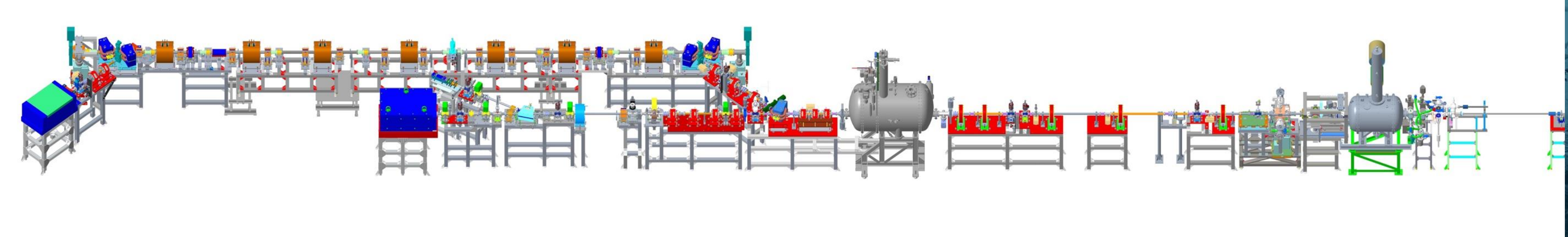
Coherent electron Cooling Experiment

Vladimir Litvinenko for CeC project

January 22, 2025



Main goal of the proposal – CeC demonstration

Side effect – classical e-cooling of 18.5 GeV ion beam

25-02 Coherent electron Cooling Experiment – 168 hours

1. *Ramp development, establishing beam orbit, low charge bunch setting – 12 hours*
2. *CW e-beam propagation and loss control in PCA mode– 2 x 12 hours*
3. *Matching beam's velocities, control of the velocity differences – 12 hours*
4. *Electron and ion beam overlap in space and time – 2 x 12 hours*
5. *Observation of the PCA affecting ion beam – 12 hours*
6. *Energy scan to observe ion beam interaction with electron beam – 2 x 12 hours*
7. *Attempt to observe CeC – 5 x 12 hours*

This proposal is replacement of all proposals involving CeC accelerator

We continue to investigate a possibility of adding one-to-weeks of dedicated time, but APEX time is critical to either for brining us close to the CeC demonstration or, if everything goes as planned, to first observation of

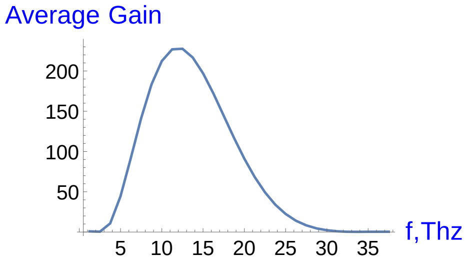
Brookhaven National Laboratory

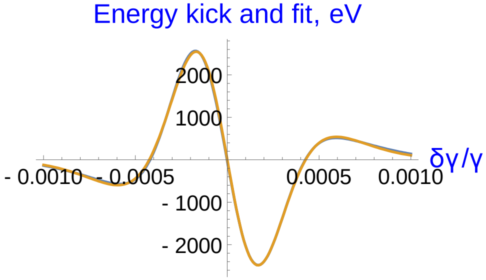
Motivation of the Proposal

- While EIC project goes ahead without cooling at the collision energy
  - Reaching average luminosity of 10^{34} $cm^{-2}sec^{-1}$ would require adding such capability
  - CeC is one of most promising methods of cooling 275 GeV proton beam in EIC
  - Run 25 is the last chance to demonstrate CeC in this decade: there is no other place in the world where it can be tested, and tens of millions of dollars will be needed for any conservable future tests
  - It is also true that we learn as much from encountering problems as from demonstrated success. Plasma Cascade instability is one of such examples: it can ruin quality of your beam by heating it or, vice versa, work as a broad band amplifier of cooling process. This is an additional argument continuing CeC experiment is beneficial for EIC
- Nice side effect
  - Experimental demonstration of traditional bunch-bunch high-energy electron cooling at 18.2 GeV/u, which is well above energies of previous e-coolers
    - *This cooling will be naturally observed during matching of the beam's velocities and overlapping of electron and ion beams (steps 3 and 4 in the proposed APEX plan)*
  - It would establish solid foundation for EIC precooler

Procedure of CeC Experiments

1. **In parallel with RHIC stores, does not require APEX time:**
   1. Establish necessary operation of CeC accelerator
   2. Propagate train of electron beam pulses through the CeC (common) section to the high power dump
   3. Establish PCA lattice with high PCA gain
2. **APEX time: operations with ion beam**
   1. Establish RHIC ramp to 18.2 GeV/u, orbit and lattice for Au ion beam (6 bunches, ≤ 10^9 ion per bunch) in Yellow ring. Establish ion beam orbit in the CeC section (through centers of 2 CeC quads). Test downward energy tunability of the RHIC beam to maximum of -0.1%
   2. Propagate CW beam through the CeC session with RHIC at 18.2 GeV/u
   3. Match beam's velocities and overlap electron and ion beams using orbit correction tools and recombination monitor. As side effect, observe regular electron cooling.
   4. Verify interaction of electron and ion beams (for example by heating ion beam by induced PCA in CeC accelerator)
   5. Dynamics in the Coherent electron Cooling requires that relativistic factor of electron beam would be higher (by ~ 0.05%) than the of the ion beam. We will attempt to observe Coherent electron Cooling by scanning either ion beam or electron beam energy with steps of 0.004%.
   6. Only one bunch will interact with electron bunches (operating at 78 kHz rep-rate).We will observe evolution of the interacting ion bunch, while non-interacting ion bunches will serve as witness bunches





Resources

Instrumentation:

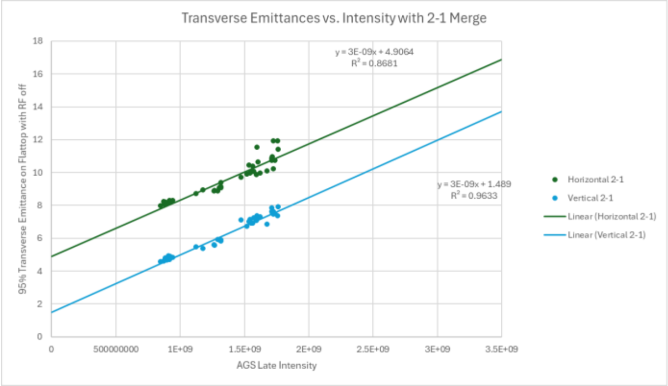
- We need all standard CeC and RHIC diagnostics, tools and applications. Nothing new is needed.

Application: CeC control pet page, CeC GPM, RHIC orbit and beam energy controls, ion bunch profile monitors, ASE monitor

Personnel: CeC team plus help from MCR and RHIC AP group

Intentional beam loss: no

Plan for data analysis: Data will be evaluated online and post process after experiments ended

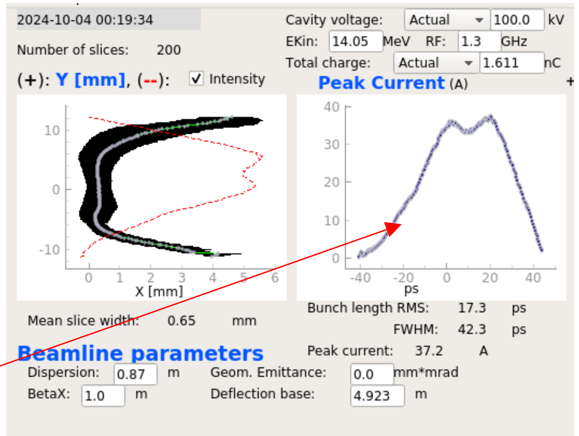


Courtesy of H. Huang

Special request: We would like to operate with very low ion bunch intensity and low ion beam emittances. Low emittance of ion beam significantly improves CeC cooling. We suggest to inject half of bunches with low intensity while keeping the rest at nominal (below ASE limit) intensity to provide reliable operation of RHIC diagnostics.

Brookhaven National Laboratory

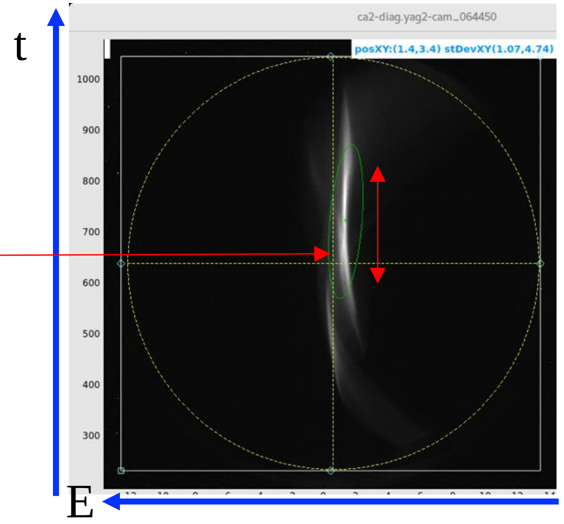
Readiness of Experiments: the 2024 CeC accelerator results

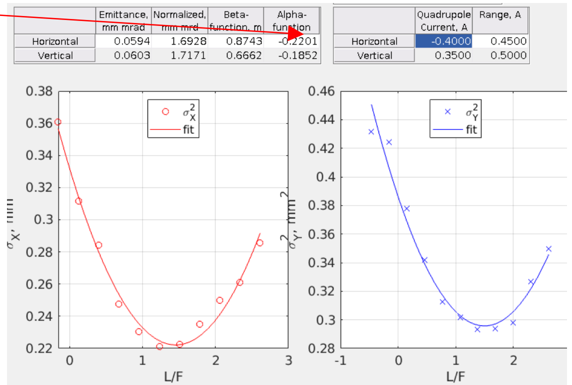


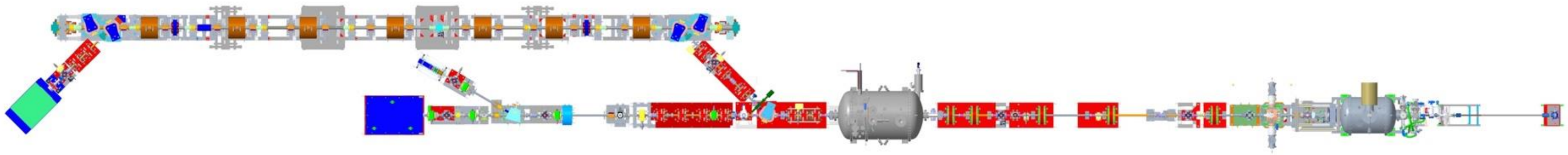
- ✓ The main improvement of the CeC system in CeC was successful installation and commissioning of the new 500 MHz bunching cavity, which eliminated strong vertical time-dependent kick in old cavities borrowed from Daresbury

- ✓ In October 2024 we demonstrated electron beam parameters, close to those needed for successful CeC operation:
  - ✓ Peak current ~ 35 A with semi-flat profile
  - ✓ Bunches with semi-flat peak-current: ~30 psec with 63% of charge
  - ✓ Flat energy profile for the core of the beam
  - ✓ Relative slice energy spread ~ 2 10^{-4}
  - ✓ Projected normalized emittance was less than 2 mm mrad, and in number of measurements as low as 1.5 mm mrad

Time-resolve energy spectrum





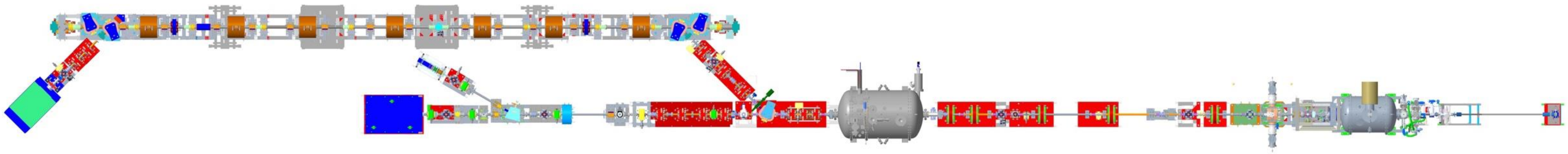


Time-resolve diagnostics

Proposed mode of operation for Run 25

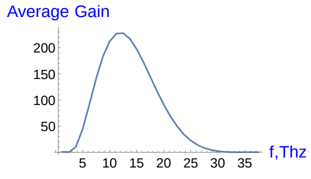
- To maximize chances for success, we will test CeC at lower ion beam energy
  - *113 MHz SRF gun frequency has limited tuning range resulting in specific choice of ion energy*
- Energy of operation below transition would provide for better quality of ion beam and easier choice of electron beam parameters, i.e. twice lower peak current
- We will test that IR diagnostics , as expected, is operating with 10 MeV beam

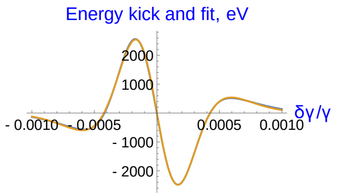
Parameter	New mode	Old mode
γ, relativistic factors of the beams	19.57	28.5
Au ion beam energy, GeV/u	18.2	26.5
Electron beam energy, MeV	10	14.56
Peak current, A (core, 50% of the beam)	≥ 22	≥ 45
Normalized emittance (core, > 50% of the beam), μm rad	≤ 1.5	≤ 1.5
RMS relative energy spread (core, > 50% of the beam), 10^{-4}	≤ 2	≤ 2
Energy flat top (core, > 50% of the beam), $\lvert 10^4\, \delta\gamma/\gamma \rvert$	< 1.5	<1.5

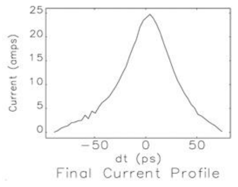


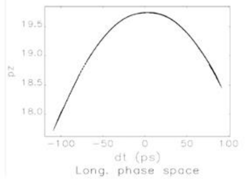
Readiness of Experiments

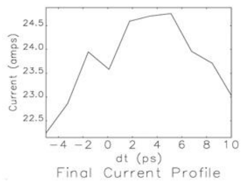
1. Our simulations show that operating at γ=19.57 (18.196 GeV/u gold ions, 10 MeV electrons) significantly simplifies beam dynamics while providing necessary cooling
    a. Plasma-cascade amplifier (PCA) at this energy requires twice lower peak current ~ 22 A, which significantly simplifies beam dynamics in the CeC accelerator as well as provides better conditions for stable operation
    b. We developed new simulation tool which fast and provide quick search for optimal beam and lattice parameters
    c. Simulation results are very encouraging with beam parameters equal or better to the specs
    d. RF group is preparing new harmonic in LLRF set-up for 10 MeV operations
    e. We will start operations with 10 MeV electron beam to demonstrate necessary beam parameters, high-gain PCA and suitability of our THz diagnostics to operate at these (lower) frequencies

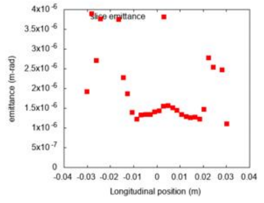










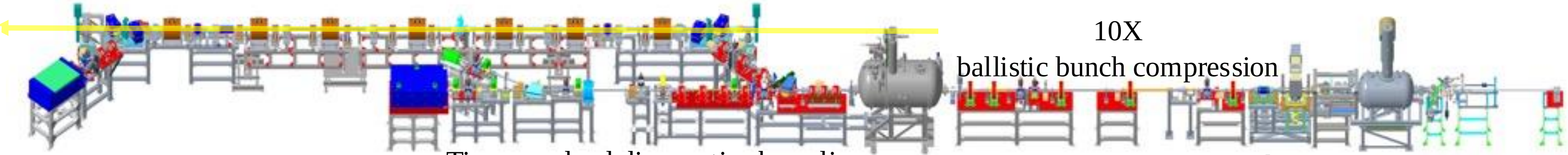


Beam Parameter	
Charge per bunch, nC	0.8
Peak current, A	25
Normalized emittance, µm	1.25
Beam energy (inj), MeV	1.75
Final beam energy, MeV	10.0
Energy spread, RMS	< 2×10^{-4}
Bunch rep-rate, kHz	78

CeC section – common with RHIC ion beam

8.25 MV SRF linac

10X ballistic bunch compression



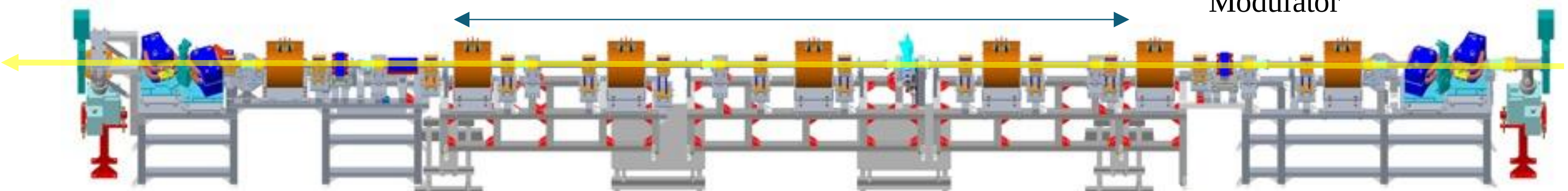
Time-resolved diagnostics beamline

Bunching cavity

Kicker

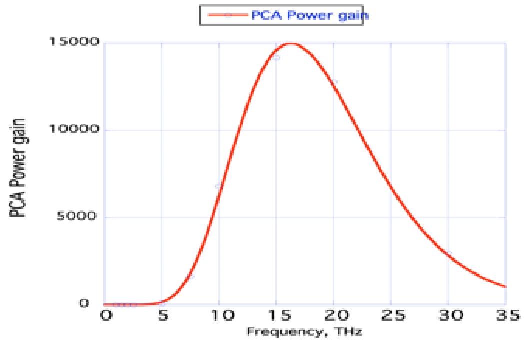
4-cell Plasma-Cascade Amplifier

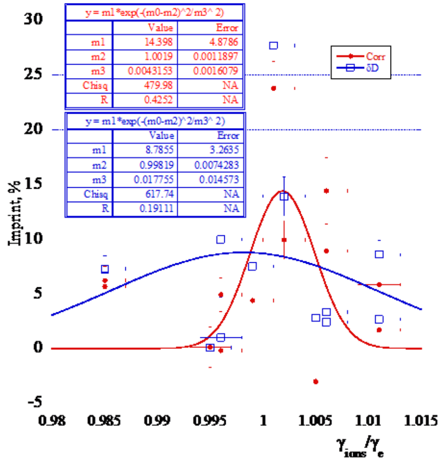
Modulator

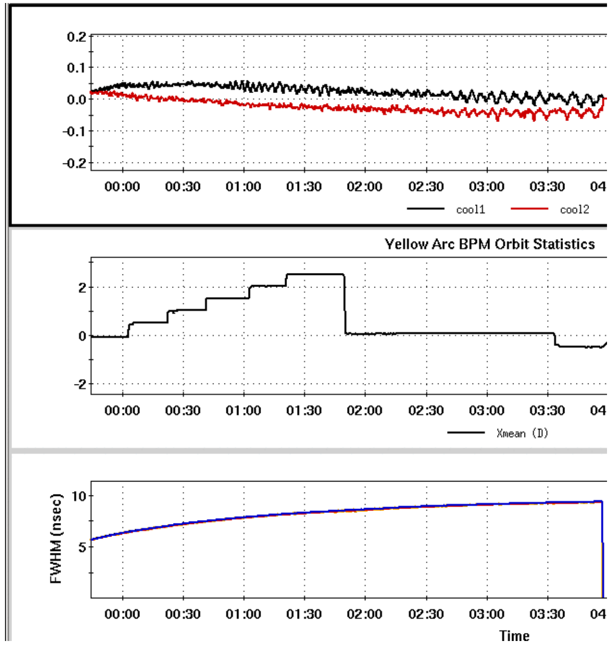


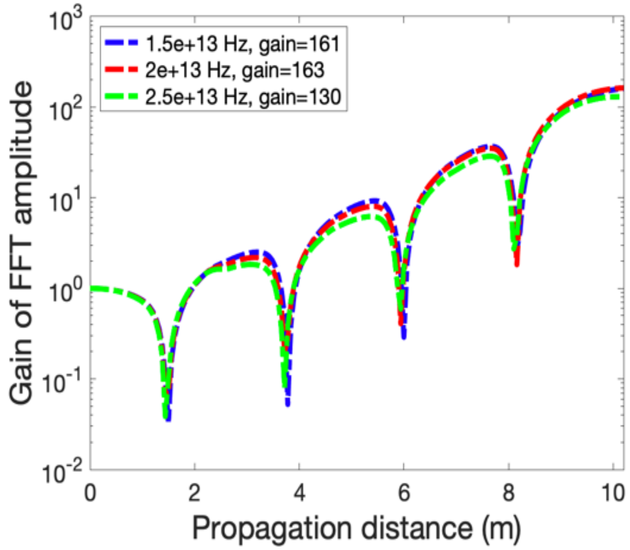
What was already demonstrated and is needed to be re-established at 18.2 GeV/u

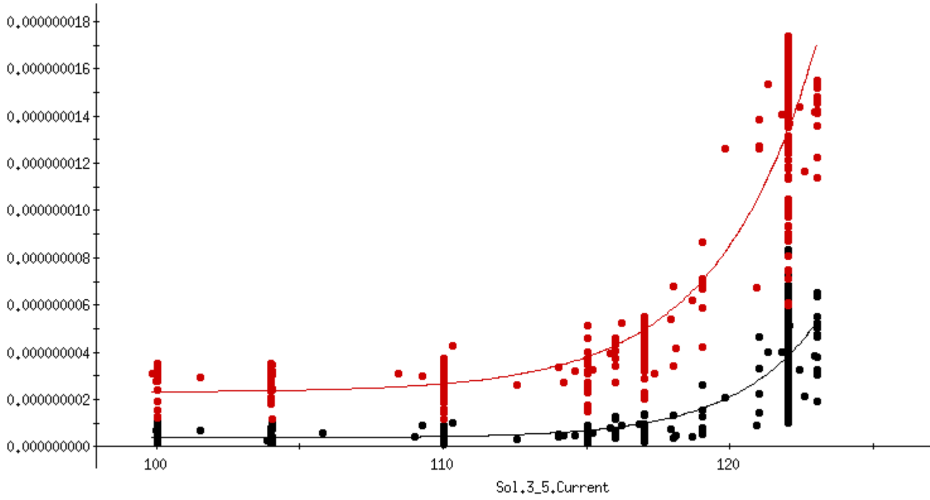
1. High quality e-beam
2. High gain plasma-cascade amplification
3. Ion imprint in the electron beam (comes naturally)
4. Cooling of 26.5 GeV/u ions
5. Recombination of cold electrons with hadrons











What will be new

1. New operation energy (10 MeV electrons, 18.2 GeV/u ions)
2. Operating below RHIC transition energy
3. Establishing stable CW beam and high gain PCA
4. Low intensity of interacting and witness ion bunches
5. Real chance of demonstrating Coherent electron Cooling

Summary

- Run 25 give us unique chance for experimental demonstration of Coherent electron Cooling
- Based on experience from past run, we decided to pick slightly lower (18.2 GeV/u instead of 26.5 GeV/u AU ions with 10 MeV instead of 14.6 MeV electrons) for this demonstrations
  - Operating at lower energy significantly simplify achievement of necessary electron beam parameters necessary for CeC cooling
  - Operating below RHIC transition energy and with low intensity ion bunches will increase cooling rates and improve chances for the demonstration
  - Our simulations show that there is high probability of success
- RHIC APEX would provide us with realistic chance of such demonstration

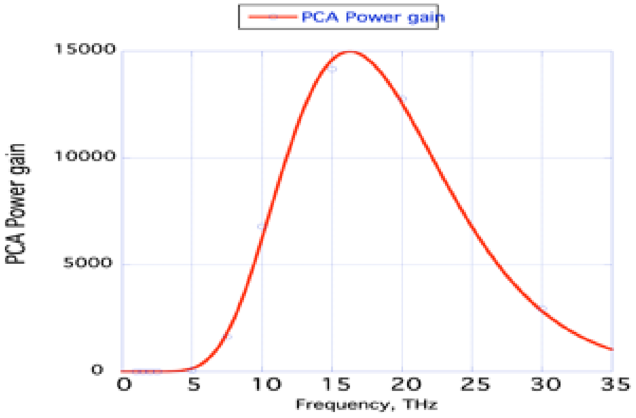
Back-up slides

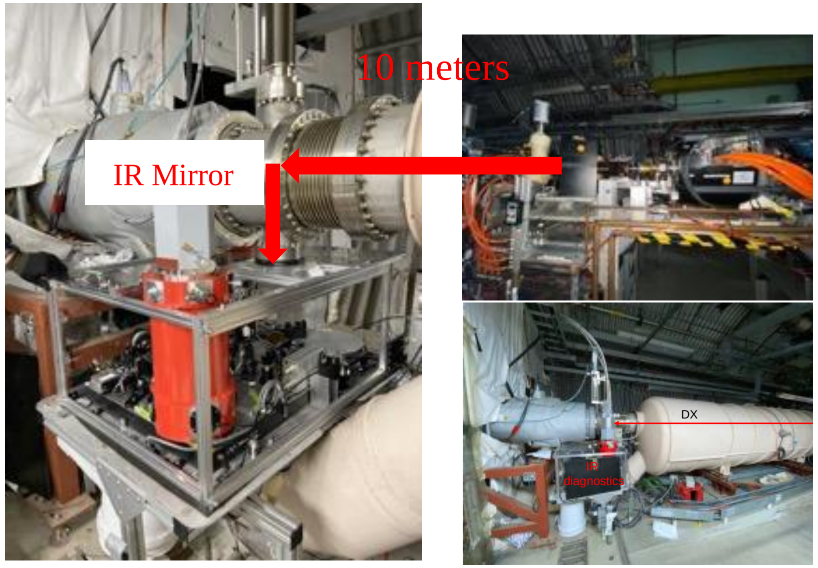
Plasma-Cascade microbunching Amplifier PCA APEX

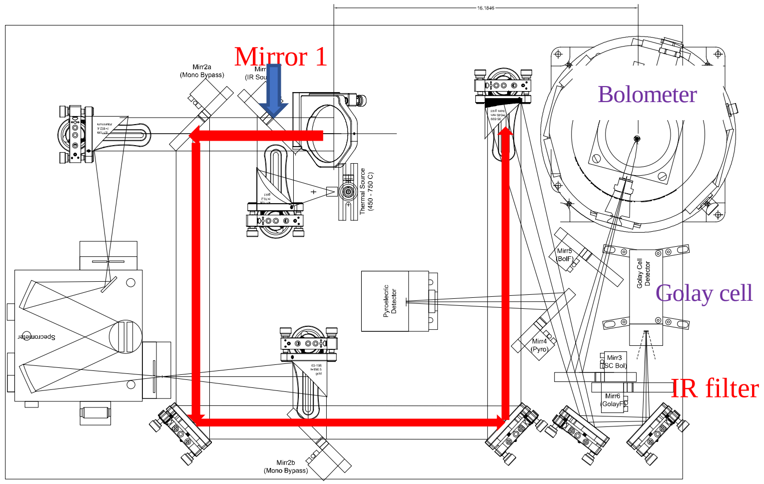
Goal of this experiment is to establish reliable high-gain in PCA

- PCA will be measured using IR diagnostics by comparing power of radiated power in the PCA (strong-focusing) lattice with that in relaxed lattice

Use this set-up to amplify and evaluate ion imprint in electron beam

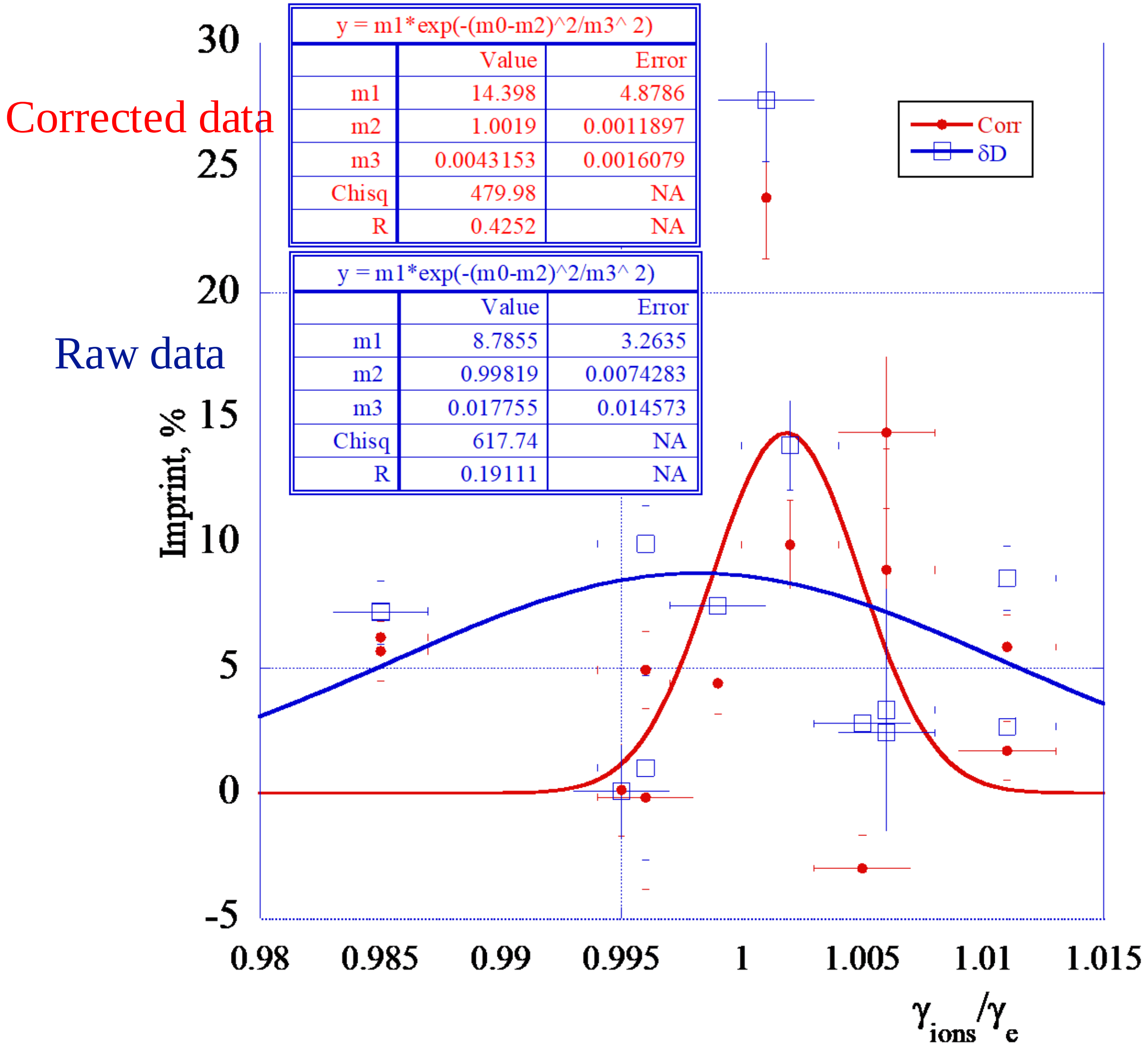






Brookhaven National Laboratory

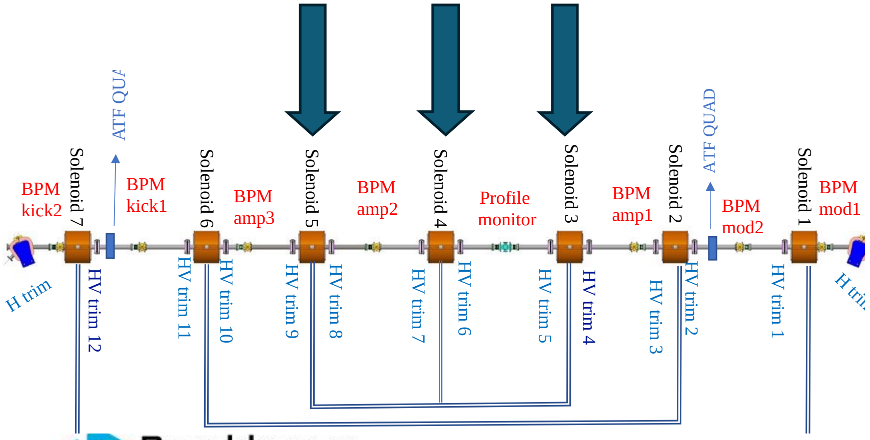
Presence of ion imprint in electron beam radiation

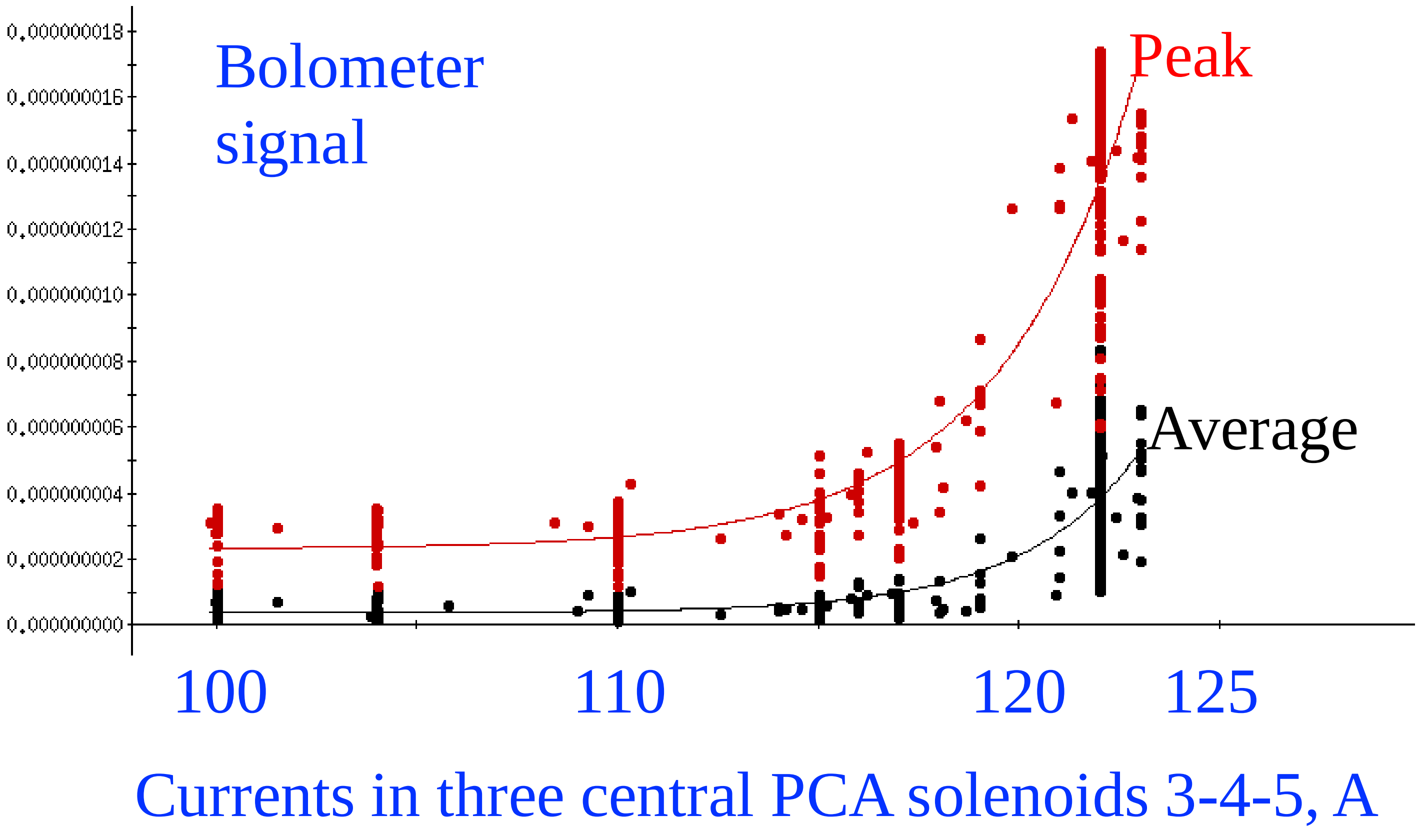


Bolometer Results: 2022

- ✓ Most convincing observation of PCA exponential gain was observed in April 2022 with cryo-cooled bolometer
- ✓ A simple increase of currents in three central PCA solenoids – with all other parameters fixed – resulted in exponential increase of radiation from the electron beam

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





Brookhaven National Laboratory