Coherent Electron Cooling Proof-of-Principle Experiment

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On behalf of CeC group:

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CASE Center for Accelerator Science and Education

Stony Brook University

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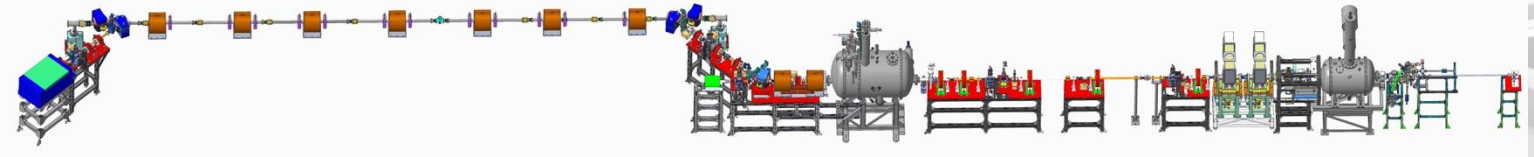

… and all people taking part in CeC project

Content

- Description of the project
- The main goal of the project
- Funding & Priority
- Results & Current status
- Future plans
- Conclusions

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Project description & its goals

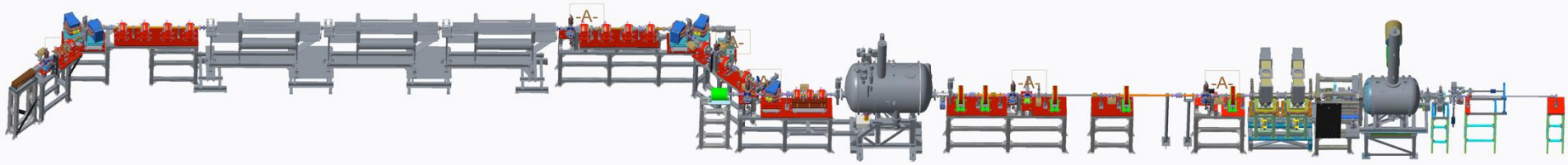
- **Project: CeC Proof-of-Principle Experiment**

Design, construction and commissioning goals

- Electron beam gun and accelerator with beam parameters sufficient for CeC demonstration (KPP)
- Common (CeC) section with a high gain FEL
- Develop CeC set-up with Au ion beam circulating in Yellow RHIC ring

Experiment goals

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



Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

Technologies and/or design concepts that address technical risks common to all concepts that must be demonstrated

- Crab cavity operation in a hadron ring
- Strong hadron cooling
- Validation of magnet designs associated with high-acceptance interaction points by prototyping
- ***High-current single-pass ERL for hadron cooling***
- ***Benchmarking of realistic EIC simulation tools against available data***
- ***Polarized ^{3}He source***

Specific R&D activities for the BNL Linac-Ring Concept

- High current polarized and unpolarized electron sources
- CeC proof of principle
- SRF high power HOM damping
- ***High-current multi-pass ERL***
- ***Concept for 3D hadron CeC beyond proof of principle***

Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

Panel priority: High, A, #3 and High, B #8 & #10

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
1	PANEL	ALL	Crab cavity operation in a hadron ring	High	A
2	PANEL	ALL	High current single-pass ERL for hadron cooling	High	A
3	**PANEL**	**ALL**	**Strong hadron cooling**	**High**	**A**
8	**PANEL**	**LR**	**Completion of the ongoing CeC demonstration (proof of principle) experiment**	**High**	**B**
10	**PANEL**	**LR**	**Concept for 3D hadron CeC beyond proof of principle**	**High**	**B**

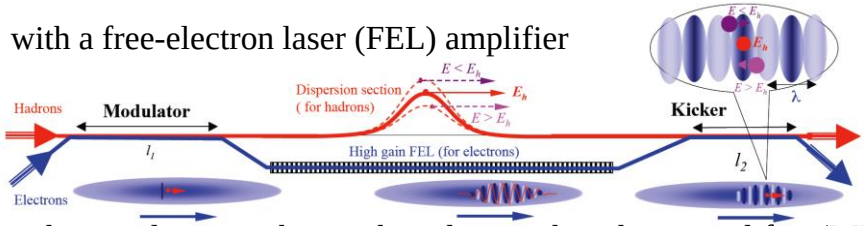
Why CeC is needed?

- High luminosity of US future electron-ion collider(EIC) is critical for success of its physics program
  - 2018 NAS Assessment of U.S.-Based Electron-Ion Collider Science states: *The accelerator challenges are two fold: a high degree of polarization for both beams, and high luminosity.*
- CeC is the most promising technique for boosting the EIC luminosity
  - 2018 eRHIC pCDR review states: *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 $10^{34}/(cm^2s)$ luminosity. Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC*

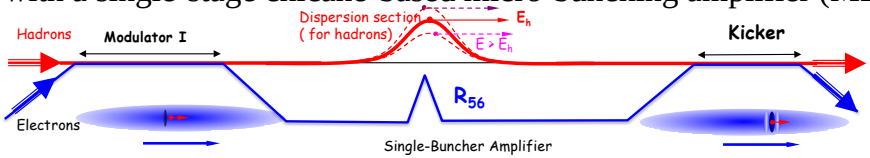
What is a CeC?
It is a stochastic cooling at optical frequencies

- All proposed CeC systems are based on the same basic scheme
- In modulator electron beam picks-up density modulation ("imprint") from individual ions
- This modulation is amplified in a broad-band high frequency amplifier (instability)
- In a kicker, ion's momentum is corrected by electric field induced in the electron beam
- Important feature of an amplifier– its frequency bandwidth
- CeC with two amplifiers: FEL and PCA does not require separating electron and hadron beams

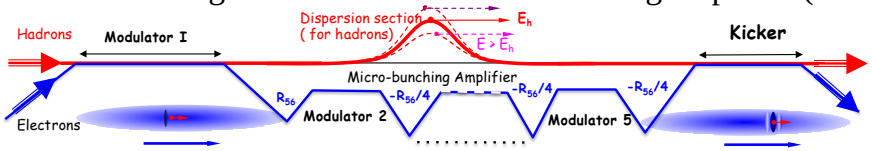
with a free-electron laser (FEL) amplifier



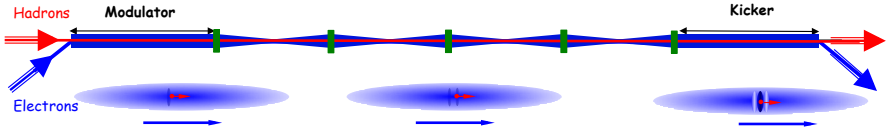
with a single-stage chicane-based micro-bunching amplifier (MBA)



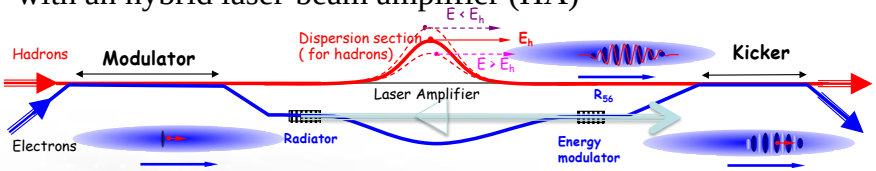
with a multi-stage chicane-based micro-bunching amplifier (MBA)



with a micro-bunching plasma-cascade amplifier (PCA)



with an hybrid laser-beam amplifier (HA)



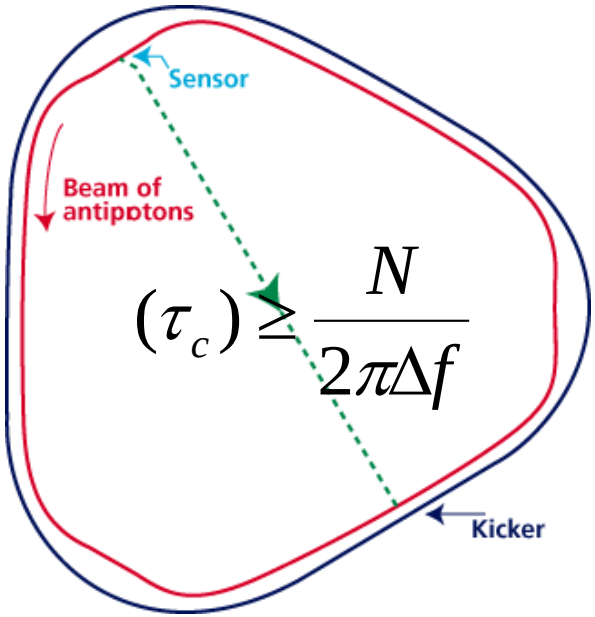
PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

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

Critical conditions for the stochastic cooler

S. van der Meer
1984 Nobel physics prize



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

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

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

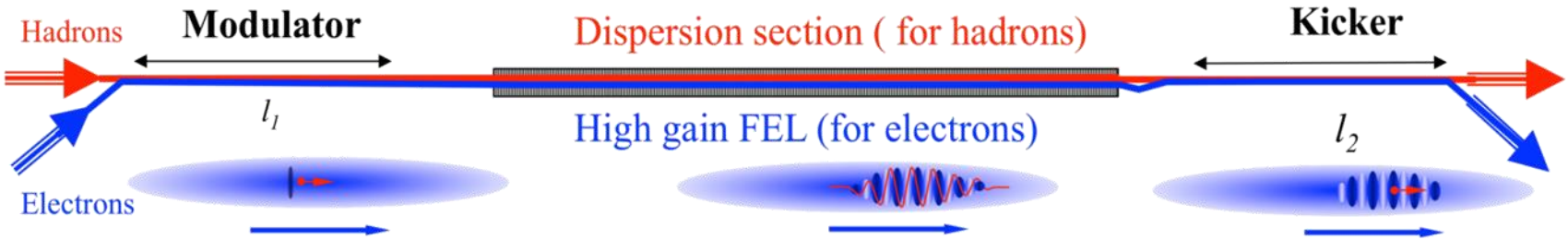
$$N_s = \frac{\dot{N}}{\Delta f} = \frac{I_{peak}}{Ze}\cdot\frac{1}{\Delta f}$$

- ✓ **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 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 proof-of-principle experiment



- By design it was a cost-effective version of CeC with FEL amplifier, which does not require expensive separation and delay system of 26.5 GeV/u ion beam
- 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

Project funding

NP FOA R&D	FY10+FY11	FY12+FY13	FY14+FY15	FY16	Totals
a) Funds allocated	1,488,000	2,690,00	1,.345,000	425,00	5,948,00
b) Actual costs to date	1,488,000	2,690,00	1,345,000	425,00	5,948,00

Lab Base R&D	FY17	Totals
a) Funds allocated	435,486	435,486
b) Actual costs to date	435,486	435,486

Other contribution from BNL, SBU, DoE BES, NSF, Daresbury Lab: $8,067,000

Main events

FY11/12
- BNL/JLab collaboration CeC PoP project based on JLab SRF accelerator received DoE NP FOA funding
- **JLab team withdraw from the project (including the gun and the SRF accelerator)**

FY13
- New CeC electron gun and accelerator had been designed
- **External CeC review endorsed the CeC design and plans**
- Main component of CeC cryo-system is installed at IP2

FY14
- CeC SRF gun is delivered and installed in IP2
- Part of the low energy beam transport is installed

FY15
- Initial commissioning of the 1.25 MeV CeC SRF gun with CsK_2Sb photocathode: 3 nC/bunch
- Damaged in-transit 704 MHz SRF linac cryo-module arrived to BNL
- FEL wigglers and vacuum system arrive to BNL

FY 16
- **Complete CeC system had been installed and passed ARR**
- 10 MeV electron beam was generated and propagated though the CeC system during RHIC Run 16
- **The full-power operation of the CeC system was approved by DoE on May 20, 2016**
- 704 MHz SRF linac cryo-module was rebuilt to eliminate SRF cavity contamination

FY 17
- The CeC system had been fully commissioned during RHIC Run 17
- 15 MeV e-beam with quality sufficient for CeC experiment was demonstrated
- New IR FEL diagnostics was procured and installed

FY18
- New (15 MeV) mode for CeC operation was established and all simulations were completed
- **15 MeV e-beam with quality sufficient for CeC experiment was re-established**
- **High gain FEL was commissioned**
- **CeC experiment ran into a previously unknown THz instability obscuring the ion imprint**
- The instability was identified and studied

Plan for RHIC Run 18

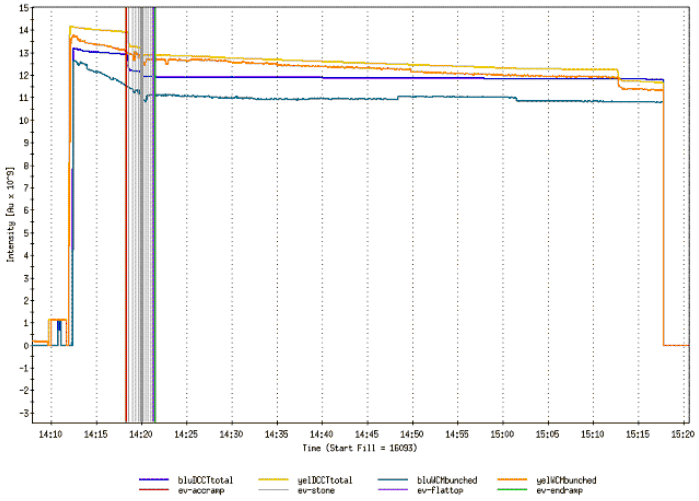
- Establish stable phase, amplitude and timing (RF and laser) to deliver stable reliable electron beam
- Commission new IR diagnostics and establish high gain FEL operation
- Align electron and ion beams transversely, synchronize electron beam with ion beam with 26.5 GeV/u
- Establish interaction of electron and ion bunches
- Tune the ion and electron beams energies using “ion beam imprint”
- Test Coherent electron Cooling
- Characterize Coherent electron Cooling

Expected deliveries if all goes well (it is R&D after all!):

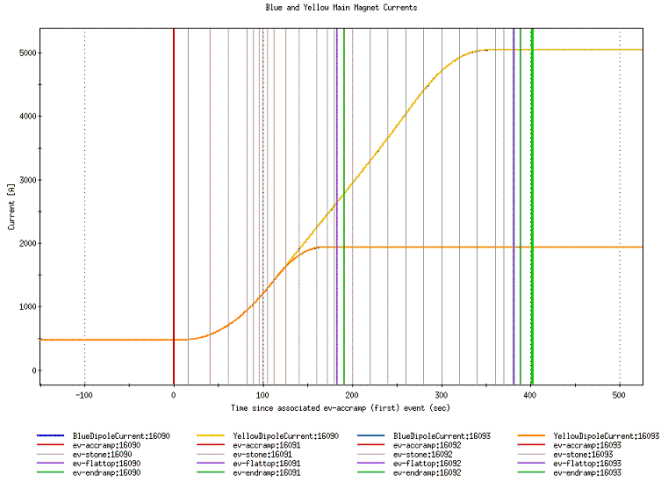
- predicted performance of CeC
- experimental demonstration of CeC
- comparison with predictions

CeC PoP RHIC Ramp & Store

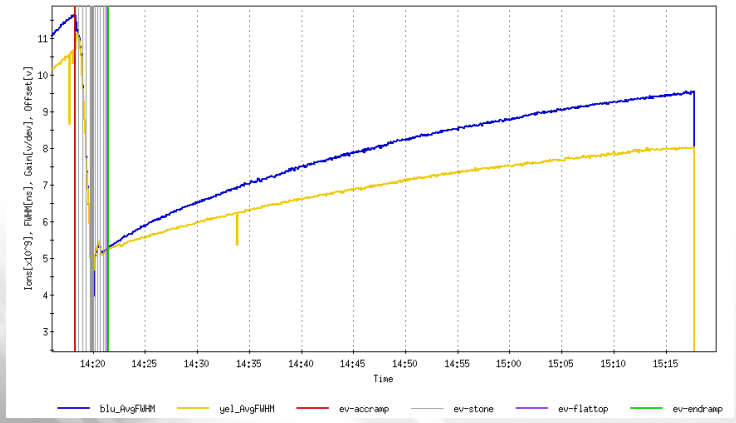
Ramp : beam intensity

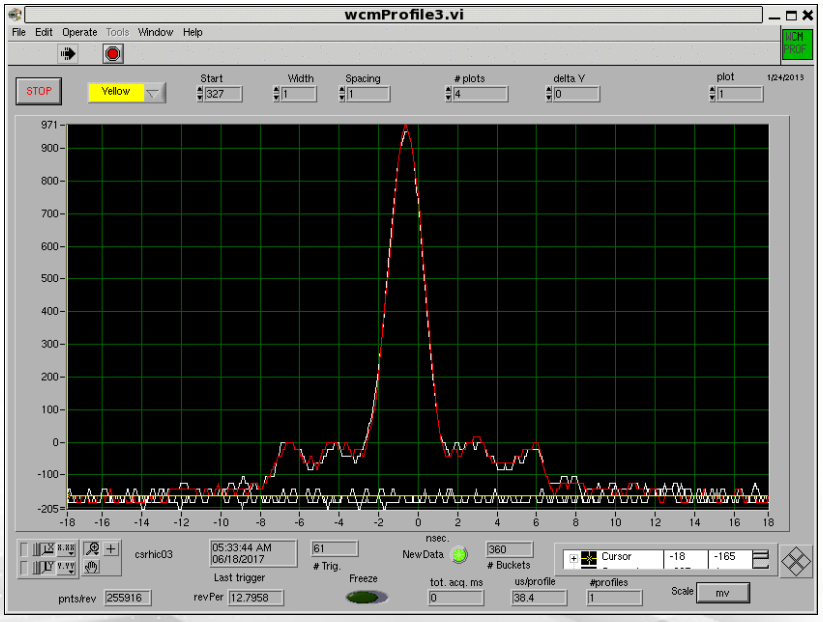


Ramp : Magnets currents



Bunch length and profiles at store

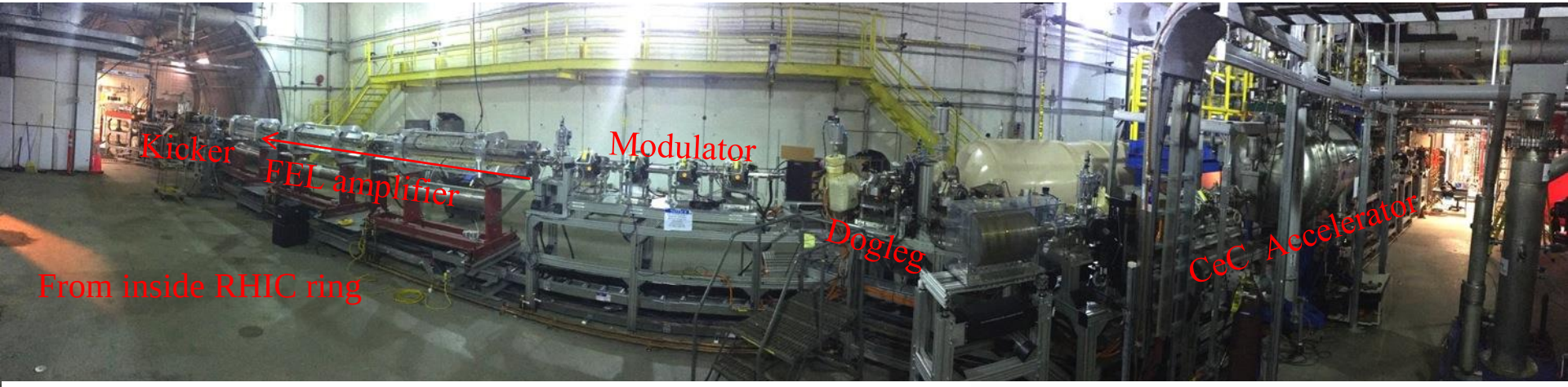




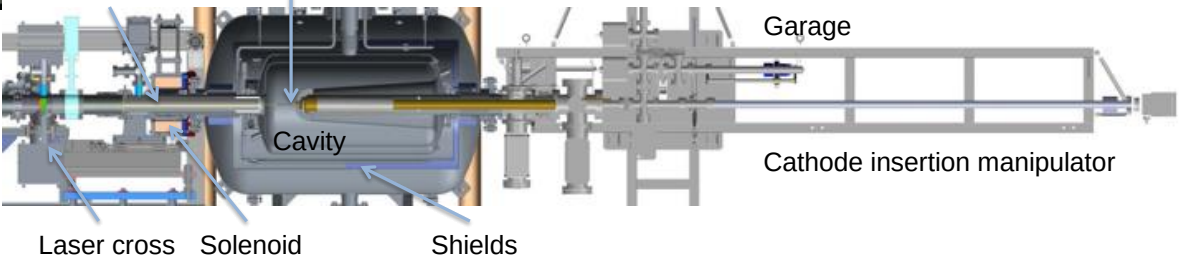
CeC Key Performance Parameters Design & Demonstration

Parameter	Design	Demonstrated	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	✓
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	3 - 5 mm mrad	✓
FEL wavelength	13 μm	**31 μm**	✓
Repetition rate	78.17 kHz	78.17 kHz	✓
CW beam	<400 μA	150 μA	✓

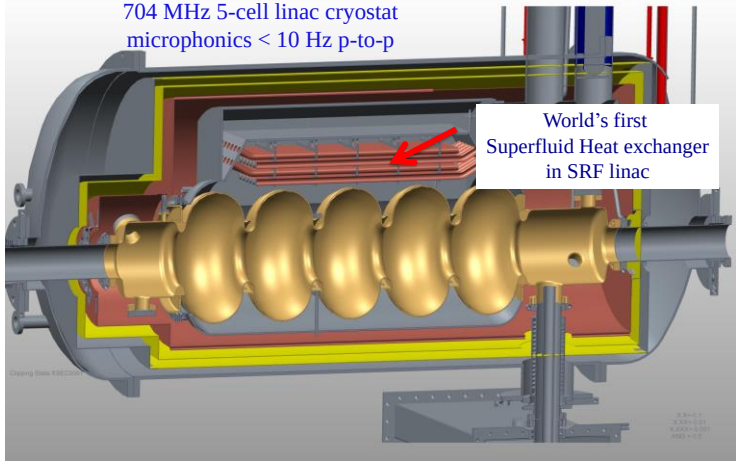
State of the art CeC system



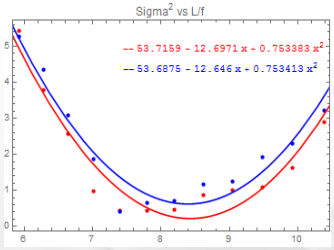
Record performing SRF Gun



704 MHz 5-cell linac cryostat
microphonics < 10 Hz p-to-p



- Quarter-wave SRF photo-electron gun
- 4 K operating temperature
- CsK_2Sb Cathode operating for months
- Up to **10.7 nC** charge per bunch
- Record low normalized emittance of 0.32 mm mrad at 0.5 nC



- quiet LiHe system
- and many more innovations in accelerator physics and technology

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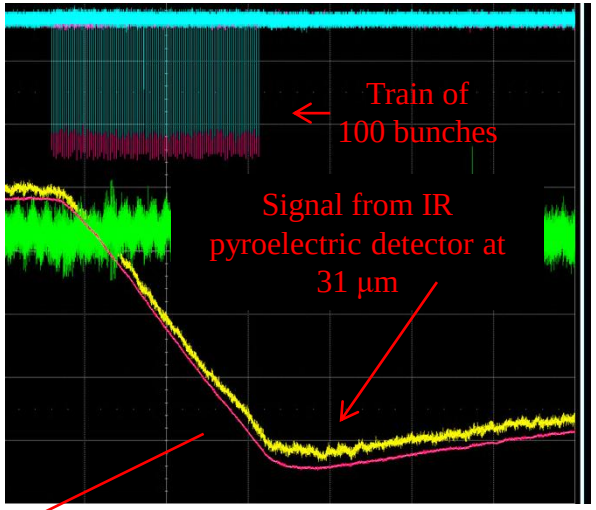
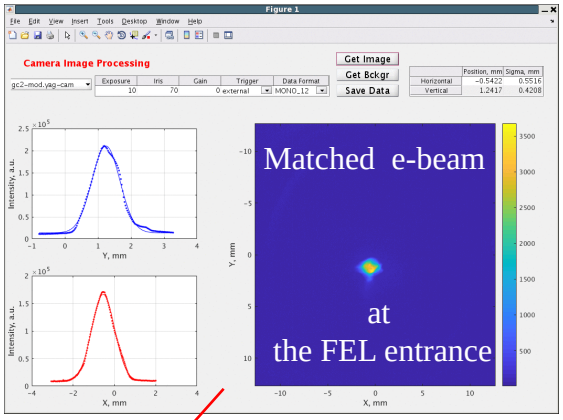
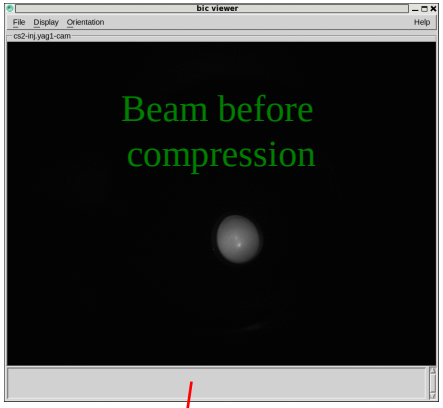
Accelerator & FEL performed well







IR diagnostics

CeC "kicker"
4 quads

CeC FEL amplifier
3 helical wigglers

CeC modulator
4 quads

Dog-leg:
3 dipoles
3 quads

13.1 MeV
SRF linac

Low energy transport
beam-line
with 5 solenoids

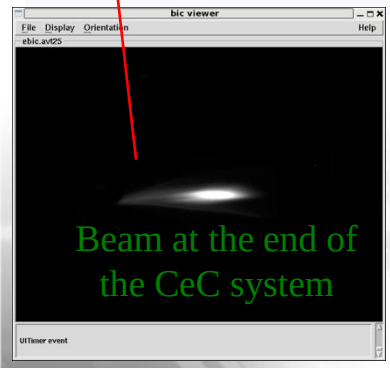
Bunching
RF cavities

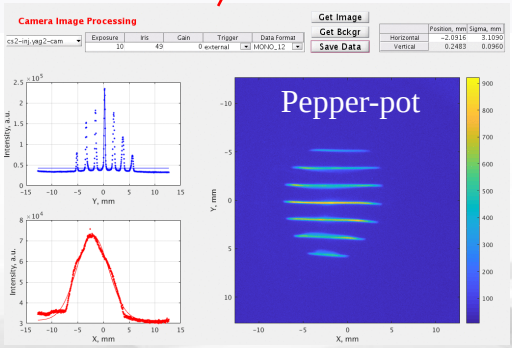
1.25 MV
SRF photo-gun

Common section with RHIC

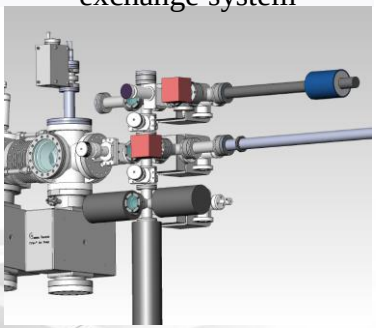
High power beam dump
1 dipole, 2 quads

Low power
beam dump



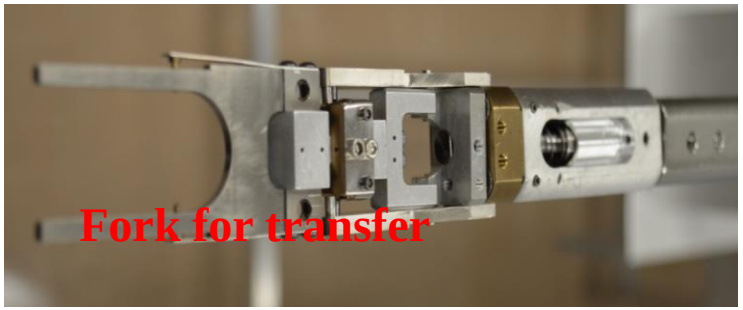


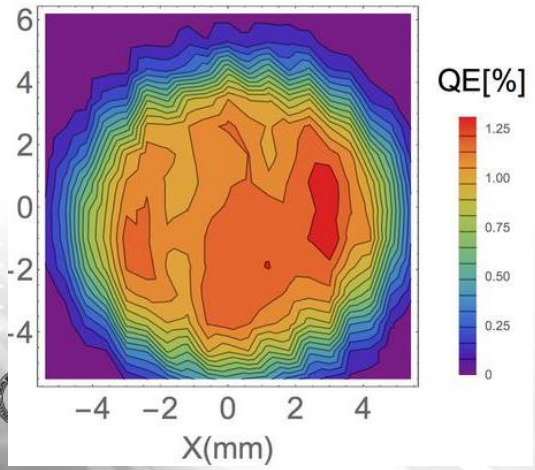
Cathode storage and
exchange system



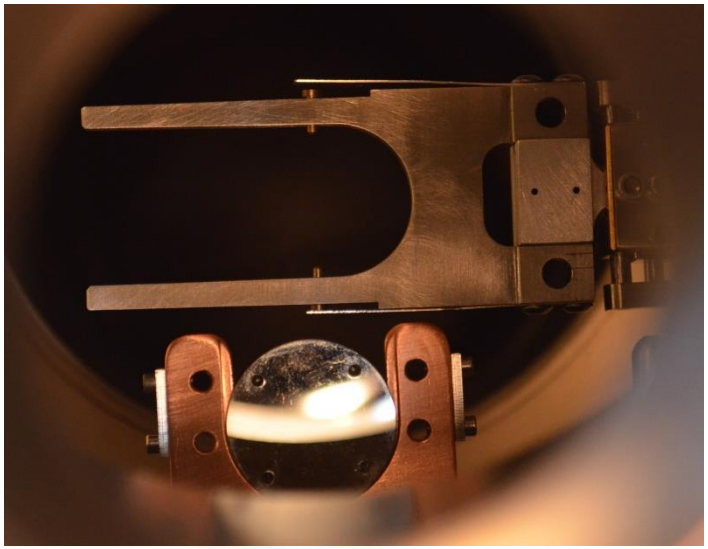
Photocathode

- The procedure for the cathode preparation was established in previous years and did not change
- NEG getters to improve vacuum
- QE monitoring system in the garage
- Cathode lifetime in the garage - months

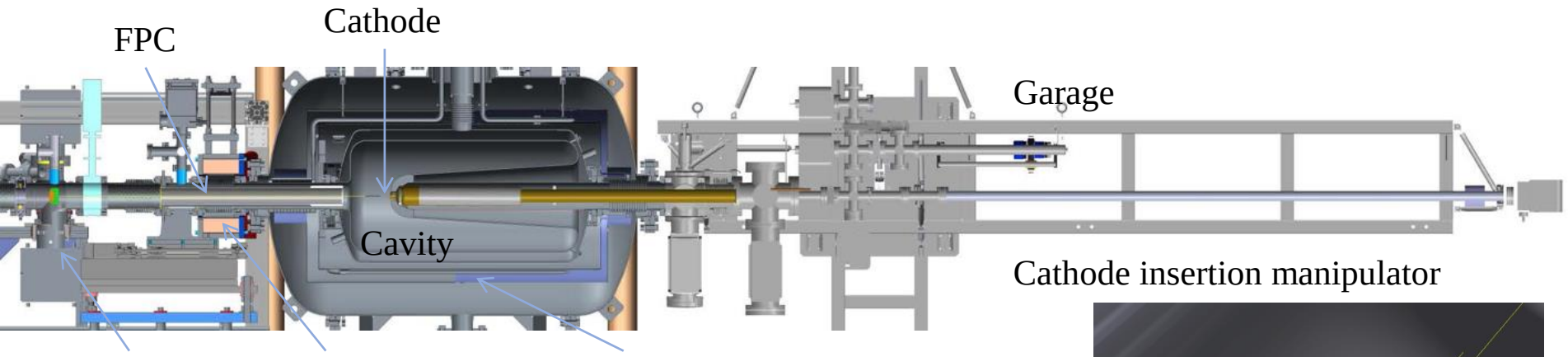


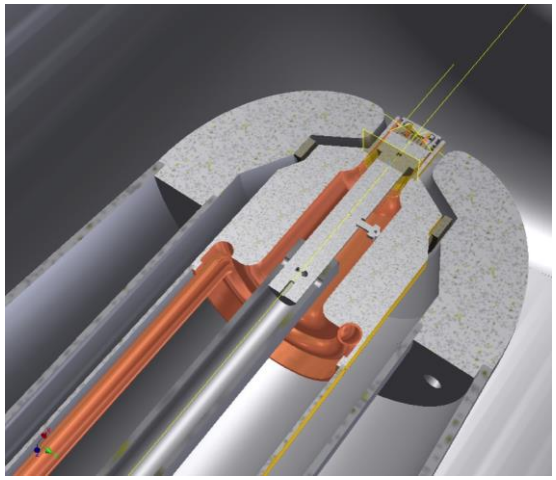


Transfer from Manipulator arm to transport suitcase



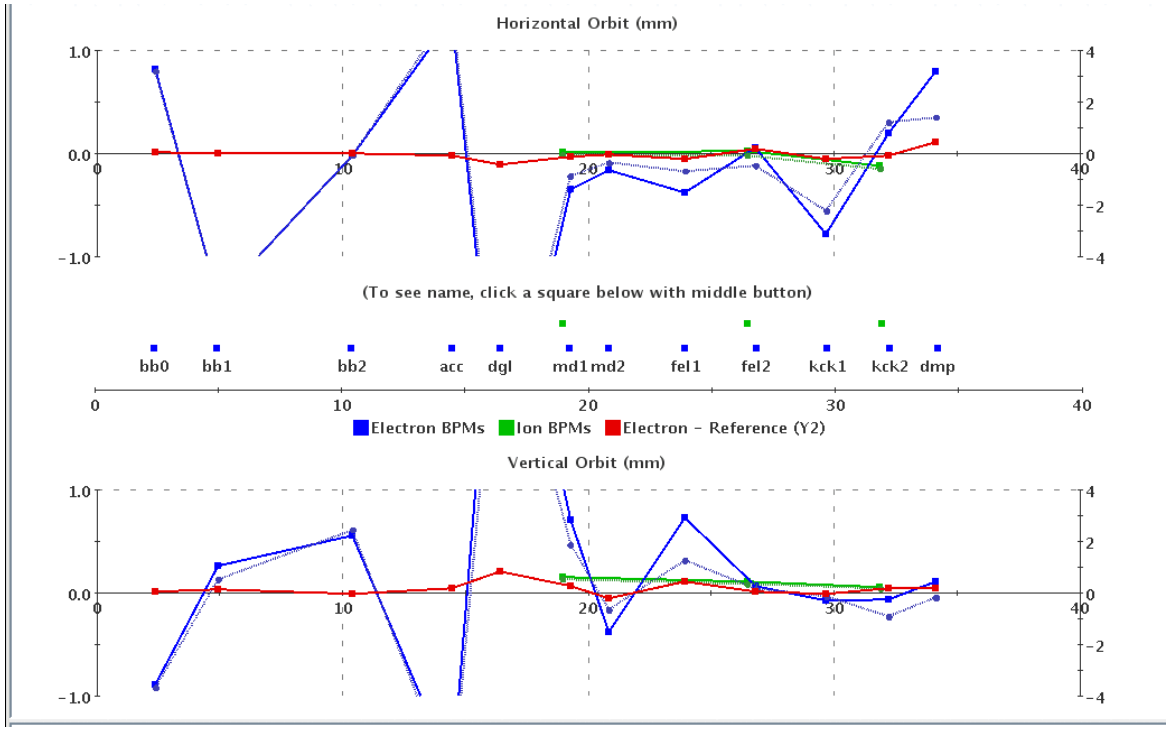
SRF Photo-Electron gun





Quarter-wave SRF 4K Nb gun cavity tuned to operation frequency
Room temperature CsK2Sb high QE photocathode inside adjustable stalk
Photocathode QE lifetime – one to two months
Nominal accelerating voltage: 1.25 MV, maximum 1.5 MV
Laser pulse duration: 100 to 500 psec
Charge per bunch – from pC to 10.7 nC
Record low normalized emittance:0.32 mm mrad at 0.5 nC
Vacuum storage & transportation suit ("garage") with three photocathod
UHV cathode manipulation system
UHV vacuum inside the SRF gun
Accurate LLRF controls
Multi-packting-free turn-on and turn-off processes

Orbit Measurement and Correction



Accuracy of the beam orbit correction ±0.1 mm
Accuracy of the quadrupoles positioning ±0.15 mm

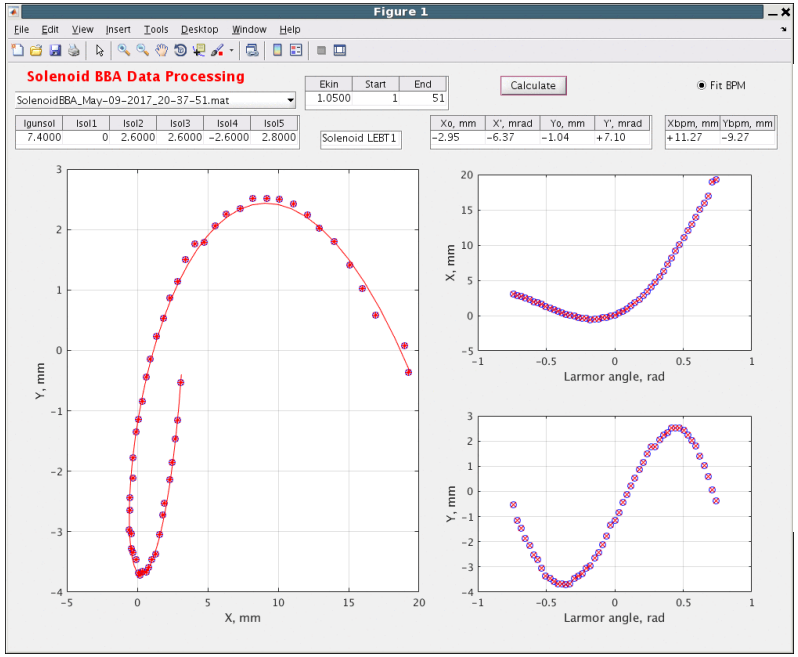
The e-beam orbit was measured using Libera Brilliance Single Pass.

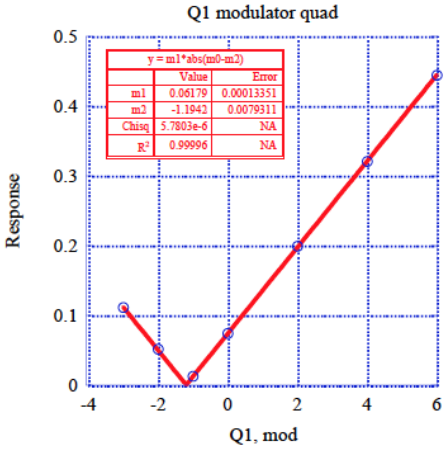
A deducted orbit correction program was used for establish and to repeat desirable orbit

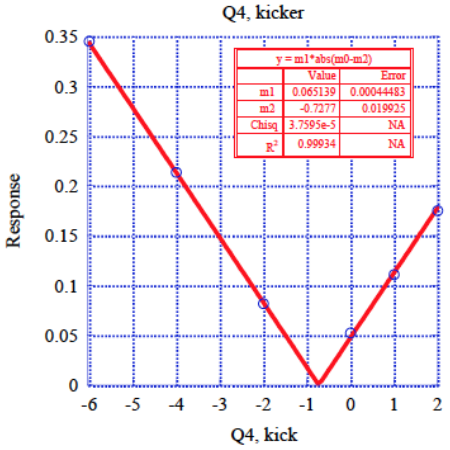
Solenoid and Quadrupole beam-based alignment were used to propagate beam along the design trajectory

The signals from three BPMs (around FEL) were split by diplexer to hadron (9 MHz) and electron (500 MHz) receivers allowing simultaneous measurement of the hadron and electron trajectories.

Beam Based Alignment
e-beam in Solenoids or Au ion beam in CeC







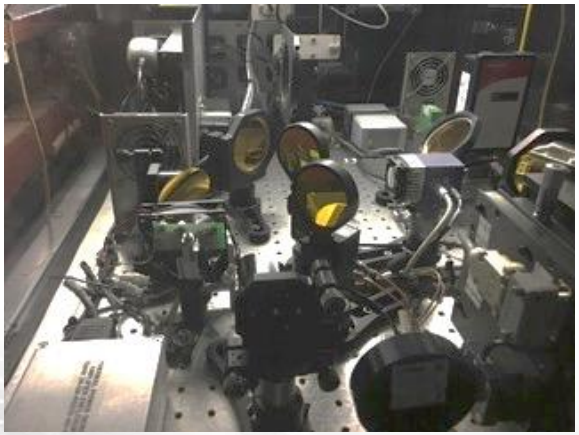
Quadrupoles in the common section were modulated and orbit variation in the RHIC was measured..

Accuracy of the ion-beam orbit ±0.1 mm

Transfer matrix is calculated for each solenoid current and beam position is measured

IR Diagnostics for 30 mm

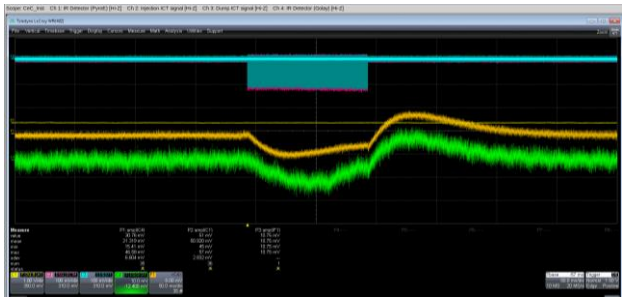
- New CVD diamond window was installed
- IR diagnostics detector system was upgraded to be sensitive at 30 mm



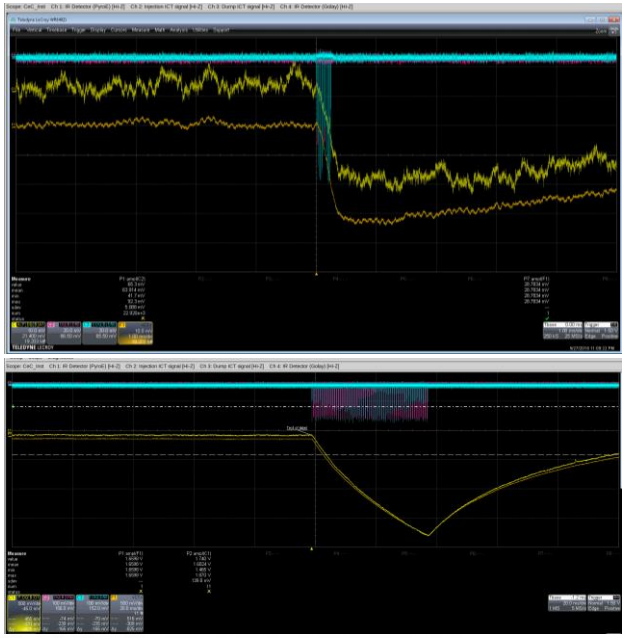
The IR diagnostics is essential for the commissioning of the CeC PoP experiment

- Aligning of the electron beam on the FEL axis
- Establishing FEL lasing/amplification
- Optimizing phasing of the FEL wigglers
- Establishing interaction with ions and fine matching energies

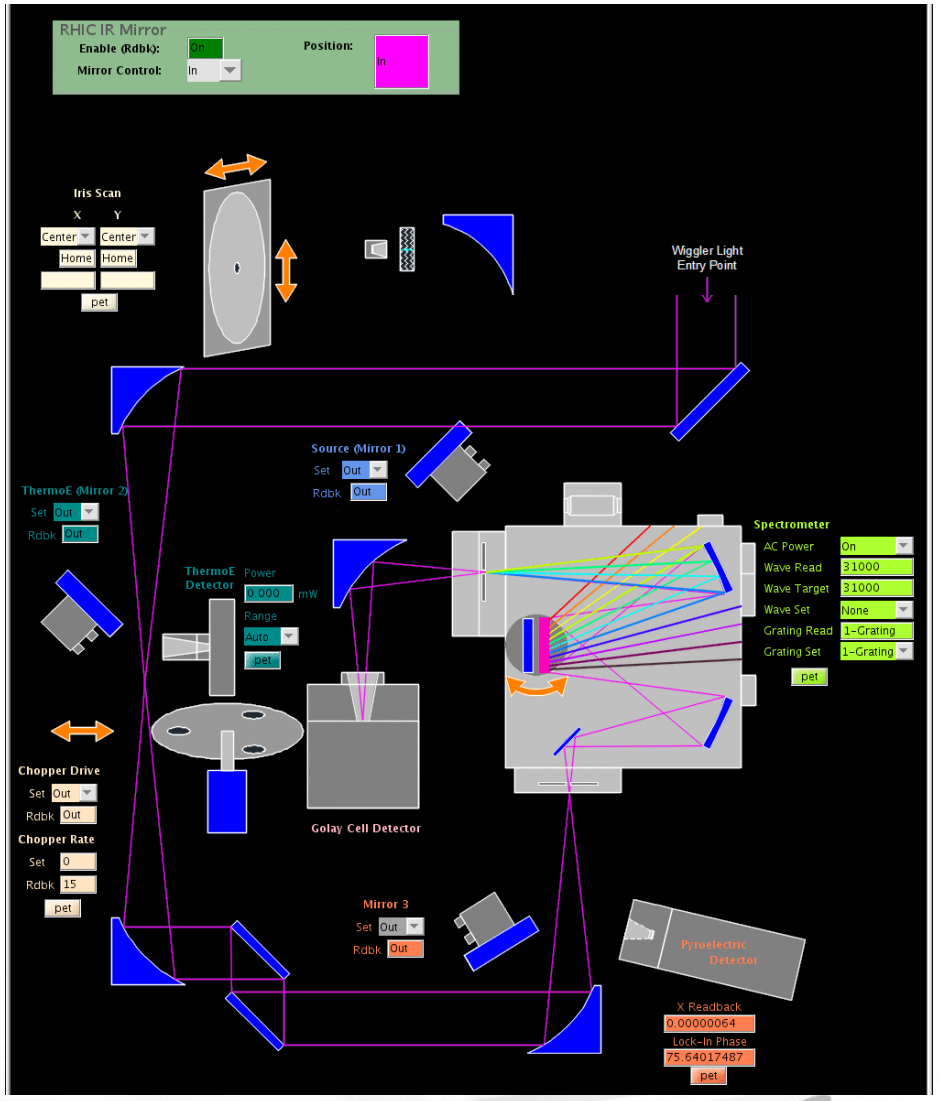
Infrared Diagnostics



Golay cell signal (green)



Pyroelectric detector signal (yellow)
ICTs signals are cyan and magenta



Progress with CeC RHIC Run 18

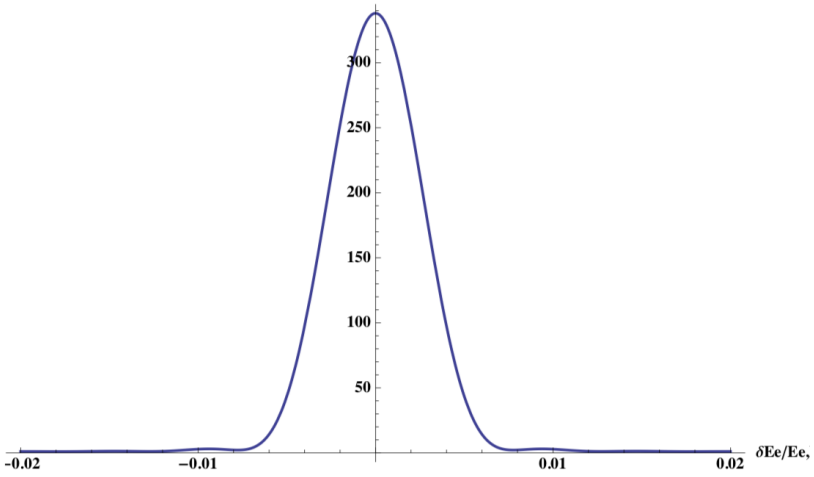
All seems to be ready for next steps of the CeC experiment

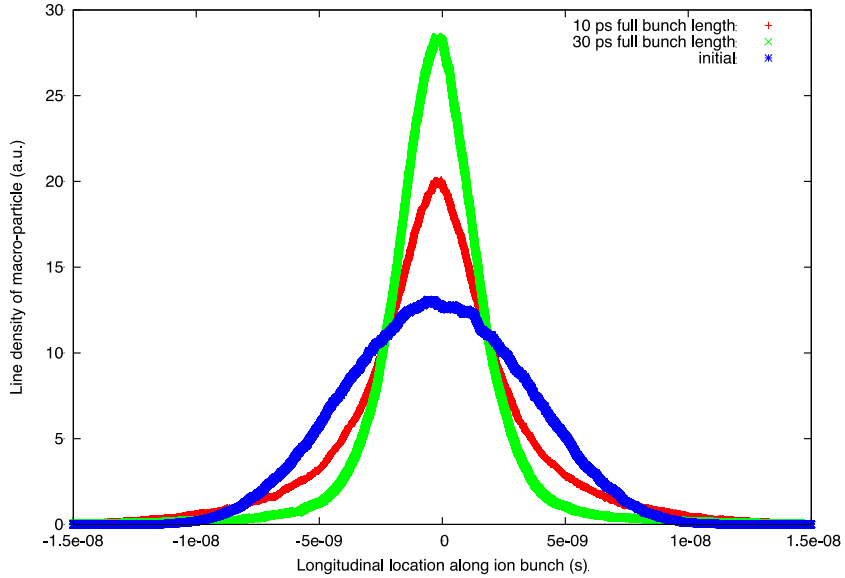
- ✓ Establish stable phase, amplitude and timing (RF and laser) to deliver stable reliable electron beam
- ✓ Commission new IR diagnostics and establish high gain FEL operation
- ✓ Align electron and ion beams transversely, synchronize electron beam with ion beam with 26.5 GeV/u
- ✓ Establish interaction of electron and ion bunches
- Tune the ion and electron beams energies using “ion beam imprint”
- Test Coherent electron Cooling
- Characterize Coherent electron Cooling

Everything was ready for next two steps

Ion imprint
Tuning energies

CeC demonstration





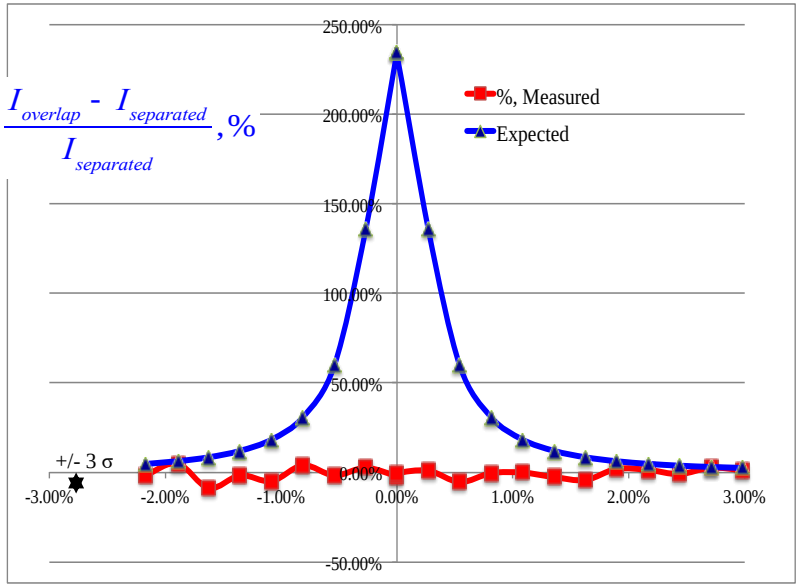
Plot of simulated increase (in %) of the FEL power resulting from the ion beam imprint as a function of the relative energy detuning of electron beam. Maximum corresponds to perfect match of beam's relativistic factors.

Cooling Au ion bunch at 26.5 GeV/u
Self-consistent simulations: 40 mins of CeC

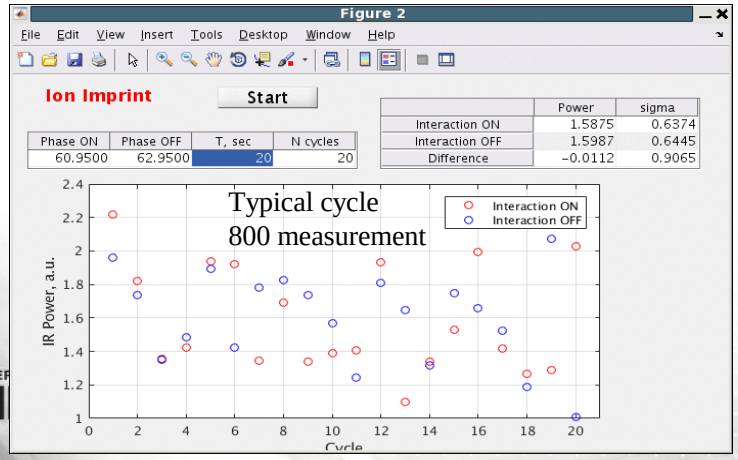
Main result = Big disappointment

Search for ion's imprint

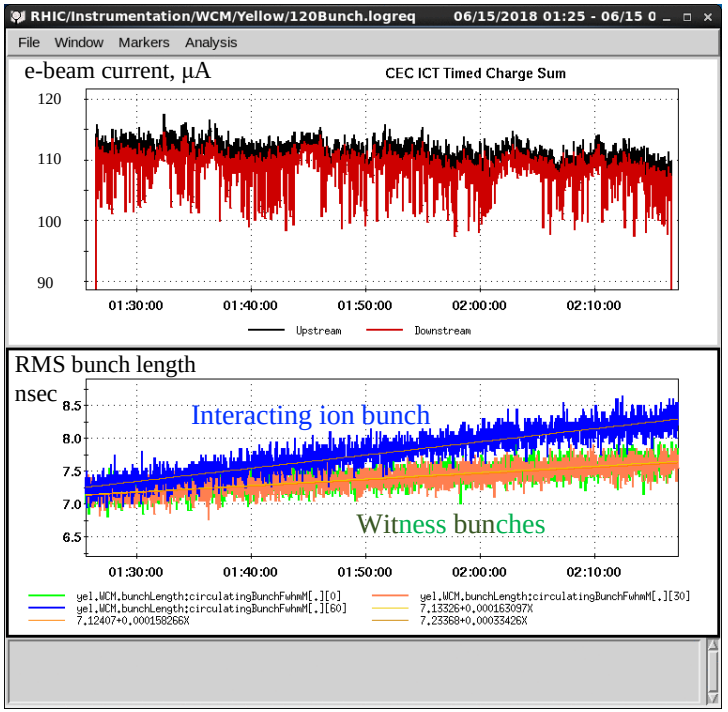
$$R = \frac{I_{overlap} - I_{separated}}{I_{separated}}, \%$$



Expected and measured relative change in the FEL signal with overlapping and separated beams. Each point corresponds to 16 or cycles of 20 FEL power measurements for overlapped and separated beams. Data analysis indicate RMS error of 2%.



Heating of ion beam by lasing e-beam



Top plot :electron beam current through the CeC ~ 110 μA or 1.4 nC per bunch at 78 kHz.

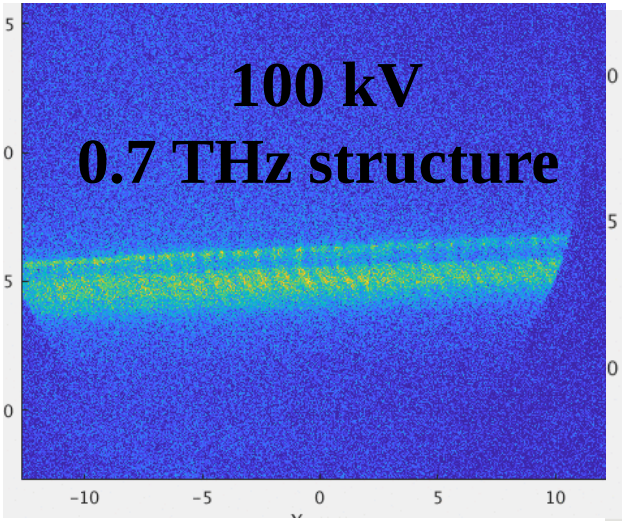
Bottom plots: evolution of the bunch lengths for interacting (blue trace) and witness bunches (orange and green traces)

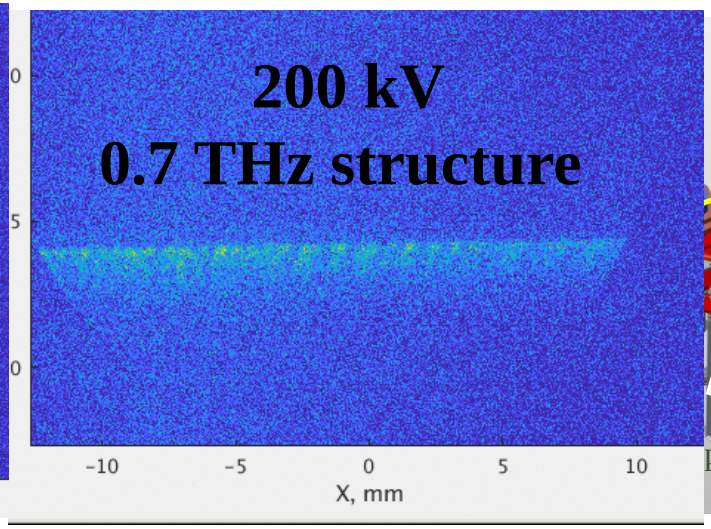
Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

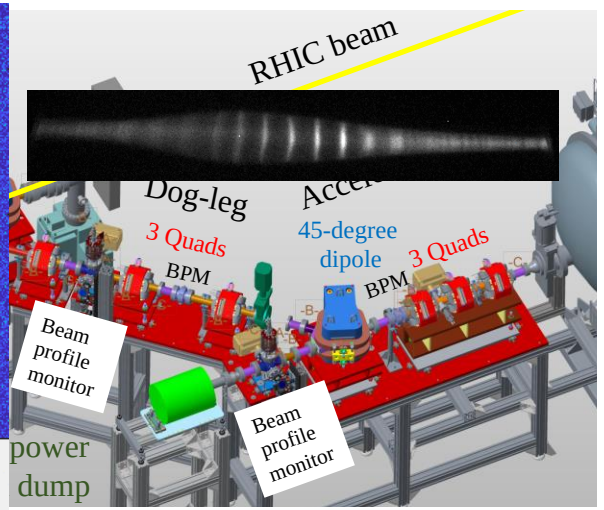
Plausible causes

- Relativistic factors of electron and ion beams are separated by more than 2.5%-3% - Very unlikely
  - This is extremely unlikely: RHIC beam energy is known with 0.1% accuracy and electron beam energy is calibrated using dipole magnet with 0.1% accuracy.
- FEL saturation - in this case increase in the input signal would be muted - Very unlikely
  - Strongly reduced FEL gain was used for the imprint studies. Genesis simulation confirmed this assumption.
- Debye screening of ions does not occur after 1/2 of plasma oscillation - Eliminated
  - Required slice energy spread of 0.75% and normalized emittance > 10 μm rad with peak current of 100 A.
- Reduced transverse overlap: either extremely low electron beam emittance ~ 1 μm rad or a large ~2.5 mm orbit separation of two beams - Eliminated
  - *+/-2 mm separation is required , measured values were within +/- 0.5 mm*
  - *Measured slice emittance of the beam and found it to be expected 5-7 μm rad*
- Shot noise of the ion beam is suppressed around 30 μm (10 THz): it would be the most profound finding.
  - *Theory: we discovered a number of effects which should prevent such "entanglement.*
  - *Simulation with SPACE code of the 26.5 GeV/u Au ion beam propagating for about 27 km in intentionally smooth lattice indicated no observable changes in the THz range shot noise.*

Turning linac & dogleg into e-beam psec time-resolved studies: *t*->*E*->*x* transformer







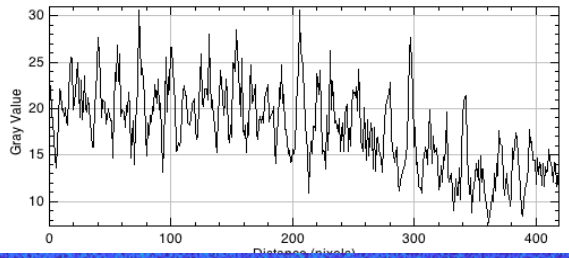
1.75 MeV e-beam

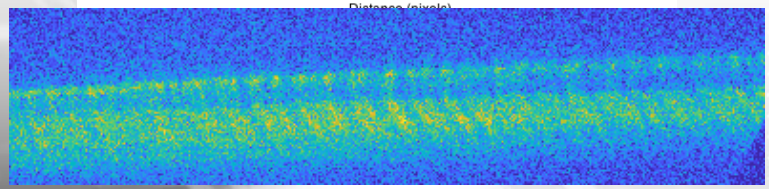
- Operate SRF linac at low 100-200 kV voltage and zero-crossing to insert t-dependent chip: *t*->*E*
- Use D=1.36 m of the dogleg (quads off) as energy spectrometer: *E*->*x*

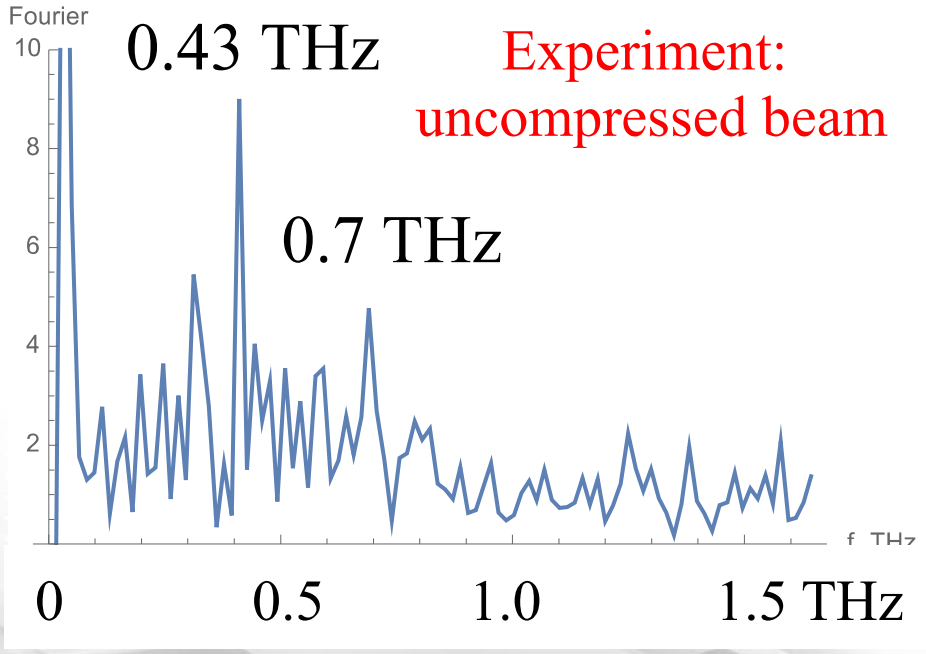
Explanation the “imprint” studies results

- Three months of intense studies excluded a number of plausible explanations except one: **excessive high frequency noise in the electron beam:**
  - Noise in e-beam exceeds that expected from Poisson statistics ($N^{-1/2}$) by orders of magnitude
  - The micro-bunching is amplified when e-beam propagates from the gun to the linac
  - The mechanism is the Plasma-Cascade Instability (PCI)
  - The modulation is upshifted via beam compression to the FEL frequency of 10 THz
- We experimentally observed a broad-band 0.4-0.7 THz density modulation in the uncompressed electron beam exiting the low-energy beamline
- The 20-fold compression used in the CeC “imprint” studies would result in 10 THz (e.g. 30 μm) e-beam density modulation

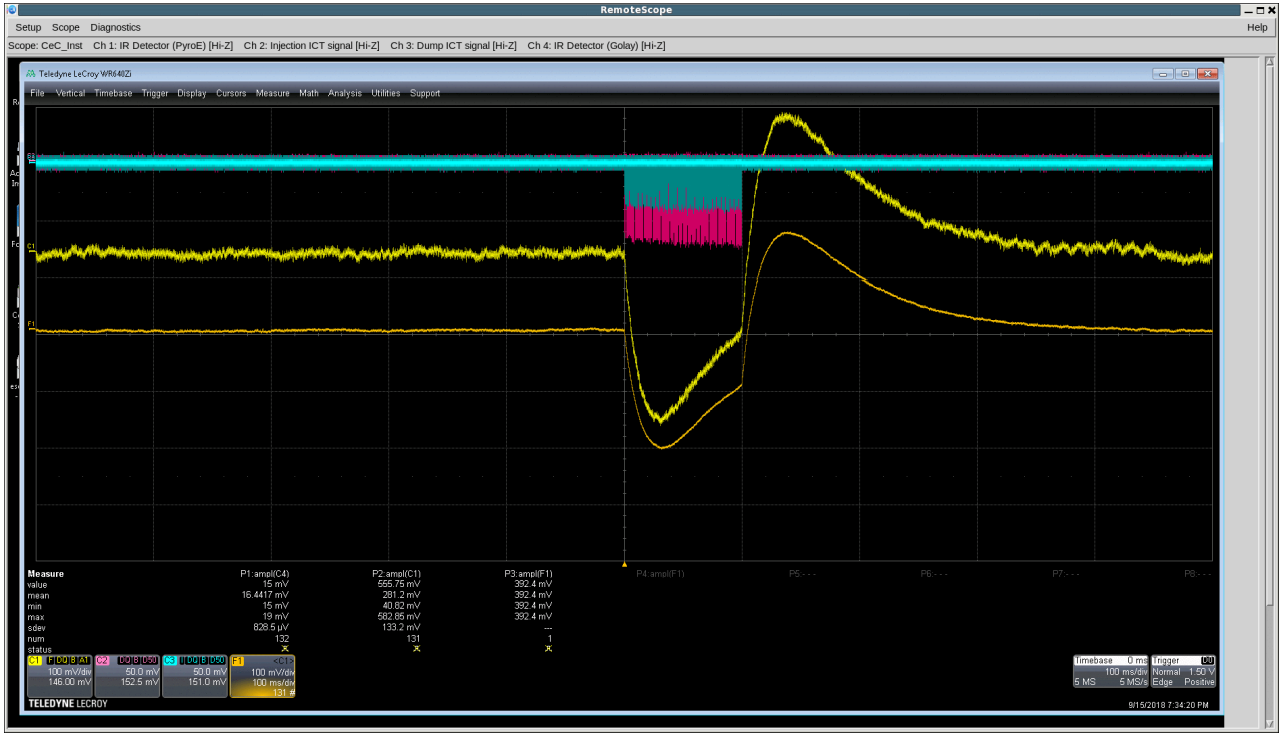
Experiment: uncompressed beam







Dumbest possible test: power of radiation from bending magnet



IR detector signal induced by radiation from 45-degree bending magnet by 7,800 electron bunches 0.65 nC per bunch charge. Radiated energy is 300x larger than natural spontaneous radiation

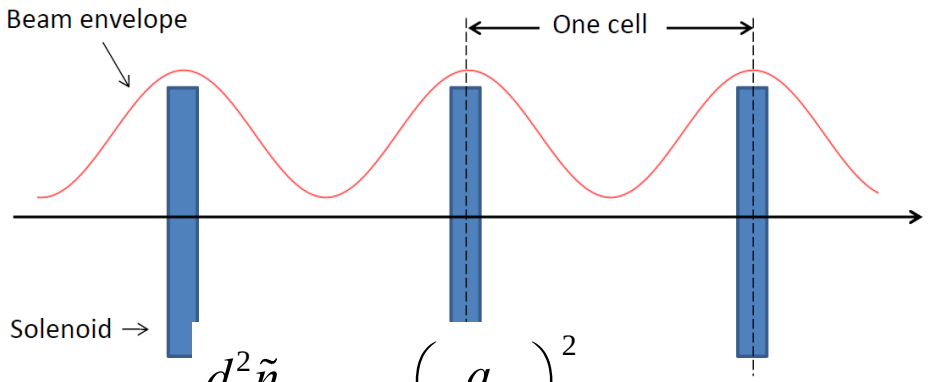
What we learned from the CeC experiment?

- We had discovered excessive high frequency (10 THz) noise in the electron beam, suppression of which is critically important for designing and building any CeC cooler
- We found explanation of this phenomenon in the beam dynamics - the Plasma-Cascade Instability
- This instability can significantly modify e-beam quality at microscopic scale and is very hard to observe experimentally
- This phenomenon was unknown before our experiment: we were first to experimentally observe (and explain) PCI in the low-energy transport of the CeC accelerator
- We had developed theory and numerical tools to accurately simulate PCI at constant beam energy. Development of theoretical and numerical tools for arbitrary accelerator lattices is in progress

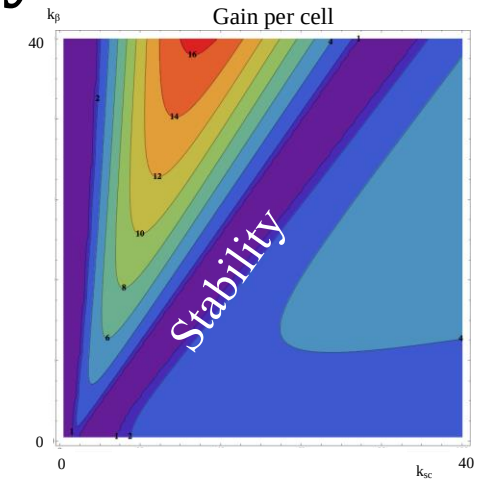
What is Plasma-Cascade Instability?

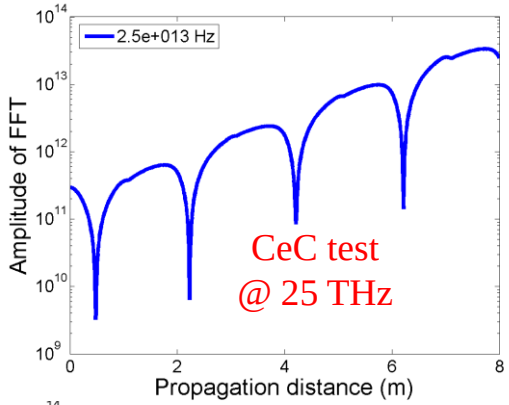
- The Plasma-Cascade Instability (PCI) is a longitudinal micro-bunching instability occurring in a beam propagating along straight trajectory
- PCI is longitudinal parametric instability driven by periodic modulation of the transverse beam size - it was discovered recently: /arxiv.org/abs/1802.08677
- We had good agreement between the theory and 3D simulations for periodic systems
- Recent experimental studies clearly demonstrated PCI in the low energy beam transport (LEBT) of the CeC accelerator at THz frequencies

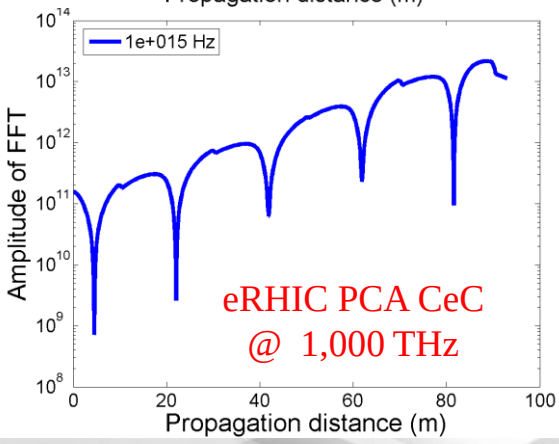
$$\hat{a}'' = k_{sc}^2 \hat{a}^{-1} + k_b^2 \hat{a}^{-3} \qquad k_{sc}^2 = \frac{2}{b^3 g^3}\frac{I_o}{I_A}\frac{l^2}{a_o^2}; k_b = \frac{el}{a_o^2} = \frac{l}{b^*}$$



$$\frac{d^2\tilde{n}}{ds^2} + 2k_{sc}^2\left(\frac{a_o}{a(s)}\right)^2 \tilde{n} = 0;$$



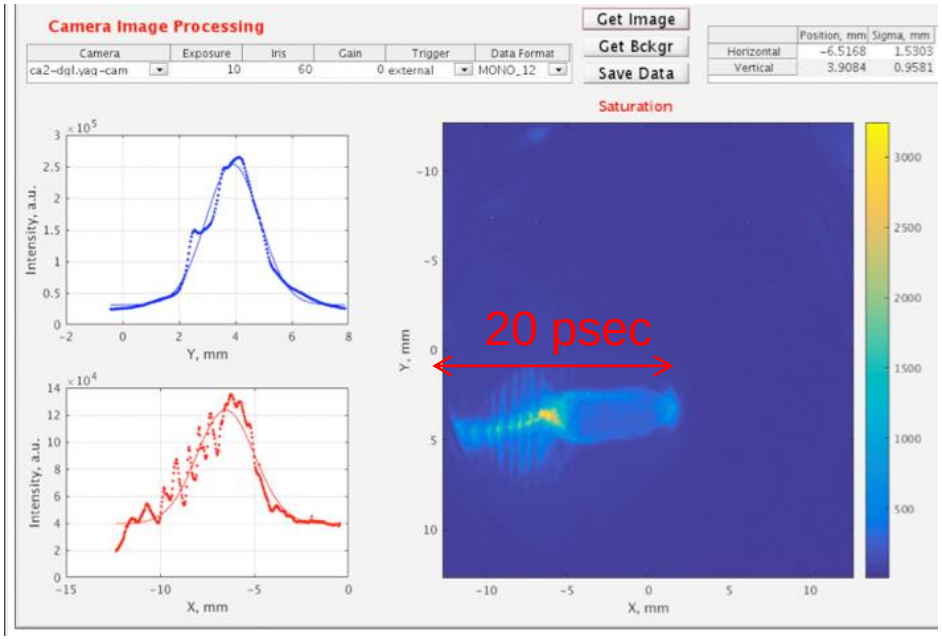


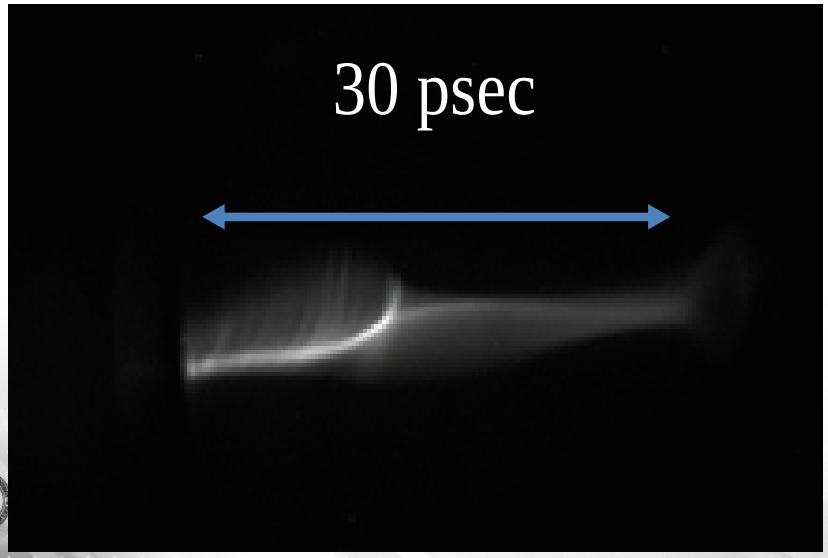


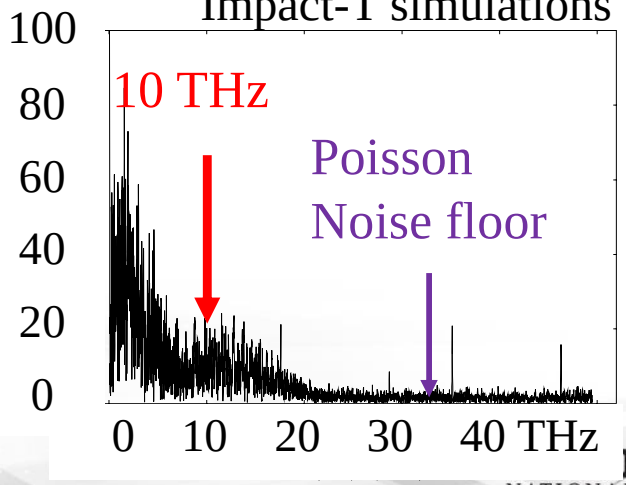
Proposed next step: RHIC Run 19

- Use existing CeC accelerator
- First – re-tune CeC accelerator to generate a quiet electron beam
  - Replace seed-laser with new quiet source
    - Ordered and will be delivered in December, 2018
- Design lattice preventing micro-bunching PCI
- Install IR diagnostics at the exit of CeC accelerator
- Experimentally confirm suppression of micro-bunching instability in CeC accelerator
- Demonstrate beam quality necessary for next step – experimental demonstration of micro-bunching CeC
- Collaborate with JLab (Rui Li team), SLAC (Daniel Ratner) and ANL (A. Zholents team) in these studies

Simulation tools

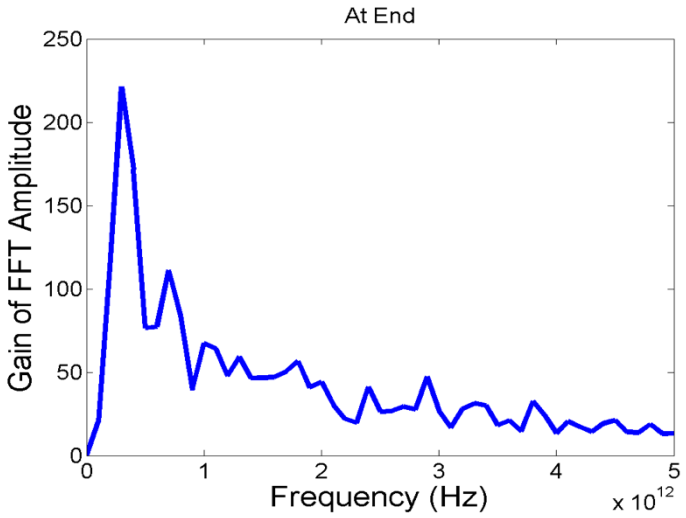






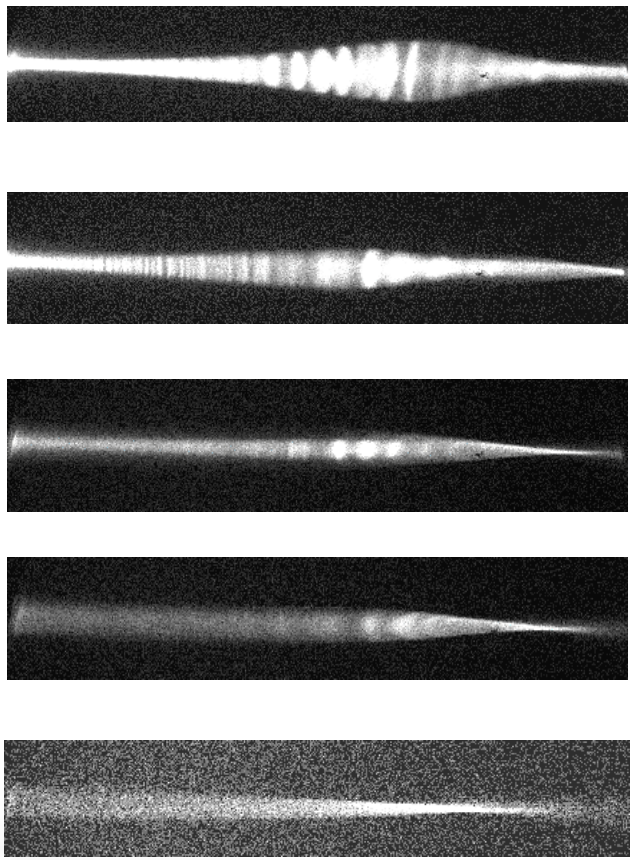
Selected results: uncompressed bunch

3D simulations (SPACE)



Experimental results

High charge - strong PCI



Low charge - weak or no PCI

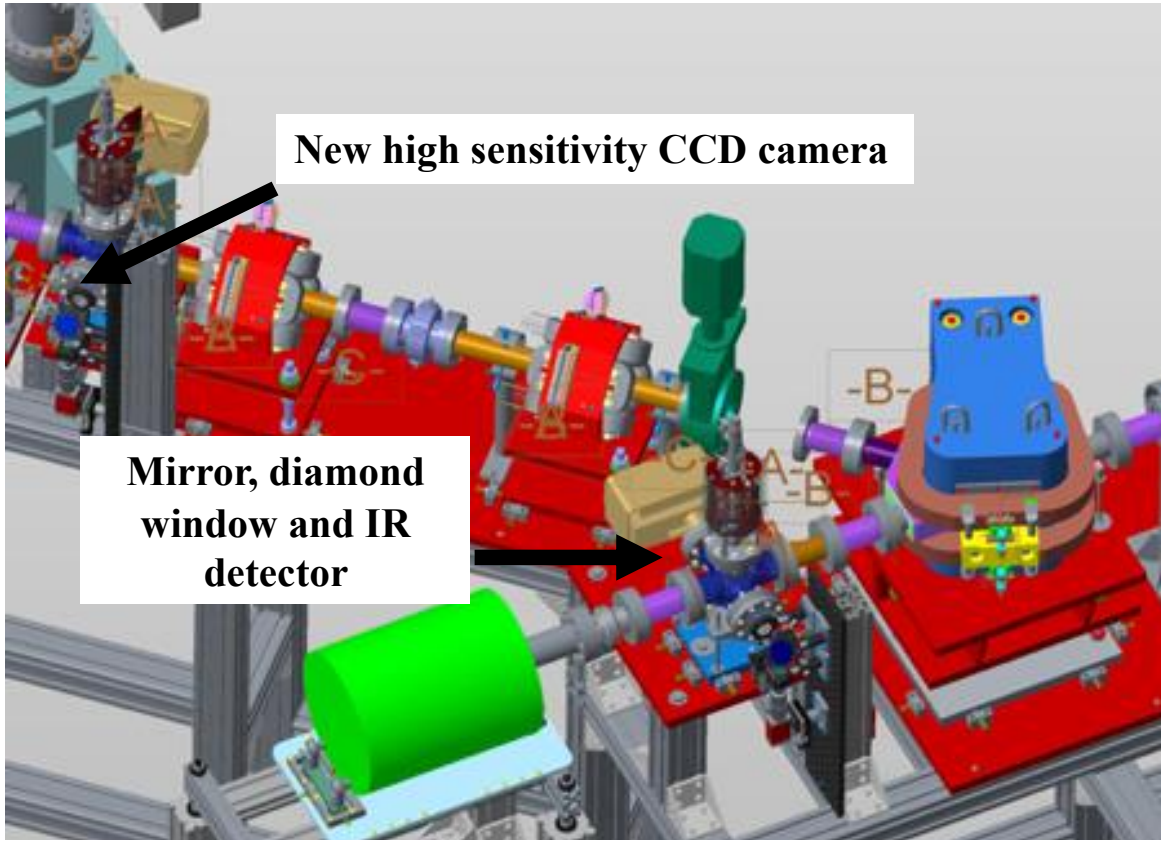
Detecting micro-bunching PCI in CeC accelerator

PCI is described by a self-consistent Hill's equation

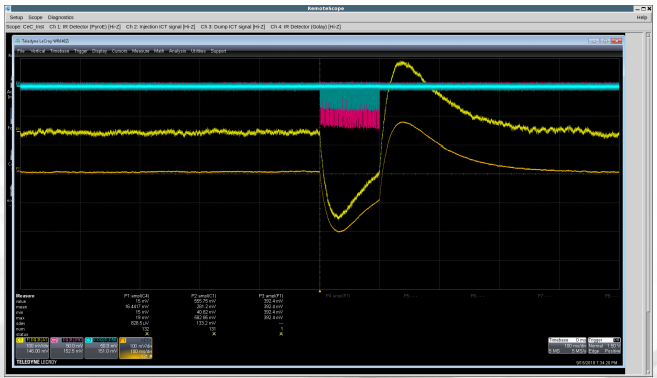
$$\frac{d^2\tilde{n}}{ds^2} + 2k_{sc}^2\left(\frac{a_o}{a(s)}\right)^2 \tilde{n} = 0;$$

$$x'' + K(s)x = 0$$

Suppressing PCI is similar to optics matching in beam-transport – a standard accelerator problem challenge

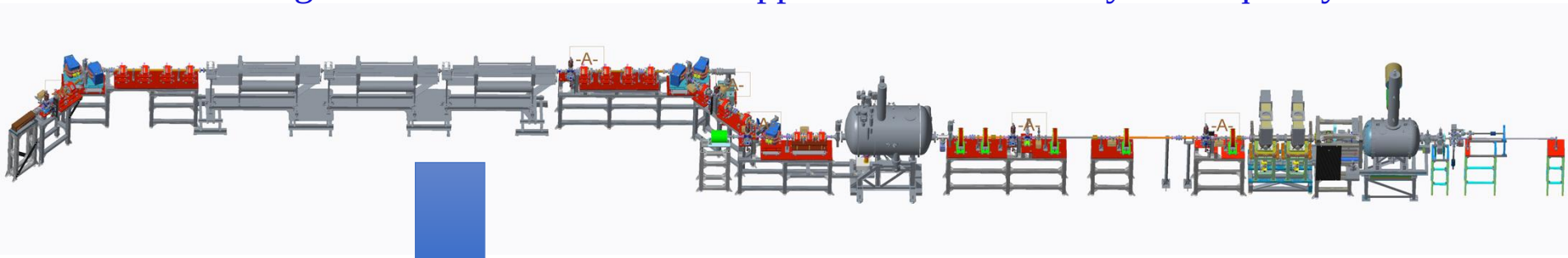


100-folfd higher sensitivity than previously used system: sufficient to see 50% increase above the shot noise level



RHIC Run 20 and beyond

If micro-bunching in the CeC accelerator is suppressed and necessary beam quality is established



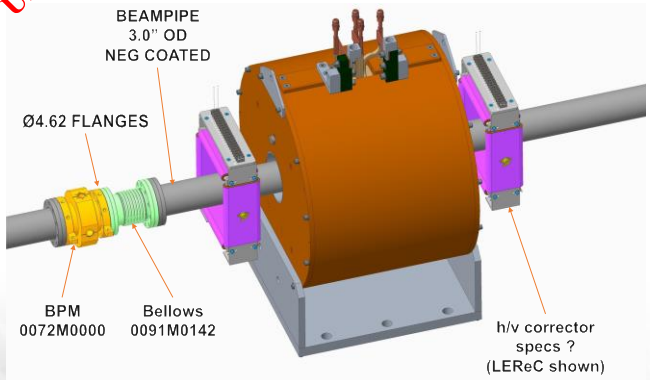
Unchanged

Modulator

Kicker

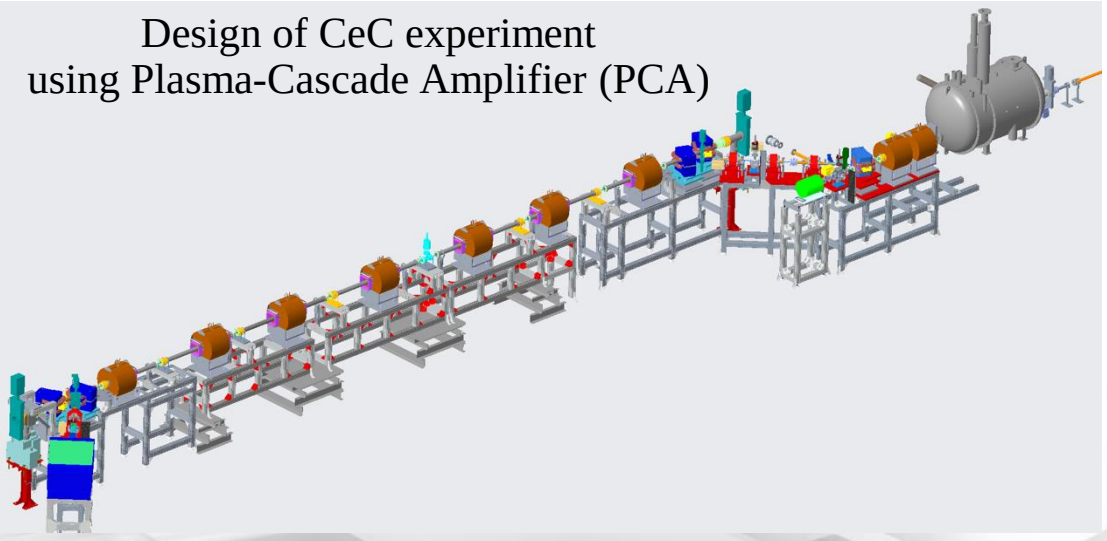
4-cell PCA

Unchanged

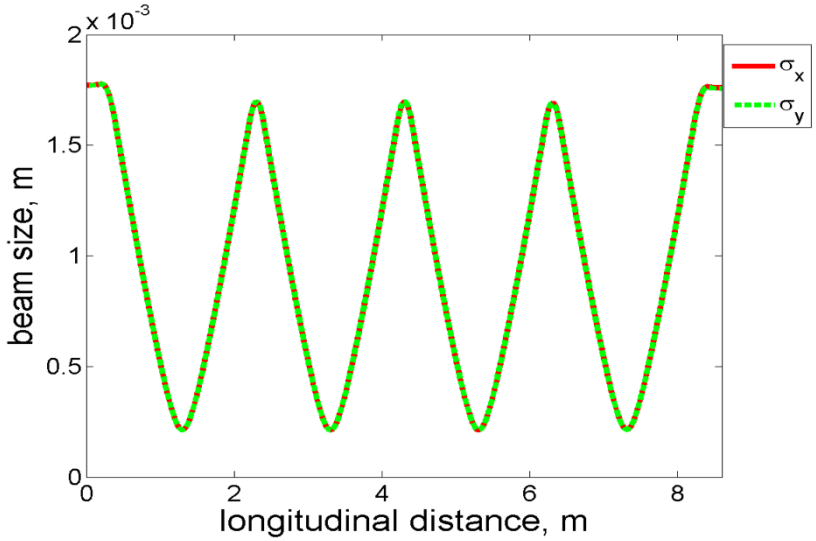


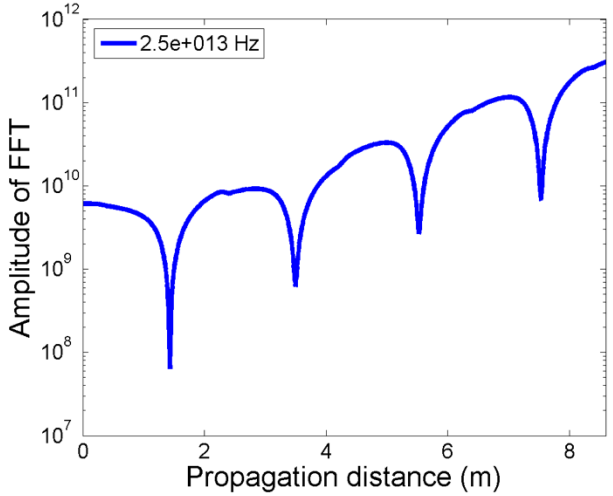
New equipment: solenoids are ordered and expect to arrive in Spring 2019

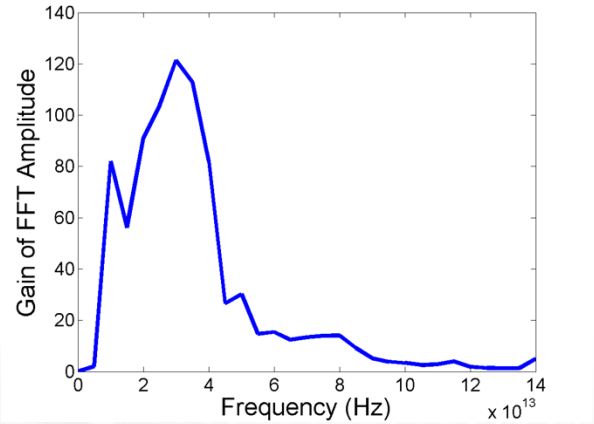
Design of CeC experiment
using Plasma-Cascade Amplifier (PCA)



Evolution of modulation in PCA

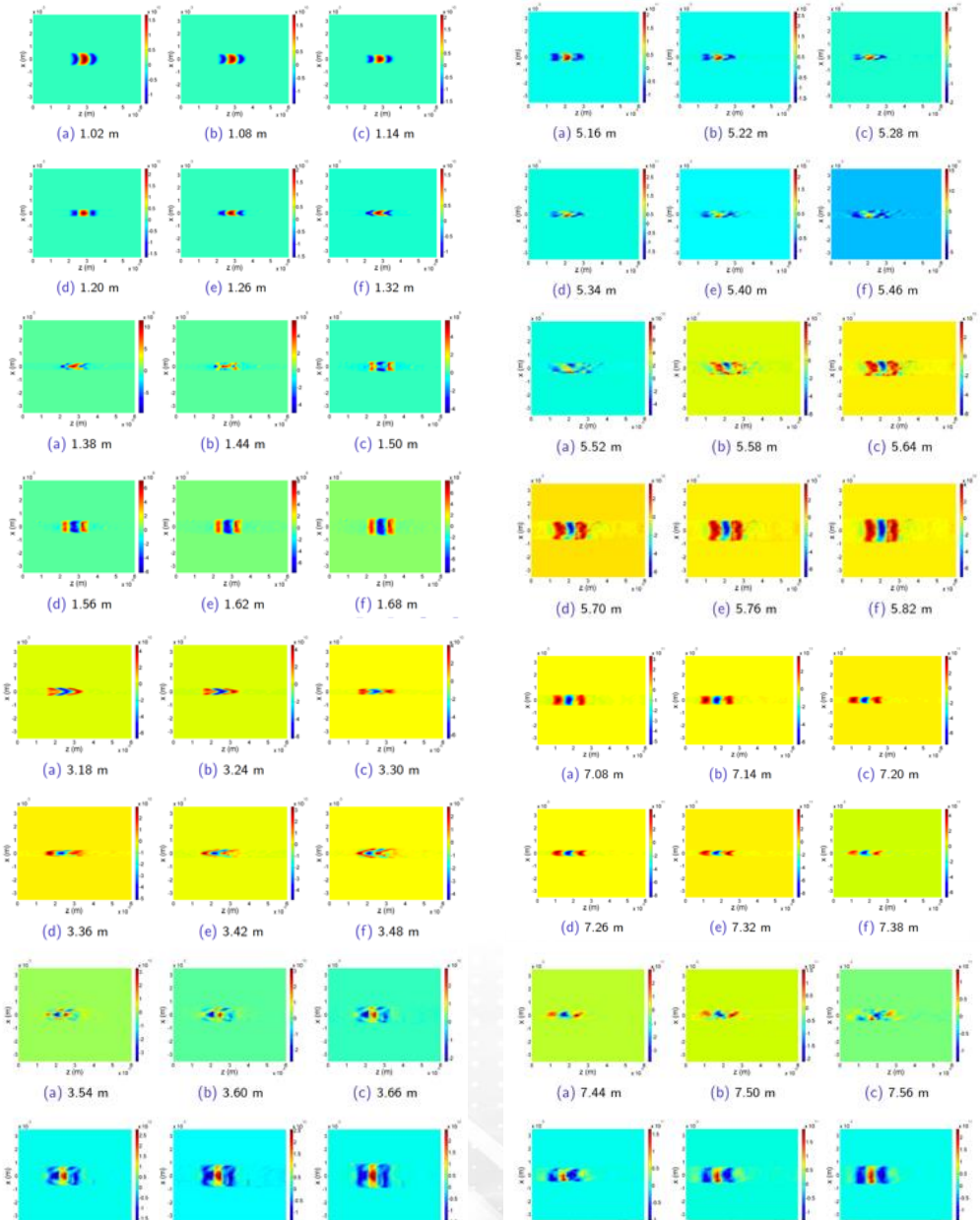


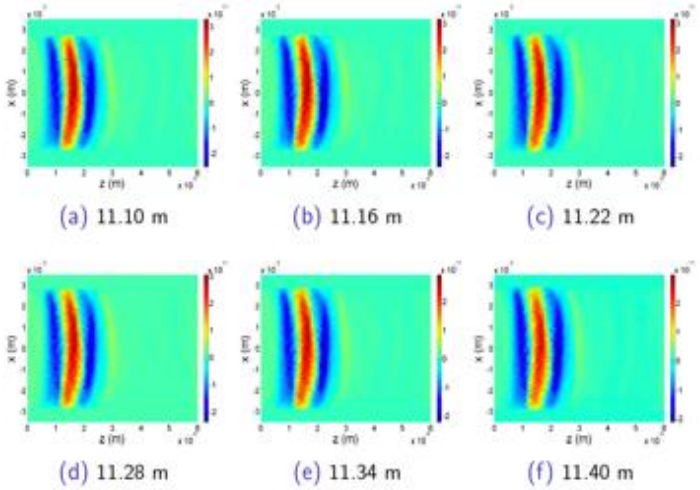




Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of Hadron Beams, V.N. Litvinenko, G. Wang, D. Kayran, Y. Jing, J. Ma and I. Pinayev, arXiv:1802.08677

Evolution of a single ion imprint in 4-cell 8-meter ling PCA

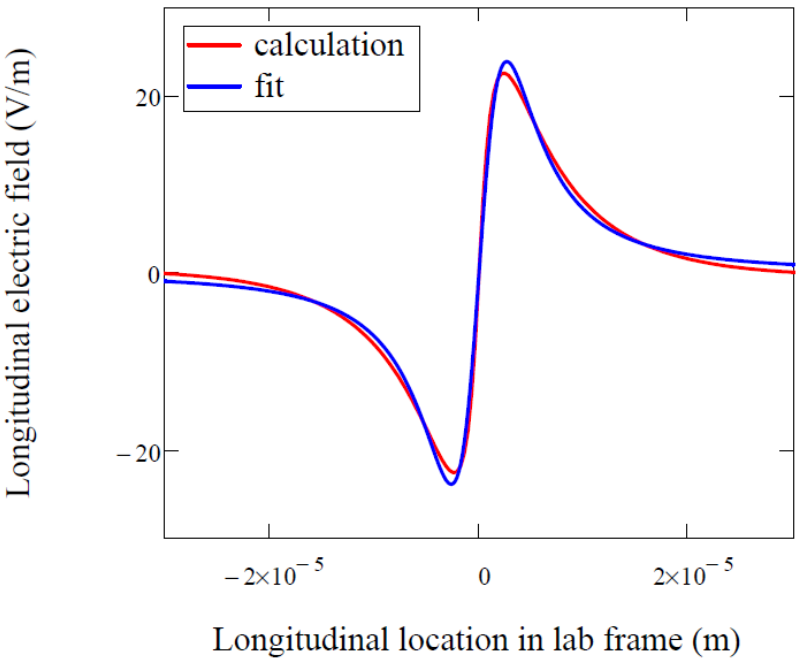




Evolution of a single ion imprint in the ACeC kicker.

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

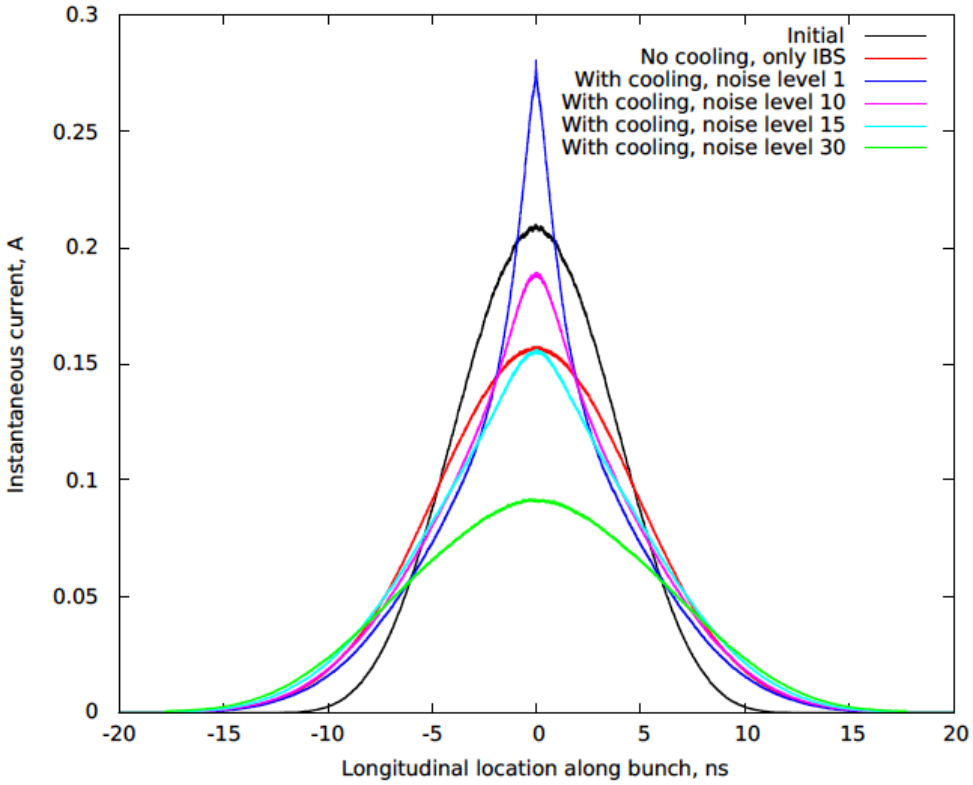
$$E_{fit}(z) = E_0 \frac{z}{\sigma_0} \cdot \left(1 + \frac{z^2}{\sigma_0^2}\right)^{-3/2}$$



$$E_0 = 62.03 \ \ V/m$$

$$\sigma_0 = 3.75 \ \mu\text{m}$$

40 mins of PCA CeC



Simulated ion bunch profile evolution with and without PCA-based CeC.
Cooling will occur if micro-bunching power in the electron beam does if less than 100-fold that of spontaneous (shot noise) radiation

Proposed experimental CeC program

- FY19 – procure all PCA hardware
  - retune CeC accelerator lattice & suppress excessive noise in the electron beam
- FY20 – install PCA equipment in the IP2 common section
  - commission PCA equipment at the IP2
  - optimize IR diagnostics for PCA
  - start PCA-based CeC experiments
- FY21 –demonstrate the PCA-based microbunching CeC at γ=28.5
- FY22 – no RHIC run
- FY23 – 3D cooling in PCA-based CeC at γ=28.5
  - evaluate PCA-based CeC performance

Conclusions

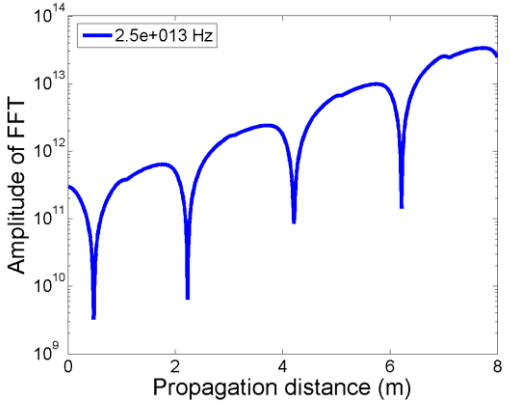
- CeC RHIC Run 18 was very challenging and partially successful
  - build the state of the art accelerator and FEL system with all beam parameters necessary for the CeC experiment had been demonstrated
  - high gain FEL amplifier was commissioned
  - a new, previously unexplored, phenomenon was discovered
- We propose to tune the sophisticated SRF accelerator – significant investment by DoE NP office - for generating beams necessary for CeC demonstration experiment at RHIC
- Experimental demonstration of the PCA-based microbunching CeC can be completed in two-to-three years. By its design PCA-based CeC is fully compatible with low energy RHIC operations
- PCA-based micro-bunching CeC is a high-performance cost-effective path towards a realistic system for high luminosity EIC independent of the design choice and site selection: either eRHIC or JLEIC
- BNL CeC group collaborates with JLab, SLAC and ANL in this studies

Back-up slides

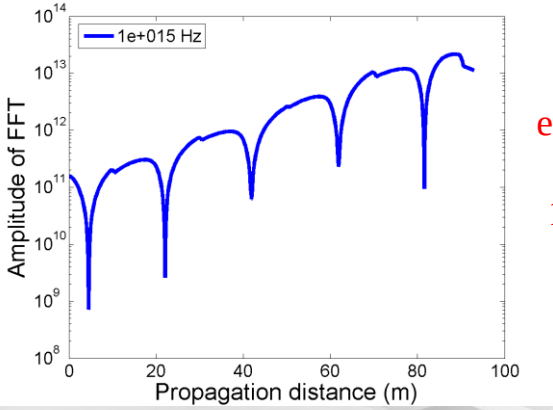
Numerical tests

- 3D simulations of a CeC with 4-cell PCA for test experiment and eRHIC
- High gain (>100) and very large bandwidth: 25 THz for test experiment and 1,000 THz (1 PHz) for CeC cooling 275 GeV protons
- These are cost effective system – they do not need expensive separation system for hadrons and will be capable of 3D cooling hadron beams in RHIC and eRHIC independently of the design choice
- Still, it will be important to demonstrate this untested micro-bunching cooling technique experimentally

Name	ACeC test	eRHIC
PCA	**4 sections**	**4 sections**
γ	28.5	275
L	2.00	20.00
a_0	2.00E-04	1.00E-04
Peak current	**100.00**	**250.00**
β^*	0.14	0.69
ε_{norm}	**8.00E-06**	**4.00E-06**
k_{sc}	3.56	3.76
k_β	7.02	14.55
ε_{geom}	2.81E-07	1.45E-08
Energy spread	3.00E-04	3.00E-04
Frequency, THz	25.00	1,000.00



ACeC test @ 25 THz



eRHIC CeC @ 1,000 THz

PCA micro-bunching CeC for EIC

Examples

Electron bunches

Energy – to match hadron beam energy

Charge per bunch – 1 nC or 2.5 nC

Peak current – 200 – 250 A

Energy spread 3×10^{-4}

Normalized emittance – 8 mm mrad

Local cooling time: 9.8 seconds for 275 GeV protons

$$t_{beam} @ t_{local} \frac{\sqrt{2ps}_p}{T_e}; T_e = \frac{Q}{I_{peak}}$$

Energy, GeV	εh, norm	εv, norm	RMS bunch length, cm	3D Cooling time, min Q=1 nC	3D Cooling time, min Q=2.5 nC
275	0.25 μm	0.25 μm	5	20	7
275	2.7 μm	0.38 μm	5	50	20
200	0.9 μm	0.18 μm	1	5	2

How to "tame" Plasma-Cascade Instability?

Beam envelope equation

$$\hat{a}\phi = k_{sc}^2 \hat{a}^{-1} + k_b^2 \hat{a}^{-3}$$

Longitudinal plasma oscillations: can be either stable or unstable

$$\frac{d^2\tilde{n}}{ds^2} + 2k_{sc}^2 \left(\frac{a_o}{a(s)}\right)^2 \tilde{n} = 0;$$

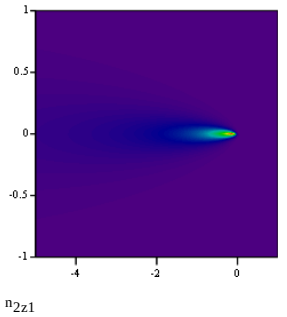
$$k_{sc}^2 = \frac{2}{b^3 g^3} \frac{I_o}{I_A} \frac{l^2}{a_o^2}; k_b = \frac{e\ell}{a_o^2} = \frac{i}{b^*}$$

- The longitudinal plasma oscillations are described by Hill's equation with time (s) dependent frequency
- The solution is presented by 2x2 unimodular matrix, which can be either stable or unstable
- Finding stable solution of Hill's equations is a standard accelerator physics problem – the process is called optics matching
- The complication for suppressing PCI is that the plasma frequency is defined by a self-consistent solution for the peak current and the beam envelope. Hence, while the process is more elaborate that a traditional "optics matching", it is still has clear path stable solutions.

”Imprint” case

- Imprint of the shot noise from ions is a directs consequence of Debye screening by electrons
- Expert in the field never questioned its validity.
- Considered to be a “slam dunk” e for matching relativistic factors of the beams
- An excellent agreement between theory and simulation
- Sophisticated 3D code simulated the imprint in a realistic bema in the quadrupole beam-line
- Sensitivity to various parameters had been checked
- In all cases the imprint from the ion beam should at least double the FEL power
- During the experimental studies, the FEL was operated well below saturation

Theory

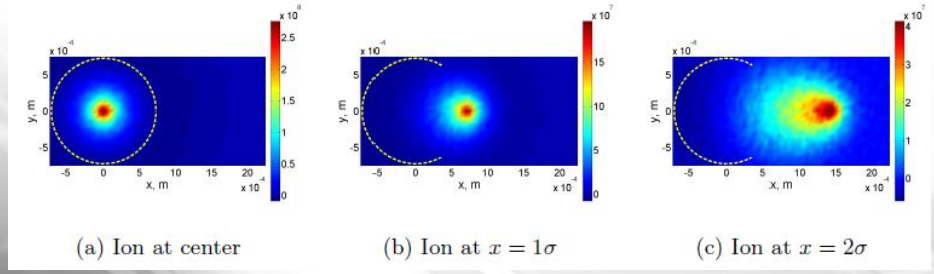


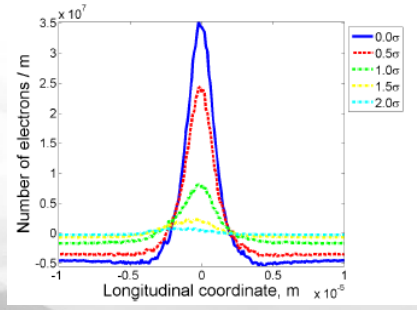
$$\tilde{n}_1(\vec{x},t) = \frac{Z_i}{p^2 a_x a_y a_z} \int_0^{w_p t} \frac{t \sin t \cdot dt}{\left[t^2 + \left(\frac{x}{a_x} + \frac{v_{0,x}}{b_x} t \right)^2 + \left(\frac{y}{a_y} + \frac{v_{0,y}}{b_y} t \right)^2 + \left(\frac{z}{a_z} + \frac{v_{0,z}}{b_z} t \right)^2 \right]^2}$$

G. Wang and M. Blaskiewicz, Phys Rev E 78, 026413 (2008)

3D simulations

J. Ma, with code SPACE





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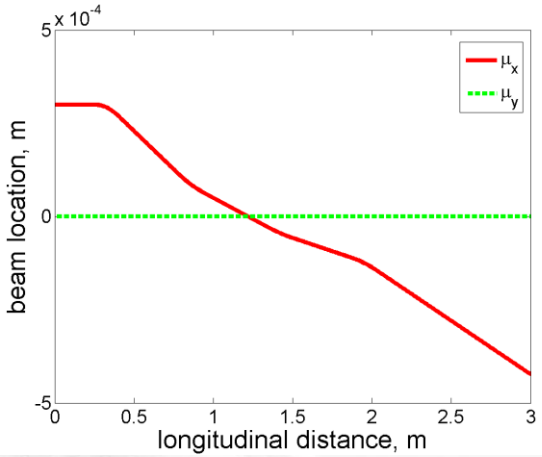
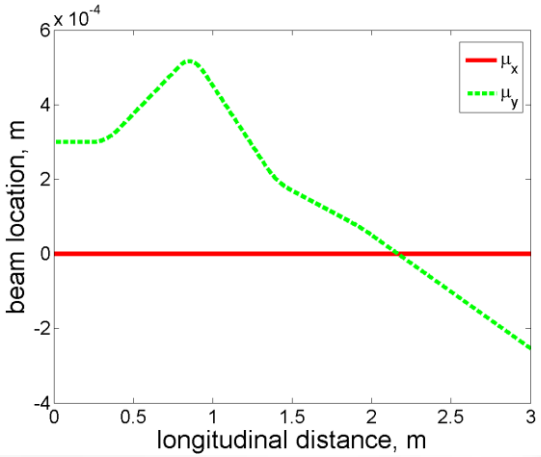
Selected numerical results

	Without Ions	With Ions	Ratio (Amplitude)	Expected FEL power increase
dE/E=1e-3, Δx = Δy = 0	6.1524e-5	1.3219e-4	2.1486	**4.6165**
dE/E=3e-3, Δx = Δy = 0	6.3565e-5	8.9365e-5	1.4059	**1.9766**
dE/E=3e-3, Δx = 3e − 4m	6.0151e-5	8.6825e-5	1.4435	**2.0834**
dE/E=3e-3, Δy = 3e − 4m	5.2372e-5	7.7714e-5	1.4839	**2.020**





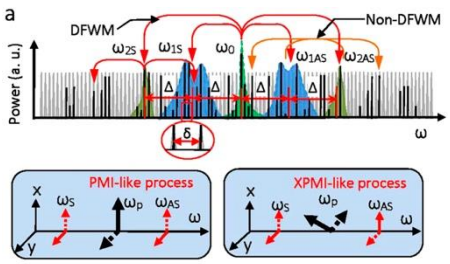
Dependence of charge induced by individual ion on its displacement from the electron beam axis in the CeC modulator

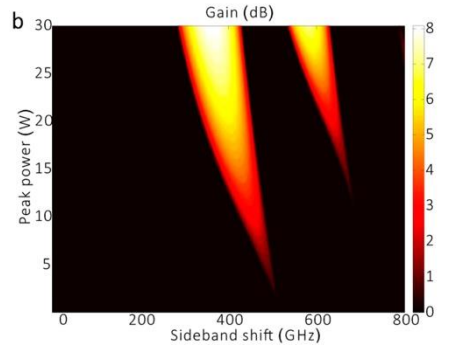
	0 σ_y	1 σ_y	2 σ_y	3 σ_y
0 σ_x	99.5	68.9	20.9	5.2
1 σ_x	69.2	53.8	16.2	3.1
2 σ_x	24.7	18.9	5.2	0.6
3 σ_x	6.1	3.5	0.6	-0.05

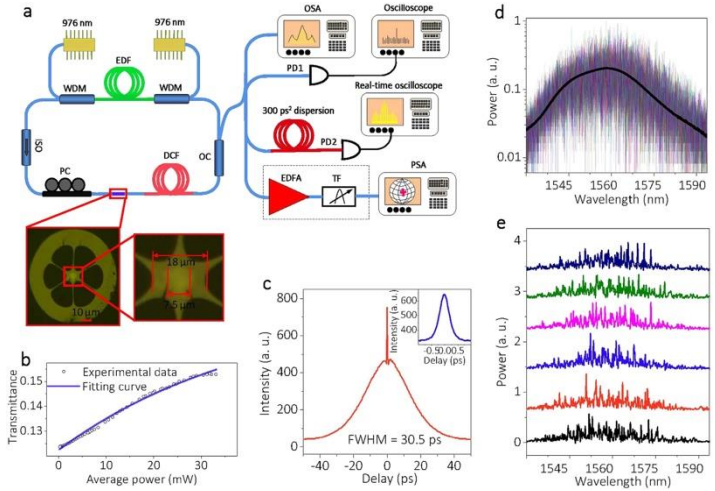
© J. Ma, with code SPACE

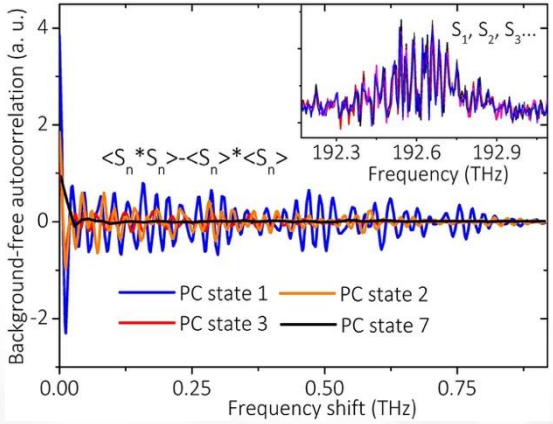
Sidebands of the fiber laser

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4850403/pdf/srep24995.pdf

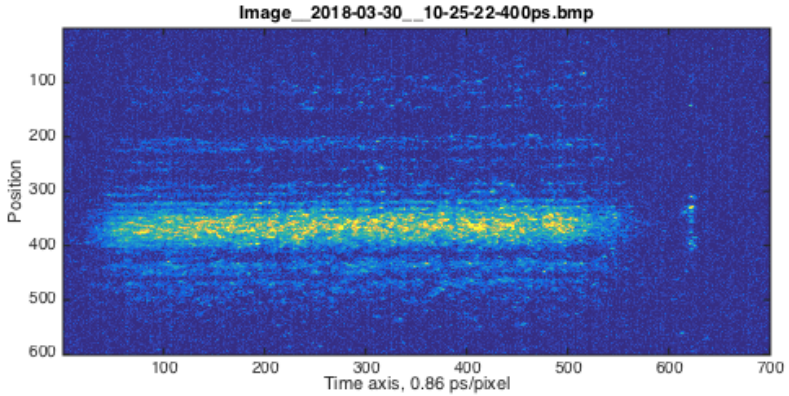


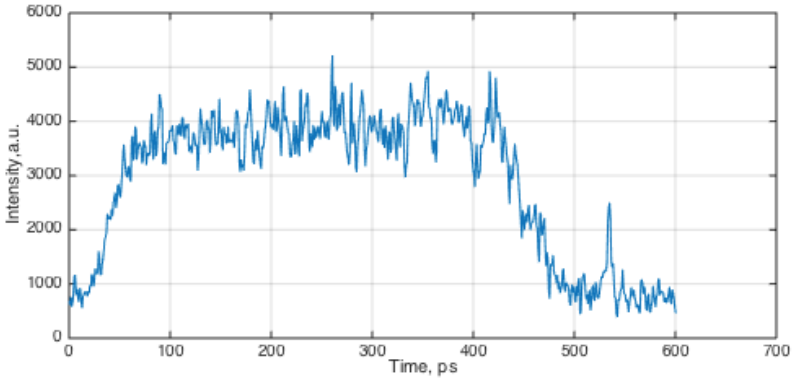






Drive Laser



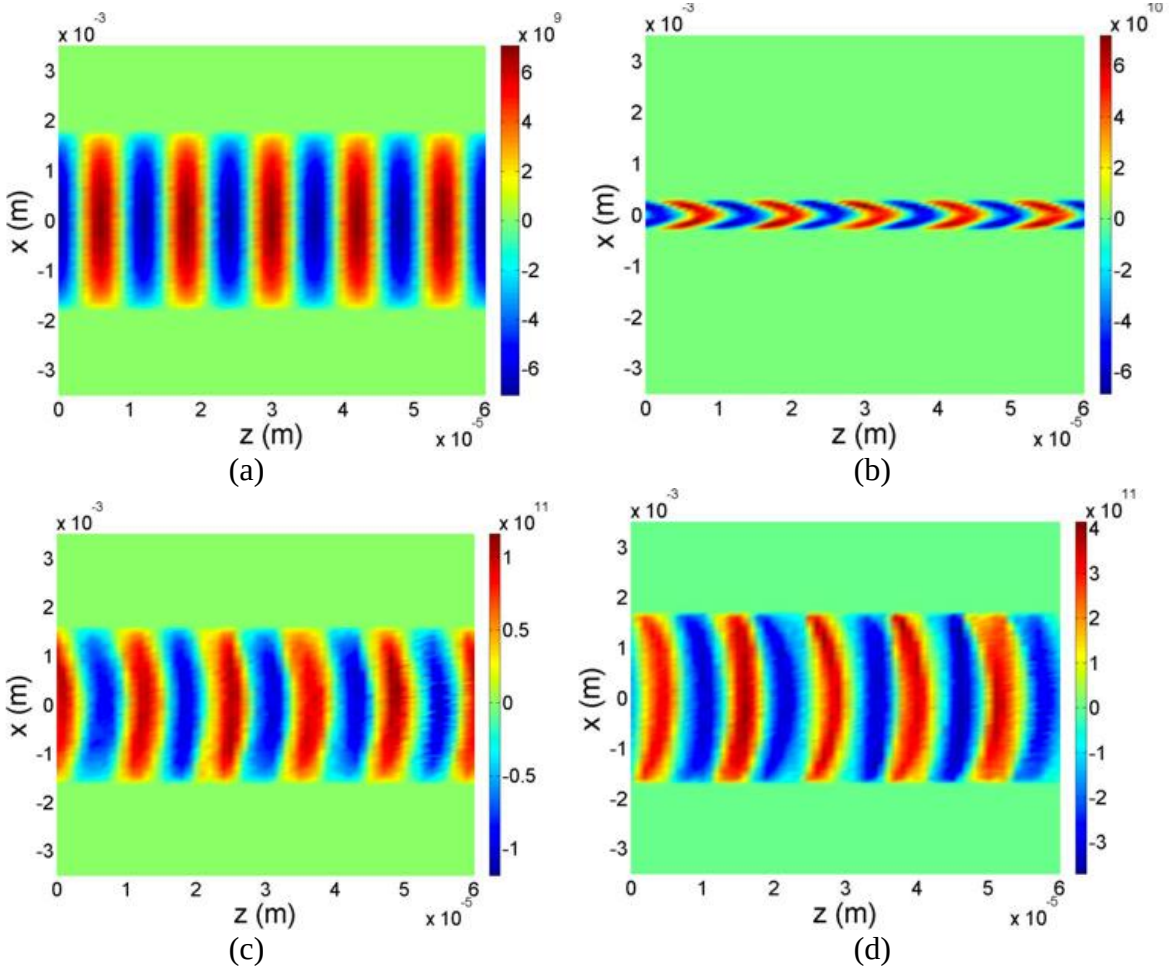


400 psec laser power profile after tuning

It was found that fiber amplifier induces power fluctuations in the temporal profile as well as shot-to-shot variations. For this reason it was replaced with regenerative amplifier which provided flat top and substantial margin on the laser power to extend cathode lifetime.

The laser trigger set-up was modified to meet the specifications on jitter.

Evolution of modulation in PCA



Evolution of the 3D profile of the e-beam density modulation at 25 THz in ACeC PCA. Only AC portion of the density is shown: red color corresponds to increased density and blue to reduced density beam density. Color density is normalized to maximum values to accommodate its exponential growth. (a) – at the PCA entrance. (b) middle of 2nd cell (beam waist); after 3rd cell and (d) at the end of the 4-cell PCA.