COOL 2019, 23-27 September 2019, Budker INP, Novosibirsk

Coherent electron Cooling (CeC) experiment at RHIC

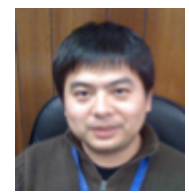
Vladimir N Litvinenko for CeC group

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

… and all contributed to the CeC project

… never can get all of your photos…

Outline

- Why we are doing this?
- The origin of Coherent electron Cooling
- CeC principle of operation and options
- CW SRF accelerator and FEL-based CeC
- Proposed experiment and its status
- Plasma-Cascade Instability (PCI) and Plasma-Cascade Amplifier (PCA)
- CeC accelerator system and Beam diagnostics
- Proposed experimental program
- Conclusions

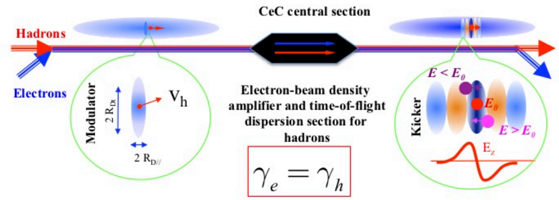
Why strong hadron cooling is needed?

- 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***."

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

- All talks at http://case.physics.stonybrook.edu/index.php/ICFA_workshop_CeC
- It was opened by Ya. Derbenev: how he conceived idea of Coherent electron Cooling
- In the nut-shell, the idea came from looking at the second "transient term" in the drag-force in 1978 Derbenev's second Doctoral thesis, which differs from the first stationary term:
- $$\vec{F}(t) = -\frac{Z^2 e^2}{2\pi^2}\int d^3k \frac{\vec{k}}{k^2}\left\{\frac{\mathrm{Im}\,\varepsilon_{\vec{k}}(\vec{k}\vec{v})}{\left|\varepsilon_{\vec{k}}(\vec{k}\vec{v})\right|^2} + i\sum_s \left[\frac{\exp(-i(\omega-\vec{k}\vec{v})t)}{(\omega-\vec{k}\vec{v})\partial\varepsilon_{\vec{k}}(\omega)/\partial\omega}\right]_{\omega=\omega_s}\right\}$$

Courtesy of Ya. Derbenev

CeC conceived: Derbenev 1980

Electric field ignited by an ion in a homogeneous co-moving electron beam:

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

- $At\ Im\omega_s > 0,$

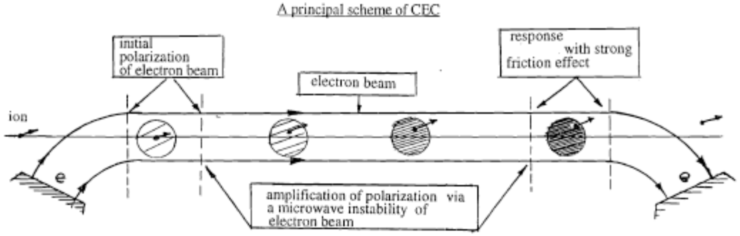
the transient (second) part grows along the cooling section

$$\vec{E}(\vec{r},t) \Rightarrow -\frac{Ze}{2\pi^2}\int d^3k\,\frac{i\vec{k}}{k^2}\sum_s\left[\frac{\exp\left(-i\left(\omega-\vec{k}\vec{v}\right)t\right)}{\left(\omega-\vec{k}\vec{v}\right)\partial\varepsilon_{\vec{k}}(\omega)/\partial\omega}\right]\exp\left(i\vec{k}(\vec{r}-\vec{v}t)\right)_{\omega=\omega_s}$$

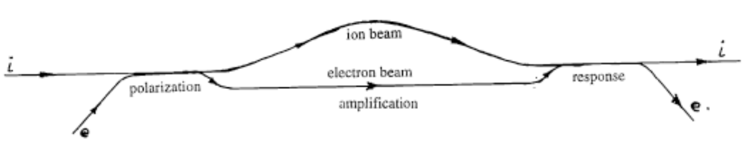
…that maybe bad…-but could'nt be even used to build the **microwave** *stochastic cooling*?! (1980)

Courtesy of Ya. Derbenev

A principal scheme of CEC



A modification:



- 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 ……….

Modern CeC: First presentation was is this conference hall, 12 years ago

FELs and high-energy electron cooling

Vladimir N. Litvinenko

Brookhaven National Laboratory, Upton, NY, USA

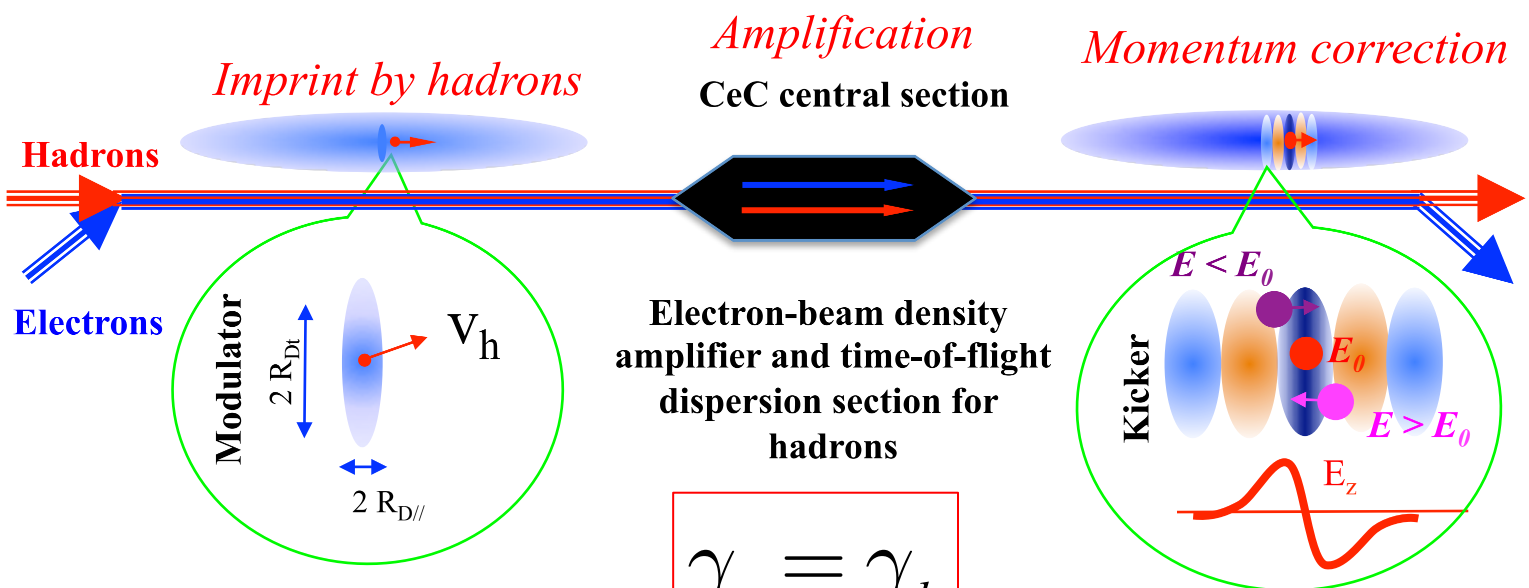
Yaroslav S. Derbenev

Thomas Jefferson National Accelerator Facility. Newport News, VA, USA

29th International Free Electron Laser Conference
August 26-31, 2007, Budker INP, Novosibirsk, Russia

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



$$\gamma_e = \gamma_h$$

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

Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

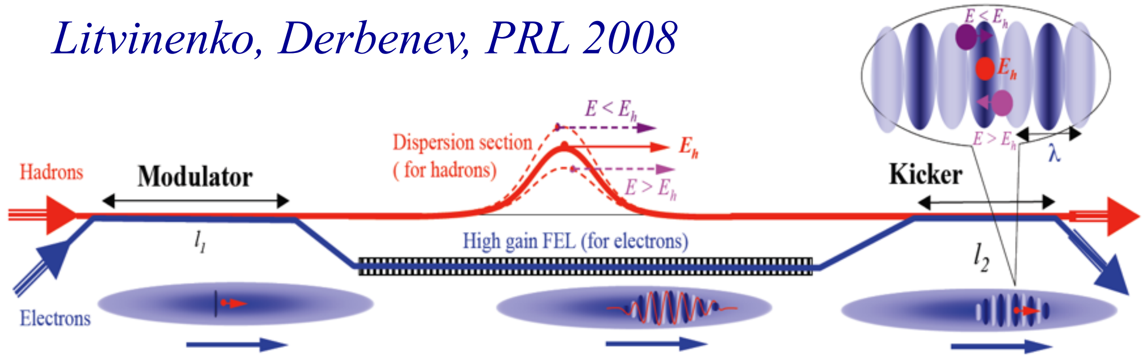
[1]*Brookhaven National Laboratory, Upton, Long Island, New York, USA*

[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA*

(Received 24 September 2008; published 16 March 2009)

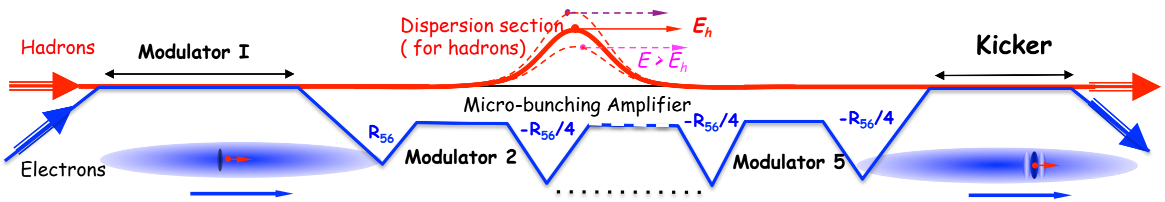
CeC schemes

Litvinenko, Derbenev, PRL 2008



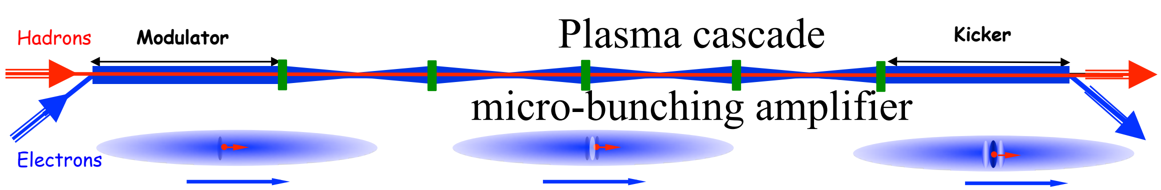
High gain FEL amplifier

Ratner, PRL 2013



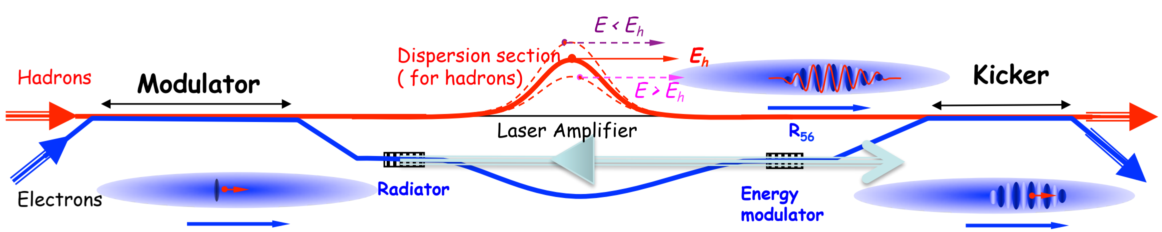
Multi- Chicane Microbunching amplifier

Litvinenko, Wang, Kayran, Jing, Ma, 2017



Plasma-Cascade Microbunching amplifier

Litvinenko, Cool 13

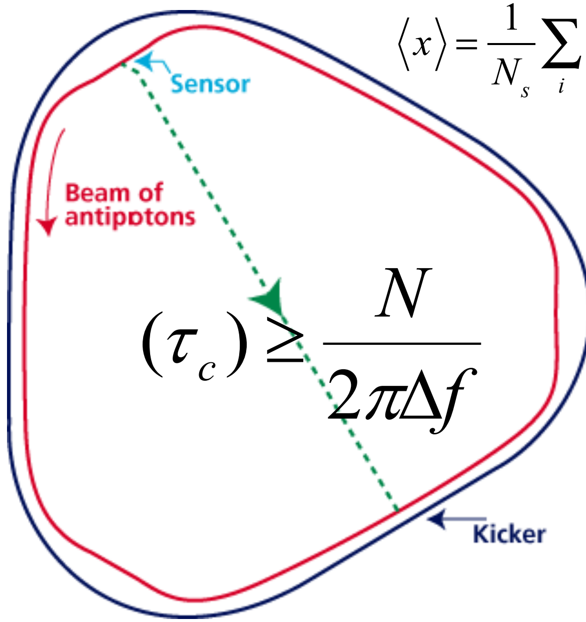


Hybrid laser-beam amplifier

Critical conditions for the stochastic cooler

S. van der Meer
1984 Nobel physics prize

RF stochastic cooling is reaching its limits at bandwidth of few GHz



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

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

- ✓ **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 amplifier, cooling decrement per turn can not exceed $1/N_s$, where is number of the particles in fitting inside the response time of the system: $\tau \sim 1/\Delta f$
- ✓ **Noise:** Noise of the amplifier reduces attainable cooling rate beyond that limited by the amplifier bandwidth. Excessive noise can make cooling rate less than IBS growth rate…

$$x_k^2 \to \left(x_k - g\left(\langle x \rangle + noise\right)\right)^2 = x_k^2 - 2gx_k\left(\langle x \rangle + noise\right) + g^2\left(\langle x \rangle + noise\right)^2$$

$$\Delta\langle x^2 \rangle = \left(-2g + g^2\right)\frac{\langle x^2 \rangle}{N_s} + g^2\langle noise^2 \rangle; g_{opt} = \left(1 + N_s\frac{\langle noise^2 \rangle}{\langle x^2 \rangle}\right)^{-1};$$

$$\tau_c = -\left(f_{rev}\frac{1}{\varepsilon}\frac{d\varepsilon}{dn}\right)^{-1} = \frac{N_{eff}}{f_{rev}}; \quad N_s = \frac{\dot{N}}{\Delta f} = \frac{I_{peak}}{Ze}\cdot\frac{1}{\Delta f}; N_{eff} = N_s\left(1 + \frac{N_s\langle noise^2 \rangle}{\langle x^2 \rangle}\right)$$

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

How to evaluate CeC: the original recipe

Free Electron Lasers and High-energy Electron Cooling,
V. N. Litvinenko, Ya. S. Derbenev, 29th International Free Electron Laser Conference, Novosibirsk, Russia, August 27-31, 2007

- Linear response of electron beam on perturbations – no saturation, superposition principle

$$\delta\vec{\mathbf{E}}_h = Ze\cdot\vec{\mathbf{G}}_{Eh}\left(\vec{r},\vec{r}_h,\gamma_h,t,t_h\right);\delta\vec{\mathbf{B}}_h = Ze\cdot\vec{\mathbf{G}}_{Bh}\left(\vec{r},\vec{r}_h,\gamma_h,t,t_h\right);$$

$$\delta\vec{\mathbf{E}}_e = -e\cdot\vec{\mathbf{G}}_{Ee}\left(\vec{r},\vec{r}_e,\gamma_e,t,t_e\right);\delta\vec{\mathbf{B}}_e = -e\cdot\vec{\mathbf{G}}_{Be}\left(\vec{r},\vec{r}_e,\gamma_e,t,t_e\right);$$

$$\vec{\mathbf{E}} = Ze\cdot\sum_h\vec{\mathbf{G}}_{Eh}\left(\vec{r},\vec{r}_h,\gamma_h,t,t_h\right) - e\cdot\sum_e\vec{\mathbf{G}}_{Ee}\left(\vec{r},\vec{r}_e,\gamma_e,t,t_e\right);$$

$$\vec{\mathbf{B}} = Ze\cdot\sum_h\vec{\mathbf{G}}_{Bh}\left(\vec{r},\vec{r}_h,\gamma_h,t,t_h\right) - e\cdot\sum_e\vec{\mathbf{G}}_{Be}\left(\vec{r},\vec{r}_e,\gamma_e,t,t_e\right)$$

$$\delta E_i = eZ\int\vec{\mathbf{E}}\cdot d\vec{r}_i;\;\; \delta\vec{p}_i = eZ\int\left(\vec{\mathbf{E}} + \frac{\left[\vec{p}_i\times\vec{\mathbf{B}}\right]}{\gamma_i m}\right)\cdot dt;$$

- Evaluation of hadron distribution function using Fokker-Plank equation with both damping and diffusion terms
- Cooling transversely using coupling with longitudinal degrees of freedom

How to evaluate CeC: the original recipe

Free Electron Lasers and High-energy Electron Cooling,
V. N. Litvinenko, Ya. S. Derbenev, 29th International Free Electron Laser Conference, Novosibirsk, Russia, August 27-31, 2007

- Linear response of electron beam on perturbations – no saturation, superposition principle

$$\delta E_i = eZ\int \vec{\mathbf{E}}\cdot d\vec{r}_i;\ \ \delta \vec{p}_i = eZ\int\left(\vec{\mathbf{E}} + \frac{\left[\vec{p}_i \times \vec{\mathbf{B}}\right]}{\gamma_i m}\right)\cdot dt;$$

- Evaluation of hadron distribution function using Fokker-Plank equation with both damping and diffusion terms

$$\bar{f} = \langle \tilde{f} \rangle; \tilde{f} = \sum_h \delta\left(X - X_i(t)\right)$$

$$\frac{\partial \bar{f}(X,s)}{\partial t} + \frac{\partial}{\partial X_i}\left[\frac{dX_i(X,t)}{dt}\bar{f}(X,s)\right] - \frac{1}{2}\frac{\partial^2}{\partial X_i \partial X_k}\left[D_{ik}(X,t)\bar{f}(X,t)\right] = 0,$$

$$\left\langle \frac{dX_i(X,t)}{dt} \right\rangle = \frac{1}{\tau}\int (X_i - Z_i)\cdot W(Z,X|\tau,t)\,dZ = \frac{1}{T_o}\langle \delta X_i \rangle;$$

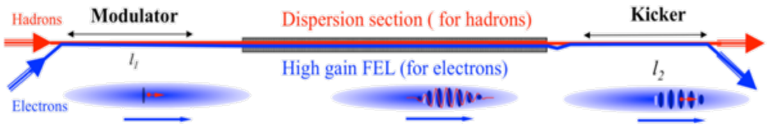
$$D_{ik}(X,t) = \frac{1}{2\tau}\int (X_i - Z_i)(X_k - Z_k) W(Z,X|\tau,t)\,dZ = \frac{1}{T_o}\langle \delta X_i \cdot \delta X_i \rangle.$$

- Cooling transversely using coupling with longitudinal degrees of freedom

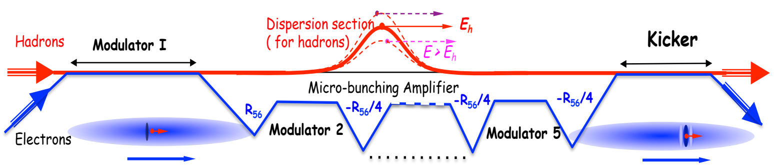
$$\delta E_h(X_h) = (eZ)^2 \cdot g_{Eh}(X_h) - Ze^2 \cdot g_{Ee}(X_h).$$

$$X^T = \left\{x, P_x, y, P_y, \tau = c(t_o - t), \delta = (E - E_o)/E_o\right\}$$

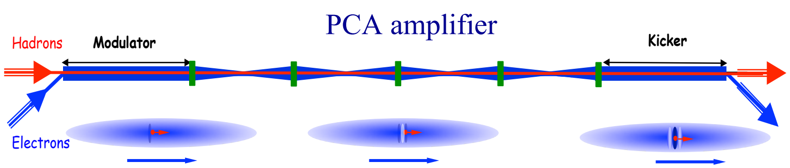
What can be tested experimentally?



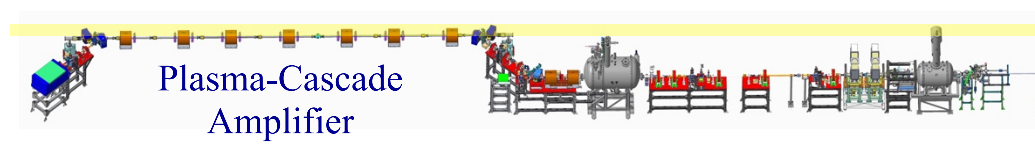
RHIC Run 18

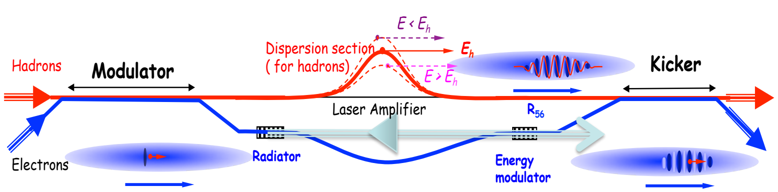


Cooling test would require significant modification of the RHIC lattice & superconducting magnets with cost exceeding $20M.



RHIC Runs 20-22

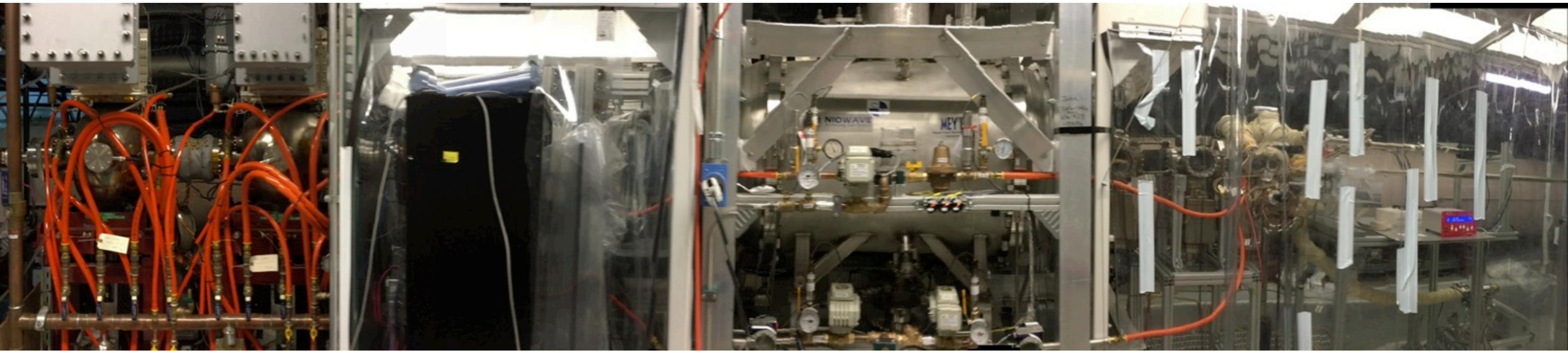




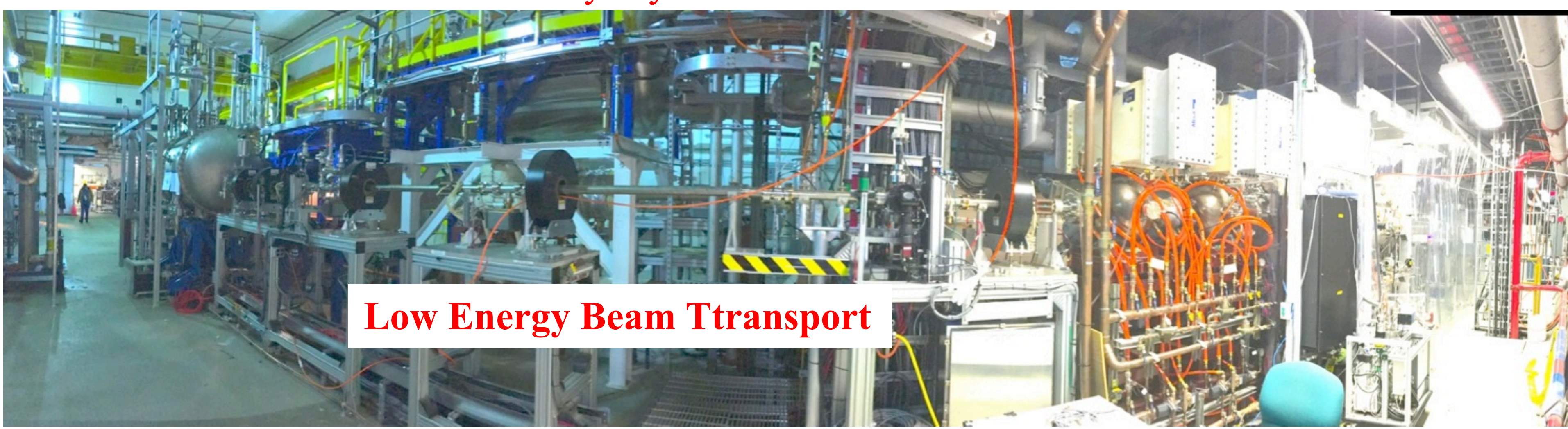
Cooling test would require significant modification of the RHIC lattice & superconducting magnets with cost exceeding $20M

Panoramic views of CeC accelerator

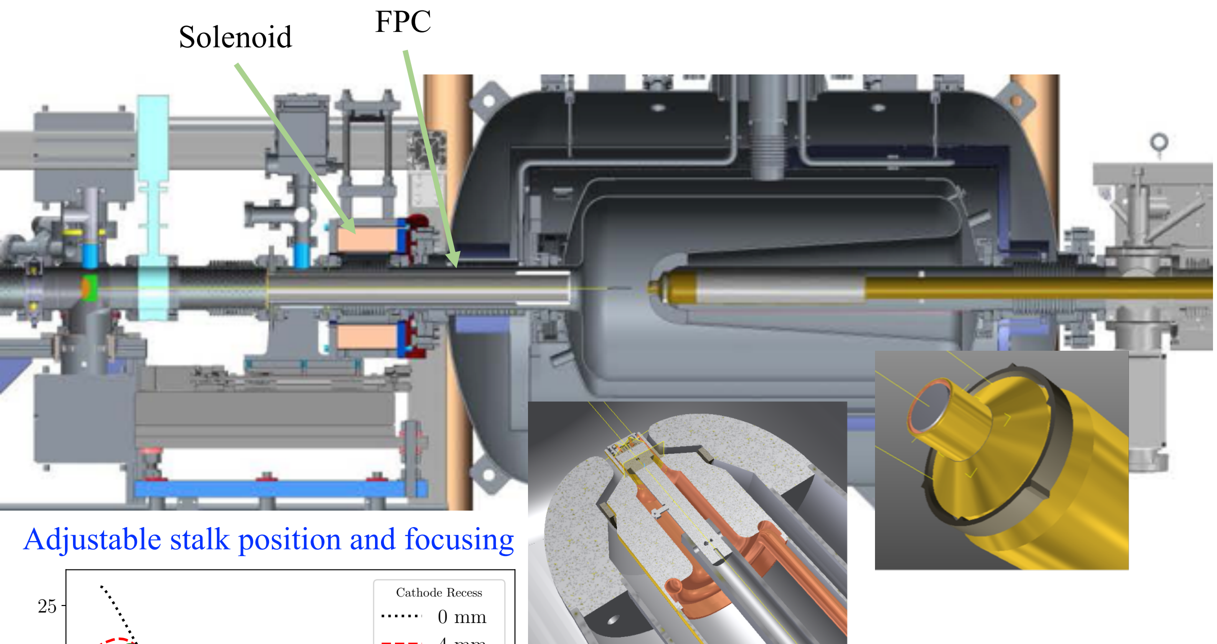
500 MHz cavities
Laser input
SRF gun
Photocathode manipulator



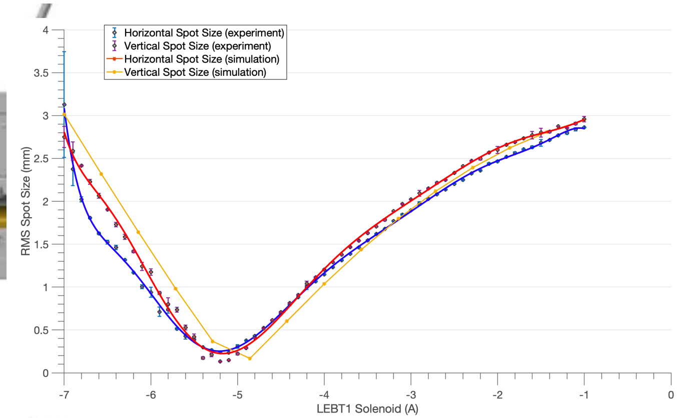
SRF linac
Part of CeC cryo system
500 MHz cavities



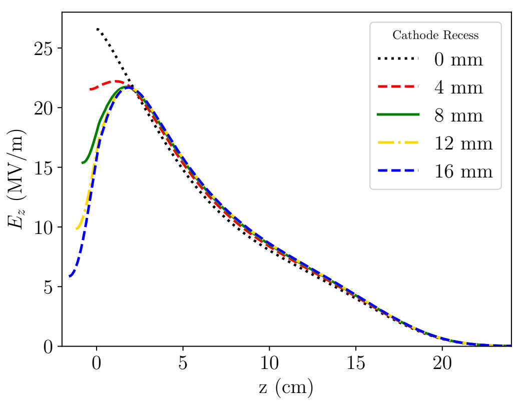
Record breaking 113 MHz CW SRF Gun



Simulations vs measurements

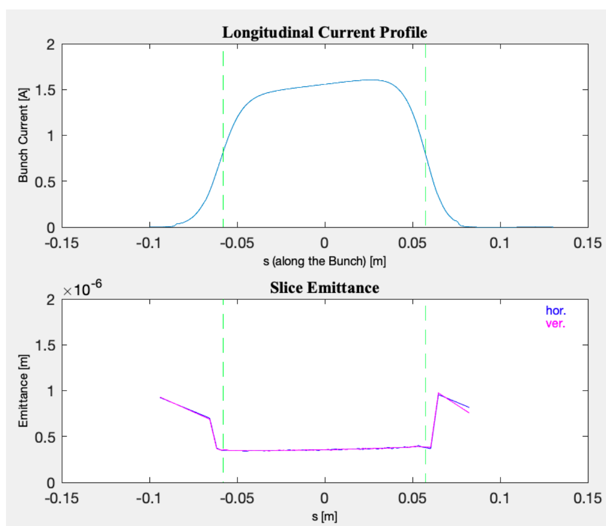


Adjustable stalk position and focusing



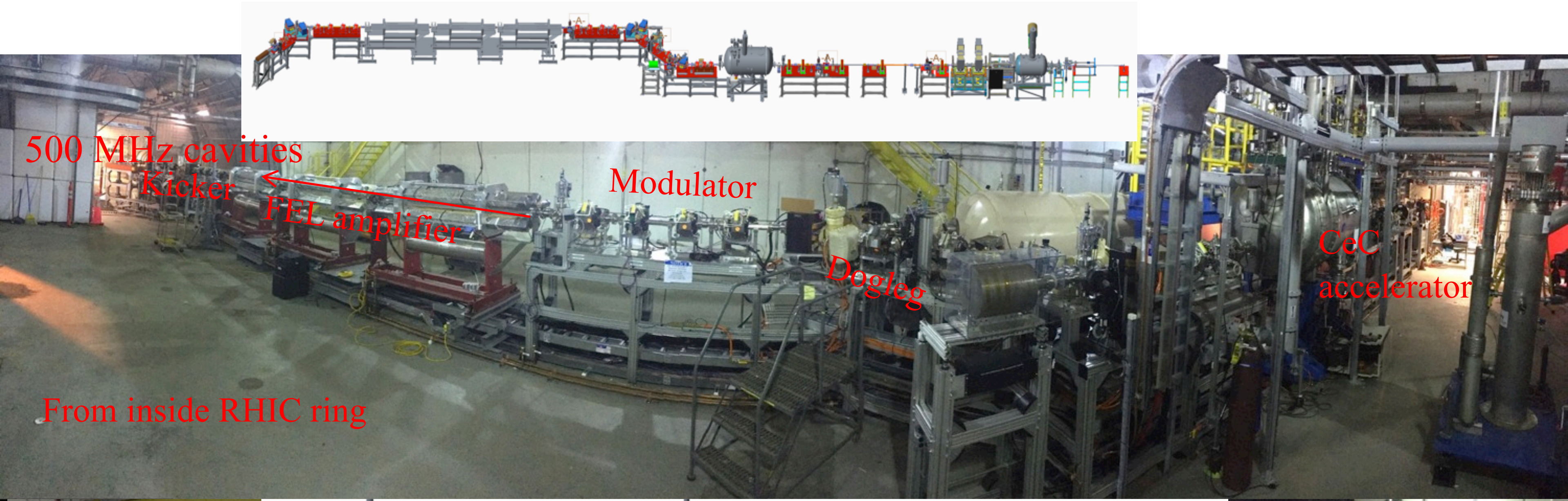
Gun energy: 1.25 MV
Laser spot on cathode r.m.s. size: 0.8mm (3.2 mm diameter)
Bunch charge: 600 pC
Bunch length: 400 ps
Gun solenoid: 8.6 A

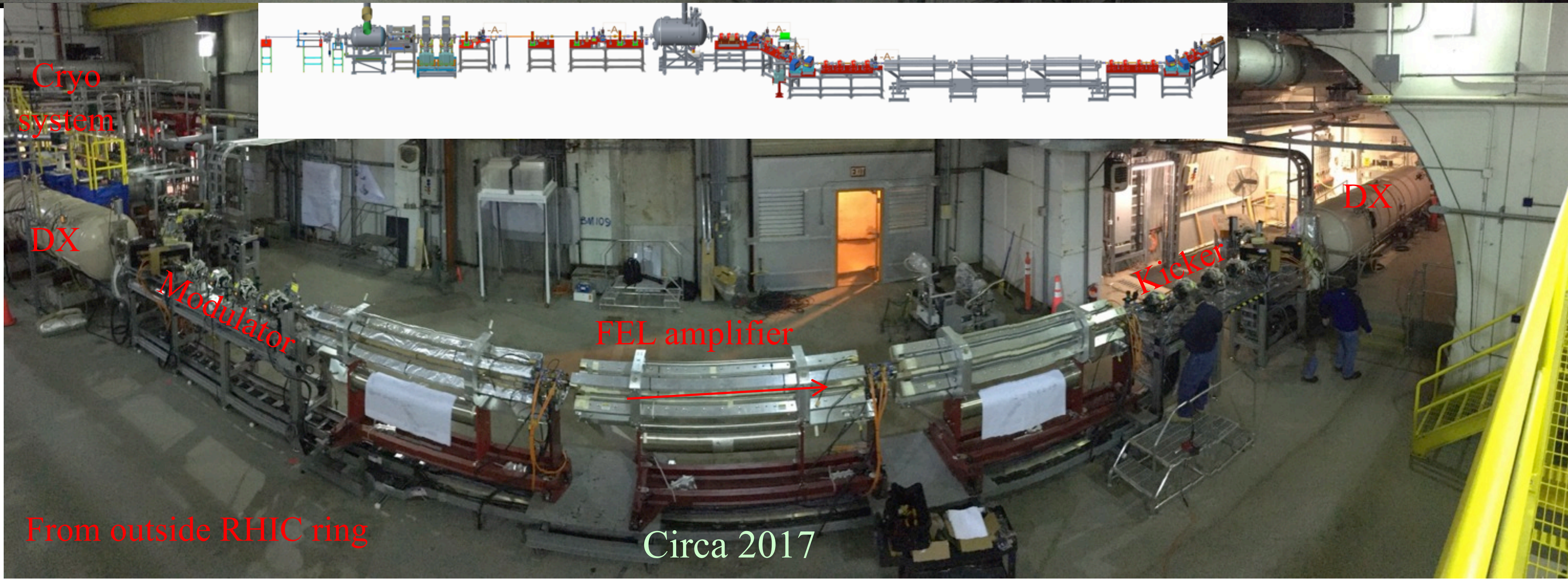
GPT simulations



- 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**

CeC system's panoramic views (before LEReC has been installed)

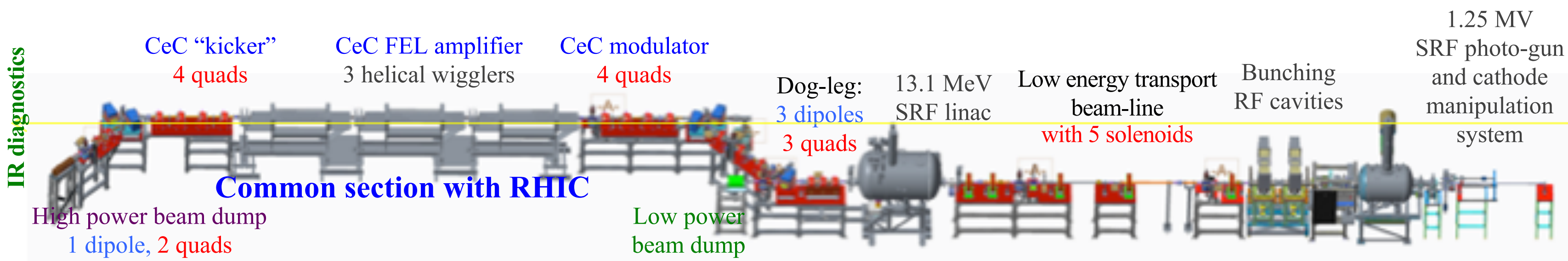




The FEL-based CeC circa 2017

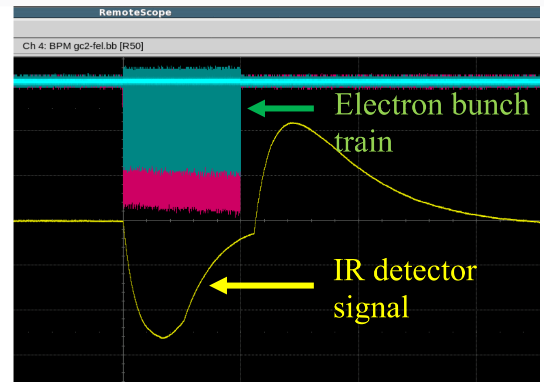
Walk from the SRF gun by to the full power beam dump

Attempt to test FEL-based CeC

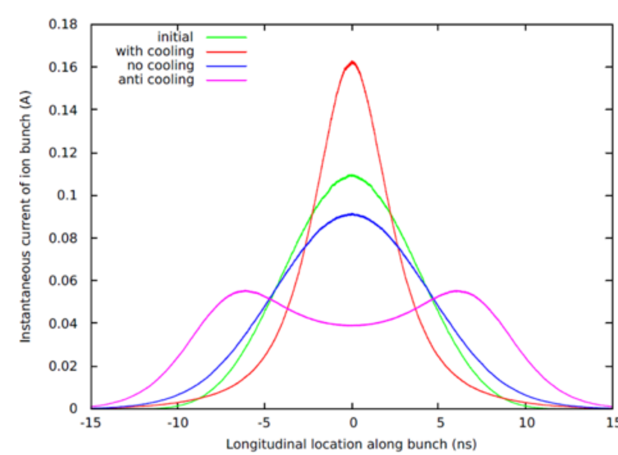


Parameter	Design	Status	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	✓ to match e-beam
Electron energy	21.95 MeV	14.56 MeV	Linac’s quench limit
Charge per electron bunch	0.5-5 nC	0.1- 10.7 nC	✓
Peak current	100 A	50 -100A	✓
Bunch duration, psec	10-50	12	✓
Normalized beam emittance	< 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	80-400 µA	150 µA	✓

FEL lasing pulse at 31 µm: April 2018



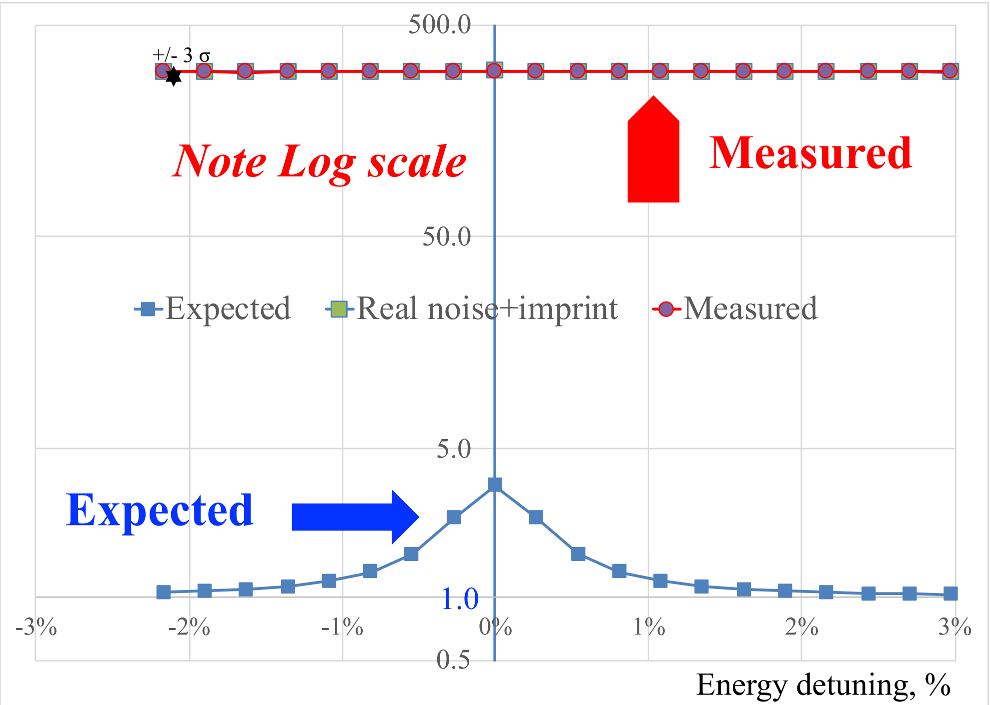
Predicted evolution of ion bunch profile in 40 minutes



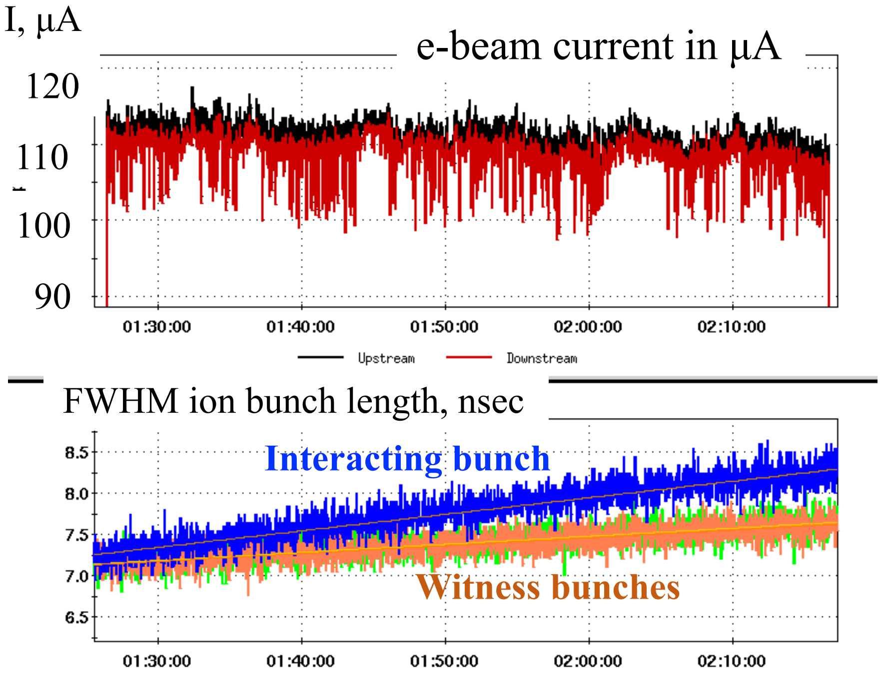
Puzzle of the CeC Run 18

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

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



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



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

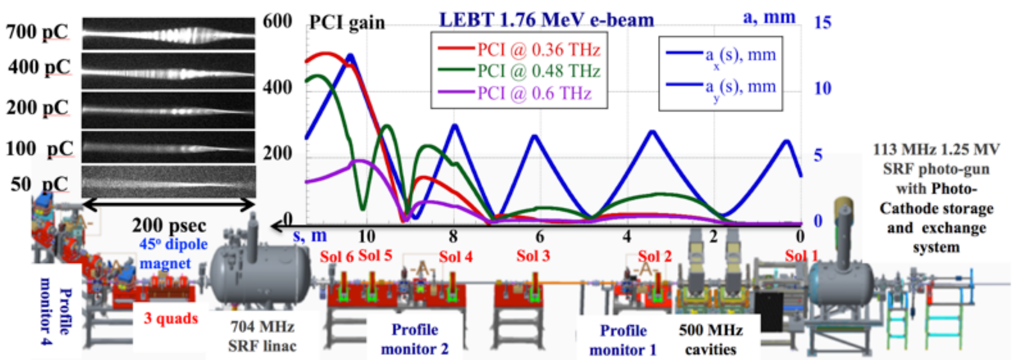
We ran out of time to demonstrate the FEL-based CeC during Run 18 with RHIC.

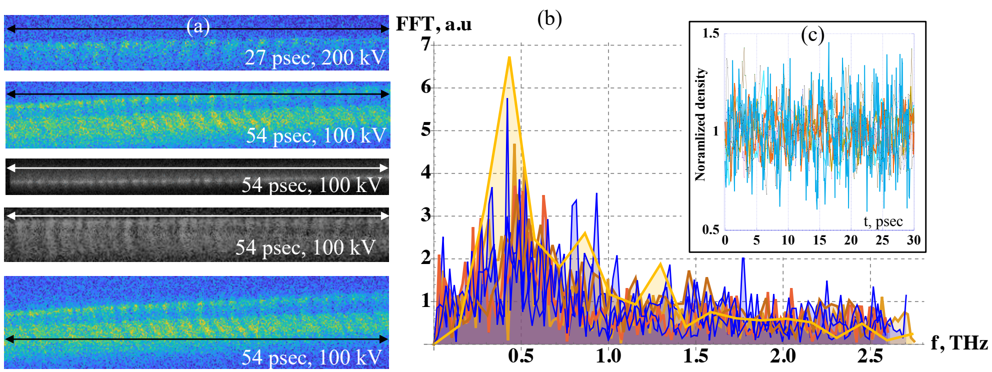
FEL-based CeC concept remains valid and awaiting for experimental demonstration.

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

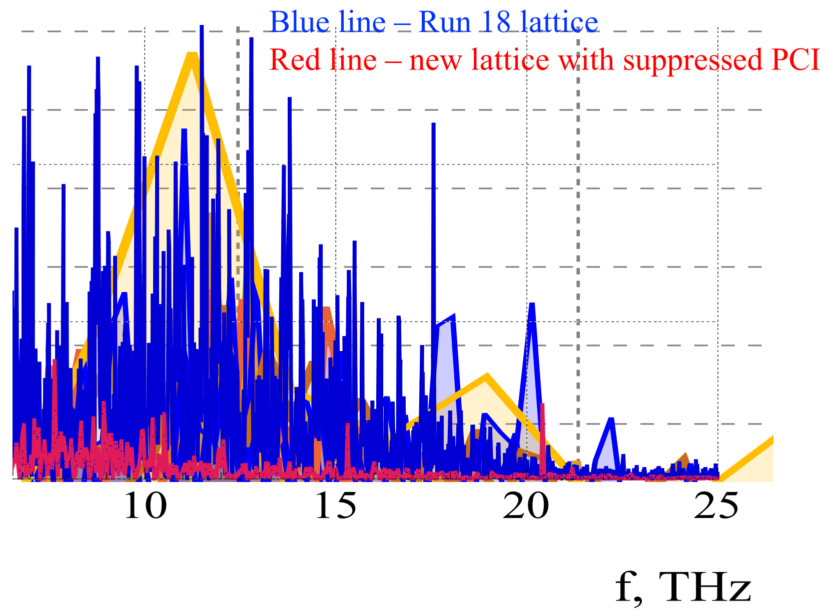
Uncompressed bunch:
simulations and experiment in Sept 2018





(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

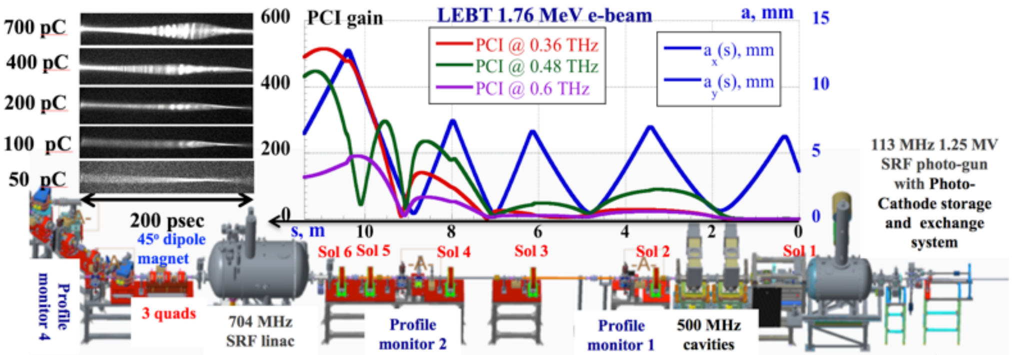


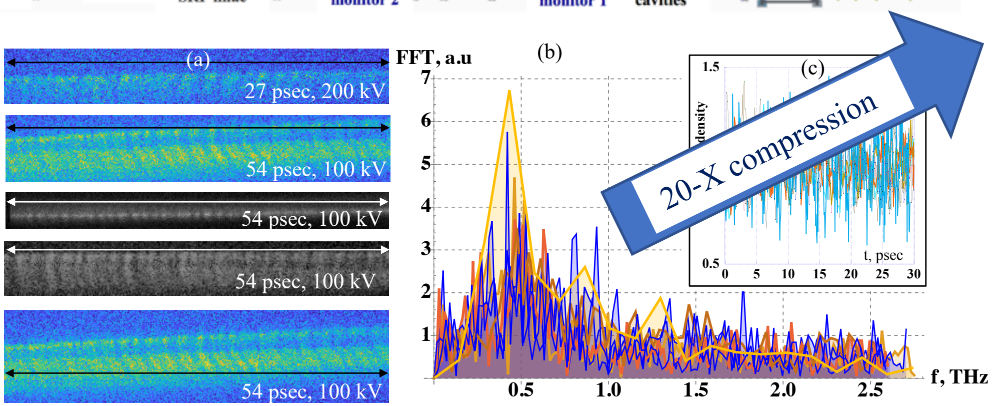
First we showed it in simulations that we can control noise level in the electron beam and confirmed this in the experiment during a short run in Summer 2019

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

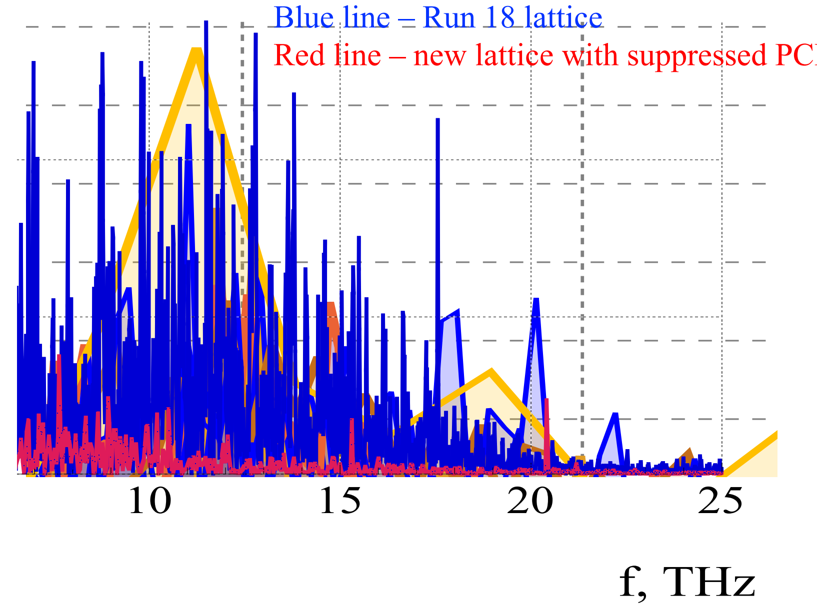
Uncompressed bunch: simulations and experiment in Sept 2018





(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

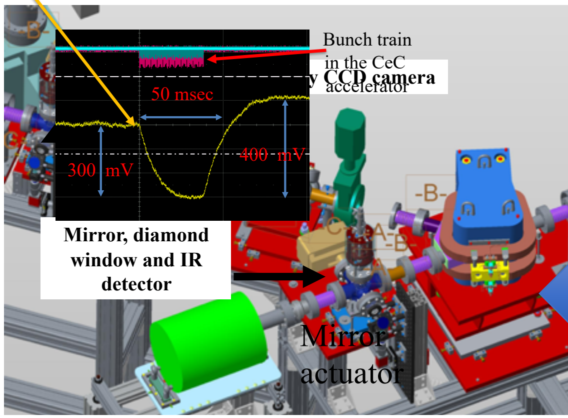


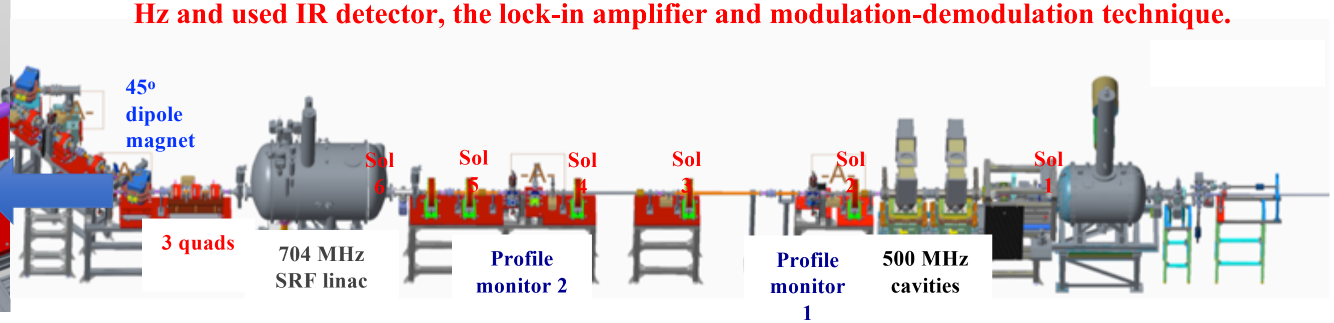
First we showed it in simulations that we can control noise level in the electron beam and confirmed this in the experiment during a short run in Summer 2019

Reliable e-beam noise measurement system -Run 19

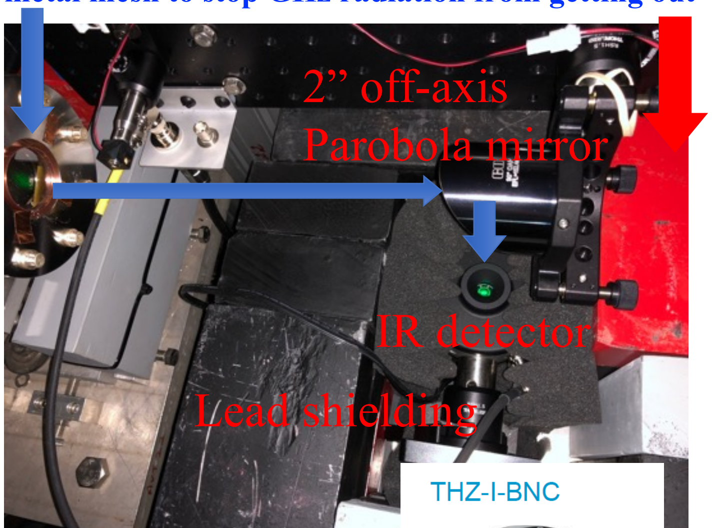
- **The goal of this short run was to control and reduce noise in electron beam below 100 times the shot noise baseline**
- **We operated CeC accelerator short 100 to 500 bunch trains repeated typically with 10 Hz and used IR detector, the lock-in amplifier and modulation-demodulation technique.**

Pyroelectric detector signal





1" CVD diamond window with 1.4 mm x 1.4 mm metal mesh to stop GHz radiation from getting out



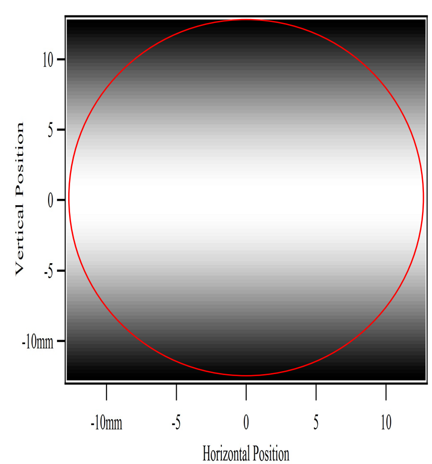
THZ-I-BNC

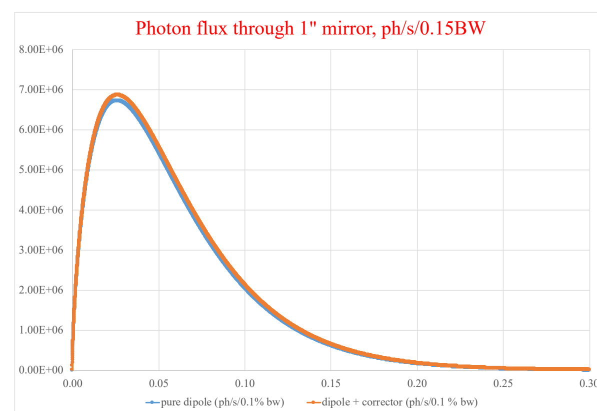
Pyroelectric detector
0.1 to 30 THz
(10 μm – 3 mm)

Response : 2.12 mV/nJ
Resolution of the system: ~0.1 nJ
Noise equivalent: 0.6 nW/Hz$^{1/2}$

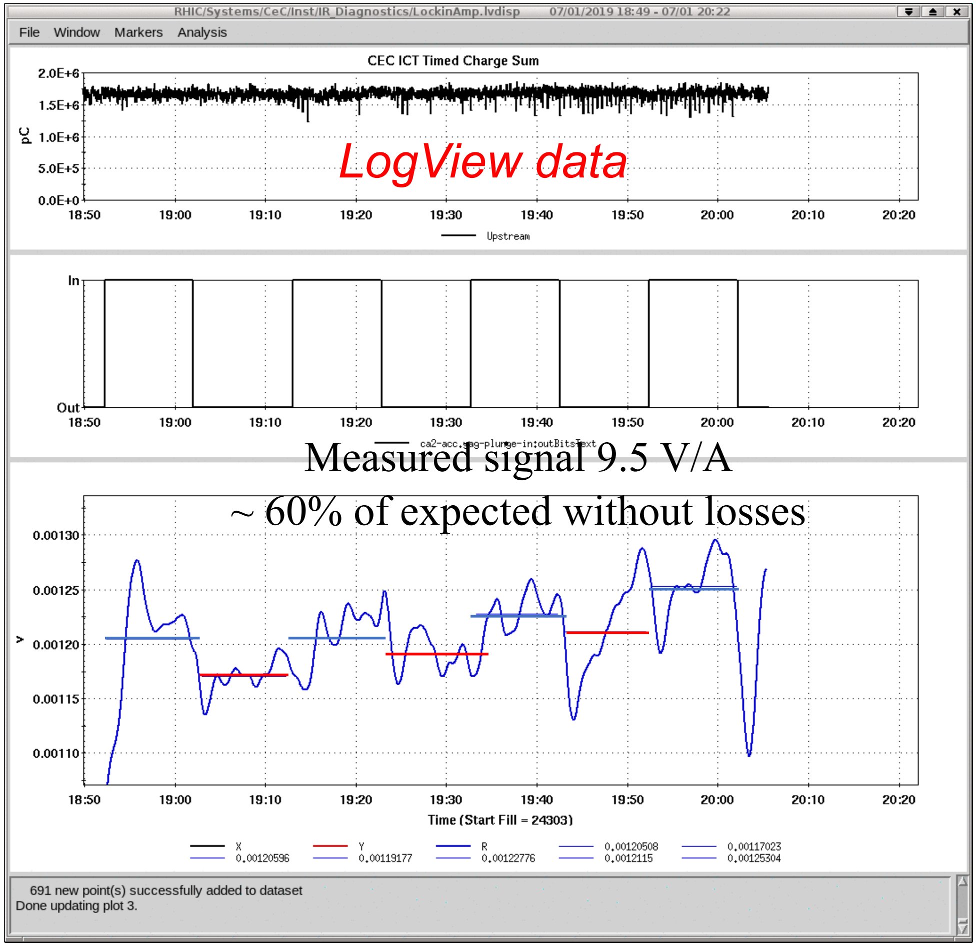
We calibrated the lock-in amplifier output for such signal to be (4±0.4)·10^5 V/W. Spontaneous radiation power – e.g. that of e-beam with shot noise - reaching the insertable the 1" Cu mirror was calculated using Igor-Pro for beam bent in a measured magnetic field of the 45-degree dipole operated at 140 A. With metal mesh ~ 50% transparency we expected ~ 50 pW power reaching IR detector with typical 1.5 μA beam current and signal from locking amplifier signal ~ 20 μV

Igor-Pro simulation of the power distribution at the extraction mirror (right, red circle) and photon spectra for normal and 2.5 mrad beam entrance.



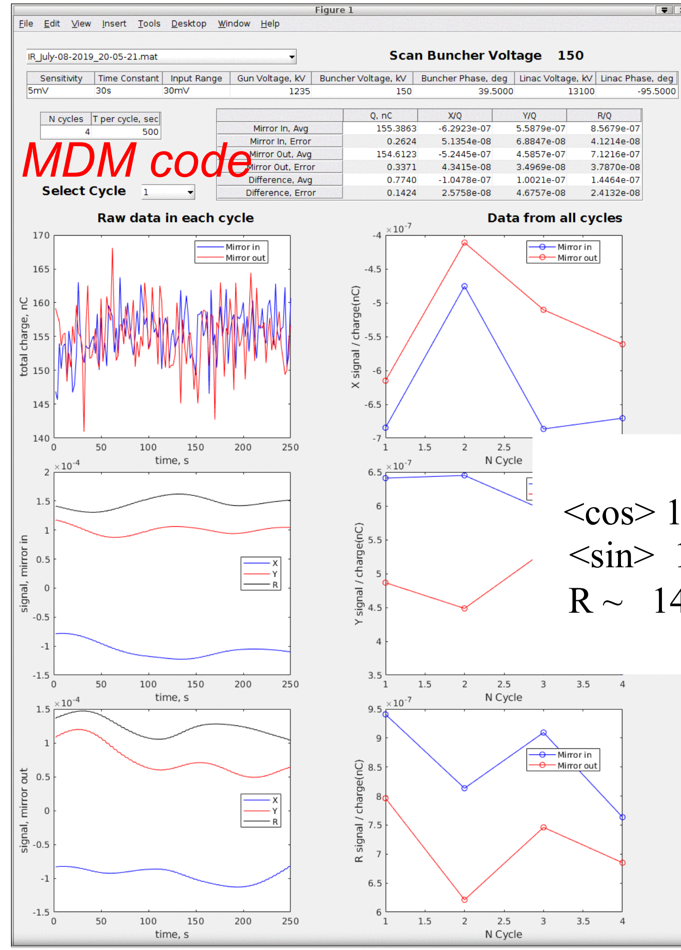


Baseline power - e.g. radiated by beam with Poison statistics shot noise level - measurements



Measured signal 9.5 V/A

~ 60% of expected without losses



<cos> 10.5 V/A

<sin> 10V/A R

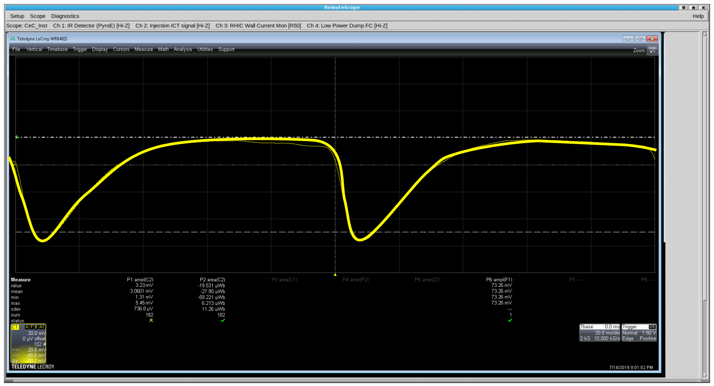
R ~ 14.5 V/A.

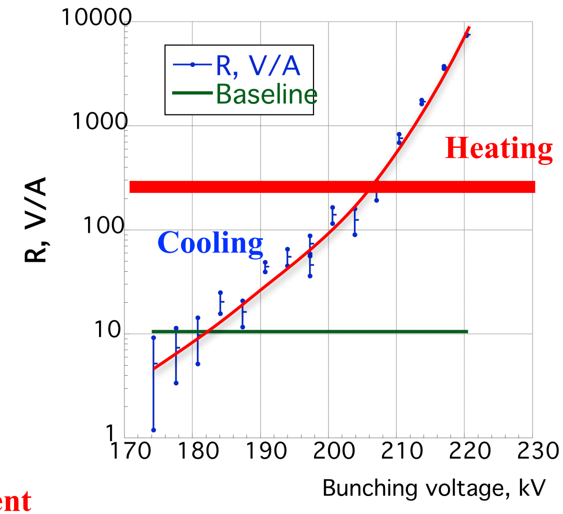
The base line was measured for modestly (4-fold) compressed beam with 1.5 and 0.3 nC charges per bunch in relaxed LEBT lattice. Averaged over 4 long scans the lock-in amplifier MDM signal was **14.5 V/A with RMS error of 1.5 V/A**

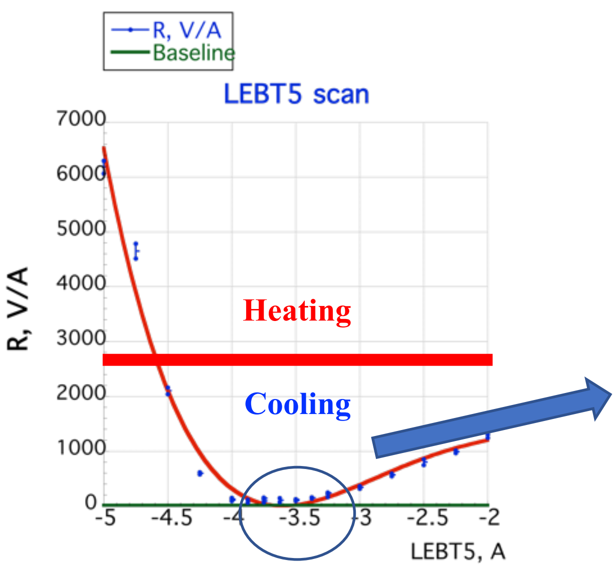
This value is ~ 50% level of synchrotron radiation that reaches the Cu mirror

Samples of the measurements

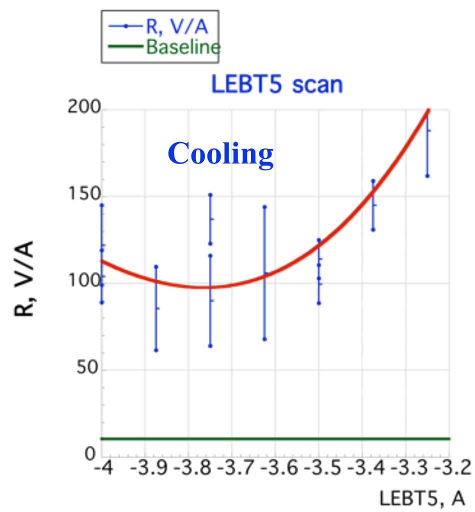
Run 18 lattice and beam: 0.6 nC per bunch
Large signal of 2,500 V/A ~ 250-fold above base line.
Can be seen both on scope and measured easily

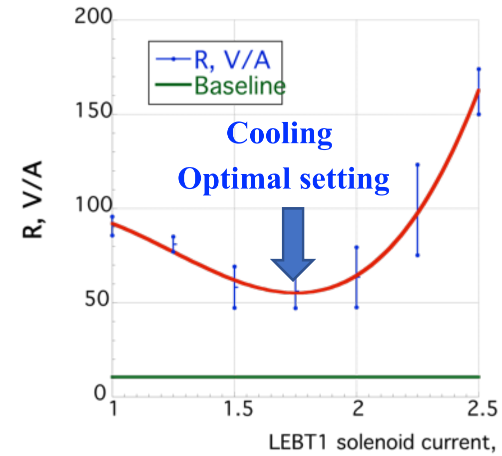






1.5 nC, 75 A peak current

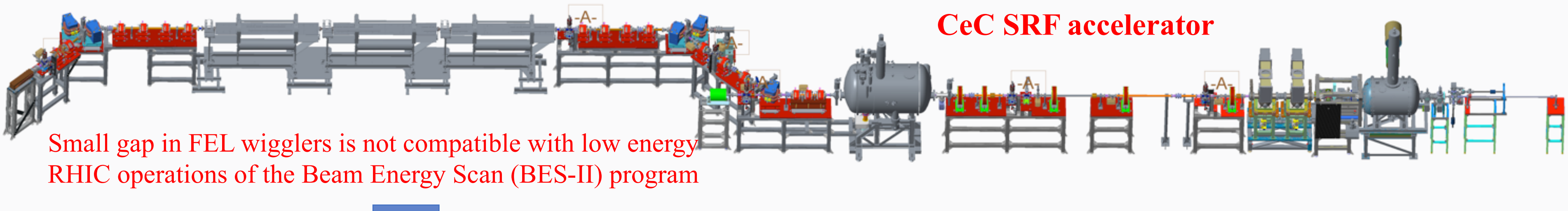


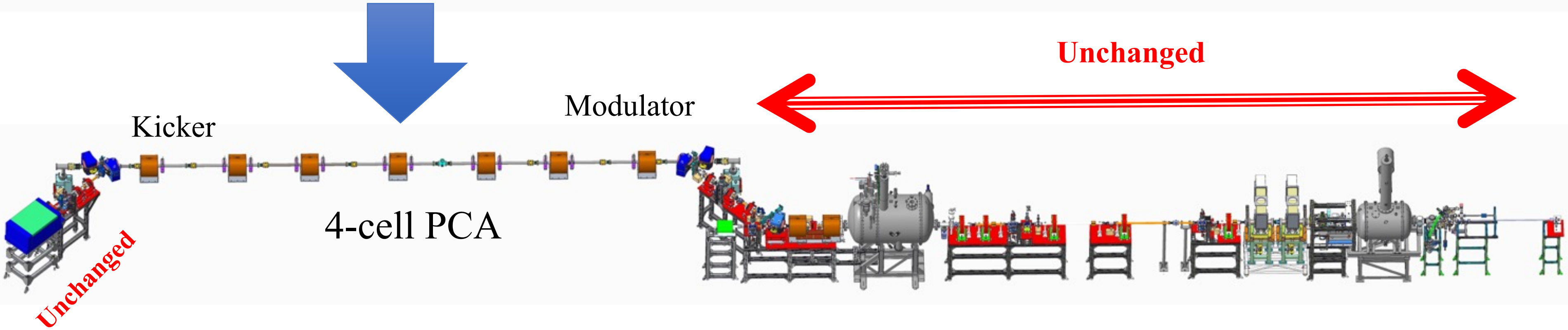


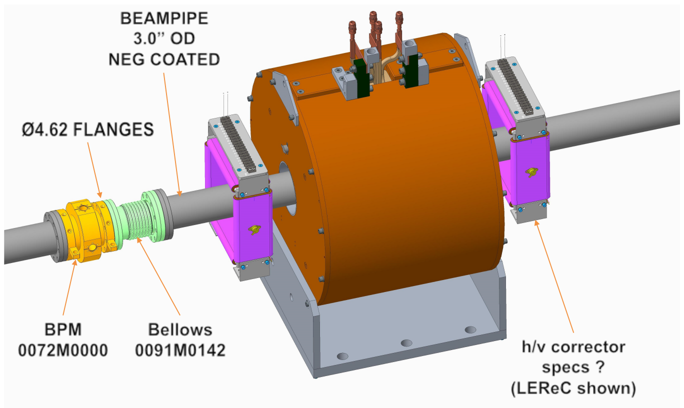
We demonstrated that with 75 A peak current we can reduce beam noise to acceptable level. It could be as low as 6-10 times above the baseline

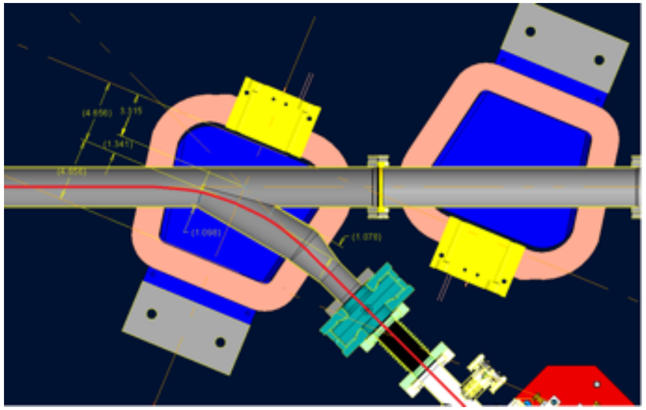
Changing CeC amplifier from FEL to PCA

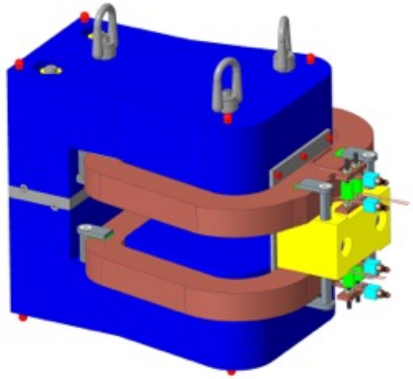
The FEL-based CeC concept is still valid – the system is stored and can be tested in the future





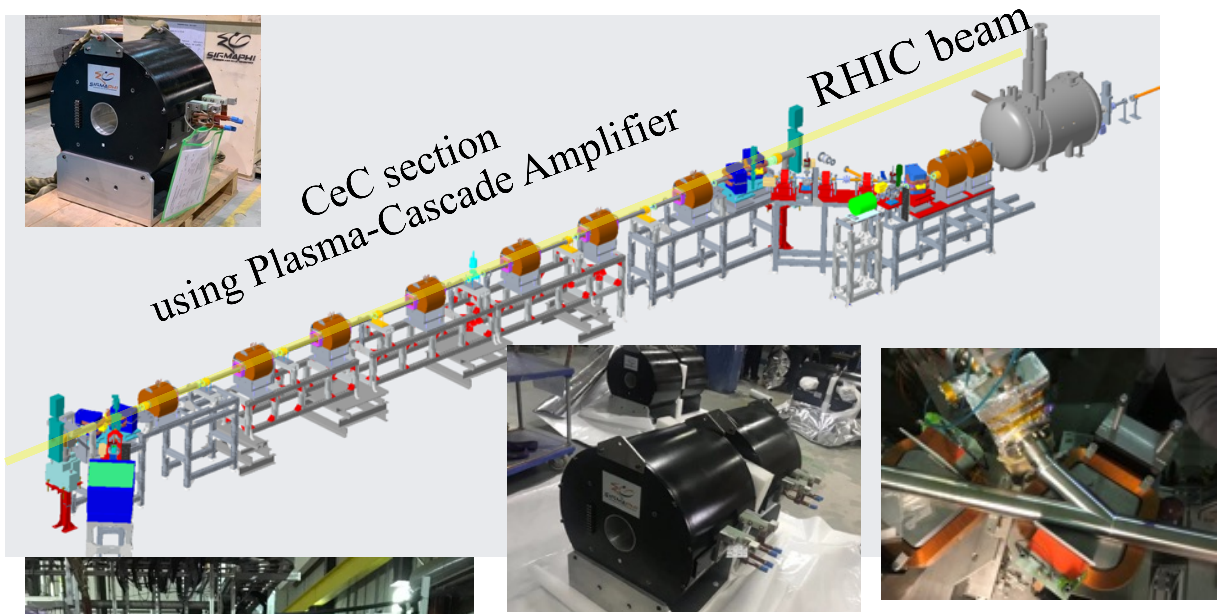


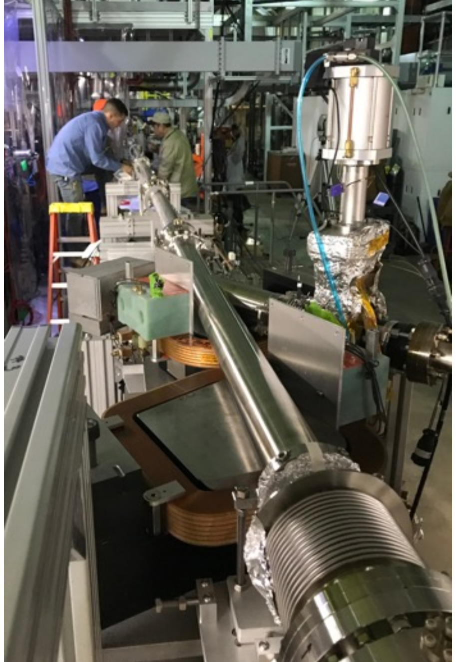




CeC with PCA: status

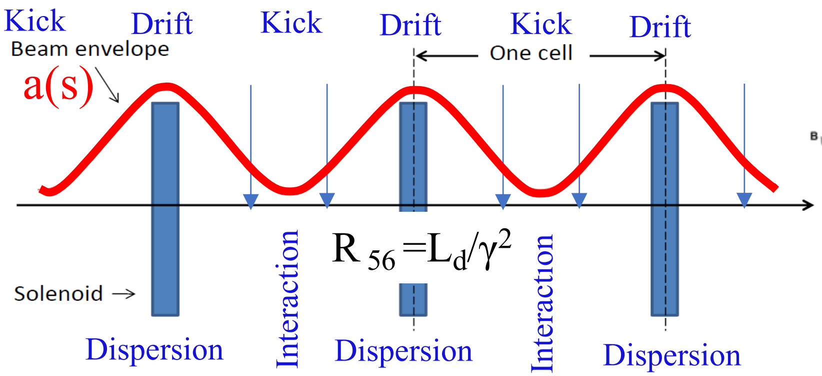
- **Mechanical design new CeC system is completed**
- **We procured and commissioned new laser system with controllable pulse structure**
- **All new vacuum with beam diagnostics are built chambers are installed**
- **All supports are built and installed**
- **All solenoids are designed, manufactured,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



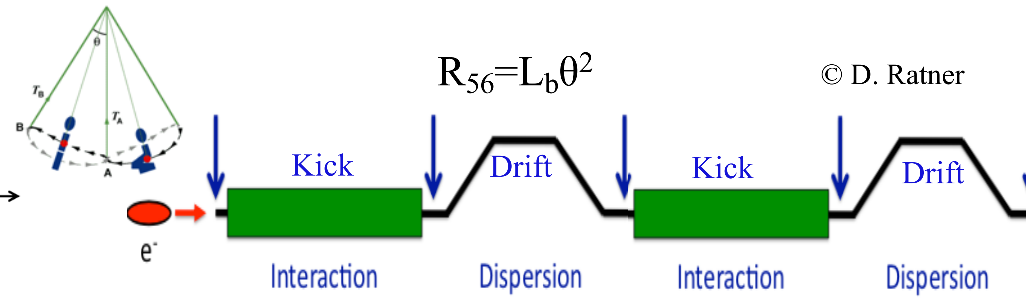


What is Plasma-Cascade Instability (PCI)?

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



PCI



MBI

Modulate beam density by changing beam radius a:

$$n_o(s)=\frac{I}{e\mathrm{v}}\cdot\frac{1}{\pi a^2(s)}$$

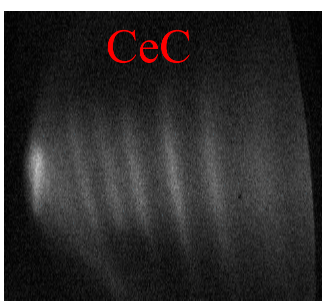
Cold beam model

$$n(t,s)=n_o(s)\cdot\{1+\tilde{\eta}(s,t)\}$$

$$\frac{\partial n}{\partial t}+div(\vec{u}n)=0;$$

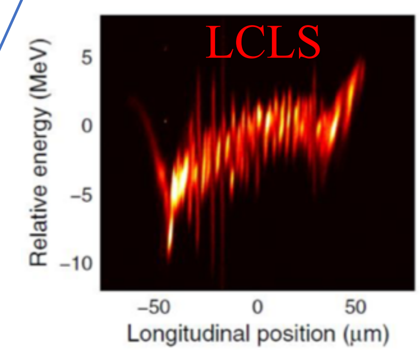
MBI: modulate effective mass (*s-mobility*) by bending beam trajectory (θ)

$$m_{eff}\approx m/(1+\gamma^2\theta^2)$$



$$\frac{d^2\tilde{\eta}}{ds^2}+k_p^2(s)\tilde{\eta}=0;\ \tilde{\eta}=\tilde{\eta}(s,t);$$

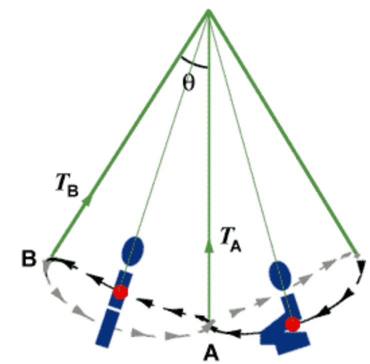
$$k_p^2(s)=\frac{4\pi e^2 n_o(s)}{\gamma\cdot\gamma_z^2(s)\cdot m\mathrm{v}^2};\ \gamma_z^2(s)=\frac{1}{1-\beta_z^2}\cong\frac{\gamma^2}{1+\gamma^2\theta^2(s)}$$

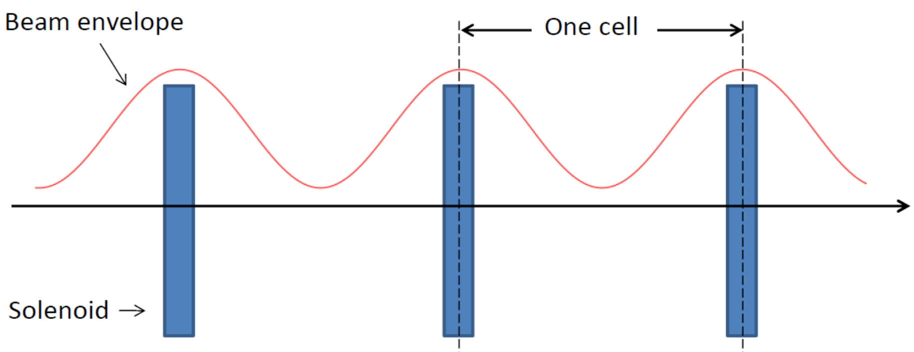


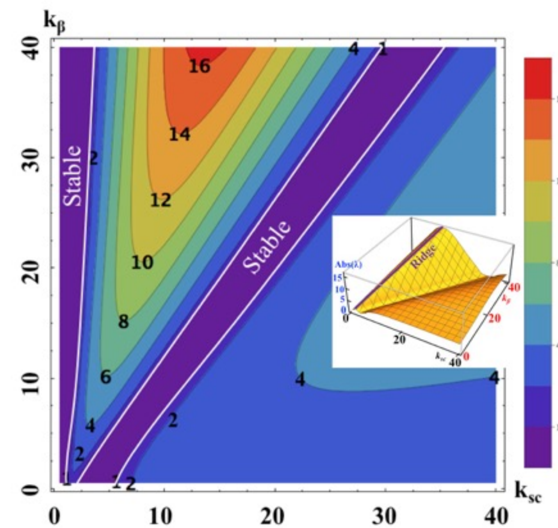
Plasma frequency does not dependent on the shape of modulation $\tilde{\eta}(t,s-\mathrm{v}t)$

What is Plasma-Cascade Amplifier

- It is a parametric instability driven by variation of the plasma frequency originating from the variation of the transverse electron beam size
- We do it by creating dramatic variations of plasma density using modulation of the transverse beam size
- Important questions – when exponential growth occurs and how fast it is? Hence, we developed a self-consistent 3D theory and simulations*





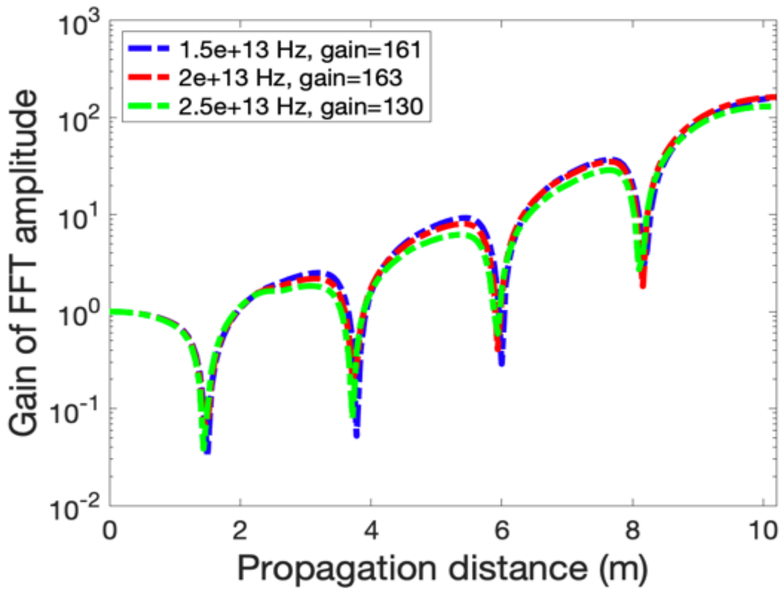


$$\hat{a}'' = k_{sc}^2 \hat{a}^{-1} + k_\beta^2 \hat{a}^{-3}$$

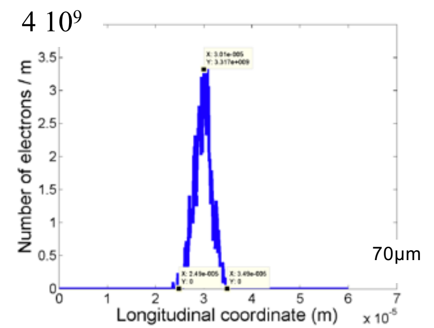
$$k_{sc}^2 = \frac{2}{\beta^3\gamma^3}\frac{I_o}{I_A}\frac{l^2}{a_o^2}; k_\beta = \frac{\varepsilon l}{a_o^2} = \frac{l}{\beta^*} \qquad \frac{d^2\tilde{n}}{ds^2} + 2k_{sc}^2\left(\frac{a_o}{a(s)}\right)^2 \tilde{n} = 0;$$

* *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, https://arxiv.org/pdf/1802.08677.pdf , 2018

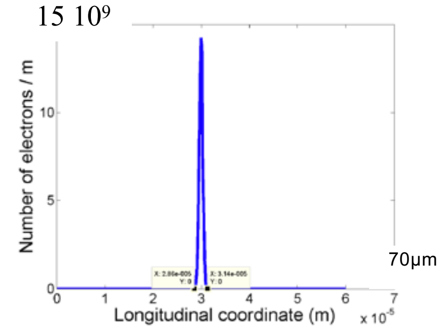
3D simulation of PCA at γ=28.5 using code SPACE*



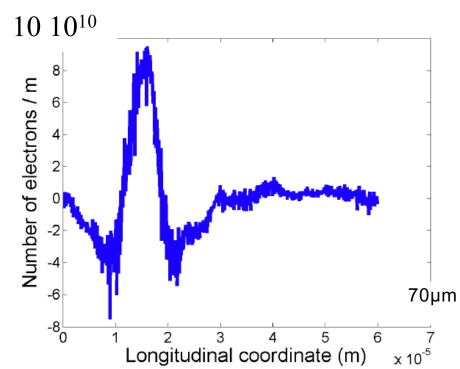
Initial seed with the same charge

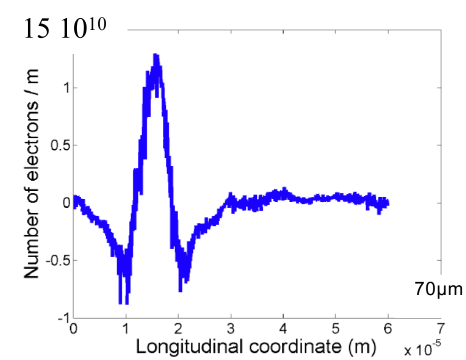


(a) 10μm

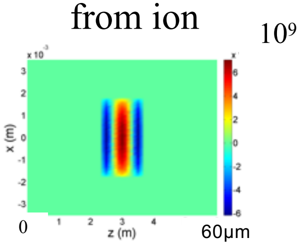


(b) 3μm

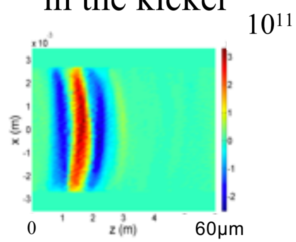




Initial seed from ion



Density modulation in the kicker



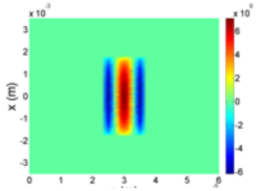
Densities normalized to maximum

Signal is delayed by 15 μm because of the angular spread in PCA and rotation in solenoids.
With CeC system R_{56} =14.8 mm, it will be compensated by 0.1% increase in the electron beam energy

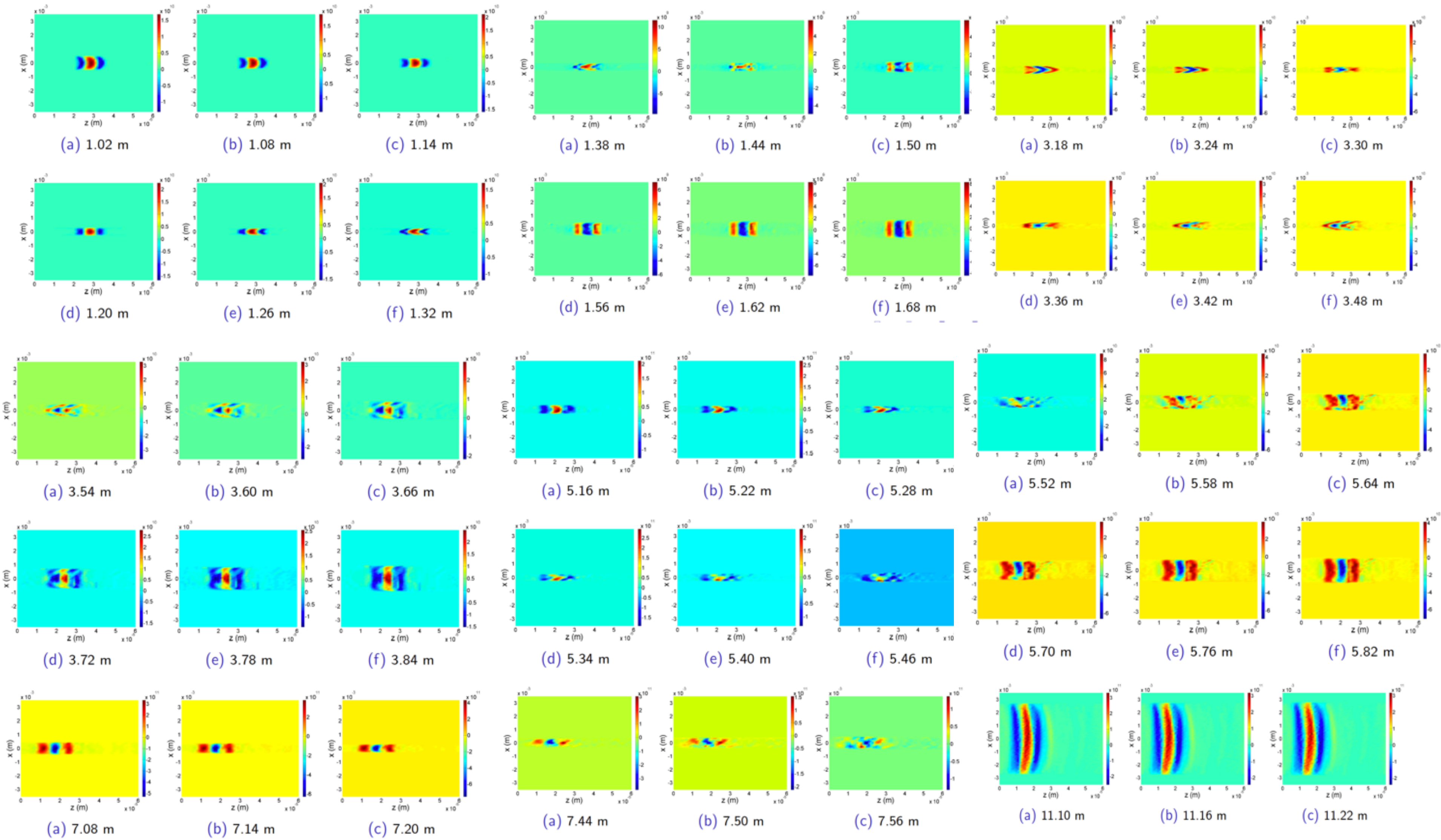
*SPACE is a PIC code, *X. Wang et al., "Adaptive Particle-in-Cloud method for optimal solutions to Vlasov-Poisson equation," J. Comput. Phys., 316 (2016), 682 - 699.*

Very complex behavior requires full 3D simulations

4-cell PCA



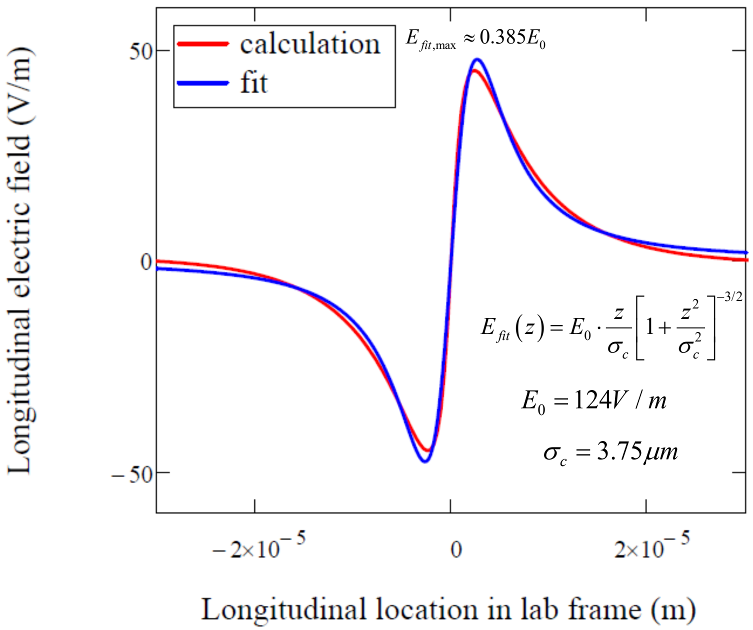
Evolution of real 3D Langmuir waves in PCA can be seen only in simulations (show movie)



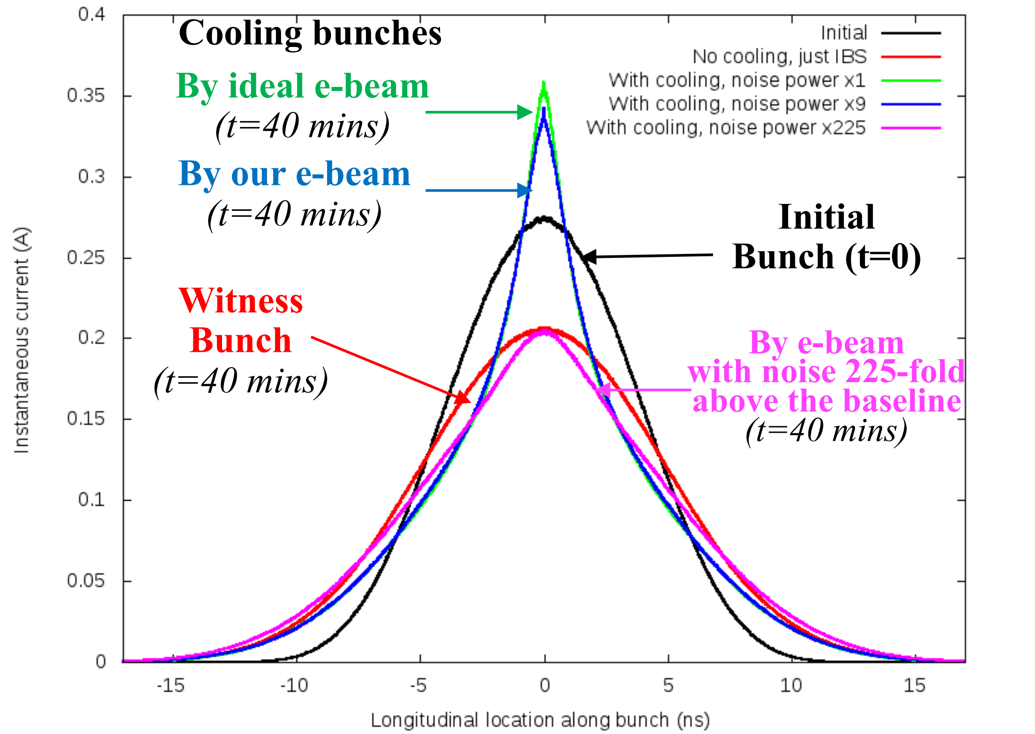
Simulated performance: full 3D treatment

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

How to cool transversely : a simple case

Only energy kick

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

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

$$\langle \Delta a_k \rangle = -\xi_k a_k \rightarrow a_k = a_{k0} e^{-n\xi_k}$$

$$\mathrm{Re}\,\xi_{(1,2)} = -\frac{i}{2}\left(Y_{(1,2)\beta}{}^T SD\right)^* \sum_{i=1}^{4} y_{(1,2)i} \cdot \zeta_i;\ \xi_s = \mathrm{Re}\,\xi_3 = \frac{1}{2}\left(\zeta_6 + \sum_{i=1}^{4} D_i \cdot \zeta_i\right),$$

No x-y coupling

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

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

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

Qx-Qy resonance

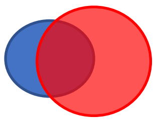
$$Y_1 = \frac{1}{\sqrt{1+|\alpha|^2}}\left(Y_x + \alpha Y_y\right);\ Y_2 = \frac{1}{\sqrt{1+|\alpha|^2}}\left(-\alpha^* Y_x + Y_y\right)$$

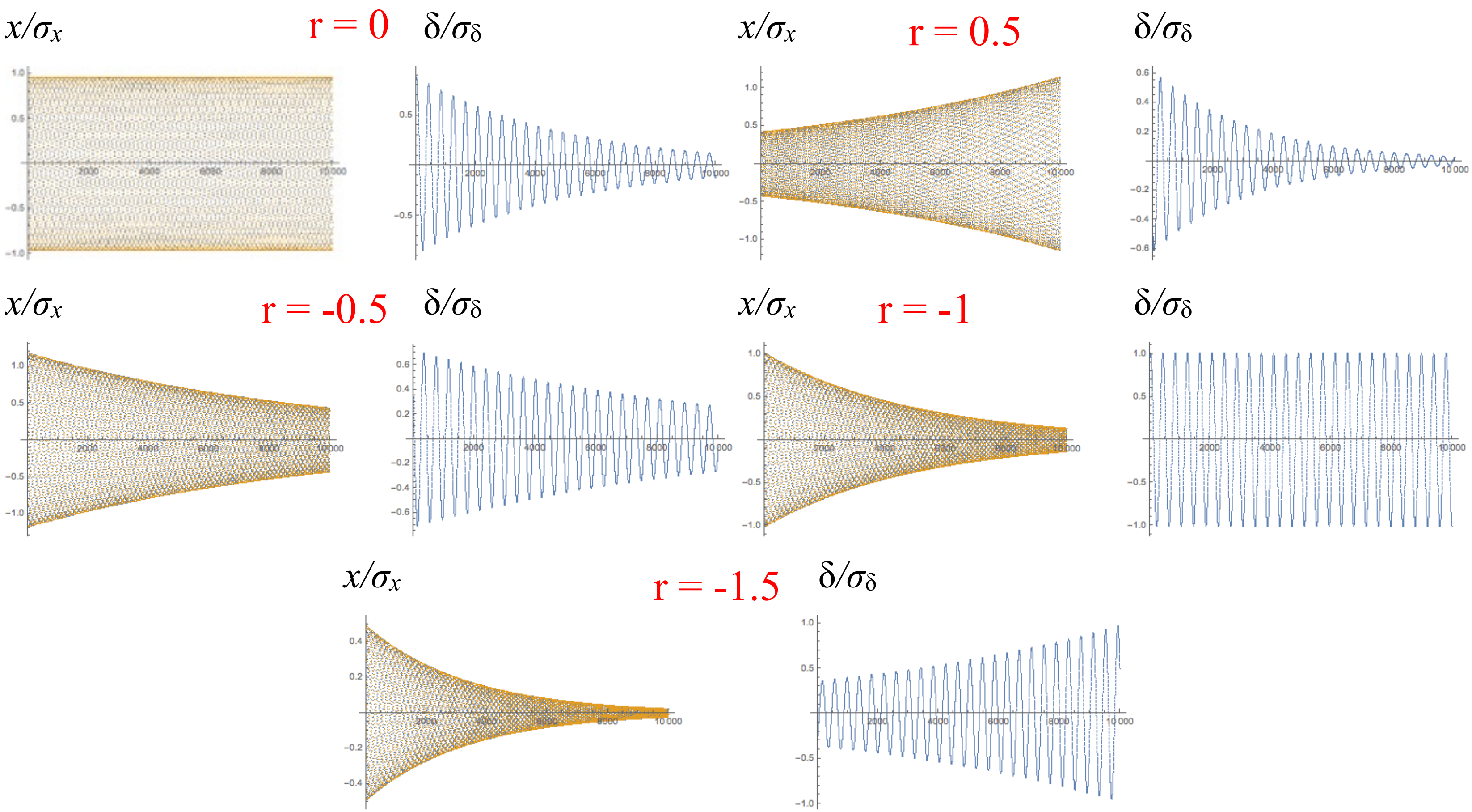
$$\mathrm{Re}\,\xi_1 = -\frac{D\zeta_1 + D'\zeta_2}{1+|\alpha|^2};\mathrm{Re}\,\xi_2 = -|\alpha|^2\frac{D\zeta_1 + D'\zeta_2}{1+|\alpha|^2}.$$

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

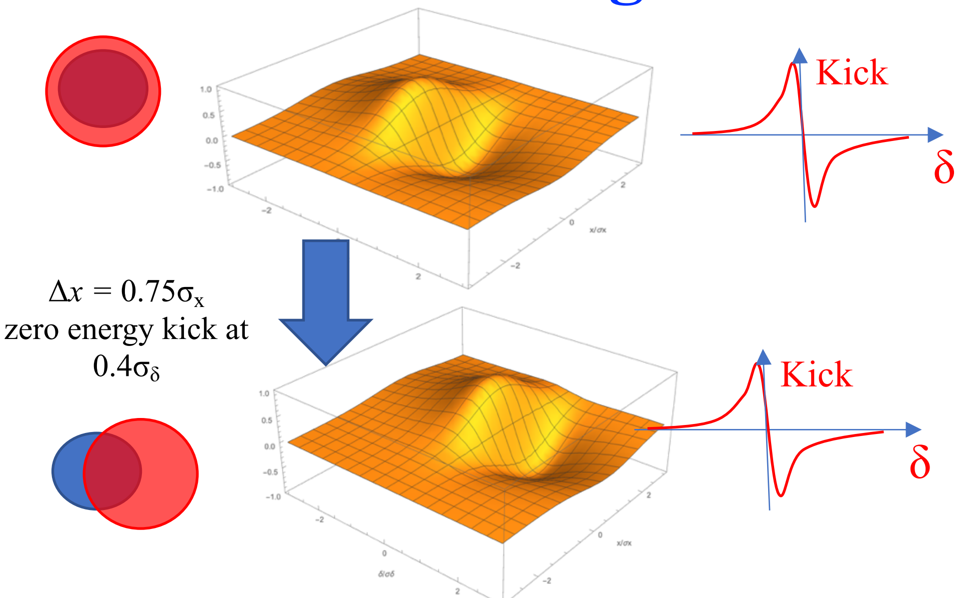
Distribution of cooling between longitudinal and transverse degrees of freedom – linearized kick

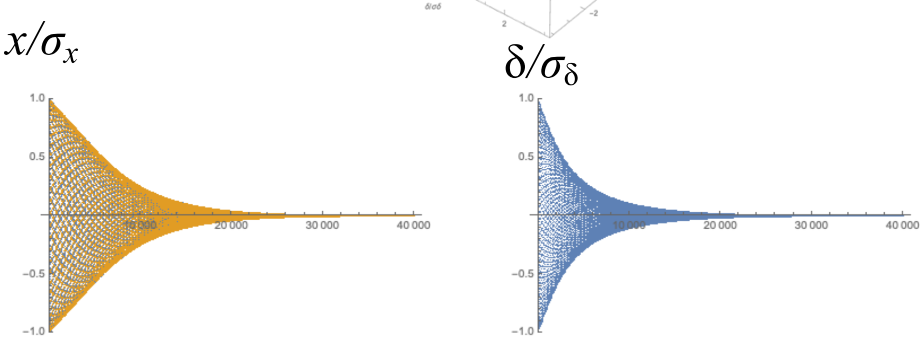
$$\frac{\delta E_h}{E_o} = const - \zeta_1 x - \zeta_6 \frac{E_h - E_o}{E_o}; \quad r = D\zeta_1 / \zeta_6$$

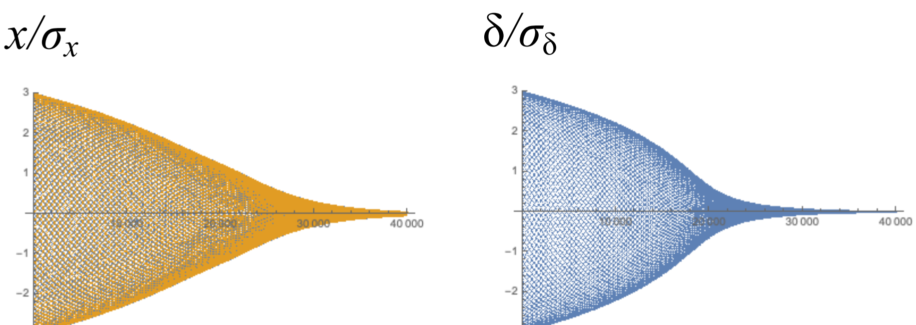




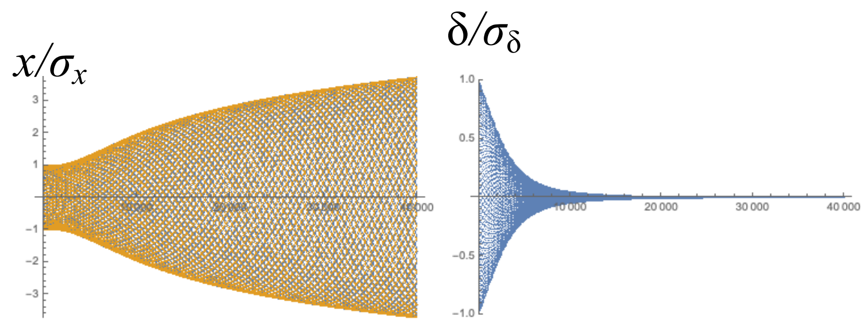
Distribution of cooling between longitudinal and transverse degrees of freedom – real kick



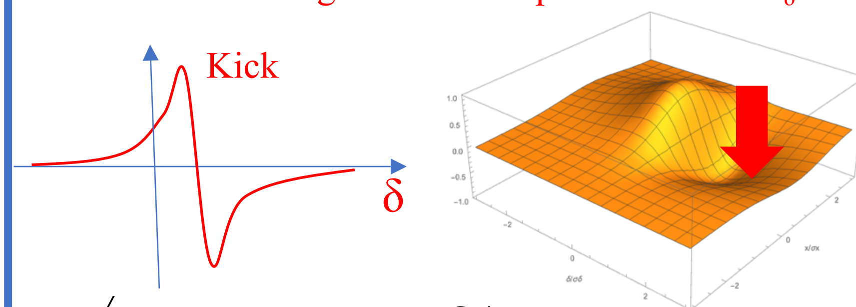


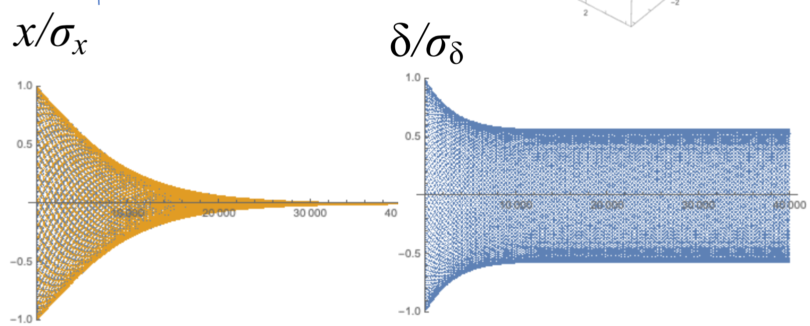


Wrong sign of displacement
$\Delta x = -0.75\sigma_x$



Excessive shifting of zero-kick point to $\delta = 0.6\sigma_\delta$



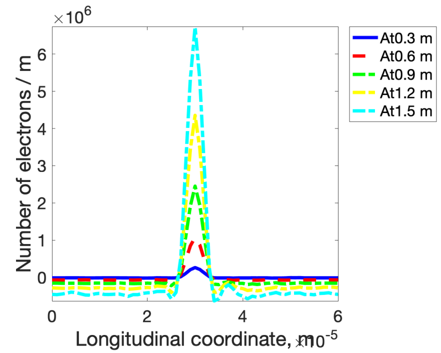


Sensitivity studies using code SPACE

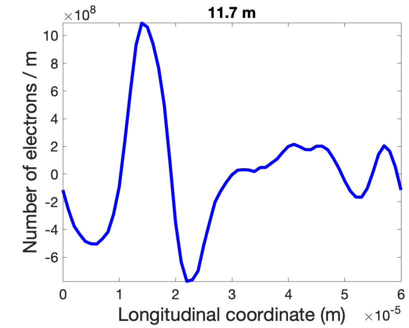
- Real electron beams are complex and imperfect. We are performing sensitivity studies of the PCA to various parameters of the beam as well as to the beam optics .The process is long and tedious with final goal to simulate PCA and CeC performance for measured beam parameters
- **We already found that PCA-based CeC required beam quality better than that sufficient for FEL-based CeC. The most stringent requirements are on the beam emittance ($\varepsilon_n \leq 3.5$ mm mrad) and energy spread ($\sigma_E/E \leq 0.08\%$)**

Single ion (ε_n=2.5 μm case)

Modulator: Peak 6 x 10^6 e/m



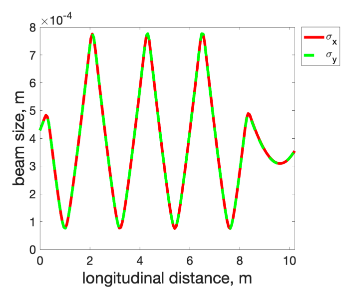
Kicker: Peak 1.1x 10^9 e/m

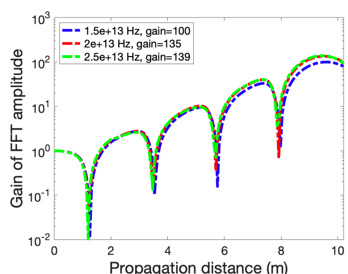


PCA gain dependence on peak current

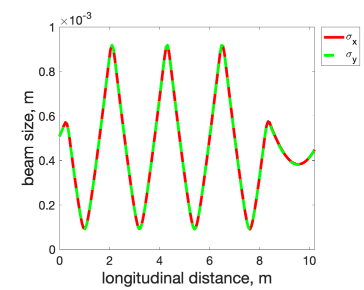
Parameter	
Species in RHIC	Au^{+79} 26.5 GeV/u
Electron energy	14.56 MeV
Charge per electron bunch	0.6 nC - 2 nC
Peak current	50 -100A
Normalized beam emittance (core)	**< 3.5 mm mrad**
RMS energy spread, (core)	**Core < 0.08%**
Repetition rate	78.17 kHz
CW beam current	~160 µA

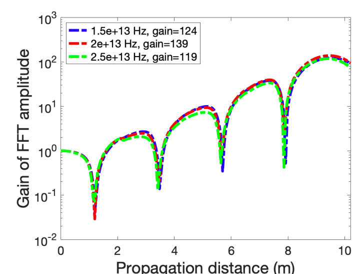
I_p=50 A



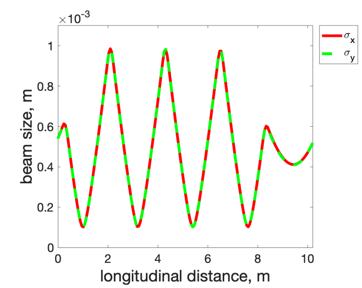


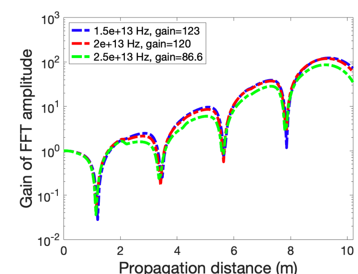
I_p=75 A





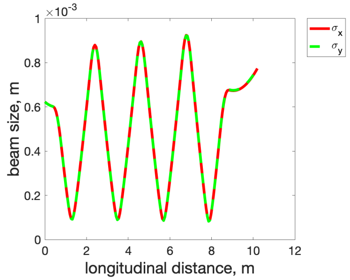
I_p=100 A

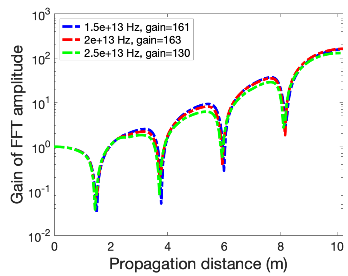


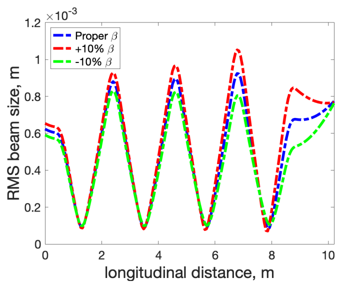


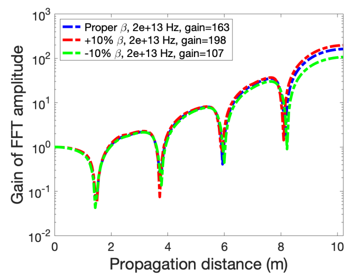
PCA performance as function of beam emittance, energy spread and optics mismatch for the beam with 75 A peak current

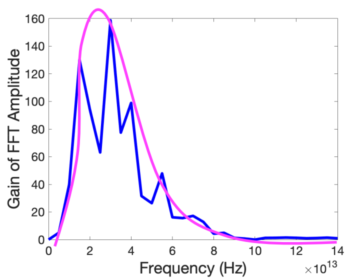
ε_n=1.75 µm (KV 7 µm)

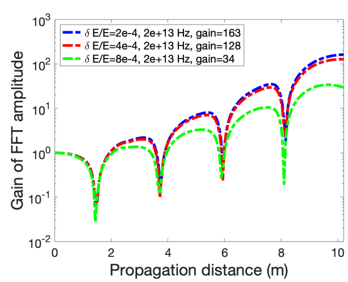






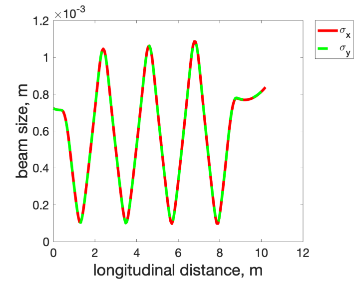


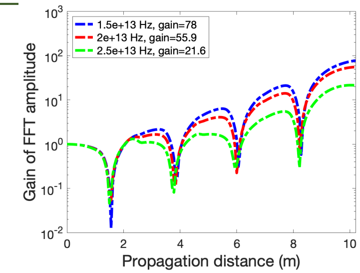


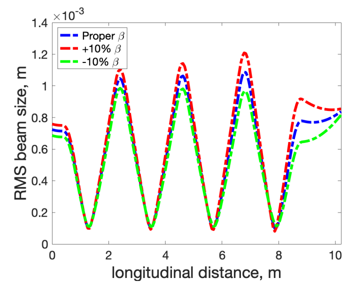


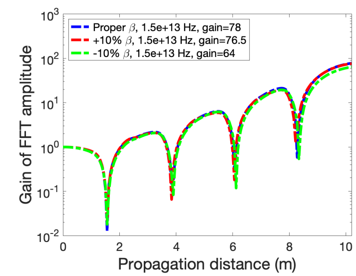
This is what we plan to have

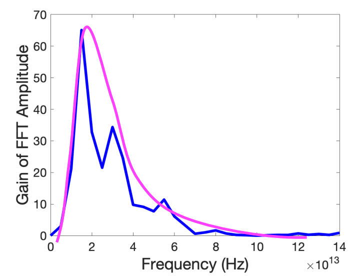
ε_n=2.5 µm (KV 10 µm)

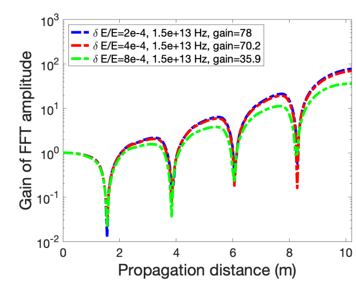




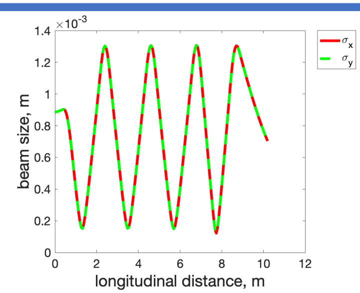


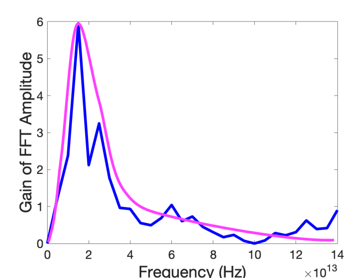




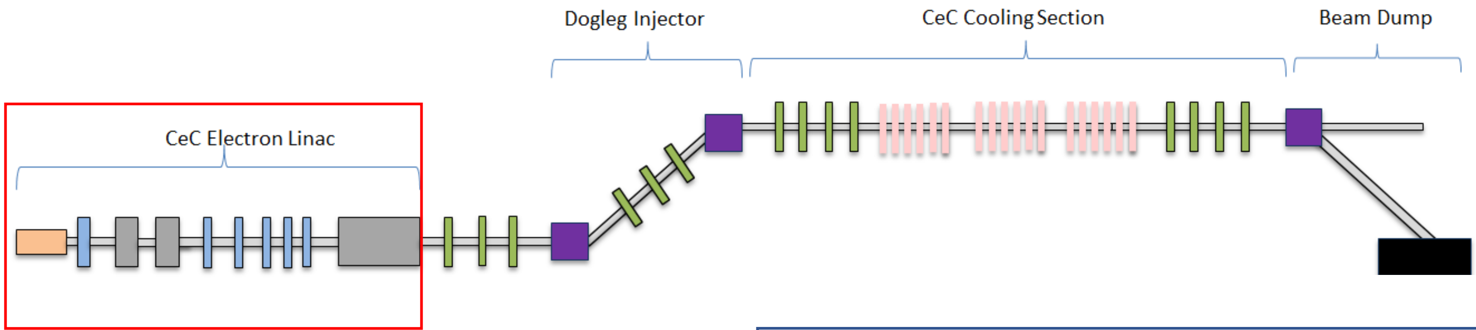


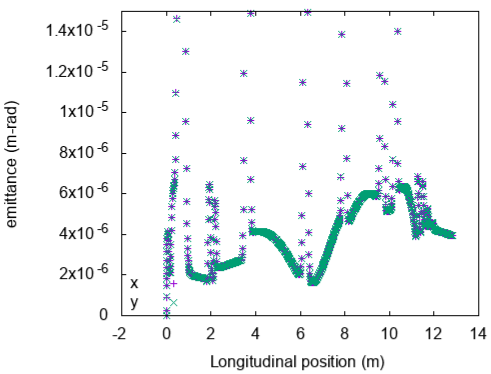
ε_n=5 µm (KV 20 µm) sets the limit at 75 A

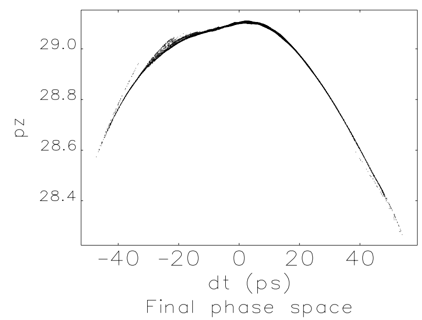


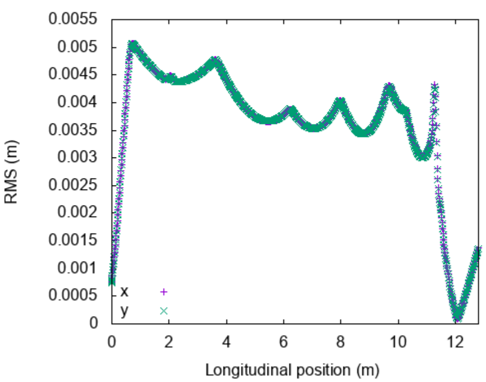


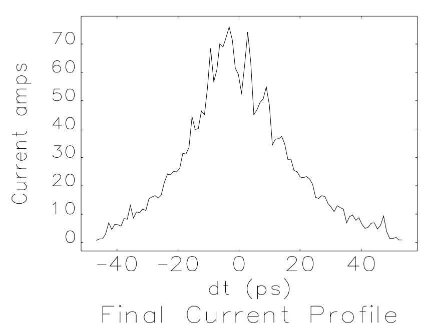
Low Energy Beam Transport Optimization

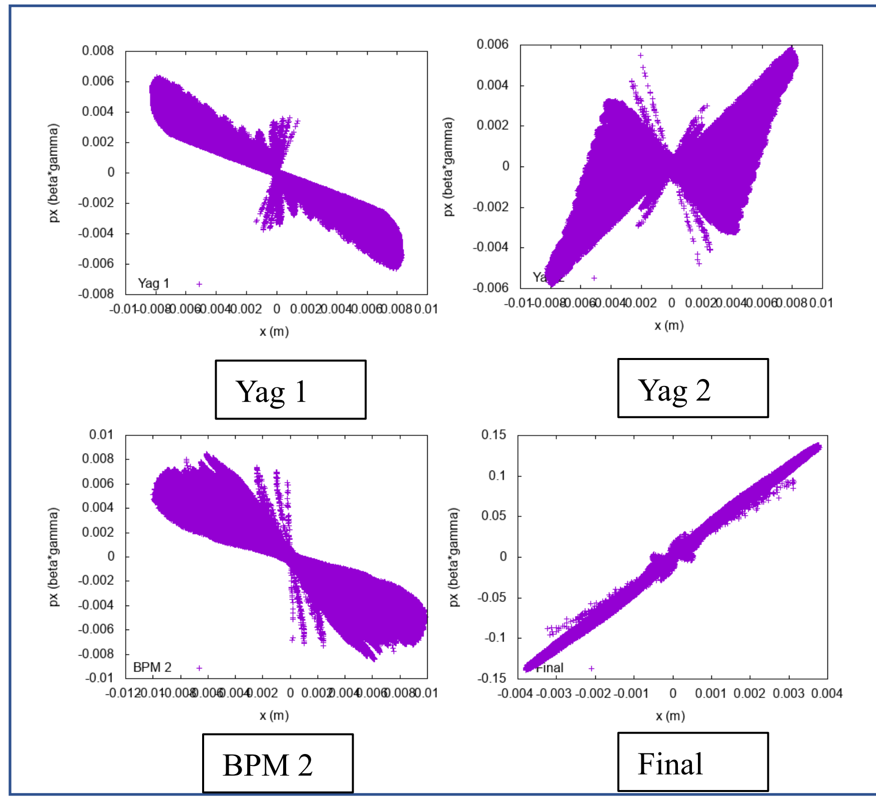












Proposed plan for experimental demonstration of PCA-based CeC

- 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

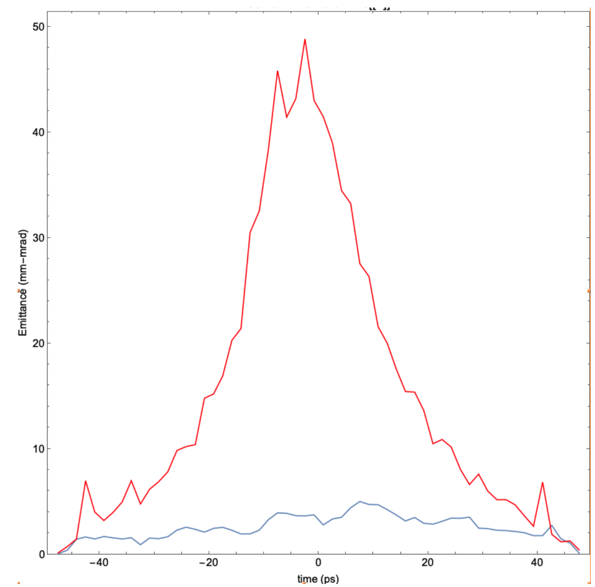
- Unsuccessful attempt of observing imprint during had a very solid explanation – very high level of noise in electron beam dwarfing the ion imprint.
- This result has nothing to do with validity of FEL-based CeC - it was and still valid.
- Small aperture of CeC FEL wigglers was incompatible with aperture requirements for for low energy RHIC operation during the Beam Energy Scan (BES-II) program – 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 ions with any 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

Back-ups

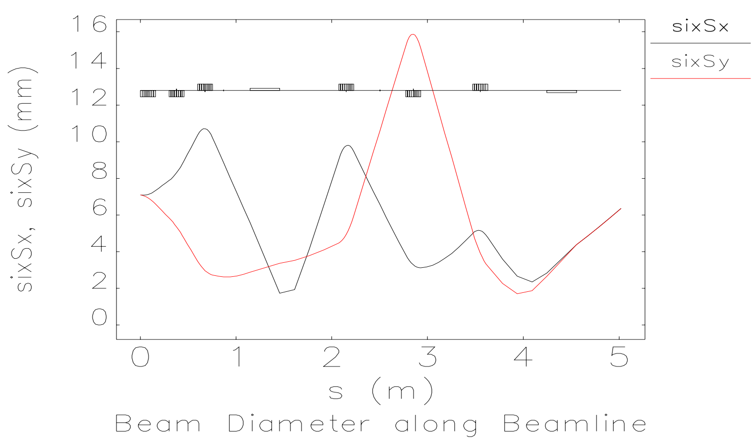
- Show Jun Ma’s movies of 3D evolution in PCA

Beam dynamics

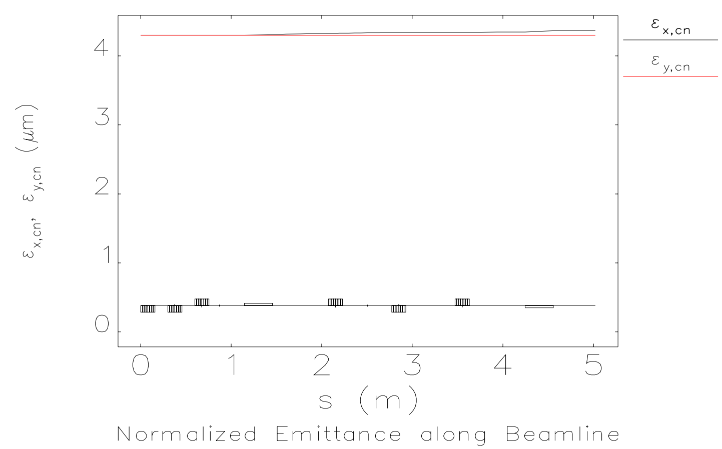
- We use large suit of accelerator and EM codes to simulate beam dynamics: *elegant*, Impact-T, GPT, ASTRA, PARMELA, MAD-X, AC3P, CST, Echo-3D, ABCI, CSR-track, SPACE, VORPAL…
- We simulated wake-functions for all components of CeC accelerator and use it for final simulation. We also include CSR and space charge effects in simulations. Most detailed simulation require weeks and weeks of simulations using super-computers
- **We developed relatively high confidence in prediction of specific effect by specific codes: it is definitely not true that all codes can reliably simulate all aspects of beam dynamics**
- Favorable comparison with the experimental is the ultimate test of trust in simulations and their prediction. Our present diagnostic is very limited
- We are trying to use linac and dog-leg for semi-time-resolved diagnostics, but interpretation of the results, even when possible, is very convoluted. We need a real time-resolved diagnostics beamline



Impact-T simulation of the bunch profile and normalized slice emittances at the exit of the SRF linac

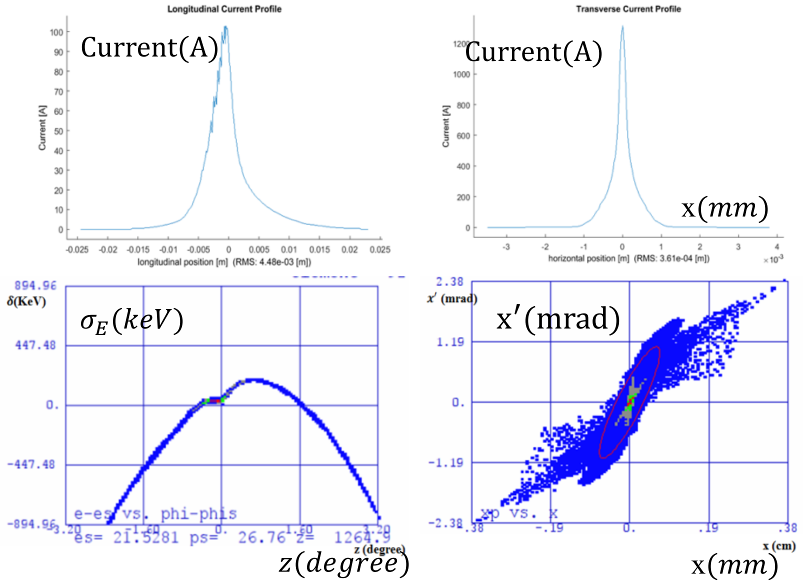


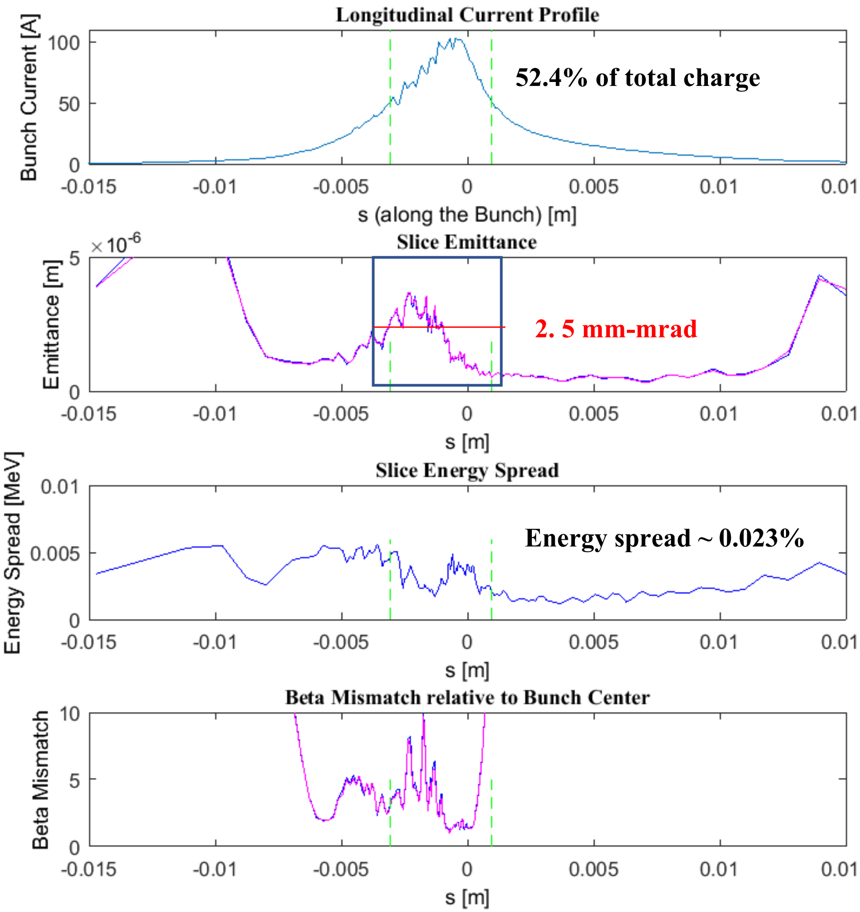
Matching round-to-round beam from the exit of the SRF linac to the entrance of the PCA-based CeC with quadrupoles in the matching section and achromatic dog-leg using *elegant*



Simulation of the CSR effect on the beam emittance passing the e dog-leg with *elegant*

Nearly Optimized Electron Beam





Number of Particles: 200002 Charge: 2 nC
Position: 0 m Beam Energy: 21.528 MeV

FWHM (distance between green bars): 4.03e+03 μ m (13.4 ps)
Charge within FWHM: 52.4 %
Projected Emittance: $\gamma\epsilon_x$ = 3.83e-06 m $\gamma\epsilon_y$ = 3.82e-06 m
Optics @ I_{peak}: α_x = -2.77 β_x = 0.986m α_y = -2.7 β_y = 0.955m

RMS Values for all Particles:

```
x = 3.61e-04 m   x' = 5.49e-04
y = 3.56e-04 m   y' = 5.47e-04
s = 4.48e-03 m   δ  = 5.10e-03
```

RMS Values within FWHM:

```
x = 2.89e-04 m   x' = 5.87e-04
y = 2.84e-04 m   y' = 5.85e-04
s = 1.05e-03 m   δ  = 7.85e-04
```

α_x	β_x	α_y	β_y
-1.94	1.44m	-1.91	1.41m

- Projected emittance within FWHM is 3.56 mm-mrad, slice emittance is close to the our nominal setting of 2 to 3 mm mrad
- Energy spread ~ 0.023%
- Peak current is 100 Amperes

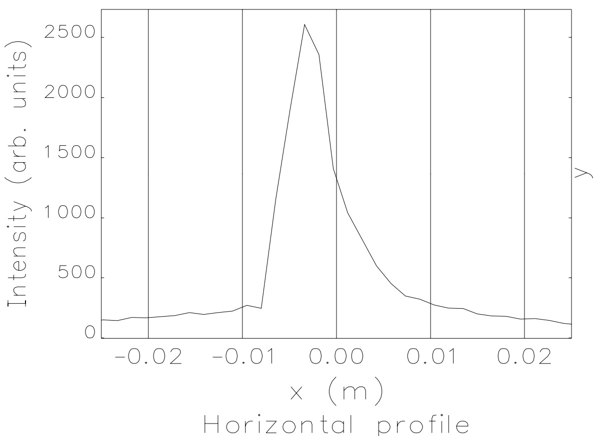
© Y.H. Wu

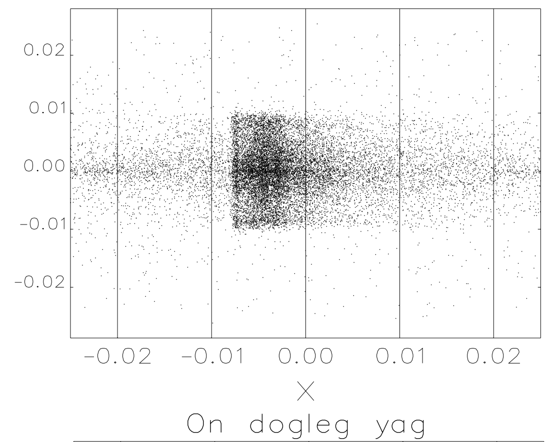
Comparison of measurements and simulations (long.)

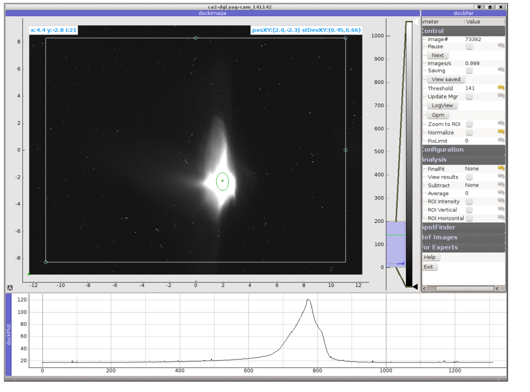
To check beam's longitudinal distribution, we need to propagate beam to yag in dogleg where dispersion function will couple energy variation to horizontal displacement. In addition, we vary the linac's phase to compare the bunch pattern on dogleg yag with simulation.

Linac phase

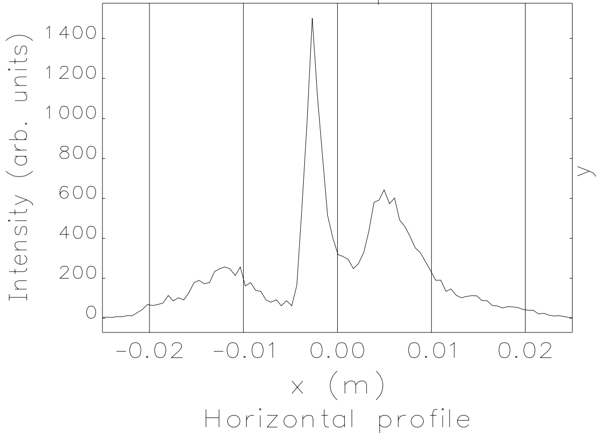
0 deg

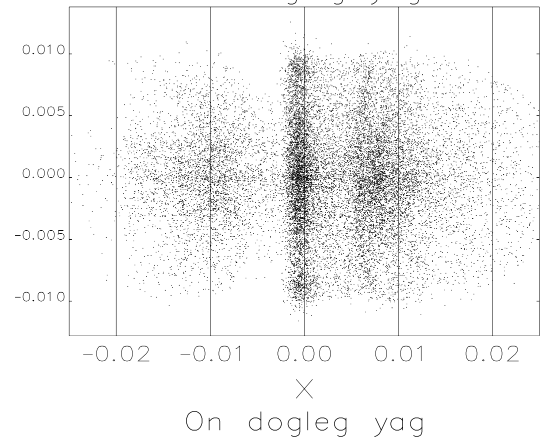


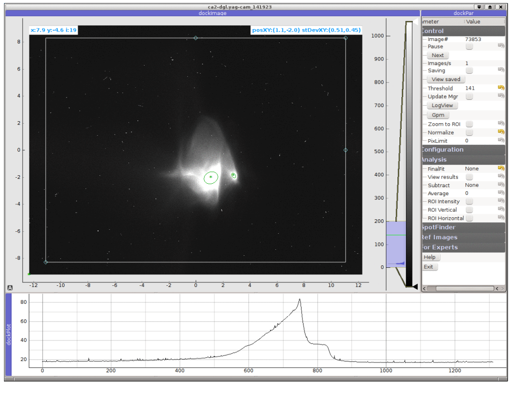




-5 deg

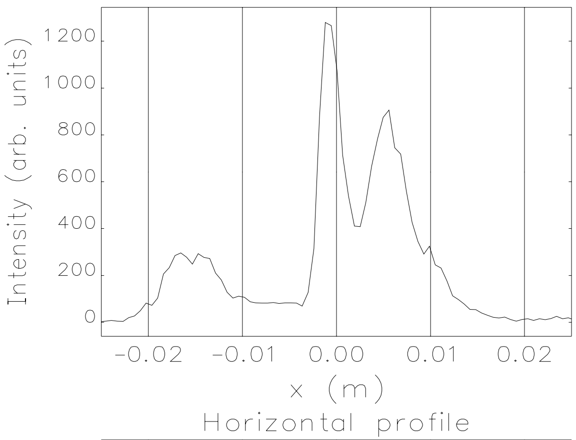


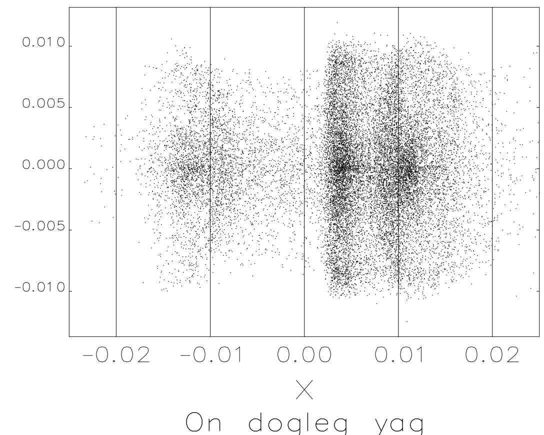


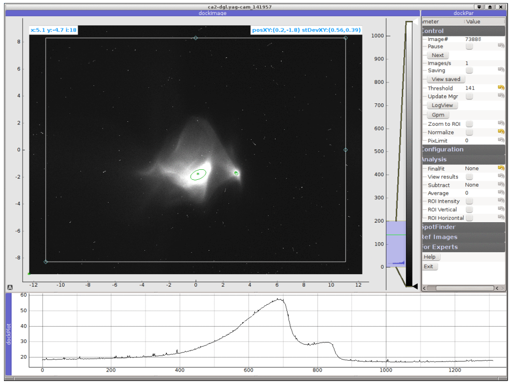


Comparison of measurements and simulations (long., cont'd)

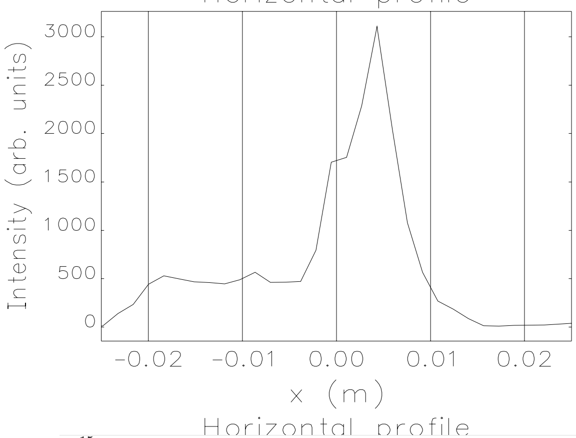
-10 deg

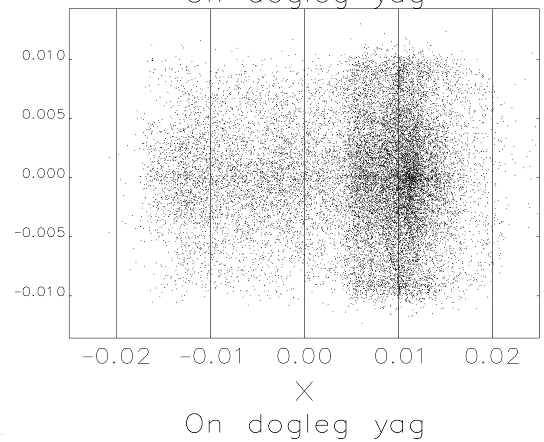


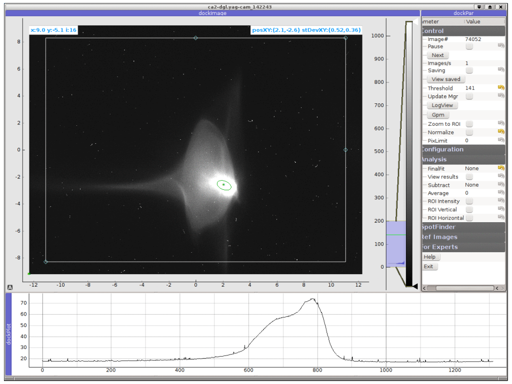


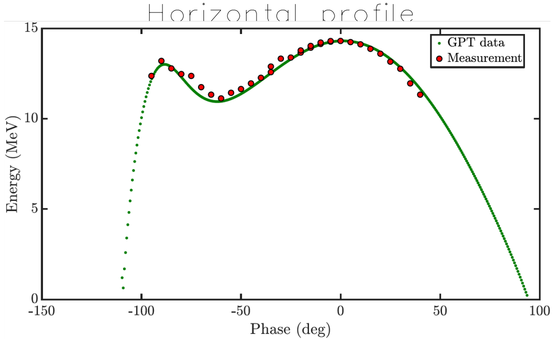


+10 deg









The asymmetry in RF phases, i.e., +10 deg and -10 deg has difference pattern can be visualized from energy gain RF phase dependency.

SR radiation and IR detector sensitivity

- IR power is measured by a very slow AC pyroelectric detector, which is calibrated for periodic 100 msec pulses separated by 100 msec: 2.12×10^6 V/W
- We cross-calibrated it for shorter 1.5 msec to 6.5 msec pulses (trains less then 600 bunches)
- We operated CeC accelerator short 100 to 500 bunch trains repeated typically with 10 Hz and used lock-in amplified. We cross-calibrated the lock-in amplifier output for such signal to be $(4\pm0.4)\cdot10^5$ V/W
- Power reaching the insertable the 1” Cu mirror was calculated using Igor-Pro for beam in a measured magnetic field of the 45-degree dipole operated at 140 A – it was is very good agreement (within 10%) with analytical estimations
- We expected that 1.4 mm x 1.4 mm metal mesh installed at he exit window has ~ 50% transparency
- With 50% reaching IR detector we expected 10-15 V/A locking amplifier signal. With typical 1.5 µA beam current, we expected signal ~ 20 µV (~ 50 pW power)
- This expectations are in reasonable agreement with the measured level of radiation from relaxed beam

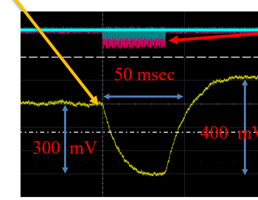
THZ-I-BNC

SPECIFICATIONS

	THZ5I-BL-BNC
MAX AVERAGE POWER	140 µW
EFFECTIVE APERTURE	5 mm Ø
INTEGRATED MODULE	Analog (BNC)
MEASUREMENT CAPABILITY	
Spectral Range [a]	
Frequency	0.1 - 30 THz
Wavelength	3000 - 10 µm
Max Measurable Power	140 µW
Noise Equivalent Power [b]	1.0 nW [1.0×10^{-9} W/(Hz)$^{1/2}$]
Rise Time (0-100%)	≤ 0.2s
Sensitivity (Typical) [b]	70 kV/W
Chopping Frequency	5 Hz (Required)

Pyroelectric detector

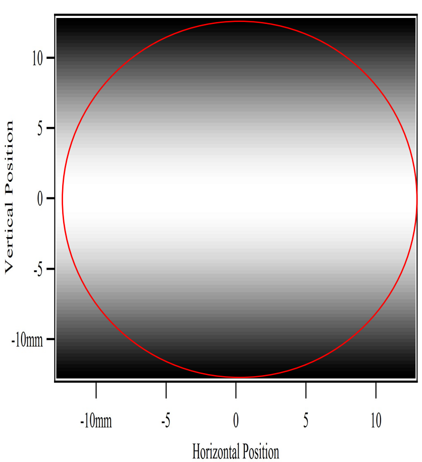
The range from 0.1 to 30 THz (10 µm – 3 mm)

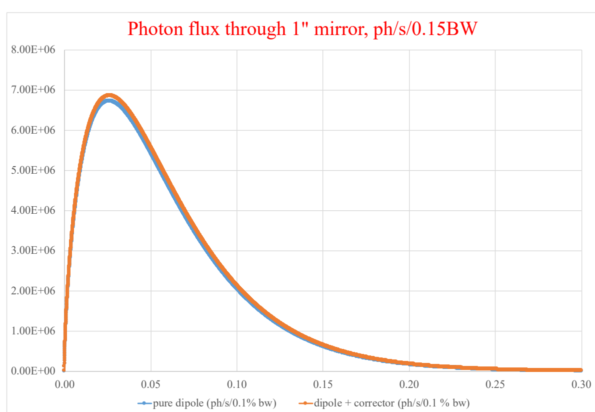


Response : 2.12 mV/nJ

Resolution of the system: ~0.1 nJ

Noise equivalent: 0.6 nW/Hz$^{1/2}$





gentec-eo

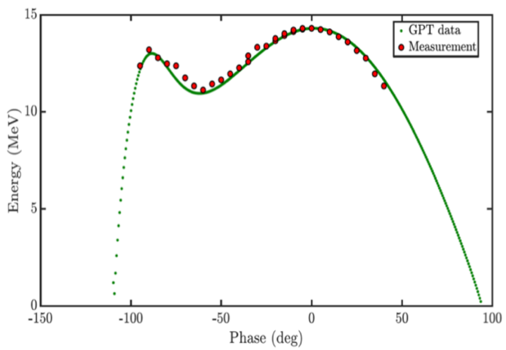
Certificate #: 506449-171103
Model Number: THz5I-BL-BNC
Head Serial Number: 506449
Cal. Procedure: 100-1025

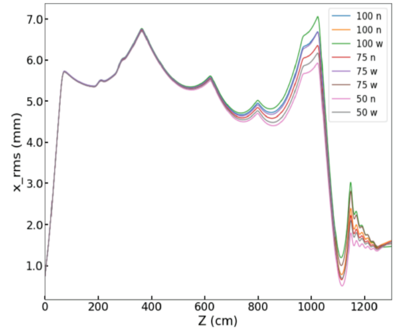
Customer Name:
Instrument ID:
Date of Calibration:
Calibration Due Date:

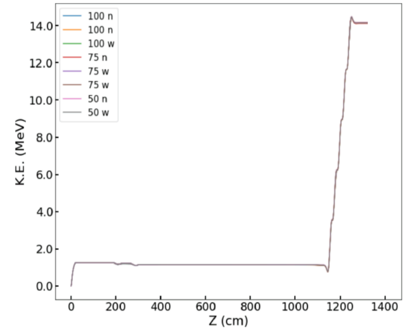
Calibration Data

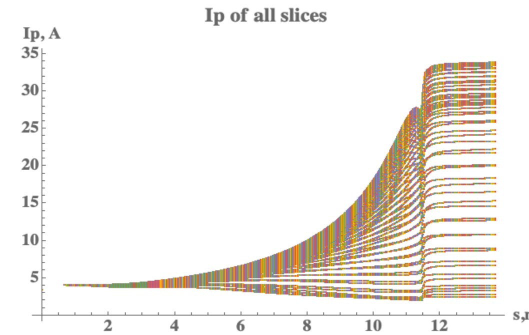
Meaurement Parameter	Sensitivity		Into Load	**Calibration** Power	Rep.Rate
@ 633 nm	V/W	%	Ω	uw	Hz
Rv (P to P)	2.12E+05	± 2.1	NA	8.2	5
Rv (RMS)	6.91E+04	± 2.1	NA	8.2	5
					Hz

SRF linac with 15 MV/m accelerating gradient has major time-dependent effects on the 1.75 MeV electron beam.









Left: Simulated (green) and measured (red dots) energy of electron beam as function of its phase at the entrance of the SRF linac; Middle – focusing of various slices in the linac and energy of the beam in CeC accelerator (SRF linac starts at 11.75 m) ; Right – bunch compression has a kink in the fist cell of 5-cell SRF linac

Proposed a dedicated diagnostic beamline is needed for accurate evaluation of electron beam

We have most of the parts, except transverse RF cavity (either build new or re-furbish 500 MHz old cavity), profile monitors system and one beam dump. Such diagnostics with resolution ~ 1 psec could be built in one year and would allow us fine tuning and comprehensive evaluation of electron beam