Coherent electron Cooling experiment at RHIC

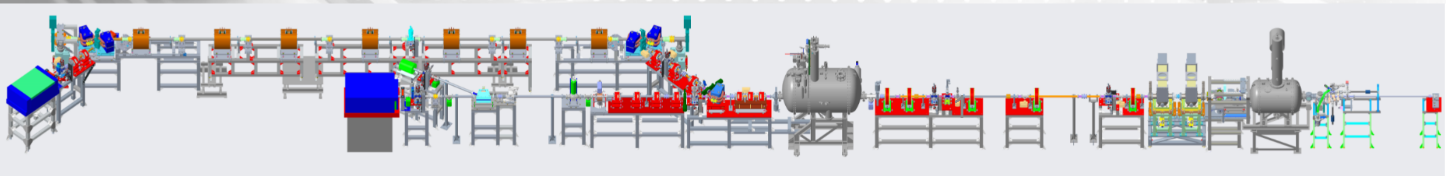
Vladimir N Litvinenko for the CeC project team

RHIC Virtual One-Day Site visit

September 15, 2020

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY



Why we doing this?

- 2018 NAS 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****.*
- April 2018 eRHIC pCDR review committee report:

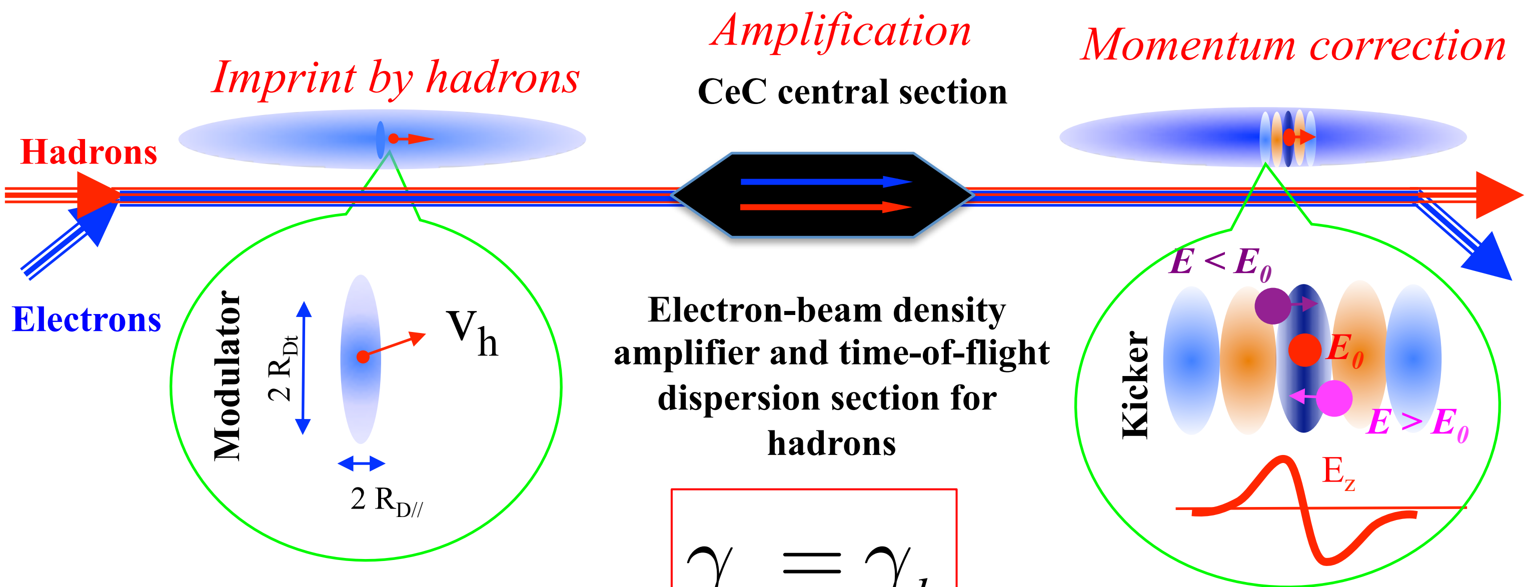
"***The major risk factors are strong hadron cooling*** *of the hadron beams to achieve high luminosity, and the preservation of electron polarization in the electron storage ring*. **The Strong Hadron cooling [Coherent Electron Cooling (CeC)] is needed to reach 10^{34}/(cm^{2}s) luminosity**. ***Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC***."

In short: CeC is critical for EIC to reach luminosity of 10^{34} cm^{-2}s^{-1} by boost it from 4- to 10-fold

Do we have report from the "EIC options" review? Will be useful to add it here…

What is Coherent electron Cooling

- Short answer – stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 10 – 10,000 THz



$$\gamma_e = \gamma_h$$

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

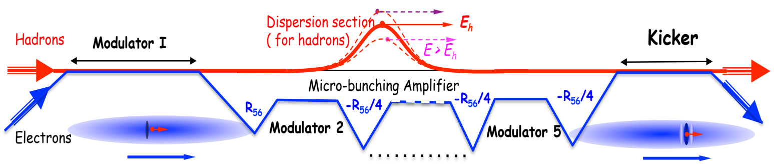
Coherent Electron Cooling

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)

What can be tested experimentally?

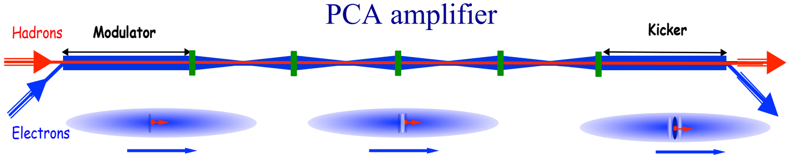
Litvinenko, Derbenev, PRL 2008

Ratner, PRL 2013

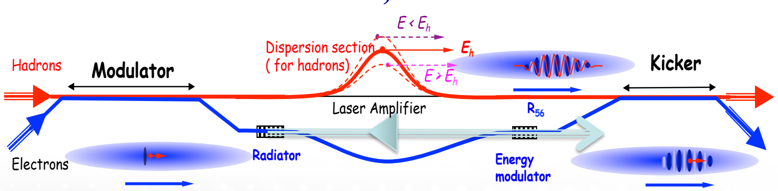


Litvinenko, Wang, Kayran, Jing, Ma, 2017

PCA amplifier



Litvinenko, Cool 2013

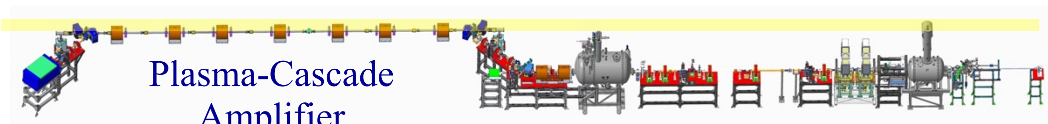


RHIC Run 18

High gain FEL amplifier with low-a_w wigglers

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

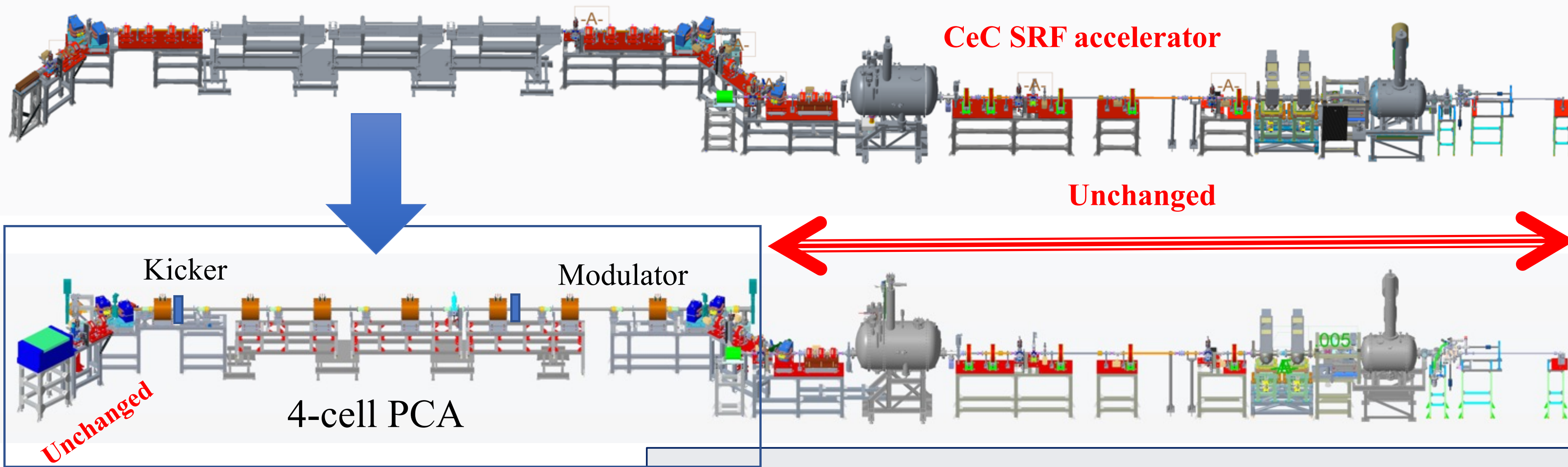
RHIC Runs 20-22



Plasma-Cascade Amplifier

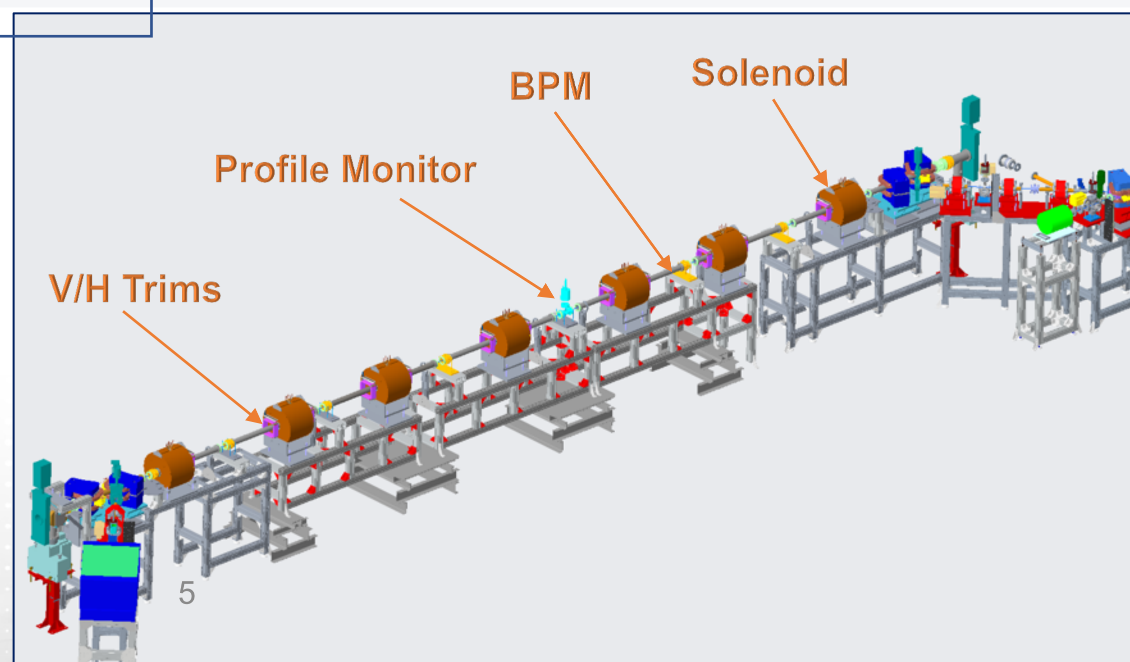
Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

CeC with Plasma-Cascade micro-bunching Amplifier (PCA)



The PCA bandwidth is 20 THz

>2,000x of the RHIC stochastic cooler



CeC project

Early completion – December 2022
Schedule contingency – 12 months
Total Project Cost: $2.2M + $0.8M Contingency

- **NPP Directorate**
  Berndt Mueller
  Associate Laboratory Director
  Maria Chamizo-Llatas
  Director Office
  Project Planning and Oversight
  - **C-AD Department**
    Thomas Roser
    Chair
    - **CeC experiment**
      Vladimir N Litvinenko
      Project Director
      Jean Clifford Brutus
      Project Manager
      - **ESSHQ**
        Lee Hammons
        C-AD/NPP COO
      - Procurement - **Ann Lamberti**
        Business Operations – **Cris Manalo**
        Project Controls - **Khianne Jackson**
      - **CeC Operations**
        Igor Pinayev
        Project Scientist
        - **RHIC OC**
          CeC operations
        - **CeC support**
          C-AD Engineers
      - **CeC**
        Jean Clifford Brutus
        Project Engineer
        - **Design**
          C-AD Engineers and
          C-AD Designers
        - **Installation**
          C-AD Engineers and
          Technicians

REPORTABLE MILESTONES

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

CeC Overview

TPC	Project Leader	Last CD Achieved	% Complete	CPI	SPI
$3M	Vladimir Litvinenko	N/A	30%	N/A	N/A

Coherent electron Cooling (CeC) experiment

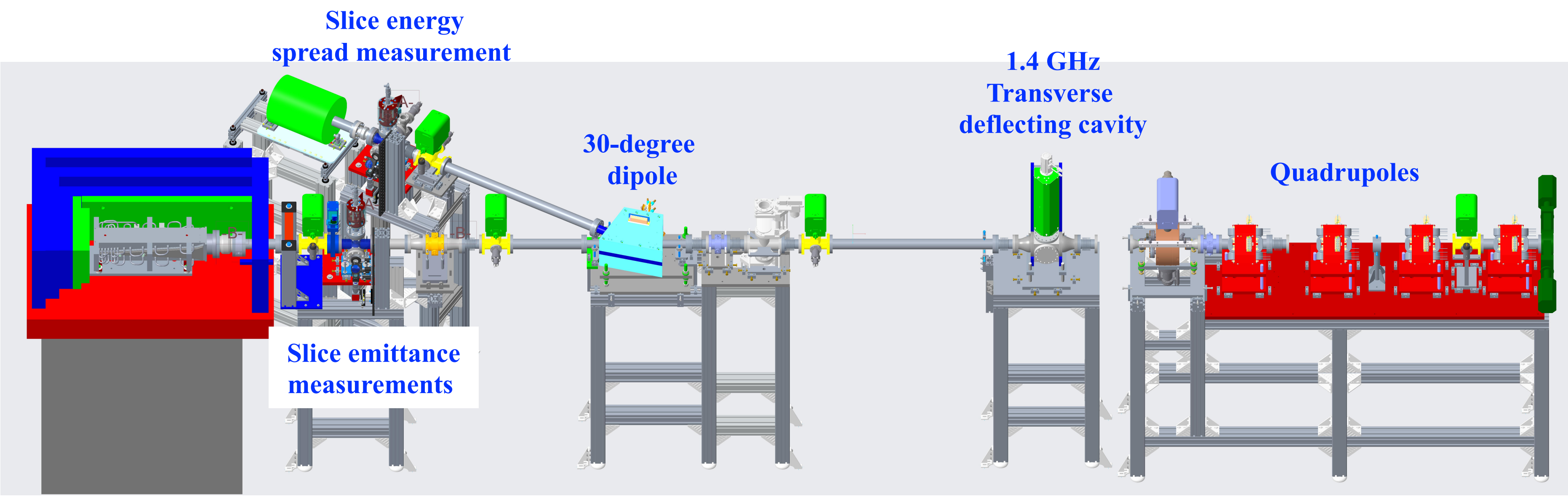
- Scope, Deliverables
  - Total Project Cost: $2.2M + $0.8M Contingency
  - Restored operation of the CeC accelerator, FY20 Run – **100%**
  - Completed design of the time-resolved diagnostic beamline – **100%**
- Schedule, Float
  - Project Start: 12/1/2019
  - Project Early Finish: 9/30/2022
  - Project Completion: 9/29/2023
  - Schedule Contingency: 1 year

Activity Type	Baseline Complete Date	% Complete Baseline	% Complete Actual
Design	11/2020	86%	67%
Procurement	09/2020	93%	60%
Construction	11/2020	13%	10%
Operations	09/2022	25%	27%

- Cost, Contingency as of 7/31/2020
  - Spent on material and trades labor: $994k
  - Procurement commitments, $421k
  - No use of contingency to date

Time-resolved Diagnostics Beamline Design

- This beamline is the most important addition to the capabilities of the CeC project – it will allow to measure the critical slice beam parameters (peak current, energy spread and emittances) with resolution of 1 psec
- The beam-line is the main cost item of the project and its timely installation and commissioning is critical for the next stage of the project
- The design of the beam-line is 100% complete and installation is scheduled for this RHIC shut-down



CeC Recent Accomplishments

- Key experimental accomplishments:
    - Milestone CEC11030: Necessary Beam Parameters (KPP) established for Run 20
    - Commissioning of the common section with 7 high field solenoids is completed
    - Observed strong amplification in Plasma Cascade Amplifies – the key process in microbunching CeC. Data is under detailed analysis.
    - Fault studies for new mode of operation parallel with RHIC stores had been approved and performed. The results proved that this mode of operation is safe – after reviews this new mode of operation is approved.
    - Design of time-resolved beamline is completed
    - The ion imprint studies are in progress
    - Procurements of the key components for the time-resolved diagnostics beamline continue
- We continue simulation of the beam-dynamics and CeC performance ~ 50%

Table 2-1: Electron beam KPP

Parameter		
Lorentz factor	28.5	✓
Repetition frequency, kHz	78.2	✓
Electron beam full energy, MeV	14.56	✓
Total charge per bunch, nC	1.5	✓
Average beam current, µA	117	✓
Ratio of the noise power in the electron beam to the Poison noise limit	<100	✓
RMS momentum spread $\sigma_p = \sigma_p/p$, rms	$\leq 1.5\times10^{-3}$	✓
Normalized rms slice emittance, µm rad	≤ 5	✓

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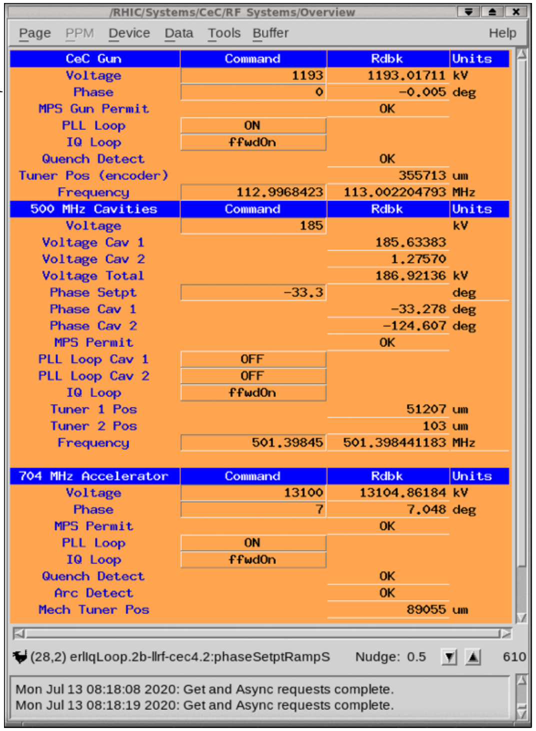
Accelerator system and Beam energy - ✓

- According to the simulation using magnetic measurements results: the dipole current should be 93.9 A for γ=28.5, pc=14.5545 MeV
- An approximate ration between *pc* and dipole current is: 0.155 MeV/A, e.g.
- pc[MeV]=0.15500*I[A].

Description	Max Curr [A]	Curr Stpt[A]	Curr Rdbk [A]
Triple Quad 1	6.4	0	0.00004
Triplet Quad 2	6.4	0	0.00003
Triplet Quad 3	6.4	0	-0.00007
First Dipole PS	112	96.2	96.20018
Dog Leg Quad 1	6.4	0	-0.00011

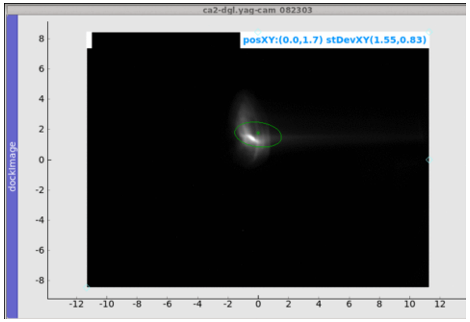

/RHIC/Systems/CeC/RF Systems/Overview

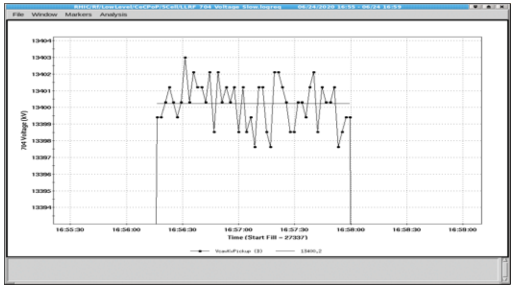
Page PPM Device Data Tools Buffer Help

CeC Gun	Command	Rdbk	Units
Voltage	1193	1193.01711	kV
Phase	0	-0.005	deg
MPS Gun Permit		OK	
PLL Loop	ON		
IQ Loop	ffwdOn		
Quench Detect		OK	
Tuner Pos (encoder)		355713	um
Frequency	112.9968423	113.002204793	MHz
500 MHz Cavities	**Command**	**Rdbk**	**Units**
Voltage	185		kV
Voltage Cav 1		185.63383	
Voltage Cav 2		1.27570	
Voltage Total		186.92136	kV
Phase Setpt	-33.3		deg
Phase Cav 1		-33.278	deg
Phase Cav 2		-124.607	deg
MPS Permit		OK	
PLL Loop Cav 1	OFF		
PLL Loop Cav 2	OFF		
IQ Loop	ffwdOn		
Tuner 1 Pos		51207	um
Tuner 2 Pos		103	um
Frequency	501.39845	501.398441183	MHz
704 MHz Accelerator	**Command**	**Rdbk**	**Units**
Voltage	13100	13104.86184	kV
Phase	7	7.048	deg
MPS Permit		OK	
PLL Loop	ON		
IQ Loop	ffwdOn		
Quench Detect		OK	
Arc Detect		OK	
Mech Tuner Pos		89055	um

(28,2) erlIqLoop.2b-llrf-cec4.2:phaseSetptRampS Nudge: 0.5 610

Mon Jul 13 08:18:08 2020: Get and Async requests complete.
Mon Jul 13 08:18:19 2020: Get and Async requests complete.





- **Maximum energy with this setting is 14.92 [MeV], γ=29.2, 2.5% above γ=28.5**
- **Linac has additional 2.2% head room to operate at 13.4 MV**

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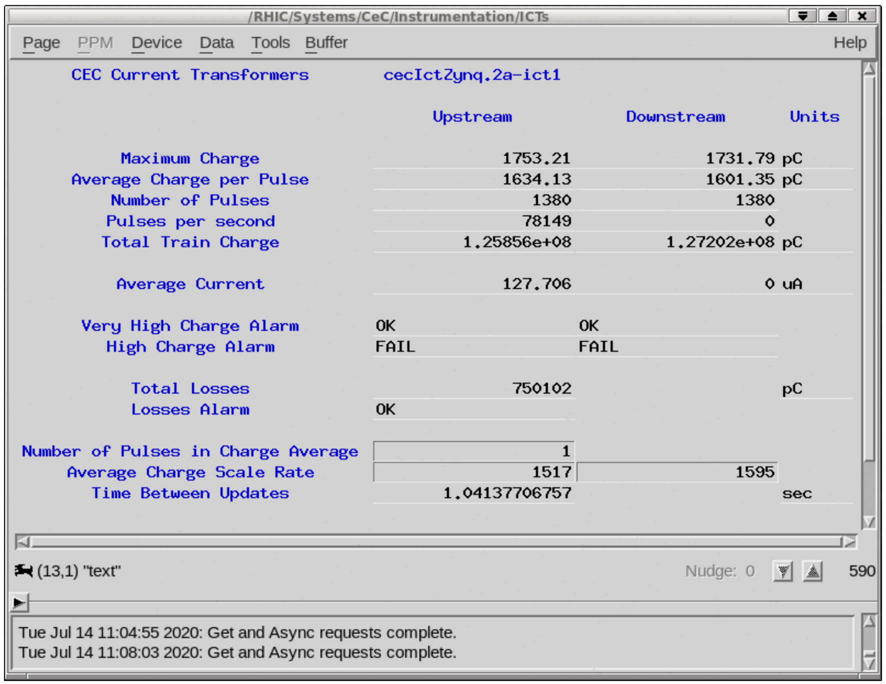
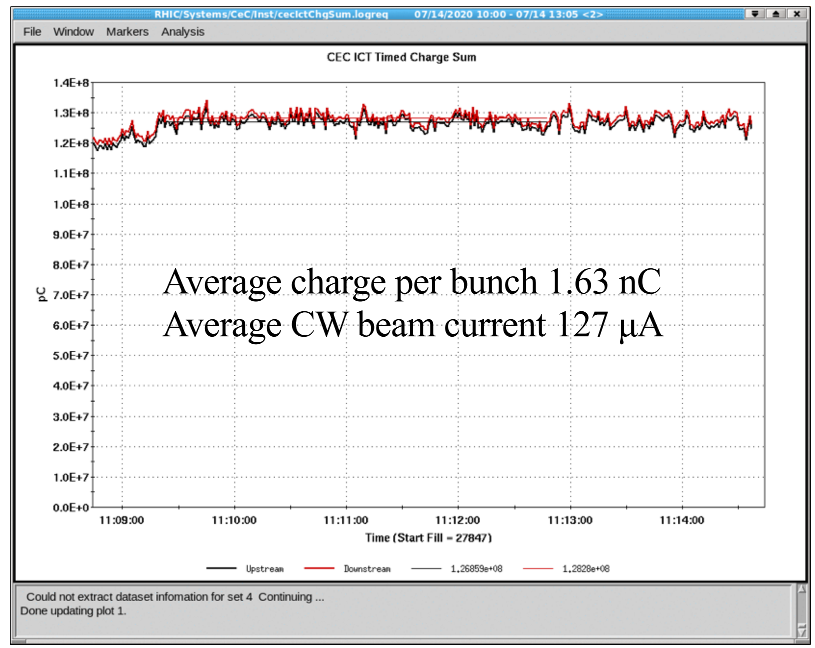
Charge per bunch and CW beam current

✓





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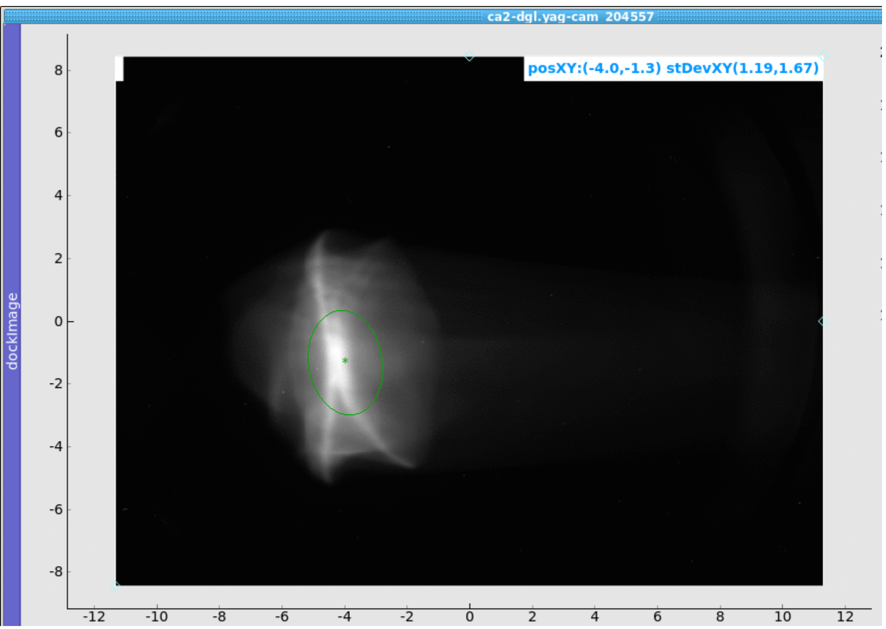
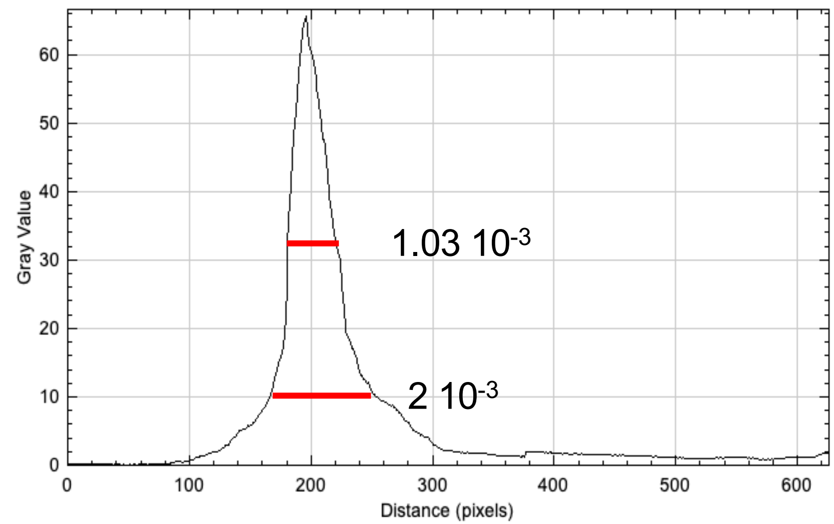
Full beam energy spread

YAG screen in the dogleg: no quadrupoles, D_h=1.3 m

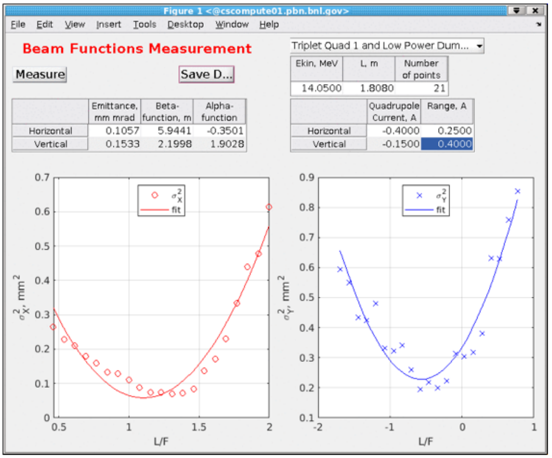


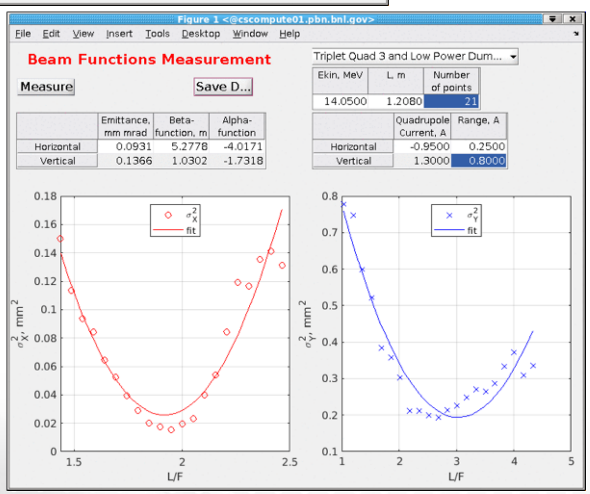


Scaling: 31 pixels per 1 mm, FWHM energy spread is 1.03 10^{-3};

RMS energy spread is 4.4 10^{-4}

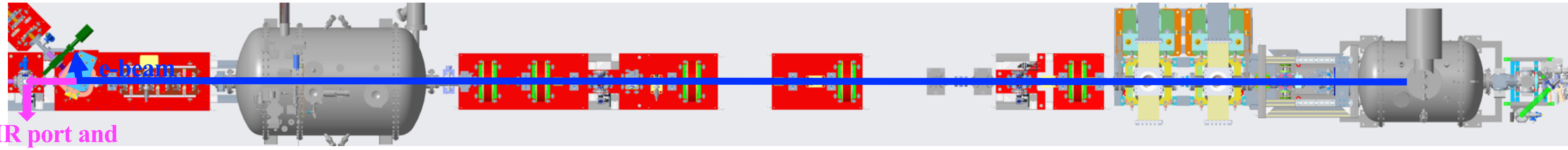
Projected emittances





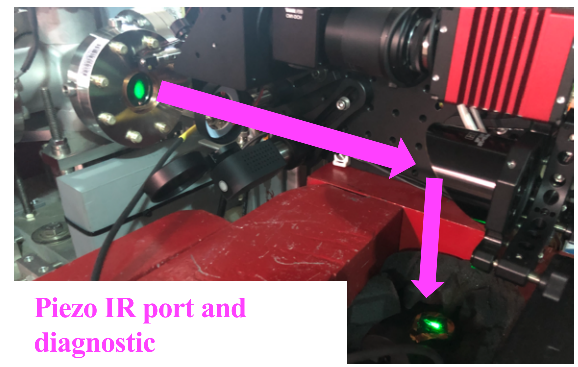
- **Projected emittances** are, by definition, larger than **slice emittances.**
- Plot shows measured geometrical projected emittance, which are $\gamma\beta\sim 28.5$ times smaller than normalized values
- Measured values of horizontal normalized emittance are 2.8 ± 0.2 mm rad and for the vertical normalized are 4.3 ± 0.6 mm rad.
- **Slice emittances definitely satisfy the KPP.**

The e-beam noise level ✓



IR port and diagnostic

- Beam noise in the electron beam was evaluated using technique established during Run 19
  - The THz beam noise power was measured using power of IR radiation from the first dipole magnet. The dipole was excited by current of 110 A current and bended the e-beam by 52.5 degrees into the dipole vacuum chamber. The IR power was measured by the Gentec broad-band IR detector connected to a lock-in amplifier synchronized with pulsing electron beam.
  - IR radiation from the bending magnet was periodically blocked, e.g. we used modulation-demodulation technique to eliminate effect of X-rays from dumped beam on the IR detector (very important!)
- The baseline power level (e.g. power from the Poisson shot noise) was measured using previously established technique: long low charge (~300 pC) propagating in relaxed low-beam transport lattice. Such measurements were in good agreement with simulation.
- In all measurements the measured IR power was normalizes to measured average beam current
- The power of electron beam with 1.5 nC per bunch and the nominal compression were compared with the baseline level



Piezo IR port and diagnostic

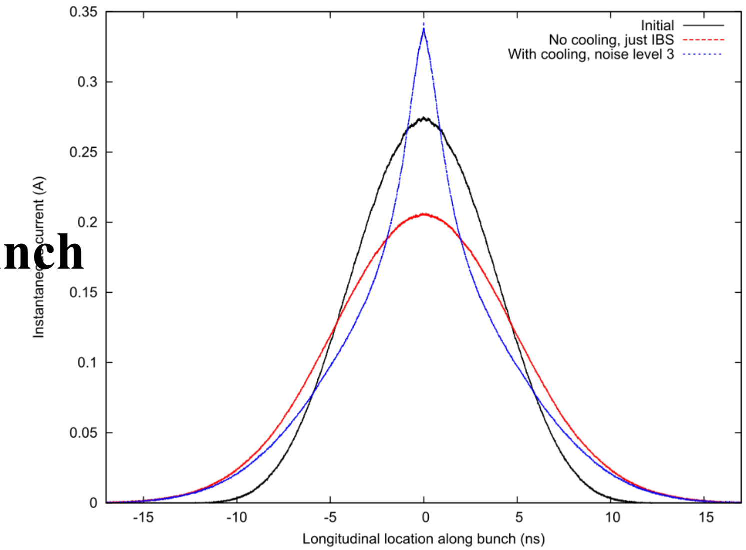
- **Summary of results (see back-up slides for details)**
  - **<u>Measured ratio of the noise power in the electron beam to the Poison noise limit is more than 2 and less then 12</u>**
- **Beam noise satisfy KPP**

The PCA commissioning and the Ion Imprint studies

- Will be updated with data collected this week

Run 21: request two weeks of dedicated time

- Commission RF diagnostics beamline
- **Demonstrate Ion Imprint**
- Optimize electron beam parameters
- Early: **Longitudinal cooling of single hadron bunch**
- Simulations
  - Cooling simulations for Run22
  - Beam dynamics simulations for Run21



Run 22 : request two weeks of dedicated time

- Re-establish electron beam operation in background mode
- Beam dynamics optimization simulations
- Final: **Longitudinal cooling of hadron bunch**
- Study longitudinal cooling of single hadron bunch
- Early: Demonstrate transverse or 3D cooling of single hadron bunch

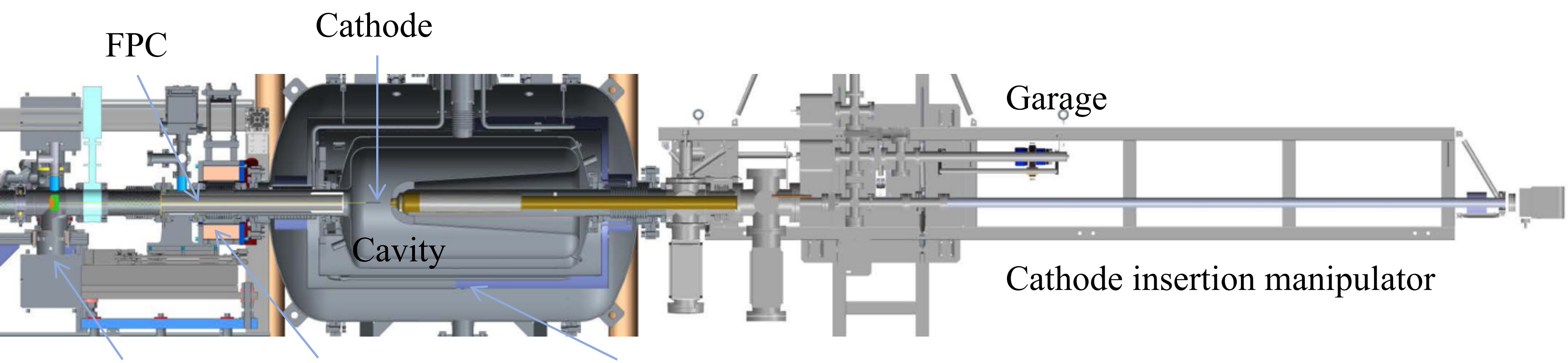
Conclusions

- We learned how to control noise in the beam and how to reduce it to the acceptable level. As the result we obtained the KPP required for the CeC experiment
- We commissioned the new CeC beamline with plasma-cascade amplifier and establish propagation of CW electron beam with low losses
- We made significant progress (*will be updated…*) in investigations of the CeC's Plasma-cascade Amplifier and ion imprint.
- New time-resolved beam diagnostics will be the key for accurate matching of the electron beam into the PCA lattice
- Next key steps
  - Run 21 – ion imprint and longitudinal cooling of 26.5 GeV/u ion beam
  - Run 22 – simultaneous transverse and longitudinal cooling
- Successful experimental demonstration of PCA-based CeC will serve as a perfect starting point for design of cooler for future Electron-Ion Collider

- **Required run time**

Icing on the cake

- Our CW SRF gun demonstrated record performance in the charge and the beam quality – it is the envy of each-and-every e-beam development group in the world
- **It is now considered as the driver for CW hard X-ray FELs both in the USA (LCLS II) and Germany (Euro X-FEL)**
- **It has potential to be a better choice than DC gun for EIC cooler**



PHYSICAL REVIEW LETTERS 124, 244801 (2020)

High-Brightness Continuous-Wave Electron Beams from Superconducting Radio-Frequency Photoemission Gun

I. Petrushina,[1,2] V. N. Litvinenko,[1,2] Y. Jing,[1,2] J. Ma,[2] I. Pinayev,[2] K. Shih,[1] G. Wang,[1,2] Y. H. Wu,[1] Z. Altinbas,[2] J. C. Brutus,[2] S. Belomestnykh,[3] A. Di Lieto,[2] P. Inacker,[2] J. Jamilkowski,[2] G. Mahler,[2] M. Mapes,[2] T. Miller,[2] G. Narayan,[2] M. Paniccia,[2] T. Roser,[2] F. Severino,[2] J. Skaritka,[2] L. Smart,[2] K. Smith,[2] V. Soria,[2] Y. Than,[2] J. Tuozzolo,[2] E. Wang,[2] B. Xiao,[2] T. Xin,[2] I. Ben-Zvi,[2] C. Boulware,[4] T. Grimm,[4] K. Mihara,[1] D. Kayran,[1,2] and T. Rao[2]

Notes

- Too many slides – will cut

The CeC project involved the following:

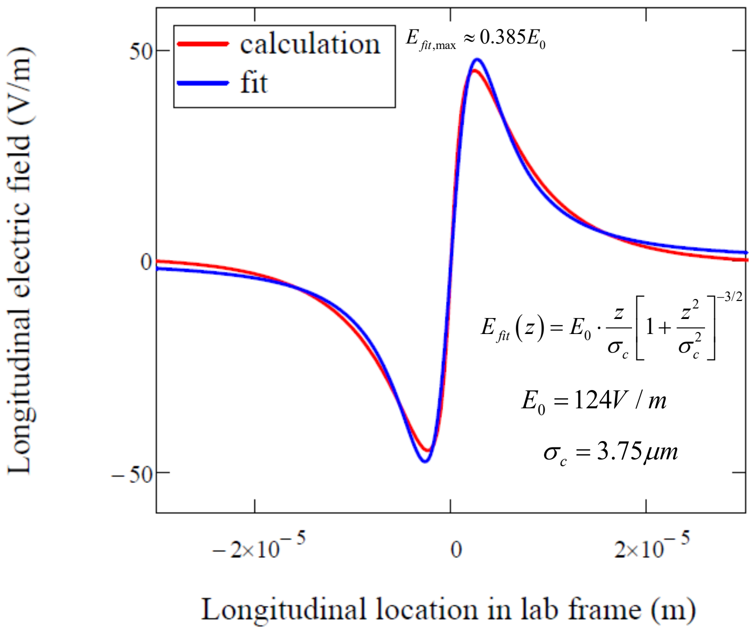
… never can get all of your photos…

Back up Slides

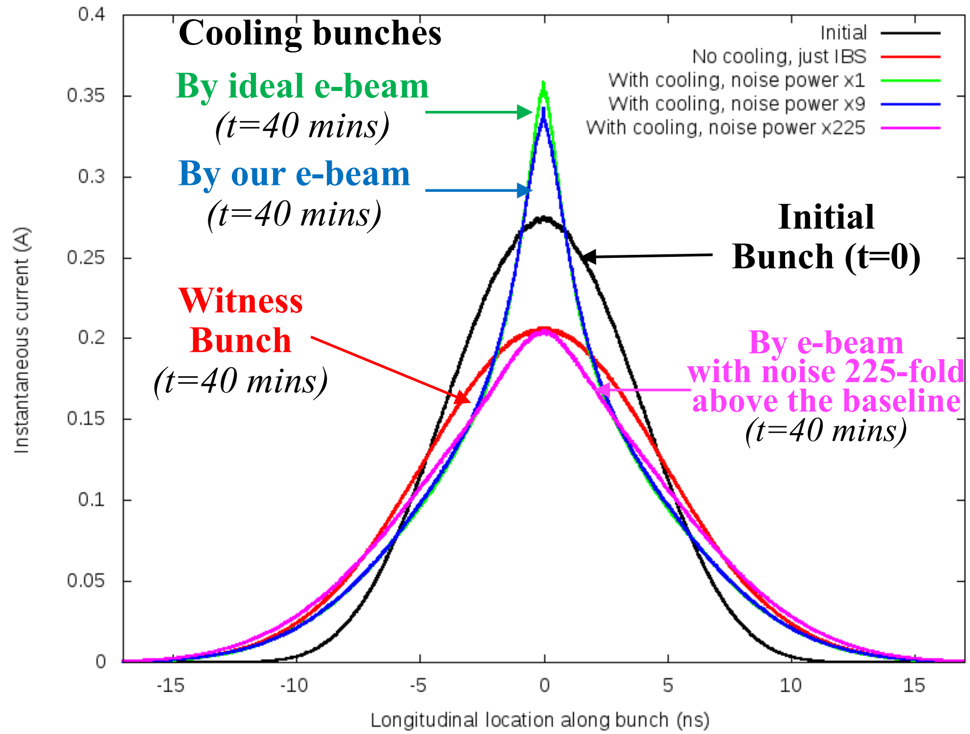
Simulated performance: full 3D treatment

CeC theory is important for scaling and for benchmarking of codes – full 3D simulations is the must for any reliable predictions, which have to be tested experimentally

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 <u>white noise amplitude</u> 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

Key Performance Parameters

Met the milestone CEC_11030:
Necessary Beam Parameters (KPP) established for Run 20

Parameter	KPP	Demonstrated
Lorentz factor	28.5	28.5 (+2.5%)
Repetition frequency, kHz	78.2	78.2
Electron beam full energy, MeV	14.56	14.56 (+2.5%)
Total charge per bunch, nC	1.5	1.5 nC to 2.5 nC
Average beam current, μA	117	127
Ratio of the noise power in the electron beam to the Poison noise limit	<100	5-10
RMS momentum spread $\sigma_p = \sigma_p/p$, rms	$\leq 1.5\times10^{-3}$	5×10^{-4}
Normalized rms slice emittance, μm rad	≤ 5	H < 3, V < 4

Standard settings for 1.5 nC bunch operation

/RHIC/Systems/CeC/RF Systems/Overview

Page PPM Device Data Tools Buffer Help

CeC Gun	Command	Rdbk	Units
Voltage	1193	1193.01711	kV
Phase	0	0.005	deg
MPS Gun Permit		OK	
PLL Loop	ON		
IQ Loop	ffwdOn		
Quench Detect		OK	
Tuner Pos (encoder)		354987	um
Frequency	112.9968423	113.002204793	MHz
500 MHz Cavities	**Command**	**Rdbk**	**Units**
Voltage	185		kV
Voltage Cav 1		185.67528	
Voltage Cav 2		1.26747	
Voltage Total		186.91833	kV
Phase Setpt	-37		deg
Phase Cav 1		-36.996	deg
Phase Cav 2		-127.656	deg
MPS Permit		OK	
PLL Loop Cav 1	OFF		
PLL Loop Cav 2	OFF		
IQ Loop	ffwdOn		
Tuner 1 Pos		51165	um
Tuner 2 Pos		89	um
Frequency	501.39845	501.398441183	MHz
704 MHz Accelerator	**Command**	**Rdbk**	**Units**
Voltage	13100	13101.28055	kV
Phase	-6	-5.993	deg
MPS Permit		OK	
PLL Loop	ON		
IQ Loop	ffwdOn		
Quench Detect		OK	
Arc Detect		OK	
Mech Tuner Pos		89046	um
Tuner Piezo			V
Frequency	703.95841	703.958410	MHz

(28,2) erlIqLoop.2b-llrf-cec4.2:phaseSetptRampS Nudge: 1 363

high limit
Sat Jul 4 20:40:36 2020: Value sent for (11,2)

/RHIC/Systems/CeC/Magnet PS

Page PPM Device Data Tools Buffer Help

Low Energy Beamline	Description	Max Curr [A]	Curr Stpt[A]	Curr Rdbk [A]	Volt
cs2-gun.sol-ps	SRF gun solenoid	13.4	8.23	8.22877	
cs2-inj.sol1-ps	LEBT solenoid 1	8.4	-2.77	-2.77107	
cs2-inj.sol2-ps	LEBT solenoid 2	8.4	3.02	3.01952	
cs2-inj.sol3-ps	LEBT solenoid 3	8.4	-2.94	-2.94105	
cs2-inj.sol4-ps	LEBT solenoid 4	8.4	3.19	3.18940	
cs2-inj.sol5-ps	LEBT solenoid 5	8.4	-3.95	-3.95049	-
cs2-gun.tv1-ps	Gun Vertical Corr 1	1	0	0.00003	
cs2-gun.th1-ps	Gun Horizontal Corr 1	1	0	0.00000	
cs2-gun.tv2-ps	Gun Vertical Corr 2	5	-1.21346	-1.21336	
cs2-gun.th2-ps	Gun Horizontal Corr 2	5	-0.0534179	-0.05306	
cs2-inj.tv1-ps	LEBT Vertical Corr 1	5	0.289347	0.28938	
cs2-inj.th1-ps	LEBT Horizontal Corr 1	5	0.199696	0.19974	
cs2-inj.tv2-ps	LEBT Vertical Corr 2	0.5	-0.0437255	-0.04370	
cs2-inj.th2-ps	LEBT Horizontal Corr 2	2	0.147285	0.14678	
cs2-inj.tv3-ps	LEBT Vertical Corr 3	2	0.356849	0.35671	
cs2-inj.th3-ps	LEBT Horizontal Corr 3	2	-0.536859	-0.53678	
cs2-inj.tv4-ps	LEBT Vertical Corr 4	2	-0.104297	-0.10396	
cs2-inj.th4-ps	LEBT Horizontal Corr 4	2	-0.0279625	-0.02776	
cs2-inj.tv5-ps	LEBT Vertical Corr 5	2	-0.355008	-0.35613	
cs2-inj.th5-ps	LEBT Horizontal Corr 5	2	-0.0771666	-0.07809	
cs2-inj.tv6-ps	LEBT Vertical Corr 6	2	0.263399	0.26320	
cs2-inj.th6-ps	LEBT Horizontal Corr 6	2	-0.116311	-0.11617	
cs2-inj.tv7-ps	LEBT Vertical Corr 7	2	-0.145216	-0.14491	
cs2-inj.th7-ps	LEBT Horizontal Corr 7	2	-0.0548503	-0.05461	
cs2-inj.tv8-ps	LEBT Vertical Corr 8	2	-0.102304	-0.10316	
cs2-inj.th8-ps	LEBT Horizontal Corr 8	2	-0.466461	-0.46763	
cs2-inj.tv9-ps	LEBT Vertical Corr 9	5	-0.0504025	-0.05025	
cs2-inj.th9-ps	LEBT Horizontal Corr 9	5	-0.136048	-0.13560	
cs2-inj.tv10-ps	LEBT Vertical Corr 10	5	-0.0155594	-0.01529	
cs2-inj.th10-ps	LEBT Horizontal Corr 10	5	-1.13363	-1.13352	

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Sat Jul 4 21:12:41 2020: Value sent for (37,4)
Sat Jul 4 21:12:49 2020: Value sent for (37,4)

Budget

WBS	Total Cost (AY$)
Coherent electron Cooling Experiment	**$2,172,470**
Management	$0
Physics Support	$0
Magnets and Power Supplies	$336,252
RF Systems and Power Amplifiers	$604,958
Beam Instrumentation System	$314,167
Controls and MPS	$63,779
Vacuum/ Beamline Mechanical Systems	$144,136
Infrastructure/Installation and Global Design Updates	$186,827
Operations	$522,351
Total Estimated Cost	**$2,172,470**
Contingency	$865,683
Total Cost including Contingency	**$3,038,153**

CeC Risks, Challenges

- **Top 3 Risks**

➢ COVID-19 uncertainty and related availability of personnel are the main risk

  ➢ 12 months schedule contingency

➢ Lifetime of currently used photocathode

  ➢ Two cathodes in garage, but with potential porblems

➢ Failure of 113 MHz SRF gun or drive laser, 704 MHz accelerator cavity – *Very Unlikely but High Impact*

- **Challenges**: Insufficient signal to noise level of the IR diagnostics
  - New cryo-cooled IR detector was delayed because of COVID-19
  - Expect it to be available during next run
- **Challenge**: Some Mo pucks for the photocathodes have sharp edge as result of re-polishing.
  - We sent back a batch of Mo pucks to the manufacturer for smoothing the edges
  - We ordered a set of new Mo pucks with smooth edges
  - *See the reply to the POB recommendations*

Main concern

- Stability of the electron beam
- Variations of the electron beam parameters caused by the laser and the RF systems provide for significant changes in the signal levels observed by IR diagnostics
- We need factor 2 to 3 improvement in stability of the laser intensity and and factor 2 to 3 reduction in the time jitter

Decision points