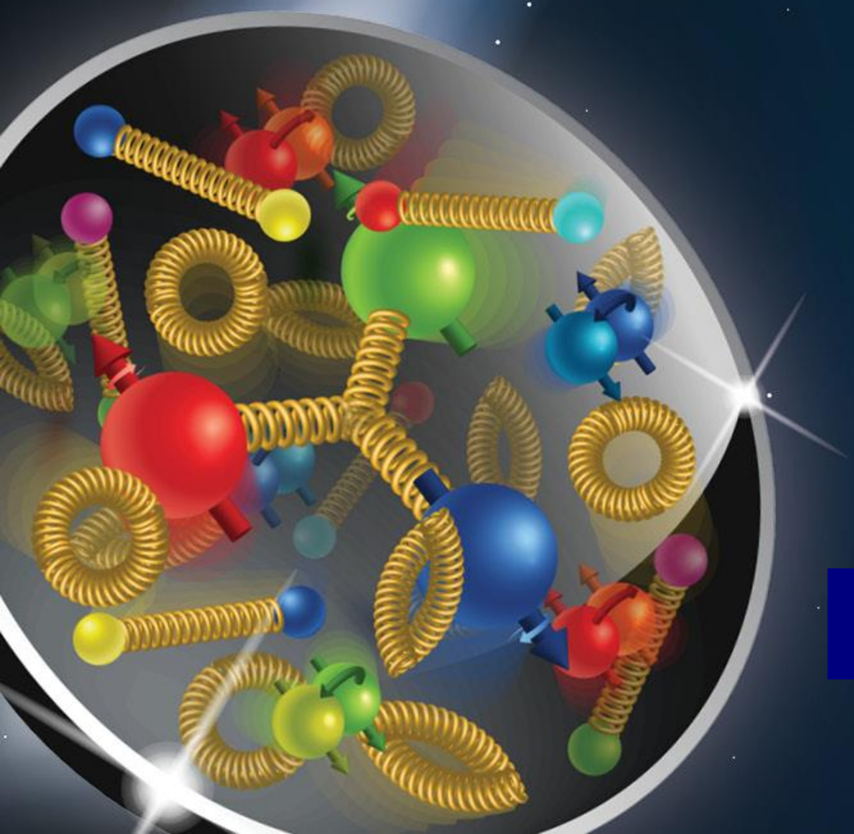
Center for Accelerator Science and Education

Coherent Electron Cooling Demonstration Experiment at RHIC

Vladimir N. Litvinenko - PI

Igor Pinayev – Project physicist

Joseph Tuozzolo – Project Engineer



Results of Run 17 and plans for Run 18

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Experimental Demonstration of Coherent Electron Cooling (CeC) at RHIC, DE-FOA-0000339

- Main goal: experimental demonstration of CeC and comparison with simulations
- FY2016 funds were received for commissioning of the CeC accelerator
- **Milestones**
  - **The CeC SRF accelerator is fully commissioned with beam energy of 15 MeV**
  - **We reliably propagated full power electron beam through the CeC system to the high power dump**
  - **Beam parameters sufficient for CeC demonstration experiment were established.**

	FY 2015	FY 2016	FY 2017
a) Funds allocated	670,000	425,000	0
b) Actual costs to date	670,000	425,000	0
c) Uncosted commitments	0	0	0
d) Uncommitted funds (d=a-b-c)	0	0	0

Summary of total expenditures:

ID #	Item/Task	Baseline Total Cost (AY$)	Costed (AY$)	Estimate To Complete (AY$)	Estimated Total Cost (AY$)
01435	Coherent Electron Cooling R&D	7,595,745	5,523,000	2,072,744	7,595,745
Totals:		7,595,745	5,523,000	2,072,744	7,595,745

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics

Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

Technologies and/or design concepts that address technical risks common to all concepts that must be demonstrated

- Crab cavity operation in a hadron ring
- Strong hadron cooling
- Validation of magnet designs associated with high-acceptance interaction points by prototyping
- ***High-current single-pass ERL for hadron cooling***
- ***Benchmarking of realistic EIC simulation tools against available data***
- ***Polarized ^{3}He source***

Specific R&D activities for the BNL Linac-Ring Concept

- High current polarized and unpolarized electron sources
- CeC proof of principle
- SRF high power HOM damping
- ***High-current multi-pass ERL***
- ***Concept for 3D hadron CeC beyond proof of principle***

BNL priority: 2-high

Specific R&D activities for the BNL Ring-Ring Concept

- Complete the design of an electron lattice with a good dynamic aperture and a ***synchronization scheme and complete a comprehensive instability threshold study for this design***
- Necessity to triple the number of and shorten bunches in the proton/ion ring
- Beam pipe copper coating with plasma ion bombardment
- ***High peak current multi-turn linac***
- ***Simulate the effect of electron bunch removal on the hadron beam***

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

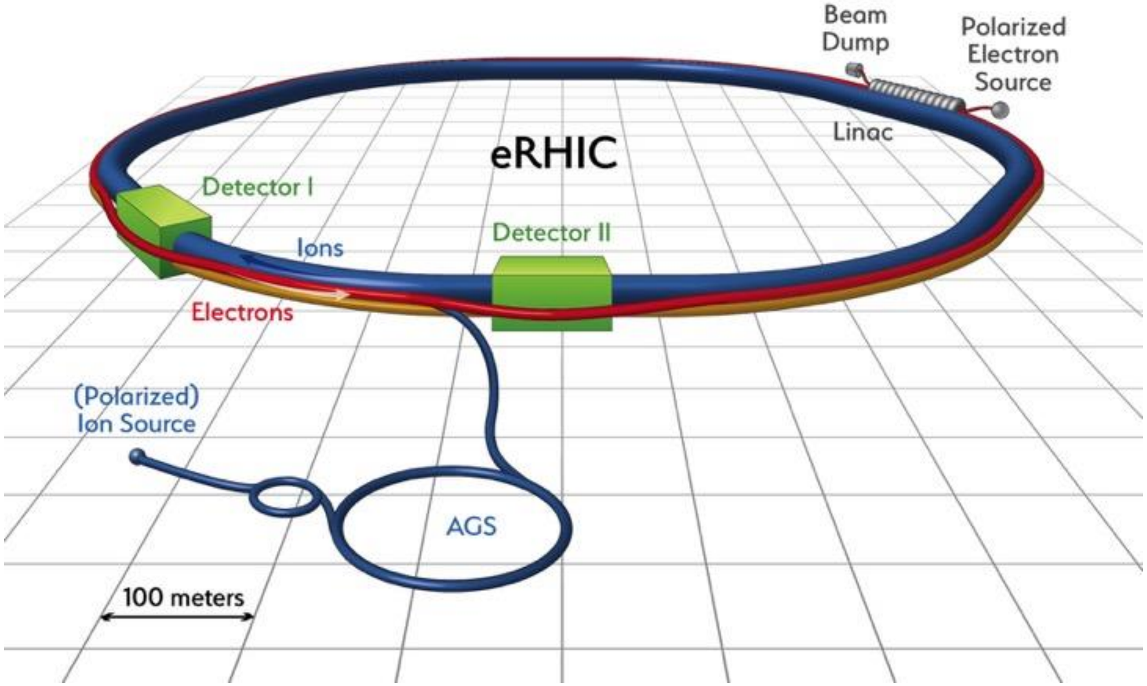
Expected deliveries if all goes well (it is R&D after all!):

- ◆ **predicted performance of CeC**
- ◆ **experimental demonstration of CeC**
- ◆ **comparison with predictions**

Content

- Why we doing it?
- Run 17
  - Main achievements
  - What worked and what did not?
- Plan for Run 18
  - Shutdown jobs
  - Plan for demonstrating CeC

MOTIVATION: HIGH ENERGY HIGH LUMINOSITY EIC REQUIRES STRONG HADRON COOLING



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

remove

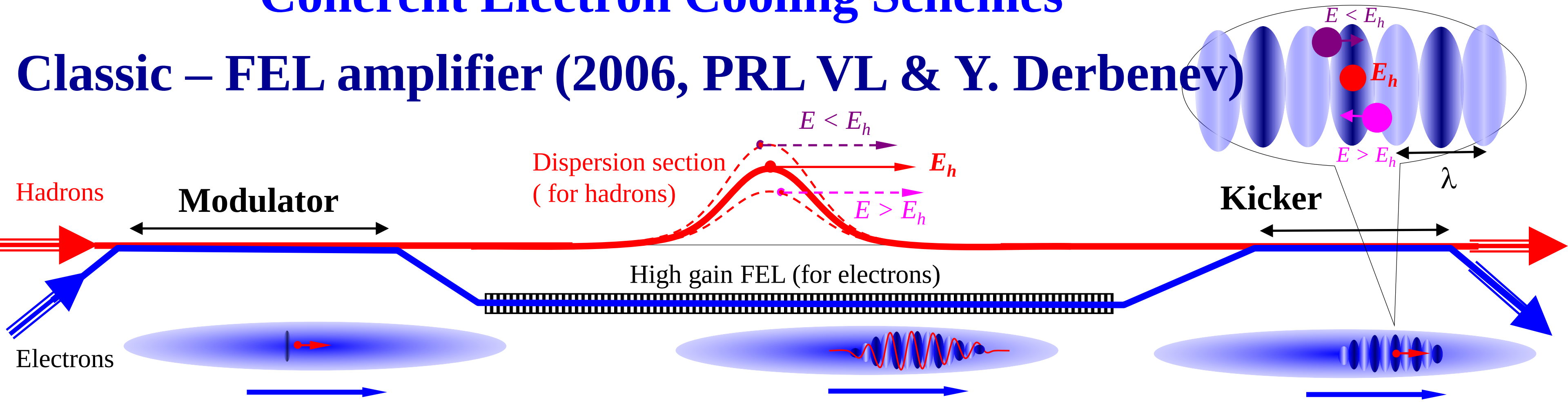
Why we are doing this

- Short term: Any high luminosity EIC requires strong hadron cooling and CeC is very likely the most promissing technique to achieve this
- Linac-ring EIC: If CeC is successful and is fully operational, eRHIC LR could reach 2×10^{33} luminosity with 5 mA polarized electron current.
- It removes main uncertainties in LR 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

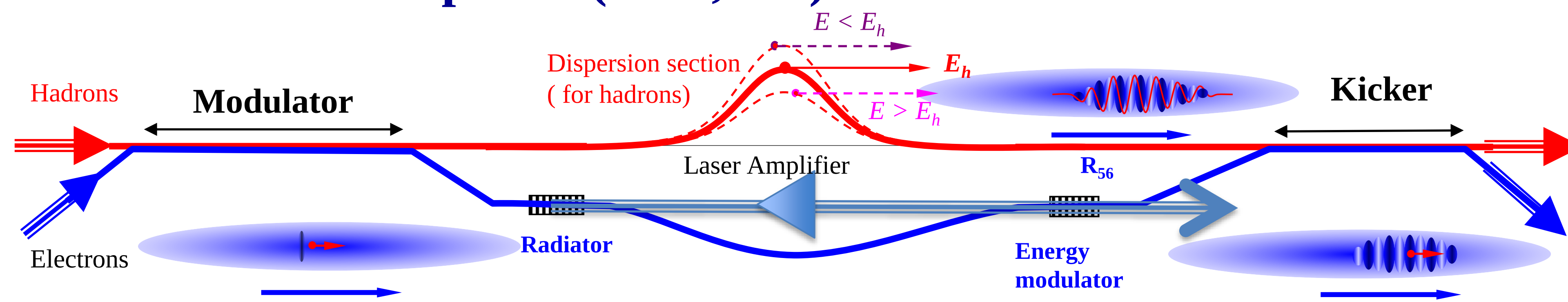
- Final goal: eRHIC/EIC with 10^{34}-10^{35} luminosity

Coherent Electron Cooling Schemes

Classic – FEL amplifier (2006, PRL VL & Y. Derbenev)

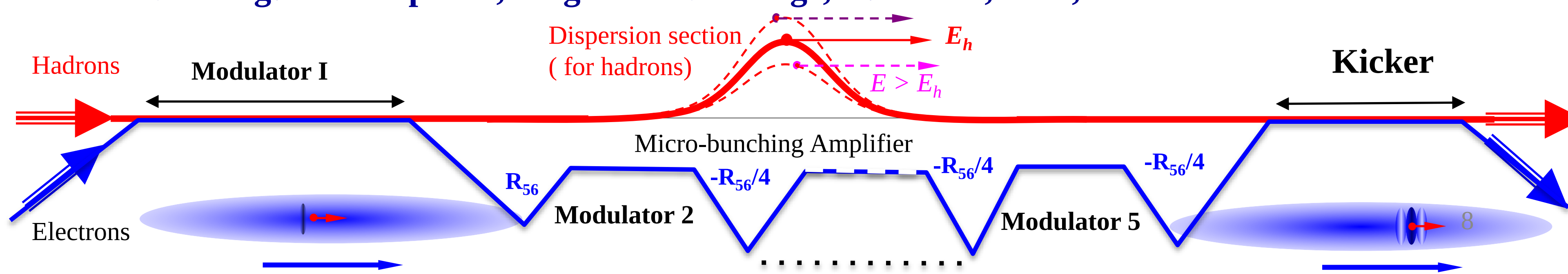


Blended – laser amplifier (2007, VL)

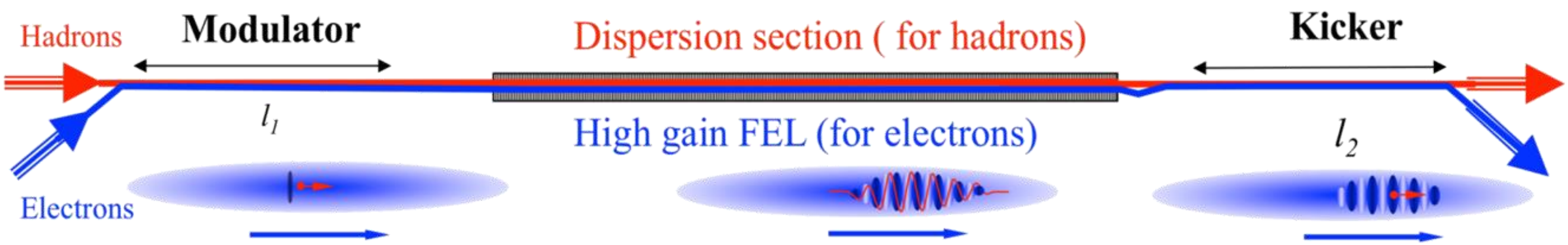


Enhanced bunching: single stage - VL, FEL 2007

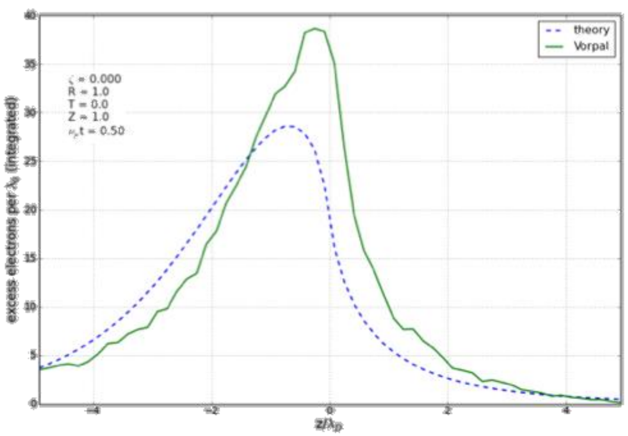
Micro-bunching: MB Amplifier, Single & Multi-stage, D. Ratner, PRL, 2013



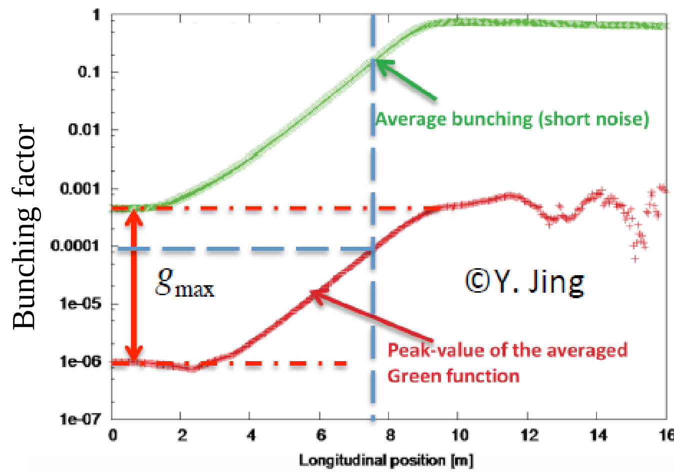
Our Proof-of-Principle is an economic version of CeC, where electrons and hadrons are co-propagating along the entire CeC system



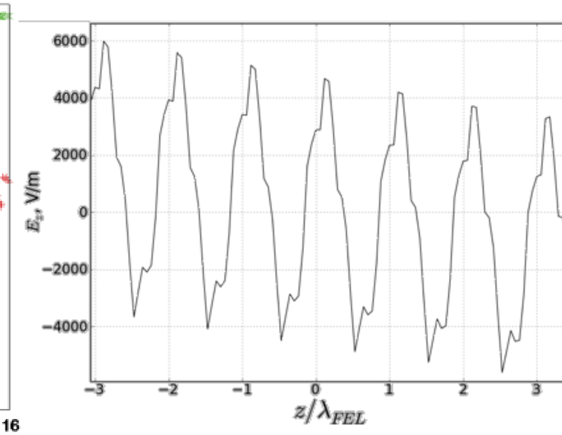
Param.' s from 40 GeV proof-of-principle exp. at BNL



VORPAL 3D δf PIC computation of e-density perturbation near Au^{+79} ion (green) vs. idealized theory (blue). On Cray XE6 cluster at NERSC.



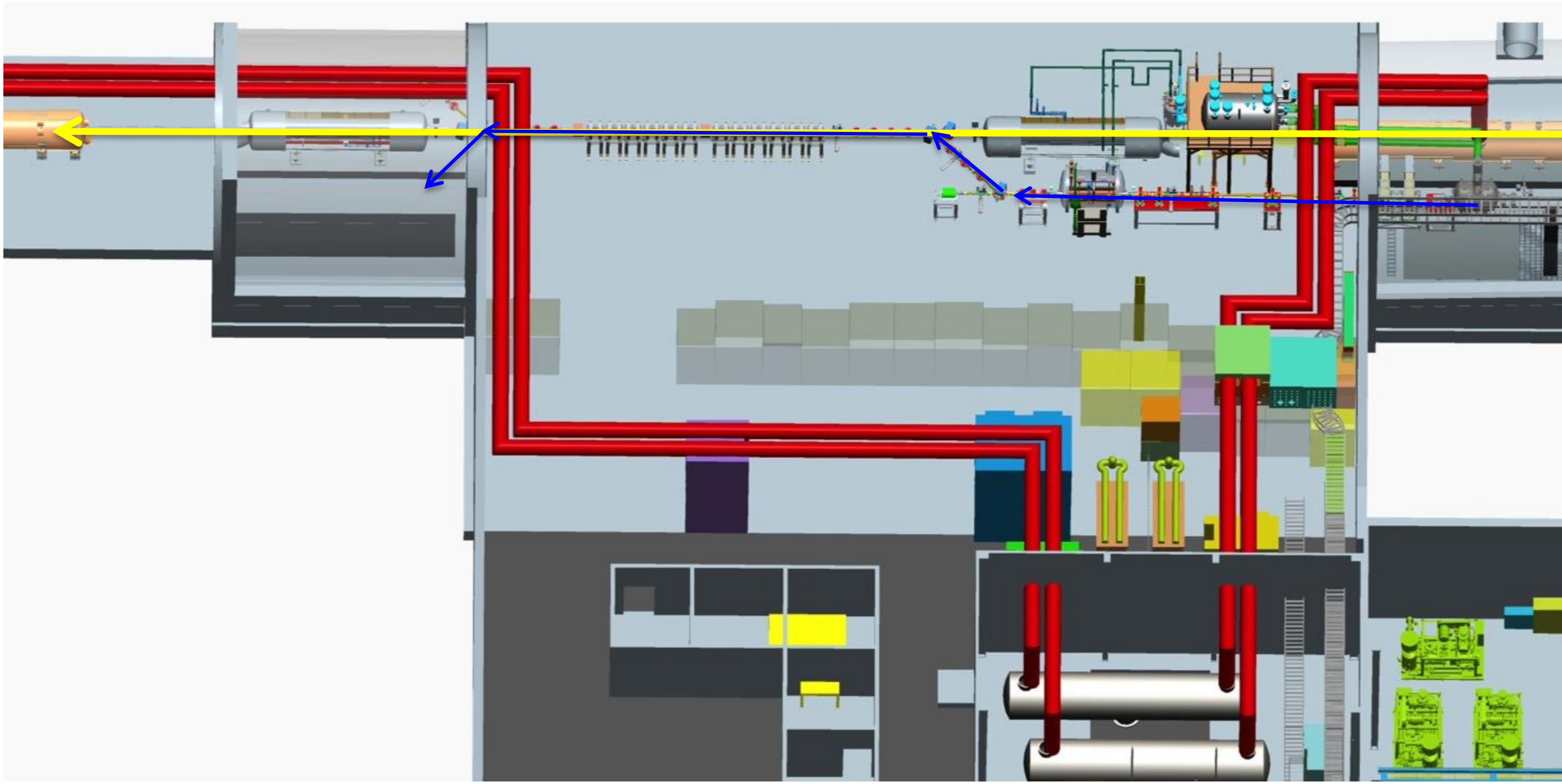
GENESIS parallel computation of electron beam bunching in free electron laser (FEL) shows amplification of modulator signal.



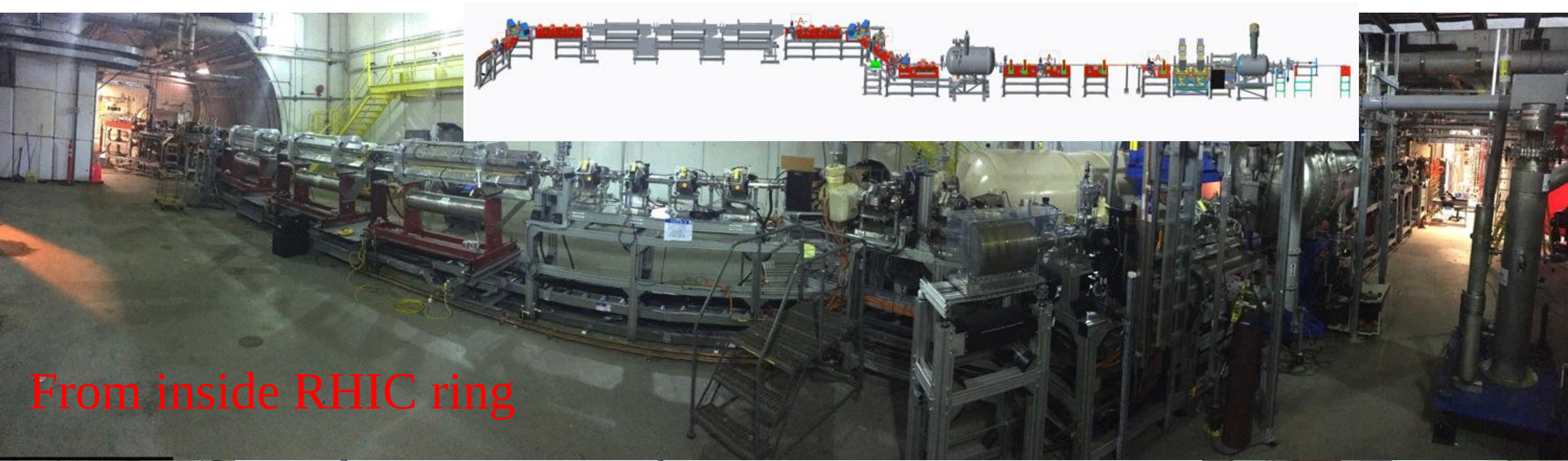
VORPAL prediction of the coherent kicker electric field E_k due to e-density perturbation from modulator, amplified in the FEL.

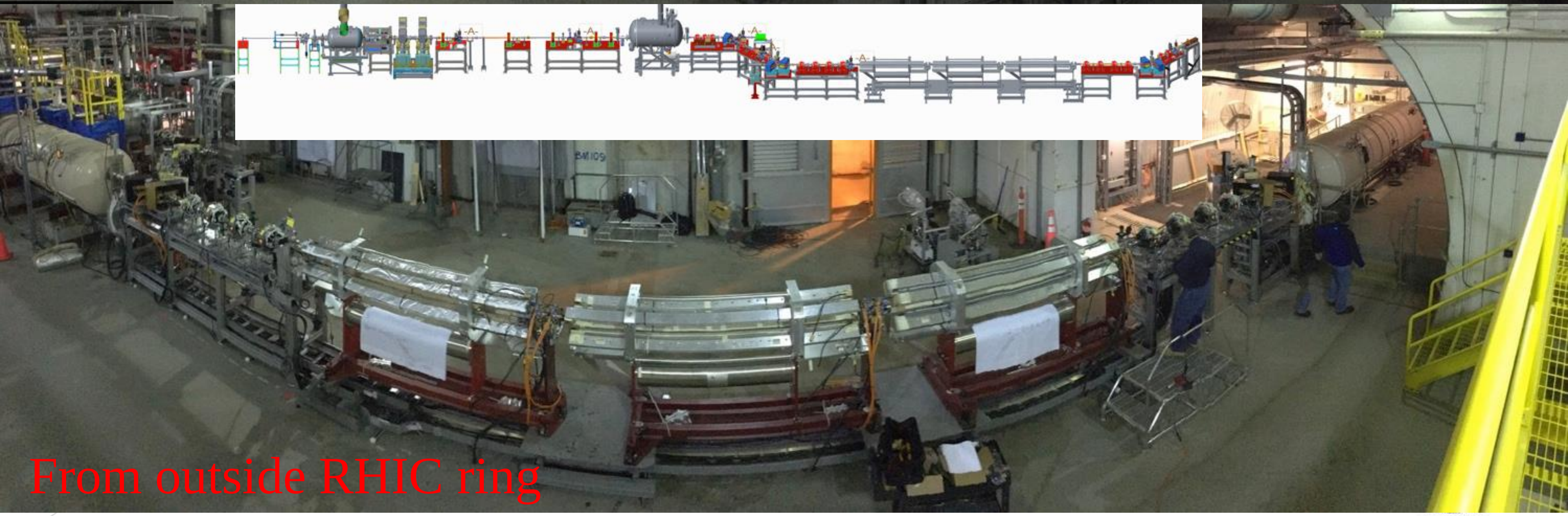
Simulations by Tech-X and Y. Jing

Test: Coherent electron Cooling (CeC) Demonstration Experiment

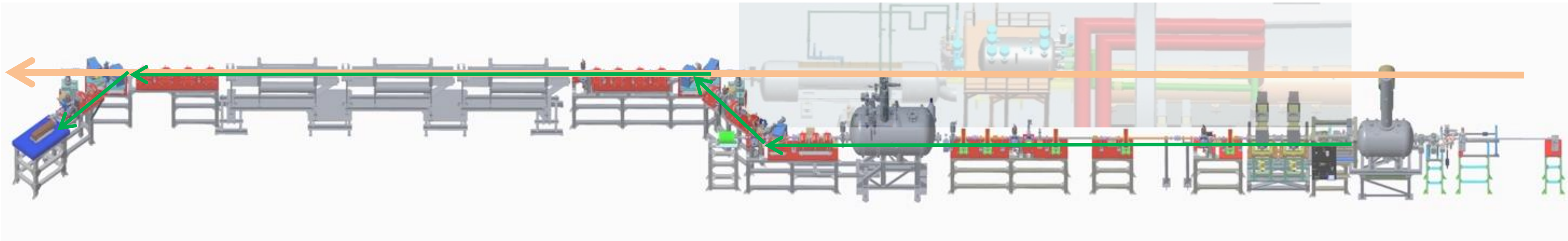


Panoramic Views





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.

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

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.

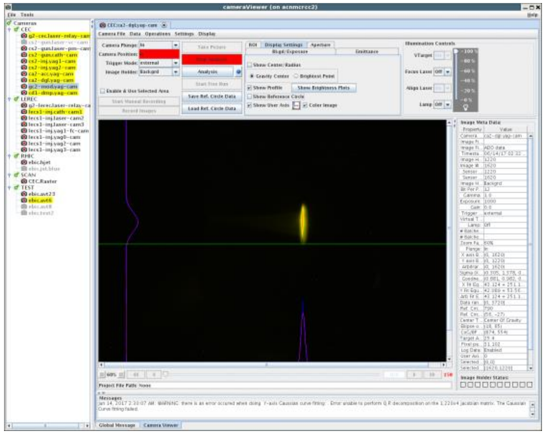
BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics

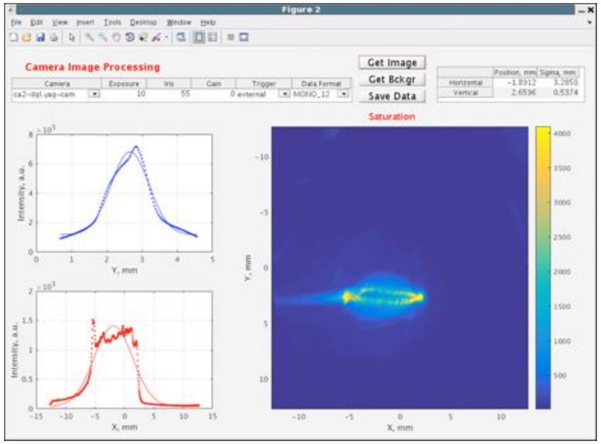
Main Advances

- 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

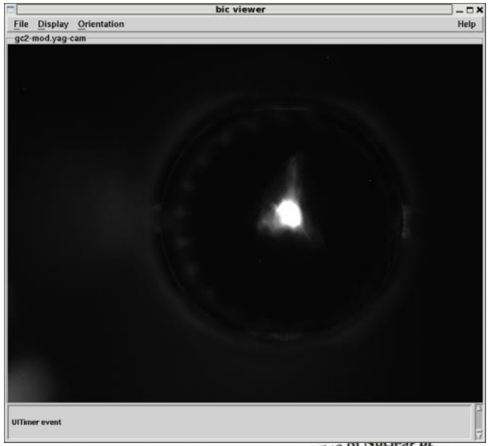
Sub 0.1% energy spread



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	78/26 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*

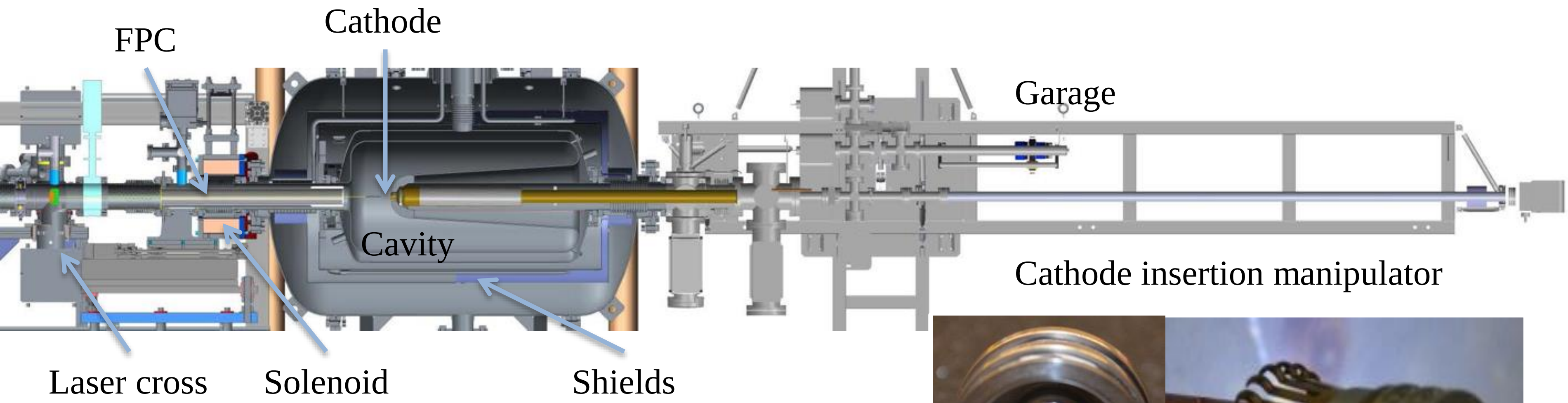
Beam parameters are sufficient for the CeC demonstration experiment

Beam Diagnostics

- Eleven electron beam position monitors (500 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)

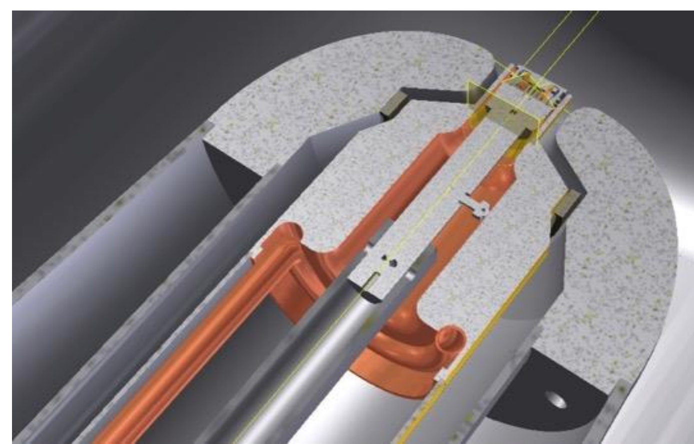
The set of diagnostics is minimal but sufficient for experiment.

CeC SRF Gun



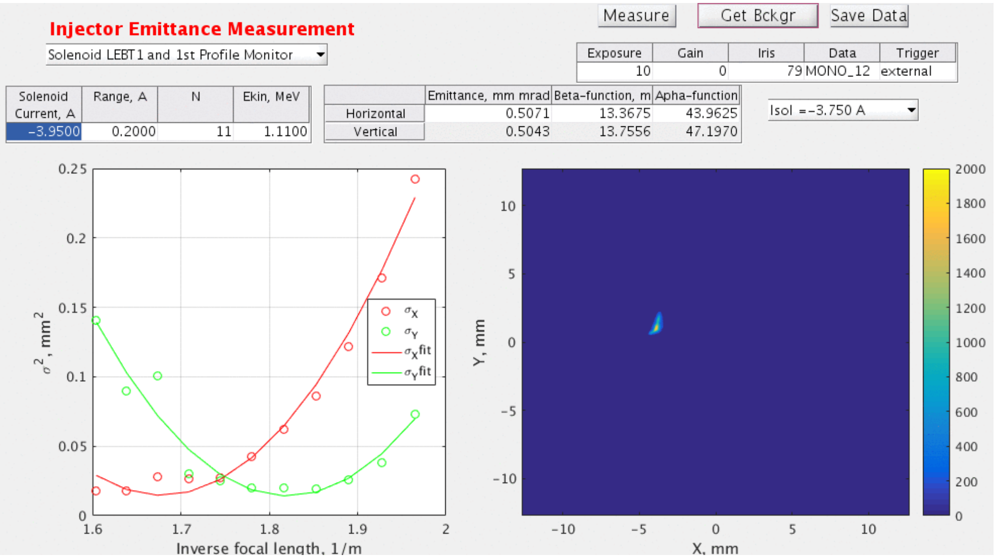
- Quarter-wave cavity
- 4 K operating temperature
- Manual coarse tuner
- Fine tuning is performed with FPC
- 4 kW CW solid state power amplifier
- CsK_2Sb Cathode is at room temperature
- Cavity field pick-up is done with cathode stalk (1/2 wavelength with capacitive pick-up)
- Up to three cathodes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

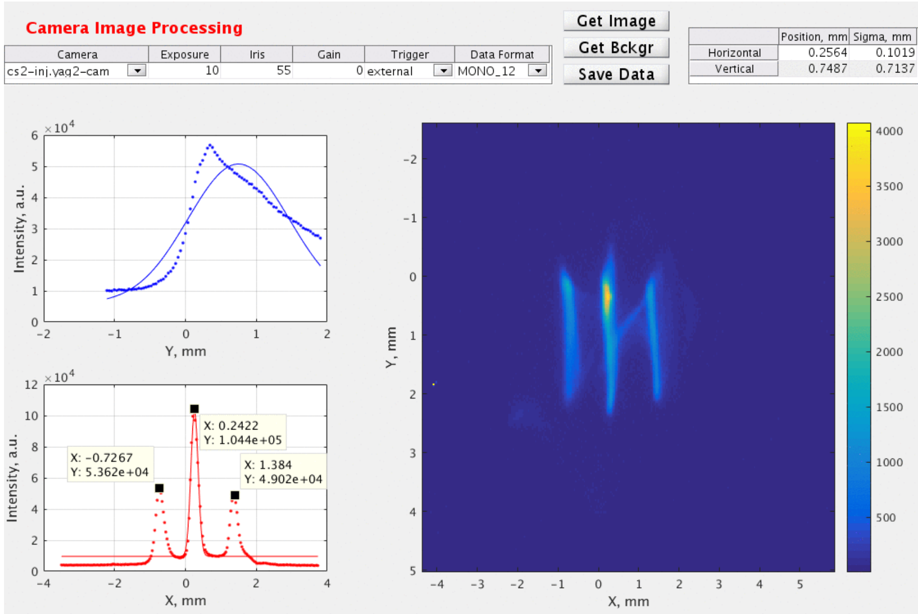
Photocathode end assembly



BROOKHAVEN NATIONAL LABORATORY

Emittance of 640 pC Beam





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

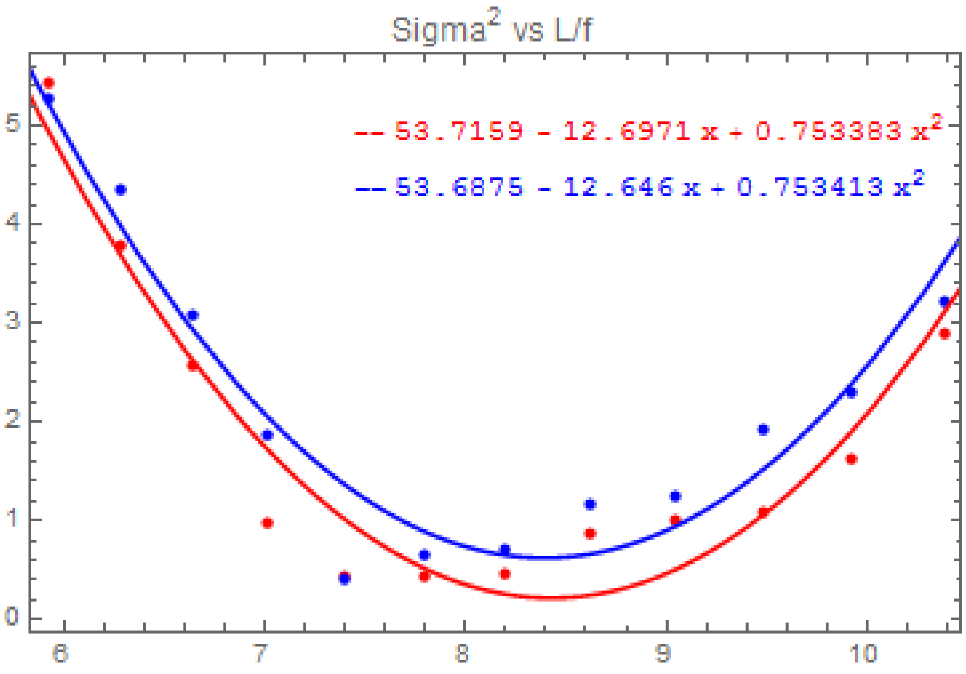
Beam size 1.3 mm
Divergence 0.29 mrad
R.m.s. emittance 0.37 mm mrad
Normalized 1.2 mm mrad

Emittance s sufficient for CeC demonstartion.

BROOKHAVEN NATIONAL LABORATORY

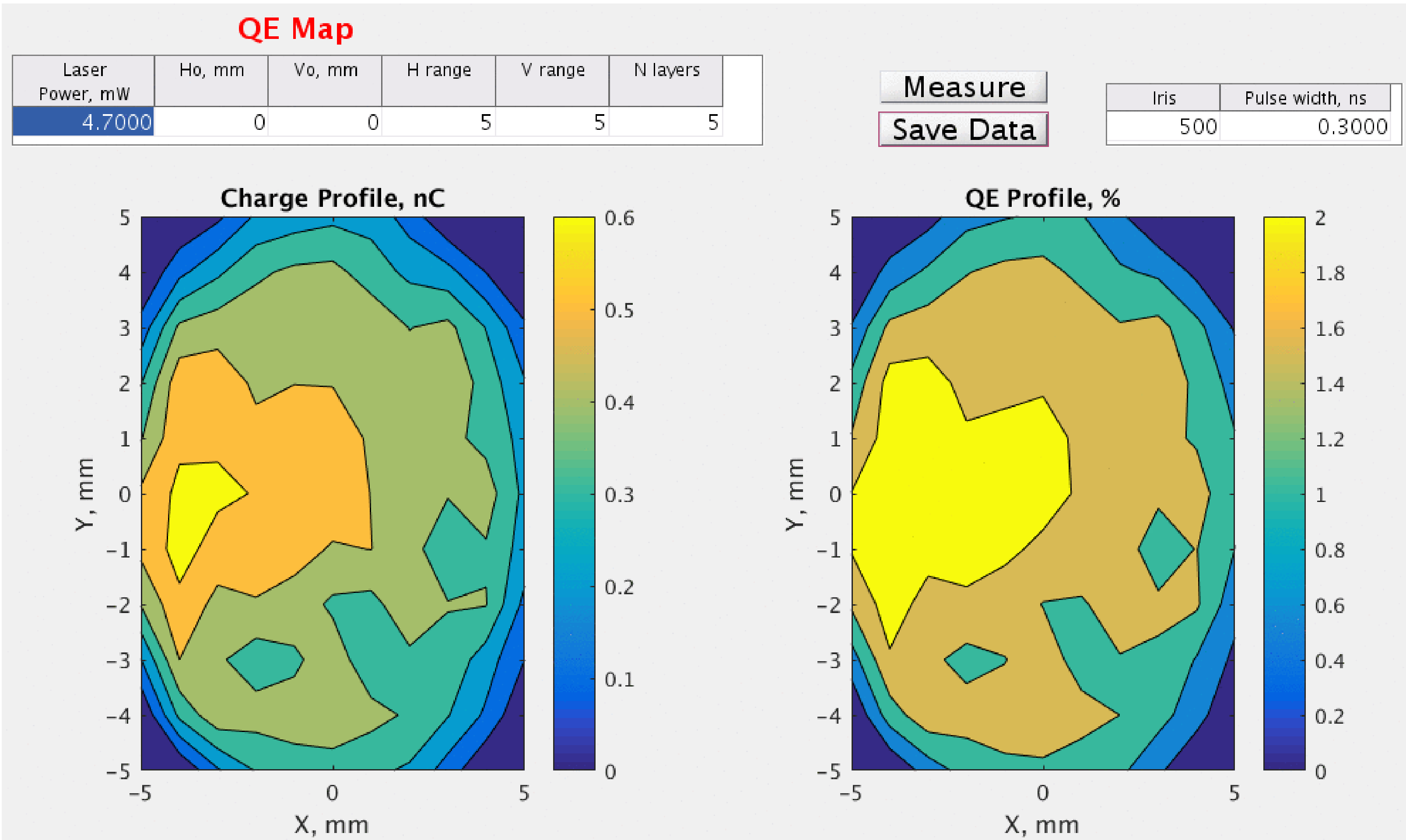
Office of Nuclear Physics

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.

High QE was maintained for months of operations



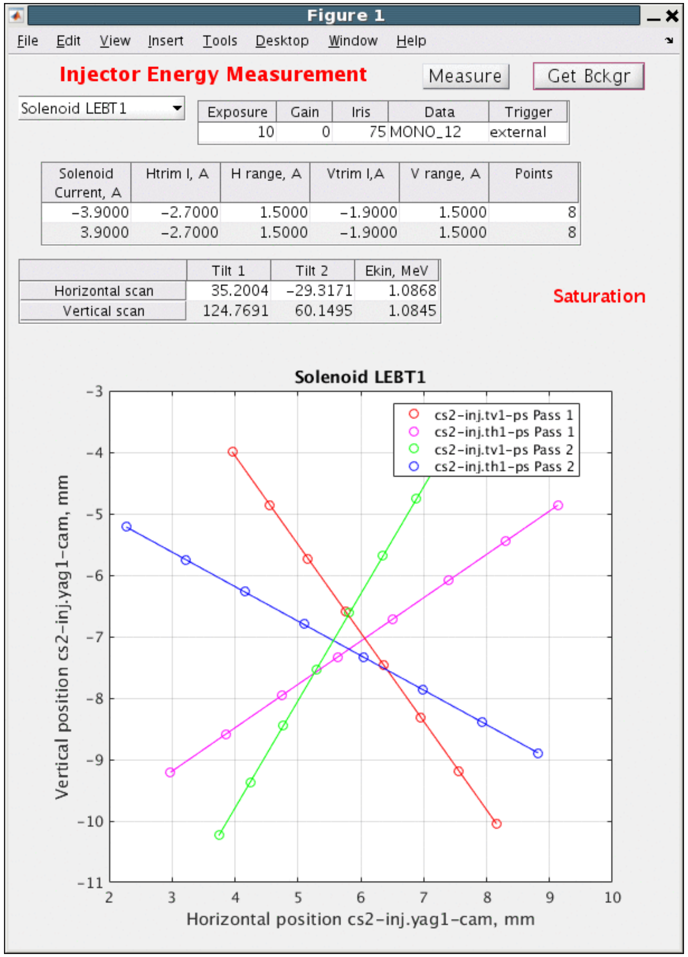
Initial (post insertion) QE is less and then improves over one week.

BROOKHAVEN NATIONAL LABORATORY

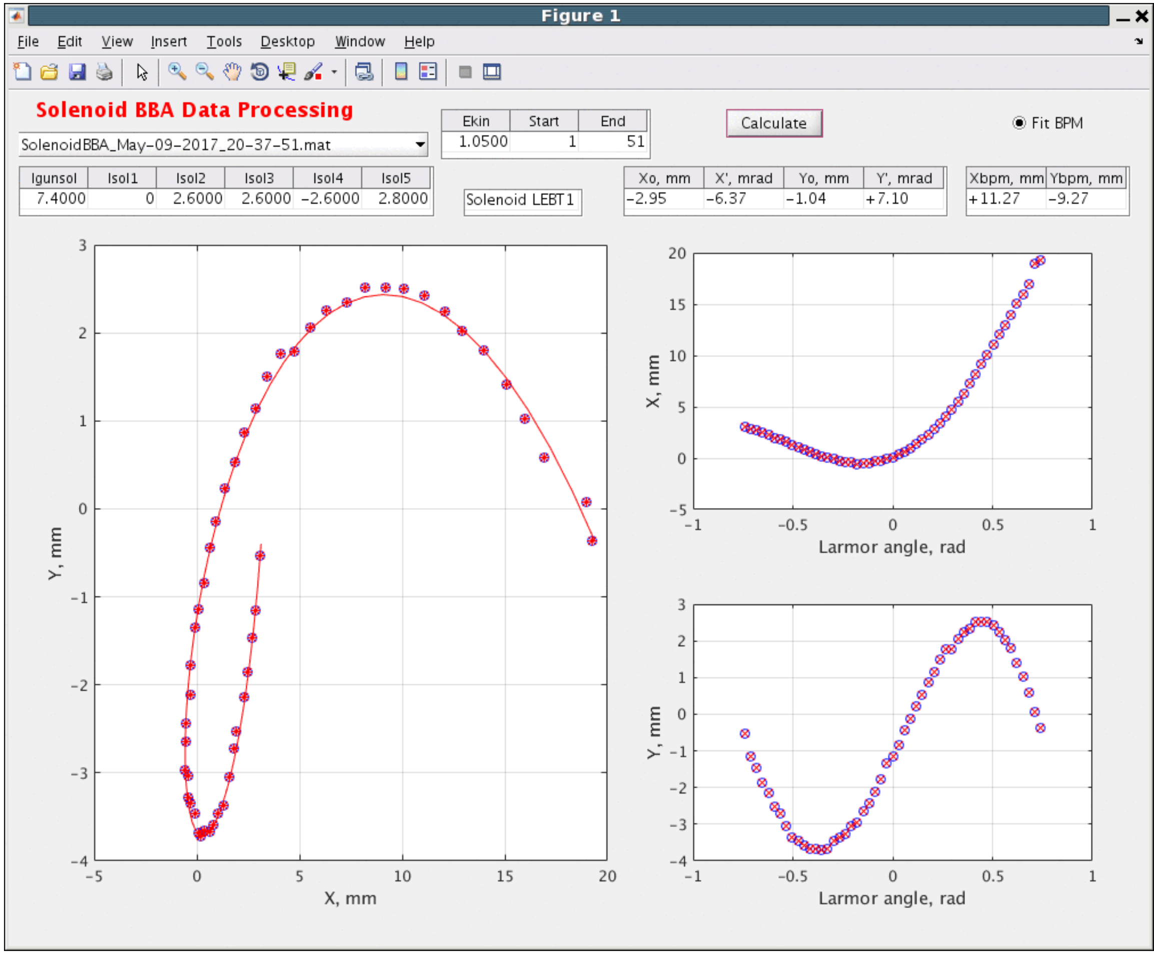
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Automated Measurement of the Beam Parameters with Solenoid

Beam Energy

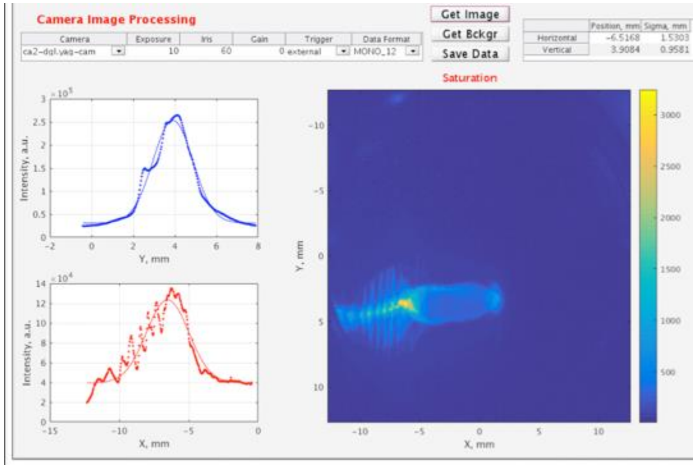


Beam Trajectory

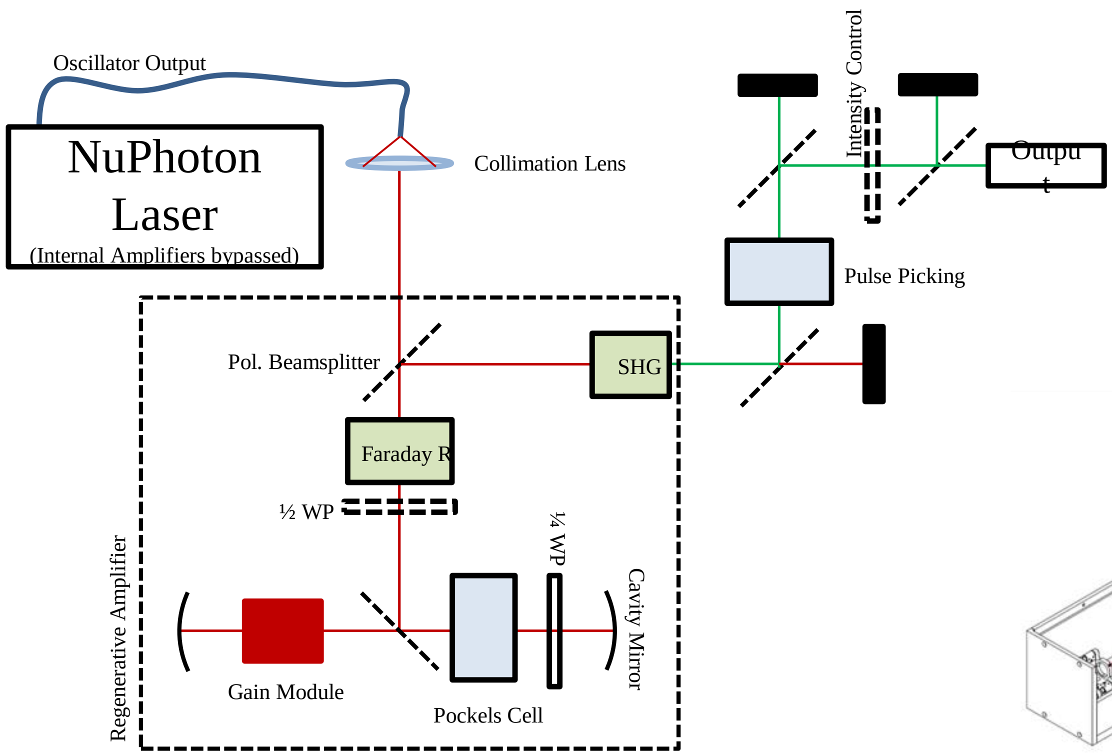


Laser

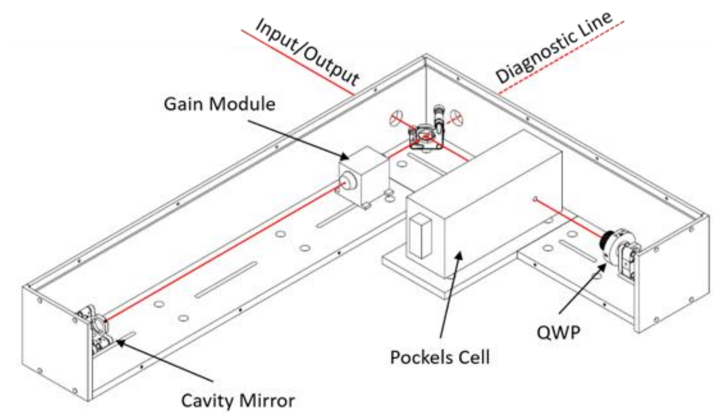
- Initially we utilized fiber based NuPhotons laser and fiber delivery system
- The Raman scattering in the fiber lengthened bunch at high peak power
- Laser was demonstrating spiky output with long pulses
- Both issues are being addressed: we have built new evacuated delivery beamline and replacing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



Replacement:
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

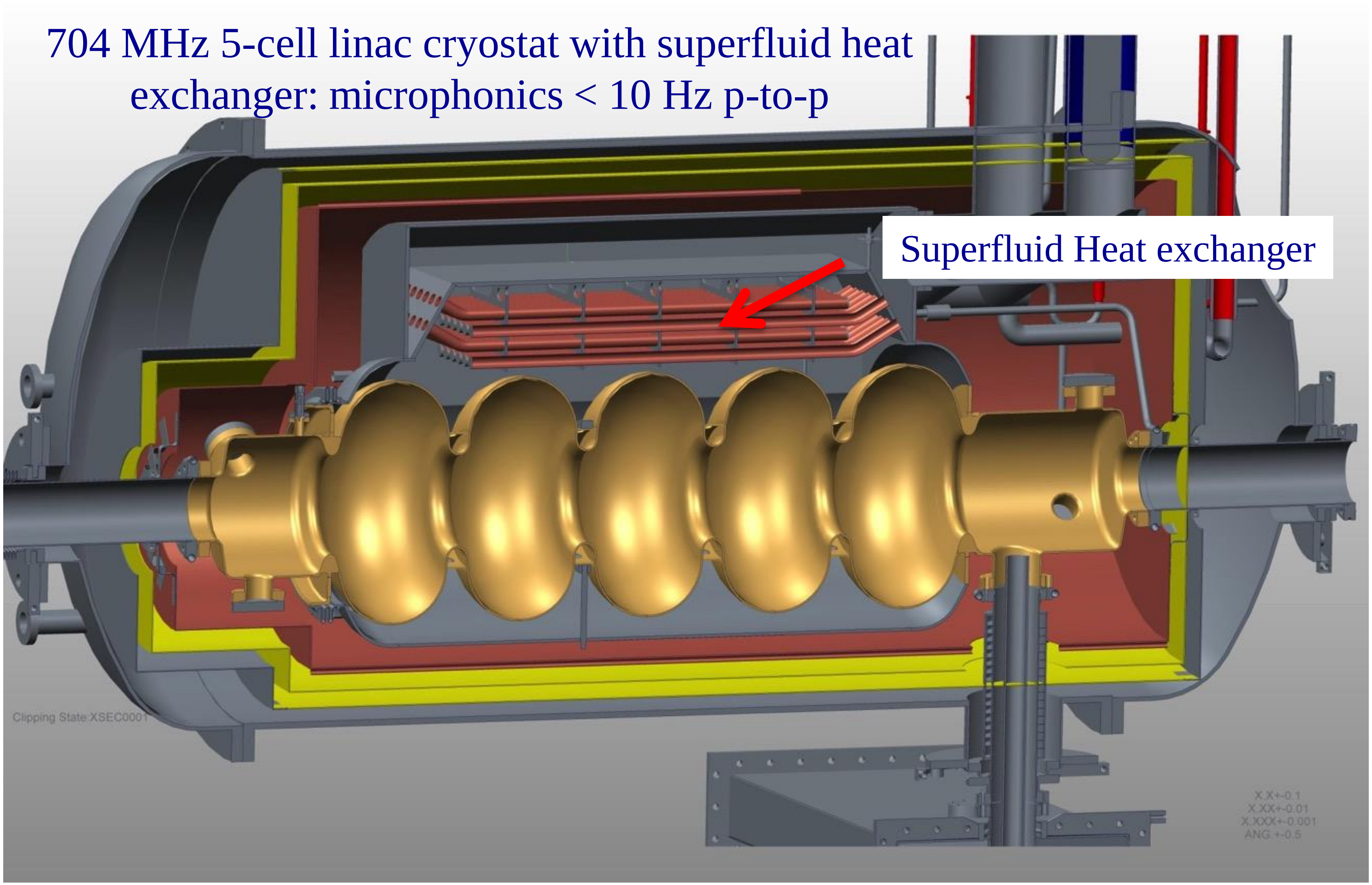


BROOKHAVEN
NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Accelerator Cavity

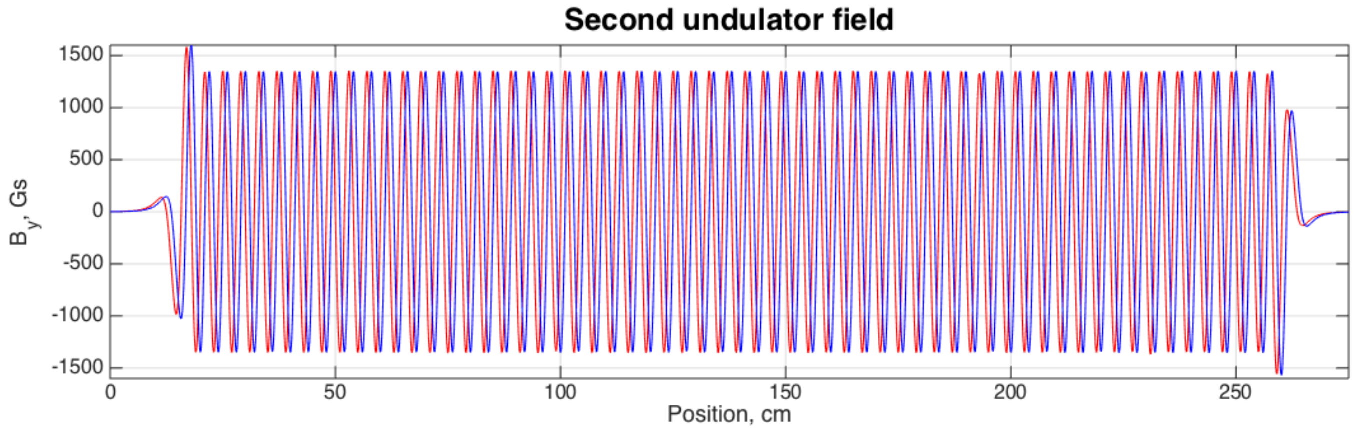
704 MHz 5-cell linac cryostat with superfluid heat exchanger: microphonics < 10 Hz p-to-p

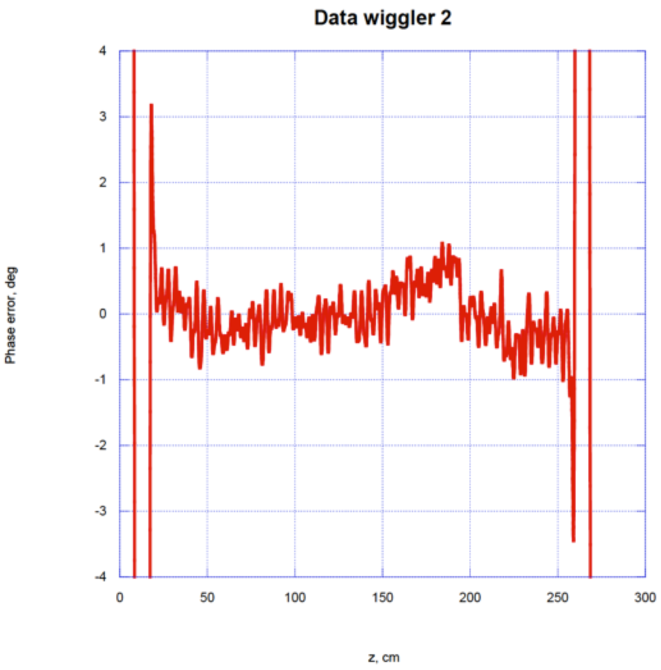


Accelerator Cavity (II)

- 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





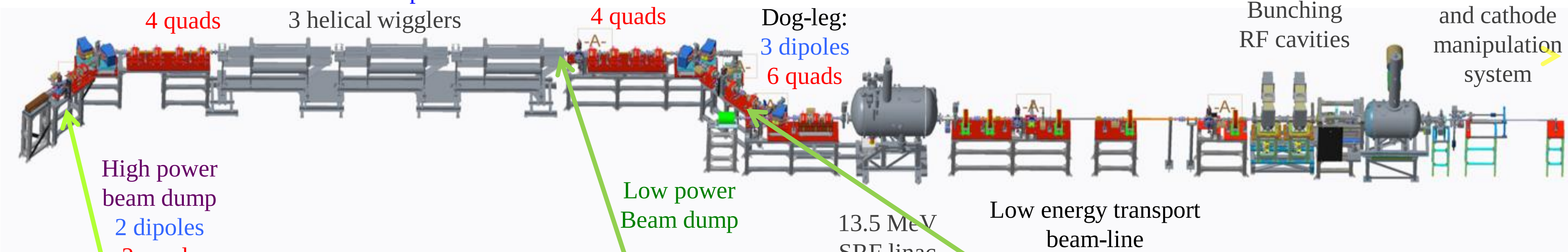
FEL system was supplied by BudkerINP from Novosibirsk and was finely tuned upon delivery. This summer we found that helicity of the third wiggler is wrong and corrected the error.

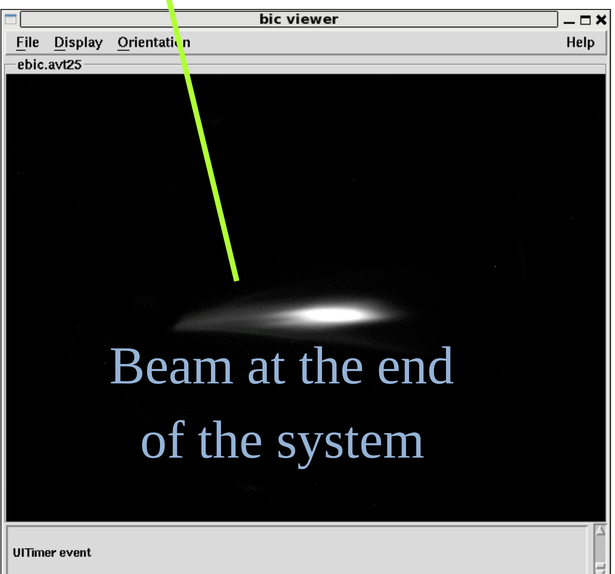
BROOKHAVEN NATIONAL LABORATORY

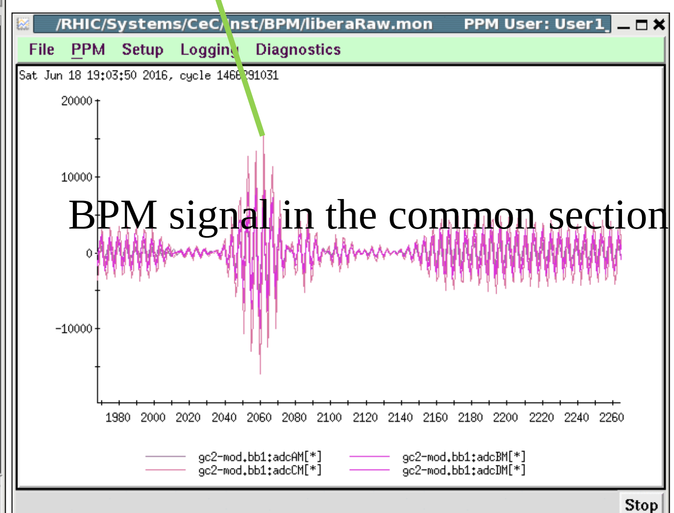
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

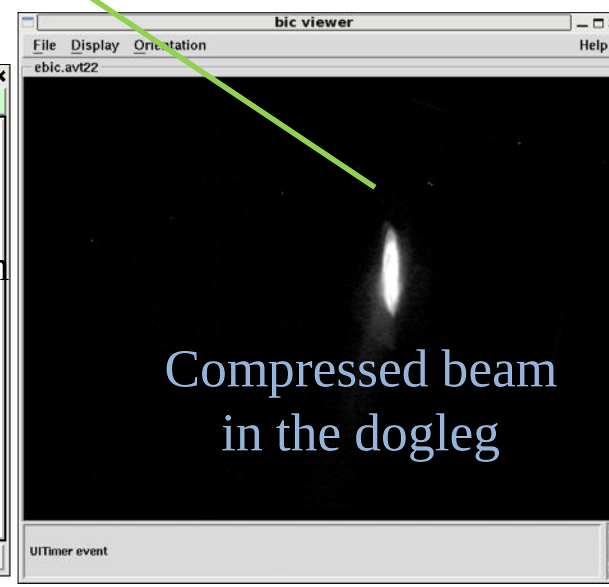
The CeC System Commissioning

Common section with RHIC



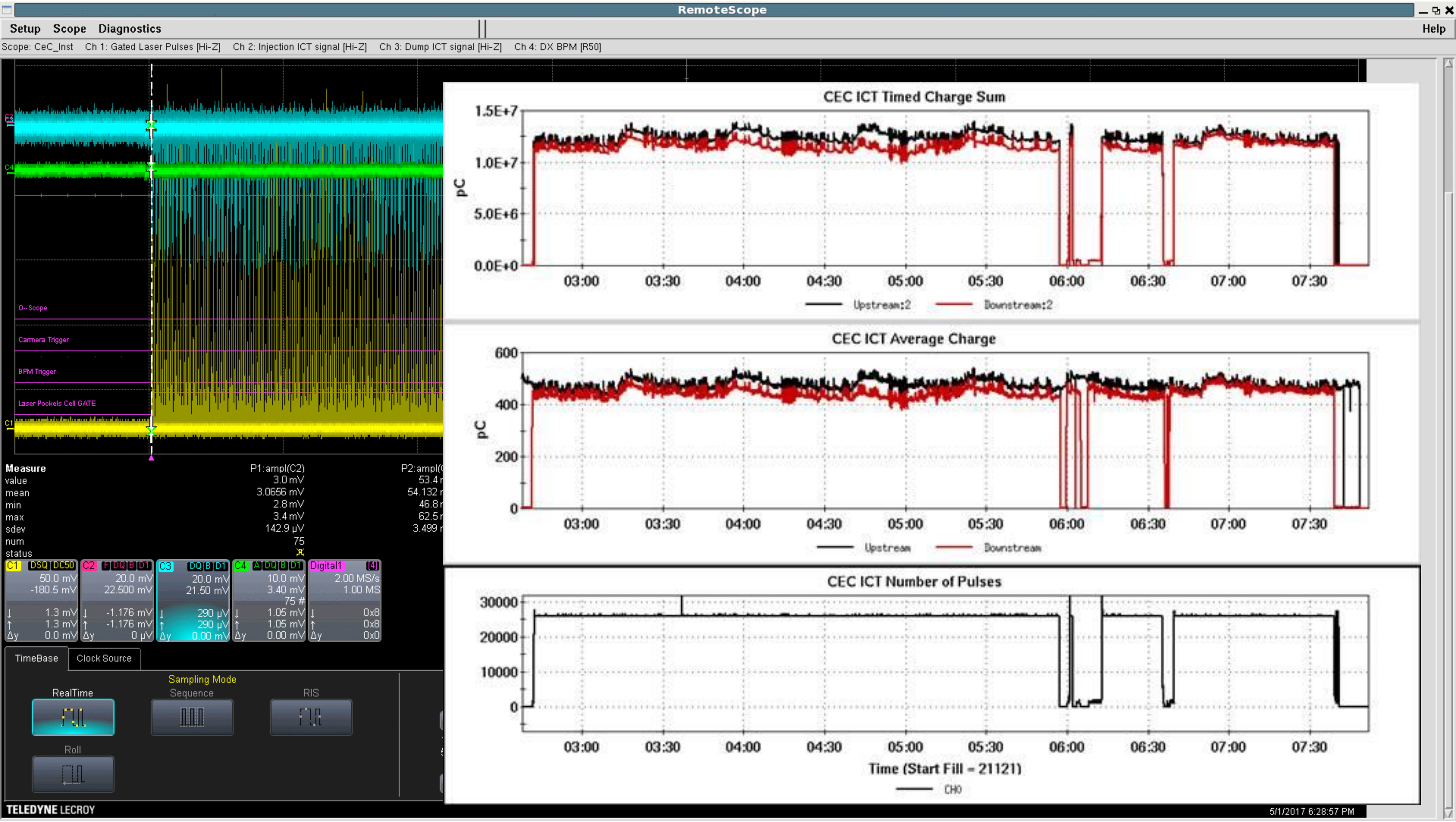






Electron beam was propagating inside 1ms abort gap

Operating in CW Mode



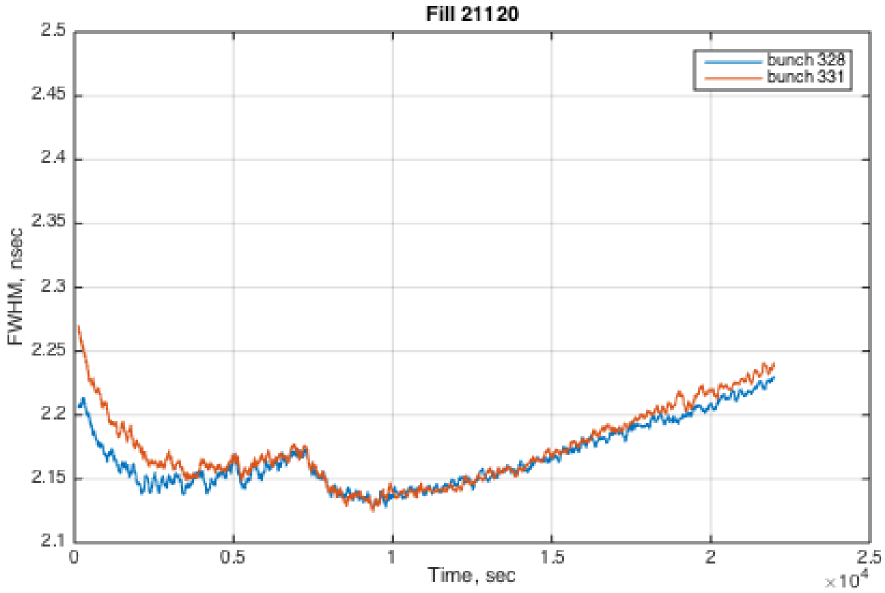
Interaction with Hadron Bunches

- 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
- 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)

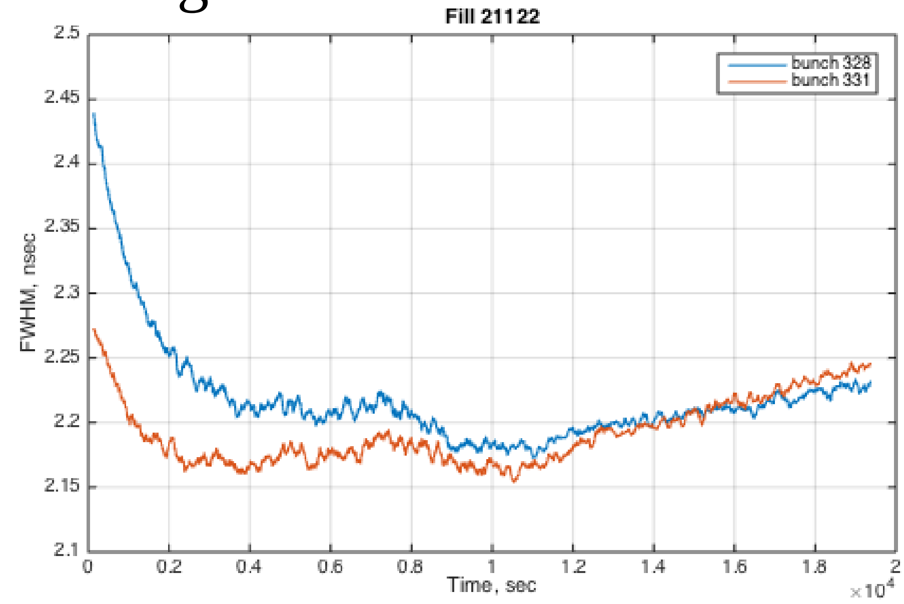
Add slide how IR diagnostics can be used for energy scan

Observation of Interaction of the Electron and Hadron Beams

no electron beam



with synchronized and aligned electron beam



Add how we want to demonstrate

Data were processed with moving average (128 samples)

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

2017 Shutdown Activity

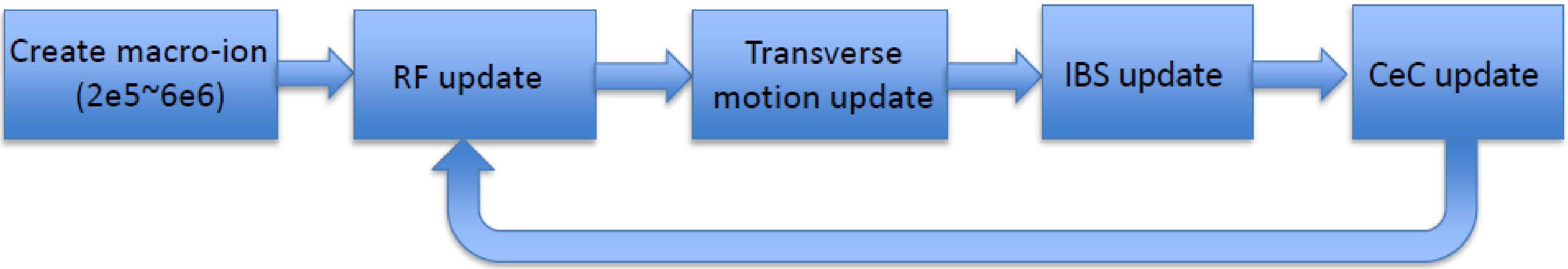
- Replaced failed ICT **v**
- Fixed wiggler helicity **v**
- Re-tune gun cavity to the required frequency **v**
- Replace IR port window **v**
- Replace IR diagnostics **v**
- Add BPM between buncher cavities (352 MHz)
- Install magnetic shielding for low-energy beamline
- Add port aligner for cathode 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

All items except the last are routine

Theory & Simulation Tool-kit

- Tools predicting electron-ion interactions in a single pass of a CeC system
  - Modulator
  - FEL amplifier
  - Kicker
- Tools to predicting evolution of hadron beam under coherent electron cooling
- Status of the CeC simulations

Simulation tools for predicting the influences of CeC to a circulating ion beam I



Energy kicks from CeC is $\Delta E_j = \Delta E_{coh,j} + \Delta E_{inc,j}$

Coherent kick induced by the ion itself $\Delta E_{coh,j} \equiv -Z_i e E_p l \sin\left(k_0 D \cdot \delta_j\right)$

Incoherent kick induced by the neighbor ions (using the Gaussian profile as obtained by quadratic expansion of FEL eigenvalues)

$$\Delta E_{inc,j} \equiv -Z_i e E_p l \sum_{i \neq j} e^{-\frac{\left(\varsigma_j - \varsigma_i\right)^2}{2\sigma_{z,rms}^2}} \sin\left(k_0\left(D\delta_j + \varsigma_j - \varsigma_i\right) - k_2^2\left(\varsigma_j - \varsigma_i\right)^2\right)$$

Since there is no correlation between any successive incoherent kicks, one can use a random kick to represent the incoherent kicks

For a random number uniformly distributed between -1 and 1 $\left\langle X^2 \right\rangle = \frac{1}{2}\int_{-1}^{1} X^2 dX = \frac{1}{3}$

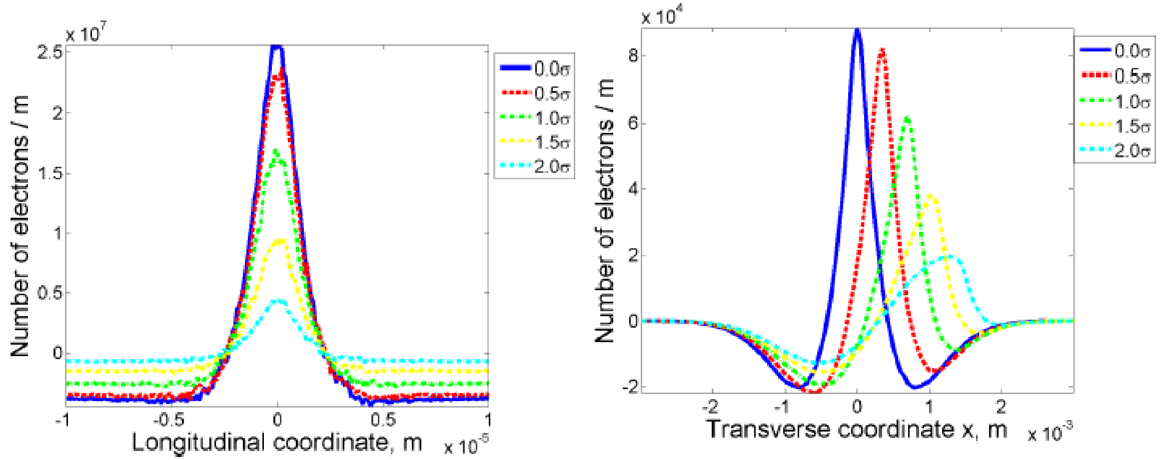
$$\Delta E_{j,N} \approx -Z_i e E_p l_1 \sin\left(k_0 D \cdot \delta_j\right) + \sqrt{\frac{\left\langle \Delta E_{inc,j}^2 \right\rangle}{\left\langle X^2 \right\rangle}} \cdot X_{j,N}$$

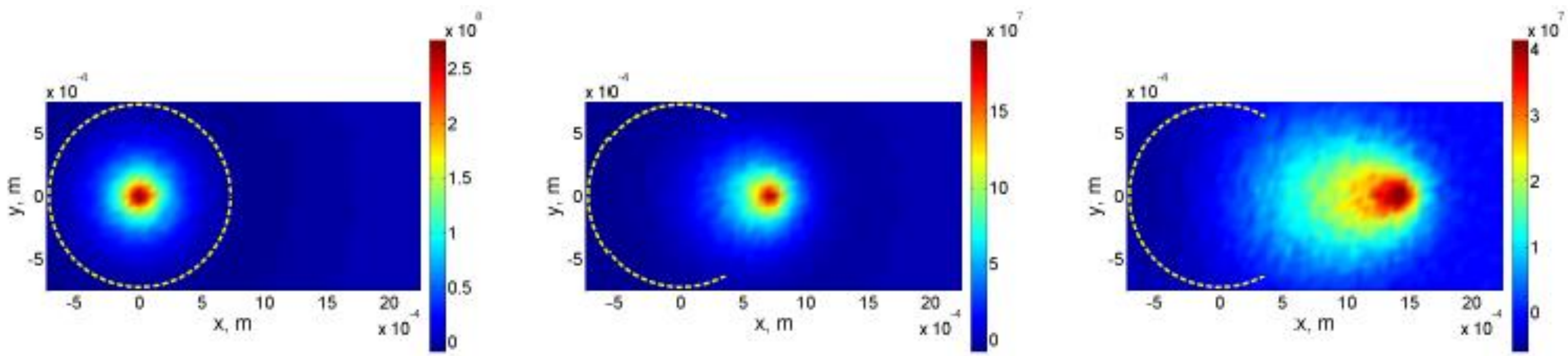
Simulation Tools for the Modulation Process III

(© J. Ma, with code SPACE)

– Simulation results for a continuous focusing channel (Beam is matched and transverse beam size does not vary.)

- Modulation is less effective for an off-centered ion. For an ion sitting at 1σ away from transverse electron beam center, the longitudinal density modulation reduces by ~40%.
- The transverse density modulation profile induced by an off-centered ion is significantly different from that induced by an ion at beam center





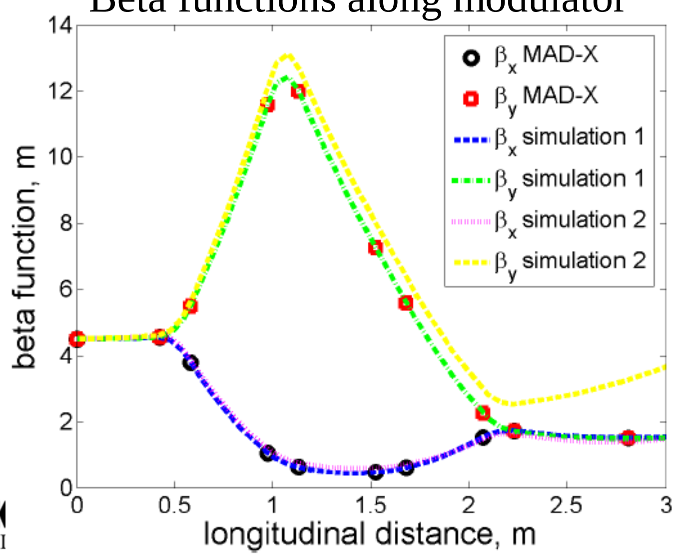
(a) Ion at center (b) Ion at $x = 1\sigma$ (c) Ion at $x = 2\sigma$

Simulation Tools for the Modulation Process III

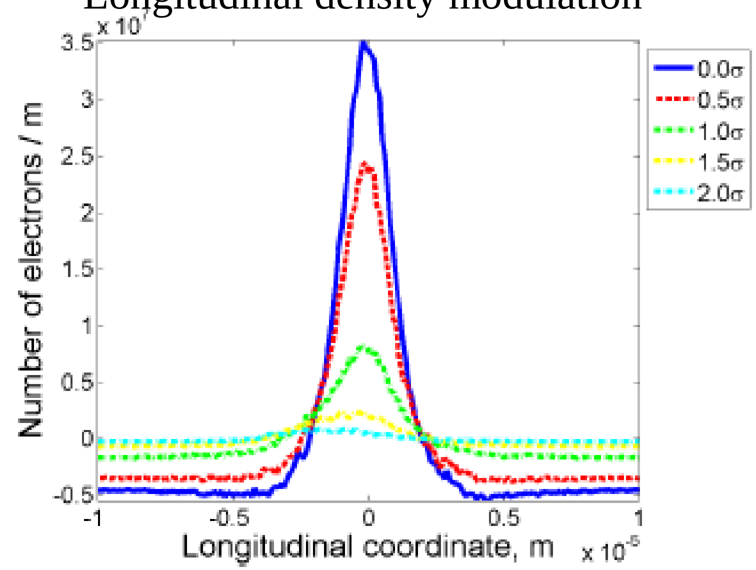
(© J. Ma, with code SPACE)

– Simulation results for a CeC quadrupole beamline with transverse beam size varying along the modulator
  - Beta functions extracted from SPACE agree with those from MAD-X calculations, when space charge is turned off in SPACE simulation.
  - When space charge is turned on, the vertical lattice function at the end of modulator deviates significantly from that calculated by MAD-X.
  - The efficiency of longitudinal density modulation depends strongly on the quadrupole settings, which has to be taken into account in optimizing the system.

Beta functions along modulator



Longitudinal density modulation

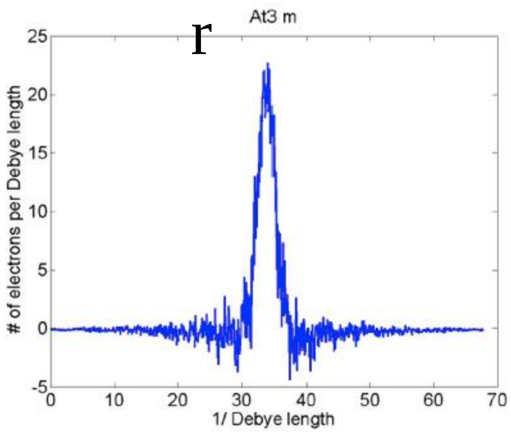


Start-to-end simulation for the single pass II

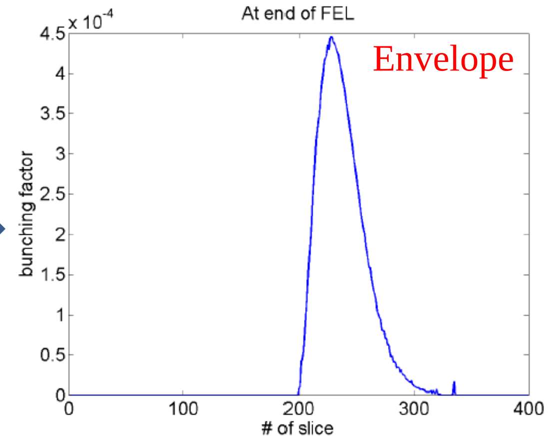
(© J. Ma, with code SPACE and GENESIS)

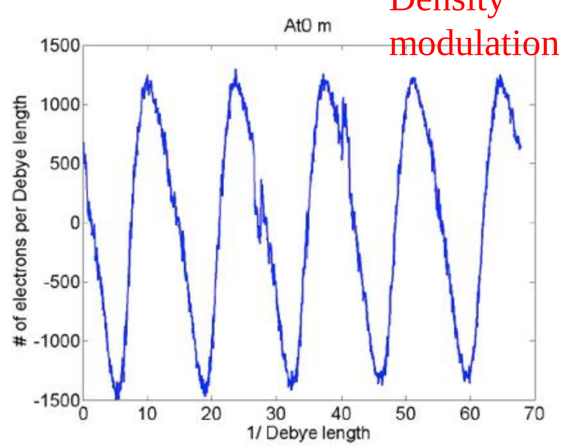
- One example of start-to-end simulation

Modulato
r

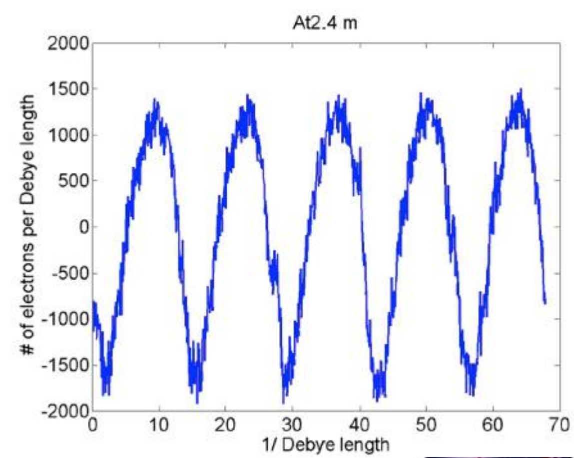


Amplifier



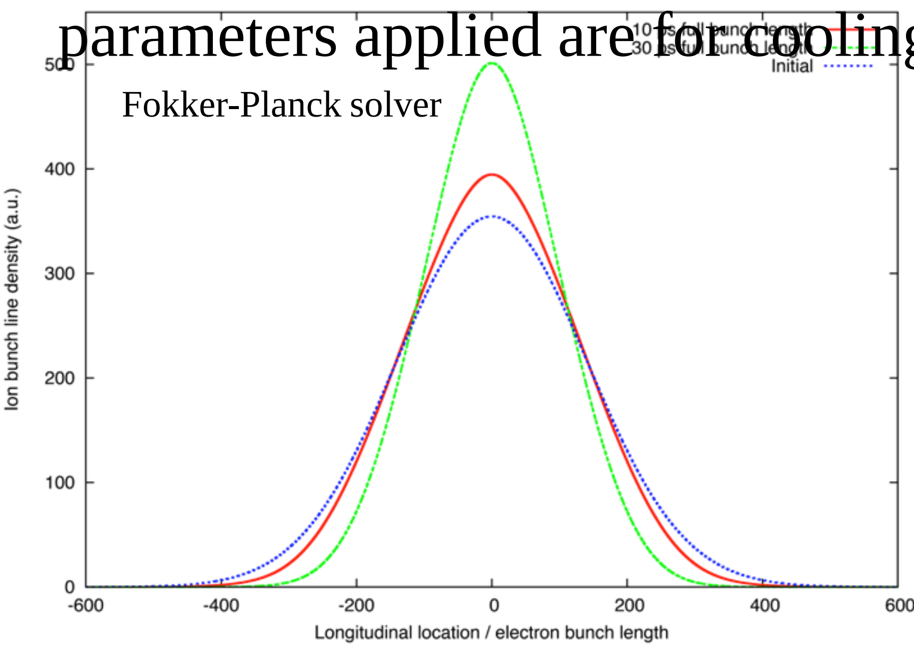


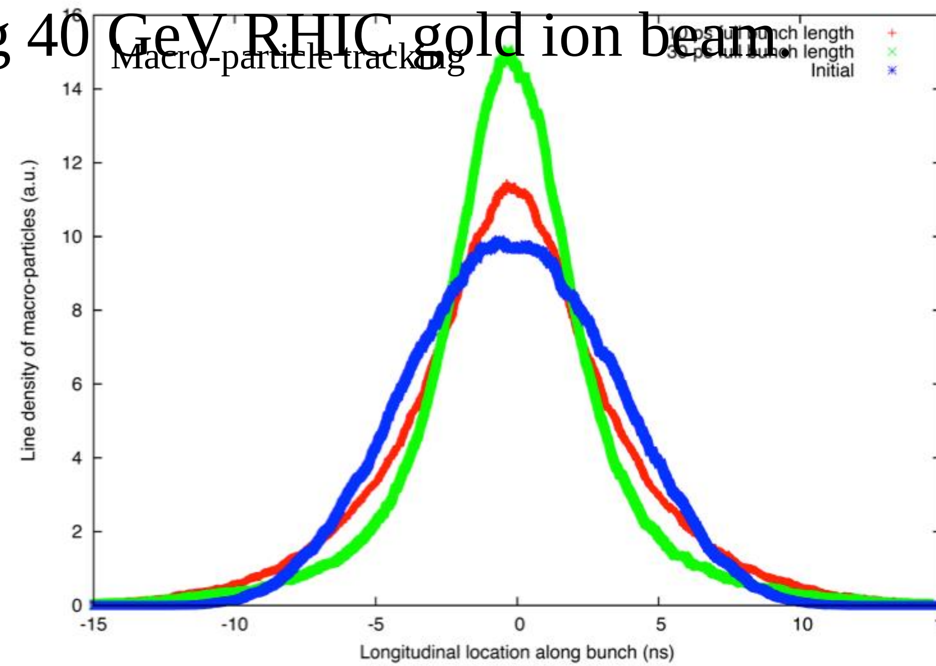
Kicker



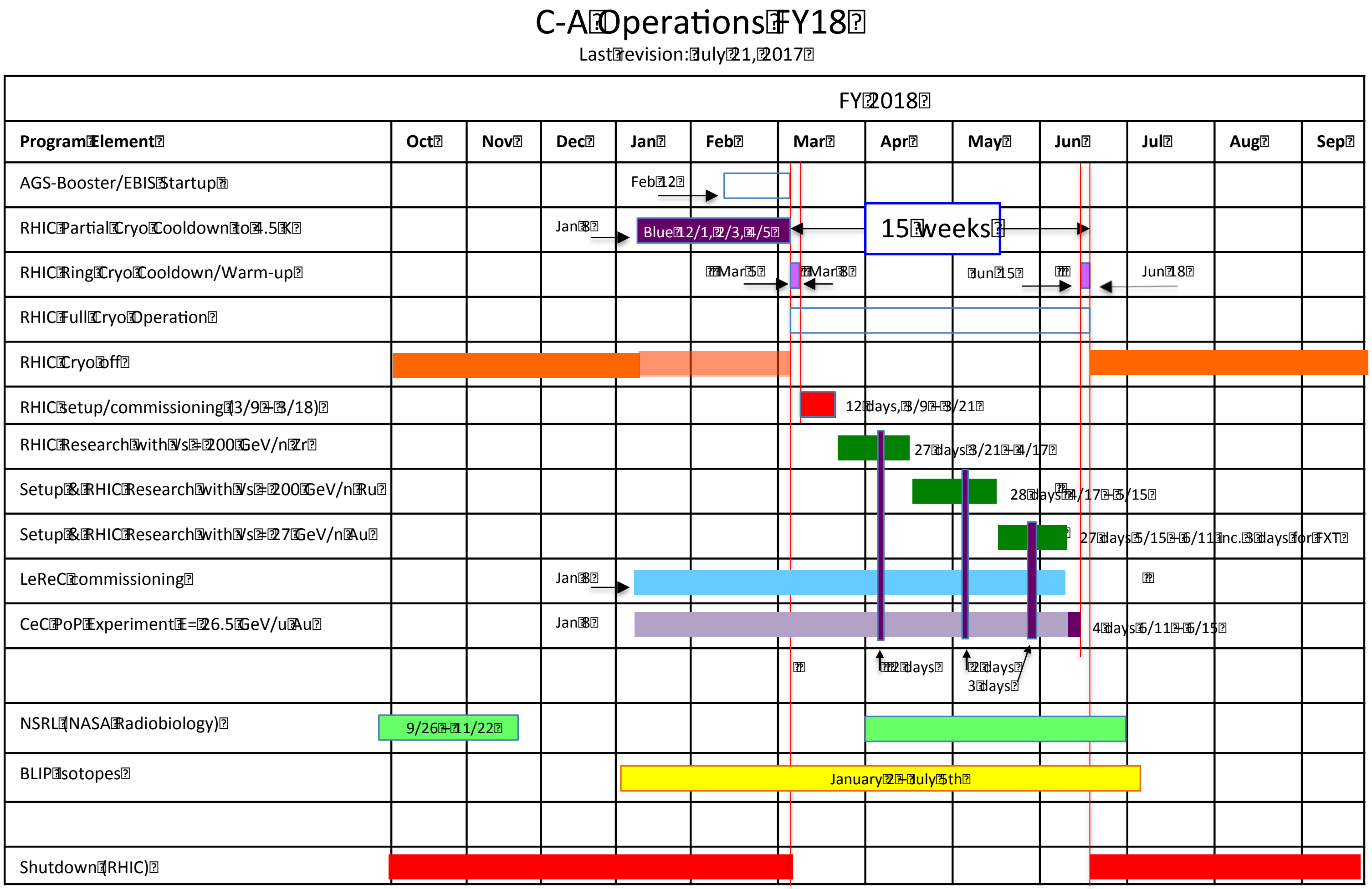
Simulation tools for predicting the influences of CeC to a circulating 40 GeV/u Au ion beam III

The plots show how the longitudinal profile of ion bunch evolves after 40 minutes of cooling with 10 ps (red) and 30 ps (green) electron bunch. The left plot is generated by solving Fokker-Planck equation as described in the previous slides and the right plot is created by the macro-particle tracking code. The parameters applied are for cooling 40 GeV RHIC gold ion beam.





Next step: demonstrating CeC



Zr run - 27 days (24.5 "physics" + 2 CeC + .5 float)
Ru run - 28 days (1.5 setup + 24.5 "physics" + 2 CeC)
Au run - 27 days (1 setup + 20 "physics" + 3 FXT + 3 CeC)
"physics" = physics + APEX + maintenance

Dates for first three CeC periods are approximate
(early April, early and late May)
CeC parasitic commissioning -
CeC Dedicated running - (Total of 11 days)

Preliminary plan for CeC experiment during Run 18

Will be coordinated with LEReC commissioning

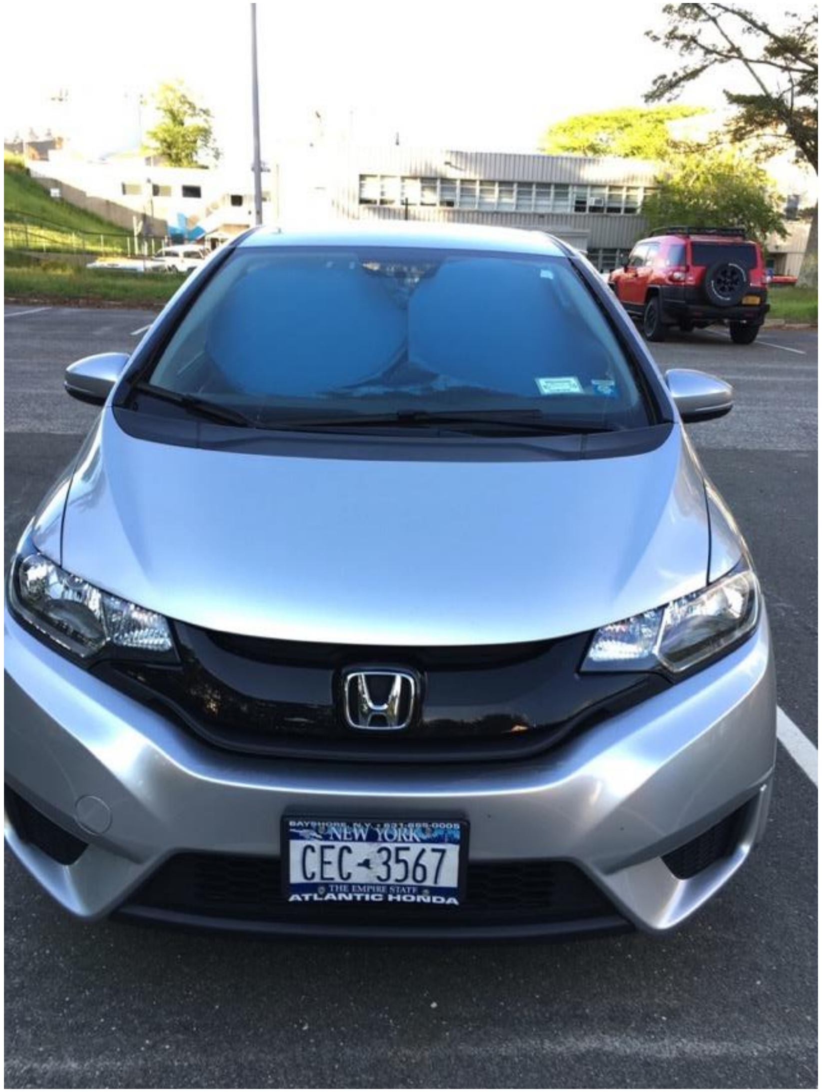
Activity	Proposed schedule
Re-establish CeC accelerator operation	1/15– 2/3
Establish required e-beam parameters CeC FEL commissioning	2/4 – 3/5
Establishing CeC system operations at various RHIC settings, compensating stray magnetic fields	3/5 – 3/21
Co-propagate, align and synchronize electron and ion beams, match relativistic factors of two beams	3/22 - 4/7 2 days dedicated
Develop control of the FEL amplification, observe amplification of density modulation induced by ions	4/8 – 5/5 2 days dedicated
Refine tools for observation of ion beam cooling, observe cooling/anti-cooling via CeC	5/6 – 5/25 3 days dedicated
Develop various CeC accelerator settings (charge, peak current, FEL gain) and characterize CeC cooling	5/26 -6/15 4 days dedicated

Conclusions

- During Run 17 the CeC was given an excellent opportunity and plenty of time to make as much progress as it was technically and physically possible
- 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 – *it is my main disappointment*
- We defined and are implementing all necessary step for demonstration CeC experiment during RHIC Run 18
- After run 18 we plan to use our system to test key components of CeC with micro-bunching amplifier as well conduct various experiments with our high brightness electron beam

Work is supported by Brookhaven Science Associates, LLC under Contract No. DEAC0298CH10886 with the U.S. Department of Energy, DOE NP office grant DE-FOA-0000632 and NSF grant PHY-1415252.

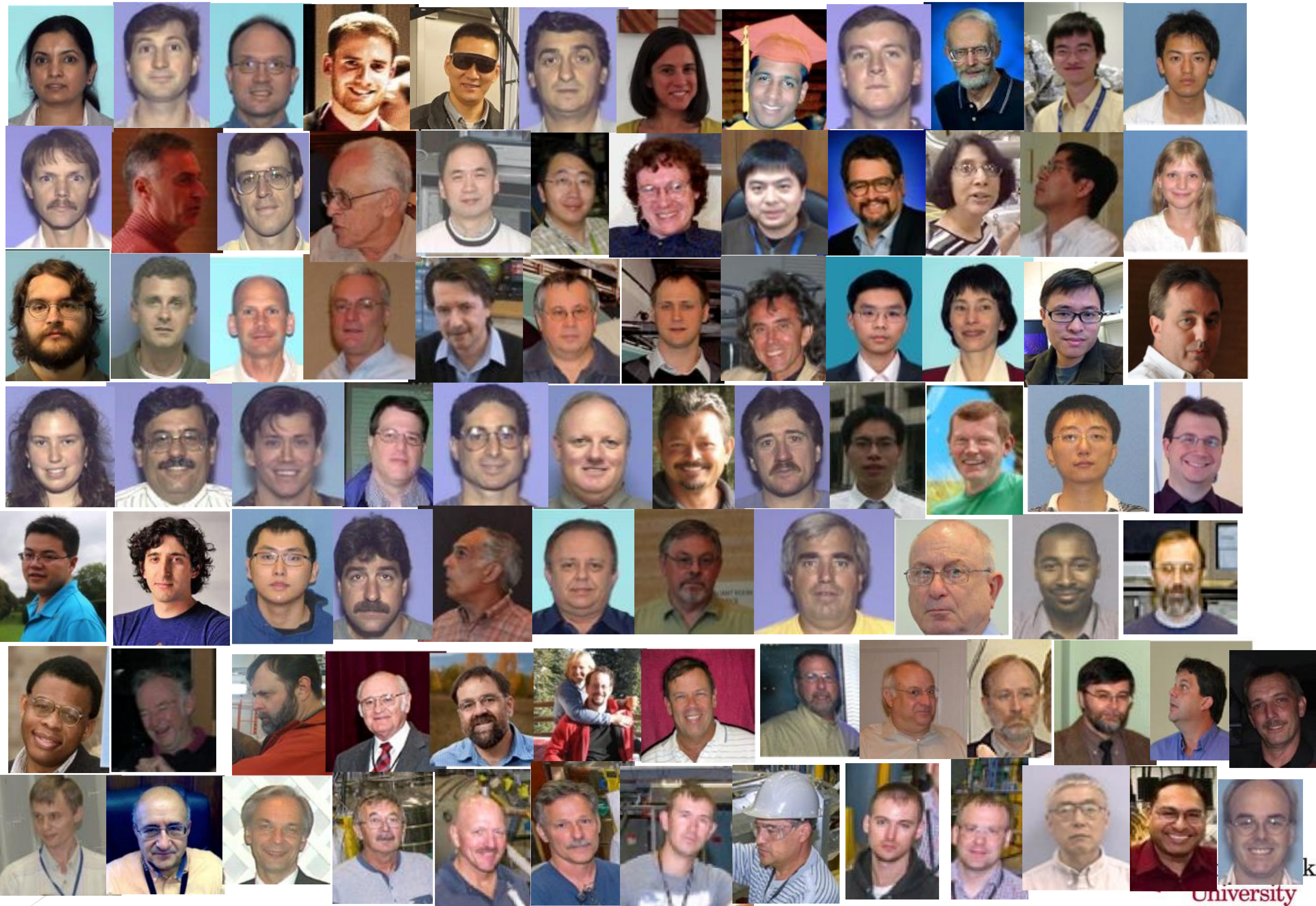
CEC fun at BNL



BROOKHAVEN
NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

It take the village… the CeC team – never can get all your pictures



Back-up

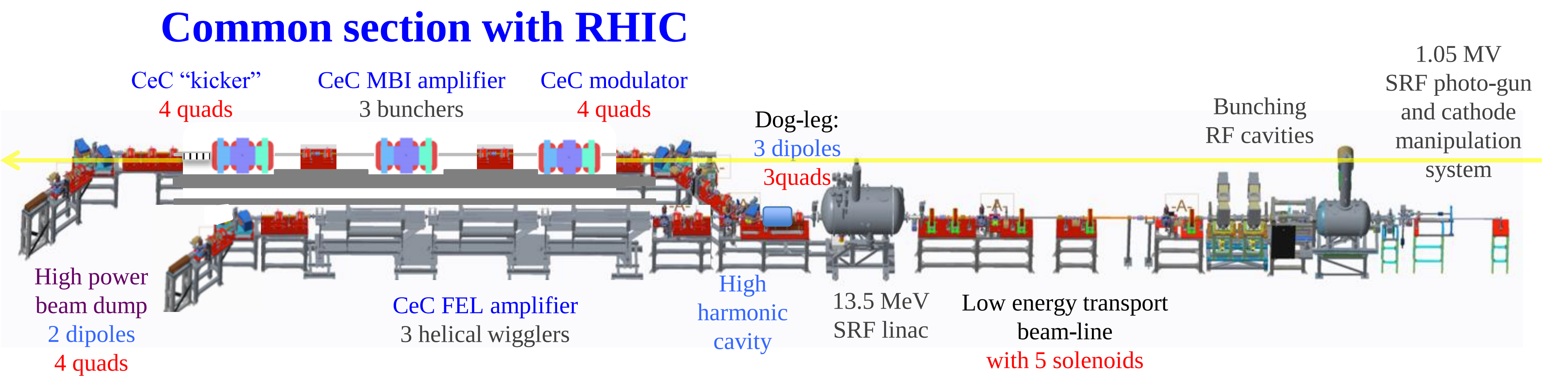
Post Run-18

- We had built an excellent accelerator and SRF photoemission gun, which will find multiple applications beyond CeC demonstration experiment during Run 18
- There are many excellent opportunities from which we will select few to pursue in 2018 and beyond
- We definitely plan to continue CeC studies with MBI amplifier (supported by NSF grant) and explore unique high brightness beams generated by our SRF gun
- Other opportunities can be pursued if resources are available

Main directions

- **Advanced CeC & FEL amplifier studies**
  - test of 3-stage MBI amplifier
  - optimization for MBI amplifier, e.g. low energy spread
  - separating electron and hadron beams for CeC cooling experiment with MBI amplifier
  - optimize FEL amplifier
- **Advanced cathode studies with dedicated emittance measurements system**
  - generation of high brightness beams from SRF gun
  - generation electron bunches with large charge per pulse (>10 nC)
  - high QE and long life-time photocathodes CsK_2Bs, $CsNa_2Sb$, diamond-amplifier
  - electron emission cathodes
  - testing polarized electron GaAs photocathode and .... in SRF gun
- **Zig-Zag merger**
  - compare emittance preservation in Zig-Zag and chicane mergers
- **ERL options**
  - re-using R&D ERL arcs & ERL linac
  - push-pull ERL
  - test novel HOM dumpers for BNL-3 5-cell linac with high charge per pulse
- **Study of linac-ring beam-beam effects**
  - We can use CeC e-beam to simulate large disruption mode of e-p collisions in linac-ring eRHIC
- **Space charge compensation**
- **Driver for PWFA**
  - generate train of the electron bunches for high transformer ratio PWFA
  - test high rep-rate and CW PWFA

The CeC MBI amplifier

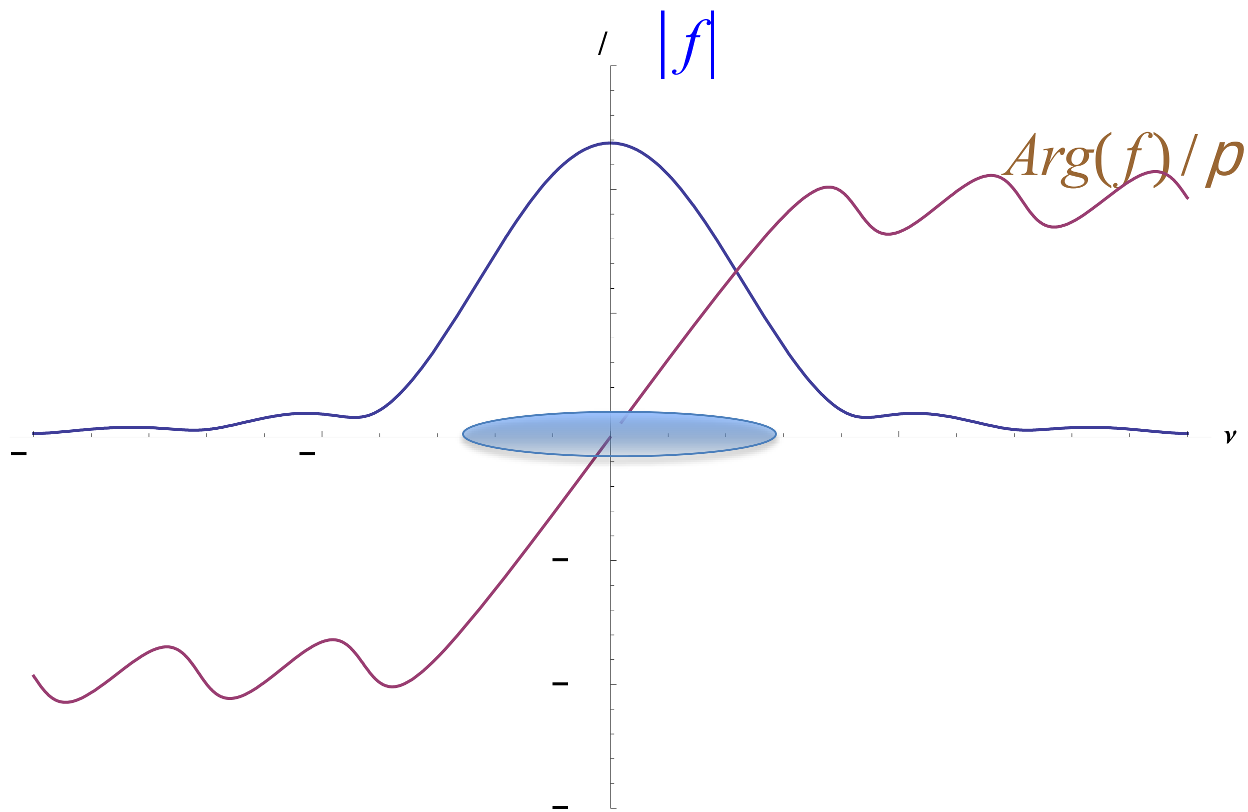


- Advance CeC studies
  - test of 3-stage MBI amplifier
  - beam optimization for MBI amplifier (low energy spread) using flat-top acceleration with HF cavity compensating the 704 MHz linac curvature
  - test maximum amplifications – prove our theory that maximum amplification by a single MBI amplifier is limited by $\sin\varphi_p \cdot (\gamma\theta)$
- FEL-based CeC
  - continue working with 3 helical wiggler FEL amplifier

Dependence of the shot-noise (e.g. spontaneous radiation) induced by an of-energy ion

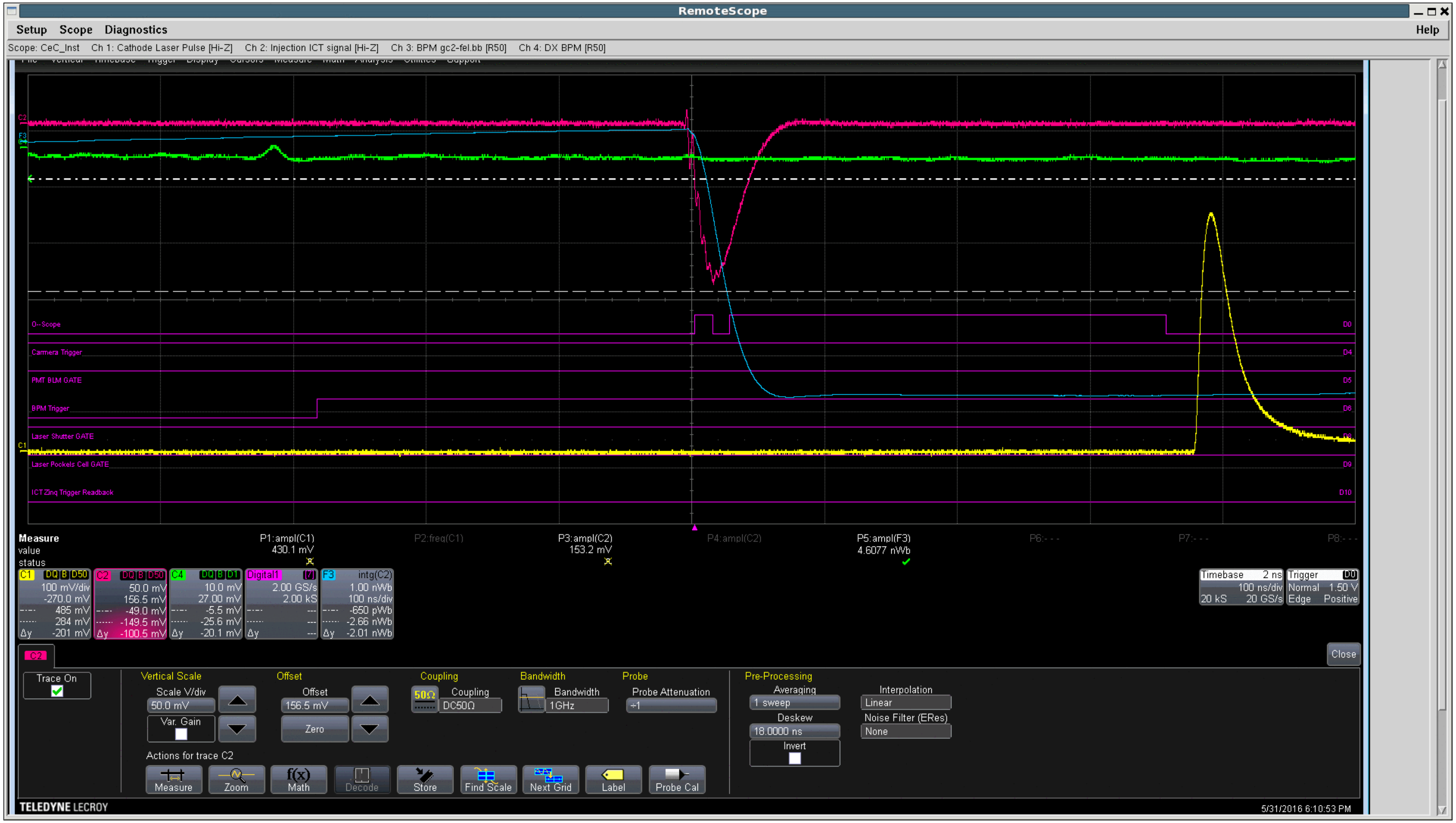
$$g_i \; 1 \; \langle g_e \rangle = g_o$$

$$n = dg_i / s_{g_e} \qquad k = 0.35,\ j_p = p$$



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

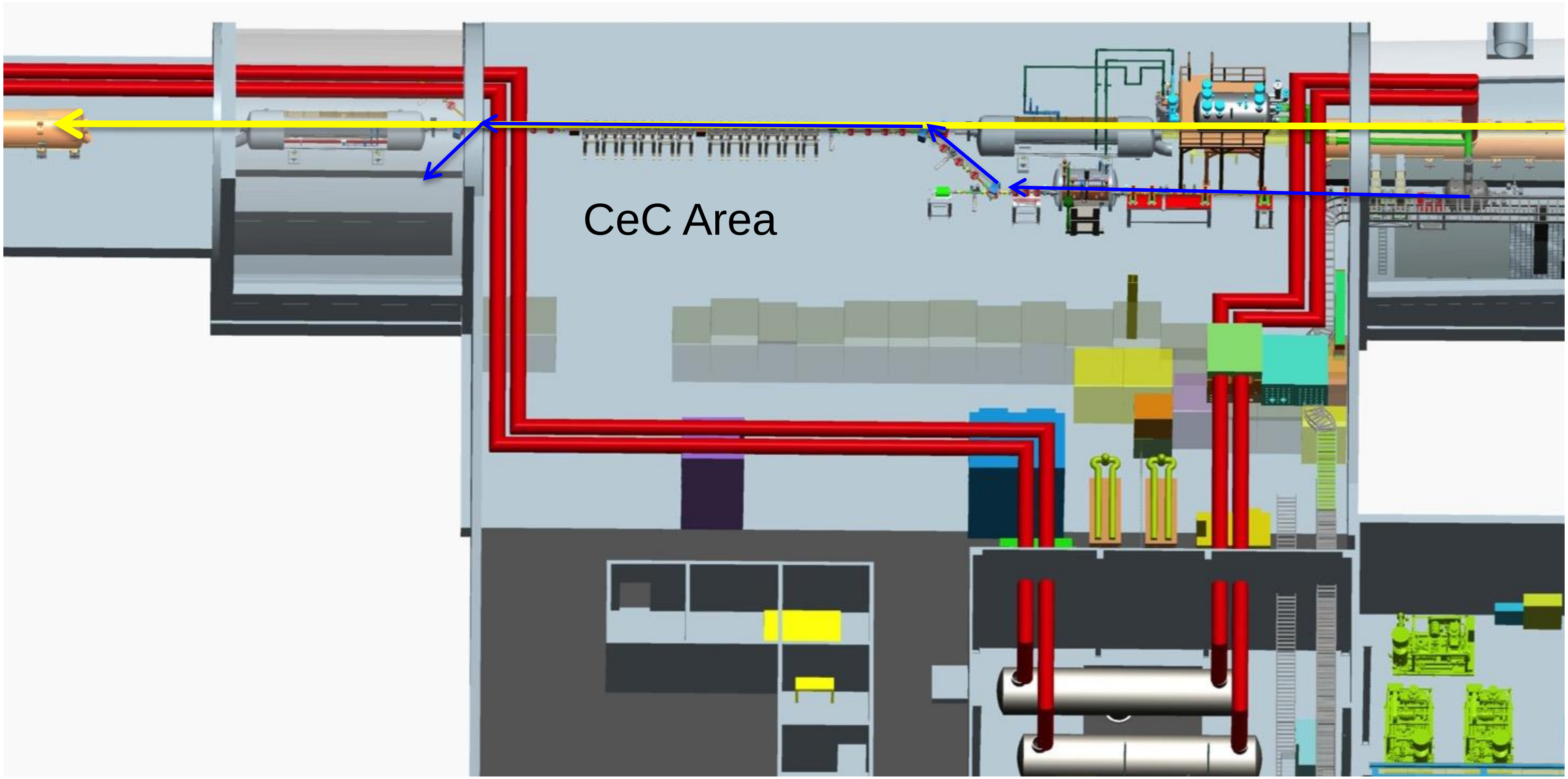
3.7 nC Charge from the Gun



Demonstrated on May 31, 2016

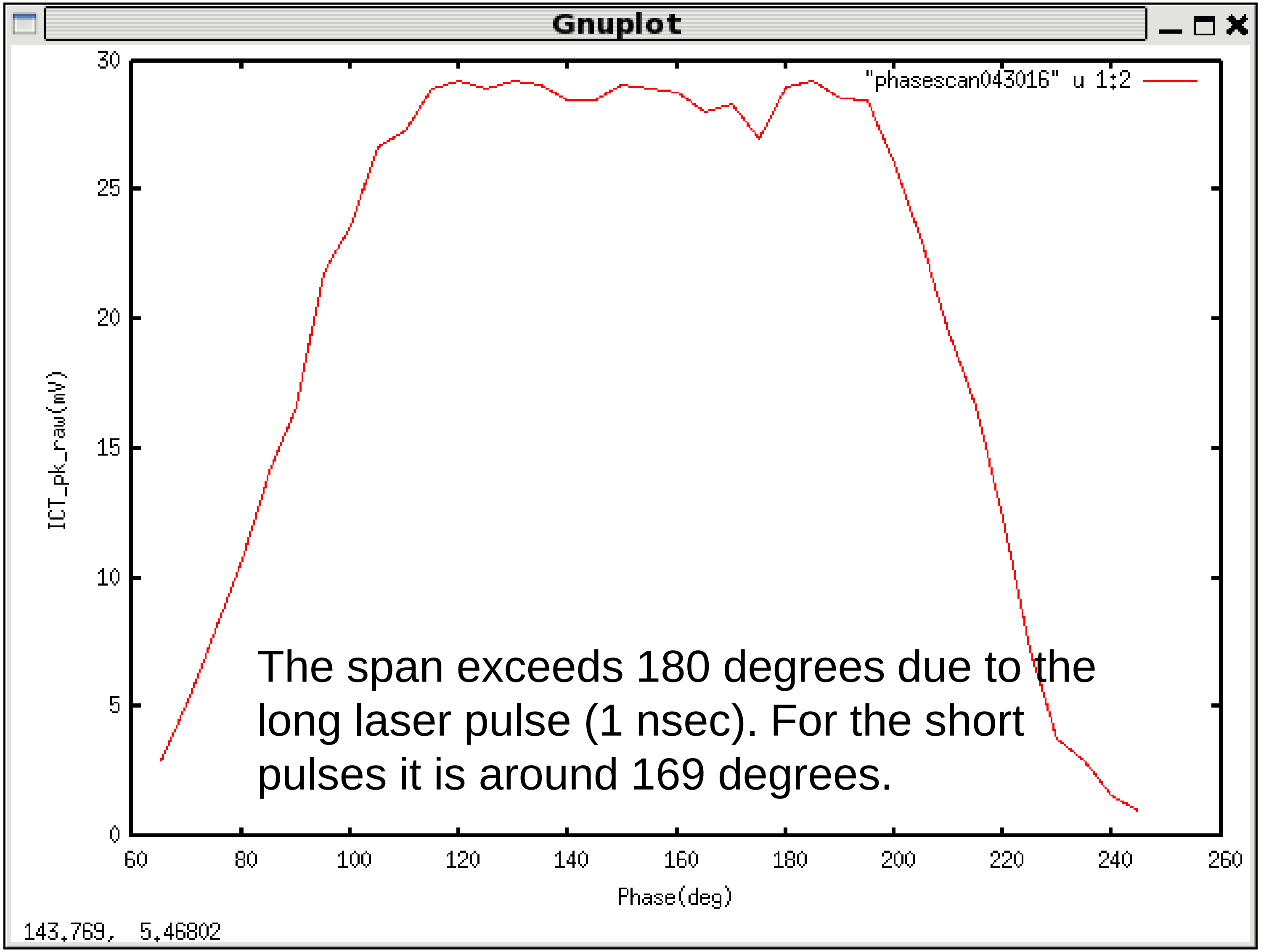
BROOKHAVEN NATIONAL LABORATORY

Top View



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

Cavity Phase Scan

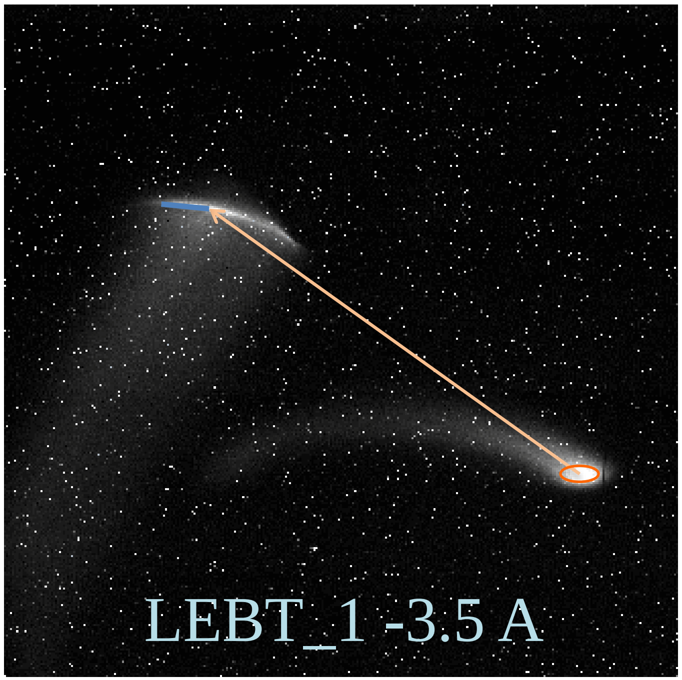


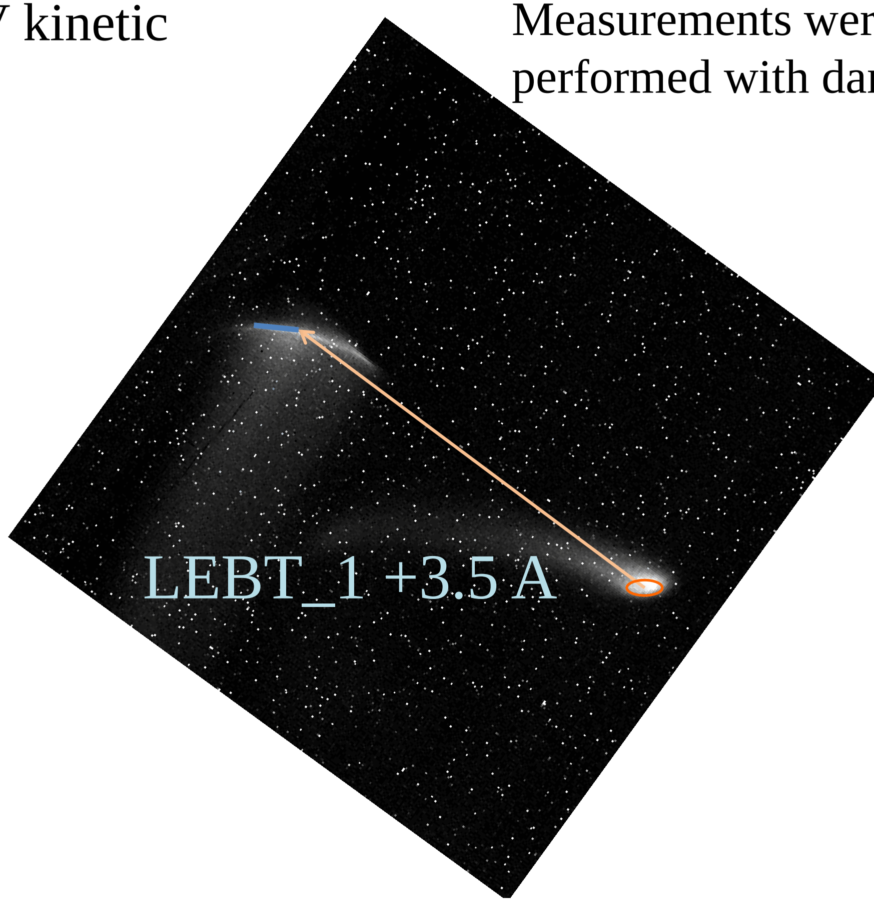
The span exceeds 180 degrees due to the long laser pulse (1 nsec). For the short pulses it is around 169 degrees.

Beam Energy Measurement

Rotation angle 54° - 1.19 MeV kinetic energy

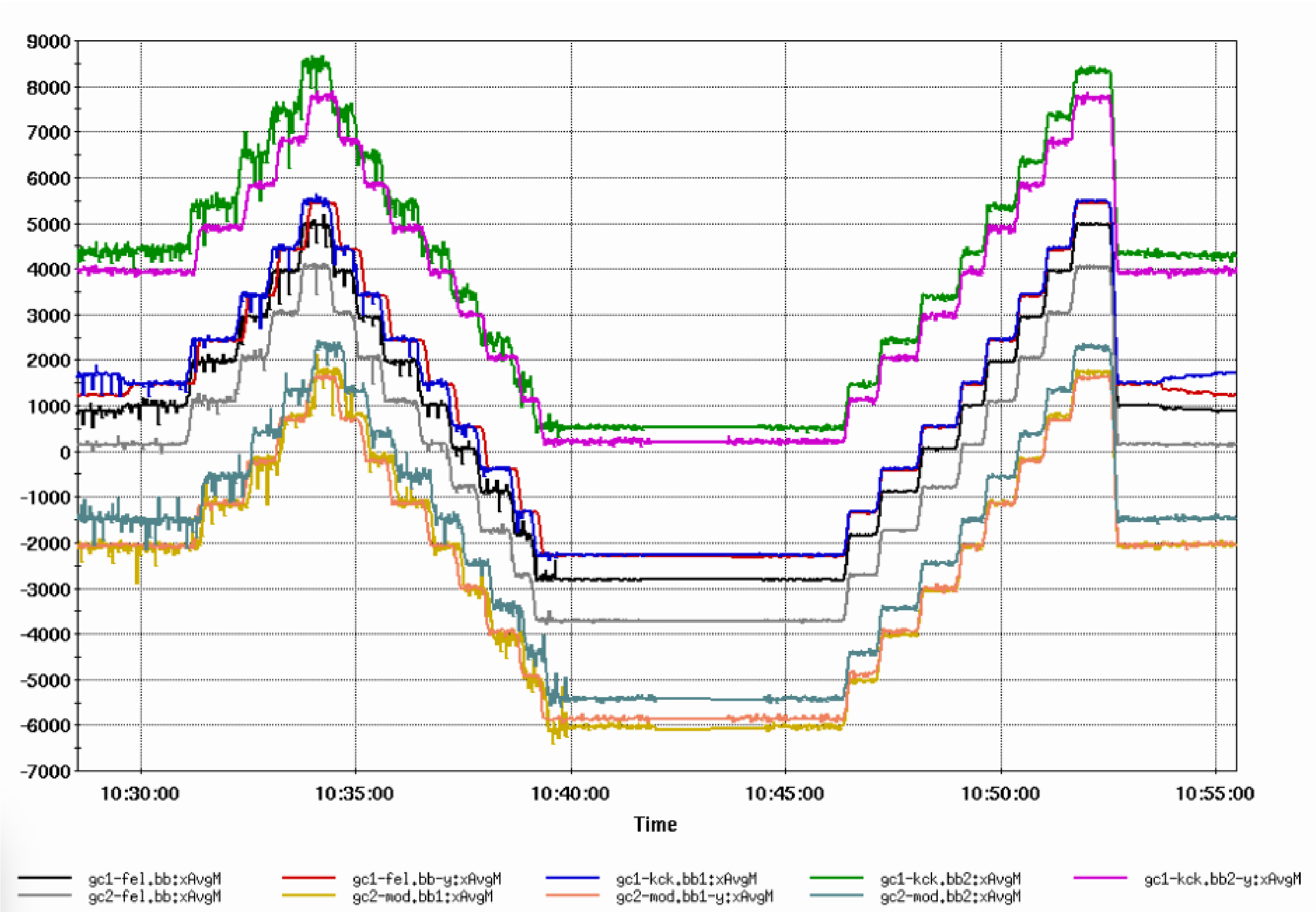
Measurements were performed with dark current





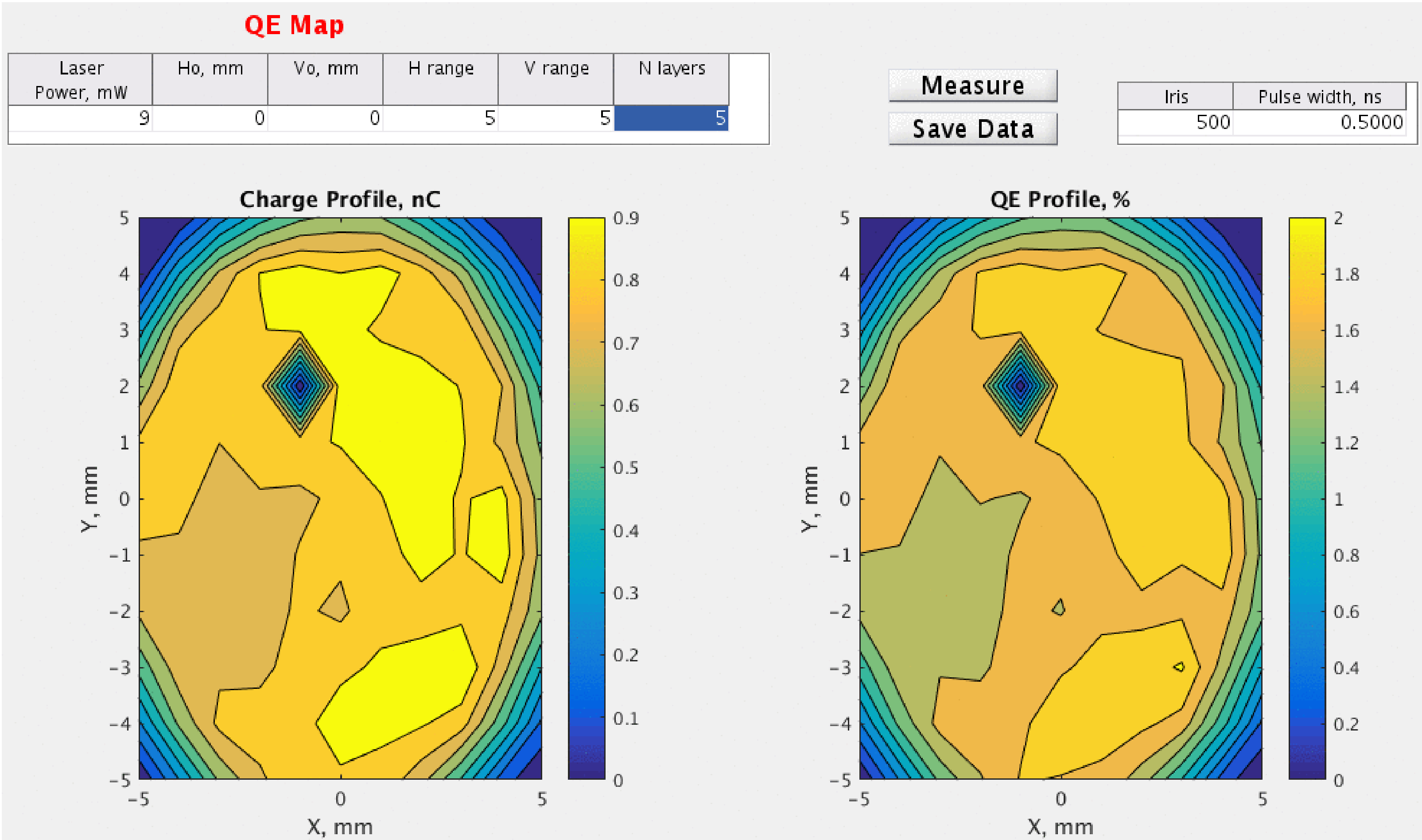
We utilized rotation of the electron beam by a calibrated solenoid to measure beam energy. The measured value was confirmed with energy spectrometer.

BPM Cross-Calibration



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

QE Map after Cathode Change (June 7th)



June 12

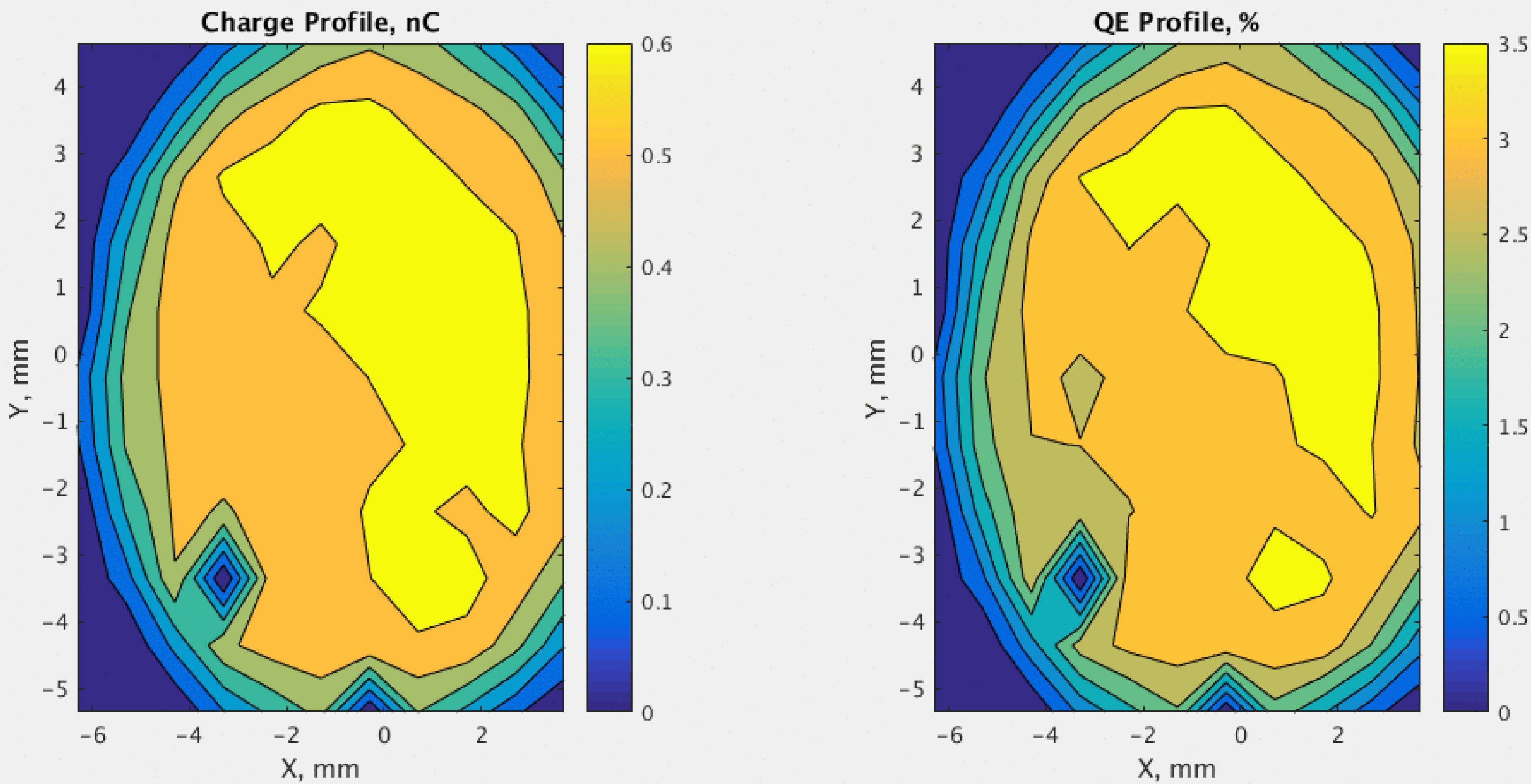
QE Map

Laser Power, mW	Ho, mm	Vo, mm	H range	V range	N layers
3.2000	-1.3000	-0.3500	5	5	5

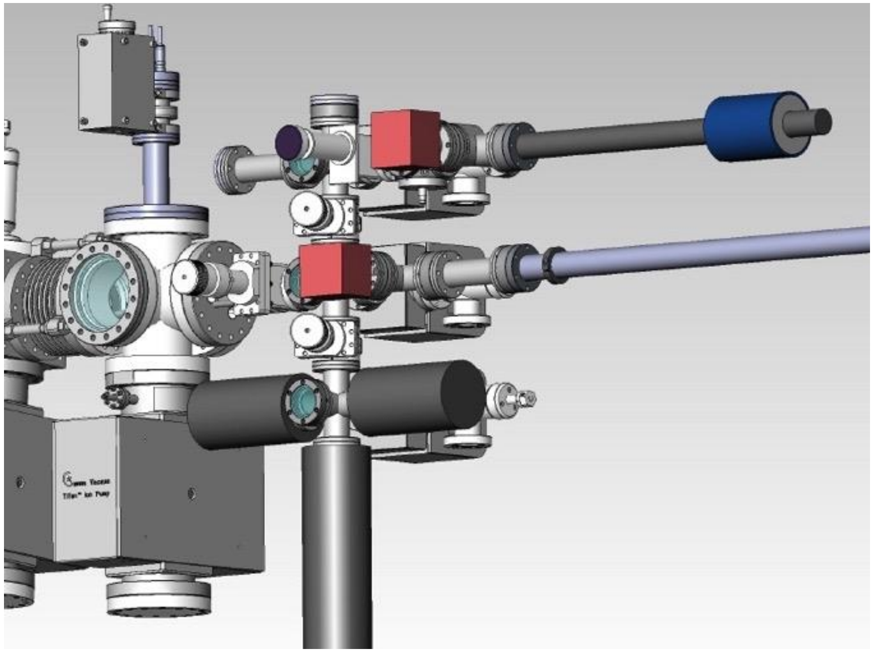
Measure

Save Data

Iris	Pulse width, ns
300	0.5000



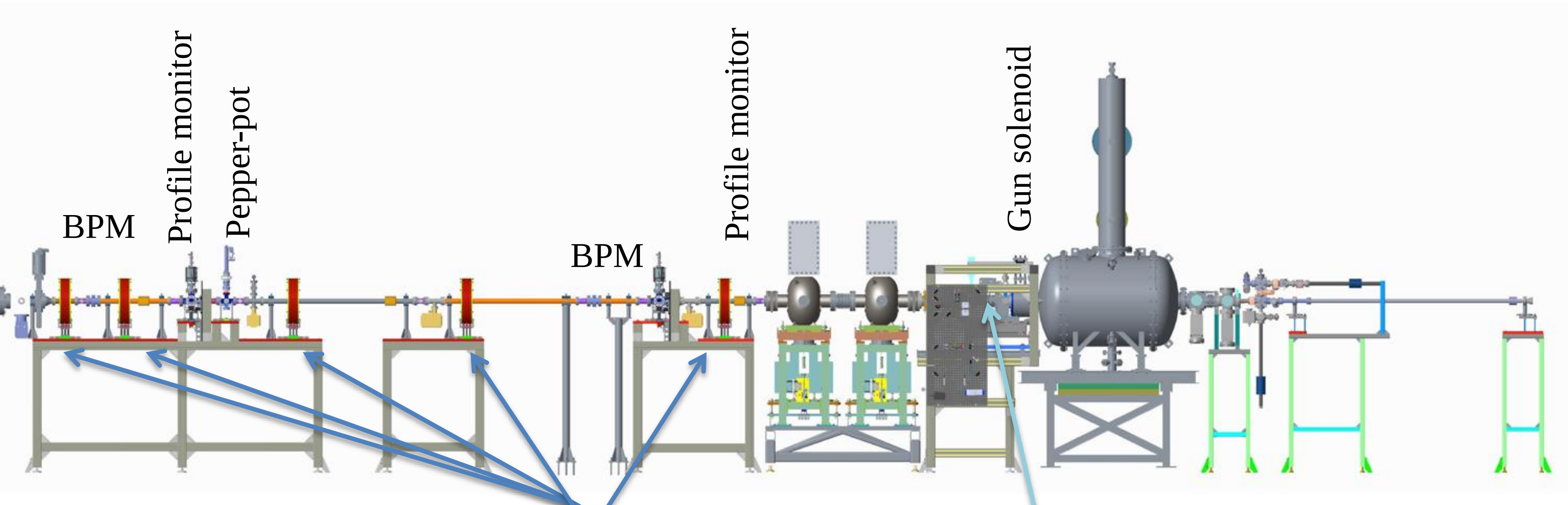
Performance Improvement during Commissioning



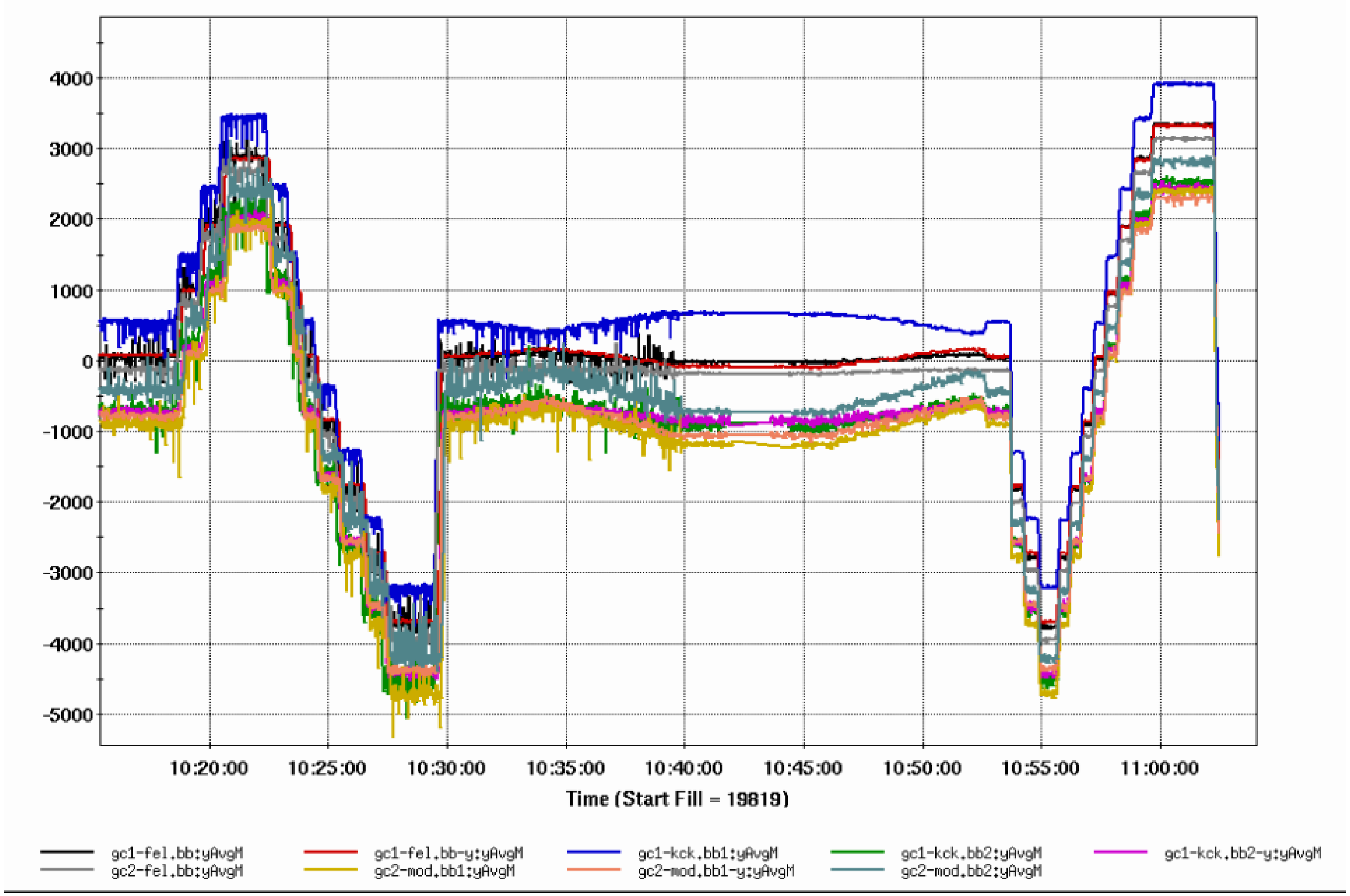
- Long conditioning cycle with molybdenum puck to suppress multipacting in the FPC area
- Helium discharge cleaning
- Rebuilt garage and cathode launch system – added port for QE monitoring inside the garage, added NEG getters
- Used mask for the cathode deposition system and developed start procedure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



Vertical Scan



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