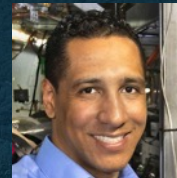


Coherent electron Cooling Proof-of-Principle Experiment – CeC X



Vladimir N Litvinenko – project director
Jean Clifford Brutus – project manager



Vladimir N Litvinenko for the CeC operation group:

Yichao Jing, Dmitry Kayran, Jun Ma, Irina Petrushina, Igor Pinayev, Kai Shih, Medani Sangroula, Sergei Seletskiy and Gang Wang



Brookhaven National Laboratory and Stony Brook University



RHIC Machine Advisory Committee, December 13, 2022

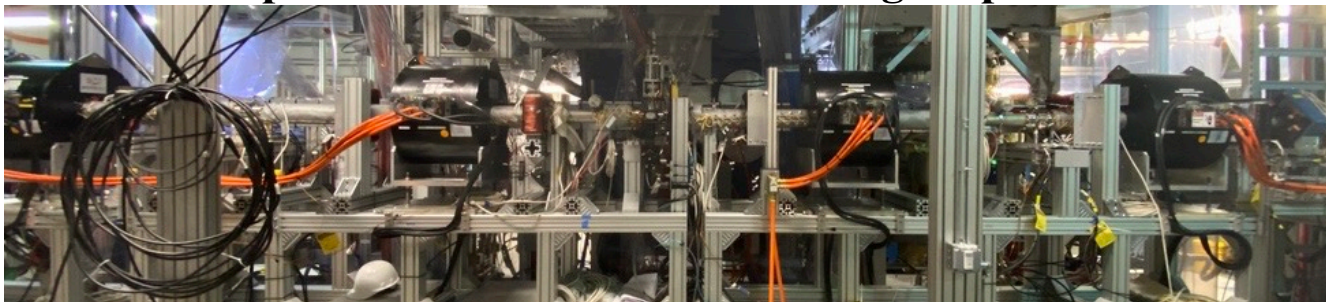
Content

- ❑ Response to MAC 2021 recommendations
- ❑ Few words about Coherent electron Cooling (CeC)
- ❑ CeC X and Results from Run 22
- ❑ Status of the CeC experiment
- ❑ Future Plans

CeC X accelerator



CeC with plasma-cascade microbunching amplifier



PCA-based CeC



CeC accelerator

Time-resolved diagnostics

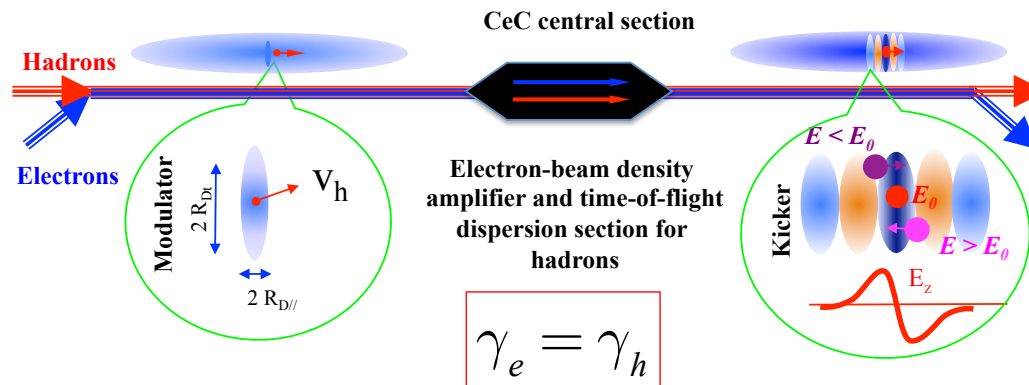
MAC 2021 recommendations

- ❑ Focus on CeC X with the goal of longitudinal cooling demonstration. From the experiment, extrapolate parameters and requirements of PCA based CeC for EIC
- ❑ CeC X was focused on the longitudinal cooling demonstration, but we were not successful and could not follow up with suggestion for EIC CeC
- ❑ Present the concept of PCA-based EIC cooler at the next MAC, including discussion of the feasibility of e-beam from 3-pass ERL.
- ❑ After failure to demonstrate CeC in Run 22, resources are devoted to improving performance of CeC X accelerator and cooler. No progress is done with design of the PCA-based EIC cooler

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

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(Received 24 September 2008; published 16 March 2009)

PRL 111, 084802 (2013)

PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

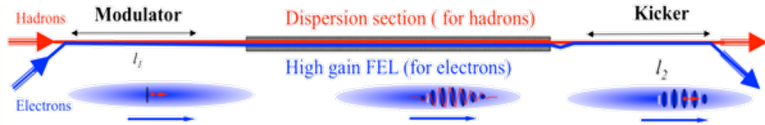
D. Ratner^{*}

SLAC, Menlo Park, California 94025, USA

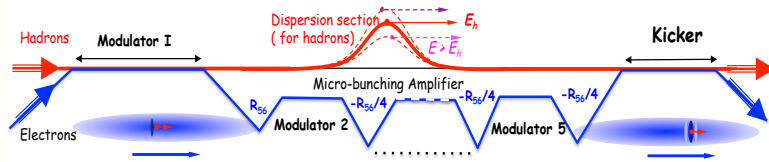
(Received 11 April 2013; published 20 August 2013)

What can be tested experimentally at RHIC?

Litvinenko, Derbenev, PRL 2008

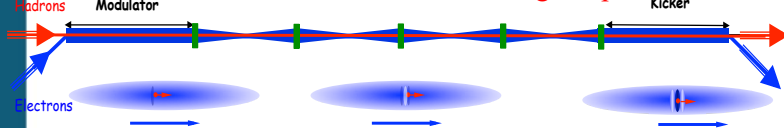


Ratner, PRL 2013



Litvinenko, Wang, Kayran, Jing, Ma, 2017

Plasma Cascade microbunching Amplifier



RHIC Run 18



High gain FEL amplifier
with low- a_w wigglers

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

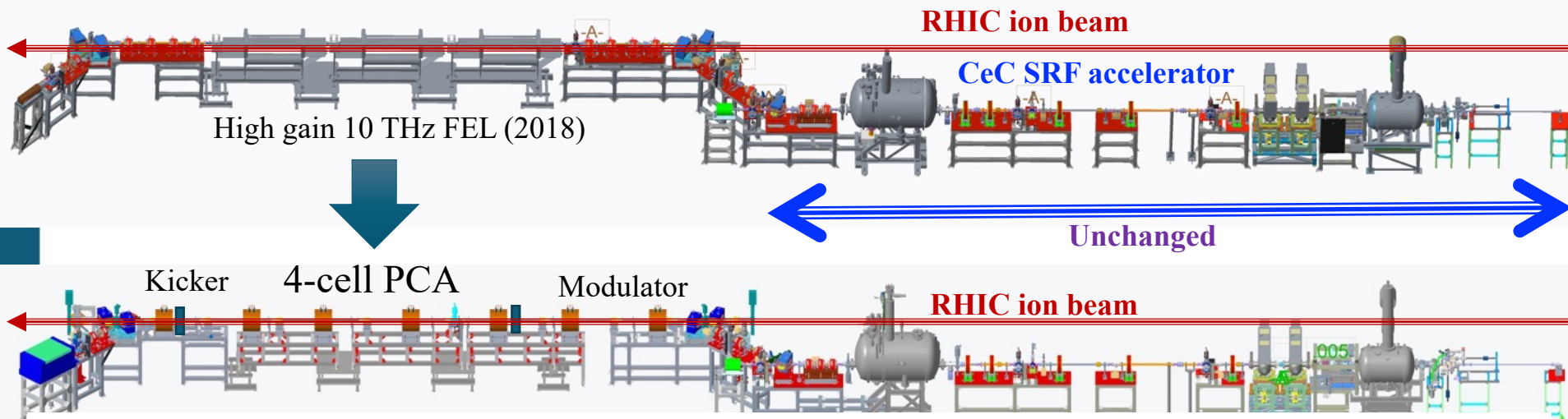
RHIC Runs 20-22



Plasma-Cascade
Amplifier

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 and developed design of Plasma Cascade Amplifier (PCA) for CeC
- ❑ In 2019-2022
 - ❑ 2019: PCA-based CeC with **75 mm** aperture was built and commissioned.
 - ❑ 2022: During Run 20, we demonstrated high gain Plasma Cascade Amplifier (PCA) and observed presence of ion imprint in the electron beam
 - ❑ 2021: 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
 - ❑ 2022: Our attempt to demonstrate CeC during Run 22 failed



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

Two main failures in the CeC Run 22

- The CeC project lost 71% of operational time (106 days out of 150) because of two major failures:
 - The main measuring devices of the electron bunch charge are called ICT (Integrated Current Transformers). We checked the calibration at the beginning of the Run 22. Few days later ICT firmware was upgraded and started reporting 2.4-fold higher measurements than the actual charge.
 - I was not informed about this change. The CeC team was tuning CeC accelerator for two month and 2 shifts per day with completely wrong charge per bunch. It was nearly a complete waist of time.
 - Only after several attempts of observing high-gain in Plasma Cascade Amplifier, and checking 100s of other parameters, I found that ICT calibration was incorrect. Because of this failure the CeC experiment lost 66 days (44%) of operational time
 - Improper handling of the cathode exchange system resulted in damage to the SRF gun and need to a very complicated and time-consuming repair the cathode transfer system and SRF gun conditioning. Maximum SRF gun cavity voltage dropped to 45% of nominal operational value.
 - Three weeks of extensive efforts by the CeC team restored the cavity to operational status.
 - It took 5 week to dismantle, repair, install and bake-out the cathode transfer. Normal operation of SRF gun were restored after 40 days – additional 27% loss of operational time

Run 22 results

- ❖ We failed demonstration of Coherent electron Cooling, which was our main goal for Run 22
- ❖ This RHIC Run had many problems. In addition, CeC project loss of 71% of operational time because of two major failures.
- ❖ Actual start of normal operation was March 5, 2022, 106 days after the original start of the Run. We tried our best to accomplish the goal but fell short. We simply ran out of time...
- ❖ New laser source resulted in reducing of timing jitter to ~ 3 psec RMS, which was sufficient to improve beam energy stability to 2×10^{-4} RMS, necessary for CeC demonstration.
- ❖ But overall beam stability remained a problem
- ❖ Cry-cooled bolometer became operational and played important role in confirming PCA gain at high frequencies
- ❖ With two weeks added to the RHIC Run 22, we managed to restore high gain in Plasma Cascade Amplifier on April 17 - one day before the end of the Run 22

CeC X status

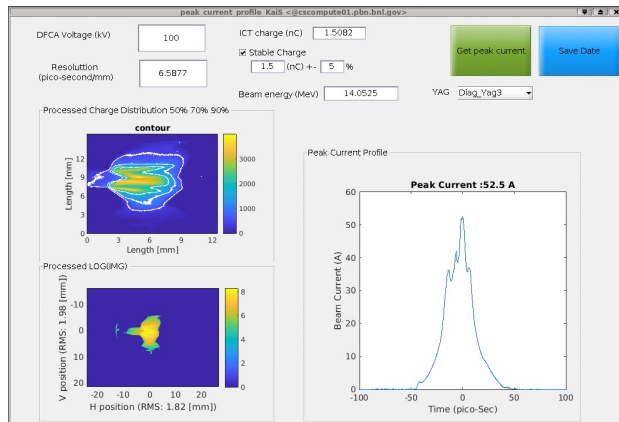
- ✓ Unique SRF accelerator generating high brightness electron beam, compressing it to 75 A at 1.25 MeV kinetic energy and accelerating it to 14.6 MeV
- ✓ Precise control of noise in electron beam: can suppress it to the level close to Poisson shot noise - for cooling - or increase thousands-fold to heat ion beam
- ✓ Demonstrated high gain in both FEL and Plasma-Cascade Amplifiers
- ✓ Observed presence of ion imprint in electron beam radiation
- ✓ Observed recombination of 14.56 MeV electrons with 26.5 GeV/ u Au ions
- ✓ Regular electron cooling of hardon beam at record energy of 26.5 GeV/ u

Electron beam KPP

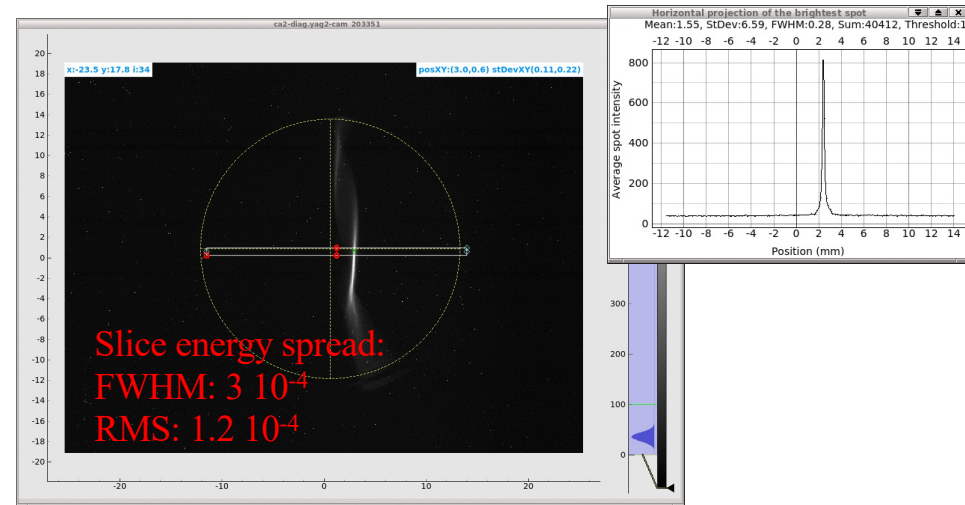
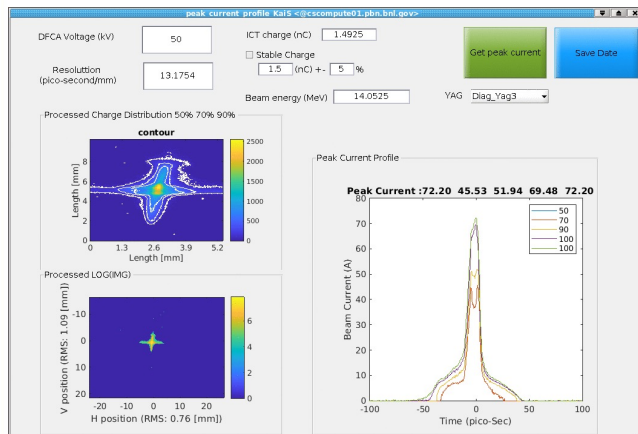
Parameter	Planned	Demonstrated	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the Poisson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

March 2022

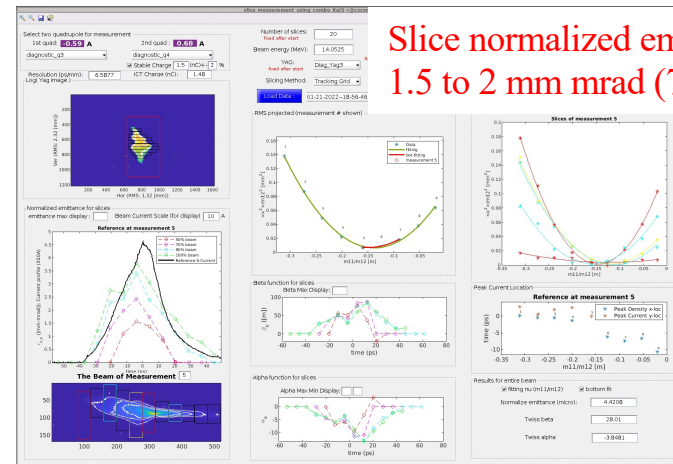
KPPs - Beam parameters with 185 kV bunching voltage



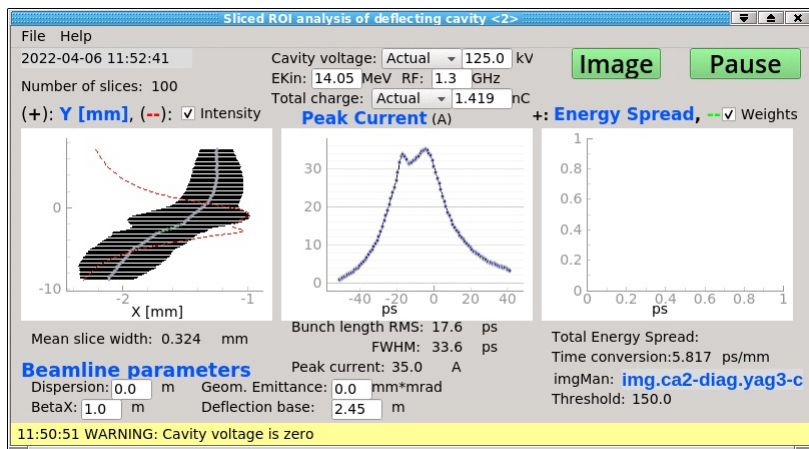
Peak current from 50A to 70 A



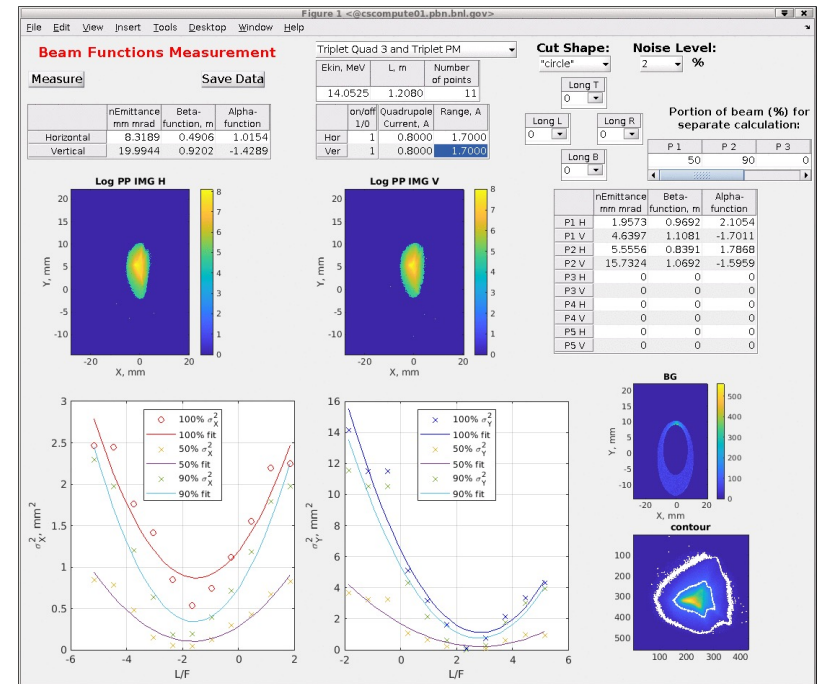
Slice normalized emittance
1.5 to 2 mm mrad (70% core)_



Bad days (or bad measurements?)



Low peak current



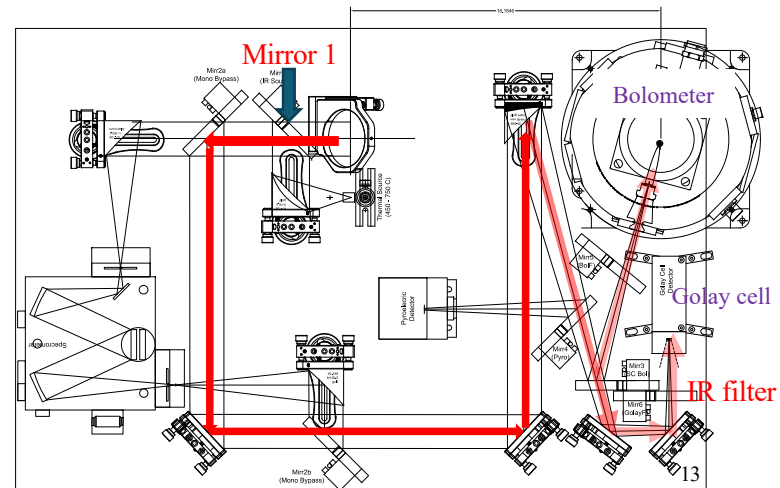
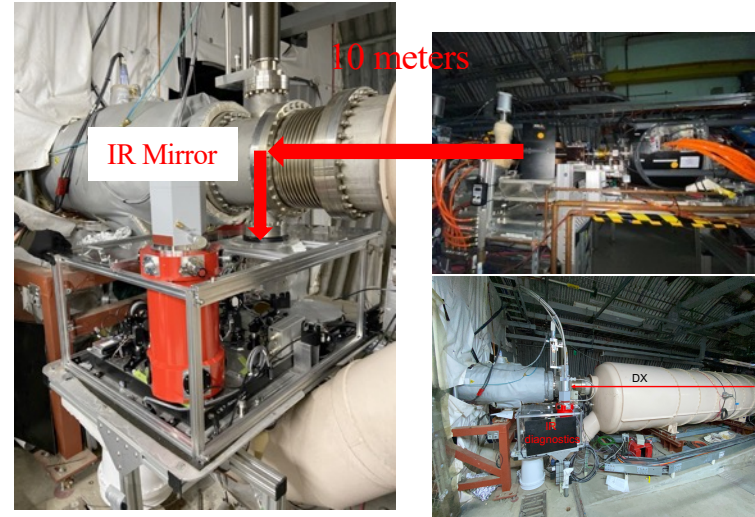
Large emittances, asymmetric beam (2x to 3x)

Run 22: Demonstration of Plasma Cascade Amplifier (PCA) gain at high frequencies

- ❑ After establishing electron beam parameters sufficient for high PCA gain, we made several unsuccessful attempts to demonstrate high PCA gain. For long time maximum observed PCA gain was ~ 5 .
- ❑ Main problem was related to increasing beam losses with solenoid's currents approaching the designed strength for PCA lattice. It is likely related to increased halo in electron beam.
- ❑ First promising signs of high PCA gain were observed during night shift on April 16, 2022
- ❑ Finally, high PCA gain was demonstrated during night shift on April 17, 2022

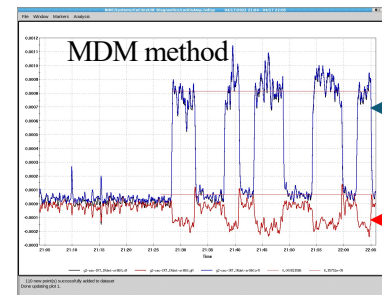
How PCA gain is measured?

- 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 these 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 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.
- 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



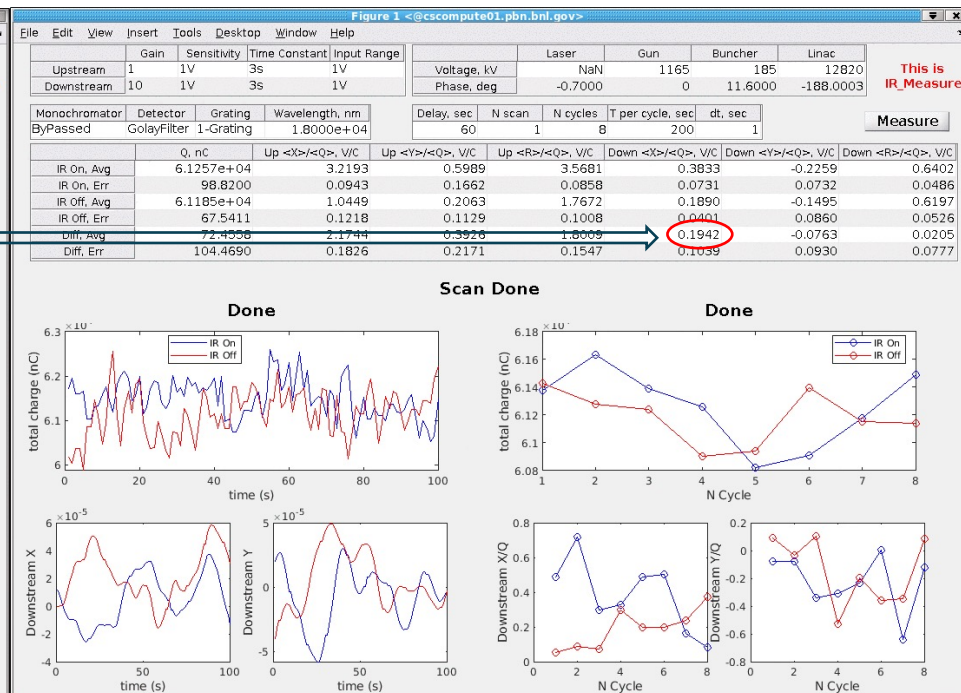
Golay cell measurement

PCA/Relaxed=65



PCA lattice

Relaxed lattice



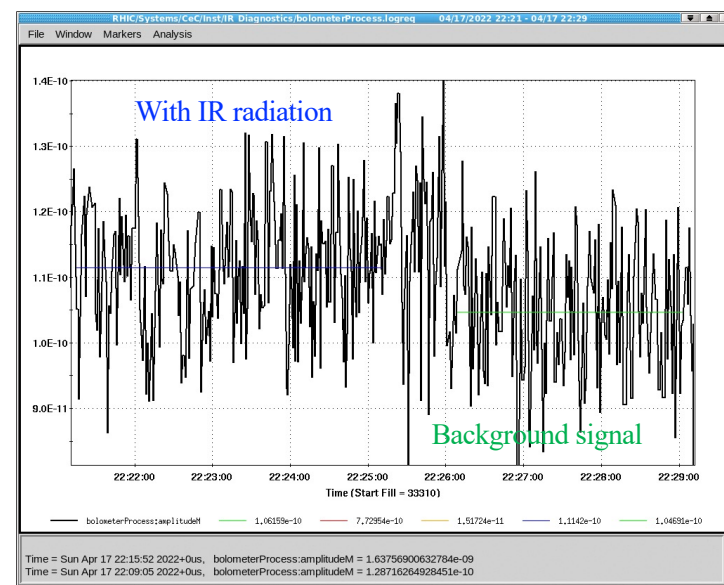
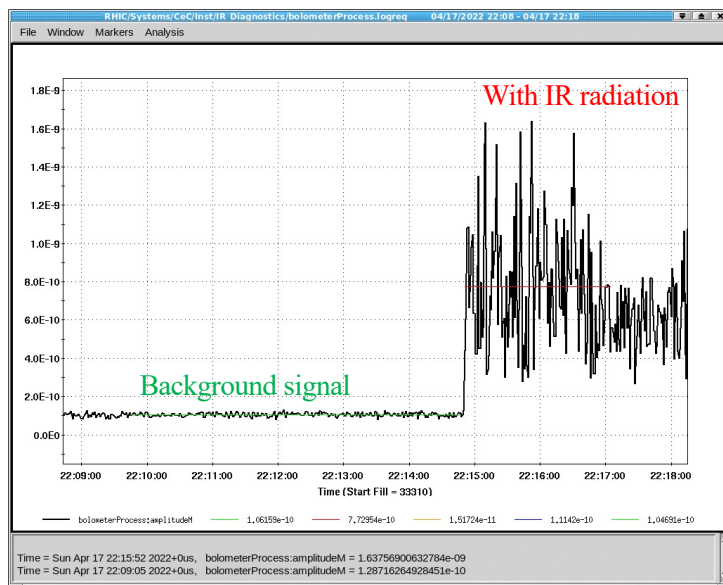
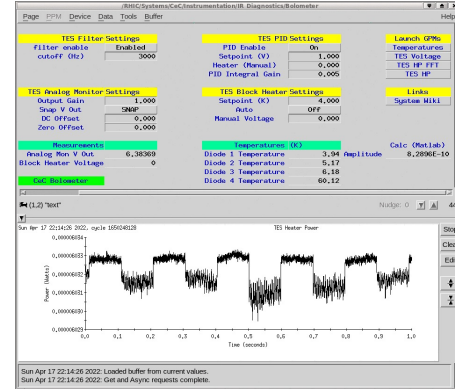
Bolometer measurement*

PCA/Relaxed:

100 +/- 20 average, 300 +/- 50 peak

PCA lattice

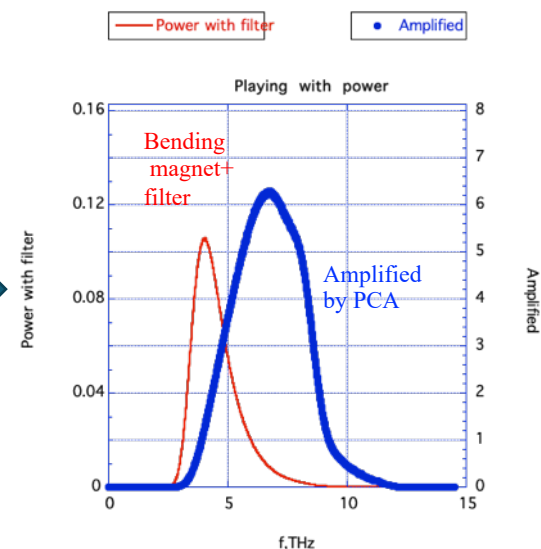
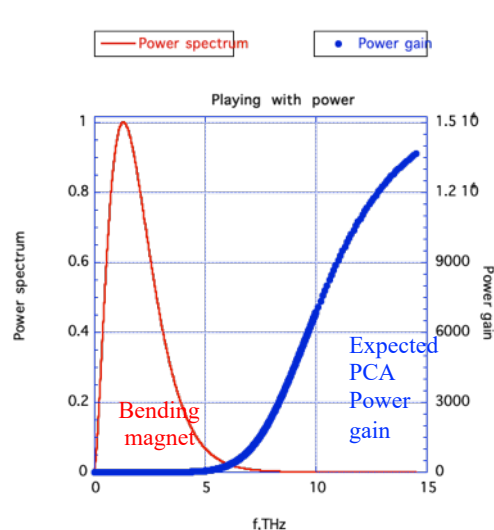
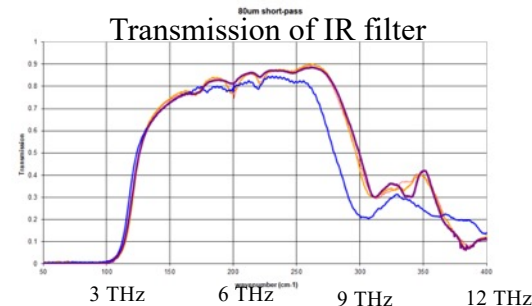
Relaxed lattice



* Important note: by unknown 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 measured by blocking IR radiation using Mirror 1 – then it is subtracted from the signal measured in the presence of IR radiation

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

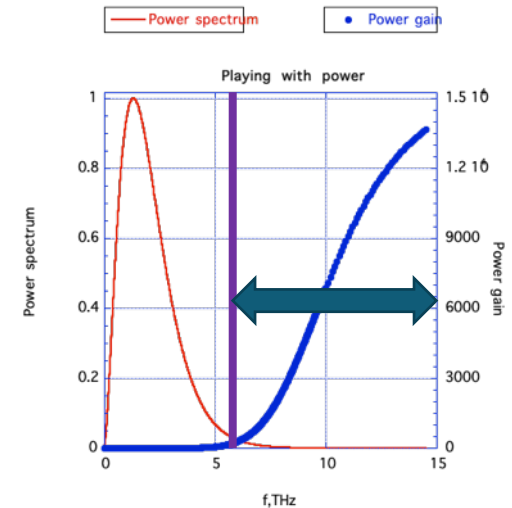


Power integrals: Relaxed: 0.2007;
Amplified : 23.84

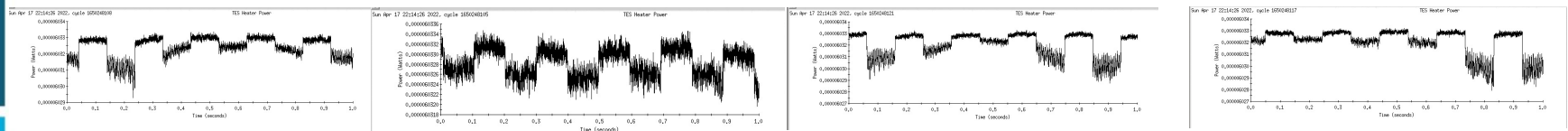
Expected PCA/relaxed power ratio: for 100% of the beam is **119**
for 50% of the beam is **60**

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 μm
- ✓ In this assumption, the measured average value for PCA/Relaxed ~ 100 and peak ~ 300 , would indicate that
 - ✓ Either peak current $\sim 50\text{A}$ 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

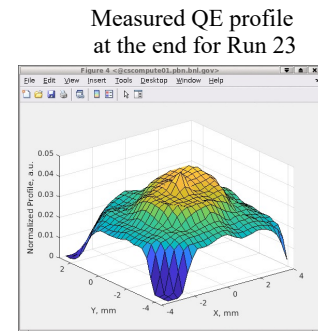
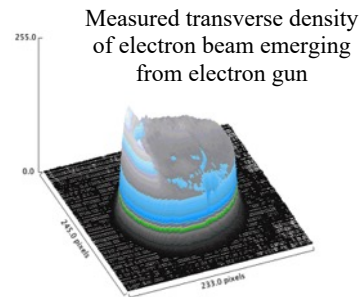


Power integrals above 6 THz
 Relaxed: 0.0206;
 Amplified : 22.08

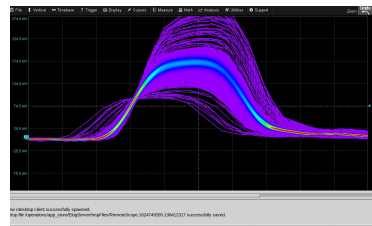


Possible sources of problem with beam quality

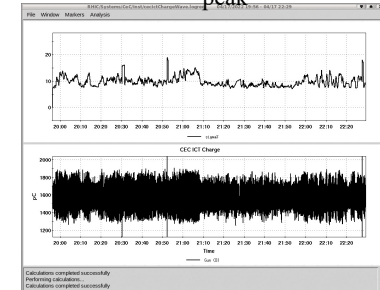
- ❑ Halo – result of the QE and laser beam non-uniformity. Large deviations of the electron bunch density on the cathode results in transverse filamentation of the electron beam
- ❑ 5% RMS, 30% peak-to-peak pulse to pulse laser power jitter causes dramatic variations in beam dynamics of our space-charge dominated beam, which are sufficient to explain observed variation in PCA gain
- ❑ 30% ramp in the temporal profile of the laser pulses caused significant modification in the beam dynamics (when compared with beer-can from previous laser) and could be cause of additional losses in the CeC system



Sample of the green laser pulses in the laser trailer. The jitter roughly doubles at the SRF gun laser table



During last days of the run, jitter in the change per bunch caused by laser power jitter was 10% RMS and 40% peak-to-peak



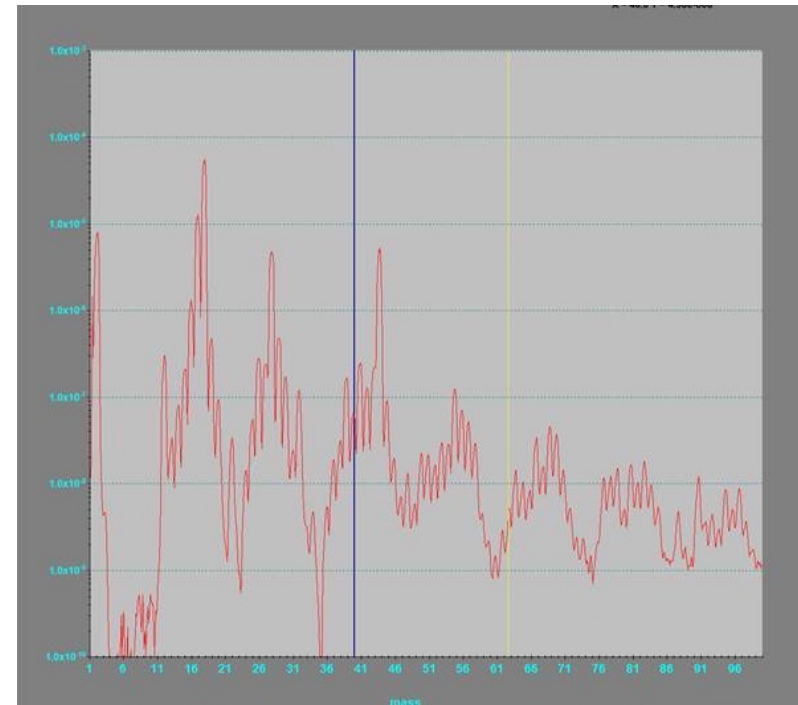
Post-Run events

- Drs. Gao and Fischer advised me not to request dedicated time for CeC in Run 23 from NPP PAC. CeC X will not have dedicated RHIC time in Run 23
- Dr. Fischer dissolved the CeC group and transferred its personnel to Beam Cooling group.
- We continue simulation studies of CeC accelerator and cooler performances using slice-by-slice distributions of simulated beam – topic for next talk by Dr. Gang Wang
- We developed and following up on 14-point plan for CeC accelerator with following key improvement:
 - Baking-out of the beam dump in diagnostics beamline to allow full current CW beam operation in this mode
 - Designing and ordering new 500 MHz bunching cavity to avoid time-dependent transverse kick originating from existing system
 - Upgrading vacuum and He conditioning system of SRF gun
 - Increasing size of the coated cathode area to allow for compensating of non-zero ejection angle from the SRF gun
 - Improving/controlling pulse shape of the drive laser

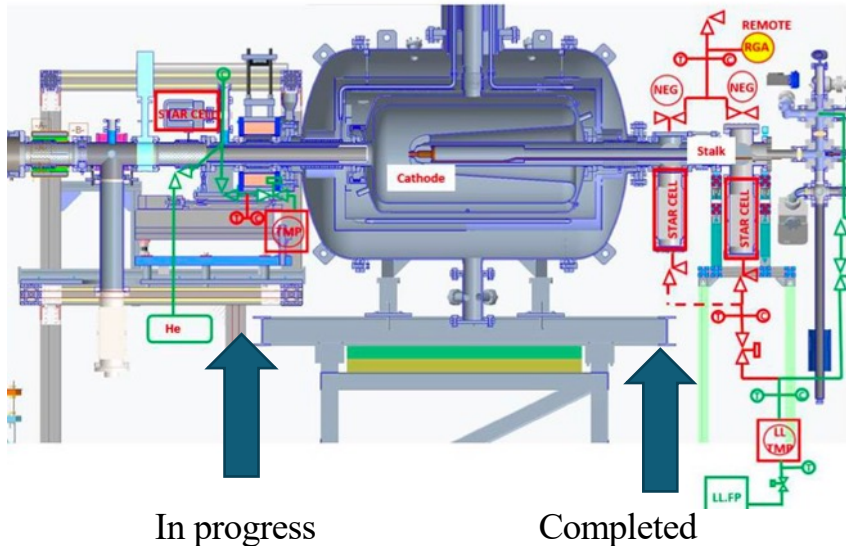
TDBL Beam Dump Bake-out



- Bake out is completed with $4\text{E-}10$ torr vacuum
- Next step will be unwrapping, connecting equipment's (FC, ICT, cables) and closing the shielding



Upgrade of CeC 113 MHz SRF gun vacuum and He conditioning systems



Upgrade includes new high speed NEG pumps and new ion vacuum pumps at the cathode stalk and in the front of the gun aimed to an order of magnitude improvement of vacuum at the cathode location. In addition, two high compression ratio turbo-pumps will improve evacuation of He and other inertial gases from the gun system.



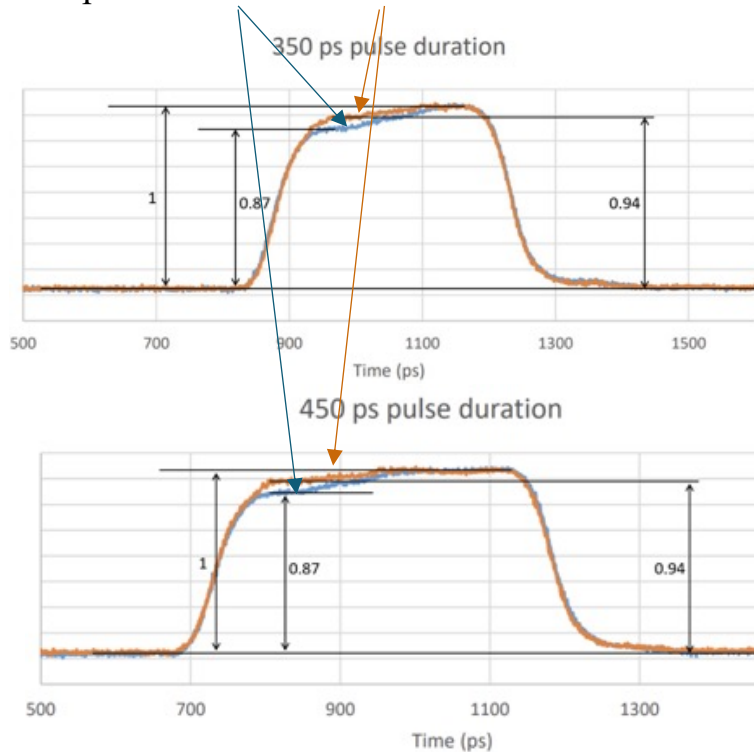
NEG Zao-2000 L/s cartridges



Laser Pulse Shape & Possible Control

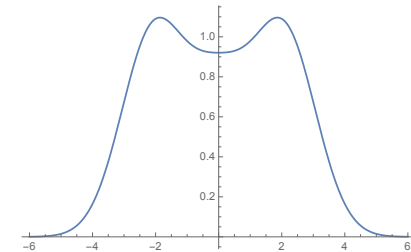
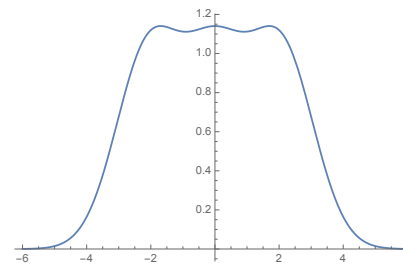
Current system

- Laser profiles: **before** and **after** modifications



Option for Run 23

- Use mode-locked seed oscillator, generate Gaussian pulse, split, delay/attenuate, combine
- Using three Gaussian pulses is easy to implement
- Three Gaussian pulses with $\sigma=53$ psec, separated by 112 psec result is laser pulse with FWHM of 350 psec. Power of the central pulse should be attenuated to control pulse shape from flat-top to double peaked with deep in the middle.



- Our preliminary simulations show that deep in the middle allow to flatten peak current profile of the compressed electron bunch

Plans for Run 23 and beyond

- ❑ Run 23 will be very challenging for CeC experiment. There will be no special dedicated time allocated for CeC X.
- ❑ We will apply for a portion of APEX time, but demonstration of PCA CeC is unlikely in this scenario.
- ❑ Run 23 plan has following objectives:
 - ❑ Generate electron beam with stable parameters
 - ❑ Enlarge bunch profile flat-top with $\geq 50\%$ of charge within $\pm 10\%$ of I_{peak}
 - ❑ Establish reliable high-gain PCA
 - ❑ Create initial CeC set-up during allocated APEX time
- ❑ Plans for Runs 24 and 25 are in flux – a lot will depend on our progress during Run 23. We are still aiming on demonstration of longitudinal CeC before RHIC stops operations

Summary

- I want to thank everybody who participated in this very challenging CeC run: RHIC operators, colleagues from Accelerator Physics, RF, Vacuum, Instrumentation, Cryogenics, 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 called Coherent electron Cooling
- We failed to demonstrate CeC during this run, but not because of lack of efforts – 29% of run time was simply insufficient to reach our goal. Still, we made new step of verifying high PCA gain at frequencies of 6 THz and above – thanks to new pieces of IR diagnostics
- CeC accelerator still suffers from lack of reliability: both in terms for beam parameter jitter and poor repeatability of operation set-ups. This is the focus of our current activities in simulations and hardware upgrades.
- CeC group was dissolved, and its personnel was integrated in Cooling group. CeC X structure remains intact: Litvinenko - project director, Brutus - project manager and Jing – project physicist. We continue our weekly CeC theory/simulation meetings and by-weekly CeC engineering meetings.
- CeC X will not have dedicated RHIC time in Run 23 and will be limited to a portion of APEX time. Most of our activities during Run 23 will be limited to improving performance of CeC accelerator and working with short bunch trains in parallel with RHIC collider operations

The CeC team – never can get all your pictures ...



Thank you for attention