Coherent electron Cooling experiment at RHIC

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CeC X at RHIC retreat, May 24, 2022

The CeC team through the years – never can get all your pictures …

Argonne NATIONAL LABORATORY
NIOWAVE Accelerating Your Particles
BERKELEY LAB Lawrence Berkeley National Laboratory
Science & Technology Facilities Council Daresbury Laboratory
Fermilab
TECH-X
SLAC NATIONAL ACCELERATOR LABORATORY
Jefferson Lab Thomas Jefferson National Accelerator Facility

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- ❑ Remaining challenges
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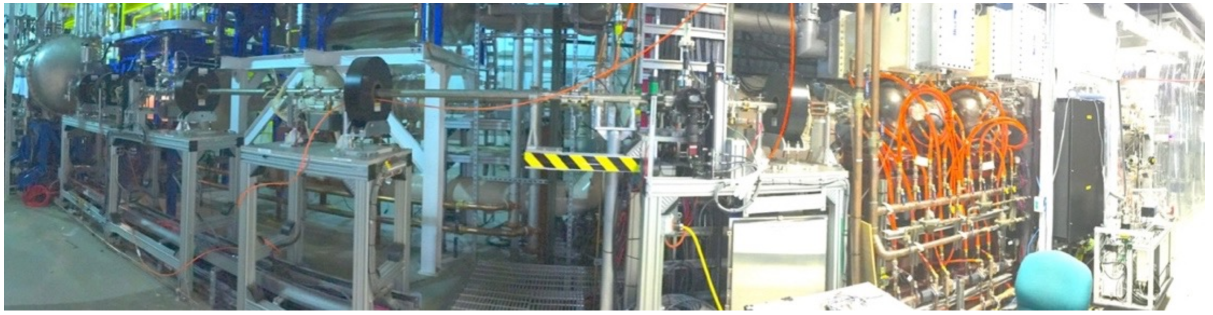
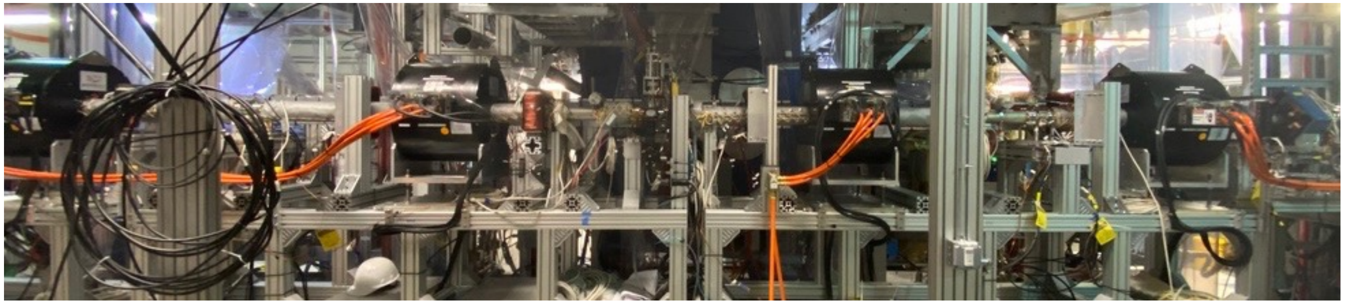
CeC X accelerator



CeC with plasma-cascade microbunching amplifier



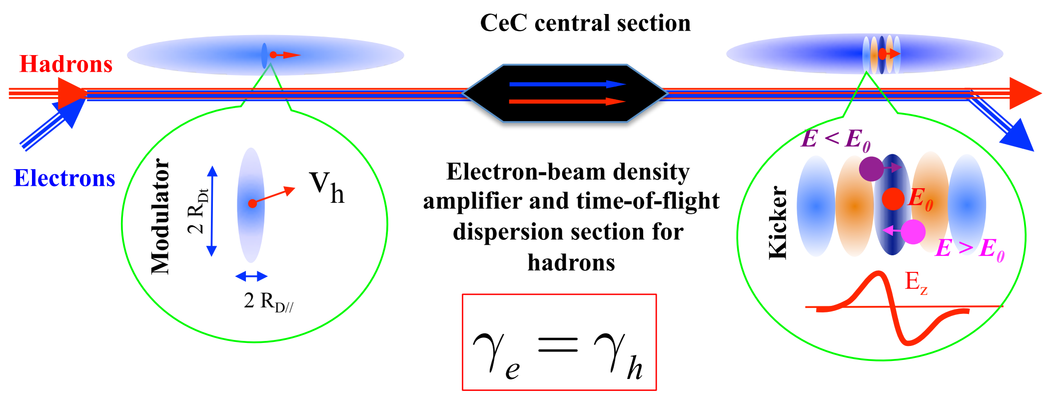
Run 22 results

- 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

Reminder: Coherent electron Cooling

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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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

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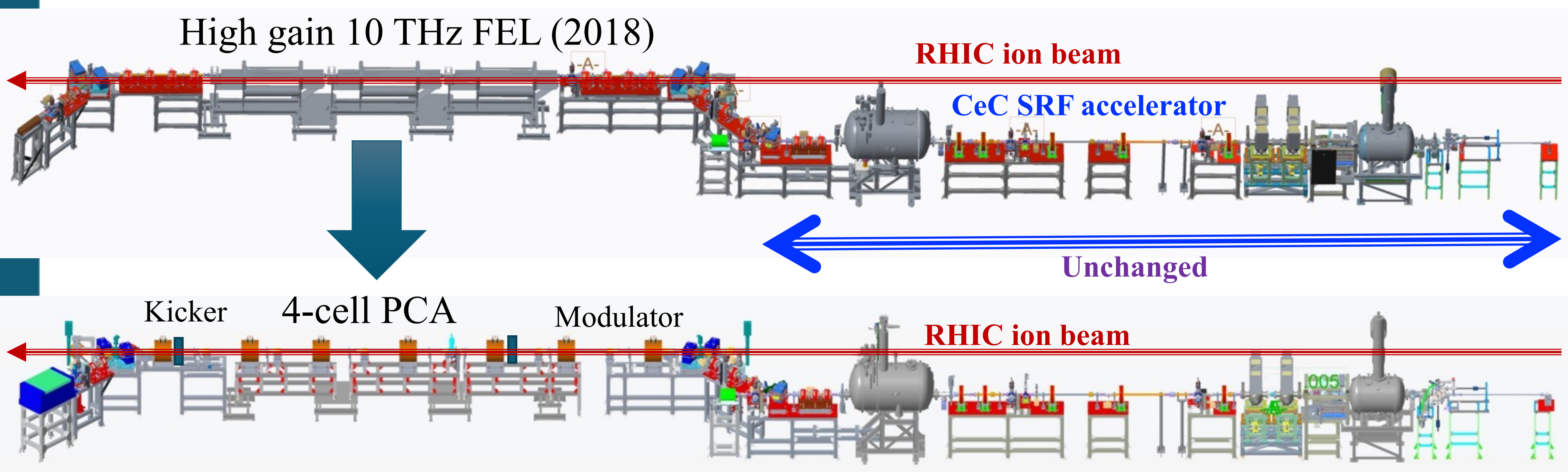
(Received 11 April 2013; published 20 August 2013)

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
- 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

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

- 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

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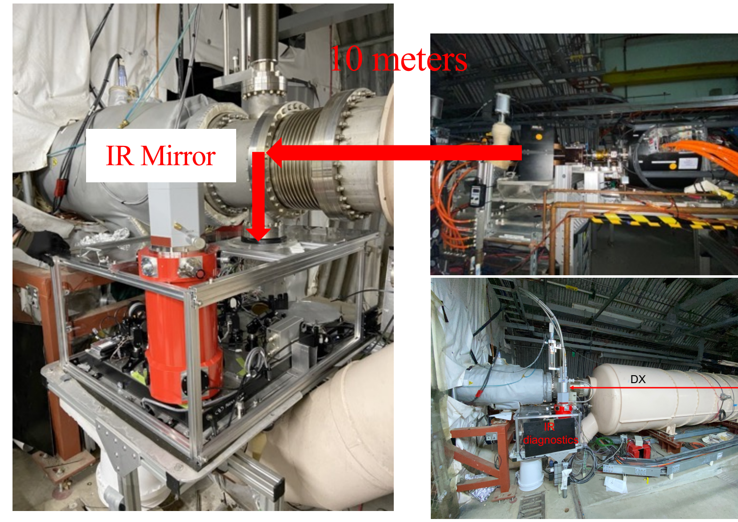
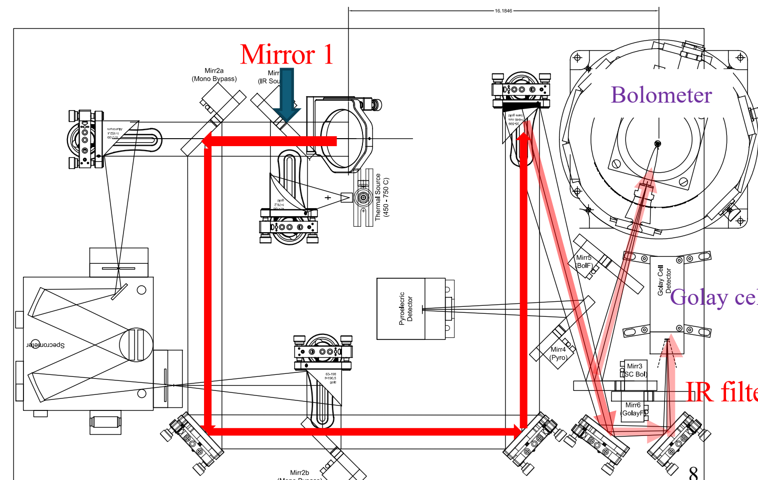
How PCA gain is measured?

- 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 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





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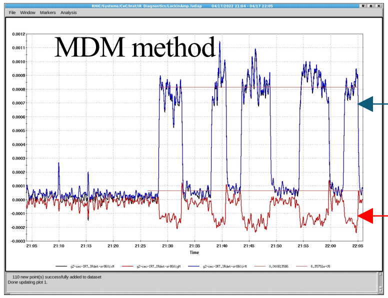
Golay cell measurement

PCA/Relaxed=65



PCA lattice

	Gain	Sensitivity	Time Constant	Input Range
Upstream	1	1V	3s	1V
Downstream	10	1V	3s	1V

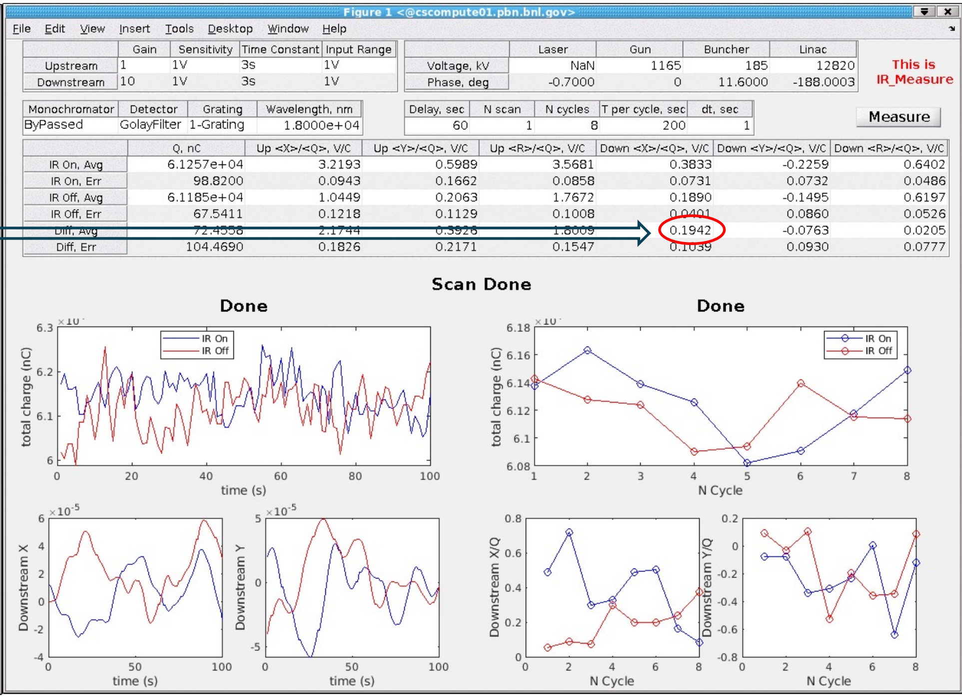
	Laser	Gun	Buncher	Linac
Voltage, kV	NaN	1165	185	12820
Phase, deg	-0.7000	0	11.6000	-188.0003

Monochromator	Detector	Grating	Wavelength, nm
ByPassed	GolayFilter	1-Grating	1.8000e+04

Delay, sec	N scan	N cycles	T per cycle, sec	dt, sec
60	1	8	200	1

	Q, nC	Up <X>/<Q>, V/C	Up <Y>/<Q>, V/C	Up <R>/<Q>, V/C	Down <X>/<Q>, V/C	Down <Y>/<Q>, V/C	Down <R>/<Q>, V/C
IR On, Avg	6.1040e+04	3.4041	0.5323	3.6860	13.6543	-2.5912	13.9082
IR On, Err	97.9296	0.2338	0.1110	0.2230	0.3908	0.0861	0.3881
IR Off, Avg	6.0963e+04	1.1199	0.4526	1.9644	0.9385	-0.1672	1.0303
IR Off, Err	98.8656	0.1257	0.1885	0.0977	0.0691	0.0460	0.0577
Diff, Avg	76.7191	2.2843	0.0797	1.7216	12.7158	-2.4240	12.8779
Diff, Err	173.6560	0.1759	0.2510	0.1834	0.4347	0.0906	0.4254

Relaxed lattice



	Gain	Sensitivity	Time Constant	Input Range
Upstream	1	1V	3s	1V
Downstream	10	1V	3s	1V

	Laser	Gun	Buncher	Linac
Voltage, kV	NaN	1165	185	12820
Phase, deg	-0.7000	0	11.6000	-188.0003

Monochromator	Detector	Grating	Wavelength, nm
ByPassed	GolayFilter	1-Grating	1.8000e+04

Delay, sec	N scan	N cycles	T per cycle, sec	dt, sec
60	1	8	200	1

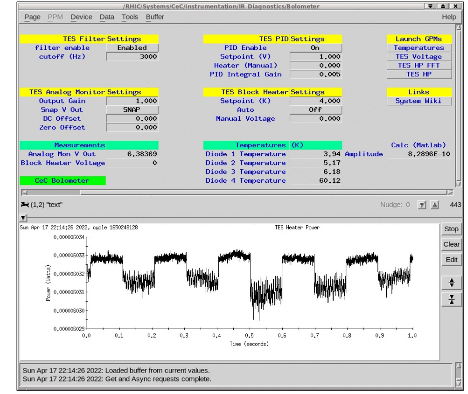
	Q, nC	Up <X>/<Q>, V/C	Up <Y>/<Q>, V/C	Up <R>/<Q>, V/C	Down <X>/<Q>, V/C	Down <Y>/<Q>, V/C	Down <R>/<Q>, V/C
IR On, Avg	6.1257e+04	3.2193	0.5989	3.5681	0.3833	-0.2259	0.6402
IR On, Err	98.8200	0.0943	0.1662	0.0858	0.0731	0.0732	0.0486
IR Off, Avg	6.1185e+04	1.0449	0.2063	1.7672	0.1890	-0.1495	0.6197
IR Off, Err	67.5411	0.1218	0.1129	0.1008	0.0401	0.0860	0.0526
Diff, Avg	72.4558	2.1744	0.3926	1.8009	0.1942	-0.0763	0.0205
Diff, Err	104.4690	0.1826	0.2171	0.1547	0.1039	0.0930	0.0777

Bolometer measurement*

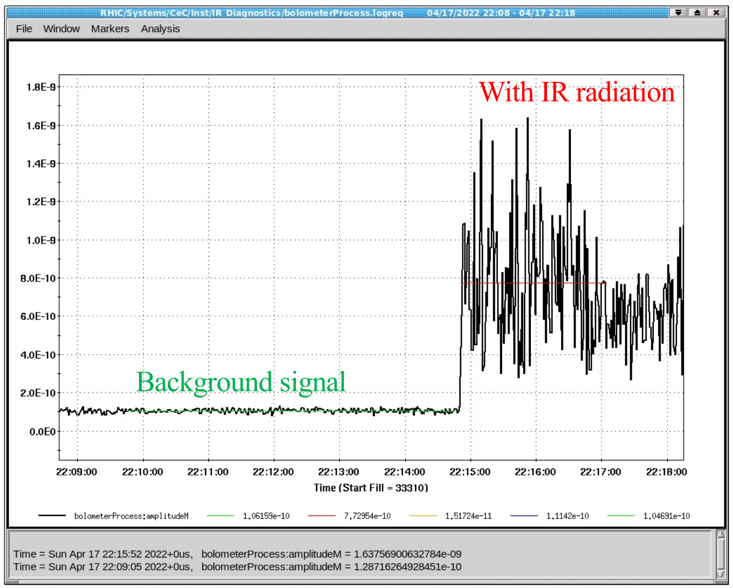
PCA/Relaxed:

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

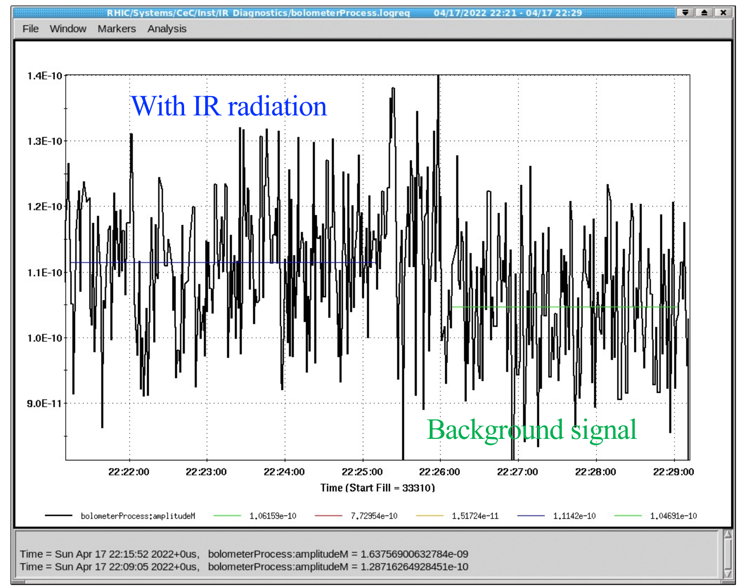
Raw
Bolometer signal



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*

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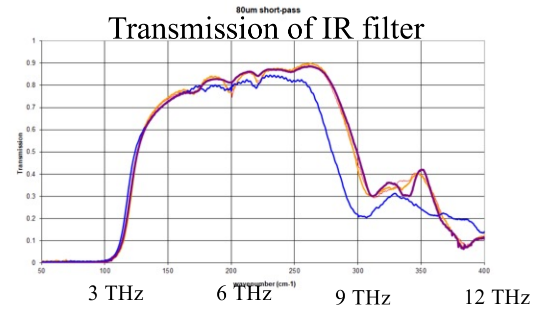
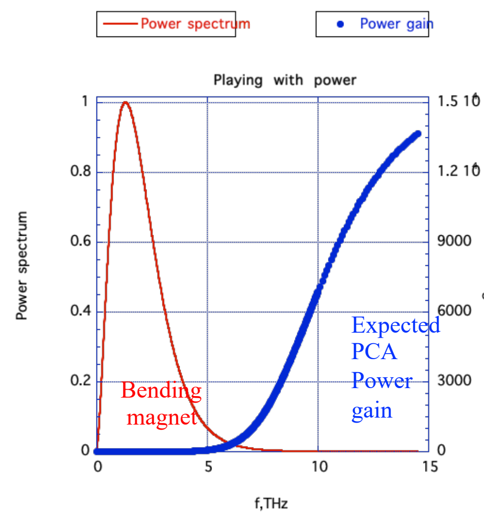
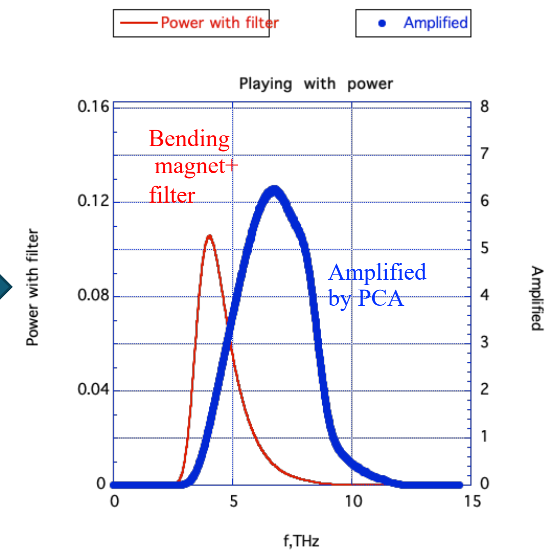
Expectations: Golay cell with IR filter

- ✓ 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



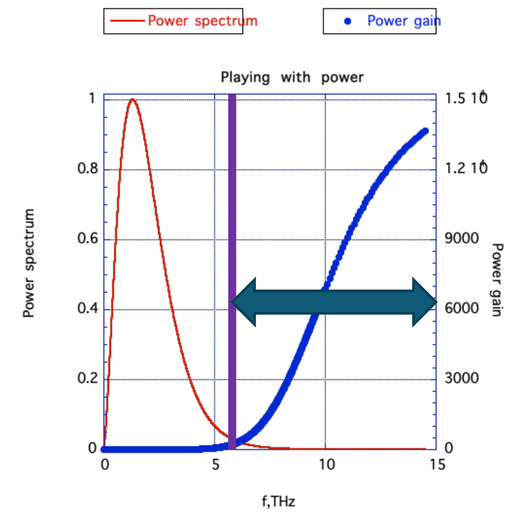




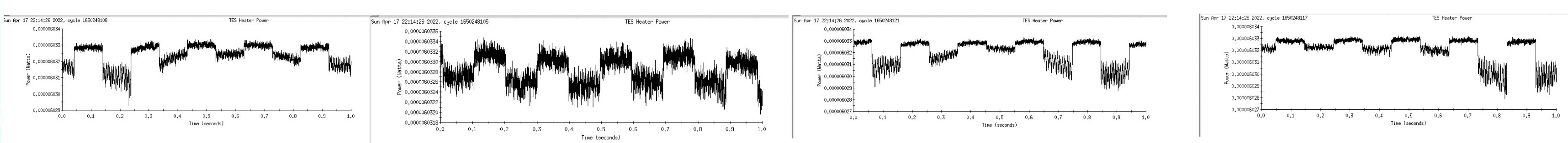
Power integrals: Relaxed: *0.2007*;
Amplified : 23.84
Expected PCA/relaxed power ratio: for100% of the beam is **119**
for 50% of the beam is **60**

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)

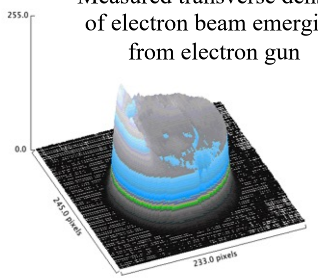
Two main failures in the CeC Run 22

- 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 an engineer decided to upgrade firmware, which 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 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 change 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. 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

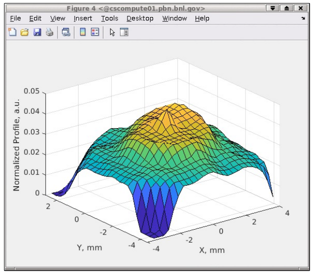
Possible sources of problem with beam quality

- Hallo – 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

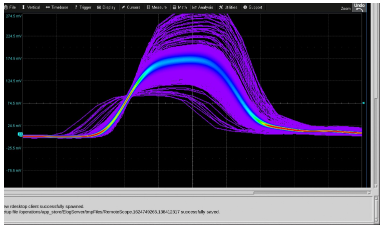
Measured transverse density of electron beam emerging from electron gun



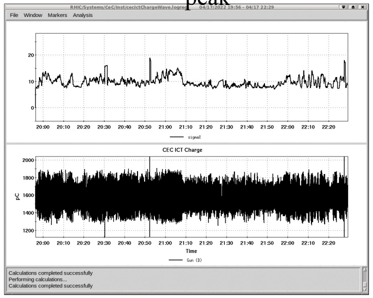
Measured QE profile at the end for Run 23



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



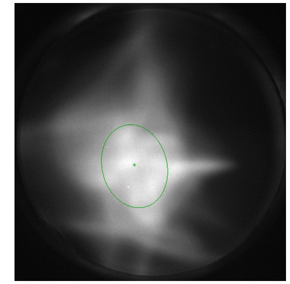
During last days of the run, jitter in the change per bunch caused by laser power jitter was 10% RMS and 40% peak-to-peak



Remaining challenges

- Variations (including pulse to pulse jitter) of the bunch charge cause significant variations of beam parameters. They are too large for both reliable measurements and for CeC operations
- Transverse non-uniformity of beam generated at the photocathode (QE x laser profile) is too large. It results in violation of axial symmetry, filamentation of beam and generation of halo.
- Time-dependent dispersion and transverse kicks originated from large offset (14 mrad horizontally, 7 mrad vertically) of the SRF gun axis and from asymmetric 500 MHz cavity design (2.25 mrad vertically and 0.7 mrad horizontally at 180 kV bunching voltage) messing up time-resolved measurements, including those of peak current and slice emittance
- Deviation of magnetic fields in the CeC solenoids from axial symmetry causes significant deviation of electron beam trajectory
- RFI ("junk" signal in each and every cable) remain major problem for reliable measurement in IP2. Sub-V interference significantly reduces our detection capabilities. At best, it dramatically slows down our measurements
- "Pink pet-pages" and very slow updates in LogView add to slowing down of operations and definitely at to irritation

CeC section



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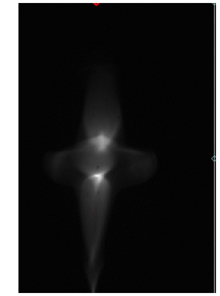

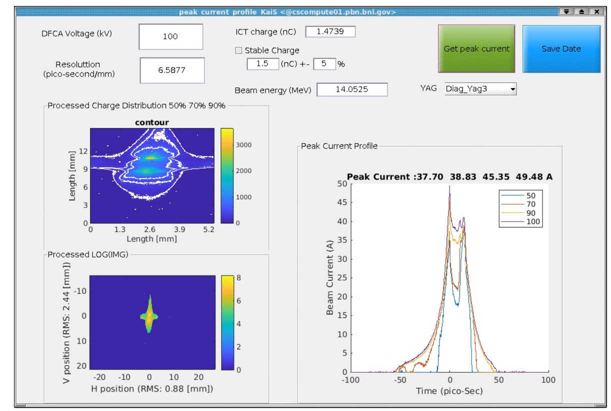

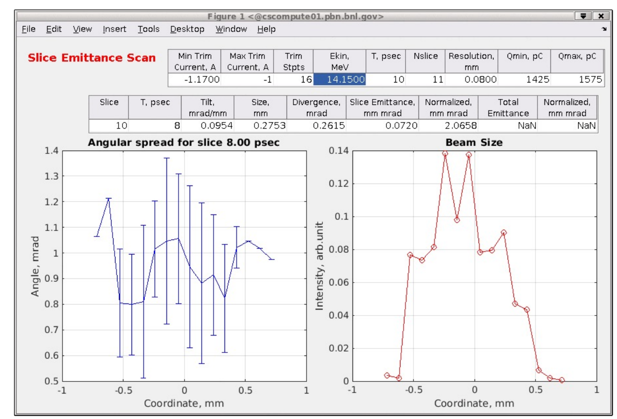

Summary

- **I want to thank everybody who participated in this very challenging CeC run: 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 demonstrated 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 repeatably of operation set-ups
- It requires several significant improvements to generate stable electron beam required for certain ability to demonstrate CeC. We did not reached this status yet.