Coherent electron Cooling demonstration experiment at RHIC

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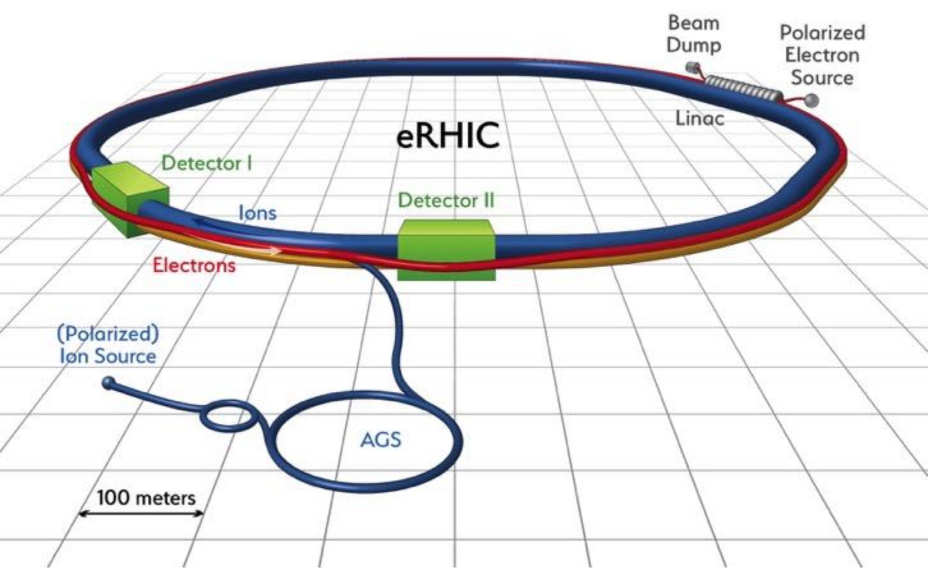
DOE-NP Accelerator R&D PI Meeting, November 14, 2016

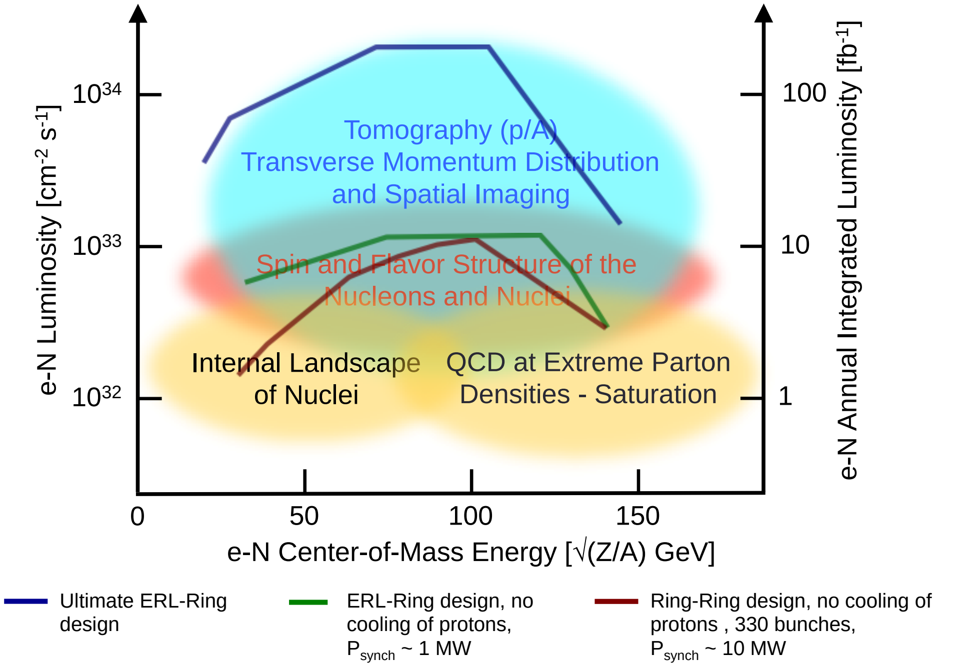
Outline

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

HIGH ENERGY HIGH LUMINOSITY EIC REQUIRES STRONG HADRON COOLING:

ULTIMATE REQUIREMENT < 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

CeC effect on eRHIC/EIC design

Short term: If CeC is successful and is fully operational, eRHIC LR would reach $2x10^{33}$ luminosity with 5 mA polarized electron current.

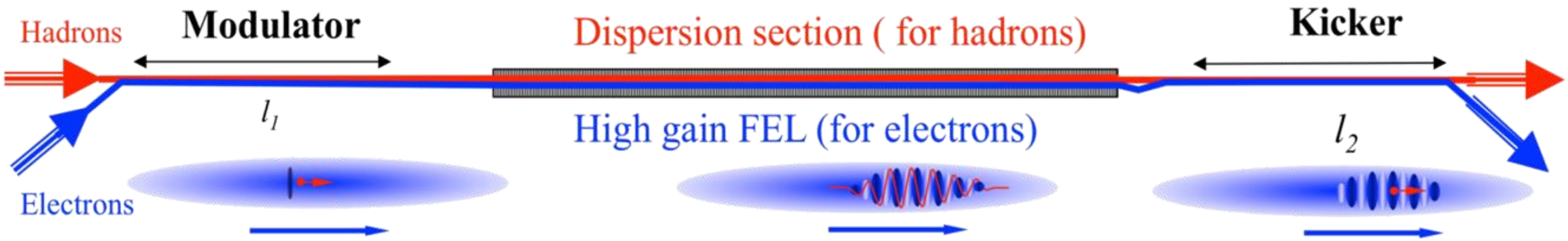
It removes main uncertainties in LR eRHIC design

- 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

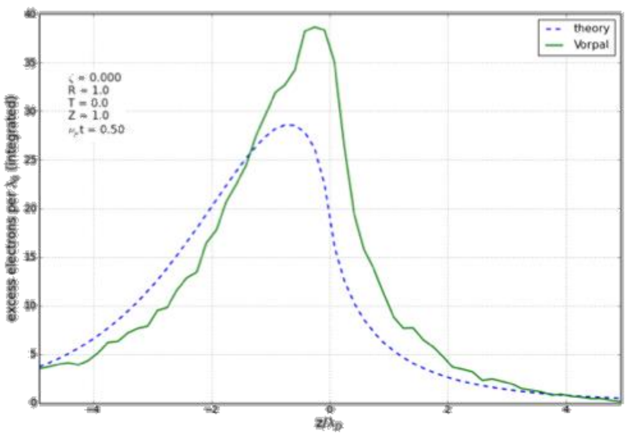
- CeC success = a major risk reduction and the pass to

final goal: eRHIC/EIC with $2x10^{34}$ luminosity

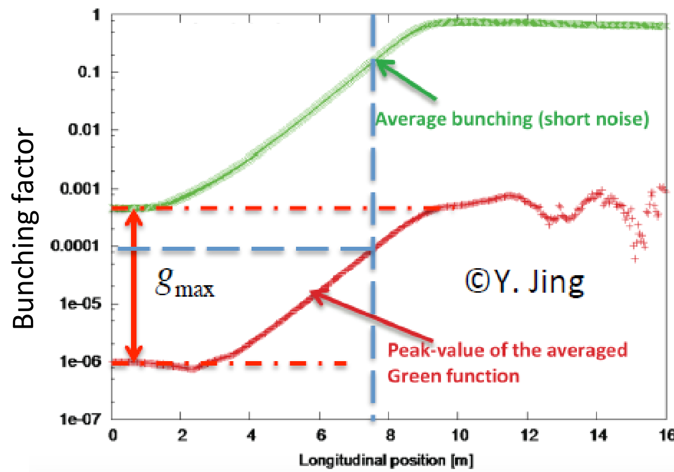
Our Proof-of-Principle is an economic version of CeC where electrons and hadrons are co-propagate along the entire CeC system



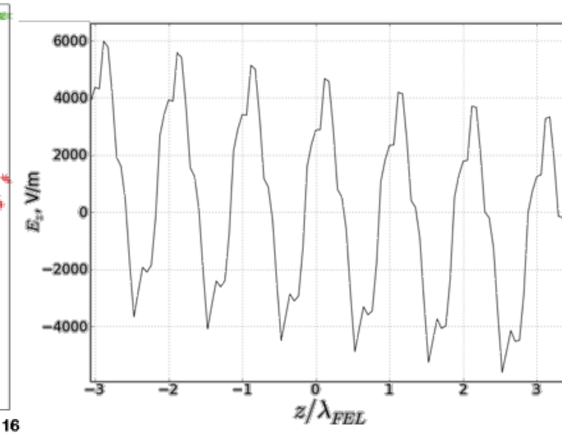
Param.' s from 40 GeV proof-of-principle exp. at BNL



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.

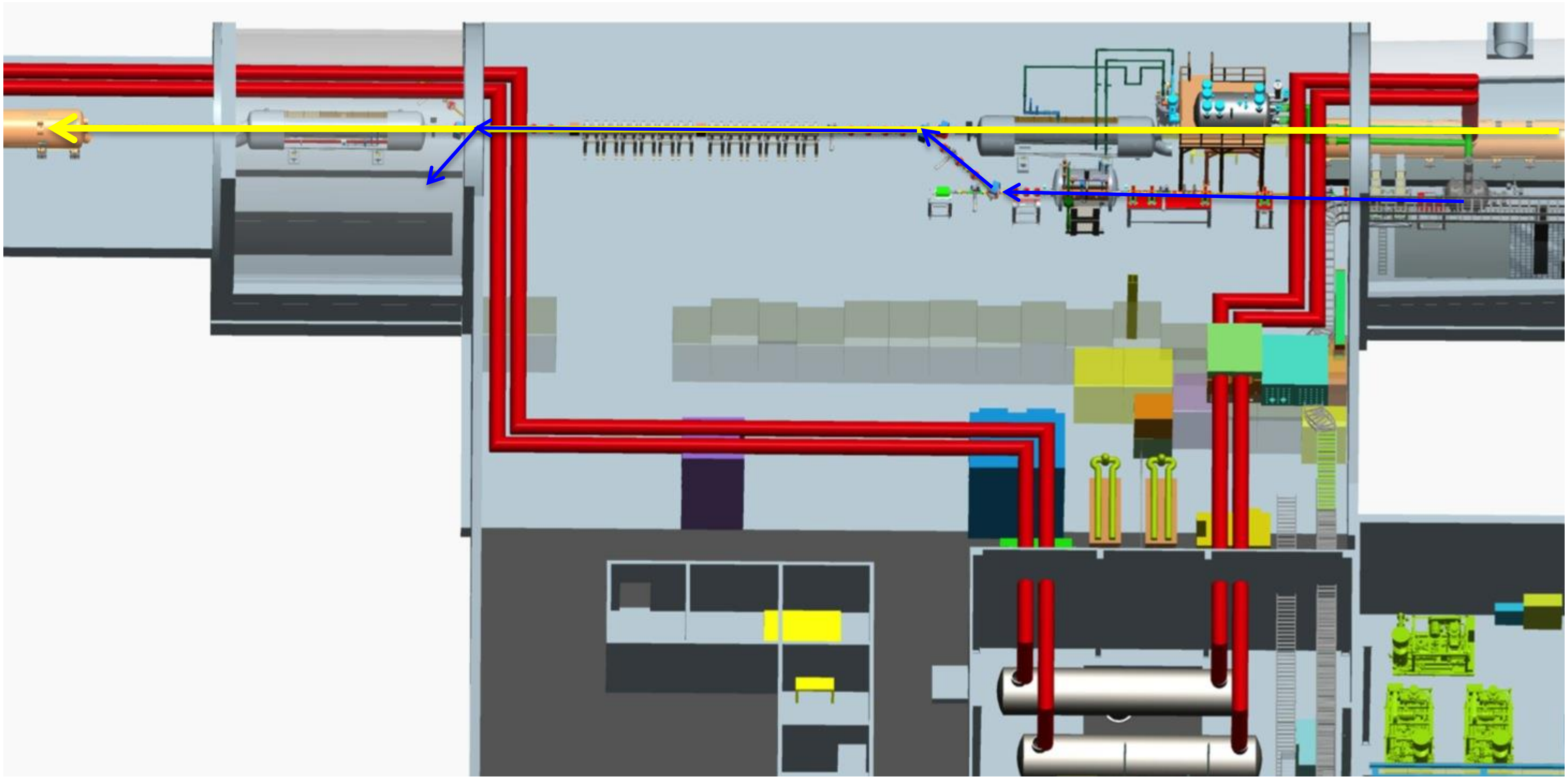
Simulations by Tech-X and Y. Jing

Office of Nuclear Physics

CeC PoP system at RHIC allows to test following EIC risks/R&D issues

- Conventional bunched electron cooling at 40 GeV/u
- Effects of electron bunch-charge modulation on cooling/heating of hadron beams
- Compensation of the tune spread in hadrob beams induced by the space charge
- Linac-ring beam-beam effects:
    - Pinch effect of electron beam
    - Kink instability
- Critical aspect of micro-bunching amplification

CeC Proof-of-Principle Experiment



Coherent electron *Cooling* PoP

Main FY16 milestones

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

MAY 20 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

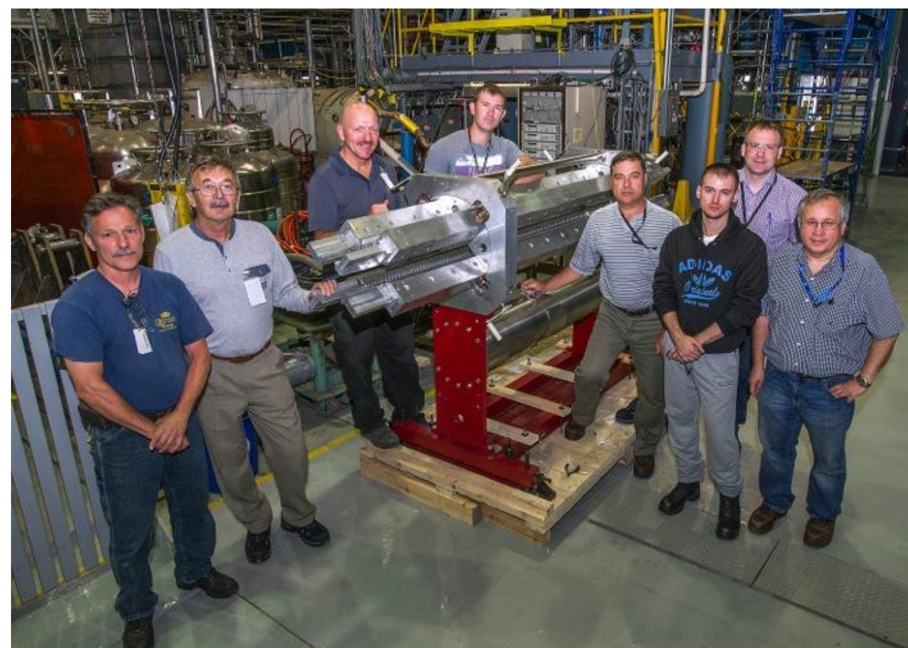
The Department of Energy (DOE) Brookhaven Site Office (BHSO) has reviewed your request to begin the commissioning and operation of the CeC PoP Experiment at full-power. Based on our review and the subsequent verification of all required pre-start actions by the Accelerator Readiness Review (ARR) team, 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,

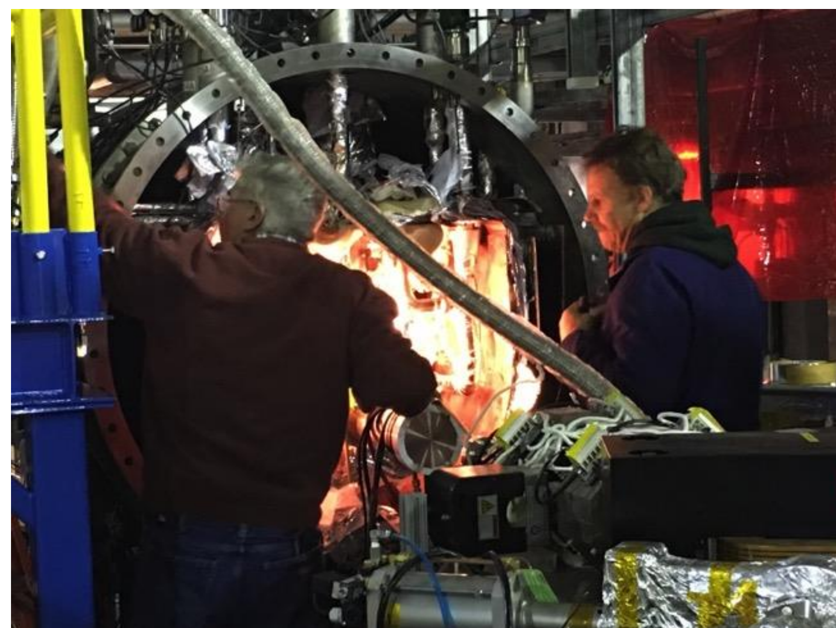
Frank J. Crescenzo
Site Manager

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

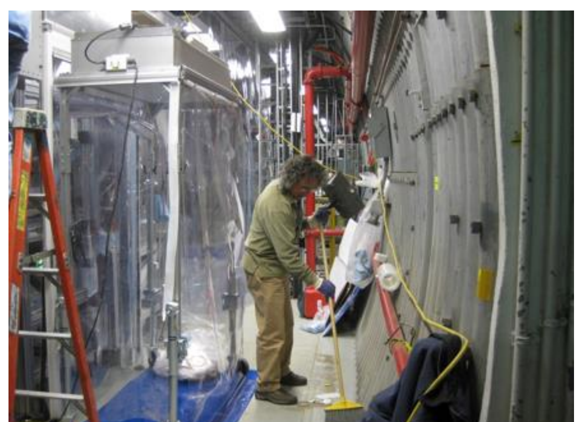




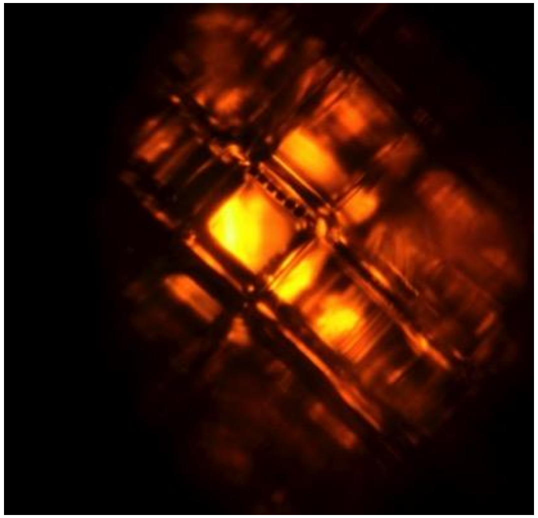



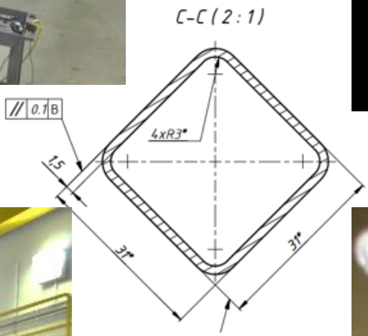


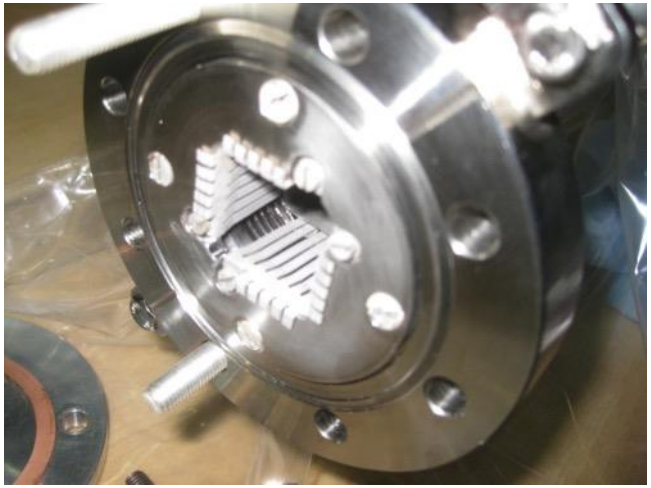


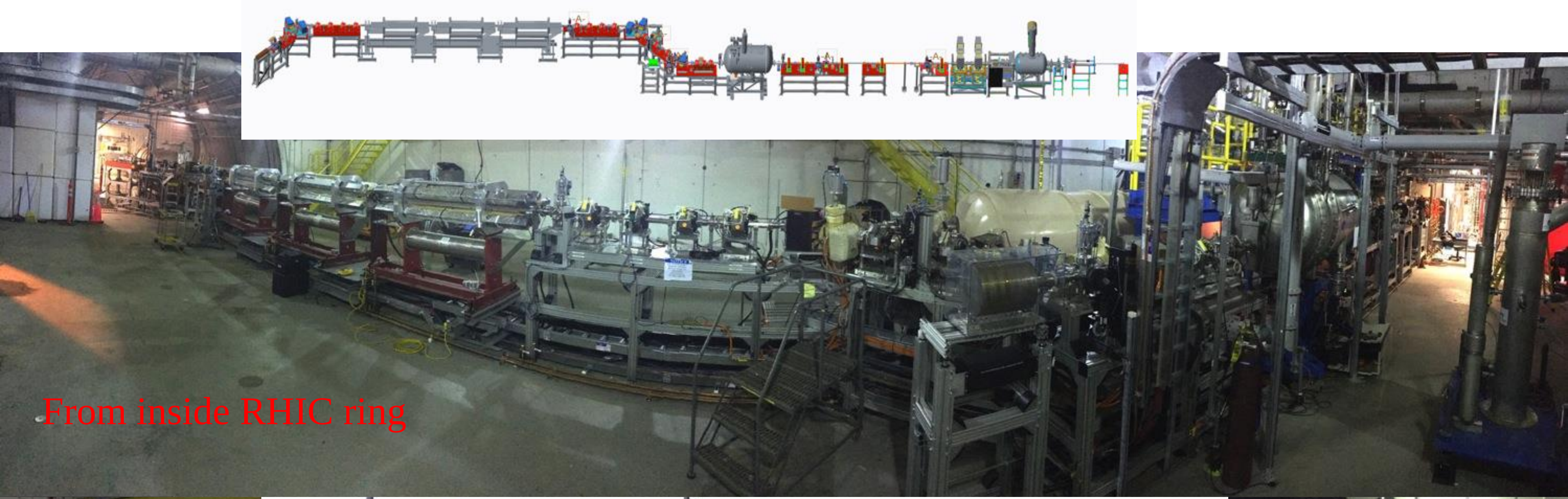

IP2 APERTURE LIMITATIONS: REQUIRED ACCURATE ALIGNMENT

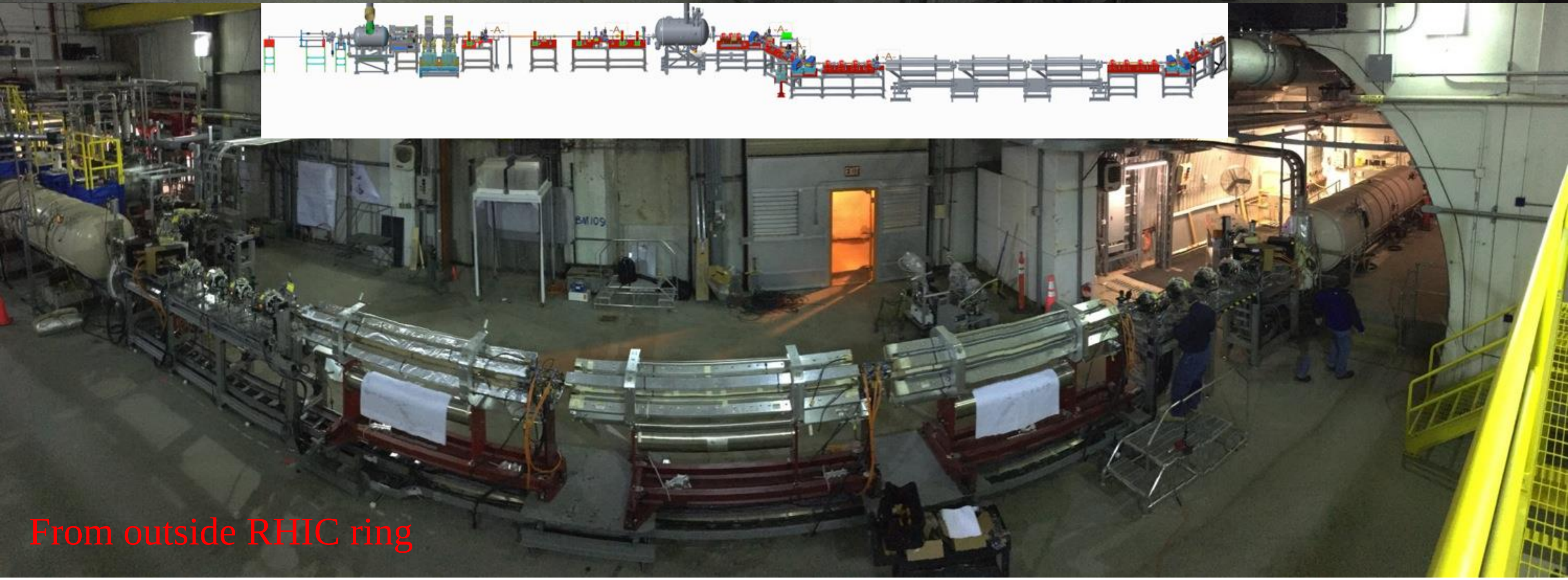




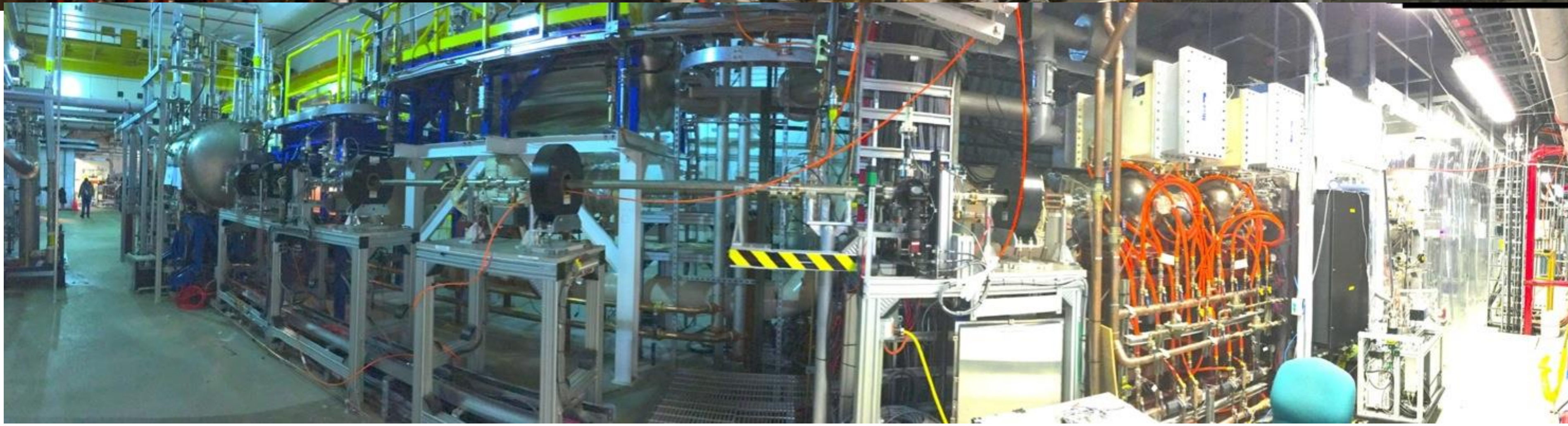


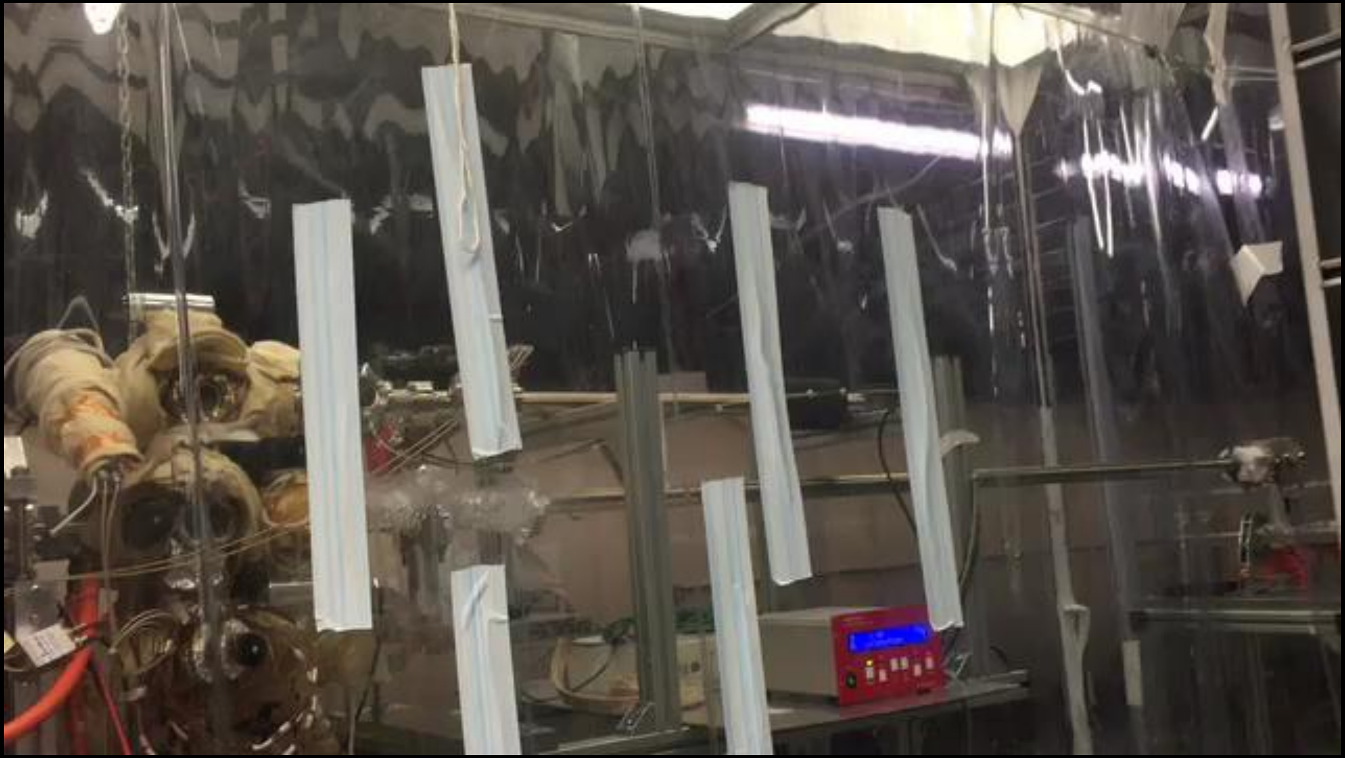
Panoramic views





Panoramic views





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 has been 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 end of the system (full power beam dump)

- ✓ "20 MeV" 744 MHz SRF linac has major problems. It can generate about 10 MV in stand along mode, but only ~ 7 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

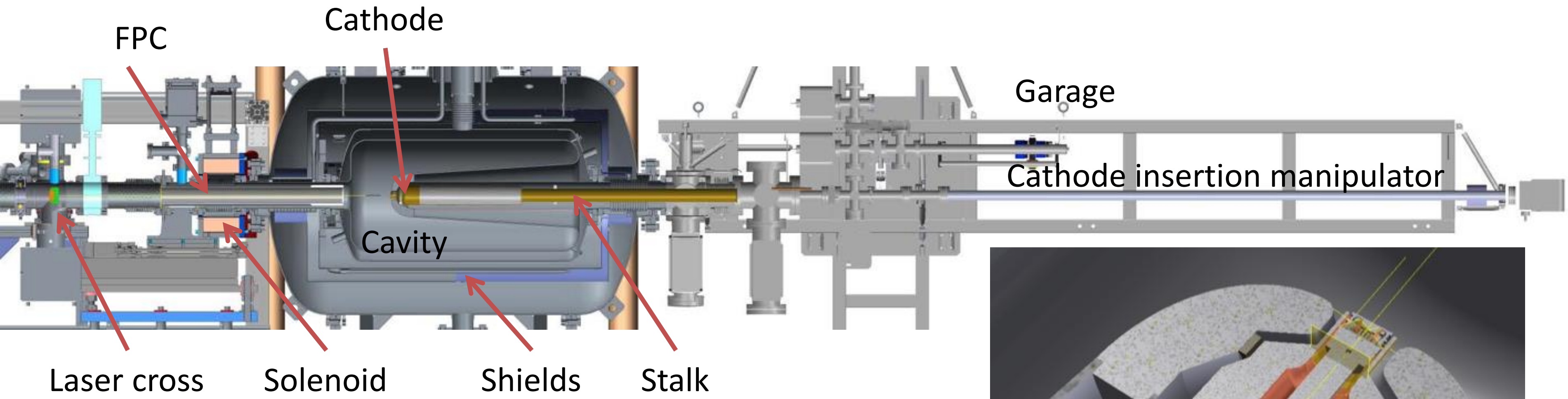
Main Beam Parameters for CeC Experiment

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

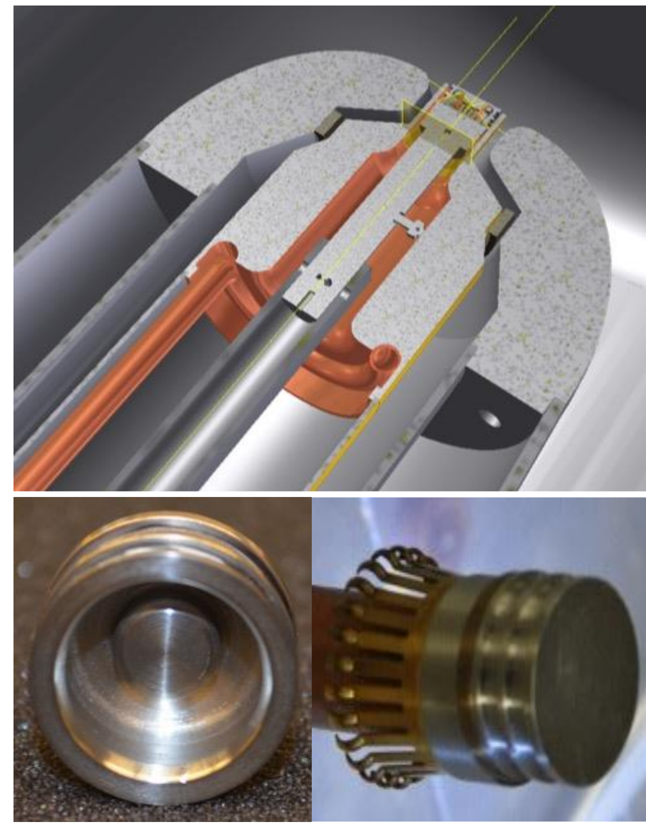
** We did not operated 5 kHz with 3.8 nC per bunch at the same time*

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

CeC SRF Gun

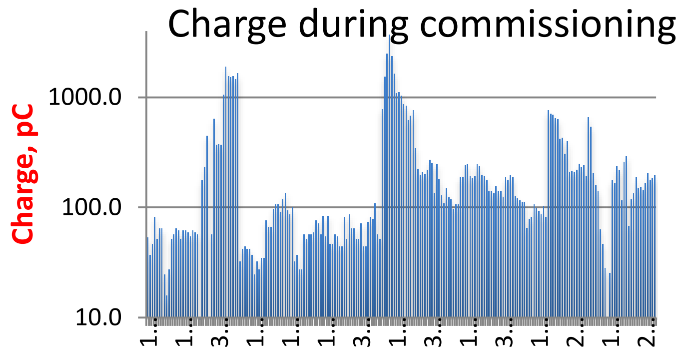


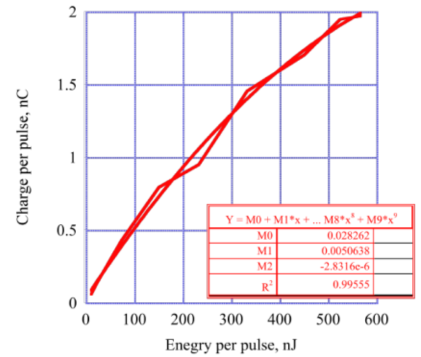
- Quarter-wave cavity
- 113 MHz operating frequency
- 4 K operating temperature
- Manual coarse tuner
- Fine tuning is performed with fundamental power coupler (FPC)
- 4 kW CW solid state power amplifier
- CsK_2Sb Cathode is at room temperature
- Cavity field pick-up is done with cathode stalk (1/2 wavelength with capacitive pick-up)
- Up to three cathodes can be stored in garage for quick change-out
- High gradient 15 MV/m (1.2 MV)

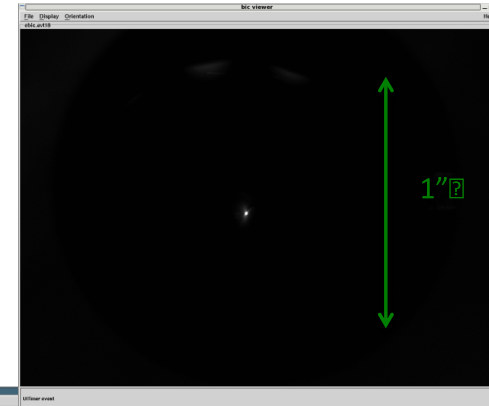


Photocathode end assembly

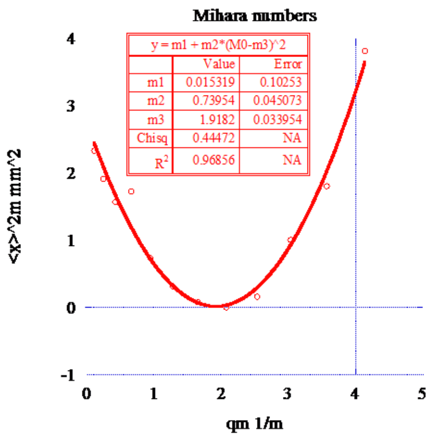
Record performance of 112 MHz SRF photo-electron gun

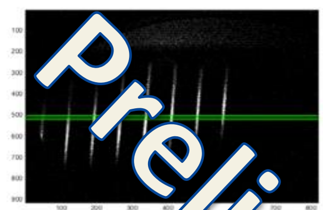


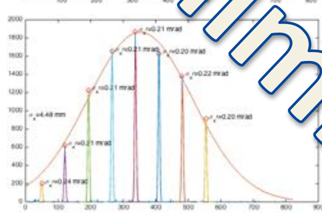




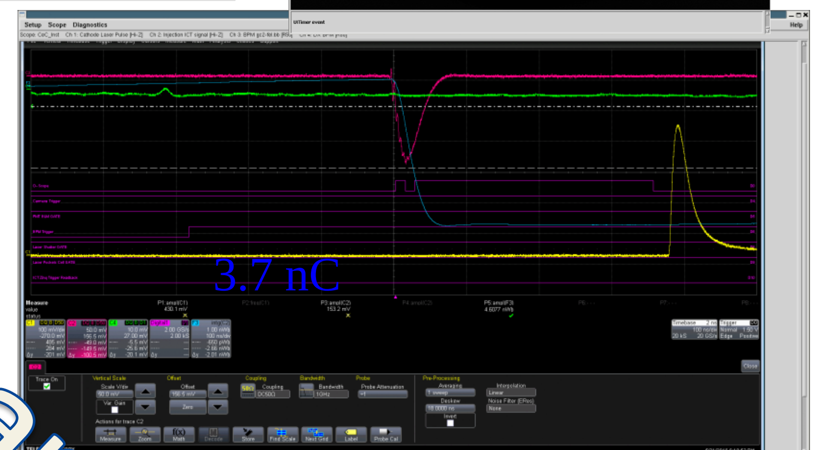
SRF gun at 1.15 MV

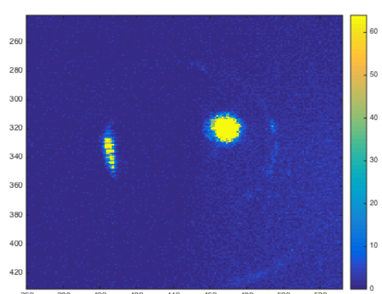


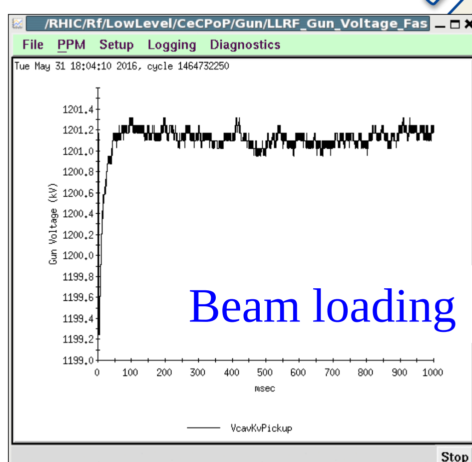


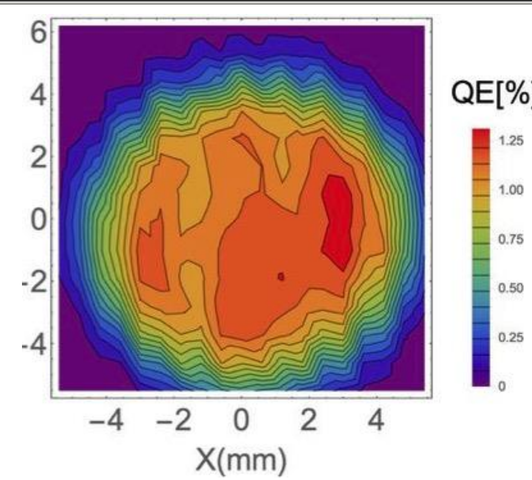


Preliminary



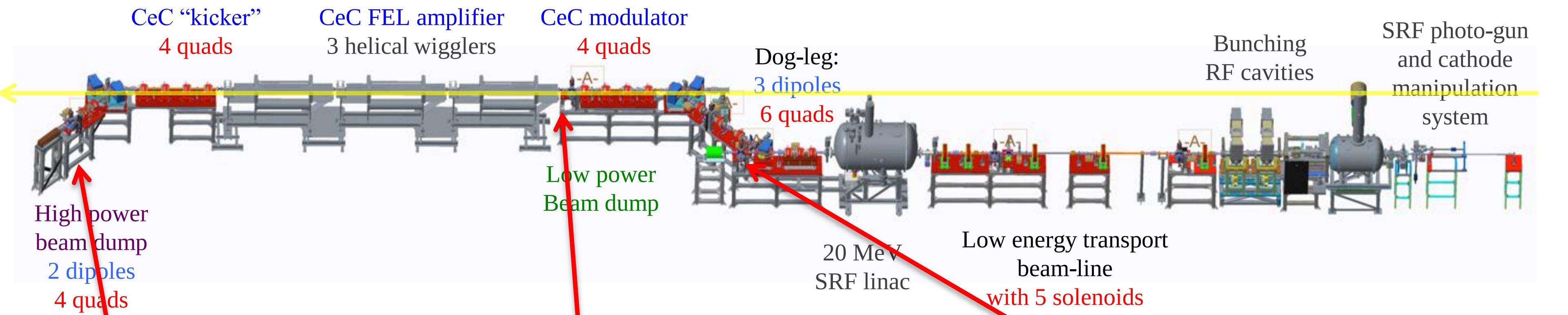


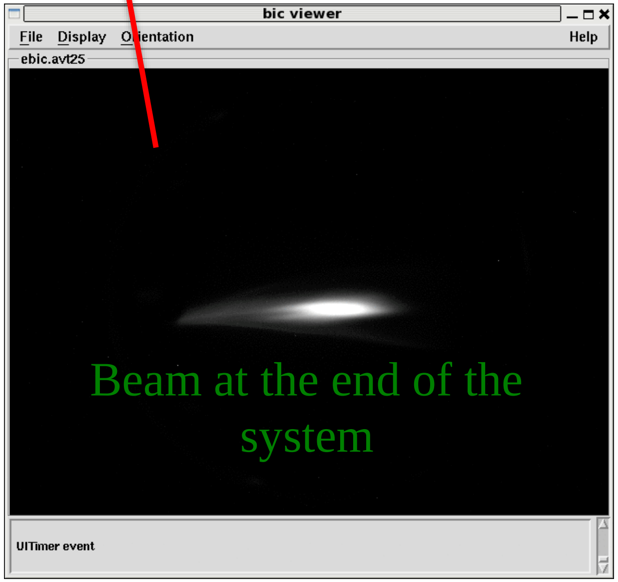


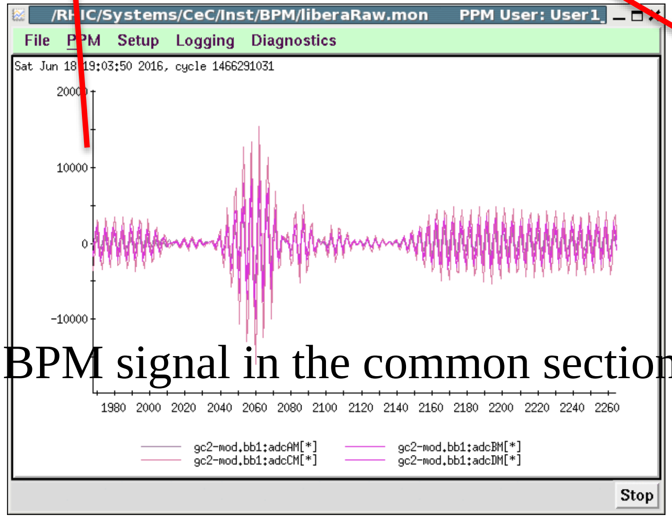


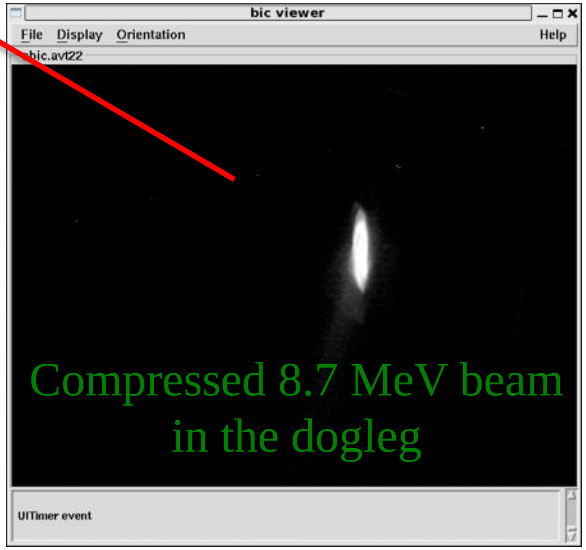
The CeC system commissioning

Common section with RHIC



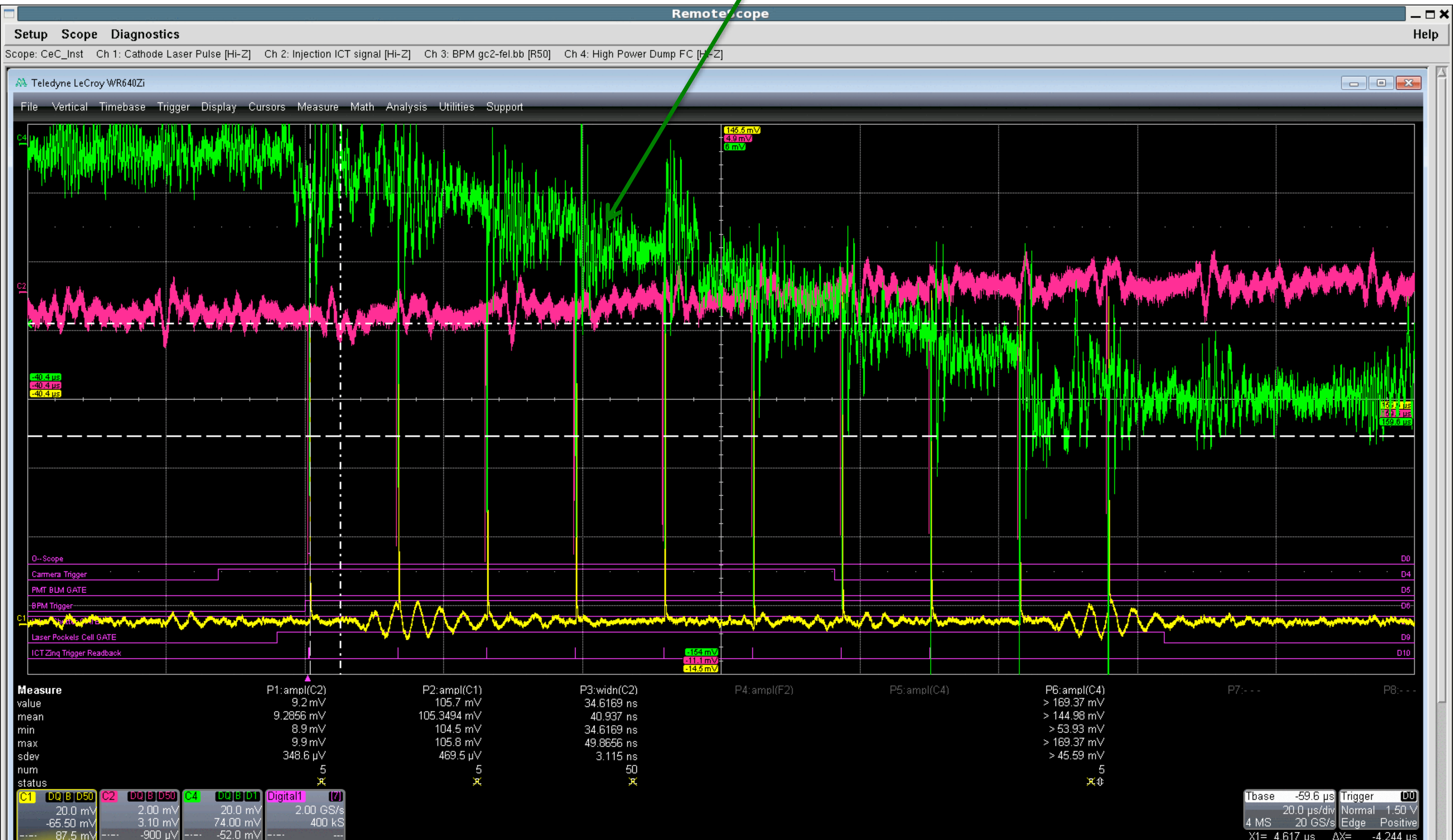






Beam was generated, compressed, accelerated to about 8 MeV and propagated through the entire system to the high power beam dump

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



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
  - In the best case: 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

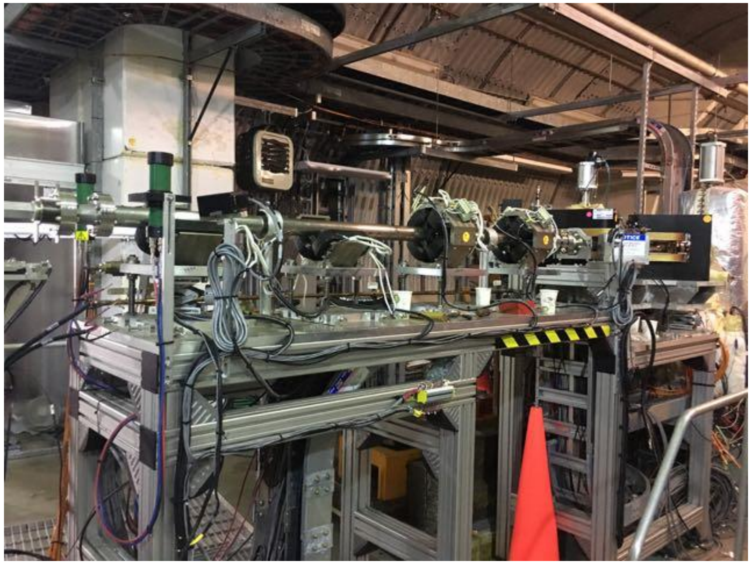
Others

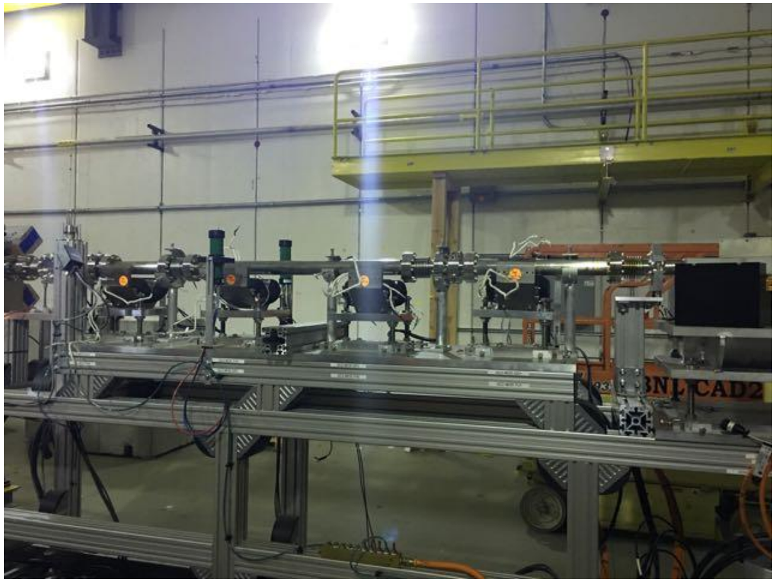
Air-core correctors in the LEBT
Suppress 500 MHz RF leak
Dedicated chassis for laser timing
500 MHz PA remote on/off
Streamline PET and Syndi pages
Set-up loggers
Develop modern acc controls

Run 17

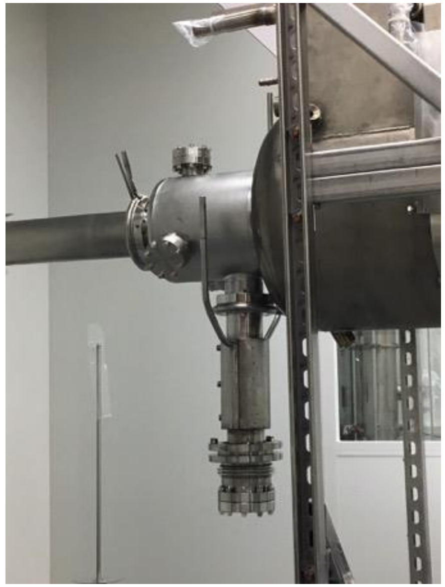
- Most of CeC activities -in parallel with RHIC operation:
  - Re-commissioning of the accelerator
  - Low power beam propagation to the HP beam dump
  - Establishing FEL amplification, Run 17
  - ….
- We plan to use APEX for establishing new modes of operation
- – 2 weeks of dedicated time is needed - spread over the run
  - Establishing interaction between the ion and e-beam
  - FEL Amplification of the interaction
- The best scenario:
  - Attempting CeC cooling of ion beam
- *Regular scenario:*
  - *CeC cooling of ion beam and its evaluation during Run 18*
- *Resources 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*

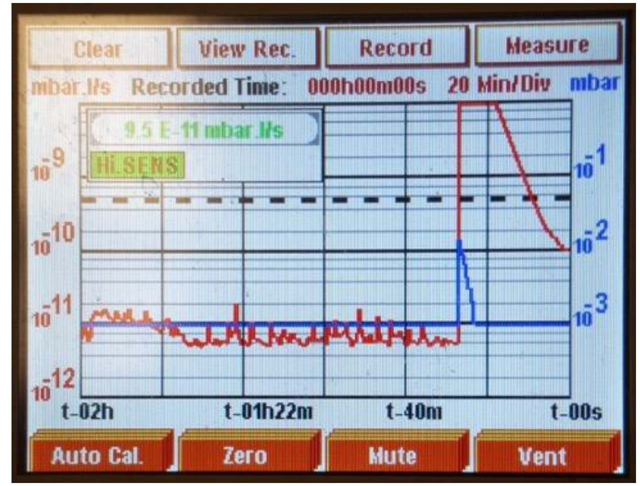
Mods and repairs



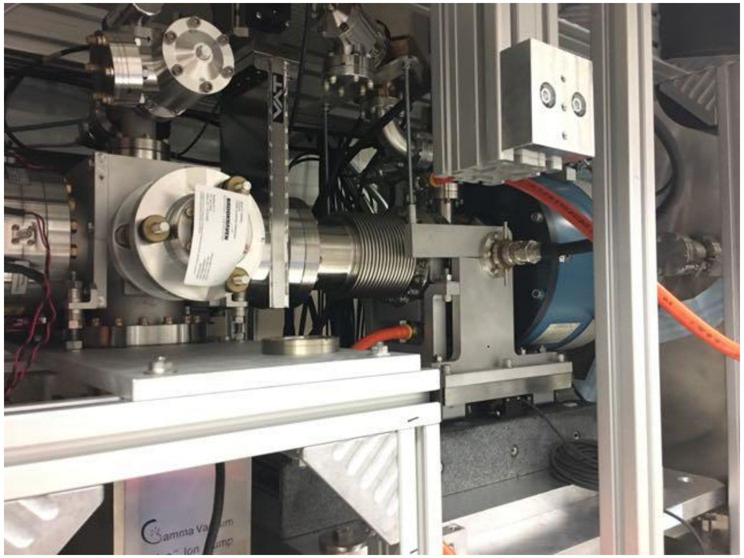


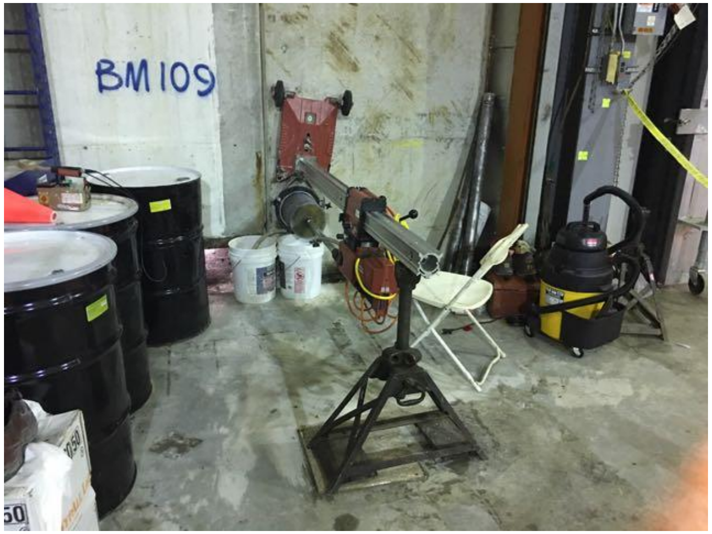
704 MHz Accelerator Cavity at ANL



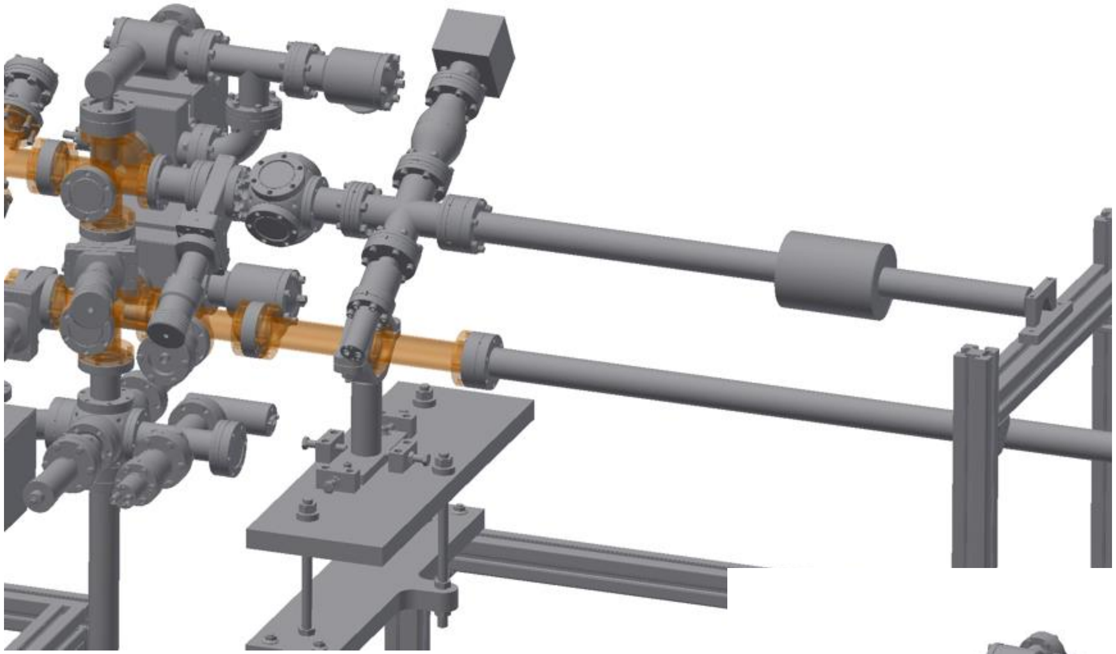


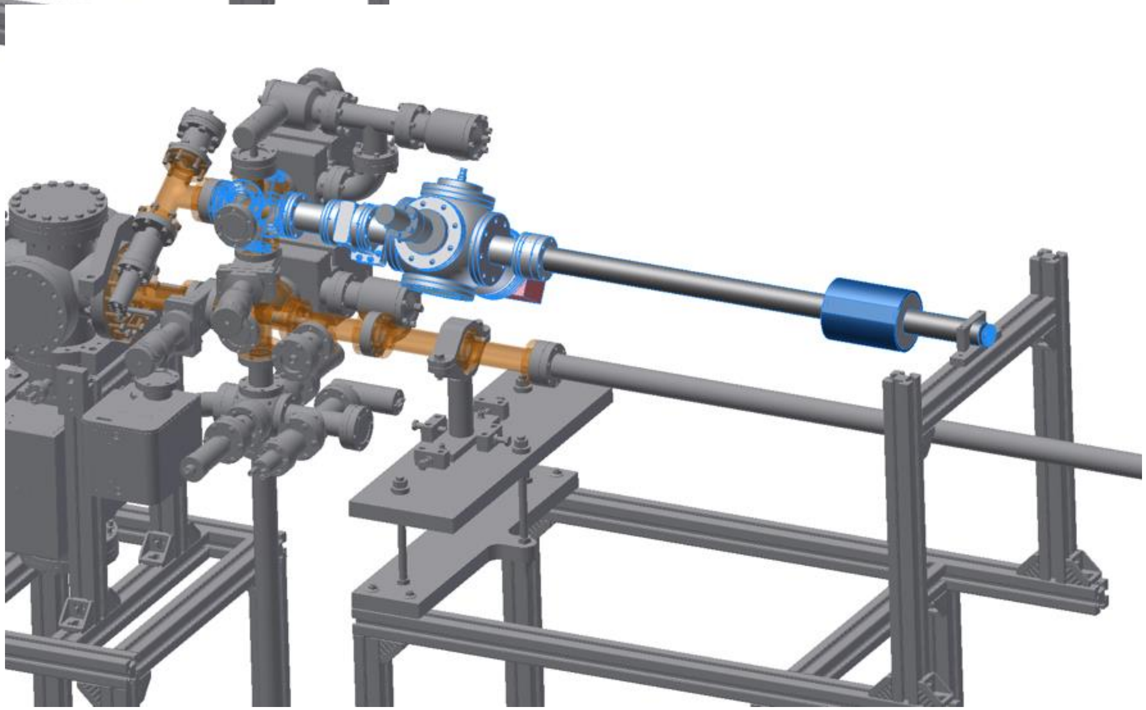
Mods and repairs



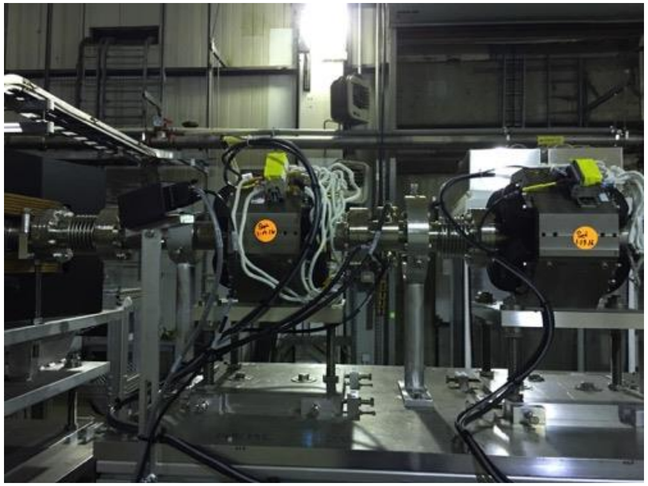


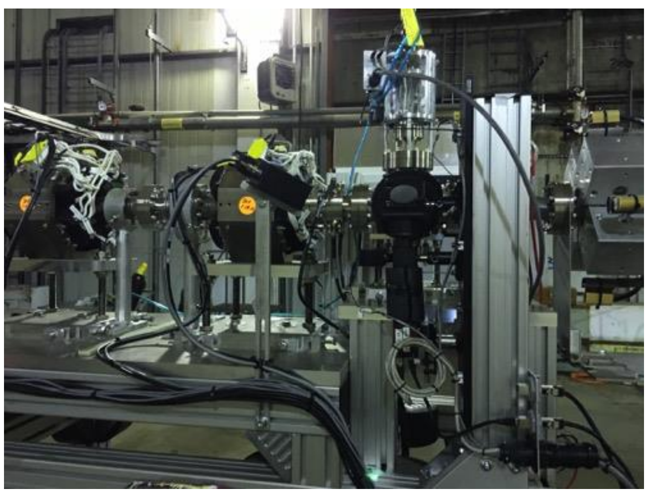
SRF Gun – Cathode exchange system

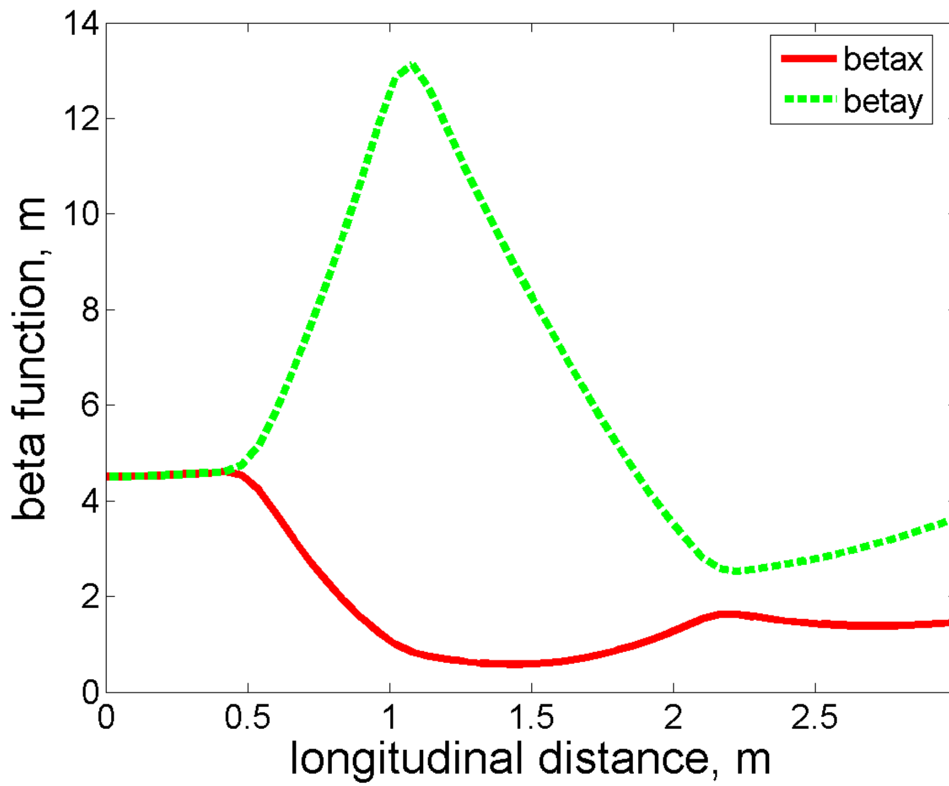




Simulation of realistic interaction of ions with with finite electron beam in a quadrupole beam-line







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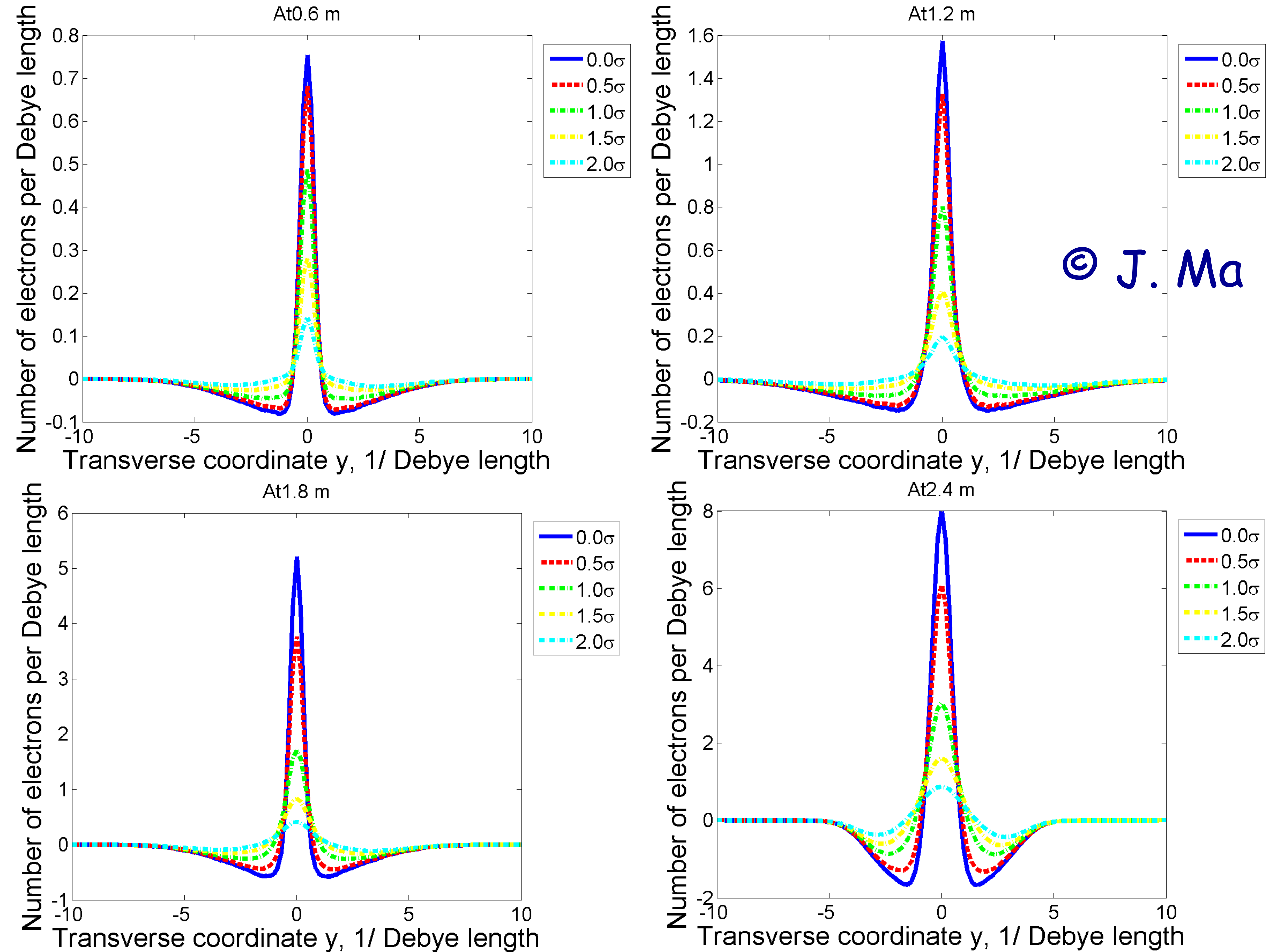
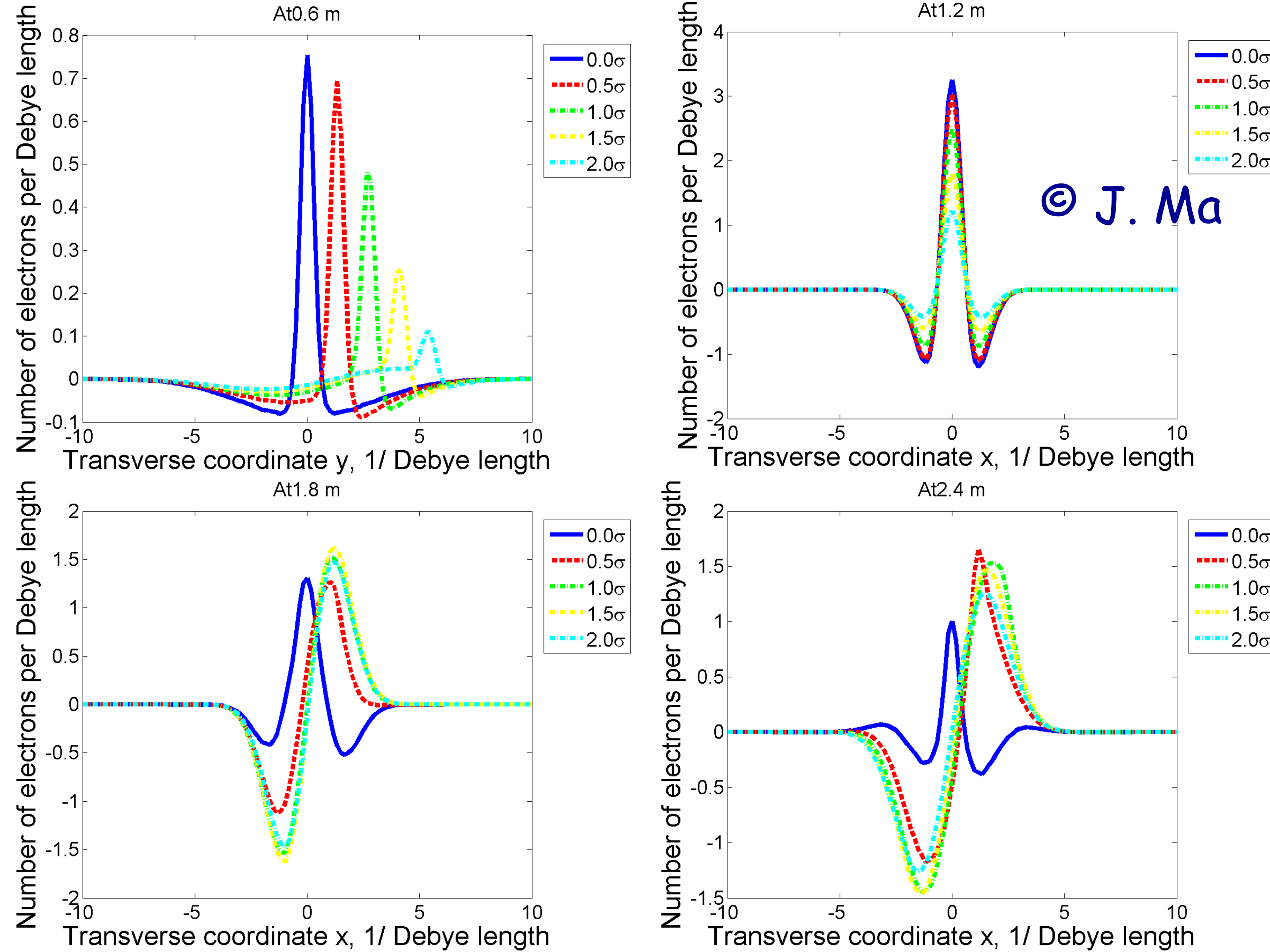
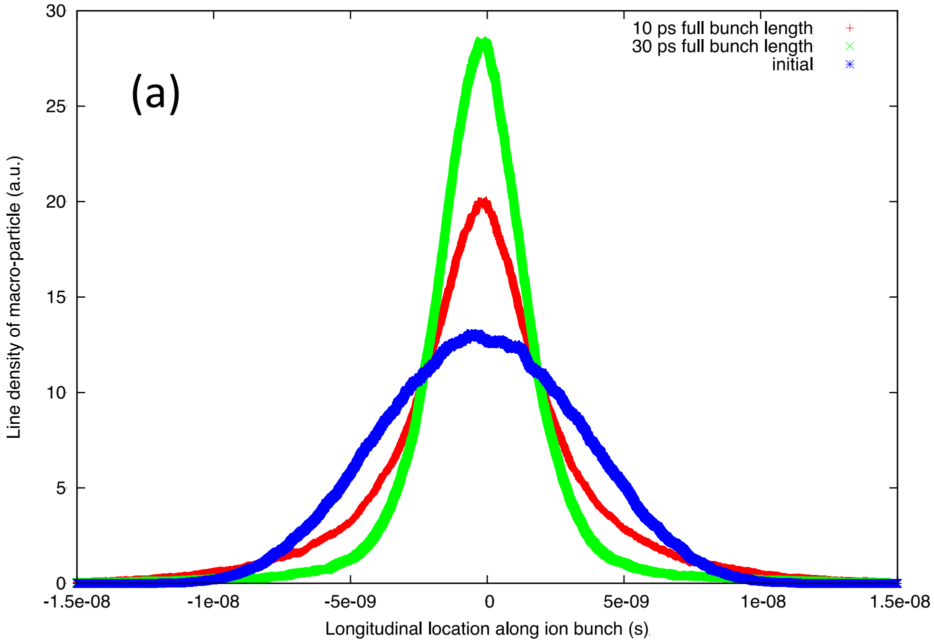
A lot of progress but still need a lot of super-computer time

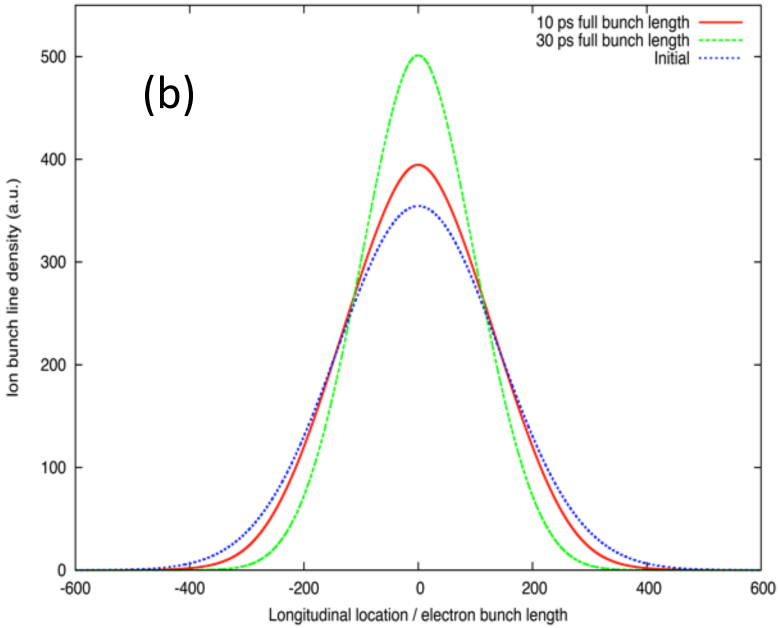


At0.6 m
At1.2 m
At1.8 m
At2.4 m
Number of electrons per Debye length
Transverse coordinate y, 1/ Debye length
0.0σ
0.5σ
1.0σ
1.5σ
2.0σ
© J. Ma


At0.6 m
Number of electrons per Debye length
Transverse coordinate y, 1/ Debye length
0.0σ
0.5σ
1.0σ
1.5σ
2.0σ
At1.2 m
Number of electrons per Debye length
Transverse coordinate x, 1/ Debye length
© J. Ma
At1.8 m
Number of electrons per Debye length
Transverse coordinate x, 1/ Debye length
At2.4 m
Number of electrons per Debye length
Transverse coordinate x, 1/ Debye length

Cooling full bunch
Self-consistent simulations

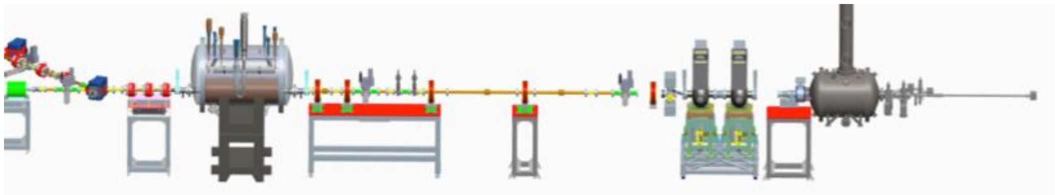




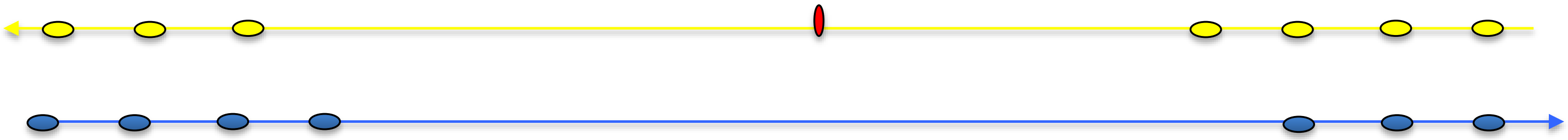
The ion bunch longitudinal profiles after 40 minutes of cooling. (a) ion bunch profiles as obtained from macro-ion tracking; (b) ion bunch profiles as obtained from numerically solving Fokker-Planck equation.

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



Run 17 – 2 weeks of dedicated time (42 8-hours shifts)

1. Propagating high power beam through IP2 and evaluating beam losses and radiation surveys
   a. At 100 W level – 3 to 4 shifts
   b. At 1 kW level – 3 to 4 shifts
   c. At full beam power – 4 to 6 shifts
   d. FEL amplification at full power – 3 to 6 shifts
2. Co-propagating electron and ion beams
   a. Aligning electron and ion beams – 3 to 4 shifts
   b. Matching beam's relativistic factors - 4 to 6 shifts
   c. Demonstrating FEL amplification of the ion imprint - 5 to 7 shifts
   d. Demonstrate repeatability of the set-up - 3 to 5 shifts

Total: 28 to 42 shifts (e.g. 9.33 to 14 days), contingency is 50%

In most optimistic scenario we will attempt to demonstrate CeC

Annual budgets and the total received: all used for hardware

	FY10-11	FY12-13	FY14-15	FY16	Total
a) Funds allocated	$1,488,000	$2,690,000	$1,345,000	$425,000	**$5,948,000**
b) Actual costs to date	$1,488,000	$2,690,000	$1,345,000	$385,000	**$5,908,000**

It is about 30% of the total cost

Conclusions

- ✓ **We have a 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
  - ✓ Naturally we encountered challenges and problems
- ✓ **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 still want to finish start-to-end simulations with full predicting power, if new funds are available**

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

…

………………

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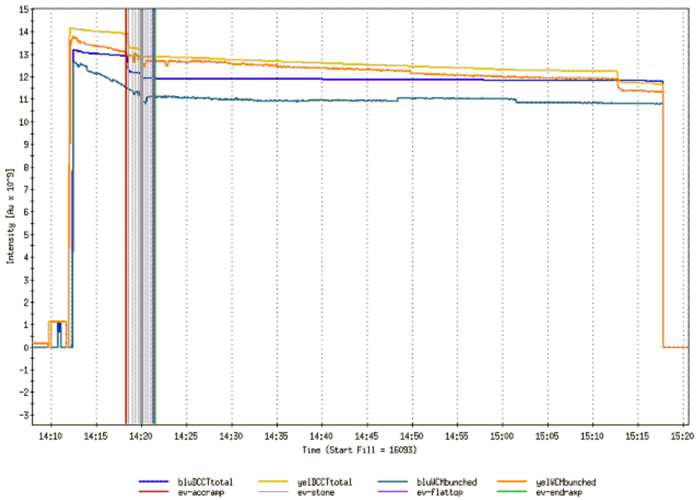
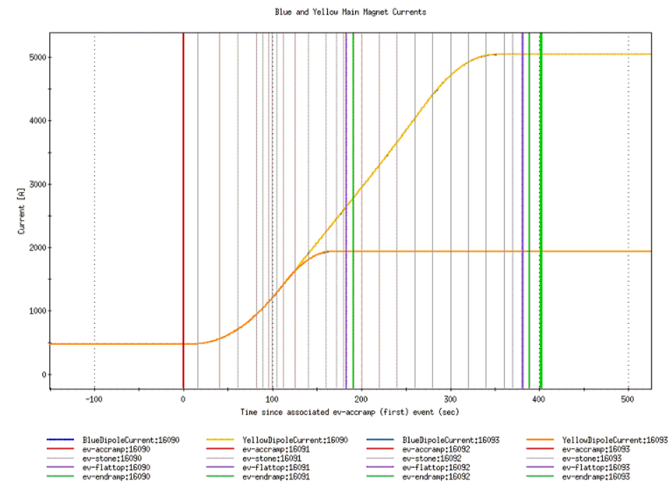
Back-up

CeC PoP RHIC Ramp Development

Ramp : beam intensity

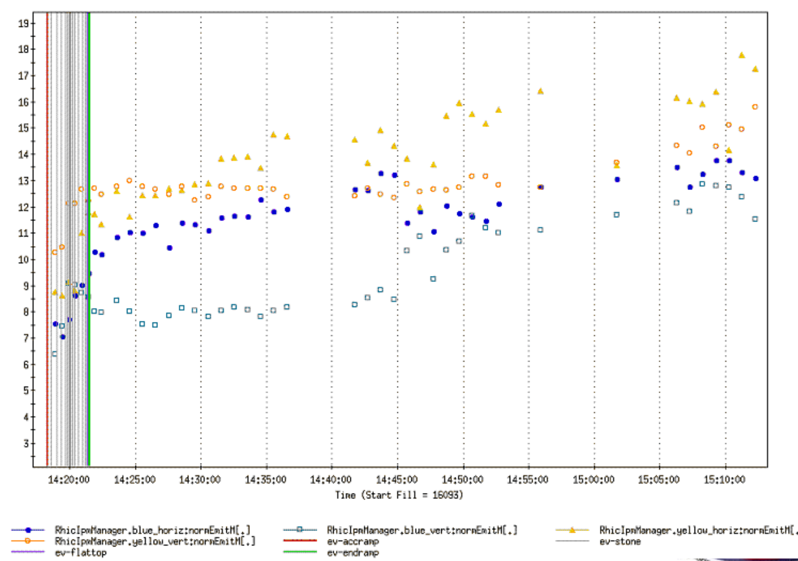


Ramp : Magnets currents

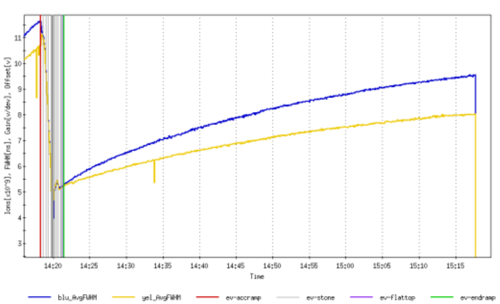


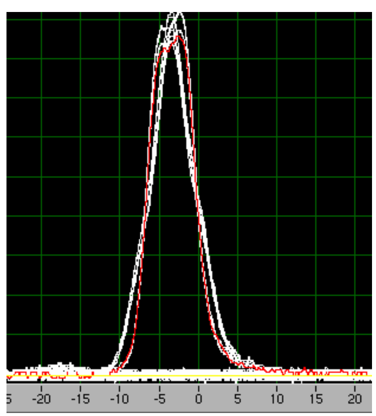
APEX on RUN 11: 2pm-4pm, June 20th , 2011 Fill: 16093

Emittance growth at 40 GeV

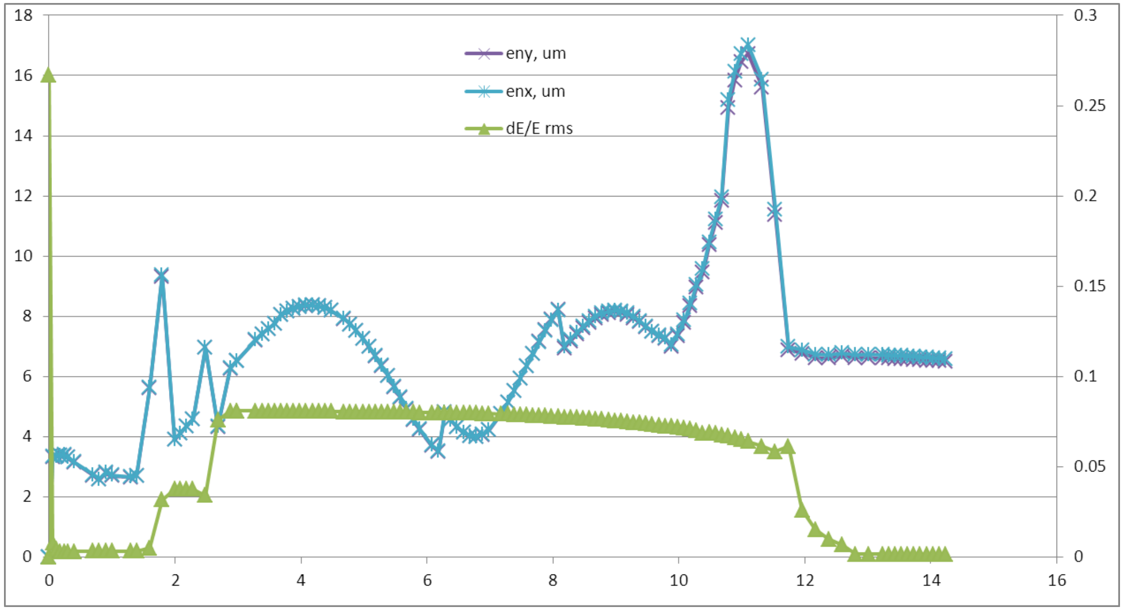


Bunch length and profiles at 40 GeV





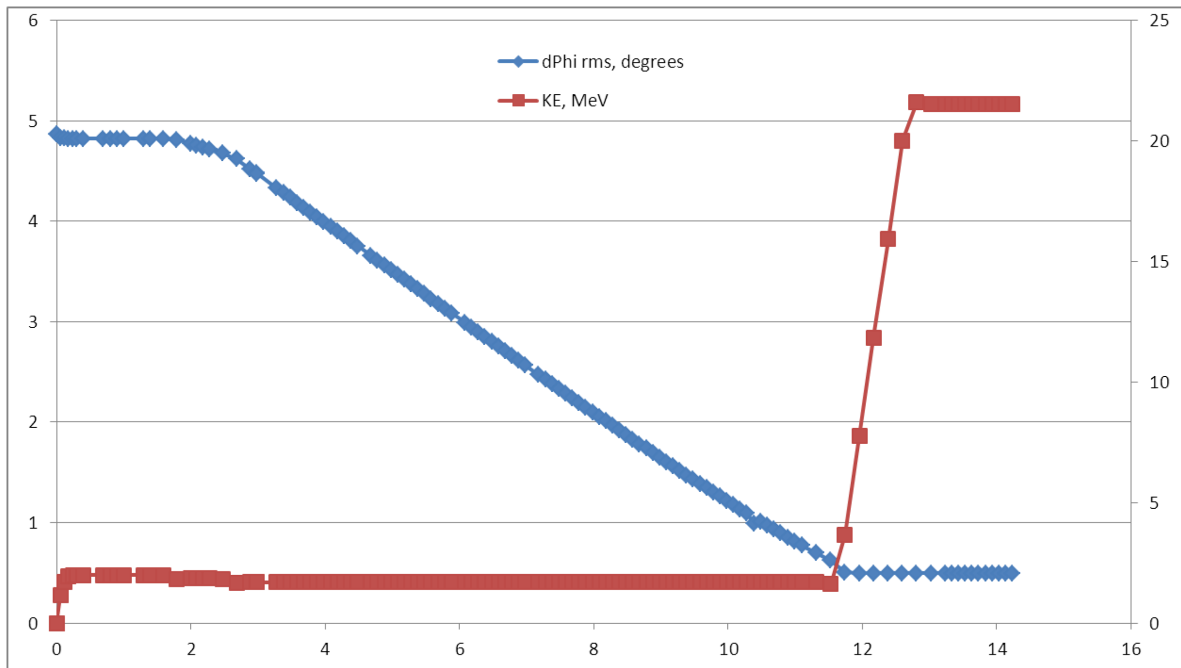
Expected Electron Beam Parameters



Calculations are done for 2 nC bunch
Core charge is 1.3 nC
Emittance is 8.6 μm, core emittance is 3.3 μm

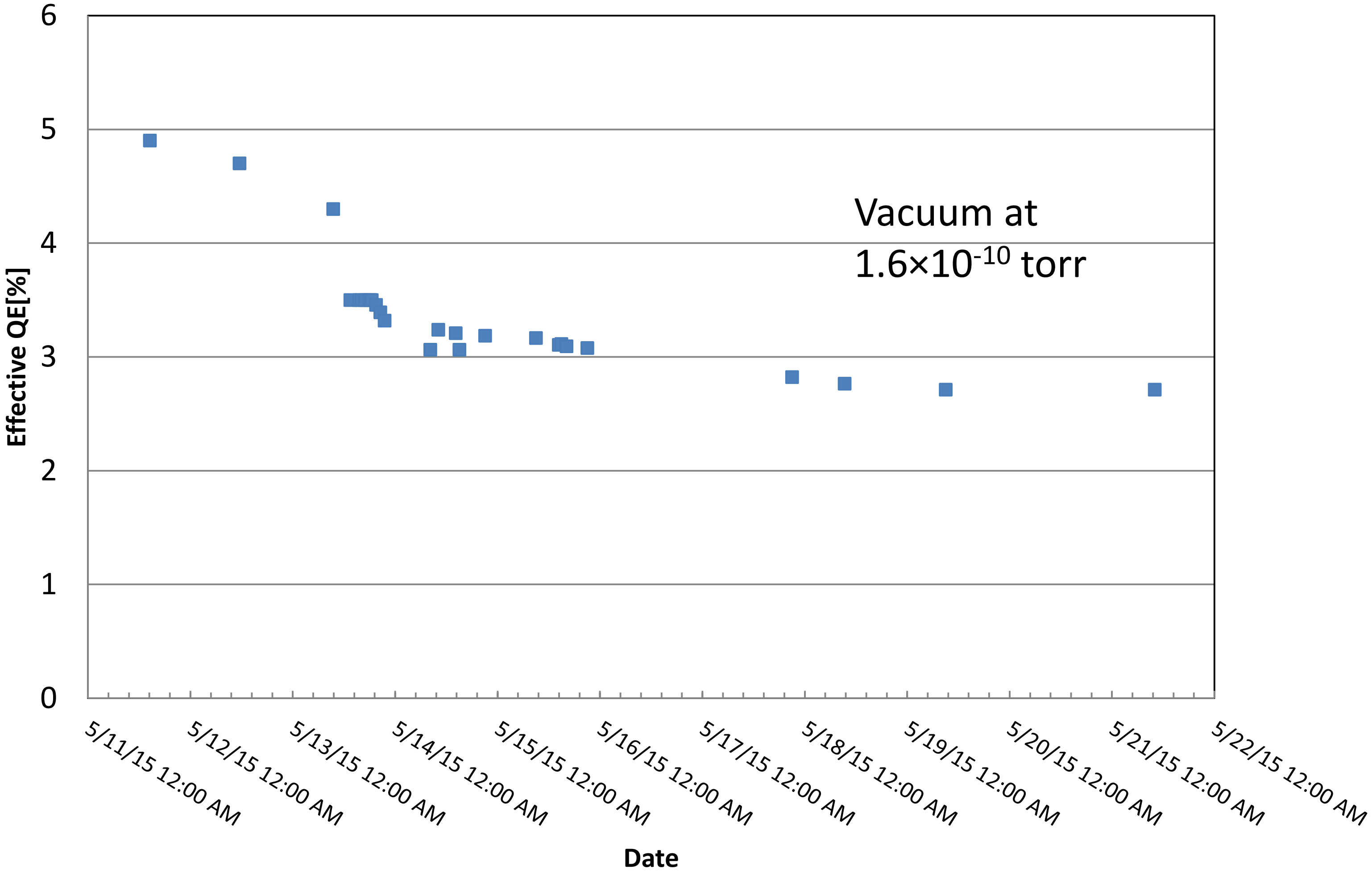
Relative energy spread is 2×10^{-3}, relative energy spread in the core is 3×10^{-4}

Courtesy D. Kayran

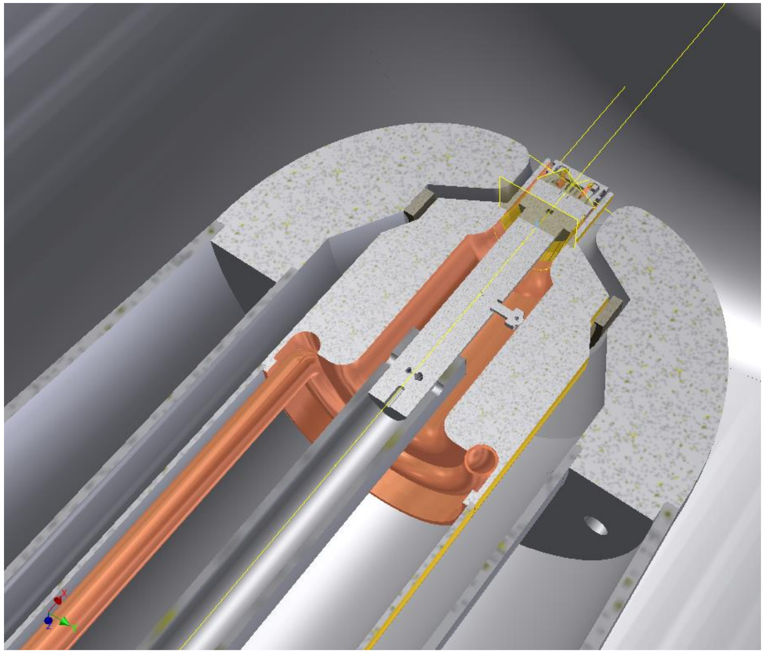


Cathode QE Evolution

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



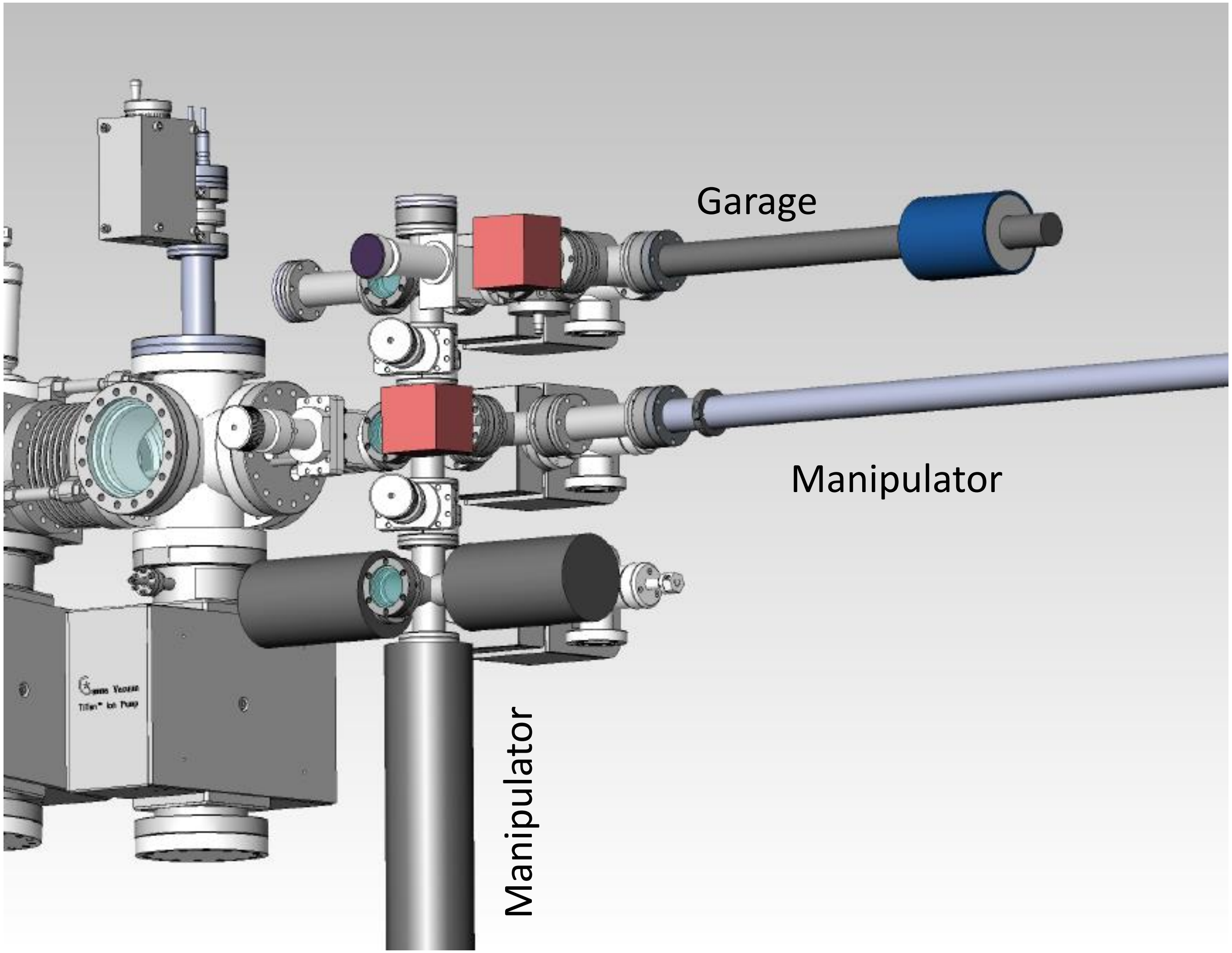
Problems Encountered



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

Modified Cathode Launch System



Diagnostics for Low Energy Beam

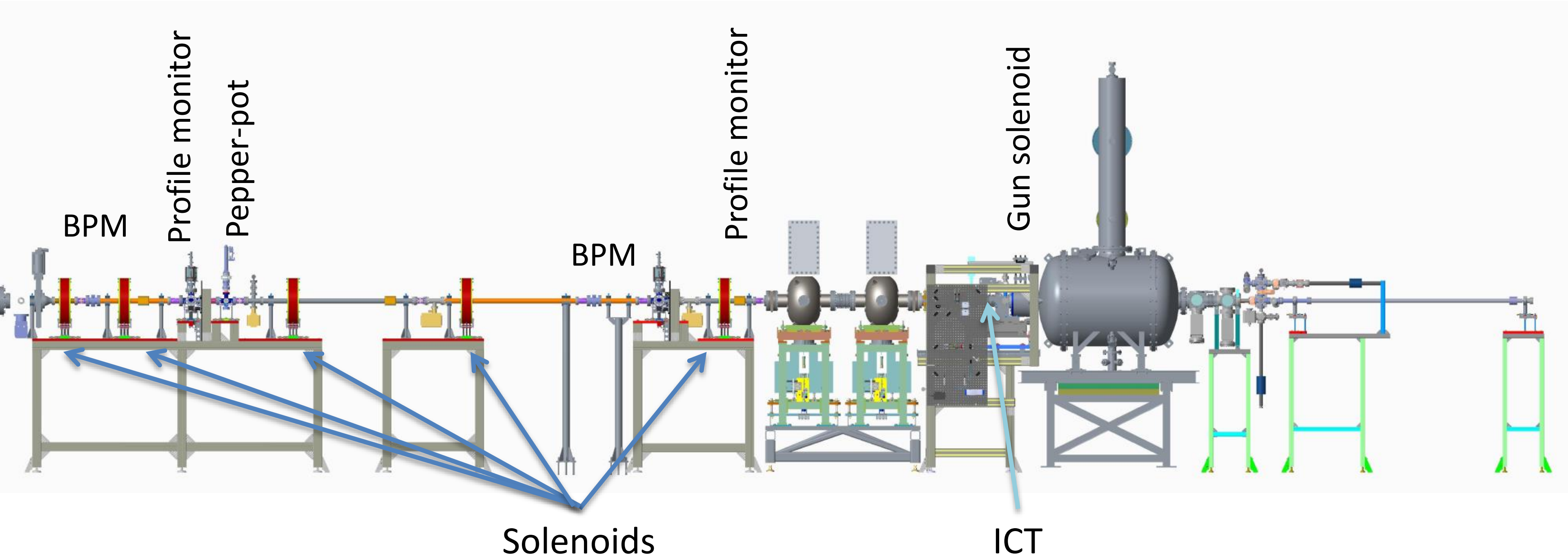
Integrating current transformer (1.25 nV s/nC)

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



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

CeC Shutdown 2016 Priorities

1. The first priority is 704 MHz cavity which includes cleaning, assembly, and installation as well as tuner work. Cavity was processed and is expected on November 10th.
2. The second priority is to replace the ICT which is expected to be delivered on November 20th. This will re-quire replacement of the SRF trim with new air-core design, which can be installed after gun conditioning.
3. Third priority is laser delivery line, which is more or less straightforward but we have not seen any design yet. Wall penetration is drilled.
4. The fourth priority is new garage. The first sample is expected to be shipped this week, port aligner was just received.
5. The fifth priority is replacement of the high power dump with aluminum one. Its expected to be ready for installation on November 10.

Replace BPM button
Update MPS
Cages for the profile monitors
Rewire SRF solenoid (eliminate loop around yoke)
Helium carts for conditioning of the SRF cavities
Water system flow meters and pressure transducers
Install infrared diagnostics (close to completion)
New cameras (with iris control and color one for gun)
Measure laser pulse profile with streak-camera (Zhie and NSLS-II staff)
Dedicated chassis for timing
500 MHz PA remote control
Install amplifiers for ICT (close to completion)
Eliminate crashing of BPM (work mostly by vendor)
Controls (multiple tasks with ongoing effort)
Develop procedure for coarse tuning of the gun

Annual budgets and the total received: all used for hardware

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b) Actual costs to date	$1,488,000	$2,690,000	$1,345,000	$385,000	**$5,908,000**

Other funds:

C-AD R&D (BNL) - $1M hardware, ~ $9M personal

PD (BNL)- $2.5M

LDRDs (BNL) - $2M

DoE BES ~ $350 K

DoE HEP ~ $350 K

NSF - $500K

Field Reduction due to Finite Transverse Modulation Size

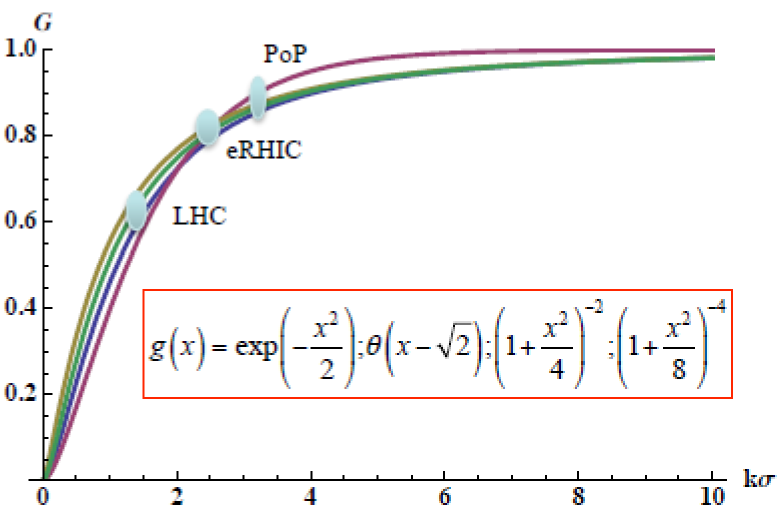
$$\rho(\vec{r}) = \rho_o(r)\cdot\cos(kz);$$
$$\Delta\varphi = -4\pi\rho \Rightarrow \varphi(\vec{r}) = \varphi_o(r)\cdot\cos(kz);$$
$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\varphi_o}{dr}\right) - k^2\varphi_o = 4\pi\rho_o(r)$$

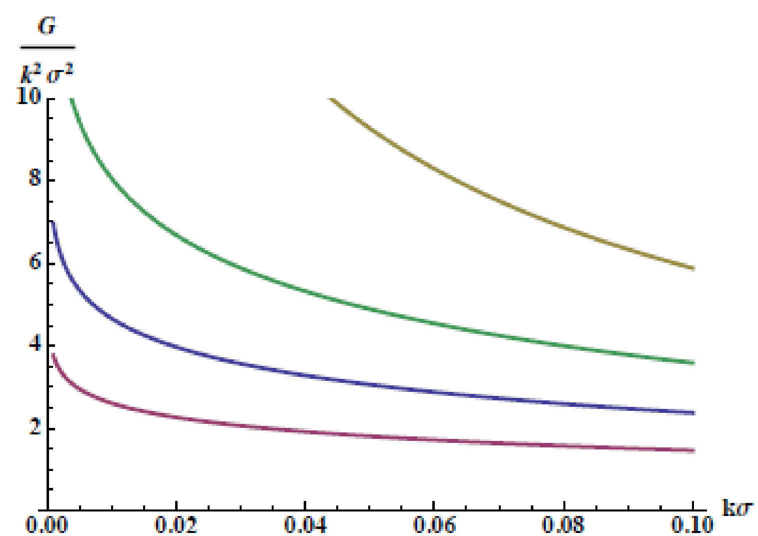
$$\varphi(\vec{r}) = -4\pi\cos(kz)\left\{ I_0(kr)\int_r^\infty xK_0(kx)\rho_o(x)\,dx + K_0(kr)\int_0^r xI_0(kx)\rho_o(x)\,dx \right\}$$
$$E_z = -\frac{\partial\varphi}{\partial z} = -4\pi k\sin(kz)\left\{ I_0(kr)\int_r^\infty xK_0(kx)\rho_o(x)\,dx + K_0(kr)\int_0^r xI_0(kx)\rho_o(x)\,dx \right\}$$
$$E_r = -\frac{\partial\varphi}{\partial r} = 4\pi k\cos(kz)\left\{ I_1(kr)\int_r^\infty xK_0(kx)\rho_o(x)\,dx - K_1(kr)\int_0^r xI_0(kx)\rho_o(x)\,dx \right\}$$

$$\rho(r) = \rho(0)\cdot g(r/\sigma)$$

$$E_{zo}(r=0) \propto -\frac{4\pi\tilde{q}}{\sigma^2}G(k_{cm}\sigma)$$

$$k_{cm}\sigma_\perp = \frac{k_o}{\gamma_o}\sqrt{\frac{\beta_\perp\varepsilon_{n\perp}}{\gamma_o}} = \sqrt{\gamma_o}\sqrt{\beta_\perp\varepsilon_{n\perp}}\,\frac{k_w}{2(1+a_w^2)}$$





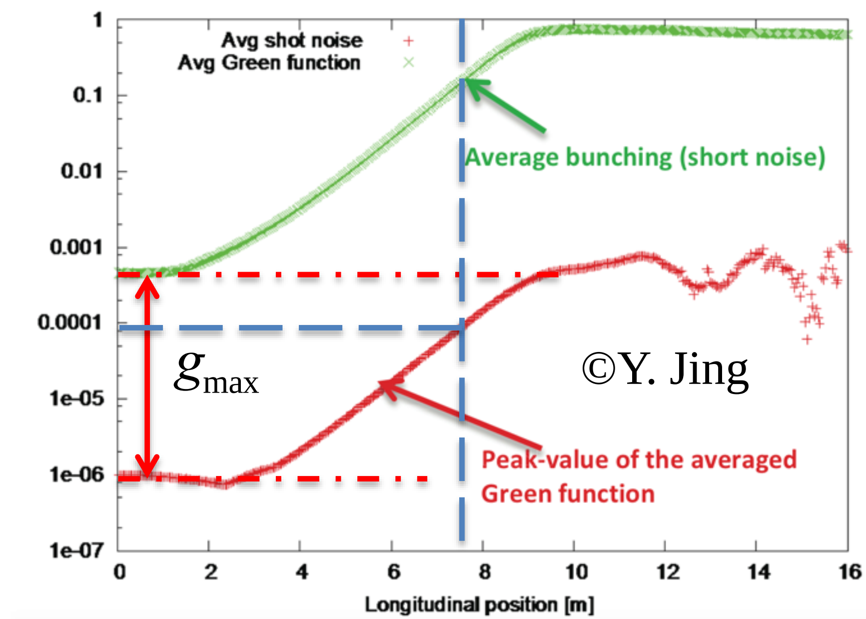
FEL amplifier simulation II:

With shot noise from electrons:

$$\left| d\hat{n} / n_0 \right|_{max} < 1 \Rightarrow \quad |g|_{max} < \frac{\lambda_o}{2}\sqrt{\frac{I_e}{ecL_c}} \Rightarrow \quad g_{max} \sim 72 \times \sqrt{\frac{I_e[A] \cdot \lambda_o[\mu m]}{M_c}} = 429$$

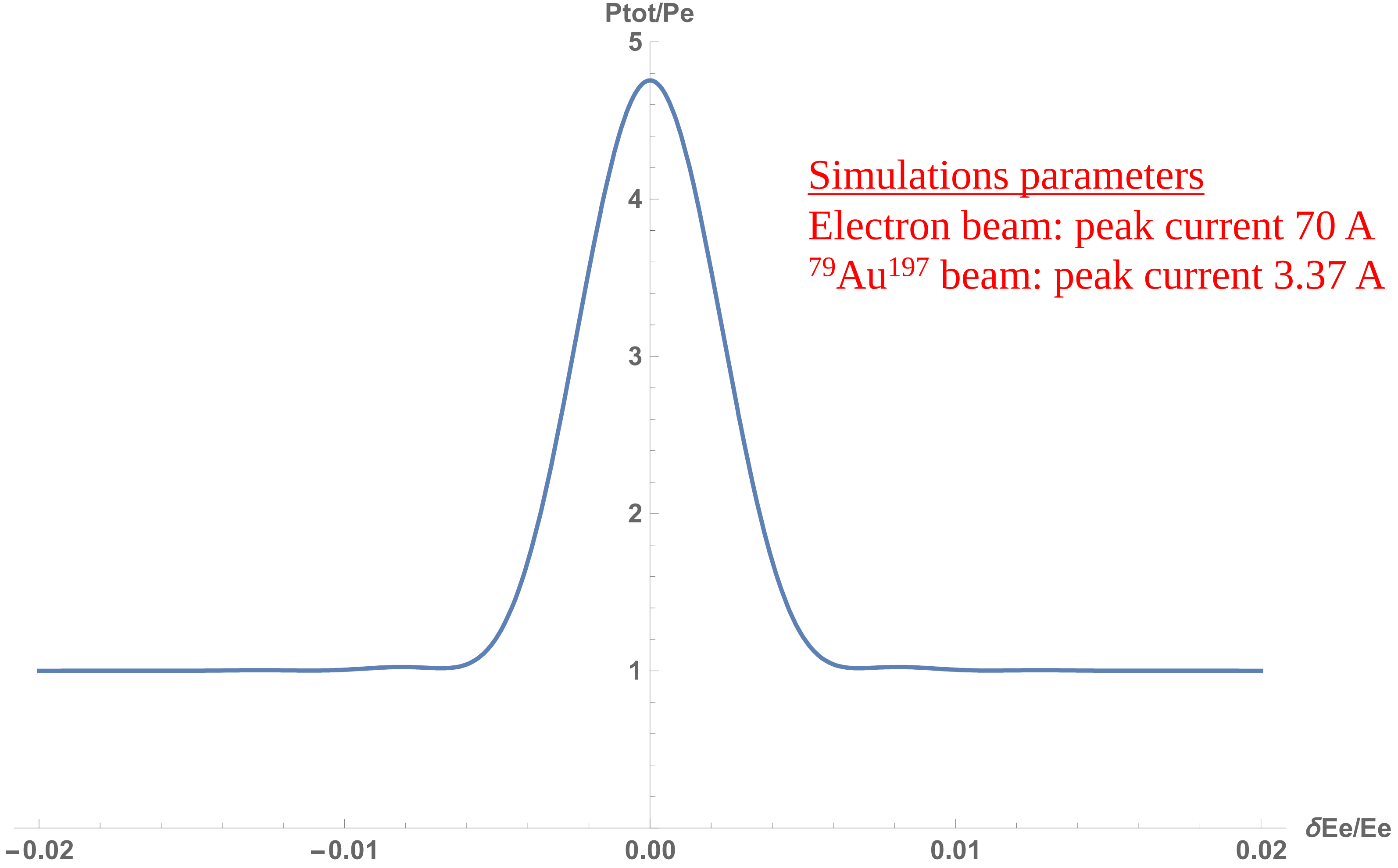
$$M_c \equiv \frac{L_c}{\lambda_1} = \frac{1}{\lambda_1 g_{max}^2} \int_{-\infty}^{\infty} |g(z)|^2 \, dz$$

γ=21.8
Peak current: 100 A
Norm emittance 5 mm mrad
RMS energy spread 1e-3
λw=4 cm
$a_w = 0.4$
λo=12.7 um
Mc = 35.8



3D Genesis simulation shows that the maximal gain in bunching factor is 409, which agrees with our estimation.

Matching velocities/relativistic factors
We rely on the increase of the shot noise in electron beam which is induced by ion's in the modulator



Simulations parameters

Electron beam: peak current 70 A

$^{79}Au^{197}$ beam: peak current 3.37 A