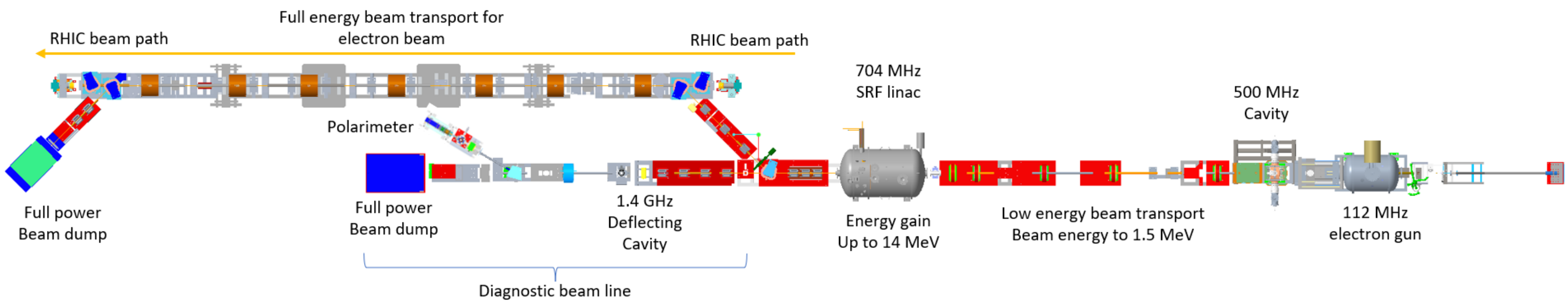
CeC status and plans for Run-25

Yichao Jing for the CeC team

CAD MAC21 12.16-12.18 2024

Outline

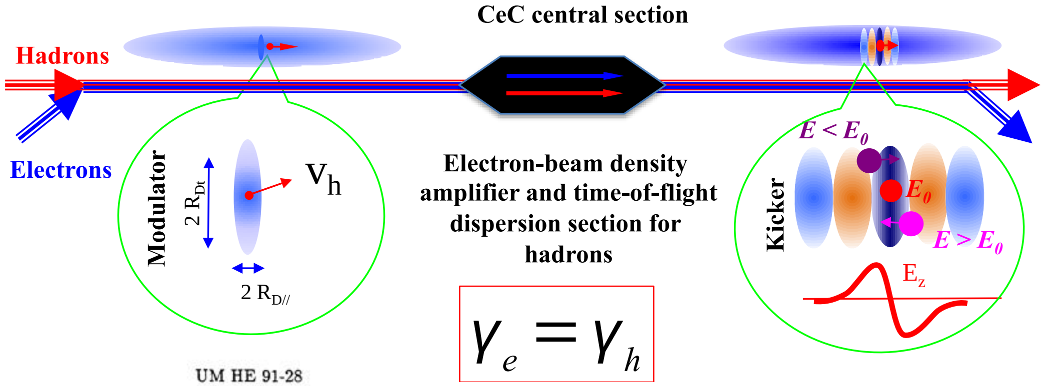
- Introduction of CeC at RHIC and Plasma-cascade Amplifier (PCA)
- Status of CeC experiment in recent RHIC runs
- Improvements for better electron beam quality
- Plan for Run 25



Coherent electron Cooling

All CeC systems are based on the identical principles:

- Hadrons create density modulation (imprint) in the 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 the longitudinal degree of freedom.



UM HE 91-28
August 7, 1991

COHERENT ELECTRON COOLING
1. Physics of the method in general

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ABSTRACT

A microwave instability of an electron beam can be used for a multiple increase in the collective response for the perturbation caused by a heavy particle, i.e. for enhancement of a friction effect in electron cooling method. The low-scale instabilities of a few kind can be

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Coherent Electron Cooling

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Microbunched Electron Cooling for High-Energy Hadron Beams

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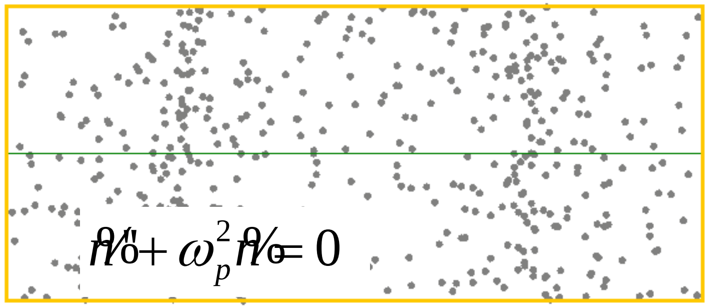
(Received 11 April 2013; published 20 August 2013)

Plasma-cascade Amplifier (PCA)

- The PCA is based on the plasma-cascade instability (PCI): a parametric instability driven by modulation of the beam's plasma frequency.
- For the CeC experiment, the modulation of the plasma frequency is realized by varying the electrons' spatial density through strong transverse focusing.



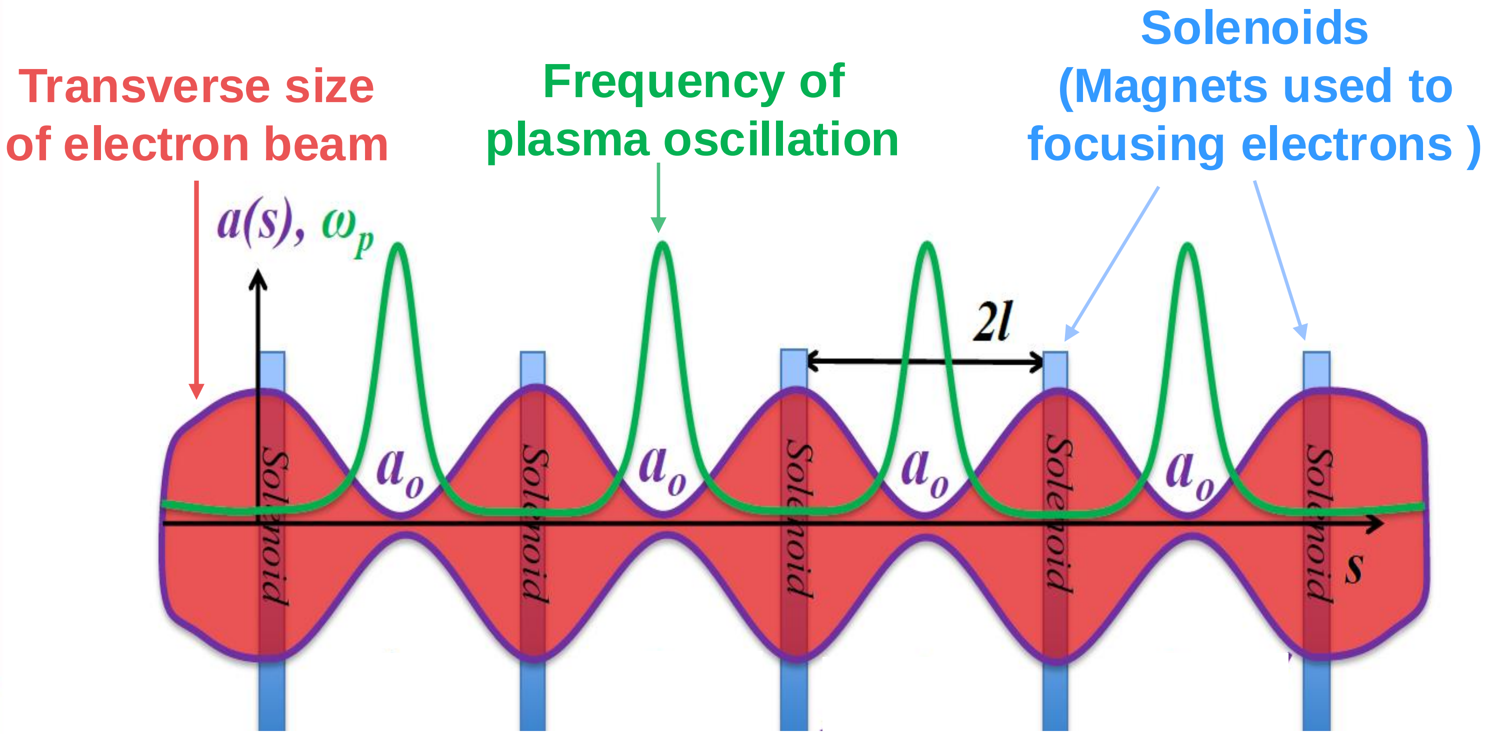
$$\tilde{n}'' + \omega_p^2 \tilde{n} = 0$$

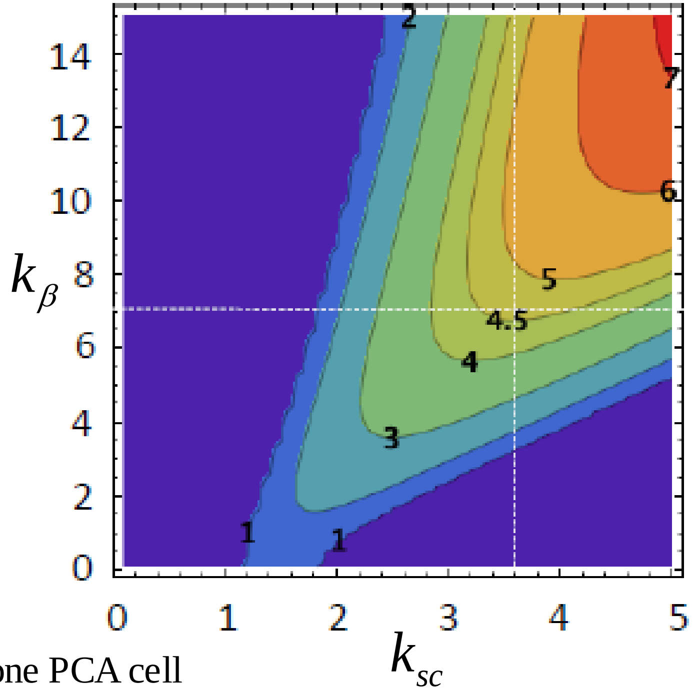
$$\hat{n}'' + 2k_{sc}^2 \hat{a}(\hat{s})^{-2} \hat{n} = 0$$

$$\hat{a}'' = k_{sc}^2 \hat{a}^{-1} + k_\beta^2 \hat{a}^{-3}$$

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

$$k_\beta = \frac{\varepsilon l}{a_o^2}$$





Gain curve for one PCA cell

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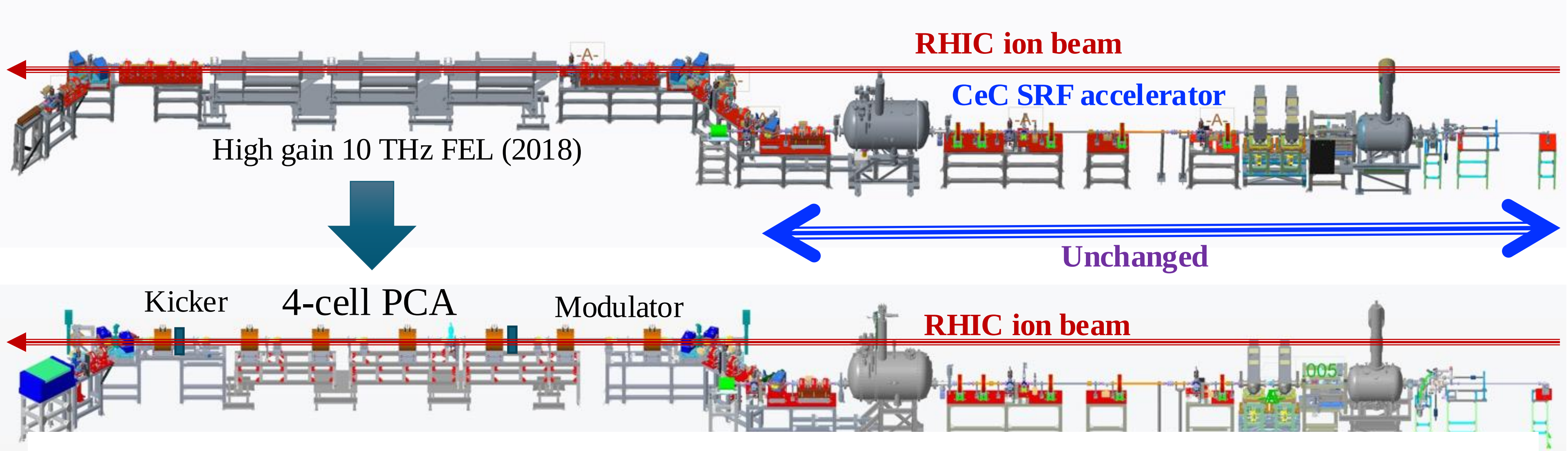
Timeline of the CeC at RHIC

- ❑ 2014-2017: built cryogenic system, SRF accelerator and FEL for CeC experiment
- ❑ 2018: started experiment with the FEL-based CeC. It was not completed: **28 mm** aperture of the helical wigglers was insufficient for RHIC with 3.85 GeV/u Au ion beams. We discovered microbunching Plasma Cascade Instability and developed design of Plasma Cascade Amplifier (PCA) for CeC
- ❑ In 2019-2024
  - ❑ 2019: PCA-based CeC with with 75 mm aperture was built and commissioned.
  - ❑ 2020: Presence of ion imprint in the electron beam was observed.
  - ❑ 2021: We observed regular e-cooling in Run 21, but CeC cooling was washed out by large timing jitter of the seed laser and resulting 0.35% RMS e-beam energy jitter.
  - ❑ 2022: Plasma Cascade Amplifier (PCA) with tunable high gain was achieved.
  - ❑ 2023: New laser profile at injector was tested to provide better final temporal distribution uniformity.
  - ❑ 2023-2024: Established key beam parameters and worked on improving beam quality.



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

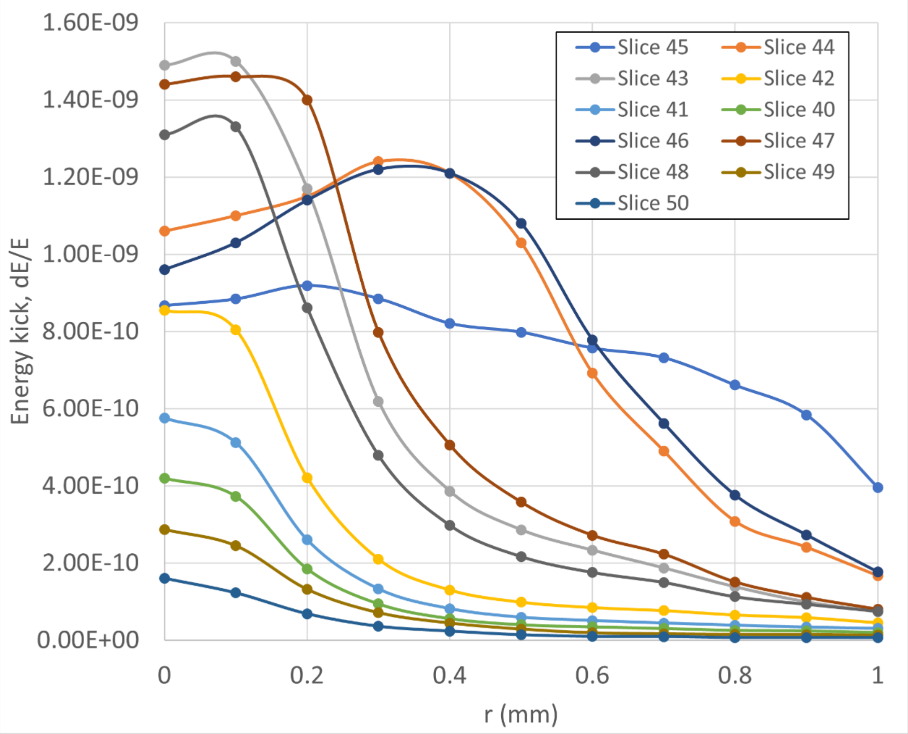
What has been achieved at CeC experiment at RHIC

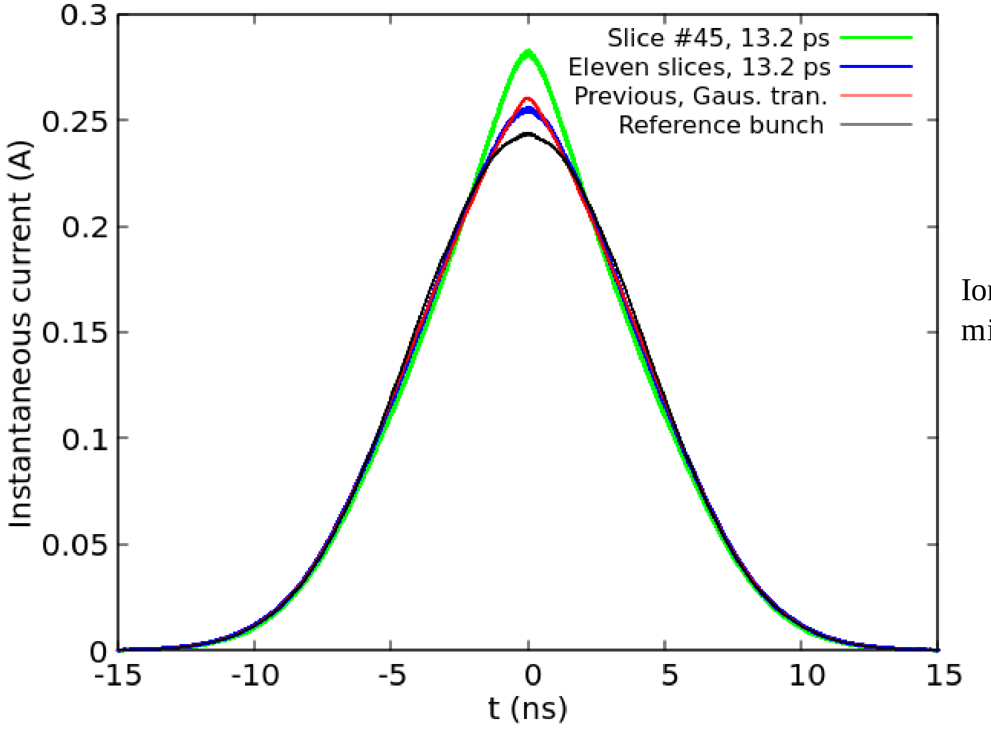
- ✓ Unique SRF accelerator generating high brightness electron beam, with peak current reaching 75 A and energy at 14.6 MeV
- ✓ Precise control of noise in electron beam, comparable to the level of Poisson shot noise (Run 18-19)
- ✓ Demonstrated high gain in the amplifier (Run 20, 22)
- ✓ Observed presence of ion imprint using electron beam's dipole radiation (Run 20)
- ✓ Observed recombination of 14.56 MeV elections with 26.5 GeV/ u Au ions (Run 21)
- ✓ Conventional electron cooling of hadron beam at ion energy of 26.5 GeV/ u (Run 21)

Parameter	Planned	Achieved
Lorentz factor	28.5	28.5
Repetition frequency, kHz	78.2	78.2
Total bunch charge, nC	1.5	1.5
Slice peak current, A	50	50
Ratio of noise to Poisson limit, in power	<100	~ 10
RMS fractional momentum spread	$< 2 \times 10^{-4}$	$<2 \times 10^{-4}$
Norm. rms slice emittance, um	1.5	< 1.5 (with 10% halo removed)

Requirements on electron beam uniformity for cooling

Slice properties from beam dynamics simulation (IMPACT-T) → 3D cooling simulation (SPACE) → Ion tracking code (CeC tracking)





Ion profile after 40 mins of cooling

@J. Ma and G. Wang

Beam properties (peak current, slice energy spread, TWISS) uniform in ~ 10 – 15 ps is critical in achieving observable longitudinal cooling.

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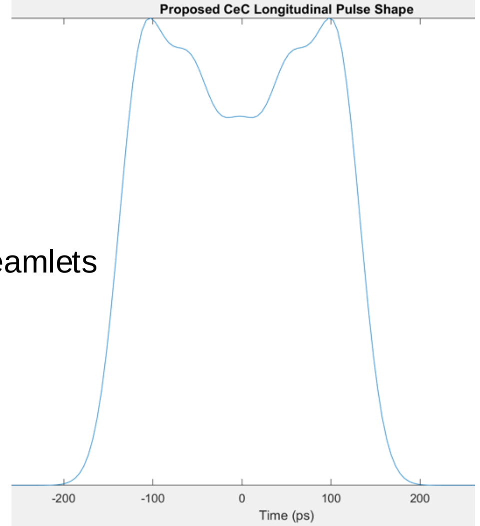
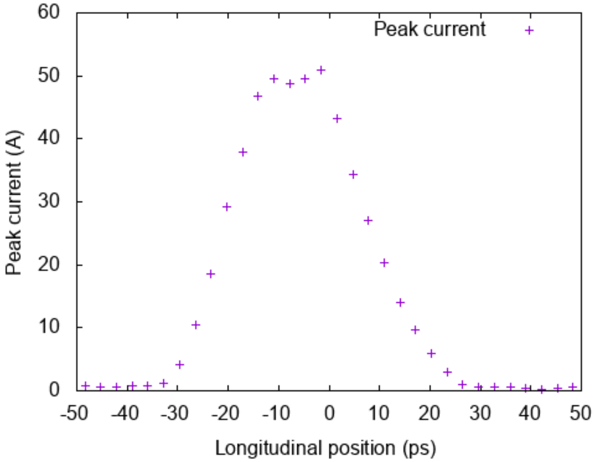
Effort to achieve temporal uniformity (Run 23)

- 3D cooling simulation requires the electron beam to have uniform current distribution (<10% peak-to-peak variation) as well as good quality over 10 - 15 ps duration or more.
- Beam dynamics simulation shows the temporal uniformity can be achieved using modified initial laser pulse shape with peaks on the sides and dip in the middle.
- New laser profile was developed to have intensity/delay control over individual Gaussian beamlets.

5 Gaussian beamlets



Initial current distribution

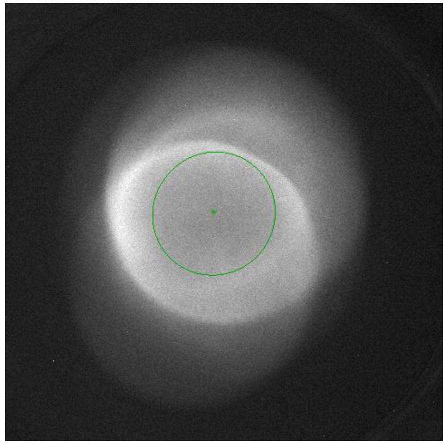


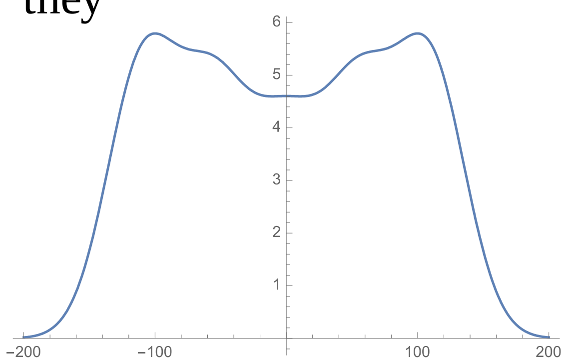
Final current distribution (simulated)

Studies of individual beamlet's properties (Run 23)

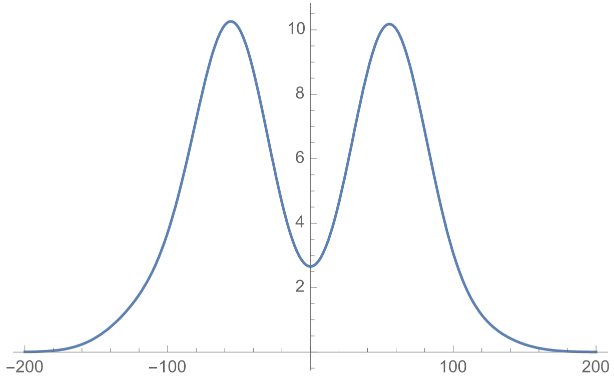
- We measured individual beamlets with same charge (transverse emittances, arrival time, longitudinal energy spread etc.) and they prove to be very consistent.
- Measured beam properties agree well with simulation predictions.
- When combining 5 beamlets, the relative strength of laser power is not as desired, #1,3,5 have significantly weaker power than #2,4 (6%, 45%, 1%, 45%, 3%).
- The transverse alignments of 5 beamlets need to be improved (smearing minimized) so that the emittance does not blow up (measured 10 um norm., slice when they combined).

Parameter	Simulated	Measured
Charge per bunch, nC	0.3	0.3
Bunch length, RMS, ps	30.8	31.7-32.4
Bunch length, FW, ps	119	120-123
Final peak current, A	3.0	3.2-3.4
Normalized emittance (slice), RMS, µm	1.0	0.9-1.0
Beamlets separation, ps	55	54-56





Proposed laser profile



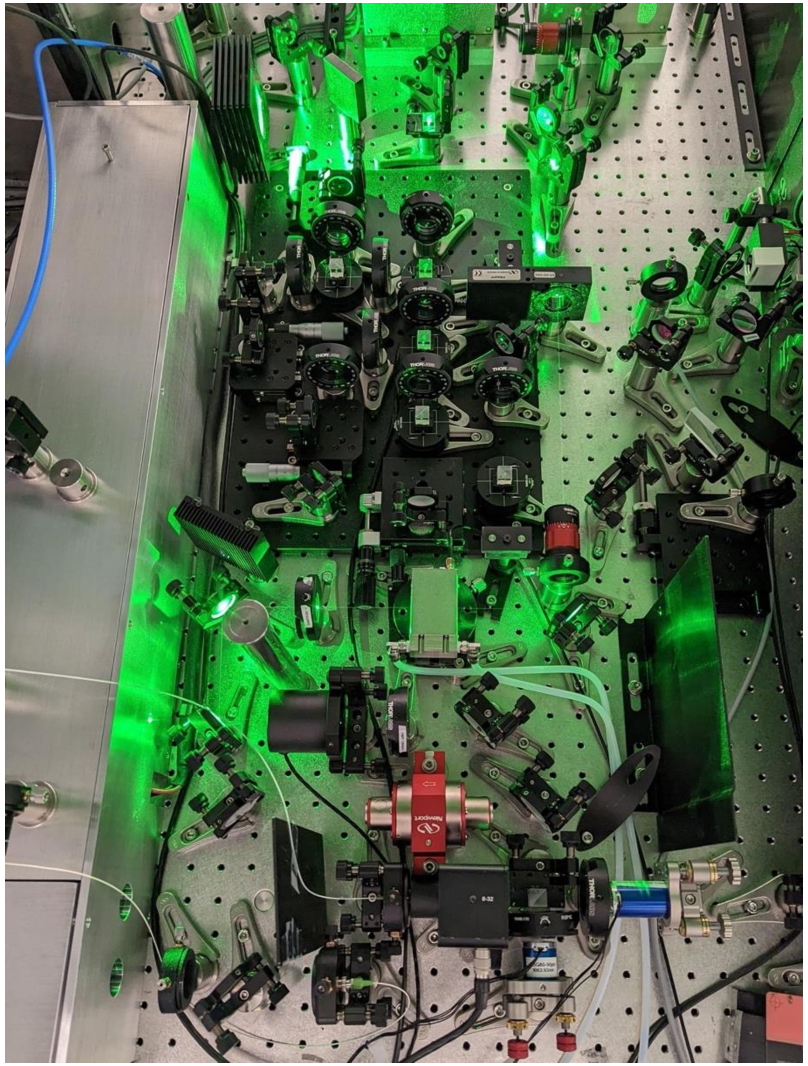
Actual laser profile

Laser system fixes/upgrades in Run 23-24

1. Detailed investigations after the end of the run revealed that low power in the three of the five beamlets (beamlets #1,3 and 5) were not related to the reflectivity of the mirror but to the error in setting splitters and combiners in the laser trailer. The problem was fixed as soon as it was found.

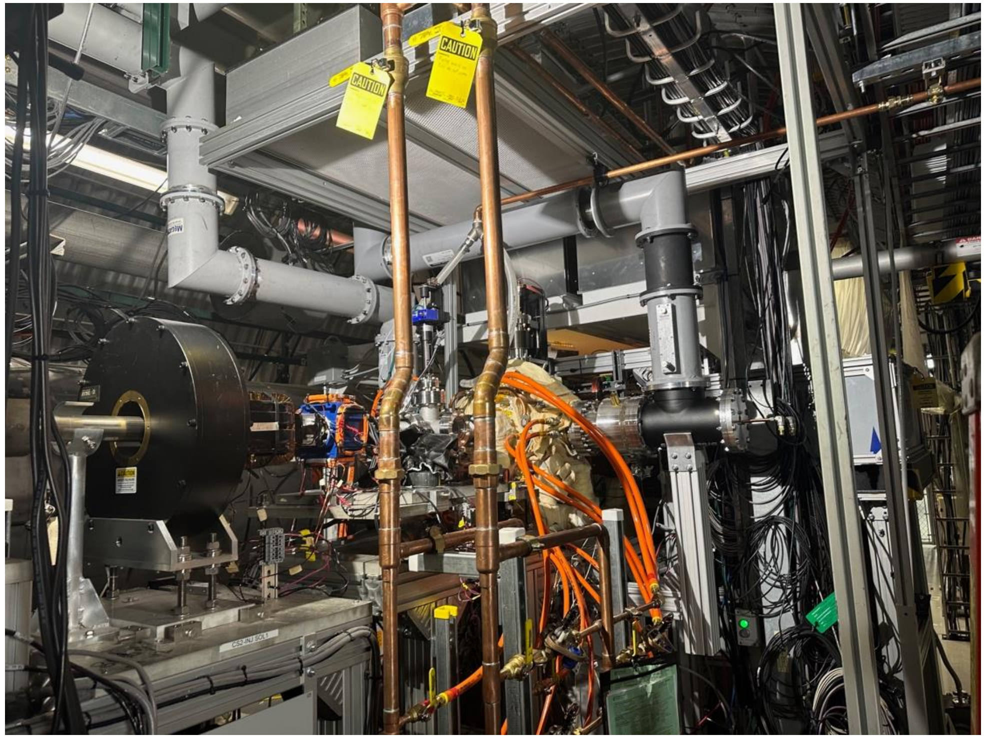
2. New fiber amplifier was procured to increase the input pulse energy from the seed laser (mode locked oscillator) from 2 pJ to 250 pJ. This allowed to set regenerative amplifier to a lower nominal gain (between 50 dB and 60 dB) and improve pulses-to-pulse stability below 1% RMS jitter. In Run 24, we measured improved power jitter (~ 1.7% RMS). Further improvement is planned during the RHIC shutdown.

3. We started discussions of new IR laser and delivery systems (likely with fibers) to improve vibrations caused by environments and improve the transverse stability of delivered laser beam at cathode. Preliminary plan will be finished in January 2025 and results will be tested before the start of Run 25.



With courtesy of P. Inacker

New bunching cavity

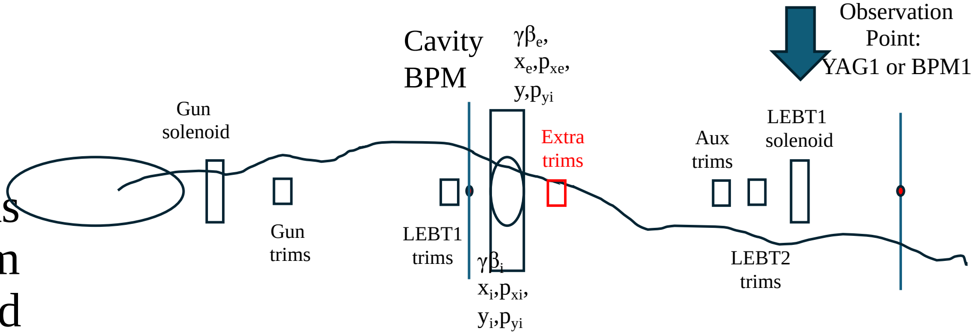


With courtesy of J.C Brutus

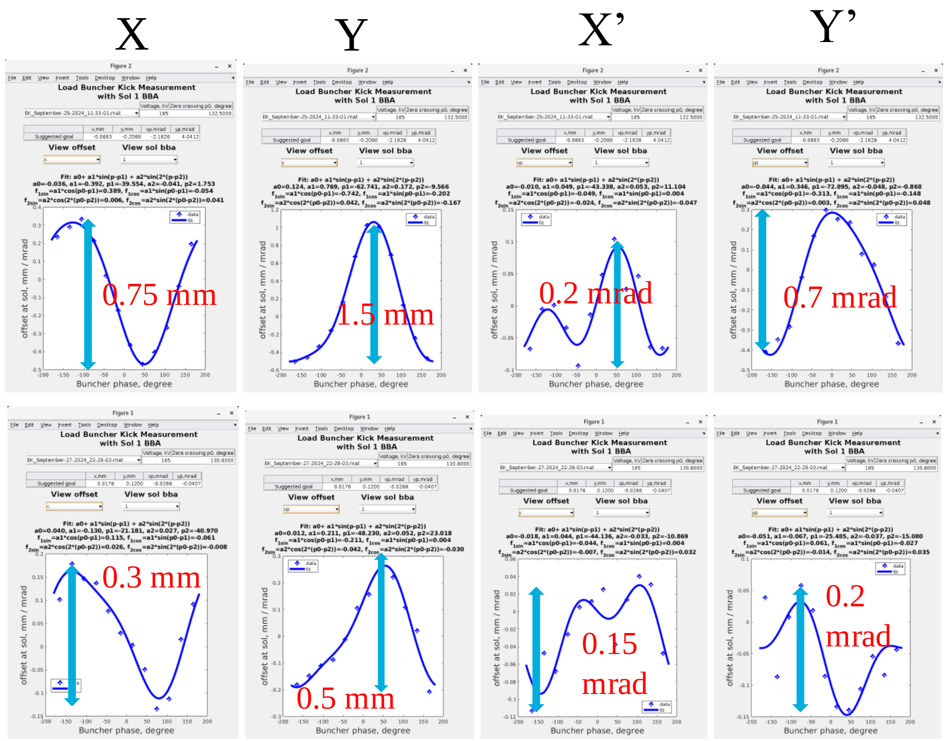
- New 500 MHz bunching cavity was installed and fully operational in Run 24 to remove the undesirable time dependent transverse kick which deteriorates the beam quality.
- Old bunching cavity loaned by UK's Daresbury laboratory with strong transverse fields resulting in **12.5 mrad/MV** vertical and **4 mrad/MV** horizontal time-dependent transverse kicks to the electron beam.
- Initial measurements with the new cavity showed that both transverse kicks are significantly smaller: ~ **2 mrad/MV** vertically and **0.5 mrad/MV** horizontally: 6- to 8-fold reduction compared with the old system.
- Two extra sets of trims around the bunching cavity were installed which allowed us to control trajectory of the electron beam though the cavity: both in position and in the angle.

Beam alignment through the bunching cavity

Rigidity of the beam is reduced by 25%

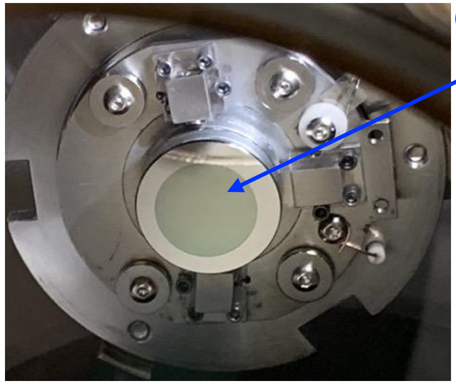


- We developed an algorithm to further reduce the time dependent kicks from the bunching cavity by investigating various aspects of beam trajectory through the bunching cavity: the cavity displacements and tilts, the beam displacement and angles, asymmetry of the cavity fields and, finally, chromatic effects and transverse dispersion coming from stray fields.
- The LEBT1 solenoid, downstream to the bunching cavity, was served as pickup of the 4D offsets (x.y.x',y') of the beam through the cavity. The response matrix to the beam trajectory through the cavity can then be measured by changing positions (x and y) and angles (x',y') in the bunching cavity.
- Using measured response matrix, we reduced the time dependent kicks by additional 2 - 3 fold. Less improvements observed in horizontal plane, which is likely caused by the defect in one of FPCs resulted in left-right asymmetry. Such asymmetry in field cannot be fully compensated by just orbit adjustments.

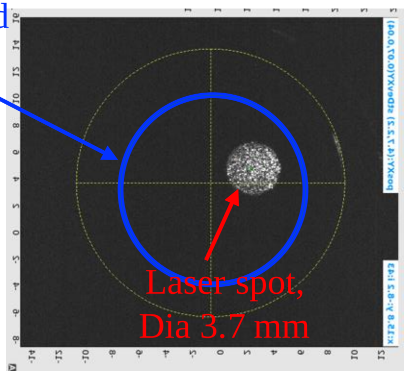


Correcting beam trajectory in injector solenoid (Run 24)

- The first injector solenoid's field axis, due to space limit, has very large angles – 14 mrad in x, 7 mrad in y versus the SRF gun's field axis. This causes severe beam distortion and beam quality degradation.
- Using larger (14 mm in diameter as comparing to 10 mm in earlier Runs) photocathode allowed us to adjust laser spot position by 3.35 mm horizontally and 1.45 mm vertically, which puts electron beam closer to the axis of the gun solenoid.
- Projected geometric emittance improves from 0.7-0.8 um to ~ 0.5 um with nominal set up.

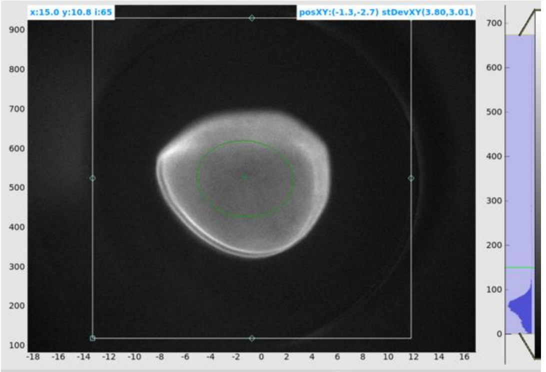


Photocathode in the preparation chamber

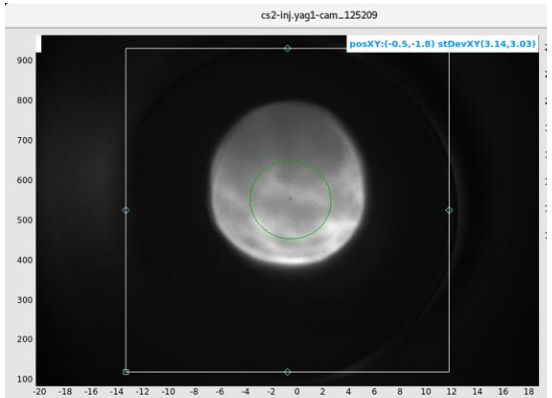


Laser spot shifted from the 3.35 mm horizontally and 1.45 mm vertically

No alignment



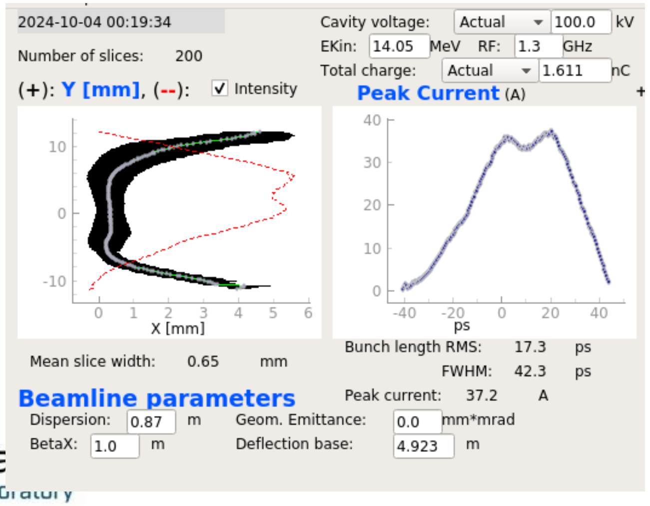
After alignment

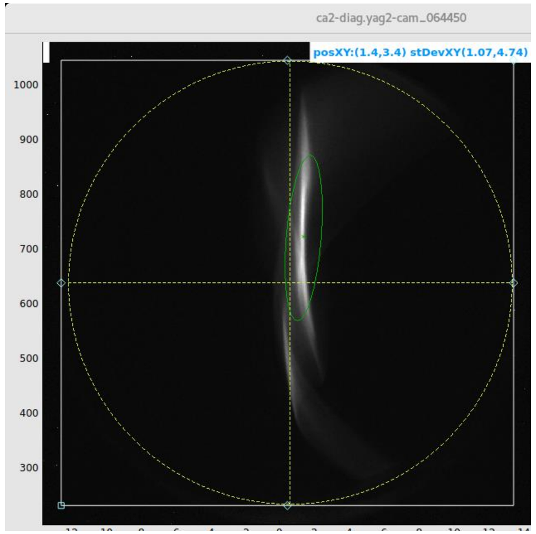


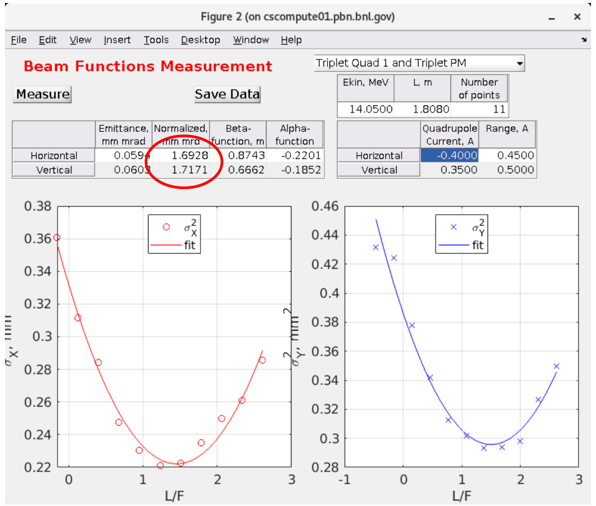
E-beam profiles at first CeC profile monitor

Measured beam quality in Run 24

- One of the main goals in Run 24 was to demonstrate the key beam parameters needed for cooling demonstration.
- Beam parameters measured in Run 24:
  - ✓ Bunches with semi-flat peak-current: ~30 psec with 60% of charge
  - ✓ Flat energy profile for the core of the beam
  - ✓ Slice energy spread ~ 2×10^{-4}
  - ✓ Projected normalized emittance less than 2 mm mrad
- We will continue improving lattice to complete demonstration of required beam parameters including the time-resolved slice emittance measurements.







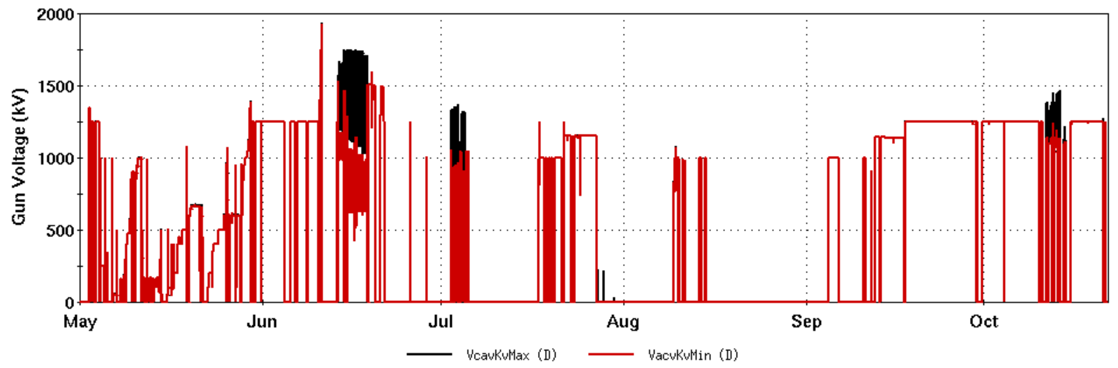
Interruptions in operation in Run 24

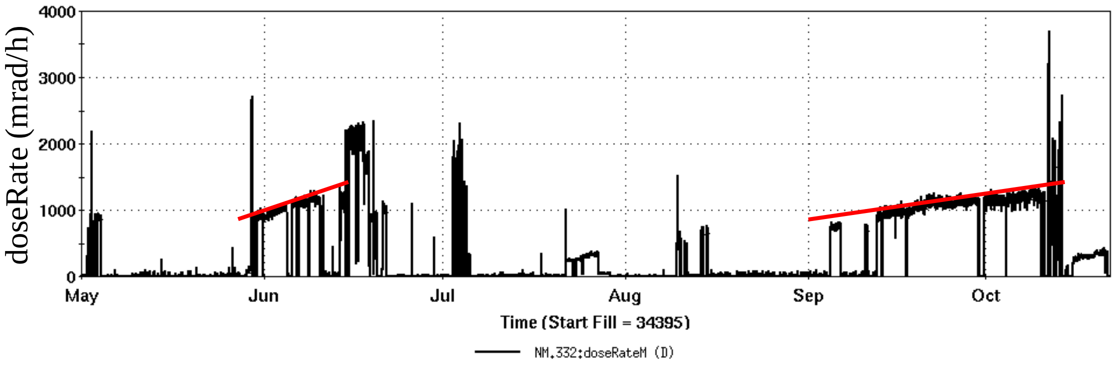
- Over the course of continuing operation of the SRF gun, we observed continuous increase in the radiation around the gun as well as increase level of dark current.

- Gun conditioning were needed to clean up the gun before it could be brought back to normal operation. This caused several interruptions in the beam operation and loss of time.

- Such behavior existed in previous years of operation with the SRF gun.

- This is likely caused by evaporation of the Cs from the CsK_2Sn photocathodes. Hence, we plan to switch to NaKSb photocathodes for the Run 25, with Na having significantly higher evaporation temperature.





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Summary of Run 24

- We managed to achieve several important milestones in Run 24 during the limited time of operation:
    1. The new 500 MHz cavity with significantly weaker transverse kicks is fully operational and we developed algorithm to further reduce the time dependent transverse kicks by 2-3 folds.
    2. Key beam parameters needed for cooling demonstration were measured close to specifications.
- We did not manage to measure all needed beam parameters for cooling demonstration simultaneously or re-establish the high gain amplification in the PCA in Run 24 due to several delays in key beamline component (500 MHz cavity) and interruptions:
    1. Delay in delivery of the new 500 MHz cavity as well as its faulty FPC caused three months delay in start of the CeC operation.
    2. Increase of radiation and dark current as well as contamination of the gun from the overheating of cathode by failure of end-effector interrupted the operation several times. Multiple times of He conditioning as well as one cavity warm-up were performed to restore normal operation of the SRF gun.

Major remaining challenges

- Improve laser system to have better stability in power for stable CeC operation. In Run 24 the best measured laser power jitter was ~ 1.7% RMS and normally went up to about 2 – 3% RMS during 8 hour shift. The power jitter causes significant variation in space-charge dominated dynamics of the electron beam and should be eliminated for reliable measurements and demonstration of CeC.

- Improve transverse stability of the beam. Various sources of the vibration that causes laser motion have been identified and plans have been made to fix the undesirable large transverse motion in the electron beam.

- Improve transverse uniformity of beam generated at the photocathode (QE and laser profile). The non-uniformity results in violation of axial symmetry, filamentation of beam and generation of halo – degradation of beam quality.

- New NaKSb cathode for more machine up time.

CeC work during shutdown 24

1. In addition to the major challenges, we plan to fix few remaining minor problems as well as check alignment of the CeC system during RHIC shutdown.
2. We plan to explore an alternative mode of CeC operation with relaxed beam requirements. Such mode would have further advantages:
   a. CeC cooling requires 22 A in peak current, down from 45 A.
   b. Ions energy at 18.2 GeV/u, below the transition energy, which will provide for better quality Au beam.
3. We plan to demonstrate this new operation mode experimentally at the beginning of next run.
4. Various shutdown items have been completed.

Scroll Pump ON & OTHER SIDE
Cryos. Rough Pump ON unclamped
He Cond. Roots Pump ON
Cryostat Turbo ON
He Cond. Turbo ON
FPC Blower OFF
Vibration Isolation Pads under Cryo Rough Cart Wheels & Roots Pump

#	Task
1	Laser: 1% RMS power jitter
2	Laser: Pulse measurements at gun table
3	Laser: Position stabilization
4	Laser: Measure time jitter of the laser pulses
5	NaKSb photocathodes for next run
6	Investigate CsK_2Sb cathodes removed from gun
7	Fix illumination and focus of all profile monitors
8	Fix cables for 2 profile monitors that are none responsive
9	Add "external" synch for Gun2 camera
10	Examine laser cross
~~11~~	~~500MHz FPC replacement ?~~
~~12~~	~~Re-align the bunching cavity?~~
13	Survey: Locate LEBT solenoids
14	Survey SRF linac: location?
15	Survey: Locate transport magnets
16	Build an air-coil sextupole magnet and install it upper LEBT section
17	LEBT gun_tv1 aux trim polarity is wrong
18	LEBT th1_aux trim strength should be increased
19	Common section sol 1 and sol 5 polarities should be corrected
20	LLRF system to operate SRF gun at h+1=1447 harmonic of RHIC operating with 18.196 GeV/u Au ion beam. Change of bunching cavity and SRF linac harmonics as well.
21	Check operation of all IR diagnostics
22	Compton polarimeter
23	Prepare GaAs cathodes
24	Adjust alignment laser on the common section profile monitor
25	Shield exist hole from High Power beamdump
26	Measure level of vibration from laser table

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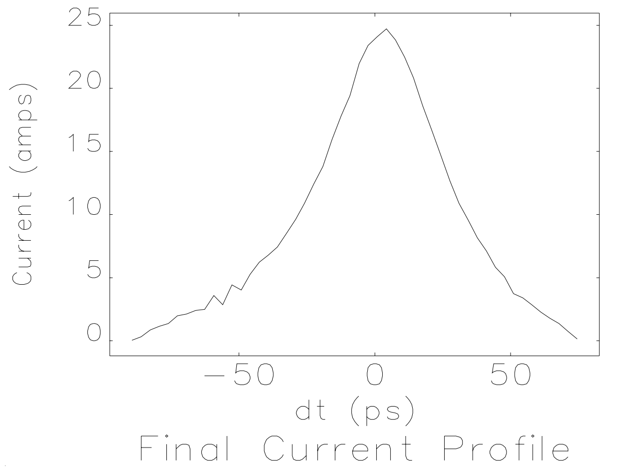
Modes of operation

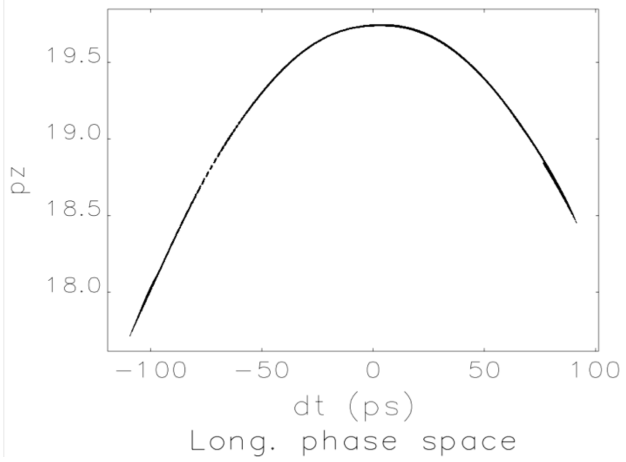
- New operation mode with hadron energy below transition was recently proposed.
- Lower energy of operation would provide for better quality hadron beam and relax the parameters of the electron beam. All needed simulations are taking place and will be finished before the start of the Run 25.
- **Best mode will be selected for the cooling demonstration**
- The required beam parameters will be demonstrated before June 2025.

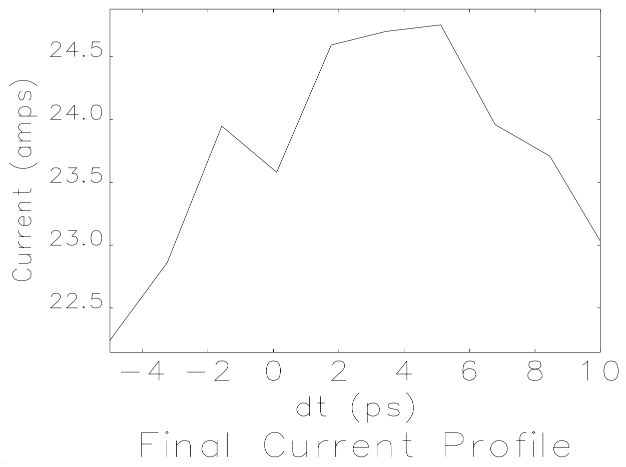
Parameter	New mode	Old mode
Lorentz factor	19.57	28.5
Au ion beam energy, GeV/u	18.2	26.5
Electron beam energy, MeV	10	14.56
Peak current, A (core)	≥ 22	50
Norm. rms slice emittance, um (core)	≤ 1.5	1.5
RMS relative energy spread (core)	$< 2 \times 10^{-4}$	$<2 \times 10^{-4}$
Energy flat top (core)	$< 1.5 \times 10^{-4}$	$< 1.5 \times 10^{-4}$

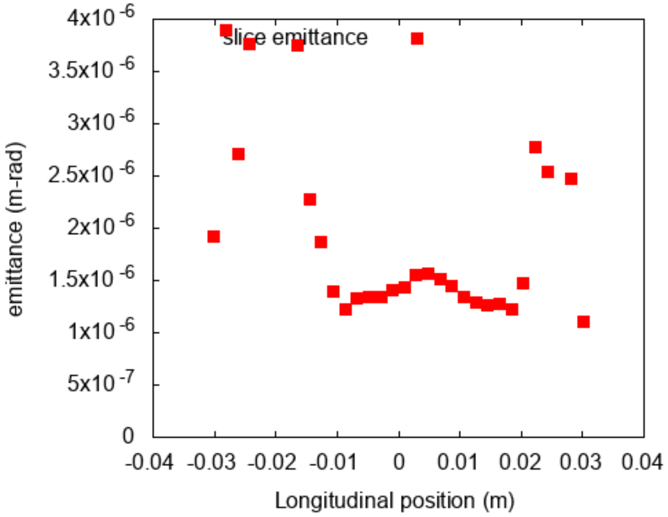
We have started beam dynamics simulation to optimize settings for this new mode. Preliminary results show reaching proposed beam parameters is easier. Optimization is on-going for better results.

Preliminary beam dynamics simulation for new mode of operation









- Preliminary simulation shows peak current for compressed beam reaching 22 A with peak-to-peak 10% variation has duration longer than 15 ps.
- Normalized slice emittance for core < 1.5 um.
- On-going optimization for better uniformity in average energy between slices.

CeC Plans for Run 25

Plans towards demonstration of CeC:

1. During RHIC physics run we will bring all CeC systems to full readiness and establish required electron beam parameters for cooling and achieve required stability (April-June, 2025).
2. We will use APEX time through Run-25 to accomplish preparational tasks prior to use of dedicated time (June-August, 2025).
3. Two weeks of dedicated time at the end of the run are requested to accomplish CeC cooling demonstration:

   - Match relativistic factors of ion and electron beams – 1 day

   - Restore High-Gain Plasma-Cascade amplification with CW e-beam – 3 days

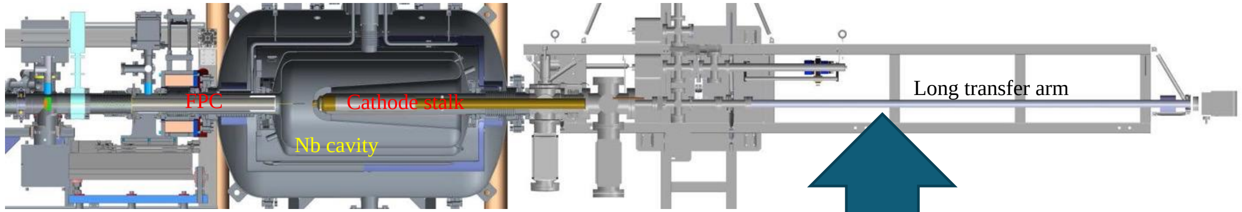
   - Fine system tuning and demonstration of Coherent electron Cooling – 10 days

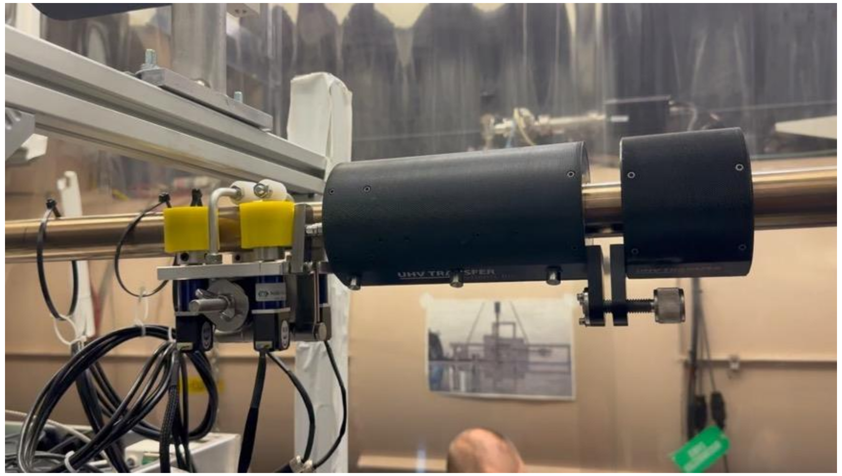
Summary

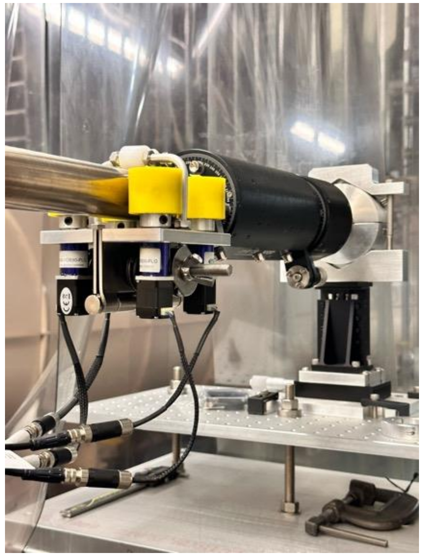
- Over the course of the years in operation, the CeC X has achieved several key milestones (low beam noise, high gain amplifier etc) along the road to final cooling demonstration.
- Recent efforts have been put in achieving better uniformities in the beam properties and elimination/compensation of all undesirable time-dependent kicks from cavities. We saw improved beam quality after several major beamline upgrades. The key beam parameters (except slice emittance) required by cooling demonstration were measured in experiments.
- The CeC accelerator still suffers from lack of reliability: both in terms of beam parameter jitter and poor repeatably of operation set-ups. This is our major challenge to overcome in the beginning of Run 25.
- New operation mode for CeC accelerator with 10 MeV electron beam has been proposed to relax the electron beam requirements for observing cooling. Beam dynamics and cooling simulations for the new mode are underway.
- We are aiming to demonstrate longitudinal Coherent electron Cooling in Run 25.

Backup slides

New “tractor" system for cathode transfers

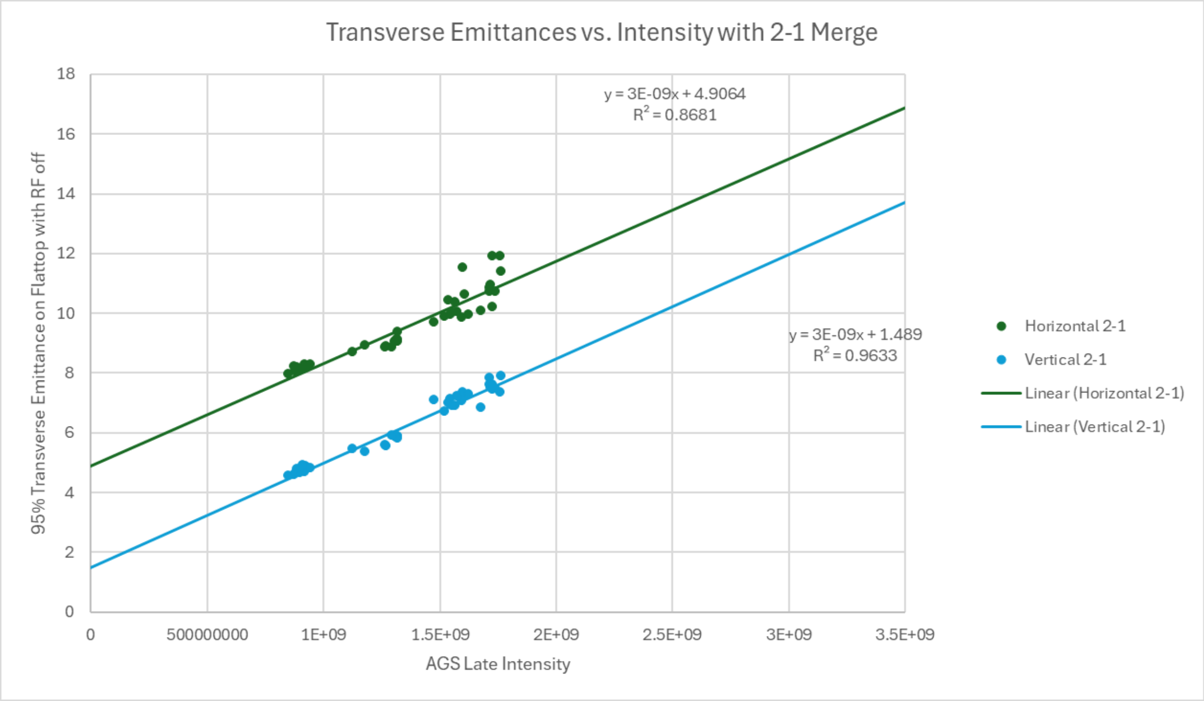






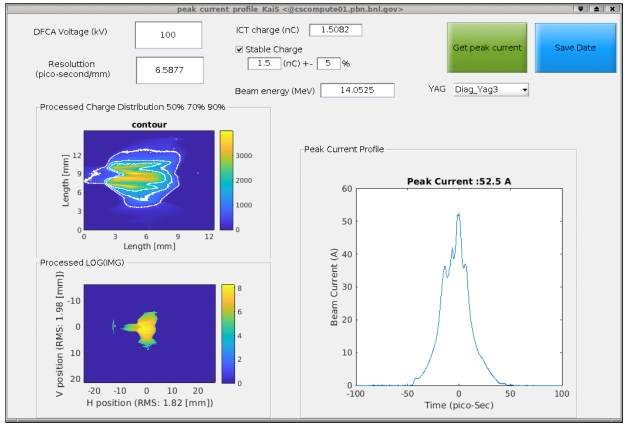
We build-up at SBU a new system – called a tractor – which provide a slow and steady insertion of the cathode in the long arm of the SRF gun cathode transfer system. The role of this device is to reduce outgassing and vacuum pressure spikes during cathode transfer. This devise was successfully tested this month.

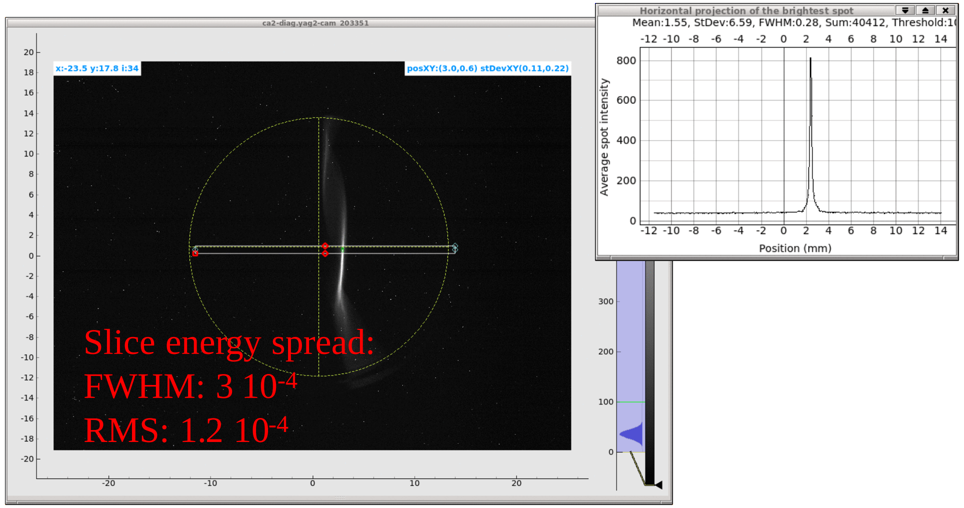
Emittances as beam intensity for Au beam in RHIC



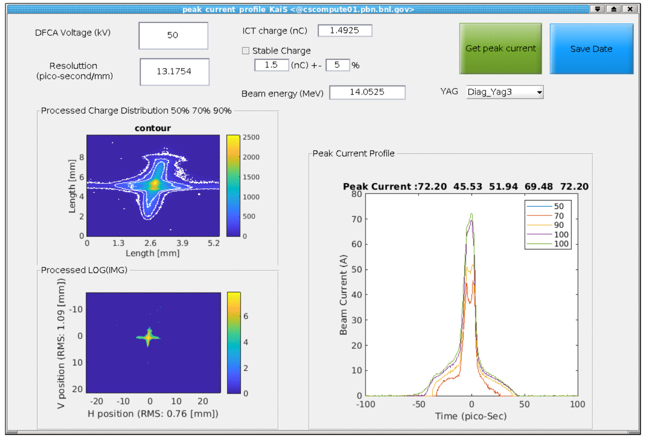
March 2022

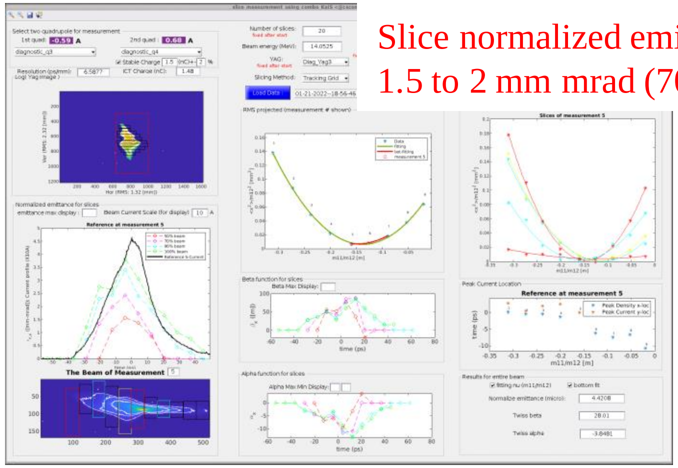
KPPs - Beam parameters with 185 kV bunching voltage





Peak current from 50A to 70 A





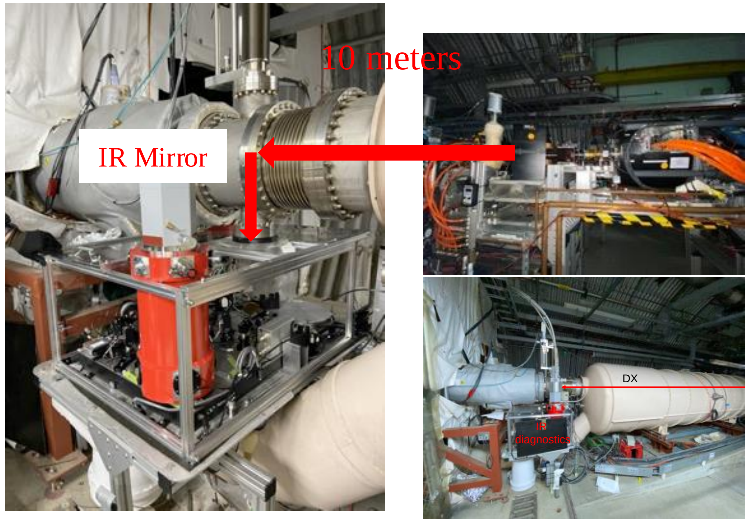
Slice normalized emittance
1.5 to 2 mm mrad (70% core)_

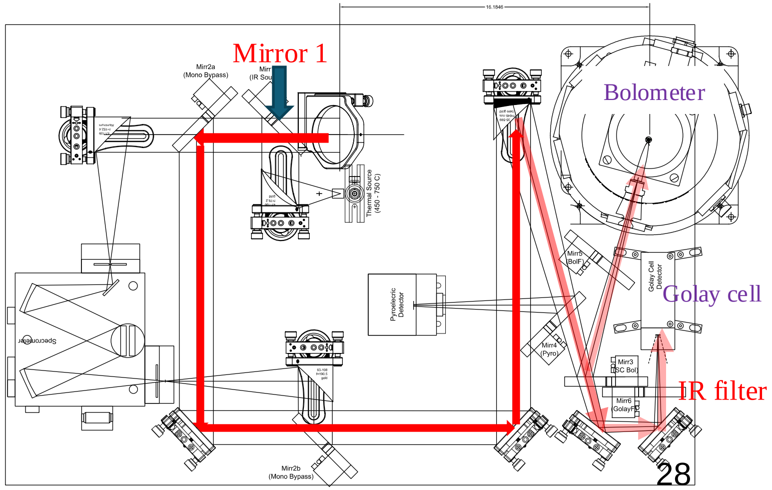
Run 22: Demonstration of Plasma Cascade Amplifier (PCA) gain at high frequencies

- After establishing electron beam parameters sufficient for high PCA gain, we made several unsuccessful attempts to demonstrate high PCA gain. For long time maximum observed PCA gain was ~ 5.
- Main problem was related to increasing beam losses with solenoid's currents approaching the designed strength for PCA lattice. It is likely related to increased halo in electron beam.
- First promising signs of high PCA gain were observed during night shift on April 16, 2022
- Finally, high PCA gain was demonstrated during night shift on April 17, 2022

How PCA gain is measured?

- We used IR radiation from the bending magnet at the exit of the CeC section. Critical frequency of synchrotron radiation from the bending magnet is 1.3 THz
- PCA gain peaks at 15 THz and there is no gain below 4 THz
- IR radiation is intercepted by 2” mirror 10 meters downstream
- For there measurements, the radiation was delivered to two most sensitive IR detectors: broad-band Golay cell or cryo-cooled Bolometer.
- IR filter with passband of 3.5-10 THz was used in front of the Golay cell to improve sensitivity at high frequencies (see next slide)
- Signal from Golay cell was detected by lock-in amplifier synched with the electron bunch pattern (typically 5 Hz, five 100 msec bunch trains per second). We used high order modulation-demodulation (MDM) technique to remove background unrelated to IR radiation, by periodically blocking IR using Mirror 1.
- Signal from Bolometer was delivered in unsynchronous mode (140 kilo-samples per second) with respect to electron beam pattern. Analog signal was not available. We developed MatLab application for asynchronous detection of this digital pattern.
- PCA gain was evaluated by comparing radiated power in the PCA lattice (strong solenoids) with relaxed lattice (weak solenoids) using the same setting of the CeC accelerator and the electron beam





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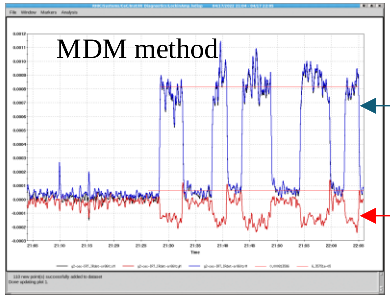
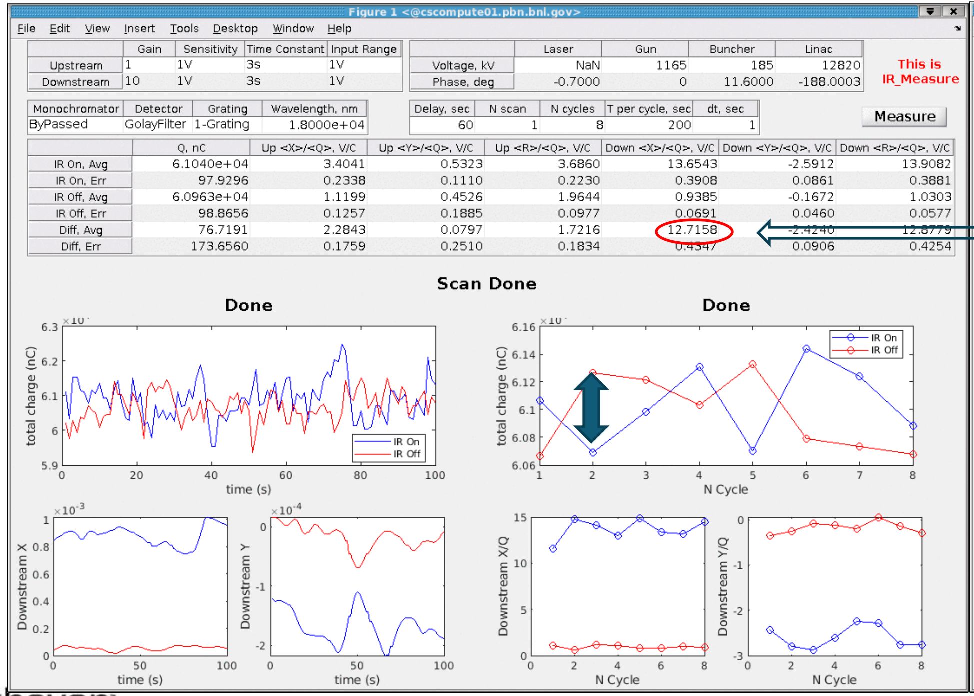
Golay cell measurement
PCA/Relaxed=65



PCA lattice



	Gain	Sensitivity	Time Constant	Input Range
Upstream	1	1V	3s	1V
Downstream	10	1V	3s	1V

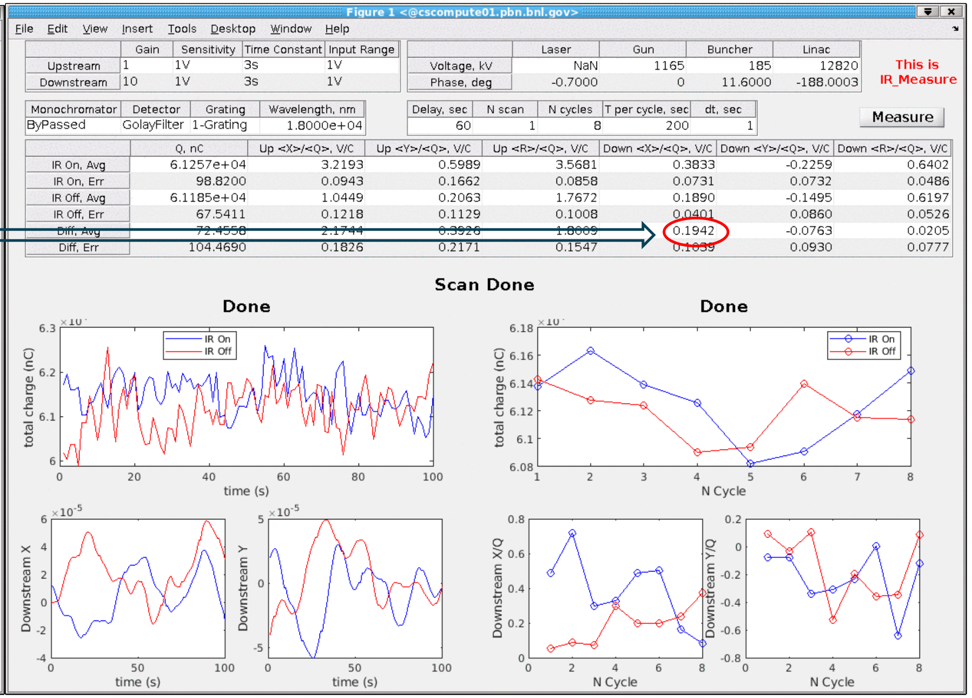
	Laser	Gun	Buncher	Linac
Voltage, kV	NaN	1165	185	12820
Phase, deg	-0.7000	0	11.6000	-188.0003

Monochromator	Detector	Grating	Wavelength, nm
ByPassed	GolayFilter	1-Grating	1.8000e+04

Delay, sec	N scan	N cycles	T per cycle, sec	dt, sec
60	1	8	200	1

	Q, nC	Up <X>/<Q>, V/C	Up <Y>/<Q>, V/C	Up <R>/<Q>, V/C	Down <X>/<Q>, V/C	Down <Y>/<Q>, V/C	Down <R>/<Q>, V/C
IR On, Avg	6.1040e+04	3.4041	0.5323	3.6860	13.6543	-2.5912	13.9082
IR On, Err	97.9296	0.2338	0.1110	0.2230	0.3908	0.0861	0.3881
IR Off, Avg	6.0963e+04	1.1199	0.4526	1.9644	0.9385	-0.1672	1.0303
IR Off, Err	98.8656	0.1257	0.1885	0.0977	0.0691	0.0460	0.0577
Diff, Avg	76.7191	2.2843	0.0797	1.7216	12.7158	-2.4240	12.8779
Diff, Err	173.6560	0.1759	0.2510	0.1834	0.4347	0.0906	0.4254

Relaxed lattice



	Gain	Sensitivity	Time Constant	Input Range
Upstream	1	1V	3s	1V
Downstream	10	1V	3s	1V

	Laser	Gun	Buncher	Linac
Voltage, kV	NaN	1165	185	12820
Phase, deg	-0.7000	0	11.6000	-188.0003

Monochromator	Detector	Grating	Wavelength, nm
ByPassed	GolayFilter	1-Grating	1.8000e+04

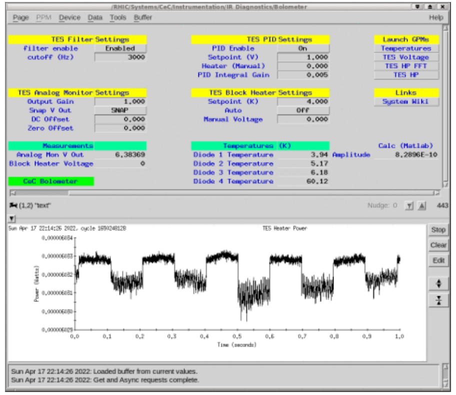
Delay, sec	N scan	N cycles	T per cycle, sec	dt, sec
60	1	8	200	1

	Q, nC	Up <X>/<Q>, V/C	Up <Y>/<Q>, V/C	Up <R>/<Q>, V/C	Down <X>/<Q>, V/C	Down <Y>/<Q>, V/C	Down <R>/<Q>, V/C
IR On, Avg	6.1257e+04	3.2193	0.5989	3.5681	0.3833	-0.2259	0.6402
IR On, Err	98.8200	0.0943	0.1662	0.0858	0.0731	0.0732	0.0486
IR Off, Avg	6.1185e+04	1.0449	0.2063	1.7672	0.1890	-0.1495	0.6197
IR Off, Err	67.5411	0.1218	0.1129	0.1008	0.0401	0.0860	0.0526
Diff, Avg	72.4558	2.1744	0.3926	1.8009	0.1942	-0.0763	0.0205
Diff, Err	104.4690	0.1826	0.2171	0.1547	0.1039	0.0930	0.0777

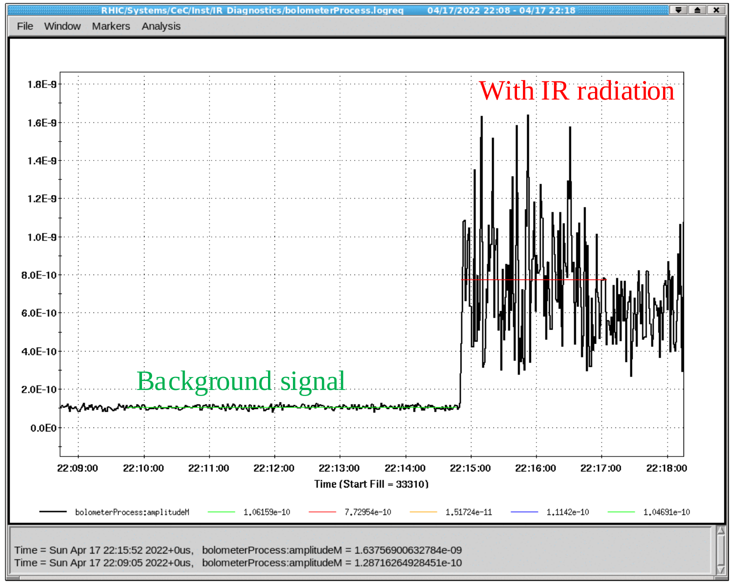
Bolometer measurement*

PCA/Relaxed:
100 +/- 20 average, 300 +/- 50 peak

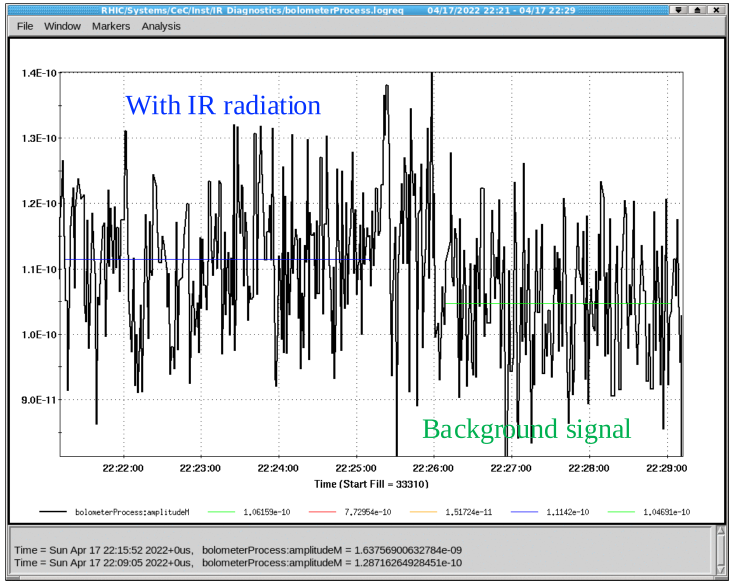
Raw
Bolometer signal



PCA lattice



Relaxed lattice



** Important note: by unknow reason, the bolometer "detects" beam pattern delivered to the heavily shielded high power dump with signal proportional to the beam intensity. It is not related to X-ray, because intercepting beam in front of the beam dump increasing radiation but eliminates the signal (it is possible to do only in low power mode, unsuitable for PCA measurement's). This background signal is is measured by blocking IR radiation using Mirror 1 – then is it subtracted from the signal measured in the presence of IR radiation*

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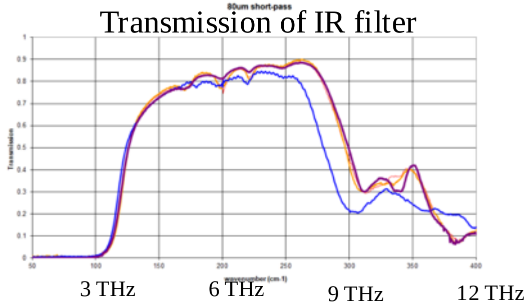
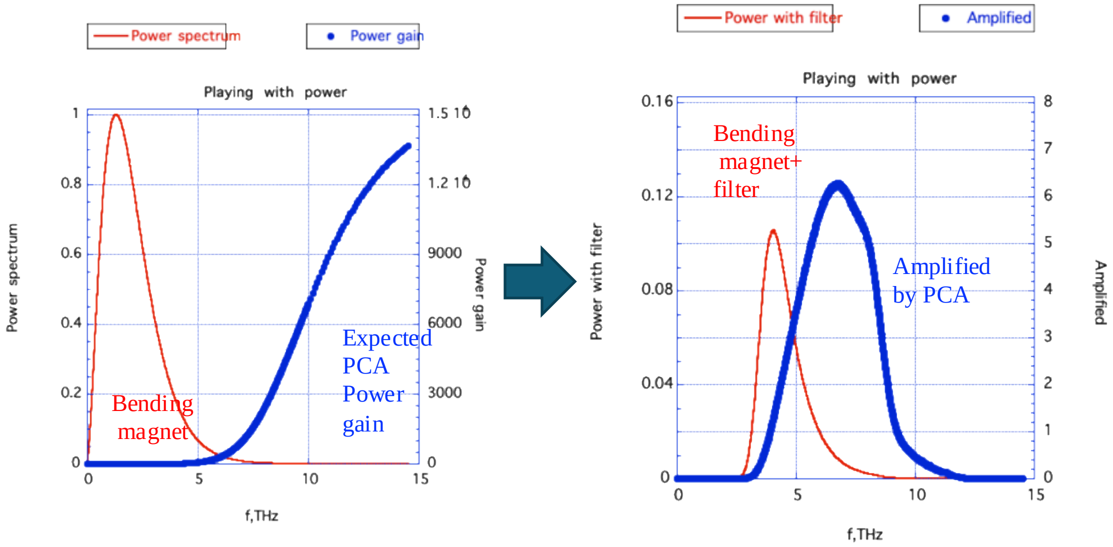
Expectations: Golay cell with IR filter



- ✓ We calculated spectrum of radiation from the edge of the bending magnet using well-benched code Igor-Pro
- ✓ For expected PCA gain we used our 3D simulations with SPACE code using uniform electron beam with 50 A peak current and 1.25 um normalized emittance
- ✓ Product of radiation power and the IR filter transmission is used and the base for the relaxed lattice (red curve in the right graph)
- ✓ This power amplified by PCA peaks at about 6.5 THz, just in the middle of the IR filter transition window
- ✓ For 50 A in 50% of the beam, expected PCA/relaxed power ratio is 60, which compares favorably with measured value of 65



Power integrals: Relaxed: *0.2007*;
Amplified : 23.84
Expected PCA/relaxed power ratio: for100% of the beam is **119**
for 50% of the beam is **60**

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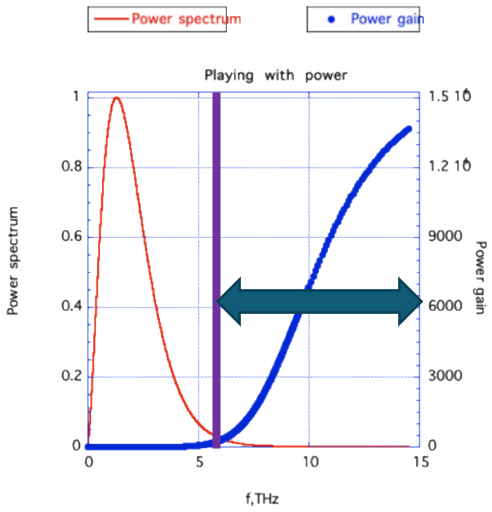
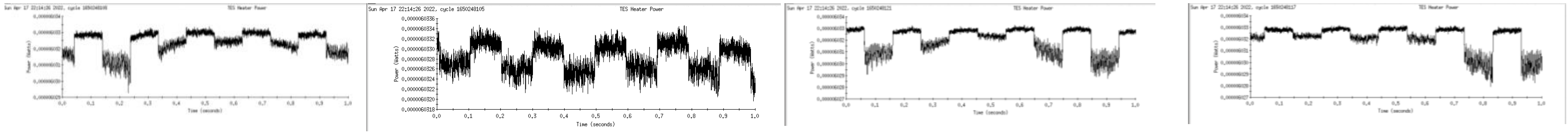
Bolometer Results

- ✓ The bolometer manual specifies the sensitivity range from 6 THz to 60 THz, but there is no calibrated spectral response. Most of the PCA amplified power is concentrated around 6.5 THz and knowledge of the spectral response is important. Hence, accurate comparison with estimations is not possible at this moment.
- ✓ Simple estimation by integrating simulated powers for relaxed and PCA case above 6 THz, gives PCA/relaxed power ratio of **1,070** if 100% of the beam has peak current of 50 A and normalized emittance of 1.25 um
- ✓ In this assumption, the measured average value for PCA/Relaxed ~100 and peak ~ 300, would indicate that
  - ✓ Either peak current ~ 50A exists in 10% to 30% of the beam
  - ✓ Or that amplitude PCA gain is 45% in average peaking at 75% (assuming that 50% of electron satisfy PCA gain condition of peak current above 50A), when compared with simulated values
- ✓ It is important to note that PCA gain changes dramatically both on the fast (1/3 kHz) and slow (1 sec) time scales, as indicated by the sample of the bolometer signal. It is our understanding that it is result of jitter in electron beam parameters, including on bunch to bunch (78 kHz) scale



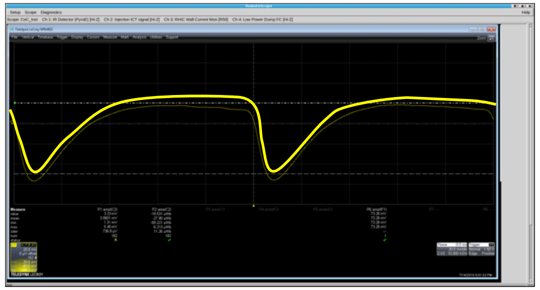
Power integrals above 6 THz
Relaxed: *0.0206*;
Amplified : 22.08

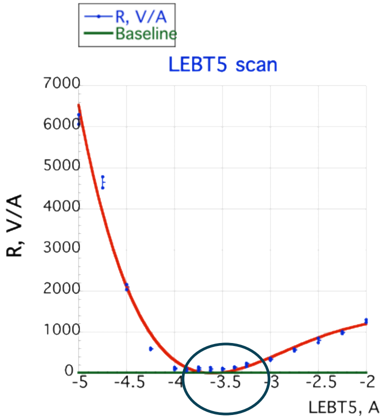


This is problem related to variation of e-beam parameters (quality)

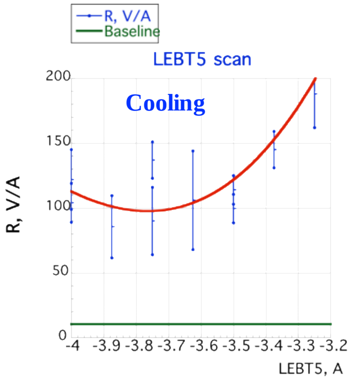
Run 18-19: control of the noise in electron beam

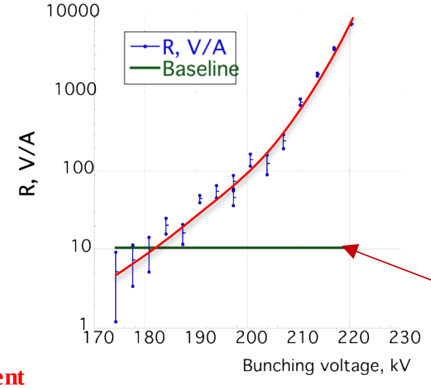
Run 18 lattice and beam: 0.6 nC per bunch
Large signal of 2,500 V/A ~ 250-fold above base line. Can be seen both on scope and measured easily

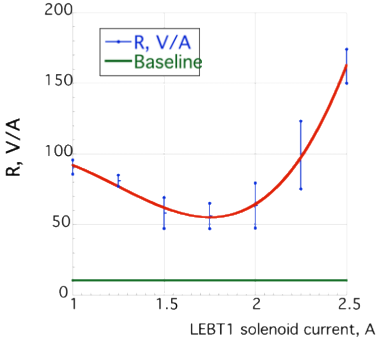




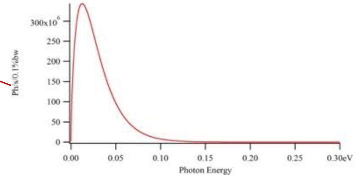
1.5 nC, 75 A peak current

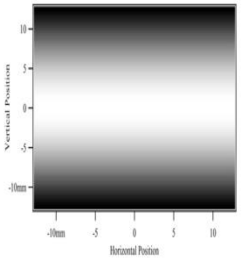






Poisson statistical shot noise was established with the radiation power simulated by Igor Pro (SRW)





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

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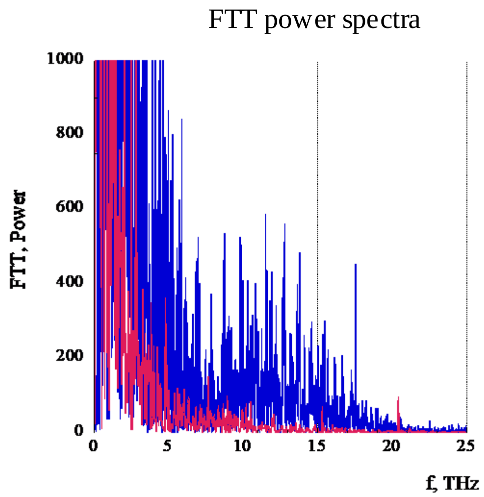
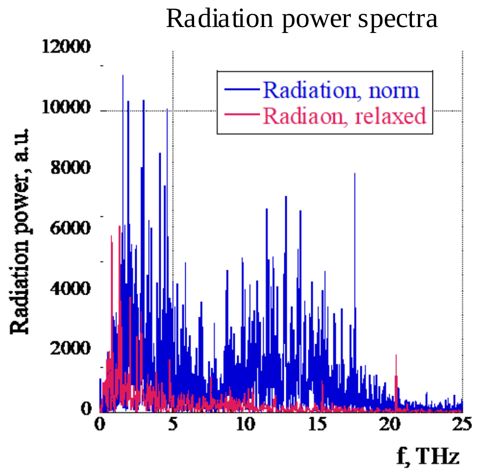
Simulation results of the PCI in CeC accelerator using Impact T for standard (Run 18) lattice (blue) and new relaxed lattice (red)



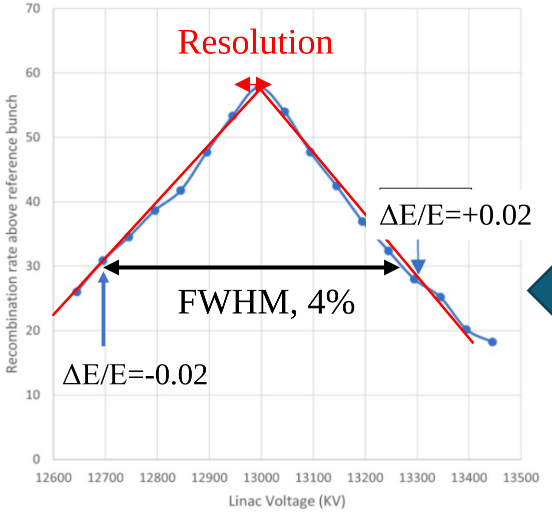


FTT and Radiation spectrum of the compressed 0.7 nC electron bunch profile at the exit of the SRF linac simulated by Impact-T. Blue color lines is for standard CeC lattice used during RHIC Run 18. Red color lines are for a new designed lattice of the CeC accelerator. Horizontal axis is the frequency measured in THz. The simulation was performed for 1.25 MV SRF gun voltage, standard bunching cavity voltages for 20-fold compression The relaxed LEBT lattice has following currents in six LEBT solenoids: 7.83 A, -2 A, 2 A, -2 A, 2 A, -2 A.

- Simulations show suppression of the PCI at frequencies ~ 10 THz down to the noise floor (defined by the code). The low frequency structures represent that of the compressed electron bunch. Red color spikes near 15 and 20 THz are computing artifacts related to the mesh and time step.
- In Run 20, measurements show that the e-beam noise in the 1.5 nC beam is from 2 to 5 times higher than the baseline (Poisson statistical shot noise).

Recombination of electrons with Au ions: Run 21

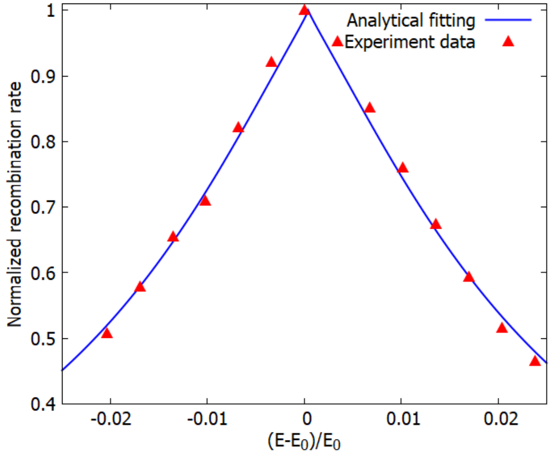
Experiment



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.

Experiment vs Calculations



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$$\alpha_r = \frac{\int_{-\infty}^{\infty} d^3v_i d^3v_e f_e(v_e) f_I(v_i) |\vec{v}_e - \vec{v}_i| \sigma(|\vec{v}_e - \vec{v}_i|)}{\int_{-\infty}^{\infty} d^3v_i d^3v_e f_e(v_e) f_I(v_i)}$$

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

$$f_I(v_i) = \frac{1}{(2\pi)^{3/2} \beta_{i,\perp}^2 \beta_{i,z}} \exp\left(-\frac{v_{i,x}^2 + v_{i,y}^2}{2\beta_{i,\perp}^2}\right) \exp\left(-\frac{v_{i,z}{}^2}{2\beta_{i,z}^2}\right)$$

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

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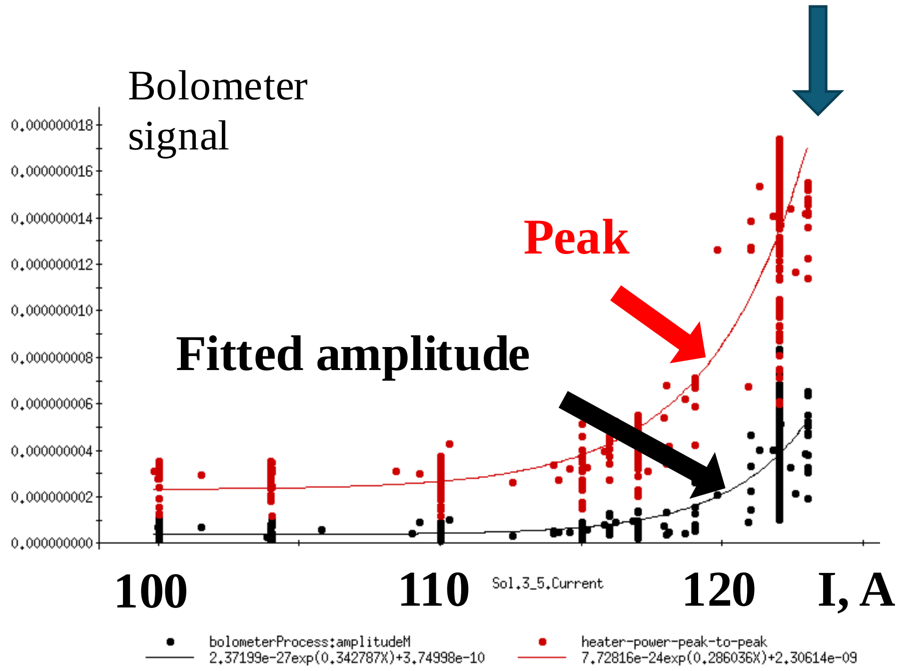
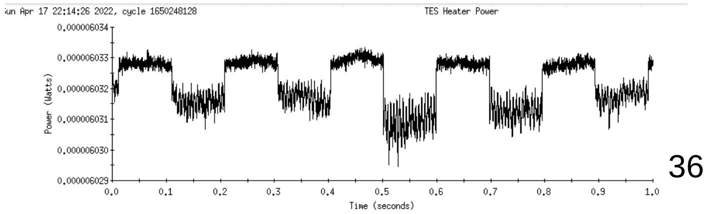
Comparing measurements with expectations

- Golay cell + IR filter measurements resulted in the average increase of IR power by factor 65 with PCA lattice
  - With 50% of electron bunch satisfying PCA condition (peak gain of 100 at 15 THz), expected increase of the measured IR power is 60
- Cryo-cooled bolometer measurements resulted in 100±20 average and 300±50 peak increase of IR power caused by PCA lattice
  - The bolometer manual specifies the sensitivity range from 6 THz to 60 THz, but absence of calibrated spectral response does not allow accurate comparison
  - Very crude estimation (using a step-function response in 6 to 60 THz) shows that with 50% of electron bunch satisfying PCA, expected increase of the measured IR power is 535
- Both results are in reasonable agreement with our expectations



Exponential growth of the IR signal at the bolometer as function of current in PCA solenoids: e-fold increase each 3 A (2.4%)



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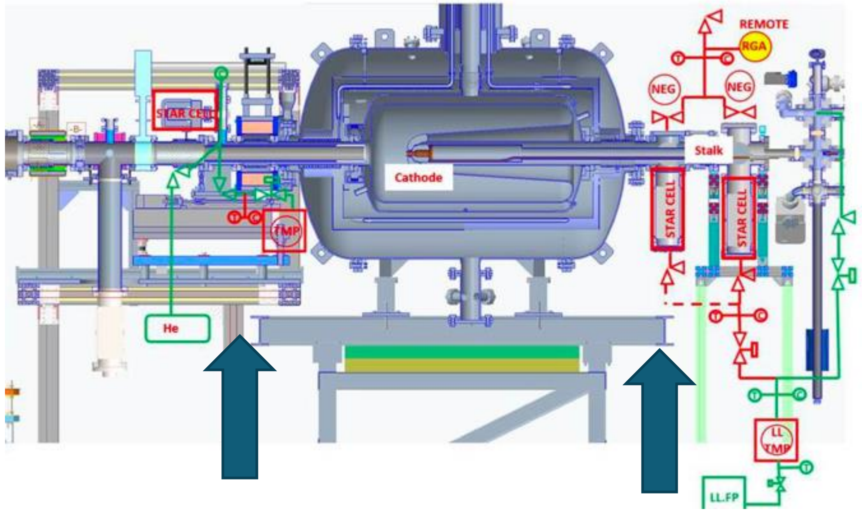
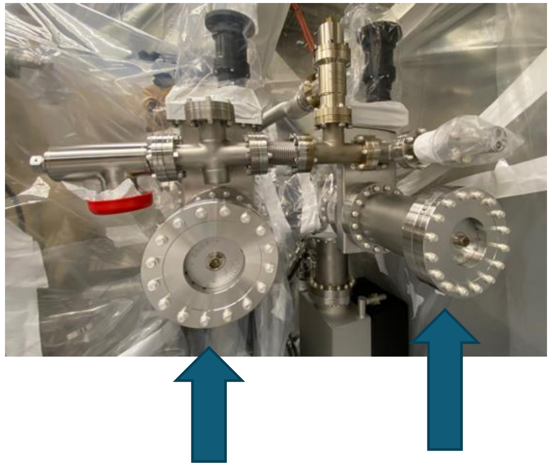
Upgrade of CeC 113 MHz SRF gun vacuum and He conditioning systems



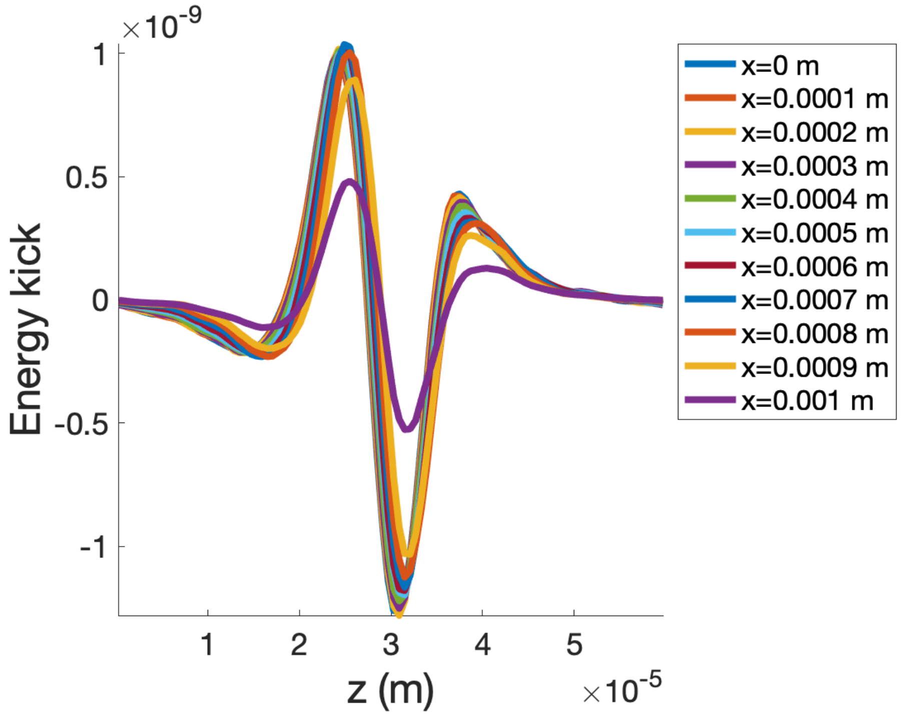
In progress Completed

Upgrade includes new high speed NEG pumps and new ion vacuum pumps at the cathode stalk and in the front of the gun aimed to an order of magnitude improvement of vacuum at the cathode location. In addition, two high compression ratio turbo-pumps will improve evacuation of He and other inertial gases from the gun system.

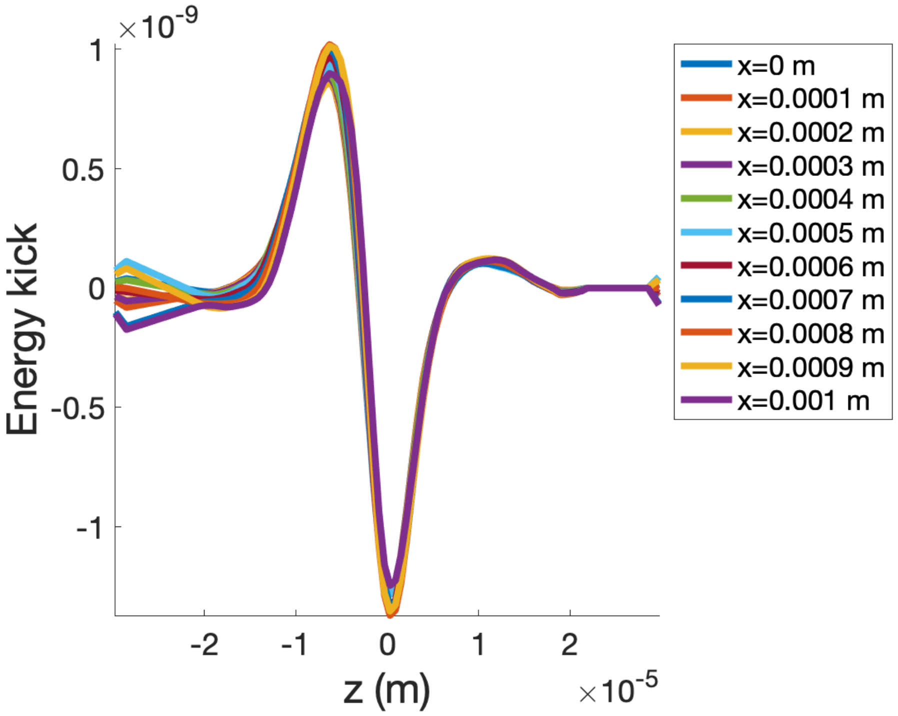


NEG Zao-2000 L/s cartridges

Preliminary cooling simulation for new CeC mode



Old mode



New mode

Preliminary cooling simulation shows the newly proposed mode of operation has similar cooling force comparing with the old mode.

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