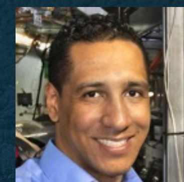
Coherent electron Cooling Proof-of-Principle Experiment – CeC X

Vladimir N Litvinenko – project director

Jean Clifford Brutus – project manager



Vladimir N Litvinenko for the CeC operation group:

Xiaofeng Gu, 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 8, 2021

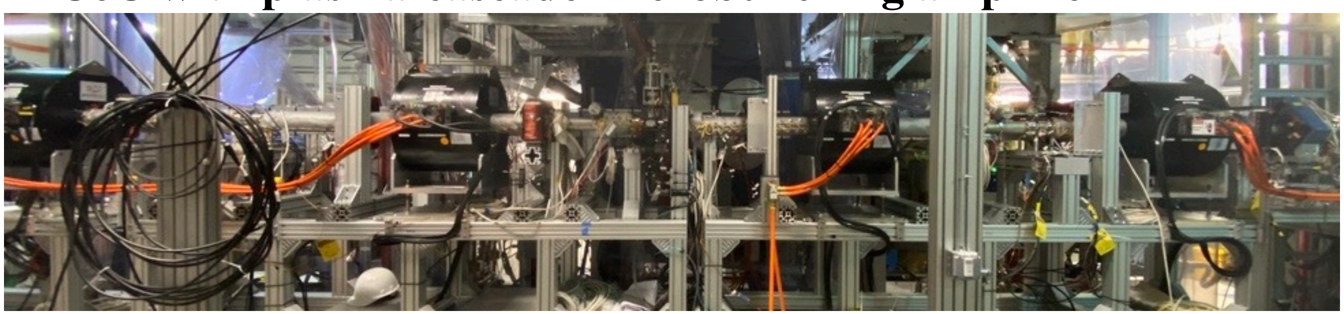
The CeC team – never can get all your pictures …

Content

- ❑ Response to MAC 2020 recommendations
- ❑ Why CeC X is important
- ❑ Status of the CeC experiment
- ❑ Results from Run 21
- ❑ Plans for 2022 and remaining risks

CeC X accelerator

CeC with plasma-cascade microbunching amplifier



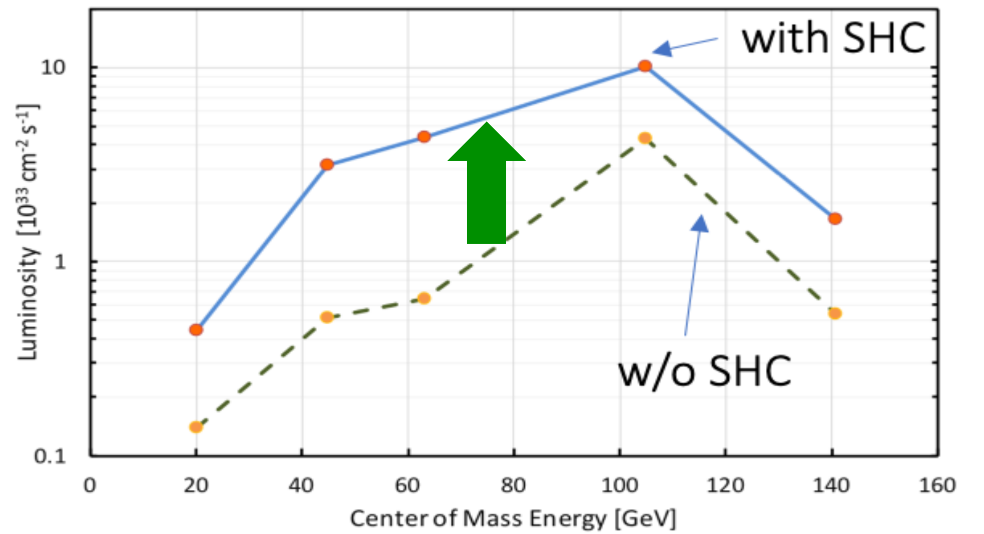
MAC 2020 recommendations

- The PCA concept is documented in 2018 and 2019 arxiv preprints and is still not published in a peer reviewed journal. Prepare a journal publication of this concept
  - We submitted very detailed 3D PCA theory paper to PR AB in January 2021
- Work out a conceptual scheme of EIC strong cooling based on PCA. Optimize and formulate a set of electron beam parameters (such as beam current, bunch length, energy spread, etc.) for such a cooling system. Compare with the cooler based on MBEC and document the result.
  - This job is partially done even before MAC 2020 and is in continuing development since then... We proposed to use PCA Type II scheme – with matching solenoids. The PCA has significant advantages vs chicane-based amplifier (CBA)*:
    - It does not require system for separation of electron and hadron beams
    - PCA gain is significantly (3-to-5 fold) larger than that of CBA
    - PCA bandwidths (500 THz) exceeds that of CBA (30 THz) by 16-folds
- Prepare a plan and possible resource request for the case if more than 14 days of RHIC beam time can be accommodated
  - Request for additional week of dedicated time was submitted, but was not accommodated

**All known CeC schemes are based in microbunching amplifiers. Therefore, using MBEC for chicane-based microbunching amplifiers only can lead to confusion implying that other CeC schemes using Plasma-Cascade or FEL amplifiers are not based on microbunching in electron beam… which is 100% wrong*

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.*

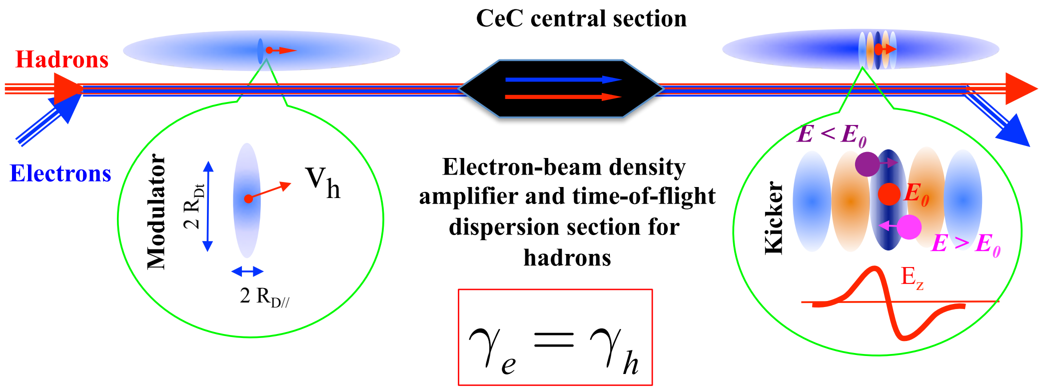
Quote from the pCDR review committee report: "*The major risk factors are strong hadron cooling of the hadron beams to achieve high luminosity, and the preservation of electron polarization in the electron storage ring. The Strong Hadron cooling [Coherent Electron Cooling (CeC)] is needed to reach $10^{34}/(cm^2s)$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

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

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
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(Received 24 September 2008; published 16 March 2009)

PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

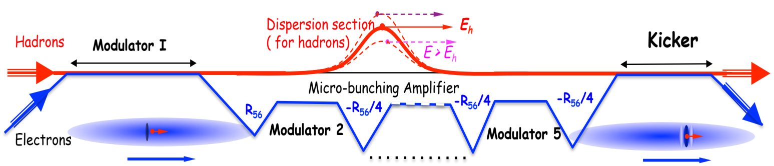
D. Ratner*
SLAC, Menlo Park, California 94025, USA

(Received 11 April 2013; published 20 August 2013)

What can be tested experimentally?

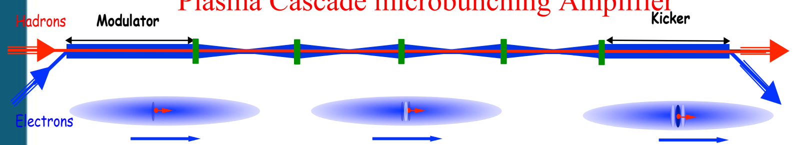
Litvinenko, Derbenev, PRL 2008

Ratner, PRL 2013

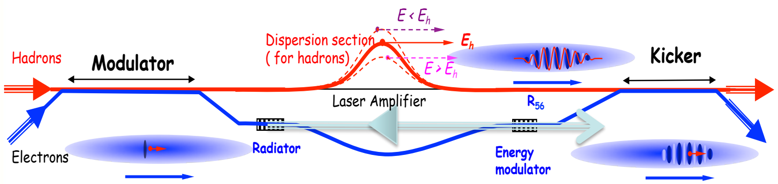


Litvinenko, Wang, Kayran, Jing, Ma, 2017

Plasma Cascade microbunching Amplifier



Litvinenko, Cool 2013



RHIC Run 18

High gain FEL amplifier with low-a_w wigglers

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

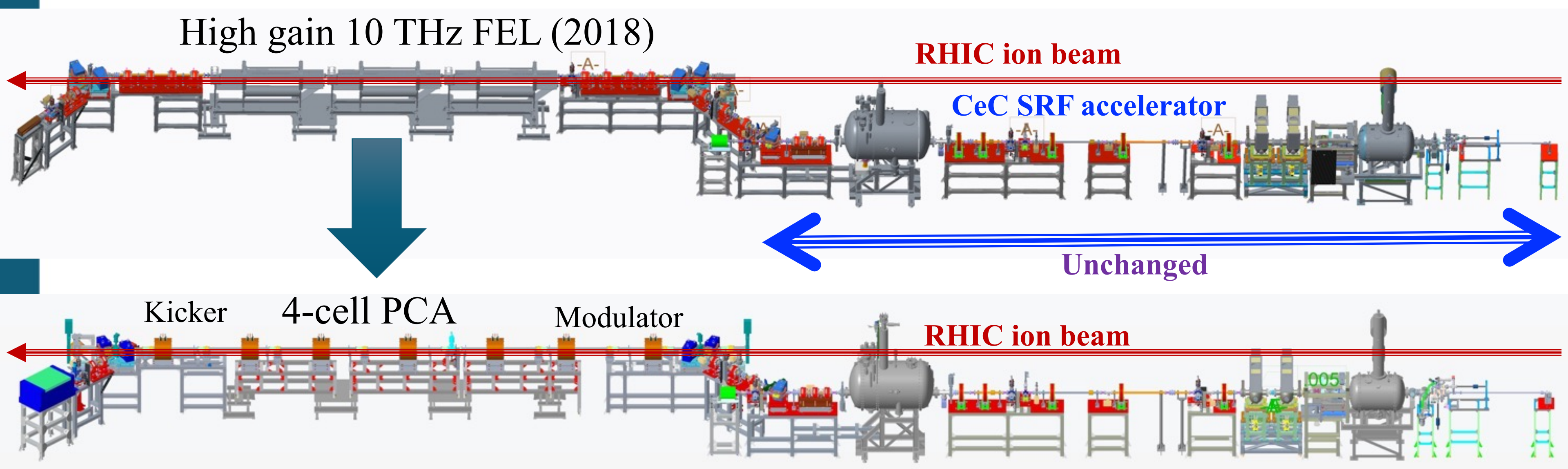
RHIC Runs 20-22

Plasma-Cascade Amplifier

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

CeC X at RHIC

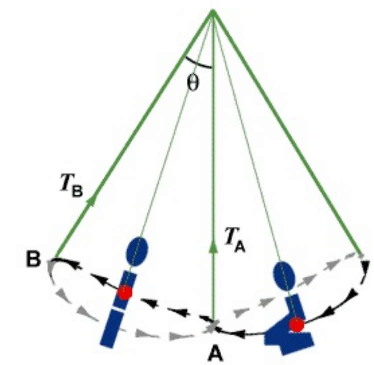
- 2014-2017: built cryogenic system, SRF accelerator and FEL for CeC experiment
- Three successful external CeC X reviews: December 2012, September 2019 and January 2021
- 2018: started experiment with the FEL-based CeC. It was not completed: 28 mm aperture of the helical wigglers was insufficient for 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 are focusing on demonstrating longitudinal CeC cooling.



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

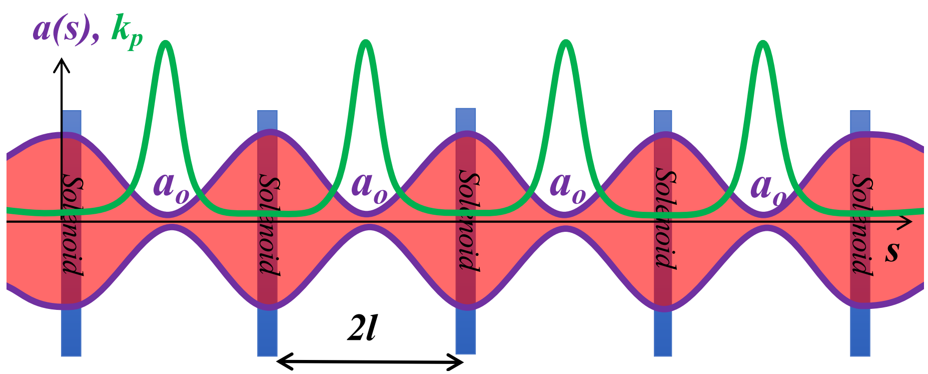
What is Plasma-Cascade Amplifier

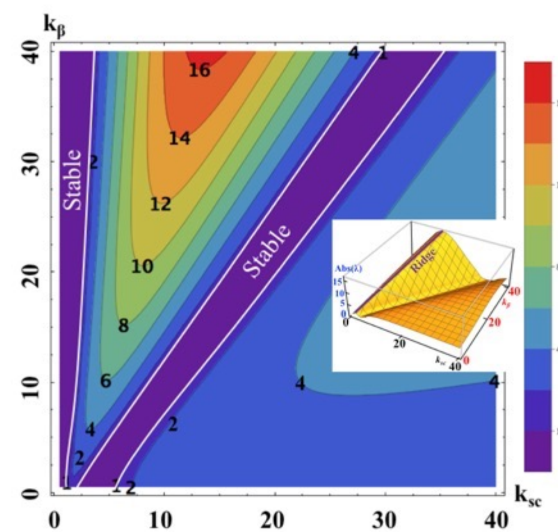
It is an exponentially growing parametric instability driven by variation of the plasma frequency and driven by the variation of the transverse electron beam size



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

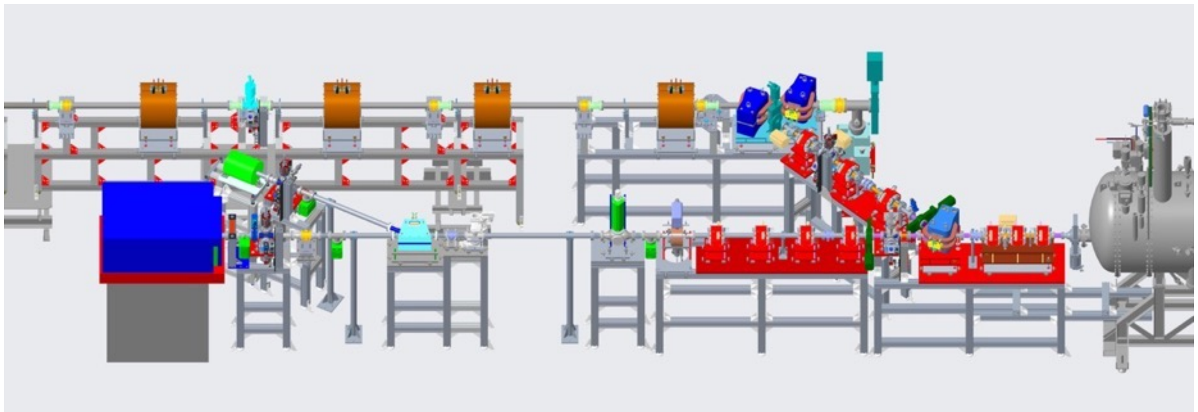
CeC X status

- ✓ 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

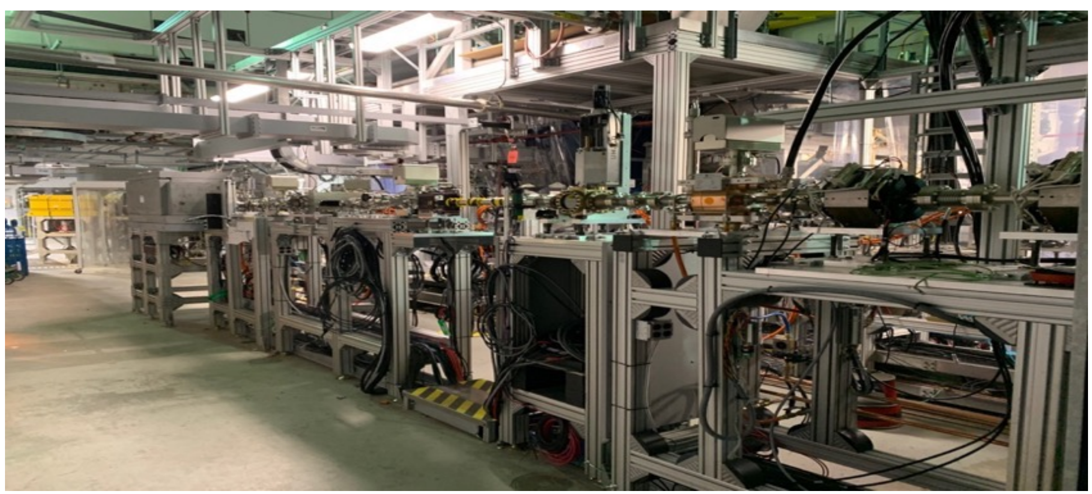
Parameter	**Planned**	**Demonstrated**	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the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

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



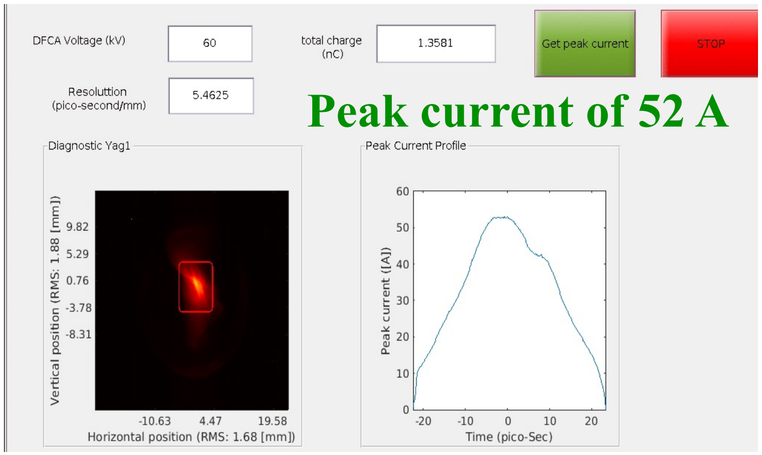
Fully Commissioned

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



New: Time-resolved measurements

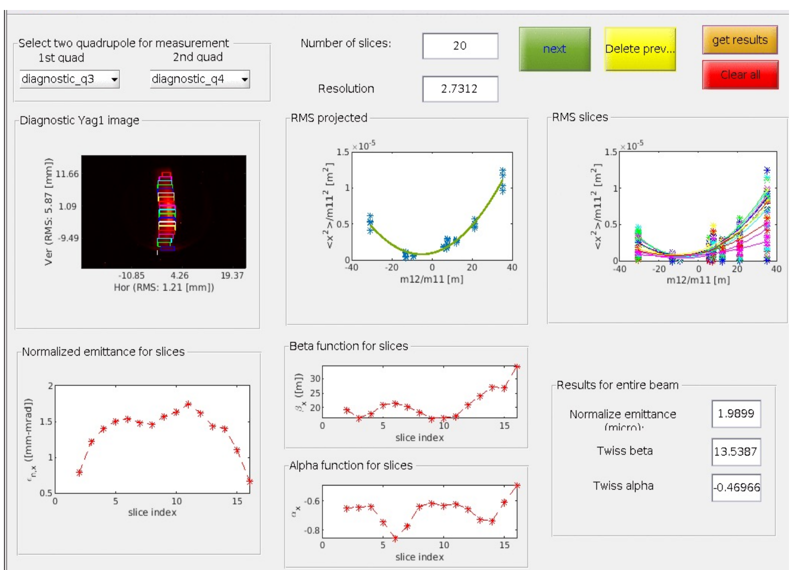
Direct pass



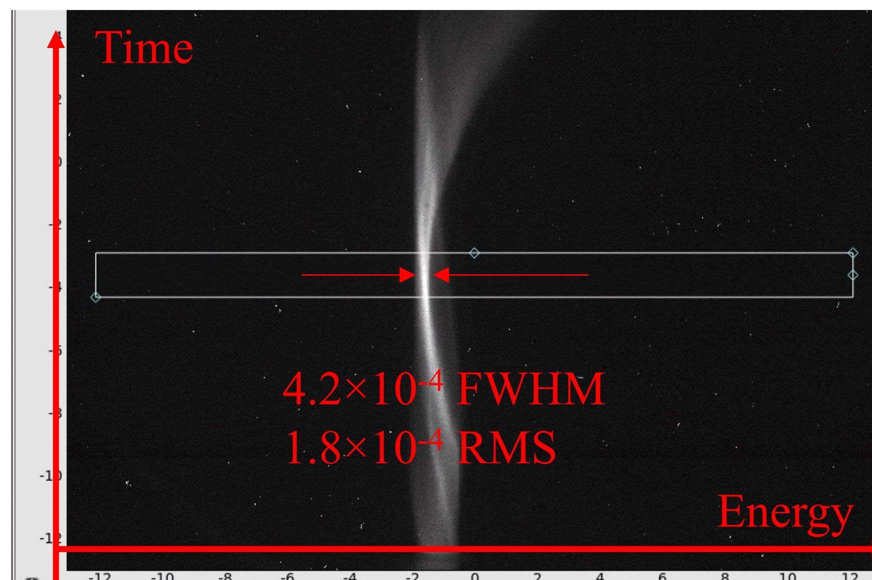
Peak current of 52 A

Fully Commissioned

Slice emittance measurements

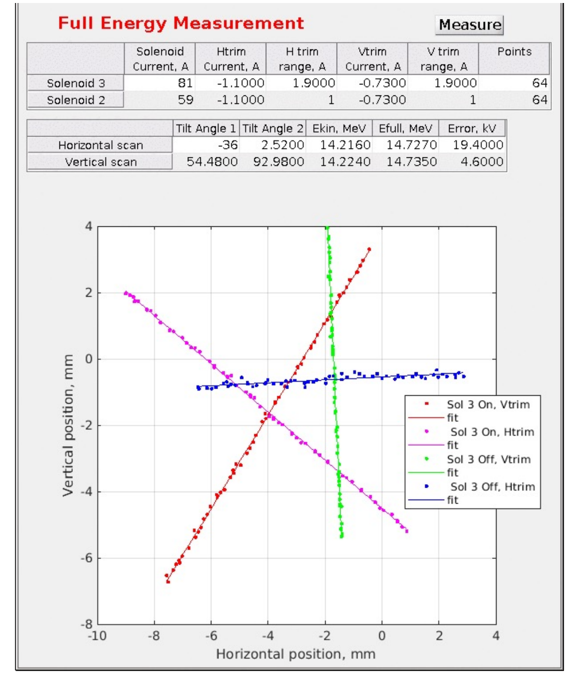


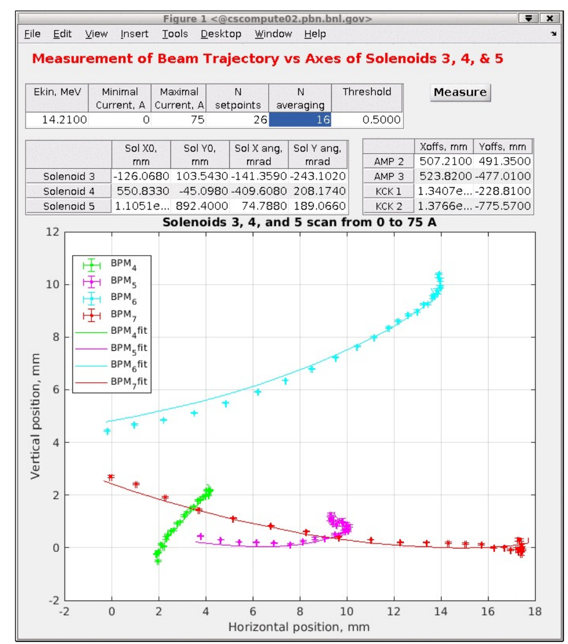
30-degree energy spectrometer

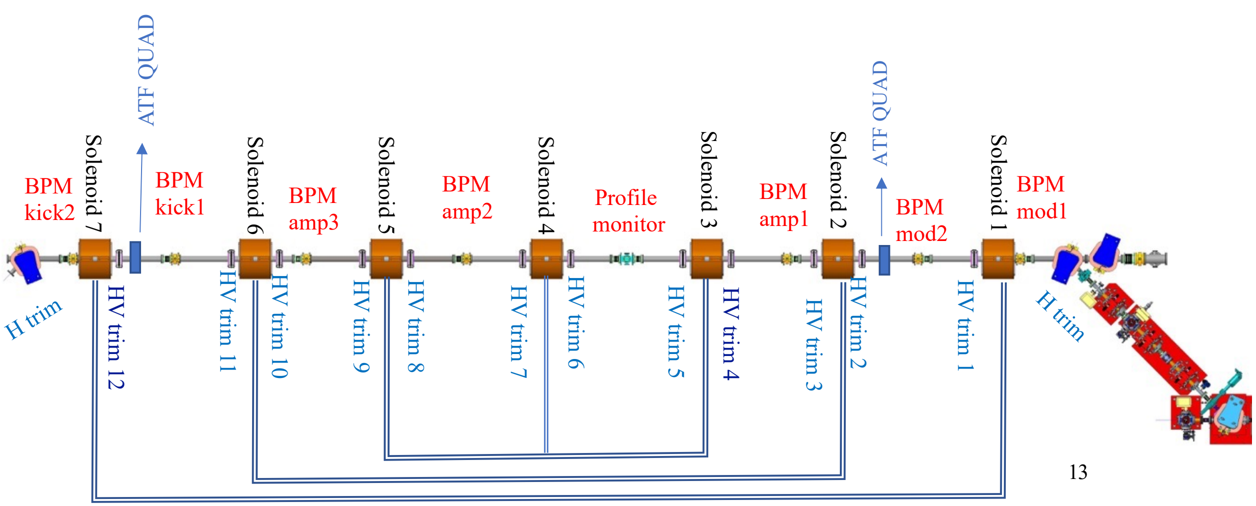


Energy measurements and novel BBA in CeC

- ✓ 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**

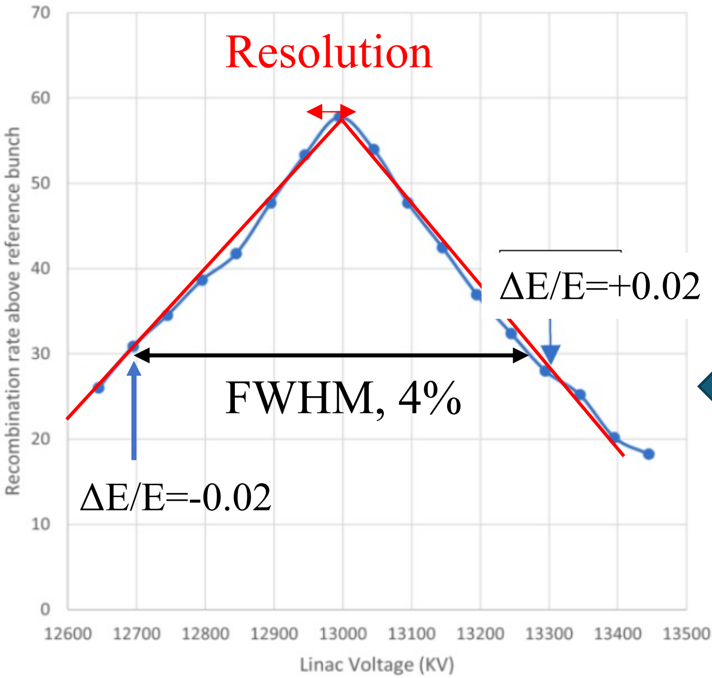






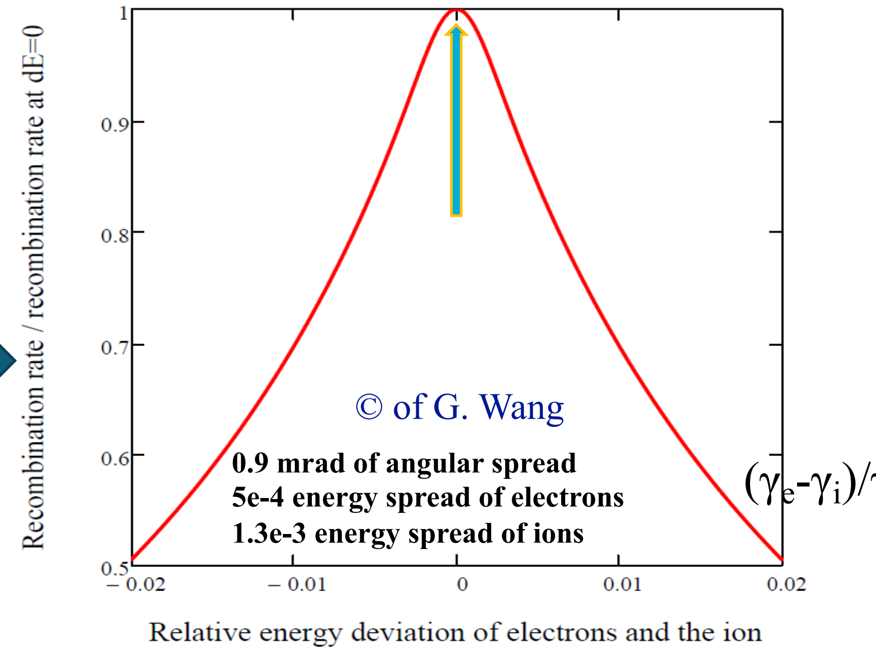
Recombination of electrons with Au ions

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



$(\gamma_e-\gamma_i)/$

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

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

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

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

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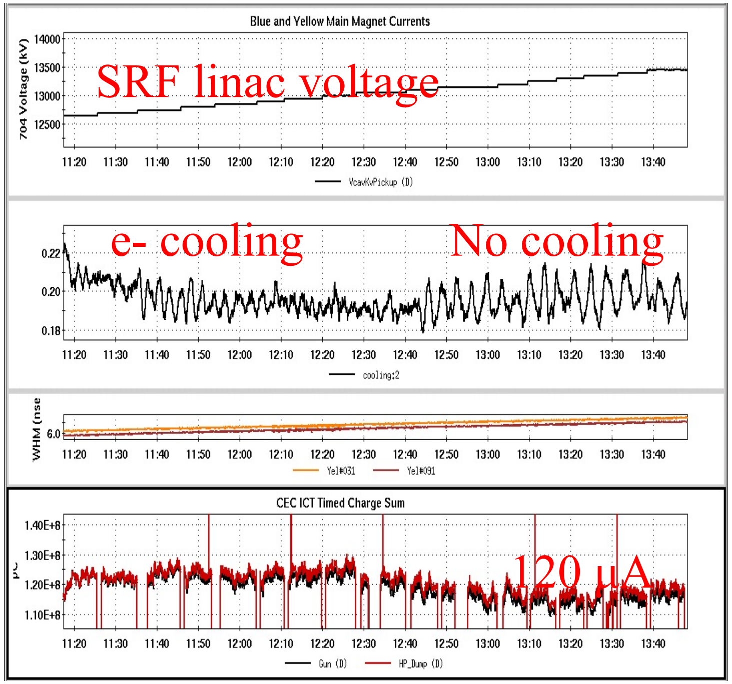
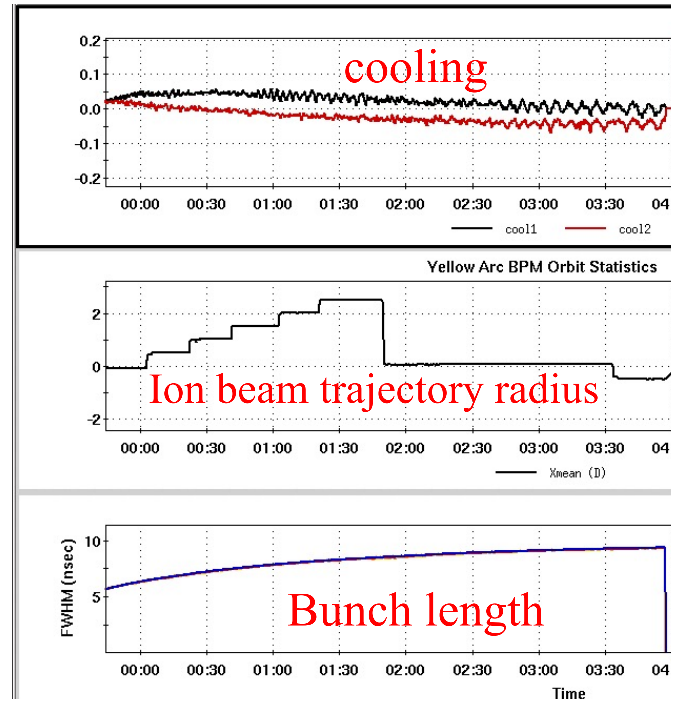
Search for CeC signature and observation of regular bunched electron cooling of 26.5 GeV/u Au ion beam



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.

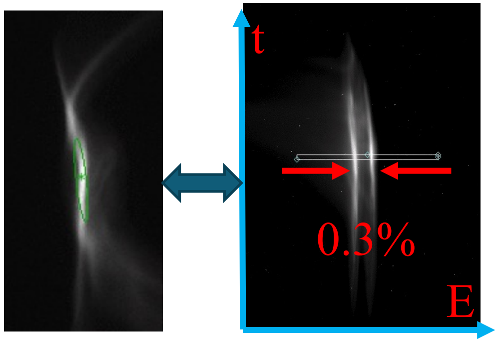
- There was no attempt of improving regular non-magnetized electron cooling – we used the lattice optimized for PCA CeC - and the best electron cooling rate was ~ 100 hours. It is consistent with cooling rate estimation made by Dmitry Kayran and 90 hours cooling rate simulated by He Zhao
- There is one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

Brookhaven National Laboratory

Solutions for Run21 set-backs and challenges

- We lost at least 7 weeks of operation from severe damage to our the SRF gun - <u>it was definitely not the result of CeC operations</u>. Fortunately, we had skills, and some luck, to restore the gun operation, but continue suffering with contamination till the very end of the run 21.
- Particulate-free preparation system of photo-cathodes with uniform QE and their transfer system underwent a major upgrade.
- The main challenge for the CeC X was 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. There is also ±10% jitter in the laser power, which create challenges for CeC operations.**
- We replaced this seed laser with new having 5 psec RMS jitter. As risk reduction, we ordered a new system capable reducing jitter to 0.2 psec.
- 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 developed 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 are installed and will be commissioned as soon as CeC accelerator is operational

Bunch-to-bunch energy jitter

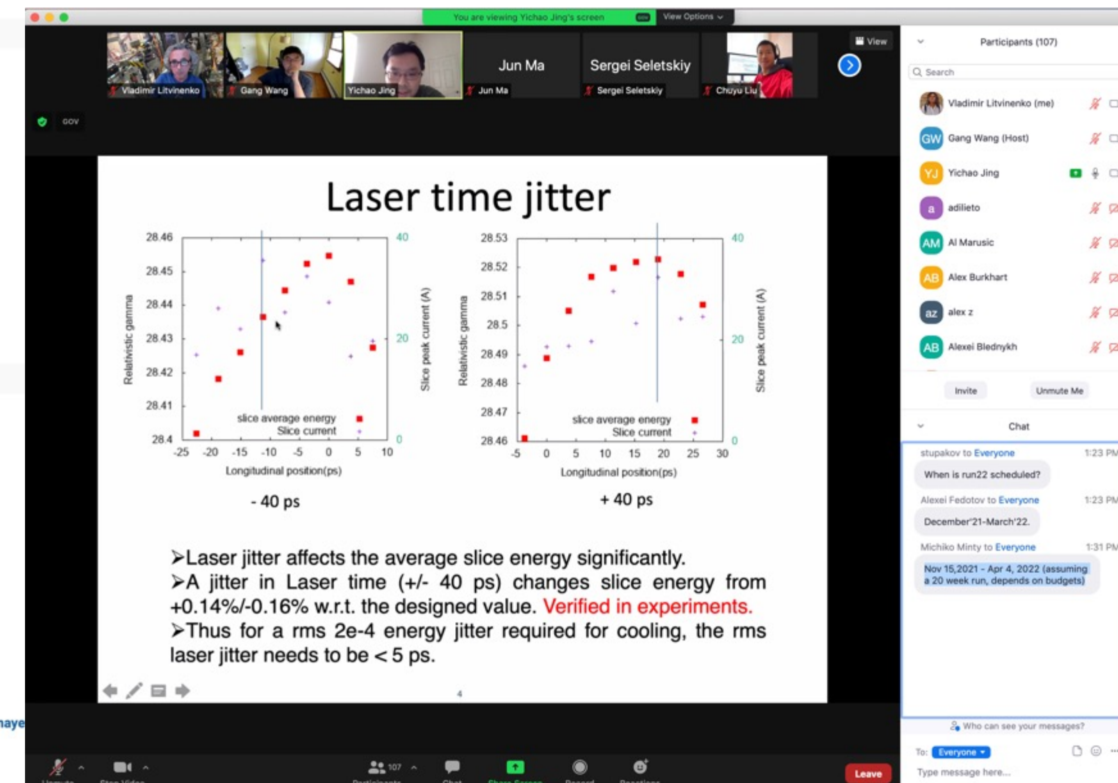


August 16, 2021: ½ day CeC X retreat

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
  - ❑ identify solutions and remedies
- ❑ In addition, we discussed planned improvements of the CeC systems during RHIC shut-downs



Main findings and implemented mitigations

Main Findings

- Energy jitter is likely results from the IR seed timing jitter ~ 20 psec RMS
- Energy drift is likely the result of temperature-dependent voltage and phase drift
- Large RFI noise in the IP2 diagnostics systems preventing from accurate measurements of any signals
- Insufficient sensitivity if IR detectors for accurate measurements of the PCA gain and spectrum

Implemented Solutions

- Replaced the seed laser with new having timing jitter ~ 5 psec
- Developed energy measurements system for slow feed-back to compensate these drifts
- Task force
  - searched for the sources of the noise
  - built insulating amplifiers
- Cryo-cooled IR detector was repaired and installed. A short diagnostics undulator was designed, built and installed

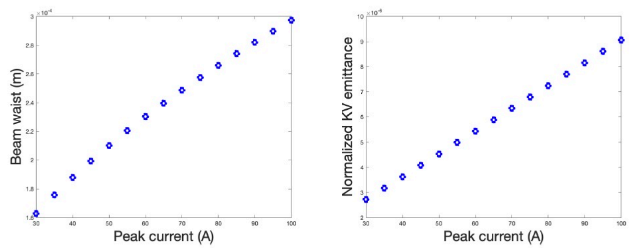
Brookhaven National Laboratory

Defining requirements for e-beam and CeC system

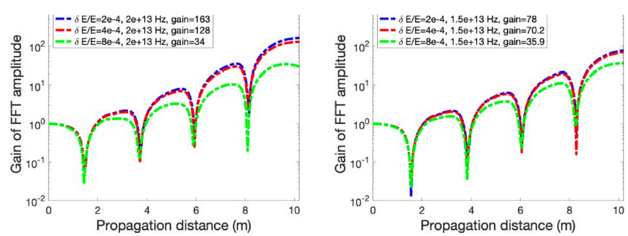
Jun Ma & team

Electron Beam Requirements for CeC Experiment

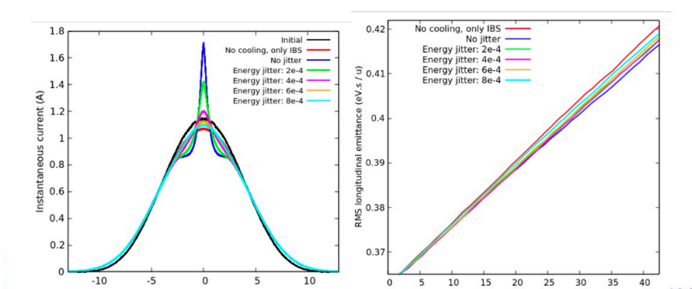
Sensitivity studies: energy spread & peak current, beam emittance and asymmetry, matching, orbit distortions, energy jitter



(a) a_o (b) ε_n



(a) $\varepsilon_{n,KV} = 7\mu m$ (b) $\varepsilon_{n,KV} = 10\mu m$



National Laboratory

Yichao Jing & team

Requirements for CeC systems

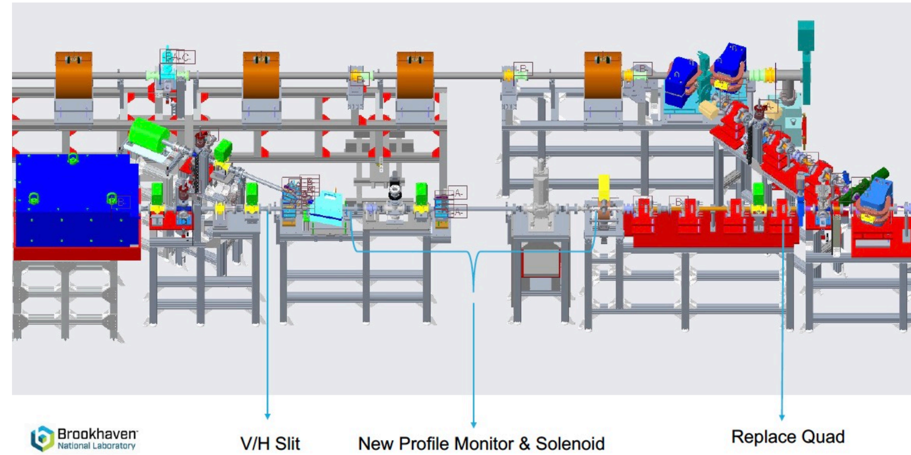
Sensitivity studies: laser intensity and timing jitter, SRF gun, Bunching cavities and SRF linac voltage and phase jitter and drifts, power supplies jitter and drifts

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

Jean Cliff Brutus: Improvements to the CeC

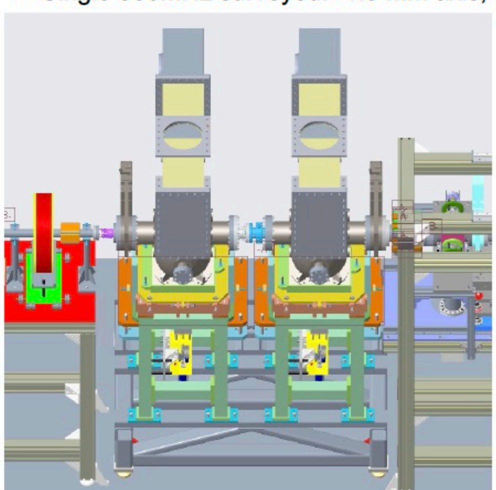
CeC Shutdown 2021 Upgrades

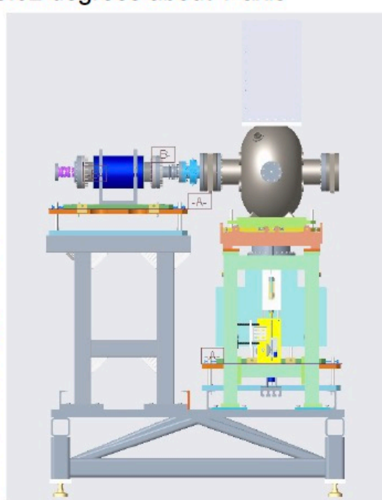
#	Work
1	500 MHz Removal
2	Horizontal/Vertical Slit
3	Profile Monitor
4	Cathode System Upgrade
5	Replace Q1 in the TRDBL by one with working trim coils - in current quad two out of 4 trim coils are broken
6	500MHz Coax Inspection
7	DCCT
8	Solenoid
9	H/V Trims relocation
10	Wiggler/Undulator
11	Heating Jackets Removal
12	Compensating Coil



500 MHz Removal

- Design completed
- Design of coax reconfiguration completed
- Parts ordered and in house
- Single 500MHz surveyed: -1.5 mm axis; 0.02 degrees about Y axis



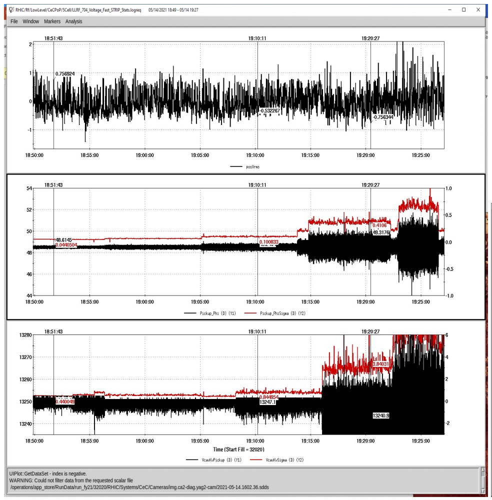


Summary

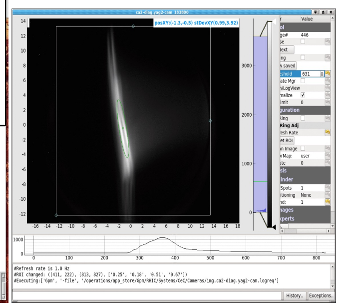
- Priority list
- Anthony is checking if we need to run new cable and order more PS for new compensating coils and H/V trims 8-12 weeks lead time
- Design modifications of beamline completed
- 500MHz removal completed
- Damaged quad replacement completed
- 500MHz coax inspection in progress
- Heating jackets removal in progress (7 correctors have to be split)
- DCCT installation in progress
- Delay of parts from KJL for H/V slit and profile monitor – looking for backup solution
- TRDBL modifications in progress
- Undulator design and fabrication in progress
- H/V trims relocation design in progress

Tom Hayes and team:
CeC RF System Stability

Short Term Performance



- Changes in loop gains show degraded regulation as expected but no measurable change in beam energy
- For changes up to a factor of 10 in gain, no change in peak to peak energy variation
- Linac regulation is not limiting performance



Short-term cavity regulation is excellent

Significant efforts have been expended to stabilize the laser and they have been extremely successful

If long term stability needs to be improved, beam based feedback is the only option left

Improvements for this year

Linac switched to using up/down conversion

Cable compensation loopbacks enabled

Laser stabilization

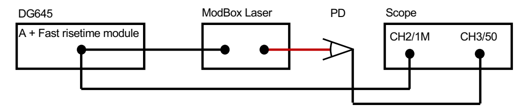
-Feedforward to correct phase steps

-Fast feedback to correct measured drifts

Patrick Inacker-Mix, Laser: Temporal & Intensity Jitter, Position Stability

Temporal Jitter Performance

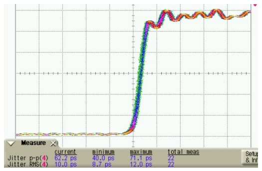
In-House Measurement

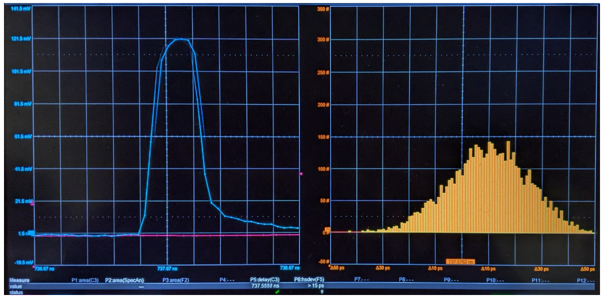


Jitter Measurement performed using a local delay generator and Oscilloscope
- Result: 14-15ps rms

Measurement is very sensitive to trigger edge slope; Result likely upper limit

Manufacturer measurement:
- Result: 8.7-12ps rms:





An update to the Jitter spec. for CeC makes a new seed laser necessary

Replacement of current seed with another function generator underway (Jitter 5.6ps rms)

Option to use a Modelocked laser instead in Proposal stage (Jitter <250fs rms)

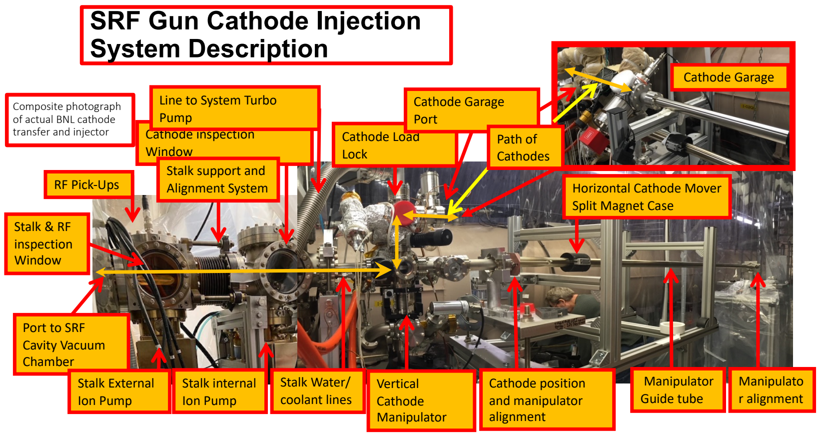
The Shot-Noise of the free-running laser was deemed to large, making a fast intensity feedback necessary

Slow Position feedback provides enough dynamic range to hold the transport alignment at all operational power levels within 0.1mm

Position stability on the Gun table aperture is close to achievable limit without direct stabilization on the gun table which would require CW beams (CoM rms < 0.25% of Aperture size)

John Skaritka and team

Photocathodes: production, transfer, QE mapping



All cathode transfer an injection system component have been designed, ordered and in an advanced state of manufacturing and deliveries

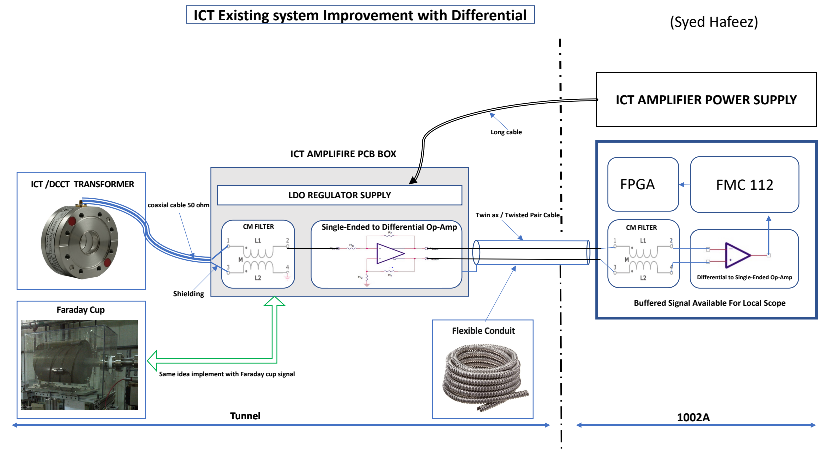
All new transfer systems components will be completed and ready for installation in early October cathode injection in early November.

Work is proceeding with a complete over-hall of the Cathode deposition system at Instrumentation Division

A QA Mapping system is under design and parts ordered for system for integration at Instrumentation Division and eventual use in tunnel.

Robert Michnoff and team

CeC Diagnostics



Beam diagnostic systems are providing important measurements for CeC operation

Enhancements to presently installed systems continue

- To provide additional operational modes
- To make measurements less susceptible to noise induced on signals from outside sources

New systems are being installed this shutdown

- DCCT
- Horzontal/Vertical slit
- Profile monitor

Brookhaven National Laboratory

Igor Pinayev and team

Orbit-drifts, noise/jitter, accuracy, slow feed-backs

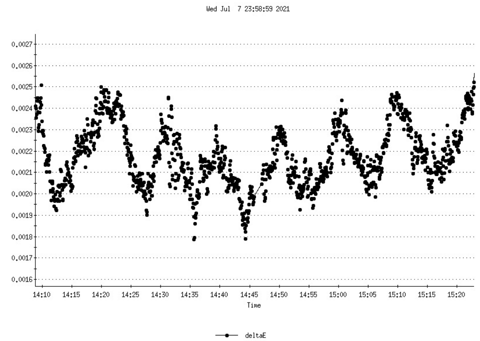
Uses triplet BPM and 1st modulator BPM for measurement of the incoming beam trajectory.

Uses dogleg BPM for energy measurement (D=0.295 m).

There are quadrupoles between the BPMs, therefore this method cannot be used for absolute energy measurement.

Coefficients k_1 and k_2 used for suppression of the betatron motion influence can be found using horizontal trims. They depend on the dogleg quadrupoles settings.

The dispersion in the common section should be close to zero.



$$\frac{\delta E}{E} = -\frac{X_{dglg} + k_1 X_{acc} + k_2 X_{mod1}}{D}$$

Possible improvements

- Reduce number of passes in the regenerative amplifier
- Find and eliminate cause of saw-tooth modulation
- Increase laser spot size before the iris
- Add monitoring of the laser pulse
- **Replace drive laser**
- Implement orbit feedback for the linac axis and common section
- Configure the RF loopback compensation for the best performance (diagnostics line can be used)
- Implement beam-based energy feedback
- Identify power supplies mostly affecting beam trajectory (swap them with spares or into the less critical location)
- Adjust phase correction in the BPM for minimal noise

Andrey Sukhanov

Time resolved emittance and energy spread

Transverse Deflecting Cavity

It will convert the beam's longitudinal distribution to transverse distribution which is measurable

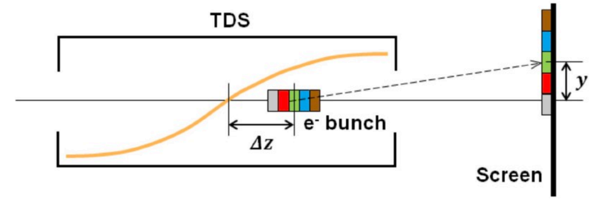


Table 1 key beam parameters of CEC 1.5nC operation

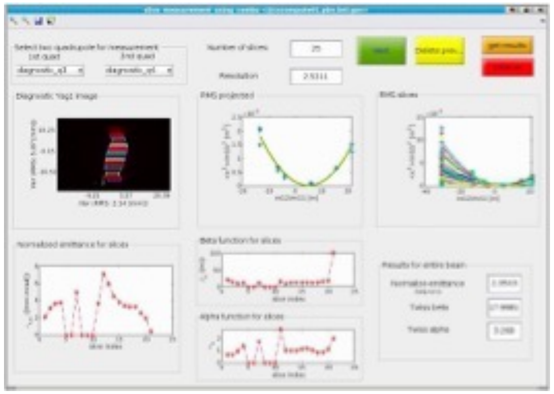
parameter	*Symbol*	Value	*Unit*
Beam size at yag without Deflecting cavity		~0.4	*mm*
Beta function at screen		0.1	*m*
Normalized rms emittance		~1.5	*mm-mrad*
Beam energy at deflector		14.5	*MeV*
Beam energy at screen		14.5	*MeV*
bunch length (edge to edge)		~30	*ps*

Table 2 Main parameters of 1.3GGHz TDS

parameter	*Symbol*	Value	*Unit*
RF deflector frequency	ω_{rf}	1.3	*GHz*
RF deflector shunt impedance	R_T	~3.5	MΩ
RF deflector unloaded quality factor	Q	9450- 10050	
RF deflector power	P_0	~10	*KW*
RF deflector maximum accelerating voltage	V_0	~ <0.26	*MV*

* resolution of <1ps (accurate to 1THz)

* measure the beam's longitudinal phase space info

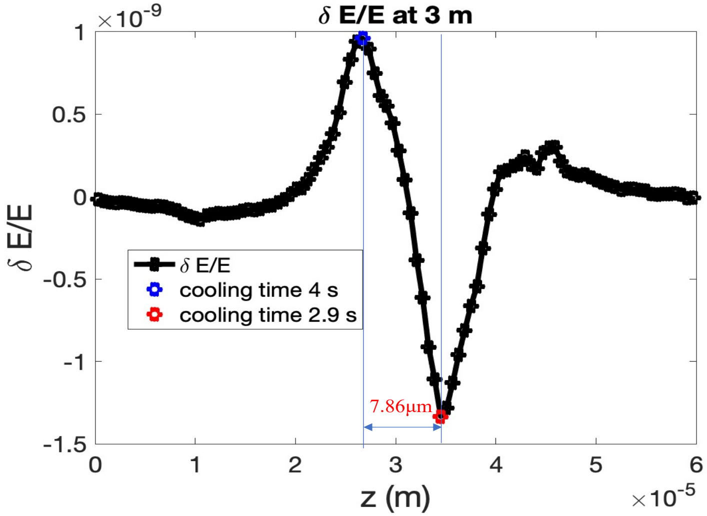


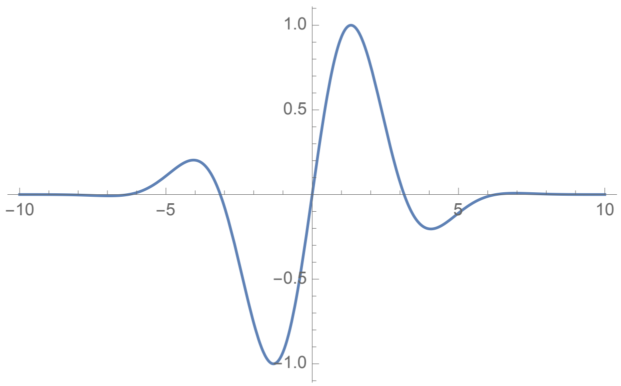
- ➢ Update the application for energy spread.
- ➢ Adopt the multi-slit application for CeC.
- ➢ Develop app for zero-crossing RF phase.
- ➢ Develop app for time-resolved emittance measurement, based on Matlab code from Yuan

Understanding results

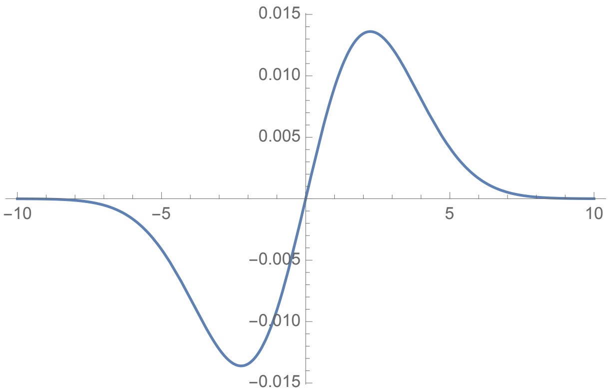
Relative e-beam energy variations of 0.02% required to stay within cooling range

Relative e-beam energy jitter with RMS value of 0.1% results in 125-fold reduction of the cooling force





No energy jitter, KPP beam



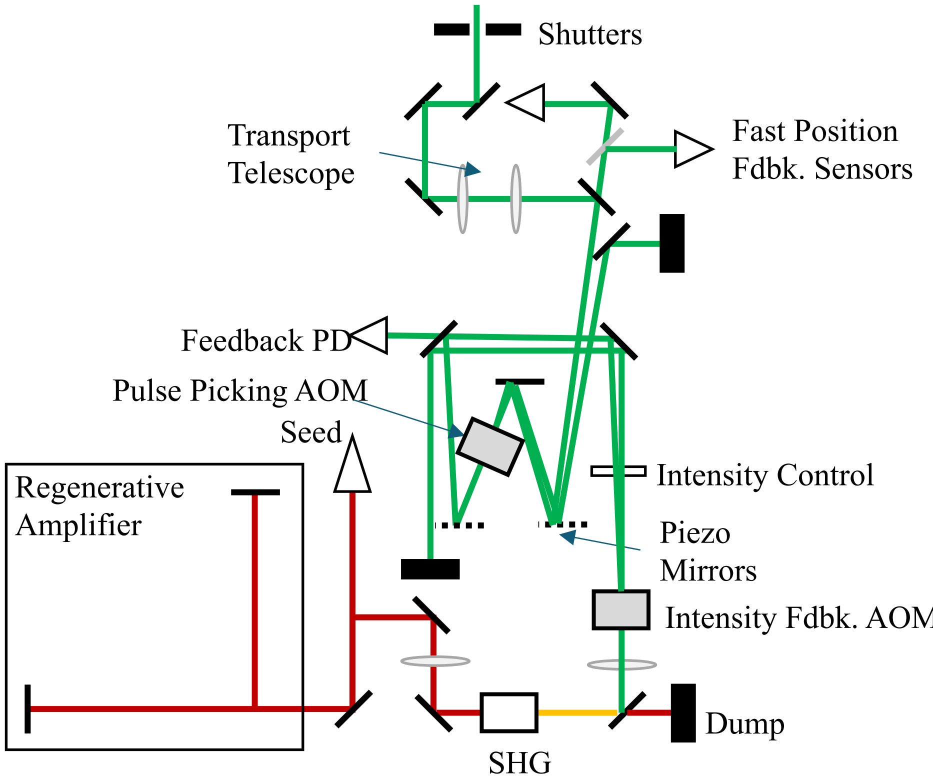
Energy jitter of 0.1% RMS, KPP beam

Laser system layout for run22

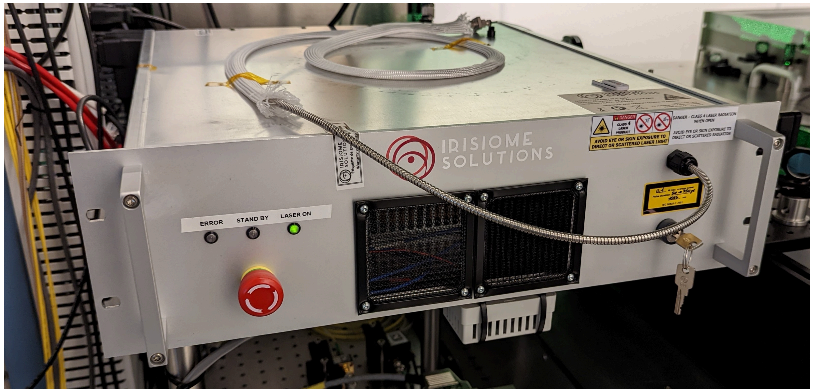
- New seed laser with 5 psec RMS time jitter is installed and is operational
- Bandwidth for operation at variable repetition rates (78kHz-5MHz)
- Exchange of IR Pockels Cell Pulse Picker with AOM to enable 0-100% duty cycle operation for high repetition rate operation (1-5MHz)
- Maintaining CW beam 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

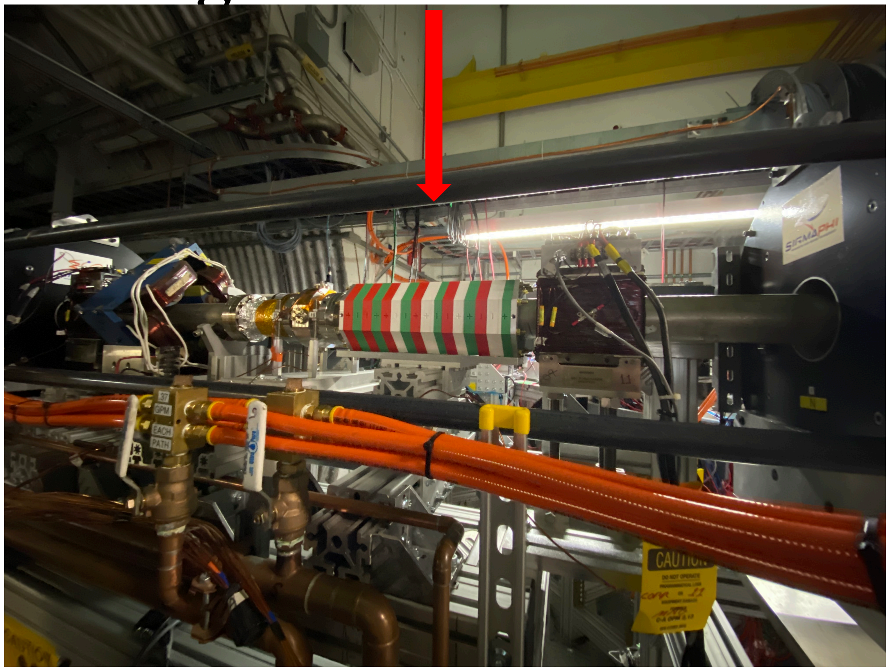
Brookhaven National Laboratory

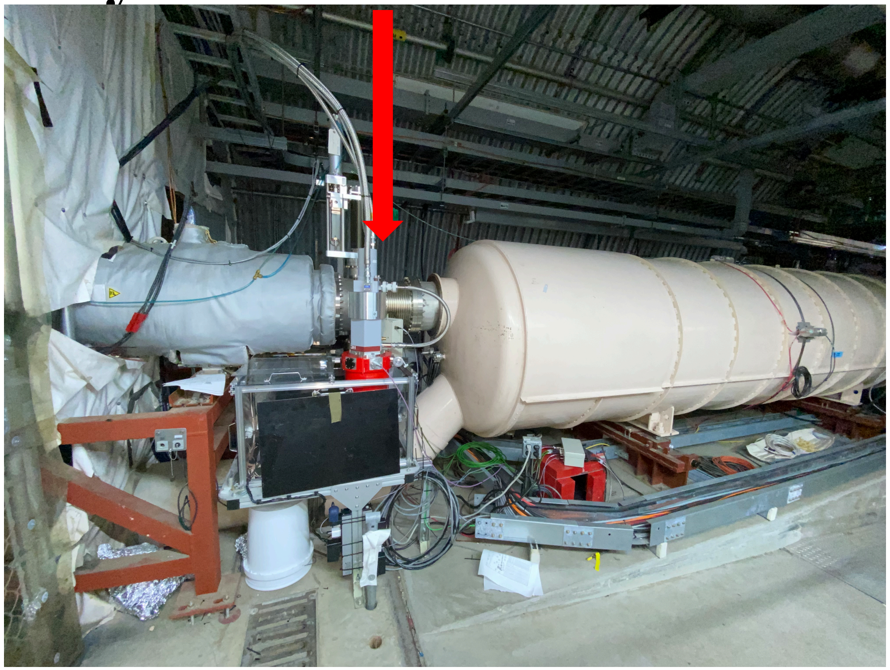


New seed laser arrived November 10, 2021
Installed & operating



Diagnostics undulator and cryo-cooled IR detector





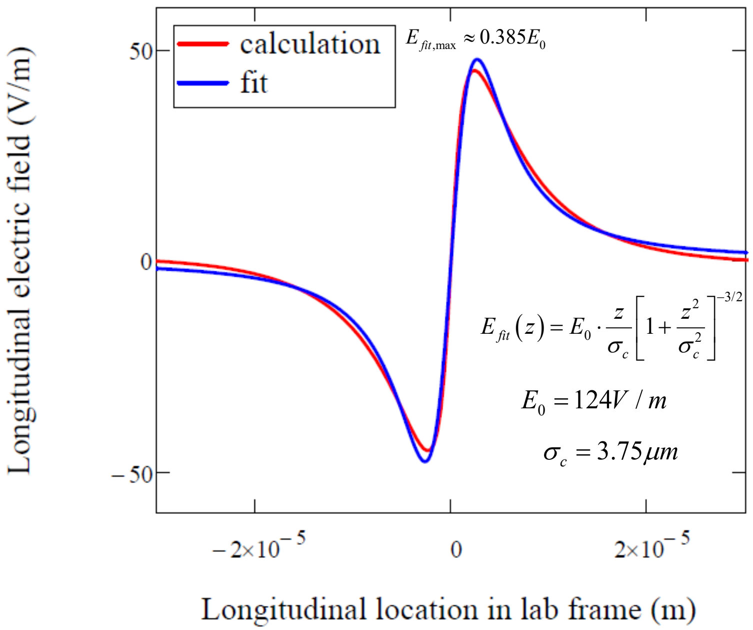
Parameter	Value	Units
Period	8	cm
Gap	7.9	cm
Peak field	0.6	kGs
Radiated power at 50% beam current	9	nW
Fundamental wavelength @ γ=28.5	54	μm
Central frequency @ γ=28.5	5.5	THz
Third harmonic	16.6	THz
F_3/F_1	0.04	

- ✓ New cryo-cooled IR detector has ~ 100 better signal to noise ratio
- ✓ Diagnostics undulator would generates radiation at 5.5 THz and 16.6 THz frequencies, which are within the bandwidth of the Plasma-Cascade Amplifier (PCA) *
- ✓ This system would allow us to evaluate both the gain and the spectrum of PCA

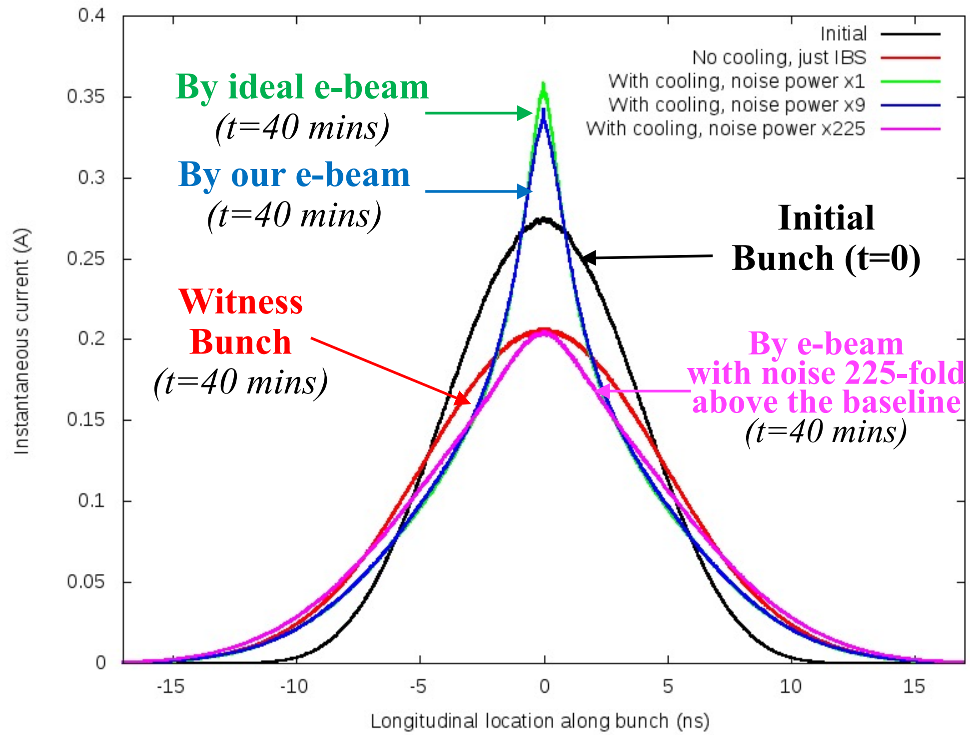
Note: **PCA gain peaks at 16 THz. In Runs 20-21 we used IR radiation from bending magnet, which peaks at 0.8 THz and is complete mismatch for the PCA*

Our predictions did not change

Predicted evolution of the 26.5 GeV/u ion bunch profile in RHIC in 40 minutes



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



Black – initial profile (t=0)
Red – witness (non-interacting) bunch at t=40 mins

Interacting bunches for various levels of noise in the e-beam: Green– nominal statistical shot noise (baseline)
Dark blue – 9 fold above the baseline
Pink – 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

Plan for Run 22 includes <u>optimizing for STAR data taking</u>

- We followed recommendations RHIC Program Advisory Committee:
  - **Early completion of the CeC X to allow STAR using of increasing RHIC performance towards the end of RHIC run**
  - **36-hrs blocks of dedicated time reduce loss of time for RHIC switching between pp to Au-ion operations**
- Plan for CeC Run 22 with16 days of dedicated time was fully developed. Delay with the RHIC start-up cause modification to the plans
  - Restore operation of CeC accelerator – in progress
  - Establish electron beam KPP (including low energy jitter) – in progress
  - Align electron and ion beams trajectories and γ-factors – just starting
  - Restore operation of the high-gain Plasma-Cascade Amplifier
  - Attempt to demonstrate/investigate longitudinal CeC
  - Decision point: continue investigate longitudinal CeC or switch to 3D cooling CeC studies
- Key improvements to the CeC operations in Run 22:
  - New seed laser for reduced time jitter improving the electron beam energy stability
  - Strengthen CeC operation group by adding some scientists from LEReC group

Plans for Run 23

- We would like 2 weeks of dedicated time to demonstrate 3D (both longitudinal and transverse) CeC
- This cooling will be obtained by shifting electron beam orbit in kicker by ~ 3/4 of the hadron beam size and adjusting arrival time of the micro-bunching peak by ~20% of it's width.
- With hadron beam horizontal dispersions ~ 1 m in the kicker, this condition will provide for about equal splitting cooling between horizontal betatron and longitudinal oscillations
- Cooling of vertical emittance will be done by adjusting coupling between horizontal and vertical degrees of freedom
- Run 23 will be very challenging - competing for RHIC time with sPHENIX – but this will be best chance for CeC experiment to demonstrate 3D cooling

Summary

- Project remains on schedule and on budget
- Damage to the SRF gun and laser timing jitter impeded demonstrating longitudinal CeC during Run 20.

  New low-jitter laser has arrived. It was installed and is operating.
- CeC X retreat was very successful – we plan to repeat it next year
- We developed detailed plan with 16 days of dedicated time for Run 22 for RHIC Run 22.
- We adjusting it to evolving RHIC start-up schedule with goal to accomplish as many tasks as possible
- **Our goal is to demonstrate the longitudinal CeC during Run 22 and 3D CeC in Run 23**
- Main remaining concern
  - COVID-19 and its effect on the schedule
  - Short RHIC runs may affect dedicated time available to CeC
- We continue developing theory and 3D CeC simulations:
  - CeC X: PCA amplitude gain 100, bandwidth 15 THz
  - Alternative EIC CeC: PCA amplitude gain 400, Bandwidth 500 THz

Thank you for attention