Results of the Coherent electron Cooling (CeC) experiment at RHIC

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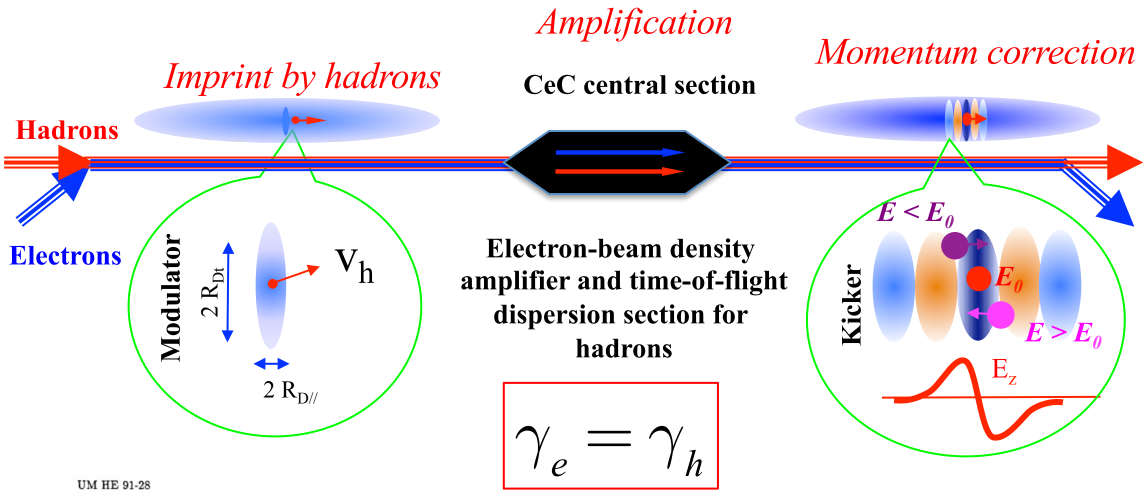
IPAC 2022, Bangkok, Thailand, June 15, 2022

What is Coherent electron Cooling (CeC)

- It is stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz. All CeC systems are based on the identical principles:
    - Hadrons create density modulation in 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 longitudinal degrees of freedom.



UM HE 91-28
August 7, 1991

COHERENT ELECTRON COOLING
1. Physics of the method in general

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Randall Laboratory of Physics, University of Michigan
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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PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

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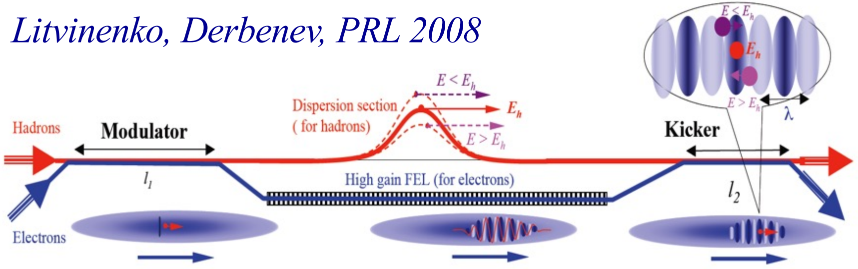
(Received 11 April 2013; published 20 August 2013)

- ✓ **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:** 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 system should not significantly exceed system signal introduced by shot noise in the hadron beam

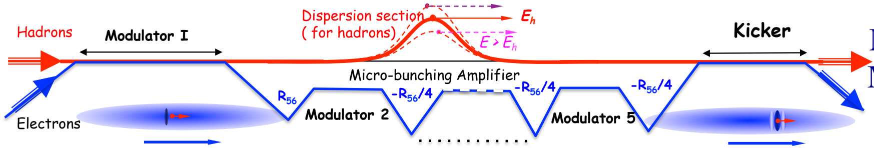
CeC schemes

Litvinenko, Derbenev, PRL 2008



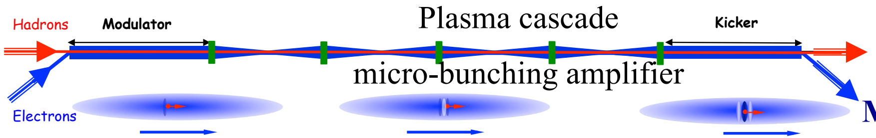
High gain FEL amplifier

Ratner, PRL 2013



Multi- Chicane Microbunching amplifier

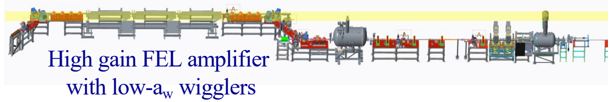
Litvinenko, Wang, Kayran, Jing, Ma, 2017



Plasma-Cascade Microbunching amplifier

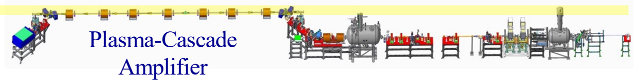
Can be tested experimentally at RHIC

RHIC Run 18



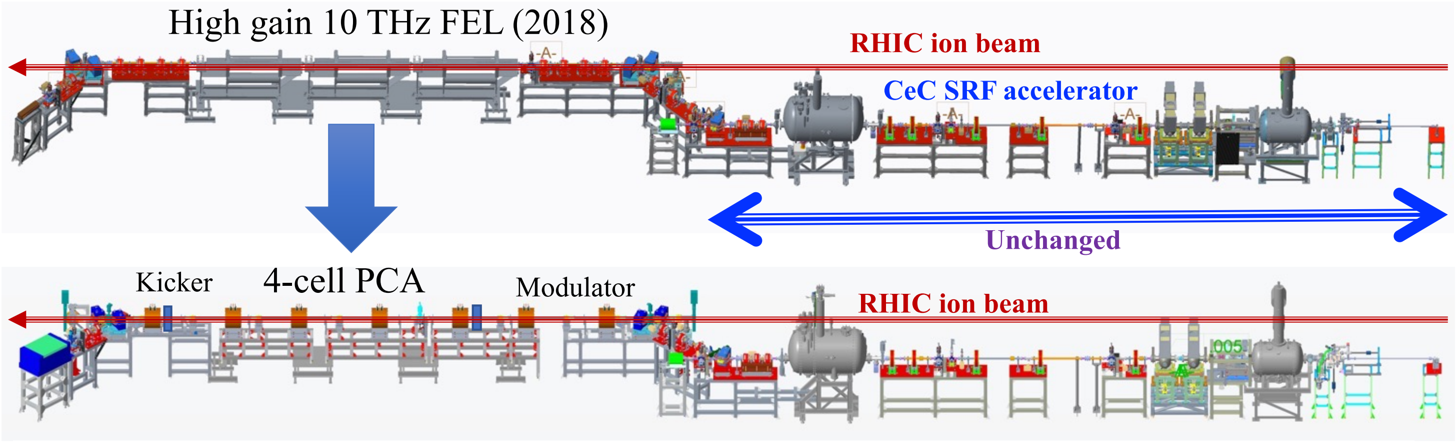
Cooling test would require significant modification of the RHIC lattice & superconducting magnets

RHIC Runs 20-22



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 program with low energy 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
- We observed regular e-cooling in Run 21, but CeC cooling was washed out by large timing jitter of the seed laser and resulting 0.35% RMS e-beam energy jitter



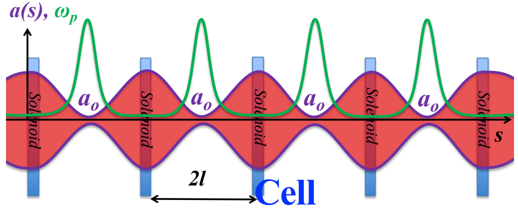
The CeC Plasma Cascade Amplifier has a bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

Encountered challenges

- In Run 2018, while operating with FEL amplifier, we discovered that electron beam in the low energy (ballistic compression) section was developing very strong longitudinal instability. Detailed studies showed that this was Plasma-Cascade Instability caused by strong transverse focusing. We developed lattice of the CeC accelerator suppressing this instability and providing quiet electron beam with noise comparable with that of the shot-noise.
- In Run 2021, we attempted to demonstrate CeC, but 5×10^{-4} relative beam energy jitter - caused by 15 psec RMS time jitter of the seed laser pulses - prevented us from observing CeC. It simply was washed away.
- In Run 2022, a new seed laser with 3 psec RMS time jitter was incorporated, and we achieved beam parameters sufficient for observation of the CeC cooling. Unfortunately, two major failures, both caused by human errors, consumed 71% of the run time and we were unable to complete the experiment – we simply run out of time
- Main remaining challenge is large (5% RMS) jitter in the energy of the laser pulses and corresponding variations of the electron bunch charge. This jitter causes significant variation in space-charge dominated dynamics of the electron beam and should be eliminated for reliable measurements and demonstration of CeC
- One of challenges for diagnostics is presence of vary large (sub–V) broad-band interference signals in all cables coming out of RHIC tunnel. It is likely a result on multiple ground loops.

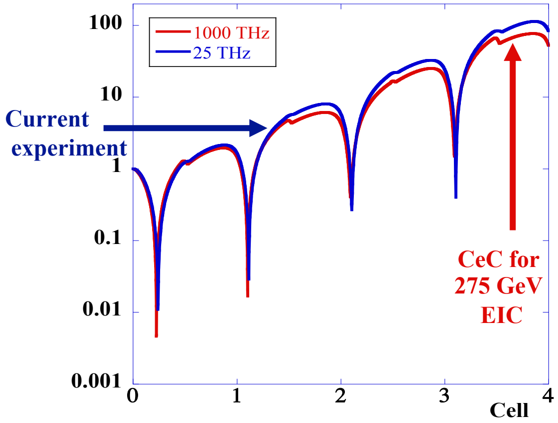
What is PCA? : Parametric instability caused by strong transverse focusing

"Standard" 4-cell PCA



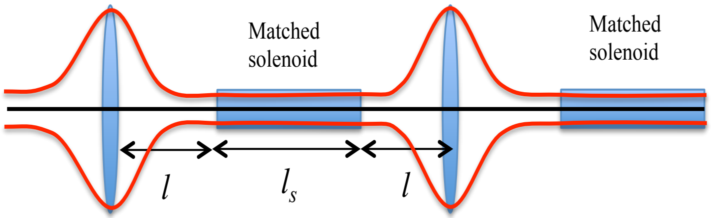
$$k_{sc} = \sqrt{\frac{2}{\beta_o^3 \gamma_o^3} \frac{I_o}{I_A} \frac{l^2}{a_o^2}};\ k_\beta = \frac{\varepsilon l}{a_o^2}$$

Density modulation, a.u.

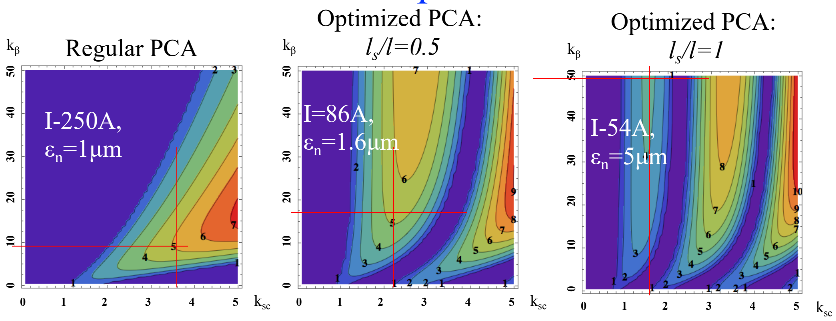


Results of 3D simulations with code SPACE

Optimized PCA cell



PCA Gain per cell



Simulations of Coherent Electron Cooling with Two Types of Amplifiers, Jun Ma, Gang Wang, Vladimir Litvinenko, International Journal of Modern Physics A (IJMPA), Vol. 34 (2019) 1942029 (

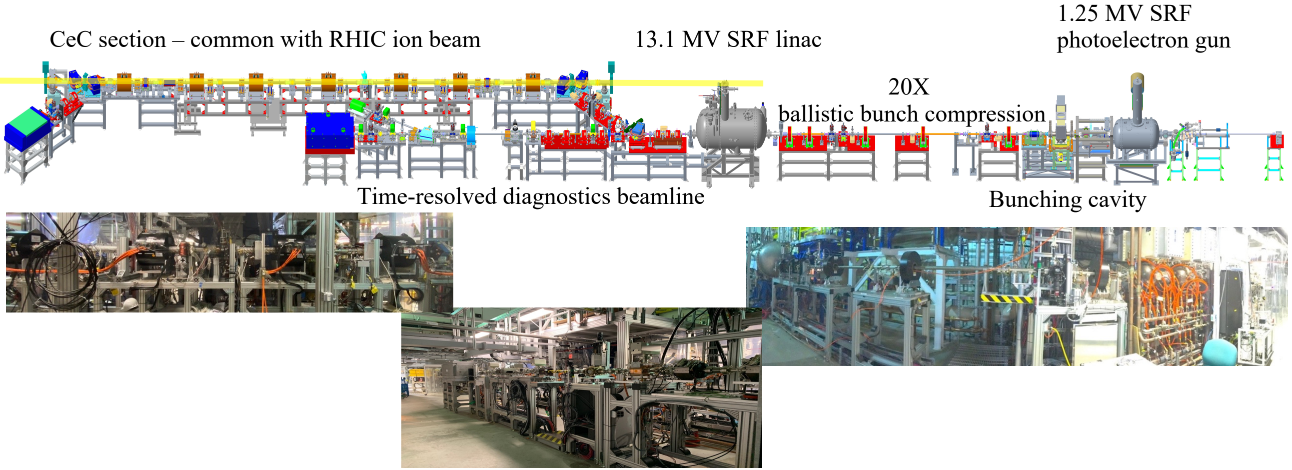
Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams, V.N. Litvinenko, G. Wang, D. Kayran, Y. Jing, J. Ma, I. Pinayev, arXiv preprint arXiv:1802.08677, 2018

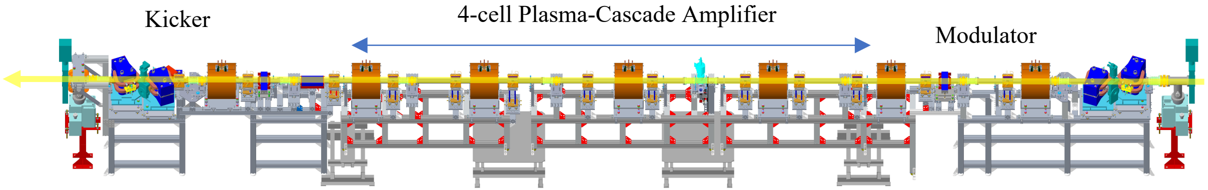
Results obtained up to the date

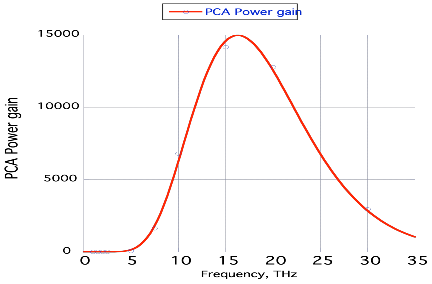
- Beam parameters are either on the target or close to the target values
- We observed high gain in FEL system used for early version of CeC
- We developed sophisticated IR diagnostics for evaluation of the PCA gain and observation of ion imprint: it includes filtering, lock-in amplifier and 3rd order modulation-demodulation technique
- Noise in the electron beam does not exceed 10 times that of the short (Poison statistics) noise level
- We observed PCA-amplified imprint of ion beam in the electron beam radiation
- We observed high PCA gain at frequencies between 5 and 10 THz
- We observed regular electron cooling – albeit very week – of 26.5 GeV/u ion beam – the highest energy electron cooling
- We observed recombination between elections from CeC accelerator and 26.5 GeV/u ions, using a system developed for LeREC.

Unique SRF accelerator and CeC amplifier

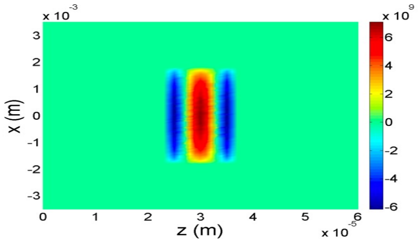
Parameter	
Charge per bunch, nC	1.5
Peak current, A	50
Normalized emittance, µm	1.5
Beam energy (inj), MeV	1.75
Final beam energy, MeV	14.56
Energy spread, RMS	< $2\text{x}10^{-4}$
Bunch rep-rate, kHz	78







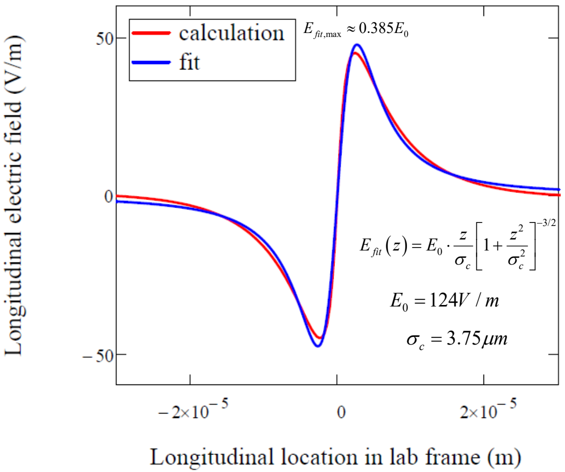
Self-consistent 3D simulations: imprint + PCA



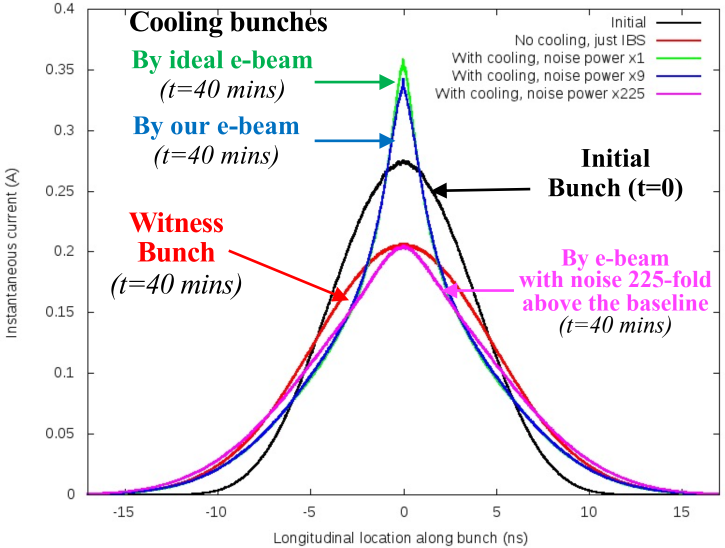
Expectations: full 3D treatment

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

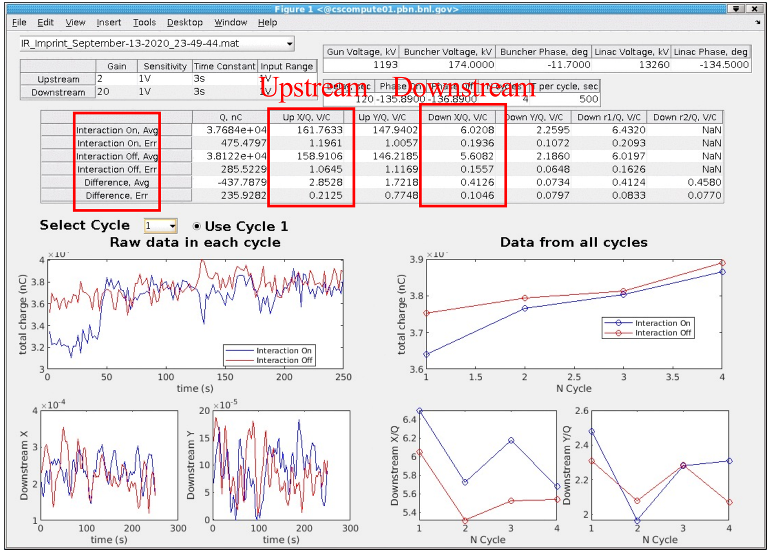
The Ion Imprint studies: Run 2020

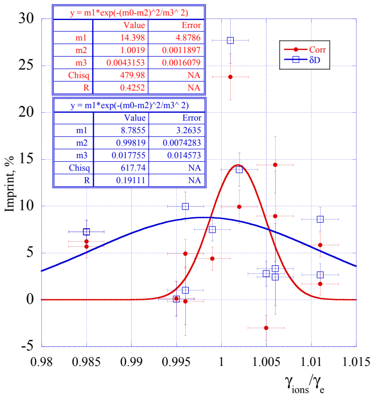
- We observed clear presence of the ion imprint in the electron beam resulting in increase of the e-beam radiation at 35 μm with average imprint of

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

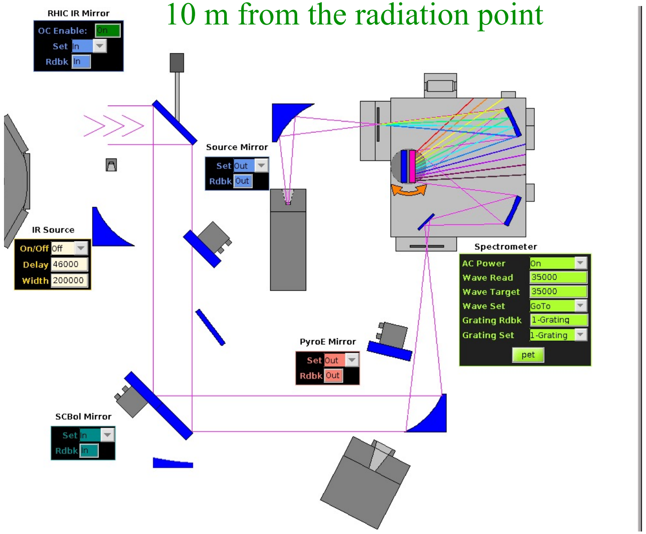
- We applied PCA to boost radiation at 35 μm at the level detectable by current IR detectors after the spectrometer

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



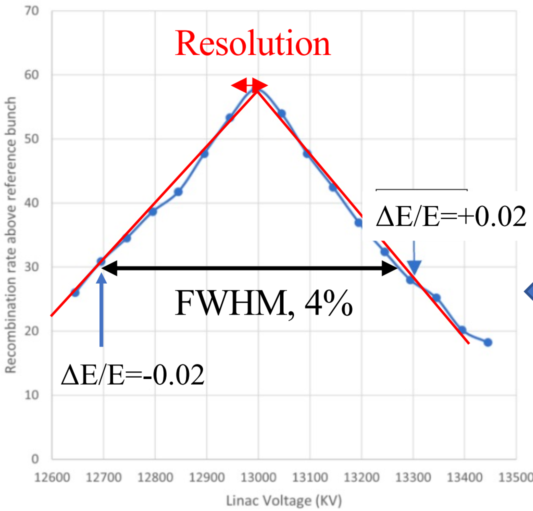


Downstream IR diagnostics
10 m from the radiation point



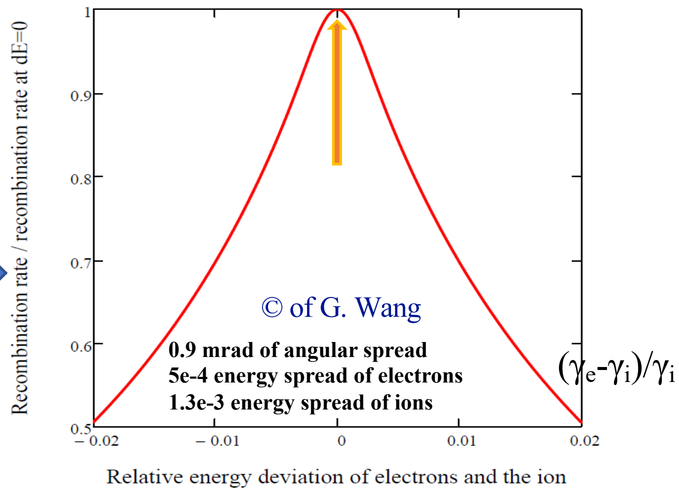
Recombination of electrons with Au ions: Run 2021

Experiment



Triangular shape of the measured dependence allows to define matching of the relativistic factors with accuracy ~ 0.2%, which is significantly smaller than 4% FWHM.
This finding will reduce the range where we need to search for the CeC signature by 5-to-10 fold.

Calculations



$$\sigma(v_x,v_y,v_z)=A\frac{2h\nu_0}{m_e(v_x^2+v_y^2+v_z^2)}\left[\ln\left(\sqrt{\frac{2h\nu_0}{m_e(v_x^2+v_y^2+v_z^2)}}\right)+\gamma_1+\gamma_2\left(\frac{m_e(v_x^2+v_y^2+v_z^2)}{2h\nu_0}\right)^{1/3}\right]$$

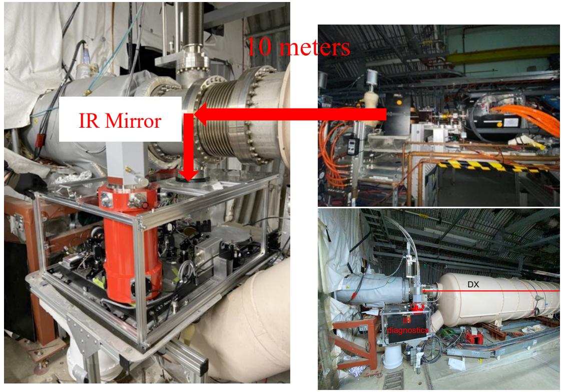
$$f_e(v_e)=\frac{1}{(2\pi)^{3/2}\beta_{e,\perp}^2\beta_{e,z}}\exp\left(-\frac{v_{e,x}^2+v_{e,y}^2}{2\beta_{e,\perp}^2}\right)\exp\left(-\frac{(v_{e,z}-v_{z0})^2}{2\beta_{e,z}^2}\right)$$

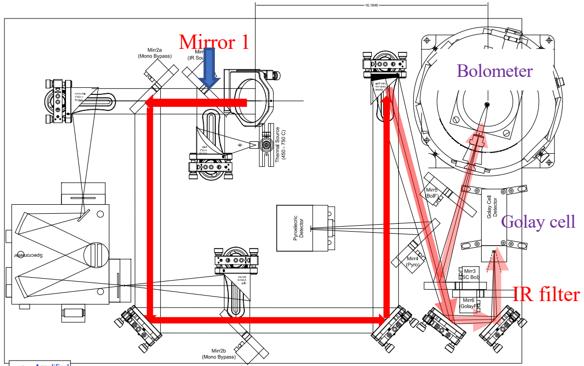
$$f_I(v_i)=\frac{1}{(2\pi)^{3/2}\beta_{i,\perp}^2\beta_{i,z}}\exp\left(-\frac{v_{i,x}^2+v_{i,y}^2}{2\beta_{i,\perp}^2}\right)\exp\left(-\frac{v_{i,z}{}^2}{2\beta_{i,z}^2}\right)$$

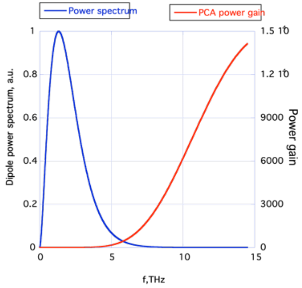
This results include convolution of the exact formula recombination cross-section (in the commoving frame) with distributions of two beams

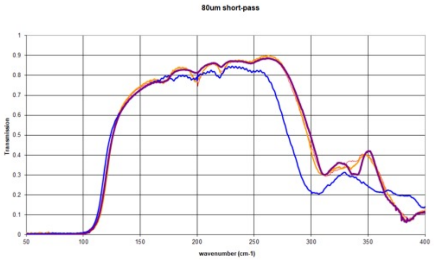
How PCA gain is measured?

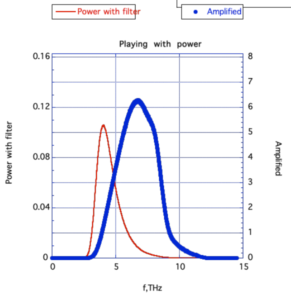
- We used IR radiation from the bending magnet at the exit of the CeC section. Critical frequency of synchrotron radiation from the bending magnet is 1.3 THz
- PCA gain peaks at 15 THz and there is no gain below 4 THz
- IR radiation is intercepted by 2” mirror 10 meters downstream
- For there measurements, the radiation was delivered to two most sensitive IR detectors: broad-band Golay cell or cryo-cooled Bolometer.
- IR filter with passband of 3.5-10 THz was used in front of the Golay cell to improve sensitivity at high frequencies (see next slide)
- Signal from Golay cell was detected by lock-in amplifier synched with the electron bunch pattern (typically 5 Hz, five 100 msec bunch trains per second). We used 3rd order modulation-demodulation (MDM) technique to remove background unrelated to IR radiation, by periodically blocking IR using Mirror 1.
- Signal from Bolometer was delivered in unsynchronous mode (140 kilo-samples per second) with respect to electron beam pattern. Analog signal was not available. We developed MatLab application for asynchronous detection of this digital pattern.
- PCA gain was evaluated by comparing radiated power in the PCA lattice (strong solenoids) with relaxed lattice (weak solenoids) using the same setting of the CeC accelerator and the electron beam





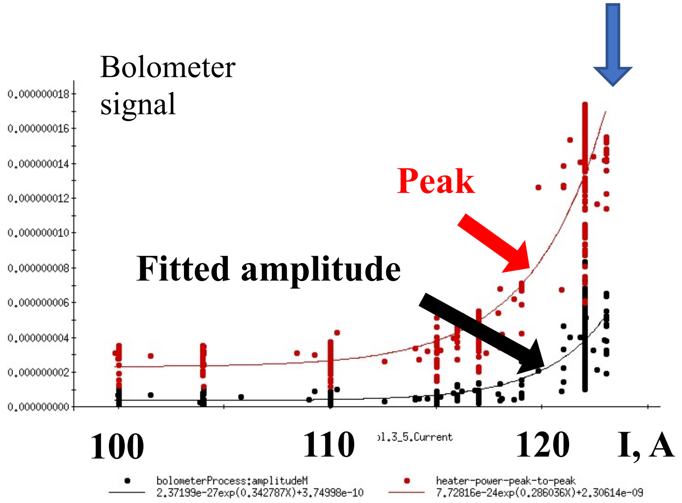




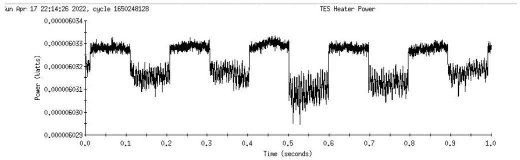


Comparing measurements with expectations

- Golay cell + IR filter measurements resulted in the average increase of IR power by factor 65 with PCA lattice
  - With 50% of electron bunch satisfying PCA condition (peak gain of 100 at 15 THz), expected increase of the measured IR power is 60
- Cryo-cooled bolometer measurements resulted in 100±20 average and 300±50 peak increase of IR power caused by PCA lattice
  - The bolometer manual specifies the sensitivity range from 6 THz to 60 THz, but Absence of calibrated spectral response does not allow accurate comparison
  - Very crude estimation (using a step-function response in 6 to 60 THz) shows that with 50% of electron bunch satisfying PCA, expected increase of the measured IR power is 535
- Both results are in reasonable agreement with our expectations



Exponential growth of the IR signal at the bolometer as function of current in PCA solenoids: e-fold increase each 3 A (2.4%)



Conclusions

- Experimental demonstration of Coherent electron Cooling was and remains very challenging endeavor
- I want to thank everybody who participated in very challenging CeC run 2022: RHIC operators, colleagues from Accelerator Physics, RF, Vacuum, Instrumentation, Cryogens, Control, Mechanical systems and ES&F division, as well as the CeC team, for their dedicated and steadfast support of our attempt to demonstrate this stubbornly resisting phenomenon
- It is unfortunate that we failed to reach our main goal for this Run – demonstration of longitudinal Coherent electron Cooling – because of two major set-backs
- Nevertheless, all main components of the CeC process were successfully demonstrated. With modest improvement of the CeC accelerator systems we should be able to demonstrate CeC in near future

The CeC project involved the following:

… never can get all of your photos…