Stony Brook University

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Measuring beam noise at 10 - 100 THz and production of intense, low noise electron beams

Irina Petrushina (Stony Brook University)
on behalf of the Coherent electron Cooling team

@BrookhavenLab

February 3, 2022

Extreme Storage Rings Workshop (ESRW22)

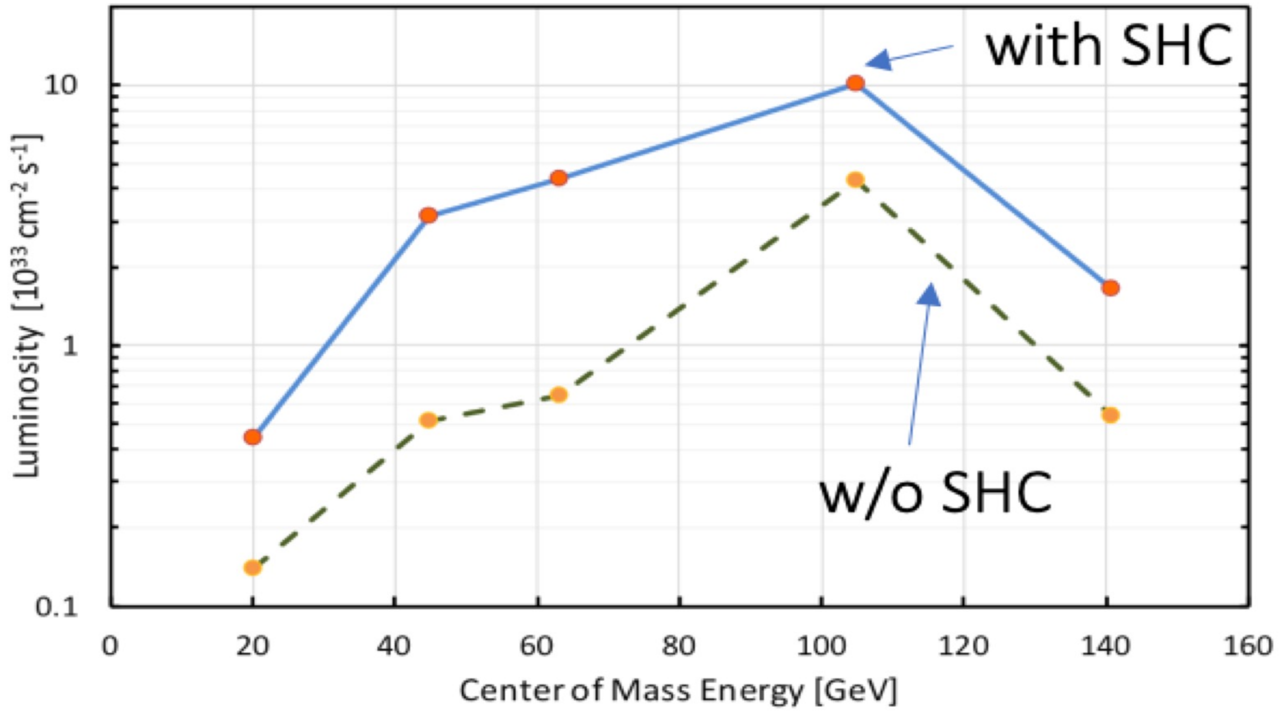
Outline

- Concept of Coherent electron Cooling (CeC)
- CeC Proof of Principle experiment
- Generation of high-brightness electron beams
- Measuring beam noise at 10-100 THz: Plasma-Cascade Instability
- Future Directions and Outlook

Motivation: Need for novel cooling methods

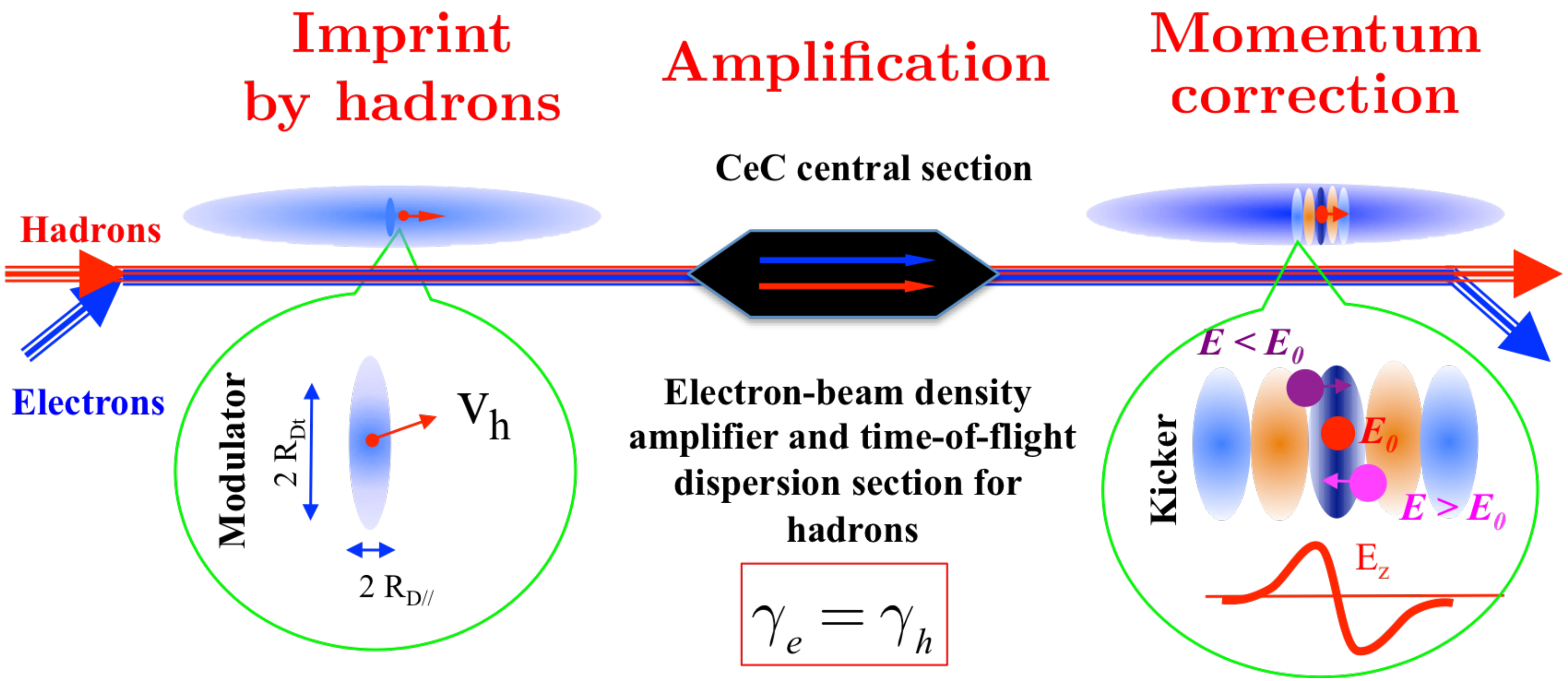
National Academy of Sciences Assessment of U.S.-Based Electron-Ion Collider Science:

*The accelerator challenges are two-fold: a high degree of **polarization** for both beams, and high **luminosity**.*



Coherent electron Cooling (CeC): Theory

- 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.



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)

PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Microbunched Electron Cooling for High-Energy Hadron Beams

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

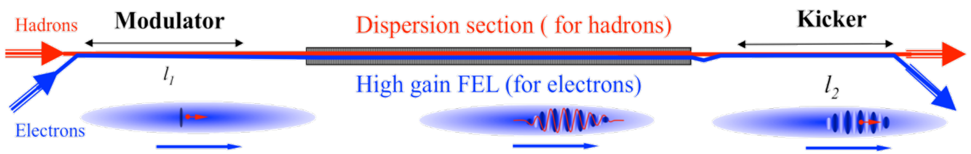
Brookhaven National Laboratory

CeC Proof of Principle experiment

Brookhaven National Laboratory

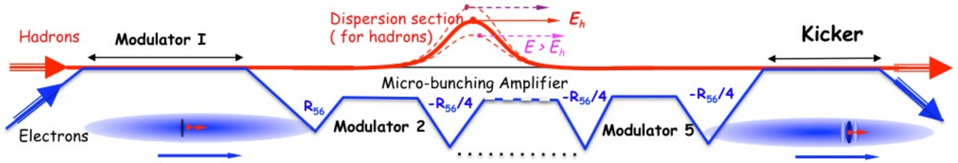
Coherent electron Cooling (CeC): Experiment

Litvinenko, Derbenev, PRL 2008



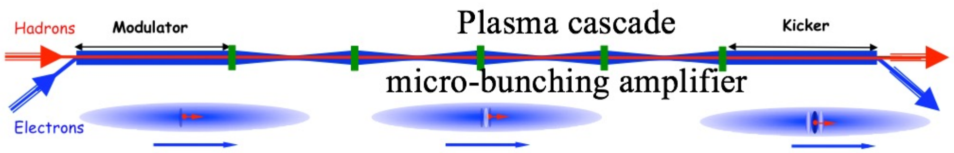
High gain FEL amplifier

Ratner, PRL 2013



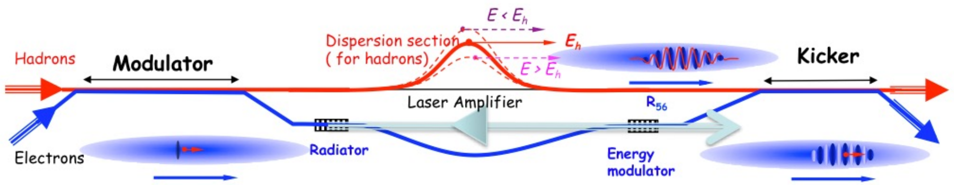
Multi- Chicane Microbunching amplifier

Litvinenko, Wang, Kayran, Jing, Ma, 2017



Plasma-Cascade Microbunching amplifier

Litvinenko, Cool 13

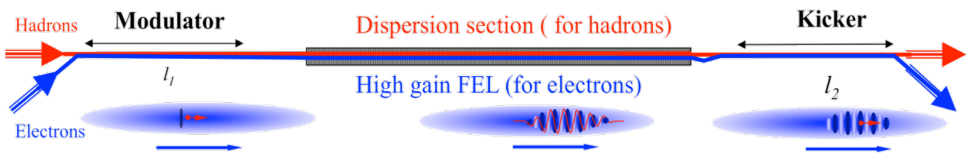


Hybrid laser-beam amplifier

Brookhaven National Laboratory

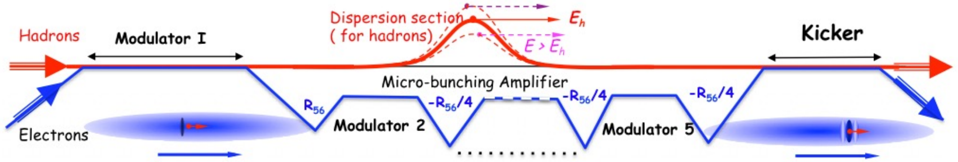
Coherent electron Cooling (CeC): Experiment

Litvinenko, Derbenev, PRL 2008



High gain FEL amplifier

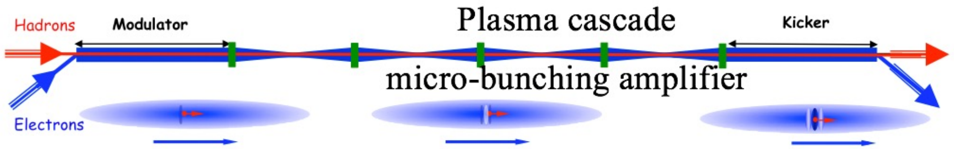
Ratner, PRL 2013



Multi- Chicane Microbunching amplifier

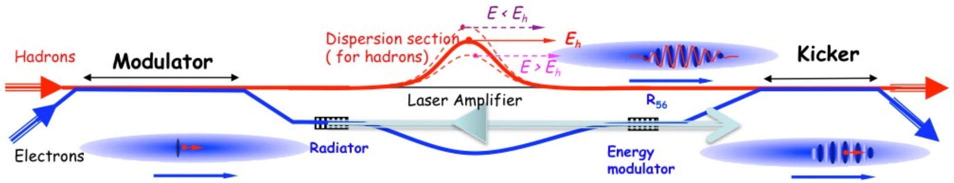
Requires significant and expensive modifications of the RHIC lattice & superconducting magnets

Litvinenko, Wang, Kayran, Jing, Ma, 2017



Plasma-Cascade Microbunching amplifier

Litvinenko, Cool 13



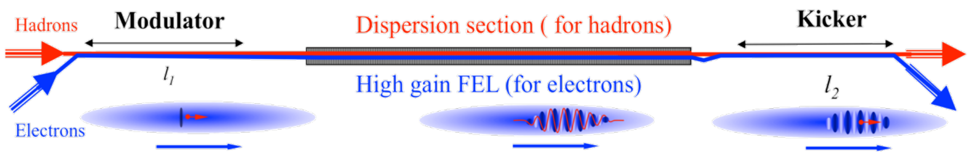
Hybrid laser-beam amplifier

Requires significant and expensive modifications of the RHIC lattice & superconducting magnets

Brookhaven National Laboratory

Coherent electron Cooling (CeC): Experiment

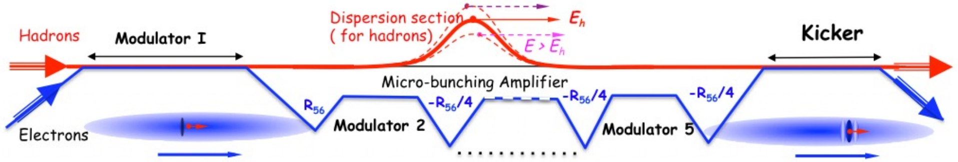
Litvinenko, Derbenev, PRL 2008



High gain FEL amplifier

RHIC Run 18

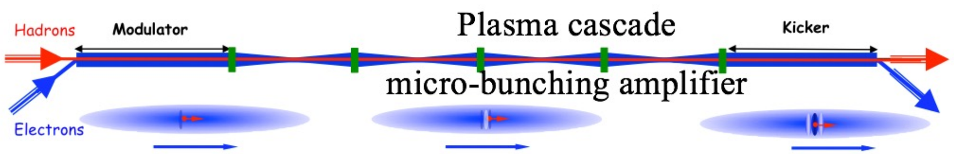
Ratner, PRL 2013



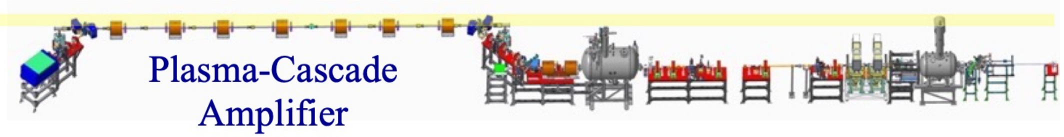
Multi- Chicane Microbunching amplifier

Litvinenko, Wang, Kayran, Jing, Ma, 2017

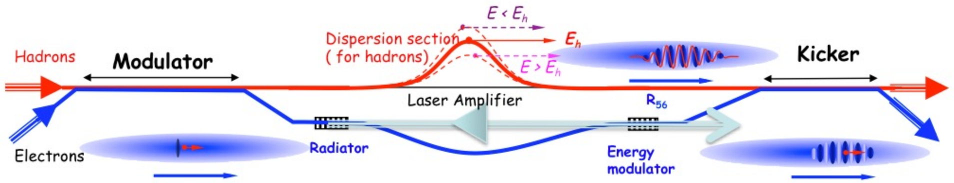
RHIC Runs 20-22



Plasma-Cascade Microbunching amplifier



Litvinenko, Cool 13



Hybrid laser-beam amplifier

Brookhaven National Laboratory

CeC Proof of Principle Experiment: Timeline

2014-2017

- Built and commissioned cryogenic system, SRF accelerator and FEL

2018-2019

- Started the FEL-based CeC experiment.
- It was not completed: 28 mm aperture of the helical wigglers was insufficient for RHIC with 3.85 GeV/u Au ion beams
- Discovered microbunching Plasma Cascade Instability - new type of instability in linear accelerators.
- Developed the design of Plasma Cascade Amplifier (PCA) for CeC

2019-2020

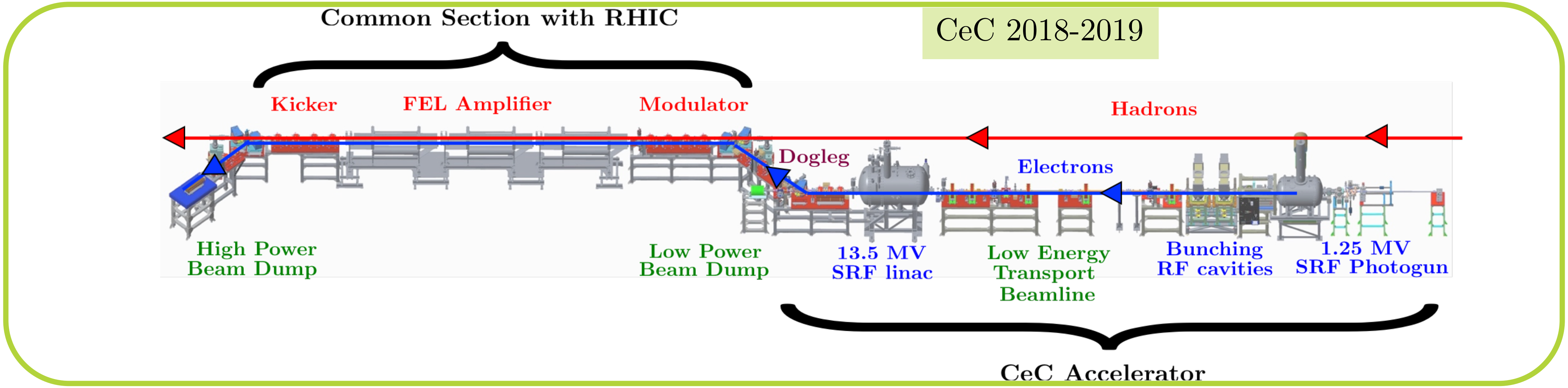
- PCA-based CeC with seven solenoids and vacuum pipe with 75 mm aperture was built and commissioned.
- Demonstrated high gain Plasma Cascade Amplifier (PCA) and observed presence of ion imprint in the electron beam

2021-2022

- New time-resolved diagnostics beamline is built and commissioned
- Focusing on the demonstration of the longitudinal CeC cooling

CeC Proof of Principle Experiment: Facility

Goal: demonstrate longitudinal cooling of a single Au^{+79} bunch in the Relativistic Heavy Ion Collider.



Hadron beam parameters

Energy, GeV/u	27
Intensity, hadron/bunch	10^9
RMS bunch length, ns	5
Revolution frequency, kHz	78

Required e-beam parameters

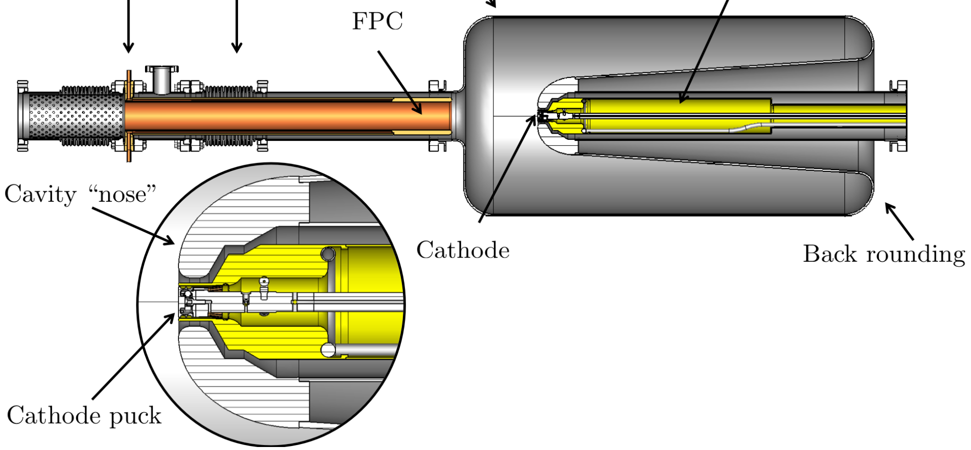
Normalized emittance, mm-mrad	<5
Relative energy spread σ_E/E	10^{-3}
Bunch charge, nC	0.5-1.5
Pulse repetition rate, kHz	78
RMS bunch length, ps	10-50
Peak current, A	>75
Kinetic energy, MeV	14.5
FEL wavelength, μm	30

Brookhaven National Laboratory

Generation of high-brightness electron beams

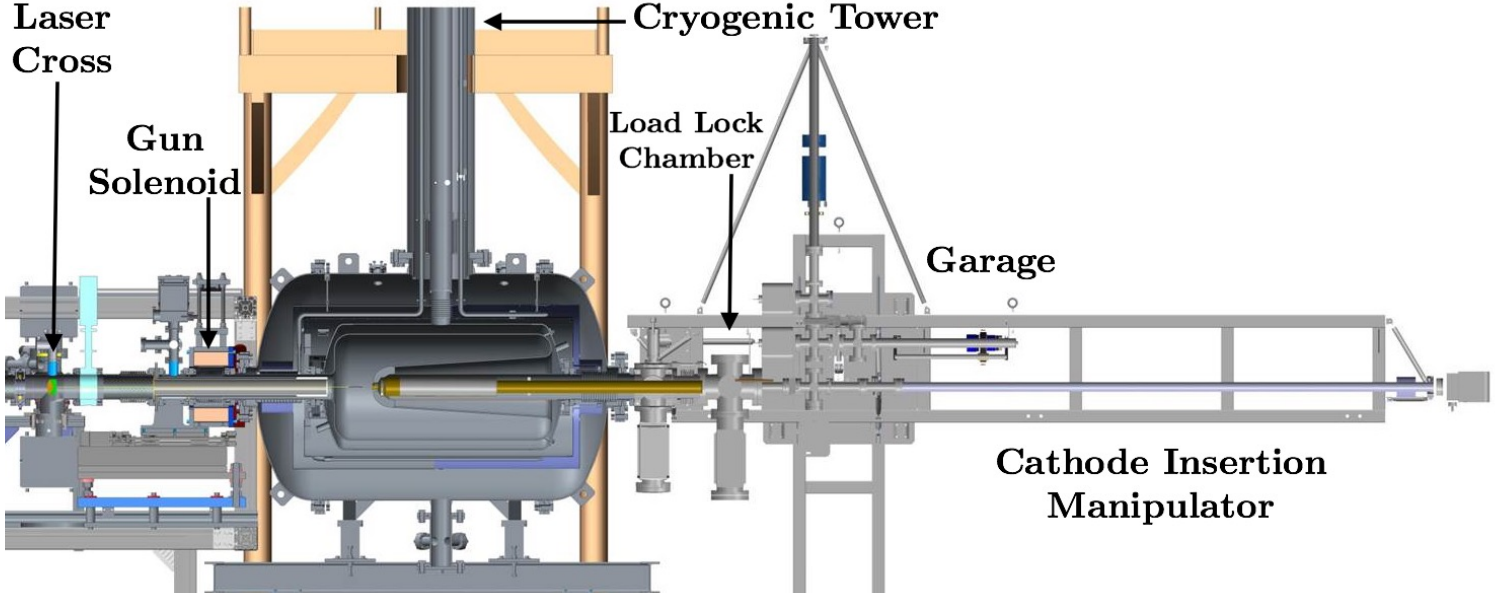
Generation of high-brightness electron beams:

BNL 113 MHz SRF gun with warm CsK_2Sb photocathode



Highlights:

- Routine operation for the Coherent electron Cooling (CeC) experiment since 2016
- 1-2 months lifetime of high-QE CsK_2Sb cathodes
- Dedicated procedure for the cavity start-up – no issues with multipacting
- 0.15 mm-mrad normalized RMS slice emittance measured for 100 pC bunches



Parameters	Value
RF Frequency, MHz	113
Operational Temperature, K	4
E_{max}, MV/m	18
Accelerating Voltage, MV	1.25 (CeC), 1.5 (max CW)
Max. Bunch Charge, nC	**20**
Dark current, nA	<1
Photocathode	CsK_2Sb
Laser wavelength, nm	532

PHYSICAL REVIEW LETTERS **124,** 244801 (2020)

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

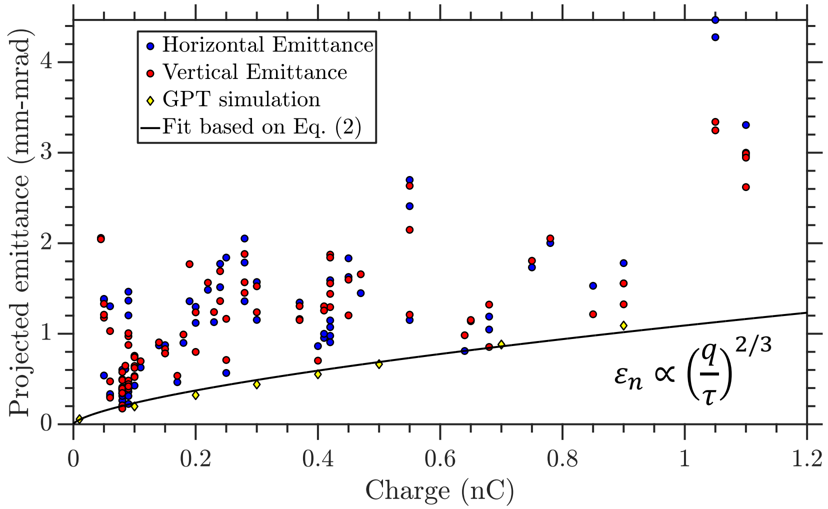
I. Petrushina,[1,2] V. N. Litvinenko,[1,2] Y. Jing,[1,2] J. Ma,[2] I. Pinayev,[2] K. Shih,[1] G. Wang,[1,2] Y. H. Wu,[1] Z. Altinbas,[2] J. C. Brutus,[2] S. Belomestnykh,[3] A. Di Lieto,[2] P. Inacker,[2] J. Jamilkowski,[2] G. Mahler,[2] M. Mapes,[2] T. Miller,[2] G. Narayan,[2] M. Paniccia,[2] T. Roser,[2] 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]

[1]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4]*Niowave Inc., Lansing, Michigan 48906, USA*

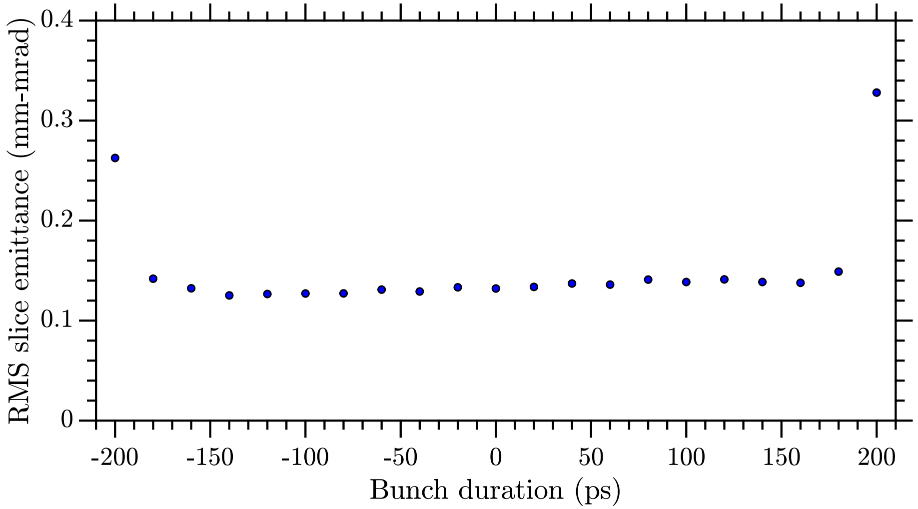
(Received 16 March 2020; accepted 29 May 2020; published 18 June 2020)

Generation of high-brightness electron beams:

BNL 113 MHz SRF gun with warm CsK_2Sb photocathode

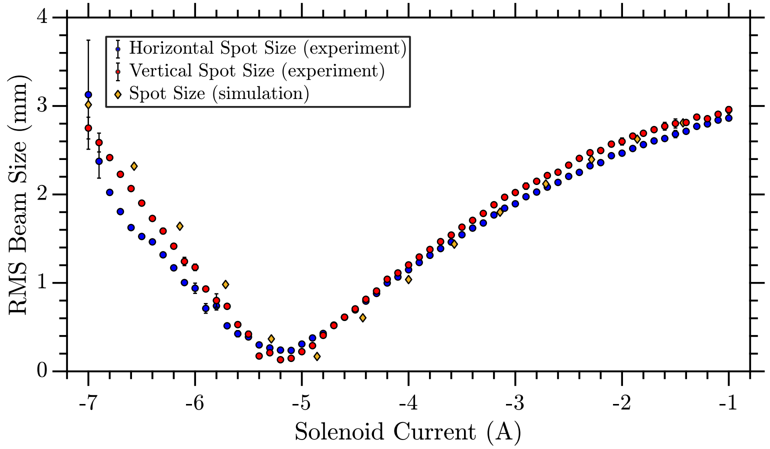


Summary of the emittance measurements in 2017-2018



Slice emittance for a 100 pC, 400 ps bunch (GPT)

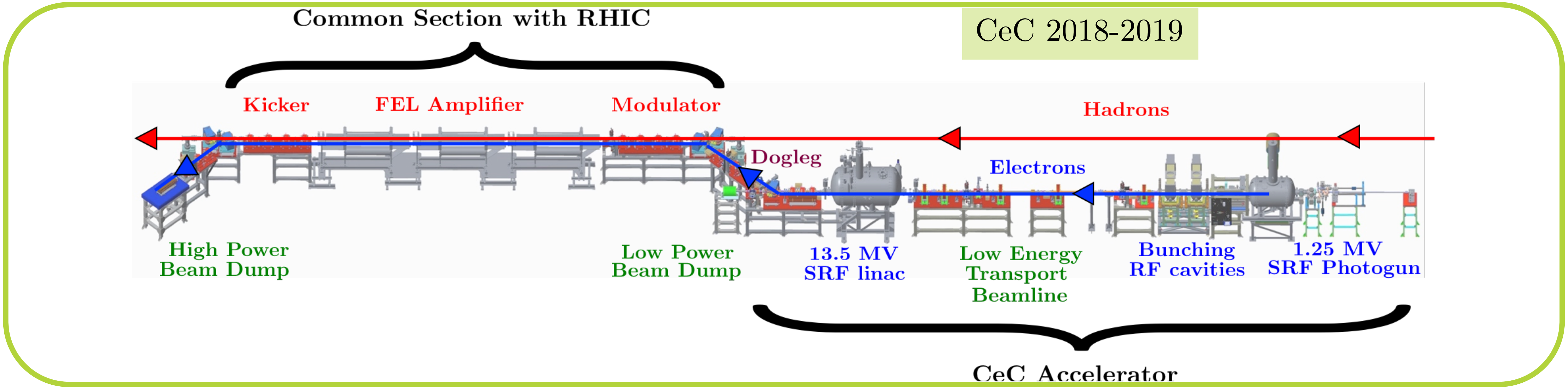
Parameters	Value
Gun Voltage, MV	1.25
Charge per Bunch, pC	100-20,000
Average Beam Current, mA @ 1500 pC	0.15
Normalized transverse RMS slice emittance @ 100 pC, mm-mrad	0.15
Normalized transverse RMS projected emittance @ 100 pC, mm-mrad	0.3
Longitudinal RMS slice emittance @ 100 pC, keV-ps	0.7
Quantum Efficiency, %	1-4



Solenoid scan – good agreement between the simulations (ASTRA) and measurements

Measuring beam noise at 10-100 THz: Plasma-Cascade Instability

CeC PoP: Ion Imprint Studies



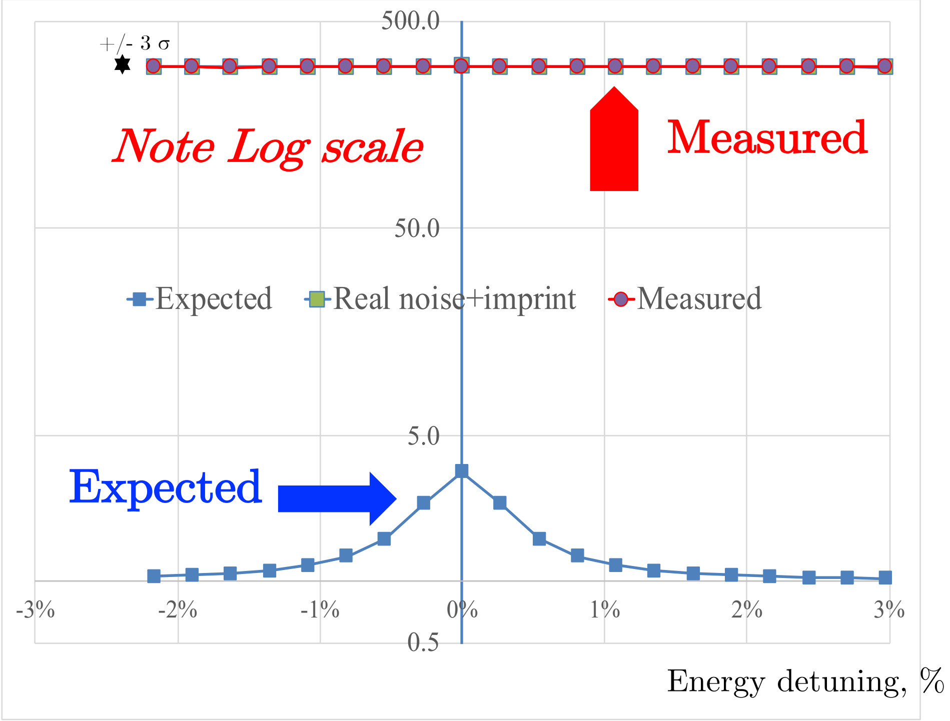
First milestone: demonstrate ion imprint

- Fundamental process of Debye screening that plays a critical role in CeC
- Dependence of the imprint on the difference in the electron and hadron beam velocities can be used to match the relativistic factors between the two beams
- Can be measured by detecting the increase in IR radiation power at ~10 THz during the interaction

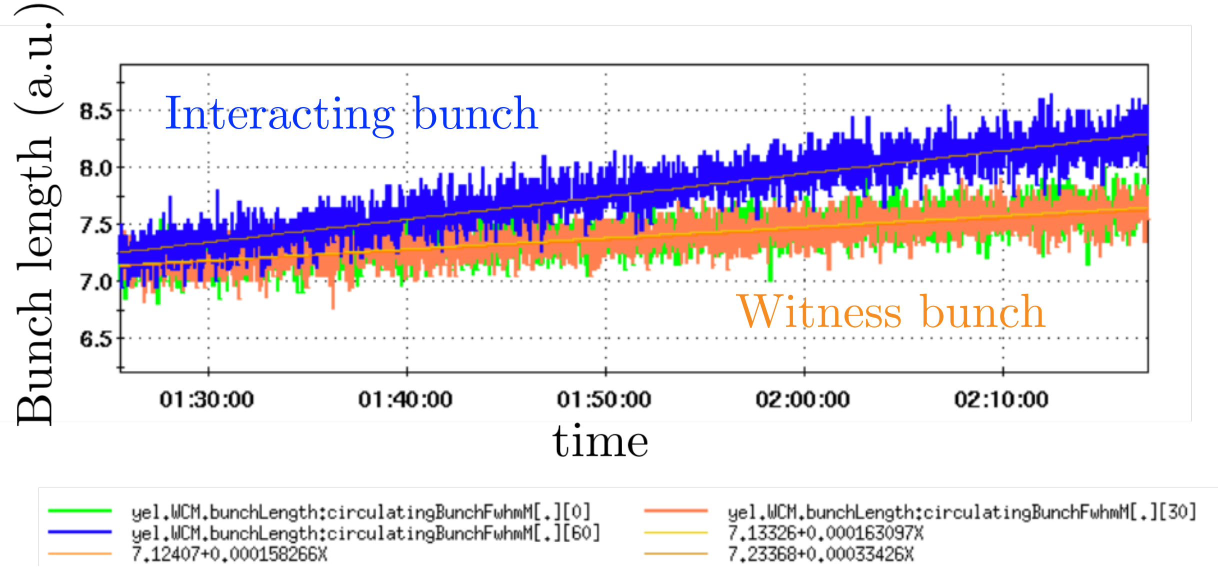
CeC PoP: Mystery of 2018

Goal: demonstrate imprint from the ion beam through modulation/demodulation technique

Imprint was screened by very high level of noise in the electron beam



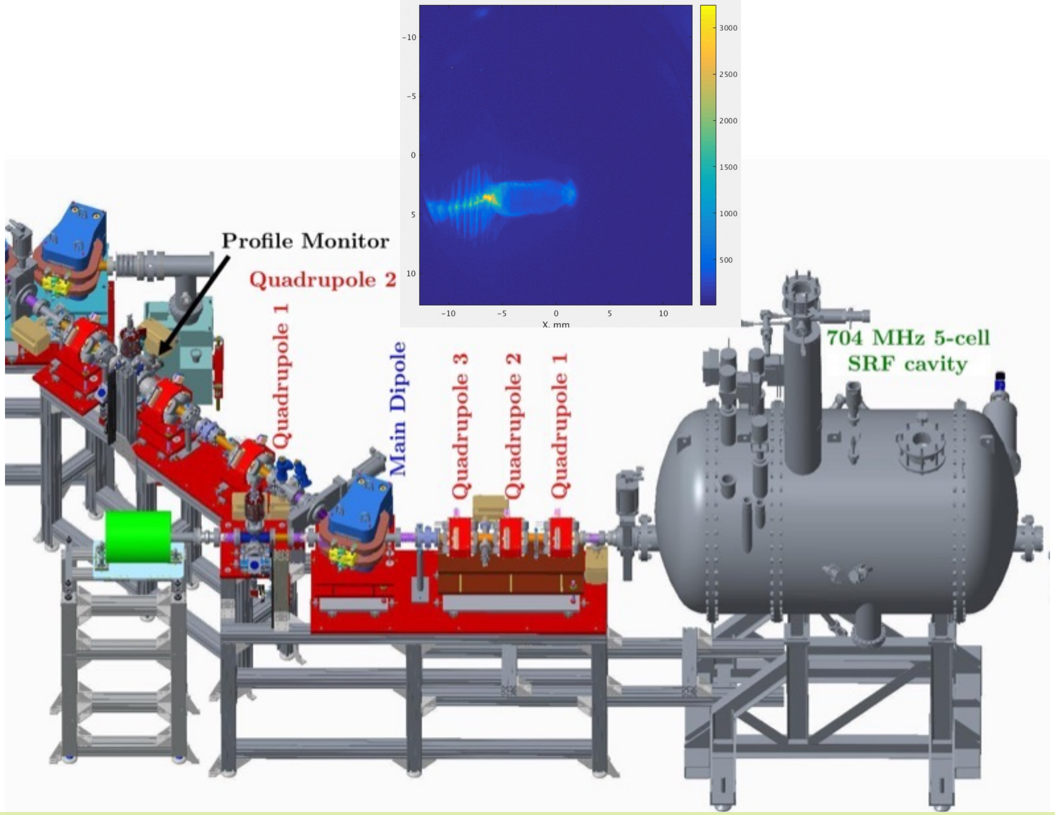
Expected and measured relative change in the FEL signal with overlapping and separated beams. Measurements RMS error was 2%.

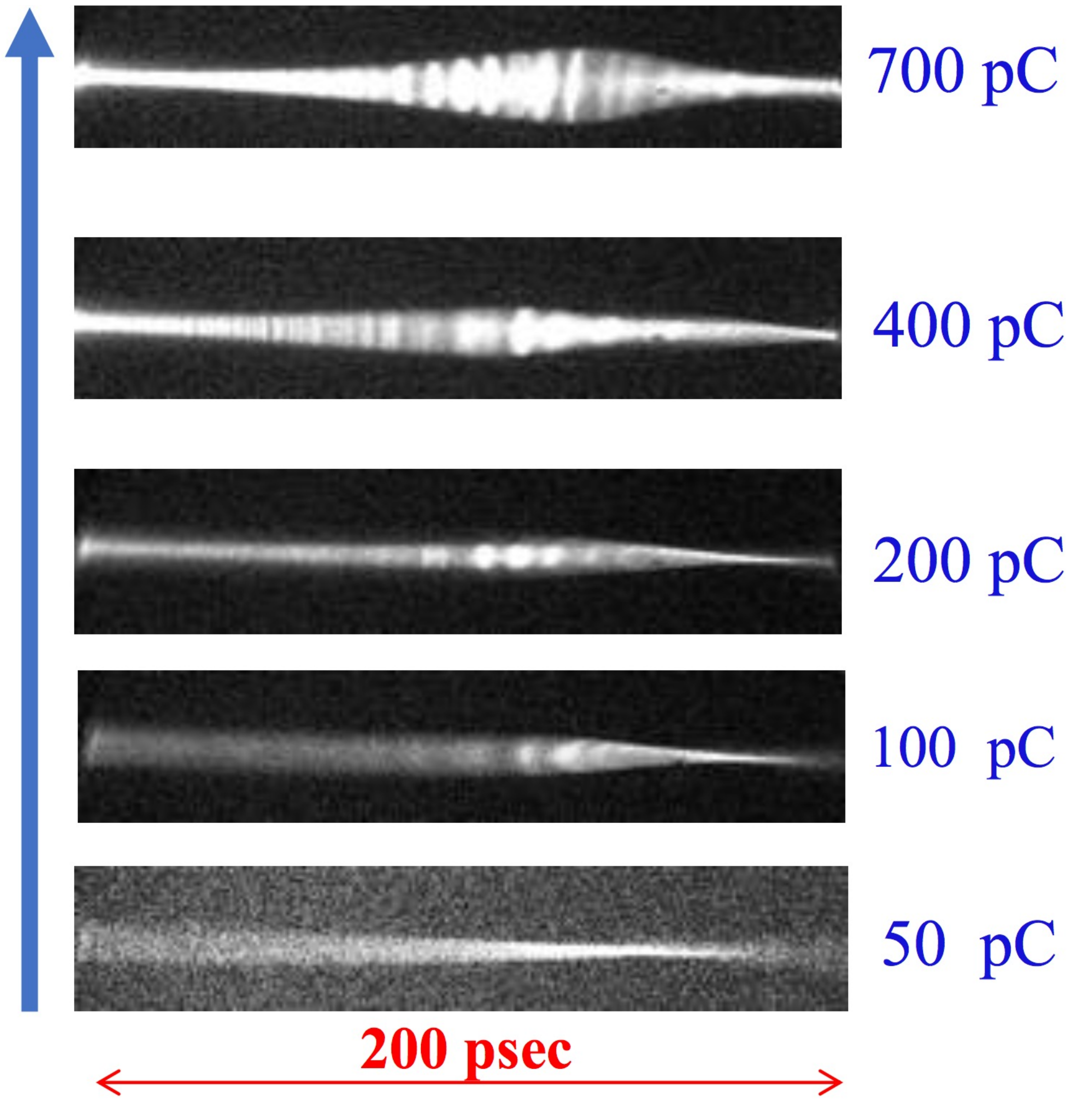


Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

Brookhaven National Laboratory

CeC PoP: Mystery of 2018





- Bunch spectra have demonstrated a broadband gain peaking at 0.4 THz in an uncompressed beam
- Bunched beam spectrum has a peak at 10 THz.
- The measurements were confirmed through simulations done by SPACE and Impact-T.

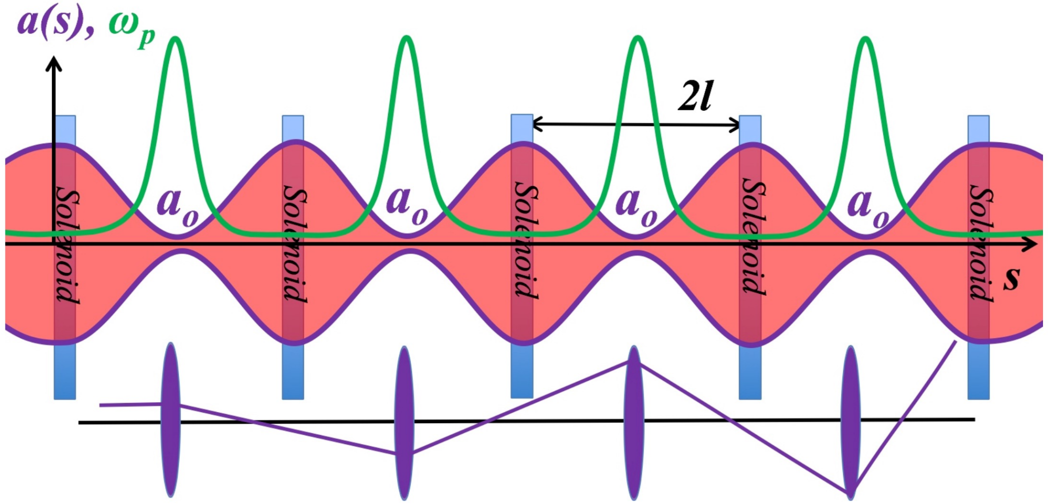
Brookhaven National Laboratory

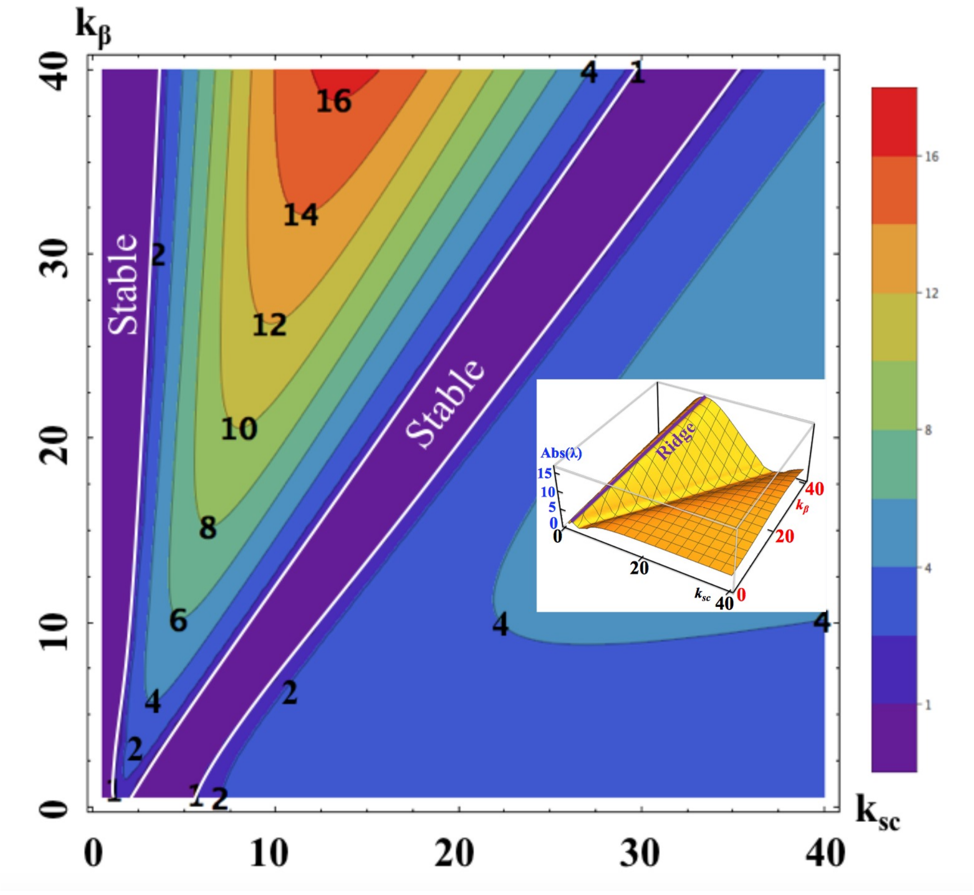
Plasma-Cascade Instability (PCI)

longitudinal plasma oscillation with periodically varying plasma frequency

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

$$\tilde{n}'' + \omega_p^2(s)\tilde{n} = 0$$





$$\hat{a}'' - k_{sc}^2 \hat{a}^{-1} - k_\beta^2 \hat{a}^{-3} = 0, \quad \hat{n}'' + 2k_{sc}^2 \hat{a}^{-2}\hat{n} = 0.$$

$$\hat{a} = \frac{a}{a_0}, \; \hat{s} = \frac{s}{l} \in \{-1, 1\}$$

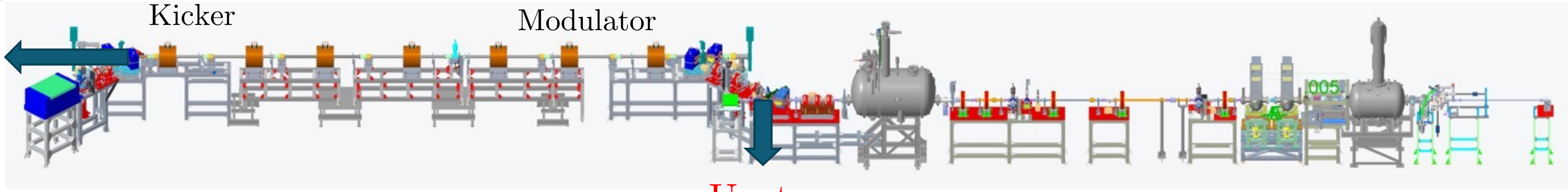
$$k_{sc} = \sqrt{\frac{2}{\beta^3\gamma^3}\frac{I_0}{I_a}\frac{l^2}{a_0^2}}, \; k_\beta = \frac{\varepsilon l}{a_0^2}$$

Brookhaven National Laboratory

CeC PoP Experiment: from FEL to PCA

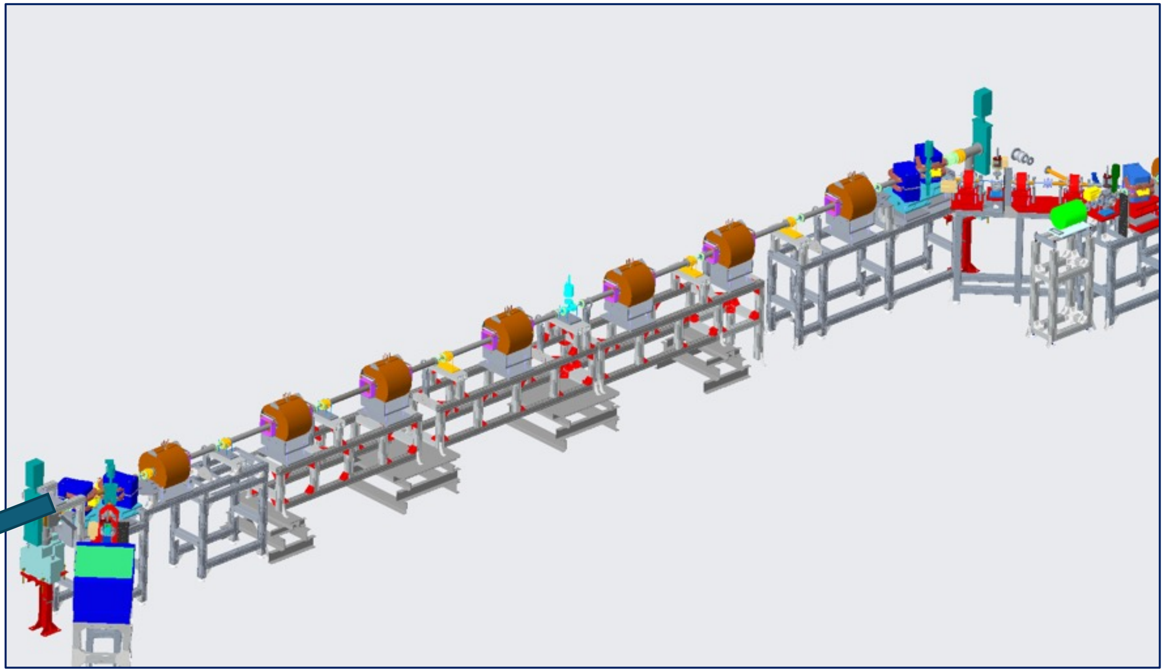
To Downstream
IR detector

4-cell PCA



Upstream
IR detector

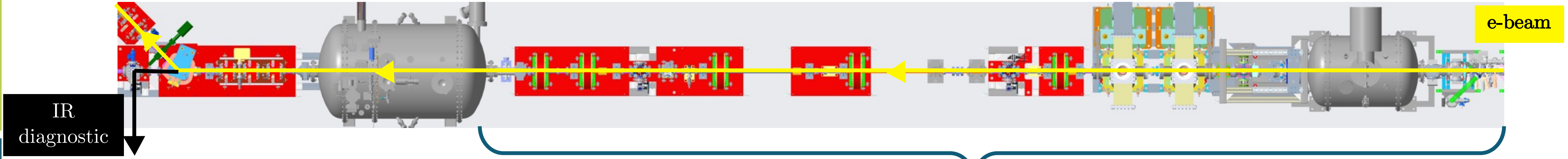
10 m to
Downstream
IR detector

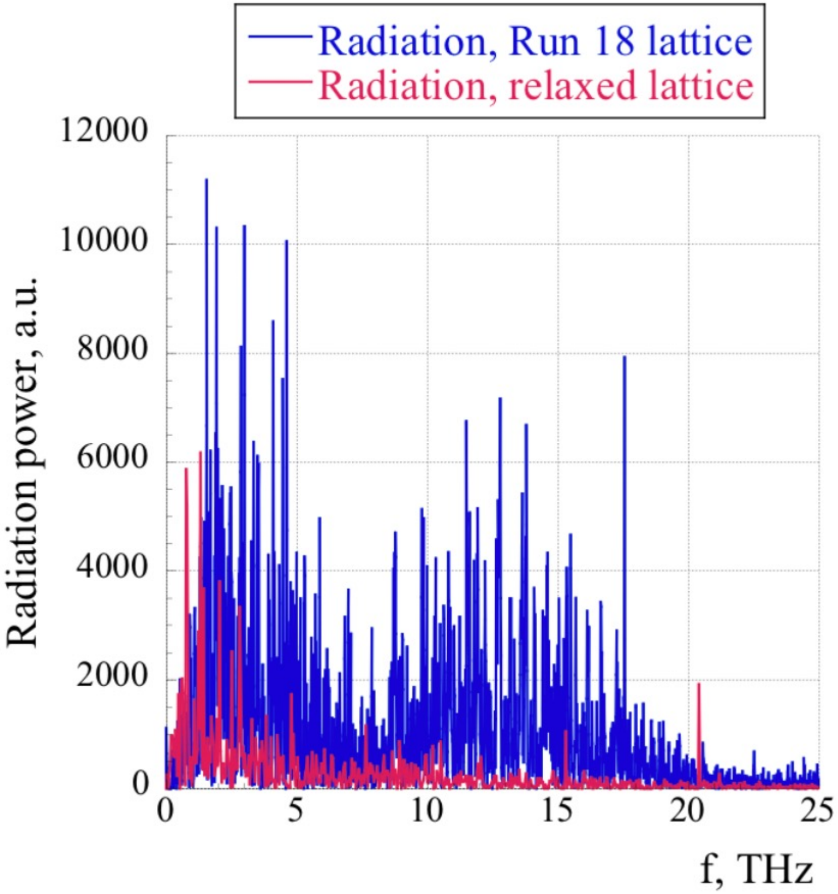


1 m to
Upstream
IR detector

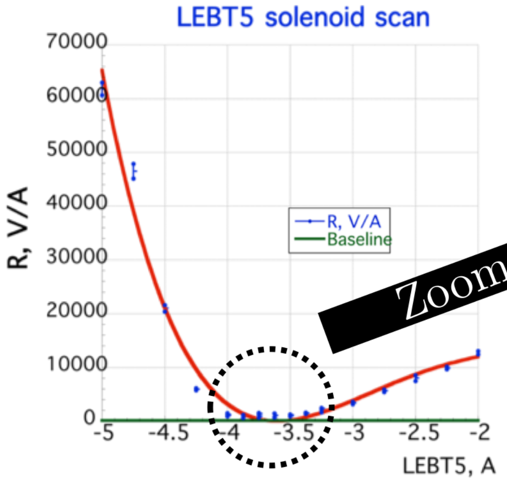
Brookhaven National Laboratory

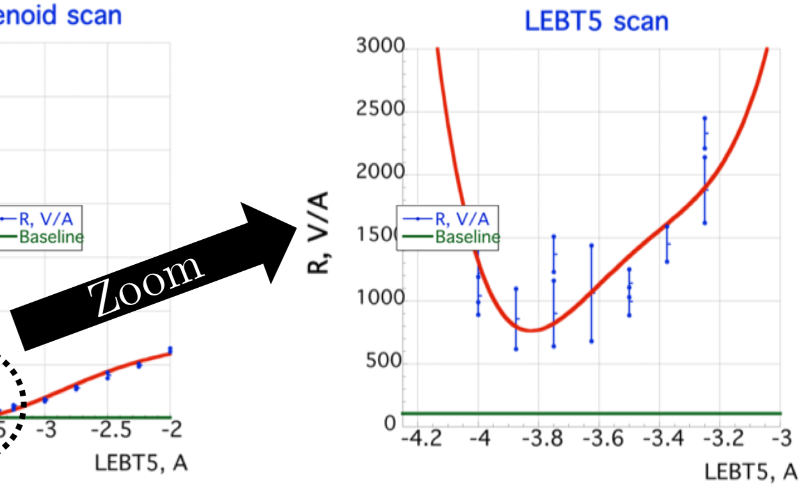
CeC PoP Experiment: e-beam noise level





- THz noise results in IR radiation from the dipole magnet.
- Power is measured by a Gentec broad-band IR detector connected to a lock-in amplifier synched with the pulsing e-beam.
- IR radiation measured through modulation/demodulation technique to eliminate effect of X-rays from the dumped beam on the IR detector.
- The baseline power level (e.g. power from the Poisson shot noise) was measured using long low charge (~300 pC) beam propagating in relaxed lattice. Measurements were in good agreement with simulations.



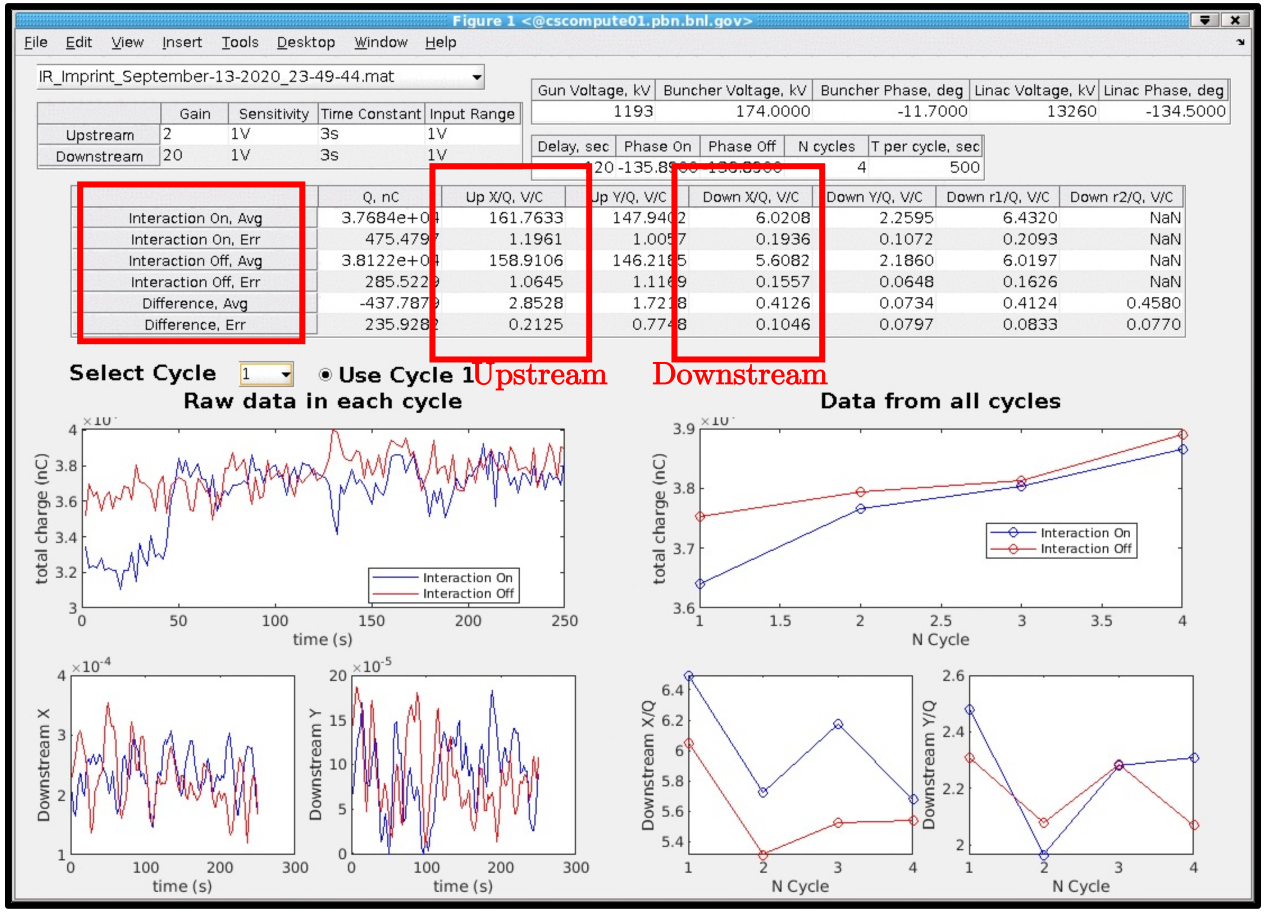


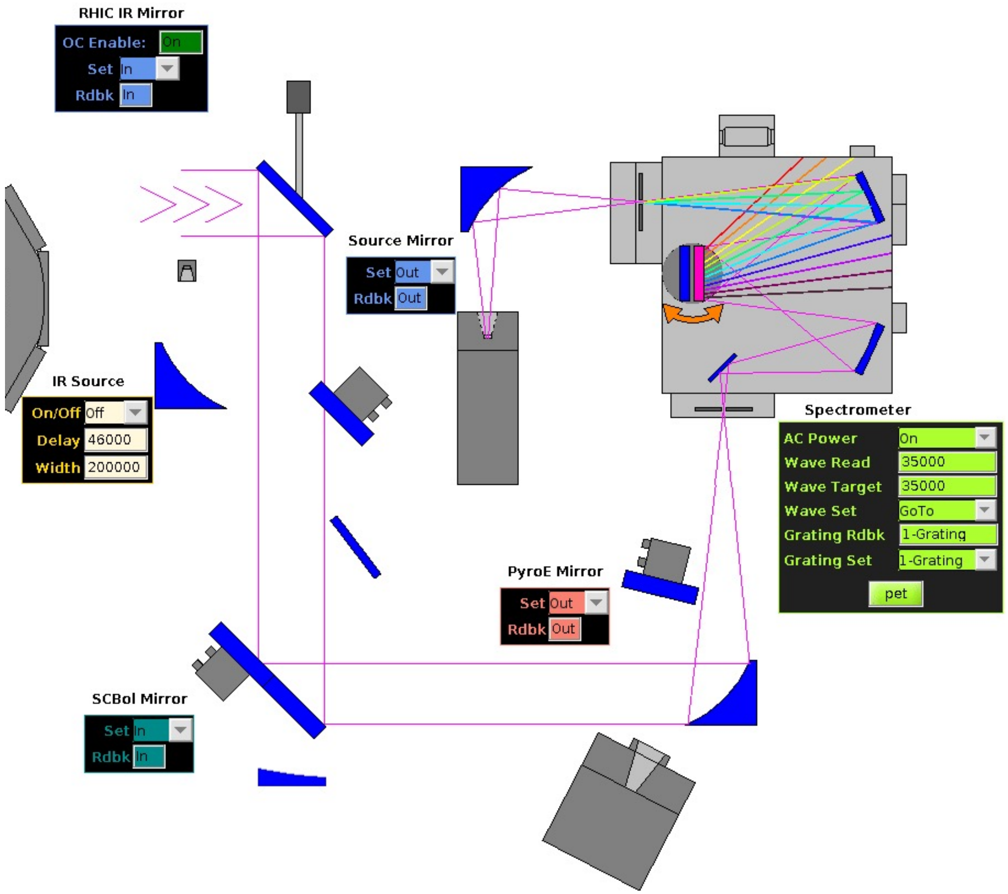
Brookhaven National Laboratory

CeC PoP: Ion Imprint Studies

We observed clear presence of the ion imprint in the electron beam resulting in increase of the e-beam radiation at 35 μm

$$\langle imprint \rangle = 4.7\% \pm 0.4\%(systematic) \pm 0.3\%(random)$$

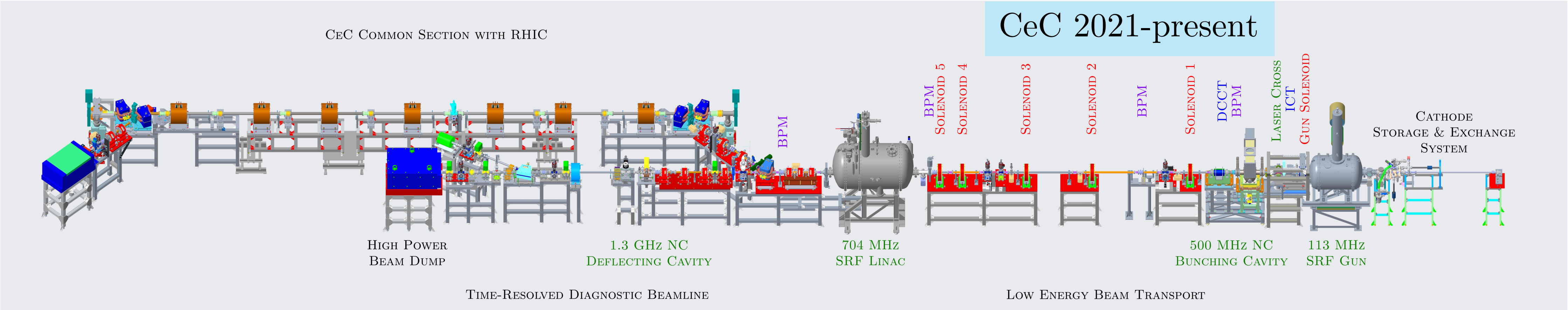




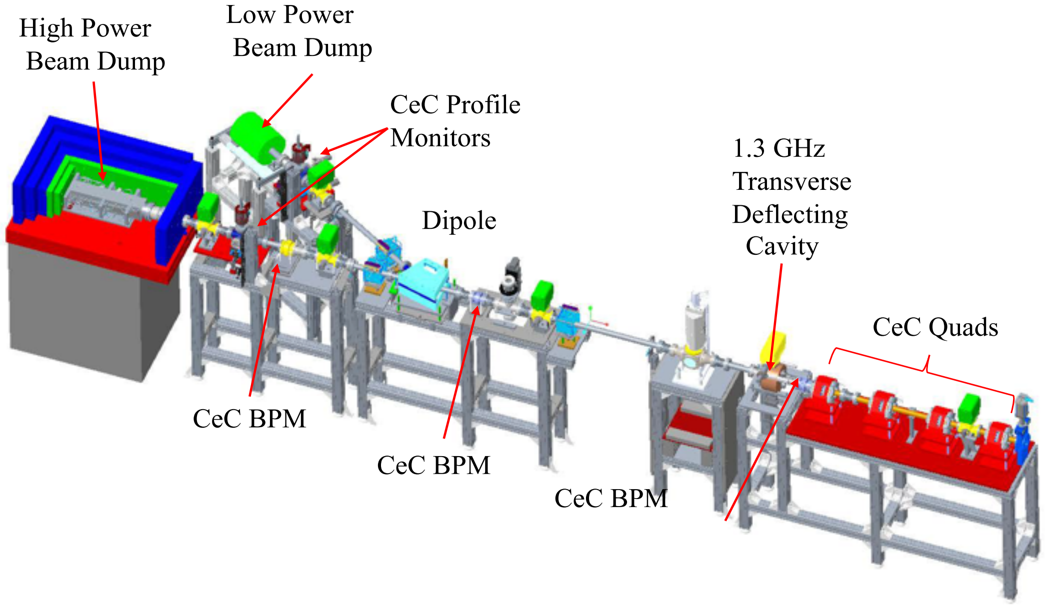
Brookhaven National Laboratory

Future Directions and Outlook

CeC PoP: Time-resolved diagnostics beam-line (TRDBL)

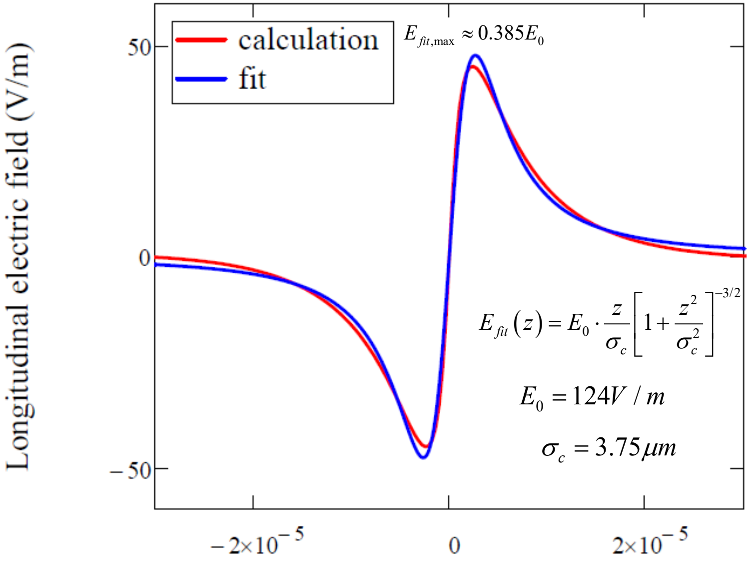


- Allows to evaluate local beam quality of electron beam with time resolution of 1 psec
- Critical for achieving KPP for Run 2022

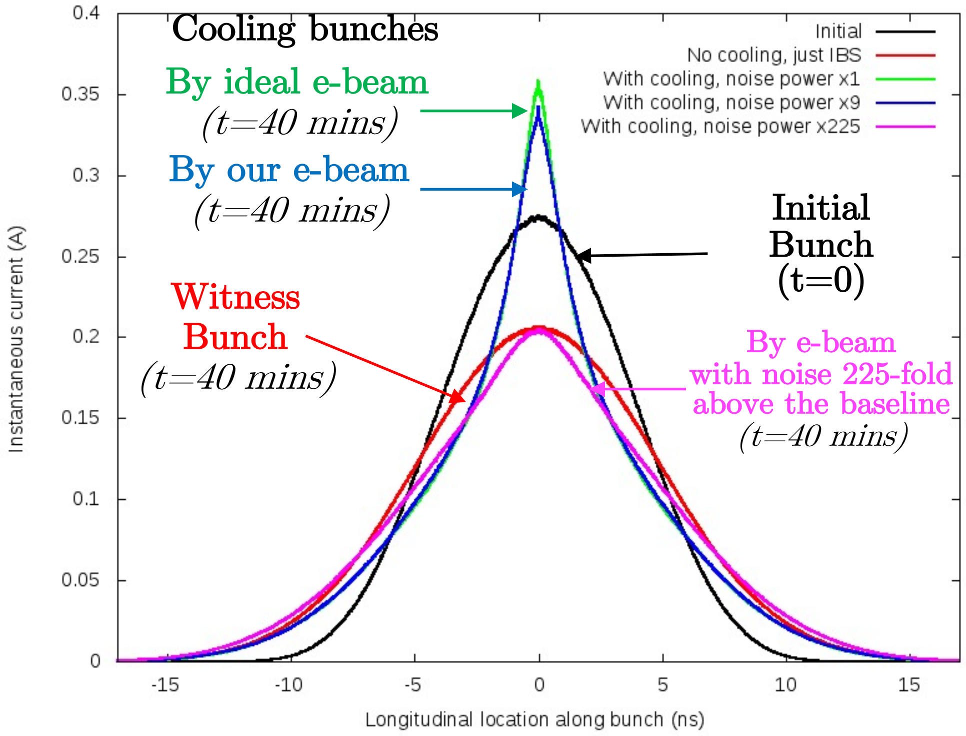


CeC PoP: prediction for 2022/2023

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



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

Brookhaven National Laboratory

Conclusions

- A unique 113 MHz SRF photo-injector demonstrated an exceptional performance and the ability to deliver high-quality high-brightness electron beams
- We learned how to control noise in the electron beam and how to generate electron beams with the quality necessary for the CeC demonstration
- The Plasma-Cascade Amplifier gain is characterized, and the PCA-amplified ion imprint in the electron beam is demonstrated
- The system upgrade includes the Time-Resolved Diagnostic Beamline and Cryo-Cooled IR detector
- We are determined to demonstrate longitudinal cooling of 26.5 GeV/u ion beam in RHIC in the near future

Thank you!

Back-up

Necessary Beam Parameters for Run 20

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 = σ_p/p, rms	$\leq 1.5\times10^{-3}$	✓
Normalized rms slice emittance, µm rad	≤ 5	✓

Brookhaven National Laboratory

Accelerator system and Beam energy

KPP: E_e=14.56 MeV

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

/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) erllqLoop.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.

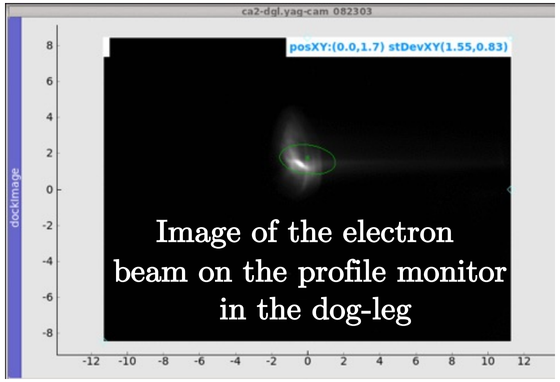
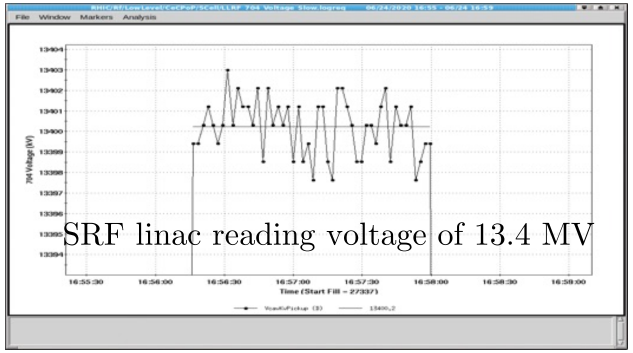


Image of the electron beam on the profile monitor in the dog-leg

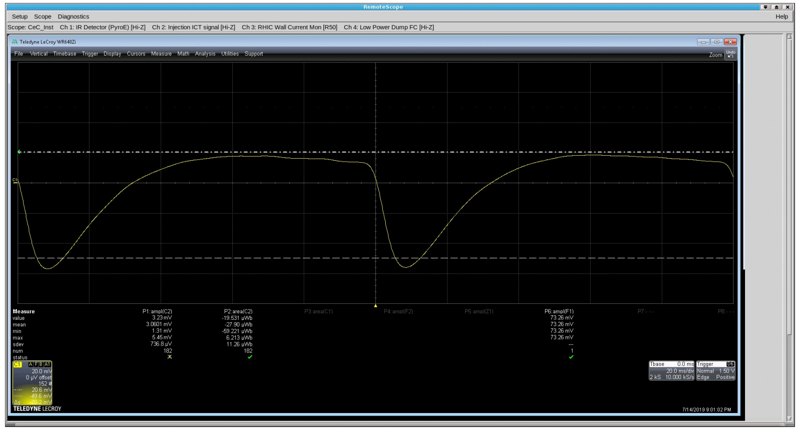

SRF linac reading voltage of 13.4 MV

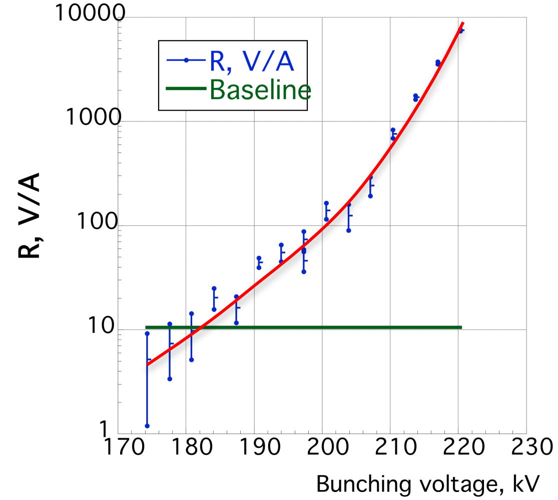
- Maximum energy with this setting is 14.92 [MeV], γ=29.2, 2.5% above γ=28.5
- Linac has additional 2.2% head room to operate at 13.4 MV

Brookhaven National Laboratory

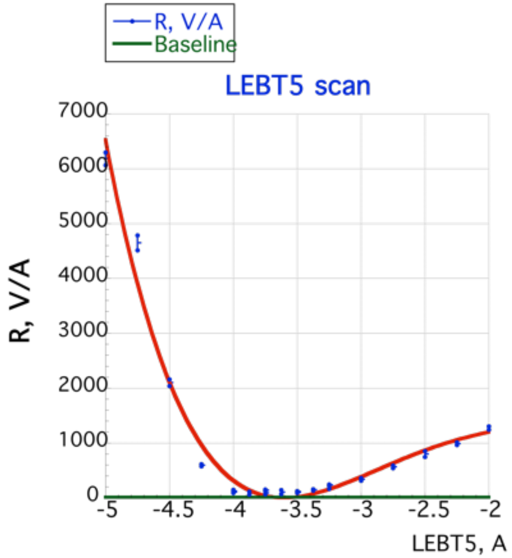
Run 19: control of the noise in electron beam

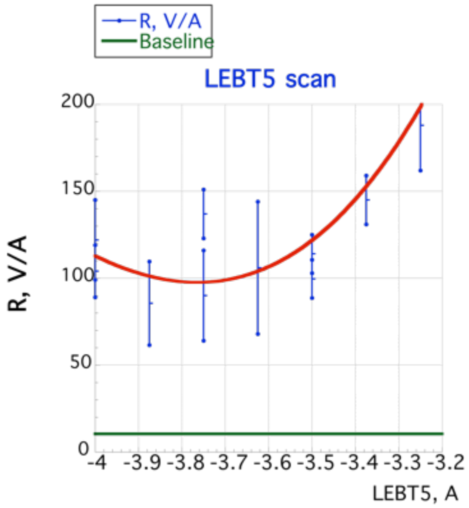
Run 18 lattice and beam: 0.6 nC per bunch
Large signal of 2,500 V/A ~250-fold above base line.
Can be seen both on scope and measured easily

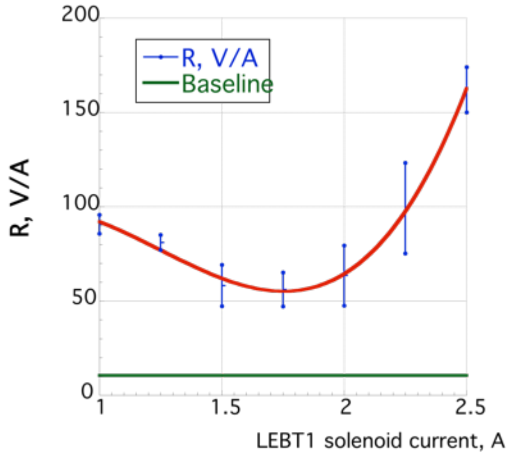




1.5 nC, 75 A peak current





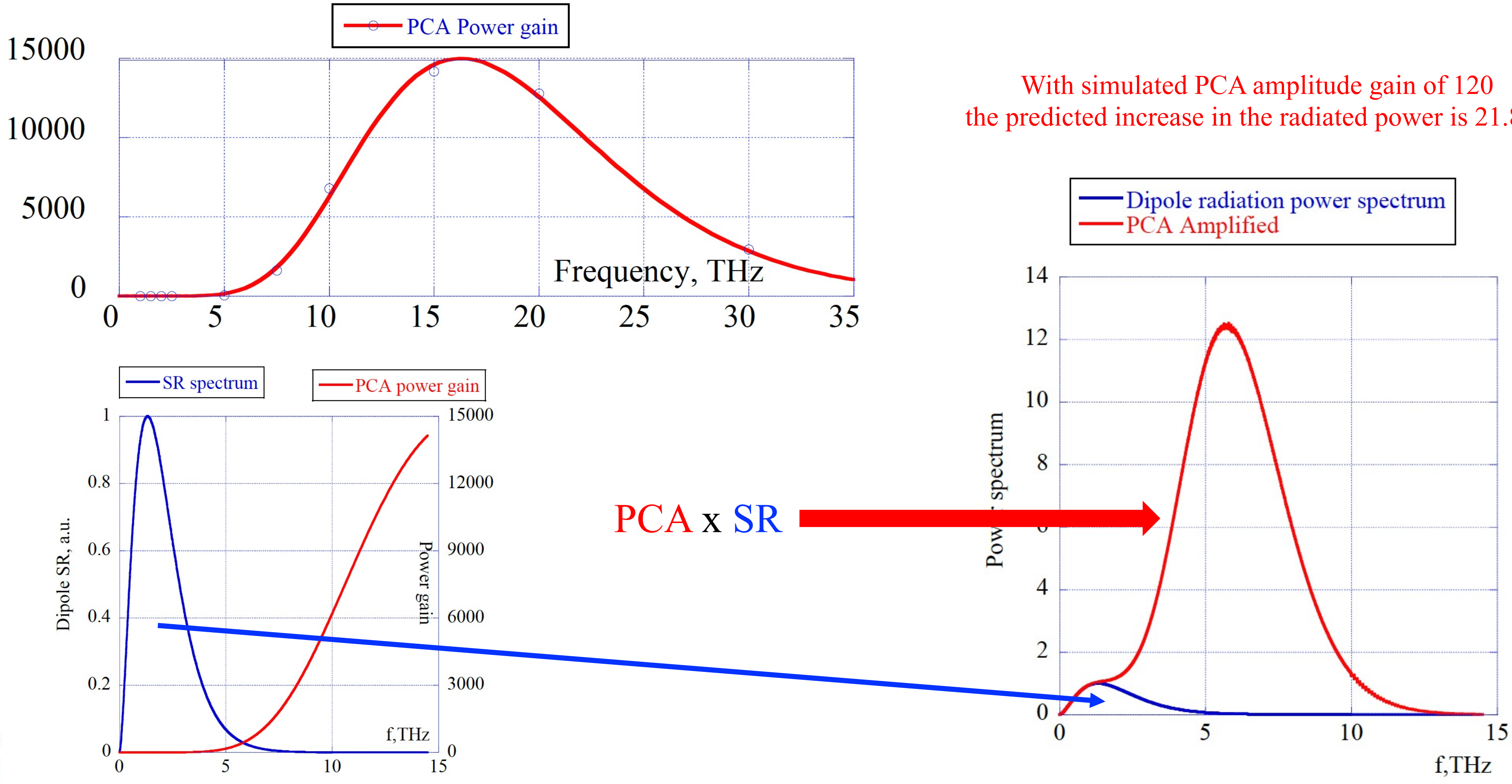


Brookhaven National Laboratory

We demonstrated that with 75 A peak current we can reduce beam noise to acceptable level. It could be as low as 6-10 times above the baseline

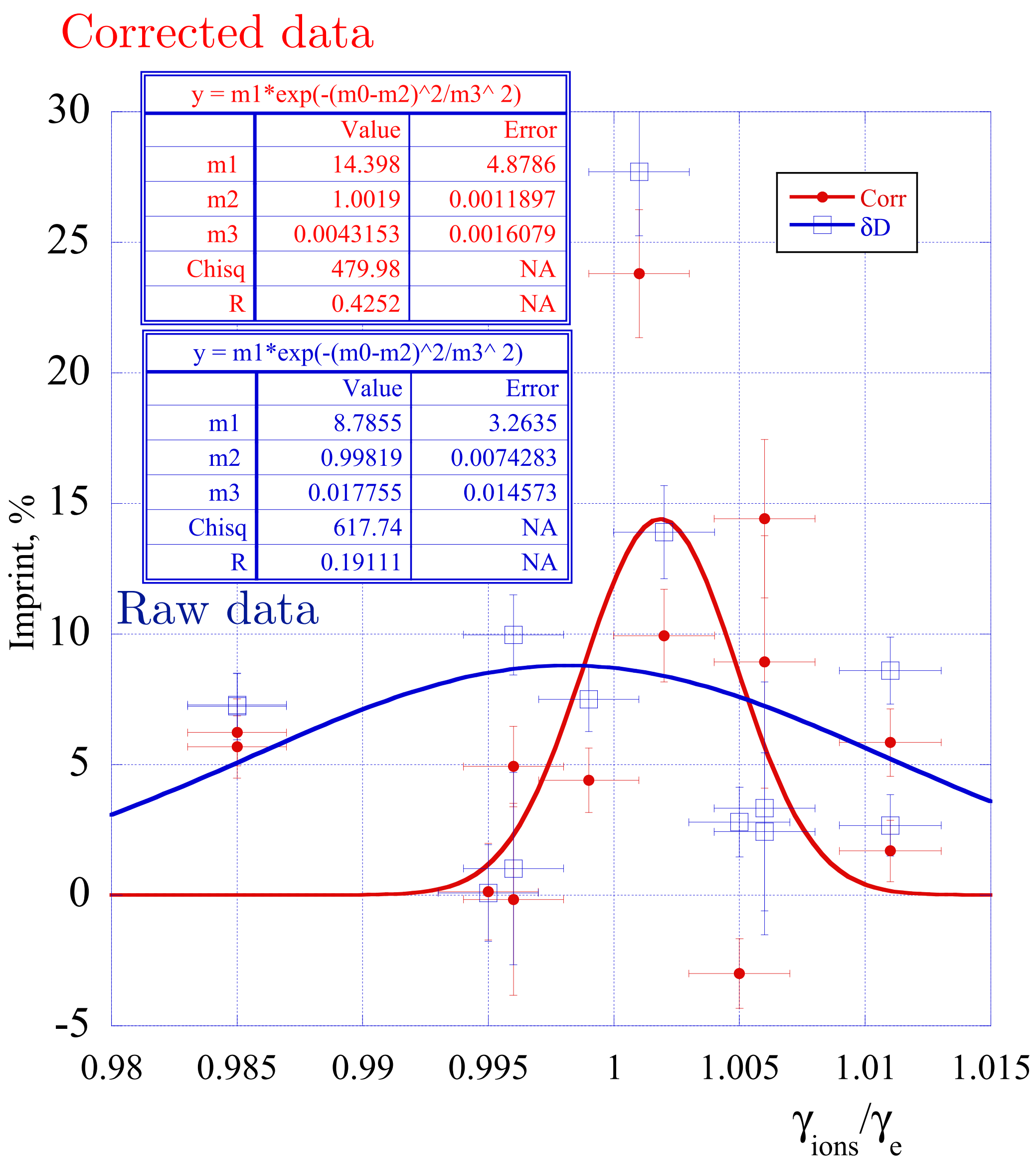
Investigation of plasma cascade amplification

- We used the power of the broad-band radiation from the dipole magnet to evaluate PCA.
- Sensitivity of the IR detectors was insufficient to measure the PCA gain spectrum.
- Initial 5-fold PCA power was increased in July-August to **200-fold**
- Weak overlap of the PCA gain and the dipole radiation spectra are the reason of the measured PCA boost in hundreds, not in thousands.
- Detailed analysis: PCA amplitude gain ~ 380, 3-fold the design value of 122.5 at 16.5 THz.



Brookhaven National Laboratory

Ion Imprint Studies



Quality of the data is insufficient to accurately determine when $\gamma_i = \gamma_e$

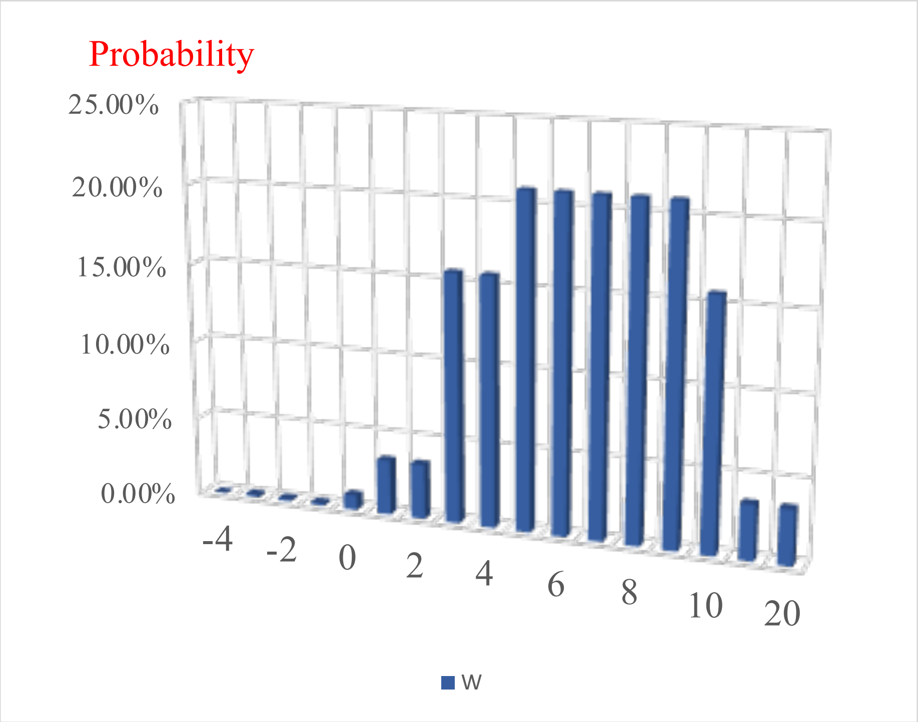
Running in the summer was challenging – temperature swings were affecting controls

Each point represents a scan (typically with 4 cycles)

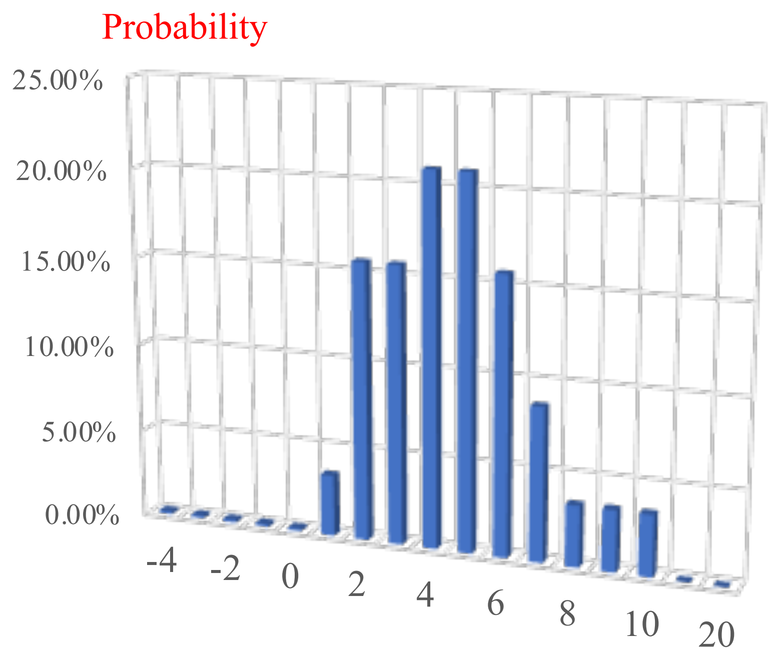
Probabilities

- Probability that average measured imprint above zero, is 99% with raw data and and 99.8% for corrected data. There is 0.2% probability that we miss the imprint
- The most probable value of observed imprint:

Imprint: Raw data



Imprint: corrected by the upstream data



Parameters of the IR detector

gentec-eo

Certificate #:	**506449-171103**	**Customer Name:**	
Model Number:	**THz5I-BL-BNC**	**Instrument ID:**	
Head Serial Number:	**506449**	**Date of Calibration:**	**November 3, 2017**
		Calibration Due Date:	*****
Cal. Procedure:	**100-1025**		

Calibration Data

Calibration									
Meaurement Parameter	Sensitivity			Into Load	**Power**	Rep.Rate	Ambient Temp.	Relative Humidity	**Beam Ø**
@ 633 nm	V/W		%	Ω	**uw**	Hz	°C	%	**mm**
Rv (P to P)	2.12E+05	±	2.1	NA	8.2	5	21	33	1
Rv (RMS)	6.91E+04	±	2.1	NA	8.2	5	21	33	1
						Hz	°C	%	**mm**
Vn (RMS) @ 1 Hz BW	1.30E-04	±	NA	NA	NA	5	21	33	NA
	$W/Hz^{1/2}$					Hz	°C	%	**mm**
NEP (P to P)	6.10E-10		NA	NA	NA	5	21	33	NA
NEP (RMS)	1.90E-09	±	NA	NA	NA	5	21	33	NA