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

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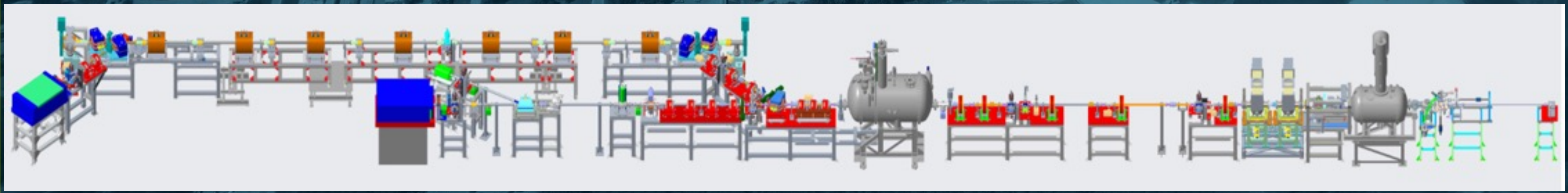

CeC X retreat, August 16, 2021

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- ❑ Why CeC X is important
- ❑ Run 21 achievements and results
- ❑ Remaining challenges
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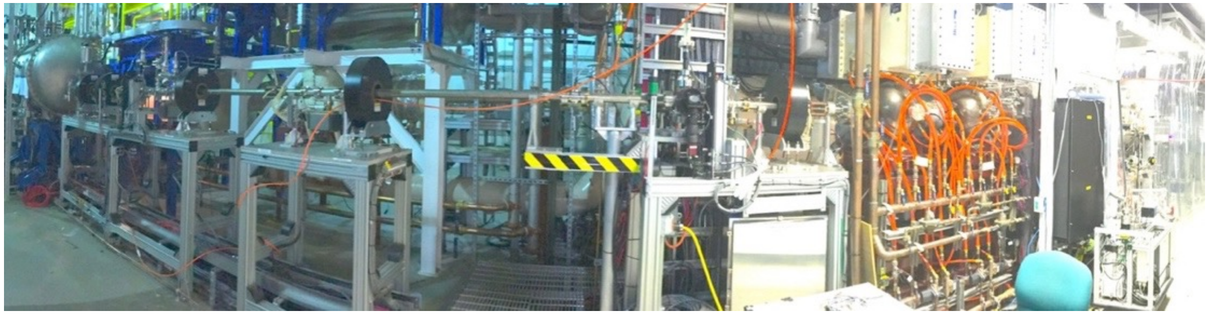
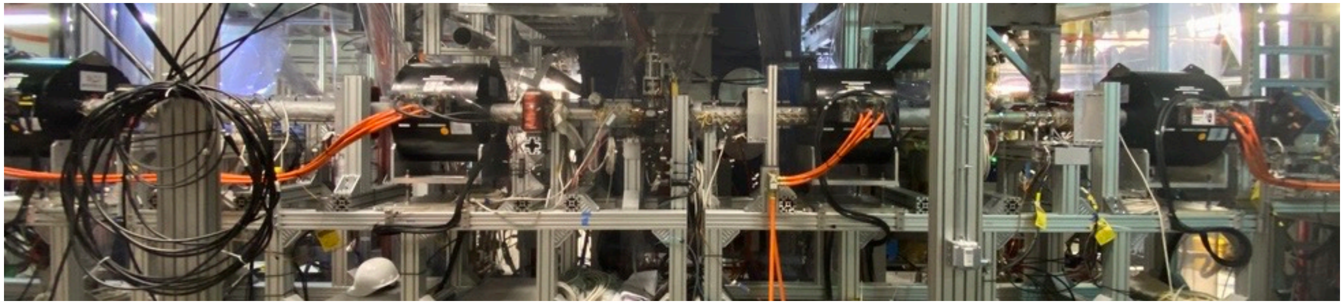
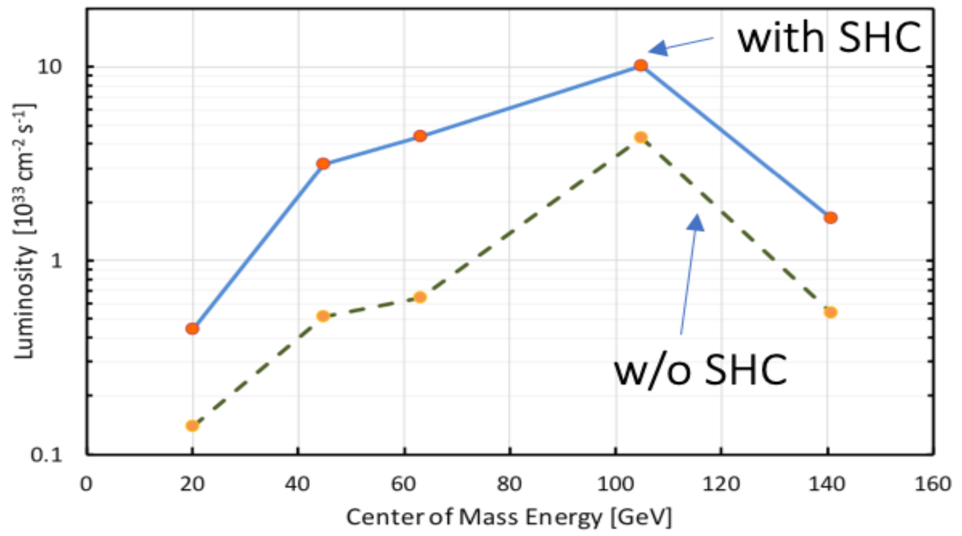
CeC X accelerator



CeC with plasma-cascade microbunching amplifier



Why CeC X is needed?



- 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.*

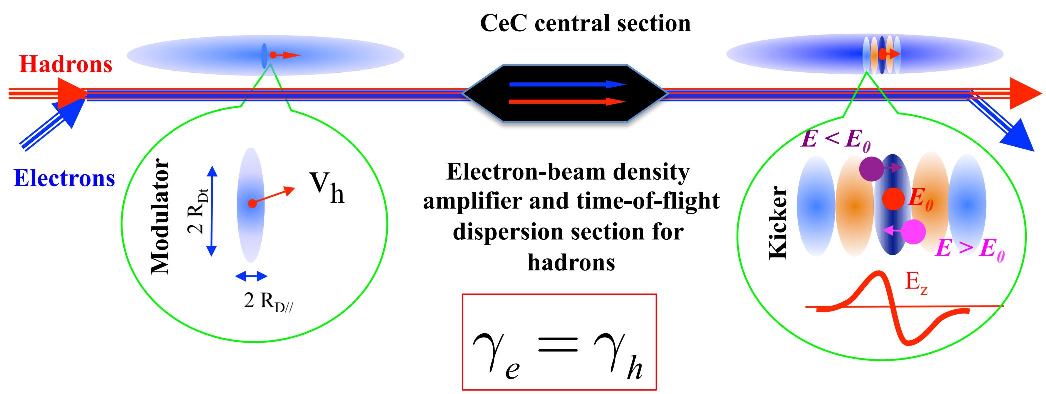
Quote from the pCDR review committee report:

"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 $10^{34}/(cm^2 s)$ luminosity. ***Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC***."

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

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Coherent Electron Cooling

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PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

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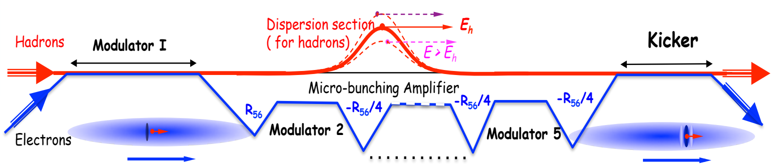
(Received 11 April 2013; published 20 August 2013)

What can be tested experimentally?

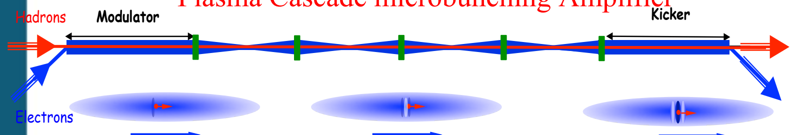
Litvinenko, Derbenev, PRL 2008

Ratner, PRL 2013

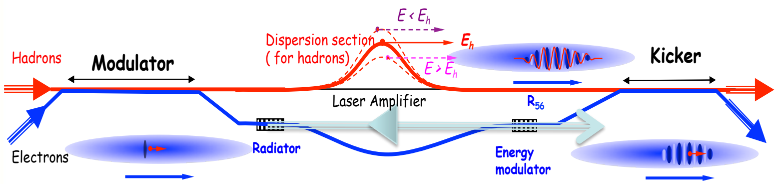


Litvinenko, Wang, Kayran, Jing, Ma, 2017

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

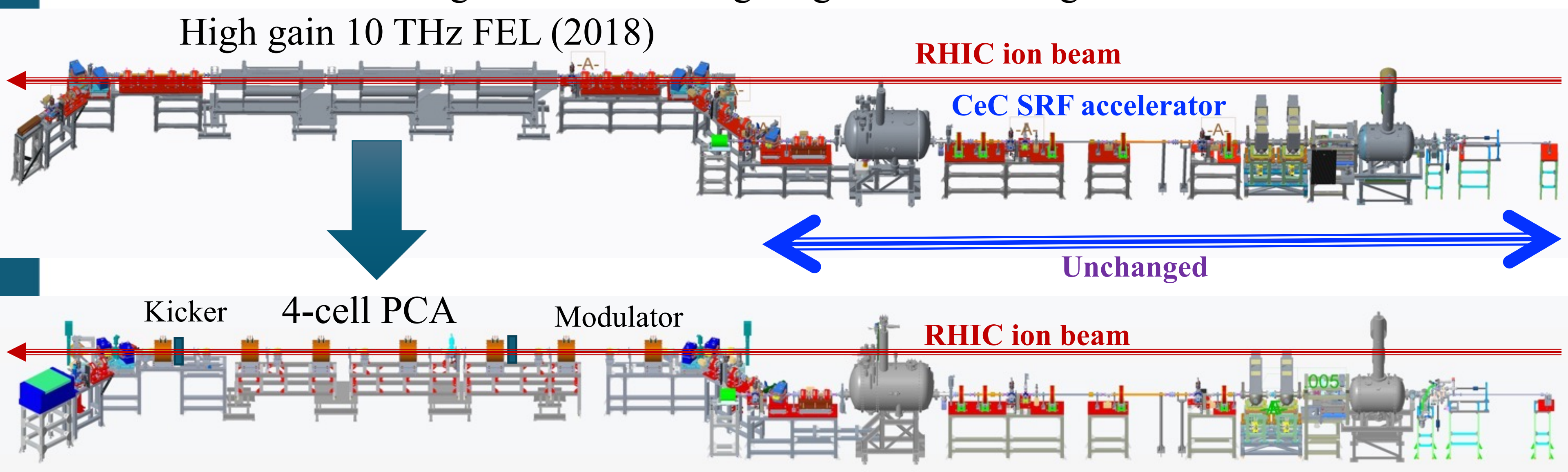
RHIC Runs 20-22

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

Derbenev is suggesting to explore CSR as an CeC amplifier

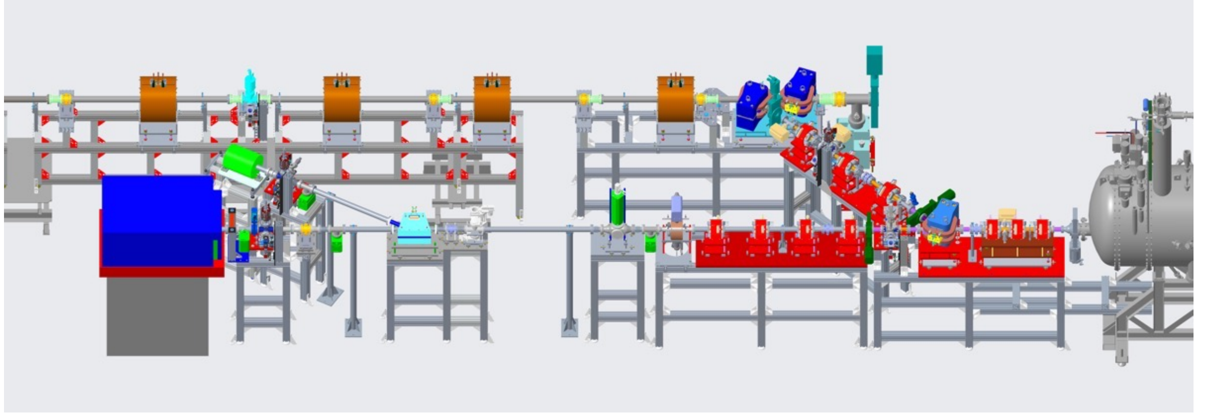
CeC X at RHIC

- 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 - 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
- New time-resolved diagnostics beamline was built last year and commissioned during this run. Now we focusing on demonstrating longitudinal cooling.



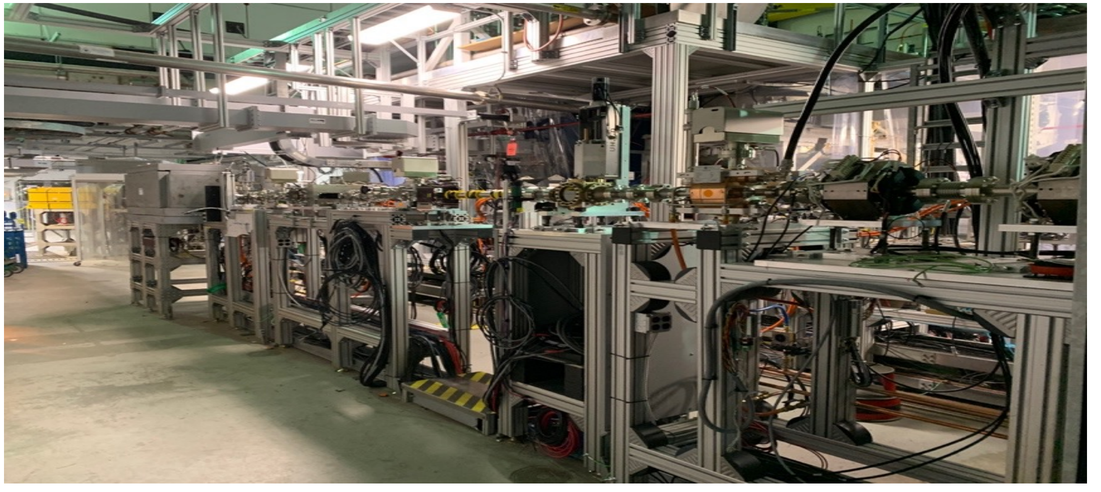
The CeC Plasma Cascade Amplifier has a bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

Time-resolve diagnostics beam-line: the key for accurate measurements of beam parameters



Fully Commissioned

- Run 21' main addition is the time-resolved diagnostics beam-line
  - To evaluate local beam quality of electron beam with time resolution of 1 psec
  - Played critical role for achieving Key Performance Parameter for this run



CeC X achievements summary

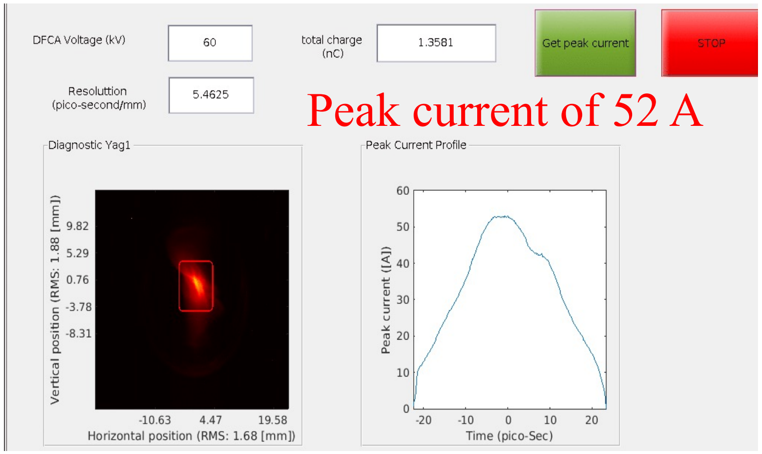
Milestone ID	Reportable milestone	Date
1	Experiment start	FY20Q1 ✓
2	Necessary Beam Parameters (KPP) established for Run 20	FY21Q4 ✓
3	Investigation of plasma cascade amplifier complete	FY21Q4 ✓
4	Investigation of the ion imprint in the electron beam complete	FY22Q1 ✓
5	Receive Approval for CeC TRDBL commissioning	FY22Q1 ✓
6	Necessary Beam Parameters (KPP) established for Run 21	FY22Q3 ✓
7	Investigation of the CeC longitudinal cooling complete	FY22Q4
8	Necessary Beam Parameters (KPP) established for Run 22	FY23Q3
9	Investigation of the 3D CeC Cooling complete	FY23Q4
10	Final report to DOE NP	FY23Q4
11	Experiment Complete	FY23Q4

Electron beam KPP

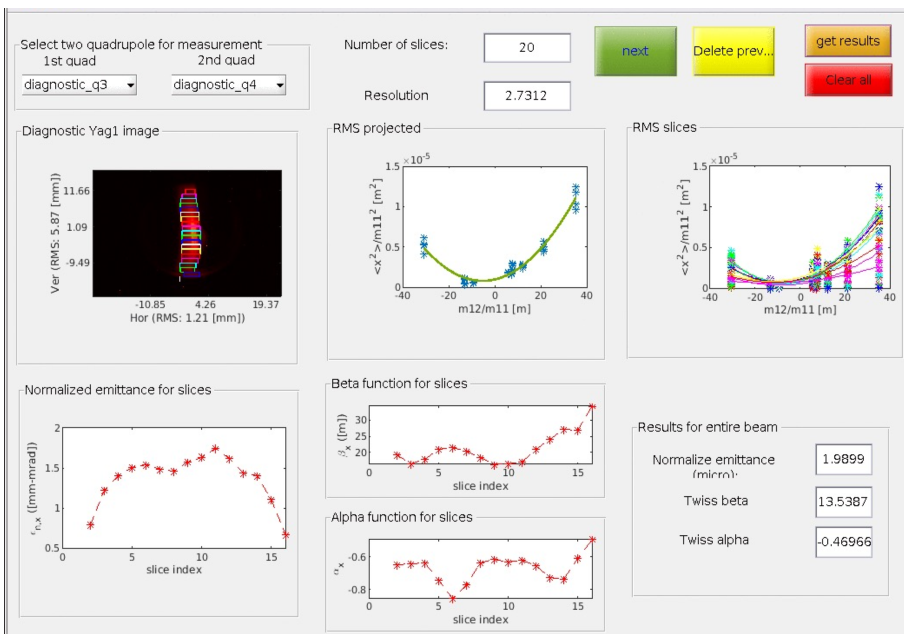
Parameter	Planned	Demonstrated	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the Poison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

Time-resolved measurments

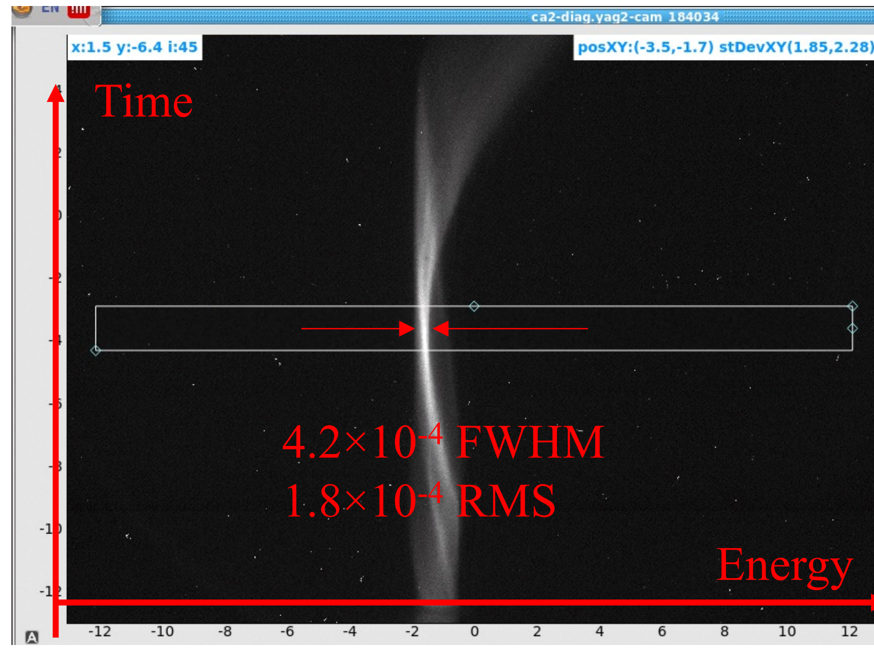
Direct pass



Slice emittance measurements

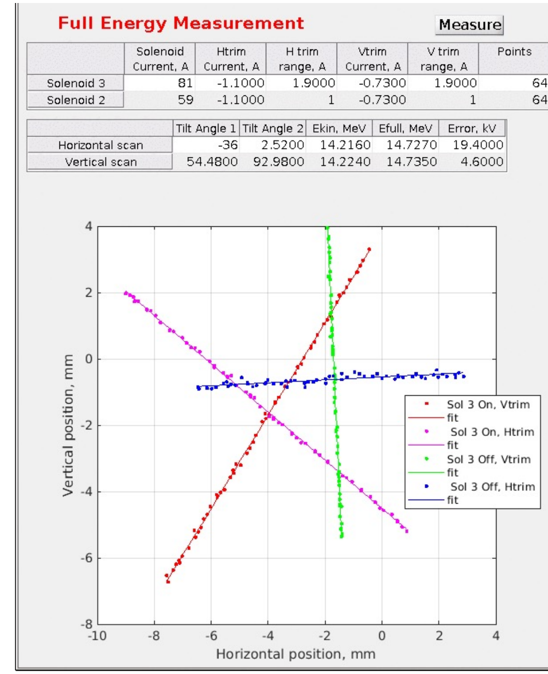


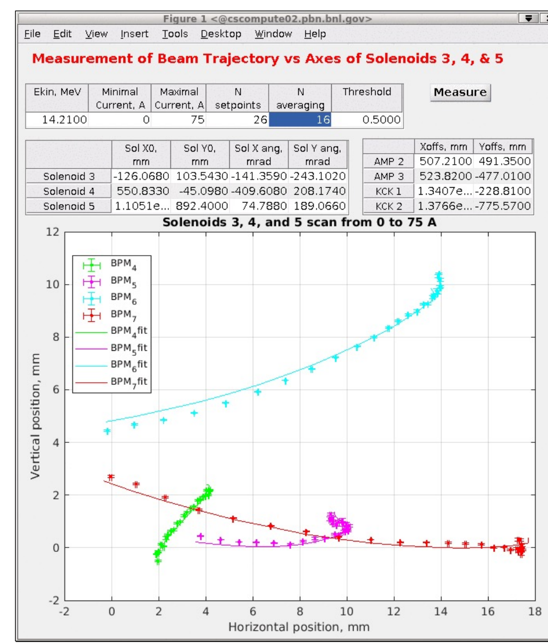
30-degree energy spectrometer

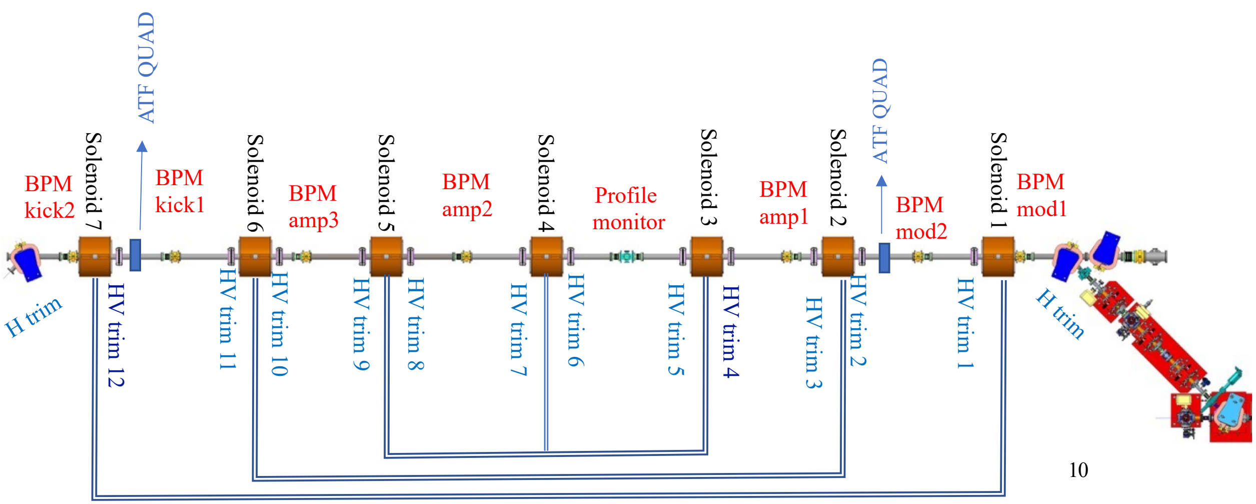


Energy measurements and novel BBA in CeC

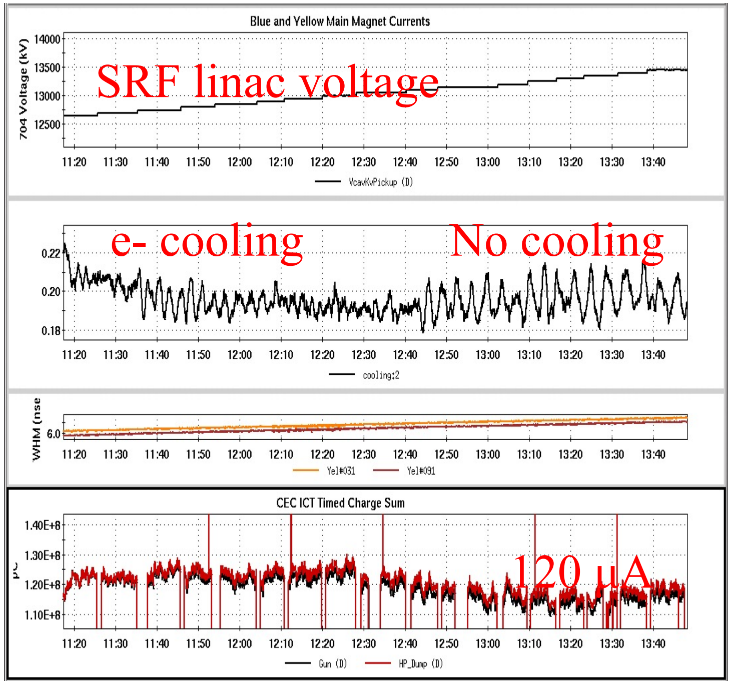
- ✓ Novel method of absolute beam energy measurement – based on Ampere law and knowing value of current and number of turns in solenoid: accuracy ~ 0.2%. Main source of errors is in the orbit jitter.
- ✓ Accurate alignment of the electron beam trajectory is critically important - we developed a well-defined 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



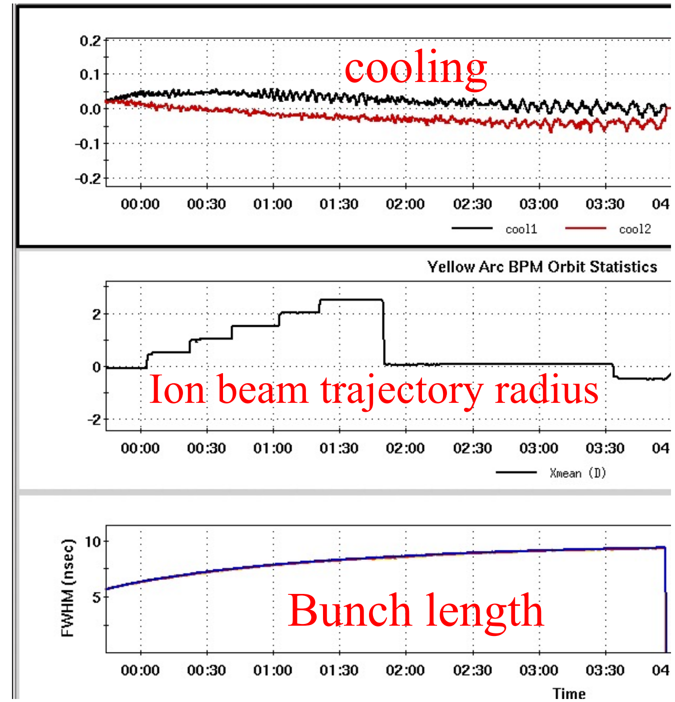




Search for CeC signature and observation of regular bunched electron cooling of 26.5 GeV/u ion beam



Changing e-beam energy requires multiple adjustments



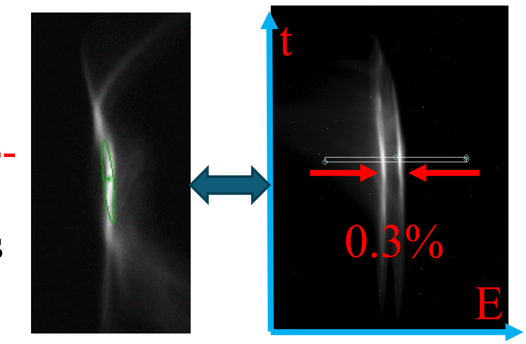
Adjusting ion beam energy – 1 mm x_{mean} corresponds to 0.1% change in the ion beam energy.

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 hrs cooling rate simulated by He Zhao

Major set-back and remaining challenges

- We lost at least 7 weeks of operation from severely damage to our the SRF gun - it was not the result of operations performed by the CeC team. Fortunately, we had skill, and some luck, to restore the gun operation, but continue suffering with contamination till the very end of the run 21. Particulate-free preparation of photo-cathodes with uniform QE and their transfer is challenge that we need to solve during this shut-down.
- The main challenge for the CeC X is up 0.35% peak-to-peak bunch-by-bunch energy jitter. Our understanding that this is result of 100 psec peak-to-peak laser pulse timing jitter. It results in washing out the CeC cooling by 125-fold. There is also ±10% jitter in the laser poser, which crate challenges for CeC operations Finding solution for significant - 2-to-4-fold - reduction of the time and intensity jitter is critical for CeC demonstration.
- There are also significant slow energy drifts (> 0.1% per shift), most likely resulting from the residual dependences of the RF voltages and phases on ambient temperature. We need to develop reliable feedbacks to compensate these drifts.
- Absence of high sensitivity cryo-cooled IR detector and very large (sub-V) RFI in the IP2 diagnostics cables preclude us from evaluating PCA gain spectrum and optimizing CeC cooling. We need to solve this challenge during this shut-down
- There are number of there important developments which are needed for successful demonstration of CeC in Run 22, including orbit feedback, reliable slice emittance measurements, solving noise problem in the CeC diagnostics as well as improvement in the CeC systems (removing unnecessary cavity, new trims and undulator, new profile monitor and pepper-pot…)

"Elephant in the china shop"



Summary

- **Our goal is to demonstrate the PCA CeC during Run 22**
- We requested 16 days of CeC dedicated time for RHIC Run 22 operations
- Run 22 is very shot and CeC operations would be very challenging. The NPP PAC requested that "*C-AD is strongly encouraged to optimize RHIC operations to fulfill the goals of both CeC and STAR*" and specifically that "*BNL Management and CeC work together to ensure that the CeC beam use request can be accommodated as early as possible in Run 22 in order to allow for optimized STAR data taking*".
- We have significant number of challenges for successful experiment that we need to overcome during this shutdown. But we *must hit the ground running* at the beginning of the Run 22 – *no delays and dragging installation and commissioning of subsystems into the run are allowed*.
- We also need to reduce loss of the time for transition from 275 GeV p-p STAR operation to 26.5 GeV/u Au ion CeC operation – it means that we need to have a well-defined plan with large chunks (24 hrs or longer) of dedicated time. Load on the CeC operation team will be enormous and we are welcoming new members to share this challenge
- CeC X involved and continue involving many people at C-AD, SBU and beyond. We wholeheartedly welcome new member of the CeC X team.
- **Let's make it happen.**

The CeC team – never can get all your pictures …