CeC Demonstration Experiment: Status and Plans

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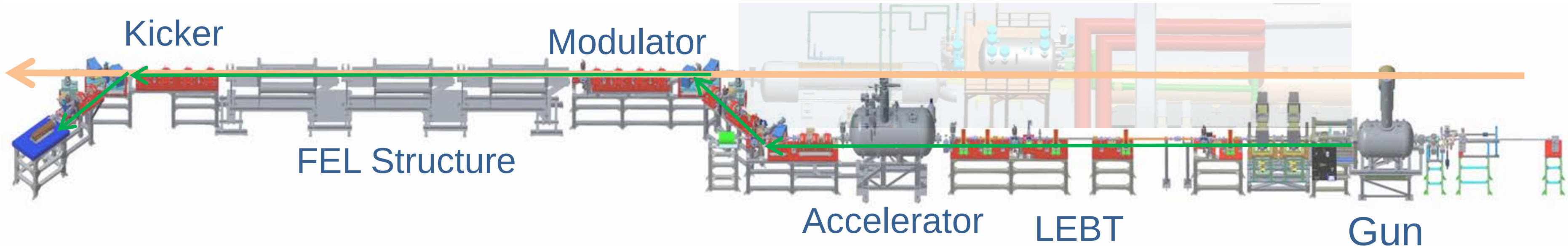
Outline

- System Description
- Main Advances
- Subsystem Performance
- CeC System Commissioning
- 2017 Shutdown Activity
- Plan for Run 18

Coherent Electron Cooling Project



Electron beam is generated by 113 MHz SRF gun with CsK_2Sb photocathode driven by a 532 nm laser. Two 500 MHz copper cavities provide energy chirp and beam is compressed to desired peak current. After compression beam is accelerated by a 704 MHz SRF cavity and merged into CeC PoP structure having three helical undulators and three phase shifters.

Coherent electron cooling experiment relies on the supply of the liquid helium available only during RHIC operation (January-June). Stray field form dipoles affect low energy beam.

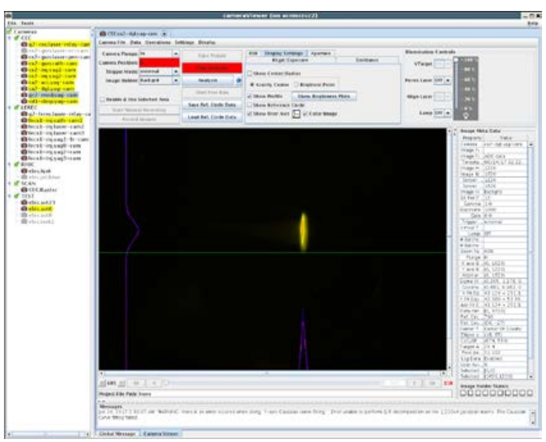
Accelerator Physics Highlights

- 113 MHz SRF gun with room-temperature CsK_2Sb cathodes demonstrated excellent performance
  - CsK_2Sb cathodes survived for months of operation (and exhibit QE improvement during operation)
  - Beam with charge up to 4 nC per bunch were demonstrated
  - Projected normalized emittance of 0.32 mm mrad was demonstrated for 0.5 nC bunches
  - Multipacting is well understood and a process of avoiding it is developed, tested and implemented
- World's first 2K cryostat with superfluid heat exchanger (used for 5-cell 704 MHz linac) demonstrated excellent performance and good microphonics isolation (Δf~10 Hz pk-to-pk)
- Beam-based alignment using solenoids was demonstrated with full restoration of the beam trajectory
- Method of beam energy measurement using trajectory rotation by solenoid was developed

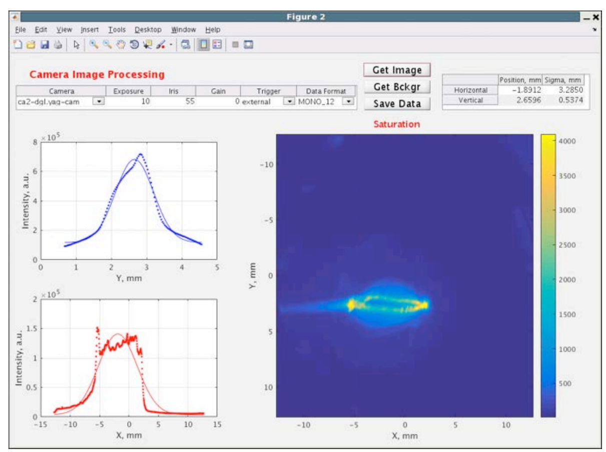
Main Advances

- We were able to generate electron beam with quality sufficient for the CeC experiment and FEL amplification
- Electron beam at full power was propagated through the entire system to the high power beam dump with low losses
- Synchronization of electron and ion beams was established and interaction between the beams was detected

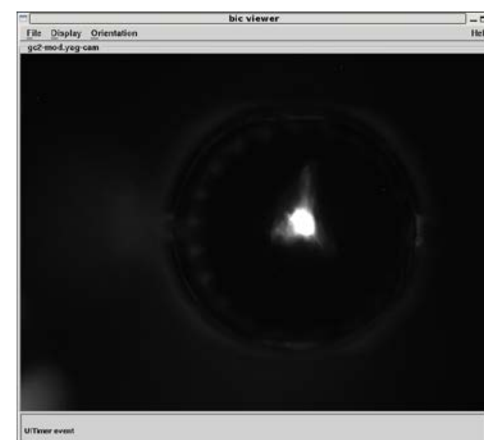
Sub 0.1% energy spread



40 A peak current in the bunch



Low emittance beam in FEL



Beam Parameters

Parameter	Design	Status	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	To match e-beam
Particles per bucket	10^8 - 10^9	10^8 - 10^9	✓
Electron energy	21.95 MeV	**15 MeV**	**SRF linac quench**
Charge per electron bunch	0.5-5 nC	0.1- 4 nC	✓
Peak current	100 A	50 A	Sufficient for this energy
Bunch duration, psec	10-50	12	✓
Normalized beam emittance	<5 mm mrad	3 - 4 mm mrad	✓
FEL wavelength	13 μm	**30 μm**	**New IR diagnostics**
Repetition rate	78.17 kHz	26 kHz**	Temporary
Electron beam current	Up to 400 μA	40 μA	Temporary
Electron beam power	< 10 kW	600 W	Temporary

***Will be changed to 78 kHz after retuning the gun frequency*

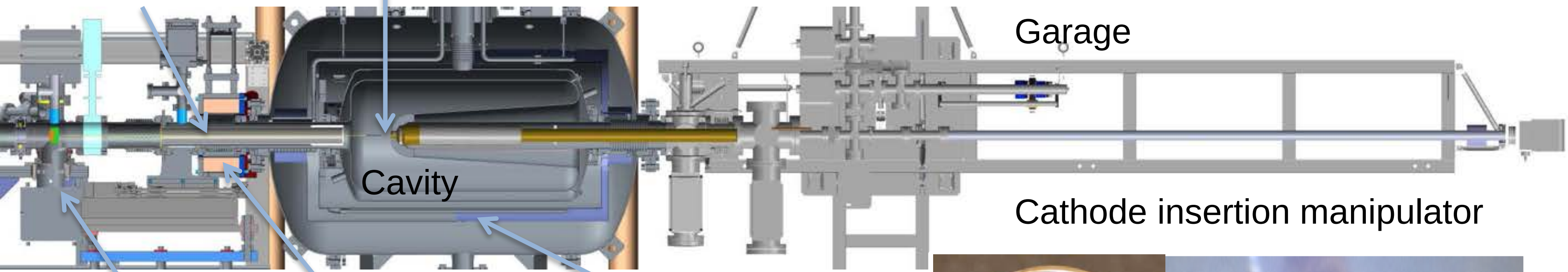
Beam parameters are sufficient for the CeC demonstration experiment

Beam Diagnostics

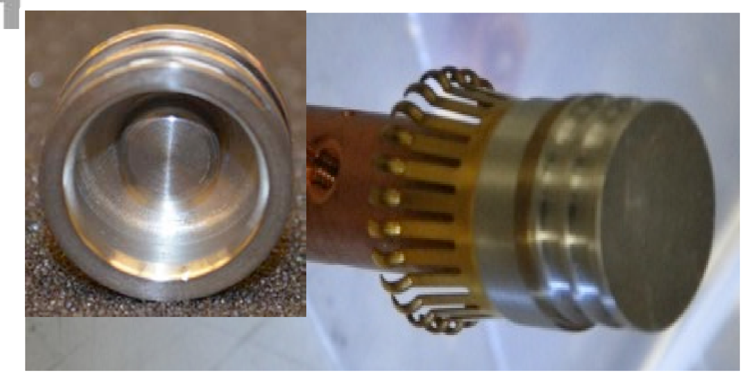
- Eleven electron beam position monitors (500 MHz). We are adding one more tuned to 350 MHz.
- Three hadron beam BPMs (common pick-up electrodes, tuned to 9 MHz). BPMs were cross calibrated.
- Six profile monitors (two in the dispersive region)
- Pepper-pot
- Two Faraday cups combined with beam dumps
- Two ICT (after the gun and in front of the high power beam dump)
- IR diagnostics for FEL (power meter, monochromator)

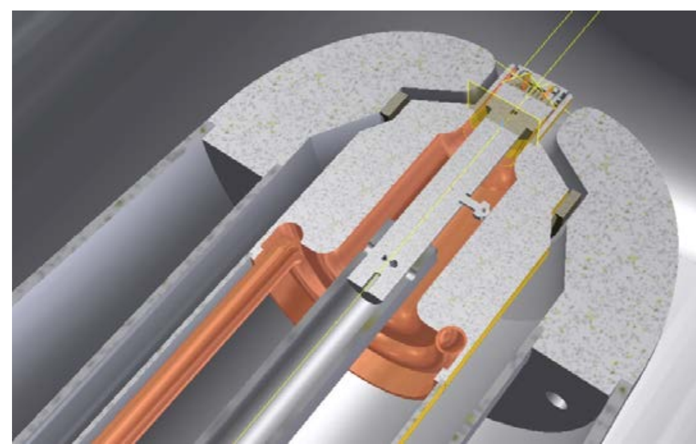
The set of diagnostics is minimal but sufficient for experiment.

CeC SRF Gun



- Quarter-wave cavity
- 4 K operating temperature
- Manual coarse tuner
- Fine tuning is performed with FPC
- 4 kW CW solid state power amplifier
- CsK_2Sb Cathode is at room temperature
- Cavity field pick-up is done with cathode stalk (1/2 wavelength with capacitive pick-up)
- Up to three cathodes can be stored in garage for quick change-out


Photocathode end assembly



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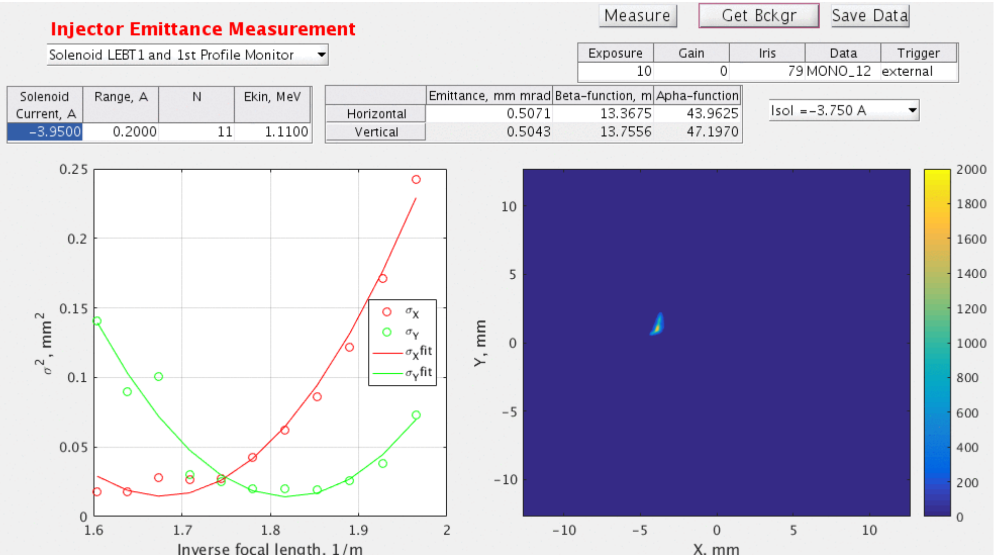
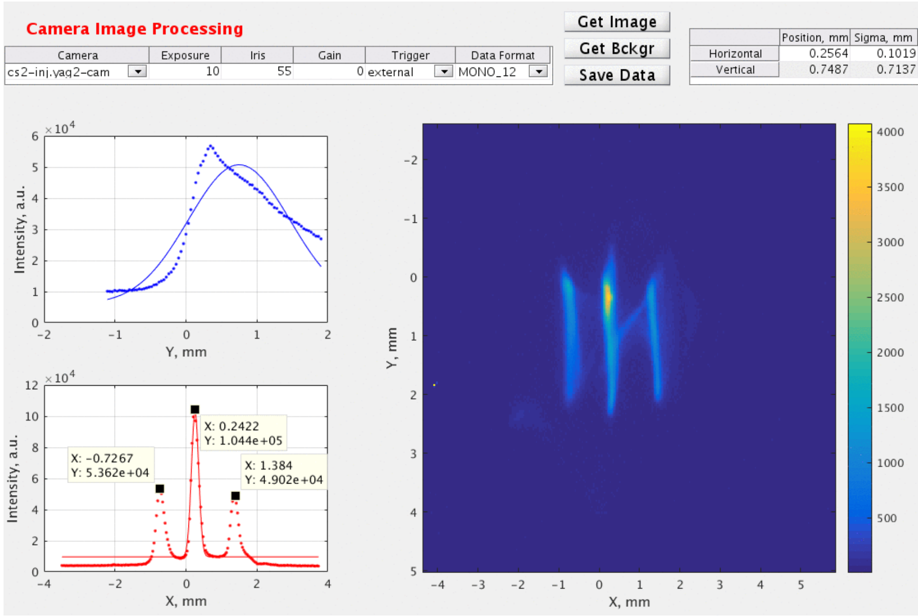
Emittance of 640 pC Beam





R.m.s. emittance of 0.5 mm mrad measured with solenoid scan

Beam size 1.3 mm
Divergence 0.29 mrad
R.m.s. emittance 0.37 mm mrad
Normalized 1.2 mm mrad

Emittance is sufficient for CeC demonstration.

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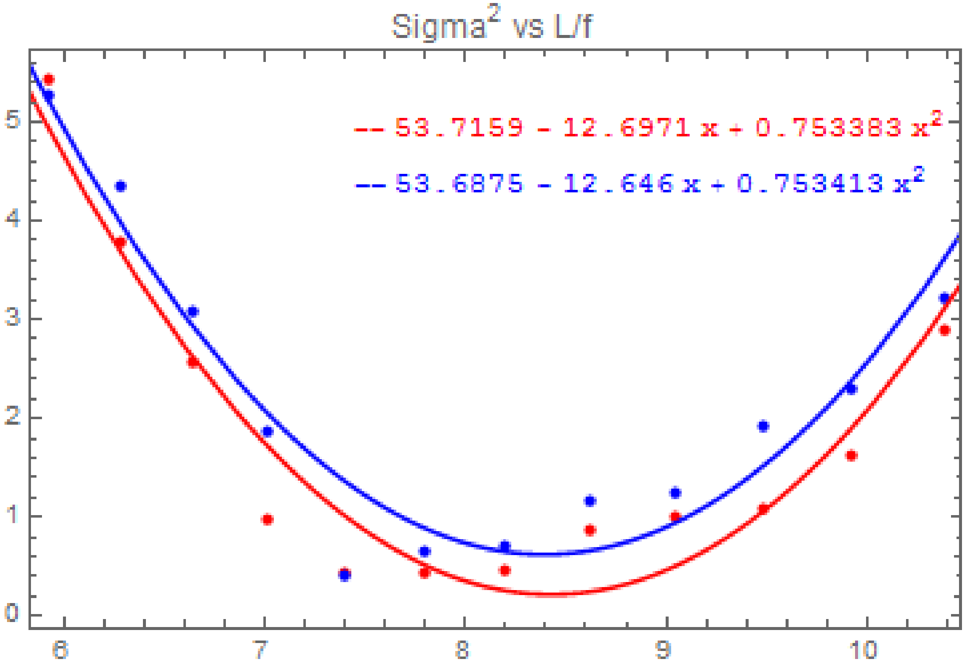
Best Achieved Emittance



The beam size was measured on the first profile monitor with scan of the gun solenoid. Beam kinetic energy is 1.04 MeV, beam charge 0.5 nC. Normalized emittance is 0.32 mm mrad.

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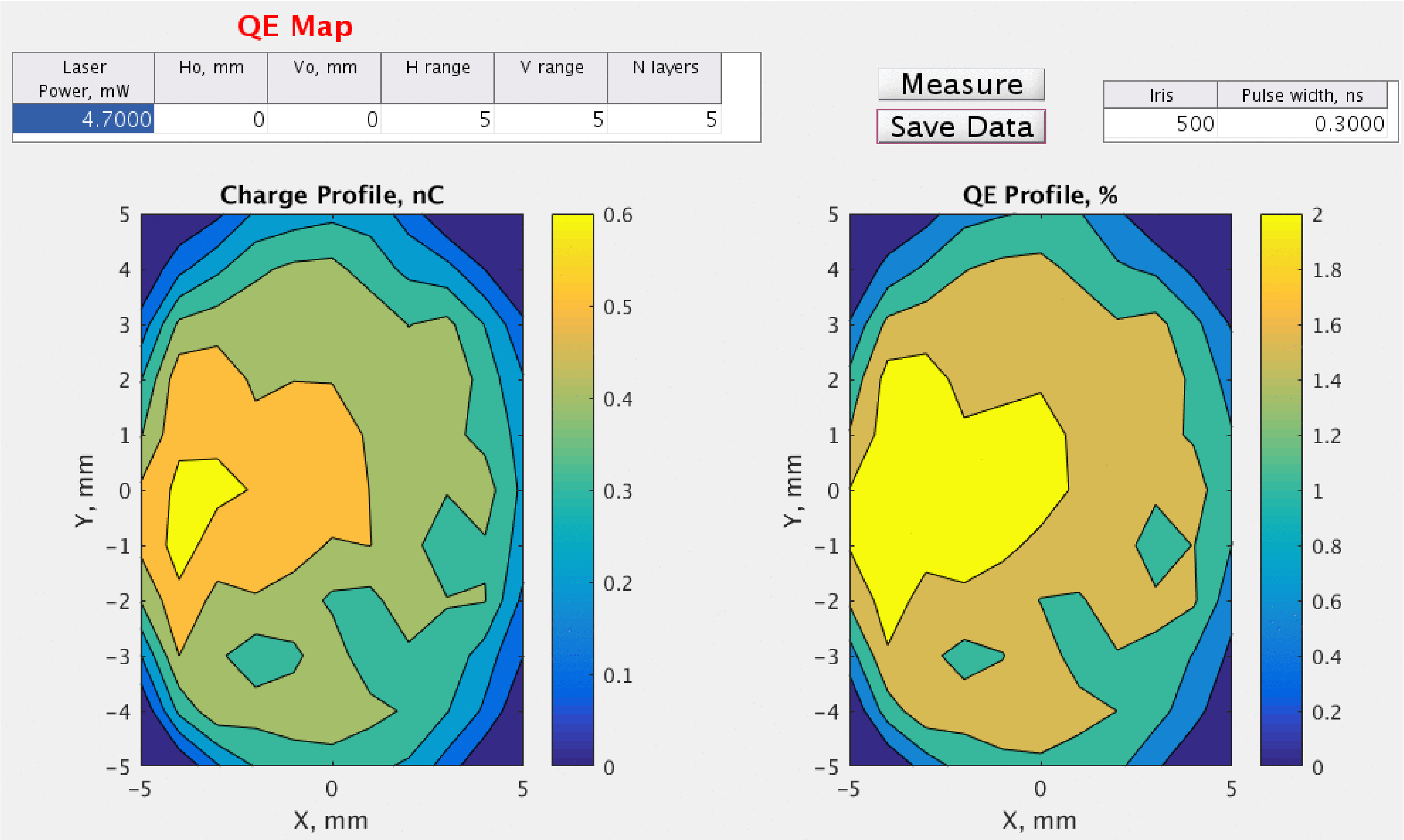
QE Map after Seven Weeks of Operation



After insertion the extracted charge was 0.4 nC.

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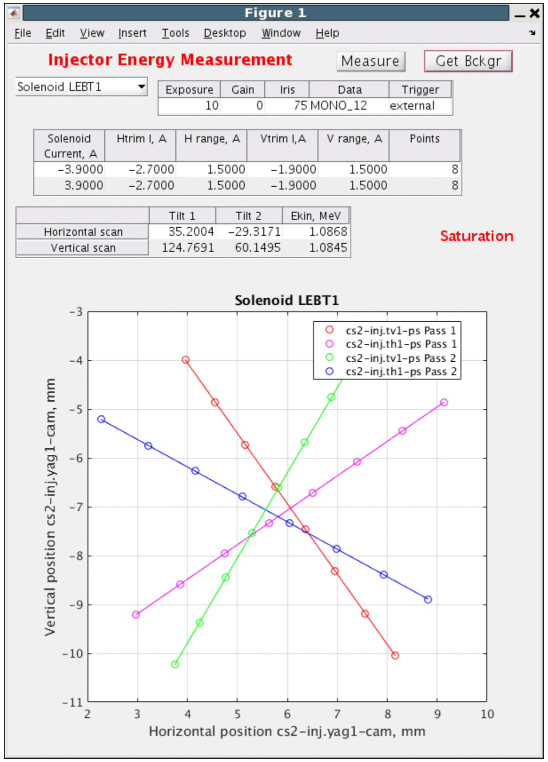
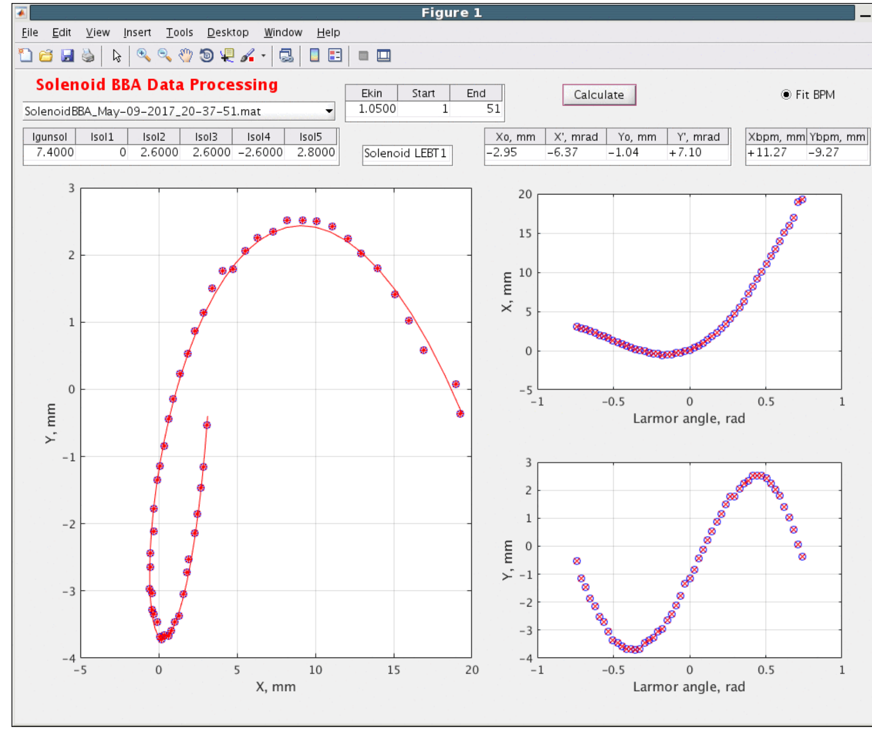
Automated Measurements of the Beam Parameters with Solenoid



$$\begin{pmatrix} x \\ y \end{pmatrix} = M_{rot} M_{foc} \begin{pmatrix} x_0 \\ x_0' \\ y_0 \\ y_0' \end{pmatrix}$$



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.

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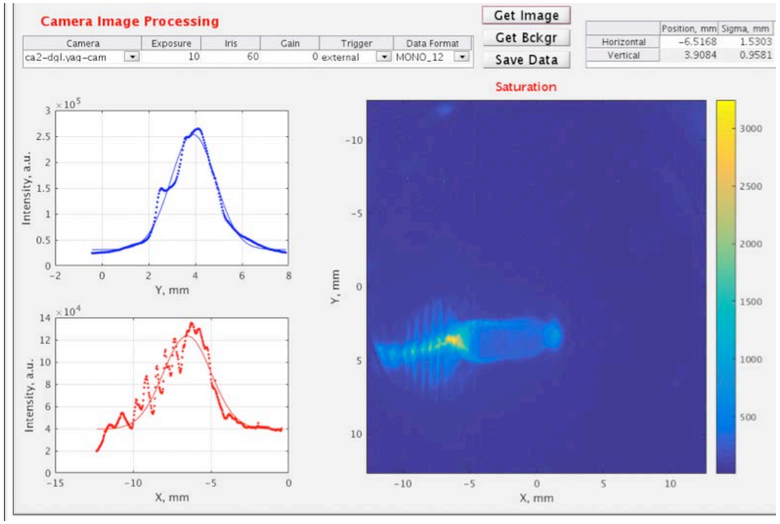
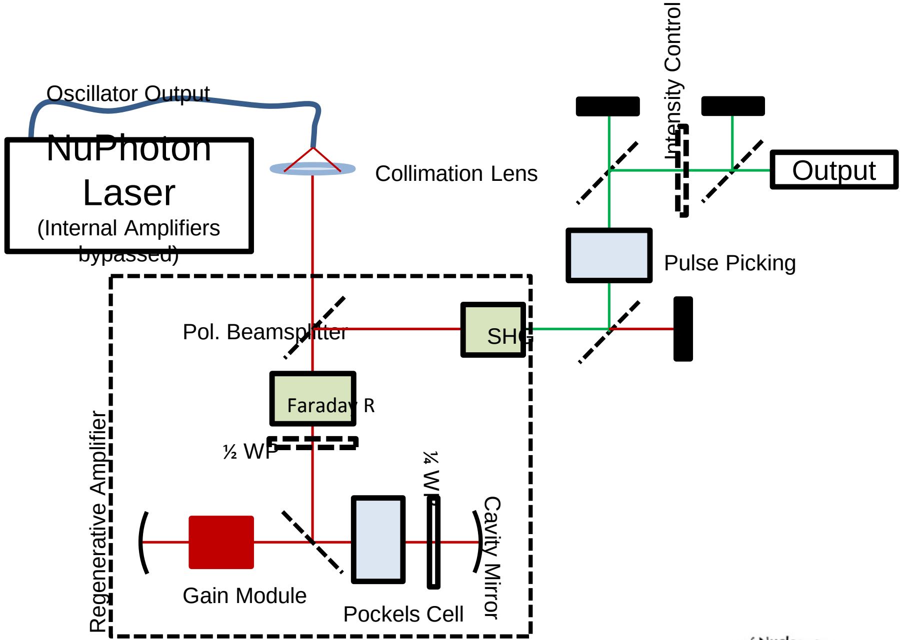
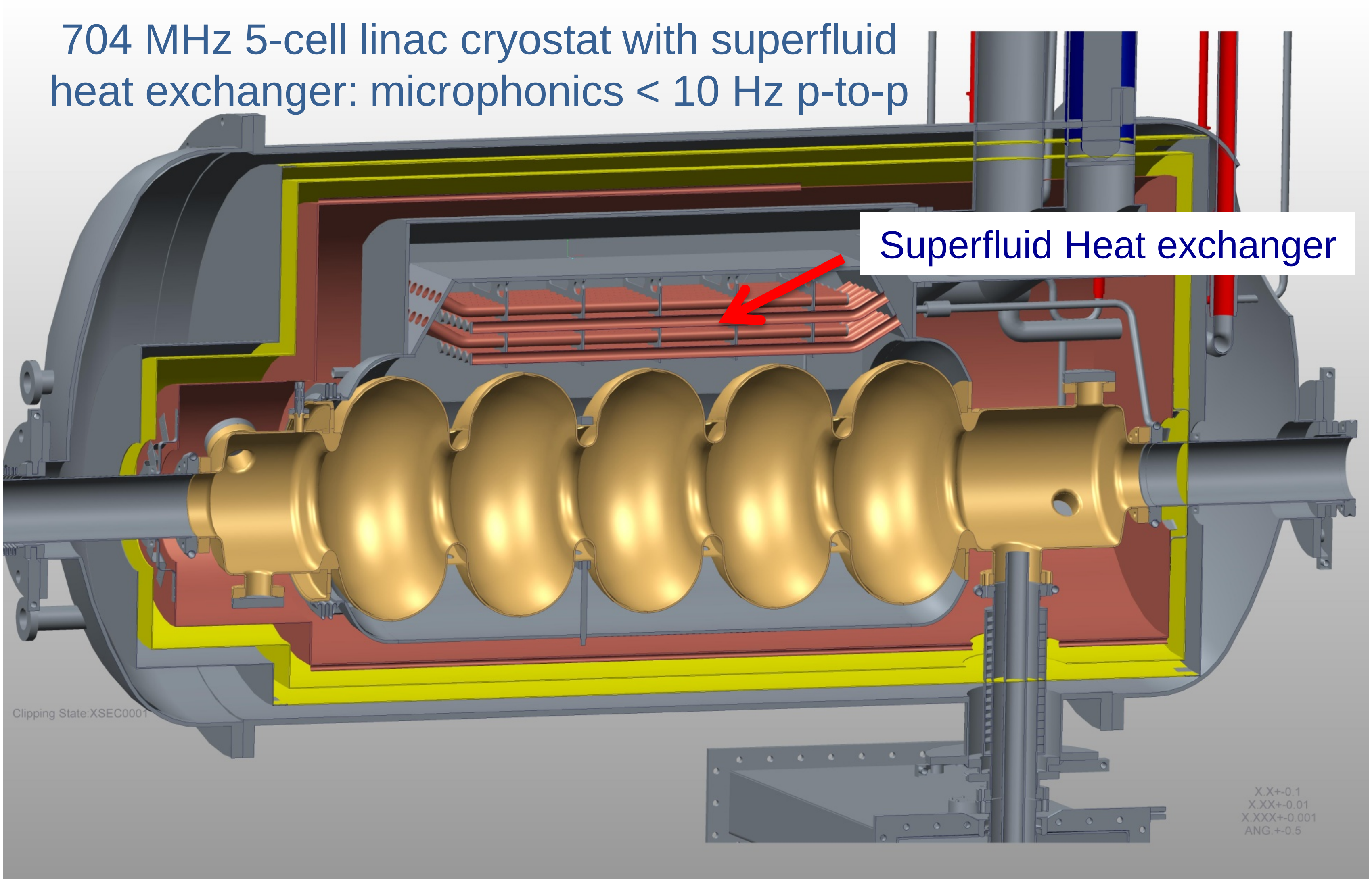
Laser

- Initially we utilized fiber based NuPhoton laser and fiber delivery system
- The Raman scattering in the fiber lengthened bunch at high peak power
- Laser was demonstrating spiky output with long pulses
- We have built new evacuated delivery beamline and replacing the power laser power amplifier





Accelerator Cavity



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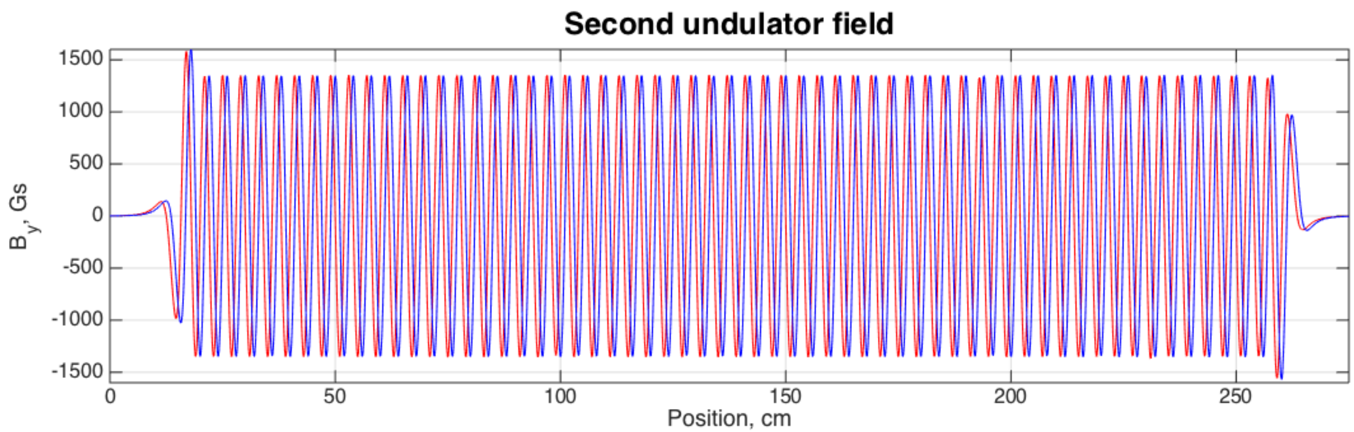
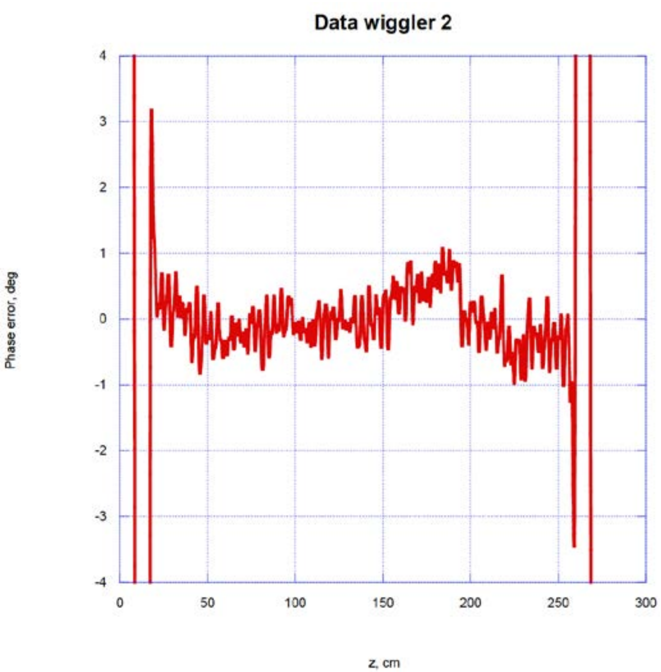
Accelerator Cavity (II)

- The design value of the accelerating voltage is 20 MV (20 MV/M) was demonstrated during vertical test.
- However, few accidents and further cavity processing revealed defect and we unable operate above 13.5 MV due to the quenches
- This lead to shift of the FEL wavelength to 30 microns and made IR diagnostics unusable. It also substantially changed revolution frequency and the SRF gun was operating at harmonic of 3^{rd} sub-harmonic of RHIC revolution frequency for 26.5 GeV/u , e.g. 26 kHz

FEL System





FEL system was supplied by BudkerINP from Novosibirsk and was finely tuned upon delivery. This summer we found that helicity of the third wiggler is wrong and corrected the error.

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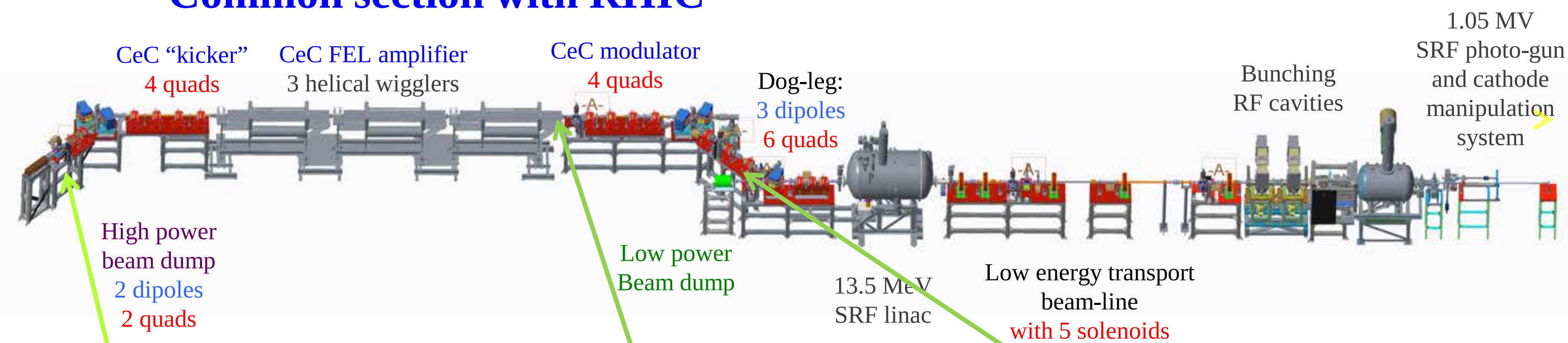
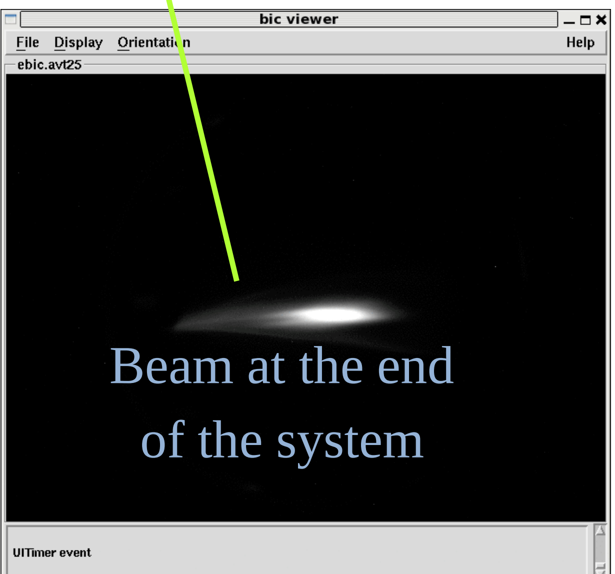
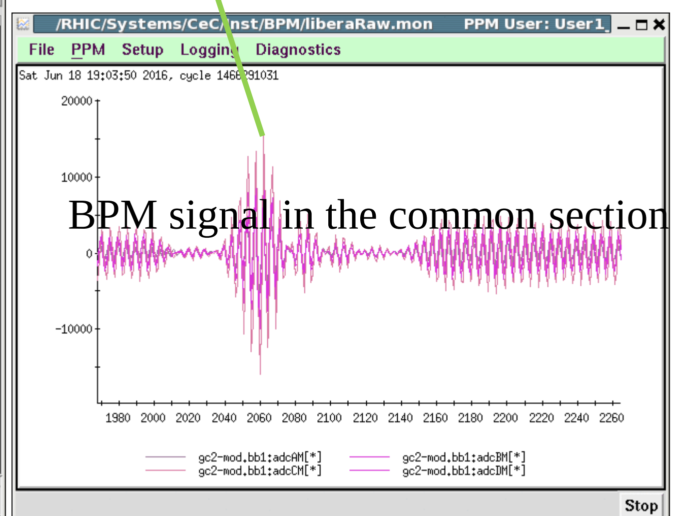
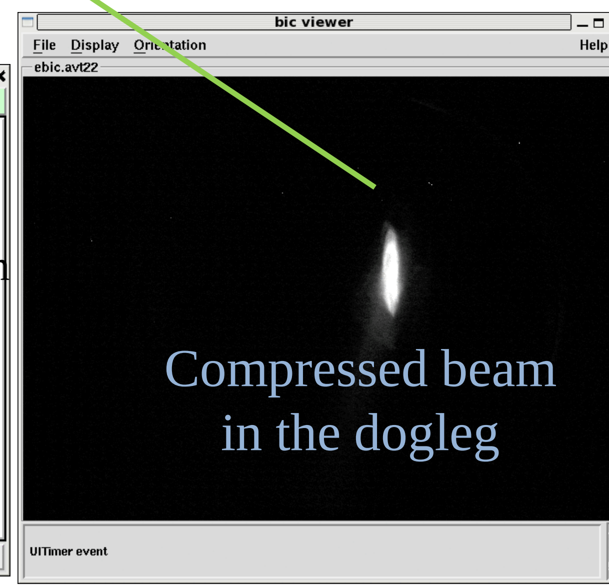
The CeC System Commissioning

Common section with RHIC



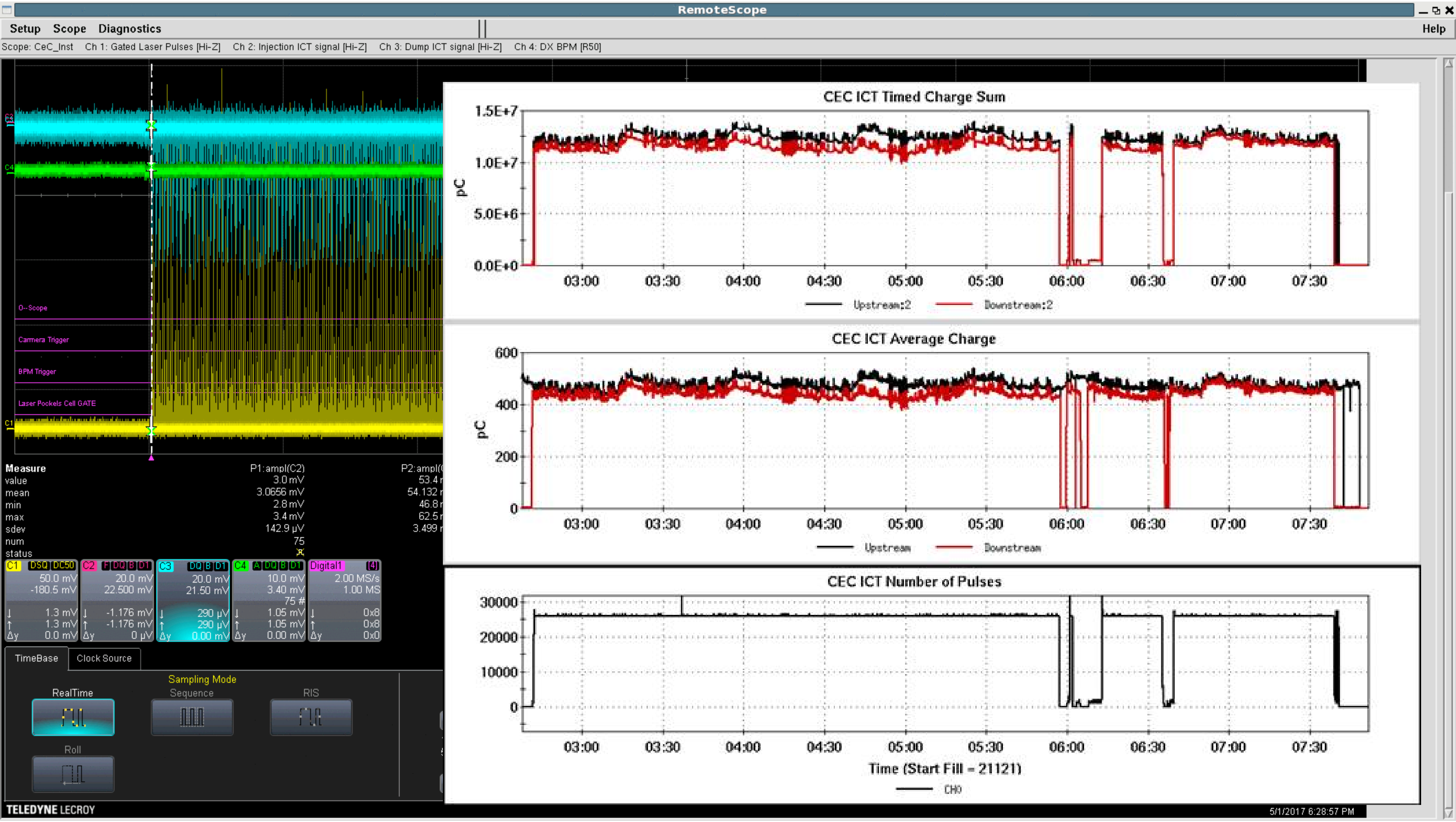






Electron beam was propagating inside 1μs abort gap

Operating in CW Mode

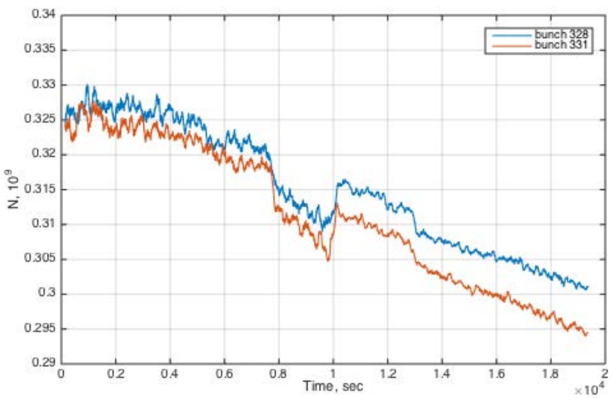


Interaction with Hadron Bunches

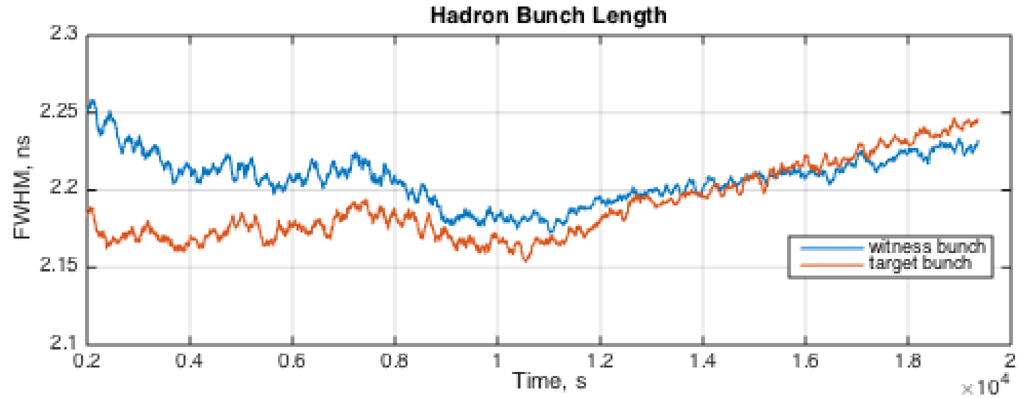
- We were operating in parallel with other RHIC experiment with low energy gold ions
- Two dedicated "CeC" ion bunches were operated in parallel with colliding RHIC bunches
- We synchronized hadron and the electron beam (26 kHz train of bunches, overlapping with ion bunch each 3rd turn – one of compromises we have to do during Run 17) with one of the bunches, while the second hadron bunch served as a reference (observing BPM pick-up signal on oscilloscope)
- We transversely aligned the electron beam with hadrons using BPMs
- We changed the e-beam energy and also adjusted the phase shifters between the undulators – 2 parameter scan. Scan took 8 hrs.
- We detected some interaction between the ion and electron beam (next slide)

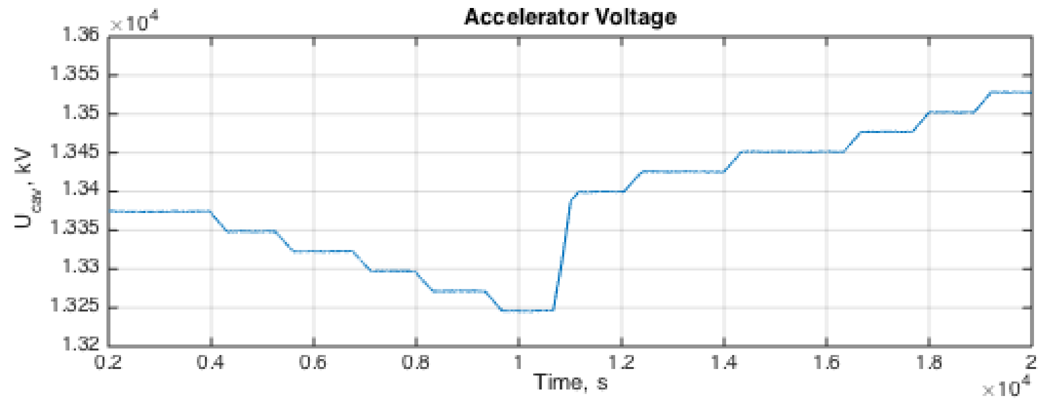
Observation of Interaction

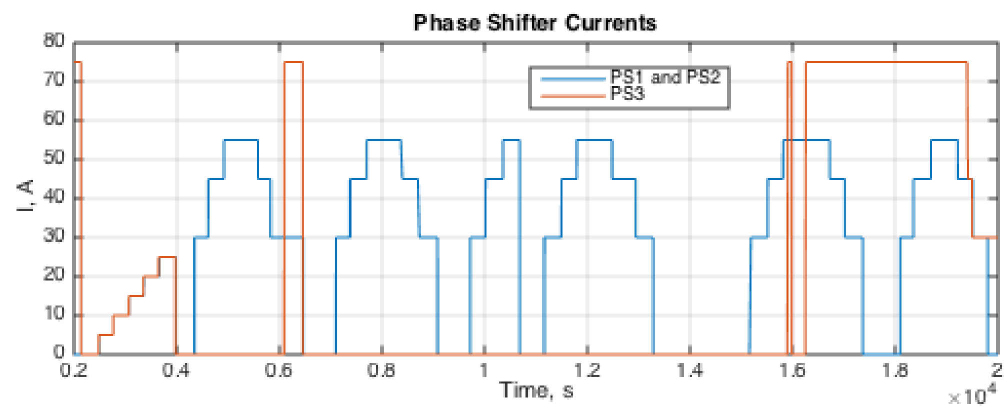
There is no blow up of the hadron beam with short electron bunch.



Data were processed with moving average (128 samples)







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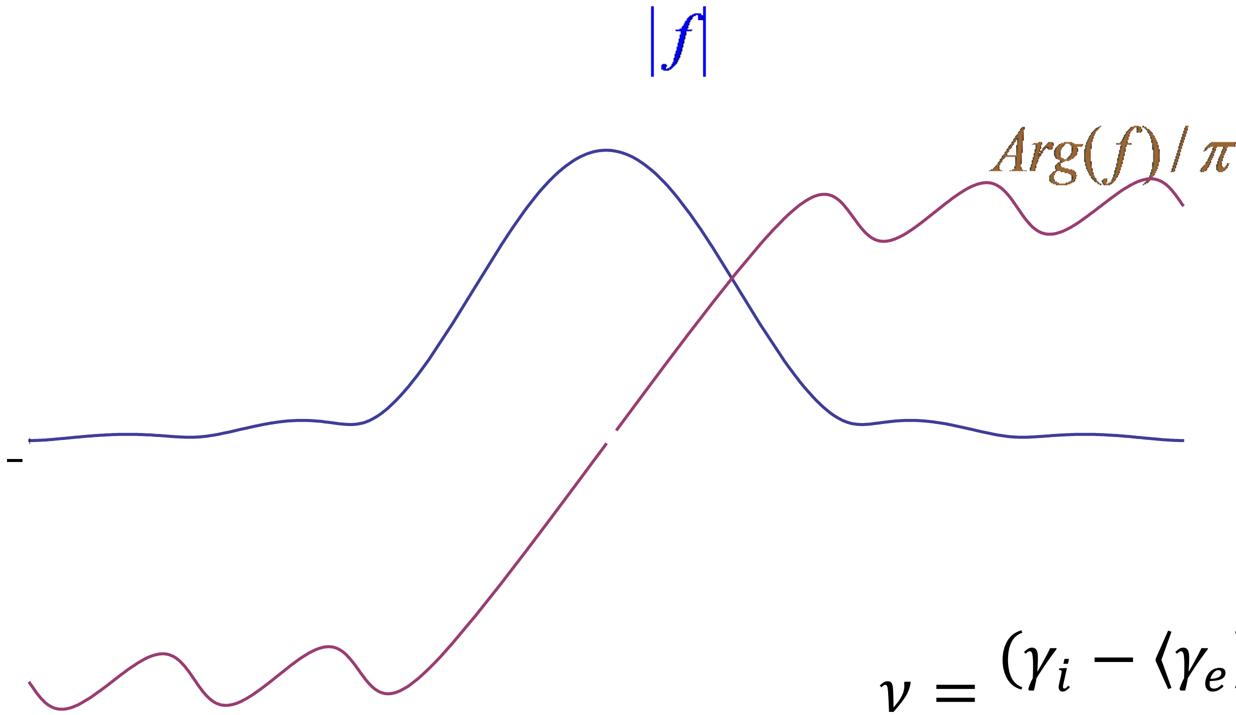
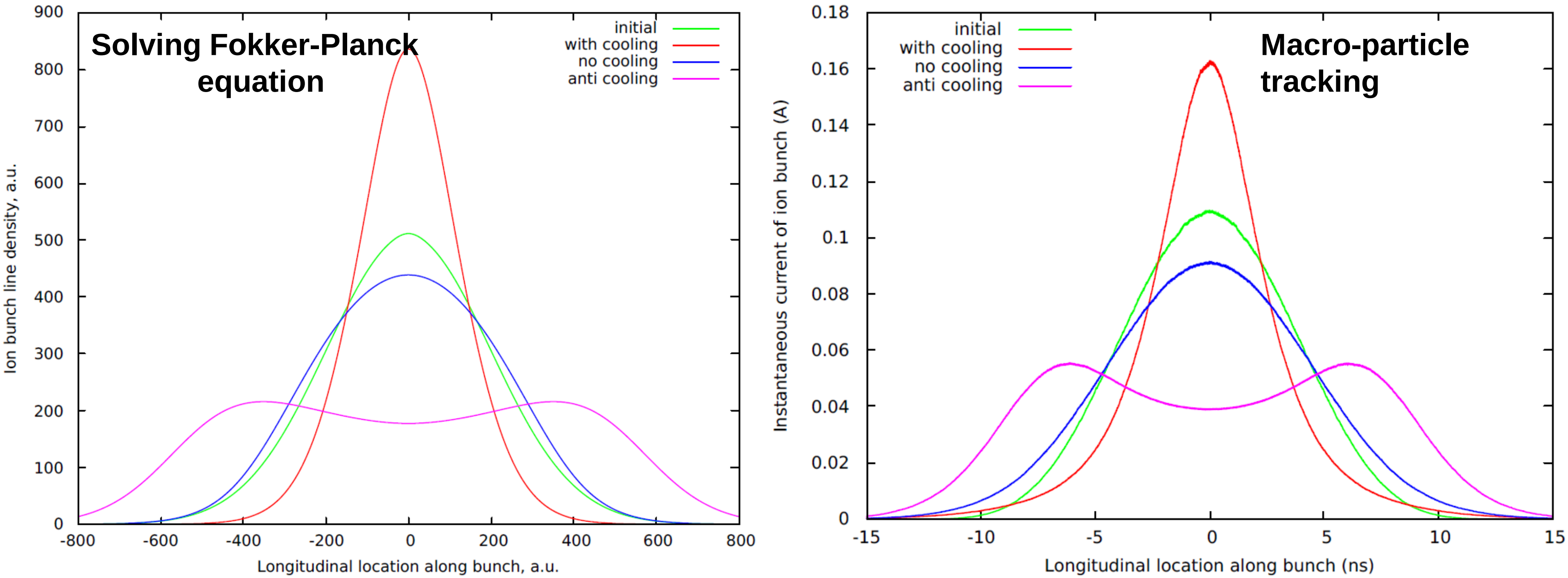
Matching of Hadron and Electron Beam Energies



$$\nu = {(\gamma_i - \langle\gamma_e\rangle)}/{\sigma_{\gamma_e}}$$

Interaction with ions double the intensity of spontaneous radiation: we will use this dependence to tune the energies of the beams to exact synchronism.

Observation of the Cooling during Run 18



We will study the evolution of the hadron bunch shape with different currents in the phase shifter (cooling/heating)

2017 Shutdown Activity

- Replaced failed ICT √
- Fixed wiggler helicity √
- Re-tune gun cavity to the required frequency √
- Replace IR port window √
- Replace IR diagnostics √
- Add BPM between buncher cavities (352 MHz)
- Install magnetic shielding for low-energy beamline
- Add port aligner for cathode launcher
- Replace drive laser with regenerative power amplifier √
- Add He return line
- Replace trims for low energy beamline
- Improve stability (phase, amplitude, timing) of RF and laser systems

Plan for RHIC Run 18

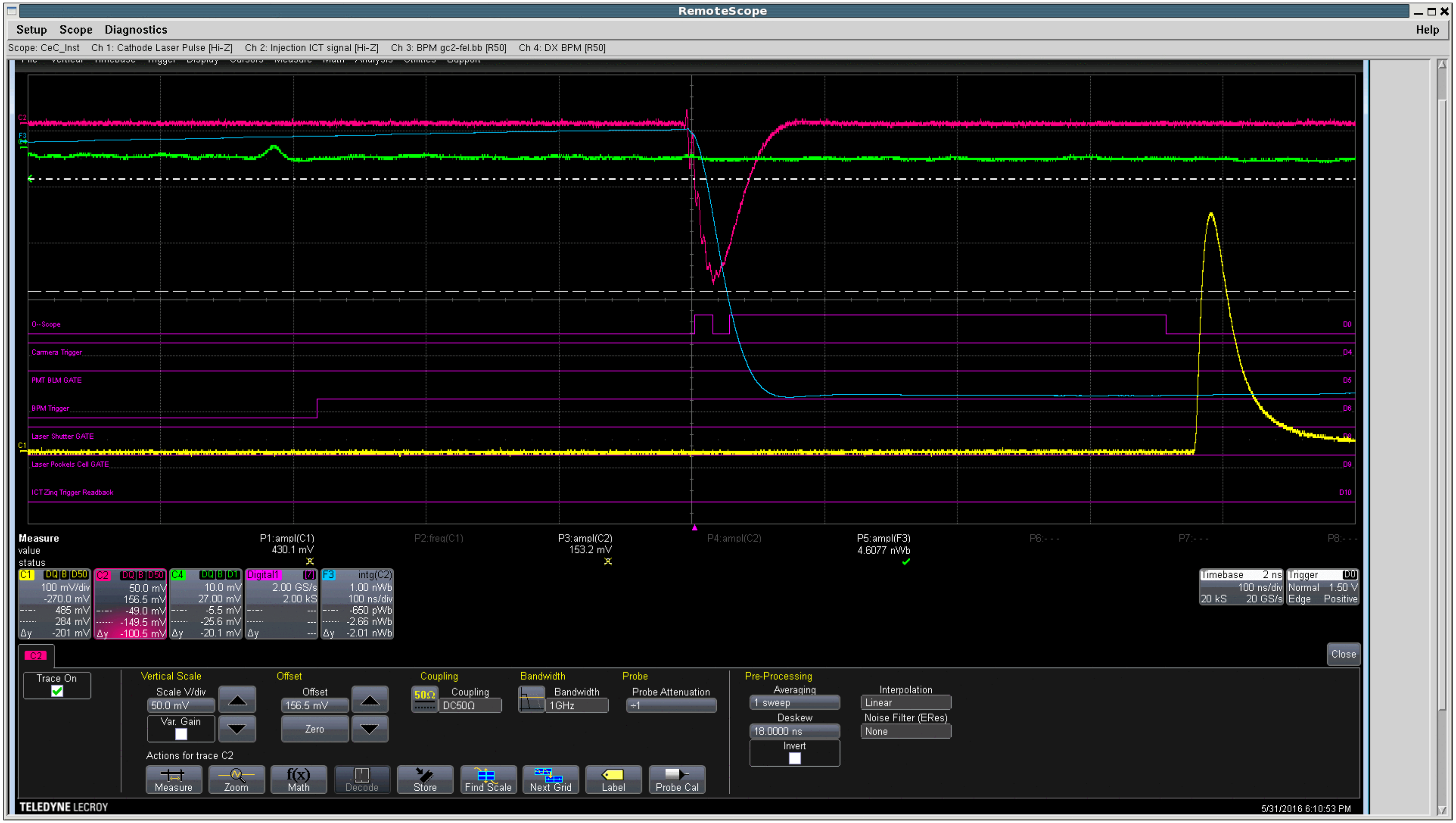
- ✓ Start operation of all room temperature systems prior to RHIC start and start operation of the whole CeC system as soon as our SRF cavities are cold
- ✓ Establish stable phase, amplitude and timing (RF and laser) to deliver stable reliable electron beam
- ✓ Commission new IR diagnostics and establish FEL operation
- ✓ Align electron and ion beams transversely, synchronize electron beam with ion beam with 26.5 GeV/u
- ✓ Synchronize the ion and electron beams energies using IR diagnostics
- ✓ Establish interaction of electron and ion bunches
- ✓ Test Coherent electron Cooling
- ✓ Characterize Coherent electron Cooling

Conclusions

- The CeC accelerator is fully commissioned
  - But low energy gain of the SRF linac prevented us from demonstrating the FEL amplification and the CeC cooling
- We were able to generate electron beam with quality sufficient for the CeC experiment and FEL amplification
  - 0.5 nC, 50 A bunches were generated, accelerated and propagated through the system
- We have demonstrated record performance of the SRF gun
- We have developed new diagnostics tools
- We defined and are implementing all necessary steps for demonstration CeC experiment during RHIC Run 18

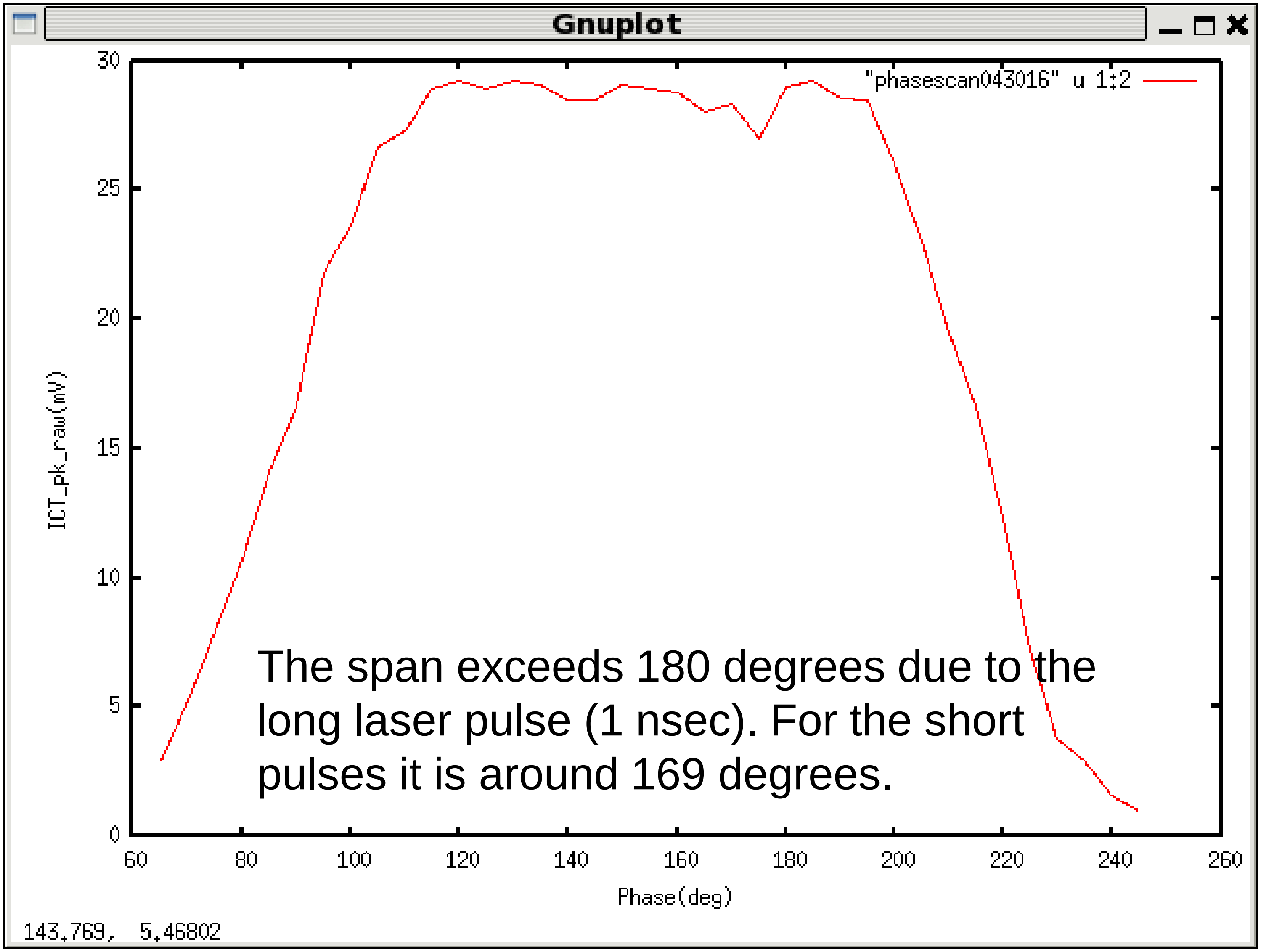
Back-up

3.7 nC Charge from the Gun



Demonstrated on May 31, 2016

Cavity Phase Scan



The span exceeds 180 degrees due to the long laser pulse (1 nsec). For the short pulses it is around 169 degrees.

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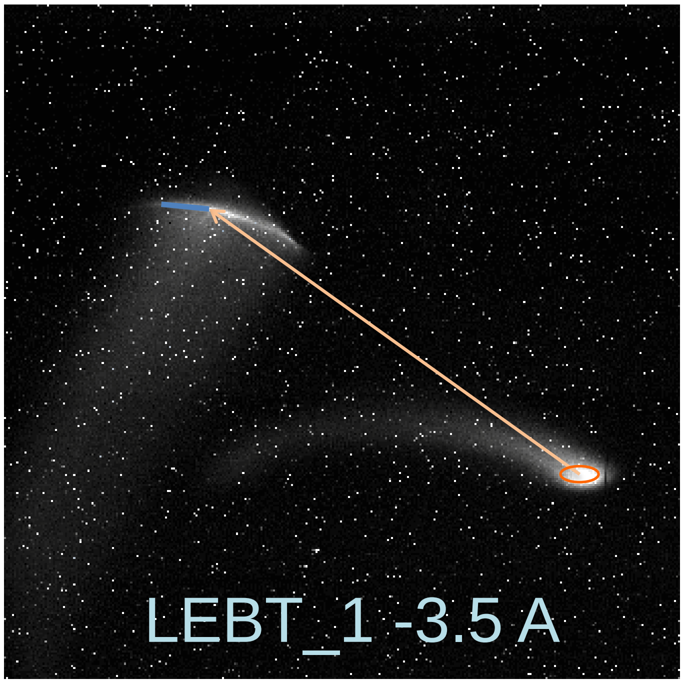
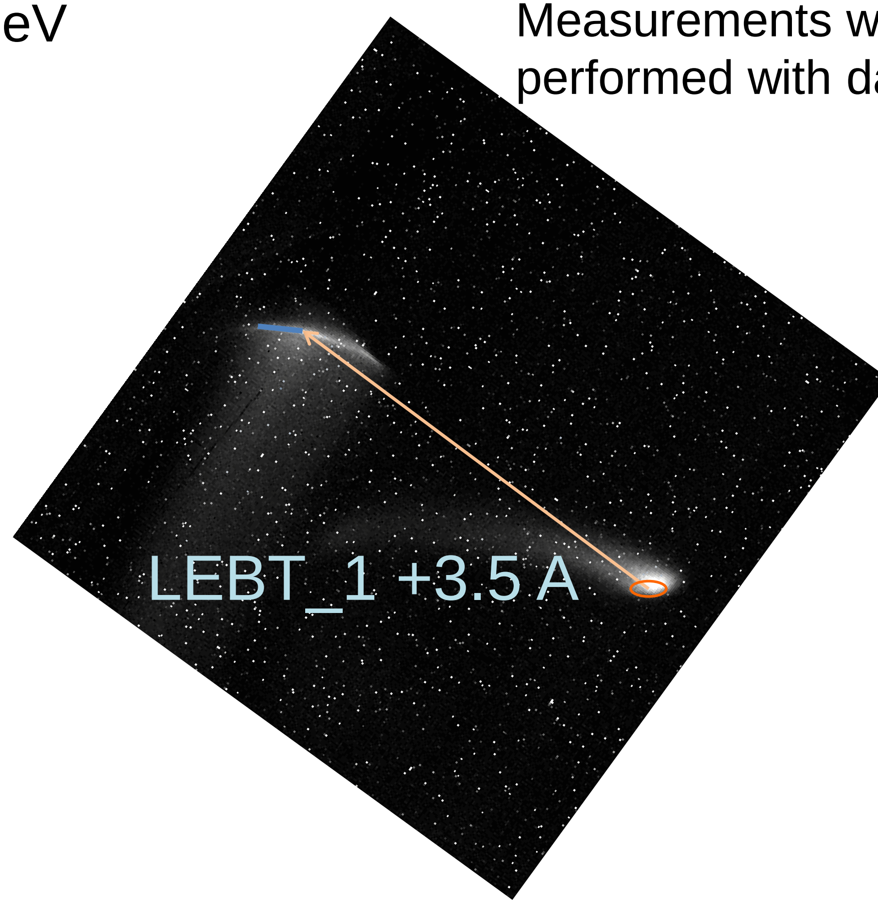
Beam Energy Measurement

Rotation angle 54˚ - 1.19 MeV kinetic energy

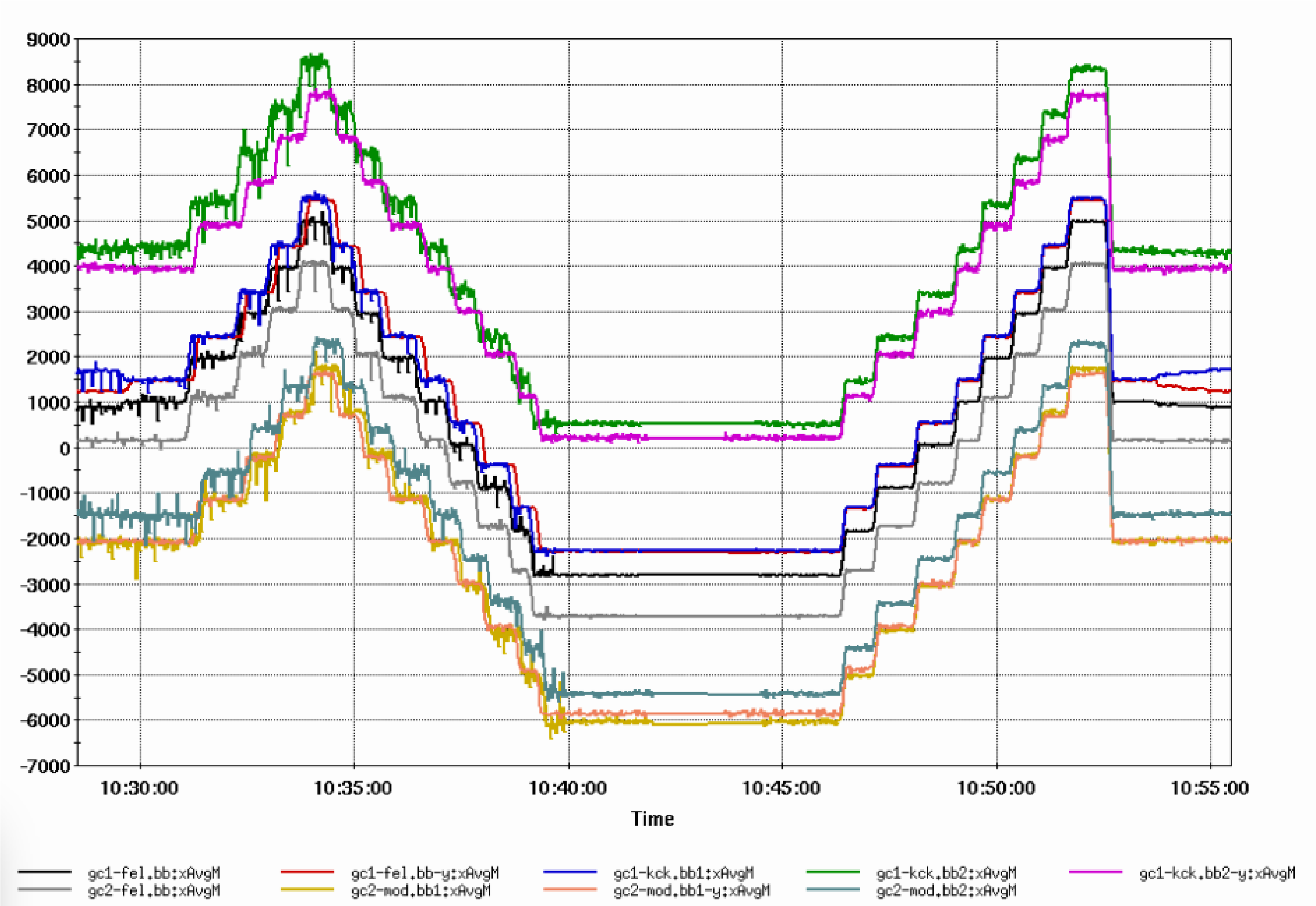
Measurements were performed with dark current





We utilized rotation of the electron beam by a calibrated solenoid to measure beam energy. The measured value was confirmed with energy spectrometer.

BPM Cross-Calibration



We have checked cross-calibration of the BPMs in the common section with a hadrons beam.

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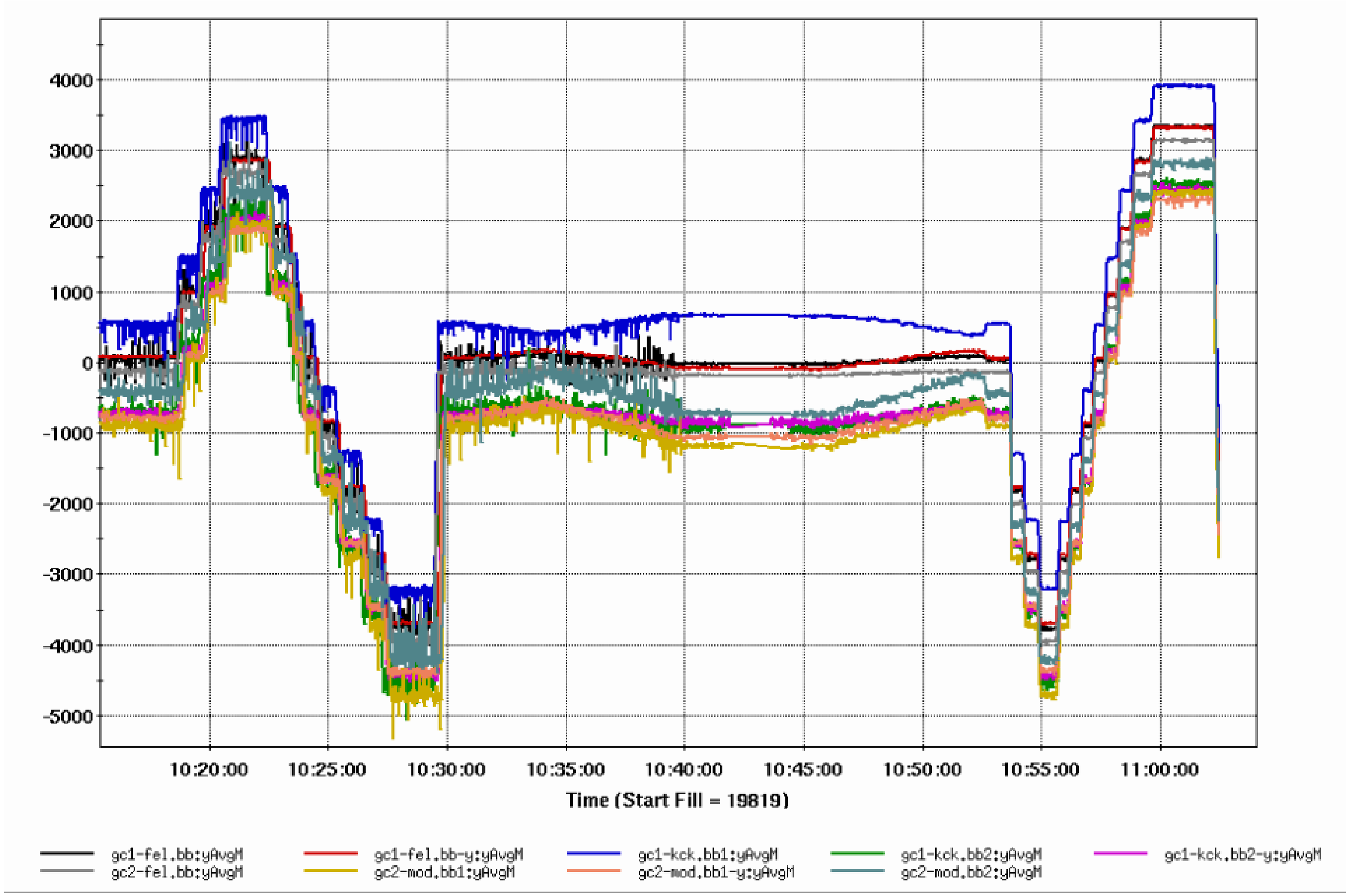
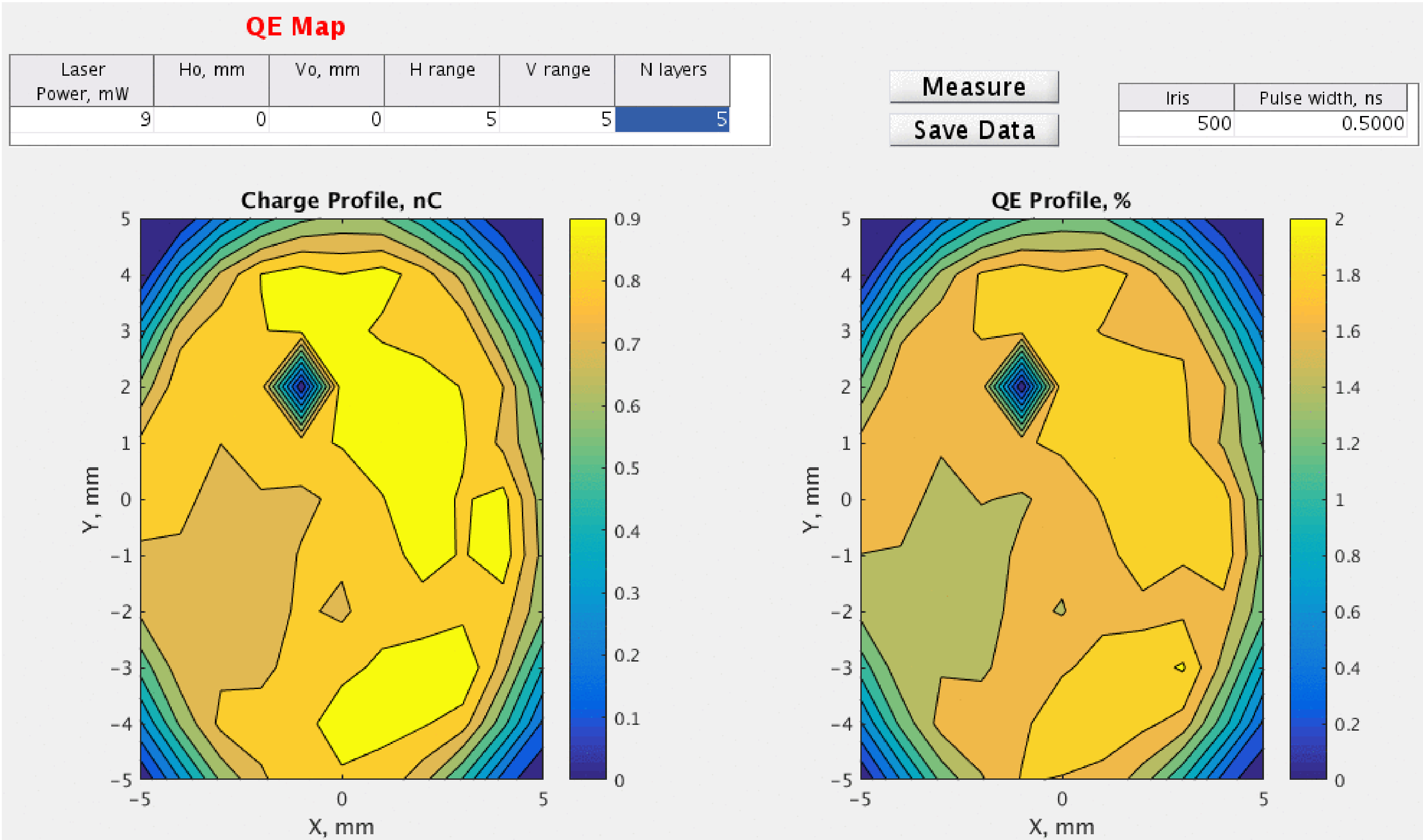
Vertical Scan

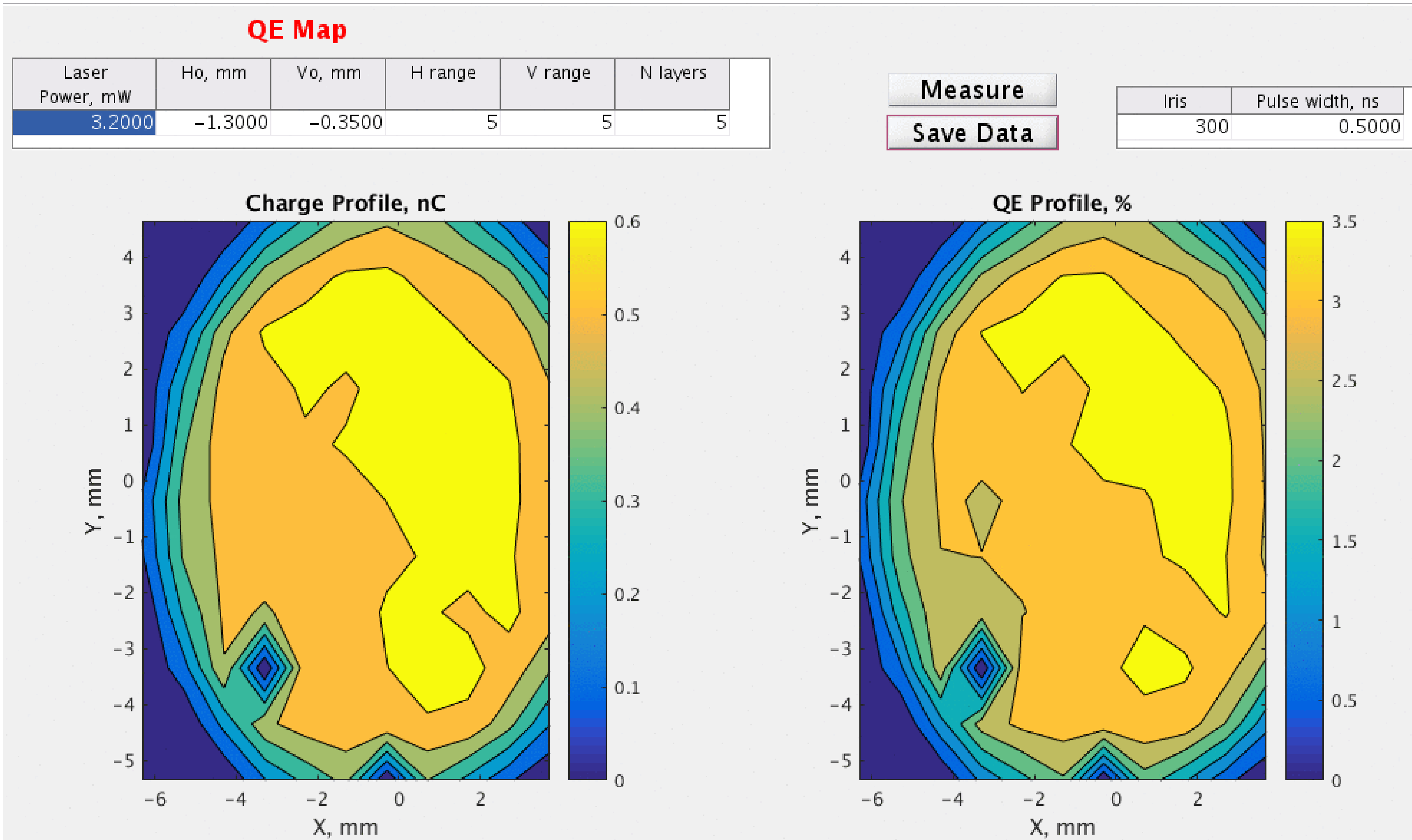


There are small offsets in both planes between hadron and electron BPMs.

QE Map after Cathode Change (June 7th)



June 12



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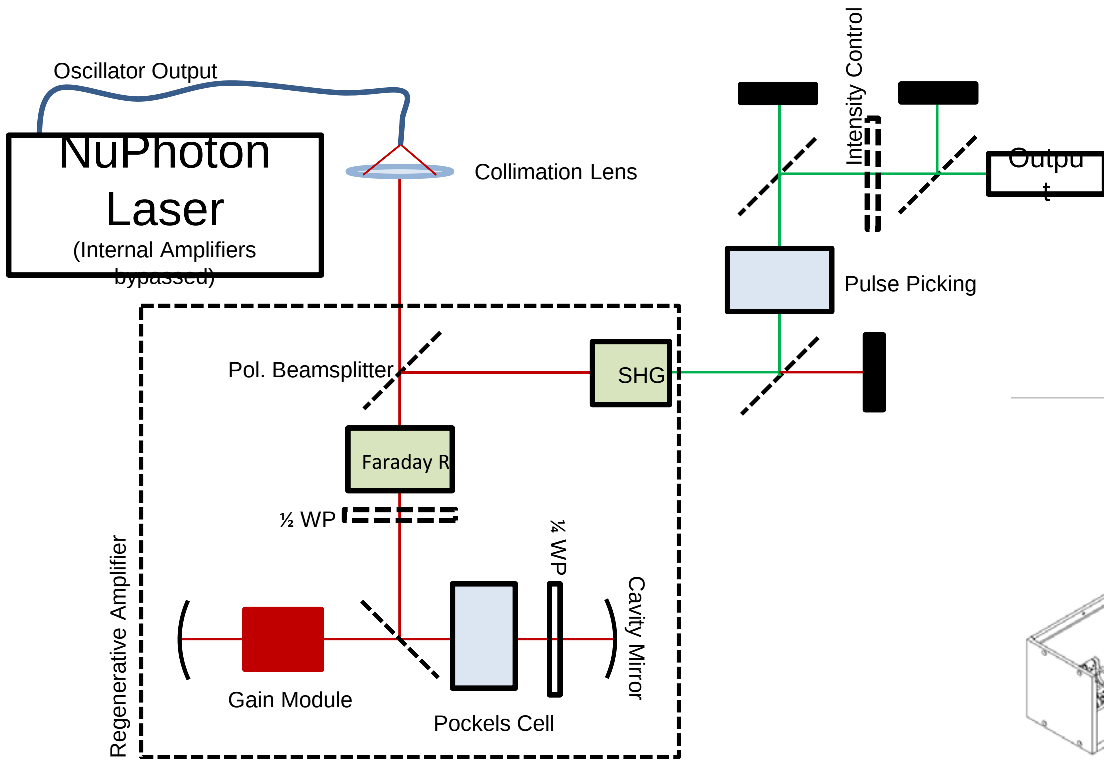
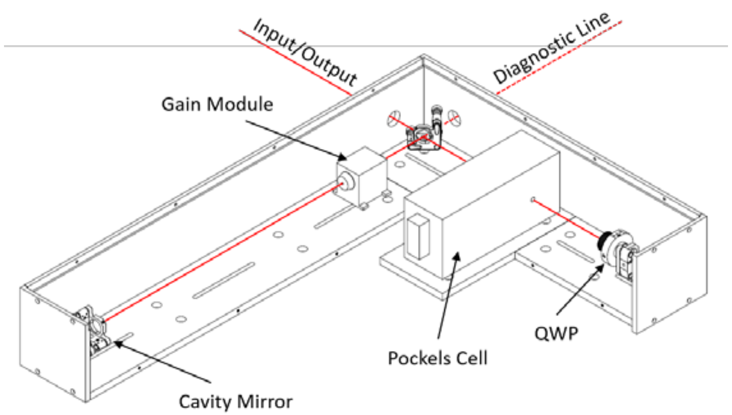
CeC Regenerative Amplifier Upgrade



	Estimate
Avg. Output Power (80kHz)	5W
Pulse Energy	60µJ (IR) 12µJ (Green)
Pulse Duration	up to 700ps
Profile Spatial	Gaussian
Profile Temporal	Flat Top



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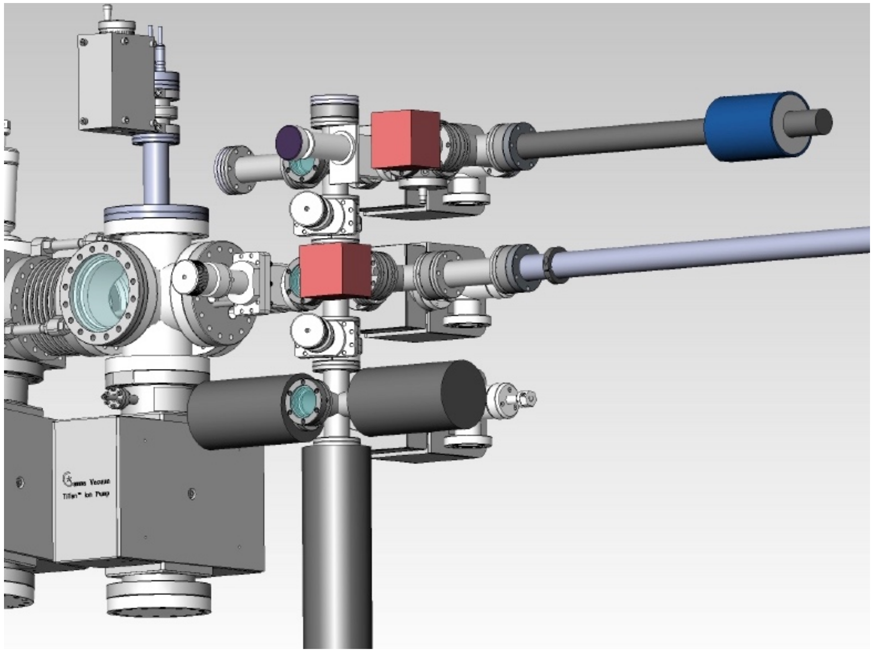
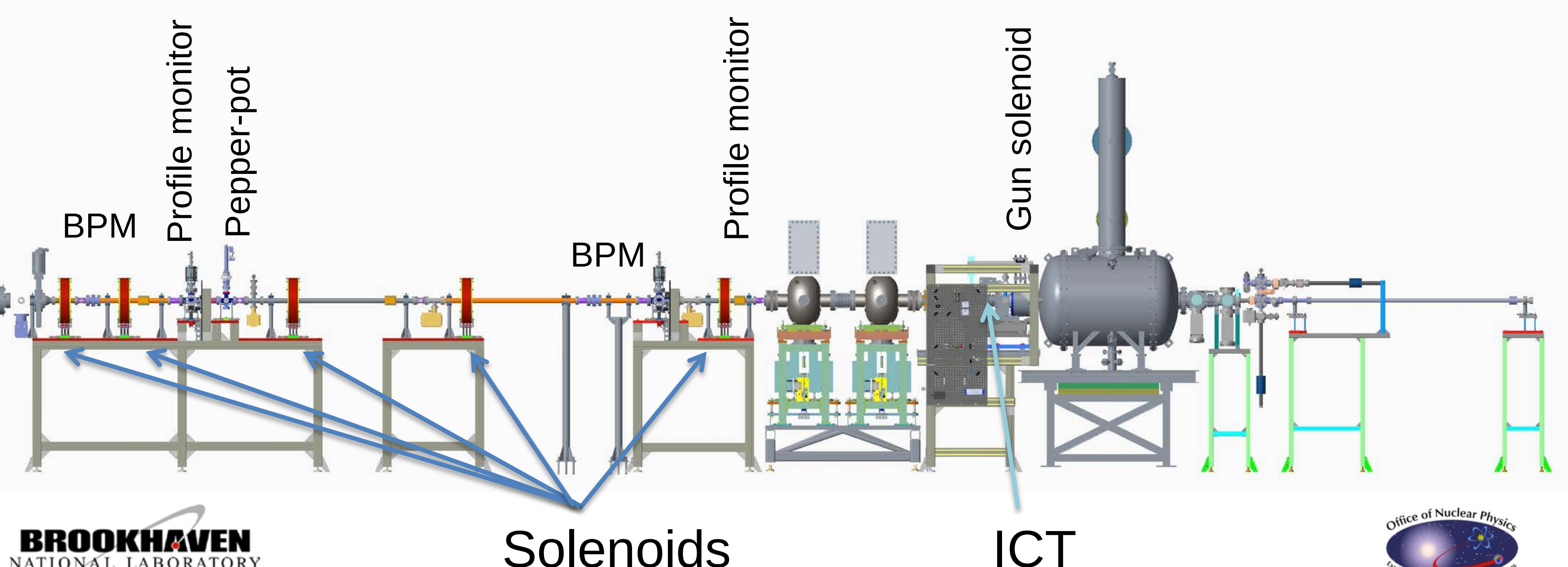
Performance Improvement during Commissioning



- Long conditioning cycle with molybdenum puck to suppress multipacting in the FPC area
- Helium discharge cleaning
- Rebuilt garage and cathode launch system – added port for QE monitoring inside the garage, added NEG getters
- Used mask for the cathode deposition system and developed start procedure to avoid multipacting inside the gun
- Increased PA power to 4 kW

Diagnostics for Low Energy Beam

- Integrating current transformer ICT (1.25 nV s/nC)
- Two beam profile monitors with 1.3 megapixel cameras
- Pepper-pot in front of the second profile monitor
- Two BPMs (Libera Brilliance Single Pass tuned to 500 MHz)
- Low power beam dump with Faraday cup



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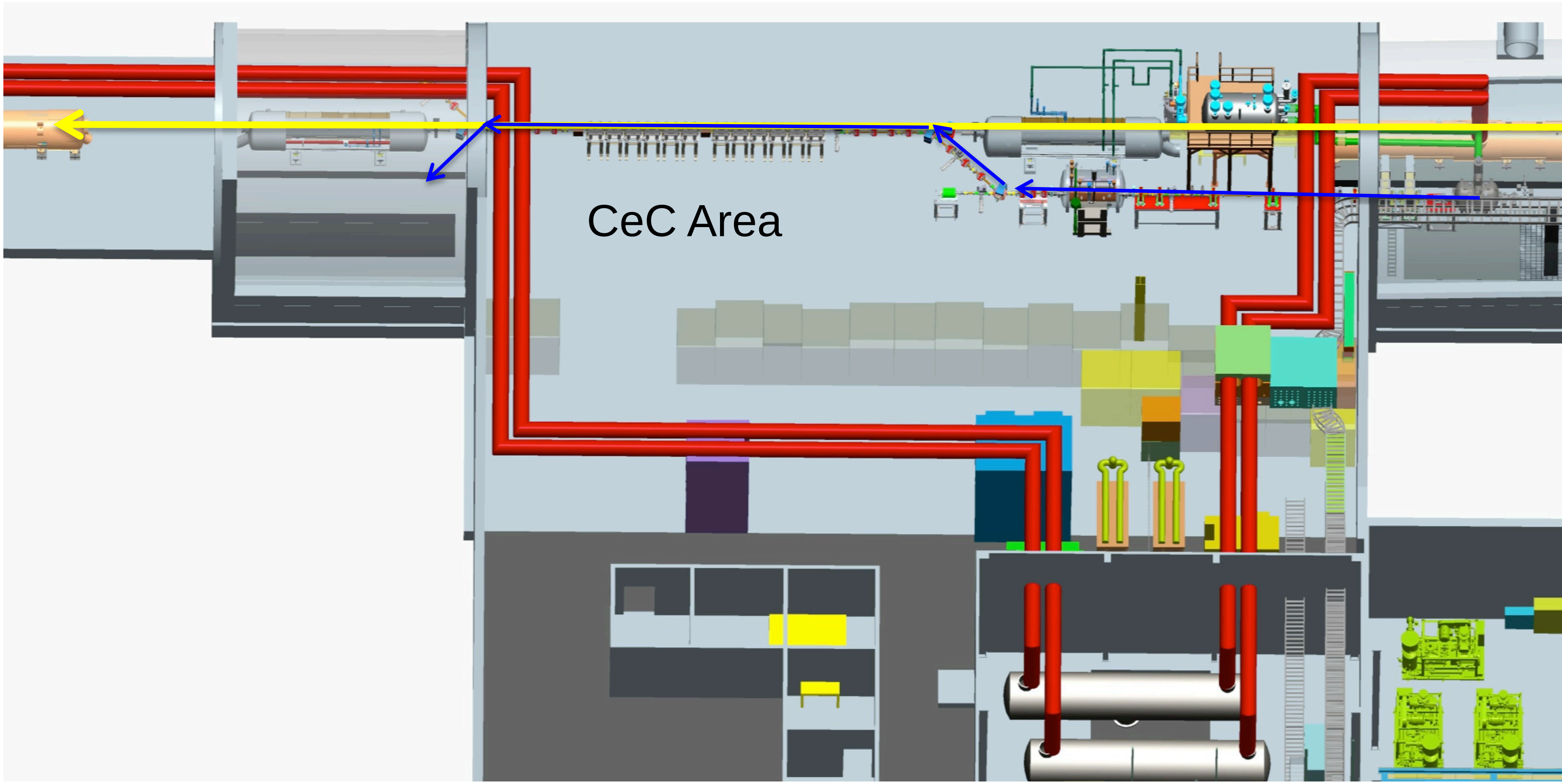
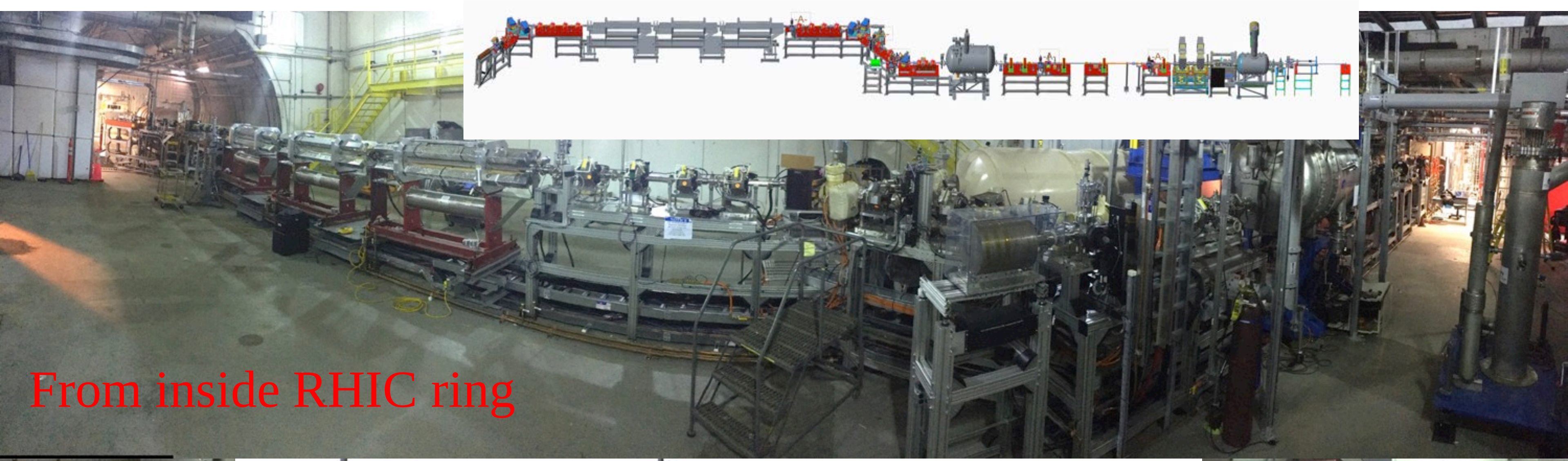
Top View

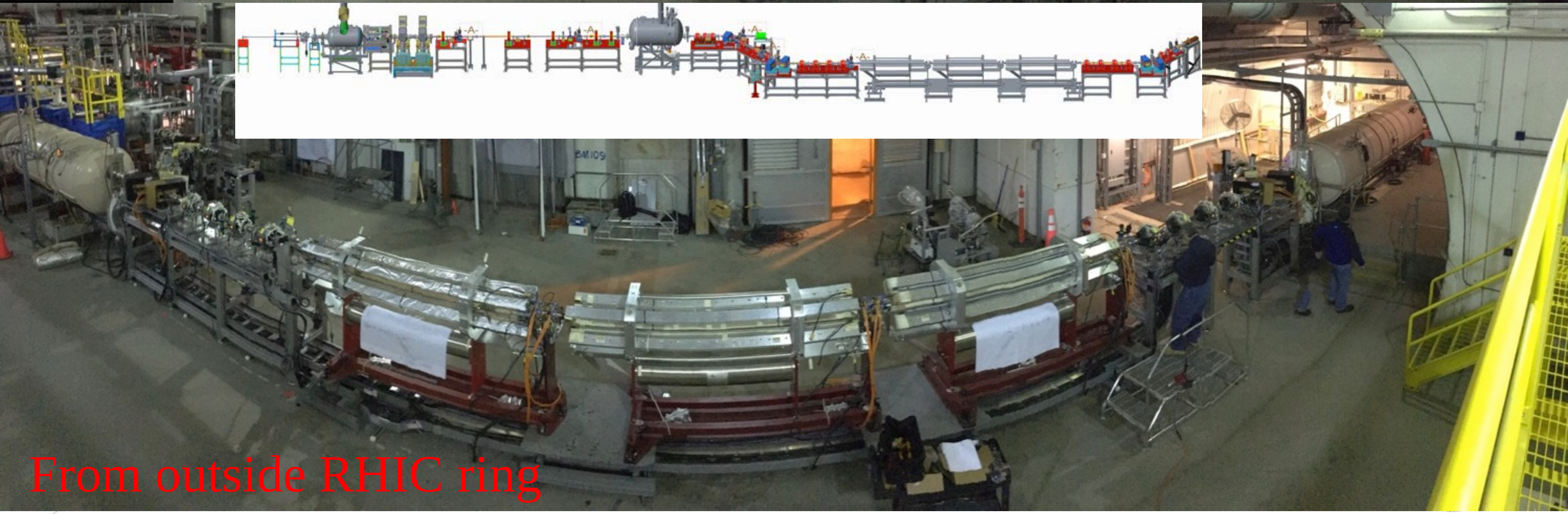


Coherent electron cooling experiment relies on the supply of the liquid helium available only during RHIC operation (January-June)

Panoramic Views



From inside RHIC ring



From outside RHIC ring