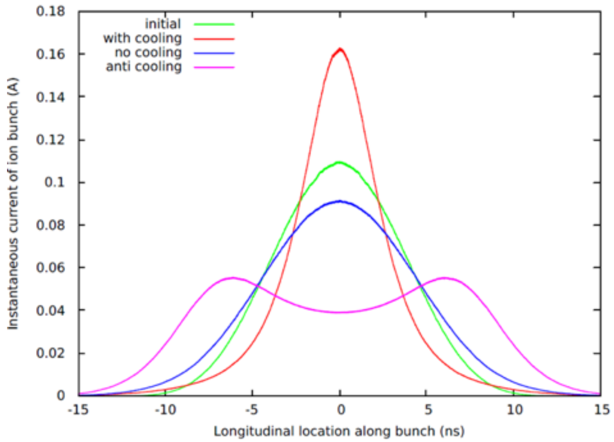


Parameter	Design	Status	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	✔ to match e-beam
Electron energy	21.95 MeV	14.56 MeV	Linac's quench limit
Charge per electron bunch	0.5-5 nC	0.1- 10.7 nC	✔
Peak current	100 A	50 -100A	✔
Bunch duration, psec	10-50	12	✔
Normalized beam emittance	< 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	✔

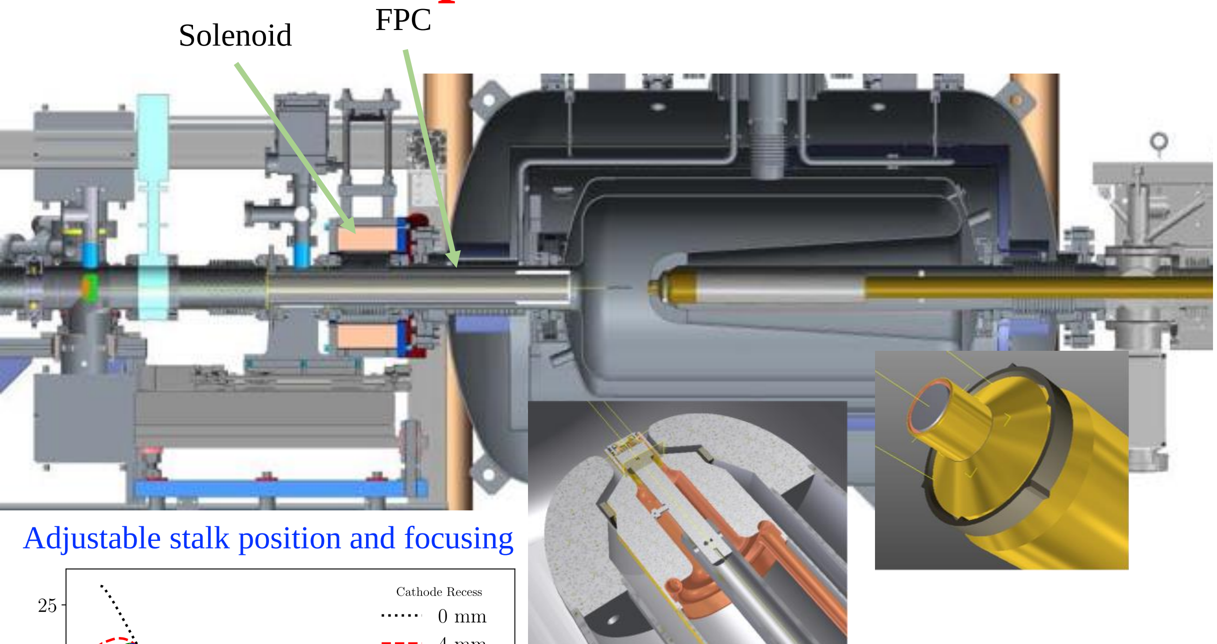
FEL lasing pulse at 31 µm: April 2018

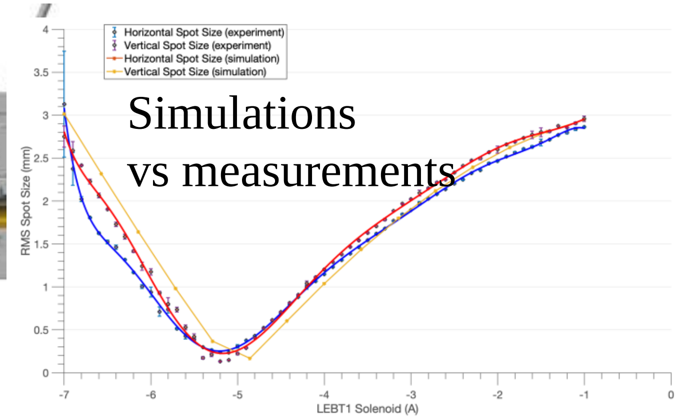


Predicted evolution of ion bunch profile in 40 minutes

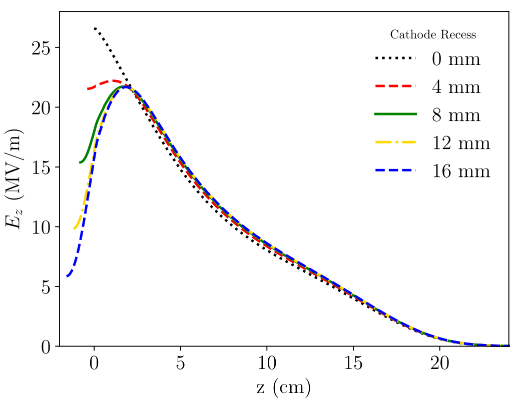


Record breaking 113 MHz CW SRF Gun: perfect source for EIC cooling systems

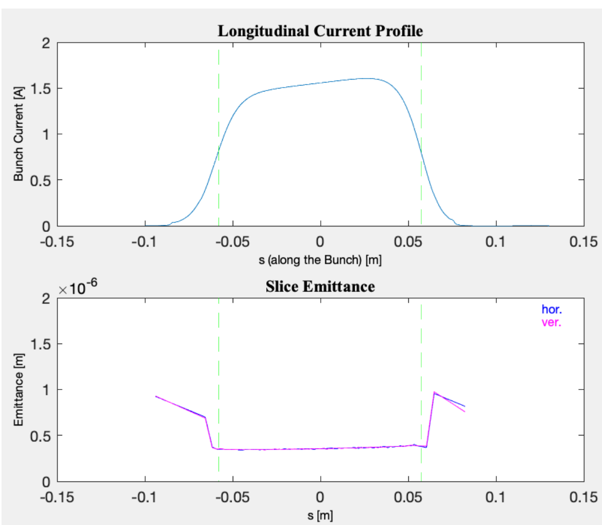




Adjustable stalk position and focusing



GPT simulations

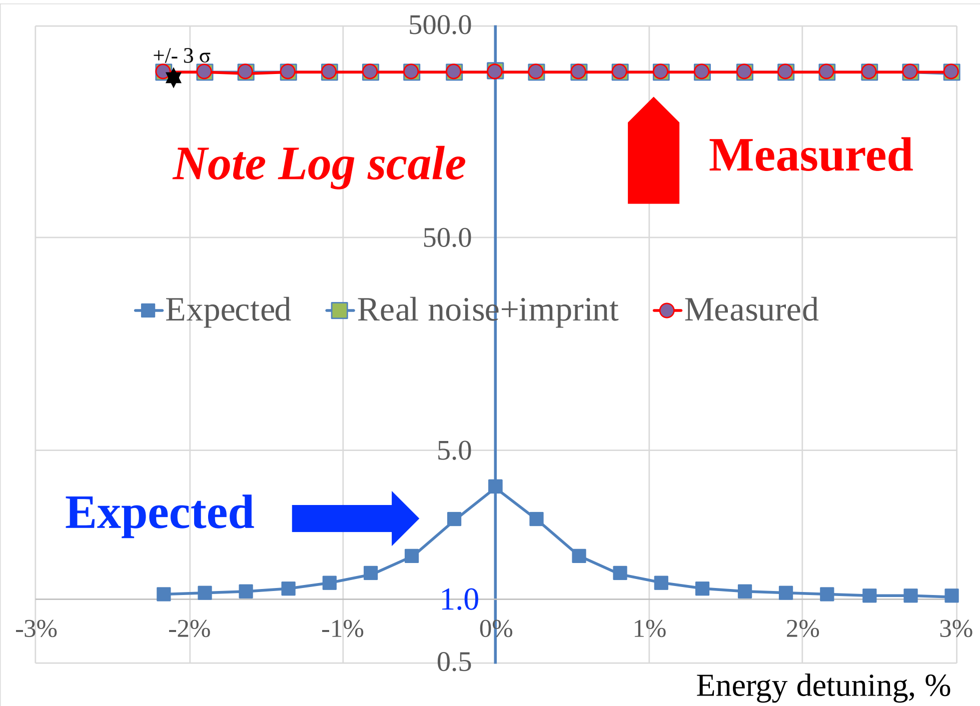


- Quarter wave design
- Operates at 4.2ºK
- CsK_2SB Cathode is at room temperature
- Stalk is RF choke and field pick-up
- Manual coarse tuners
- FPC serves as fine tuner
- Operational CW voltage 1.25 MV
- **Maximum charge 10.7 nC**
- Dark current < 1nA
- **Very low normalized emittance**
    - **0.15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

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

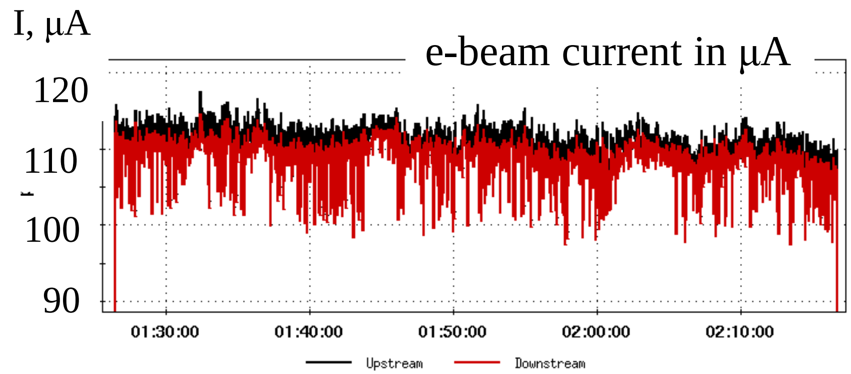
Puzzle of the CeC Run 18

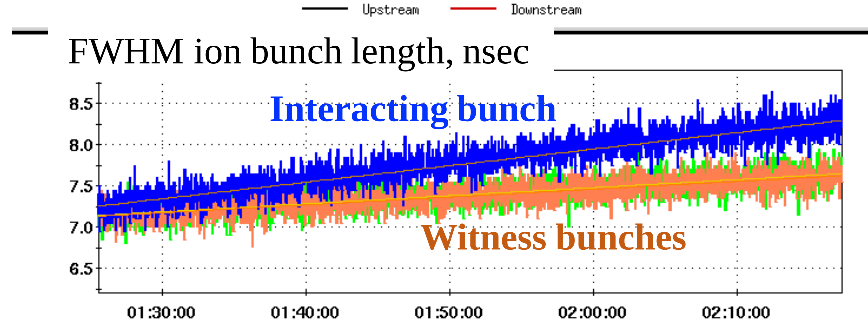
Search for ion's imprint in electron beam and matching beam's relativistic factors was the first important step in CeC experiment



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)

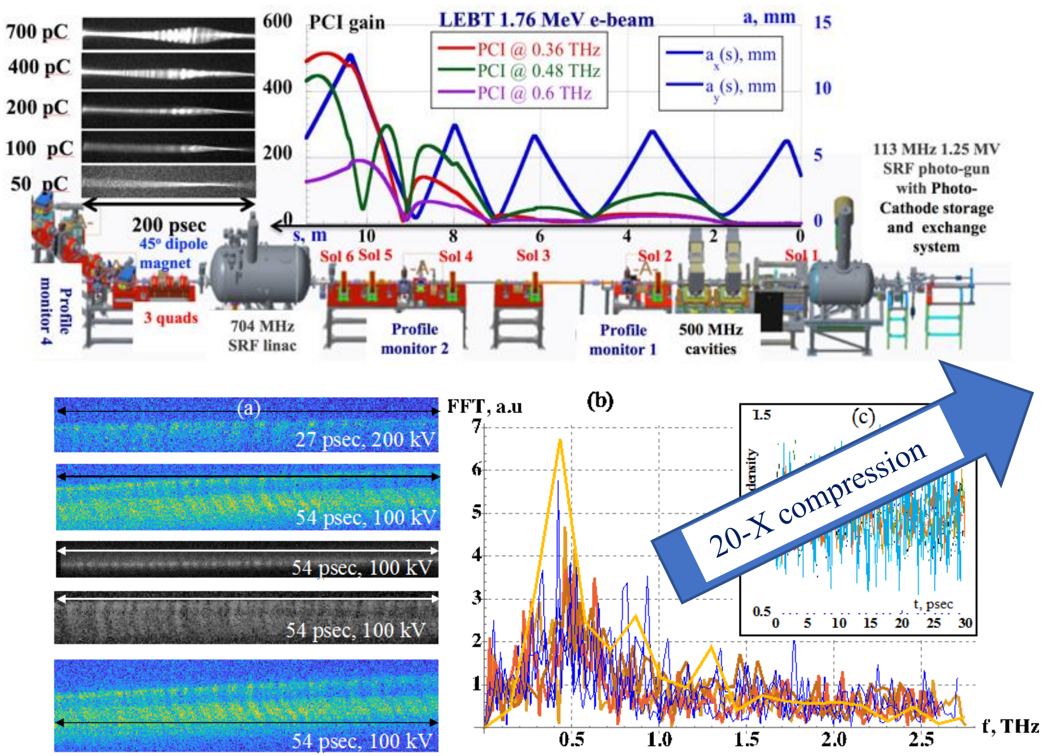
We ran out of time to demonstrate the FEL-based CeC during Run 18 with RHIC.

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

Solving the Puzzle

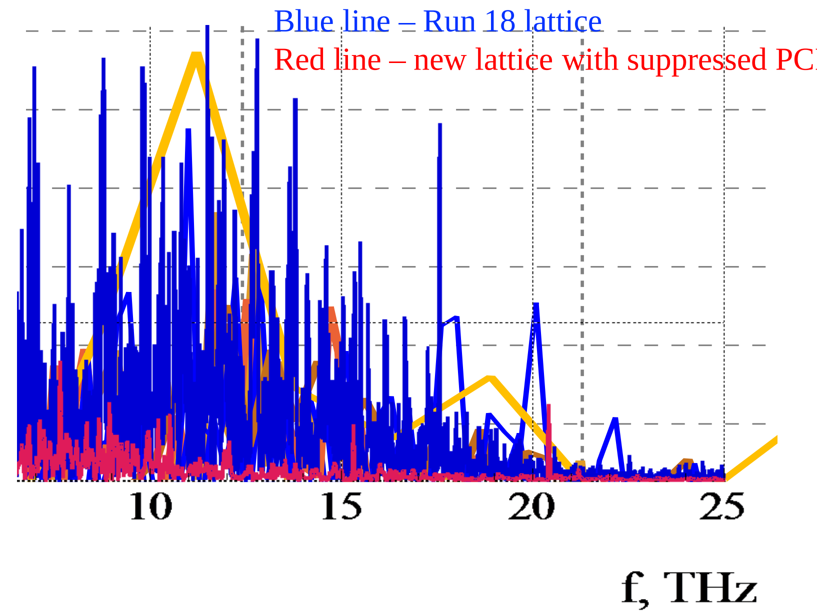
RHIC cryo system extended operation for LEReC mid-September and we used it to find the culprit:
THz noise in the electron beam (300-fold above the shot noise!) dwarfing the ion beam imprint.
This was not a failure of the FEL-based CeC concept, but unexpected excessive noise in the beam

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



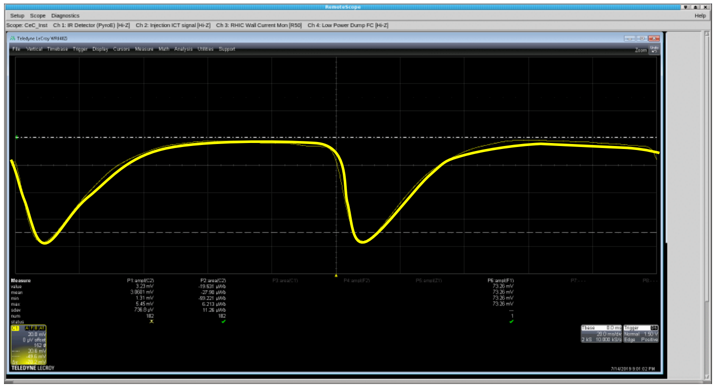
First we showed it in simulations that we can control noise level in the electron beam and confirmed this in the experiment during a short run in Summer 2019

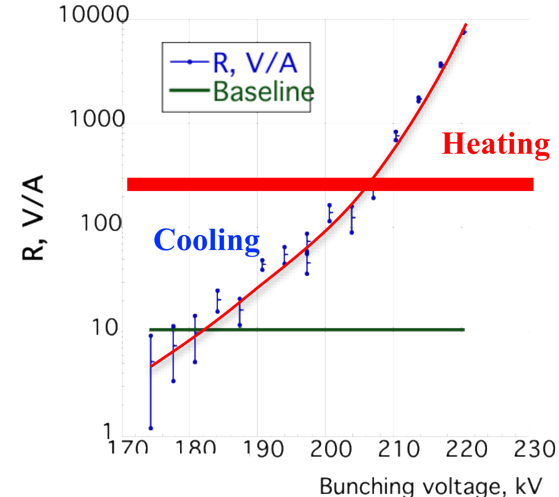
Control of the noise in electron beam

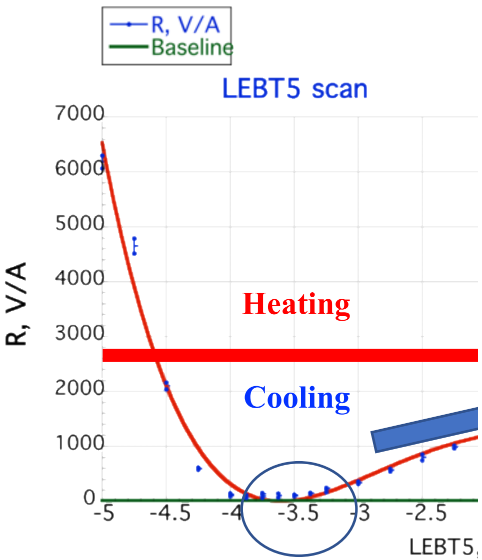
Run 18 lattice and beam: 0.6 nC per bunch

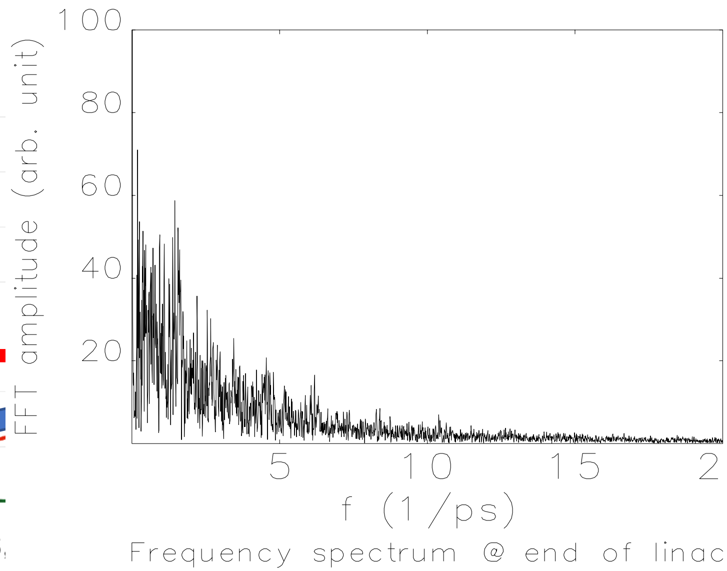
Large signal of 2,500 V/A ~ 250-fold above base line.

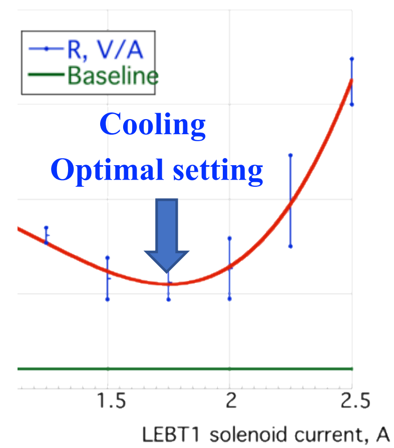
Can be seen both on scope and measured easily







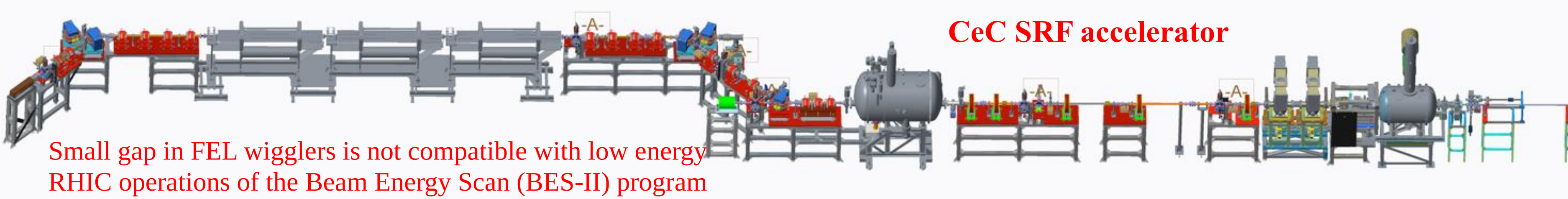




We demonstrated that with 75 A peak current we can reduce beam noise to acceptable level. It could be as low as 6-10 times above the baseline

Changing CeC amplifier from FEL to PCA

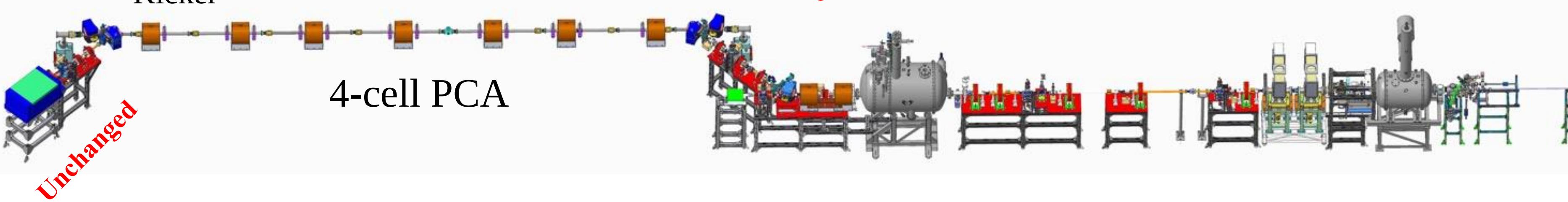
The FEL-based CeC concept is still valid – the system is stored and can be tested in the future

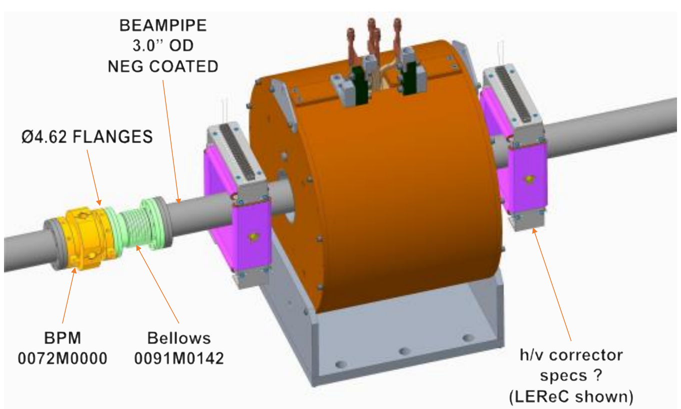


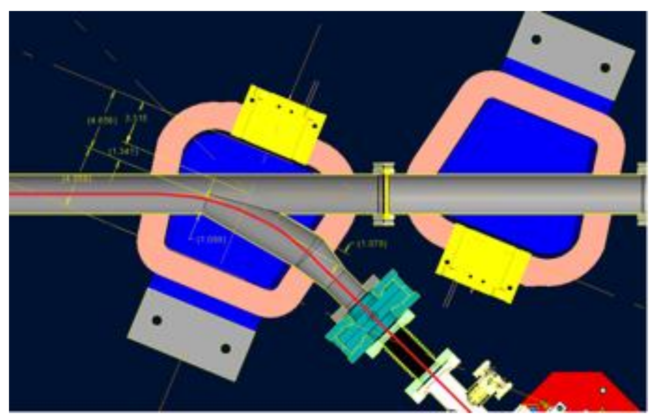
Unchanged

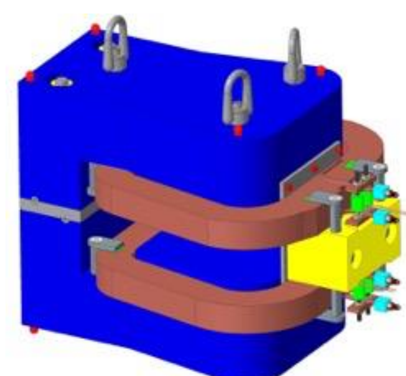
Kicker

Modulator



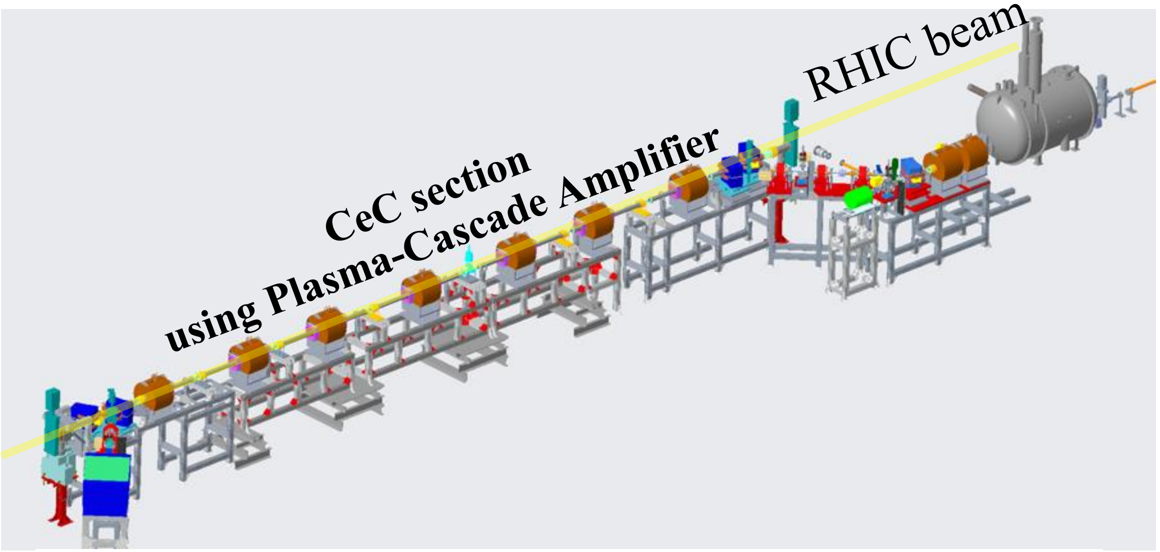




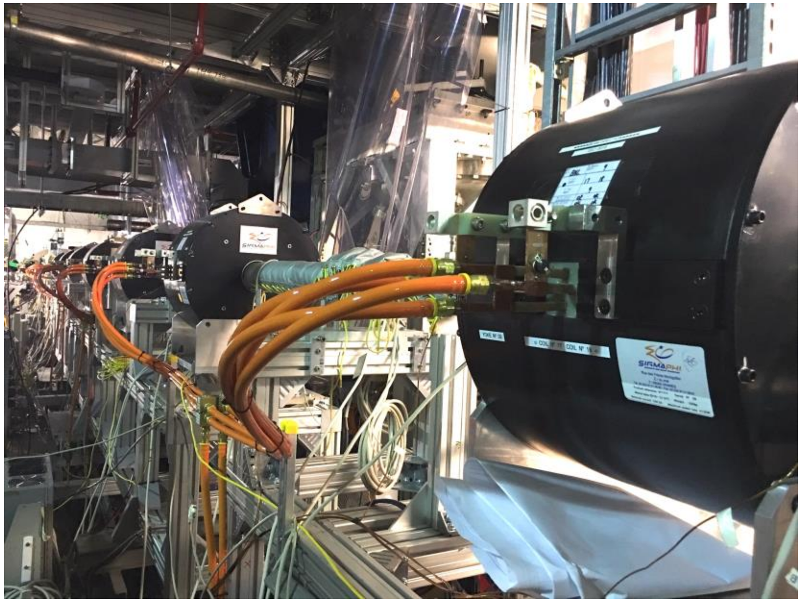


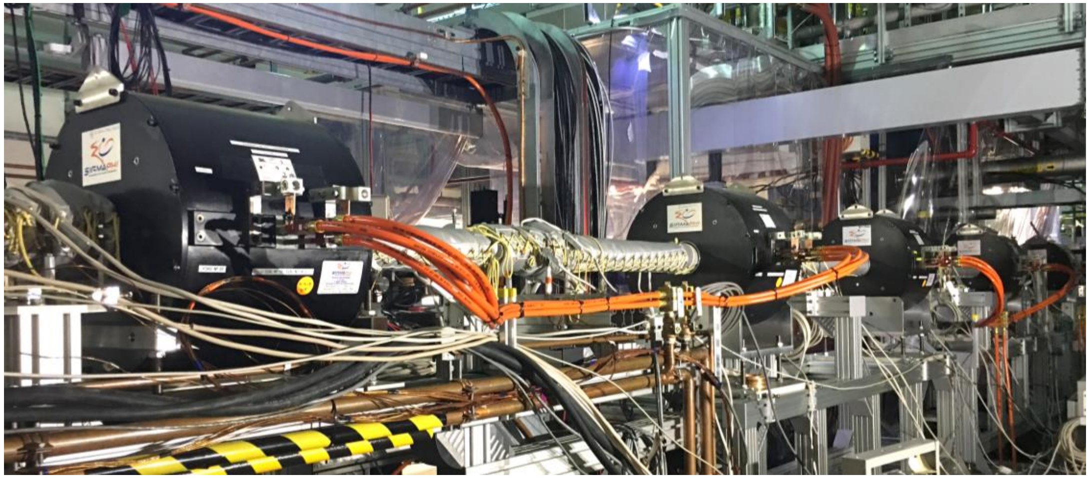
CeC with PCA: status

- 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 planned to be completed before the Run 19

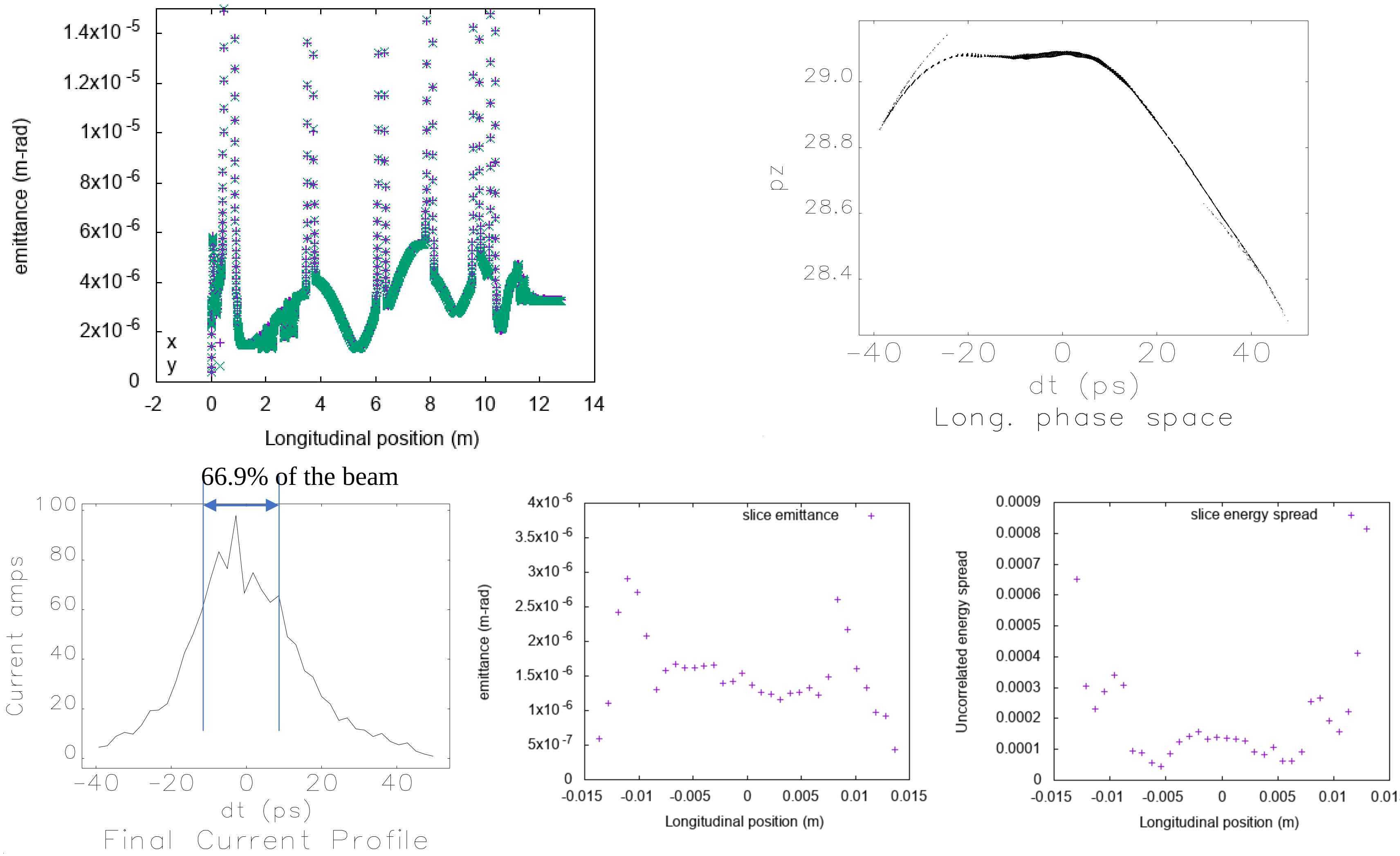


PCA-based CeC installed at RHIC IP2





Optimized electron beam



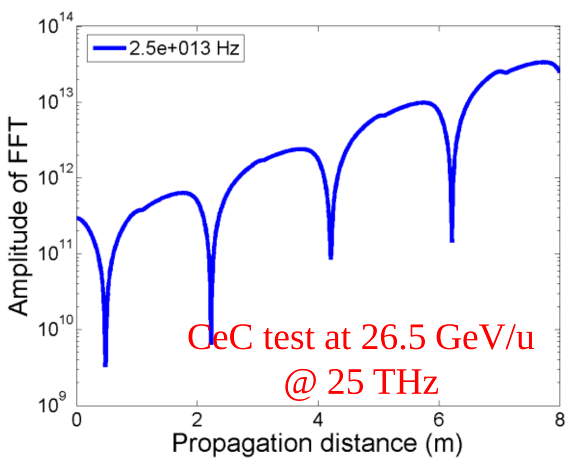
Core part of the beam has < 1.5 um emit., ~ 1e-4 slice energy spread, ~ 70 A peak current, satisfies beam requirement for cooler.

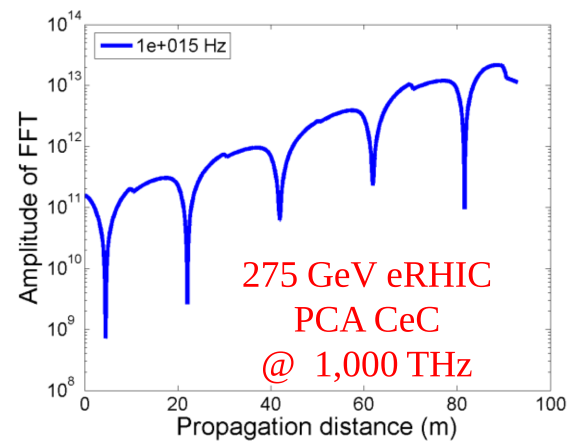
More in talk by Yichao Jing

Simulation of Plasma-Cascade Instability

- SPACE code was modified to solve 3D beam dynamics of PCI self-consistently for a beam with a constant energy
- We had a good agreement between the theory and the SPACE 3D simulations for periodic systems and constant beam energy
- We can comfortably predict performance of microbunching Plasma Cascade Amplifier (PCA) for CeC: either for CeC test experiment or for eRHIC energy
- We are still exploring possibility of using a generic code Impact-T for simulating PCI in arbitrary accelerator (e.g. including acceleration and compression)
- While we have initial indication that this approach could work, this work is still in progress.

SPACE code simulations of microbunching PCA for CeC

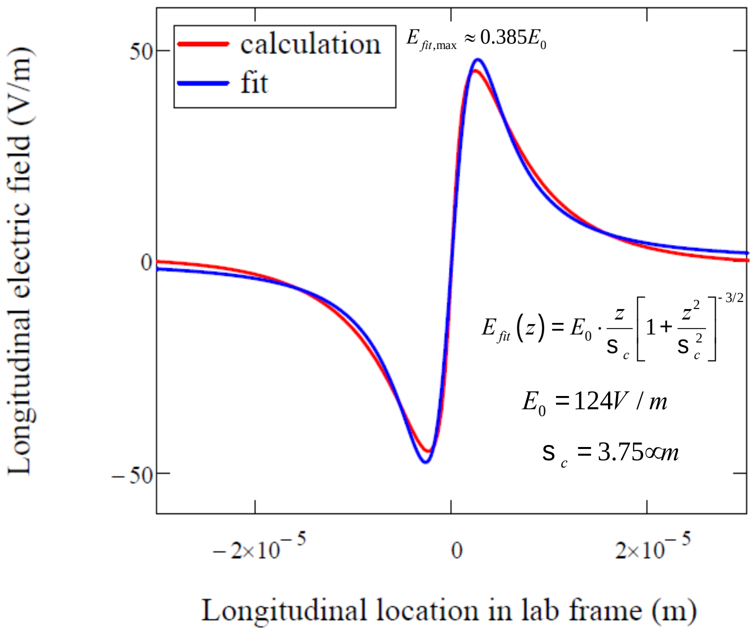




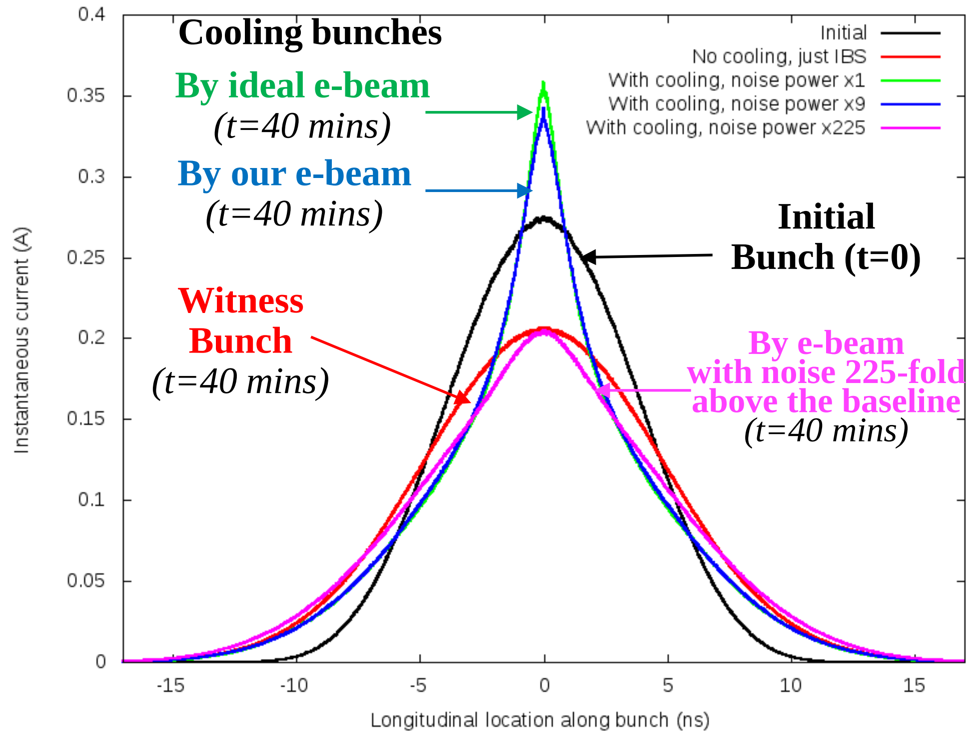
Simulated performance: full 3D treatment

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



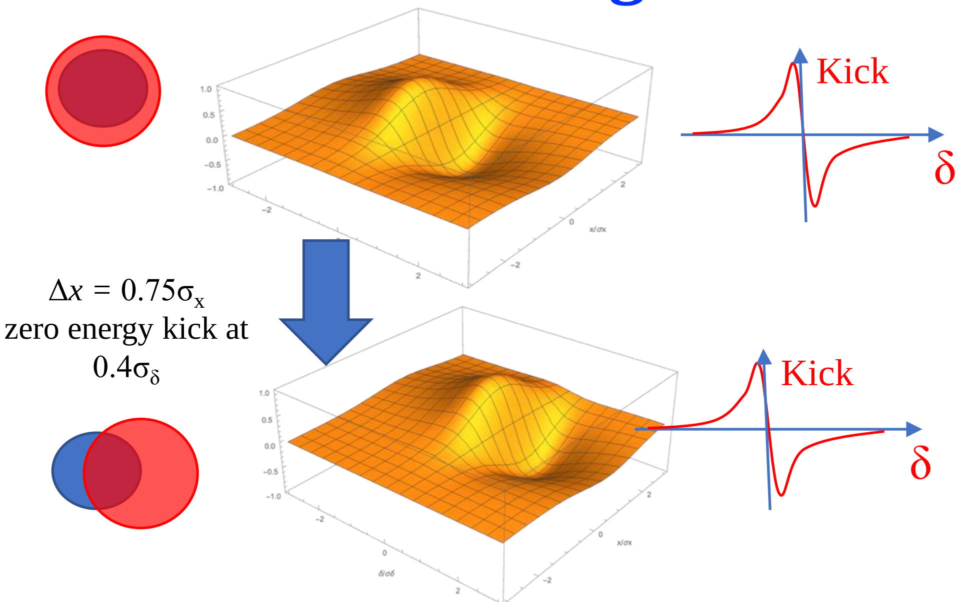
Simulated and fitted (used in simulations of the ion beam cooling) energy kick in the PCA-based CeC experiment system

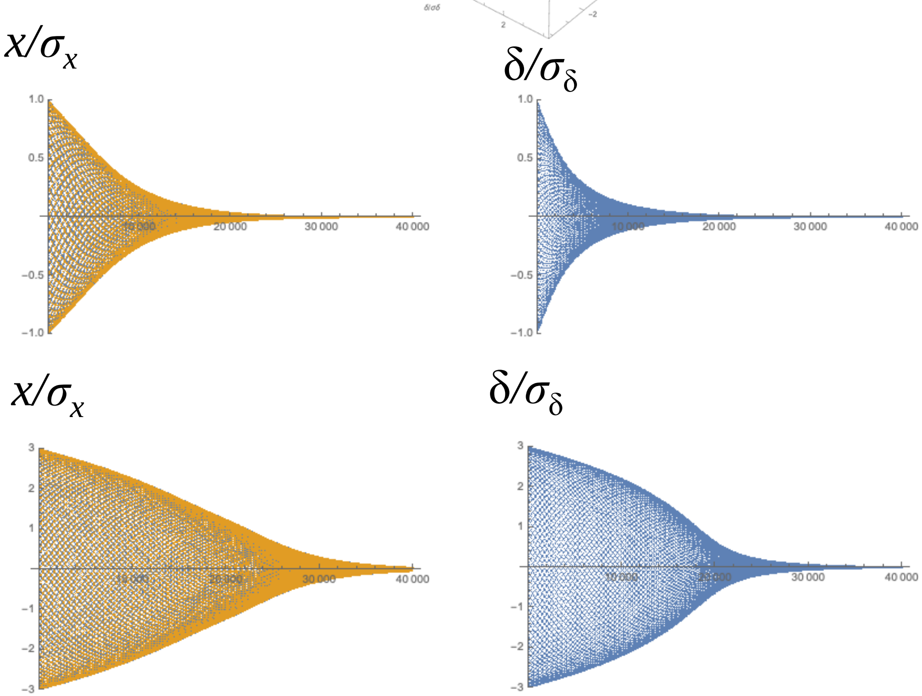


Black – initial profile, red – witness (non-interacting) bunch after 40 minutes. Profiles of interacting bunches after 40-minutes in PCA-based CeC for various levels of white noise amplitude in the electron beam: green– nominal statistical shot noise (baseline), dark blue – 9 fold above the baseline,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

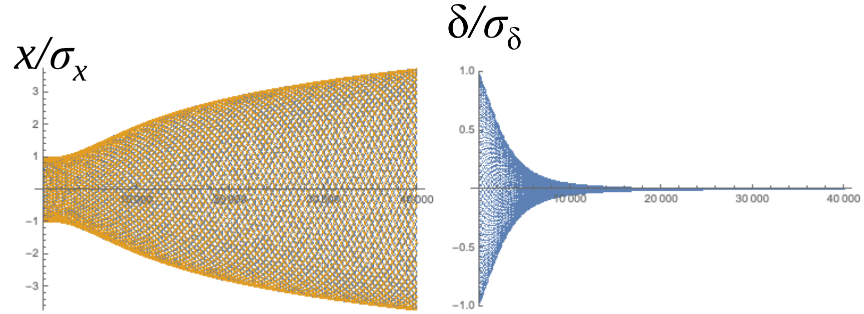
Cooling will occur if electron beam noise is below 225-times the base-line (shot noise)
We demonstrated beams with noise as low as 6-times the baseline

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

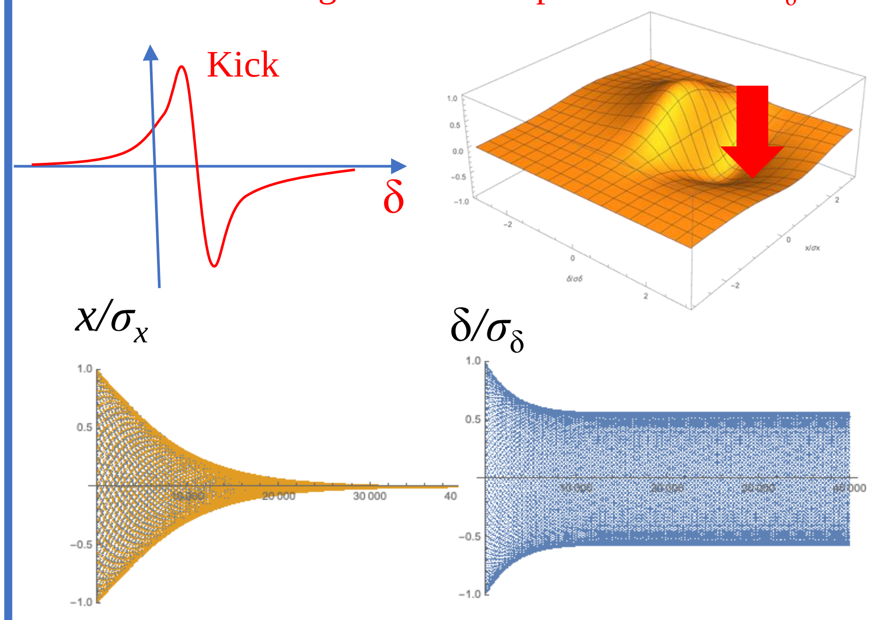




Wrong sign of displacement
Δx = -0.75σ_x



Excessive shifting of zero-kick point to δ = 0.6σ_δ



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…

Back-ups

Dates: July 24 (Wednesday)- July 26 (Friday), 2019

Location: Center for Frontiers in Nuclear Science, Peter Paul Seminar Room (C-120, Physics Building) https://www.stonybrook.edu/cfns/
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA

- **Goal of the workshop** is in depth discussion of progress and challenges in the Coherent Electron Cooling theory, simulations and experiment.
- **Workshop format:** In contrast with conference style workshops, this will be a real workshop with full length discussion sessions. Few invited presentations are designed to stimulate discussions.
- **Logistics:** Workshop is by invitation only – send expression of interest to Vladimir Litvinenko vladimir.litvinenko@stonybrook.edu and Gang Wang gawang@bnl.gov.
- There will be **no workshop fees** and no offered support – all participants will be responsible for their travel and living expenses.
- Wednesday, July 24
- Session 1: Convener – Rui Li (JLab)/ Local session chair - Sergei Seletskiy
- 9:00 Thomas Roser, Why strong hadron cooling is needed?
- 9:30 Yaroslav S Derbenev,How Coherent electron Cooling was conceived?
- 10:00 **Discussion lead by the convener** - coffee break at 10:30
- 12:00 – 14:00 Lunch break
- Session 2: Convener – Yue Hao (MSU)
- 14:00 Vladimir N Litvinenko, Variety of CeC systems
- 14:15 Gang Wang, CeC theory
- 15:00 – 17:00 **Discussion lead by the convener** - coffee break at 15:30
-
- Thursday, July 25
- Session 3: CeC. Convener – David Bruhwiler (RadiaSoft)
- 9:00 Jun Ma, CeC simulations
- 9:30 Yichao Jing, Beam dynamics in CeC accelerator
- 10:00 **Discussion lead by the convener** - coffee break at 10:30
- 12:00 – 14:00 Lunch break
- Session 3: CeC. Convener – Dmitry Kayran (BNL)
- 14:00 Igor Pinayev, CeC experiment – physics
- 14:30 Jean Clifford Brutus, CeC experiment – engineering
- 15:00 – 17:00 **Discussion lead by the convener** - coffee break at 15:30
-
- Friday, July 26
- Session 4: CeC. Convener –Vladimir Litvinenko (SBU)
- 9:00 Short discussion of possible collaborations
- 9:15 – 12:00 **Summaries** - coffee break at 11 am
- Rui Li, "CeC & Hadron cooling"
- Yue Hao, *CeC theory*
- David Bruhwiler, CeC simulations
- Dmitry Kayran, CeC experiment
- 12:00 Close up

Stony Brook University

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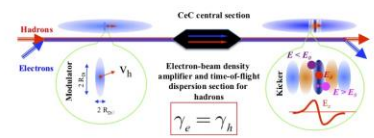
ICFA mini-workshop CeC 2019



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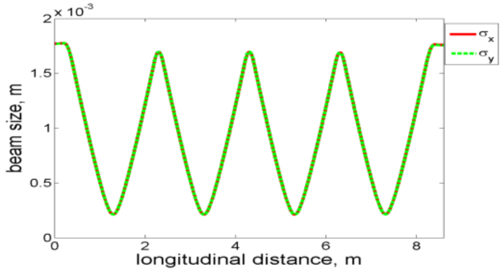
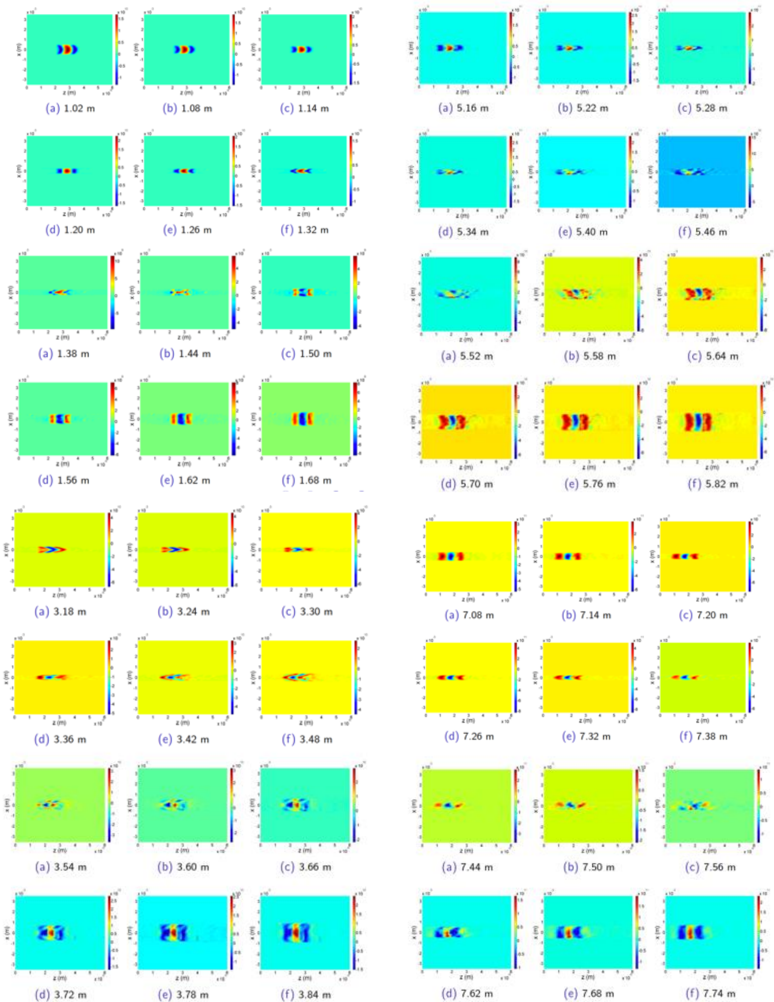
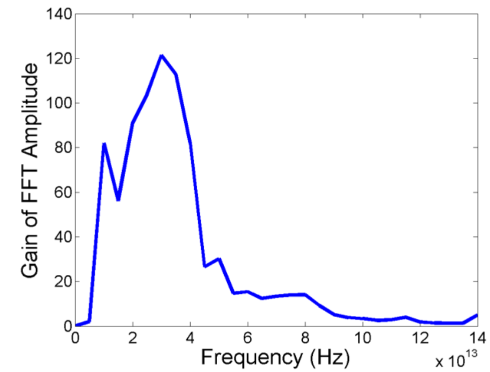
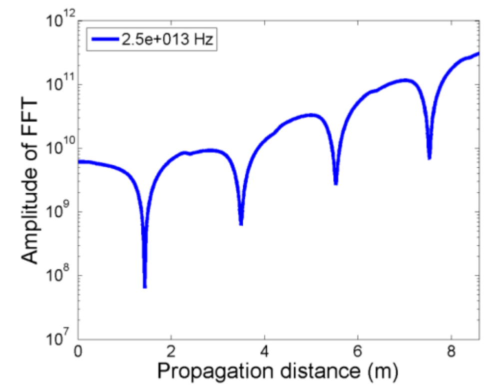
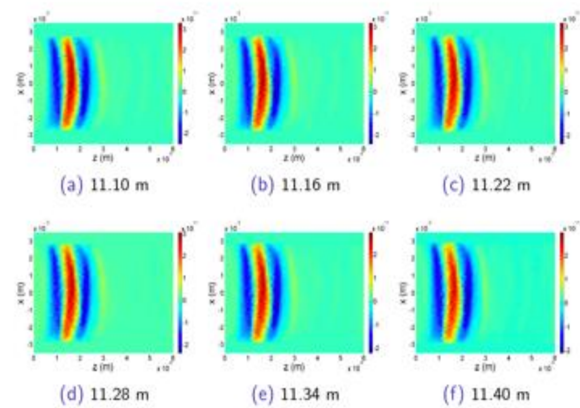
Evolution of a single ion imprint in 4-cell 8-meter PCA
3D SPACE code









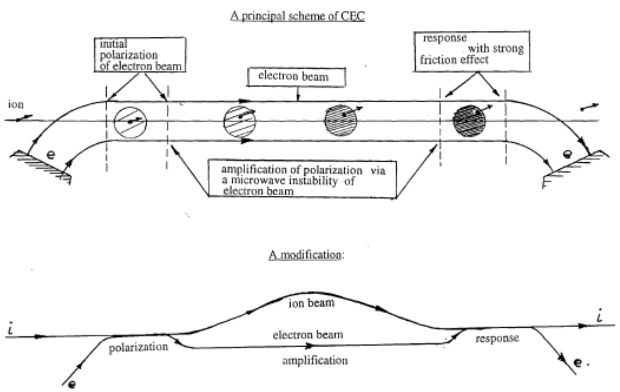


Evolution of a single ion imprint in the ACeC kicker.

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

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 ………*

How to cool transversely : a simple case

Only energy kick

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

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

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

No x-y coupling

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

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

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

Qx-Qy resonance

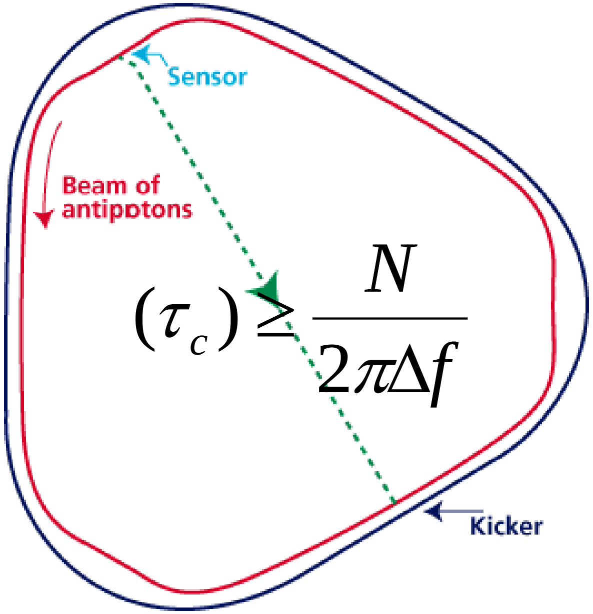
$$Y_1 = \frac{1}{\sqrt{1+|a|^2}}\left(Y_x + a Y_y\right); \quad Y_2 = \frac{1}{\sqrt{1+|a|^2}}\left(-a^* Y_x + Y_y\right)$$

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

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

Critical conditions for the stochastic cooler

S. van der Meer 1984 Nobel physics prize



$$(\tau_c) \geq \frac{N}{2\pi\Delta f}$$

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

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

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

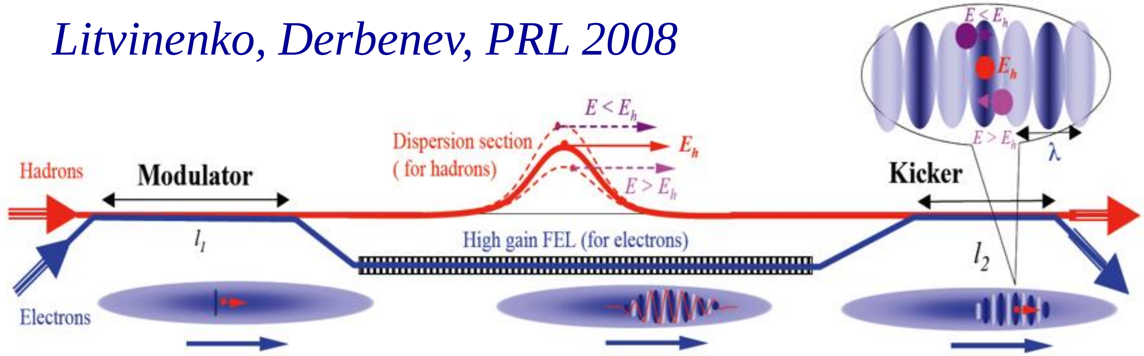
- ✓ **Linearity:** Amplifier must be linear (no saturation) and low noise
- ✓ **Overlapping:** Amplified signal induced by individual particle in the modulator (pick-up, sensor) must overlap with the particle in the kicker
- ✓ **Bandwidth:** Does not matter how high is the gain of the amplifier, cooling 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 stochastic cooling system should not significantly exceed system signal introduced by shot noise in the hadron beam

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

S. van der Meer, Rev. Mod.Phys. 57, (1985) p.689
S. van der Meer, 1972, Stochastic cooling of betatron oscillations is ISR, CERN/ISR-PO/72-31

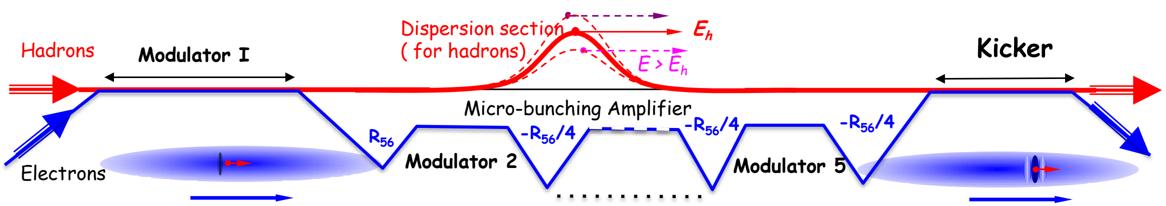
CeC schemes

Litvinenko, Derbenev, PRL 2008



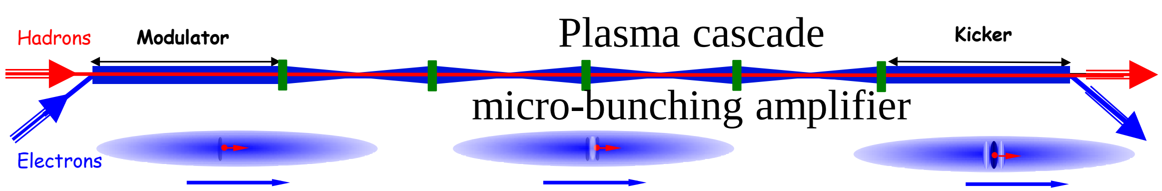
High gain FEL amplifier

Ratner, PRL 2013



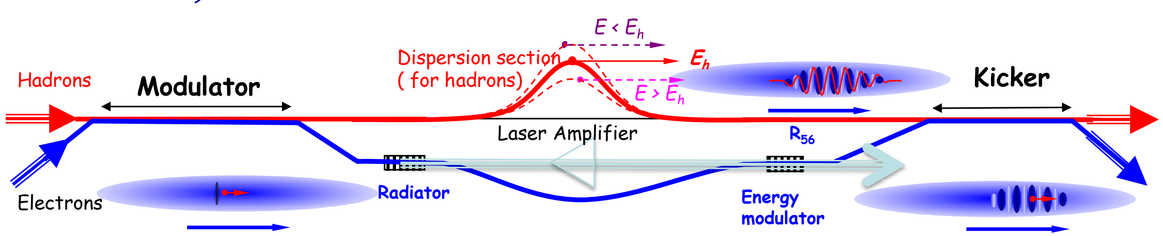
Multi- Chicane Microbunching amplifier

Litvinenko, Wang, Kayran, Jing, Ma, 2017



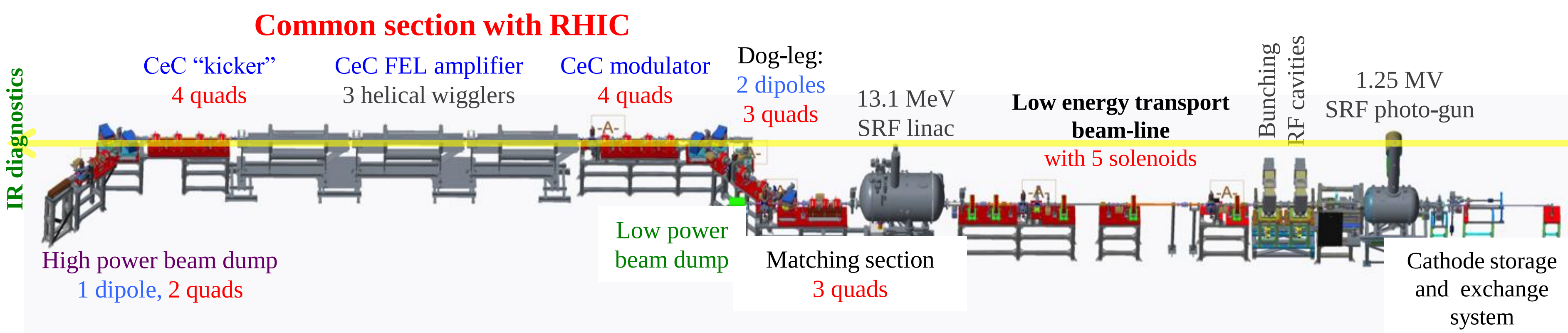
Plasma-Cascade Microbunching amplifier

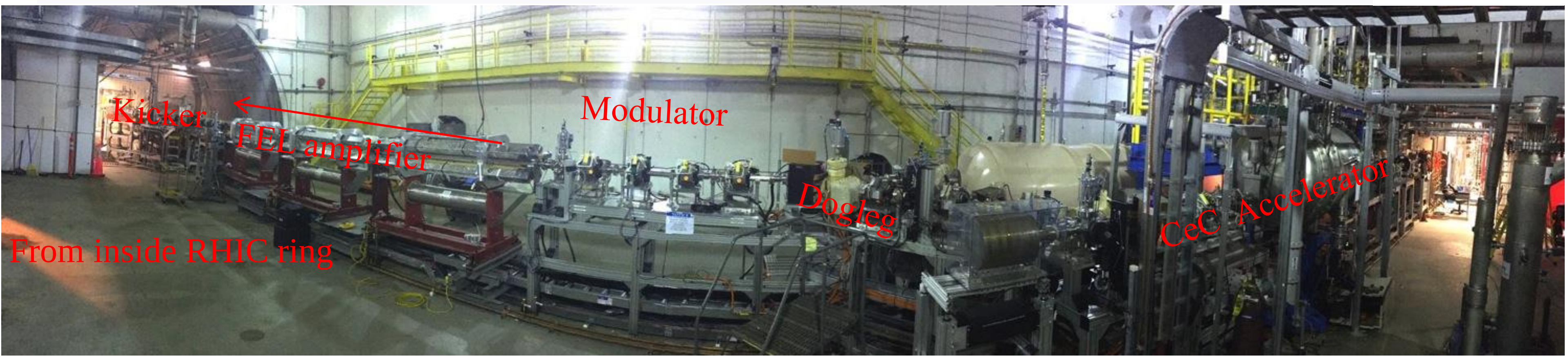
Litvinenko, Cool 2013



Hybrid laser-beam amplifier

CeC proof of principle experiment at RHIC





CeC experiment goals

- Main - demonstration of Coherent electron Cooling of an Au bunch circulating in RHIC
- Second - comprehensive 3D simulations of CeC
- Third - comparison of simulations and experiment

We designed, built it and commissioned

- **We took advantage of available equipment from DoE's SBR program, DoE BES project at SBU and our UK collaborators**
- **All through the years CeC was strongly supported by C-AD personnel and management**