COOL23

Advances and Challenges in Coherent electron Cooling experiment at RHIC

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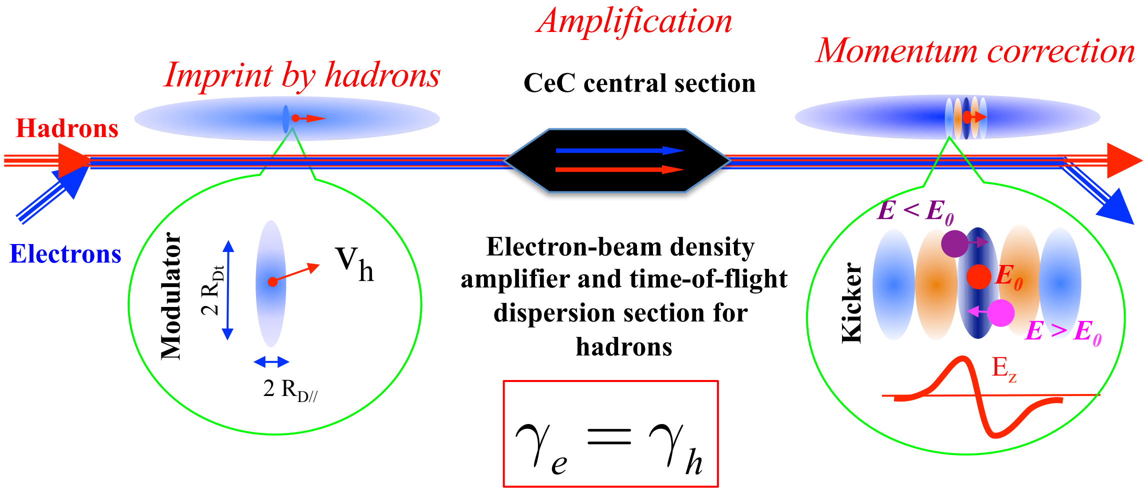
Stony Brook University

CASE Center for Accelerator Science and Education

Brookhaven National Laboratory

What is Coherent electron Cooling (CeC)

- It is stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz. 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.



- CeC is promising technique, but it never was demonstrated – hence our proof-of-principle CeC X at RHIC

My personal observations

- In my long carrier as accelerator physicist, I played my part in designing, building and successfully commissioning of many sophisticated systems, including world's first UV FEL and EUV harmonic generation, high brightness storage ring at Duke and BNL, FEL-driven high intensity mono-energetic γ-ray source with tunable energy….
- But coherent electron cooling proof-of-principle experiment at RHIC (we call it CeC X), while being deceivingly so easy conceptually, has being and remains being most challenging project I ever worked with
- In this talk I want to share the achievements and advances with CeC X, but also challenges (including our own errors!) the CeC team and CeC X collaborators faced in last 15 years, starting from CeC X conception in 2008 when original idea of Derbenev was given specific pass-way to a reality
- I will focus on experimental aspects of the project: two my collogues will provide you with details of beam dynamics and CeC simulations and analysis this Thursday.
- *This recollection is my own and it may differ from that of other participants in the project*

Short history of CeC X at RHIC

- In 1991, Ya. Derbenev published preprint titled "Coherent electron Cooling", where he developed further his ideas from 1980s exploring a possibility to use broad-band instabilities in electron beam to enhance traditional electron cooling
- In 2007, in collaboration with Derbenev, I developed specific FEL-based approach of such system that could be theoretically evaluated, designed and built: it was first presented at FEL'2007 conference, and later published as PRL 102, 114801 (2009)
- The CeC concept promised very fast cooling of hadron beams in eRHIC and CeC X design development and prototyping of FEL wiggler were supported by BNL LDRD awards, starting in 2009
- In 2010 the CeC X project was officially established and was supported for eight years till 2018 by DOE office of Nuclear Physics. CeC project was also receiving support from accelerator R&D program at Collider-Accelerator Department and BNL's LDRD and PD programs.
- Initial (2010) proposal included an electron gun and an SRF linac from JLab, but this part of the proposal was blocked by JLab administration in about a year. BNL, with help from SBU, Daresbury Lab, BINP, Tech X, AEC and Niowave Inc completed design, manufacturing and construction of the FEL-based CeC system and its SRF accelerator. Daresbury laboratory loaned us 500 MHz cavity taken from decommissioned storage ring, BINP built us three helical wigglers and Niowave Inc built us two SRF systems: 113 MHz SRF and 5-cell 704 MHz SRF linac (with Nb cavity supplied by AES and funded by SBU DOE Dasic Science award).
- **2014-2017: we built the cryogenic system, the SRF accelerator and the FEL for CeC experiment. CeC using LiHe from RHIC and can operate only during RHIC runs**

- **2018: We started experiment with the FEL-based CeC, demonstrated high gain FEL operation, but did not complete the project – FEL wigglers with small apertures had to be removed for RHIC low energy program**

Short history of CeC X at RHIC

- In 2018 we discovered microbunching Plasma Cascade Instability and conceived design of Plasma Cascade Amplifier (PCA) for CeC
- After detailed internal and external reviews of our new design and proposal, the CeC X was approved as a project and became part of RHIC's physics experimental program for RHIC runs 20-22.
- In 2019-2020 a PCA-based CeC with seven solenoids and vacuum pipe with 75 mm aperture was built and commissioned. Funding for this part of the program provided were partially by SBU NSF award, but also by CEC project funds from Collider Accelerator Department
- **Run in Summer 2020 was very successful: we demonstrated high gain Plasma Cascade Amplifier (PCA) and observed presence of ion imprint in the electron beam**
- Time resolved beam diagnostics beamline was added to the CeC system during RHIC shutdown and commissioned during run 21.
- During 2021 run we restored high gain PCA and attempted to observe CeC cooling – but not successfully. Instead, we observed regular weak e-cooling
- Runs 22 and 23 were prone to a lot of problems, both man-made problem, and equipment and weather-related failures. While we made improvements in accelerator and laser system, we did not come even close to demonstrating CeC during these runs.

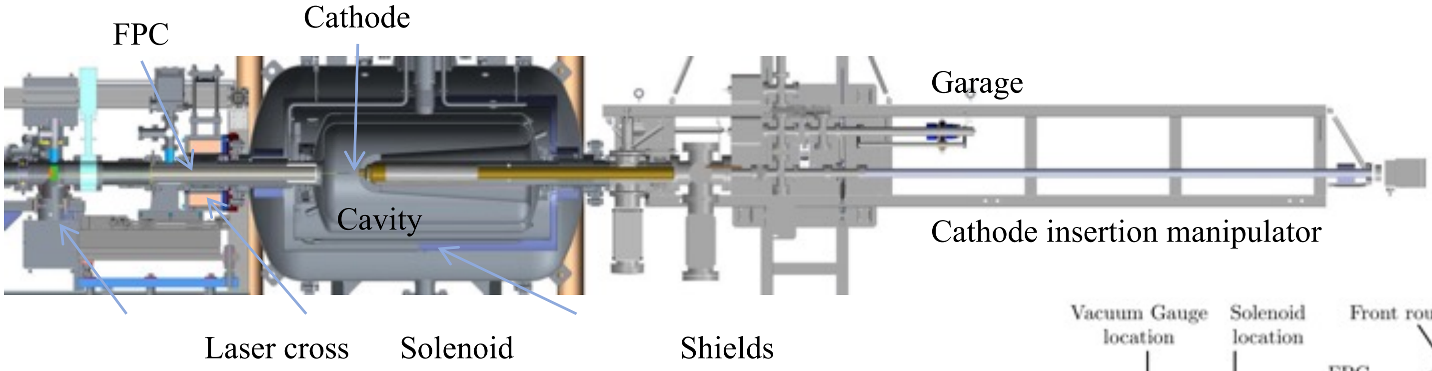
Advances and firsts-ever in CeC X

- Unique *"one-and-only"* 1.25 MV quarter-wave 113 MHz CW SRF electron gun
    - Real operational CW SRF gun with months-long lifetime of CsK_2Sb photocathodes
    - World best brightness of CW e-beams – sufficient for hard X-ray FELs
    - Stalk for room temperature photocathodes in 4K SRF environment
    - SUHV photocathode transfer and exchange system
    - Adjustable recess of the photocathode puck in the stalk for initial focusing of the e-beam
    - Demonstrated ability to generate bunches with charge up to 20 nC
    - We developed successful multipacting-free turn-on and turn-off procedures
    - We developed and successfully used He conditioning methide for SRF QW gun
- 10-to-20-fold ballistic compression of 1.25 MeV 1.5 nC bunches
- Precise beam energy measurement using solenoid and H/V dipole trim scans
- Beam-based alignment of e-beam trajectories on solenoid's axes
- Methods for measuring EM axes of SRF gun and linac
- Accurate measurements and control of THz noise in electron beam as the level of Poison short noise power

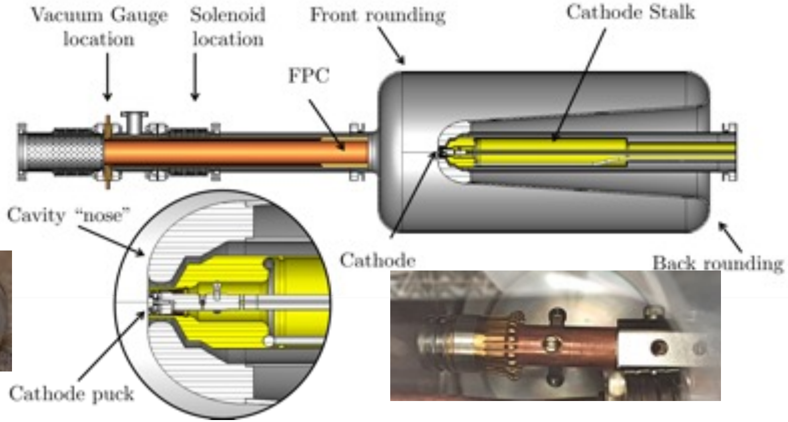
Advances and firsts-ever in CeC X

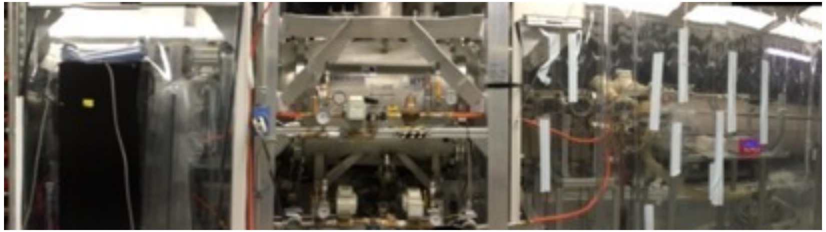
- First ever SRF linac with 2K LiHe superfluid heat-exchanger
- Novel method of measuring positions and angles of solenoid's axis using high-energy circulating hadron beam – used to align solenoids in CeC section
- Using solenoid scan to measure beam's 4D phase-space parameters, including eigen emittances
- Sophisticated IR diagnostics
- Experimental confirmation of ion imprint (was reported yesterday)
- Experimental demonstration of high gain FEL and Plasma-Cascade amplifiers
- Demonstration of electron recombination with 26.5 GeV/n Au ions and using it for matching relativistic factors of two beams
- Demonstration conventional electron cooling of 26.5 GeV/n Au beam – the higher energy where electron cooling was observed
- All these is in addition to all conventional hardware and diagnostics, including but limited to BPMs, YAG profile monitors, laser systems, vacuum, PS, solenoids, quadrupoles, dipoles, trims, beam dumps, time-resolved and time averaged diagnostic: emittances, energy spread, bunch charge and current….
- It is impossible to present all of them – hence, I have time show just few

Probably world's best SRF Photo-Electron gun

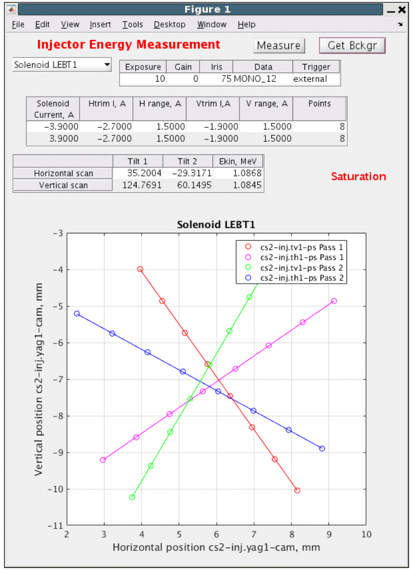


Quarter-wave SRF 4K Nb gun cavity tuned to operation frequency
Room temperature CsK2Sb high QE photocathode inside adjustable stalk
Photocathode QE lifetime – one to two months
Nominal accelerating voltage: 1.25 MV, maximum 1.5 MV
Laser pulse duration: 100 to 500 psec
Charge per bunch – from pC to 20 nC
Record low normalized emittances:
0.15 mm mrad at 100 pC
0.32 mm mrad at 500 pC
Vacuum storage & transportation suit ("garage") with three photocathodes
UHV cathode manipulation system
UHV vacuum inside the SRF gun
Accurate LLRF controls
Multipacting-free turn-on and turn-off processes
Successfully tested He conditioning method

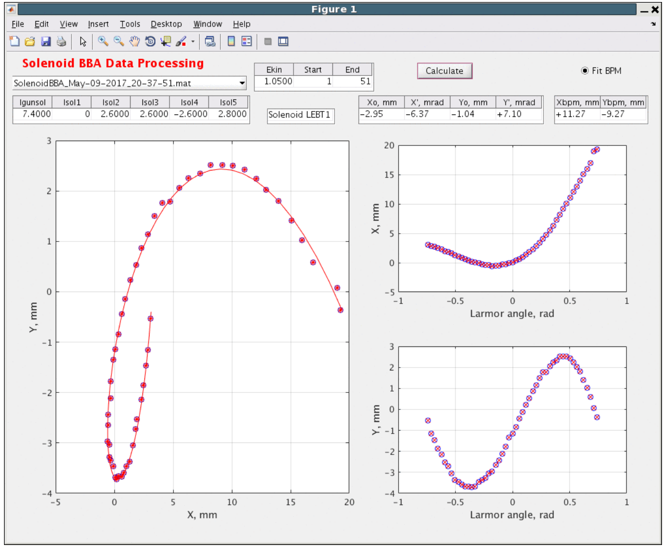




Automated Measurements of the Beam Parameters with Solenoid

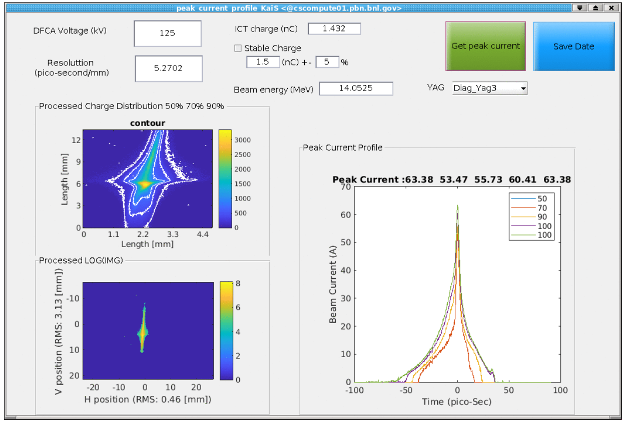


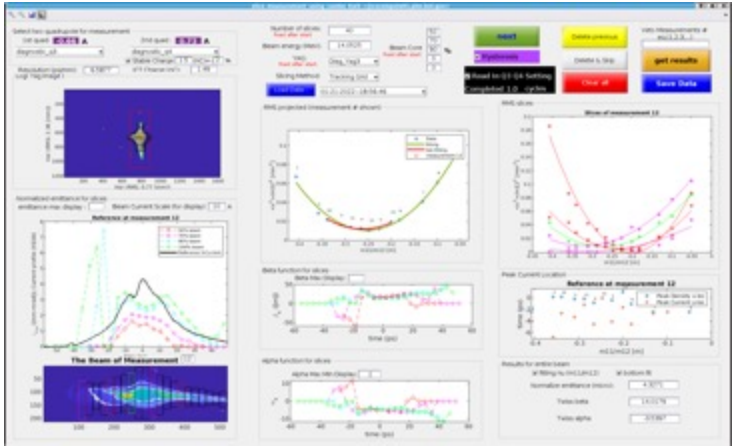
The electron beam is steered with trims before solenoid and beam position is observed on a profile monitor (or BPM). Change of the slope in the X-Y coordinates with different solenoid current gives beam energy.

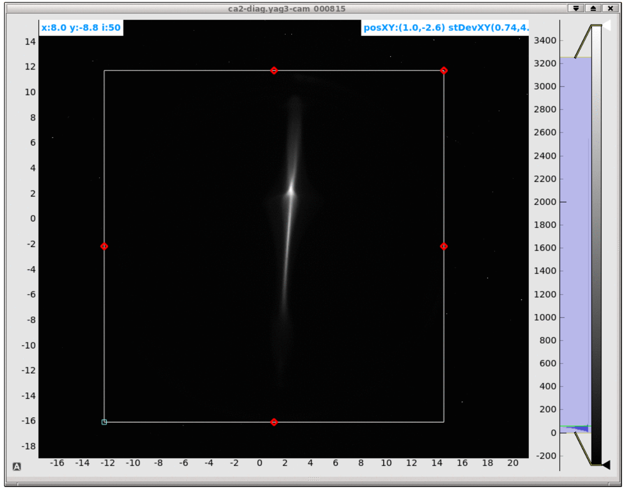


The solenoid current is varied (N points) and beam position is recorded (2xN values). 6(4)xN matrix is formed from the elements of the transport matrix (beamline can include other elements). Solving set of linear equations gives the required parameters.

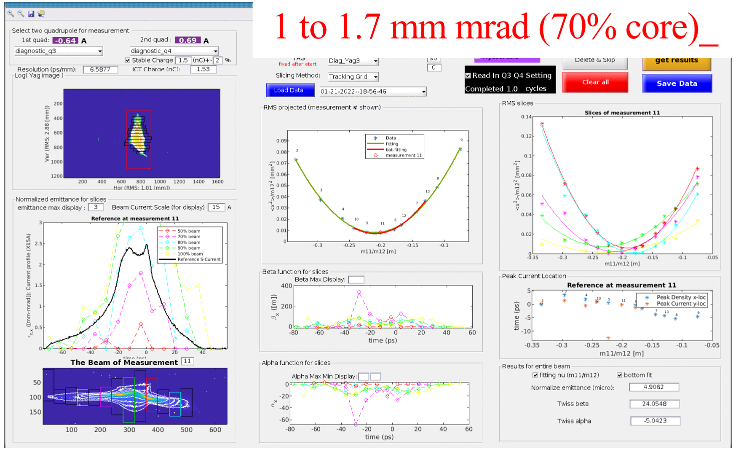
Time resolved diagnostics of 1.5 nC/bunch e-beam





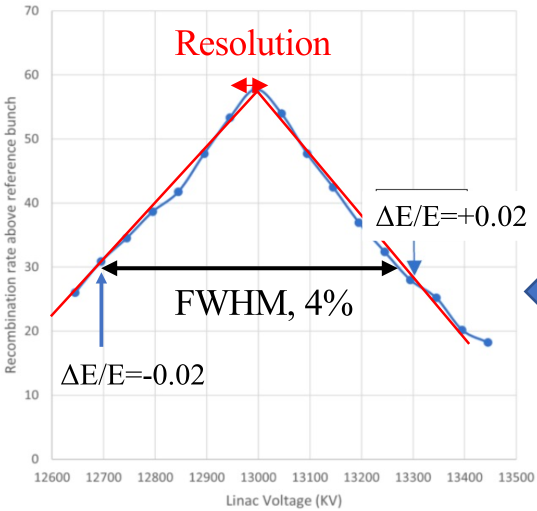


Slice normalized emittance
1 to 1.7 mm mrad (70% core)_



Recombination of electrons with Au ions: Run 2021

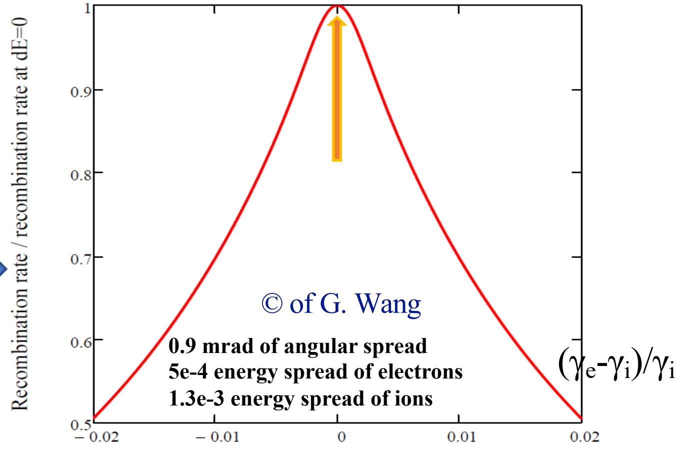
Experiment



Triangular shape of the measured dependence allows to define matching of the relativistic factors with accuracy ~ 0.2%, which is significantly smaller than 4% FWHM.

This finding will reduce the range where we need to search for the CeC signature by 5-to-10 fold.

Calculations



$$\sigma(v_x,v_y,v_z) = A\frac{2\hbar\nu_0}{m_e(v_x^2+v_y^2+v_z^2)}\left[\ln\left(\sqrt{\frac{2\hbar\nu_0}{m_e(v_x^2+v_y^2+v_z^2)}}\right)+\gamma_1+\gamma_2\left(\frac{m_e(v_x^2+v_y^2+v_z^2)}{2\hbar\nu_0}\right)^{1/3}\right]$$

$$f_e(v_e) = \frac{1}{(2\pi)^{3/2}\beta_{e,\perp}^2\beta_{e,z}}\exp\left(-\frac{v_{e,x}^2+v_{e,y}^2}{2\beta_{e,\perp}^2}\right)\exp\left(-\frac{(v_{e,z}-v_{z0})^2}{2\beta_{e,z}^2}\right)$$

This results include convolution of the exact formula recombination cross-section (in the commoving frame) with distributions of two beams

Challenges in CeC X

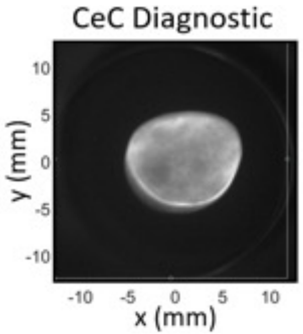
- One of the main challenges was insufficient budget during initial construction of the project: funding was typically provided at ~50% of requested level.
  - It resulted in necessity to re-use existing equipment, using lowest bids and minimal diagnostics in order to proceed with construction and commissioning… I am sure this is not only our unique experience.
  - But it resulted in number of lingering problems, some of which we solved by upgrades to the systems, but some are still unresolved. I will give some examples of challenges related to this issue.
- Number of problems and related to them challenges were man-made:
  - Most regrettably in Run 22, two serious human errors resulted in the loss of three quoters of CeC X beam-time. One of errors was failure to report 2.4-fold scaling of the bunch charge, resulting in CeC team "spinning wheels" 24/7 for nearly half of the run…
  - Other human errors resulted in damage of CeC equipment, including damage to the cathode transfer system and contaminations of SRF gun. The later required time-consuming recovery and repairs.
- One of most prominent challenges are related to drive laser for SRF gun: pulse to pulse energy and pulse time jitter as well as control of the lase pulse shape caused us a lot grief. I'll show some of accounted problems, progress of solving them as well remaining challenges.
- But most of challenges were natural: something unexpected delivered by mother nature ranging from surprising beam instability or simple overhearing of equipment during Summer time (especially prevalent during short run this Summer)

Some of Encountered challenges

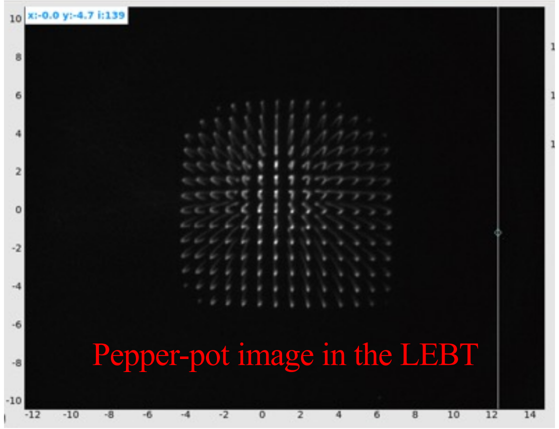
- Time-dependent variation of beam centroid create complications in time-resolved beam diagnostics as well with generating compact e-beam. These challenges are coming from
  - 113 MHz SRF gun EM axis has significant (~ 15 mrad) offset from the CeC accelerator beam-line
  - 500 MHz bunching cavity is not axis-symmetric has very strong transverse field components
- In Run 2018, while operating with FEL amplifier, we discovered that electron beam in the low energy (ballistic compression) section was developing very strong longitudinal instability. Detailed studies showed that this was Plasma-Cascade Instability caused by strong transverse focusing. We developed lattice of the CeC accelerator suppressing this instability and providing quiet electron beam with noise comparable with that of the shot-noise. (I reported details in my talk yesterday)
- In Run 2021, we attempted to demonstrate CeC, but $5{\times}10^{-4}$ relative beam energy jitter - caused by 15 psec RMS time jitter of the seed laser pulses - prevented us from observing CeC. It simply was washed away.
- Main remaining challenge is large (5% RMS) jitter in the energy of the laser pulses and corresponding variations of the electron bunch charge. This jitter causes significant variation in space-charge dominated dynamics of the electron beam and should be eliminated for reliable measurements and demonstration of CeC
- Nonlinearities in the bunch compression (mostly induced by space-charge effects) results in triangular current profile of compressed bunch, which result in very small portion of electron bunch participating in CeC process
- Because of problem with manufacturing (as well as errors of inexperienced SRF engineers) accelerating voltages of SRF systems are below initial specification: SRF gun operates at 1.25 MV instead of designed 2 MV and SRF linac operates at 13.1 MV instead of designed 20 MV. This reduction dramatically affected beam dynamics and required new IR diagnostics
  - Lower injection energy results in very strong time-dependent focusing of electron beam in first cell of the SRF linac, the main cause of the beam emittance growth
  - Reduction of beam energy resulted in 2.4-fold increase in wavelength of wiggler radiation and 3.5-fold of that from bending magnet

Effect of of-axis ejection from the SRF gun and time-dependent variation of beam centroid

Distortions of 1.5 nC bunch profile caused by off-axis ejection from SRF gun

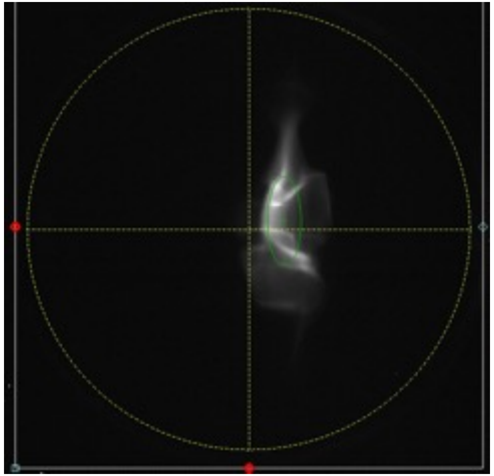


Samples



Pepper-pot image in the LEBT

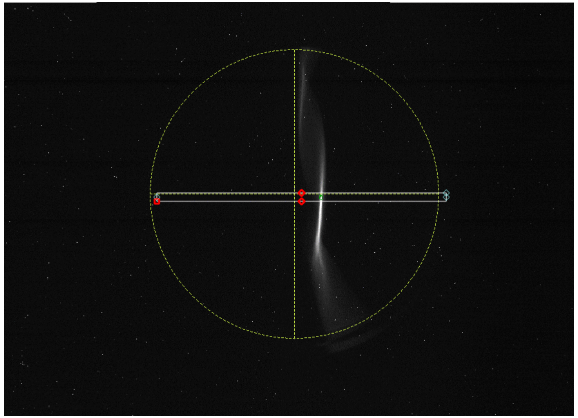
time



x

Current profile measurements

time

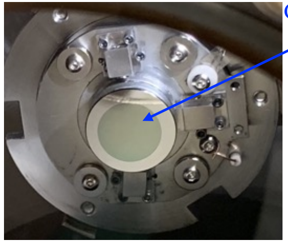


x+DδE/E

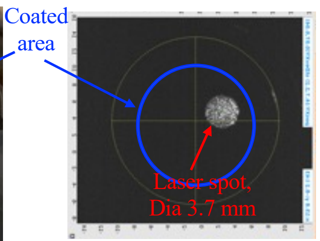
Slice energy and energy spread

Where are we with solving this gun and bunching cavity challenges

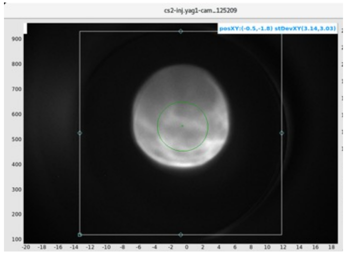
- Experts consider that adjusting SRF gun caving position and angle inside the cryostat is very dangerous and can result in catastrophic failure
- Hence, we are exploring possibility of correcting trajectory of the electron beam exiting SRF gun by moving laser spot of the cathode axis
- We increased diameter of coated area from 8 mm to 14 mm and we able to correct the exit trajectory with good accuracy



Photocathode in the preparation chamber



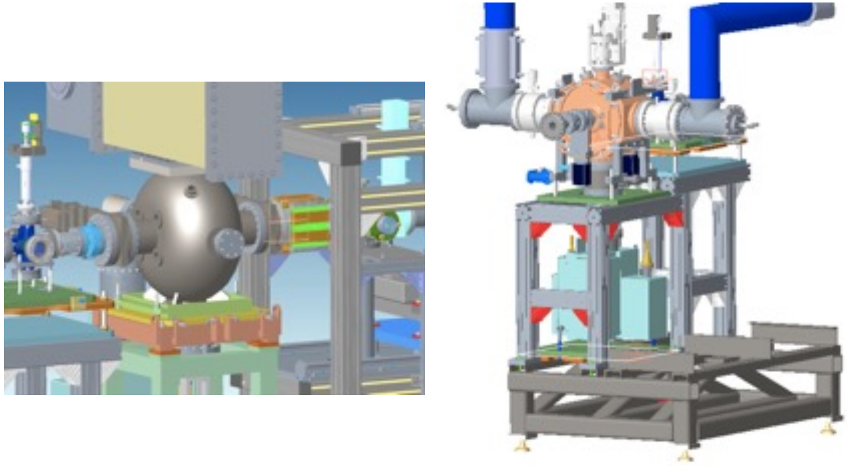
Laser spot shifted from the 3.35 mm horizontally and 1.45 mm vertically



E-beam profile at first CeC profile monitor

- We did not find cost-effective solution for 500 MHz bunching cavity and are replacing it with a new one with axial symmetry.
- Design of the cavity is completed, and simulations show that this cavity should satisfy our requirement
- New 500 MHz 200 kV cavity is in production scheduled to be delivered to BNL in early December, and then installed into CeC system

- With these to important improvements, we expect getting much better time-averaged and time-resolved parameters of the electron beam

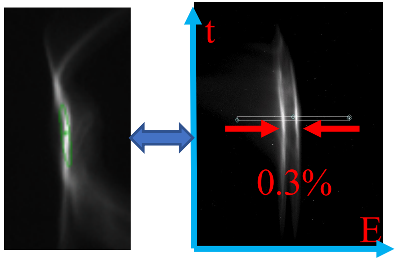


Rendering of new 500 Cu bunching cavity for CeC accelerator

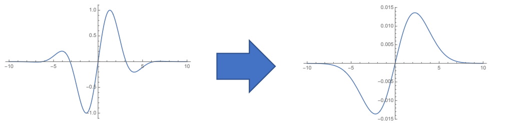
Drive laser and related challenges

- We are exploring sixth configuration of the CeC driving laser system: their goal is to provide stable laser pulses with 78 kHz repetition rate phase-locked to the SRF gun voltage. It is also desirable to have adjustable pulse duration (with nominal operational value of 350-375 psec), if possible – adjustable pulse shape. We operating with 1064 nm IR laser converted to second harmonic: 532 nm green light that delivered to the SRF gun cathode
- Low time jitter and good stability of the laser pulse energy are very important for generating stable space-charge dominated beams
- First NUPHOTON system (including delivery to RHIC tunnel) was faber-based. It exhibited number of problems related to instabilities occurring in fibers at high peak power… It also managed to degrade after couple years of operation and was replaced
- High gain IR regenerative amplifier was built for CeC system to boost laser power. Since then, the laser system required just a new seed IR laser
- New seed laser for Run 20 had nearly everything: controllable pulse duration from 125 psec to 1.5 nsec as well as controllable pulse shape. We were able to generate high quality beam using this laser and demonstrate high gain PCA, but failed to demonstrate CeC cooling: time jitter ~ 10 psec RMS was causing too much energy jitter, sufficient to wash out CeC cooling… has to be replaced
- Next seed laser from Irisome Solutions has much better jitter (~ 3 psec RMS) and control of the pulse duration – energy jitter was indeed reduced in Run 21. But instead of quoted “flat-top” pulses it generated semi-trapezoidal pulses, which resulted in lower quality of the beam. Compressed electron bunches had
- In parallel, laser engineer was developing system based on very Menlo Systems mode-locked IR oscillator generating very short (psec) lase pulses with sub-psec time jitter. In order to built laser pulses for CeC operation, seed pulses were amplified and filtered by Volume Bragg Grating to increase pulse length to 30 psec and then to split, polarize and delay 5 beamlet to generate laser pulse with deep in the center: the idea is to use this feature to flatten current profile of compressed electron bunches
- This system went into initial tests during run this Summer, but unfortunately there were a number of mistakes ranging from transverse misalignment of beamlets to mistakes resulting in diminishing power in three of beamlets. All these errors were discovered and will be corrected for the next run, including generating stable laser pulses with energy jitter less than 1%

Run 20: Bunch-to-bunch energy jitter



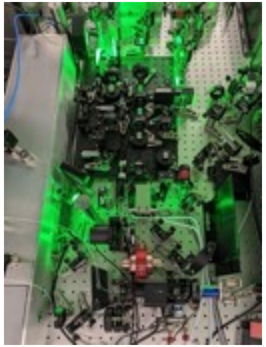
Energy jitter washes out CeC kick

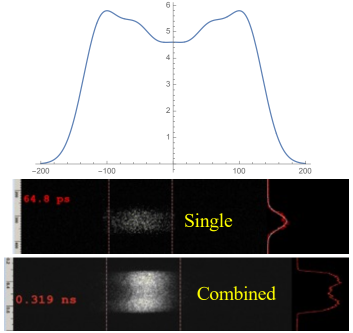


No energy jitter, KPP beam

Energy jitter of 0.1% RMS, KPP beam

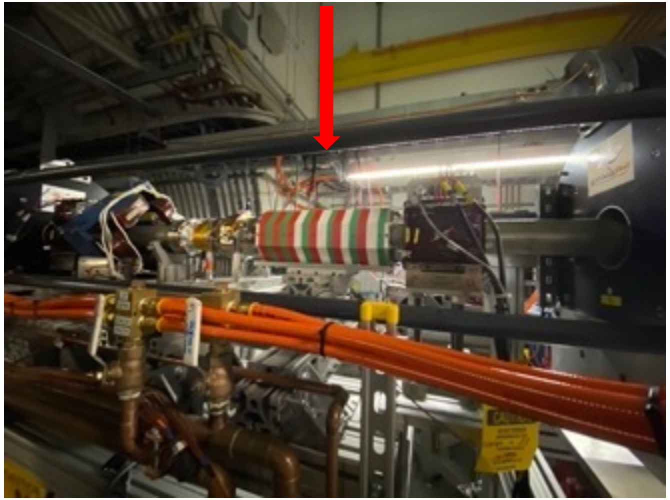
Latest laser system and proposed lase pulse shape





Laser pulse shapes measured by streak-camera in laser trailer

Diagnostics undulator and cryo-cooled IR detector for PCA gain evaluation

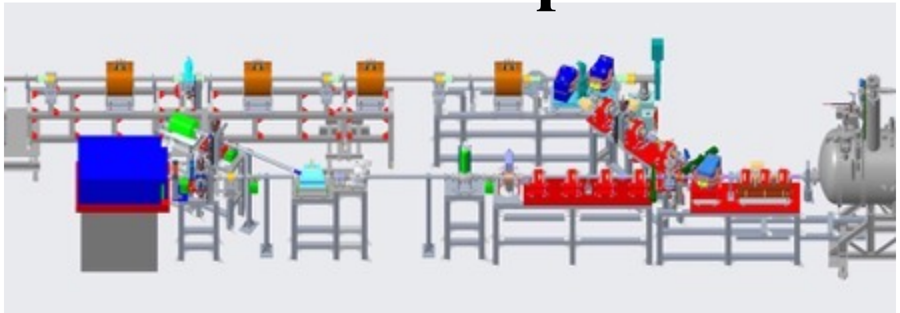


Parameter	Value	Units
Period	8	cm
Gap	7.9	cm
Peak field	0.6	kGs
Radiated power at 50% beam current	9	nW
Fundamental wavelength @ γ=28.5	54	µm
Central frequency @ γ=28.5	5.5	THz
Third harmonic	16.6	THz
F_3/F_1	0.04	

- ✓ New cryo-cooled IR detector has ~ 100 better signal to noise ratio
- ✓ Diagnostics undulator would generates radiation at 5.5 THz and 16.6 THz frequencies, which are within the bandwidth of the Plasma-Cascade Amplifier (PCA) *
- ✓ This system would allow us to evaluate both the gain and the spectrum of PCA

**PCA gain peaks at 16 THz. In Runs 20-21 we used IR radiation from bending magnet, which peaks at 0.8 THz and is complete mismatch for the PCA*

Time-resolve diagnostics beam-line: the key for accurate measurements of beam parameters



Fully
Commissioned

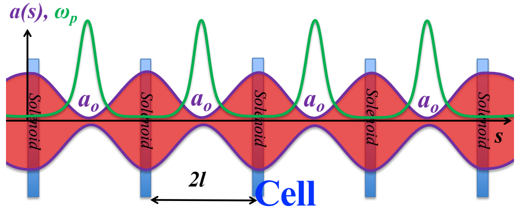
- Run 21' main addition is the time-resolved diagnostics beam-line

Conclusions

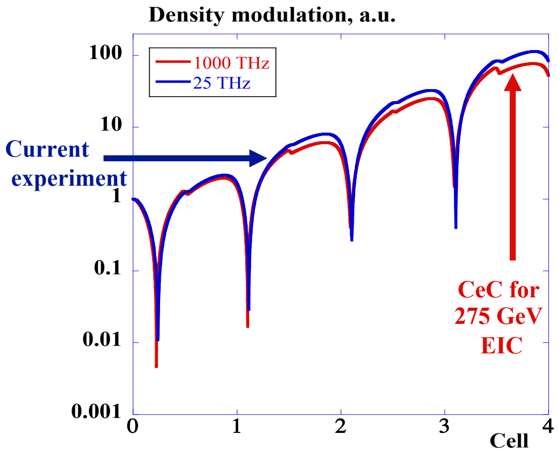
- I want to acknowledge support for CeC X from US DOE office of Nuclear Physics, US NSF, BNL LDRD and PD programs, and especially from Collider-Accelerator Department – without this support CEC X would not exist
- I am privileged to work and to continue working on CeC X with most talented, inventive, hard-working and dedicated team of scientists, engineers and technicians. It is because of their talents we made serious breakthroughs and overcame a lot of unexpected challenges and problems
- The CeC turn out to be a very stubborn process to demonstrate experimentally, but the team learned from mistakes and made a lot upgrades and tune-ups, which gradually moving us towards the ultimate goal
- We still have two more RHIC runs and we will do everything possible to get to the finish line and to observe CeC X cooling ion beam
- If this happens, it will serve as a boost for CeC cooler prospect in EIC, either current design or with PCA passed amplifier

Possible option for EIC cooler

"Standard" 4-cell PCA

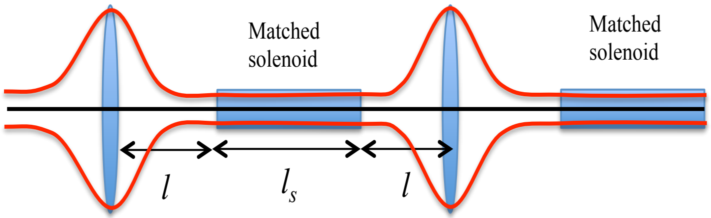


$$k_{sc} = \sqrt{\frac{2}{\beta_o^3 \gamma_o^3} \frac{I_o}{I_A} \frac{l^2}{a_o^2}};\; k_\beta = \frac{\varepsilon l}{a_o^2}$$

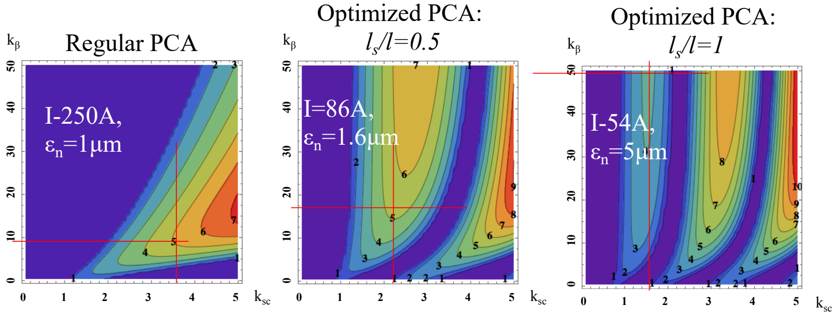


Results of 3D simulations with code SPACE

Optimized PCA cell



PCA Gain per 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

The CeC project involved the following:

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