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

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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

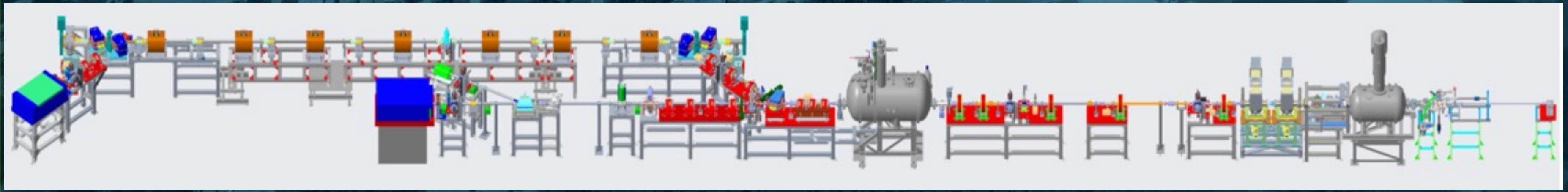








Brookhaven National Laboratory and Stony Brook University



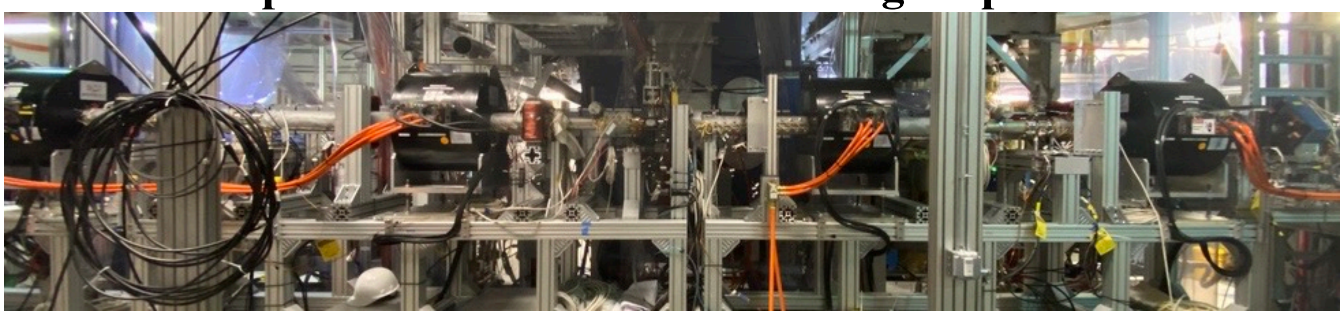
RHIC Machine Advisory Committee, December 13, 2022

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



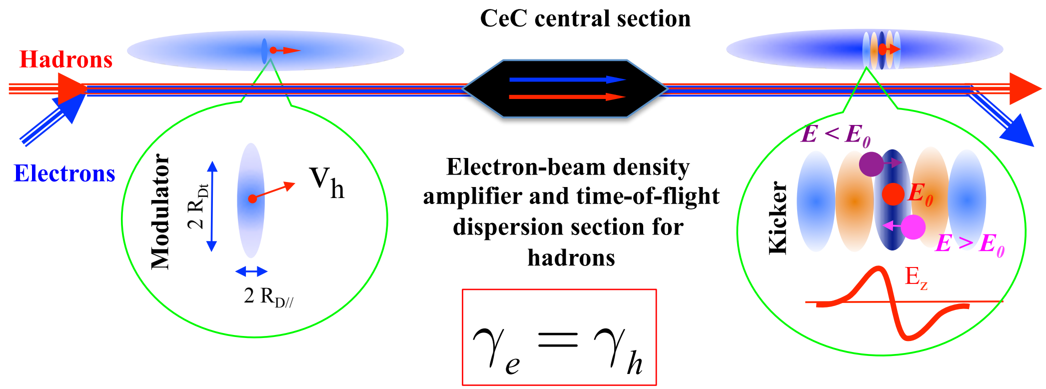
MAC 2021 recommendations

- ❑ 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

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

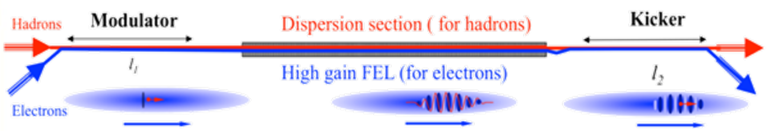
Microbunched Electron Cooling for High-Energy Hadron Beams

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

(Received 11 April 2013; published 20 August 2013)

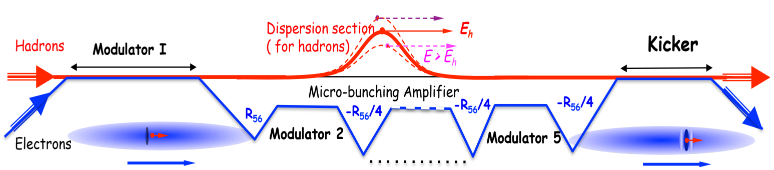
What can be tested experimentally at RHIC?

Litvinenko, Derbenev, PRL 2008



RHIC Run 18

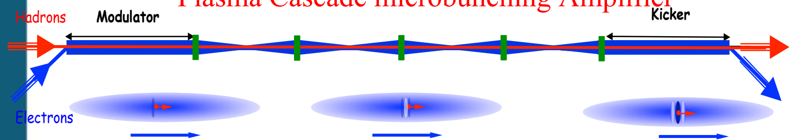
Ratner, PRL 2013



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

Litvinenko, Wang, Kayran, Jing, Ma, 2017

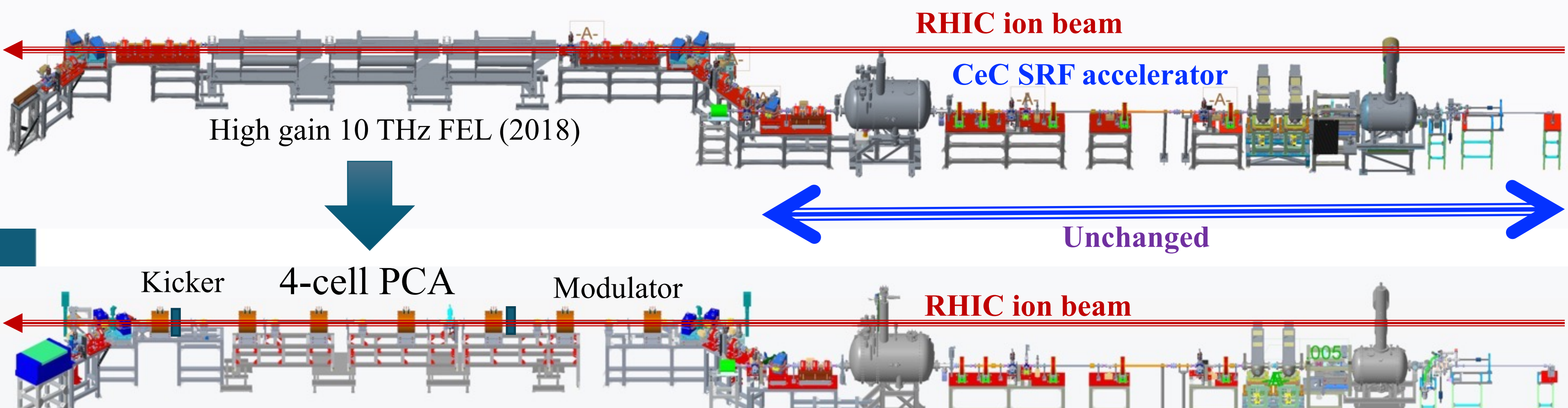
Plasma Cascade microbunching Amplifier



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 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 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

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CeC X status

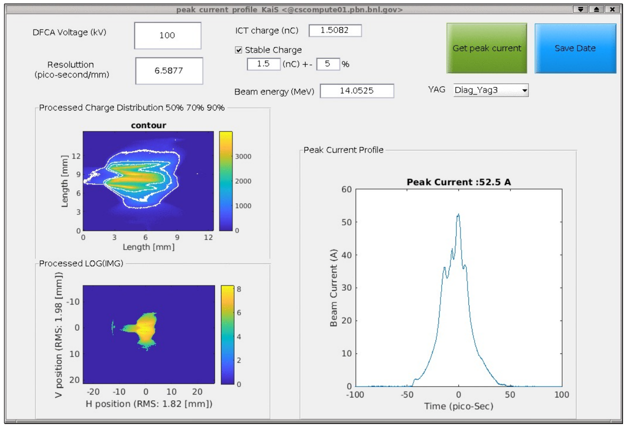
- ✓ Unique SRF accelerator generating high brightness electron beam, compressing it to 75 A at 1.25 MeV kinetic energy and accelerating it to 14.6 MeV
- ✓ Precise control of noise in electron beam: can suppress it to the level close to Poisson shot noise - for cooling - or increase thousands-fold to 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 elections with 26.5 GeV/ u Au ions
- ✓ Regular electron cooling of hardon beam at record energy of 26.5 GeV/ u

Electron beam KPP

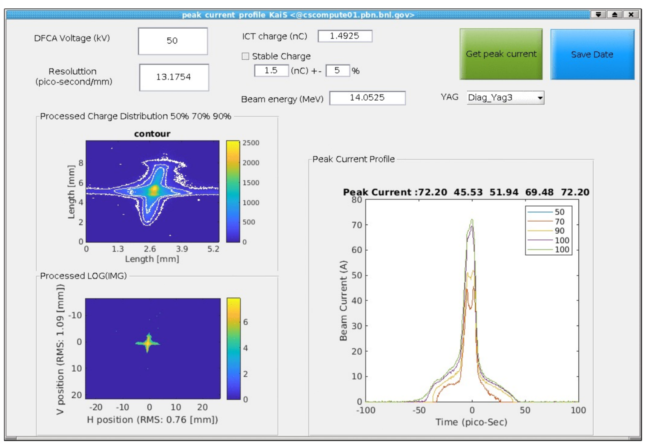
Parameter	**Planned**	**Demonstrated**	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the 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	✓

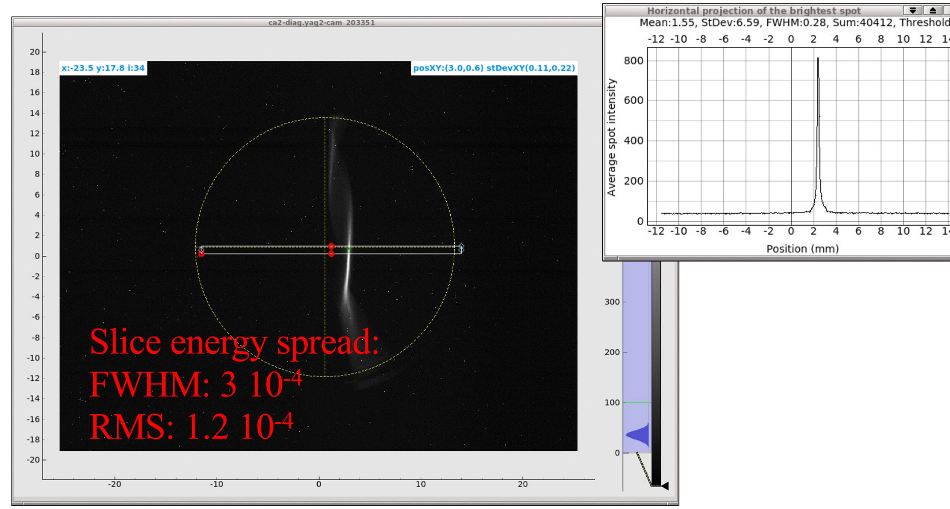
March 2022

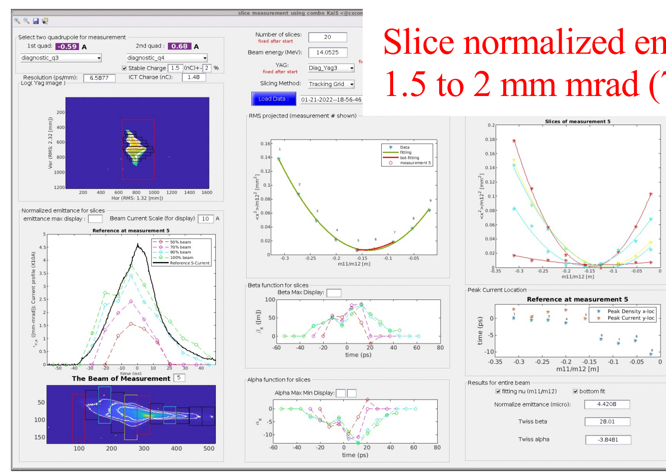
KPPs - Beam parameters with 185 kV bunching voltage



Peak current from 50A to 70 A



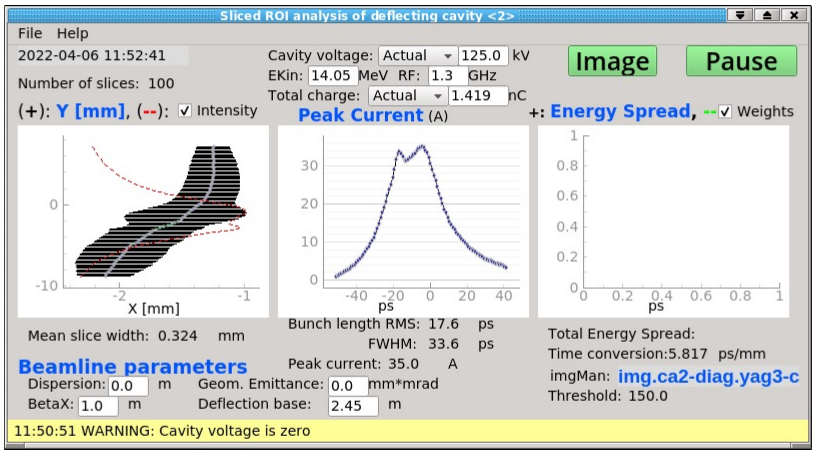




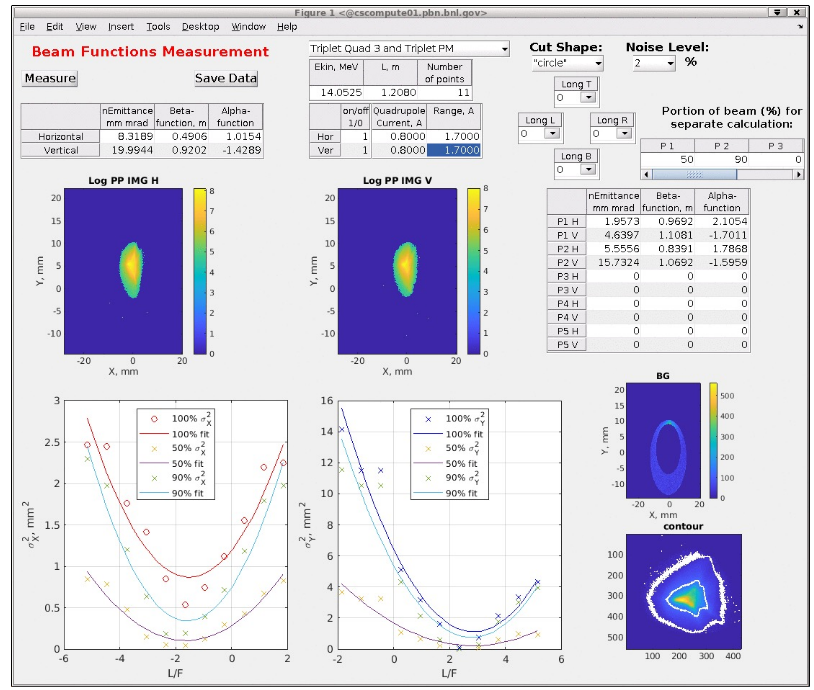
Slice normalized emittance
1.5 to 2 mm mrad (70% core)_

Beam stability remained to be a problem

Bad days (or bad measurements?)



Low peak current



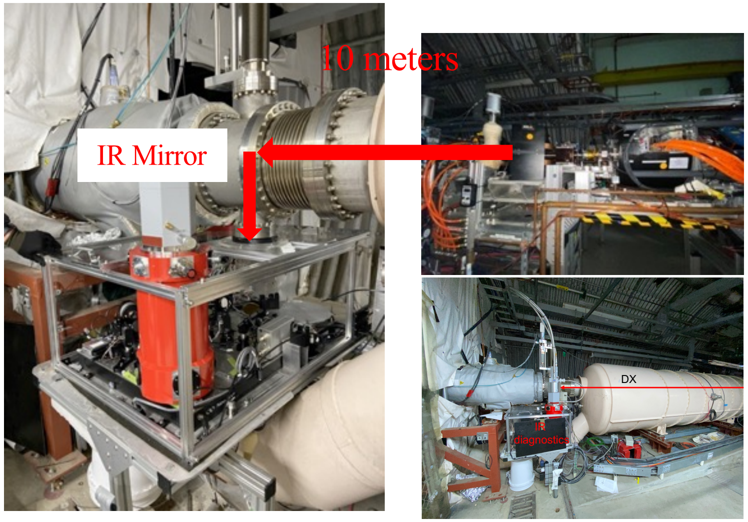
Large emittances, asymmetric beam (2x to 3x)

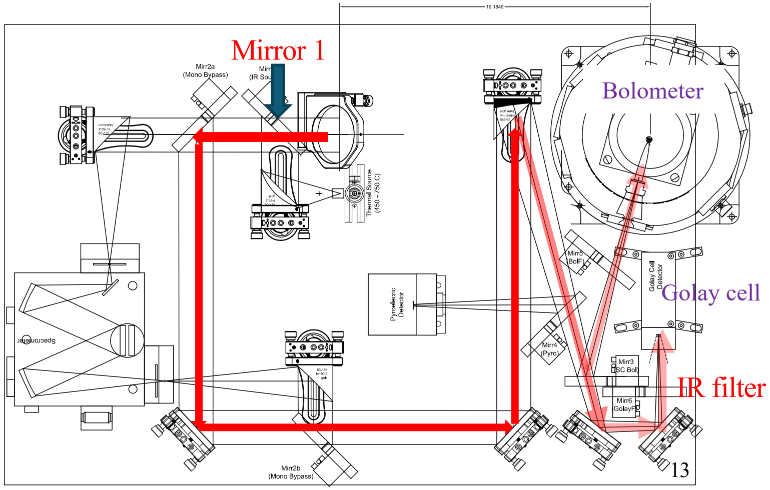
Run 22: Demonstration of Plasma Cascade Amplifier (PCA) gain at high frequencies

- 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 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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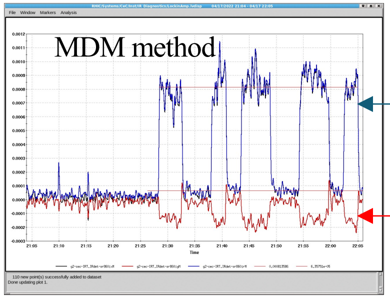
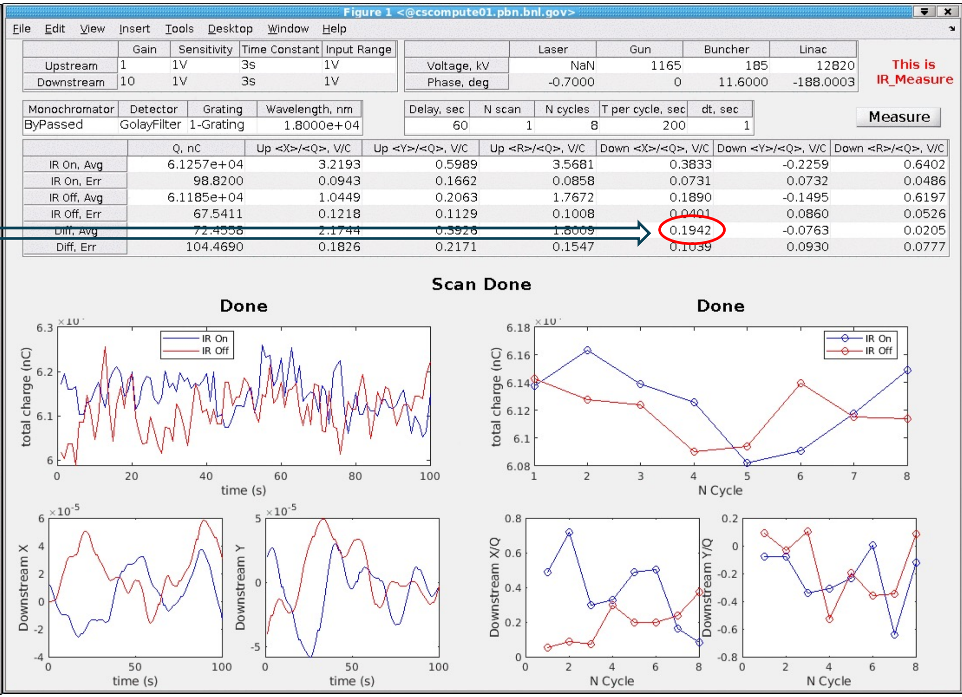
Golay cell measurement
PCA/Relaxed=65



PCA lattice

Relaxed lattice

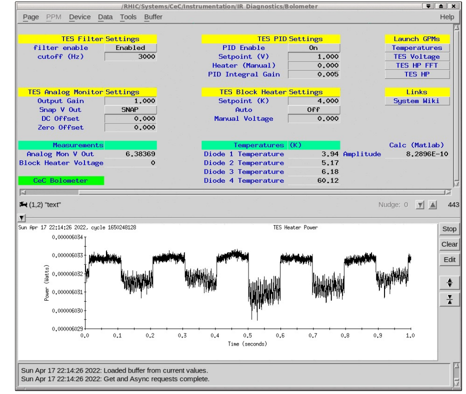


Bolometer measurement*

PCA/Relaxed:

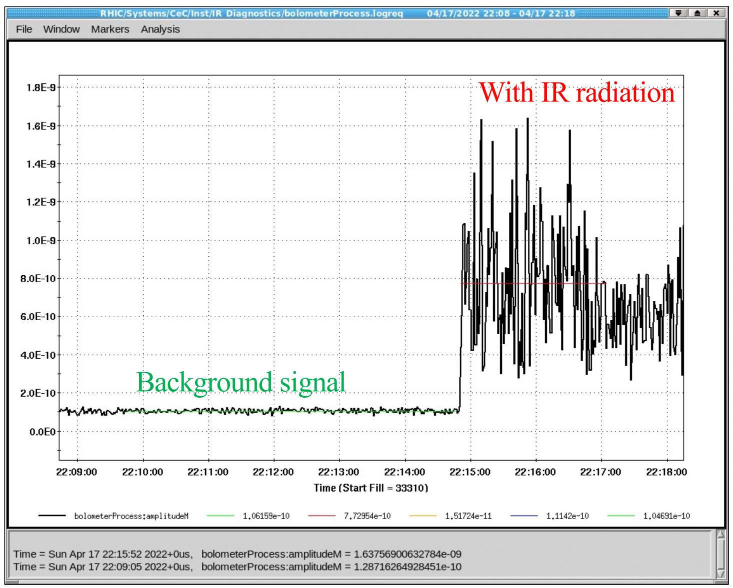
100 +/- 20 average, 300 +/- 50 peak

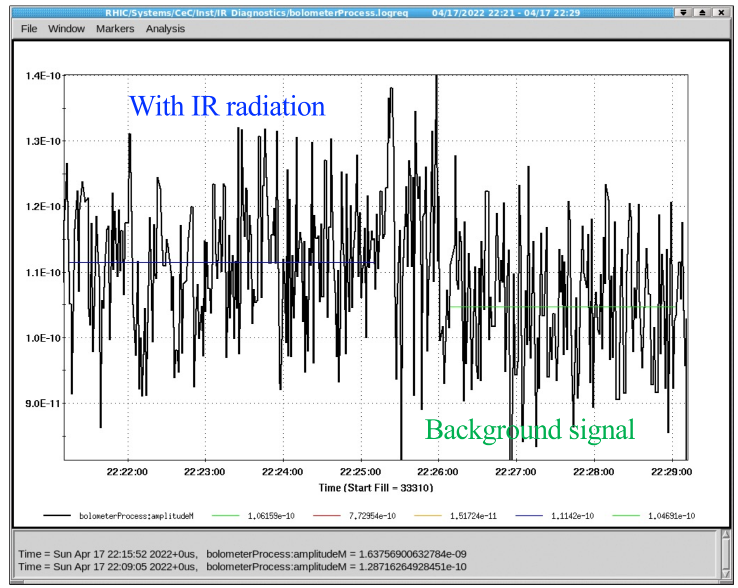
Raw
Bolometer signal



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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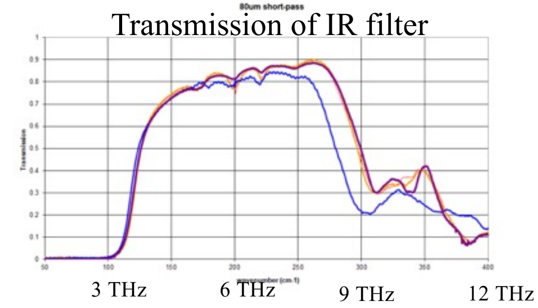
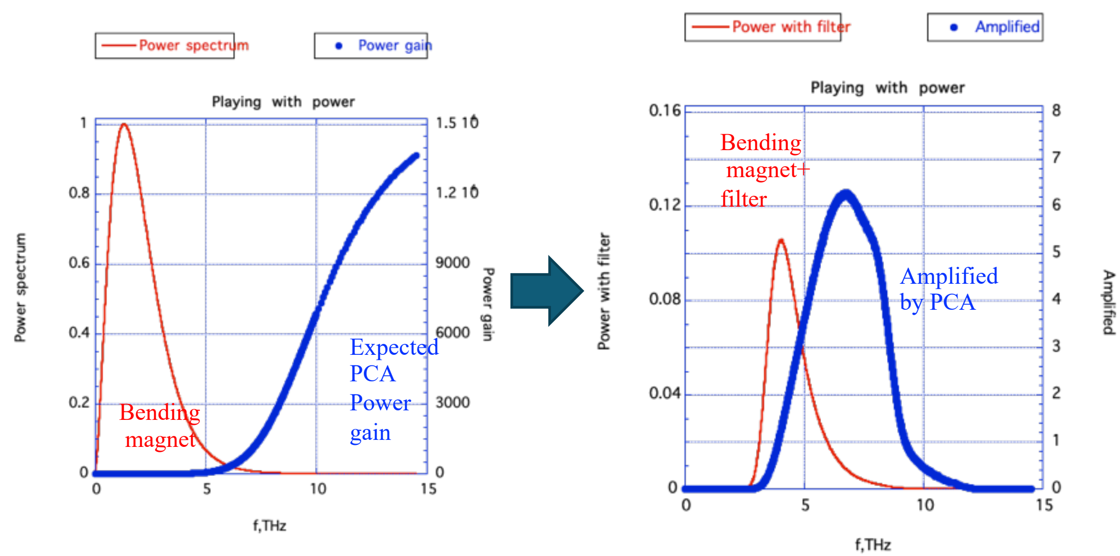
Expectations: Golay cell with IR filter



- ✓ 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**

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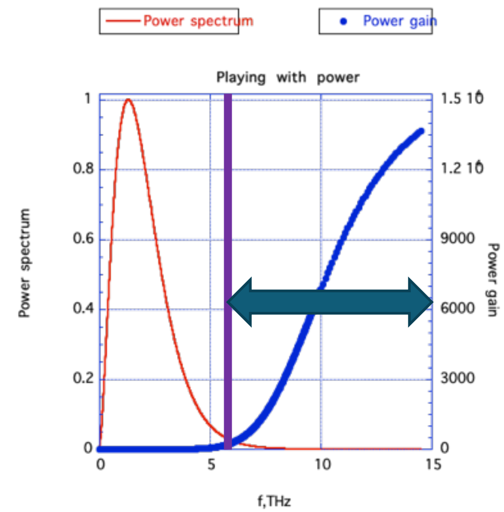
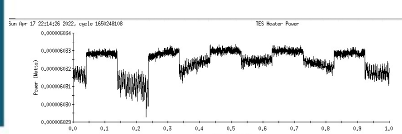
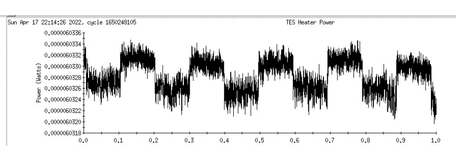
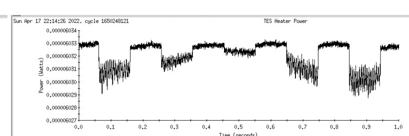
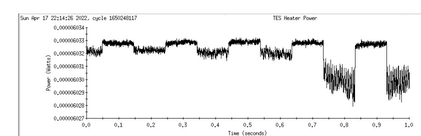
Bolometer Results

- ✓ 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)

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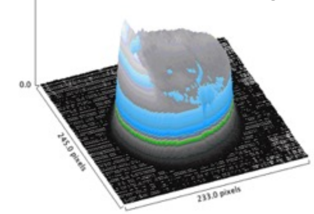
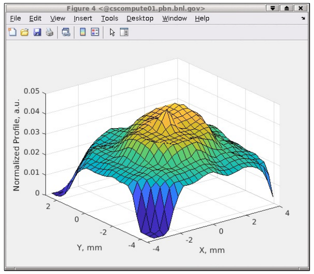
Possible sources of problem with beam quality

- 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

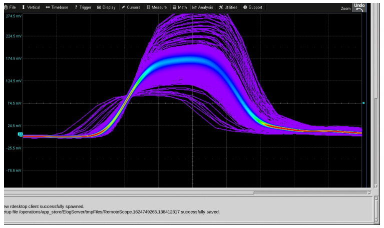
Measured transverse density of electron beam emerging from electron gun



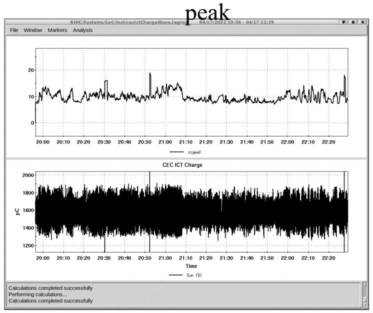
Measured QE profile at the end for Run 23



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



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

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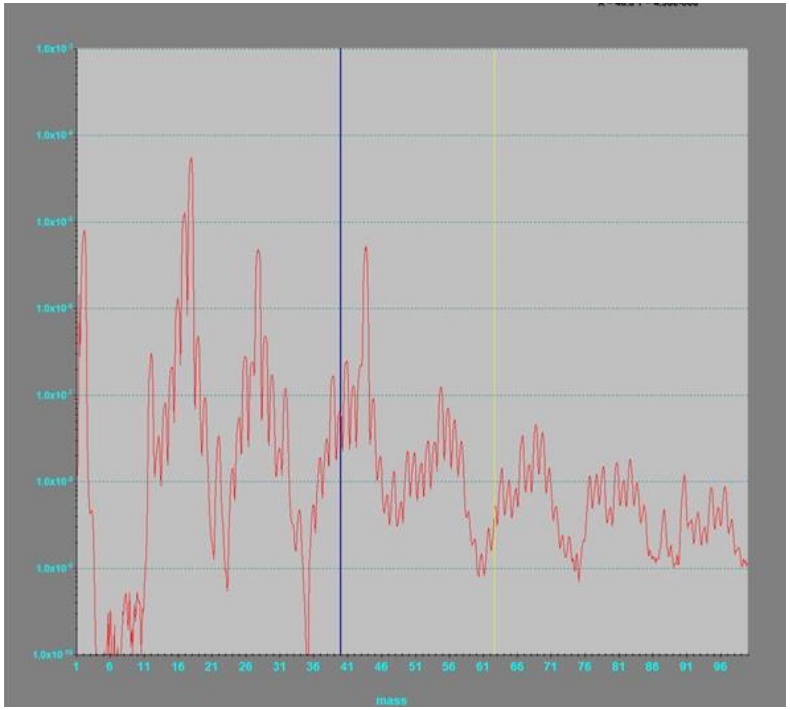
TDBL Beam Dump Bake-out

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



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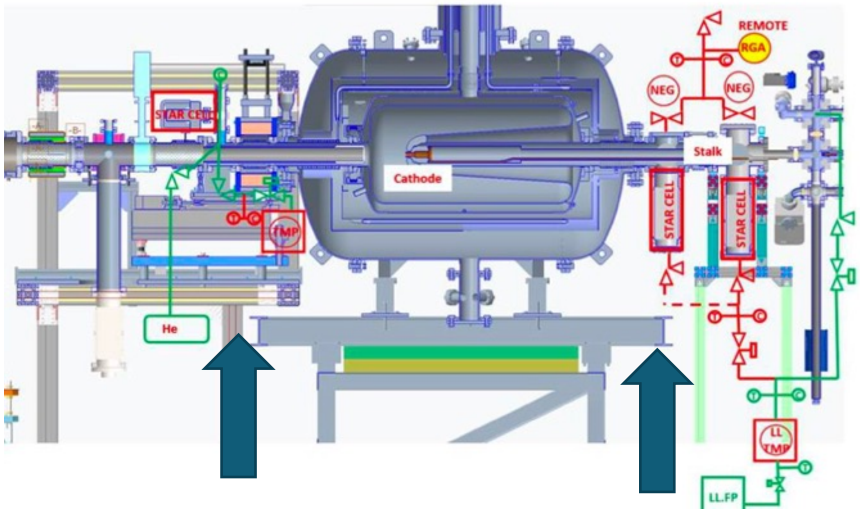
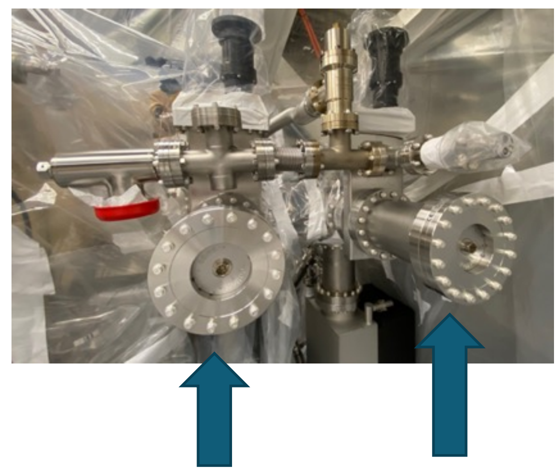
Upgrade of CeC 113 MHz SRF gun vacuum and He conditioning systems



In progress

Completed

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

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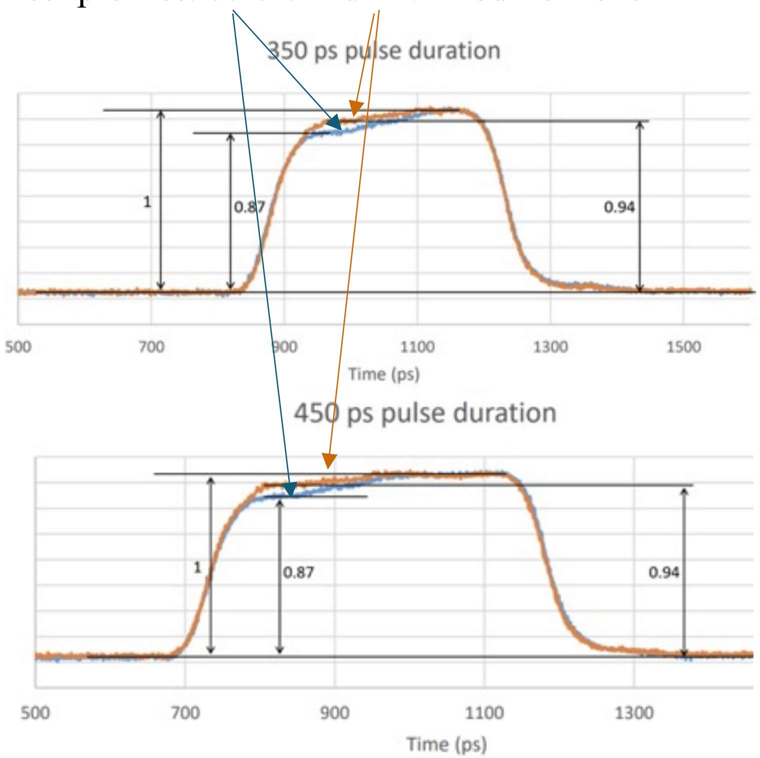
Laser Pulse Shape & Possible Control

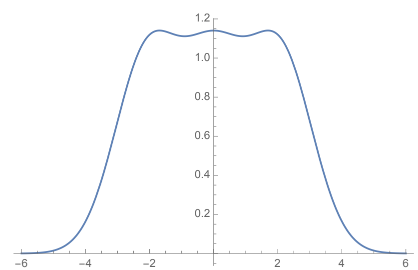
Current system

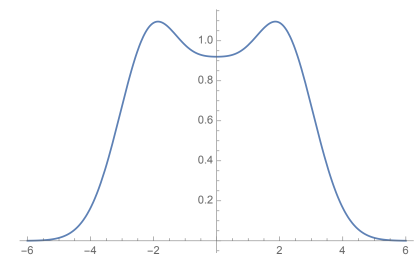
- Laser profiles: before and after modifications



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 σ=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

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Plans for Run 23 and beyond

- Run 23 will be very challenging for CeC experiment. There will be no special dedicate 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 ≥50% of charge withing ±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

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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. 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 will short bunch trains in parallel with RHIC collider operations

The CeC team – 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

Thank you for attention

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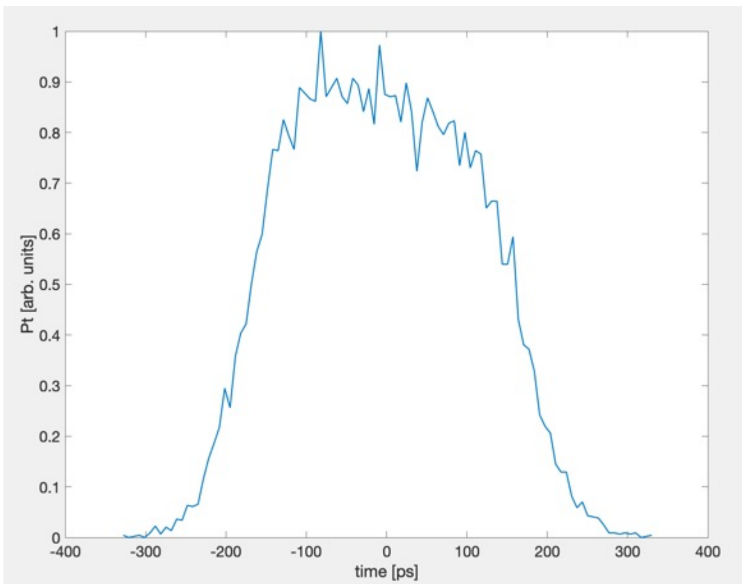
Back-up slides

Effect of the laser spot motion at the cathode on the beam dynamics in the gun

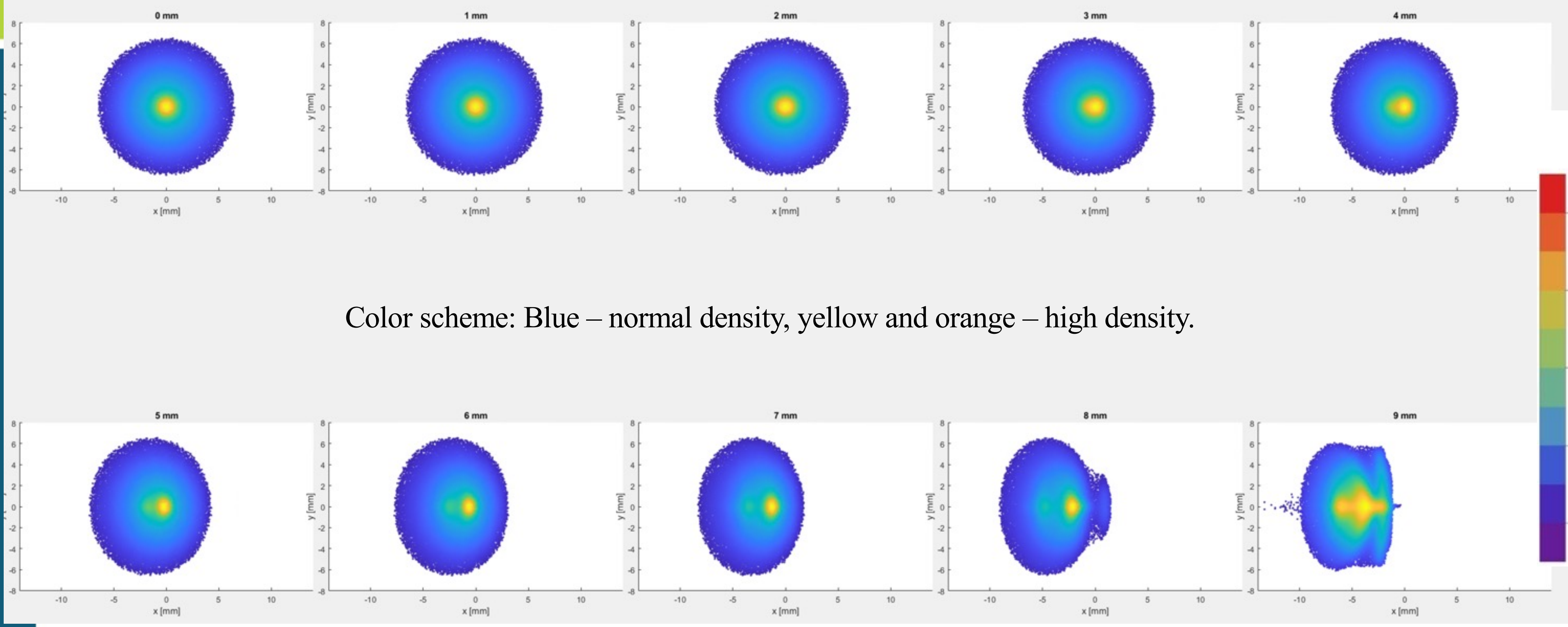
Simulation parameters:

- 2D RF field of the SRF gun from Superfish; cathode recess -10.5 mm; 1.25 MV; phased on crest.
- 50,000 particles; 1.5 nC; spot size diameter 3.54 mm.
- Beampipe screening with square pipe included.
- No solenoid, distribution is dumped ~0.3 m from the cathode surface.
- Laser profile:



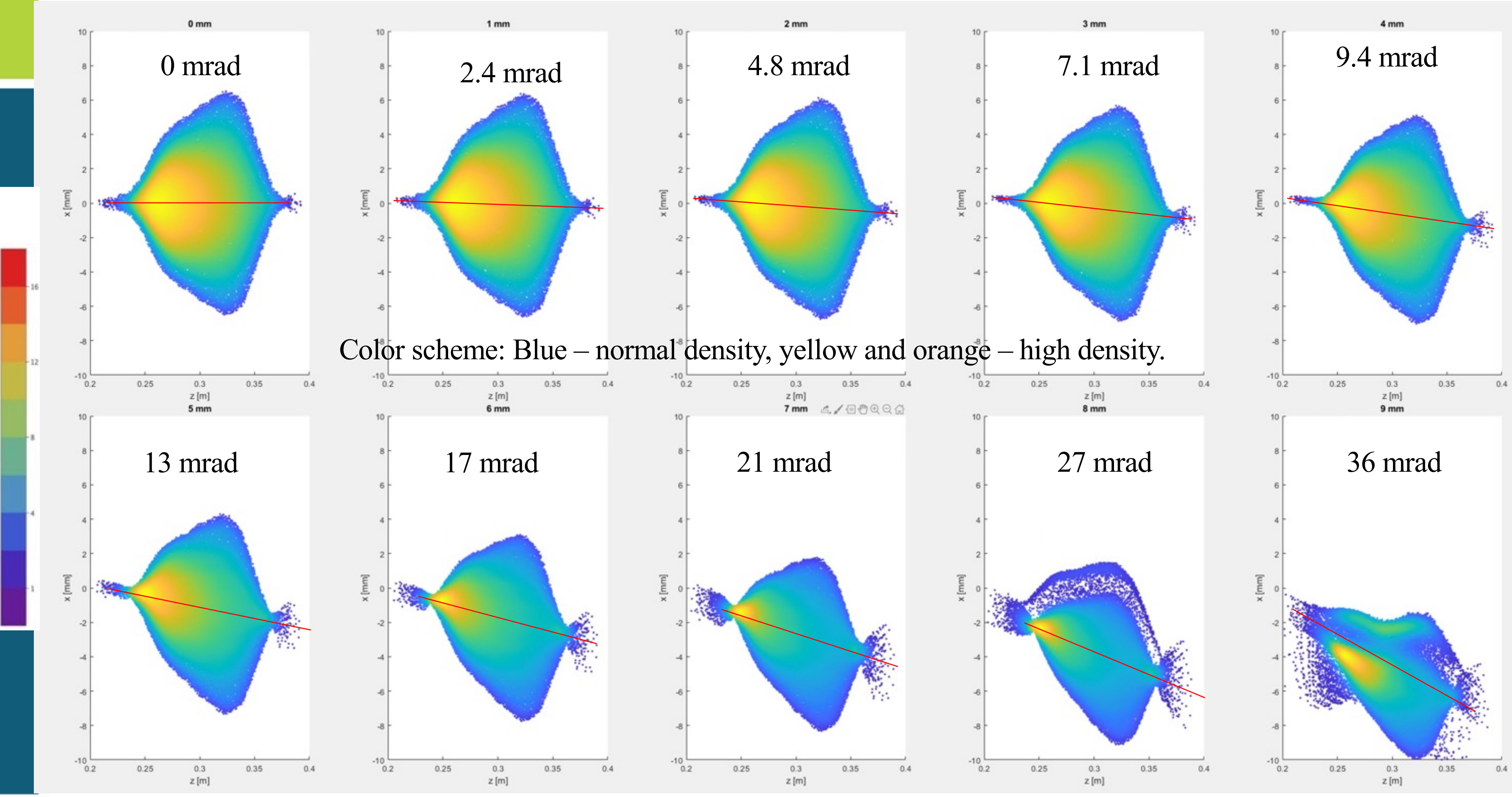
Irina Petrushina

X-Y distribution at ~0.3 m from the cathode for various initial shifts in x-direction



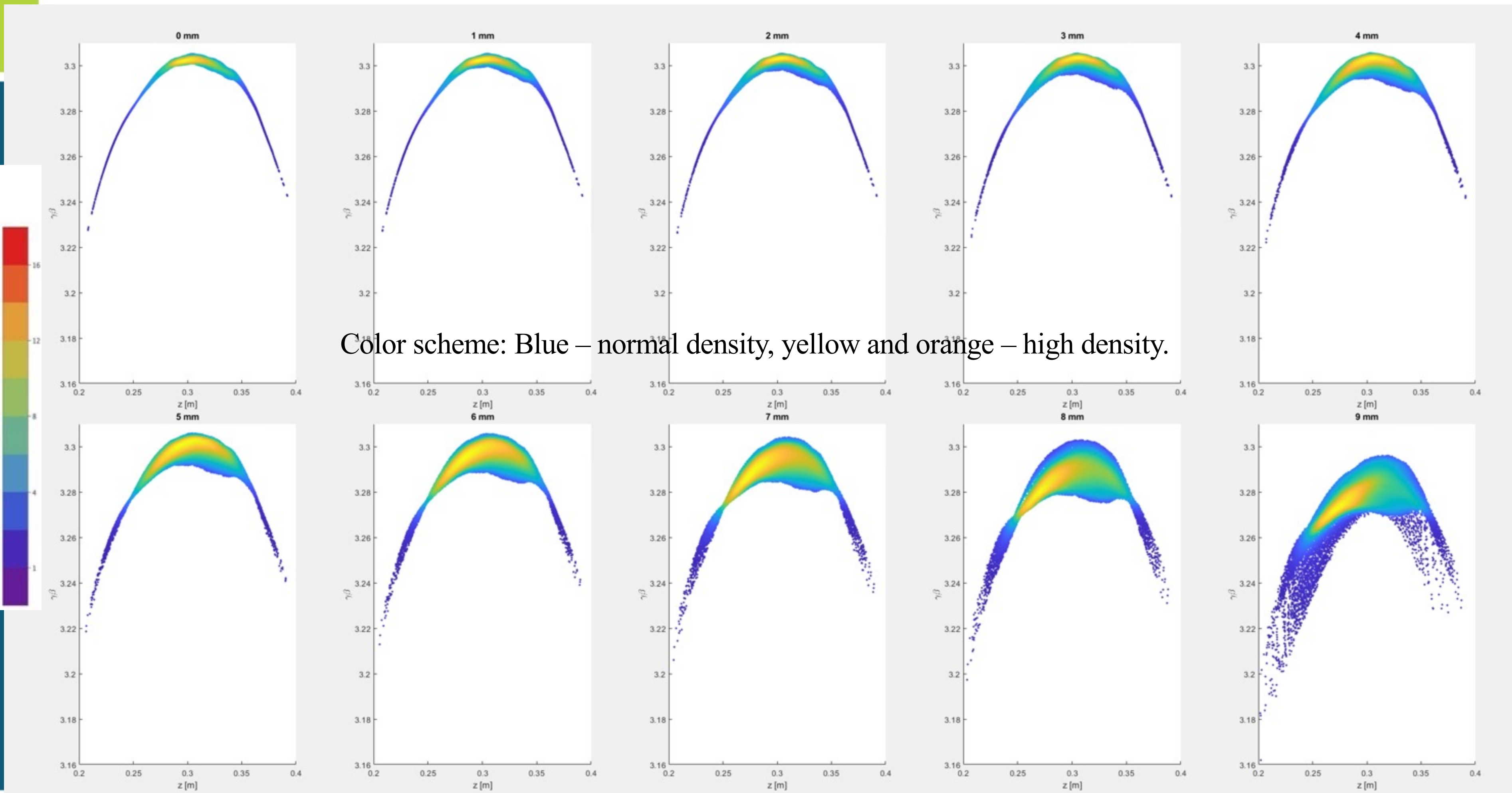
Color scheme: Blue – normal density, yellow and orange – high density.

Z-X distribution at ~0.3 m from the cathode for various initial shifts in x-direction



Color scheme: Blue – normal density, yellow and orange – high density.

z - $\gamma\beta$ distribution at ~0.3 m from the cathode for various initial shifts in x-direction



Color scheme: Blue – normal density, yellow and orange – high density.

14-point plan for 2022 RHIC shutdown

1. Stabilize laser pulses power jitter to <1% RMS
2. Bake-out the high power dump in the diagnostics beamline
3. Add 3 power supplies for the CeC solenoids 5,6 and 7
4. Survey solenoids and identify if support system needs modification
5. Increase radius of the photocathode coated area from 4 to 8 mm
6. ~~Design and install 500 MHz kickers to compensate transverse time-dependent kicks from 500 MHz bunching cavity.~~
7. ~~Build up RF system (2 power amplifiers and LLRF) to control 500 MHz kickers~~
8. Improve/rebuild gun cathode camera and illumination
9. Add 2,000 l/s NEGs, new ion pumps and high compression turbo-pumps to the SRF gun vacuum system
10. Bake-out the cathode stalk
11. Provide analog output from IR bolometer
12. Fix controls of the filter-amplifier for IR diagnostics
13. Re-build saturating gun trim dipole
14. New H/V slit for diagnostics beamline

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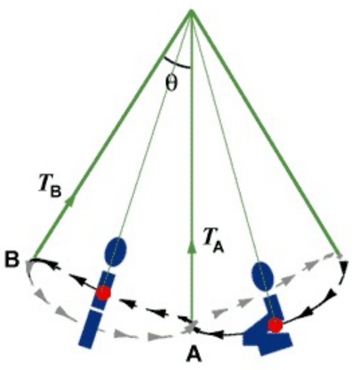
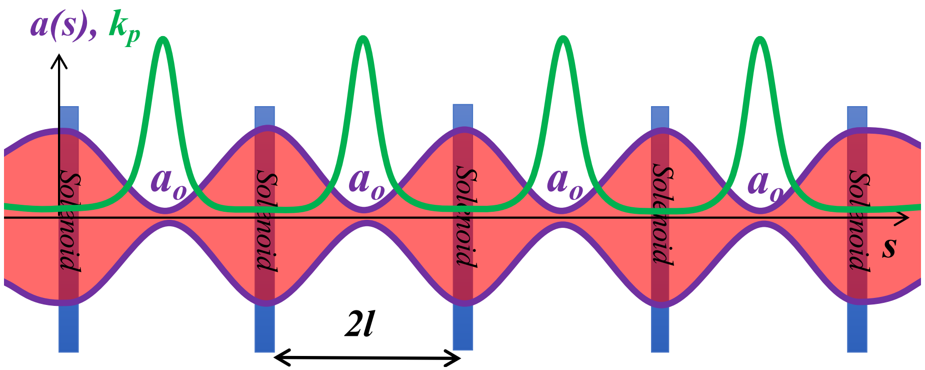
What is Plasma-Cascade Amplifier

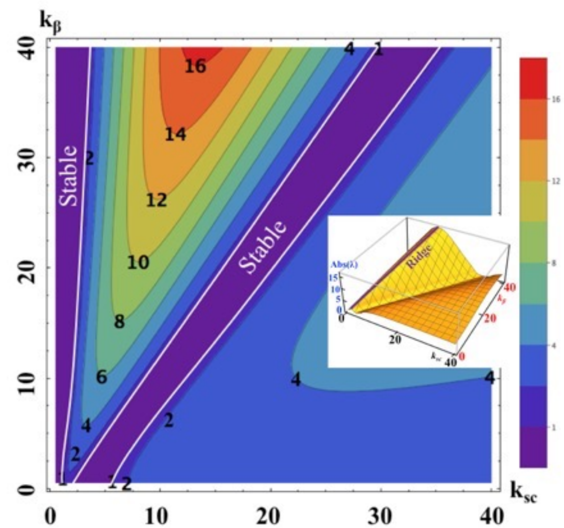
It is an exponentially growing parametric instability driven by variation of the plasma frequency and driven by the variation of the transverse electron beam size

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







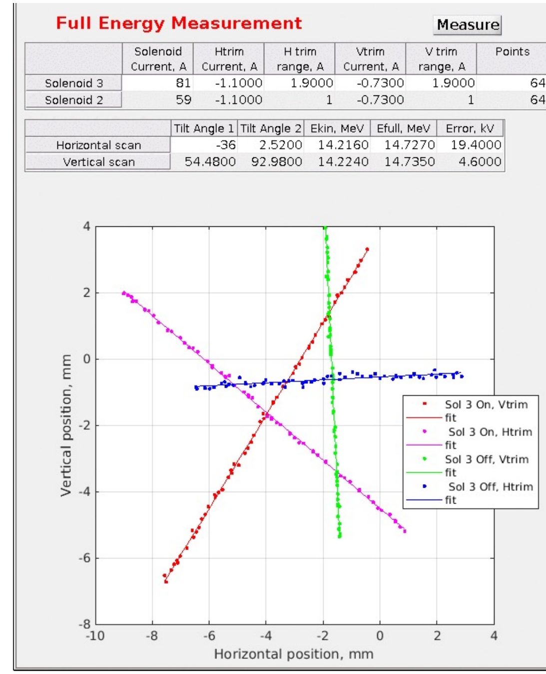
$$\hat{a}'' = k_{sc}^2 \hat{a}^{-1} + k_\beta^2 \hat{a}^{-3}$$

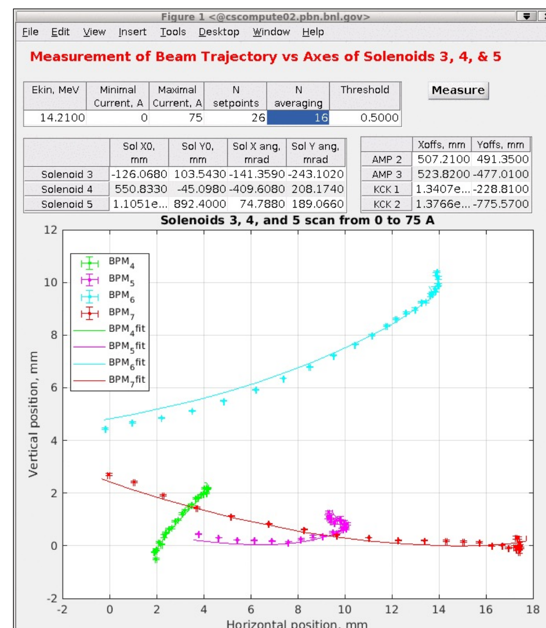
$$k_{sc}^2 = \frac{2}{\beta^3\gamma^3}\frac{I_o}{I_A}\frac{l^2}{a_o^2}; k_\beta = \frac{\varepsilon l}{a_o^2} = \frac{l}{\beta^*} \qquad \frac{d^2\tilde{n}}{ds^2} + 2k_{sc}^2\left(\frac{a_o}{a(s)}\right)^2 \tilde{n} = 0;$$

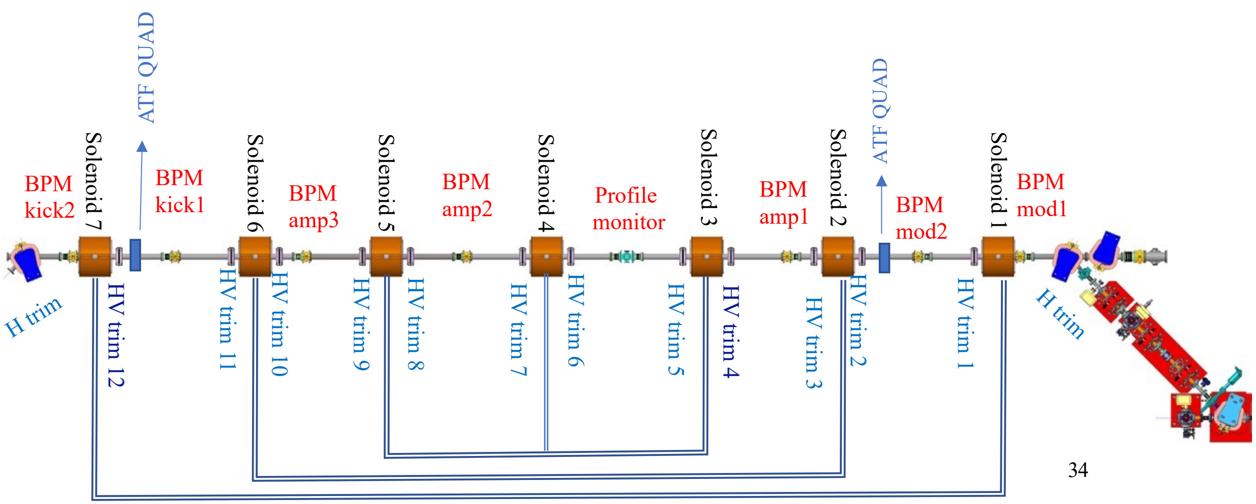
- *Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams*, arXiv:1802.08677, 2018
- *Plasma-Cascade Instability*, under review in Physical Review Accelerators and Beams

Energy measurements and novel BBA in CeC

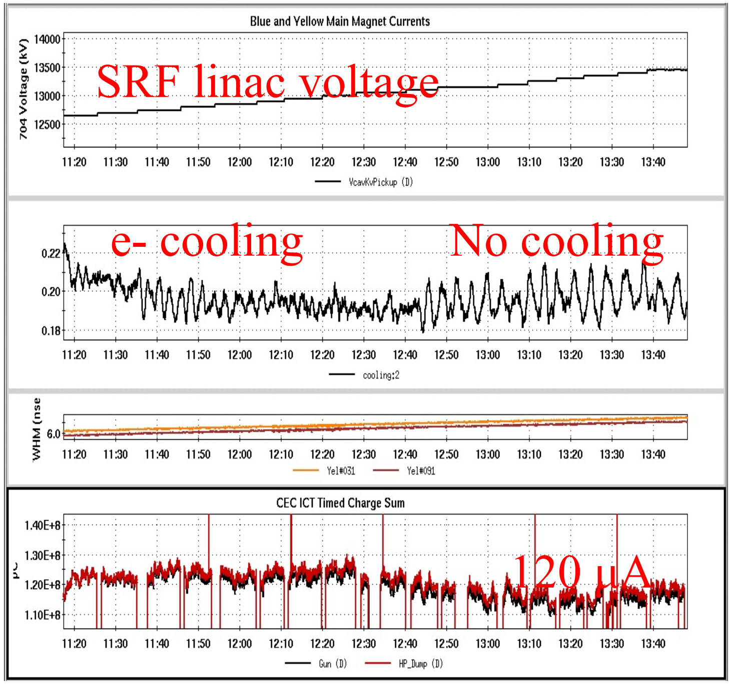
- ✓ Novel method of absolute beam energy measurement – based on Ampere law and knowing value of current and number of turns in solenoid: accuracy ~ 0.2%. Main source of errors is in the orbit jitter.
- ✓ Accurate alignment of the electron beam trajectory is critically important - we developed a well-defined process to achieve these goals:
  - ✓ Align ion beam with the centers of two quadrupoles installed in the CeC section;
  - ✓ Developed novel method of measuring both the location and the angle of the solenoid's axes using ion beam and RHIC. Solenoids are aligned with best accuracy the survey group can provide
  - ✓ Aligned electron beam onto the axes of solenoids
- ✓ **Success of this method was verified by observing recombination of the electrons and Au ion and observation of regular electron cooling**



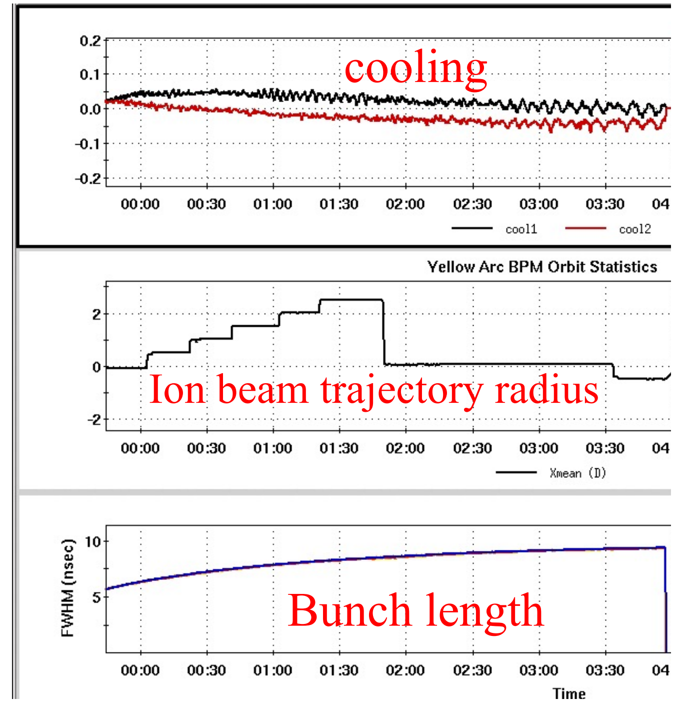




Search for CeC signature and observation of regular bunched electron cooling of 26.5 GeV/u Au ion beam



Changing e-beam energy requires multiple adjustments



Adjusting ion beam energy – 1 mm x_{mean} corresponds to 0.1% change in the ion beam energy.

- There was no attempt of improving regular non-magnetized electron cooling – we used the lattice optimized for PCA CeC - and the best electron cooling rate was ~ 100 hours. It is consistent with cooling rate estimation made by Dmitry Kayran and 90 hours cooling rate simulated by He Zhao
- There is one exception – on the 4th of July CeC evening shift we observed cooling rate of 16 hours: this event is possibly a first indication of the CeC cooling, but it is not conclusive

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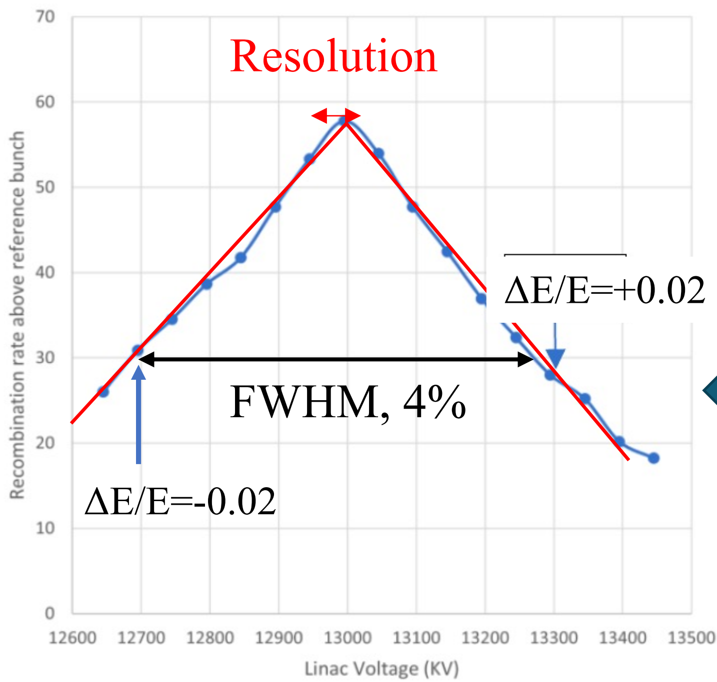
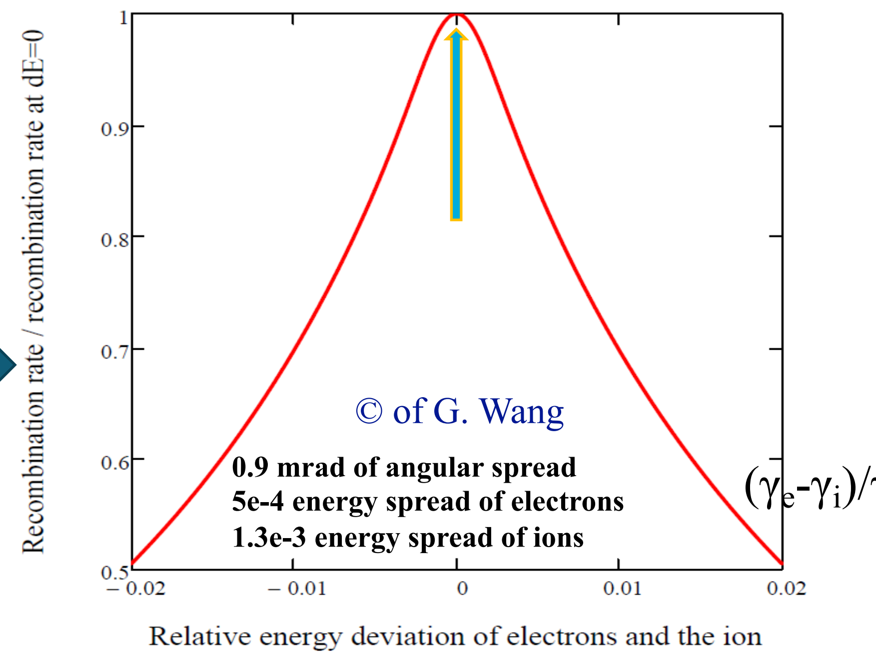
Recombination of electrons with Au ions

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



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

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

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

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

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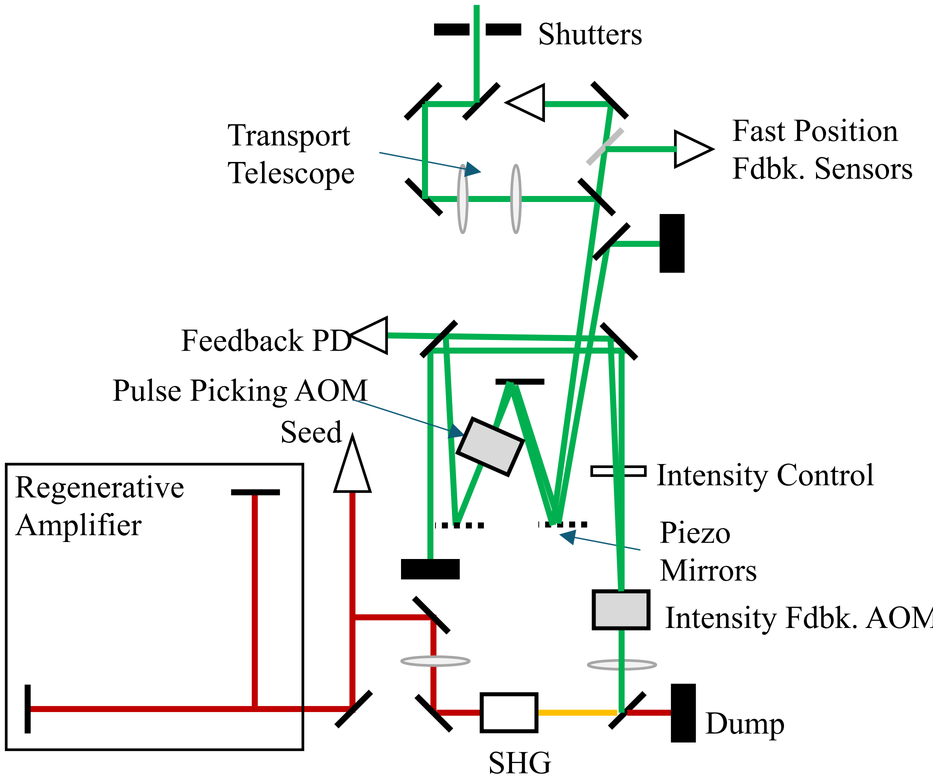
Laser system layout for run22

- New seed laser with 5 psec RMS time jitter is installed and is operational
- Bandwidth for operation at variable repetition rates (78kHz-5MHz)
- Exchange of IR Pockels Cell Pulse Picker with AOM to enable 0-100% duty cycle operation for high repetition rate operation (1-5MHz)
- Maintaining CW beam throughout the entire system to enable high bandwidth position and intensity feedbacks and limit thermal effects from repetition rate changes
- Addition of second AOM for fast intensity feedback
    - Still need to work out efficient noise detection method to reach 2kHz feed-back.

As risk reduction strategy, we used contingency funding and ordered a new back-up seed mode-locked laser system capable of 0.2 psec jitter



New seed laser arrived November 10, 2021
Installed & operating

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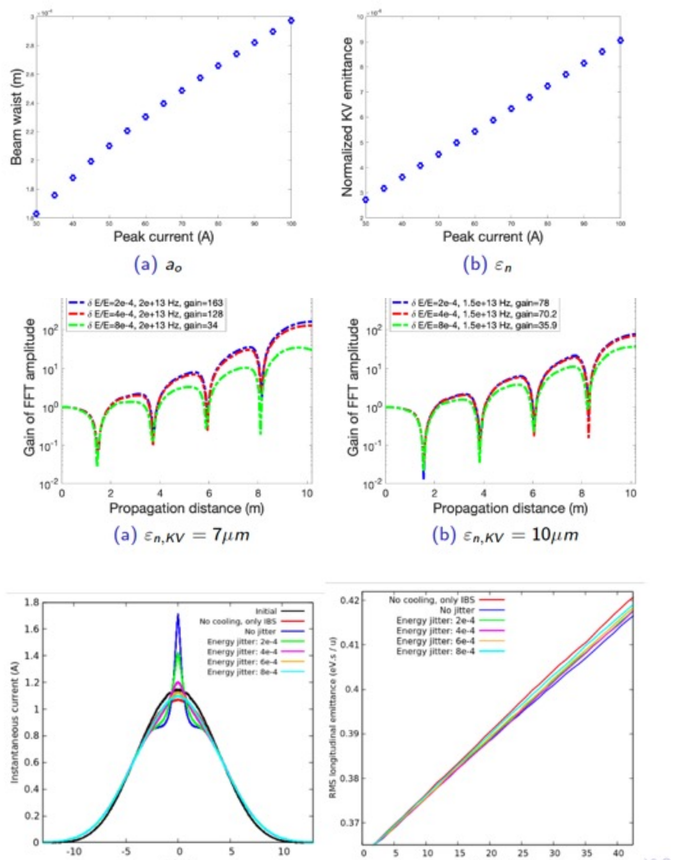
Defining requirements for e-beam and CeC system

Jun Ma & team

Electron Beam Requirements for CeC Experiment

Sensitivity studies: energy spread & peak current, beam emittance and asymmetry, matching, orbit distortions, energy jitter



Yichao Jing & team

Requirements for CeC systems

Sensitivity studies: laser intensity and timing jitter, SRF gun, Bunching cavities and SRF linac voltage and phase jitter and drifts, power supplies jitter and drifts

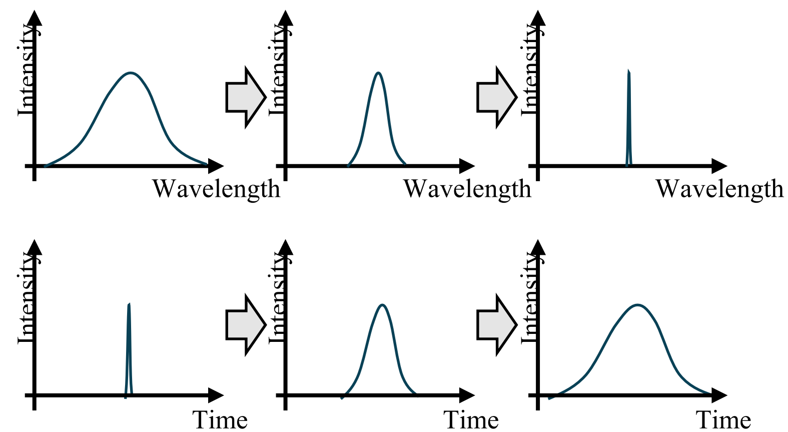
Items	requirements	Beam parameter effect
Laser jitter (ps, rms)	5	2e-4 energy jitter
Laser intensity (rms)	1%, transverse uniformity needs improvement	Peak current variation
Trim PS (A, rms)	5e-5	10 um orbit jitter in common section
Gun phase (deg, rms)	< 0.1	<0.2 kV/ps energy chirp for core
Gun voltage (kV, rms)	< 0.5 kV	For less than < 1 ps separation between peak current and energy slices
buncher phase (deg, rms)	0.2	Energy jitter < 2e-4, chirp jitter < 0.2 kV/ps
buncher voltage (kV, rms)	1.4	Chirp jitter < 0.2 kV/ps

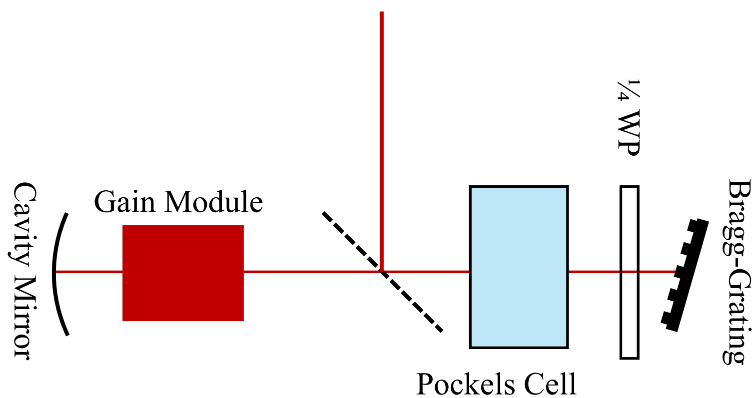
Risk reduction: Mode-locked seed laser

- Mode-locked Oscillator - Jitter: ~200fs rms
- 2-4ps pulse duration, 5-10nm Bandwidth
- Chirped gaussian output

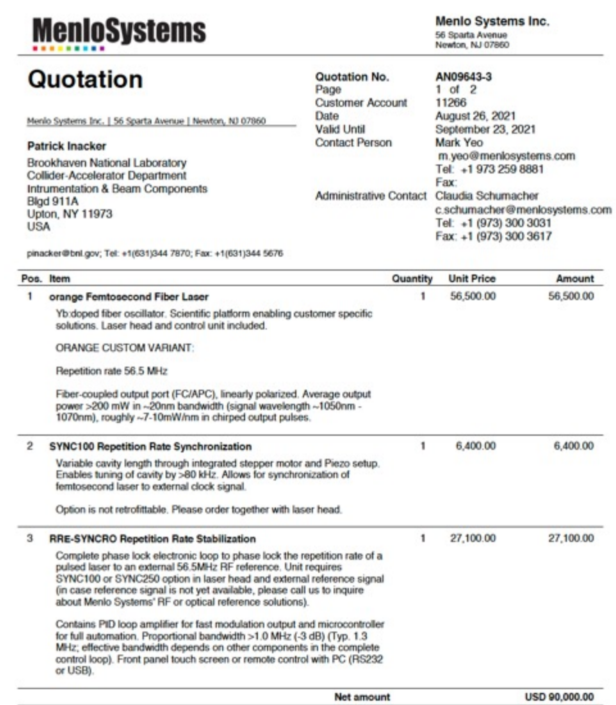
Bragg Grating inside of Regenerative amplifier narrows spectral bandwidth and increases pulse duration with each roundtrip:
Target duration: 350ps FWHM => 1.25GHz Bandwidth

Spectral filtering to reduce bandwidth of seed pulse





Regenerative Amplifier
2 Grating bounces per roundtrip



MenloSystems

Menlo Systems Inc.
56 Sparta Avenue
Newton, NJ 07860

Quotation

Menlo Systems Inc. | 56 Sparta Avenue | Newton, NJ 07860

Patrick Inacker
Brookhaven National Laboratory
Collider-Accelerator Department
Intrumentation & Beam Components
Blgd 911A
Upton, NY 11973
USA

pinacker@bnl.gov; Tel: +1(631)344 7870; Fax: +1(631)344 5676

Quotation No.: AN09643-3
Page: 1 of 2
Customer Account: 11266
Date: August 26, 2021
Valid Until: September 23, 2021
Contact Person: Mark Yeo, m.yeo@menlosystems.com, Tel: +1 973 259 8881, Fax:
Administrative Contact: Claudia Schumacher, c.schumacher@menlosystems.com, Tel: +1 (973) 300 3031, Fax: +1 (973) 300 3617

Pos.	Item	Quantity	Unit Price	Amount
1	**orange Femtosecond Fiber Laser** Yb:doped fiber oscillator. Scientific platform enabling customer specific solutions. Laser head and control unit included. ORANGE CUSTOM VARIANT: Repetition rate 56.5 MHz Fiber-coupled output port (FC/APC), linearly polarized. Average output power >200 mW in ~20nm bandwidth (signal wavelength ~1050nm - 1070nm), roughly ~7-10mW/nm in chirped output pulses.	1	56,500.00	56,500.00
2	**SYNC100 Repetition Rate Synchronization** Variable cavity length through integrated stepper motor and Piezo setup. Enables tuning of cavity by >80 kHz. Allows for synchronization of femtosecond laser to external clock signal. Option is not retrofittable. Please order together with laser head.	1	6,400.00	6,400.00
3	**RRE-SYNCRO Repetition Rate Stabilization** Complete phase lock electronic loop to phase lock the repetition rate of a pulsed laser to an external 56.5MHz RF reference. Unit requires SYNC100 or SYNC250 option in laser head and external reference signal (in case reference signal is not yet available, please call us to inquire about Menlo Systems' RF or optical reference solutions). Contains PID loop amplifier for fast modulation output and microcontroller for full automation. Proportional bandwidth >1.0 MHz (-3 dB) (Typ. 1.3 MHz; effective bandwidth depends on other components in the complete control loop). Front panel touch screen or remote control with PC (RS232 or USB).	1	27,100.00	27,100.00
	Net amount			**USD 90,000.00**

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Linearized case: cooling decrements

We will neglect transverse kicks, which are very weak in CeC

Sorry for repeating trivial formulae from my AP class

Only energy kick

$$\Delta x_6 = \frac{\delta E_h}{E_o} = const - \sum_{i=1}^{6} \zeta_i \cdot x_i$$

$$X = \frac{1}{2}\sum_{k=1}^{3}\left(a_k Y_k(s) e^{i\psi_k} + c.c.\right);\ \mathbf{Y}_{k=1,2} = \begin{pmatrix} Y_{k\beta} \\ -Y_{k\beta}^T SD \\ 0 \end{pmatrix};\ \mathbf{Y}_3 \cong \frac{1}{\sqrt{\Omega}}\begin{pmatrix} D \\ -i\Omega \\ 1 \end{pmatrix};\ Y_{k\beta} = \begin{bmatrix} y_{k1} \\ y_{k1} \\ y_{k2} \\ y_{k4} \end{bmatrix};\ D = \begin{bmatrix} D_x \\ D'_x \\ D_y \\ D'_y \end{bmatrix};$$

$$\langle \Delta a_k \rangle = -\xi_k a_k \rightarrow a_k = a_{k0} e^{-n\xi_k}$$

$$\operatorname{Re}\xi_{(1,2)} = -\frac{i}{2}\left(Y_{(1,2)\beta}{}^T SD\right)^* \sum_{i=1}^{4} y_{(1,2)i} \cdot \zeta_i;\ \xi_s = \operatorname{Re}\xi_3 = \frac{1}{2}\left(\zeta_6 + \sum_{i=1}^{4} D_i \cdot \zeta_i\right),$$

No x-y coupling

$$Y_{1\beta} \equiv Y_x = \begin{bmatrix} w_x \\ w'_x + \frac{i}{w_x} \\ 0 \\ 0 \end{bmatrix};\ Y_{2\beta} \equiv Y_y == \begin{bmatrix} 0 \\ 0 \\ w_y \\ w'_y + \frac{i}{w_y} \end{bmatrix};D = \begin{bmatrix} D \\ D' \\ 0 \\ 0 \end{bmatrix};$$

$$\beta_{x,y} = w_{x,y}^2;\ \alpha_{x,y} = -w'_{x,y} w_{x,y}$$

$$\xi_x = \operatorname{Re}\xi_1 = -\left(D\zeta_1 + D'\zeta_2\right);\quad \xi_s = \xi_6 - \xi_x.$$

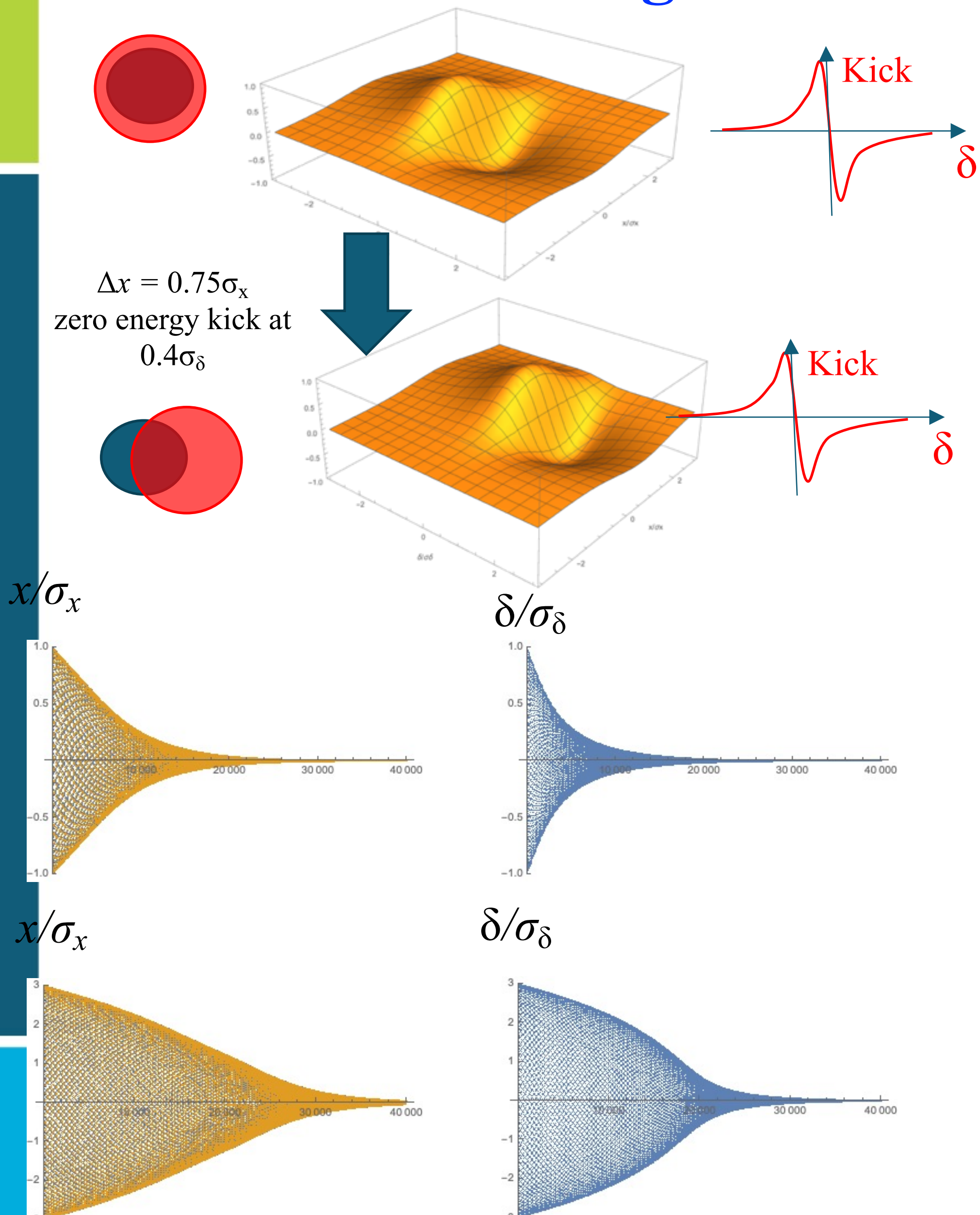
Qx-Qy resonance

$$Y_1 = \frac{1}{\sqrt{1+|\alpha|^2}}\left(Y_x + \alpha Y_y\right);\ Y_2 = \frac{1}{\sqrt{1+|\alpha|^2}}\left(-\alpha^* Y_x + Y_y\right)$$

$$\operatorname{Re}\xi_1 = -\frac{D\zeta_1 + D'\zeta_2}{1+|\alpha|^2};\operatorname{Re}\xi_2 = -|\alpha|^2\frac{D\zeta_1 + D'\zeta_2}{1+|\alpha|^2}.$$

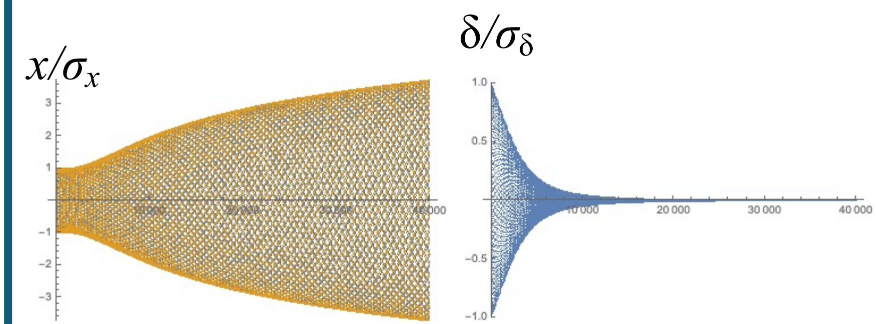
Can use a non-achromatic transport (time of flight dependence) or transverse beam separation to couple longitudinal and transverse cooling

Distribution of cooling between longitudinal and transverse degrees of freedom – real kick

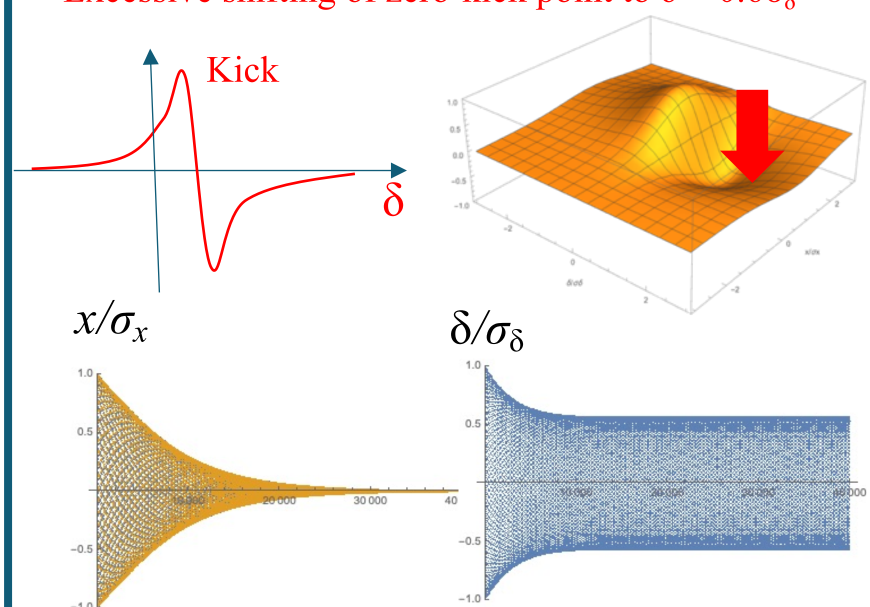


Wrong sign of displacement

$\Delta x = -0.75\sigma_x$

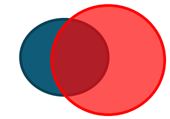


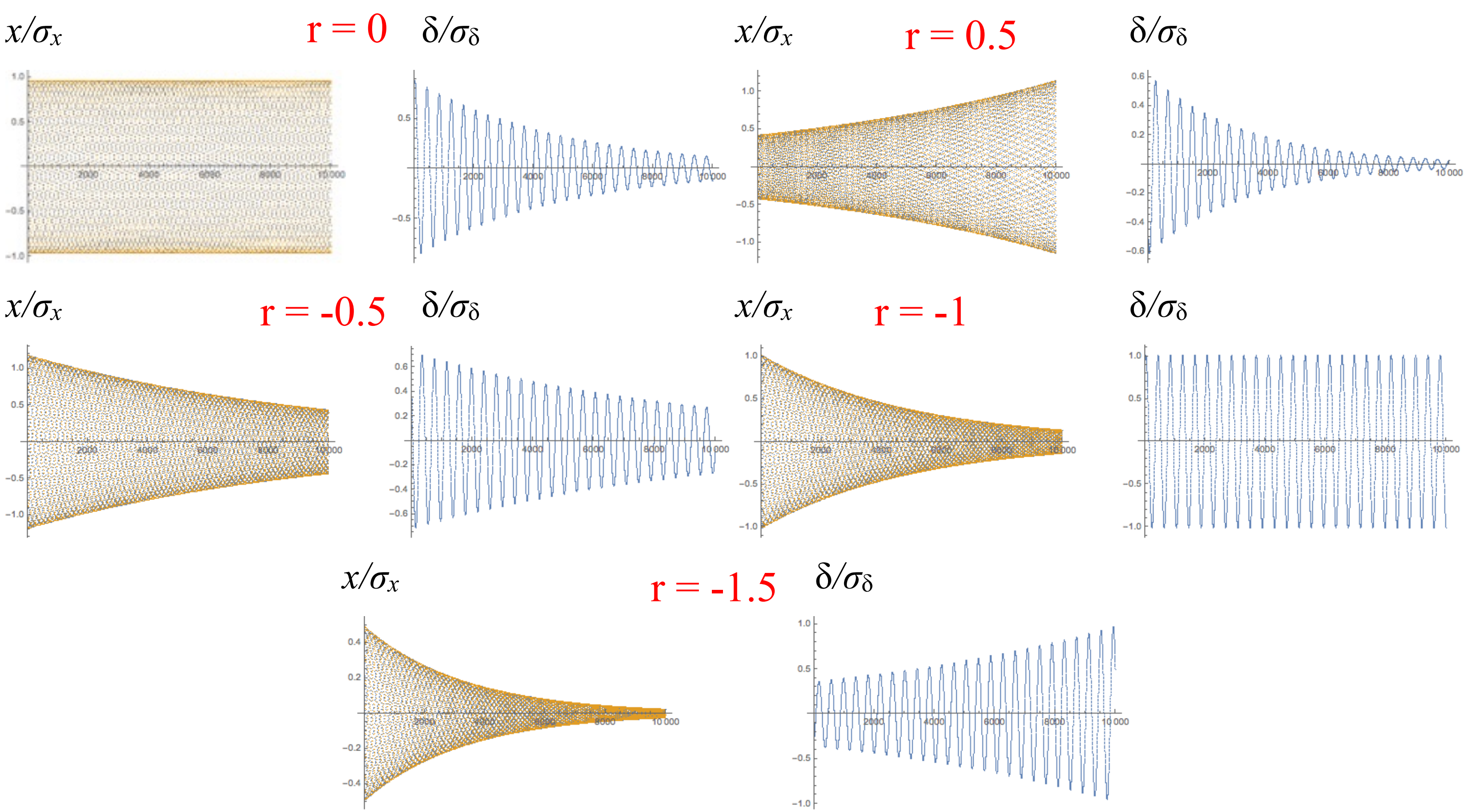
Excessive shifting of zero-kick point to $\delta = 0.6\sigma_\delta$



Distribution of cooling between longitudinal and transverse degrees of freedom – linearized kick

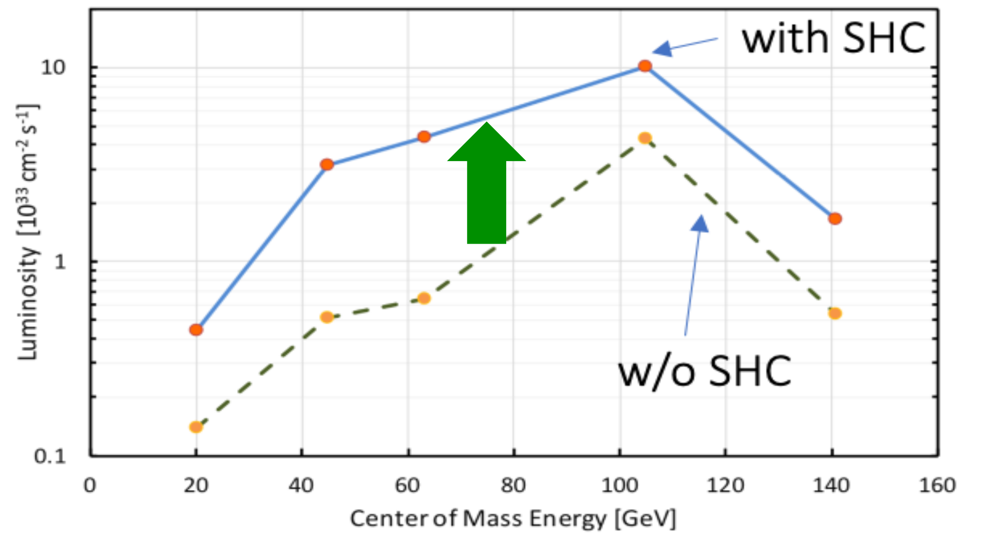
$$\frac{\delta E_h}{E_o} = const - \zeta_1 x - \zeta_6 \frac{E_h - E_o}{E_o}; \quad r = D\zeta_1 / \zeta_6$$





Why CeC X is needed?

To boost EIC luminosity



National Academy of Sciences Assessment of U.S.-Based Electron-Ion Collider Science: *The accelerator challenges are two fold: a high degree of polarization for both beams, and high luminosity.*

Quote from the pCDR review committee report: "*The major risk factors are strong hadron cooling of the hadron beams to achieve high luminosity, and the preservation of electron polarization in the electron storage ring. The Strong Hadron cooling [Coherent Electron Cooling (CeC)] is needed to reach $10^{34}/(cm^2s)$ luminosity.*

Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC."