CEC experiment: summary

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ICFA mini-workshop CeC 2019

'Coherent Electron Cooling-Theory, Simulation and Experiment'

July 24-26 , 2019

BROOKHAVEN
NATIONAL LABORATORY

Stony Brook University

U.S. DEPARTMENT OF
ENERGY

CEC experiment session

This session had two presentations and discussions

Link to presentation slides:

- CeC experiment – physics
- CeC experiment – engineering

The goal of the experiment is to demonstrate longitudinal cooling of a single Au^{+79} bunch in the Relativistic Heavy Ion Collider at energy 27 GeV/u.

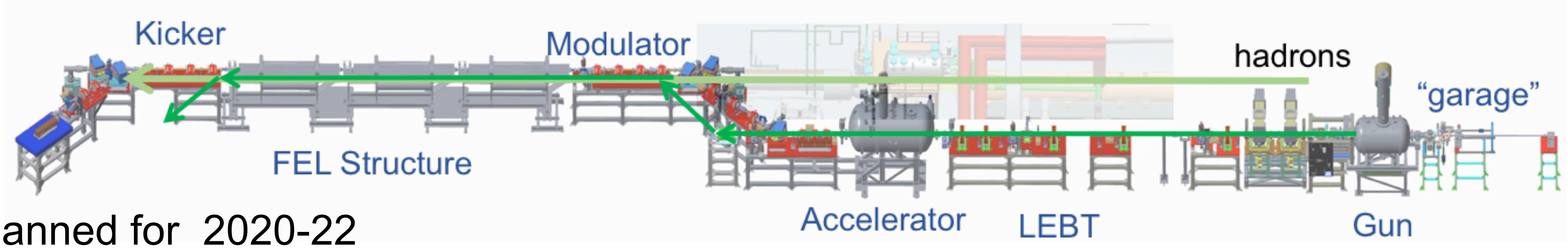
The principle of coherent electron cooling is to 1) imprint the ion beam distribution as a longitudinal charge modulation on an electron bunch, to (2) to amplify this modulation in the electron bunch and 3) to use the electron field to feed back to the ion bunch such that it is cooled

CEC demonstration at BNL

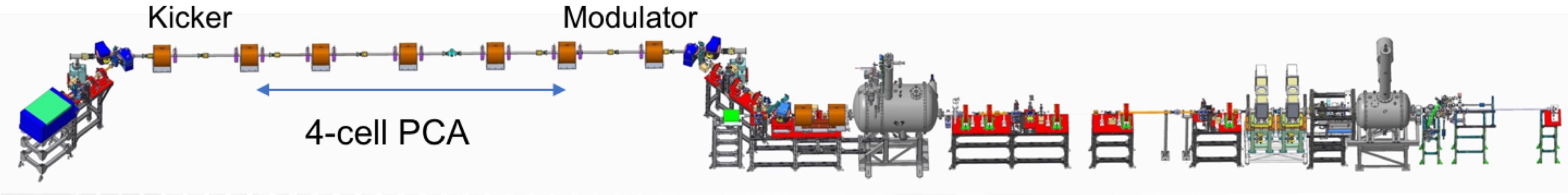
Two possible signal amplification systems have been considered :

1) based on FEL amplification (studied during 2016-2018)
   - a) three helical undulators with phase shifters and matching quadrupoles have been installed in common (cooling) section
2) based on plasma cascade amplification (planned)
   - a) 7 strong focusing solenoids to be installed in cooling section

2017-18



Planned for 2020-22



Advantages and Disadvantages (from Vladimir's talk)

CeC with High gain FEL amplifier

- The best studied and fully explored scheme
- Experimentally demonstrated both as instability and amplifier
- 3D FEL theory and simulation are very advanced
- Can operate at relatively low electron beam peak currents
- Allows – in principle – economic option without separating electron and hadron beams

- When compared with micro-bunching amplifier, it has relatively lower bandwidth ~ few % of the FEL frequency
- FEL saturates at lower gain than micro-bunching amplifier
- Semi-periodic structure of the modulation limits the range where cooling occurs

Plasma-Cascade Microbunching amplifier

- Very broad band amplifier, can operate at significant gain without saturation
- Plasma-cascade micro-bunching instability was experimentally demonstrated
- Has good theoretical model and is extensively studied in 3D numerical simulations
- Cool hadrons with all energy deviation (no anti-cooling)
- Does not require (full) separation of electron and hadron beams

- Micro-bunching amplifier was not demonstrated
- Requires better quality electron beam than FEL amplifier
- Can operate for medium hadron energies (up to hundreds of GeV, such as US EIC), but can not be extended to LHC energies
- Less studied than FEL-based CeC

PCA system is more relax for noise requirement

Accelerator System Commissioning

- The accelerator for CEC experiment consist of a 113 MHz SRF gun with a photocathode, two 500 MHz copper cavities, a 704 MHz SRF accelerator cavity, various focusing/corrector magnets and beam instrumentation.
- All elements of the experiment have been successfully commissioned during run 18 and provide beam quality required for CEC such as bunch charge, emittance, energy, energy spread, peak current and etc.
- Methods for energy and emittance measurement, trajectory correction, RF phasing, synchronization and characterization of the produced light were implemented.

Required electron beam parameters

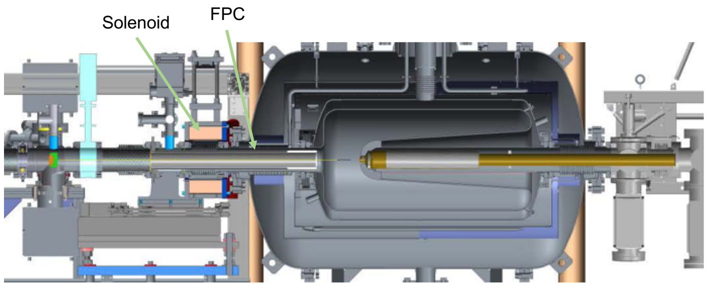
- Normalized emittance < 5 mm mrad
- Relative energy spread $\sigma_E/E < 10^{-3}$
- Bunch charge 500 pC – 1.5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10-50 psec
- Peak current > 75 A
- Kinetic energy 14.5 MeV
- IR FEL wavelength 30 microns

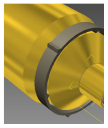
Demonstrated electron beam parameters

- Normalized emittance 3 – 4 mm mrad
- Relative energy spread $\sigma_E/E < 3\times10^{-4}$
- Bunch charge 0.03 – 10.7 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10 – 500 psec
- Kinetic energy 14.5 MeV

Accelerator System

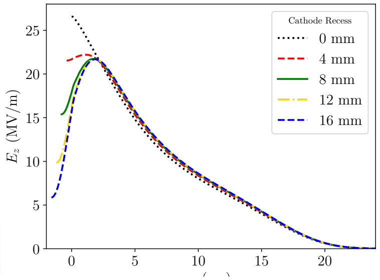
113 MHz RF Gun

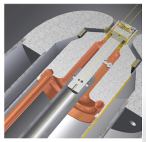

Solenoid
FPC



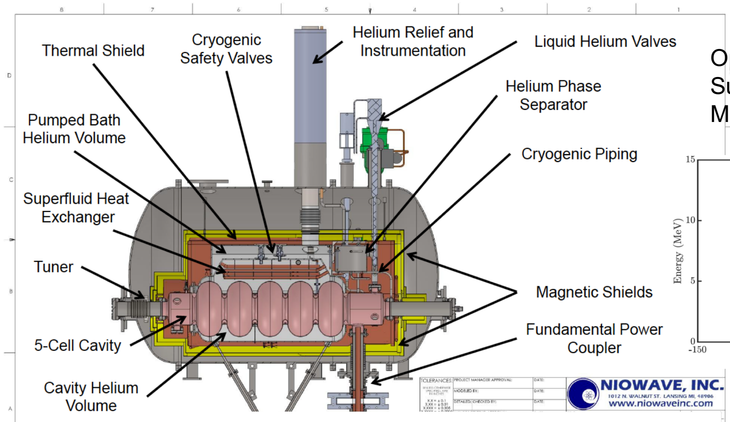
Challenges
- Strong multipacting barrier at 30-40 kV
- Dependence of the cavity frequency on coupling
- Location of the cathc puck vs nose is not f

- Quarter wave design
- Operates at 4.2ºK
- Cathode is at room temperature
- Stalk serves as field pick-up
- Manual coarse tuners
- FPC serves as fine tuner
- Maximal CW voltage 1.25 MV
- Maximal charge 10.7 nC

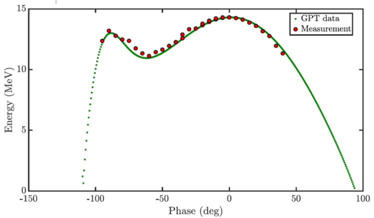


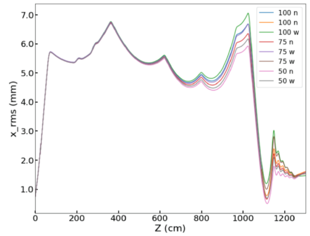


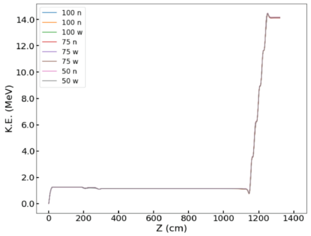
704 MHz SRF Linac


Thermal Shield
Cryogenic Safety Valves
Helium Relief and Instrumentation
Liquid Helium Valves
Helium Phase Separator
Pumped Bath Helium Volume
Cryogenic Piping
Superfluid Heat Exchanger
Tuner
Magnetic Shields
Fundamental Power Coupler
5-Cell Cavity
Cavity Helium Volume
NIOWAVE, INC.
1012 N. WALNUT ST. LANSING MI, 48906
www.niowaveinc.com

Operation temperature 2 ºK
Superfluid head exchanger
Maximal voltage – 13.5 MV







Very complicated beam dynamics in the first cell – beam is decelerated and strongly focused

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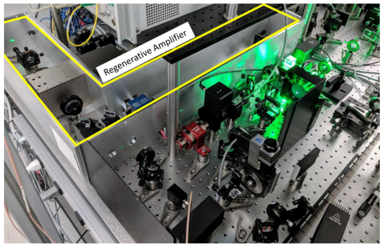
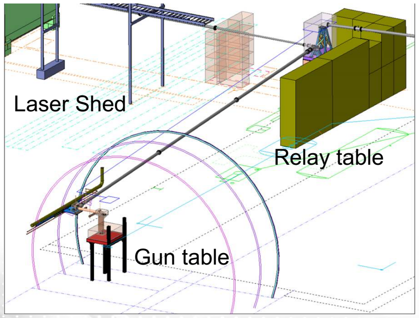
Drive Laser



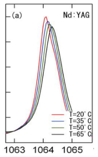


The seed laser with tunable longitudinal profile provides the input for the regenerative amplifier.

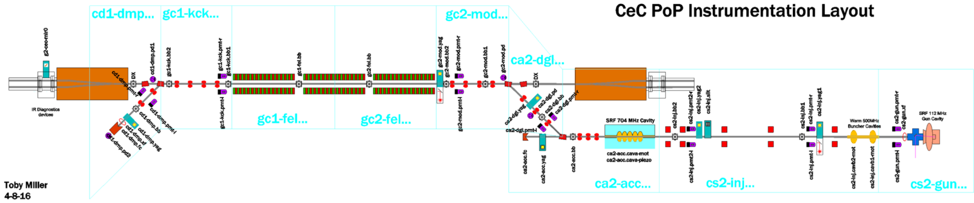
The regenerative amplifier has successfully suppressed the accumulation of nonlinear effects that caused the distortion of the temporal pulse profile which is crucial for CeC operations. In addition, the power fluctuations of the seed laser have been significantly mitigated.

The resulting excess power produced by the amplifier offers two additional advantages:
- the high available power allows for electron beam generation at a lower photocathode quantum efficiency
- the higher power allows for producing a significantly more uniform transverse intensity distribution on the photocathode due to overfilling of the aperture imaged onto the photocathode.

Challenges
- Pointing stability
- Pulse jitter
- Temperature drift of diode laser causes two lines generation and hence charge modulation at high frequencies



Instrumentation


CeC PoP Instrumentation Layout

Toby Miller
4-8-16

- Two integrating current transformers by Bergoz
- Two beam dumps with incorporated Faraday cups
- Fifteen single pass BPMs by Instrumentation Technologies (11 tuned to 500 MHz, 1 tuned to 352 MHz, 3 tuned to 9.37 MHz)
- 15-mm diameter buttons BPM pick-ups designed at BNL and manufactured by MPF
- Six profile monitors with YAG:Ce screens
- Set of slits for emittance measurement
- IR diagnostics (sensors, monochromator, iris for profile scan)
- 4 GHz Teledyne LeCroy WR640Zi oscilloscope
- PMT based beam loss monitors (JLab development)
- RHIC instrumentation for hadrons (orbit, tunes, profiles, …)
- No longitudinal beam profile diagnostics

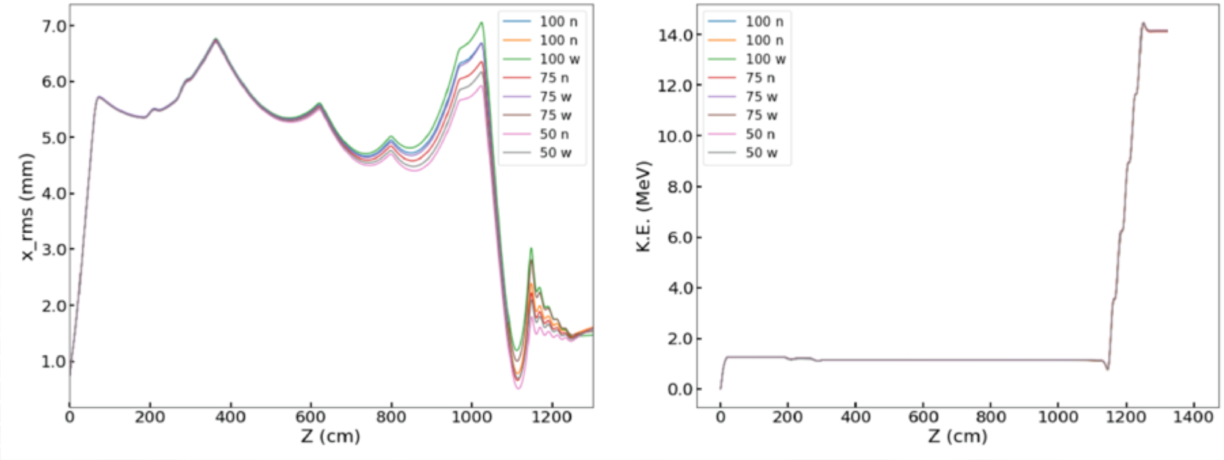
Some alignment relative challenges

- Gun axis is tilted by 11.1±0.1 mrad
- Buncher cavities generate time-dependent transvers kick
- Linac axis is 3 mm lower than median plane

Recommendation:

Study tolerance for these misalignments and if possible reduce the most critical one, for example SRF booster due to

very complicated beam dynamics in the first cell of SRF linac – beam is decelerated and strongly focused

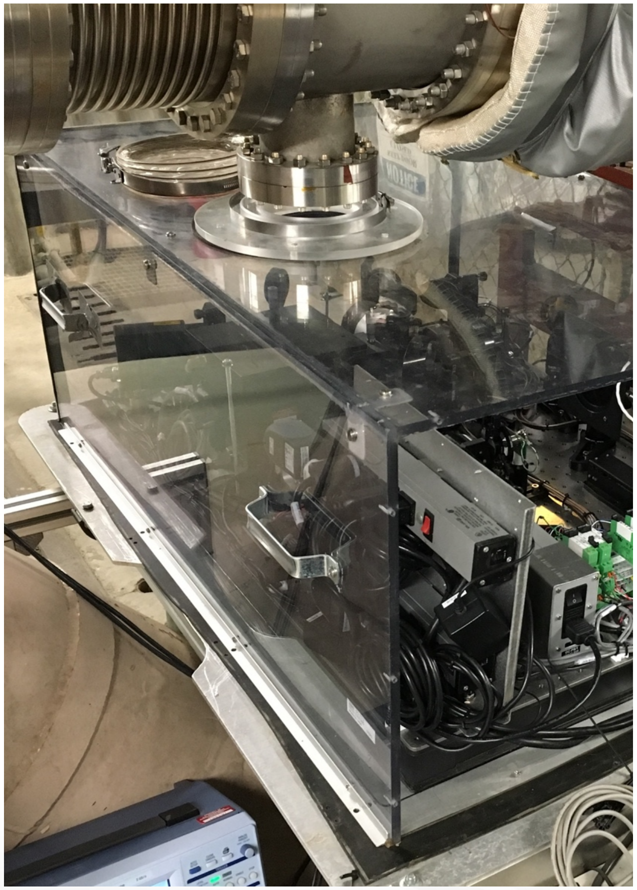


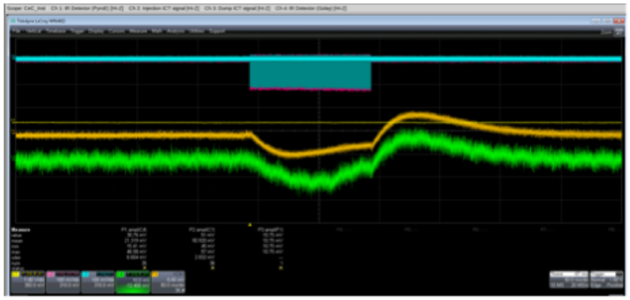
FEL signal detection

Infrared Diagnostics

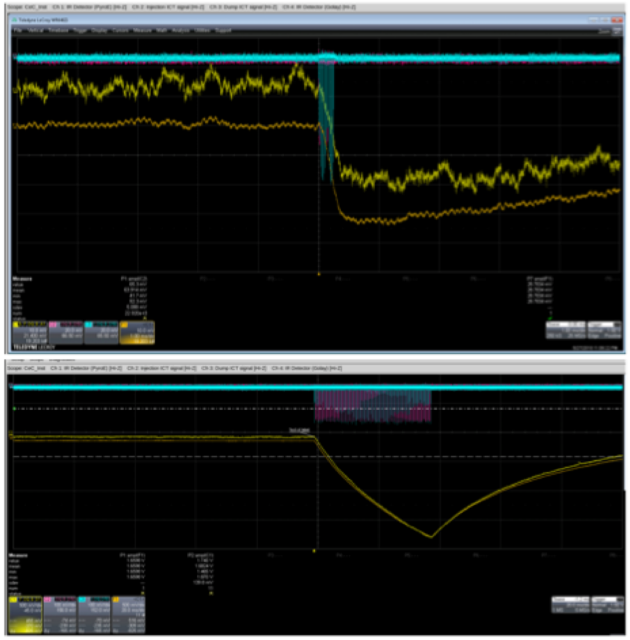
- Insertable copper mirror
- ZnSe window was replaced with diamond window transparent at 30 microns
- Chopper
- Golay cell
- Pyroelectric detector
- Monochromator

The power meters were intended to tune FEL (up to 6 orders of magnitude power level change). We expected 3-fold increase in power when electron beam intersects with hadrons.
Monochromator is used to measure FEL wavelength and precise measurement of the beam energy.





Golay cell signal (green)



Pyroelectric detector signal (yellow)
ICTs signals are cyan and magenta

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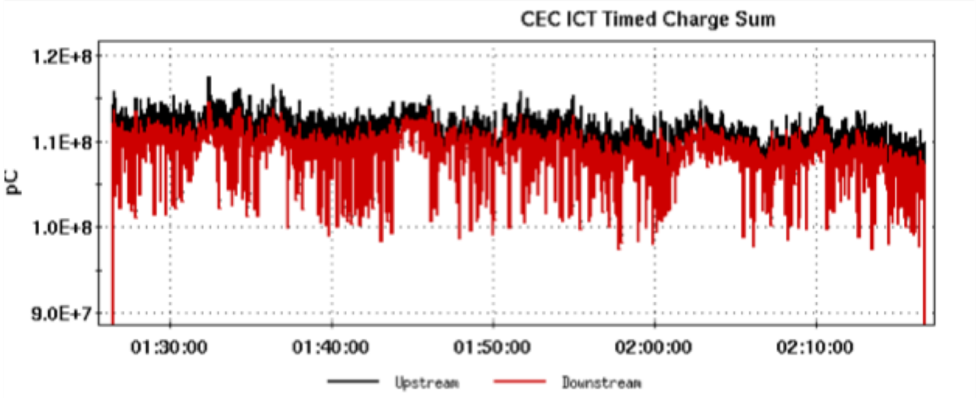
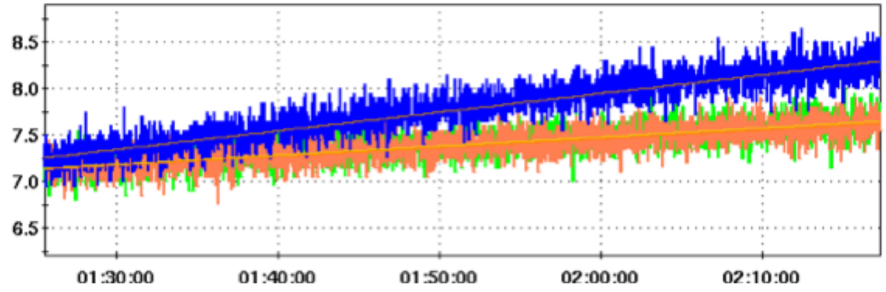
Electrons effects to ions has been observed

Top plot: electron beam current through the CeC ~ 110 μA or 1.4 nC per bunch at 78 kHz. Bottom plots: evolution of the bunch lengths for interacting (blue trace) and witness bunches (orange and green traces).

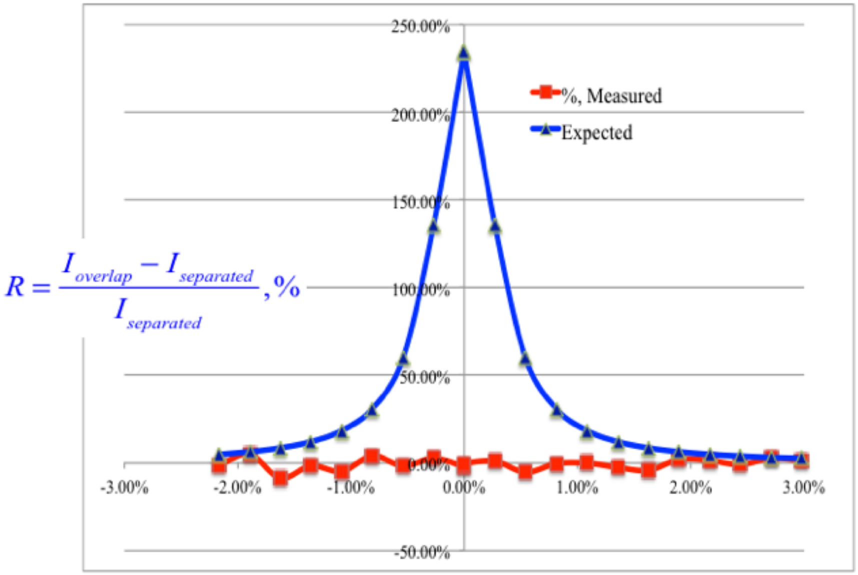




Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

Ions effect to electrons was not observed

Search for ion's imprint



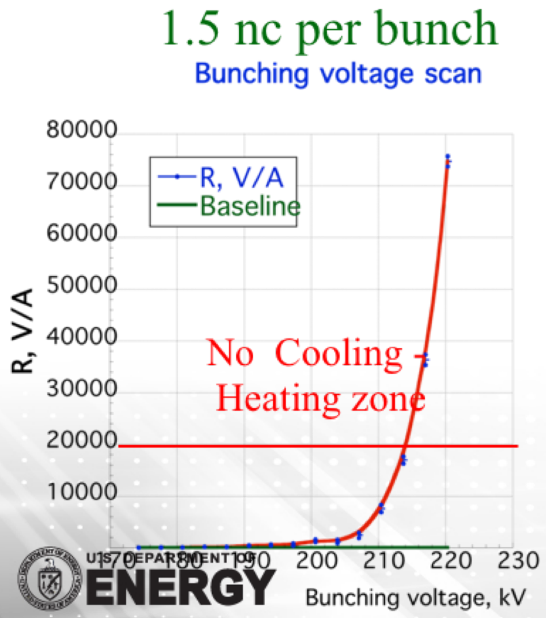
$$R = \frac{I_{overlap} - I_{separated}}{I_{separated}}, \%$$

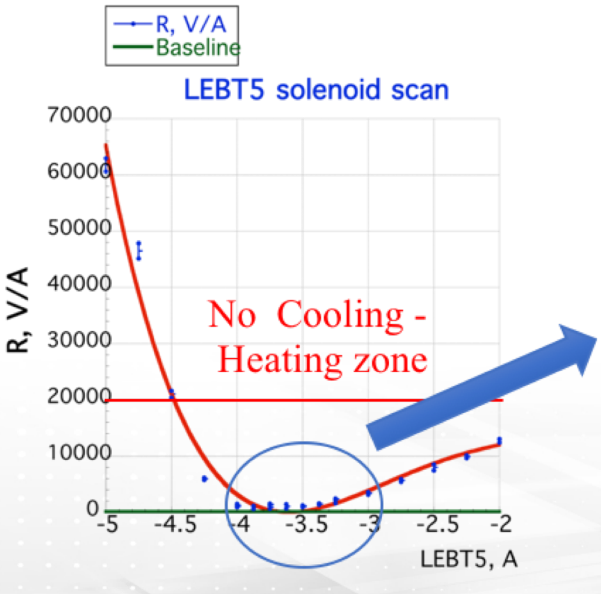
Expected and measured relative change in the FEL signal with overlapping and separated beams. Each point corresponds to 16 or more cycles of 20 FEL power measurements for overlapped and separated beams. Data analysis indicate RMS error of 2%.

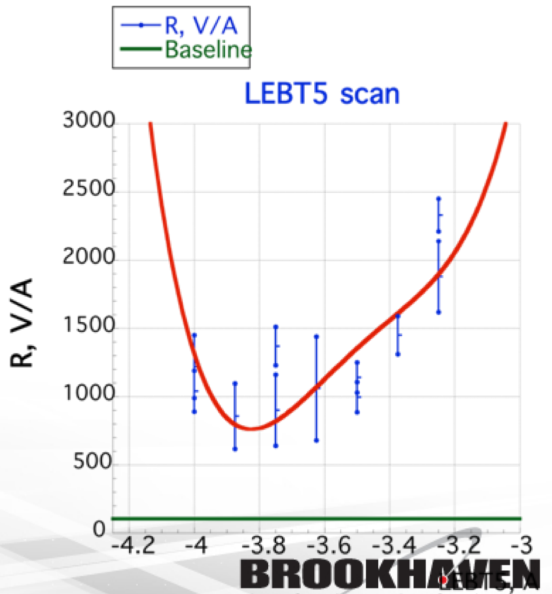
Noise studies

PUZZLE: growth of the FEL power due to the interactions with hadrons has not been observed.

- Current understanding the problem: the beam instability due to Plasma Cascade Instability and/or overbunching.
- The development of the PCI was experimentally confirmed in the dedicated studies and methods for it suppression were developed
- As a result of proper bunching cavities settings and solenoids in LEBT optimization the noise level sufficient for CEC demonstration using PCA has been achieved

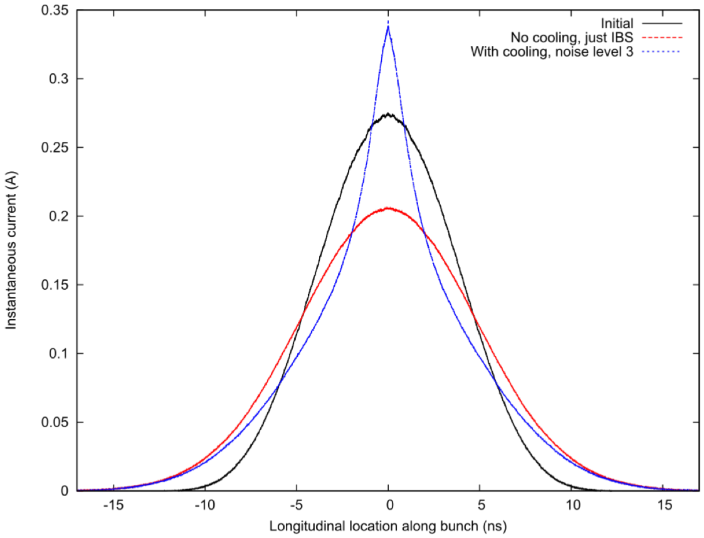

1.5 nc per bunch





Plans for PCA based CeC

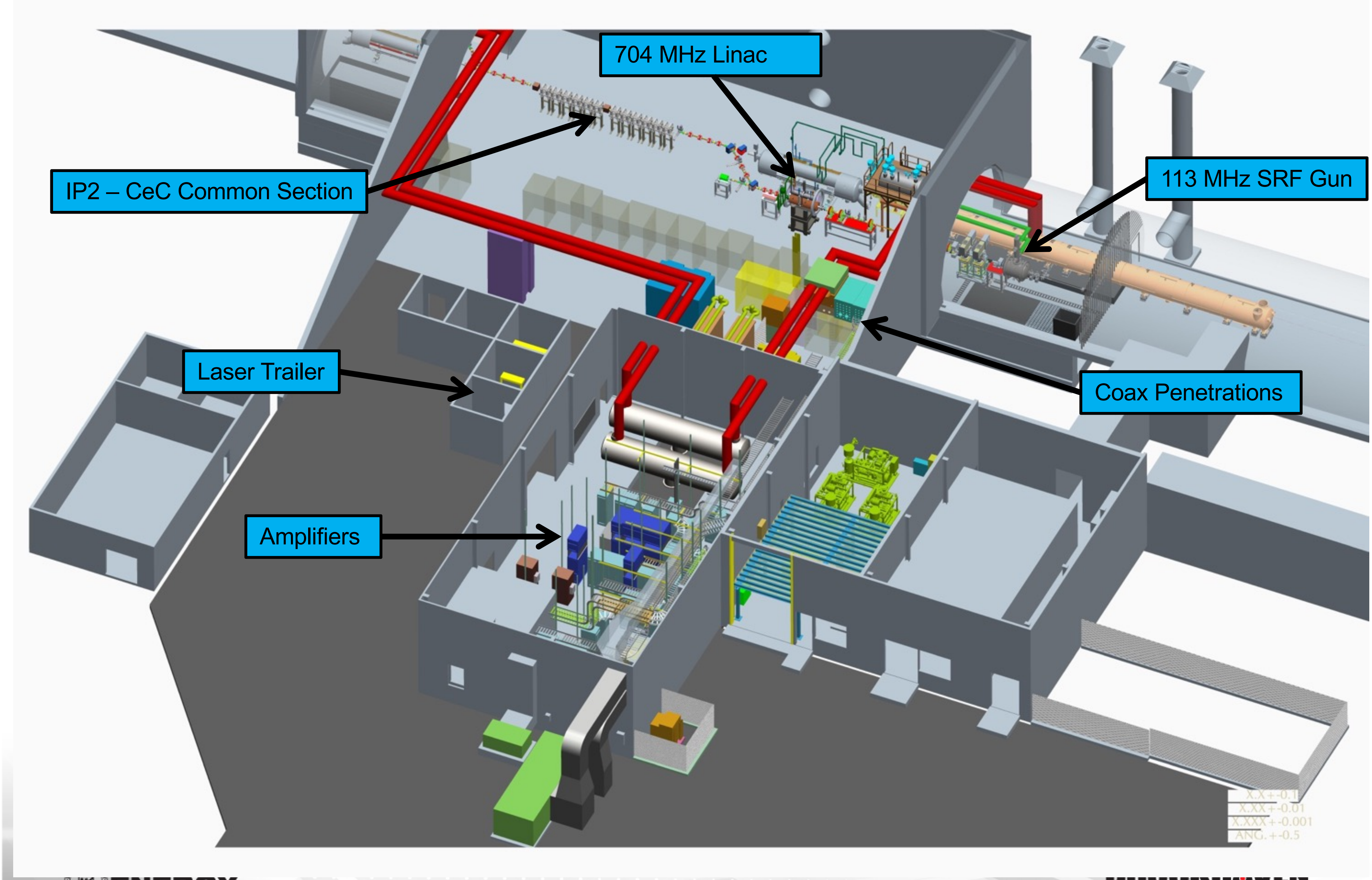
- Shutdown jobs
  - Install new elements into the common section
  - Add IR diagnostics: two sets – one after DX magnet, another at low power dump
- Run 20
  - Establish electron beam operation in the background mode in parallel with RHIC operation
  - Optimize electron beam parameters
  - Establish high-current operation and demonstrate interaction with hadrons circulating in RHIC
- Demonstrate longitudinal cooling during Run 21
- Perform cooling experiments including transverse and/or 3D cooling during Run 22



Conclusions (physics)

- Accelerator delivered the beam with parameters suitable for the CeC PoP experiment
  - Electron normalized emittance as low as 0.3 mm mrad was measured
  - Relative energy spread 3×10^{-4} was demonstrated
- Two new methods for measuring beam trajectory vs. solenoid axis (position and angle) and energy utilizing solenoid were developed
- We were unable to demonstrate the imprint of the hadrons on the electron beam due to the discovered plasma cascade instability and/or overbunching
- The development of the PCI was experimentally confirmed in the dedicated studies and methods for it suppression were developed
- The PCA based CeC system will be tested during Runs 20-22

1002 Building Layout



704 MHz Linac

IP2 – CeC Common Section

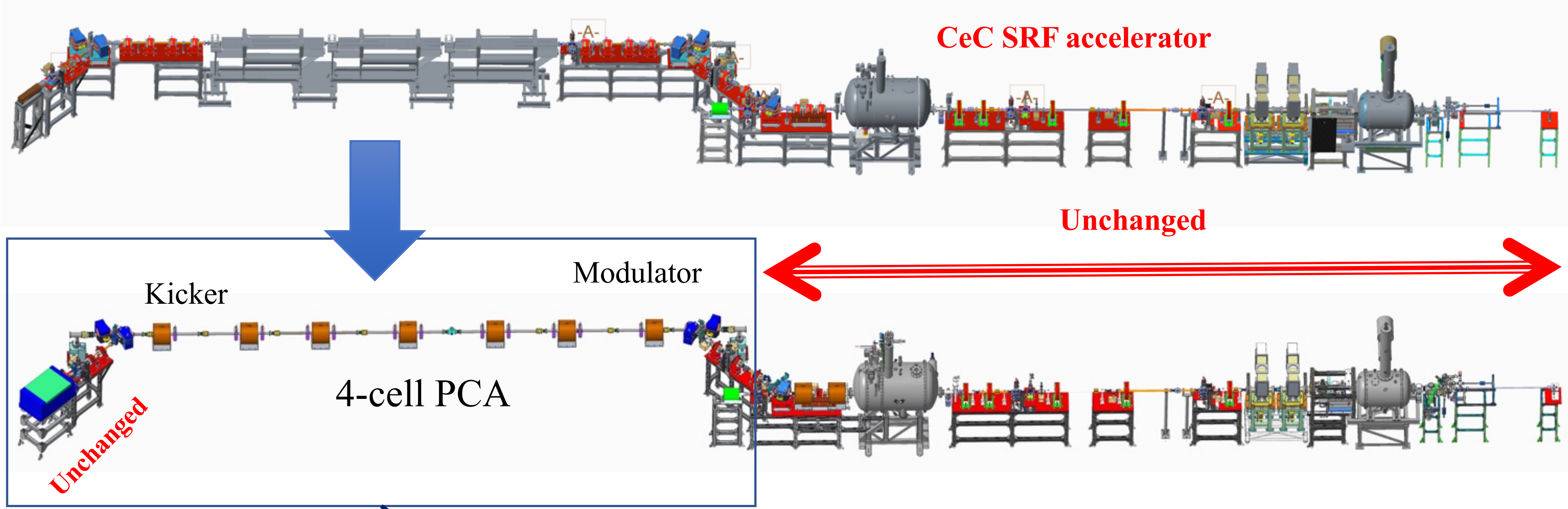
113 MHz SRF Gun

Laser Trailer

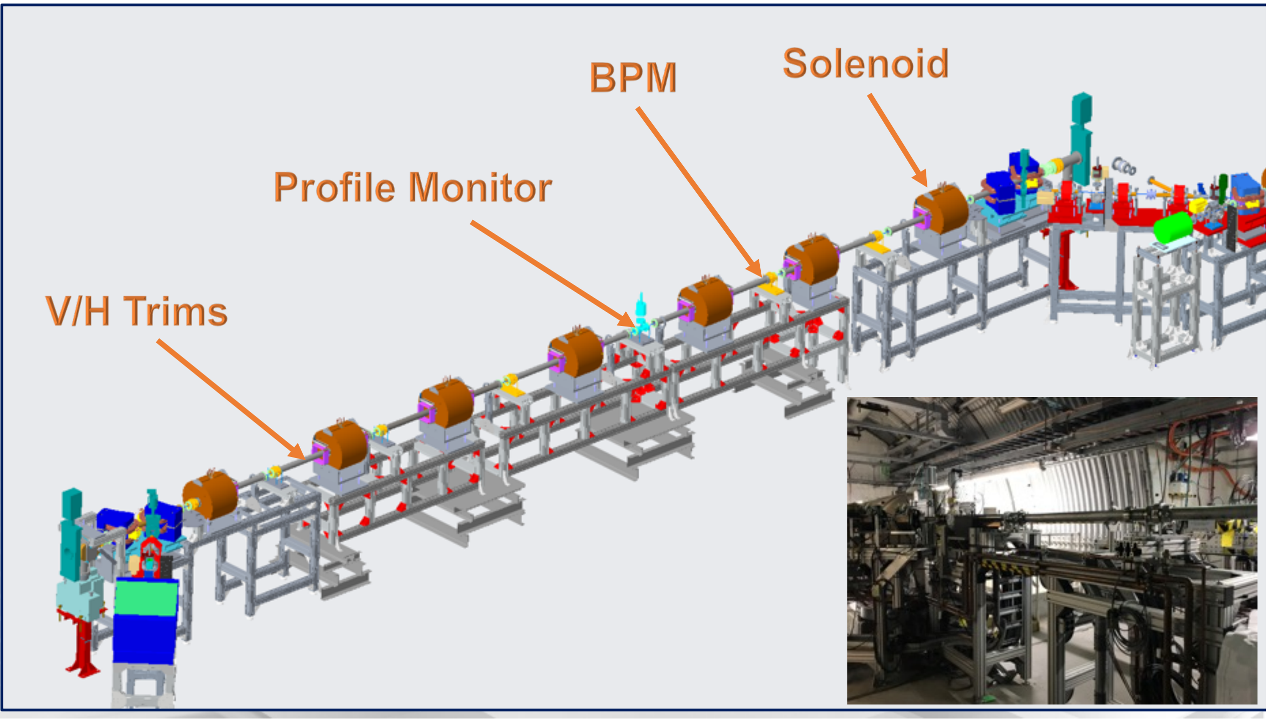
Coax Penetrations

Amplifiers

CeC PCA Beam Line



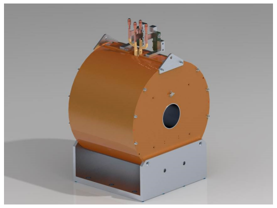
1) New water cooled solenoids
2) Dipoles gap modification
3) New Stands
4) New Profile Monitor
5) New BPM housing and buttons
6) 6 pairs of corrector magnets
7) New Y vacuum chamber for dipoles
8) New NEG coated beam line vacuum chambers
9) New stand supports for magnets
10) New RF shielded bellows
11) New conical transitions to RHIC
12) New beam line supports
13) Water Manifold for Solenoids

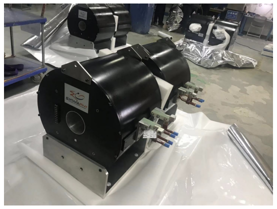


New and modified Magnets

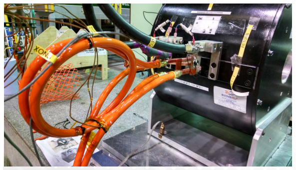
Solenoids

- Sigmaphi China
- Magnetic Field Measurement in progress
- Installation RHIC shutdown 2019
- New water manifold required at IP2

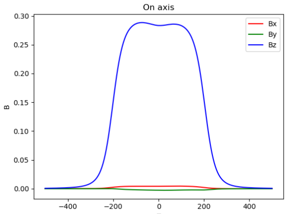




Number of Wraps, Na	36
Number of layers	18
Number of circuits	2
Circular Flow Diameter [in]	0.25
Pressure Drop, psi	76.5
Flow, GPM/ path	.375
Velocity, ft/s	2.5

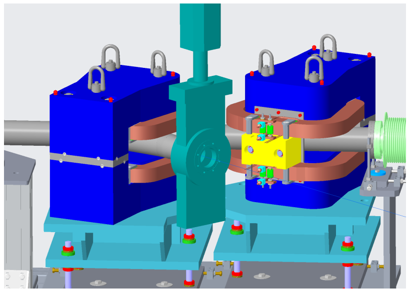


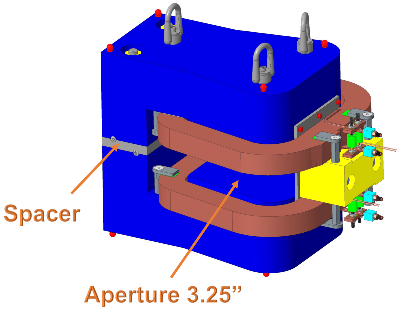
Hollow Conductor Size, mm	9.52 x 9.52
Conductor Area, in^2	0.09
Power, W	3860
Current Density, J [amps/mm2]	2.48
Total Voltage, V	26.75
Resistance, ohms	.186
Current, A	144.3

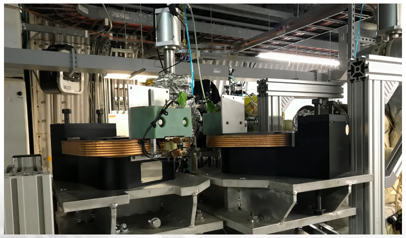


Measured on-axis Bz,
Bz = 0.283 T at center (0,0,0)
Max Bz = 0.288 T, ~7.5 cm away from center

Dipole Gap Modification

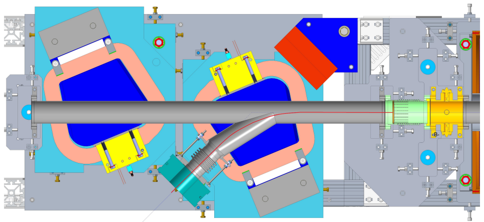


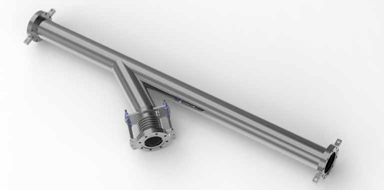


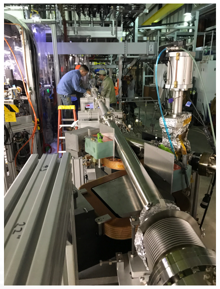


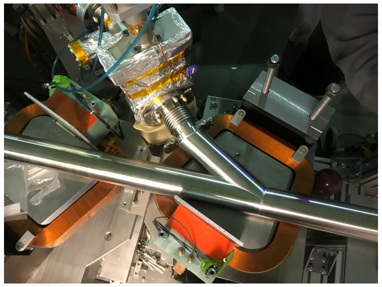
Vacuum parts modification

Y dipole chamber







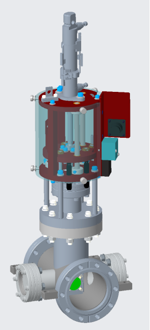


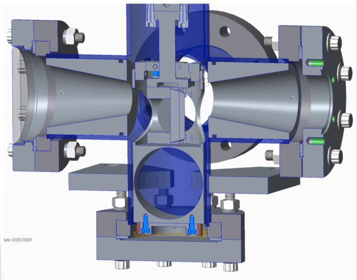
Old Y chamber

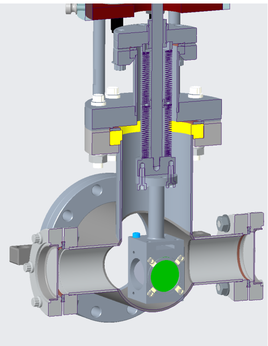
New Y chamber

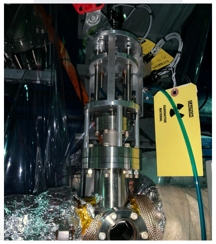
Profile Monitor

- Simplified design
- Removed RF finger, RF shields
- Using existing actuator assembly
- 2.75CF viewport with a glass size of 1.44” instead of a 4.5CF viewport
- ID of the nipple tube is 1.375”









Summary (engineering)

- Many challenges during commissioning were addressed with design changes:
    - 704 MHz: tuner, microphonic suppression, repair
    - Aluminum beam dump
    - Shielding from RHIC magnets
    - Cathode injection stand
    - Profile monitor RF shielding
    - New BPMs
    - Ion pump shielding
    - Wriggler polarity and RF shield fingers
    - New correctors
    - water interlock system

- 704 MHz booster limited at 13.4 MeV even after repair

- Magnetic field measurement of solenoid in progress

- Installation RHIC Shutdown 2019

Comments and recommendation from general discussion:

Good Laser, good accelerator, and excellent diagnostics are the key. Any possible improvement in any of these systems should be considered

Longitudinal beam quality is critical:

- explore option to use deflecting cavity for longitudinal phase space tuning and slice emittance characterization

Ion-electrons energy matching is critical:

- Magnetic measurements of dipoles after modification is recommended
- Check if RHIC recombination signal could be used for better matching energies

Consider to install set of quadrupoles in the common section for better matching beam envelopes

Benchmarking ions heating observations during run 2018 with simulation is recommended

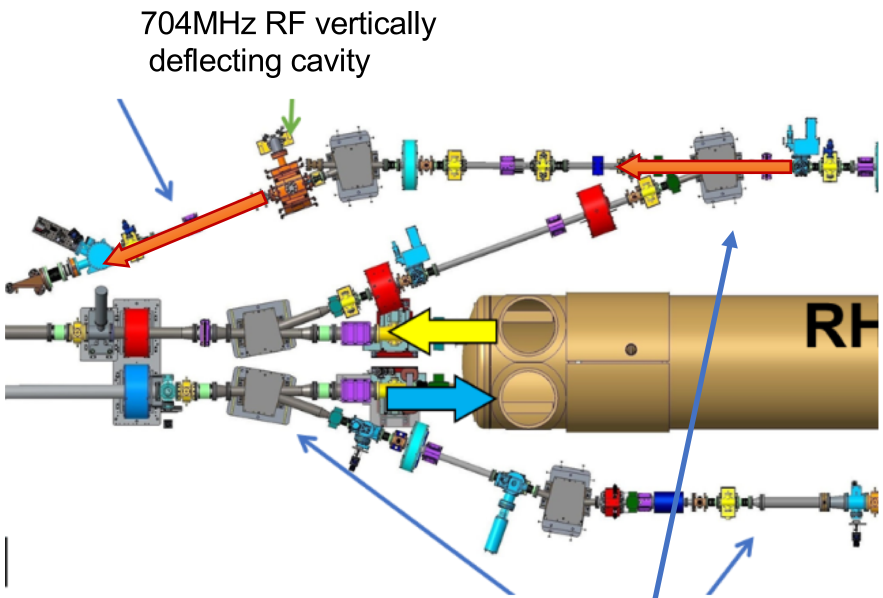
Summary

- The experimental proof of CEC is very important
- Recent demonstration of agreement between simulation and measurement of beam parameters and noise control is very encouraging
- Experimentally reaching noise level close to PCA requirement looks very promising for success of CEC demonstration

- Back up slides

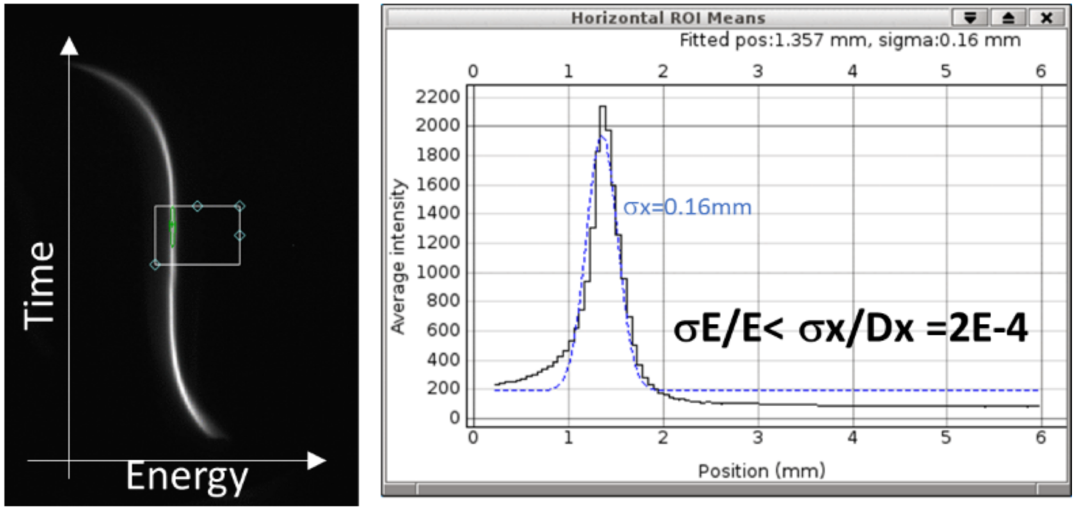
LEReC longitudinal phase space measurement in RF diagnostic line

704MHz RF vertically deflecting cavity



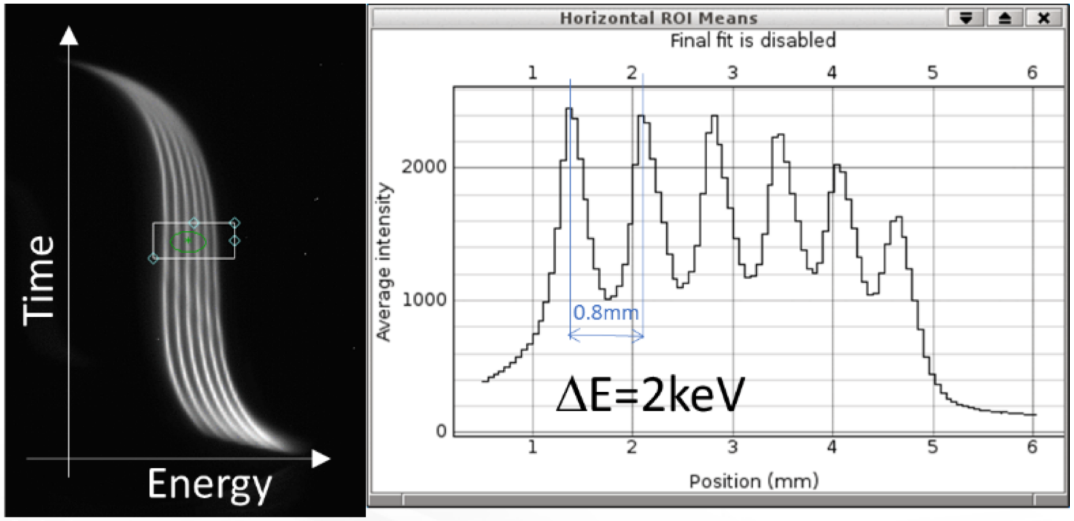
- First dogleg merger dipole is off
- Beam goes to RF diagnostic line
- 20 degree dipole produced dispersion
- Deflecting cavity produces time dependent vertical kick

1 macrobunch, 3 nC



$\sigma E/E < \sigma x/Dx = 2E-4$

6 macrobunches, 3 nC each



ΔE=2keV

In pulsed mode dueto beam loading effect followed bunches have lower energy