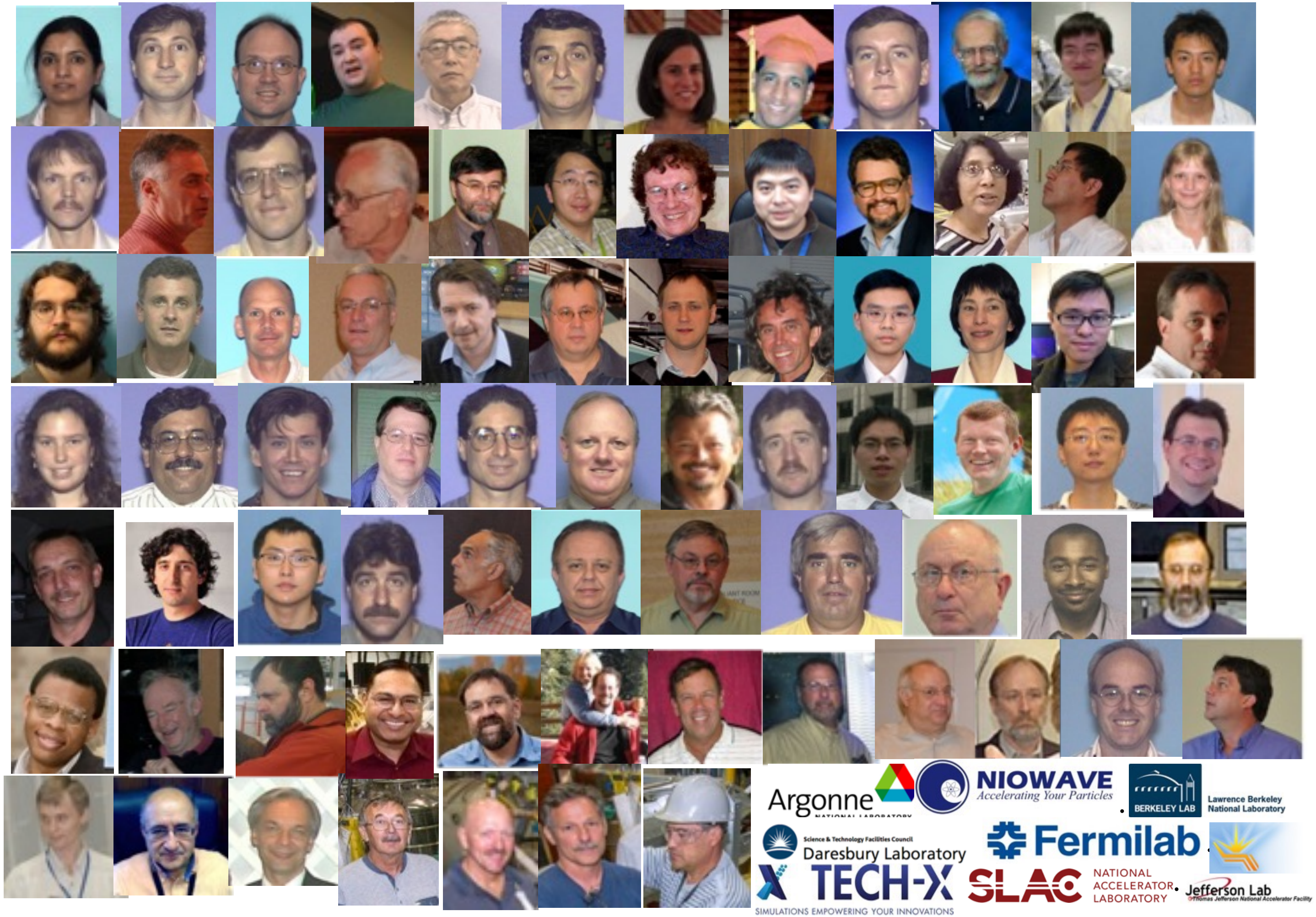
Experimental demonstration of High-Gain Plasma Cascade Amplifier

Vladimir N Litvinenko for the CeC operation group:
Yichao Jing, Dmitry Kayran, Jun Ma, Irina Petrushina, Igor Pinayev, Kai Shih, Gang Wang and Jean Clifford Brutus

Brookhaven National Laboratory and Stony Brook University

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

The CeC team – never can get all your pictures …

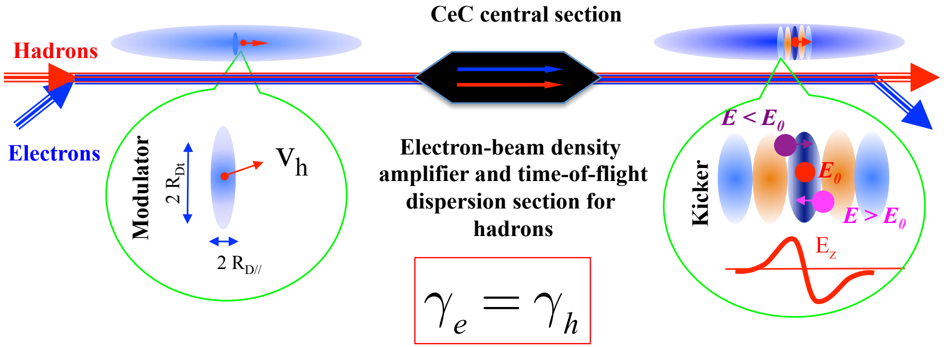


Content

- ❑ Options for Coherent electron Cooling (CeC)
- ❑ Micro-bunching Plasma-Cascade Amplifier
- ❑ Theory of Plasma Cascade Instability
- ❑ Theory and simulations of Plasma-Cascade Amplifier
- ❑ PCA-based CeC and its diagnostics
- ❑ Experimental demonstration of the Plasma-Cascade Amplifier
- ❑ Conclusions

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

Ya. S. Derbenev
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

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]
[1]Brookhaven National Laboratory, Upton, Long Island, New York, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

(Received 24 September 2008; published 16 March 2009)

PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS

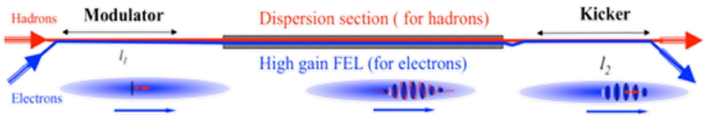
Microbunched Electron Cooling for High-Energy Hadron Beams

D. Ratner*
SLAC, Menlo Park, California 94025, USA

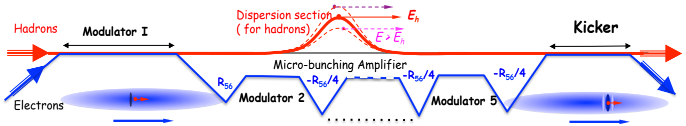
(Received 11 April 2013; published 20 August 2013)

What can be tested experimentally?

Litvinenko, Derbenev, PRL 2008

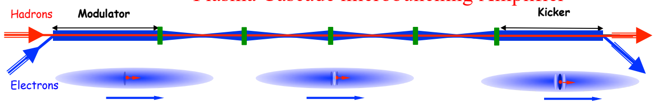


Ratner, PRL 2013

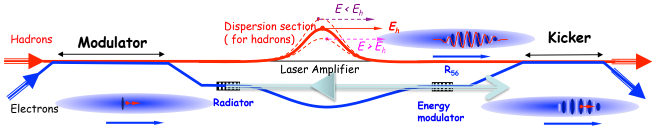


Litvinenko, Wang, Kayran, Jing, Ma, 2017

Plasma Cascade microbunching Amplifier



Litvinenko, Cool 2013



RHIC Run 18

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

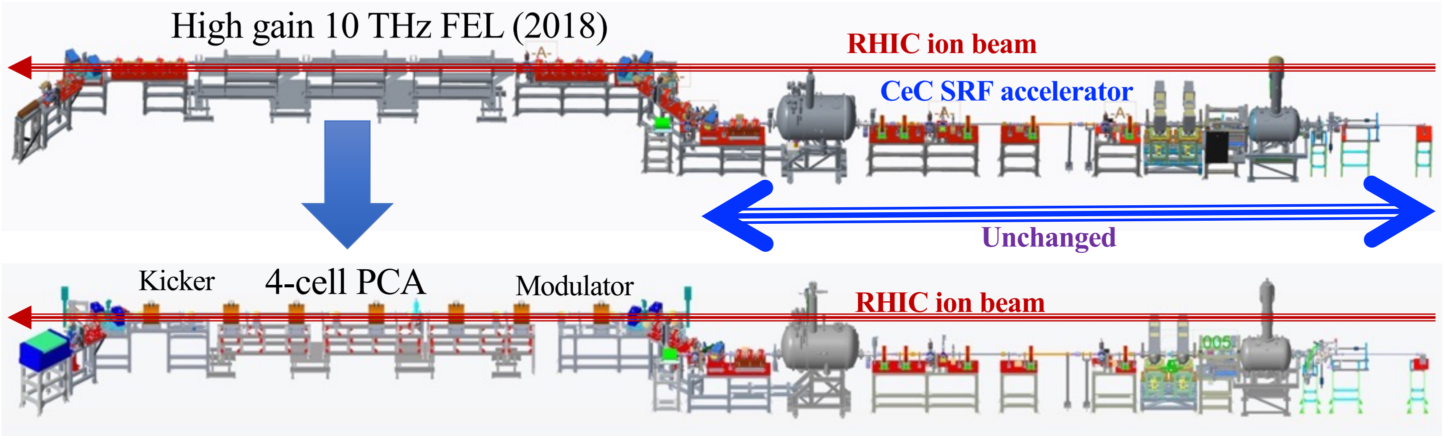
RHIC Runs 20-22

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

Derbenev also suggesting to explore CSR as an CeC amplifier

Search for microbunching instability occurring in linear accelerators

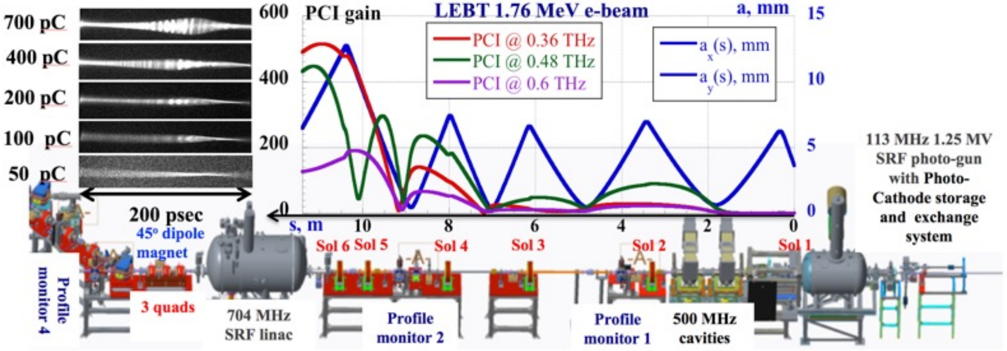
- In 2018 we were facing possible end of the CeC experiment at RHIC: 28 mm aperture of FEL wiggler was too small for RHIC program requiring 3.85 GeV Au ion beam
- We were looking for alternative way if exiting longitudinal microbunching instability without traditional method of using chicanes: adding chicane would require separating and delaying ion beam (not an option!). We needed to find longitudinal instability occurring in electron beam propagating along straight line… There was no papers or theory suggesting that it is possible.
- It is well known that plasma oscillations do not grow in a beam with slowly evolving parameters.. We were exploring possibility of parametric instability caused by strong modulation of beam's density using transverse focusing structures. First estimations and simulations indicated that it is a possibility.
- We developed theory of microbunching Plasma Cascade Instability - new type of instability in linear accelerators – and by a chance discovered it in CeC linac. Next – we designed of Plasma Cascade Amplifier (PCA) for CeC



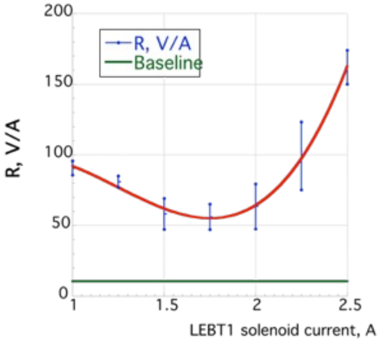
Plasma-Cascade Instability, Physical Review Accelerators and Beams 24, 014402 (2021)

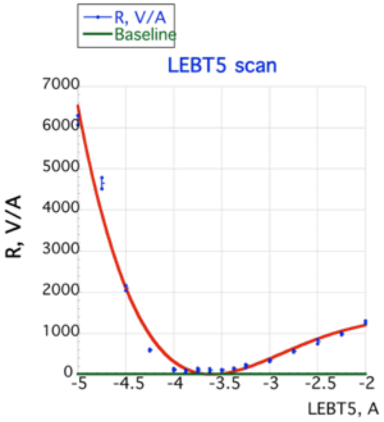
Experimental observation of PCI in 1.75 MeV e-beam in CeC linac

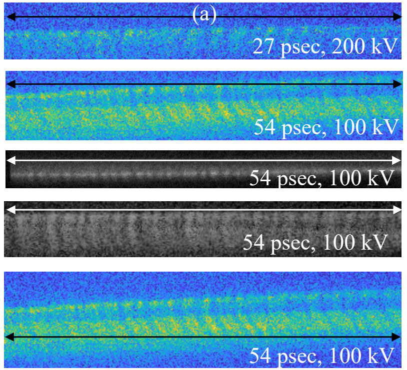
Uncompressed bunch: simulations and experiment in September 2018



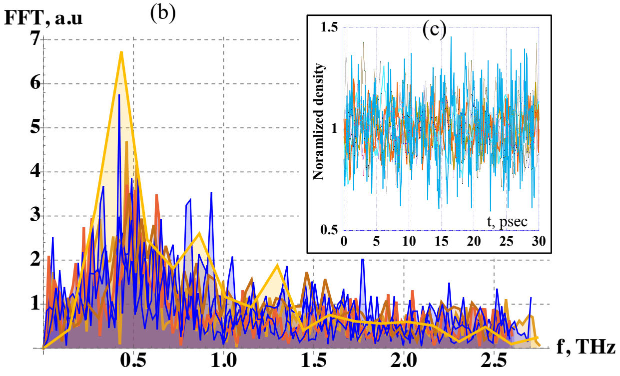
Noise power in the e-beam as function of focusing by two solenoids







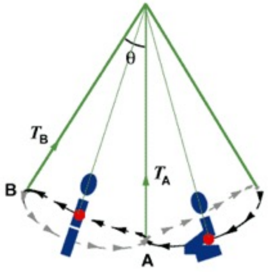
Measured time profiles of 1.75 MeV electron bunches with 0.45 nC to 0.7 nC;

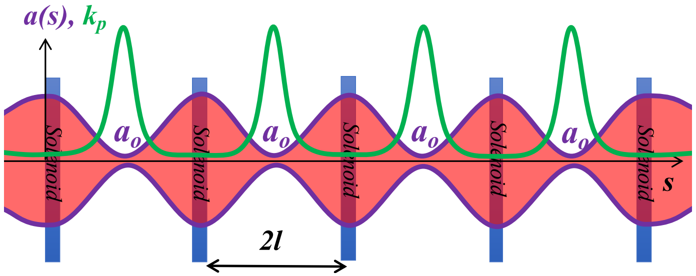


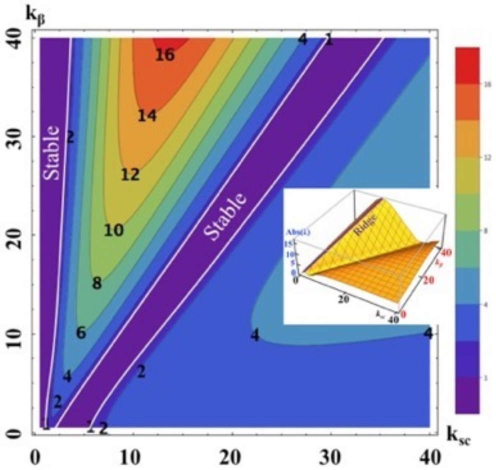
Seven measured overlapping spectra and PCI spectrum simulated by SPACE (slightly elevated yellow line). Clip shows a 30-psec fragment of seven measured relative density modulations.

What is Plasma-Cascade Instability or Plasma-Cascade Amplifier ?

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







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

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

- *Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams*, arXiv:1802.08677, 2018
- *3D Theory of Microscopic Instabilities Driven by Space-Charge Forces*, Physical Review Accelerators and Beams 26, No.5, 054402, 2023

3D PCA theory and 3D simulations

Complete 3D Theory

$$\tilde{\rho}\left(s,\vec{k}(s)\right)=-\int_{o}^{s}\tilde{\rho}\left(\zeta,\vec{k}(\zeta)\right)\cdot K(\zeta)\left(u(s)-u(\zeta)\right)L_d(s,\zeta)\,d\zeta+\tilde{\rho}_{o\underline{k}}(s);$$

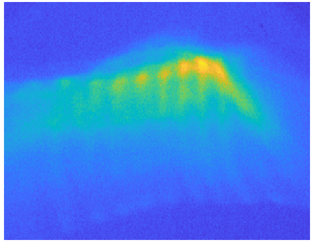
$$K(\zeta)=\frac{4\pi n_o e^2}{c\det\mathbf{A}(\zeta)\upsilon(\zeta)};\ L_d\left(\underline{k},s,\zeta\right)=\int e^{i\left(\vec{k}(\zeta)\cdot\vec{\mathbf{B}}(\zeta)-\vec{k}(s)\cdot\vec{\mathbf{B}}(s)\right)\cdot\underline{P}}\,\underline{f}_o\left(\underline{P}\right)d\underline{P}^3;$$

$$u(\zeta)=\vec{k}(\zeta)\cdot\vec{\mathbf{B}}(\zeta)\cdot\underline{k}\equiv\underline{k}(\zeta)\cdot\vec{\mathbf{U}}(\zeta)\cdot\underline{k};\ \upsilon(s)=\gamma_o(s)^2\beta_o(s)^2\vec{k}_\perp(s)^2+k_3(s)^2;$$

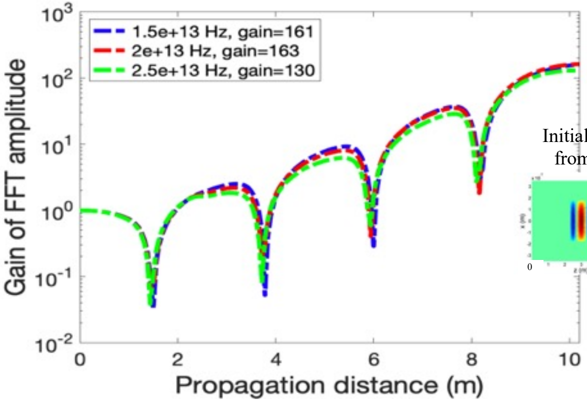
$$\xi(s_2)\equiv\begin{bmatrix}q(s_2)\\P(s_2)\end{bmatrix}=\mathbf{M}(s_1|s_2)\xi(s_1)\equiv\mathbf{M}(s_1|s_2)\begin{bmatrix}q(s_1)\\P(s_1)\end{bmatrix}$$

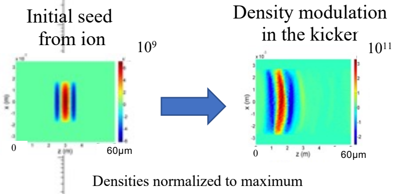
$$\mathbf{M}^T\mathbf{S}\mathbf{M}=\mathbf{M}\mathbf{S}\mathbf{M}^T=\mathbf{S};\ \mathbf{M}^{-1}=-\mathbf{S}\mathbf{M}^T\mathbf{S};$$

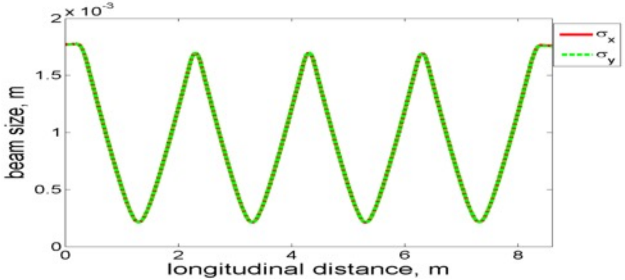
$$\mathbf{M}=\begin{bmatrix}\mathbf{A}&\mathbf{B}\\\mathbf{C}&\mathbf{D}\end{bmatrix};\mathbf{M}^{-1}=\begin{bmatrix}\mathbf{D}^T&-\mathbf{B}^T\\-\mathbf{C}^T&\mathbf{A}^T\end{bmatrix};$$



3D simulations with SPACE code



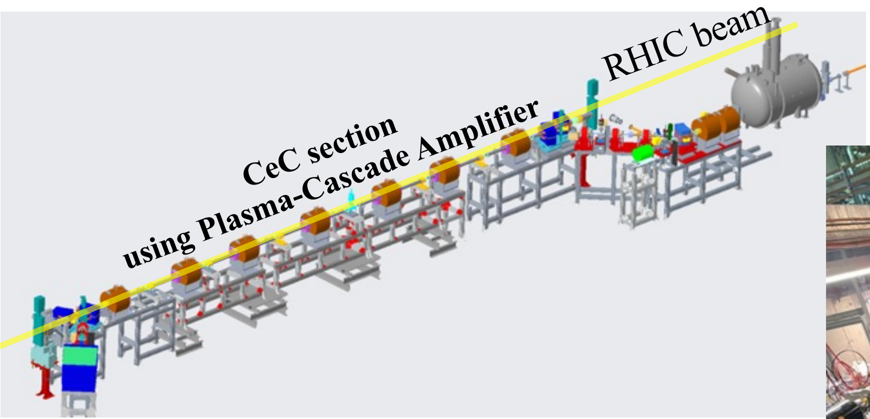


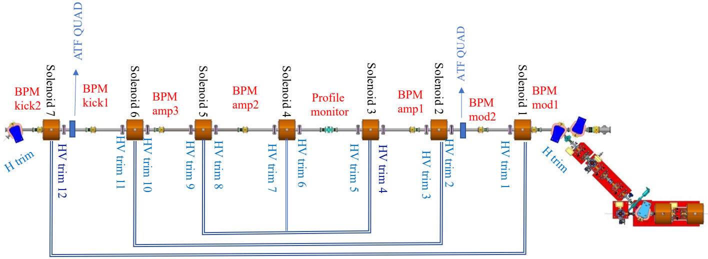


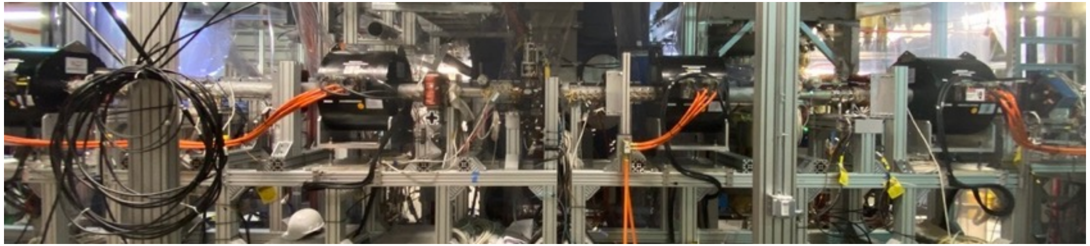
- *3D Theory of Microscopic Instabilities Driven by Space-Charge Forces*, Physical Review Accelerators and Beams 26, No.5, 054402 (2023)
- *Simulations of Coherent Electron Cooling with Two Types of Amplifiers*, International Journal of Modern Physics A (IJMPA), Vol. 34 (2019)
- *3D Start-to-End Simulations of the Coherent Electron Cooling, J. Ma, G. Wang, V. N. Litvinenko,* IPAC2019, May 2019, p. 3329
- *Simulation Studies of Plasma Cascade Amplifier, J. Ma, G. Wang, V. N. Litvinenko*, IPAC2021, Campinas, Brazil, May 2021, p. 3265

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







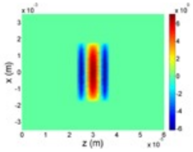
CeC X status

- ✓ Unique SRF accelerator generating high brightness electron beam, compressing it to 75 A at 1.25 MeV kinetic energy and accelerating it to 14.6 MeV
- ✓ Precise control of noise in electron beam: can suppress it to the level close to Poisson shot noise - for cooling - or increase thousands-fold to heat ion beam
- ✓ We demonstrated all necessary beam parameters from the CeC accelerator
- ✓ Remaining challenge is stability of the system (will discuss in in my talk tomorrow)

Electron beam KPP

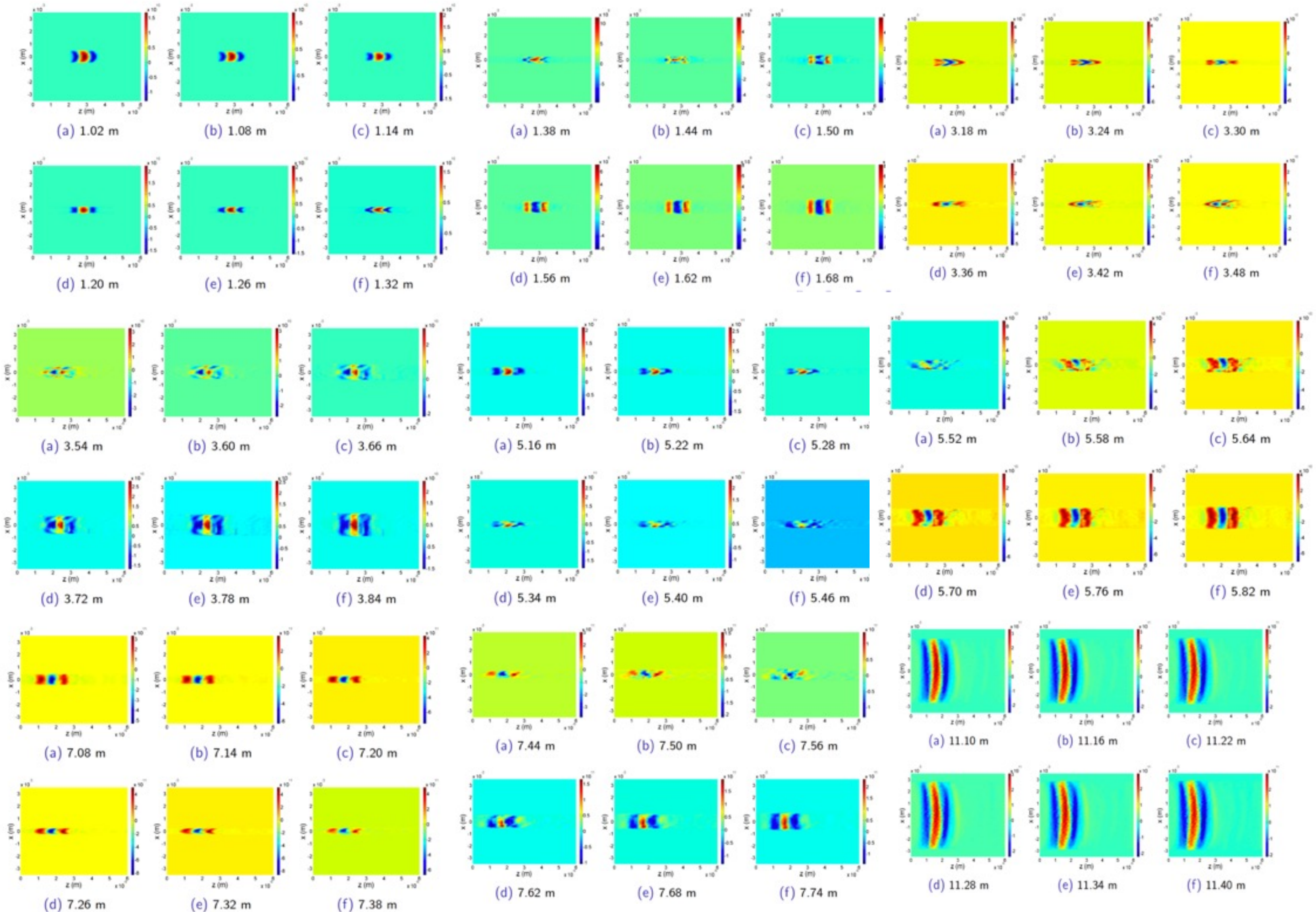
Parameter	**Planned**	**Demonstrated**	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the Poison noise limit	<100	<10 (lattice of Run20)*	✓
RMS momentum spread $\sigma_p = \sigma_p/p$, rms	$\leq 1.5\times10^{-3}$	$<5\times10^{-4}$, slice 2×10^{-4}	✓
Normalized rms slice emittance, μm rad	≤ 5	2.5	✓

Very complex behavior requires full 3D simulations



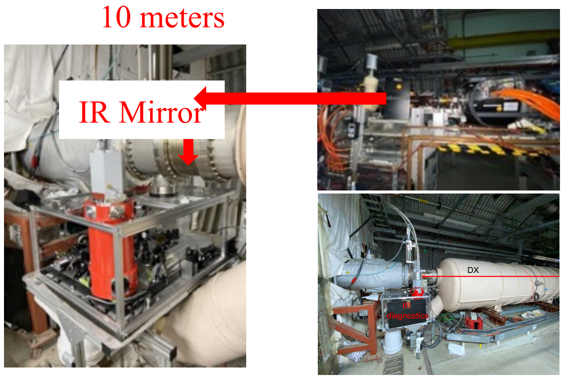
4-cell PCA

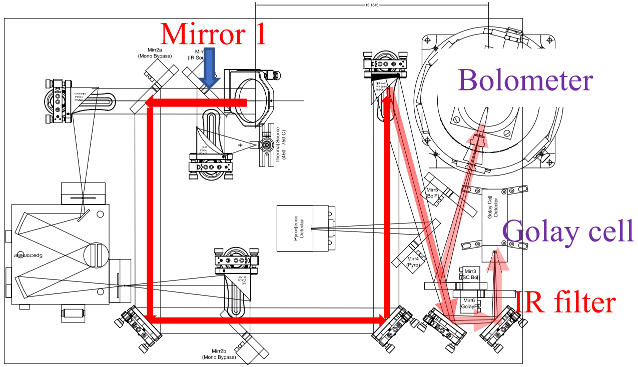
Evolution of real 3D Langmuir waves in PCA can be seen only in simulations (show movie)

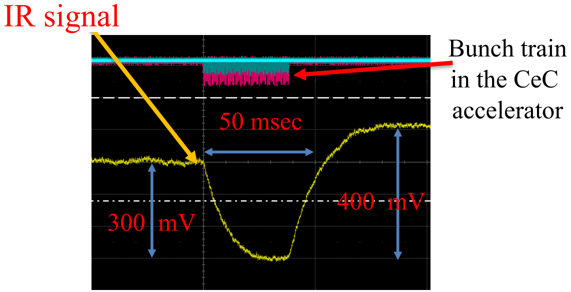


How PCA gain is measured?

- PCA gain was evaluated by comparing radiated power in the strong focusing PCA lattice (strong solenoids) with relaxed lattice (weak solenoids) using the same setting of the CeC accelerator and the electron beam
- We used IR radiation from the bending magnet at the exit of the CeC section. IR radiation is intercepted by 2” mirror 10 meters downstream of the magnet.
- 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
- All IR diagnostics is AC – it requires periodic intensity modulation, which was provided by operating with electron beam as periodic trains of bunches
- Signal from Golay cell was detected by lock-in amplifier synched with the electron bunch pattern (typically 5 to 10 Hz). We used high 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.

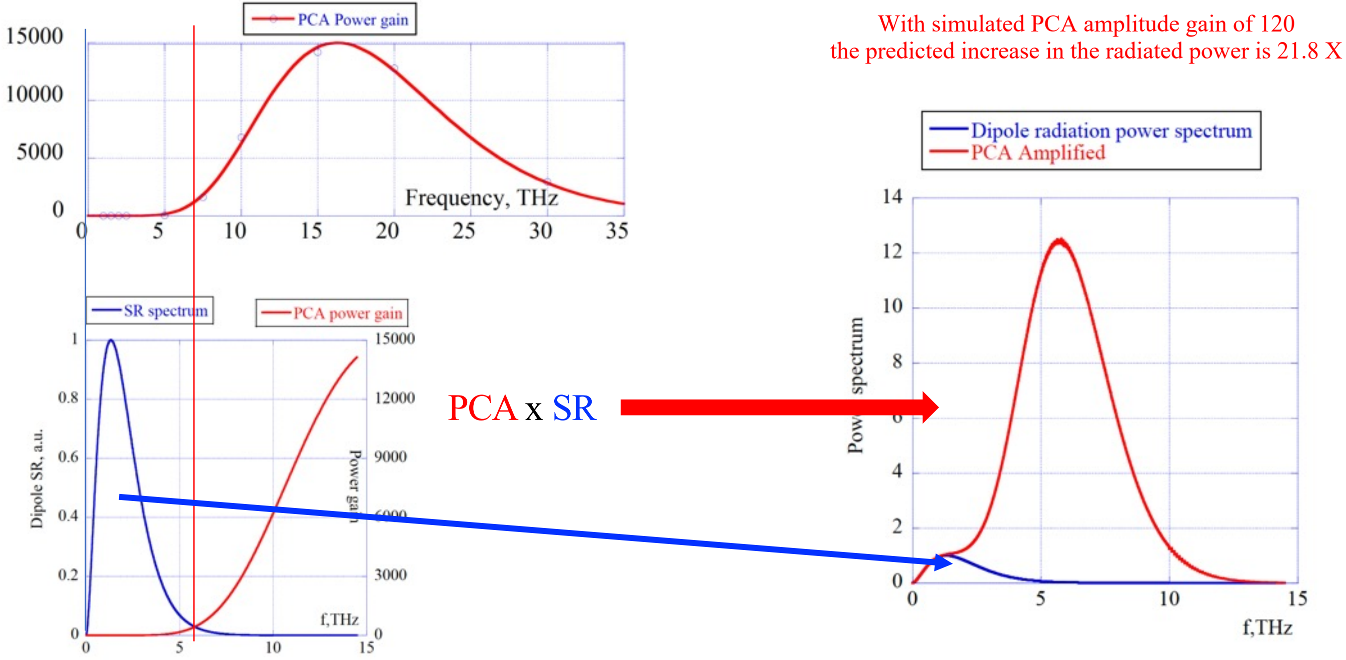






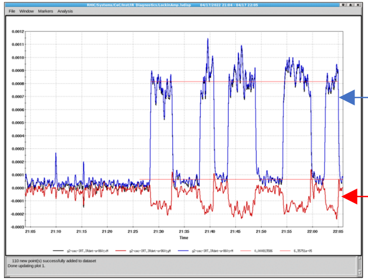
Best result: Measuring Plasma Cascade Amplifier gain in 2020/21

- We used the power of the broad-band radiation from the dipole magnet to evaluate PCA.
- Sensitivity of the IR detectors was insufficient to measure the PCA gain spectrum.
- Maximum measured PCA *power* gain was **200-fold**
- Weak overlap of the PCA gain and the dipole radiation spectra are the reason of the measured PCA boost in hundreds, not in thousands.
- Detailed analysis: PCA *amplitude* gain ~ 380, 3-fold the design value of 122.5 at 16.5 THz.



Run 2022
Golay cell measurement
PCA/Relaxed=65

MDM method

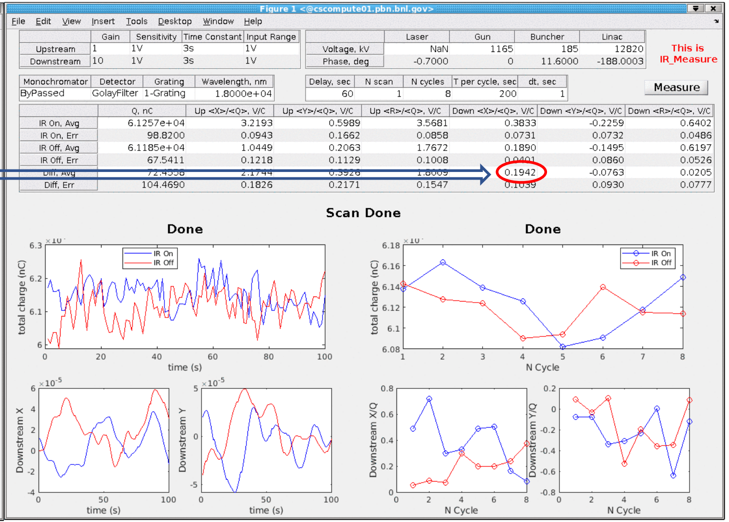


In-phase (cos) signal

90°-phase (sin) signal

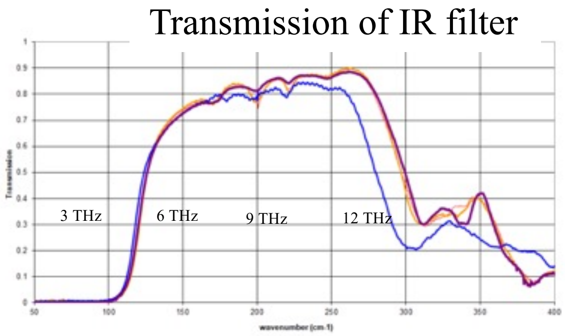
PCA lattice

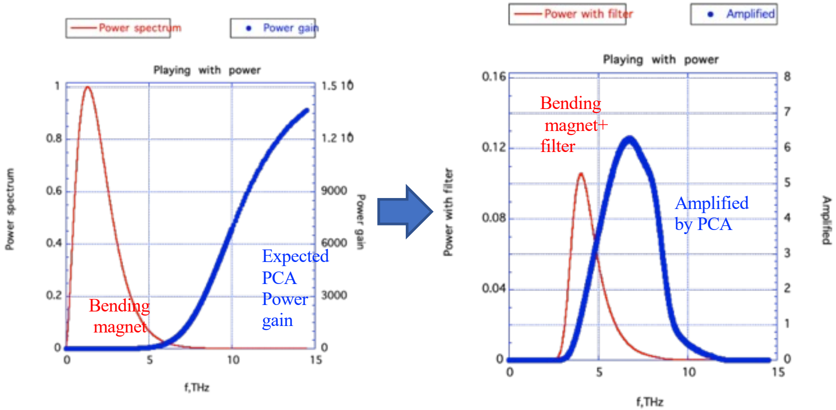
Relaxed lattice



Expectations:
Golay cell with IR filter

- ✓ We calculated spectrum of radiation from the edge of the bending magnet using well-benched code Igor-Pro
- ✓ For expected PCA gain we used our 3D simulations with SPACE code using uniform electron beam with 50 A peak current and 1.25 um normalized emittance
- ✓ Product of radiation power and the IR filter transmission is used and the base for the relaxed lattice (red curve in the right graph)
- ✓ This power amplified by PCA peaks at about 6.5 THz, just in the middle of the IR filter transition window
- ✓ For 50 A in 50% of the beam, expected PCA/relaxed power ratio is 60, which compares favorably with measured value of 65



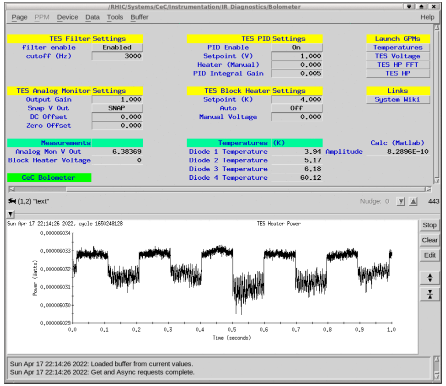


Power integrals: Relaxed: *0.2007*;
Amplified : 23.84
Expected PCA/relaxed power ratio: for100% of the beam is **119**
for 50% of the beam is **60**

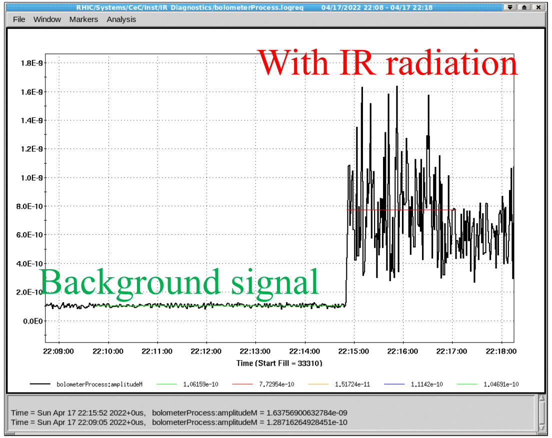
2022 Bolometer measurement with bending magnet*

PCA/Relaxed:
100 +/- 20 average, 300 +/- 50 peak

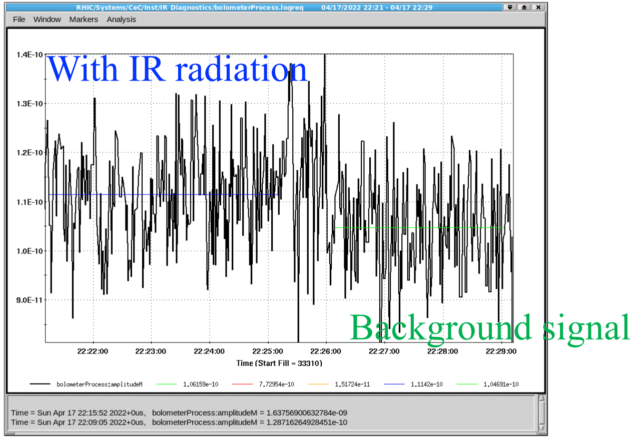
Raw Bolometer signal



PCA lattice



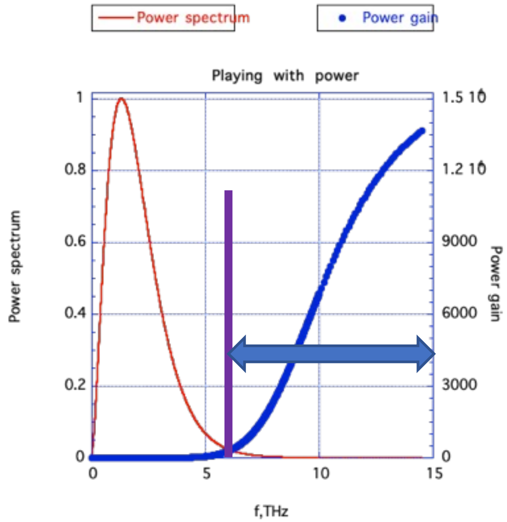
Relaxed lattice



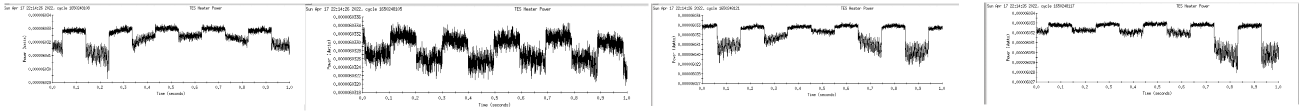
** Important note: by unknow reason, the bolometer "detects" beam pattern delivered to the heavily shielded high power dump with signal proportional to the beam intensity. It is not related to X-ray, because intercepting beam in front of the beam dump increasing radiation but eliminates the signal (it is possible to do only in low power mode, unsuitable for PCA measurement's). This background signal is is measured by blocking IR radiation using Mirror 1 – then is it subtracted from the signal measured in the presence of IR radiation*

Bolometer Results

- ✓ The bolometer manual specifies the sensitivity range from 6 THz to 60 THz, but there is no calibrated spectral response. Most of the PCA amplified power is concentrated around 6.5 THz and knowledge of the spectral response is important. Hence, accurate comparison with estimations is not possible at this moment.
- ✓ Simple estimation by integrating simulated powers for relaxed and PCA case above 6 THz, gives PCA/relaxed power ratio of **1,070** if 100% of the beam has peak current of 50 A and normalized emittance of 1.25 um
- ✓ In this assumption, the measured average value for PCA/Relaxed ~100 and peak ~ 300, would indicate that
  - ✓ Either peak current ~ 50A exists in 10% to 30% of the beam
  - ✓ Or that amplitude PCA gain is 45% in average peaking at 75% (assuming that 50% of electron satisfy PCA gain condition of peak current above 50A), when compared with simulated values
- ✓ It is important to note that PCA gain changes dramatically both on the fast (1/3 kHz) and slow (1 sec) time scales, as indicated by the sample of the bolometer signal. It is our understanding that it is result of jitter in electron beam parameters, including on bunch to bunch (78 kHz) scale



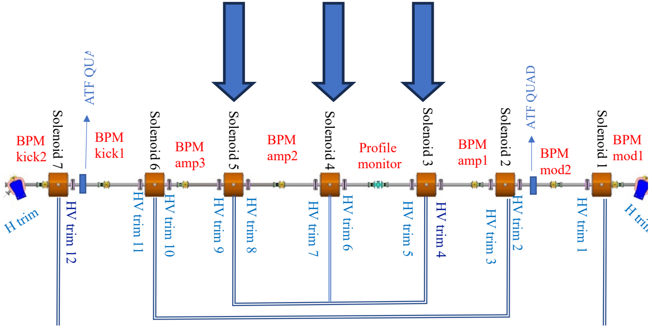
Power integrals above 6 THz
Relaxed: *0.0206*;
Amplified : 22.08



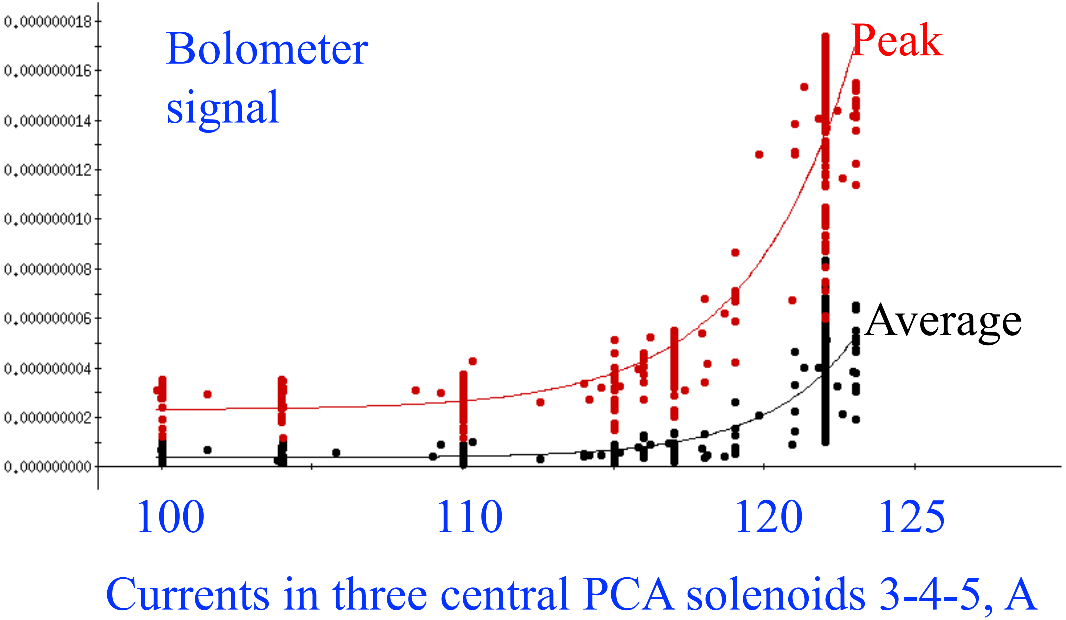
This is problem related to variation of e-beam parameters (quality)

Bolometer Results: 2022

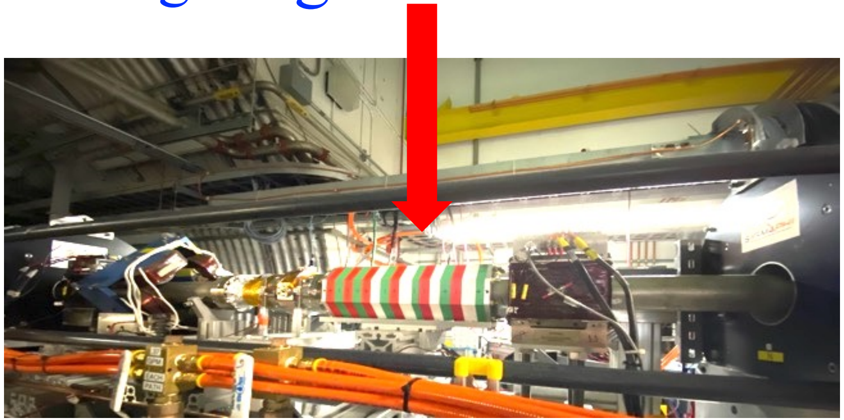
- ✓ Most convincing observation of PCA exponential gain was observed in April 2022 with cryo-cooled bolometer
- ✓ A simple increase of currents in three central PCA solenoids – with all other parameters fixed – resulted in exponential increase of radiation from the electron beam

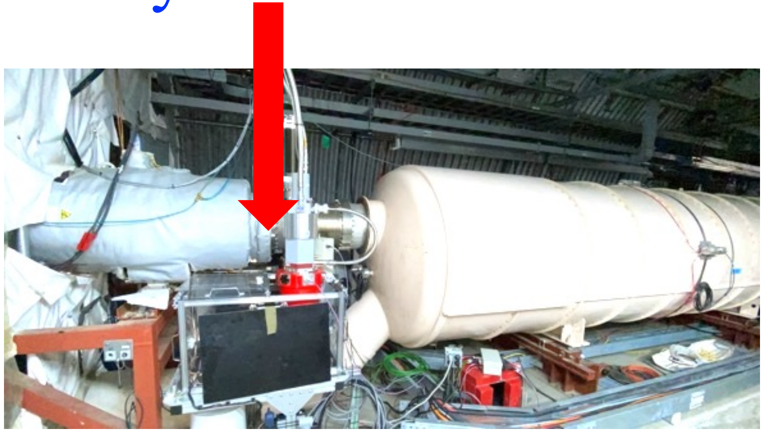


Exponential growth of the IR signal at the bolometer as function of current in PCA solenoids: e-fold increase each 3 A (2.4%)



Adding diagnostics undulator and cryo-cooled IR detector





Parameter	Value	Units
Period	8	cm
Gap	7.9	cm
Peak field	0.6	kGs
Radiated power at 50% beam current	9	nW
Fundamental wavelength @ γ=28.5	54	µm
Central frequency @ γ=28.5	5.5	THz
Third harmonic	16.6	THz
F_3/F_1	0.04	

- ✓ New cryo-cooled IR detector has ~ 100 better signal to noise ratio
- ✓ Diagnostics undulator generates radiation at 5.5 THz frequency, which are within the bandwidth of the Plasma-Cascade Amplifier (PCA) *
- ✓ This system allows us to evaluate PCA gain better in future runs

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PCA gain peaks at 16 THz. In the past we used IR radiation from bending magnet, which peaks at 0.8 THz and is complete mismatch for the PCA

Conclusions

- Being challenged to think out-of-the-box we discovered and to explored previously unknown microbunching plasma-cascade instability
- Shockingly, it was actually evolving in low-beam transport of the CeC accelerator
- We designed, built and commissioned Plasma-Cascade Amplifier (PCA) with bandwidths from 10 to 20 THz for our test CeC system
- We experimentally demonstrated high-gain PCA operation
- Remaining challenge is a stable operation of the PCA-based CeC. It requires electron beam with stable parameters (energy, charge per bunch, emittance, peak current…) – the goal of our current program: *details are in my talk tomorrow and two talks by G. Wang and Y. Jing this Thursday*

Thank you for attention