Coherent electron Cooling (CeC) as an EIC cooler

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for the CeC group (*Yichao Jing, Jun Ma, Irina Petrushina, Igor Pinayev, Kai Shih, Gang Wang, Yuan Wu*),

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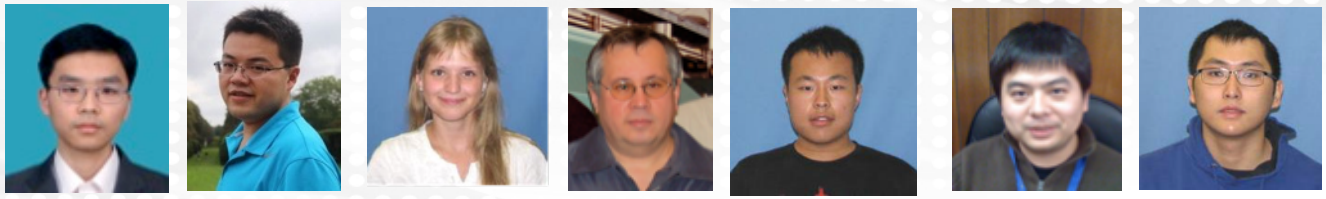


personnel from Collider-Accelerator Department, Instrumentation and Superconducting Divisions (BNL) involved in the CeC project, and collaborators from Argonne National Laboratory, Lawrence Berkeley National Laboratory, Budker Institute of Nuclear Physics, Daresubry Laboratory, Fermi National Accelerator Laboratory, Thomas Jefferson National Facility (JLab), Niowave Inc., Tech-X and SLAC National Accelerator Laboratory

What the CeC group is doing?

- Investigating CeC with plasma-cascade, chicane-based- microbunching and high gain FEL amplifiers
- Develops CeC theory in collaboration with Y. Derbenev (JLab) and D. Ratner (SLAC)
- Develops self-consistent 3D simulations in collaboration with Tech-X and CASE
- Pursues experimental CeC demonstration of 26.5 GeV/u Au ion beam circulating in Relativistic Heavy Ion Collider (RHIC, BNL)
- Developing the best – performance-wise and the cost-wise – CeC design to cool hadron beams in future EIC

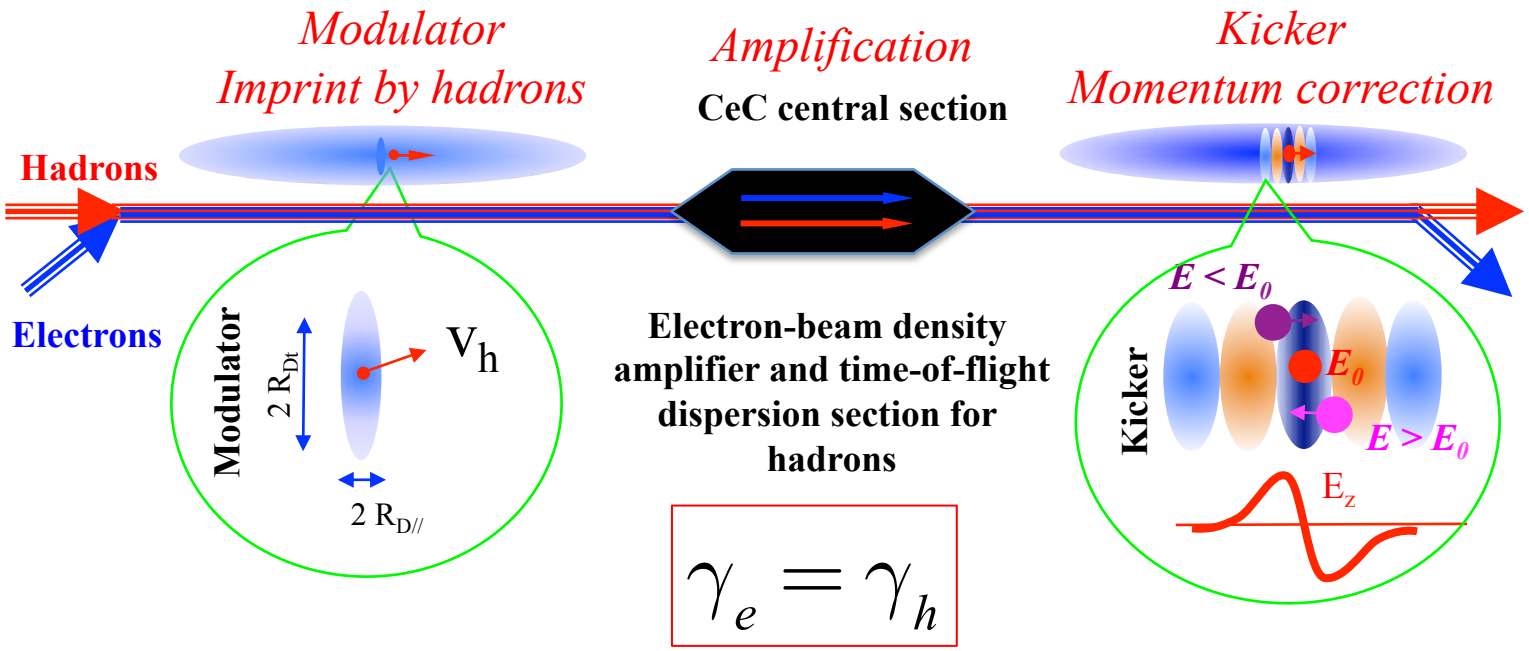
And why doing this?

In short: CeC is critical for EIC to reach luminosity of 10^{34} $cm^{-2}s^{-1}$

"The Strong Hadron cooling [Coherent Electron Cooling (CeC)] is needed to reach $10^{34}/(cm^2s)$ luminosity. Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC" , *from April 2018 EIC pCDR review committee report*

What is Coherent electron Cooling

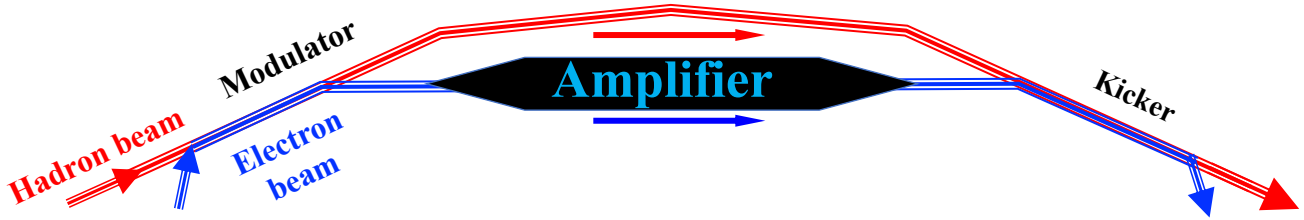
- Short answer – stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 10 – 10,000 THz



Important detail

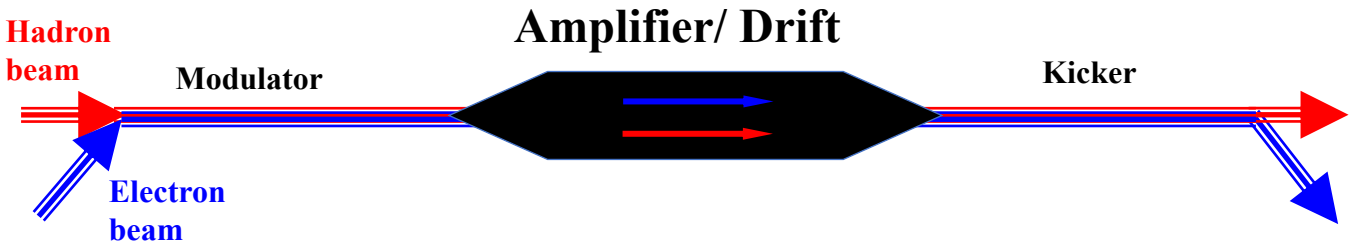
$\gamma_e = \gamma_h$

- For cooling to work y, each hadron must overlap with its own amplified imprint
- Because of huge difference in beam rigidities, any delay of electron (for example in a chicane or high K-wiggler) can not be matched by that of the hadron beam, unless beams are separated
- Hence there are two possible CeC layouts:
- *Expensive "Cadillac" option with separating electron and hadron beams*



Main advantage: additional flexibility, R_{56} control, Main disadvantages: high cost and CSR effects

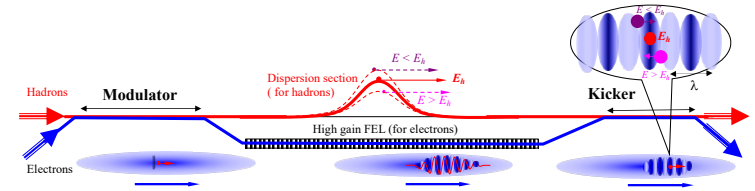
- *Low-cost "Chevy" option with co-propagating electron and hadron beams*



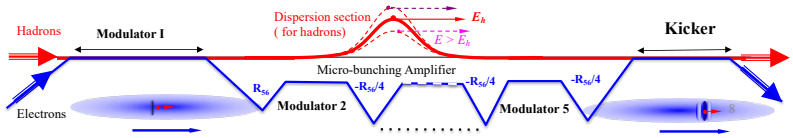
Main advantage: no CSR, low cost; Main disadvantages: reduced flexibility

Four CeC schemes

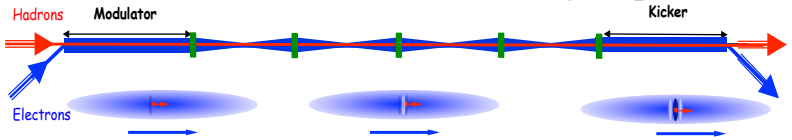
Litvinenko, Derbenev, High gain FEL, PRL 2008



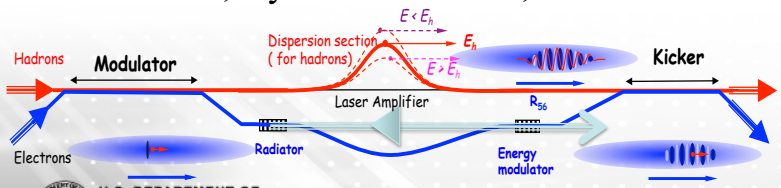
Ratner, micro-bunching amplifier, PRL 2013



Litvinenko, Wang, Kayran, Jing, Ma, 2017
Plasma cascade micro-bunching amplifier



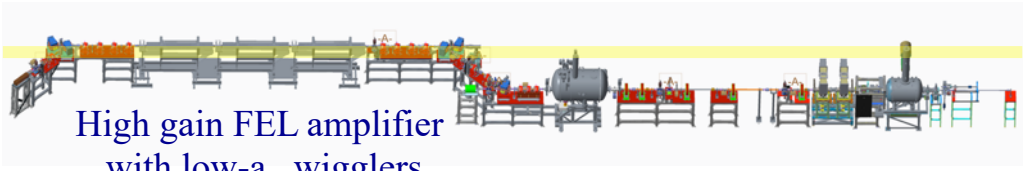
Litvinenko, Hybrid Laser-MBI, Cool 2013



What can be tested experimentally at RHIC?

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

RHIC Run 18



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

RHIC Runs 20-22

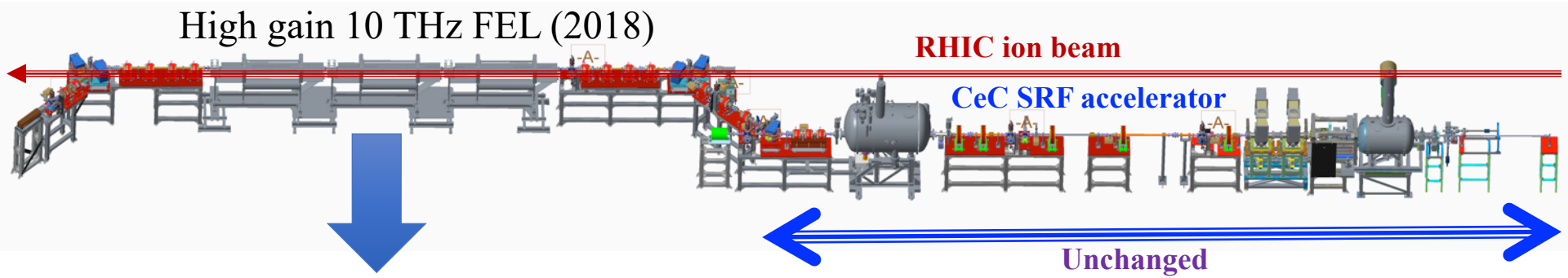
Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

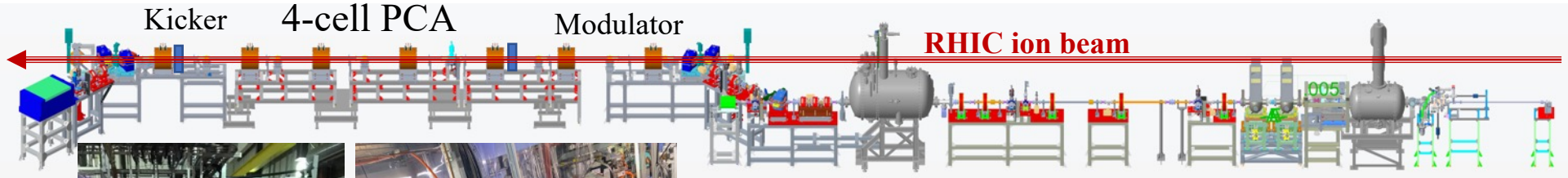
CeC performance is critical impacted by:

- Electron beam quality: peak current and energy spread, beam emittances
- Gain in the CeC amplifier (increment of the instability in electron beam) – the CeC cooling rate is proportional to the CeC amplifier gain
- Bandwidth of the CeC amplifier: in stochastic coolers it defines the maximum possible cooling rate $\tau_c > -\left(f_{rev} \frac{1}{\varepsilon} \frac{d\varepsilon}{dn} \right)^{-1} = \frac{N_s}{f_{rev}} \propto \frac{I_{peak}}{Z} \cdot \frac{1}{\Delta f}$ because random kicks generated by the amplified imprints of the neighboring hadrons cause diffusion and heating of the hadron beam
- Random noise in the electron beam is also amplified by the instability and adds to the heating of the hadron beam. Hence noise in the electron beam must be controlled and maintained low

CeC experiment at RHIC

- The experiment with the FEL-based CeC started in 2018 and was not completed.
- The **28 mm** aperture of the FEL helical wigglers was insufficient for 250 GeV RHIC to collide 3.85 GeV/u Au ion beams required for the physics program
- In 2019-2020 we replaced the FEL-based CeC with PCA-based CeC comprised of seven solenoids and vacuum pipe with 3" (**75 mm**) aperture. Experiments re-started this year.

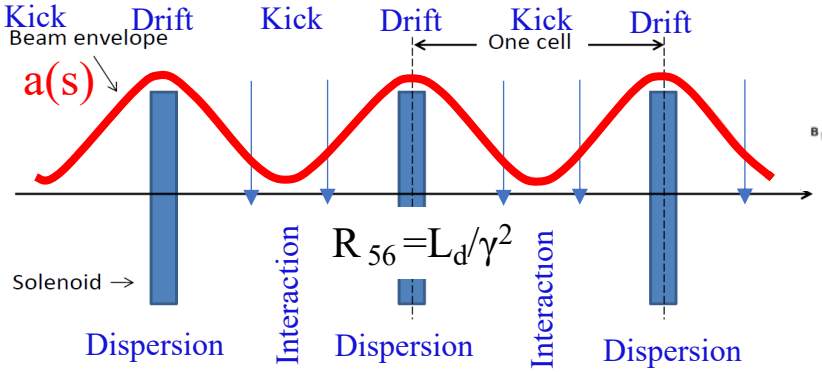




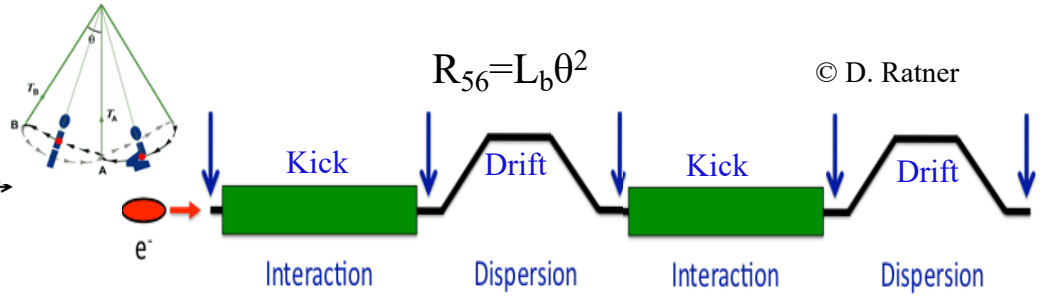
The CeC Plasma Cascade Amplifier has bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

What is Plasma-Cascade Instability (PCI)?

How is it different from the previously known micro-bunching instability (MBI)?



PCI

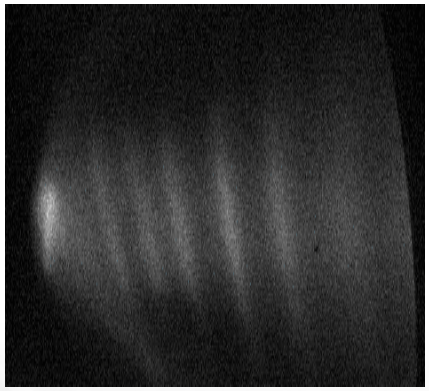


MBI

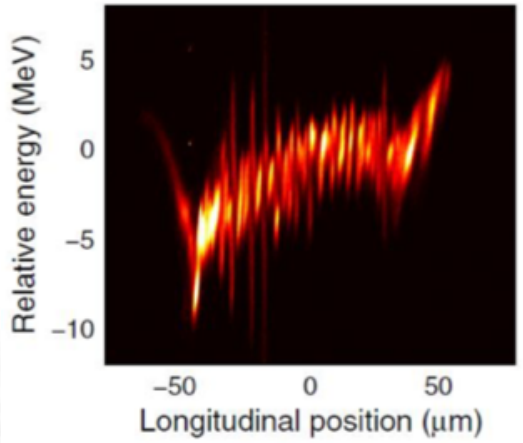
Modulate beam density by changing beam radius

MBI: modulate effective mass (*s-mobility*) by bending beam trajectory (θ)

CeC accelerator PCI experiment



LCLS

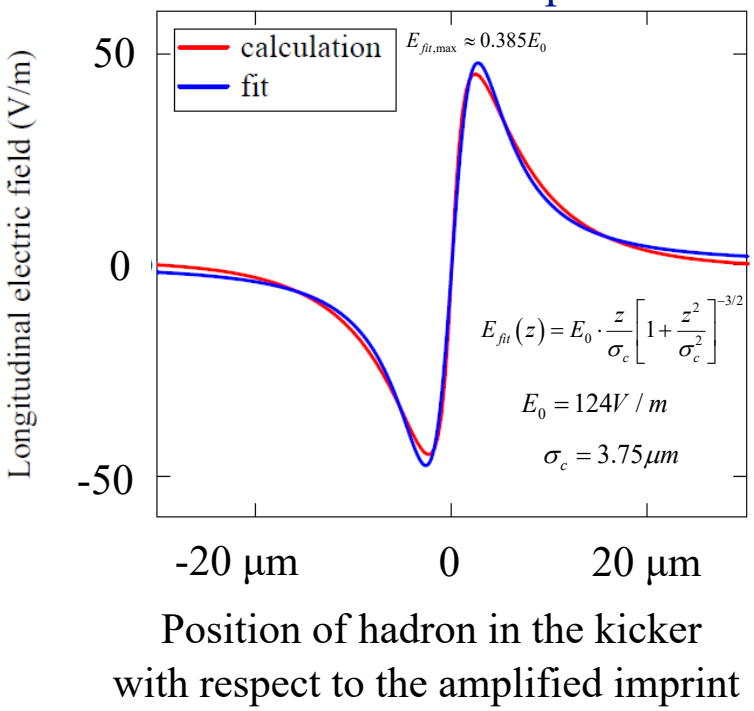


Both instabilities can be used a broad-band amplifier in CeC

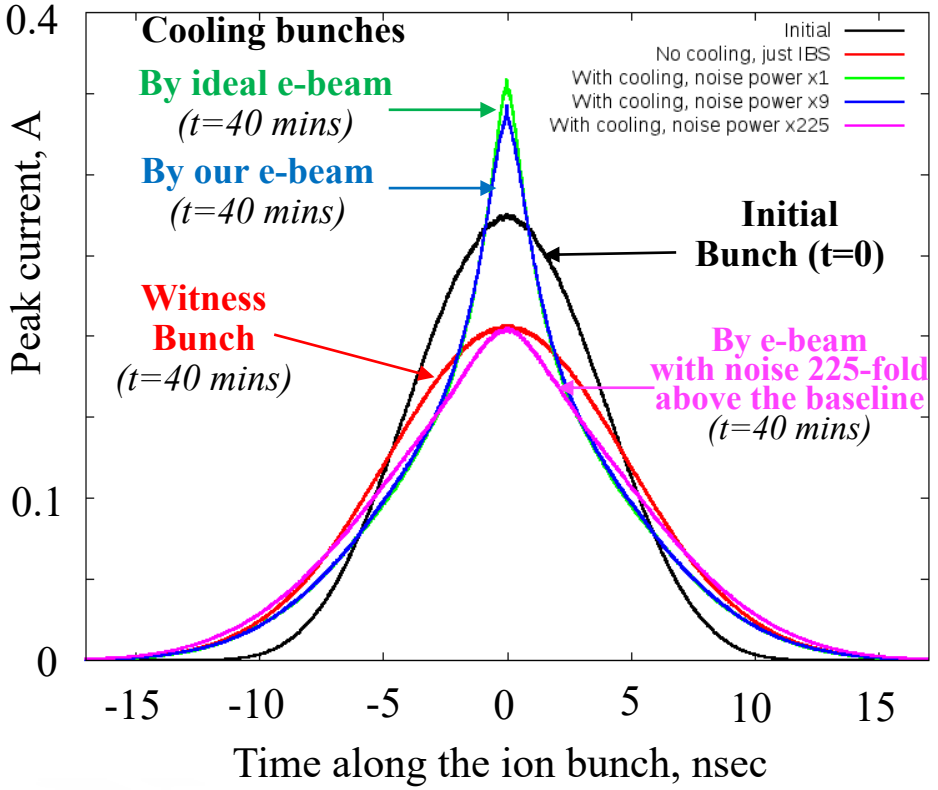
Simulated performance: full 3D treatment

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

Simulated shape of electric field in the kicker of the PCA-based CeC in current experiment



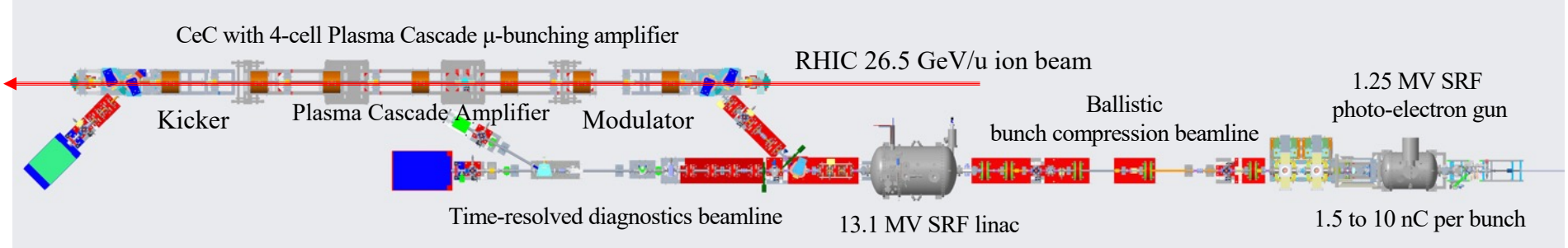
Predicted evolution of the 26.5 GeV/u ion bunch profiles in RHIC



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

Evolution of ion bunch profile in the presence of longitudinal coherent electron cooling, G. Wang, , Physical Review Accelerators and Beams, 22 (2019) 111002

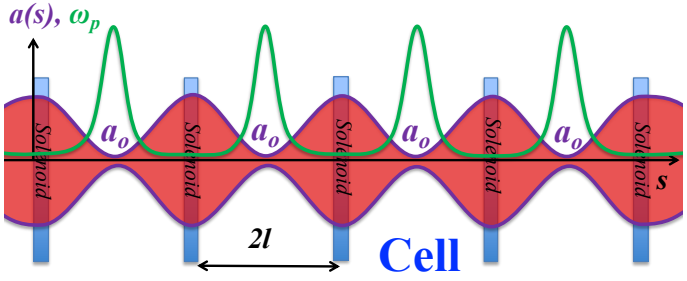
Coherent electron Cooling experiment at RHIC



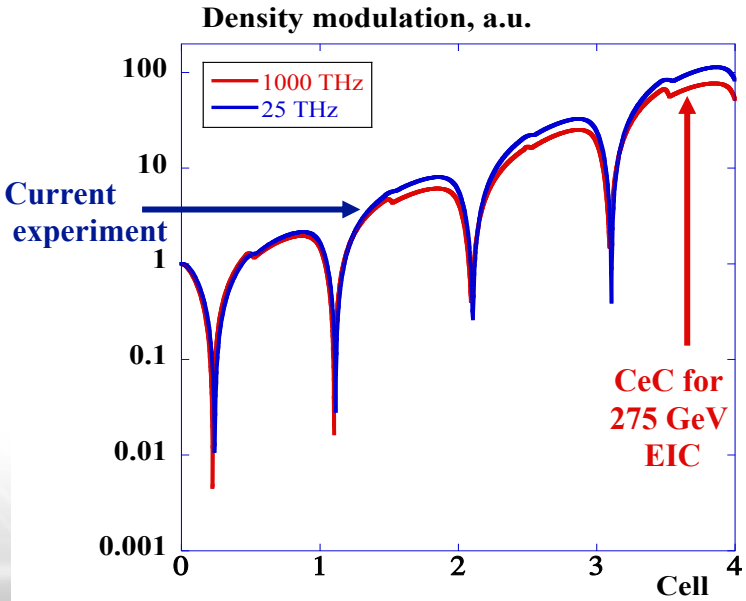
- The 14.5 MeV CW SRF accelerator with unique SRF electron gun generating electron beams with quality sufficient for the current experiment and for the future IEC cooler.
- Electron bunches are compressed to peak current of 50-100 A ,is accelerated to 14.5 MeV and merged with RHIC's 26.5 GeV/u ion beam in the CeC system
- Current CeC system has seven high field solenoids, five of which serve as a 4-cell Plasma-Cascade μ-bunching Amplifier with 15 THz bandwidth and amplitude gain exceeding 100.
- Experimental program with this system started this year
- All necessary electron beam parameters – the beam energy and peak current, the beam emittances and energy spread, the low noise in the beam (*critical and most not-trivial requirement*) - had been demonstrated. The full power CW beam was propagated with low losses through the newly built PCA CeC
- The CeC run was completed in mid-September with preliminary analysis indicating that all goals for this run had been achieved, including the ion imprint amplifier by PCA.
- The project plans are to demonstrate longitudinal CeC in 2021 and 3D (both longitudinal and transverse) CeC in 2022.

Current experiment and Cooling protons in the EIC

"Standard" 4-cell PCA

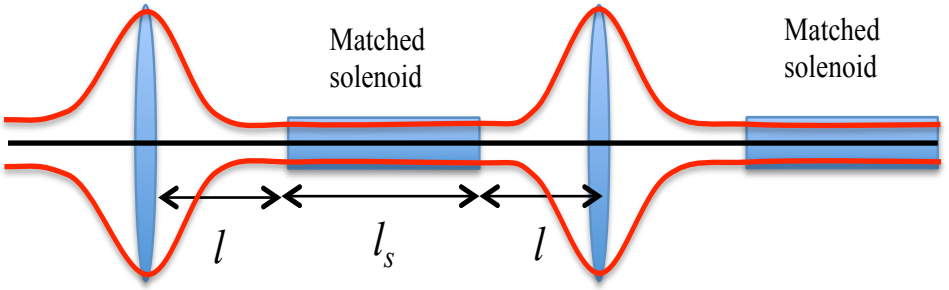


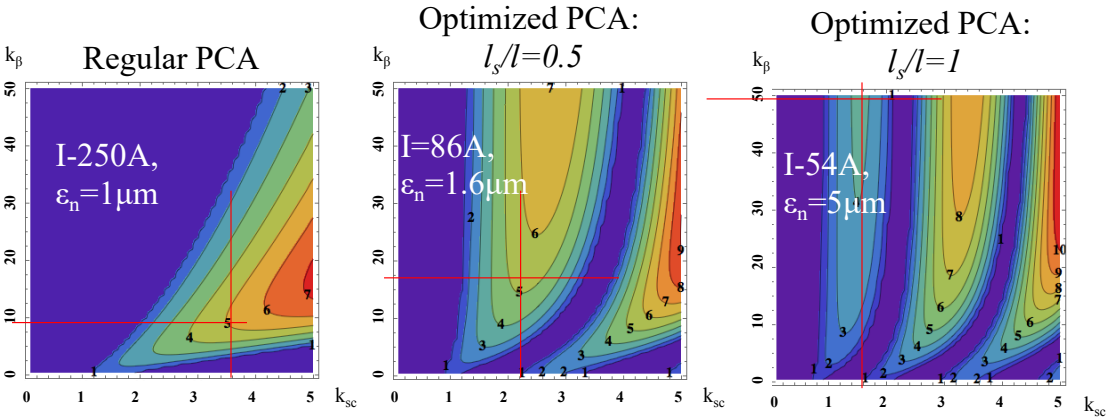
$$k_{sc} = \sqrt{\frac{2}{\beta_o^{\,3}\gamma_o^{\,3}}\frac{I_o}{I_A}\frac{l^2}{a_o^{\,2}}};\quad k_\beta = \frac{\varepsilon l}{a_o^{\,2}}$$



Results of 3D simulations with code SPACE

Optimized PCA cell





Simulations of Coherent Electron Cooling with Two Types of Amplifiers, Jun Ma, Gang Wang, Vladimir Litvinenko, International Journal of Modern Physics A (IJMPA), Vol. 34 (2019) 1942029 (

Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams, V.N. Litvinenko, G. Wang, D. Kayran, Y. Jing, J. Ma, I. Pinayev, arXiv preprint arXiv:1802.08677, 2018

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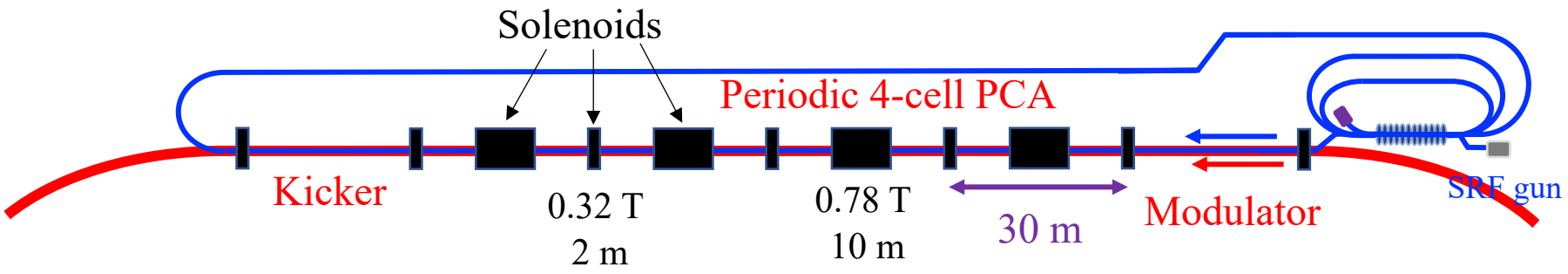
EIC CeC with PCA

3-path 150 MeV ERL



Name	Current experiment	CeC cooler for EIC
PCA Lattice	Periodic, 4 cells, regular	Periodic, 4 cells, optimized
γ	28.5	293
Hadrons	Au ions	Protons
E_h, GeV	26.5	275
E_e, MeV	14.56	150
l, m	2x1	2x15
a_0, mm	0.2	0.15
Q, nC	1.5	1.5
I_0, A	75	150
ε_{norm}, m	$5\ 10^{-6}$	$5\ 10^{-6}$
Frequency, THz	25	500
PCA gain	100	400
Lattice	regular	1:2
3D emittance Cooling time, min	15-20	<5

Summary

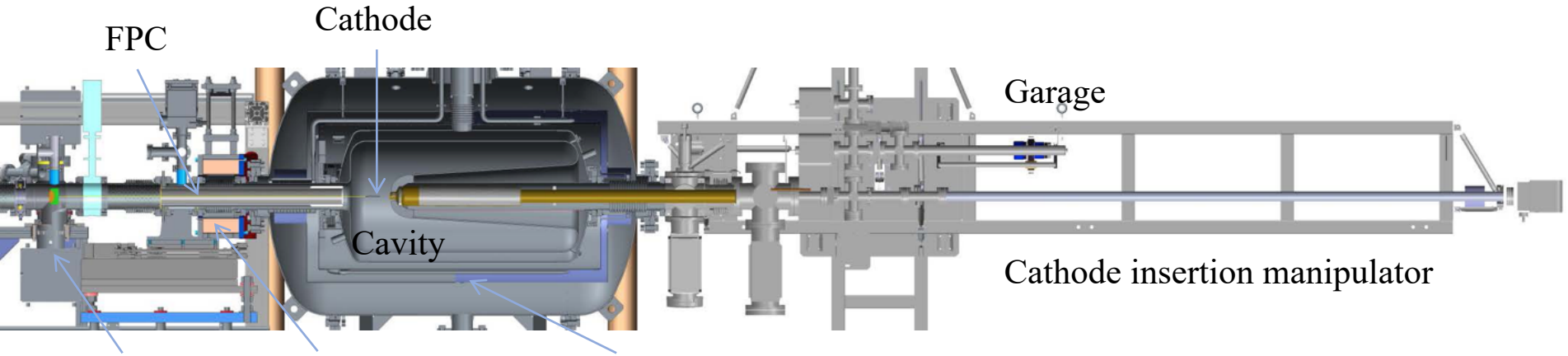
- **We learned how to control noise in the electron beam** and how to reduce it to the acceptable level. As the result we obtained the all necessary required for the CeC experiment
- **We commissioned the new CeC beamline with plasma-cascade** amplifier and establish propagation of CW electron beam with low losses
- We made significant progress in investigations of the CeC's Plasma-Cascade Amplifier and observation **the PCA-amplified ion imprint** in the electron beam
- New time-resolved beam diagnostics beam-line and new cryo-cooled IR detector will significantly improve out diagnostics
- Next key steps
  - Run 21 –longitudinal cooling of 26.5 GeV/u ion beam
  - Run 22 – simultaneous transverse and longitudinal (3D) CeC cooling

Areas of potential collaborations

- Because of its location, the CeC project involves many scientist, students, engineers, technicians from BNL and Stony Brook University
- Experts from Argonne National laboratory, Lawrence Berkeley National Laboratory, Budker Institute of Nuclear Physics, Daresubry Laboratory, Fermi National Accelerator Laboratory, Thomas Jefferson National Facility (JLab), Tech-X and SLAC National Accelerator Laboratory contributed in various critical aspects of the CeC project
- **The CeC group invites all interested parties to continue collaboration on this incredibly challenging project in the CeC theory, simulations, experiment, diagnostics and an optimal EIC CeC cooler design**
- There are a lot of unanswered question and challenges where your participation can play critical role. Here is an incomplete list:
  - *CSR effects in the CeC cooler and CeC accelerator*
  - *Self-consistent 3D start-to-end simulation of the beam dynamics in CeC*
  - *"Low-noise" 3D CeC simulations including hadron beam evolution*
  - *Design of optimal CeC and ERL for EIC, 3D cooling…..*
- The CeC project can greatly benefit from
  - *Experts in CSR simulation (both in μ-bunching chicanes and ERL)*
  - *Experts in beam instabilities (both the advanced theory and simulations)*
  - *Avid experimentalists with good understanding of beam diagnostics*
  - *Experts in generating, compressing and accelerating high quality electron beam …..*

Icing on the cake

- Our CW SRF gun demonstrated record performance in the charge (>10 nC per bunch) and the beam quality (0.15 mm mrad norm. emittance at 0.1 nC)
- **It is now considered as a possible 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**



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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]