Coherent electron Cooling (CeC) PoP experiment

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for CeC team

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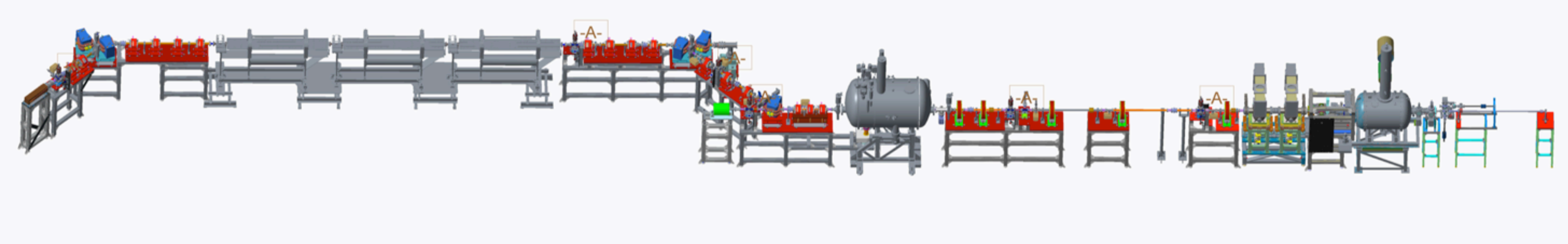
Stony Brook University, Stony Brook, NY, USA
Niowave Inc., Lansing, MI, USA, Tech X, Boulder, CO, USA
Budker Institute of Nuclear Physics, Novosibirsk, Russia
STFC, Daresbury Lab, Daresbury, Warrington, Cheshire, UK



RHIC retreat, July 29, 2016

The CeC team – never can get all your pictures …

…

……………….

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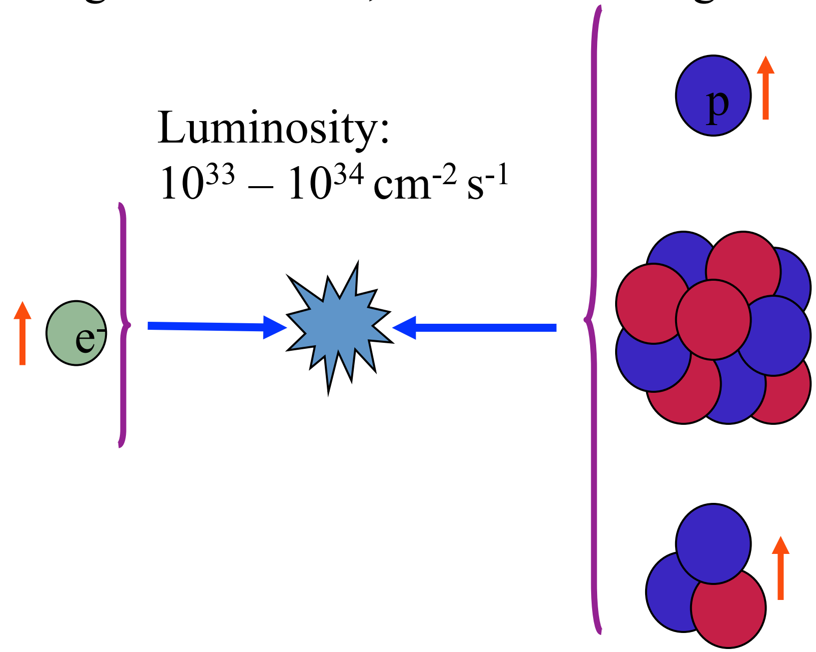
Outline

- Why we doing this?
- What is CeC PoP?
- Where are we?
    - Things achieved
    - Thing missing
    - Challenges
- Where are we going?
- Conclusions

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing \$2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

80% polarized electrons:
2.6 – 21.2 GeV



70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

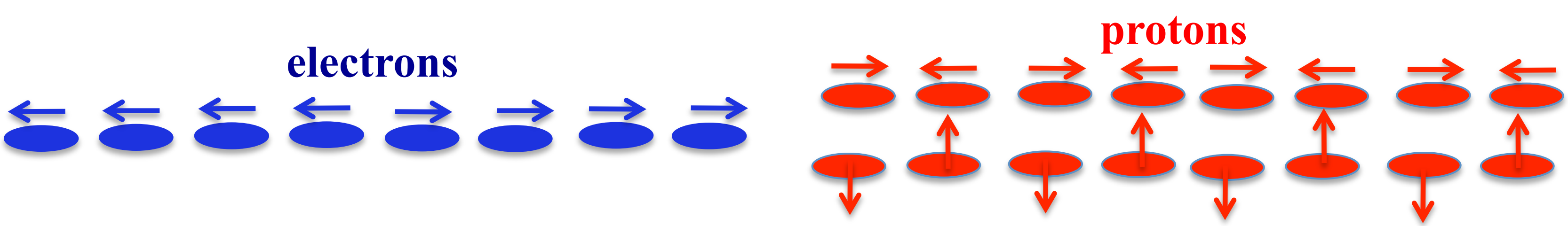
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

Center-of-mass energy range: 20 – 145 GeV

Full electron polarization at all energies

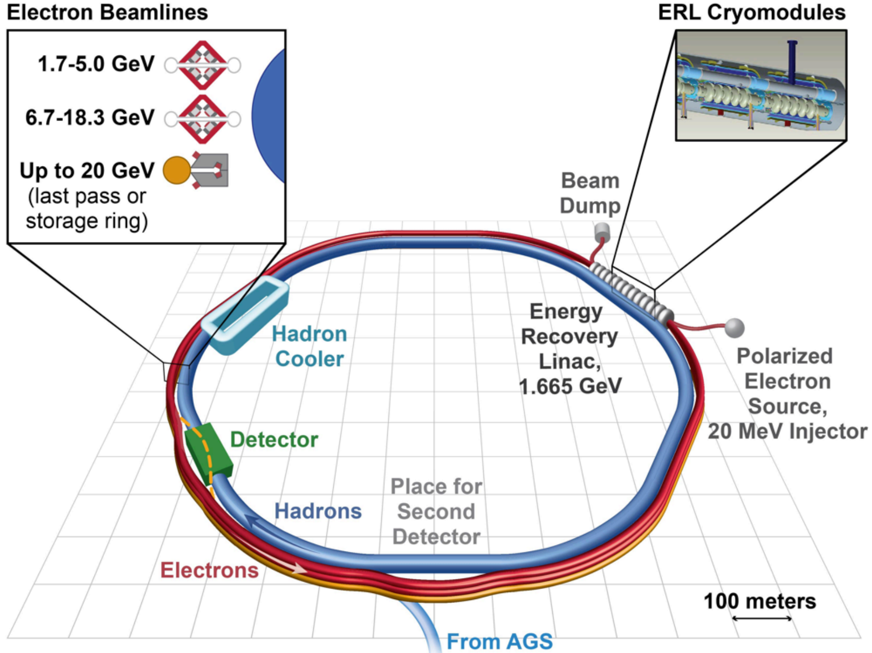
Full proton and He-3 polarization with six Siberian snakes

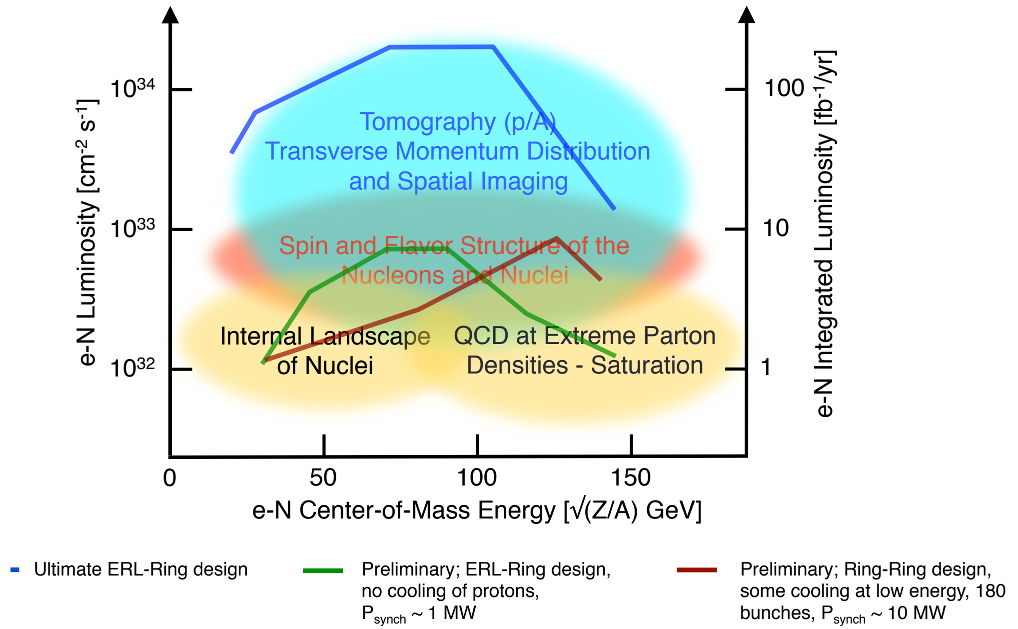
Any polarization direction in electron-hadron collisions:



* It is possible to increase RHIC ring energy by 10%

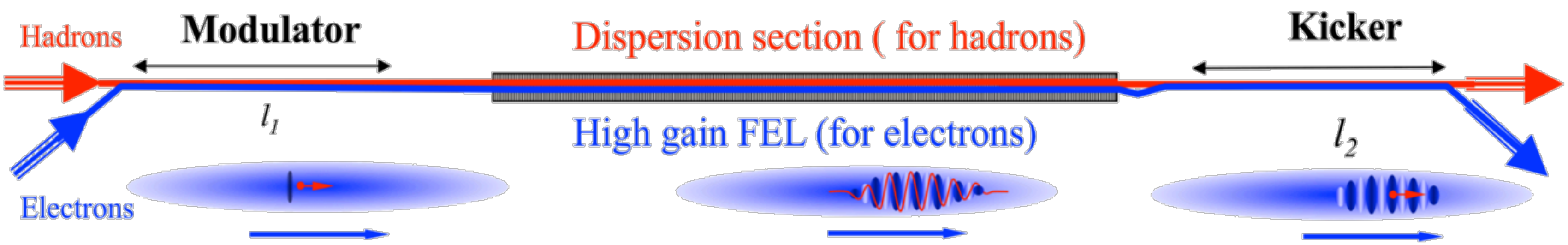
ERHIC REQUIRES STRONG HADRON COOLING:
ULTIMATE REQUIREMENT < 1 MIN COOLING TIME @ 250 GEV PROTONS



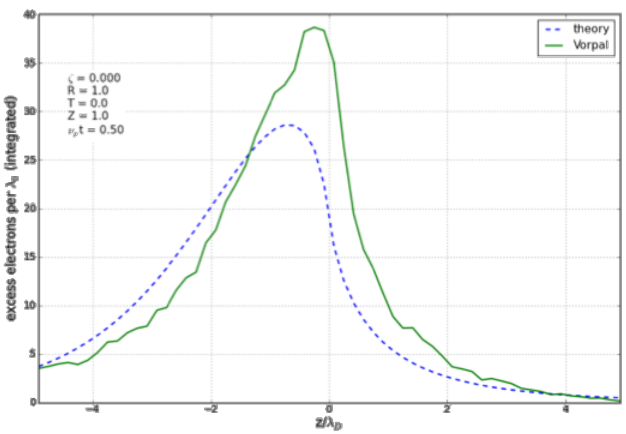


Coherent electron Cooling is needed to achieve the ultimate luminosity and has to be tested -> CeC PoP

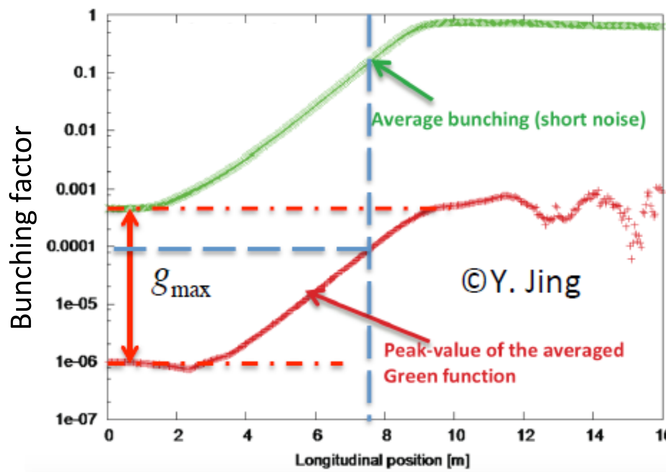
Our Proof-of-Principle is an economic version of CeC where electrons and hadrons are co-propagate along the entire CeC system



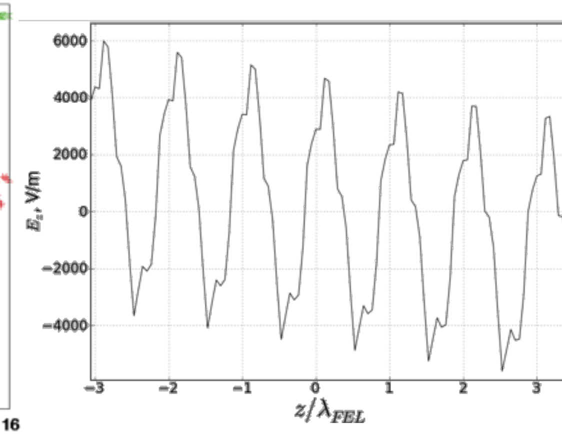
Param.'s from 40 GeV proof-of-principle exp. at BNL



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



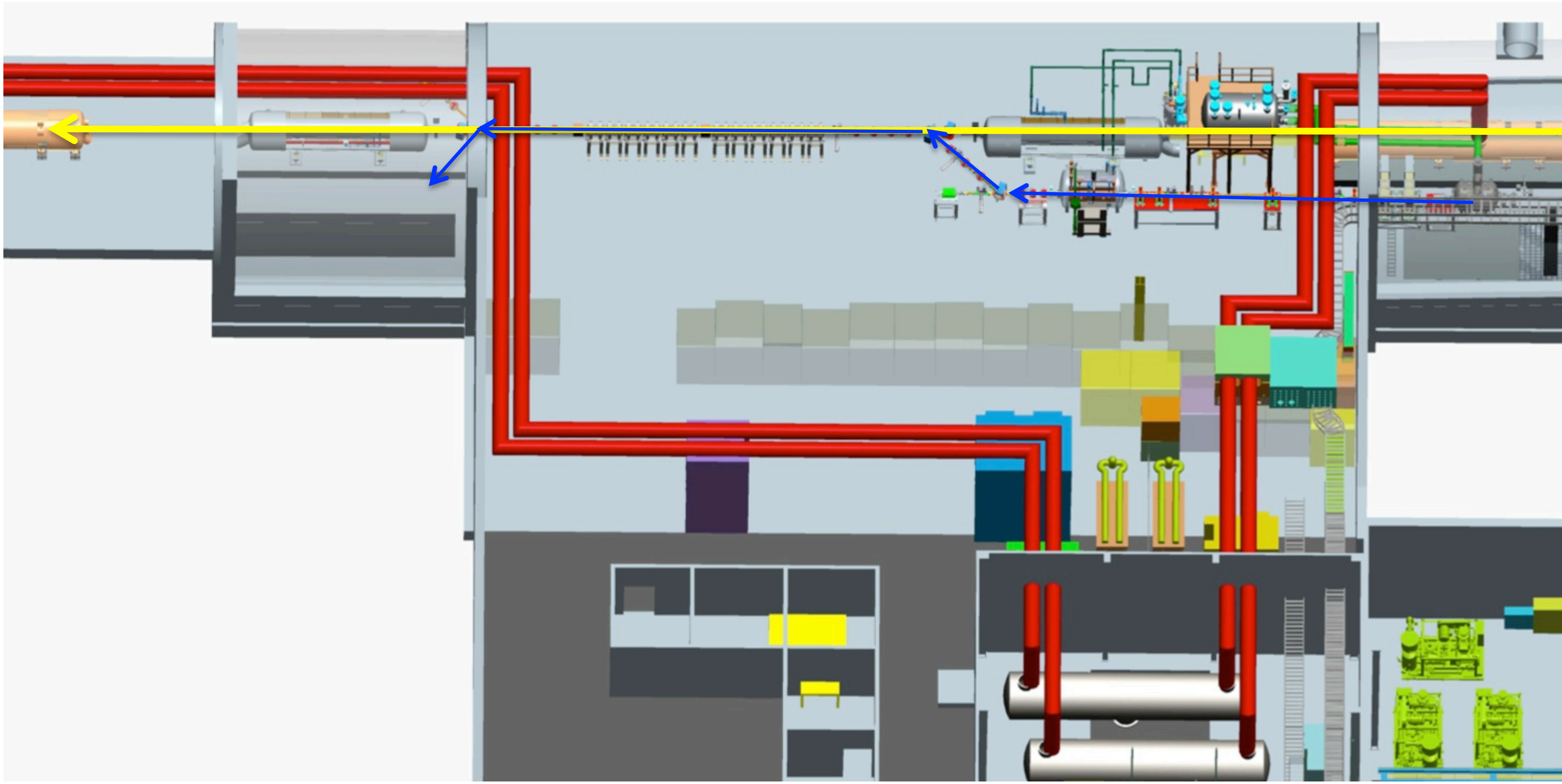
GENESIS parallel computation of electron beam bunching in free electron laser (FEL) shows amplification of modulator signal.



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

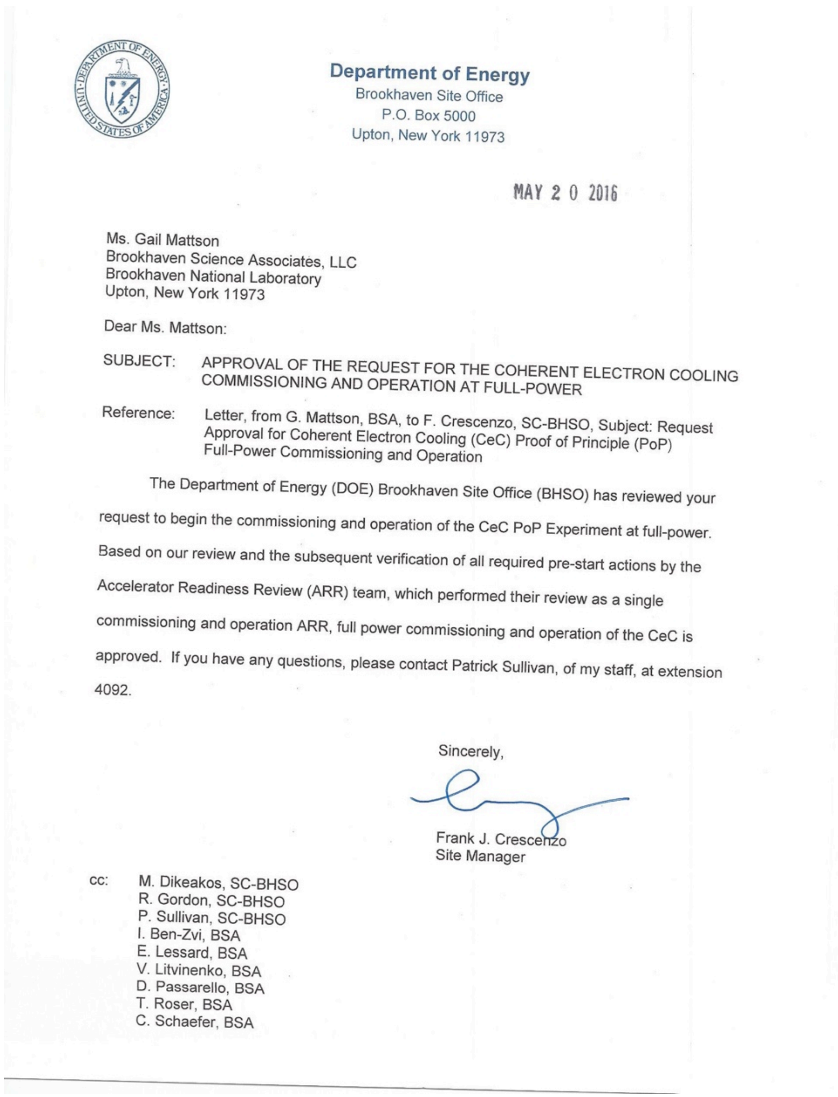
Simulations by Tech-X and Y. Jing

CeC Proof-of-Principle Experiment



Coherent electron *Cooling* PoP

Main milestones


Department of Energy
Brookhaven Site Office
P.O. Box 5000
Upton, New York 11973

MAY 2 0 2016

Ms. Gail Mattson
Brookhaven Science Associates, LLC
Brookhaven National Laboratory
Upton, New York 11973

Dear Ms. Mattson:

SUBJECT: APPROVAL OF THE REQUEST FOR THE COHERENT ELECTRON COOLING COMMISSIONING AND OPERATION AT FULL-POWER

Reference: Letter, from G. Mattson, BSA, to F. Crescenzo, SC-BHSO, Subject: Request Approval for Coherent Electron Cooling (CeC) Proof of Principle (PoP) Full-Power Commissioning and Operation

The Department of Energy (DOE) Brookhaven Site Office (BHSO) has reviewed your request to begin the commissioning and operation of the CeC PoP Experiment at full-power. Based on our review and the subsequent verification of all required pre-start actions by the Accelerator Readiness Review (ARR) team, which performed their review as a single commissioning and operation ARR, full power commissioning and operation of the CeC is approved. If you have any questions, please contact Patrick Sullivan, of my staff, at extension 4092.

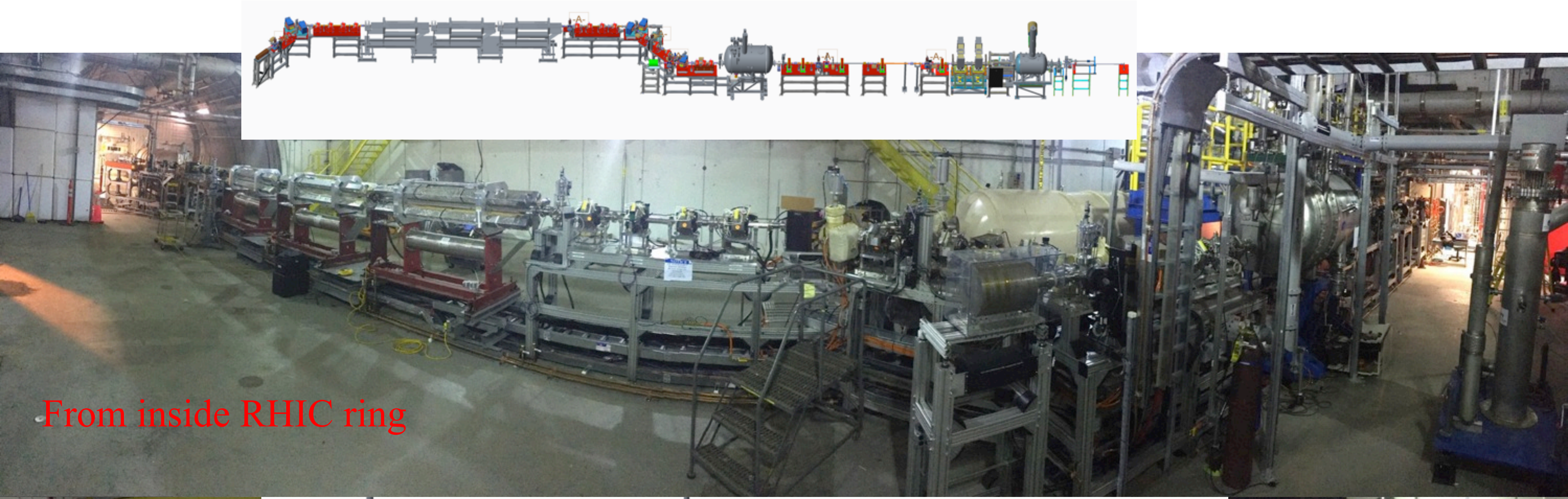
Sincerely,

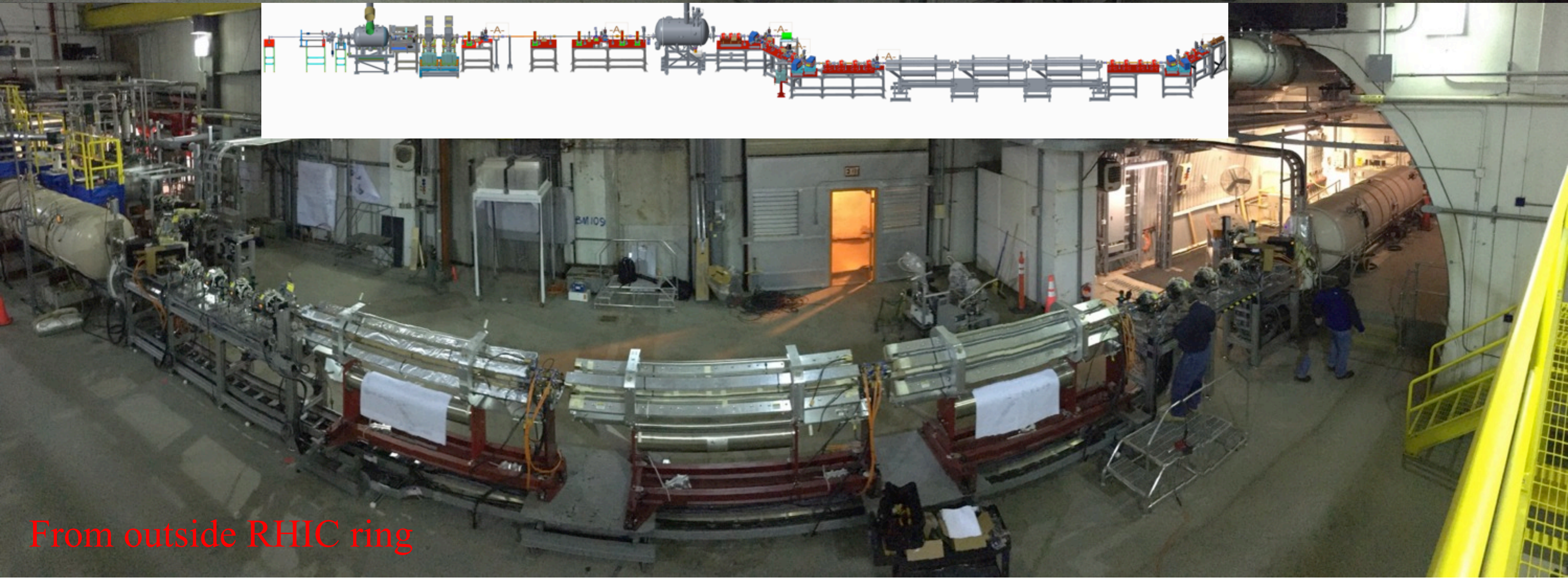
Frank J. Crescenzo
Site Manager

cc: M. Dikeakos, SC-BHSO
R. Gordon, SC-BHSO
P. Sullivan, SC-BHSO
I. Ben-Zvi, BSA
E. Lessard, BSA
V. Litvinenko, BSA
D. Passarello, BSA
T. Roser, BSA
C. Schaefer, BSA

- ✓ IRR – **December 21-22, 2015**
- ✓ CeC PoP is installed in IR2
  February 15, 2016
- ✓ ARR – **March 1-2, 2016**
- ✓ Low power test exemption
  March 8, 2016
- ✓ First beam
  March 10, 2016
- ✓ Approval for CeC PoP commissioning and full power operation
  May 20, 2016
- ✓ Beam propagated through the entire CeC system
  June 14, 2016
- ✓ End of the run
  June 27, 2016 8 am

Panoramic views





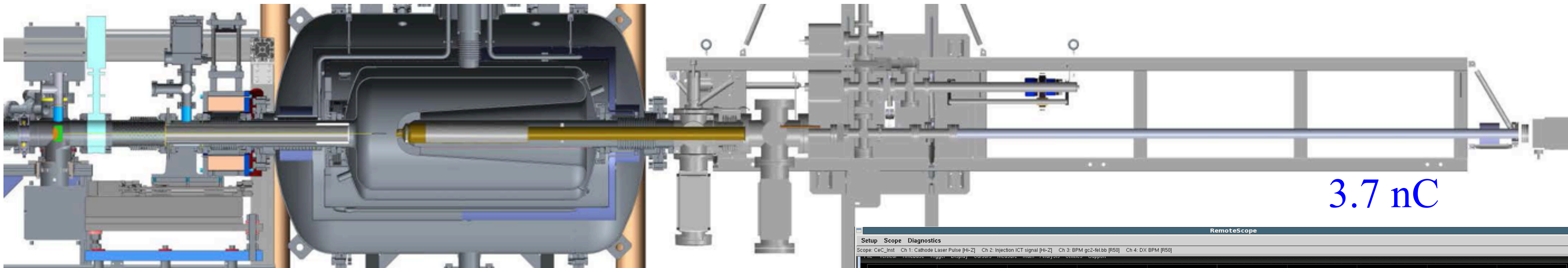
Main Beam Parameters for CeC Experiment

Parameter	Value	Status
Species in RHIC	Au^{+79} ions, 40 GeV/u	✔
Relativistic factor	42.96	✔
Particles/bucket	10^8 - 10^9	✔
Electron energy	21.95 MeV	< 10 MeV
Charge per e-bunch	0.5-5 nC	✔ (> 3.5 nC)
Rep-rate	78.17 kHz	5 kHz*
e-beam current	0.39 mA	Few μA
Electron beam power	8.6 kW	< 10 W

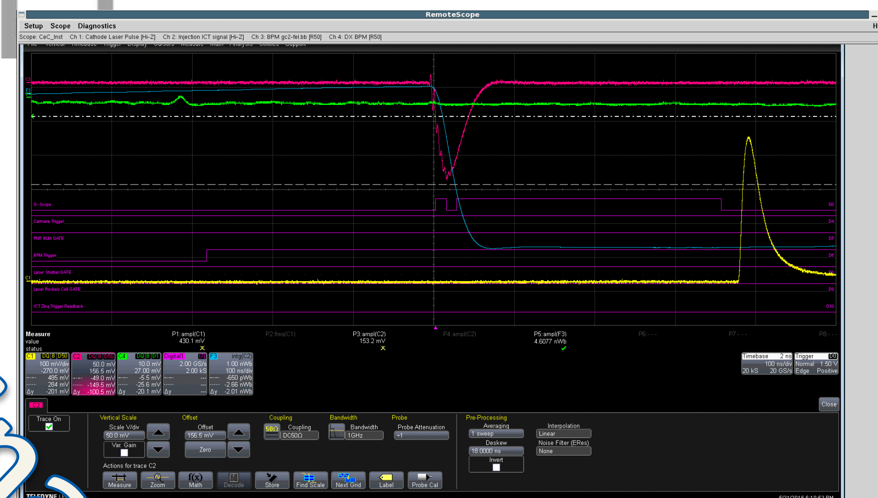
** We did not operated 5 kHz with 4.6 nC per bunch at the same time*

*** Numbers listed in blue do not require modification of equipment*

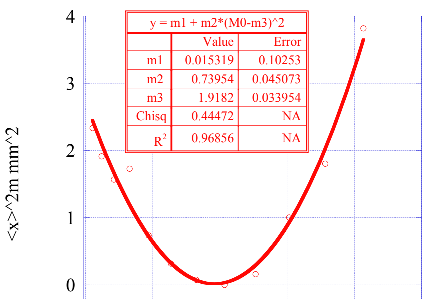
Record performance of 112 MHz SRF photo-electron gun

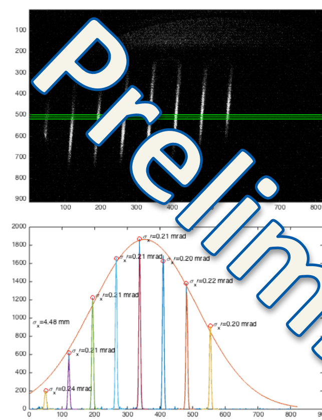


3.7 nC



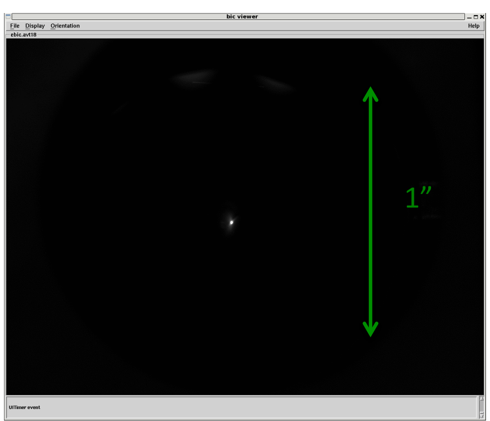
SRF gun at 1.15 MV

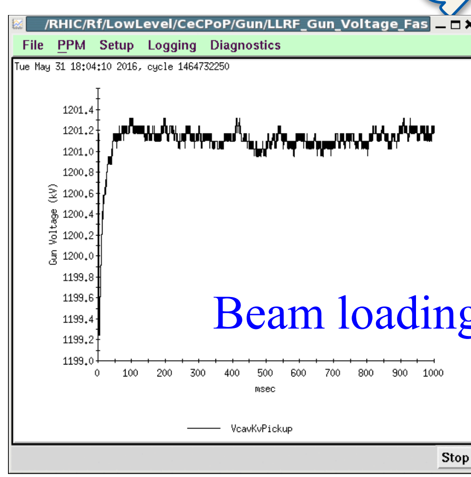




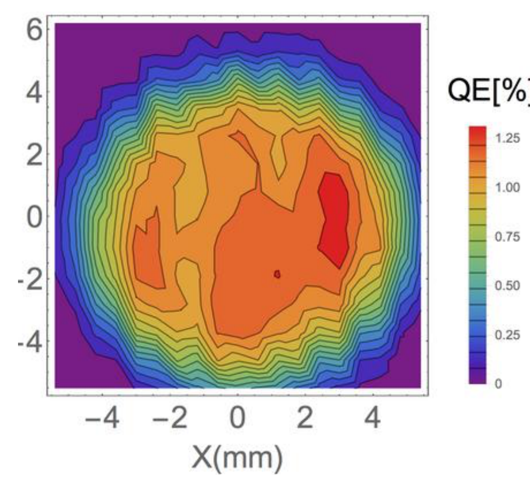
Preliminary

$\varepsilon_n < 0.5$ mm mrad at 0.5 nC

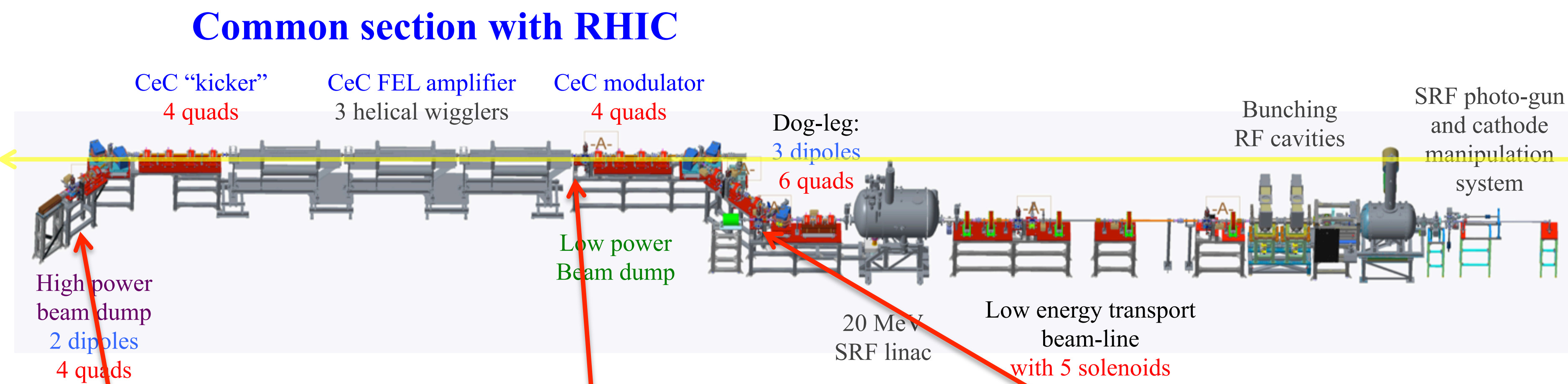


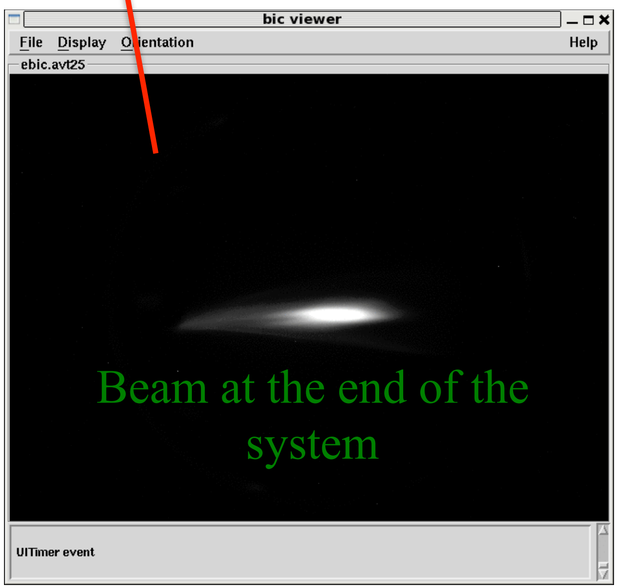


Beam loading

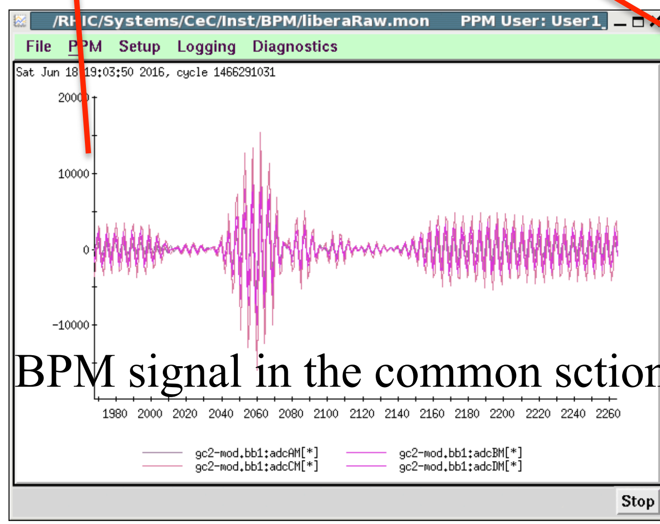


The CeC system commissioning

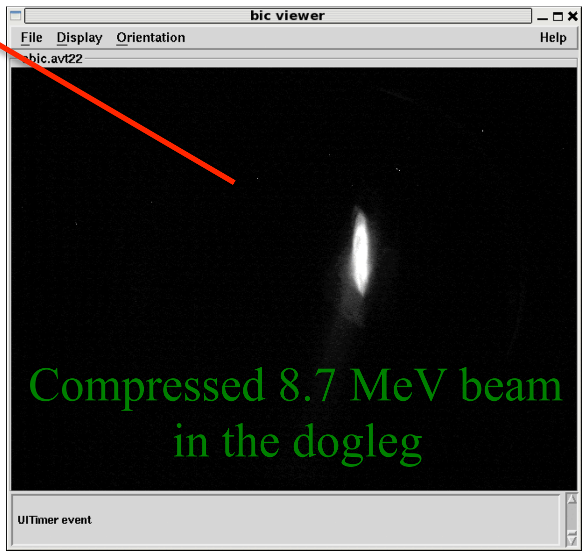




Beam at the end of the system



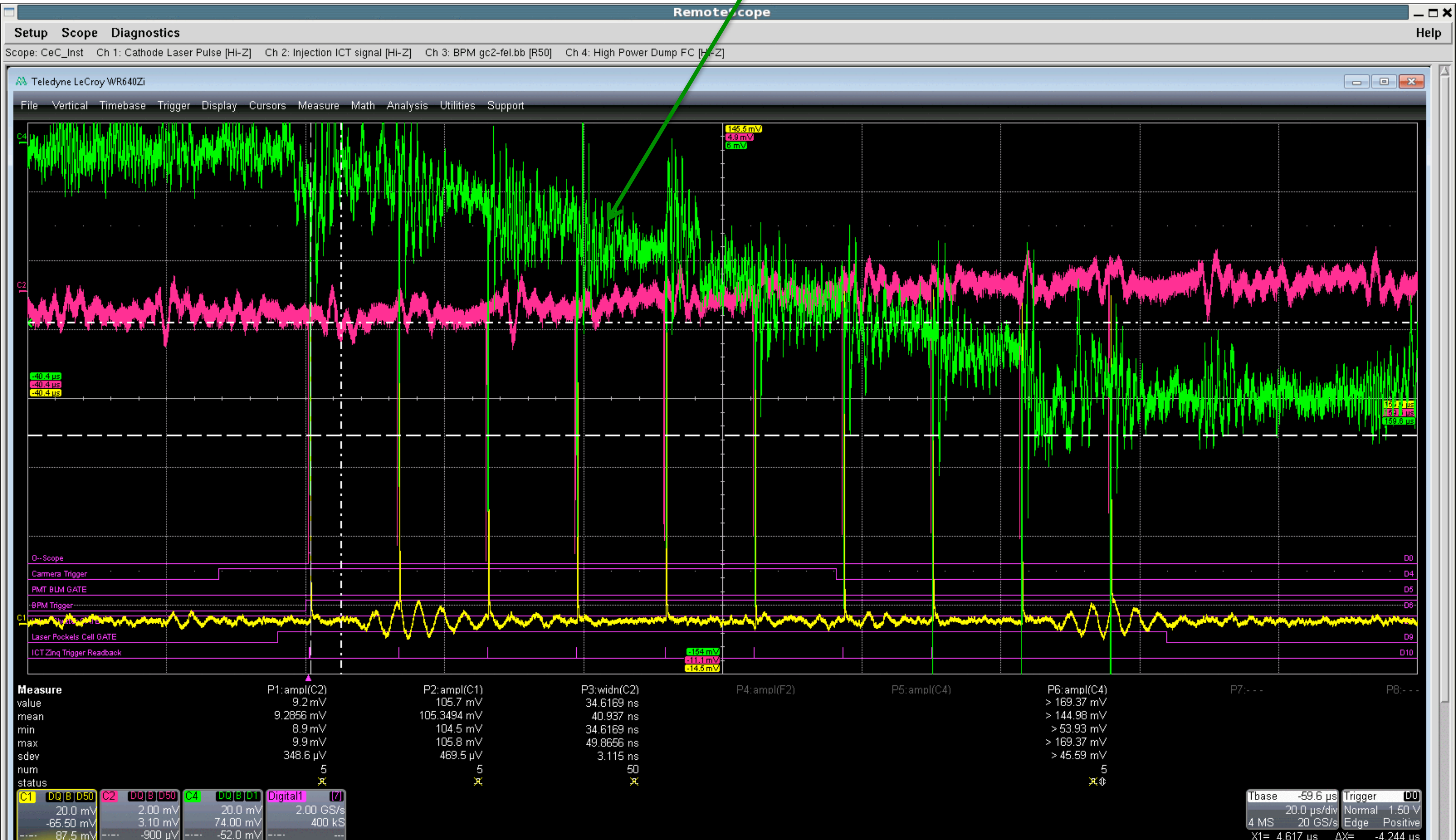
BPM signal in the common sction



Compressed 8.7 MeV beam in the dogleg

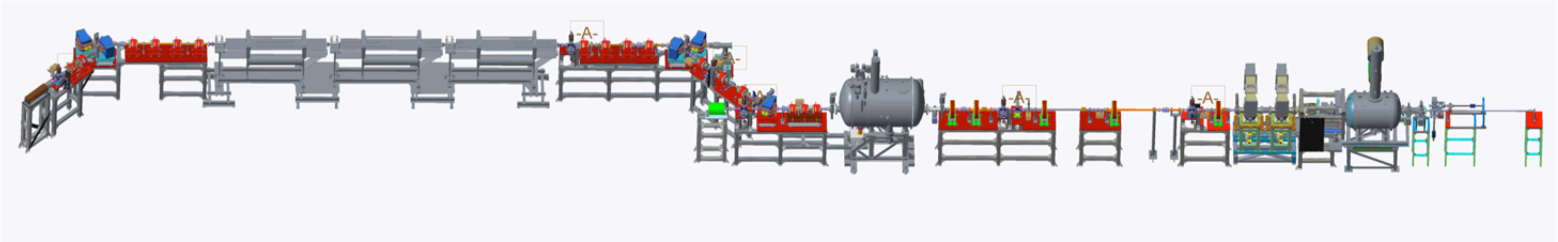
Beam was generated, compressed, accelerated to about 8 MeV and propagated through the entire system to the high power beam dump

June 14, 2016 – beam at the high power beam dump/ Faraday cup



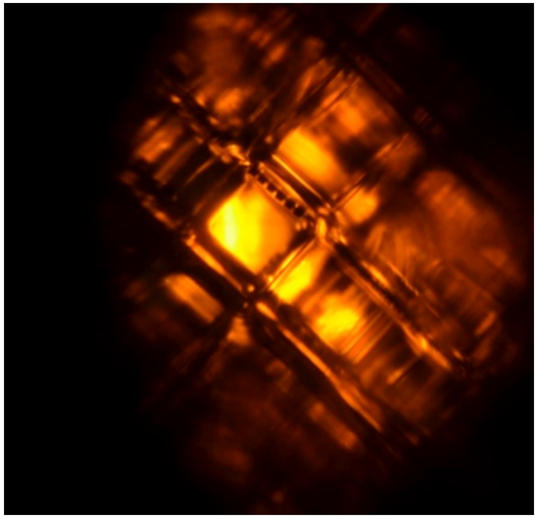
Where are we at the moment?

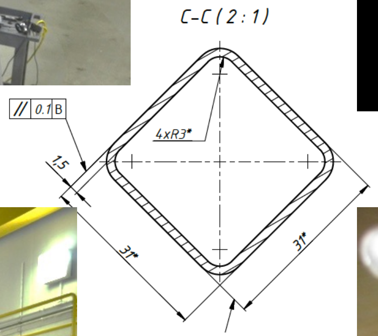
- ✓ SRF gun is operational at 1.15 MV CW , cathodes are available, laser is operational, designed charge per bunch can achieved
- ✓ 500 MHz RF bunching RF cavities are fully operational and synched with SRF gun
- ✓ Most of the beam diagnostics is working, beam is propagated to the entrance to the common section

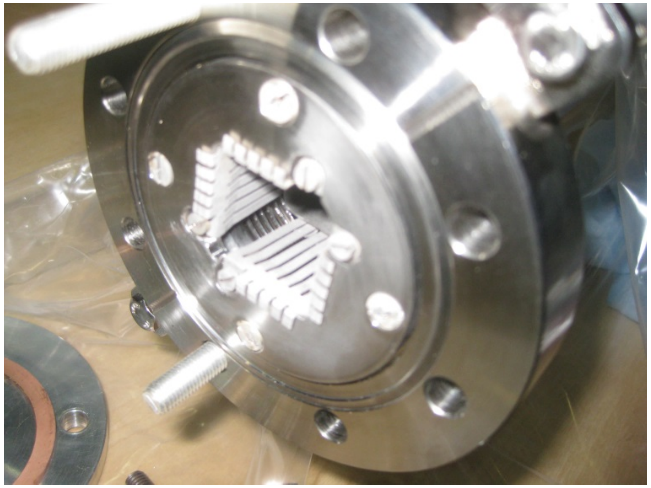


- ✓ "20 MeV" 744 MHz SRF linac has major problems. It can generate about 10 MV in stand along mode, but only ~ 5-6 MV when synched to the gun
- ✓ Beam energy was sufficient to propagate full current beam to the full power beam dump, but not for CeC commissioning
- ✓ Control system a very basic and unreliable, resulted a major time loss during the commissioning

IP2 APERTURE LIMITATIONS: REQUIRED ACCURATE ALIGNMENT







Big picture

- Shutdown – repairs and improvements
- Run 17
  - Finish commissioning of CeC accelerator at full energy and power: 21 MeV, 78 kHz, few nC
  - Establish interactions with ion beam
  - Establish FEL amplification
  - Cool ion beam
- Run 18
  - Reestablish CeC operation
  - Characterize CeC cooling

Plans for CY 2016 shutdown

704 MHz SRF Accelerator

- Disassemble
- Repair and clean cavity
- Clean FPC
- Assemble and re-install
- Repair/re-build tuner
- Suppress microphonics

113 MHz SRF gun

- Replace gun power amplifier
- Improve coupling control
- Replace FPC drive
- Align the gun (need to verify)
- Improve cathode garages
- Laser transport/pulse shape
- Test multialkaline cathodes

Diagnostics

- Cages in the profile monitors
- Color camera for gun
- Lenses with controlled aperture
- Update MPS
- Install IR diagnostics
- ICTs signal conditioning
- Shield gun ICT
- Fix "crashing" BPMs software

Others

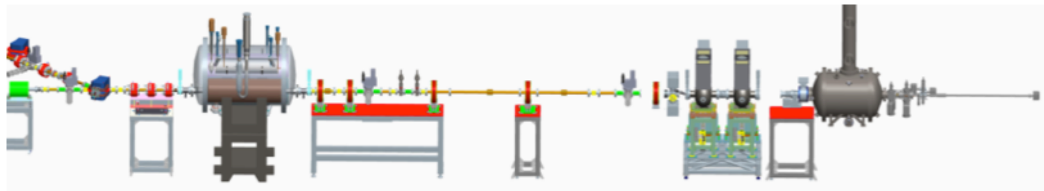
- Air-core correctors in the LEBT
- Suppress 500 MHz RF leak
- Dedicated chassis for laser timing
- 500 MHz PA remote on/off
- Streamline PET and Syndi pages
- Set-up loggers
- Develop modern acc controls

Run 17

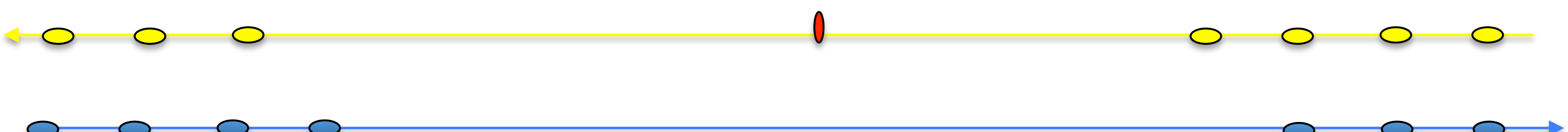
- Most of CeC activities -in parallel with RHIC operation:
  - Re-commissioning of the accelerator
  - Low power beam propagation to the HP beam dump
  - Establishing FEL amplification, Run 17
  - ….
- We plan to use APEX for establishing new modes of operation
- – 2 weeks of dedicated time is needed - spread over the run
  - Establishing interaction between the ion and e-beam
  - FEL Amplification of the interaction
  - Attempting CeC cooling of ion beam
- Recourses needed
  - Technical support for cathode making/transport/exchange
  - Technical support for maintaining all CeC systems: cryo, SRF/RF, magnets, vacuum, diagnostics, controls, MPS, PPS
  - Help for RHIC operators with RF conditioning and maintaining "routine" operation mode of CeC systems

How we will operate in parallel with RHIC

- Commissioning of CeC accelerator
  - Parallel to RHIC operation, except occasional requests for access



- Propagating electron beam through the IP2 to the dump
- Parallel to RHIC operation: electron bunches passing through the IP2 during Blue abort gap and between 2 yellow bunches



What means to do it safe?

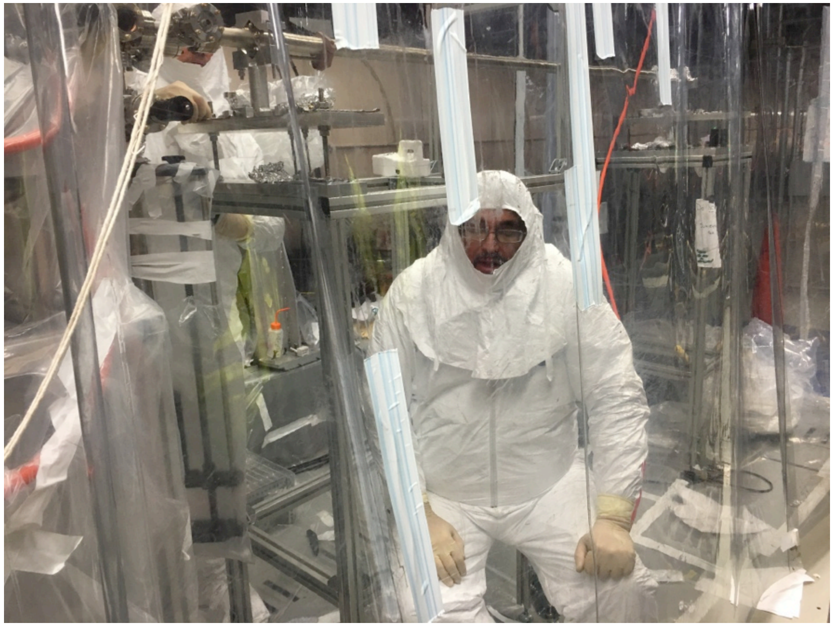
1. Conditioning – re-commissioning of CeC RF system (112 MHz, 500 MHz & 704 MHz) to design voltage, synchronized with 78 kHz tone, full control of voltage and phase
2. Accelerate beam to 20 MeV and beam power under 1W
3. Measure beam parameters (charge, emittance, peak current, energy spread…)
4. Increase beam power 10x: 1W -> 10 W ->100 W – 1kW -> full power
    - follow increases by radiation surveys (and fault studies <10 W)
5. Propagate full power 20 MeV e-beam to the beam dump, match the beam into FEL
6. Commission IR FEL diagnostics and demonstrate FEL amplification
7. Co-propagate, align and synchronize electron and ion beams
8. Match relativistic factors (velocities) of hadron and electron beams
9. Observe amplification of the density modulation
10. Attempt to observe local cooling

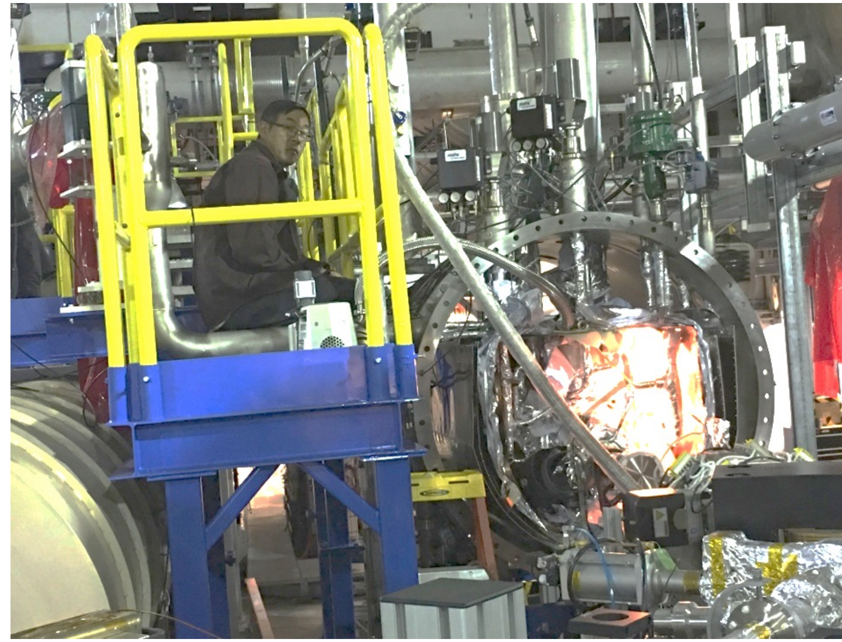
Conclusions

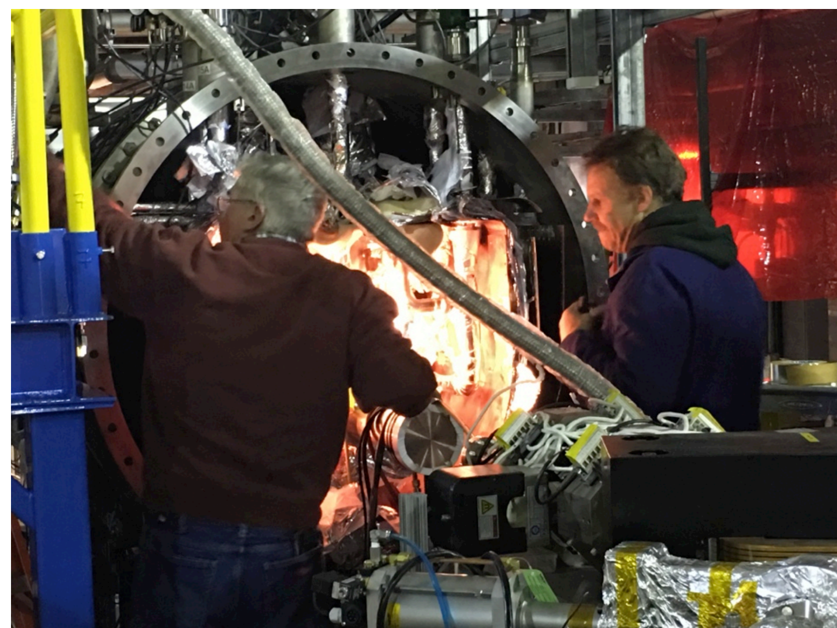
- ✓ **We have a very successful CeC commissioning during Run 16**
  - ✓ Our SRF gun is establishing world-record performance
  - ✓ Beam was propagated from the gun to the end of the CeC beamline
- ✓ **Repairs/Improvements during RHIC shutdown are critically important**
  - ✓ Main items: 20 MeV SRF linac and IR diagnostics
- ✓ **RHIC Run17 is critical for demonstrating CeC as viable cooling technique**
  - ✓ We need all help we can get, especially from cryo, RF, vacuum, control and MCR groups

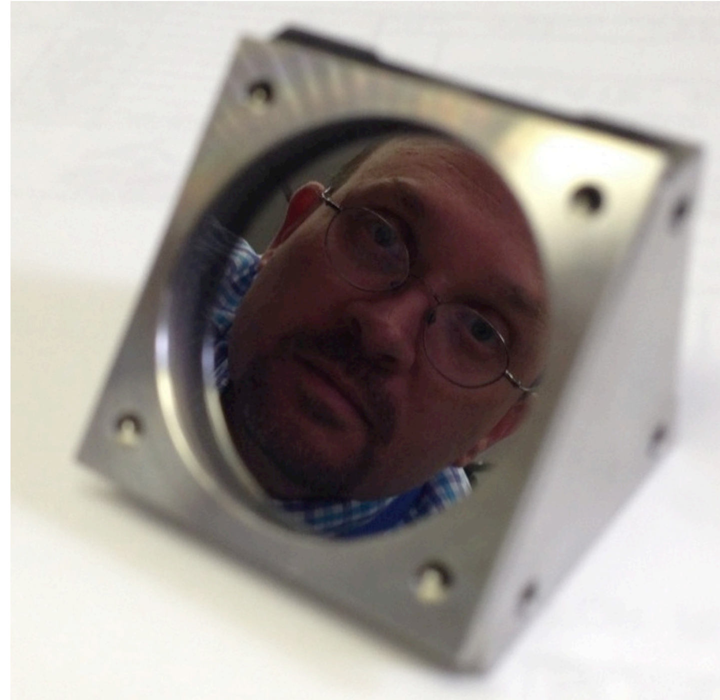
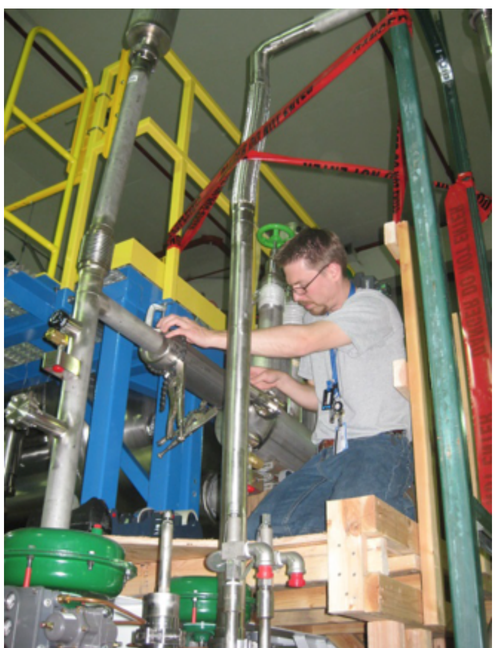
Back-up slides


ADIDAS









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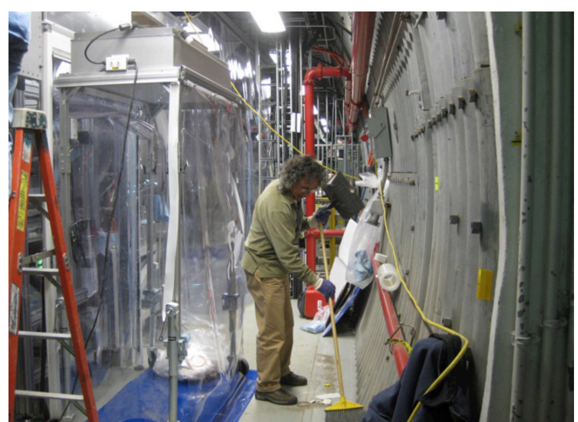
CLEANROOM
APPAREL!



Main steps for CeC

0. Finish installation of CeC PoP system into IP2
1. Developing RHIC ramp with proper beam envelope (beta*) in IP2
2. Developing RHIC ramp for CeC PoP experiment
3. CeC ARR
4. Conditioning of CeC RF system (112 MHz, 500 MHz & 704 MHz): design voltage, synchronized to RHIC beam, full control of voltage and phase
5. Re-commission the SRF gun, 500 MHz bunching cavities and accelerate beam to 20 MeV and beam power < 1W
    1. 704 MHz SRF linac is contaminated and accelerating voltage is limited to 10 MV in PLL mode and **to 5-6 MV in IQ mode, which is REQUIRED for operating beam**
6. Measure beam parameters (charge, emittance, peak current, energy spread…)
7. Increase beam power 10x. follow by radiation surveys (and fault studies <10 W)
8. Propagate full power 20 MeV e-beam to the beam dump, match the beam into FEL
9. Commission IR FEL diagnostics and demonstrate FEL amplification
10. Co-propagate, align and synchronize electron and ion beams
11. Match relativistic factors (velocities) of hadron and electron beams
12. Observe amplification of the density modulation
13. Attempt to observe local cooling

Record Beam Generated by SRF Gun Operating in CW Mode

Bunch charge exceeds 4 nC

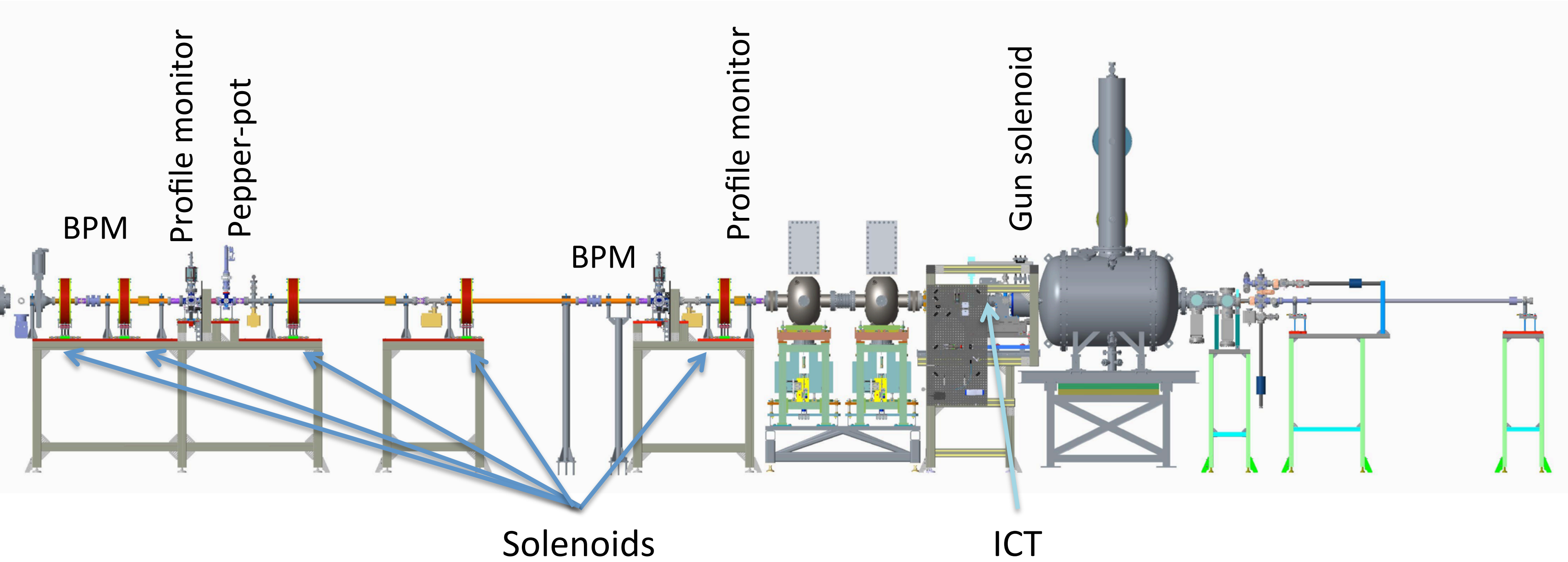
Beam energy 1.6-1.7 MeV (CW), >2 MeV (pulse)

We have demonstrated electrical field at time of emission exceeding 21 MV/m

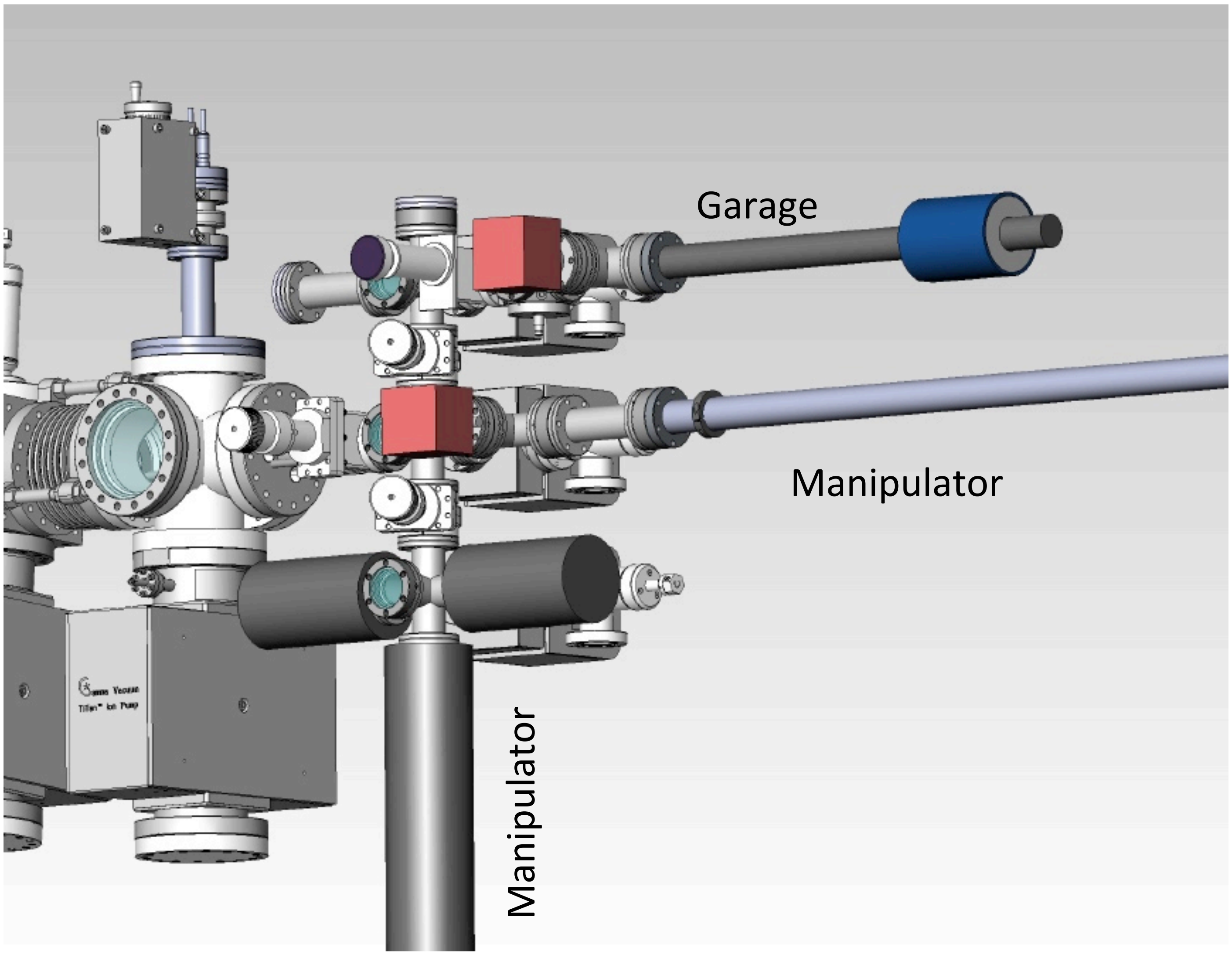
	FZD	HZD	NPS	Wisconsin	CeC
Charge, pC	300	6	78	100	4600
E, MV/m	5	5-7	6.5	12	21
Frequency	1.3 GHz	1.3 GHz	500 MHz	200 MHz	113 MHz
Cathode	Cs_2Te	Pb	Nb	Cu	CsK_2Sb

Diagnostics for Low Energy Beam

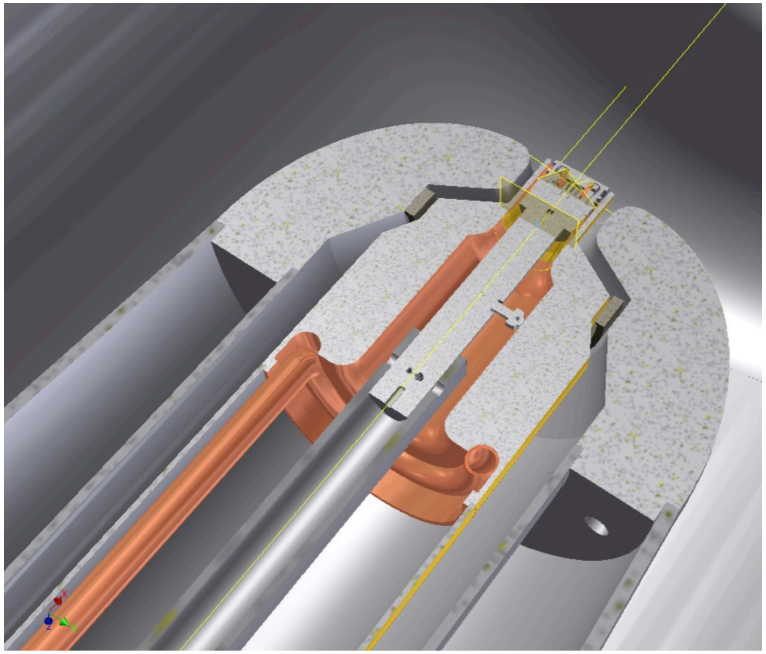
- Integrating current transformer (1.25 nV s/nC)
- Two beam profile monitors with 1.3 megapixel cameras
- Pepper-pot in front of the second profile monitor
- Two BPMs
- Low power beam dump with Faraday cup

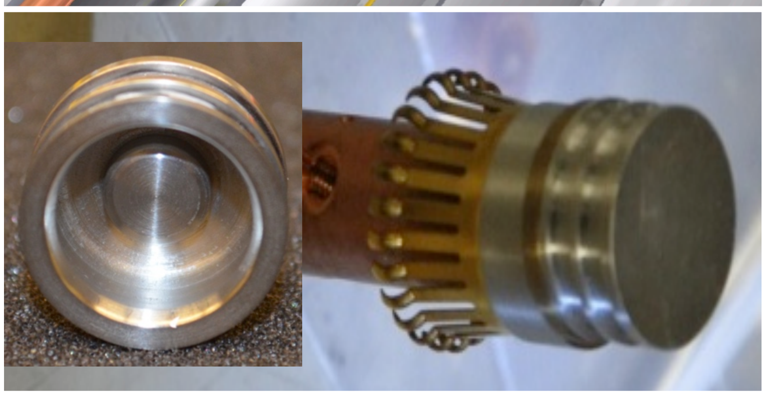


Modified Cathode Launch System



Problems Encountered





Photocathode end assembly

Multipacting in the FPC area – long conditioning cycle with molybdenum puck

Excessive dark current – helium discharge cleaning

Photocathodes found dead prior insertion into the gun – added port for QE monitoring inside the garage

Substantial spikes in the residual pressure during insertion into the gun – added NEG getters

Multipacting inside the cathode stalk – used mask for the cathode deposition system, developing start procedure

Continuous vacuum problem with cathode launch system – re-build

Principle of Coherent Electron Cooling

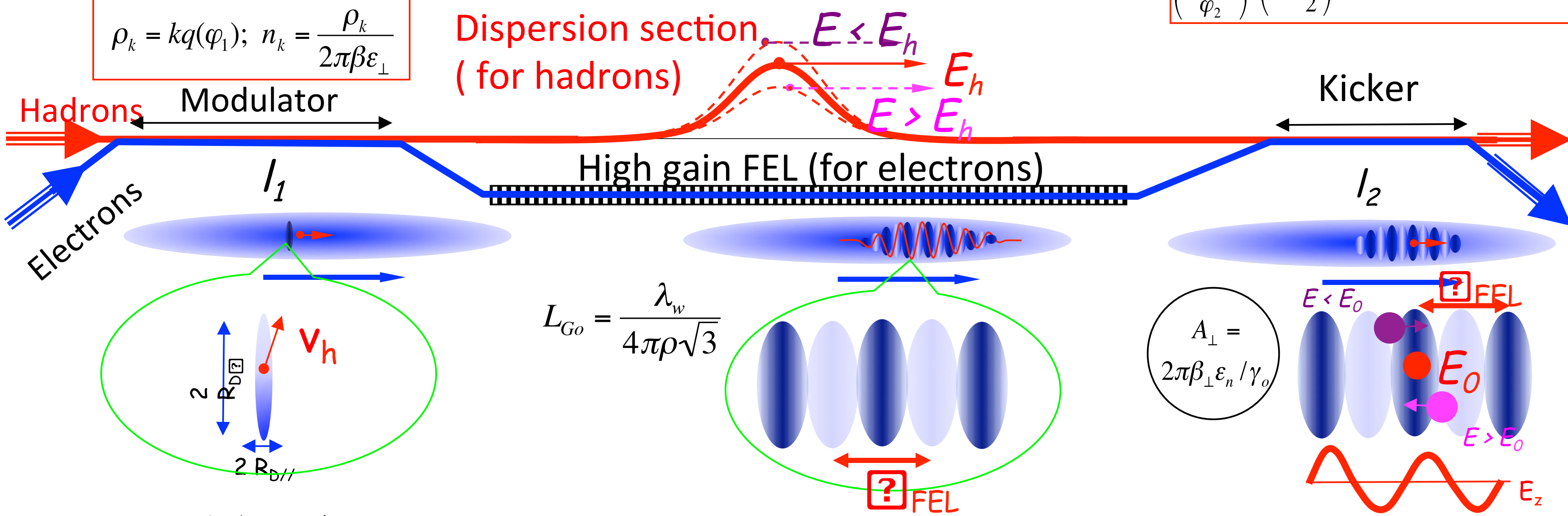
At a half of plasma oscillation

$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

$$\rho_k = kq(\varphi_1);\ n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

$$c\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D_{free} = \frac{L}{\gamma^2};\ \ D_{chicane} = l_{chicane}\cdot\theta^2 \ldots\ldots$$

$$\Delta E_h = -e\cdot\mathbf{E}_o\cdot l_2\cdot\sin\left(k_{FEL}D\frac{E-E_o}{E_o}\right)\cdot\left(\frac{\sin\varphi_2}{\varphi_2}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2\cdot Z\cdot X;\ \ \mathbf{E}_o = 2G_o e\gamma_o/\beta\varepsilon_{\perp n}$$



Debye radii

$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_p}\qquad R_{D\perp} >> R_{D//}$$

$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_p} << \lambda_{FEL}$$

Amplifier of the e-beam modulation in an FEL with gain G_{FEL}~10^2-10^3

$$\mathbf{E}_o = 2G_o\gamma_o\frac{e}{\beta\varepsilon_{\perp n}}$$

$$n_{amp} = G_o\cdot n_k\cos(k_{cm}z)$$

$$k_{cm} = \pi/\gamma_0\lambda_{FEL}$$

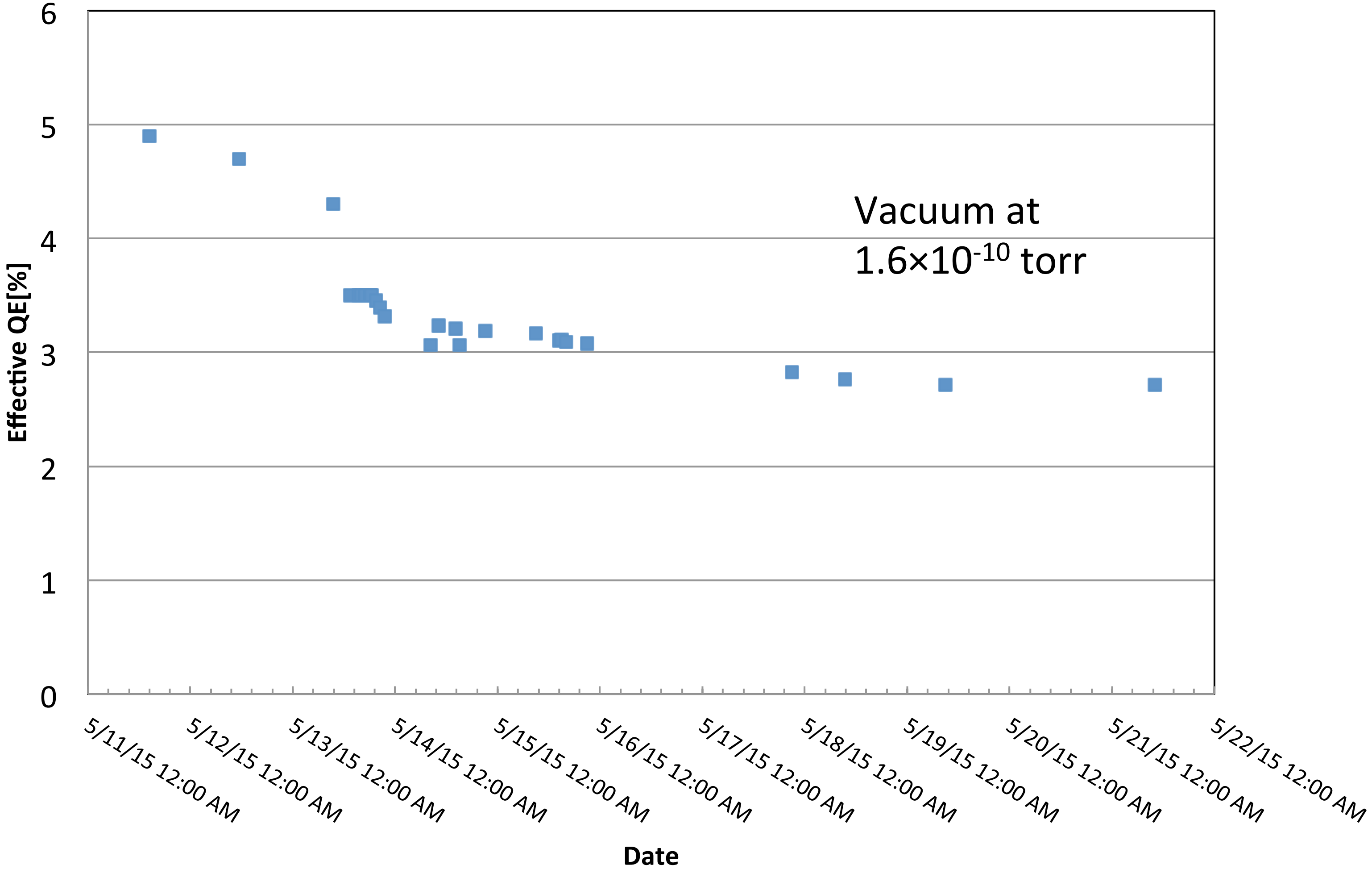
$$\Delta\varphi = 4\pi en \Rightarrow \varphi = -\varphi_0\cdot\cos(k_{cm}z)$$

$$\vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\mathbf{E}_o\cdot X\sin(k_{cm}z)$$

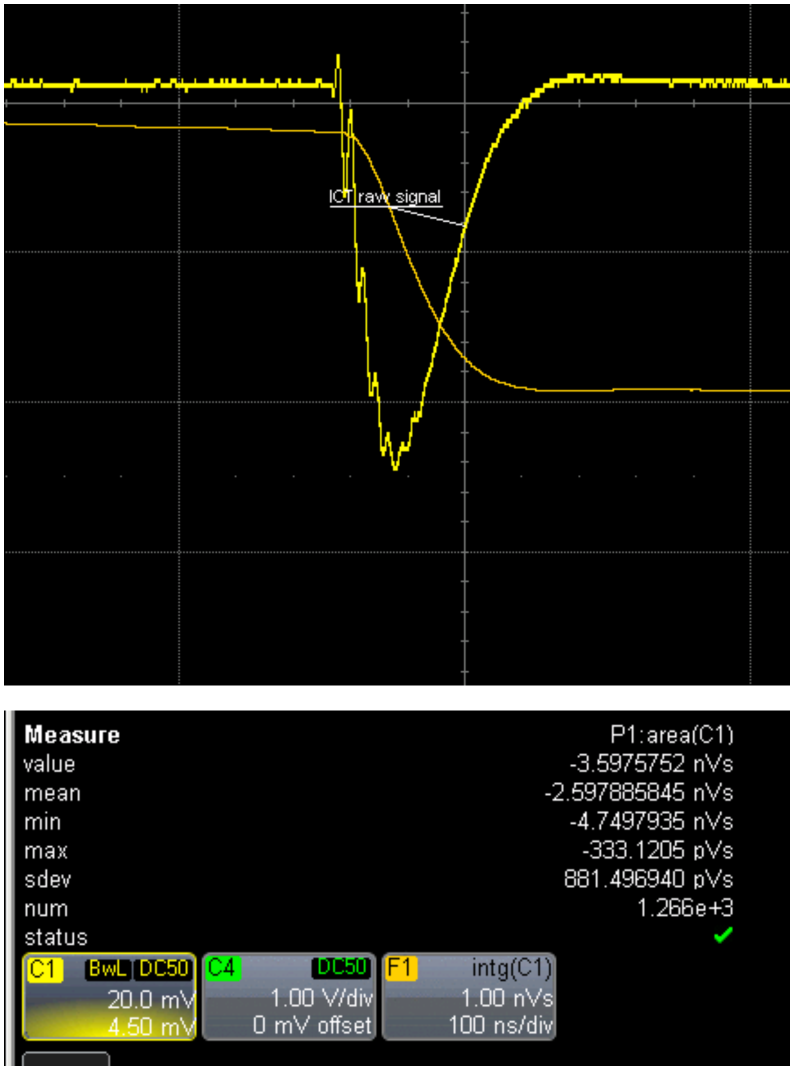
$$X = q/e \cong Z(1-\cos\varphi_1) \sim Z$$

Cathode QE Evolution

Initial QE is 8-10%, the evolution after transfer is shown below.



First Beam Observation



First beam was observed in 2015 with integrating current transformer during phase scan. The charge was 0.5 nC.

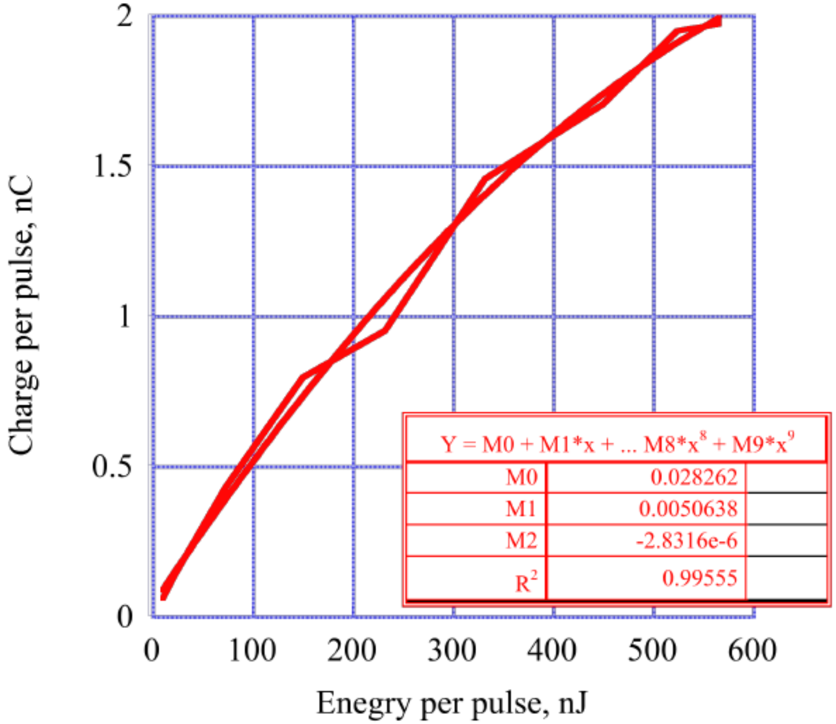
Emission was observed over 100 degrees span.

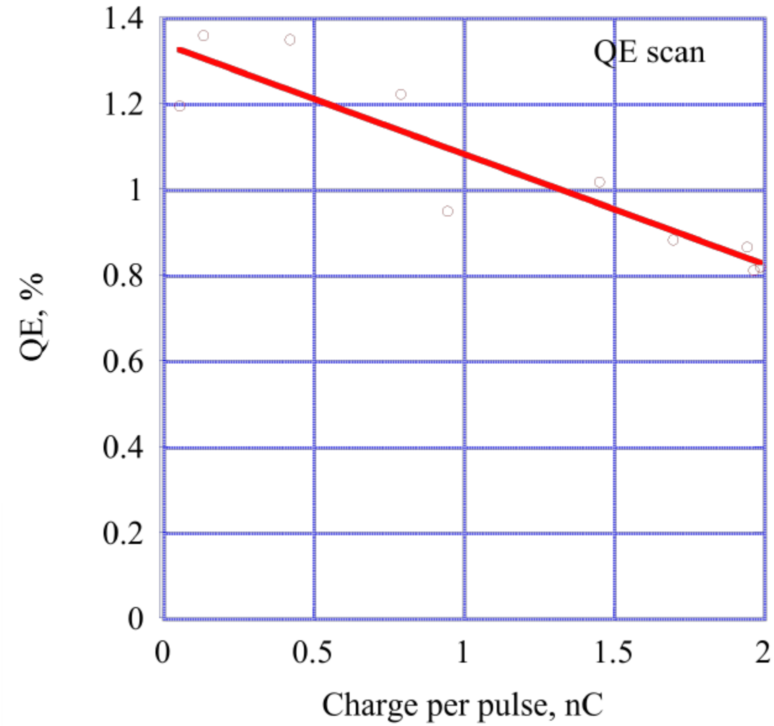
We have found that beam charge is limited by space charge forces

E_{laser}	Q	QE
375 nJ	0.5 nC	0.3%
1 μJ	0.66 nC	0.15%
6 μJ	1.24 nC	0.05%

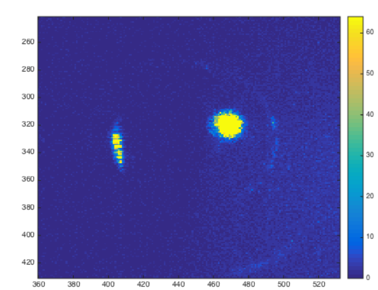
After 50% laser spot size increase we were able to observe 1.4 nC charge.

Measuring Quantum Efficiency

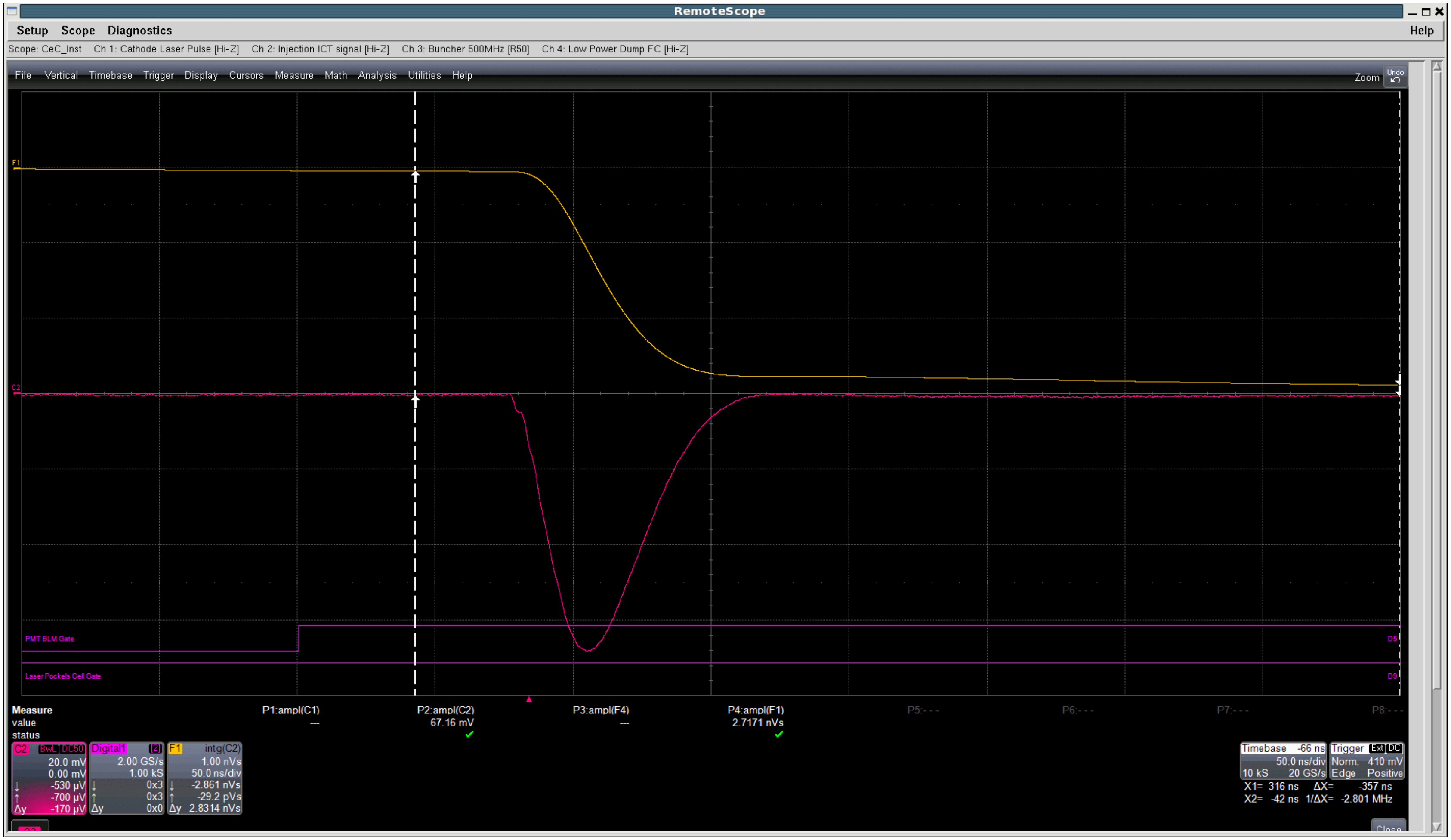




The photocathode was excited with 1 nsec laser pulse with varied optical energy. Gun voltage was 1.2 MV and laser spot size 1 mm r.m.s.



Run 16 Beam Observation



Beam was excited with 1 ns laser pulse with 0.5 mJ energy. 2.7 nVs ICT voltage integral corresponds to 2.1 nC charge. On the second day cathode was demonstrating 1 nC charge (100 pC at the end of the week).

Our gun: preliminary

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OPERATIONAL EXPERIENCE WITH NANOCOULOM

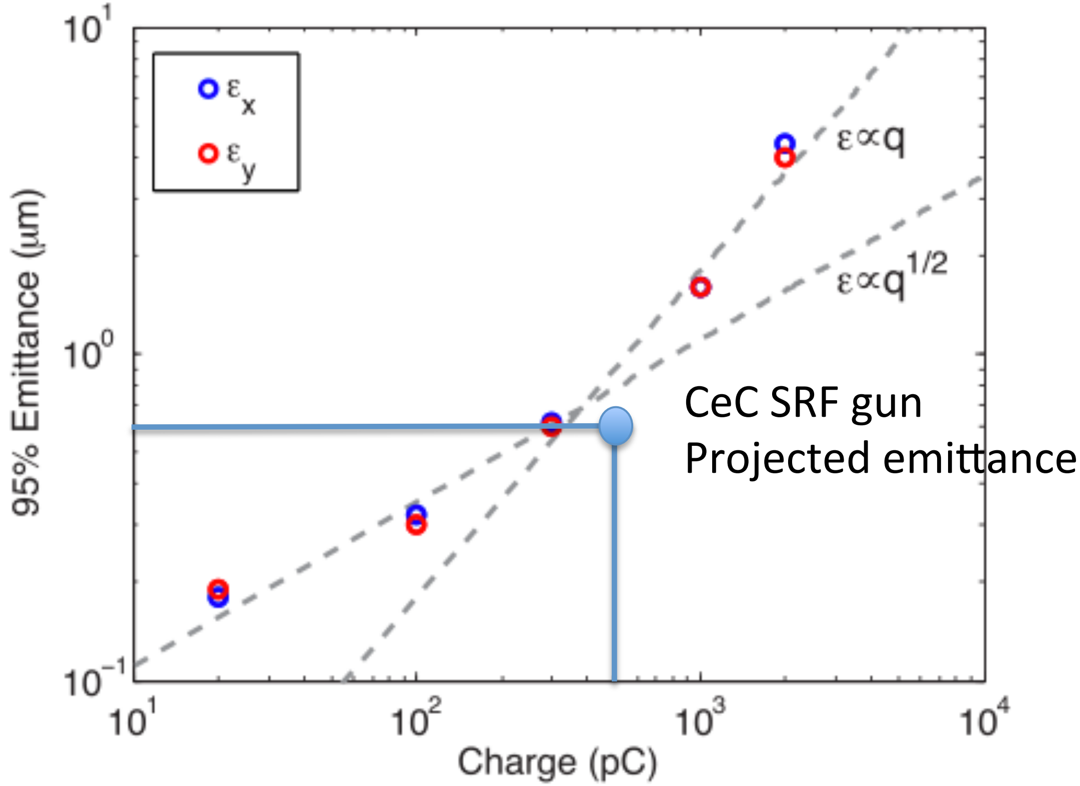

FIG. 8. Trend of the emittance as function of bunch charge.