Observation of the Ion Imprint in CeC Electron Beam

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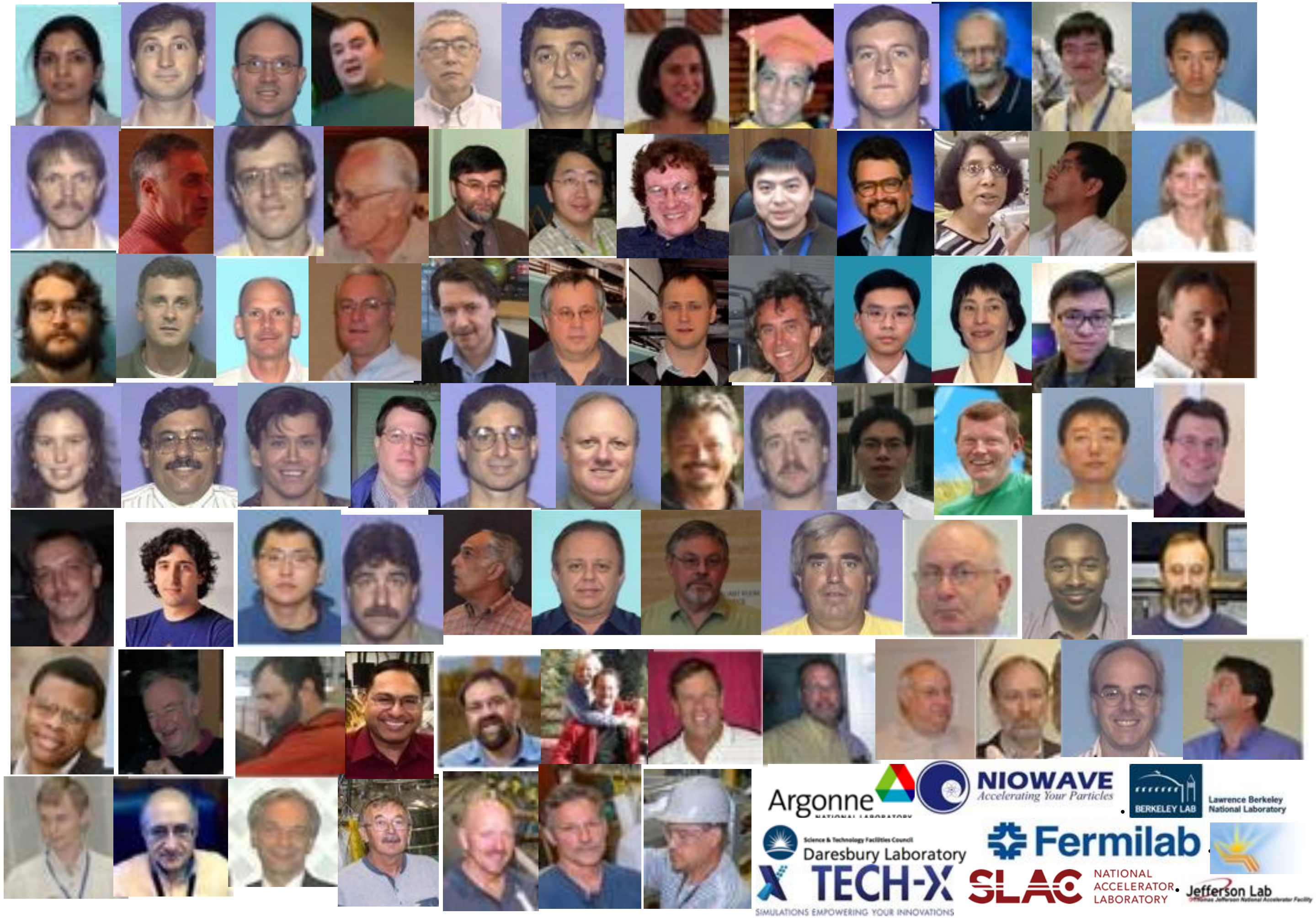
COOL'23 Workshop, Montreux, Switzerland – October 10, 2023

Results belong to all people contributed to CeC project – never can get all your pictures …

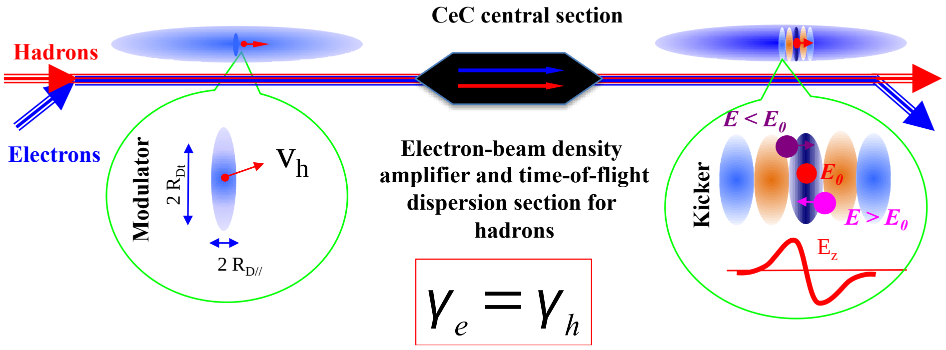


Content

- ❑ Main processes in Coherent electron Cooling (CeC)
- ❑ Process of the hadron imprint into electron beam
- ❑ Theory of the imprint process
- ❑ Simulation of the imprint process
- ❑ First (unsuccessful) attempt to observe the imprint
- ❑ Experimental observation of the imprint
- ❑ Conclusions and discussions

Coherent electron Cooling

- All CeC systems are based on the identical principles:
  - Hadrons create density modulation (imprint) in the co-propagating electron beam
  - Density modulation is amplified using broad-band microbunching instability
  - Time-of-flight dependence on the hadron's energy results in energy correction and in the longitudinal cooling. Transverse cooling is enforced by coupling to the longitudinal degree of freedom.



UM HE 91-28
August 7, 1991

COHERENT ELECTRON COOLING
1. Physics of the method in general

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Ann Arbor, Michigan 48109-1120 USA

ABSTRACT

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

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS

Coherent Electron Cooling

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Microbunched Electron Cooling for High-Energy Hadron Beams

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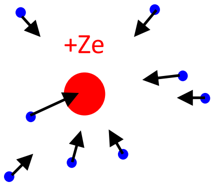
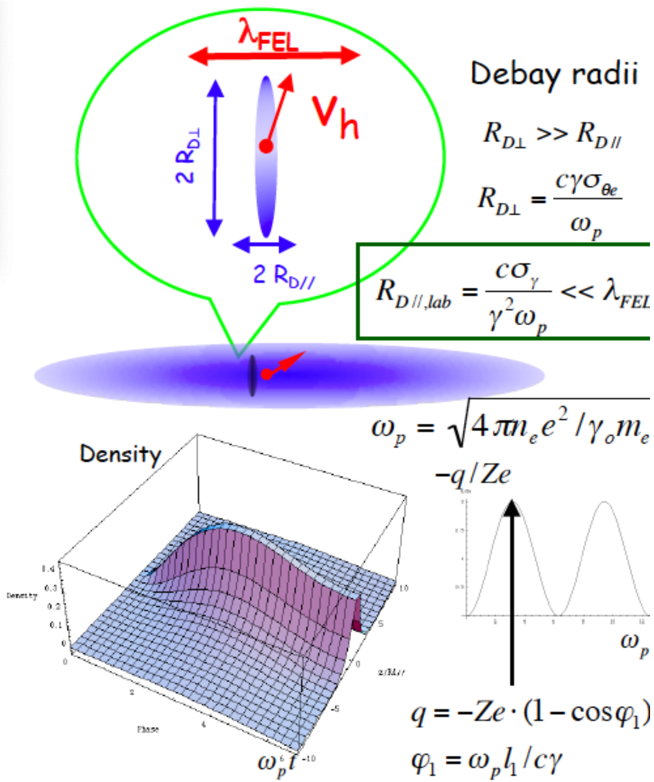
Simple models of the imprint: Debye shielding in infinite cold plasma (e-beam) and estimates

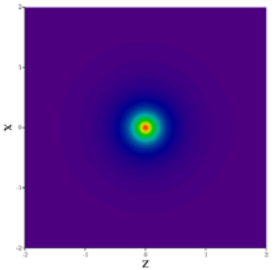


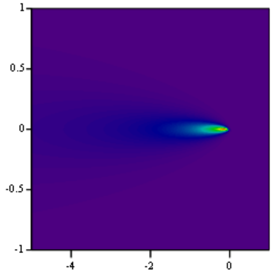
- Equations for reaction of cold infinite plasma on sudden appearance of a heavy positively charged ion (with *Ze* charge) can be solved analytically
- Solution is simple: total screening charge oscillates with plasma frequency and peaks at *2Ze*. *The density is infinite at the location of the ion!*
- Handwaving arguments can say that for e-beam with velocity spread, size of the electron imprint has typical size of $R_D \sim \sigma_v / \omega_p$
- For ultra relativistic beams, where $\sigma_{vt} >> \sigma_{v//}$, it implies that the imprint has a shape of a pancake large in transverse direction $R_t >> R_{//}$



Solution for infinite beam with κ-2 distribution of velocities

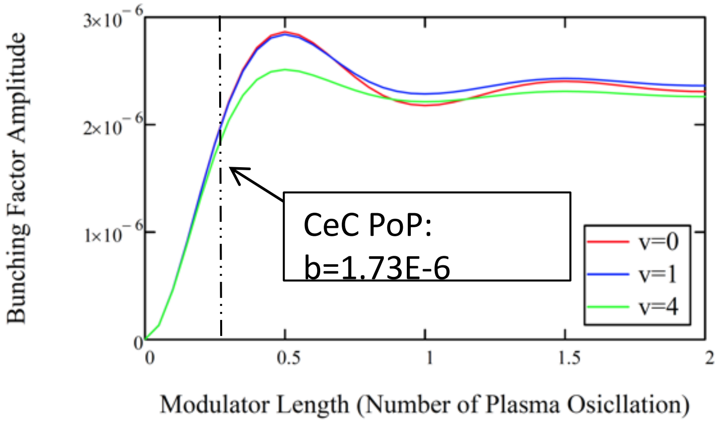
G. Wang and M. Blaskiewicz, Phys Rev E 78, 026413 (2008)





$$f = const / \left(\frac{v_x{}^2}{\sigma_{vx}} + \frac{v_y{}^2}{\sigma_{vy}} + \frac{v_z{}^2}{\sigma_{vz}} \right)^2$$

$$\tilde{n}(\vec{r},t) = \frac{Z n_o \omega_p^3}{\pi^2 \sigma_{vx}\sigma_{vy}\sigma_{vz}} \int_0^{\omega_p t} \tau \sin\tau \left(\tau^2 + \left(\frac{x - v_{hx}\tau/\omega_p}{r_{Dx}} \right)^2 + \left(\frac{y - v_{hy}\tau/\omega_p}{r_{Dy}} \right)^2 + \left(\frac{z - v_{hz}\tau/\omega_p}{r_{Dz}} \right)^2 \right)^{-2} d\tau$$



Parameters of the problem

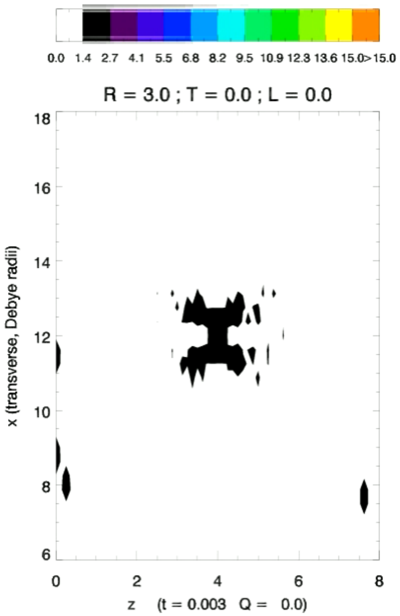
$$R_{D_\alpha} \propto \left(|v_\alpha| + \sigma_{v_\alpha} \right)/\omega_p; \quad \alpha = x, y, z$$

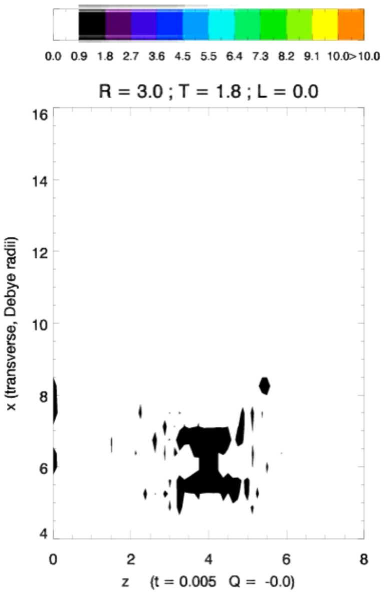
$$t = \tau/\omega_p; \quad \vec{v} = \vec{\nu}\sigma_{v_z}; \quad \vec{r} = \vec{\rho}\sigma_{v_z}/\omega_p; \quad \omega_p = \sqrt{\frac{4\pi e^2 n_e}{m}} \qquad s = r_{D_z} = \frac{\sigma_{v_z}}{\omega_p}$$

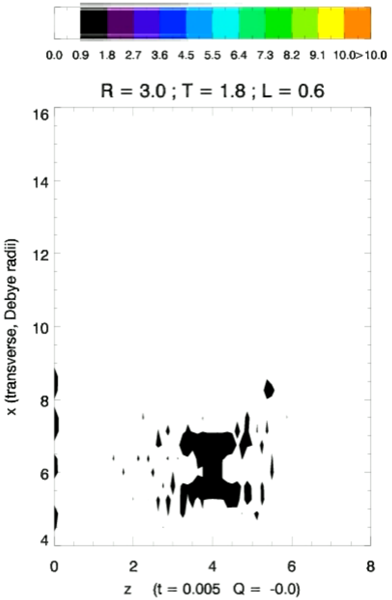
$$R = \frac{\sigma_{v_\perp}}{\sigma_{v_z}}; \quad T = \frac{v_{hx}}{\sigma_{v_z}}; \quad L = \frac{v_{hz}}{\sigma_{v_z}}; \quad \xi = \frac{Z}{4\pi n_e R^2 s^3};$$

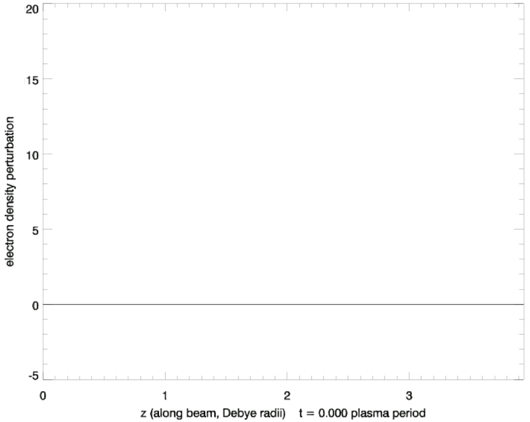
$$A = \frac{a}{s}; \quad X = \frac{x_{ho}}{a}; Y = \frac{y_{ho}}{a}.$$

Numerical simulations: VOPAL, Tech X



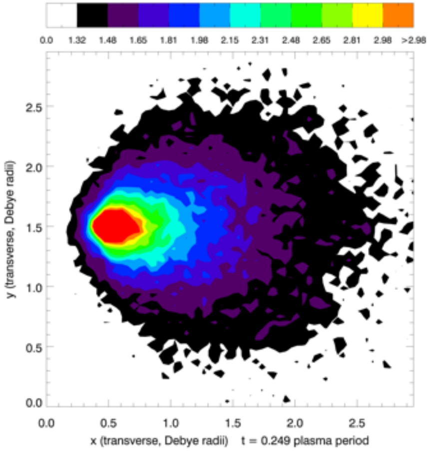


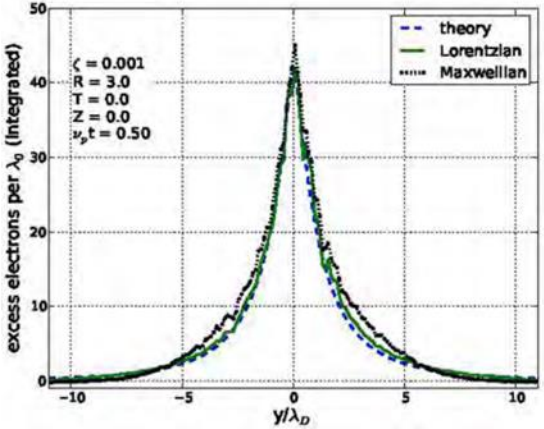


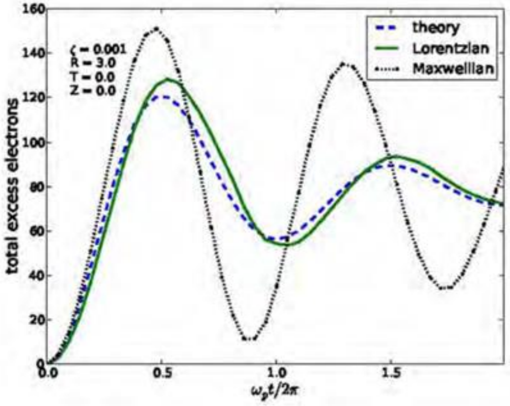


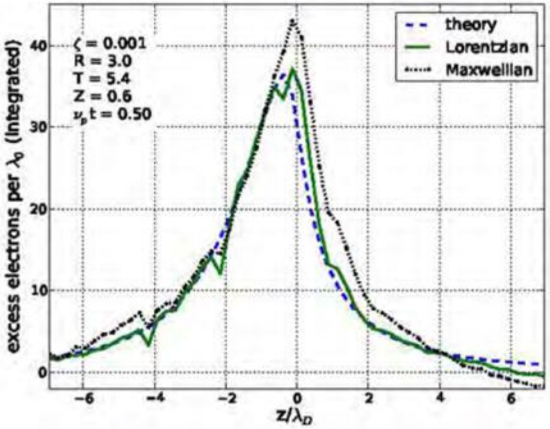
Simulations of modulator: infinite uniform beam

- Simulation of the CeC modulator agree well with the analytical results.









3D modulator simulation with finite beam...

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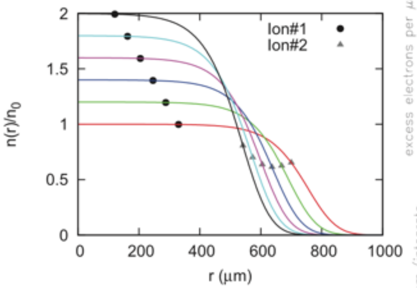
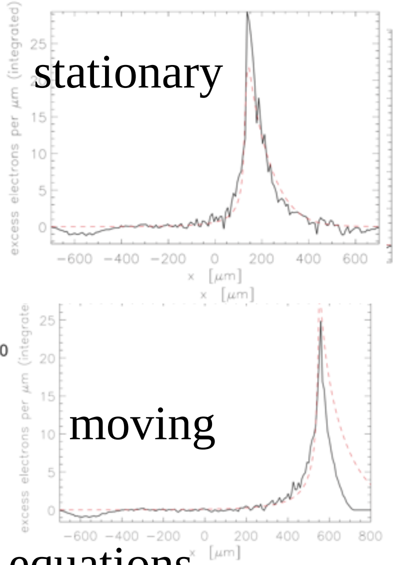
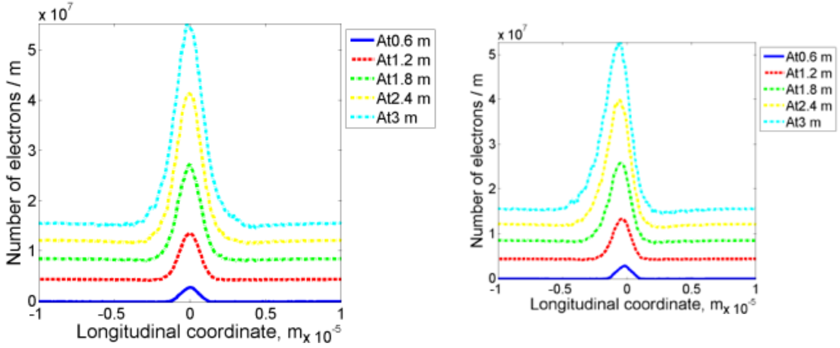
VOPRAL



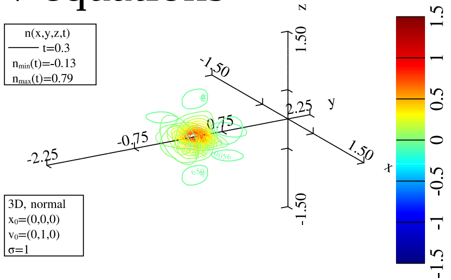


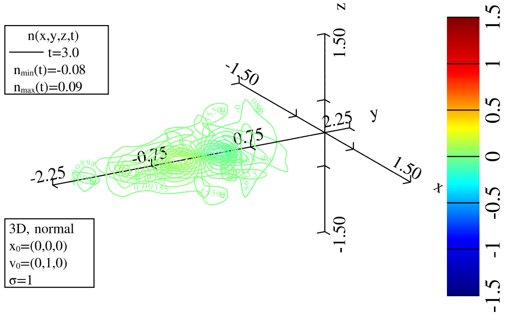
SBU/ SPACE code



stationary (left) and moving (right) ion

- Solving Vlasov equations

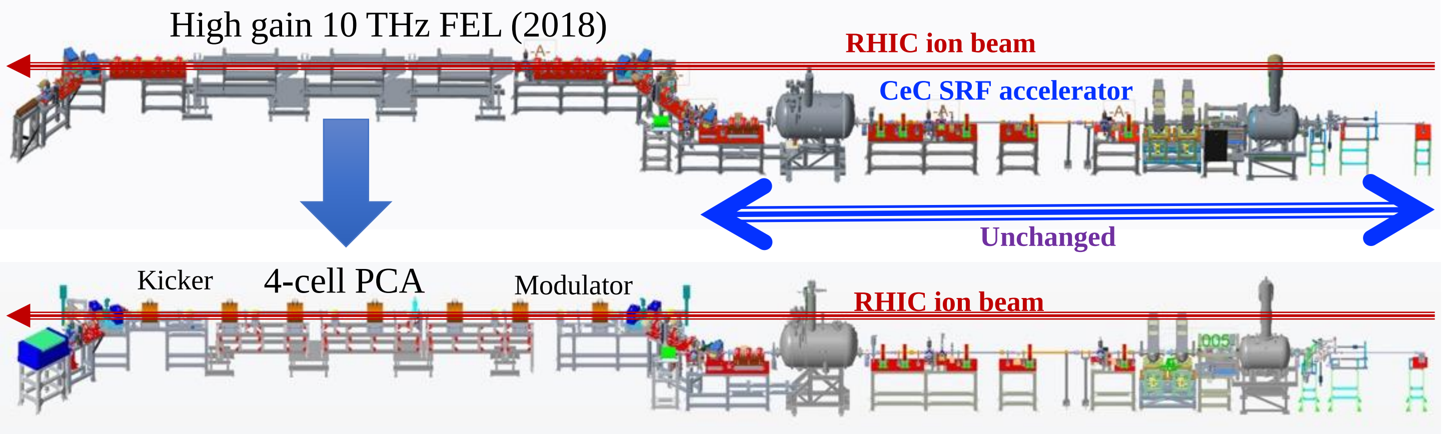




Dynamics of shielding of a moving charged particle in a confined electron plasma, A. Elizarov and V. Litvinenko, Phys. Rev. ST Accel. Beams 18, 044001.

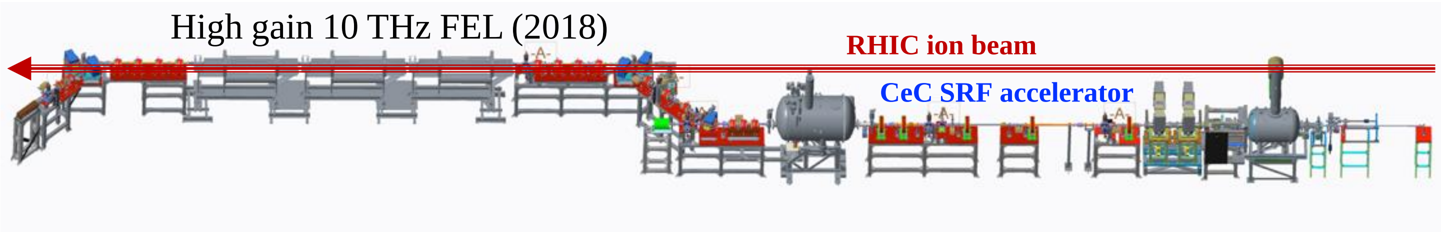
CeC X at RHIC

- 2014-2017: built cryogenic system, SRF accelerator and FEL for CeC experiment
- 2018: started experiment with the FEL-based CeC. It was not completed: 28 mm aperture of the helical wigglers was insufficient for RHIC with 3.85 GeV/u Au ion beams
- We discovered microbunching Plasma Cascade Instability - new type of instability in linear accelerators. Developed design of Plasma Cascade Amplifier (PCA) for CeC
- In 2019-2020 a PCA-based CeC with seven solenoids and vacuum pipe with 75 mm aperture was built and commissioned.
- During Run 20, we demonstrated high gain Plasma Cascade Amplifier (PCA) and observed presence of ion imprint in the electron beam
- New time-resolved diagnostics beamline was built and commissioned.
- Now we are focusing on demonstrating longitudinal CeC cooling.



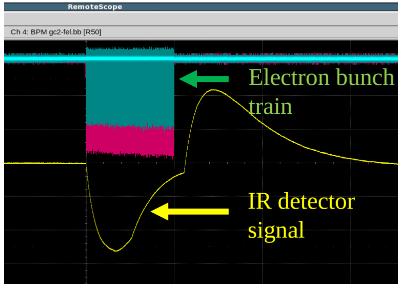
The CeC Plasma Cascade Amplifier has a bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

Attempt to test FEL-based CeC

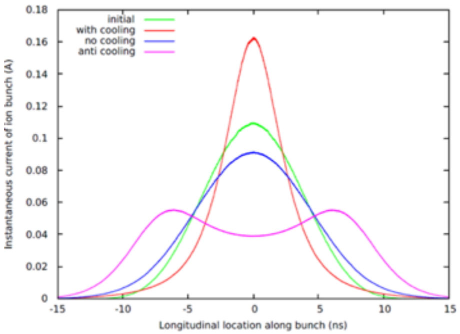


Parameter	Design	Status	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	✔ to match e-beam
Electron energy	21.95 MeV	14.56 MeV	Linac's quench limit
Charge per electron bunch	0.5-5 nC	0.1- 10.7 nC	✔
Peak current	100 A	50 -100A	✔
Bunch duration, psec	10-50	12	✔
Normalized beam emittance	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

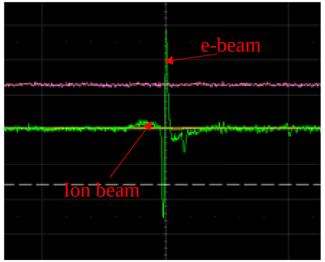


Predicted evolution of ion bunch profile in 40 minutes

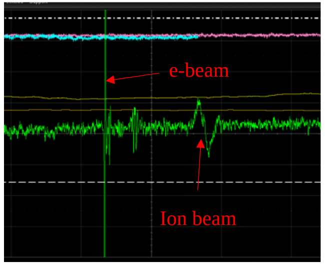


Overlapping and separating electron and 26.5 GeV/ion bunches

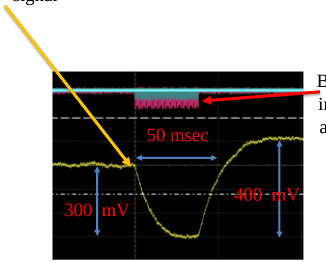
- We developed beam-based alignment technique for nearly perfect overlap of overlap electron and ion beams by aligning their trajectories in common section
- CeC accelerator generates and accelerates electron bunches with frequency of 78 kHz in CW mode (or trains of electron bunches with this frequency).
- This frequency is equal to revolution frequency of 26.5 GeV/u ion bunched in RHIC and CeC LLRF system locks locking the CeC RF system with RHIC RF system
- We typically used six or twelve equally spaced ion bunches circulating in RHIC, but only one bunch can overlap with electrons at 78 kHz – interacting bunch. The other bunches serve as witness bunches for comparison.
- The CeC LLRF system controls of the relative phase of two RF systems and allows us to overlap very short (~30 psec) electron bunch with the center of selected ion bunch with accuracy much better than ion bunches duration (~ 10 nsec RMS) – see top picture on the right
- We can establish the overlap (interaction On) or change separation it by tents of nsec to completely separate the bunches in time (interaction OFF) – see middle picture on the right
- Imprint from ion beam will result in increased power radiated by electron beam when interaction is ON
- To verify overlap both in time and space, we would intentionally induce a lot of noise in e-beam to observe heating of the interacting ion bunch



Overlap (20 ns, 10 mV per division)

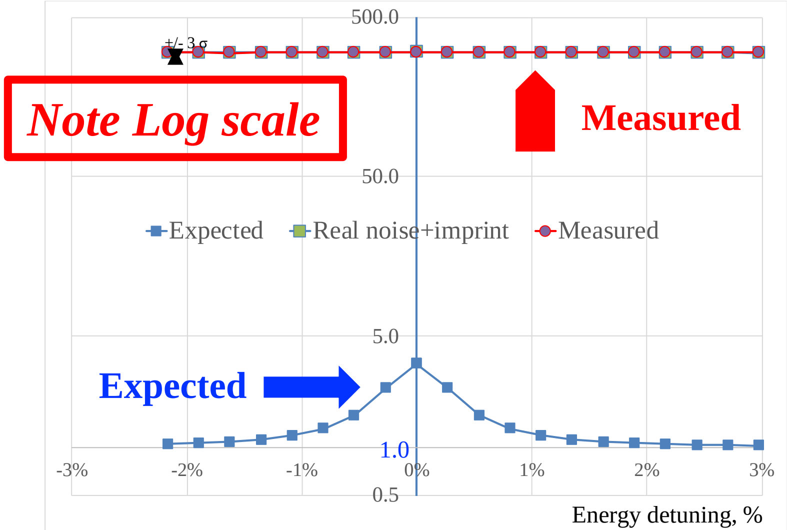


No overlap (50 ns, 2 mV per division)



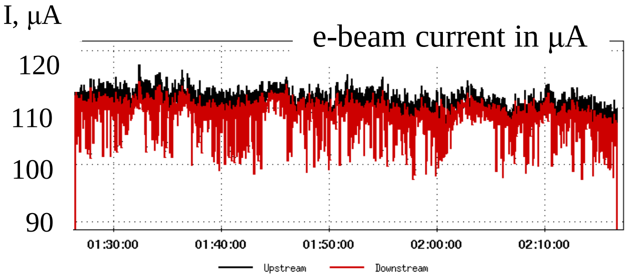
Puzzle of the CeC Run 18

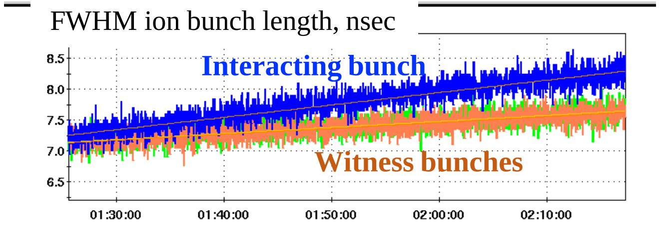
Search for ion's imprint in electron beam and matching beam's relativistic factors was the first important step in CeC experiment



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

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





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

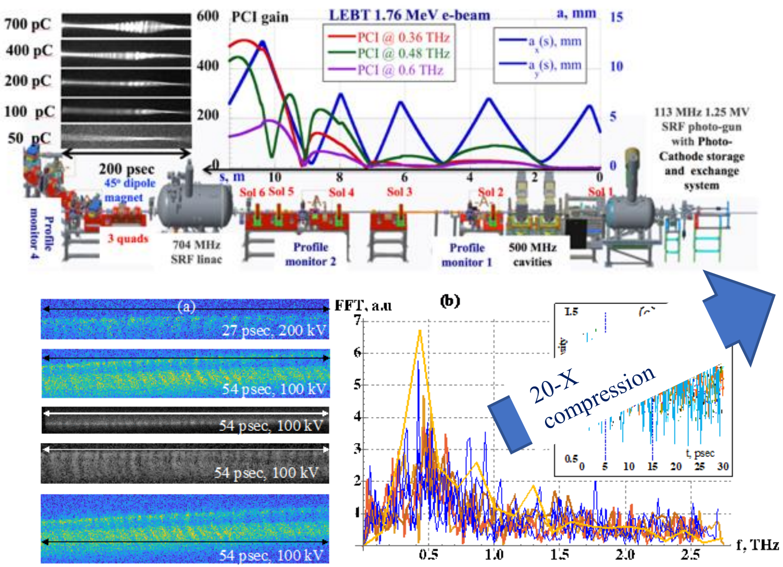
- **We ran out of time to demonstrate the FEL-based CeC during Run 18 with RHIC.**
- **FEL-based CeC concept remains valid and is waiting for experimental demonstration.**

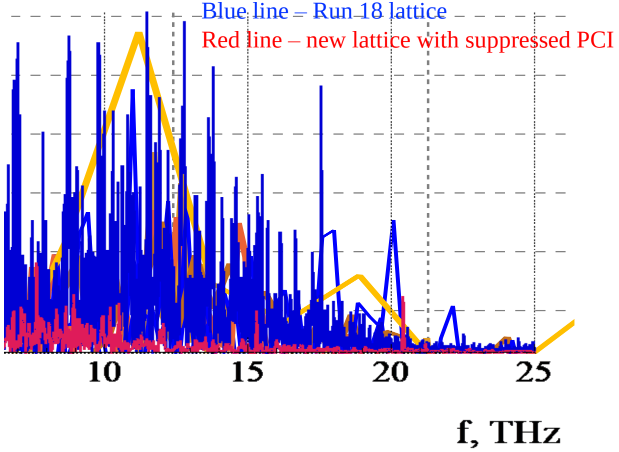
Solving the Puzzle

RHIC cryo system extended operation for LEReC mid-September 2019 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

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



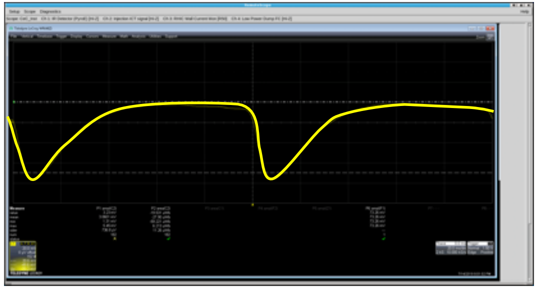


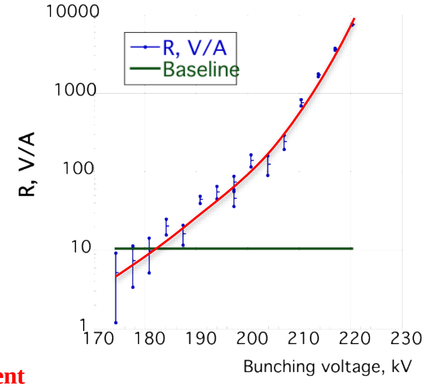
(a) Measured time profiles of 1.75 MeV electron bunches with 0.45 nC to 0.7 nC; (b) Seven measured overlapping spectra and PCI spectrum simulated by SPACE (slightly elevated yellow line); (c) Clip shows a 30-psec fragment of seven measured relative density modulations.

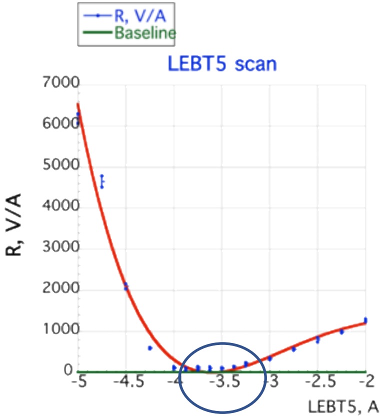
We showed in simulations that we can control noise level in the electron beam and confirmed this in the experiment during a short run in Summer 2019

Run 19: control of the noise in electron beam

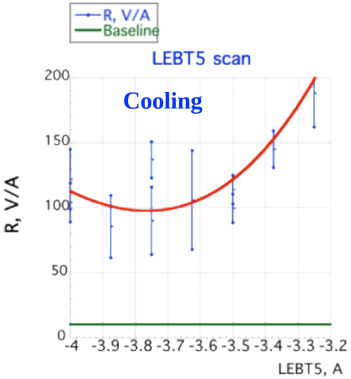
Run 18 lattice and beam: 0.6 nC per bunch
Large signal of 2,500 V/A ~ 250-fold above base line. Can be seen both on scope and measured easily

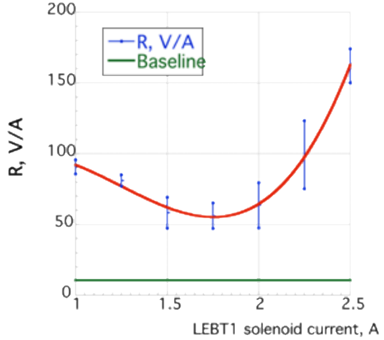






1.5 nC, 75 A peak current

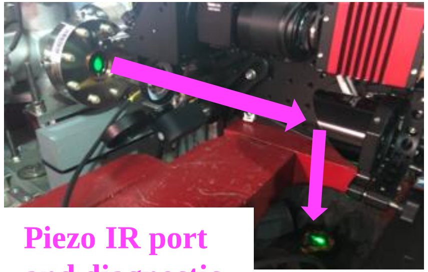




We demonstrated that with 75 A peak current we can reduce beam noise to acceptable level. It could be as low as 6-10 times above the baseline

The e-beam noise level

IR port
and
diagnostic



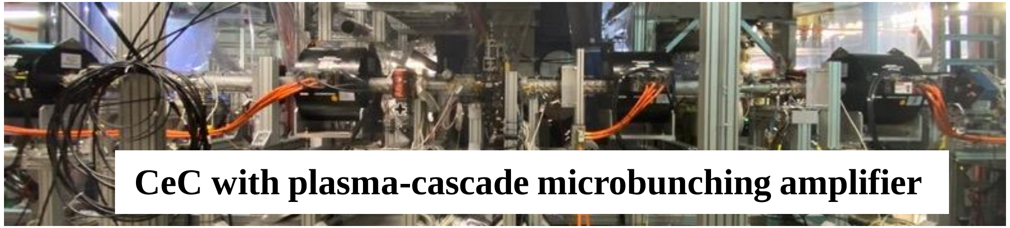
Piezo IR port
and diagnostic

- In Run 19 we established technique for the e-beam noise measuring
  - The THz noise in the e-beam results far-IR radiation from dipole magnet, whose power is measured by the Gentec broad-band IR detector connected to a lock-in amplifier synchronized with pulsing electron beam.
  - IR radiation from the bending magnet is periodically blocked, (modulation-demodulation technique) to eliminate effect of X-rays from dumped beam on the IR detector
- The baseline power level (e.g. power from the Poisson shot noise) was measured using long low charge (~300 pC) beam propagating in relaxed low-beam transport lattice. Measurements were in good agreement with simulation.
- All measurements normalizes by average beam current
- The IR power generated by electron beam with 1.5 nC per bunch and the nominal compression was compared with the base line IR power level

- **Summary of results**
- **Measured ratio κ_{stat} of the noise power in the electron beam to the Poisson noise limit is more than 2 and less then 12**
- **Beam noise satisfies requirements for cooling : $\kappa_{stat} < 100$**

Progress with CeC

- We developed complete theory and simulations of CeC with micro-bunching Plasma-Cascade Amplifier (PCA)
- We replaced the FEL-based CeC to completely new PCA-based CeC system
- We commissioned PCA-based CeC system and and demonstrated Plasma-Cascade Amplification experimentally (previous talk)
- We also built and commissioned diagnostics beam-line for time-resolved measurements of e-beam parameters
- We also improved our IR diagnostics

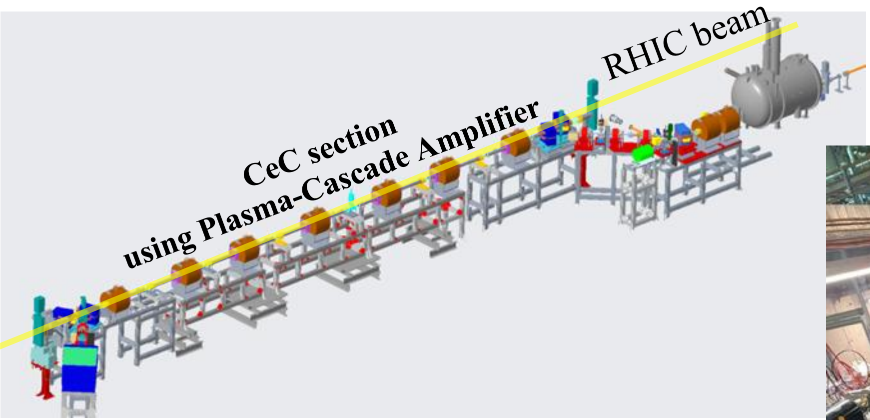


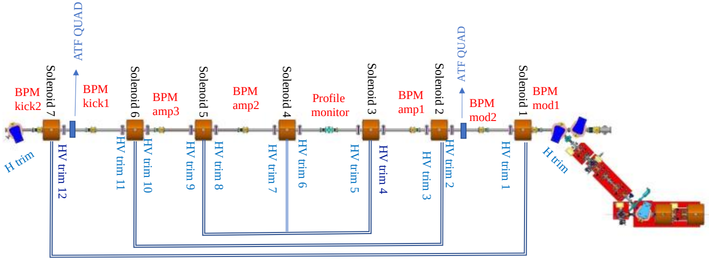
PCA-based CeC

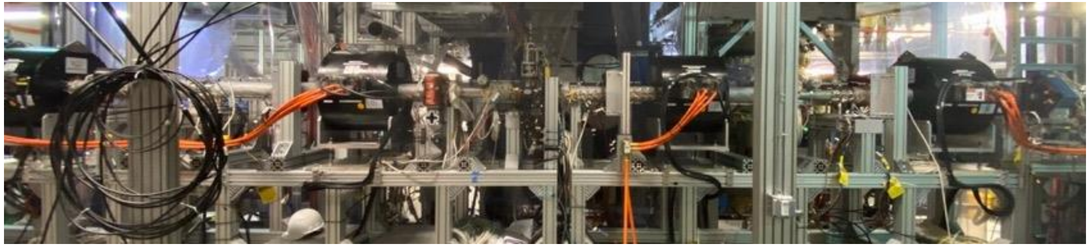
Time-resolved diagnostics

PCA was installed into CeC system in 2019-2020

- Accurate alignment of the electron beam trajectory is critically important for operation of the PCA-based CeC.
- First, we aligned ion beam with centers of two quadrupoles in the CeC section
- Second, we accurately measured both location and the angle of the solenoid's axes using ion beam and RHIC BPM – this is a novel method that we developed. Solenoids then were aligned with best accuracy the survey group can provide
- Third, we aligned electron beam with axes of solenoids
- This is a new technique we developed to guarantee overlapping of electron and ion beams as well providing straight trajectory for electron beam





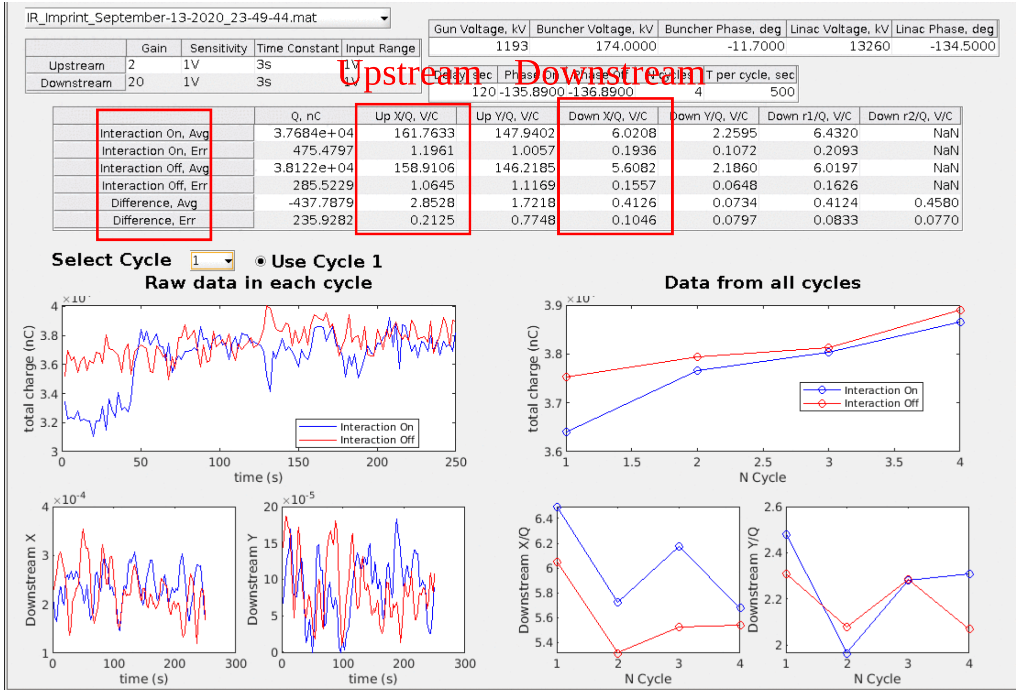


The Ion Imprint studies: Run 20

- We used high-gain PCA lattice to boost radiation at 35 μm at the level detectable by IR detectors after the spectrometer. The IR signal was then measure by lock-in amplifier with two outputs (X – in-phase, Y- out-of-phase). Without the PCA boost, signal was too low to detect reliably.
- We used high-order modulation-demodulation (MDM) technique to detect the imprint. MDM was accomplished by overlapping and separating electron and ion bunches in time: interaction ON/ interaction OFF
- We observed clear presence of the ion imprint in the electron beam resulting in increase of the e-beam radiation at 35 μm with average imprint of

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

Typical "good" measurement: 4 cycles with 500 measurements each



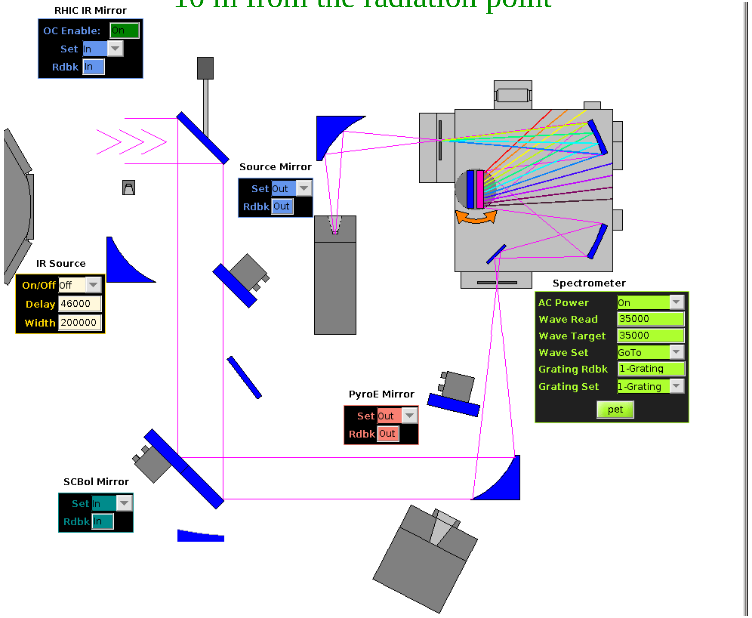
	Gain	Sensitivity	Time Constant	Input Range
Upstream	2	1V	3s	1V
Downstream	20	1V	3s	1V

Gun Voltage, kV	Buncher Voltage, kV	Buncher Phase, deg	Linac Voltage, kV	Linac Phase, deg
1193	174.0000	-11.7000	13260	-134.5000

Delay, sec	Phase On	Phase Off	N cycles	T per cycle, sec
120	-135.8900	-136.8900	4	500

	Q, nC	Up X/Q, V/C	Up Y/Q, V/C	Down X/Q, V/C	Down Y/Q, V/C	Down r1/Q, V/C	Down r2/Q, V/C
Interaction On, Avg	3.7684e+04	161.7633	147.9402	6.0208	2.2595	6.4320	NaN
Interaction On, Err	475.4797	1.1961	1.0057	0.1936	0.1072	0.2093	NaN
Interaction Off, Avg	3.8122e+04	158.9106	146.2185	5.6082	2.1860	6.0197	NaN
Interaction Off, Err	285.5229	1.0645	1.1169	0.1557	0.0648	0.1626	NaN
Difference, Avg	-437.7879	2.8528	1.7218	0.4126	0.0734	0.4124	0.4580
Difference, Err	235.9282	0.2125	0.7748	0.1046	0.0797	0.0833	0.0770

Downstream IR diagnostics
10 m from the radiation point



Summary of the imprint measurement results

#	Date	Time	N cycles	Good cycles	$\gamma_{ions}/\gamma_{elec}$ Estimation	δD	δU	σ, δD
19	12-Sep	8:22	**2**	**1**	1.006	**3.33%**	**-5.14%**	**4.84%**
20	12-Sep	8:57	**2**	**1**	1.006	**2.43%**	**-10.48%**	**3.03%**
21	12-Sep	16:55	**4**	**2**	1.005	**2.80%**	**5.98%**	**1.34%**
22	12-Sep	18:16	**4**	**2**	1.011	**8.60%**	**2.60%**	**1.29%**
23	12-Sep	20:21	**4**	**2**	1.011	**2.67%**	**0.96%**	**1.18%**
25	13-Sep	3:20	**4**	**3**	1.002	**13.90%**	**3.60%**	**1.78%**
26	13-Sep	5:13	**4**	**1**	0.999	**7.50%**	**2.97%**	**1.23%**
27	13-Sep	5:13	**2**	**1**	0.996	**1.02%**	**1.18%**	**3.68%**
28	13-Sep	8:05	**4**	**2**	0.995	**0.09%**	**-0.04%**	**1.85%**
29	13-Sep	19:34	**4**	**1**	1.001	**27.70%**	**4.37%**	**2.45%**
30	13-Sep	23:49	**4**	**4**	0.985	**7.29%**	**1.53%**	**1.19%**
31	14-Sep	1:03	**4**	**4**	0.985	**7.23%**	**0.94%**	**1.28%**
32	14-Sep	8:24	**4**	**4**	0.996	**9.97%**	**4.80%**	**1.54%**
						<δD>	**<δU>**	**<σ>**
		Weighted avarage				**7.50%**	**1.85%**	**0.32%**

$$d = \frac{\langle A_{ON}\rangle}{\langle A_{OFF}\rangle}\cdot\frac{\langle Q_{OFF}\rangle}{\langle Q_{ON}\rangle} - 1;\ \sigma_d = \sqrt{\frac{\sigma^2_{AON}}{\langle A_{ON}\rangle^2}+\frac{\sigma^2_{AOFF}}{\langle A_{OFF}\rangle^2}+\frac{\sigma^2_{QON}}{\langle Q_{ON}\rangle^2}+\frac{\sigma^2_{QOFF}}{\langle A_{OFF}\rangle^2}}$$

Weighted average

$$\langle A\rangle_W = \frac{\sum_i^{N_S} n_i\langle A_S\rangle_i}{\sum_i^{M} n_i} \circ \frac{\sum_i^{N_C}\langle A_C\rangle_i}{N_C}$$

Correlations

$$d\ln A_D \approx \frac{b\cdot A_{U0}}{a+b\cdot A_{U0}}\, d\ln A_U;$$

$$\Delta D = r\cdot\langle \delta U\rangle;\ r = \frac{b\cdot A_{U0}}{a+b\cdot A_{U0}},$$

$$r = 1.5 \pm 0.2$$

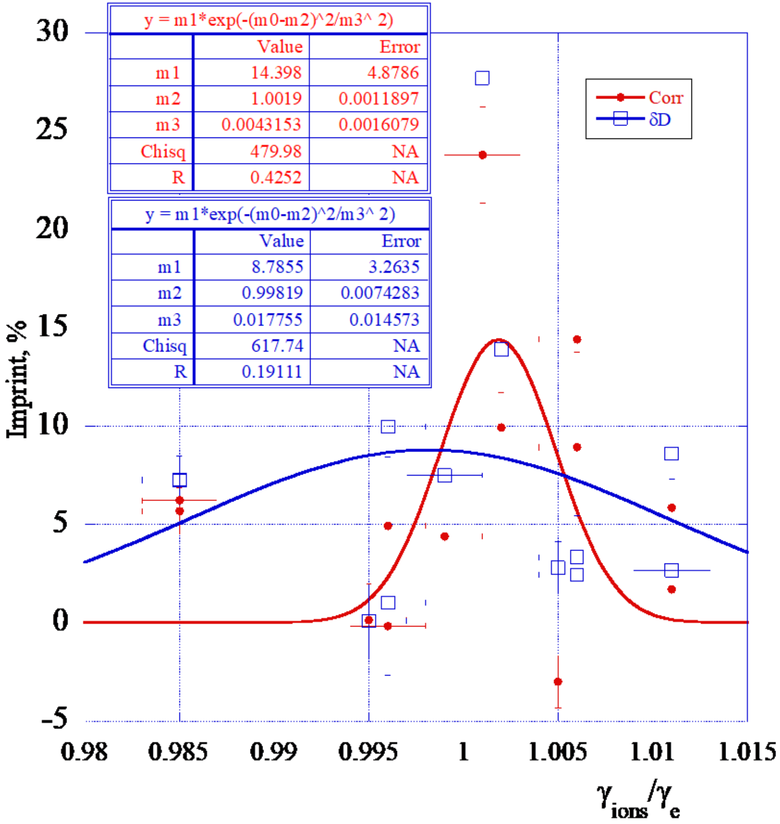
$$\delta D_C = \delta D - r\cdot\delta U = 4.7\%$$

Downstream

$$\delta D = \frac{\langle X_{D\,ON}\rangle}{\langle X_{D\,OFF}\rangle}\cdot\frac{\langle Q_{OFF}\rangle}{\langle Q_{ON}\rangle} - 1$$

$$\delta U = \frac{R_{U\,ON}}{R_{U\,OFF}}\cdot\frac{\langle Q_{OFF}\rangle}{\langle Q_{ON}\rangle} - 1;\ R_U = \sqrt{\langle X_U\rangle^2+\langle Y_U\rangle^2}$$

Presence of ion imprint in electron beam radiation



Each point represents a scan (typically with 4 cycles)

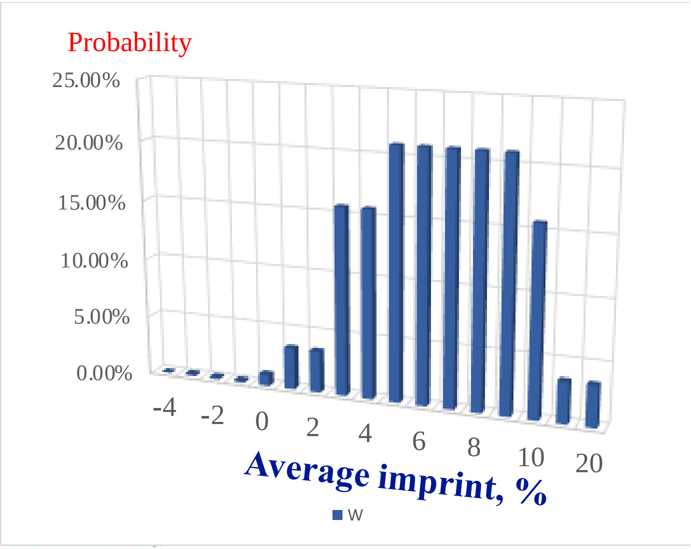
Probabilities

Probability that average measured imprint above zero, is 99% with raw data and and 99.8% for corrected data. There is 0.2% probability that we miss the imprint

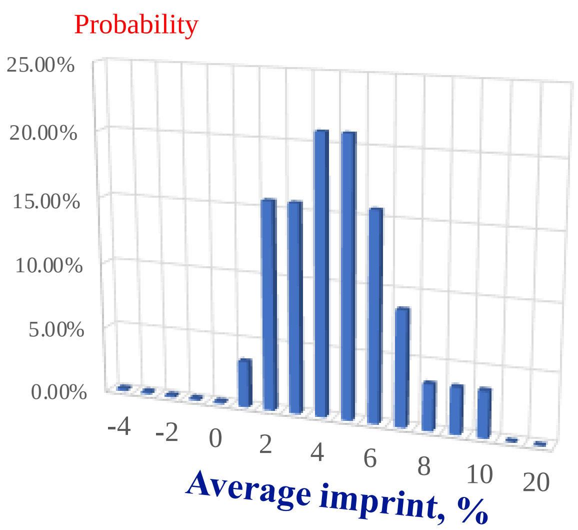
The most probable value of observed imprint:

$$4.7\% \pm 0.4\%(\text{systematic}) \pm 0.3(\text{random})\%$$

Imprint: Raw data



Imprint: corrected by the upstream data



Conclusions

- The process of demonstrating presence of ion imprint in electron beam was challenged by many obstacles, which we managed to overcome.
- We were unpleasantly surprised by huge amount of noise in electron beam which was present in electron beam from CeC linac in spite of rosy predictions from simulation codes (Parmela, Astra, Elegant, Impact-T…) . Title of PhD thesis of Irina Petrushina is a very good summary of the shock we experienced: *"The Chilling Recount of an Unexpected Discovery: First Observations of the Plasma-Cascade Instability in the Coherent Electron Cooling Experiment"*
- We solve the puzzle by developing novel theory of plasma-cascade instability and demonstrating it both experimentally and in simulations.
- Next, we learned how to control noise in the electron beam how generate electron beam with necessary quality for the CeC experiment and how to use it when it is needed
- After a very long learning process we managed to observe ion imprint experimentally. We also learned that this measurement is relatively complicated to be used for matching relativistic factors of two beams. We found a more reliable and relatively fast method to match beam's relativistic factors

Thank you for attention