Status of Proof-of-Principle Experiment of Coherent Electron Cooling at BNL

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

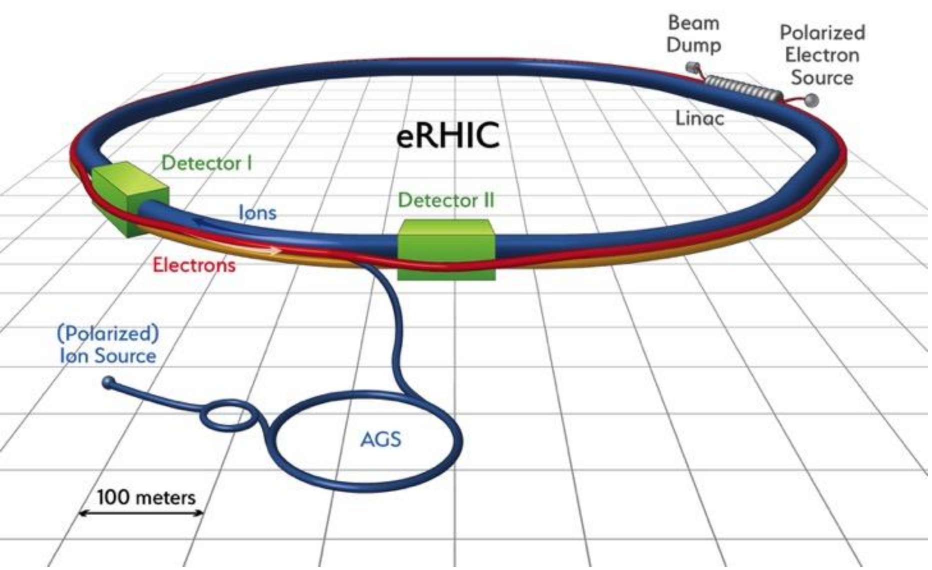
U.S. DEPARTMENT OF ENERGY | Office of Science

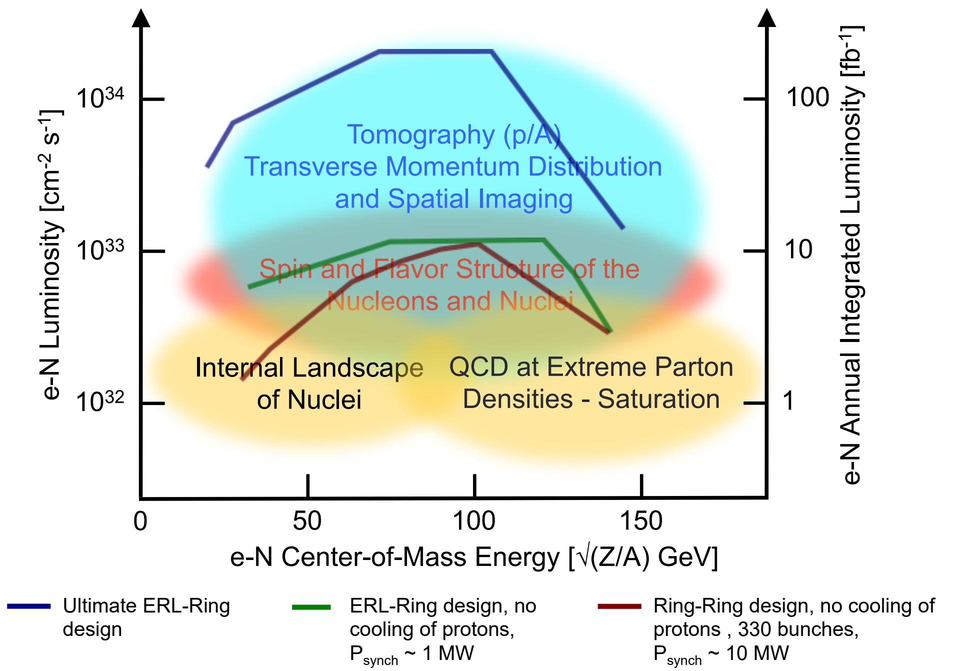
Outline

- Why we doing it?
- What is Coherent electron Cooling
- System description
- Subsystem performance
- Plan for Run 18

MOTIVATION: HIGH ENERGY HIGH LUMINOSITY EIC REQUIRES STRONG HADRON COOLING:

< 1 MIN COOLING TIME @ 250 GEV PROTONS





Coherent electron Cooling (CeC) is needed to achieve the ultimate high luminosity in any EIC and has to be tested → CeC PoP

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

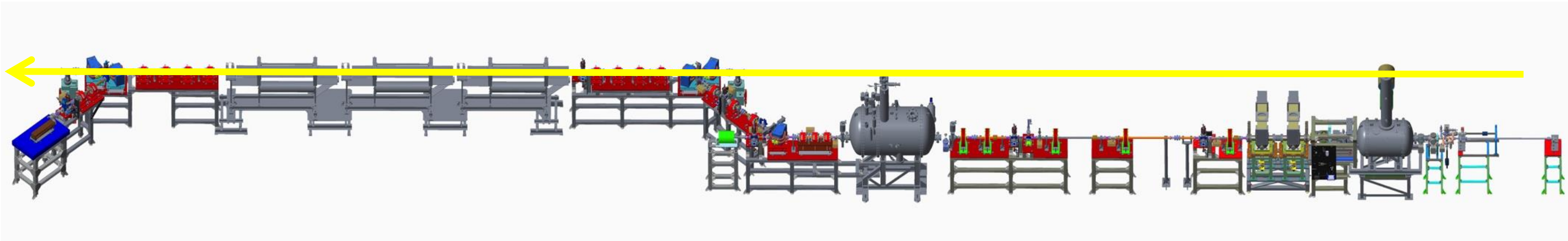
CeC Effect on eRHIC/EIC Design

- If CeC is successful and fully operational, eRHIC Linac/Ring configuration could reach 2×10^{33} luminosity with 5 mA polarized electron current

- It removes main uncertainties in Linac/Ring design of 50 mA of polarized e-beam:
  - 5 mA, 0.5 nC/bunch
  - 100x lower HOM power
  - 10x lower TBBU threshold
  - 3x shorter hadron bunches
  - 3x higher frequency of crab cavities → 1/3 of the voltage
  - Up to 3x smaller β^*
  - 10x lower SR losses
  - 10x lower SR back-ground
  - and many positive effects for EIC detector

- Final goal: eRHIC/EIC with 2×10^{34} luminosity

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.

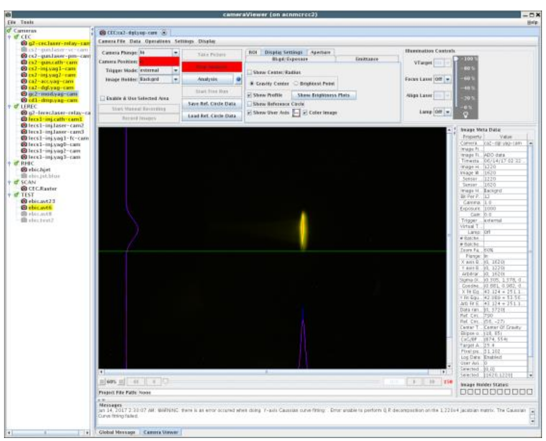
Electron Beam Parameters for CeC

- Gun energy 1.05 MeV
- Beam charge 4 nC
- Final beam energy 15 MeV
- Normalized emittance < 5 mm mrad
- Energy spread 10^{-3}
- Pulse repetition rate 78 kHz

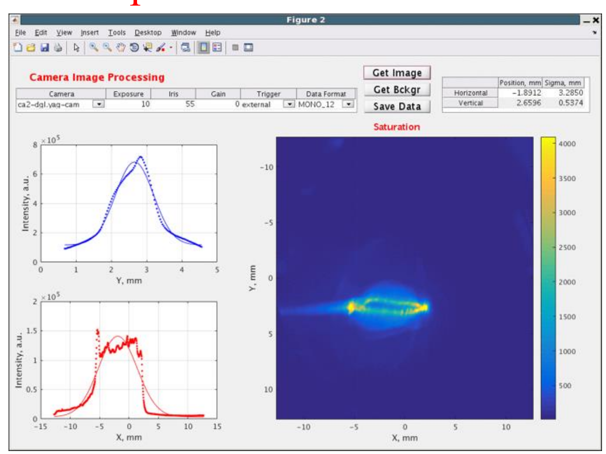
Main Advances

- 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

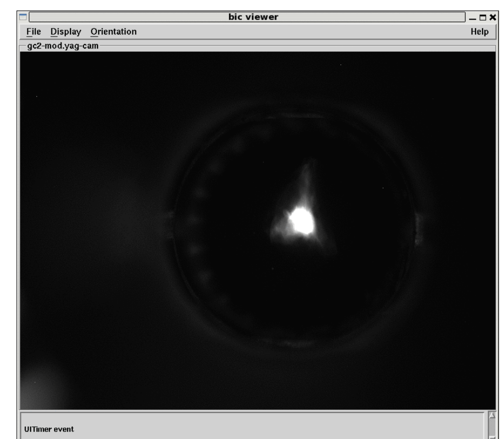
Sub 0.1% energy spread



40 A peak current in the bunch



Low emittance beam in FEL



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 ($\Delta f \sim 10$ 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

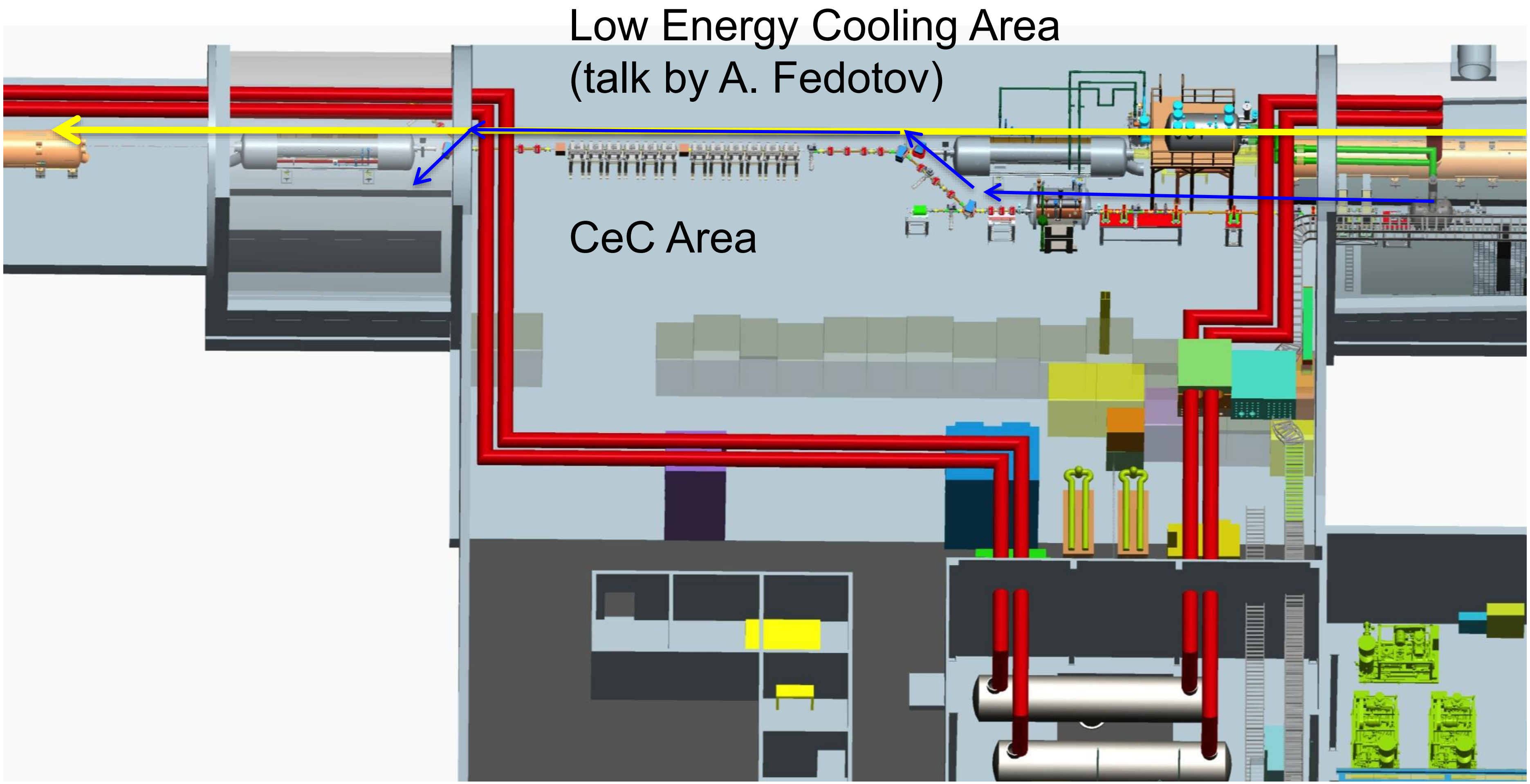
Beam Parameters

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

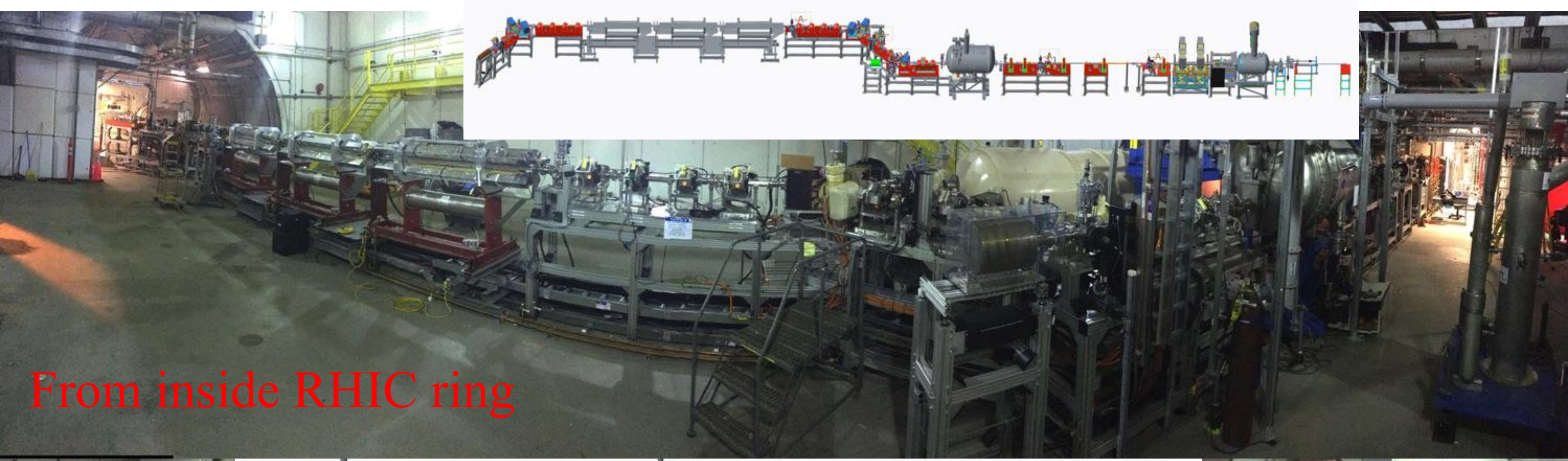
Beam parameters are sufficient for the CeC demonstration experiment

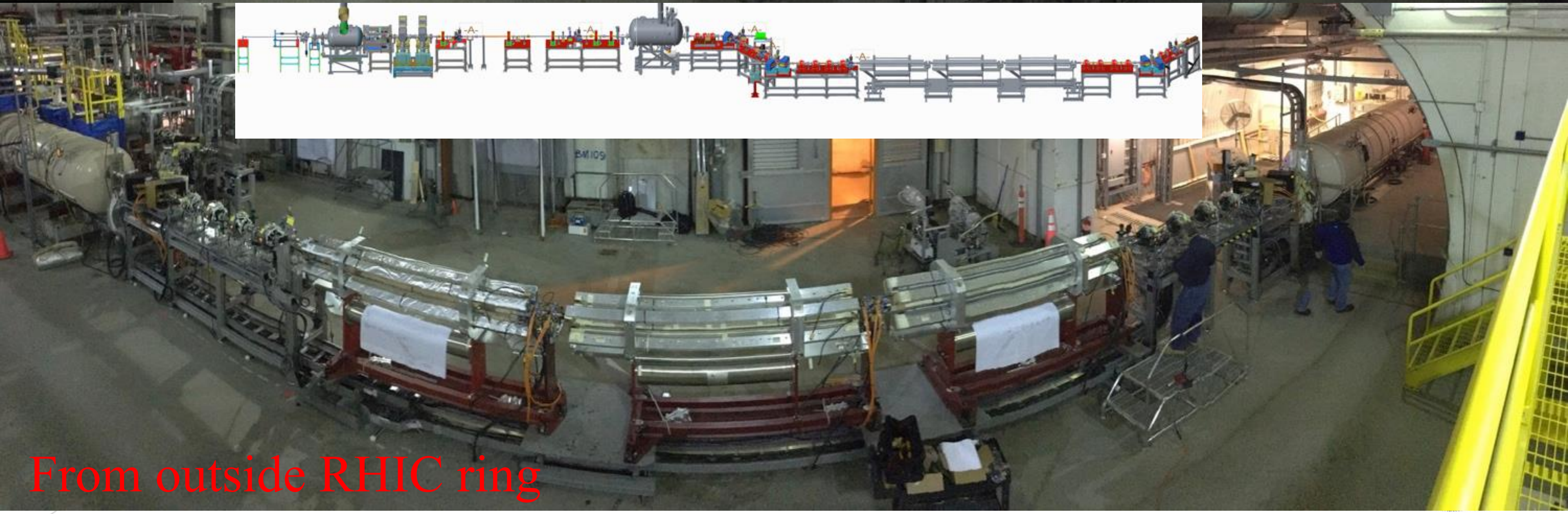
Top View



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

Panoramic Views

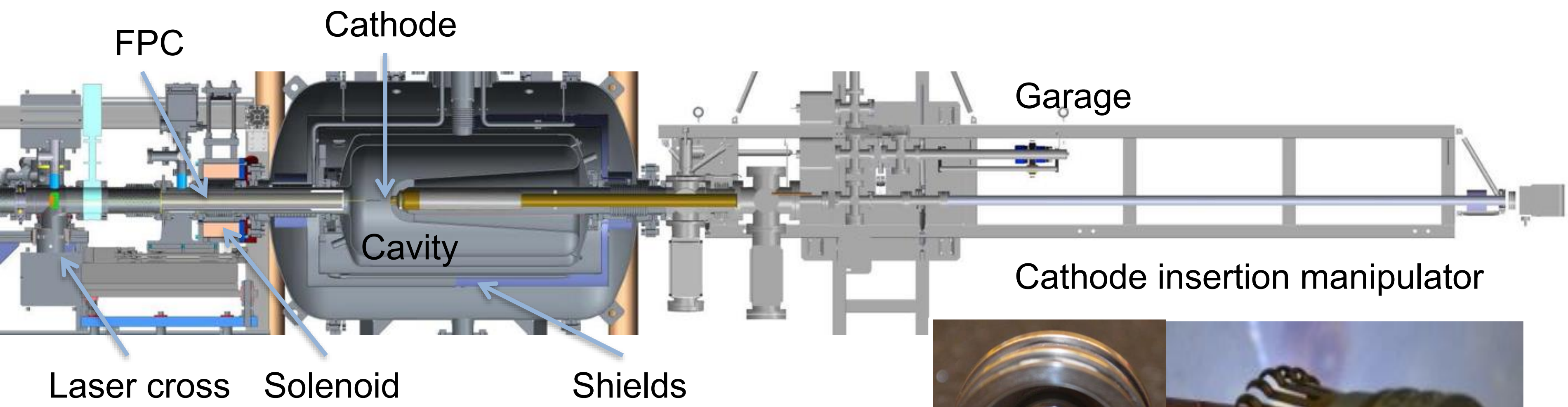




Beam Diagnostics

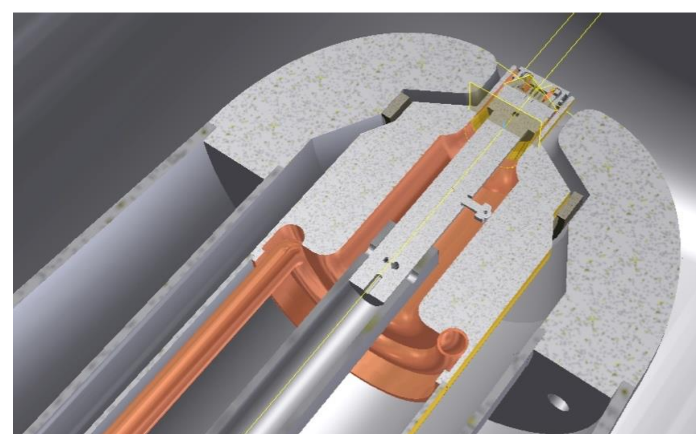
- Eleven electron beam position monitors (500 MHz)
- Three hadron beam BPMs (common pick-up electrodes, tuned to 9 MHz)
- Six profile monitors (two in the dispersive region)
- Pepper-pot
- Two Faraday cups combined with beam dumps
- Two ICT (after the gun and in front of the high power beam dump)
- IR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

CeC SRF Gun

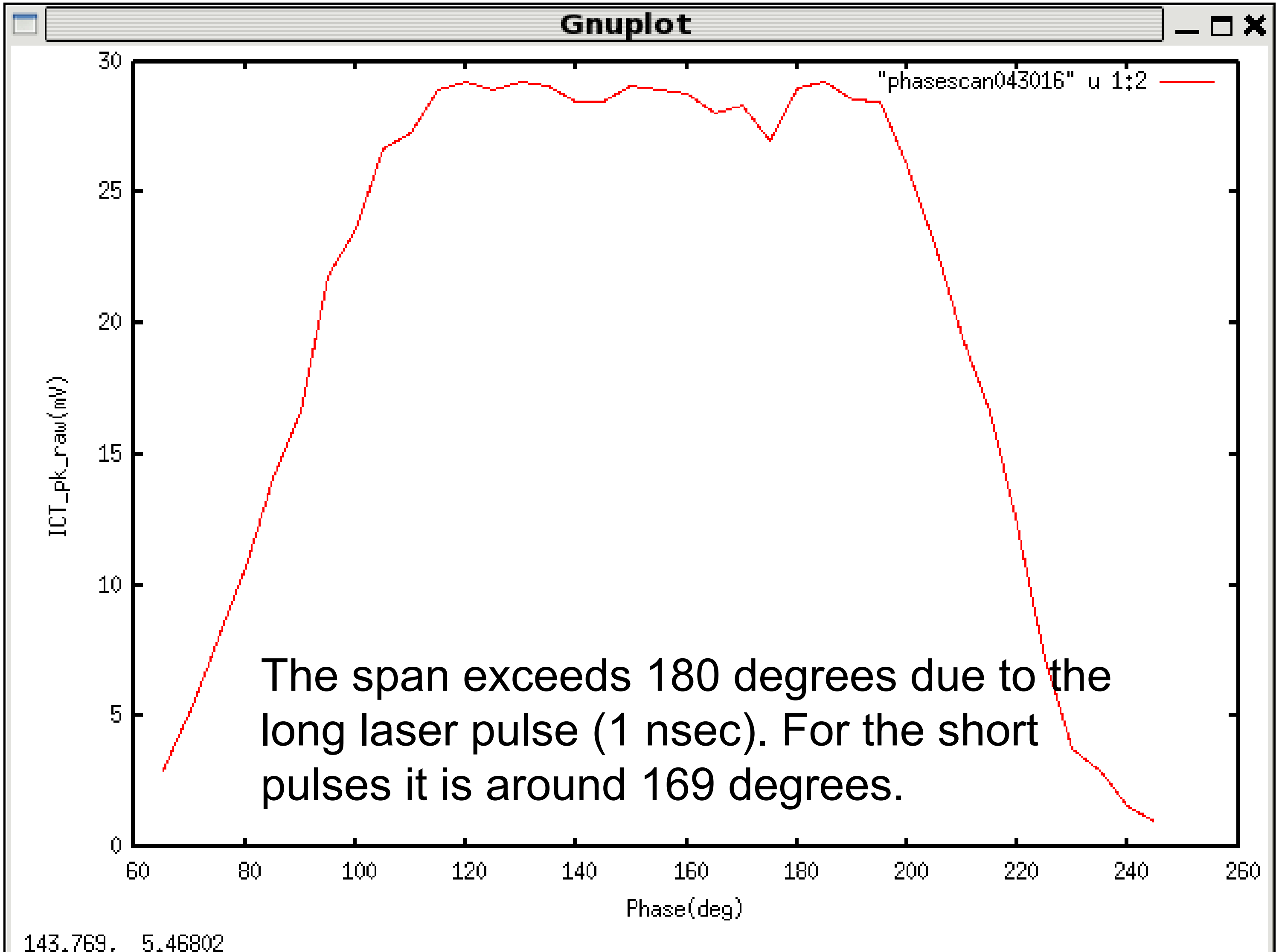


- Quarter-wave cavity
- 4 K operating temperature
- Manual coarse tuner
- Fine tuning is performed with FPC
- 4 kW CW solid state power amplifier
- CsK_2Sb Cathode is at room temperature
- Cavity field pick-up is done with cathode stalk (1/2 wavelength with capacitive pick-up)
- Up to three cathodes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

Photocathode end assembly



Cavity Phase Scan

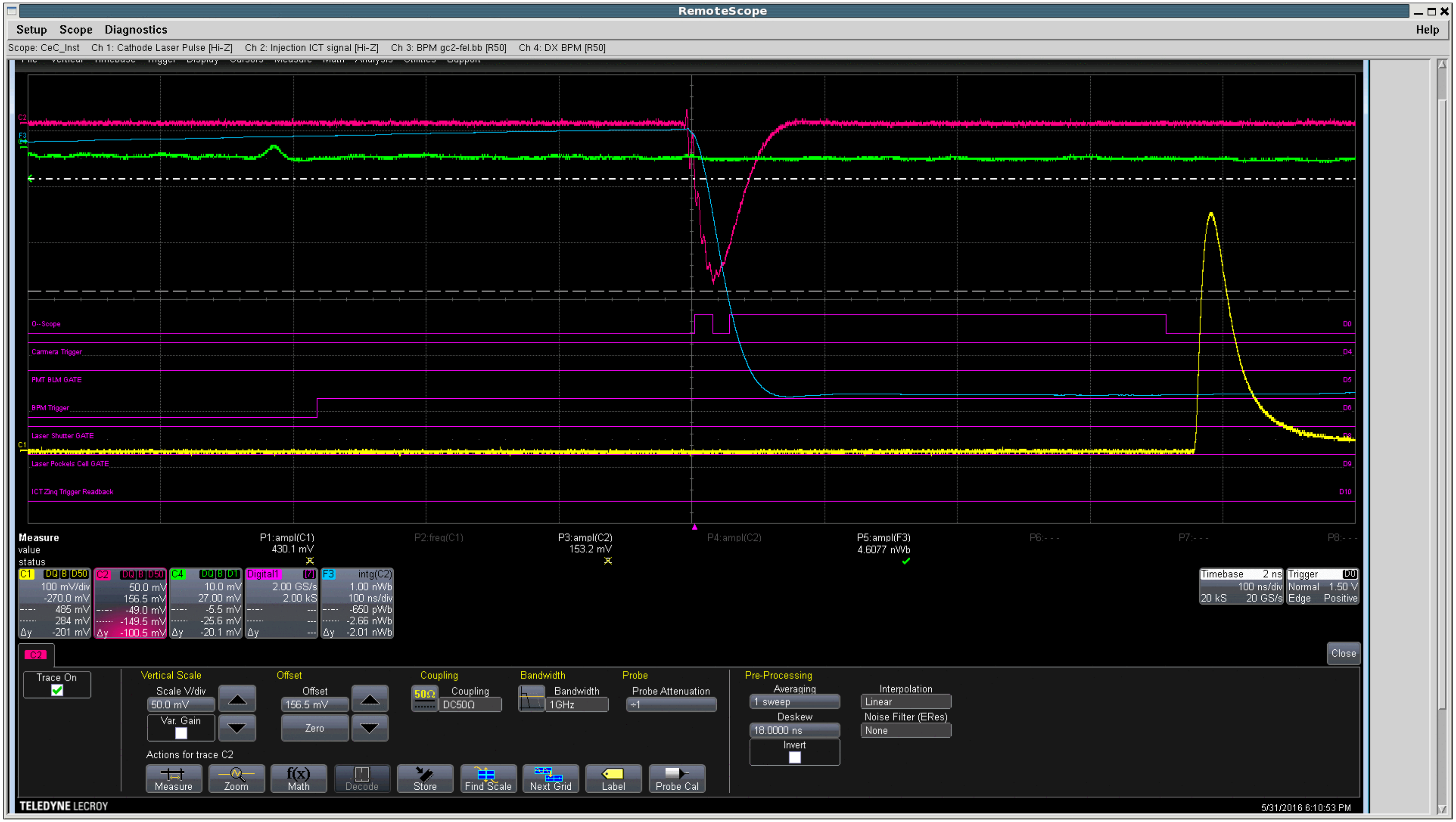


The span exceeds 180 degrees due to the long laser pulse (1 nsec). For the short pulses it is around 169 degrees.

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

3.7 nC Charge from the Gun

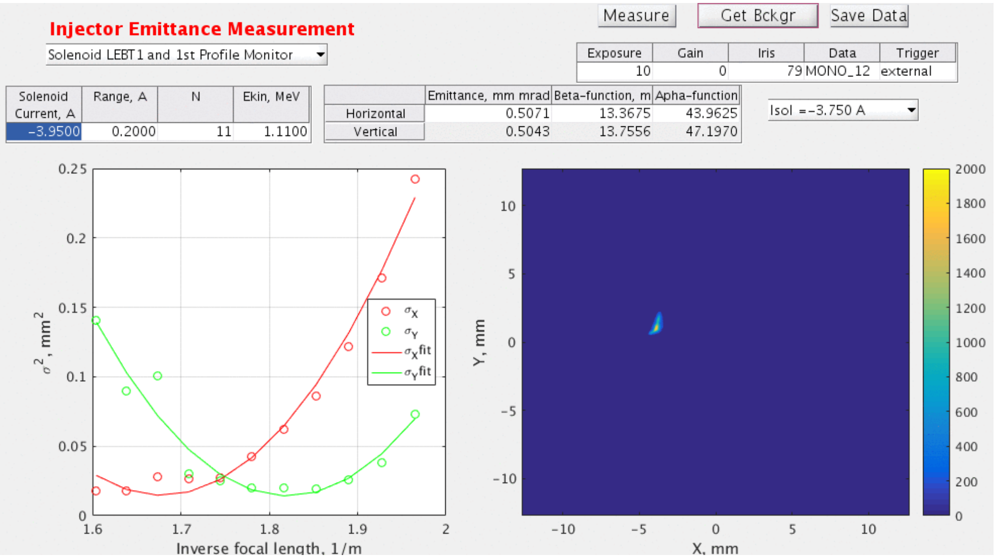


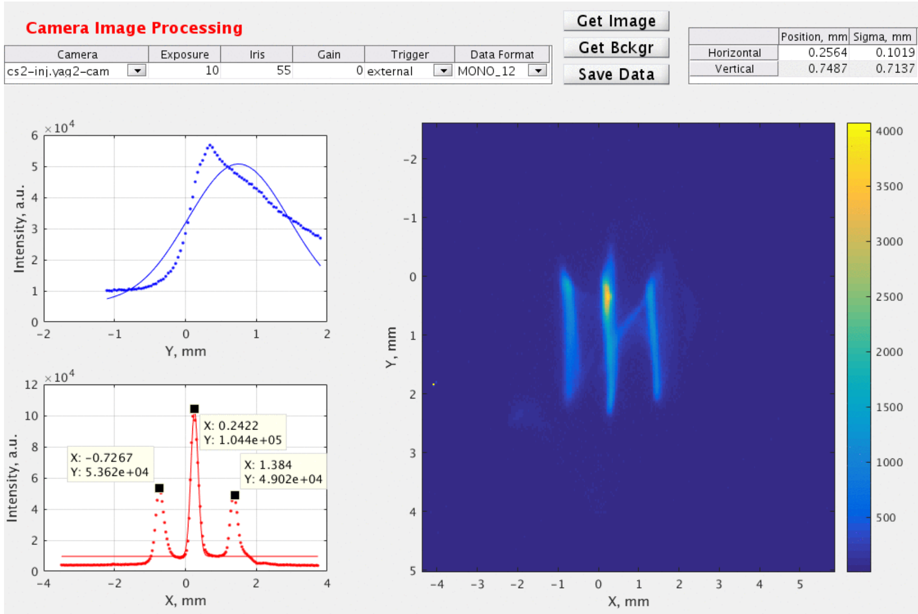
Demonstrated on May 31, 2016

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Emittance of 640 pC Beam





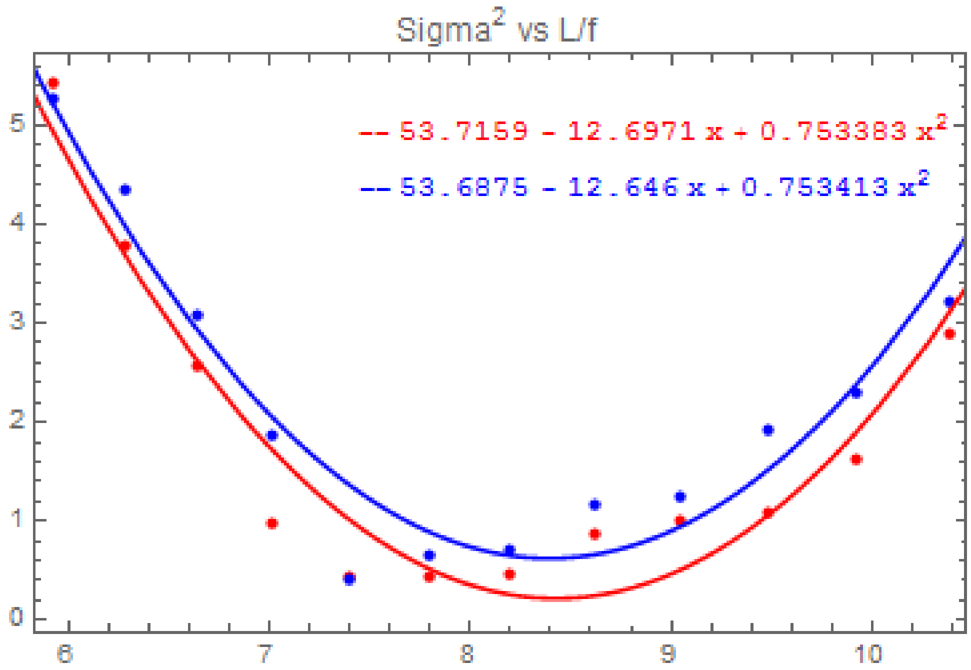
R.m.s. emittance of 0.5 mm mrad measured with solenoid scan

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

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics — Exploring Nuclear Matter - Quarks to Stars

Best Achieved Emittance



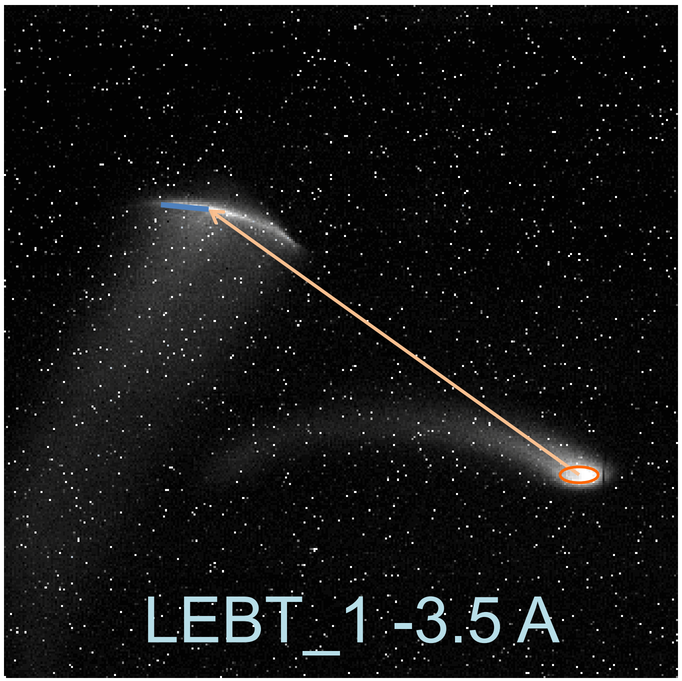
The beam size was measured on the first profile monitor with scan of the gun solenoid. Beam kinetic energy is 1.04 MeV, beam charge 0.5 nC. Normalized emittance is 0.32 mm mrad.

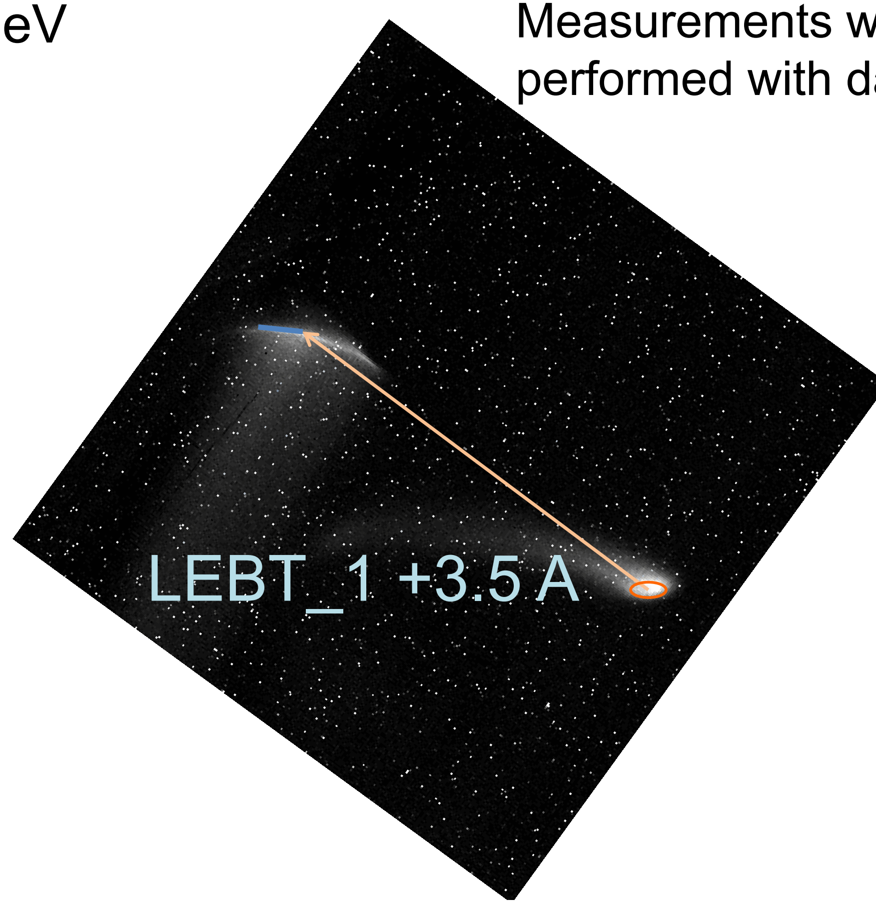
Presented at IPAC'17

Beam Energy Measurement

Rotation angle 54° - 1.19 MeV kinetic energy

Measurements were performed with dark current





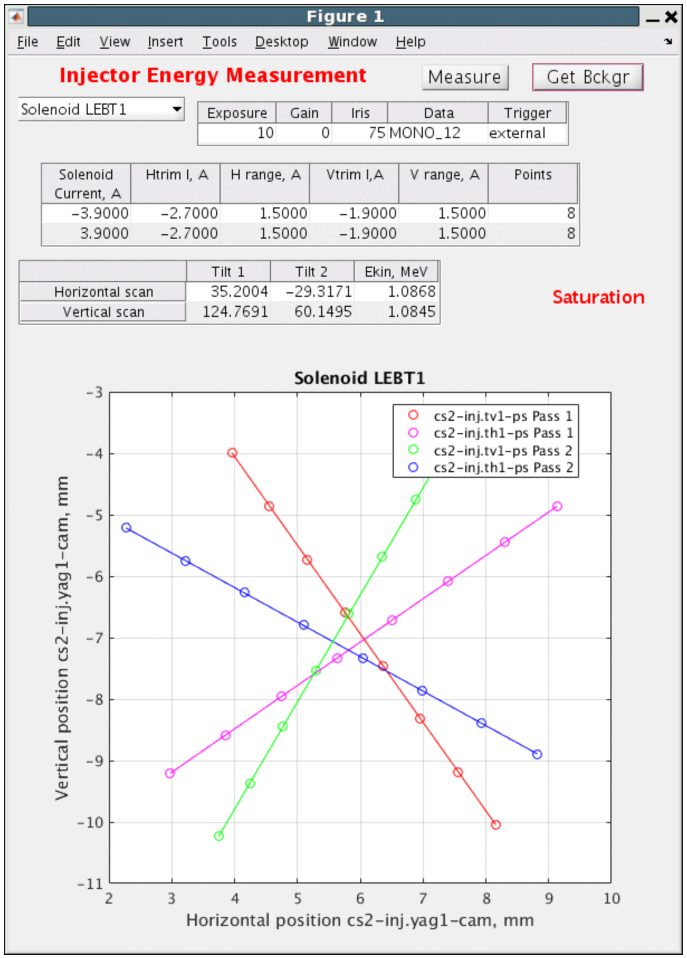
We utilized rotation of the electron beam by a calibrated solenoid to measure beam energy. The measured value was confirmed with energy spectrometer.

BROOKHAVEN NATIONAL LABORATORY

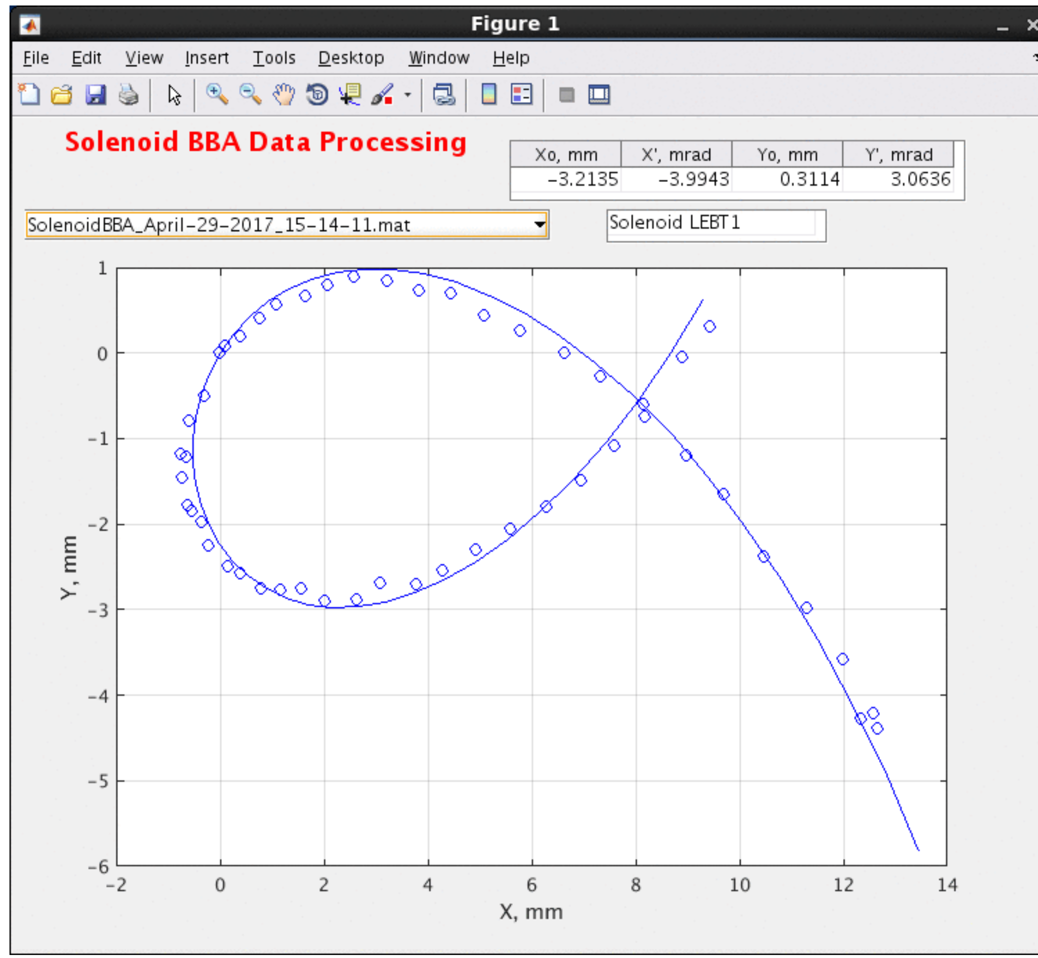
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Automated Measurement of the Beam Parameters with Solenoid

Beam Energy



Beam Trajectory

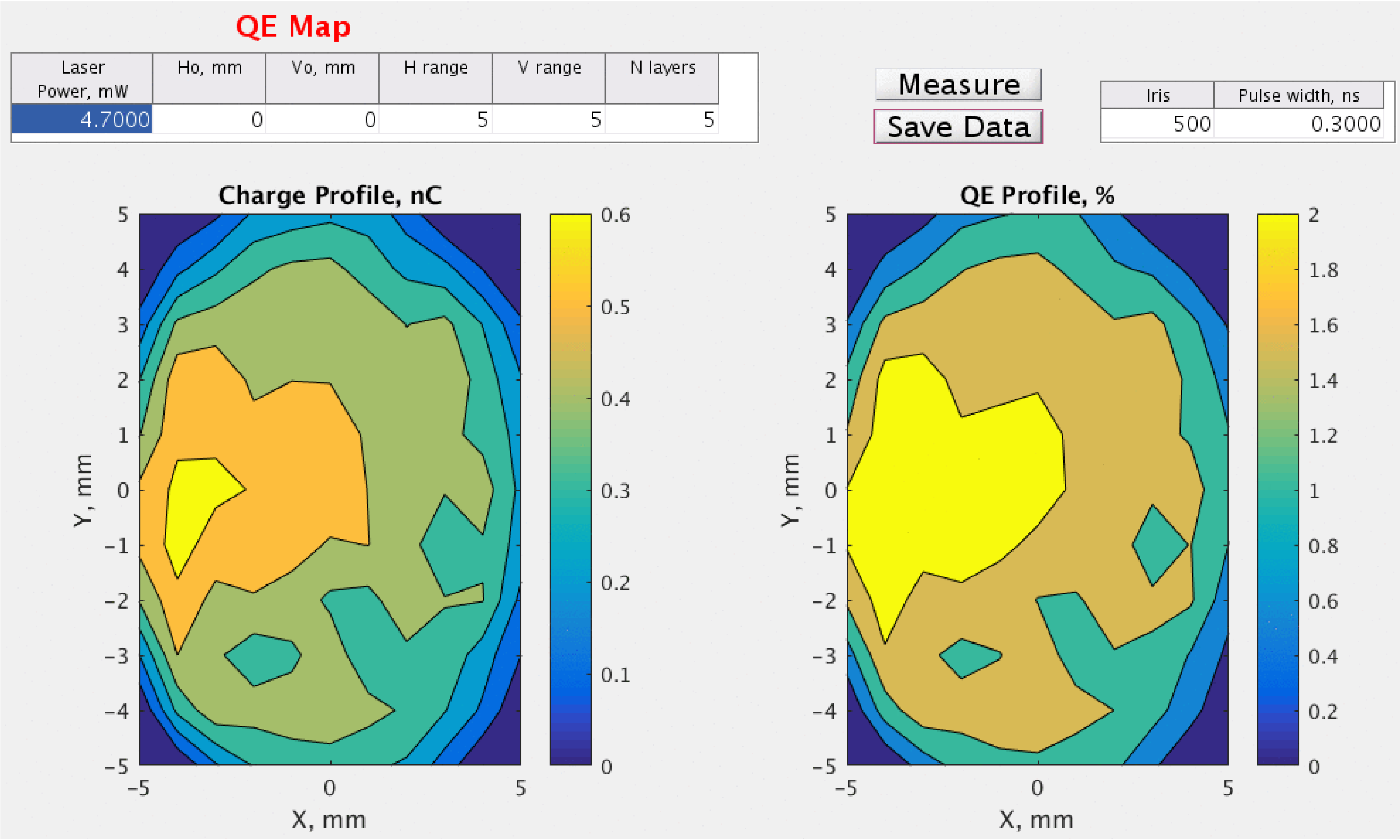


BROOKHAVEN NATIONAL LABORATORY

See IBIC'17 Proceedings

Office of Nuclear Physics

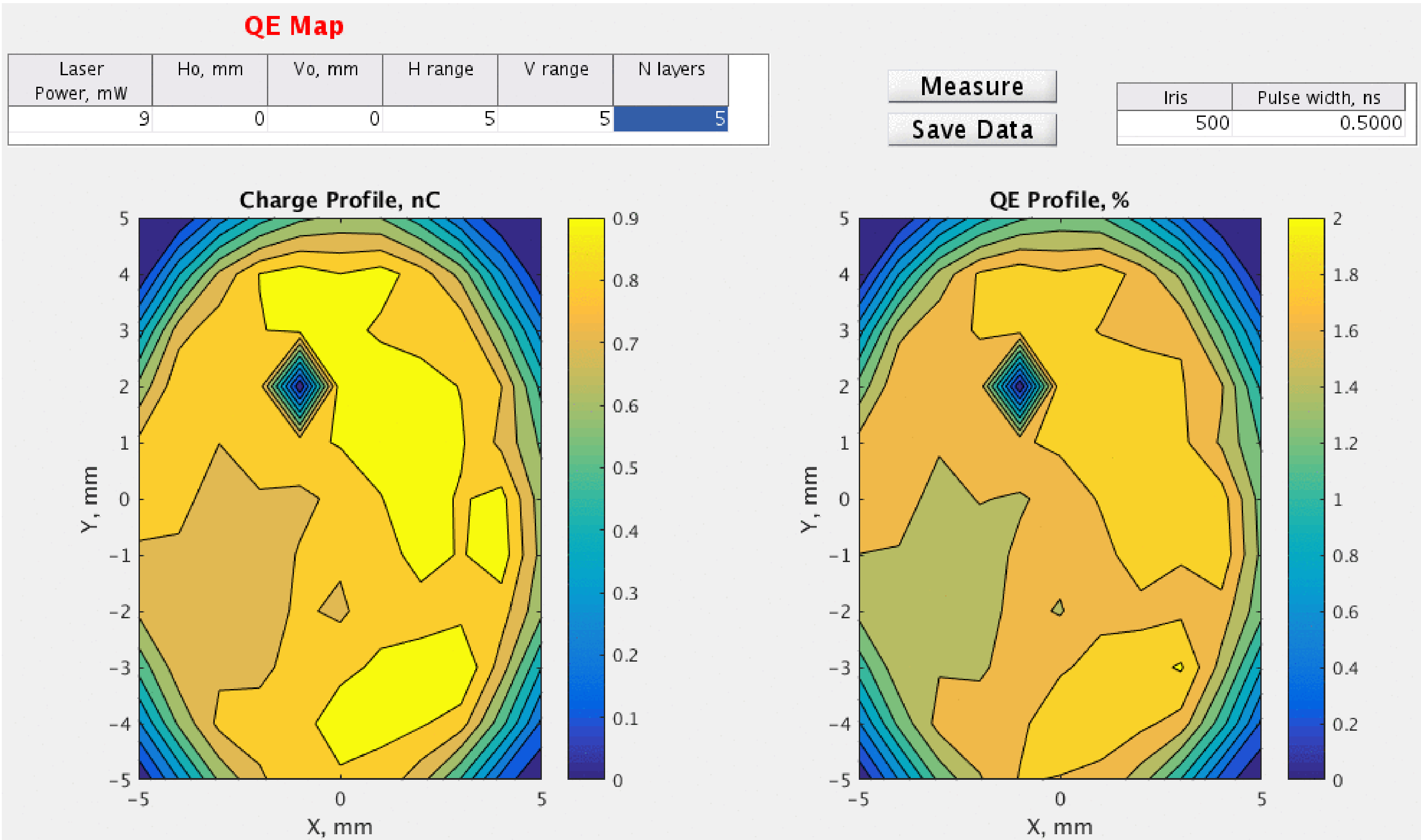
QE Map after Month of Operation



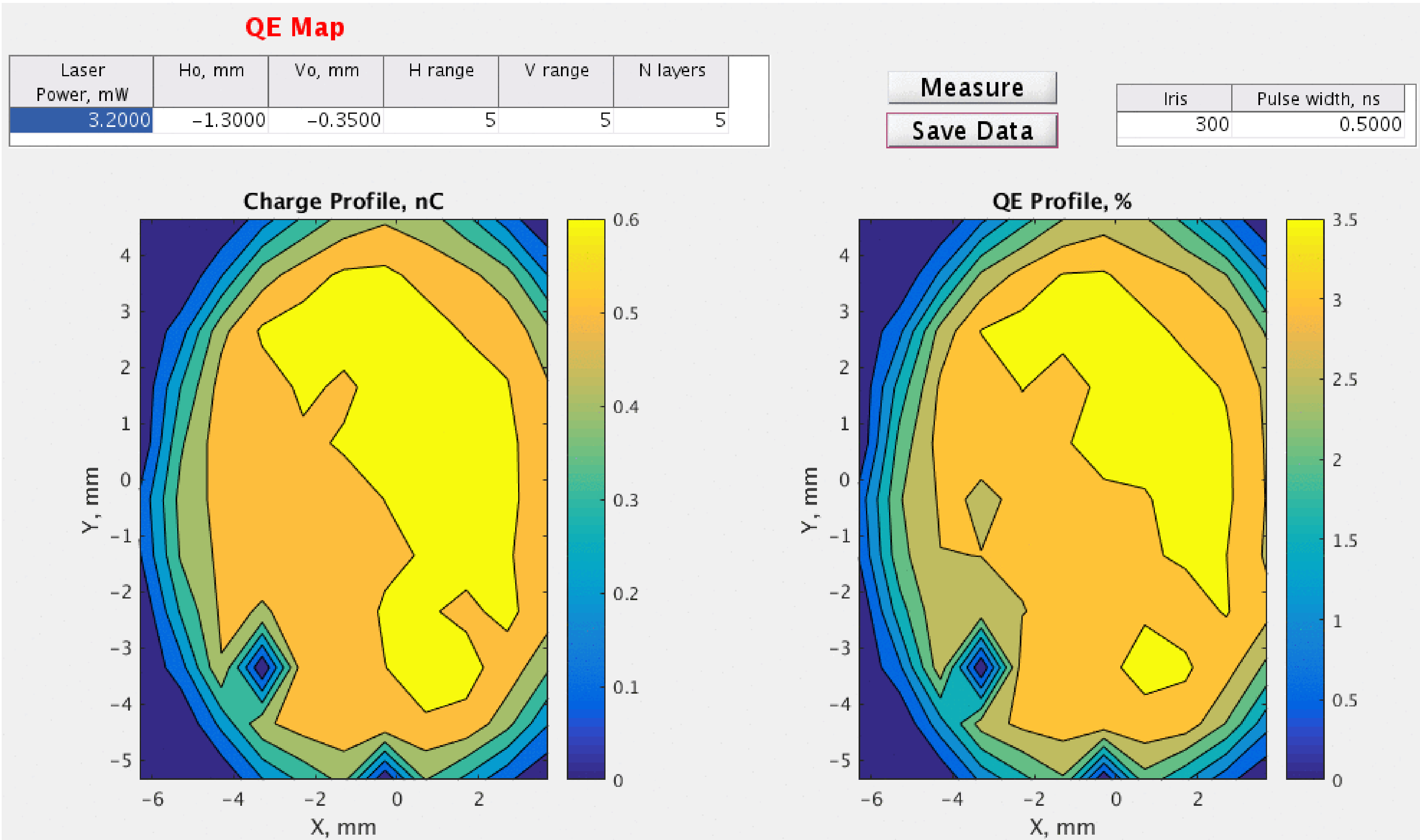
BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

QE Map after Cathode Change (June 7th)



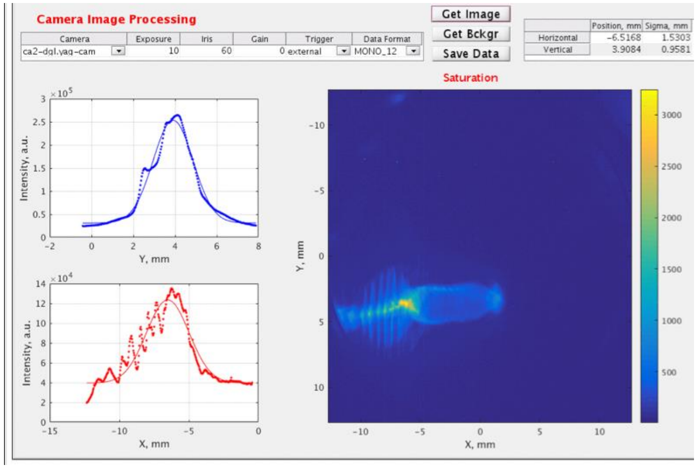
June 12



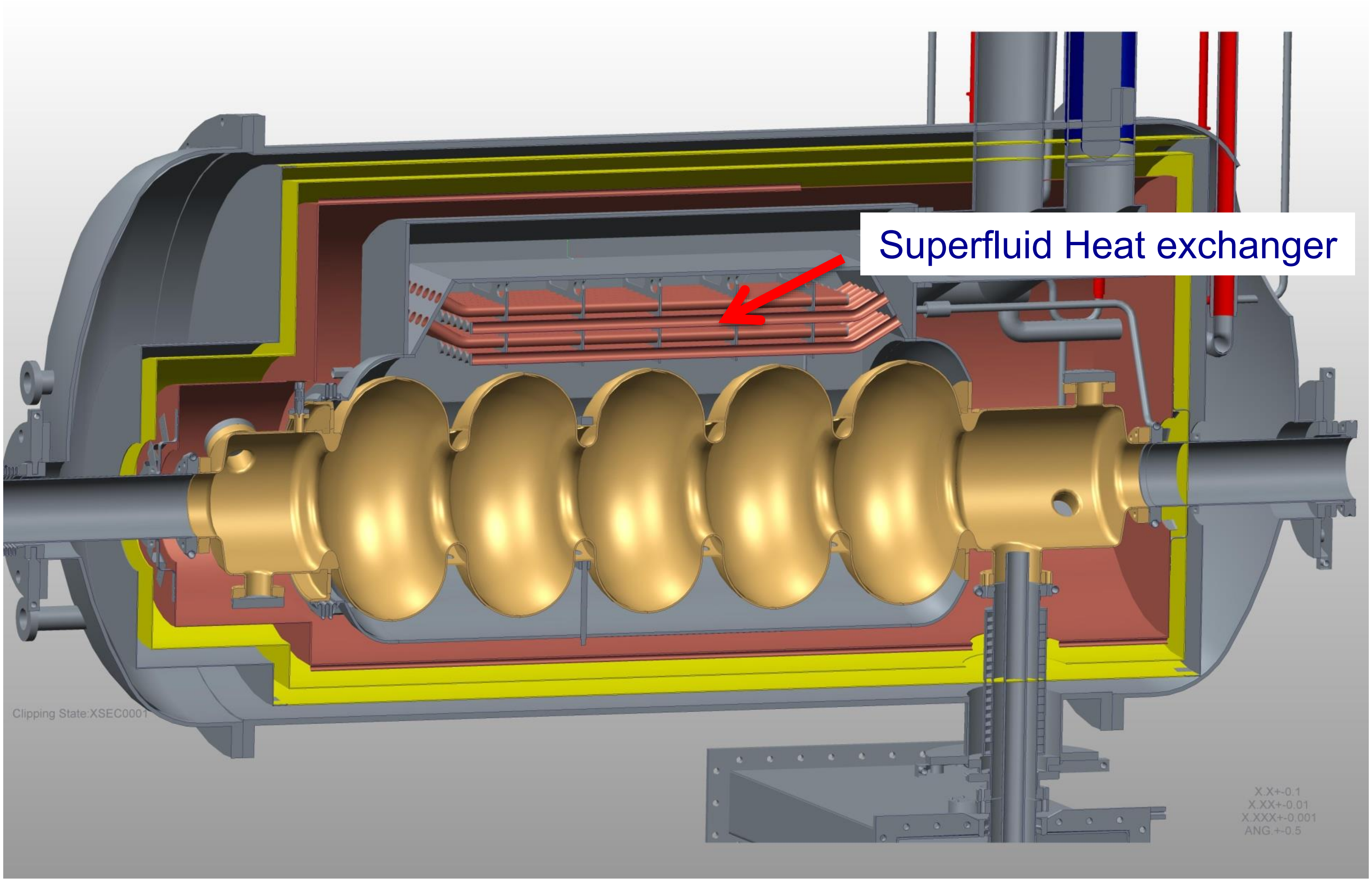
QE Map
Laser Power, mW
Ho, mm
Vo, mm
H range
V range
N layers
3.2000
-1.3000
-0.3500
5
5
5
Measure
Save Data
Iris
Pulse width, ns
300
0.5000
Charge Profile, nC
QE Profile, %
Y, mm
X, mm

Laser

- Initially we utilized fiber based NuPhotons 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
- Both issues are being addressed: we build new evacuated delivery beamline and replacing the power laser power amplifier.



Accelerator Cavity

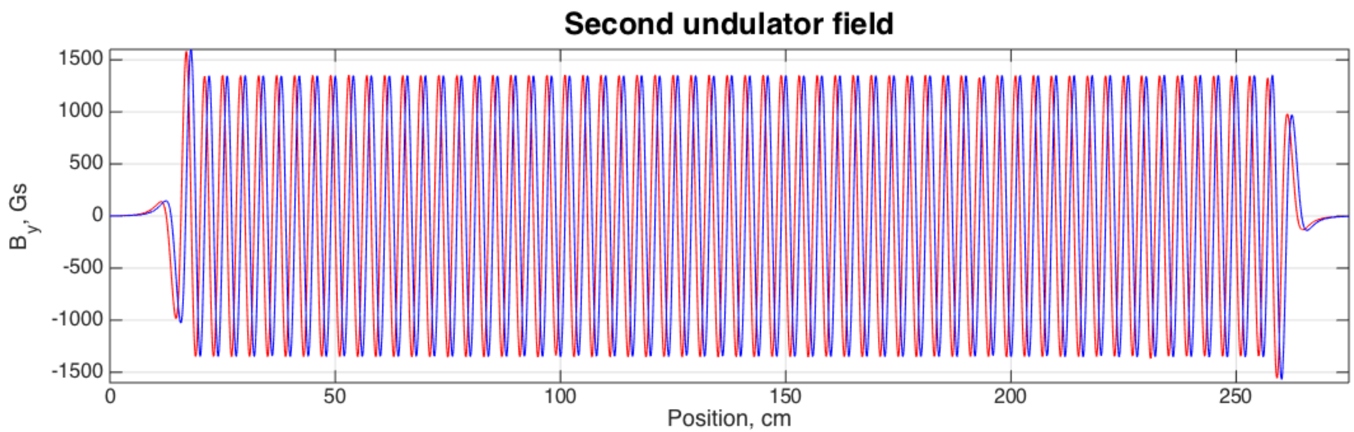


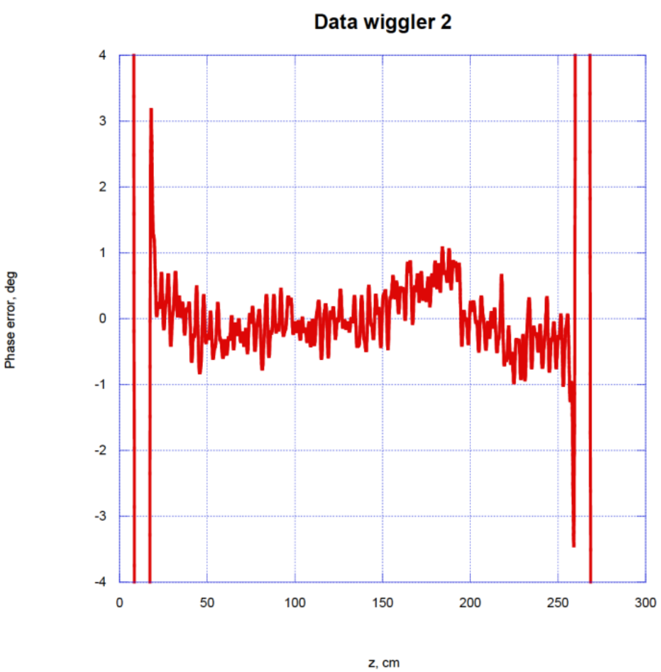
704 MHz 5-cell linac cryostat with superfluid heat exchanger: microphonics < 10 Hz p-to-p

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 3rd sub-harmonic of RHIC revolution frequency for 26.5 GeV/u , e.g. 26 kHz

FEL System





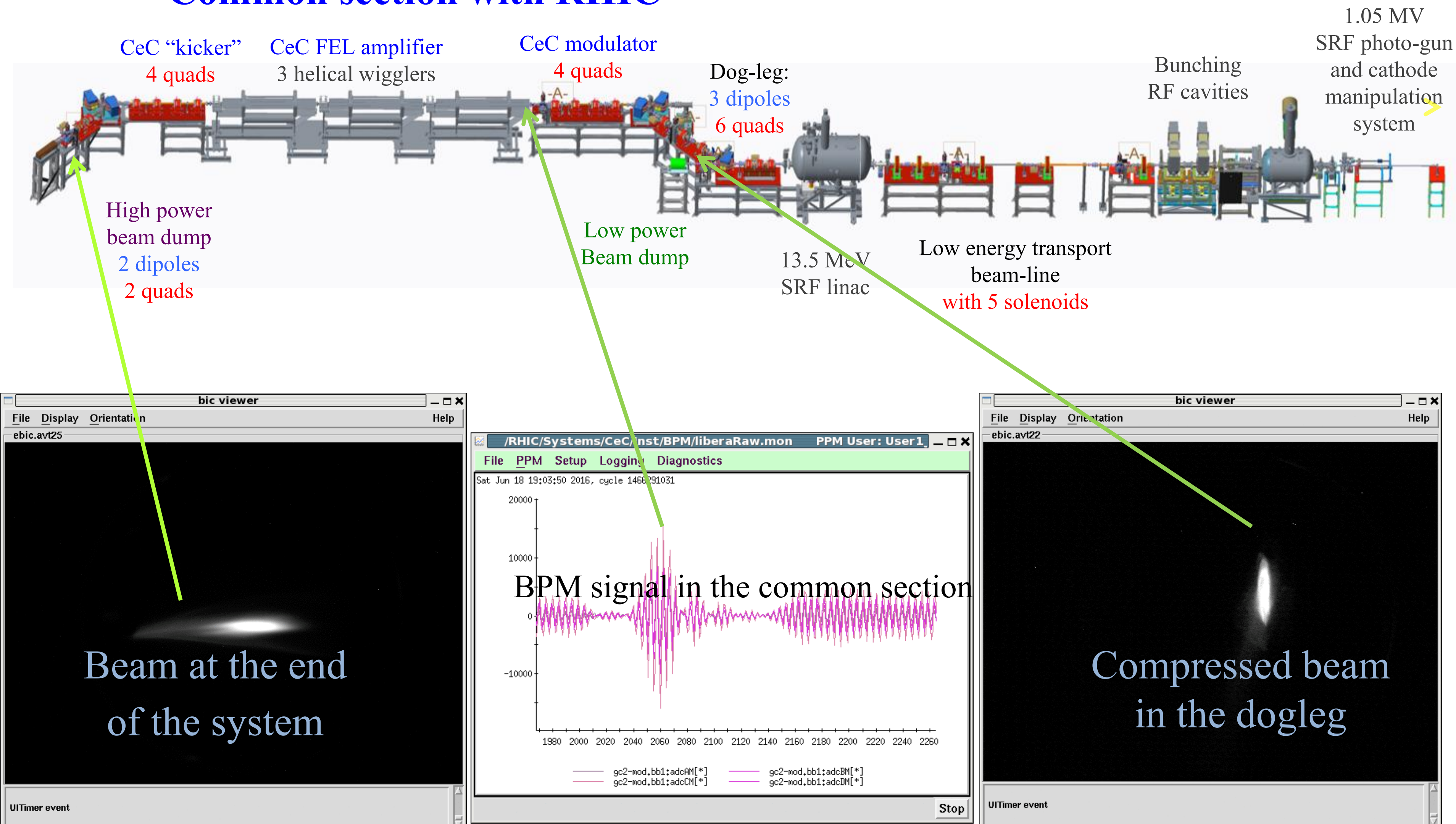
FEL system was supplied by BudkerINP from Novosibirsk and was finely tuned upon delivery. Recently we found that helicity of the third wiggler is wrong and corrected the error.

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

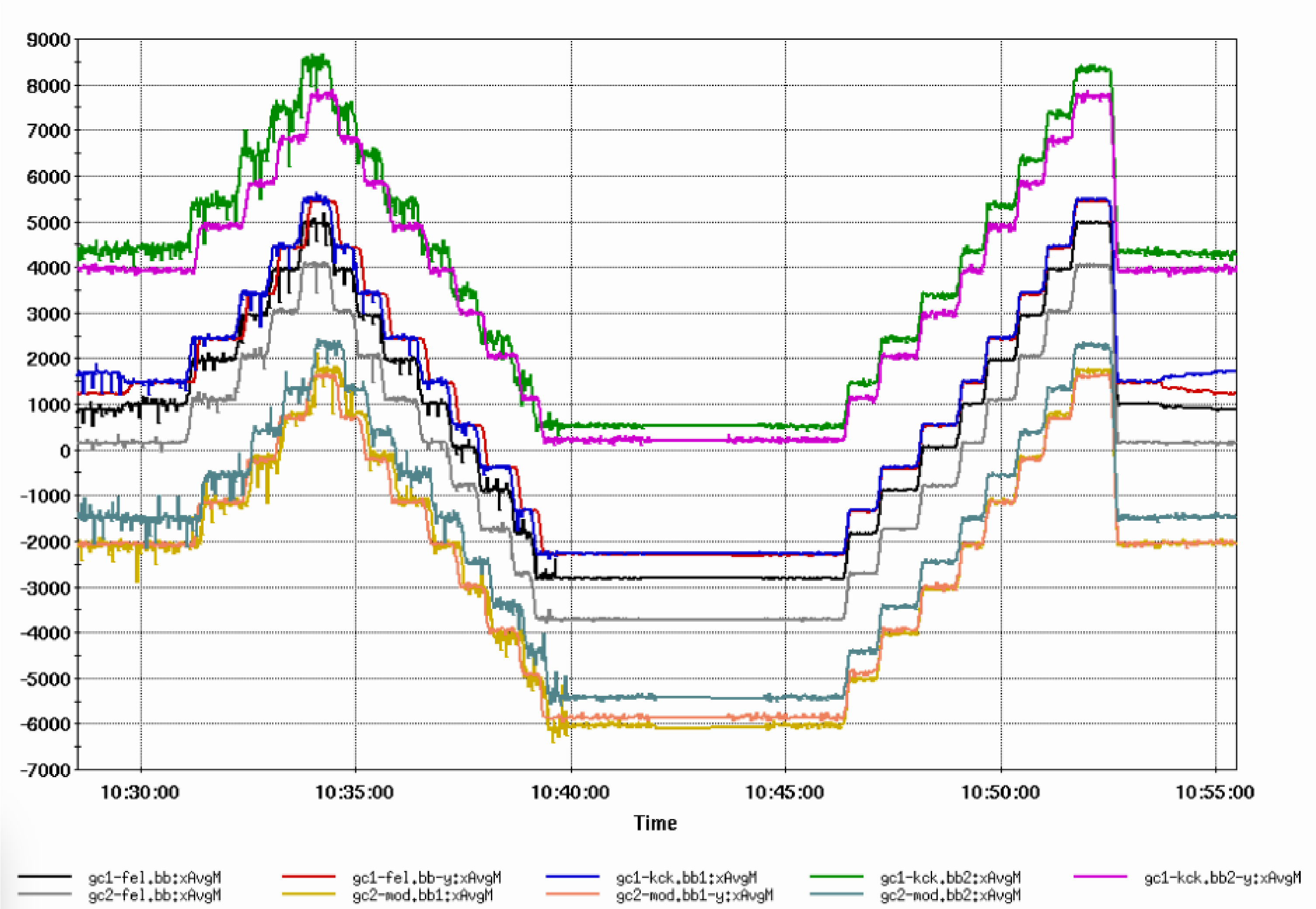
The CeC System Commissioning

Common section with RHIC



Electron beam was propagating inside 1μs abort gap

BPM Cross-Calibration

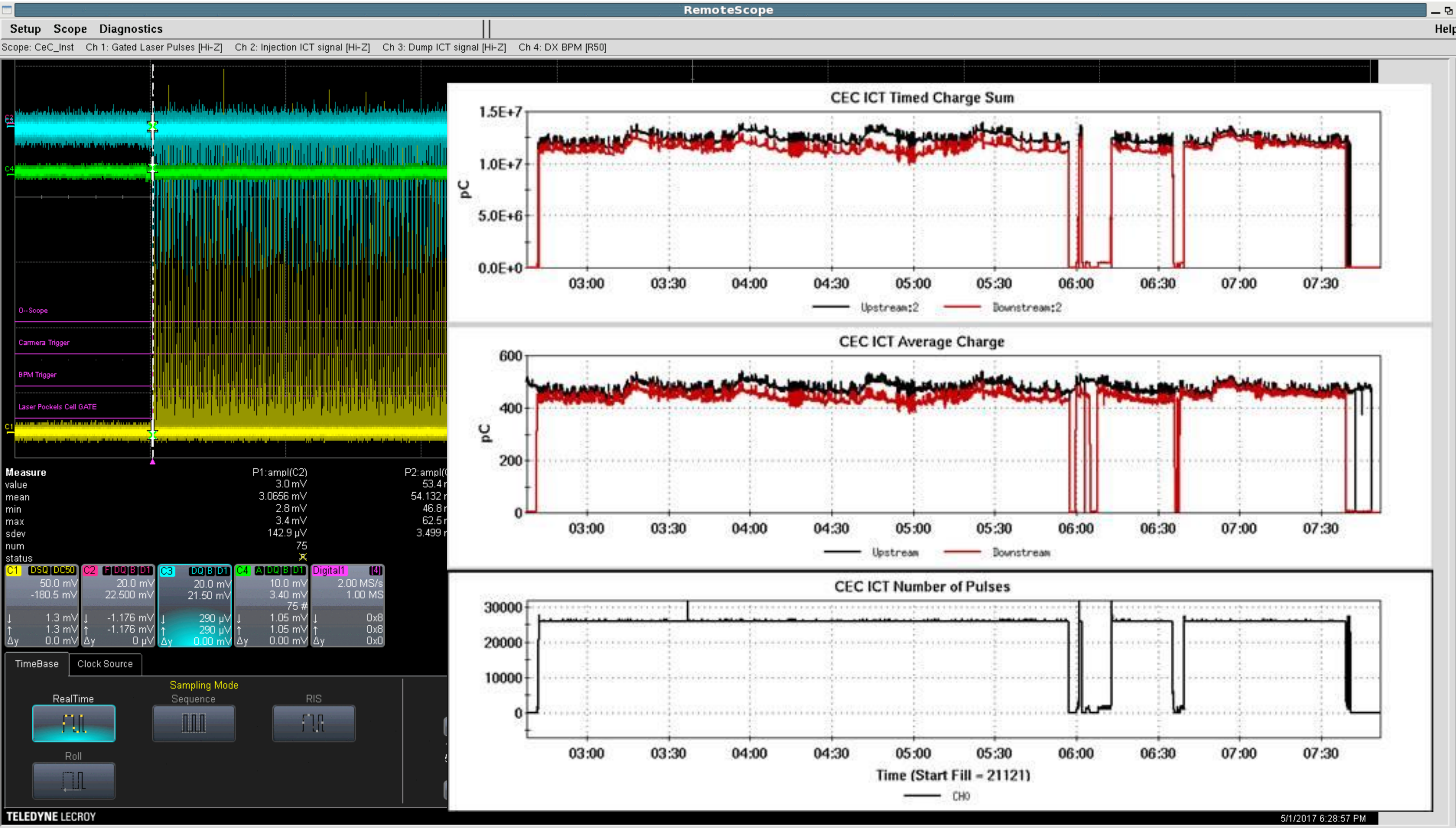


We have checked cross-calibration of the BPMs in the common section with a hadrons beam.

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Operating in CW Mode

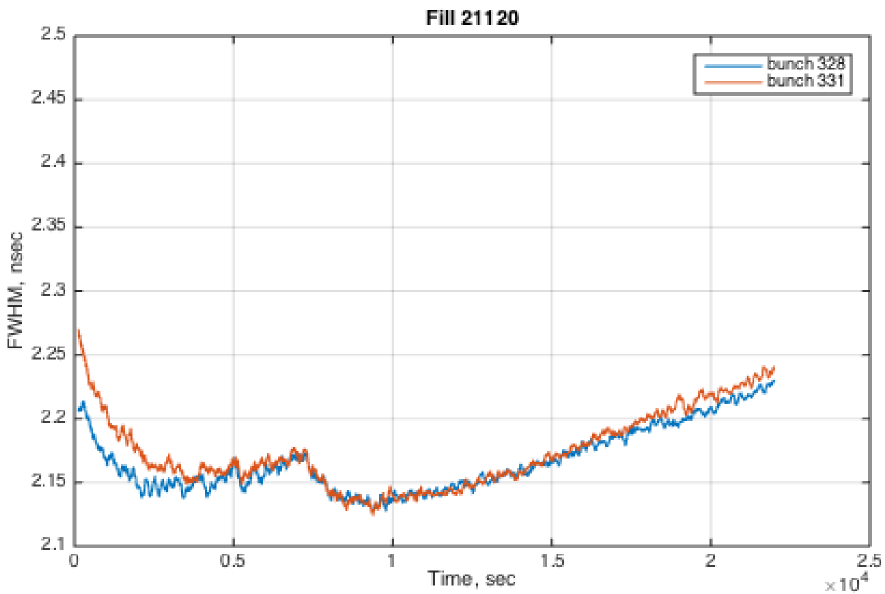


Interaction with Ion Bunches

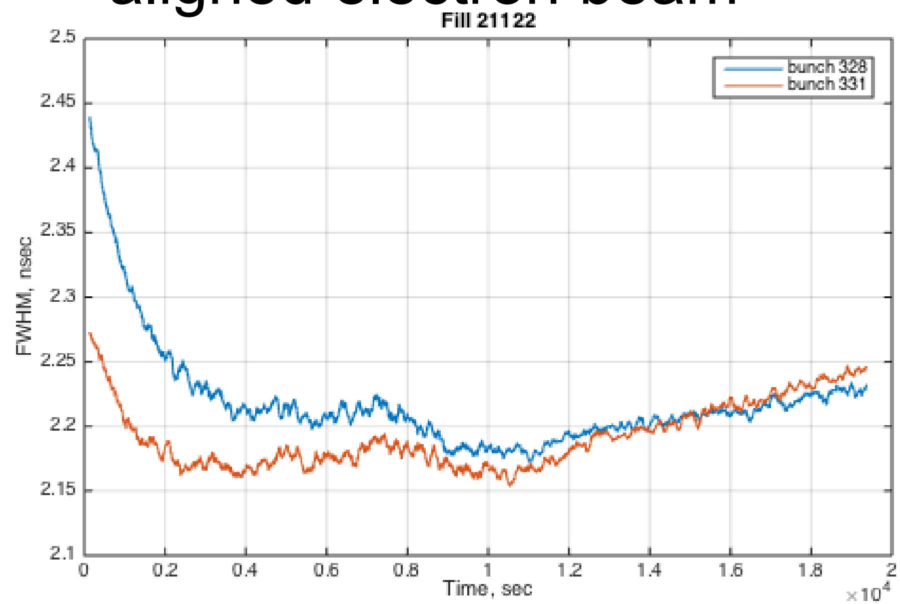
- We were operating in parallel with other RHIC experiment with low energy gold ions
- Two dedicated "CeC" ion bunches were operated in parallel with colliding RHIC bunches
- We synchronized hadron and the electron beam (26 kHz train of bunches, overlapping with ion bunch each 3rd turn – one of compromises we have to do during Run 17) with one of the bunches, while the second hadron bunch served as a reference
- We aligned the e-beam close to the IR2 axis
- 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 of the Electron and Hadron Beams

no electron beam



with synchronized and aligned electron beam



Data were processed with moving average (128 samples)

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Shutdown 2017 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

It takes the village… the CeC team