Coherent electron Cooling experiment at RHIC

Vladimir N Litvinenko for the CeC project team

RHIC retreat

October 15, 2020

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Why are 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 boosting it by 4- to 10-fold

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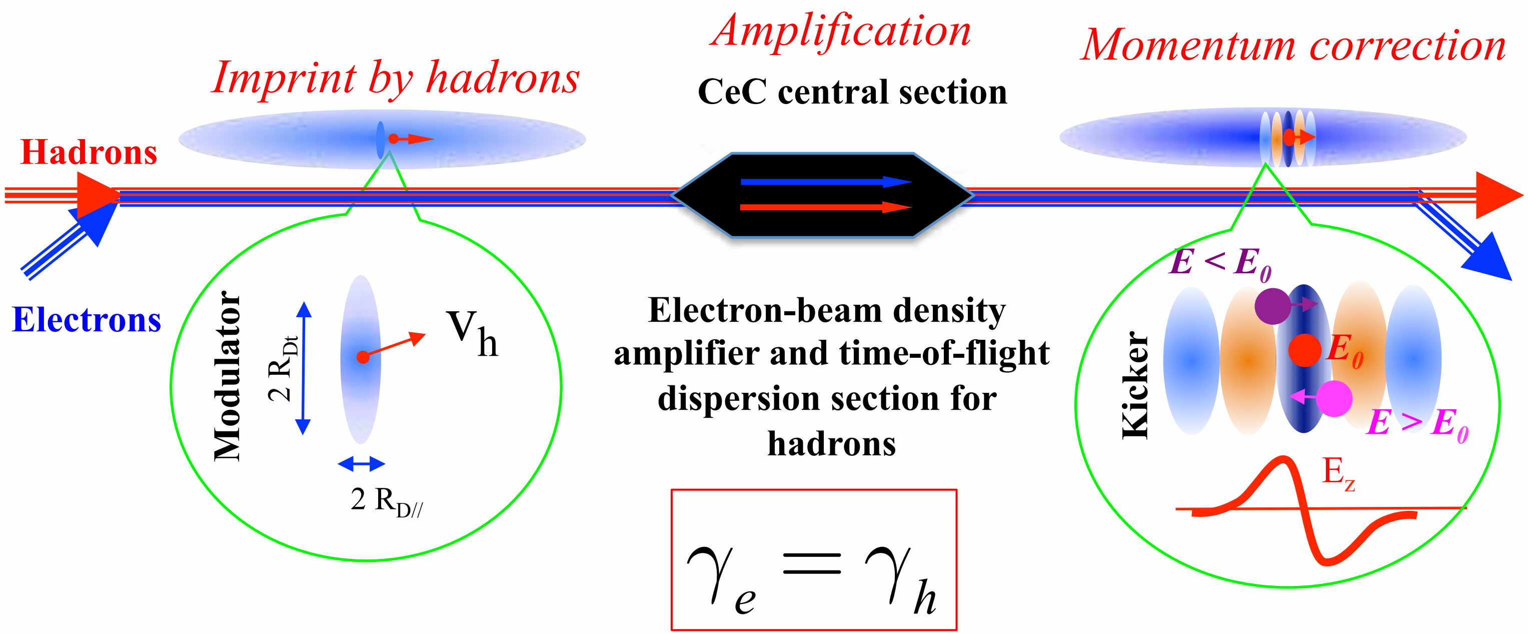
What is Coherent electron Cooling

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



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

Coherent Electron Cooling

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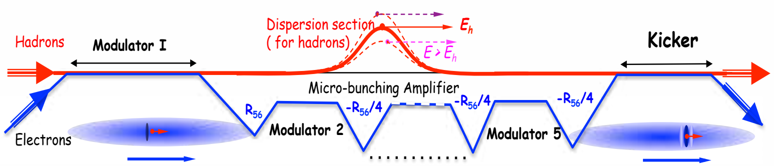
(Received 24 September 2008; published 16 March 2009)

What can be tested experimentally?

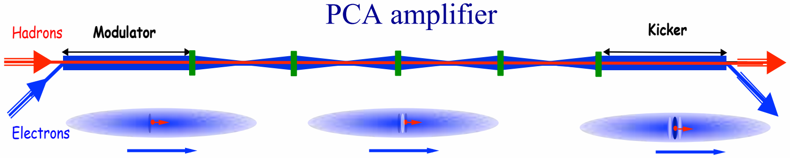
Litvinenko, Derbenev, PRL 2008

Ratner, PRL 2013

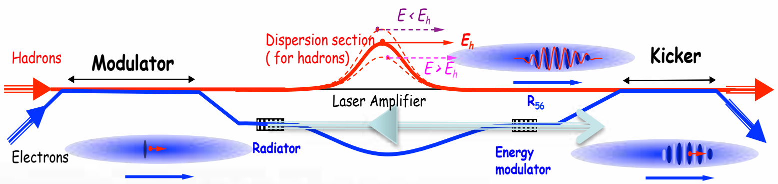


Litvinenko, Wang, Kayran, Jing, Ma, 2017

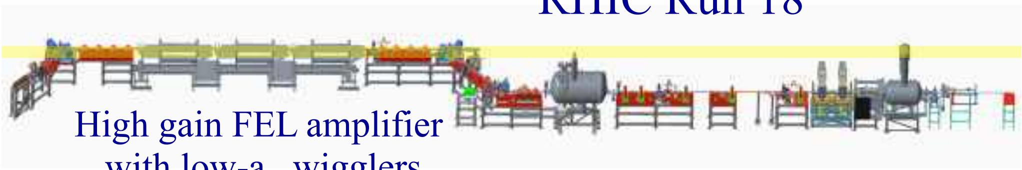
PCA amplifier



Litvinenko, Cool 2013



RHIC Run 18

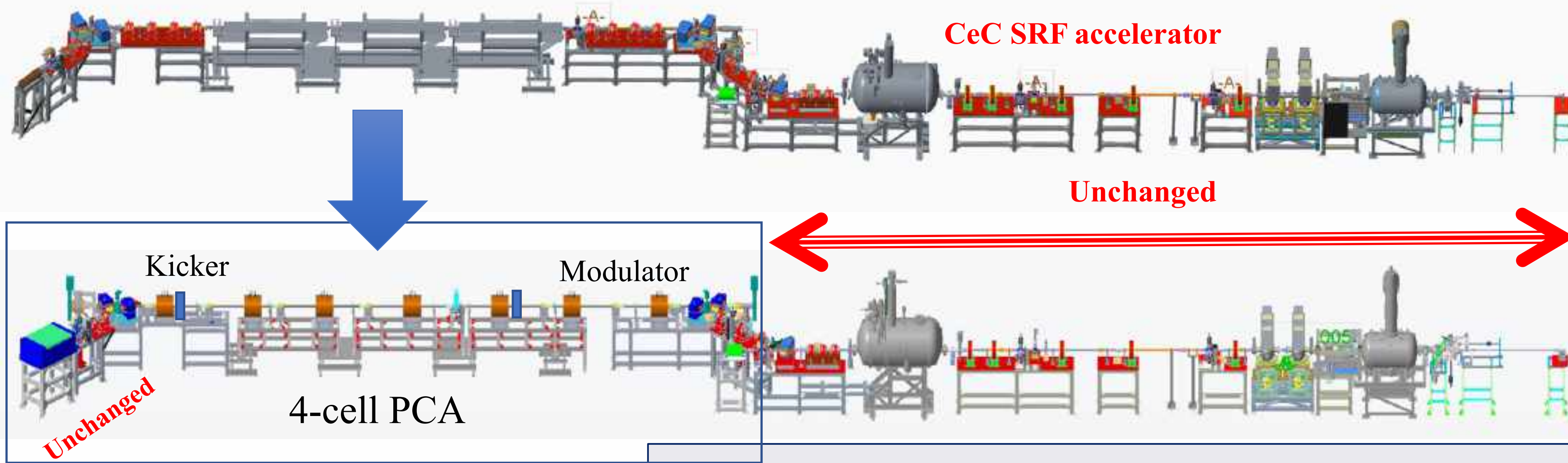


Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

RHIC Runs 20-22

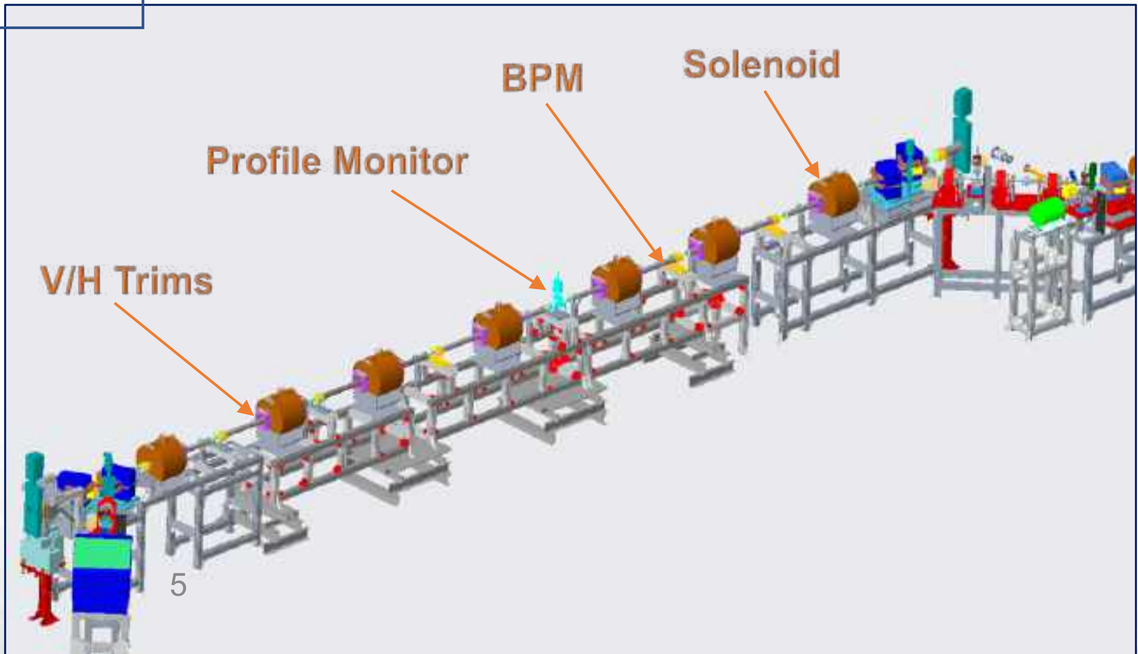
Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

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



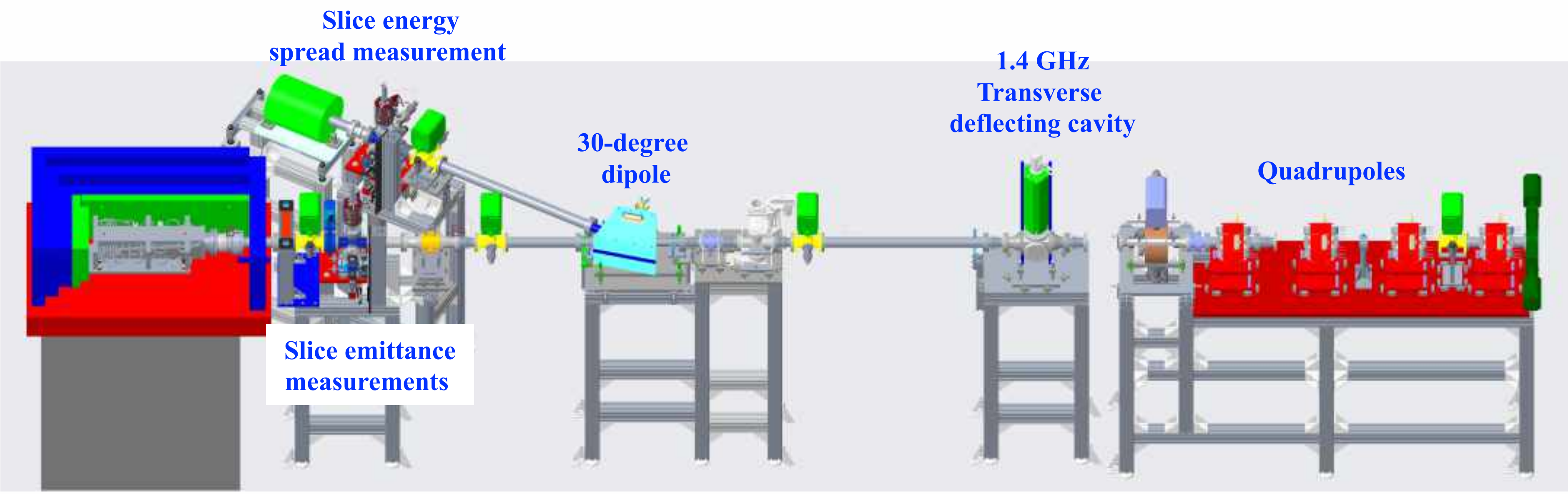
The PCA bandwidth is 15 THz

>2,000x of the RHIC stochastic cooler



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

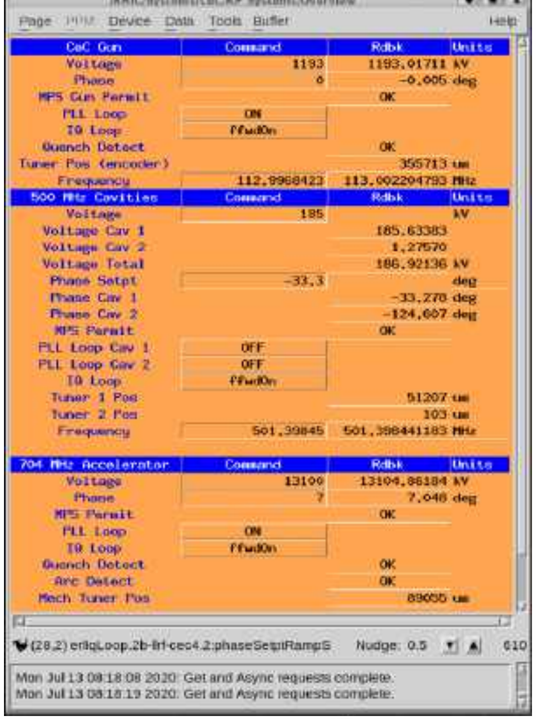


Main results from Run 20

- Key experimental accomplishments:
  - **Milestone CEC11030**: **"Necessary Beam Parameters (KPP)** established for Run 20"
  - Completed commissioning of the common section with 7 high field solenoids
  - Preliminary analysis reveals **strong amplification in Plasma Cascade Amplifier (PCA)** – the key process in microbunching CeC. Detailed analysis continues to confirm attainment of the **Milestone CEC11040 "Investigation of plasma cascade amplification complete**"
  - Preliminary analysis reveals **presence of ion imprint PCA-amplified in the electron beam** – a key process in microbunching CeC. Detailed analysis continues to confirm attainment of the **Milestone CEC11050 "Investigation of the ion imprint in the electron beam complete**"
  - **Fault studies proved that the new mode of operation parallel with RHIC stores is safe and after the reviews this new mode of operation was recently approved**.
  - **Design of time-resolved beamline is completed. Procurements of the key components for the time-resolved diagnostics beamline continue**

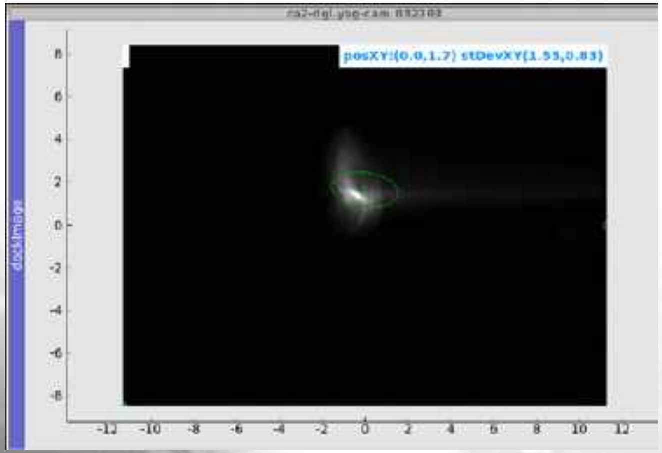
Electron beam KPP

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	✓



Accelerator system and Beam energy - ✓

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



- According to magnetic measurements the dipole current should be 93.9 A for γ=28.5, pc=14.5545 MeV
- **Energy with 96.2 A 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**

 Results from Run 20

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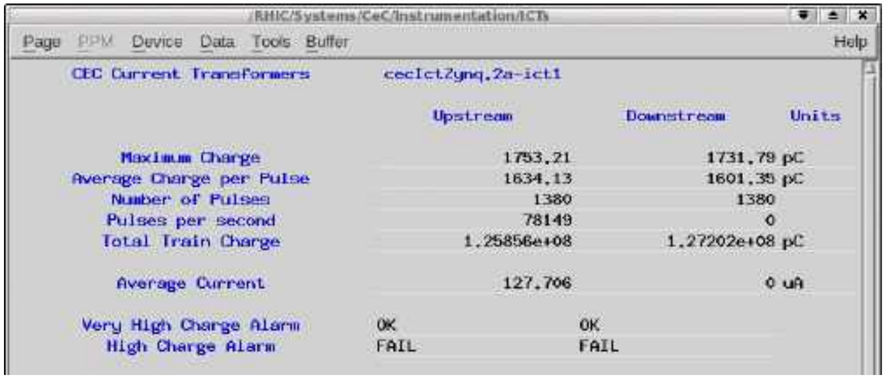
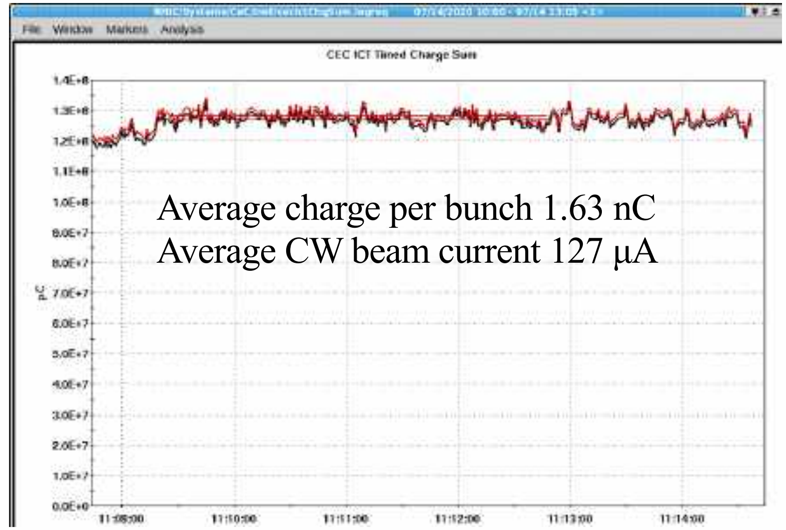
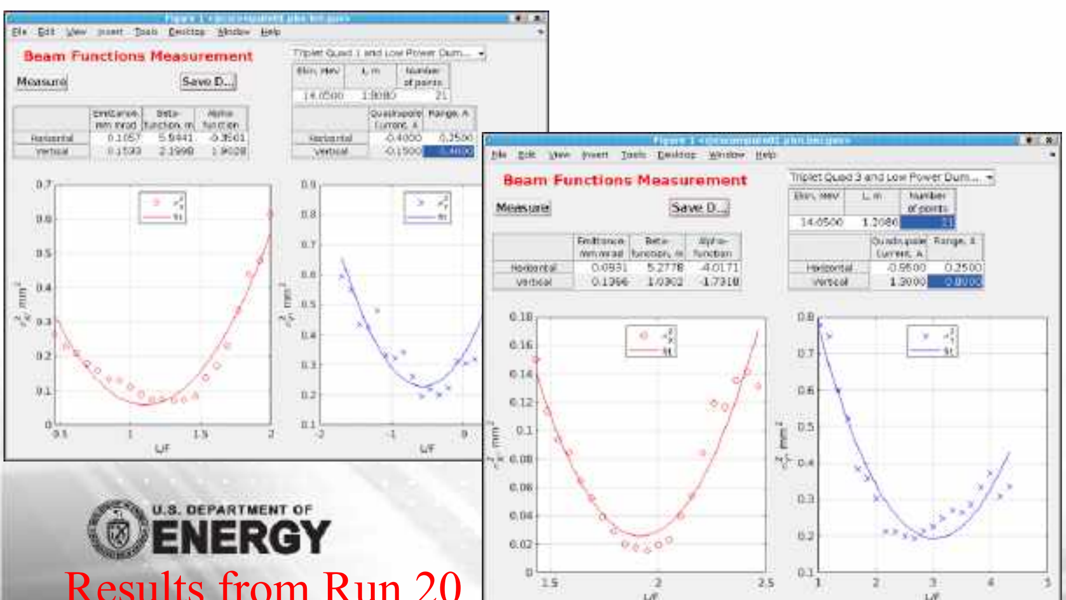
Charge per bunch and CW beam current ✓





Projected beam emittances ✓



- **Projected emittances** are, by definition, larger than **slice emittances.**
- Plot shows measured geometrical projected emittance, which are γβ~28.5 times smaller than the normalized emittance 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**

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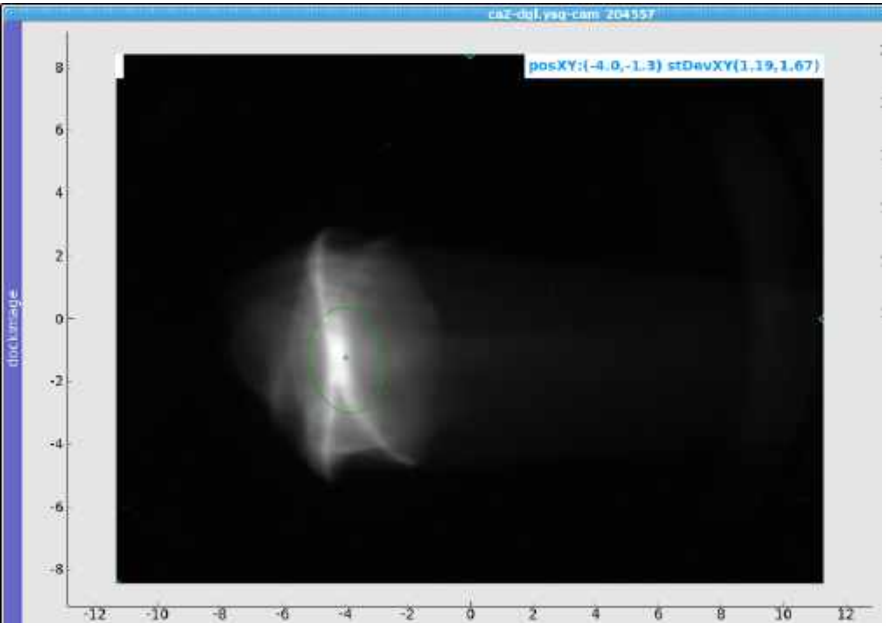
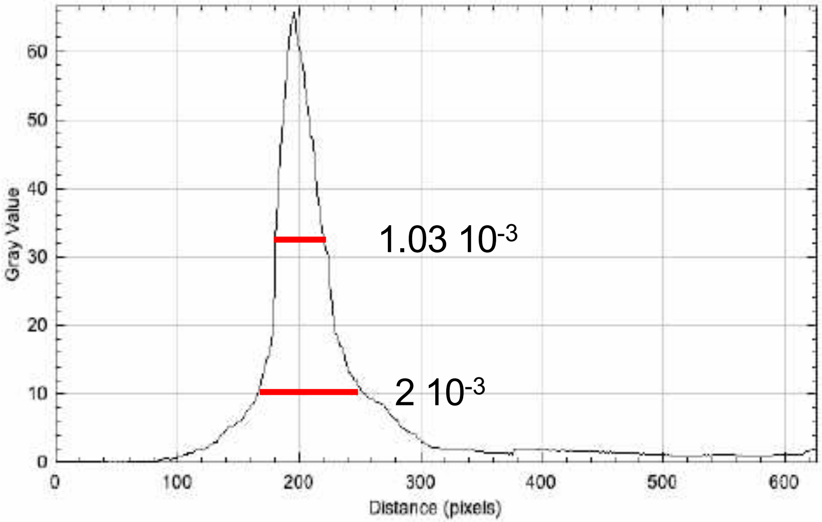
Results from Run 20

Full beam energy spread

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

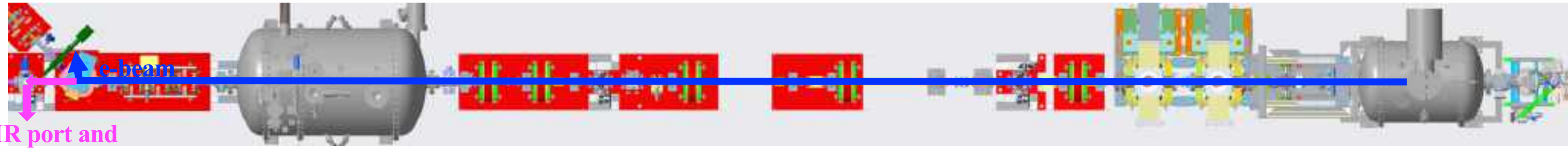




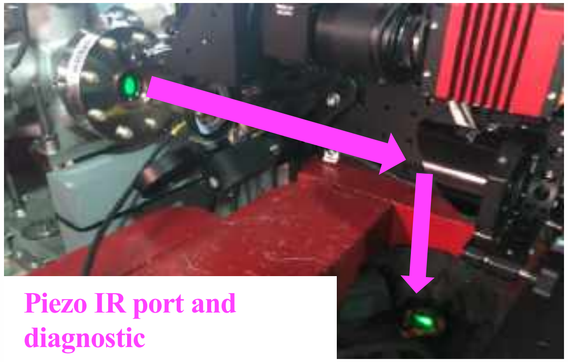
Scaling: 31 pixels per 1 mm, FWHM energy spread is 1.03 10^{-3};
RMS energy spread is 4.4 10^{-4}

Results from Run 20

The e-beam noise level ✓



- 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 Poison shot noise) was measured using previously established technique: long low charge (~300 pC) propagating in the relaxed lattice of the low-energy beam transport. Measurements are in good agreement with simulations.
- In all measurements the measured IR power was normalized 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



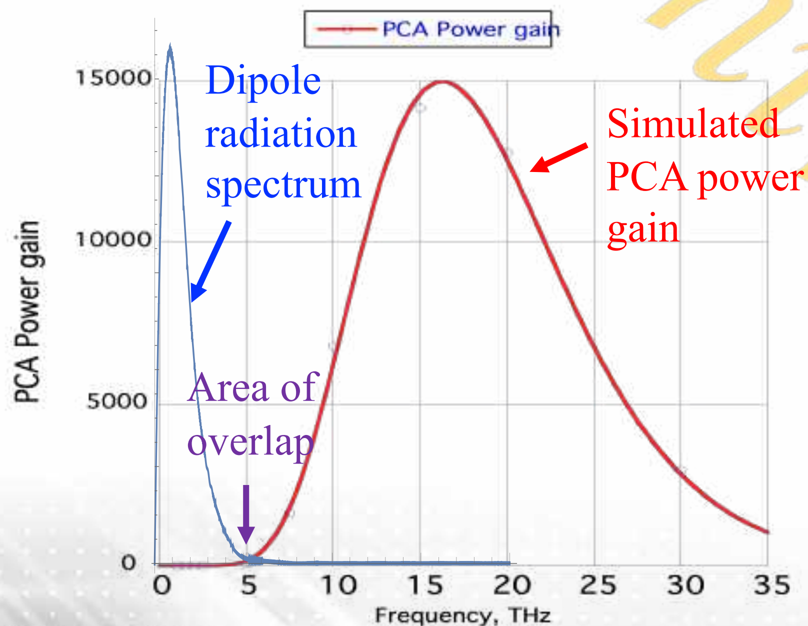
Piezo IR port and diagnostic

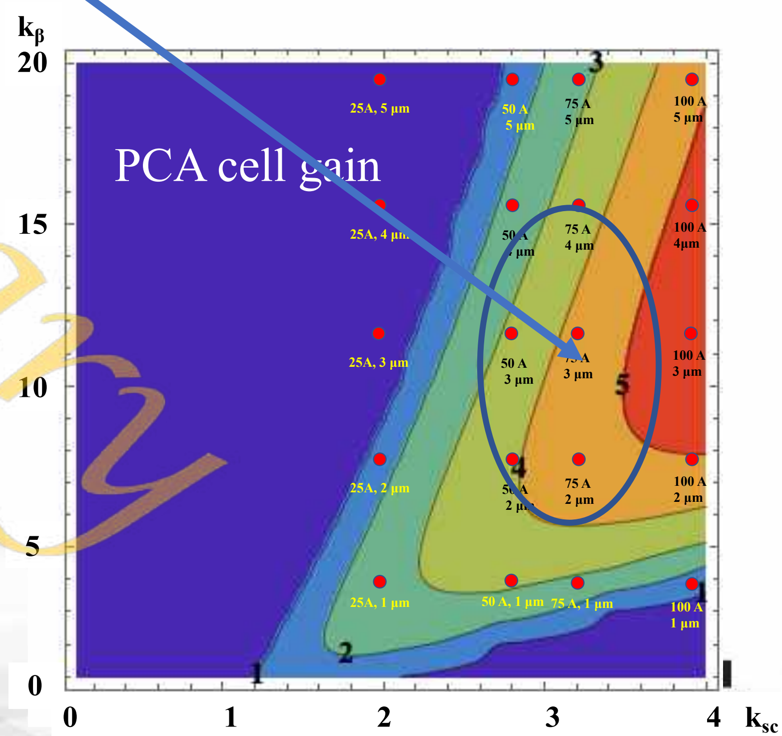
- **Summary of results (see back-up slides for details)**
  - **Measured ratio of the noise power in the electron beam to the Poison noise limit is more than 2 and less then 12**
- **Beam noise satisfy KPP**

Preliminary results from Run 20

The PCA studies

- We observed 200-fold increase in broad-band radiation from the dipole magnet when high-gain micro-bunching PCA lattice was applied. Weak overlap of PCA gain curve and the radiation spectrum from the dipole is the reason the measured PCA boost of the dipole radiation is in hundreds, not in thousands.
- We also observed signal from the PCA-boosted radiation at 8.6-15 THz range using IR spectrometer. Without the PCA-boost signal is too weak for the current IR detector – *will be available when new cryo-cooled IR detector is installed (delayed because of COVId-19)*
- Preliminary analysis indicates **PCA amplitude gain** between 65 and 180 (4,000 and 32,000 gain in power), which is in reasonable agreement with our predictions





Preliminary results from Run 20

The Ion Imprint studies

- We performed two sets of ion imprint studies
  - (A) Using low peak-current electron beam and relaxed lattice (no-PCA) in the common section and detection of the broad-band dipole radiation
  - (B) Using high gain PCA lattice and high peak current beam and detecting IR radiation in narrow band at 35 µm (8.6 THz)
- In both cases we used lock-in amplifiers to detect AC signal from IR detectors measuring radiation generated by trains of 5,000 1.5 nC bunches (spaced by 78 kHz) repeated with 5 Hz
- The imprint was measured by comparing power radiated by electron beam when it overlaps with the ion bunch (imprint present) with that radiated without the overlap (no imprint present), e.g. using modulation-demodulation technique
- The e-beam radiation level were measured from the dipole magnets upstream and downstream of the CeC section: e.g. before and after co-propagating with the ion beam and PCA amplifier.
- Measurement from the upstream IR detector are used for quality assurance of our data – overlapping or separating ion beam downstream should not affect signal in this location and it is indicator of the changes in the electron beam parameters
- We had limited success using (A) – while we overall increase of the radiation power from the ion imprint, the increase was within 3-sigma of the measurement errors – *the dipole radiation wavelength is too long for ion imprint*
- Using PCA-boosted 8.6 THz radiation we were able to observe signal from the ion imprint with high degree of certainty (e.g. outside of 5-sigma) – see next slide

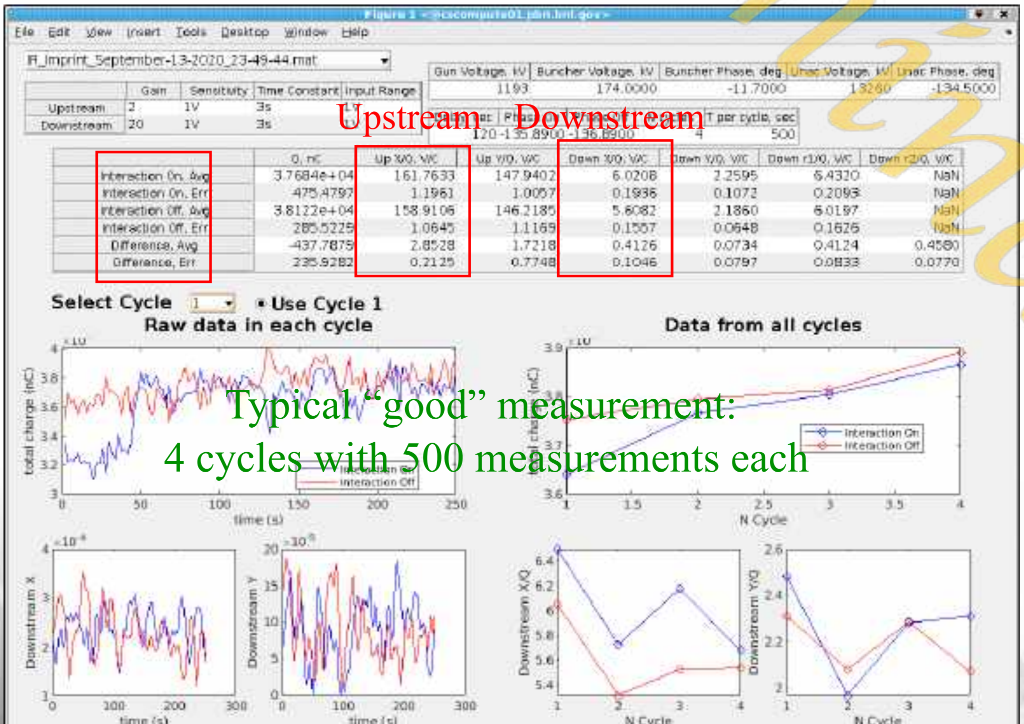
Preliminary results from Run 20

The Ion Imprint studies

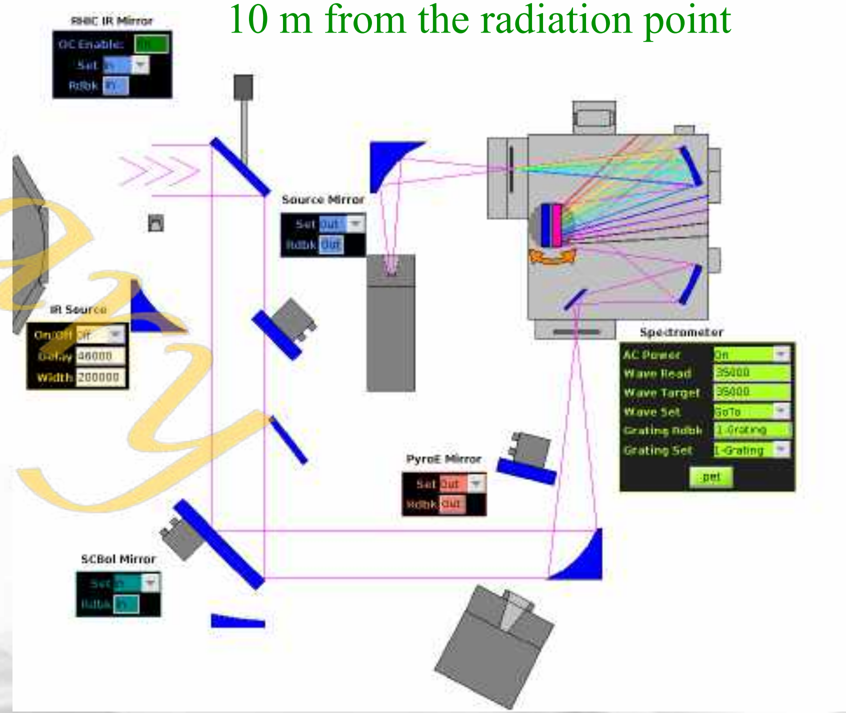
- The imprint effect depends on multiple evolving factors such as noise in the electron beam, peak current of the ions, transverse overlap of the beam in the modulator – it will take few weeks to take all these details into account
- We collected twelve completed and six partially complete measurements (e.g. interrupted by RHIC quenches or other equipment failures) – ten out of twelve completed measurements show increase in the power of electron beam radiation by the ion imprint.
- Maximum increase of radiation power from the imprint exceeds 10%, with average value impact from the imprint of 5.1%. Largest "negative result" is -3%.
- Errors in the measurements are a combination of the IR detector noise and variation of the electron e-beam parameters (e.g. CeC accelerator drifts) Detailed data analysis is in progress

Data sample

Linac, MV	Increase from imprint without correction	Corrected by the upstream detector
13.1	9.98%	4.63%
13.14	13.13%	9.77%
13.14	12.00%	6.86%

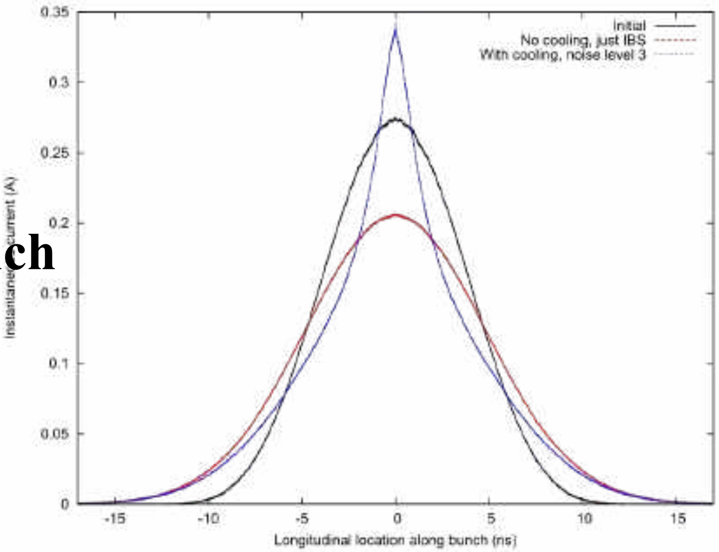


Downstream IR diagnostics
10 m from the radiation point



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

Main Risks and Challenges

- **Top Risks**

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

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

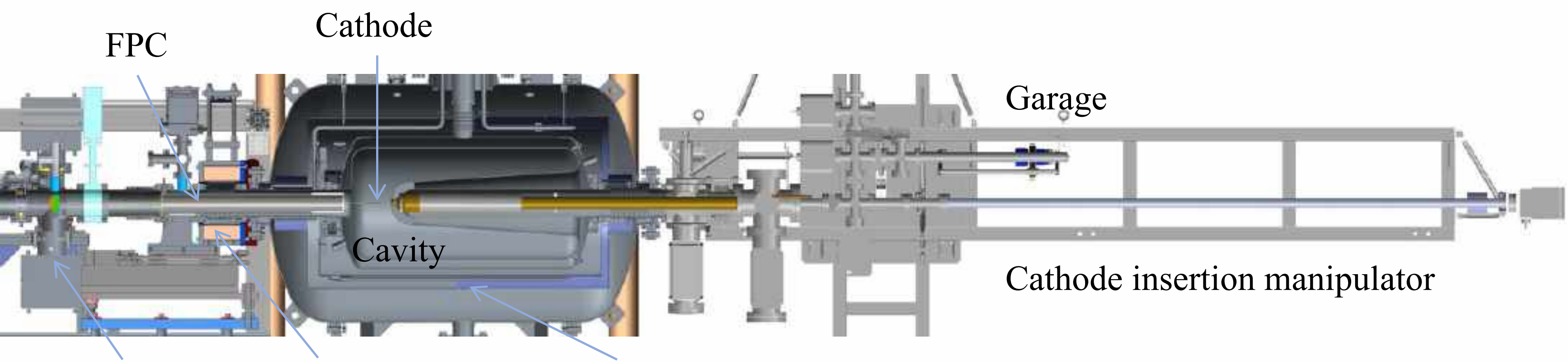
- **Challenges**:
- Timely construction and commissioning of the new time-resolved diagnostics beam-line
  - This diagnostics is critical for accurate and decisive evaluation of the electron beam parameters
  - While there is significant progress, few key pieces of equipment delayed because of COVID-19
- 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
- Significant variations of the electron beam parameters which affect efficiency of CeC operations .
  - We observed variations of the electron beam positions and charge
  - We also observed significant excisions of electron beam energy
  - It is important to improved stability of the key beam parameters by additional factor of 2 to 3 for next run

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 in investigations of the CeC's Plasma-Cascade Amplifier and observation the PCA-amplified 10-THz-range ion imprint in the e-beam
- The availability was affected by of summer running - it significantly reduced efficiency data collections. Dedication of the CeC team, professionalism of the RHIC operators, and support of CAD engineers and technicians are reasons for the CeC successes during this run
- New time-resolved beam diagnostics will be the key for accurate matching of the electron beam into the PCA lattice. New cryo-cooled IR detector will dramatically improve accuracy of the PCA-gain evaluation and the ion-imprint observation
- 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

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**

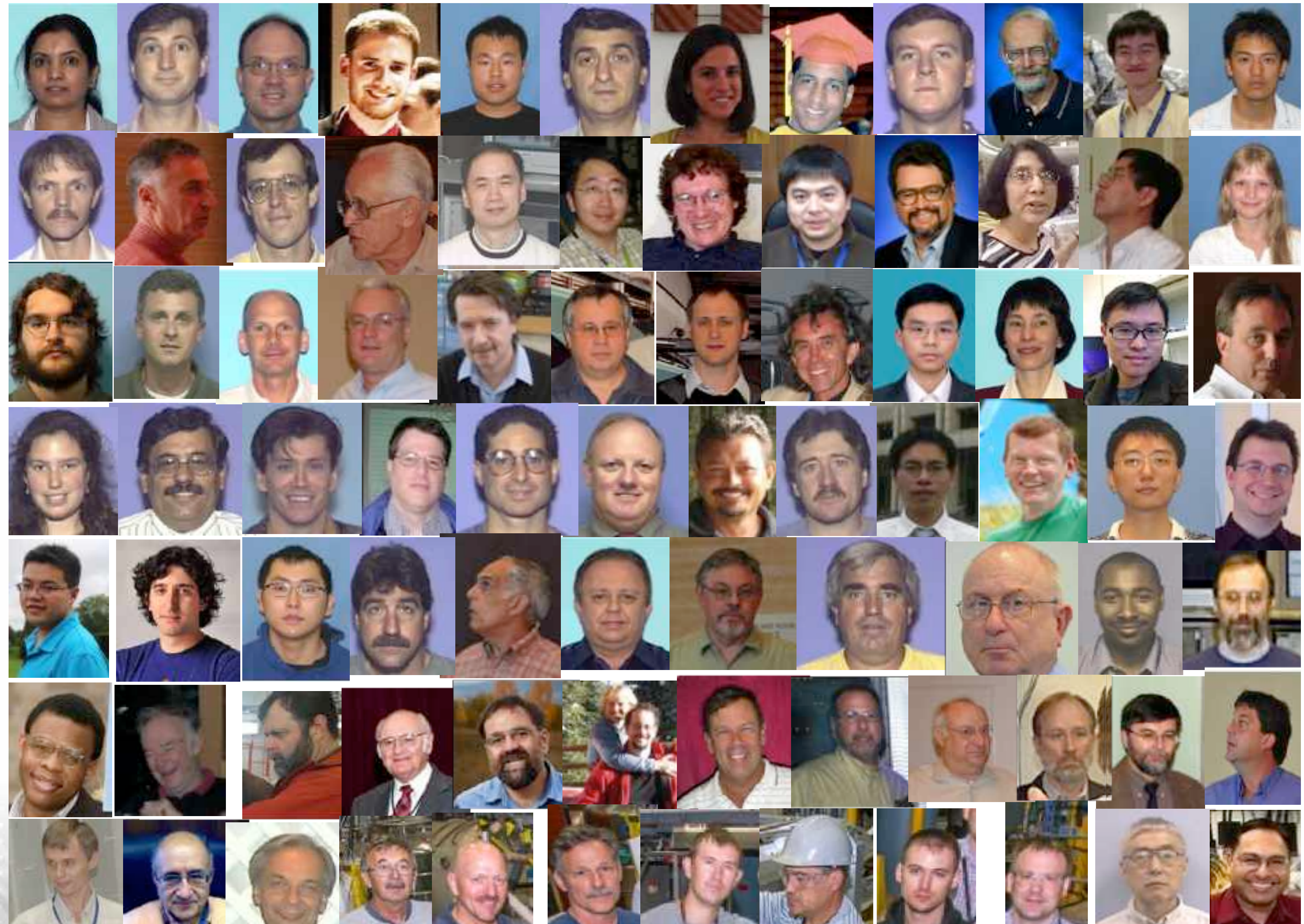


PHYSICAL REVIEW LETTERS 124, 244801 (2020)

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]

Many of you made critical contributions to the CeC project!
We need your continuing help for successful CeC demonstration!



… never can get all of your photos…