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

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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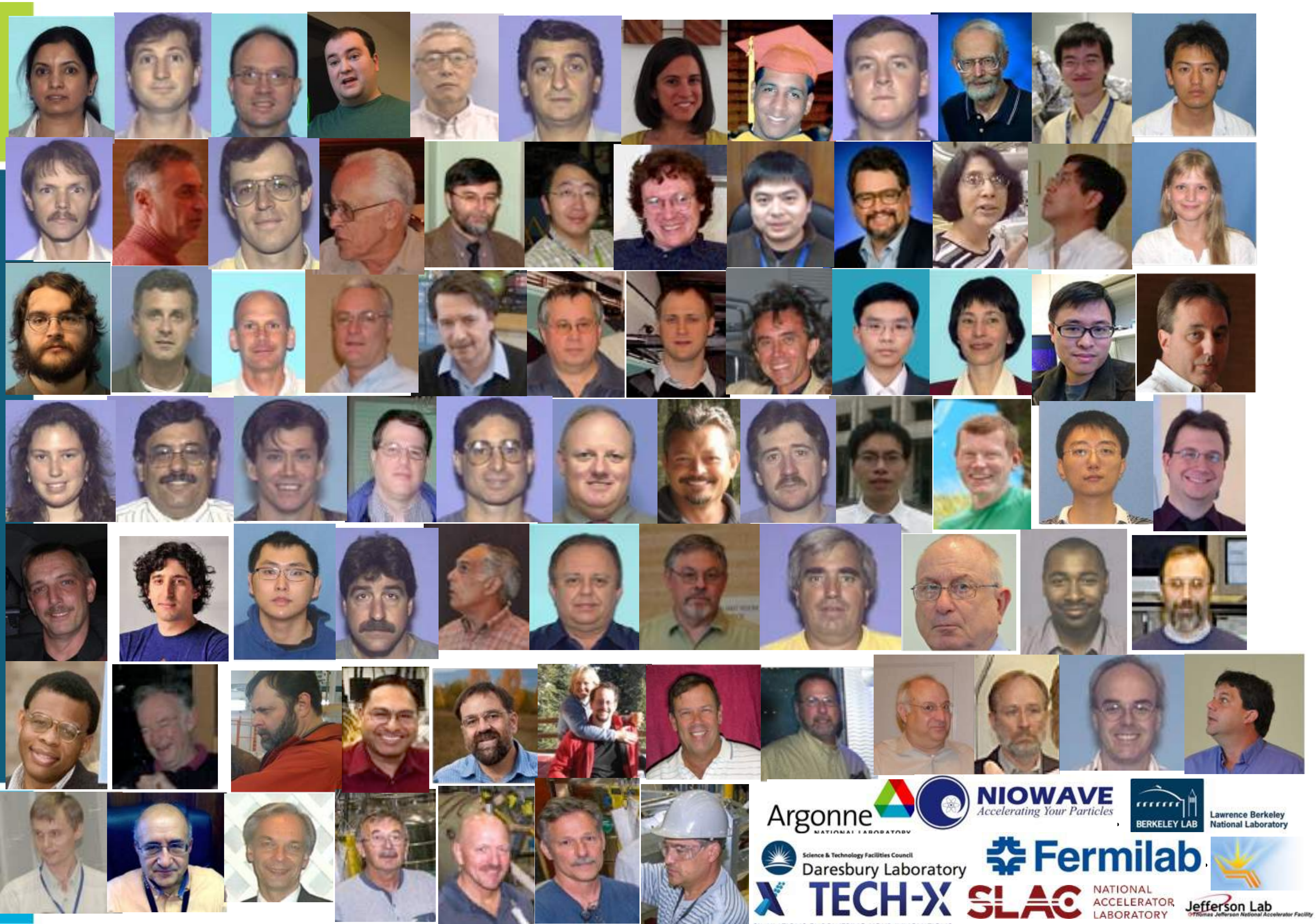
Brookhaven National Laboratory and Stony Brook University

COOL 2021workshop, Novosibirsk, Russia – November 4, 2021

The CeC team – never can get all your pictures …

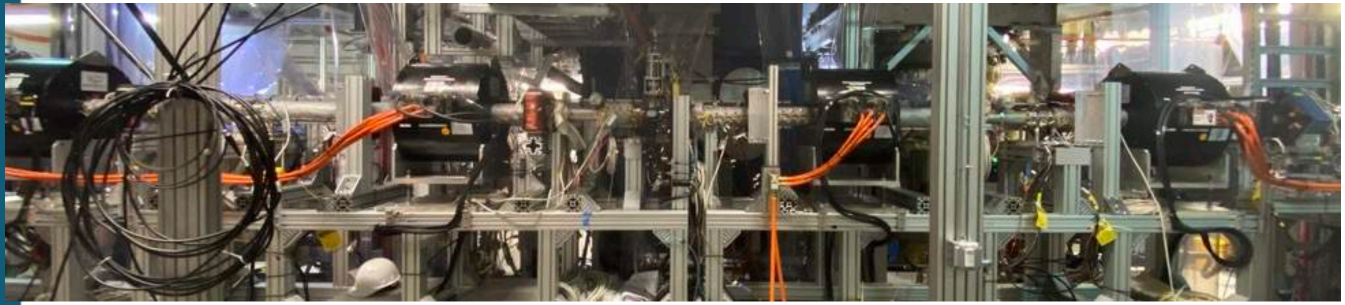


Content

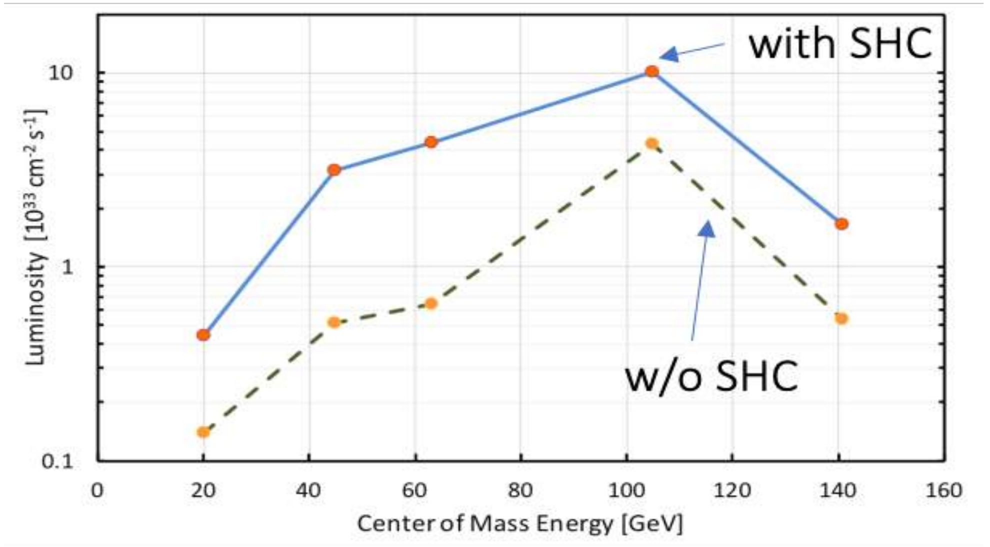
- ❑ Why CeC X is important
- ❑ Achievements
- ❑ Challenges
- ❑ Plans

CeC X accelerator

CeC with plasma-cascade microbunching amplifier



Why CeC X is needed?

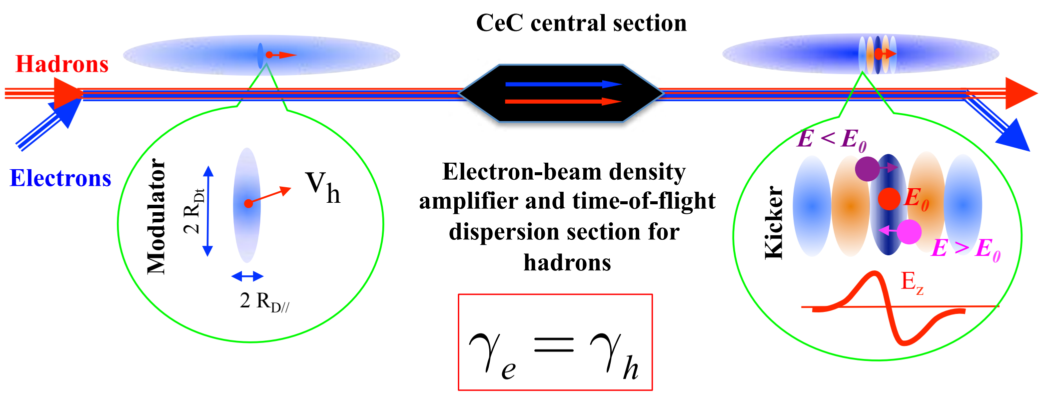


- National Academy of Sciences Assessment of U.S.-Based Electron-Ion Collider Science: *The accelerator challenges are two fold: a high degree of polarization for both beams, and high luminosity.*
- EIC pCDR review committee report: *"The major risk factors are strong hadron cooling of the hadron beams 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

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]
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[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA
(Received 24 September 2008; published 16 March 2009)

PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

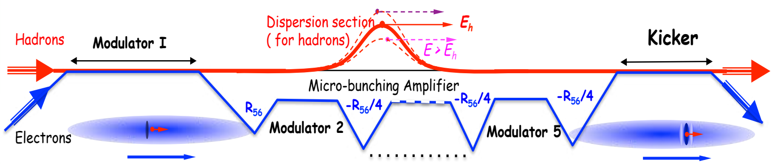
D. Ratner*
SLAC, Menlo Park, California 94025, USA
(Received 11 April 2013; published 20 August 2013)

What can be tested experimentally?

Litvinenko, Derbenev, PRL 2008

RHIC Run 18

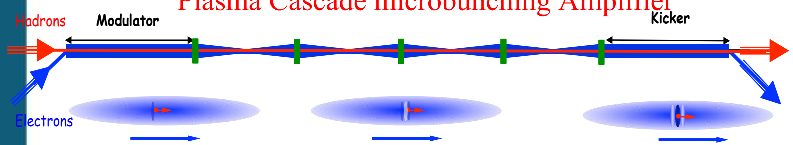
Ratner, PRL 2013



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

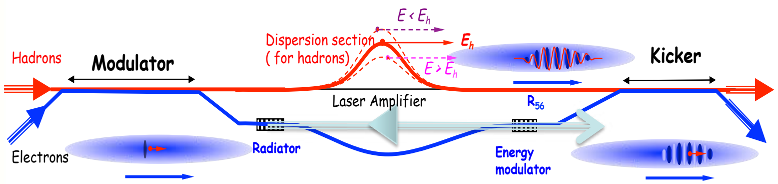
Litvinenko, Wang, Kayran, Jing, Ma, 2017

Plasma Cascade microbunching Amplifier



RHIC Runs 20-22

Litvinenko, Cool 2013

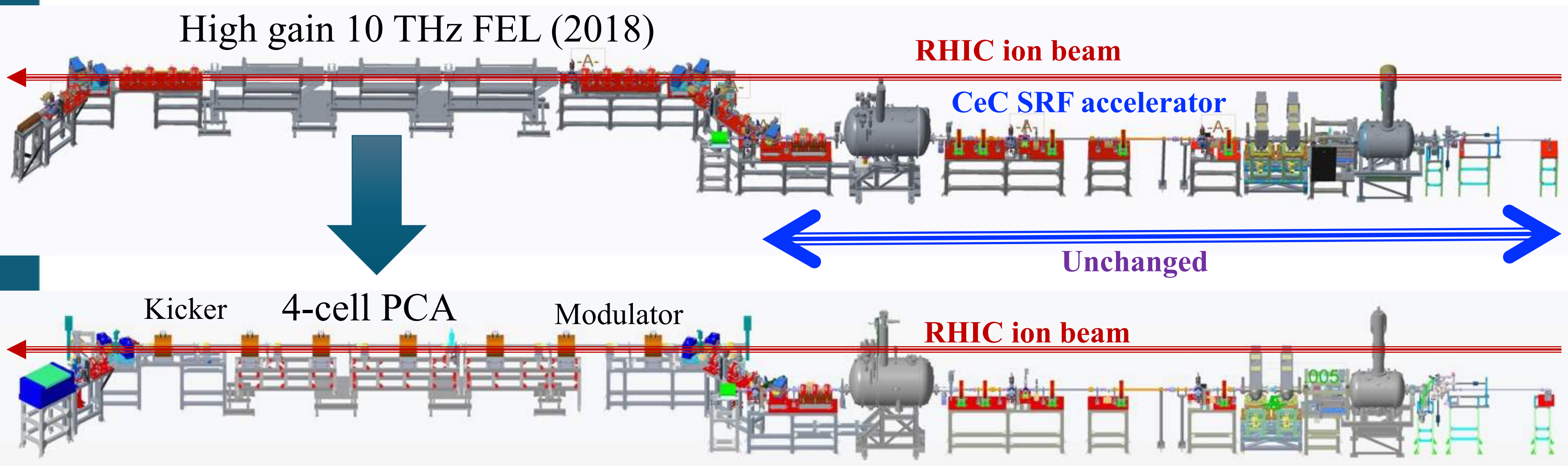


Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

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

CeC X achievements summary

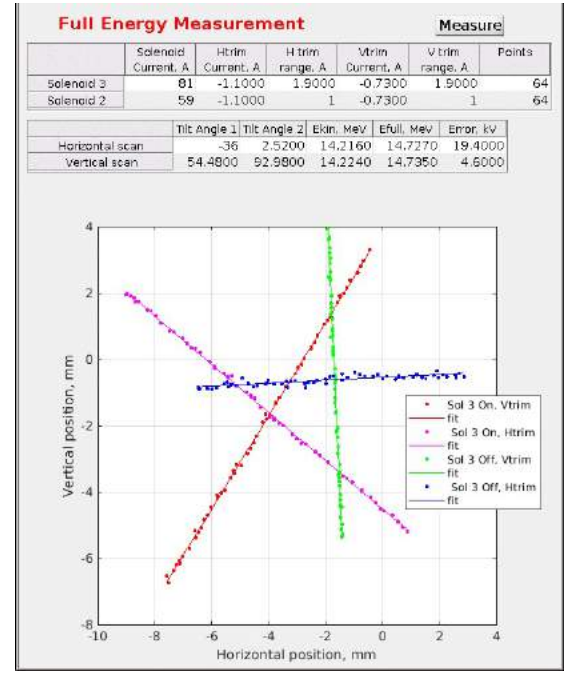
- ✓ Unique SRF accelerator generating high brightness electron beam, compressing it to 75 A at 1.25 MeV kinetic energy and accelerating it to 14.6 MeV
- ✓ Precise control of noise in electron beam: can suppress it to the level close to Poisson shot noise - for cooling - or increase thousands-fold to 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 elections with 26 GeV/ u ions
- ✓ Regular electron cooling of hardon beam at record energy of 26 GeV/ u

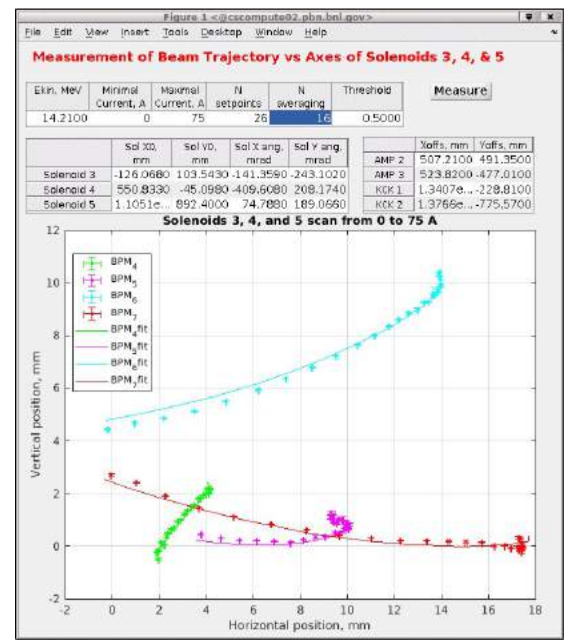
Electron beam KPP

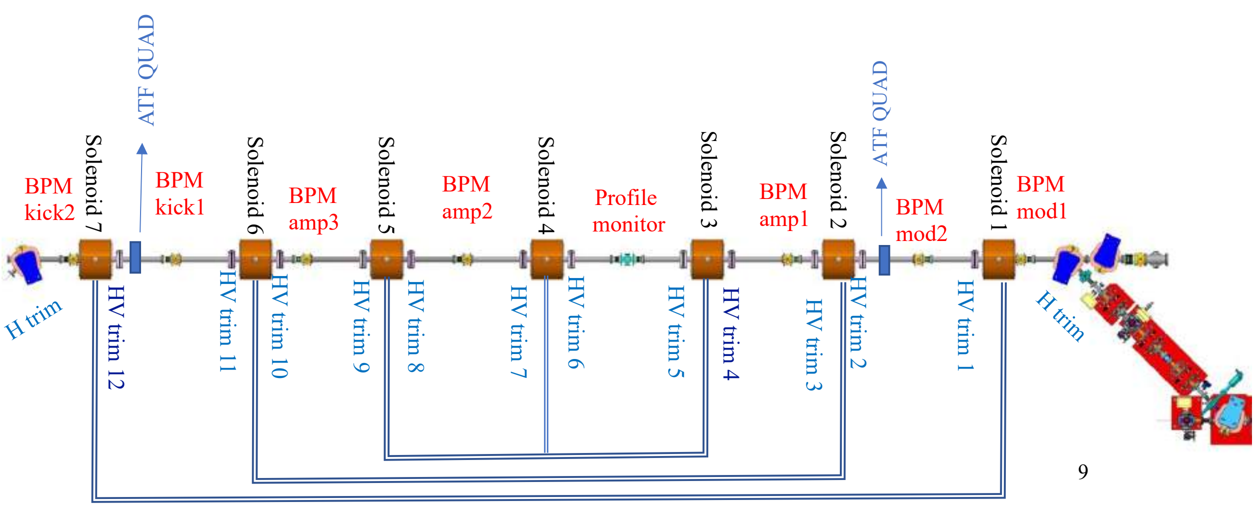
Parameter	**Planned**	**Demonstrated**	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the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

Energy measurements and novel BBA in CeC

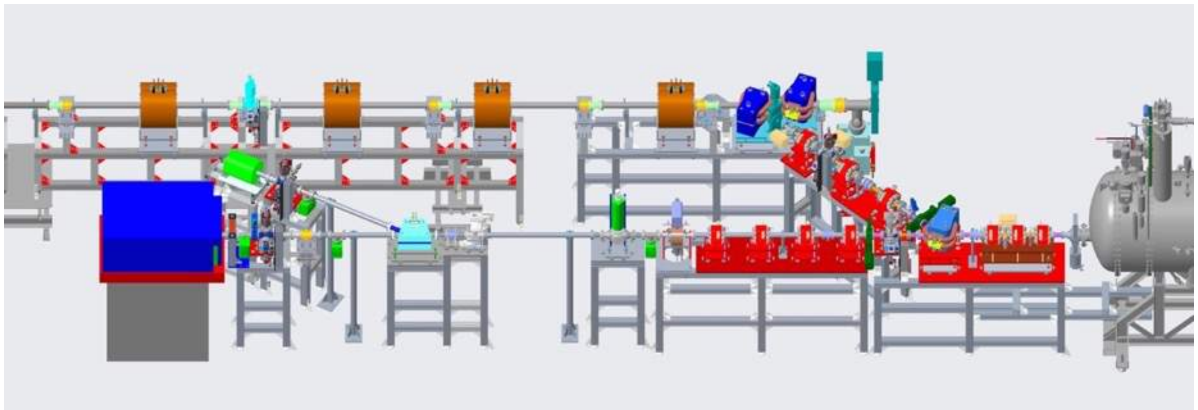
- ✓ Novel method of absolute beam energy measurement – based on Ampere law and knowing value of current and number of turns in solenoid: accuracy ~ 0.2%. Main source of errors is in the orbit jitter.
- ✓ Accurate alignment of the electron beam trajectory is critically important - we developed a well-defined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







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

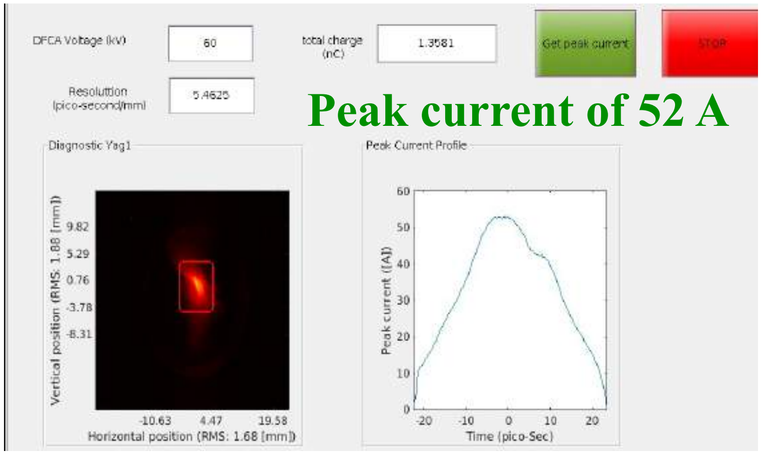


Fully Commissioned

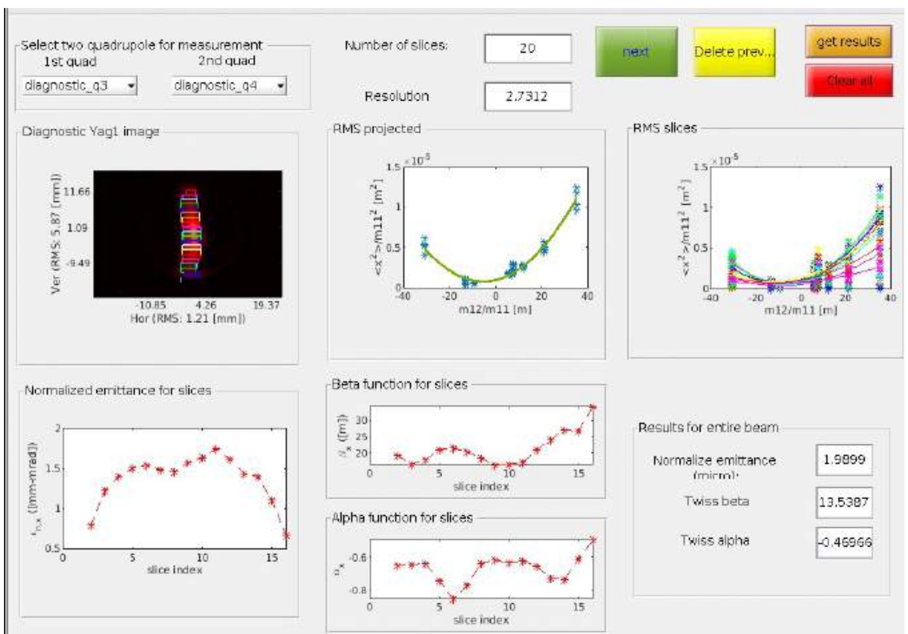
- Run 21' main addition is the time-resolved diagnostics beam-line

Time-resolved measurments

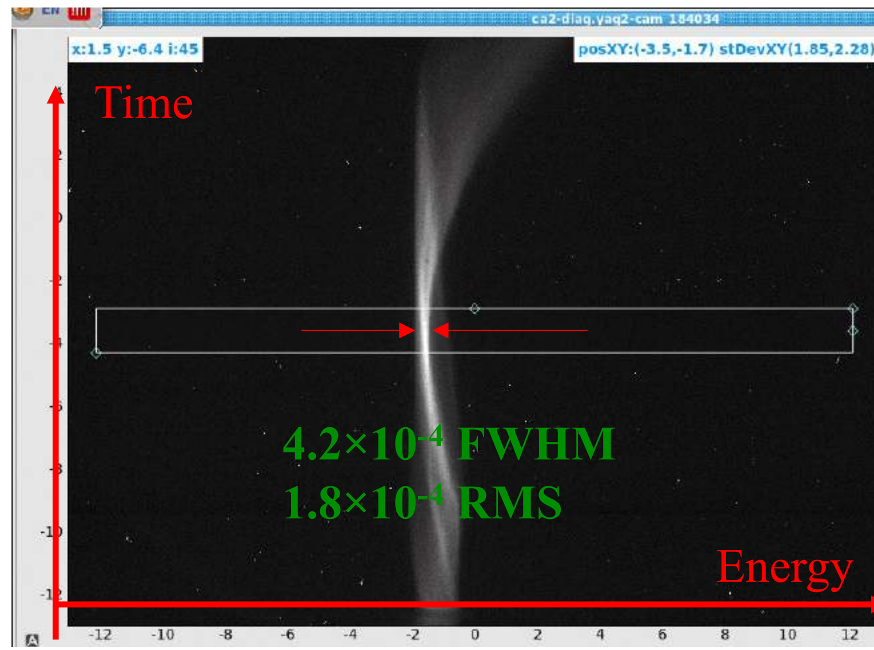
Direct pass



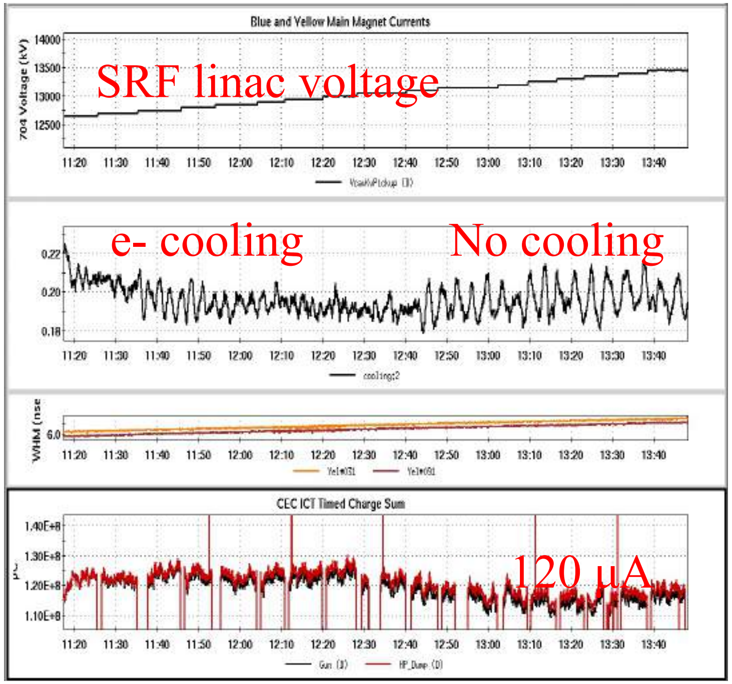
Slice emittance measurements



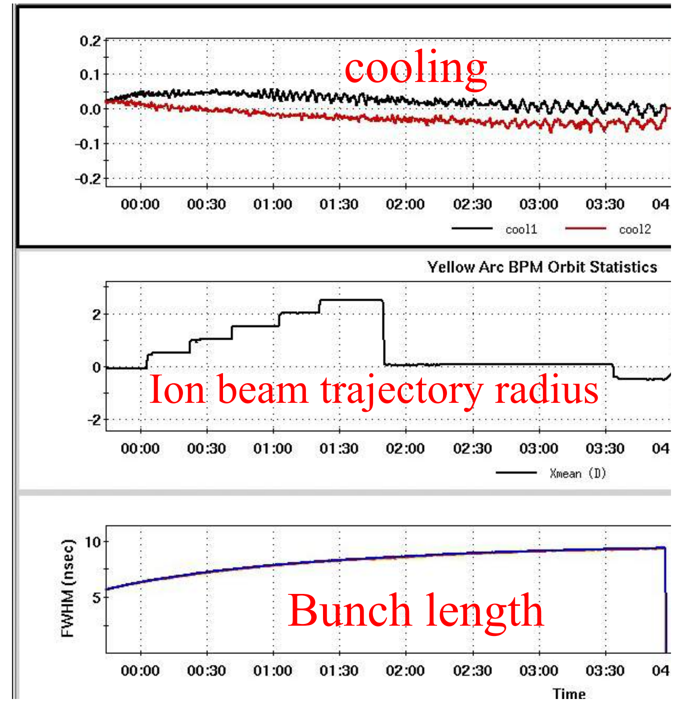
30-degree energy spectrometer



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.

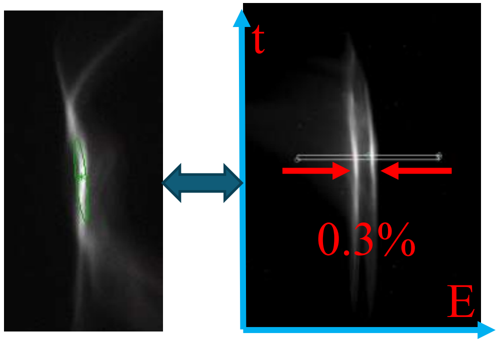
- There was no attempt of improving regular non-magnetized electron cooling – we used the lattice optimized for PCA CeC - and the best electron cooling rate was ~ 100 hours. It is consistent with cooling rate estimation made by Dmitry Kayran and 90 hours cooling rate simulated by He Zhao
- There is one 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

Brookhaven National Laboratory

Run21 set-backs and remaining challenges

- We lost at least 7 weeks of operation from severely damage to our the SRF gun - it was definitely not the result of CeC operations. 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 undergoing major upgrade.
- 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 (~20 psec RMS, twice the specs) timing jitter of the seed laser. Such energy jitter washes out the CeC cooling by 125-fold.
- We updated our specifications, replacing this seed laser with new having 5 psec RMS jitter, and ordering new system capable of 0.2 psec RMS jitter.
- 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 developing 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 made significant progress in this direction: the cryo-cooled IR detector and short diagnostics undulator

Bunch-to-bunch energy jitter

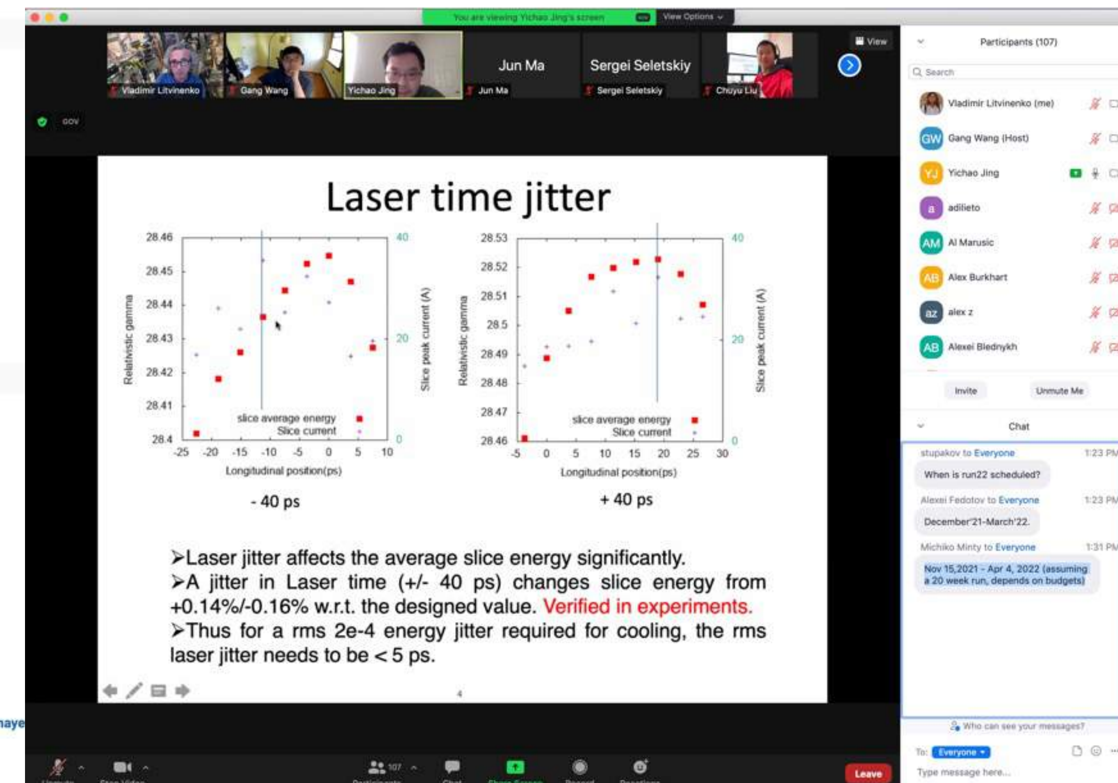


August 16, 2021: ½ day CeC X retreat

Opened for all interested parties: https://indico.bnl.gov/event/12706/

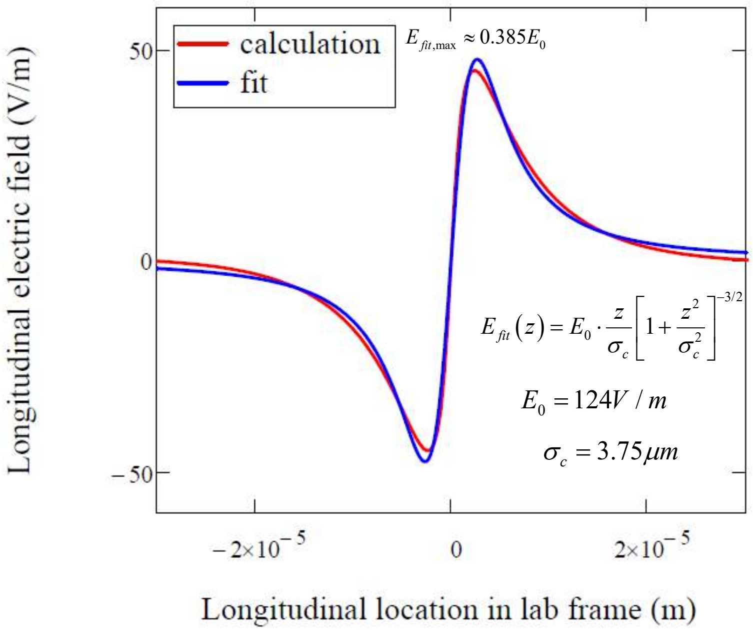
- 1:00 PM → 1:10 PM **Welcome**
  Speaker: Wolfram Fischer (BNL)
  2021-08-16 CeC ret...
- 1:10 PM → 1:30 PM **Summary of CeC X Run 21 (CeC group)**
  Speaker: Vladimir Litvinenko (BNL and Stony Brook University)
  CeC_X_Retreat_202...
- 1:30 PM → 1:50 PM **Electron beam requirements for CeC X (G. Wang)**
  Speaker: Jun Ma
  ElectronBeam.pdf
- 1:50 PM → 2:10 PM **Requirements for CeC systems (I.Petrushina, D. Kayran)**
  Speaker: Yichao Jing (BNL)
  system_requiremen...
- 2:10 PM → 2:20 PM **Break**
- 2:20 PM → 2:40 PM **Improvements to the CeC systems**
  Speaker: Jean Clifford Brutus
  CeC X Retreat - Imp... CeC X Retreat - Imp...
- 2:40 PM → 3:00 PM **Photocathodes: production, transfer, QE mapping (M. Gaowei, E. Wang, L. Cultrera, T. Rao)**
  Speaker: John Skaritka (BNL)
  CeCRetreat JS.2.pdf CeCRetreat JS.2.pptx
- 3:00 PM → 3:20 PM **Laser: time and intensity jitter, position stability, (L. Nguyen)**
  Speaker: Patrick Inacker-Mix (BNL)
  20210816_CeC_Ret... 20210816_CeC_Ret...
- 3:20 PM → 3:30 PM **Break**
- 3:30 PM → 3:50 PM **CeC RF system: voltage and phase jitter and drifts (G. Narayan, F. Severino, Y. Than)**
  Speaker: Thomas Hayes (Brookhaven National Lab)
  CeC_Retreat2021_R... CeC_Retreat2021_R...
- 3:50 PM → 4:10 PM **Orbit-drifts, noise/jitter, accuracy, slow feed-backs (R. Michnoff, P. Thieberger, A. Di Lieto)**
  Speaker: Igor Pinayev (BNL)
  Orbit.pdf Orbit.pptx
- 4:10 PM → 4:30 PM **Diagnostics (including IR) - noise and its suppression (I. Pinayev, M. Paniccia)**
  Speaker: Rob Michnoff (BNL)
  CeC-retreat-2021-In... CeC-retreat-2021-In...
- 4:30 PM → 4:50 PM **Diagnostics - time resolved emittance and energy spread, (Y. Jing, J.C. Brutus, D. Kayran, I. Pinaye**
  Speaker: Andrei Sukhanov (BNL)
  Beam_Diagnostics_...
- 4:50 PM → 5:00 PM **Closing**

- ❑ More than 100 people participated in the CeC-X retreat
- ❑ Goals of CeC X retreat were to
  - ❑ review current performance of the CeC systems
  - ❑ identify remaining problems and
  - ❑ identify solutions of the mail problems
- ❑ In addition, we discussed improvement of the CeC systems during RHIC shut0downs

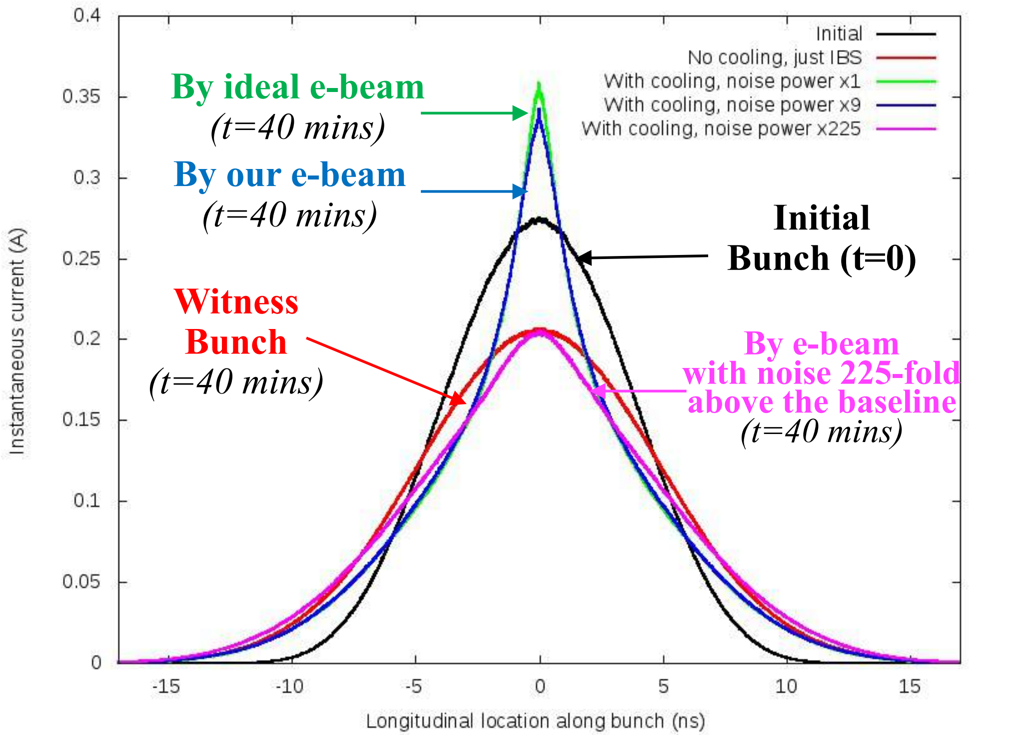


Our predictions did not change

Predicted evolution of the 26.5 GeV/u ion bunch profile in RHIC



Simulated and fitted (used in simulations of the ion beam cooling) energy kick in the PCA-based CeC experiment system



Black – initial profile, red – witness (non-interacting) bunch after 40 minutes. Profiles of interacting bunches after 40-minutes in PCA-based CeC for various levels of white noise amplitude in the electron beam: green– nominal statistical shot noise (baseline), dark blue – 9 fold above the baseline, and green – 225 fold above the baseline

Cooling will occur if electron beam noise is below 225-times the base-line (shot noise)
We demonstrated beams with noise as low as 6-times the baseline

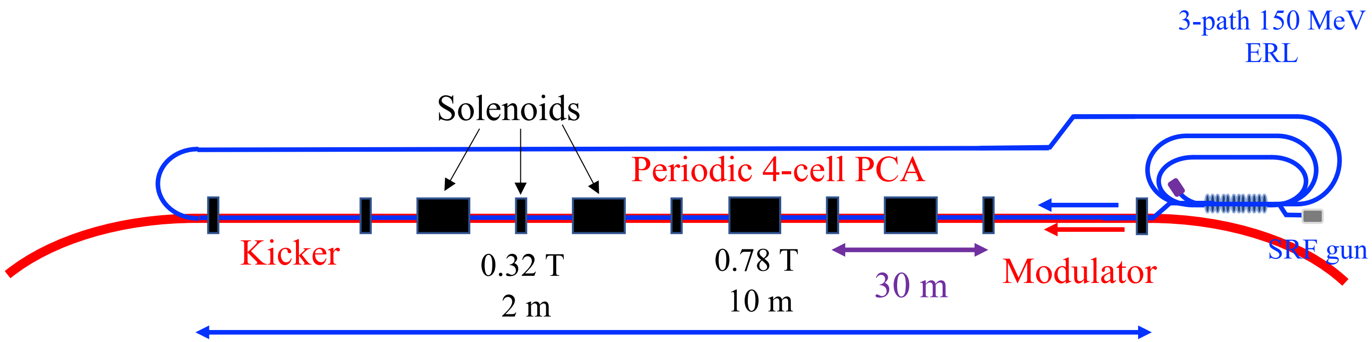
Schedule

November 20 -30	December 1-31	January 1-31
Start of the Run Align CeC solenoids Restart CeC accelerator Generate electron beam Complete all systems	Ramp Au ion beam to CeC store TRDL and e-beam KPPs Propagate electron beam through CeC Establish energy stabilizations Establish high gain PCA Align electron and ion beams Match beam's relativistic factor	Establish CeC X setting Perform energy scan: 41 set point x 4 hours Investigate longitudinal CeC Decision point: Continue 1D or switch to 3D CeC?

February 1-28	March 1 – April 4
Data Analysis Contingency: Work on improving e-beam Switching to 3D CeC setting	Contingency: Use reserved time to complete 1D CeC or investigate 3D CeC

Summary and plans

- We developed detailed plan for Run 22 – starts November 15, 2021
- We requested 16 days of CeC dedicated time for RHIC Run 22
- **Our goal is to demonstrate the PCA CeC during Run 22**
- We continue developing theory and 3D CeC simulations:
  - CeC X: PCA amplitude gain 100, bandwidth ~20 THz
  - Alternative EIC CeC: PCA amplitude gain 400, Bandwidth ~500 THz



- **We plan to make CeC happen!**