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

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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Vladimir N Litvinenko for the CeC group:

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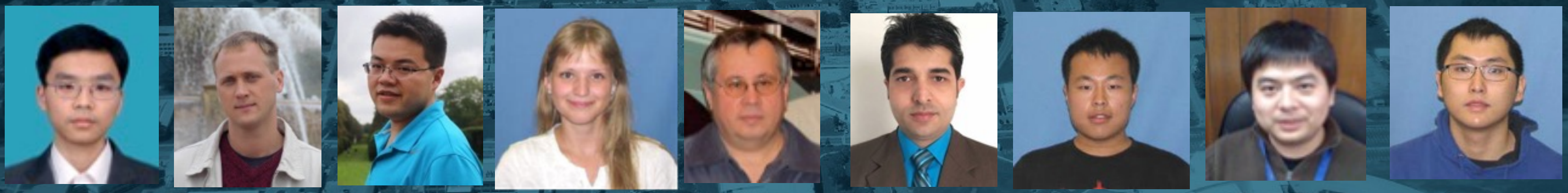


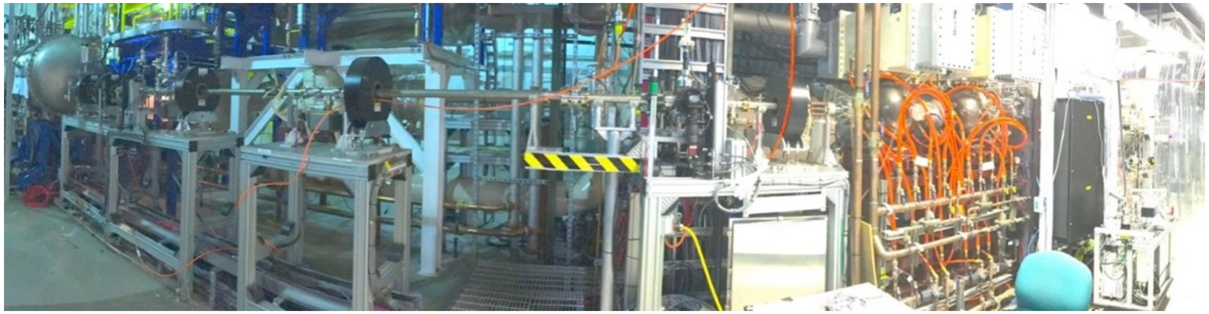
Brookhaven National Laboratory and Stony Brook University

RHIC retreat, September 16, 2021

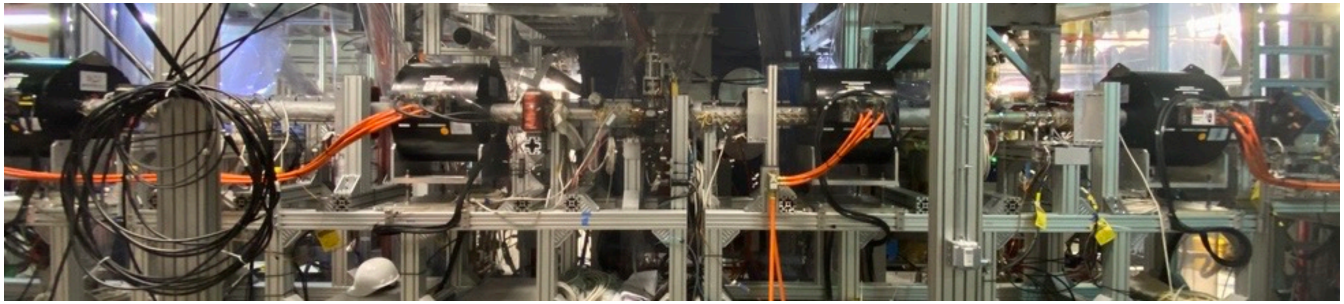
Content

- ❑ Why CeC X is important
- ❑ Run 21 achievements and results
- ❑ Remaining challenges
- ❑ Summary from CeC-X retreat

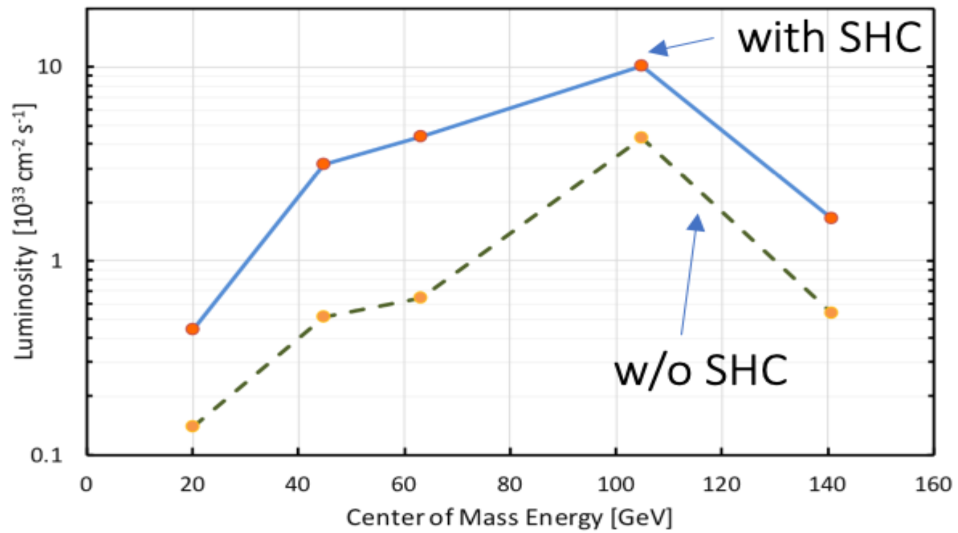
CeC X accelerator



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.*

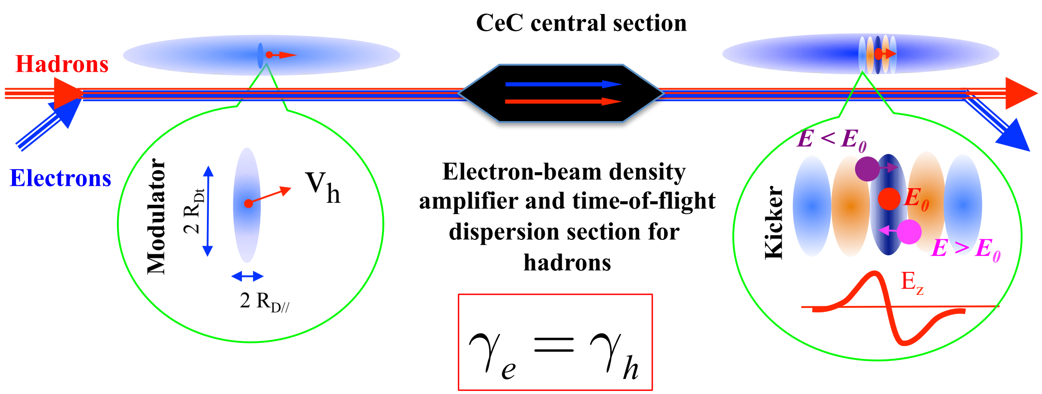
Quote from the pCDR review committee report:

"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

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

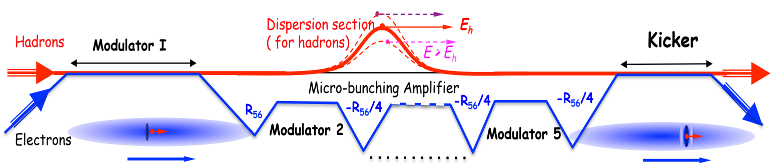
Microbunched Electron Cooling for High-Energy Hadron Beams

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

What can be tested experimentally?

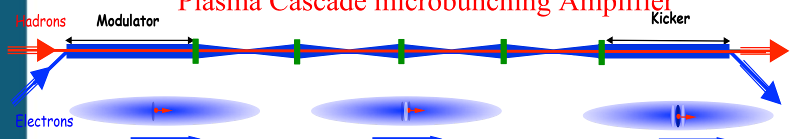
Litvinenko, Derbenev, PRL 2008

Ratner, PRL 2013

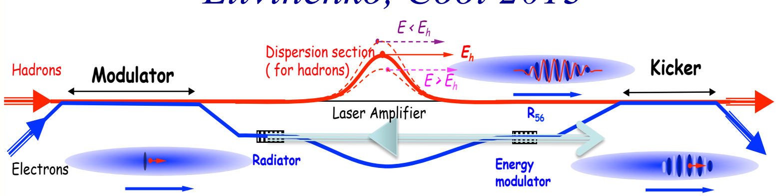


Litvinenko, Wang, Kayran, Jing, Ma, 2017

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

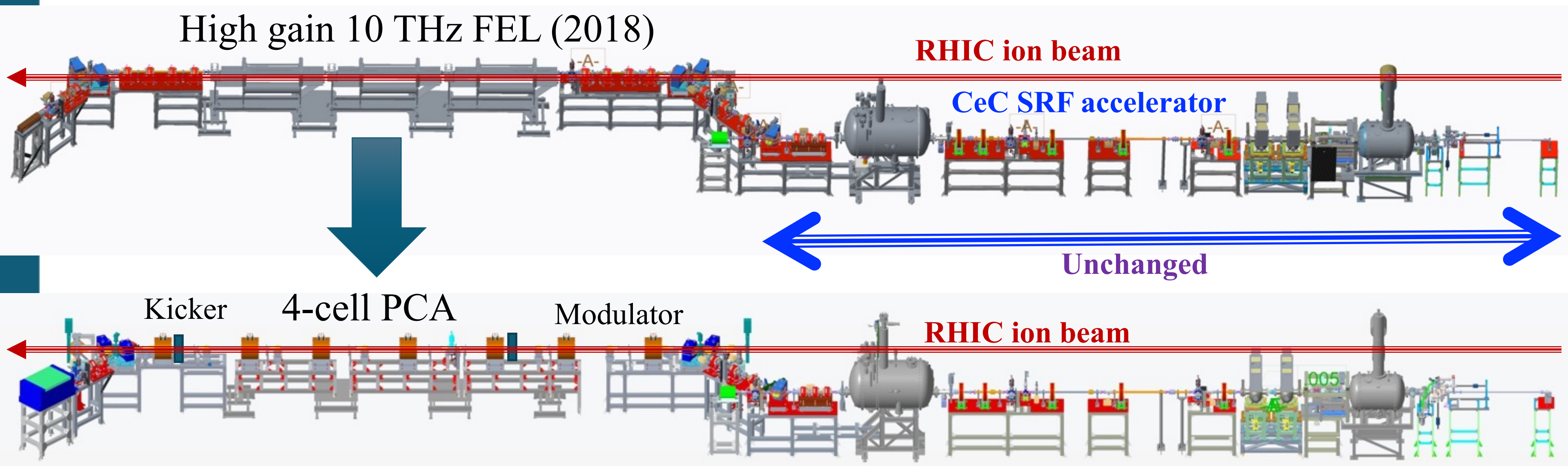
Plasma-Cascade Amplifier

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

Derbenev is suggesting to explore CSR as an CeC amplifier

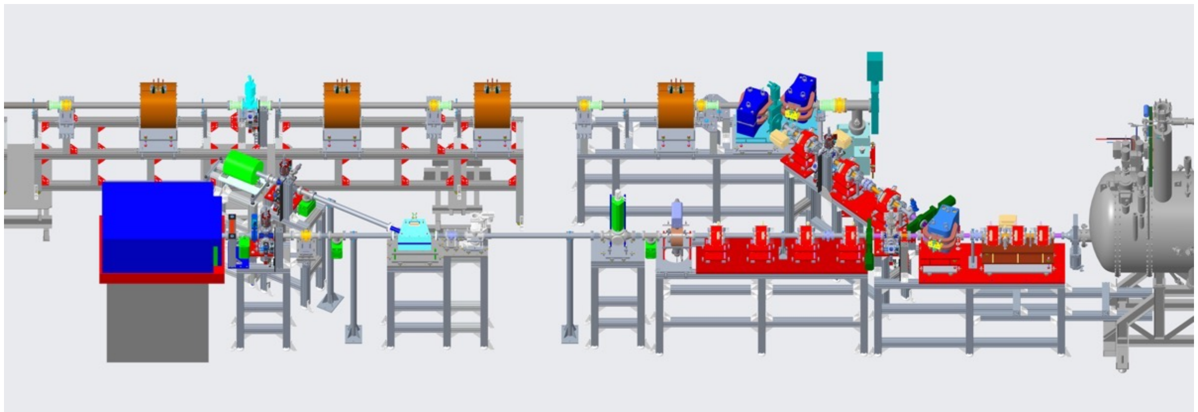
CeC X at RHIC

- 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.



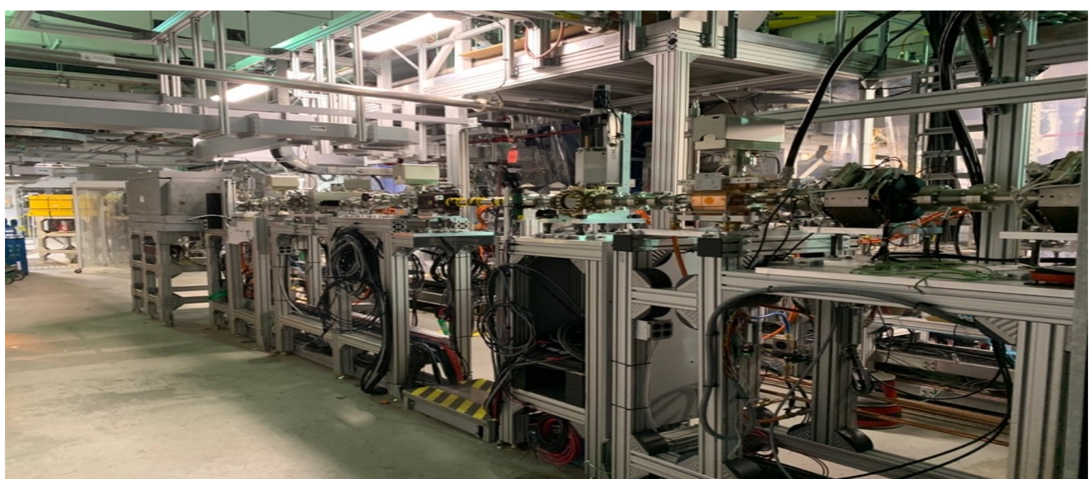
The CeC Plasma Cascade Amplifier has a bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

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

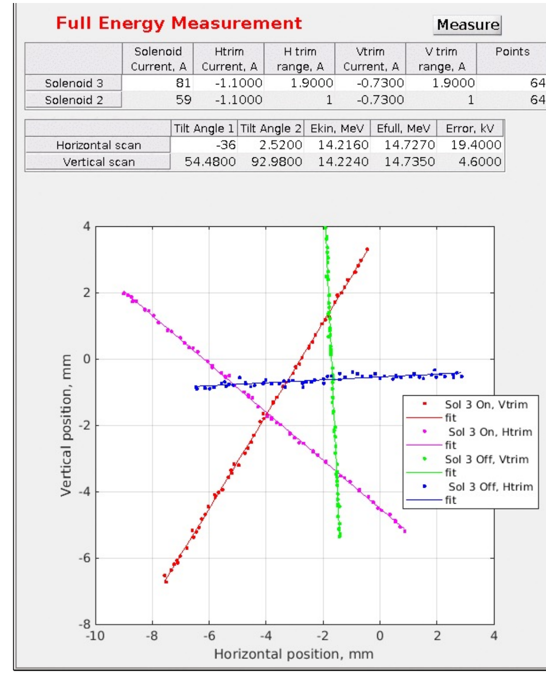
Milestone ID	Reportable milestone	Date
1	Experiment start	FY20Q1 ✓
2	Necessary Beam Parameters (KPP) established for Run 20	FY21Q4 ✓
3	Investigation of plasma cascade amplifier complete	FY21Q4 ✓
4	Investigation of the ion imprint in the electron beam complete	FY22Q1 ✓
5	Receive Approval for CeC TRDBL 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

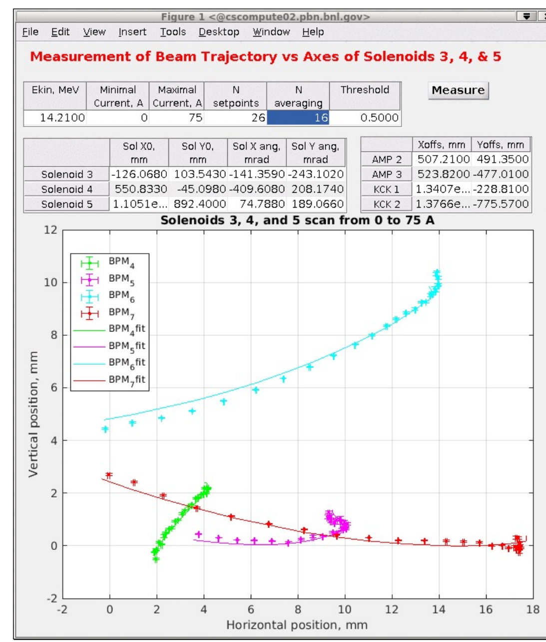
Electron beam KPP

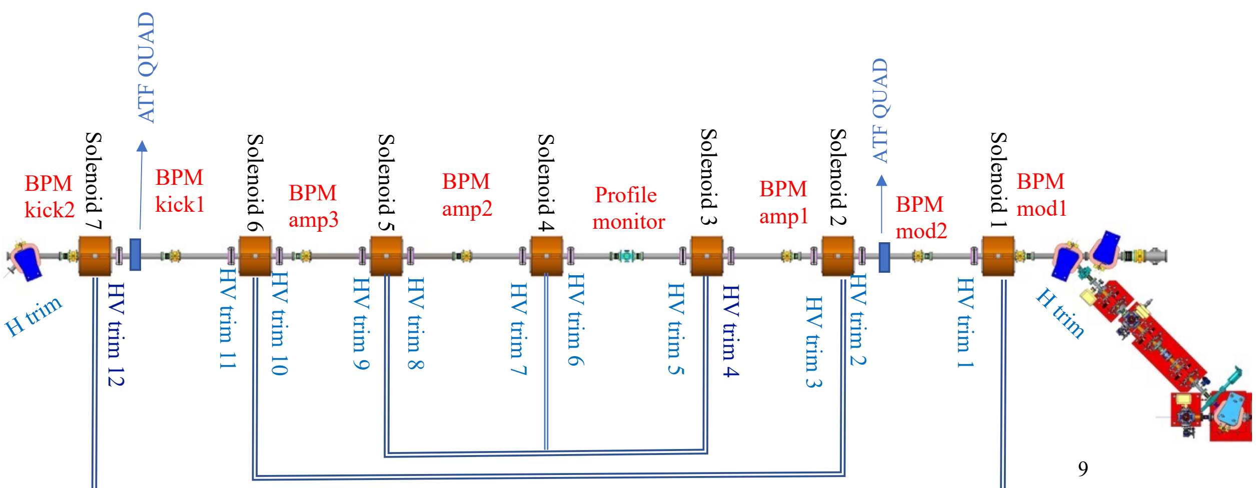
Parameter	Planned	Demonstrated	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the Poison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

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

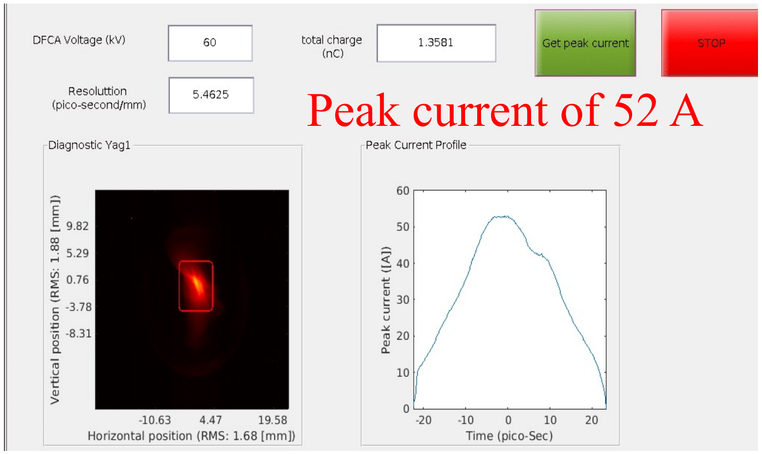




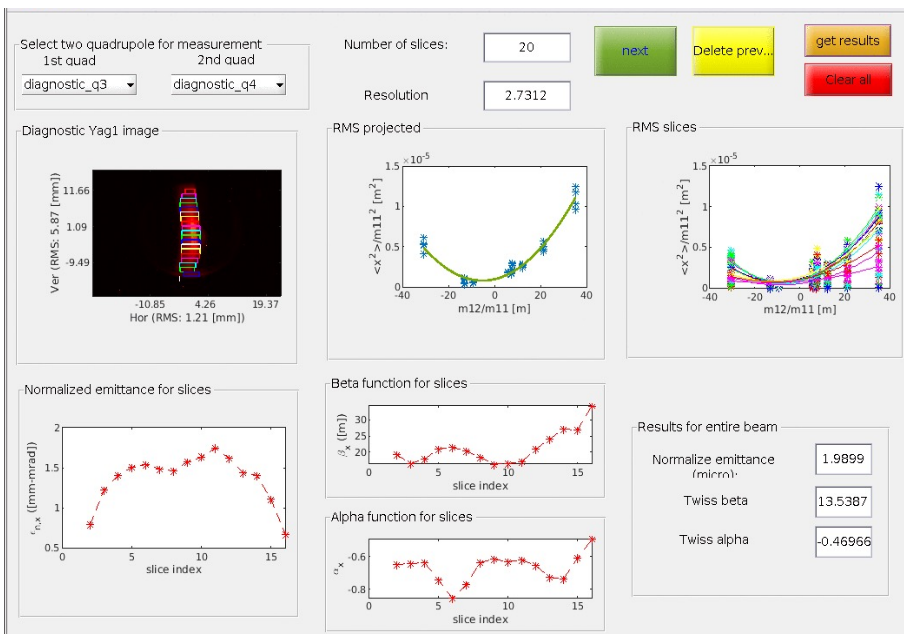


Time-resolved measurments

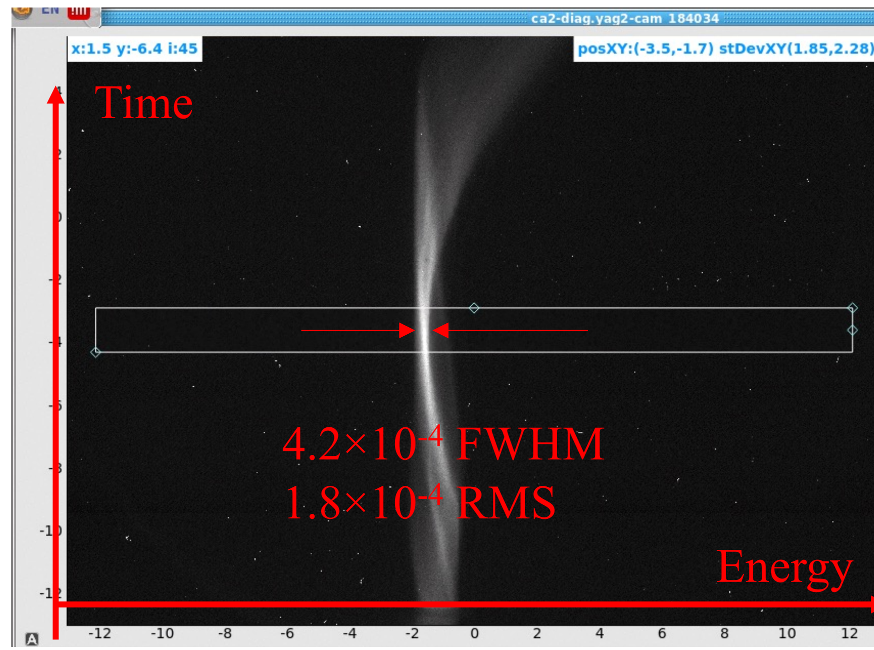
Direct pass



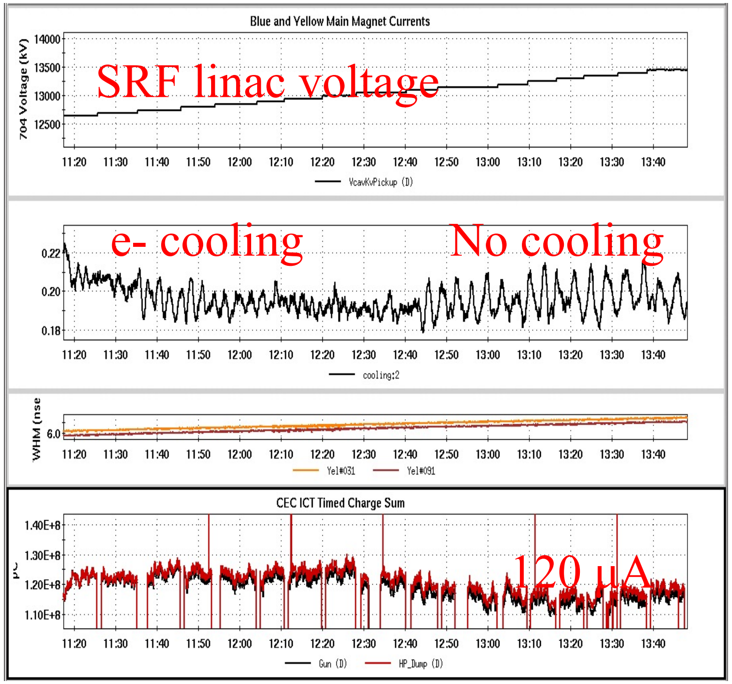
Slice emittance measurements



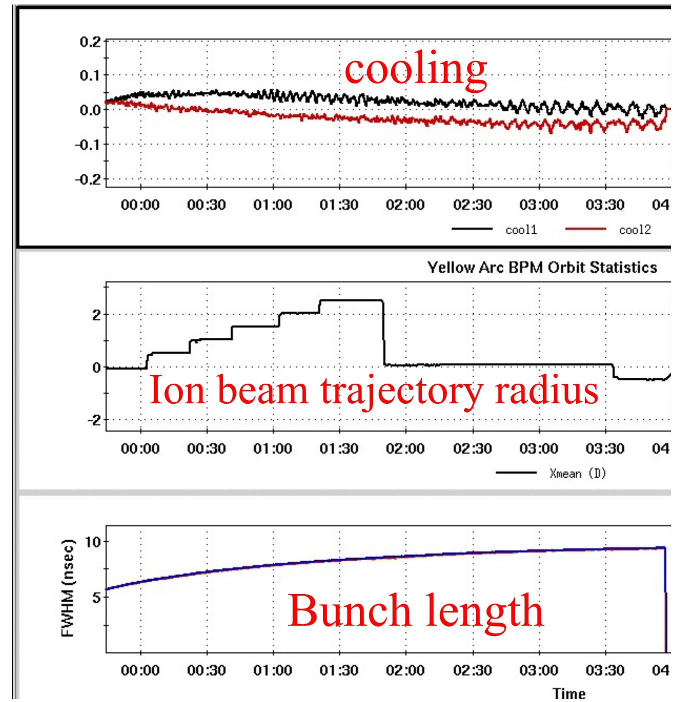
30-degree energy spectrometer



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

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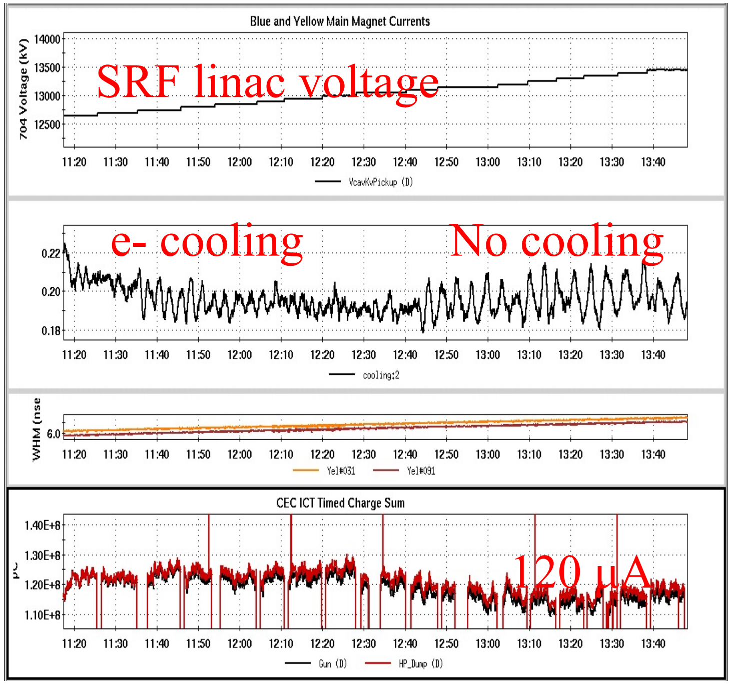
Search for CeC signature and observation of regular bunched electron cooling of 26.5 GeV/u ion beam



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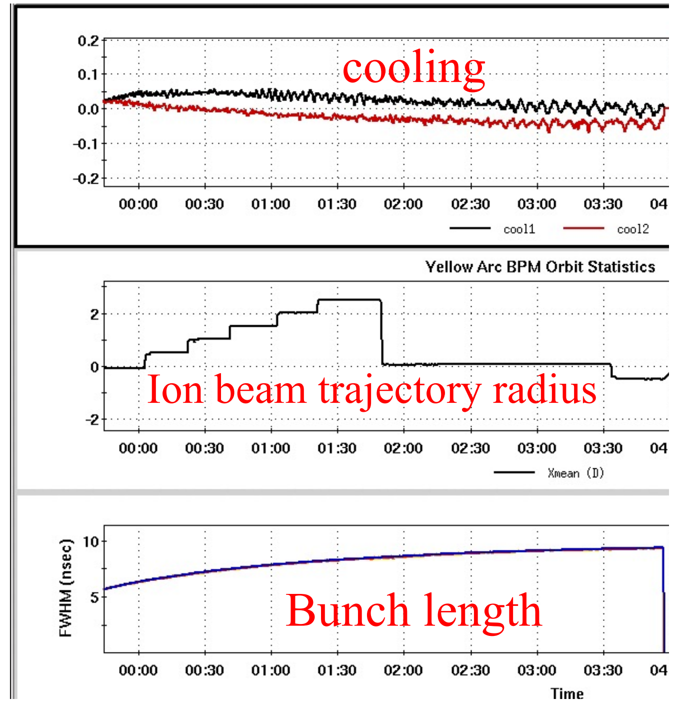

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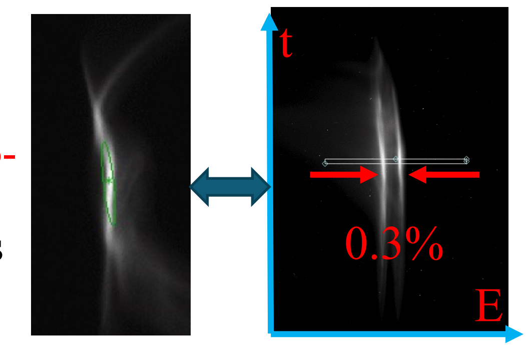
Major set-back and remaining challenges

- We lost at least 7 weeks of operation from severely damage to our the SRF gun - <u>it was not the result of operations performed by the CeC team</u>. 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 <u>is critical</u> 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"



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...

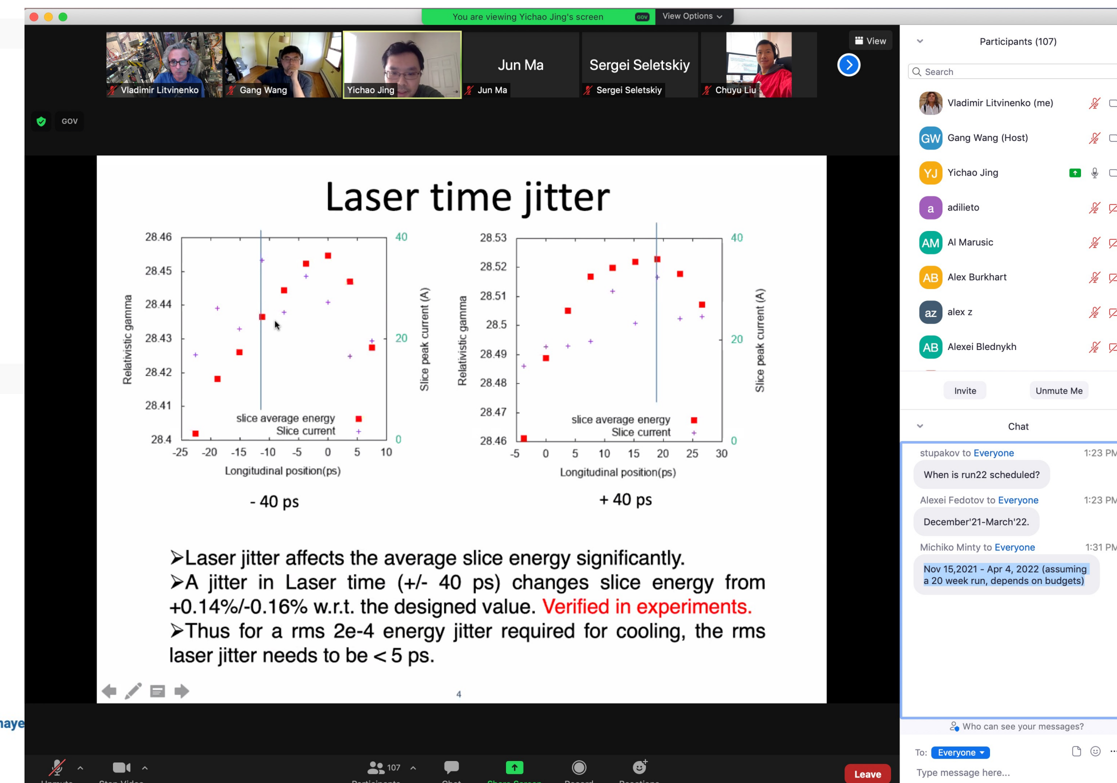
3:50 PM → 4:10 PM **Orbit-drifts, noise/jitter, accuracy, slow feed-backs (R. Michnoff, P. Thieberger, A. Di Lieto)**
Speaker: Igor Pinayev (BNL)
Orbit.pdf | Orbit.pptx

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
  - ❑ to remaining problems and
  - ❑ to identify solutions of the mail problems
- ❑ In addition, we discussed improvement of the CeC systems during RHIC shut0downs

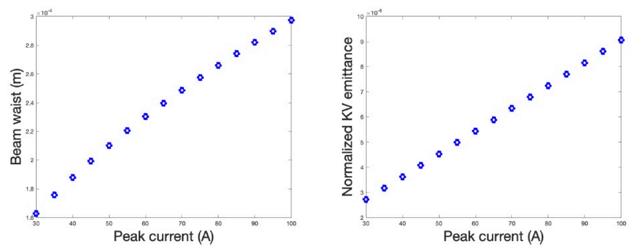


Defining requirements for e-beam and CeC system

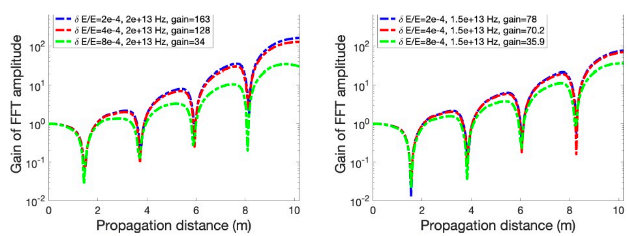
Jun Ma & team

Electron Beam Requirements for CeC Experiment

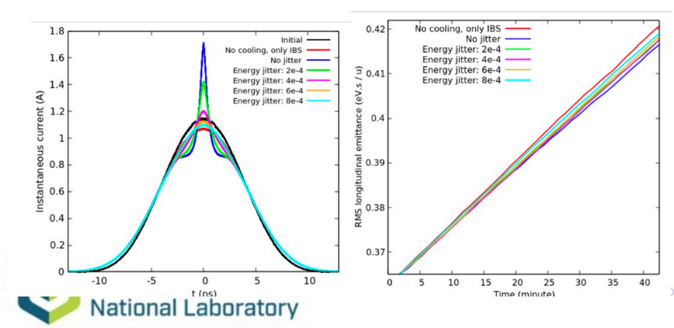
Sensitivity studies: energy spread & peak current, beam emittance and asymmetry, matching, orbit distortions, energy jitter



(a) a_o (b) ε_n



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



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

Main findings and proposed 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

Proposed Solution

- Replace the seed laser with new having timing jitter ~ 5 psec
- Develop energy measurements system and use it for slow feed-back to compensate these drifts
- Task force
  - searching for the sources of the noise
  - use insulating amplifiers
- Repair and commission cryo-cooled IR detector

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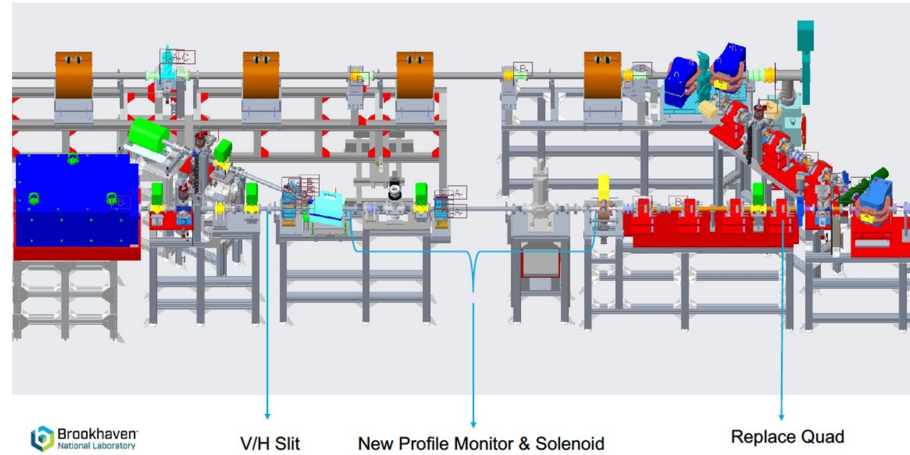
Jean Cliff Brutus: Improvements to the CeC

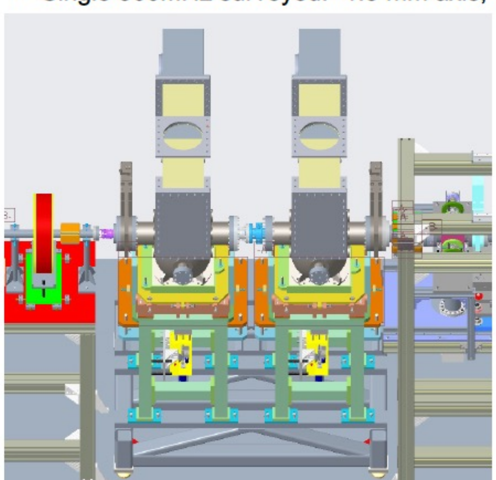
CeC Shutdown 2021 Upgrades

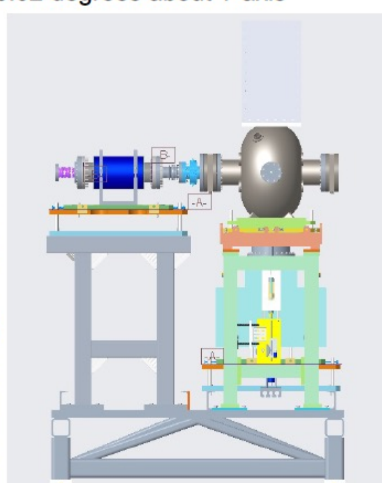
#	Work
1	500 MHz Removal
2	Horizontal/Vertical Slit
3	Profile Monitor
4	Cathode System Upgrade
5	Replace Q1 in the TRDBL by one with working trim coils - in current quad two out of 4 trim coils are broken
6	500MHz Coax Inspection
7	DCCT
8	Solenoid
9	H/V Trims relocation
10	Wiggler/Undulator
11	Heating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



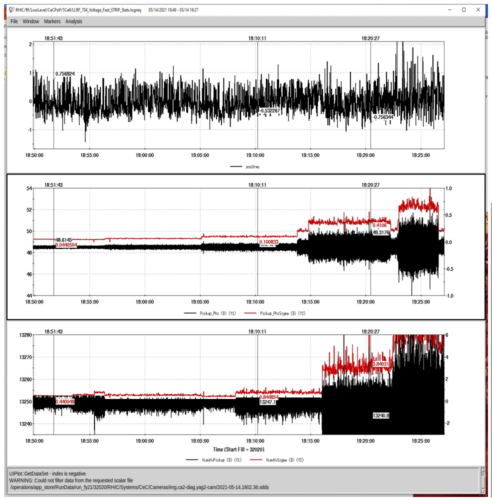


Summary

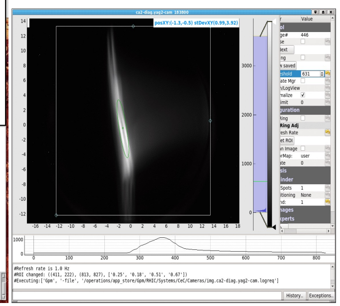
- Priority list
- Anthony is checking if we need to run new cable and order more PS for new compensating coils and H/V trims 8-12 weeks lead time
- Design modifications of beamline completed
- 500MHz removal completed
- Damaged quad replacement completed
- 500MHz coax inspection in progress
- Heating 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

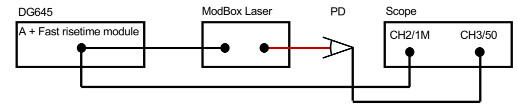
-Feedforward to correct phase steps

-Fast feedback to correct measured drifts

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

Temporal Jitter Performance

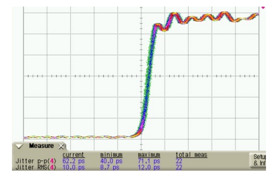
In-House Measurement

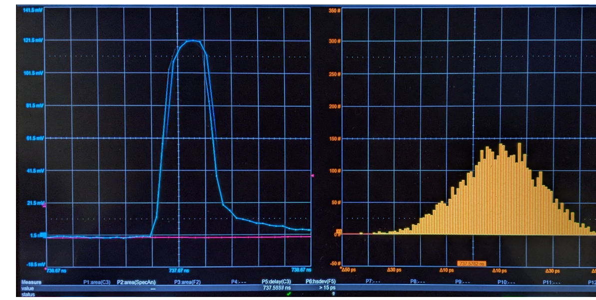


Jitter Measurement performed using a local delay generator and Oscilloscope
- Result: 14-15ps rms

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)

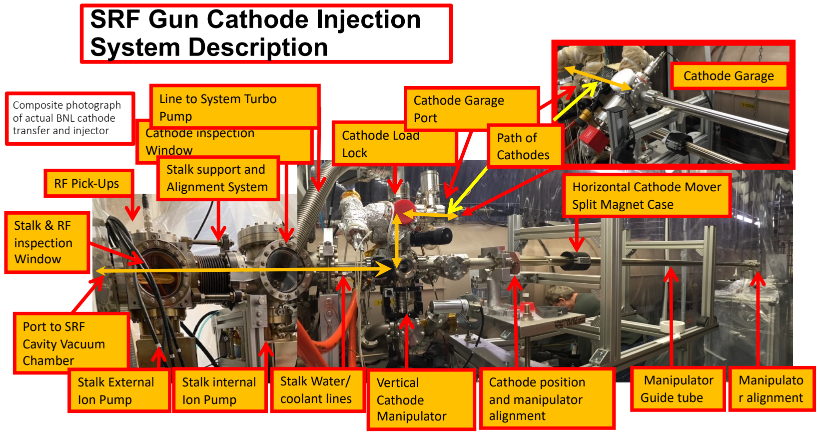
The Shot-Noise of the free-running laser was deemed to large, making a fast intensity feedback necessary

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

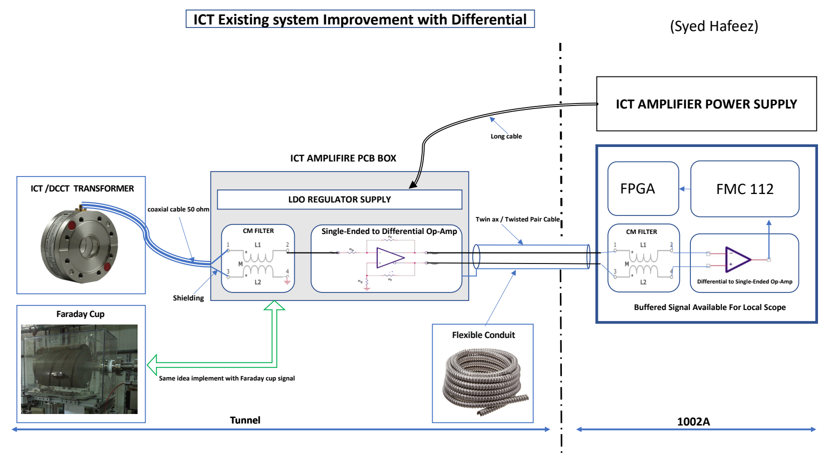
All new transfer systems components will be completed and ready for installation in early October cathode injection in early November.

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

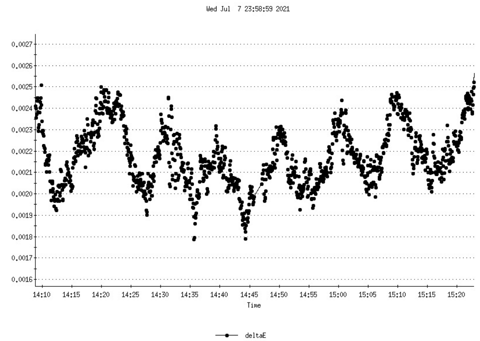
Uses triplet BPM and 1st modulator BPM for measurement of the incoming beam trajectory.

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

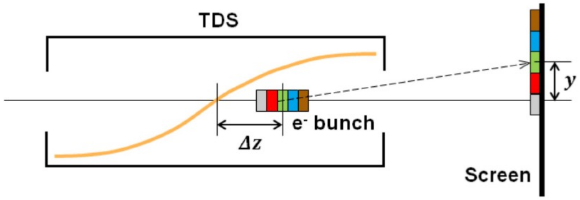


Table 1 key beam parameters of CEC 1.5nC operation

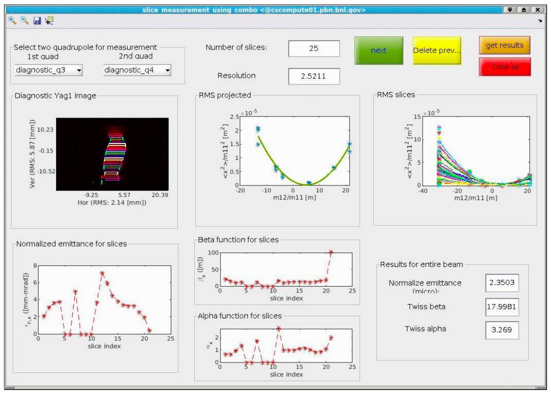
parameter	Symbol	Value	Unit
Beam size at yag without Deflecting cavity		~0.4	*mm*
Beta function at screen		0.1	*m*
Normalized rms emittance		~1.5	*mm-mrad*
Beam energy at deflector		14.5	*MeV*
Beam energy at screen		14.5	*MeV*
bunch length (edge to edge)		~30	*ps*

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

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 retreat was very successful – we plan to repeat it next year.
- **Let's make CeC happen!**

The CeC team – never can get all your pictures …

Back-up slides

Plan for Run 21

Dedicated time

- Measure and align solenoid's axes with ion beam
- Establish CeC operation mode and lattice with 75 A peak current
- Measure e-beam beam parameters (including slices) and time and energy jitter using TRDL
- Propagate beam through CeC section and establish the e-beam orbit (including Earth comp coil)
- Measure energy stability and establish slow energy feed-back
- Re-establish high gain PCA lattice and measure the gain
- Re-establish recombination measurements and identify overlap in relativistic factors
- Search for signature of Coherent electron Cooling
- If successful, investigate and optimize CeC

Parallel with RHIC p-p stores

- Restore CeC accelerator operation and develop parallel mode of operation (compensation of RHIC stay fields)
- Use this mode to commission new featured of the time-resolved diagnostics beamline
- Establish co-propagation of the e-beam through IP2
- Use this mode for PCA optimization and improving beam transmission
- Measure energy jitter and drifts

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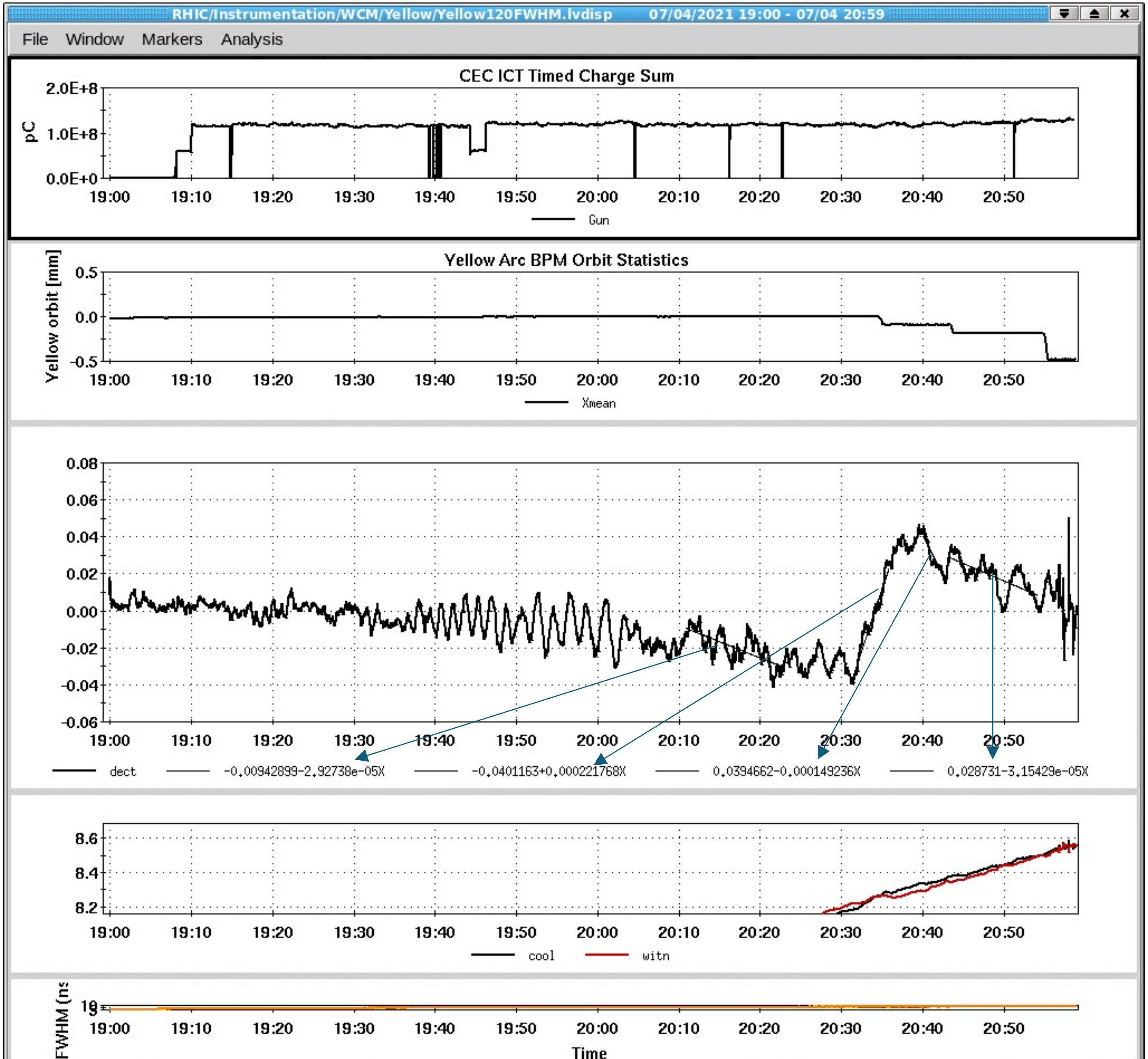

31 new calculated point(s) successfully added to dataset
Done updating plot 3 for calculations.