Recent Progress in the Coherent Electron Cooling Experiment

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for CeC team

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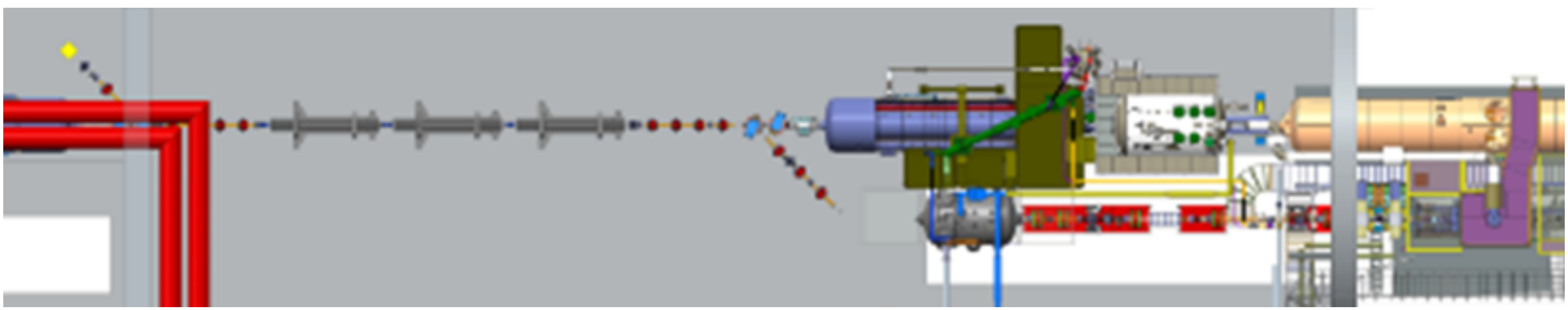
STFC, Daresbury Lab, Daresbury, Warrington, Cheshire, UK



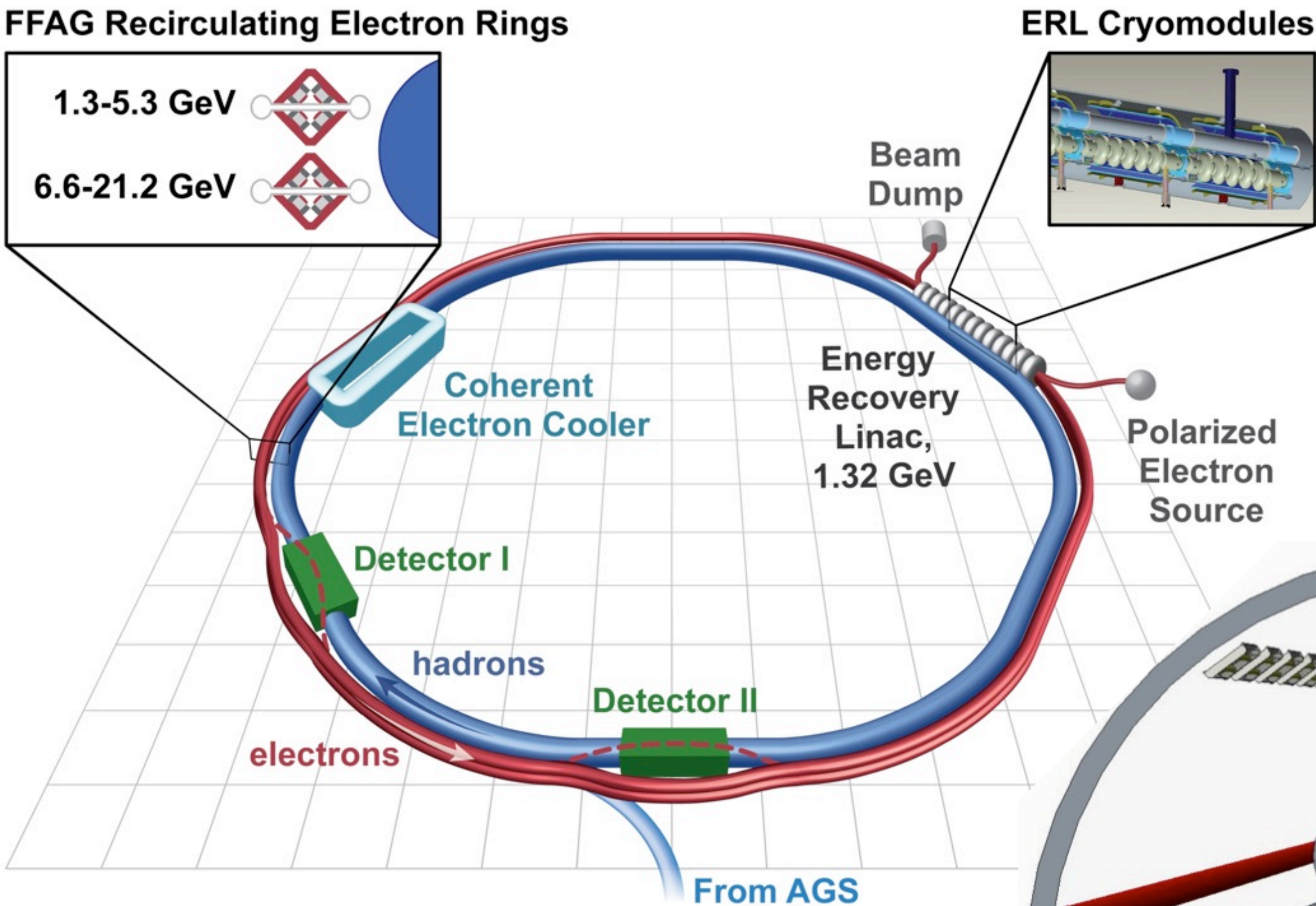
Supported by NP DoE office Accelerator R&D grant and
BNL (LDRDs & PD, C-AD R&D)

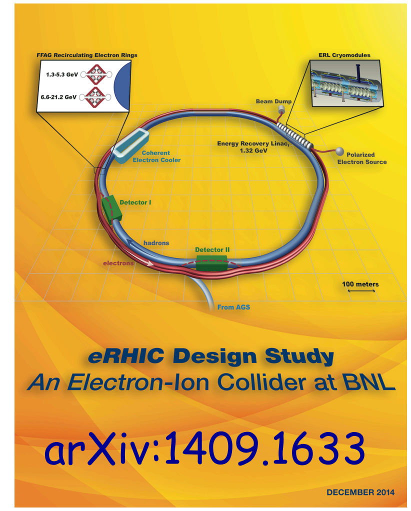
Content

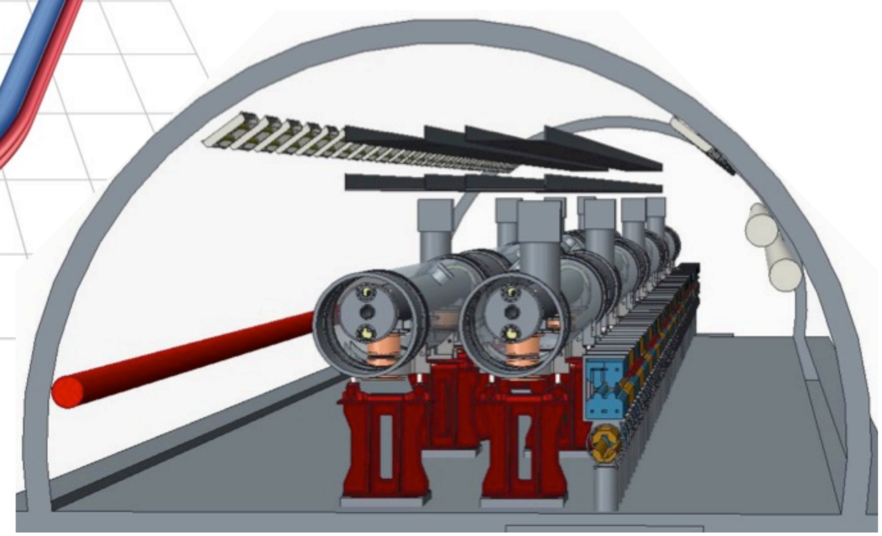
- Why we need very strong cooling at BNL
- How we plan to cool 250 GeV protons and 100 GeV/u heavy ions
- Coherent electron Cooling
- Coherent electron Cooling Proof-of-Principle Experiment
  - Goals and scheme
  - Progress with the commissioning
  - Current status and plans
- Summary

eRHIC design

Highly advanced and energy efficient accelerator

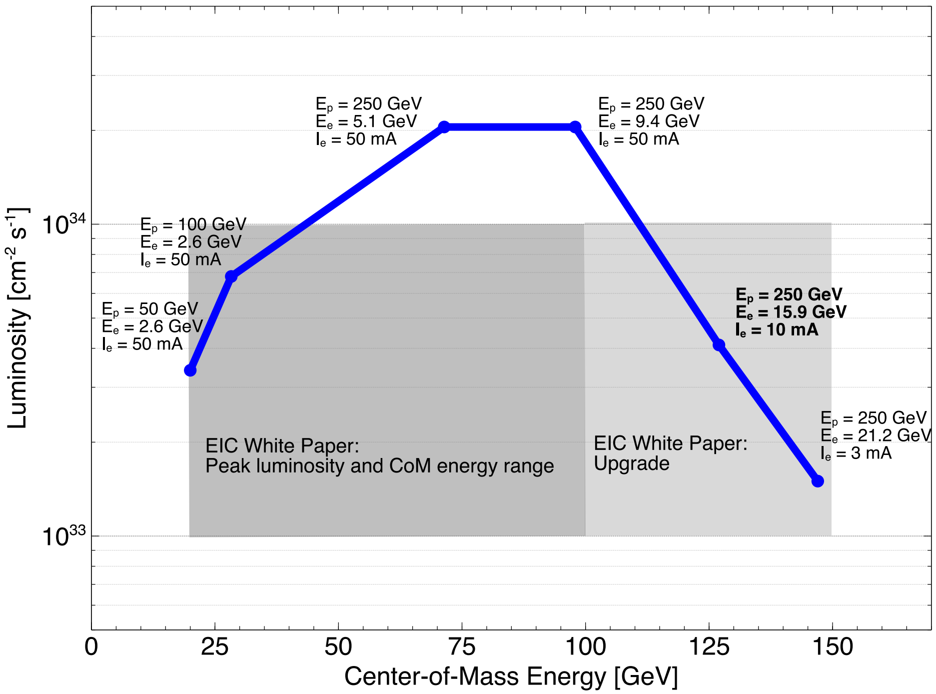


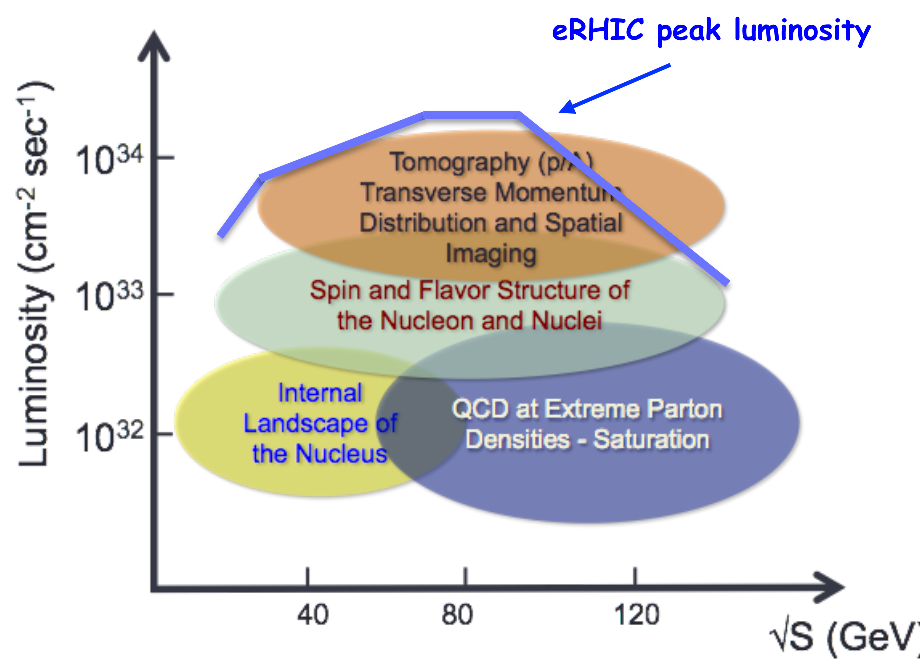




4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e↑ on 250 GeV p↑)

eRHIC peak luminosity vs. CoM energy





eRHIC design covers whole Center-of-Mass energy range, including "EIC White Paper Upgrade" region

Small beam emittances and IR design allows for full acceptance detector at full luminosity

eRHIC hadron beam is 1,000 x brighter than current RHIC beams

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		126	103	80
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.07	3.0	3.0	3.0
Bunch charge, nC	1.1	48	32	19.6
Beam current, mA	10	415	275	165
Hadron rms normalized emittance, 10^{-6} m		**0.2**	**0.2**	**0.2**
Electron rms normalized emittance, 10^{-6} m		23	35	58
β*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.004	0.003	0.008
Electron beam disruption		36	16	6
Space charge parameter		0.08	0.08	0.08
rms bunch length, cm	0.4	**5**	**5**	**5**
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} $cm^{-2}s^{-1}$		4.1	2.8	1.7

Very strong cooling is required

Requirement vs. current cooling techniques

IBS growth time for eRHIC beam is about 20 seconds (for 250 GeV protons) and have to be contra-acted by cooling. Initial operation of eRHIC can started with cooling time of few minutes, BUT NOT HOURS!

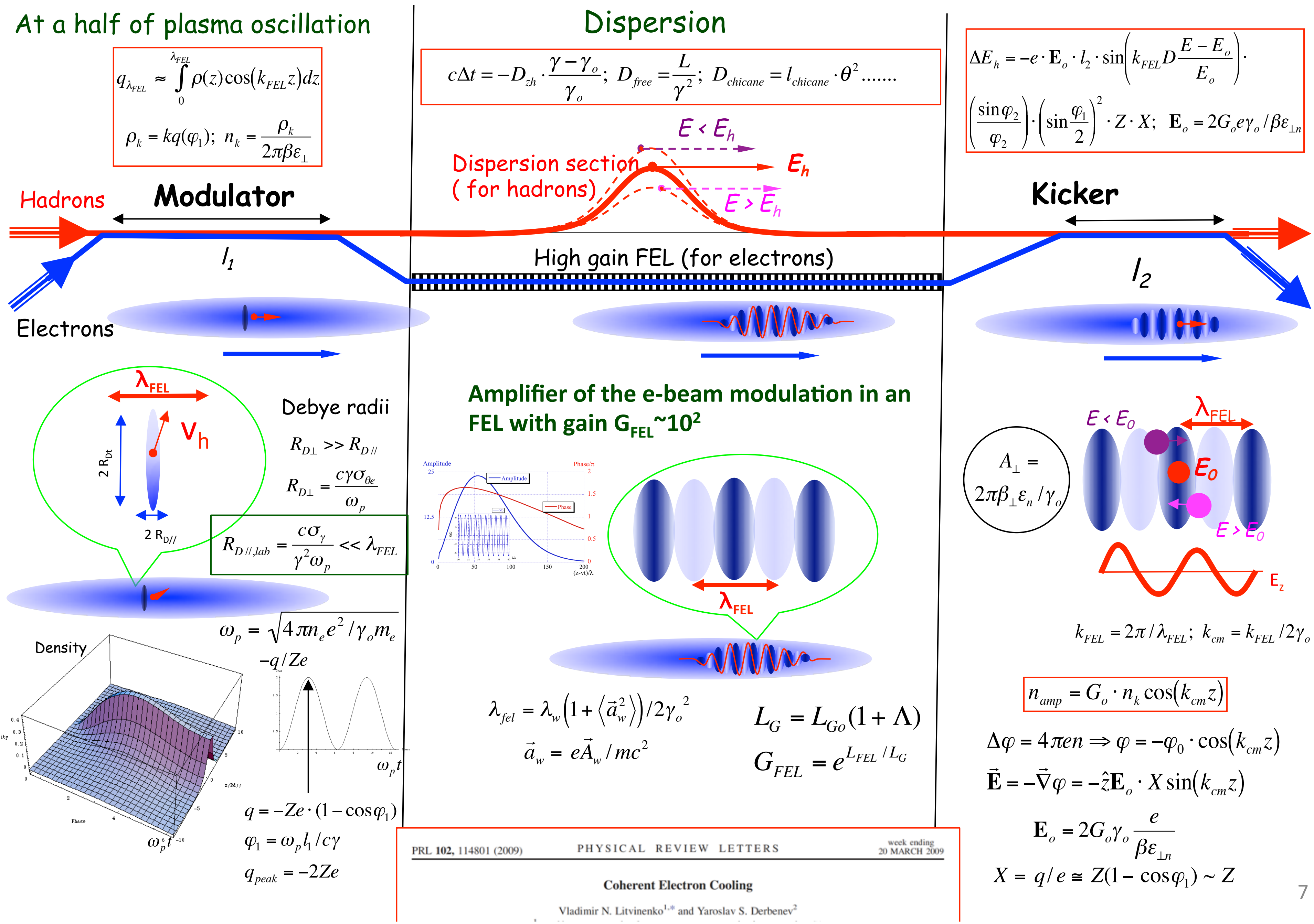
RHIC's stochastic cooling can cool 10^9 ions in 5 nsec bucket with cooling time ~ 1 hour. It is equivalent to cooling time for eRHIC 0.3 nsec bunches:

- Heavy ions > 10 hours
- Protons > 100 hours

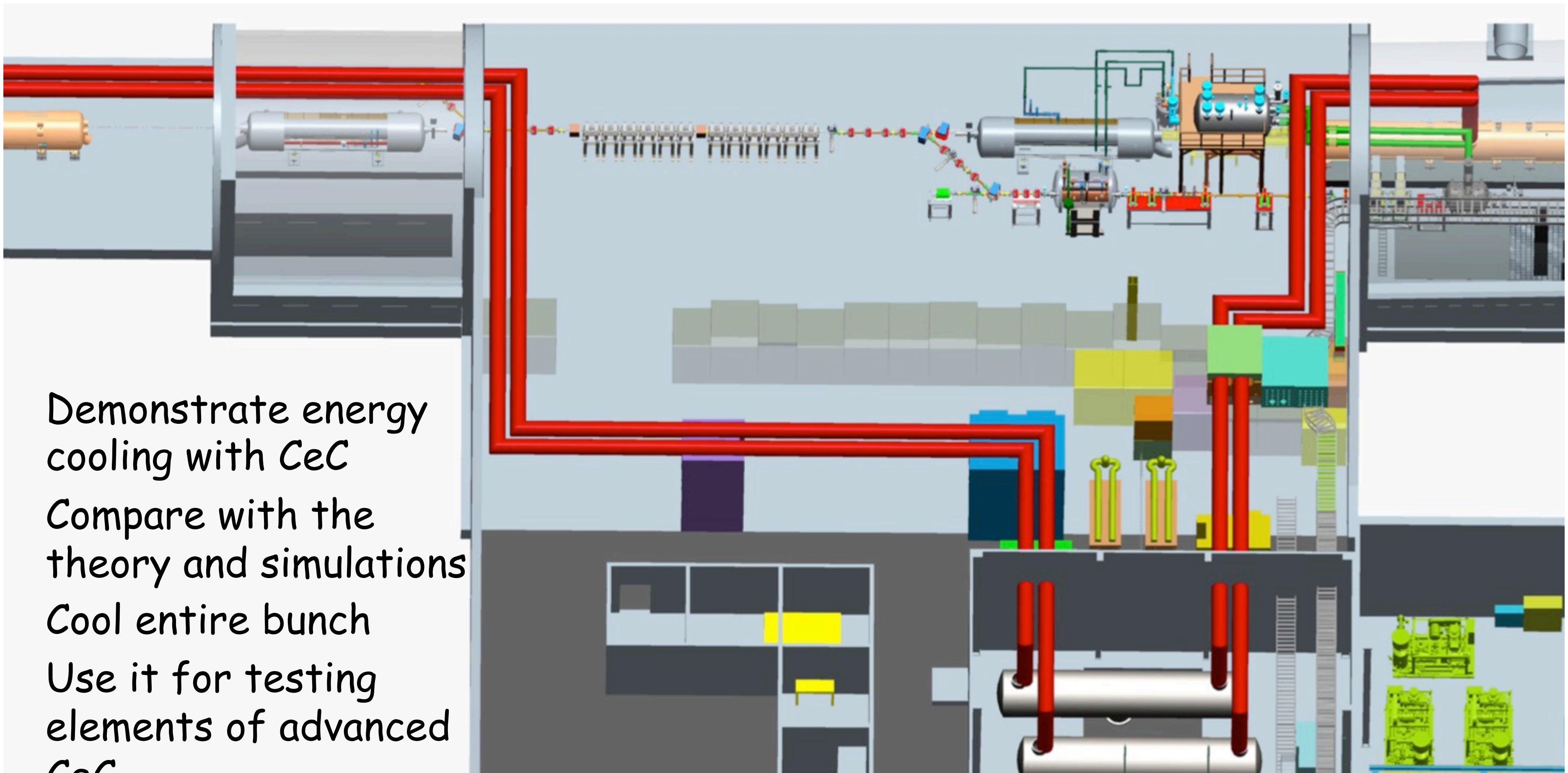
Our best design for electron cooling promised to cool ion beam at 100 GeV with cooling time of one hour. Extending this $150M facility to cool 250 GeV protons will provide cooling time of about 30 hours. It would be better than stochastic cooling, but definitely insufficient for eRHIC

We need a better cooling mechanism.

Coherent electron Cooling

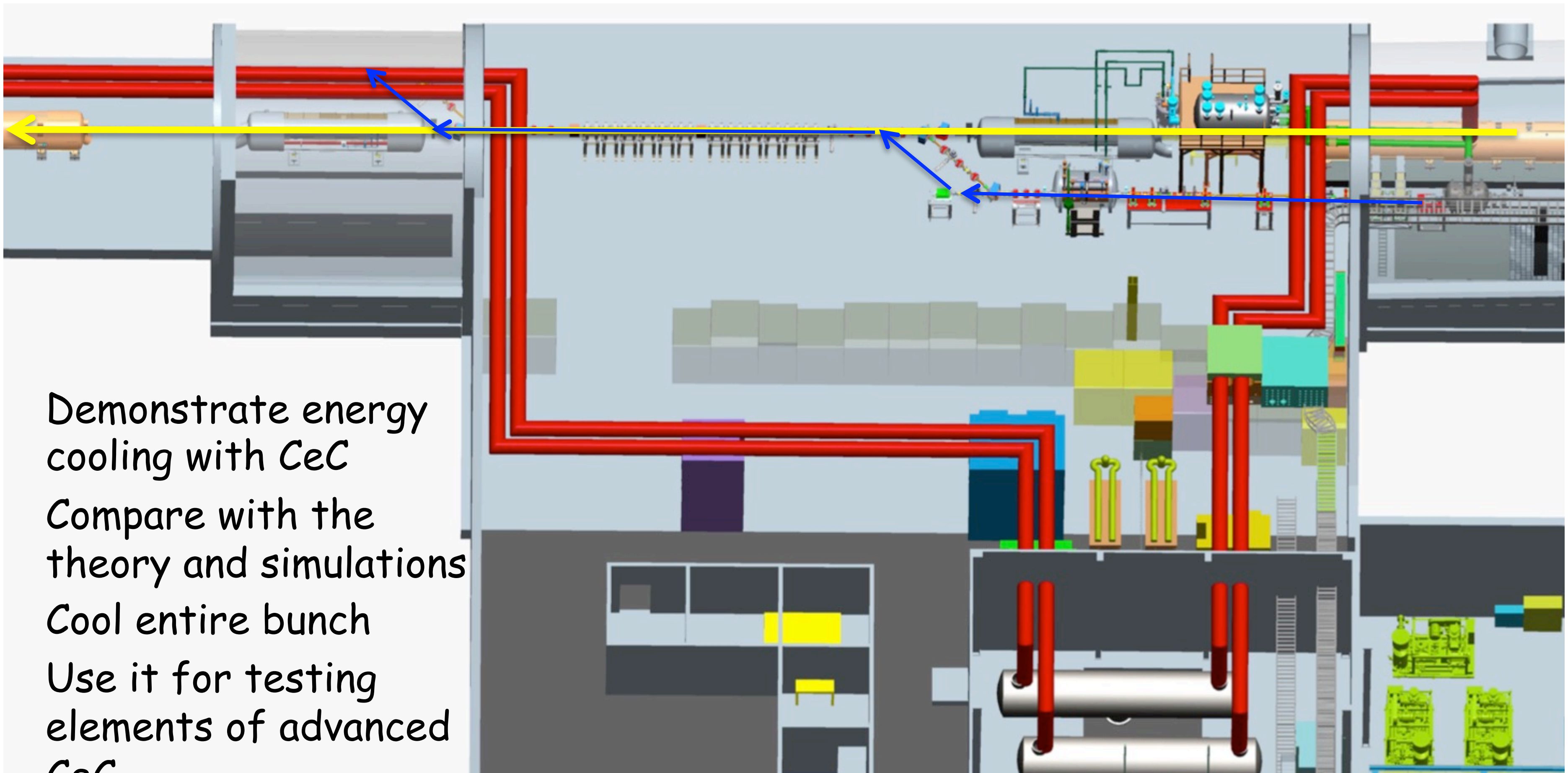


This novel untested technique needs a CeC Proof-of-Principle Experiment



- ✓ Demonstrate energy cooling with CeC
- ✓ Compare with the theory and simulations
- ✓ Cool entire bunch
- ✓ Use it for testing elements of advanced CeC

This novel untested technique needs a CeC Proof-of-Principle Experiment



- ✓ Demonstrate energy cooling with CeC
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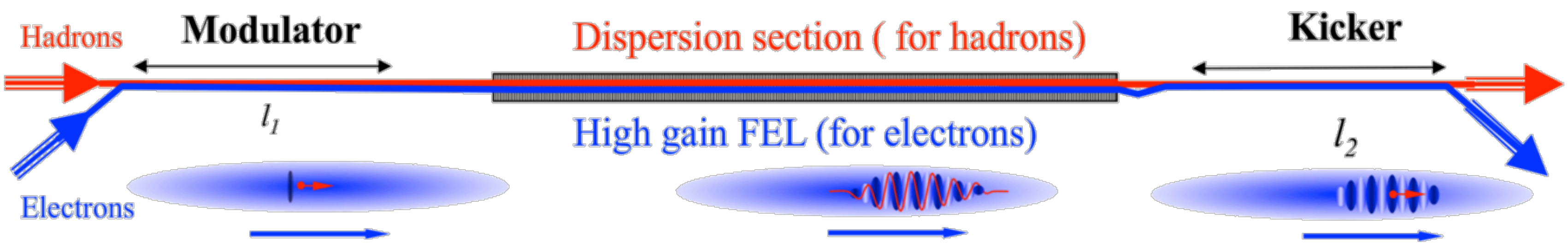
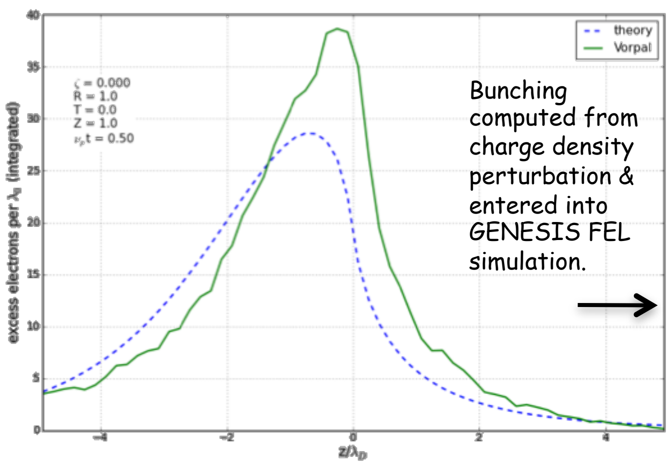
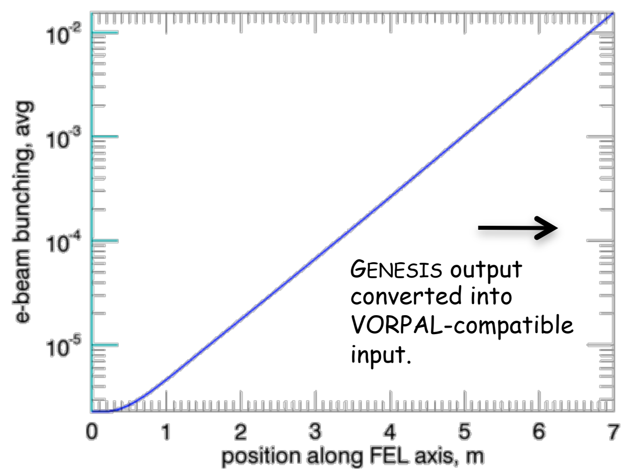
Our PoP is based on an economic version of CeC: it limits strength of the wiggler a_w to about 0.5 **but it is very cost effective**



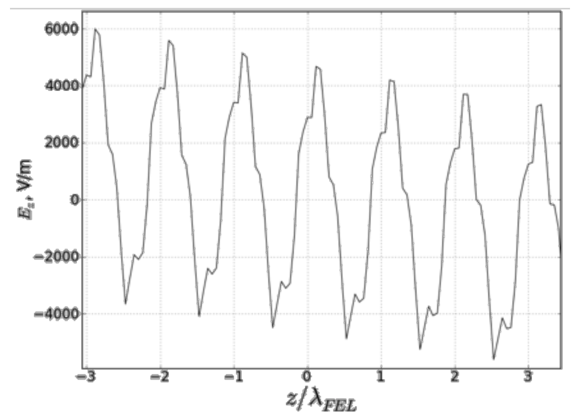
Param.' s from 40 GeV proof-of-principle exp. at BNL



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



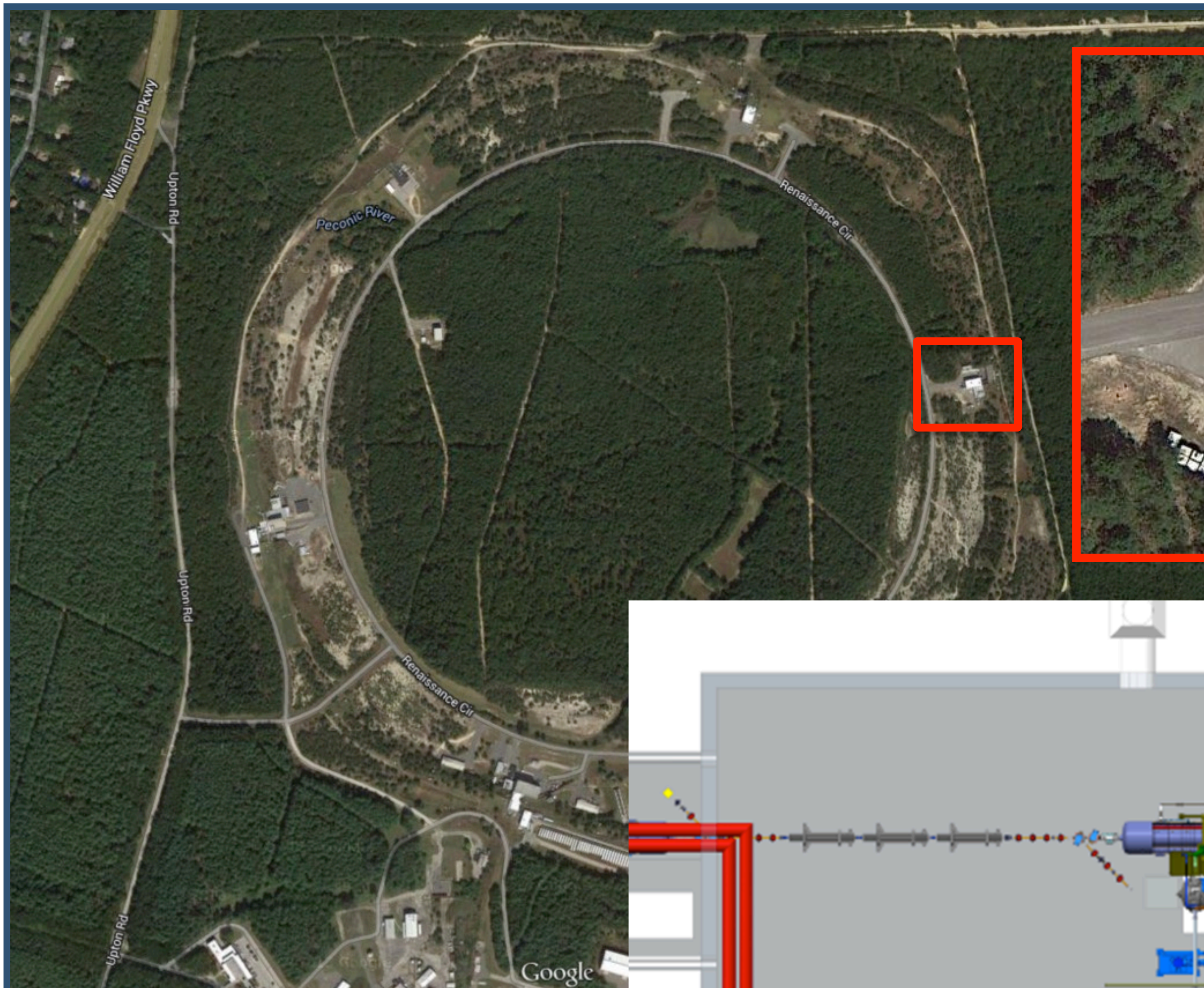
GENESIS parallel computation of electron beam bunching in free electron laser (FEL) shows amplification of modulator signal.

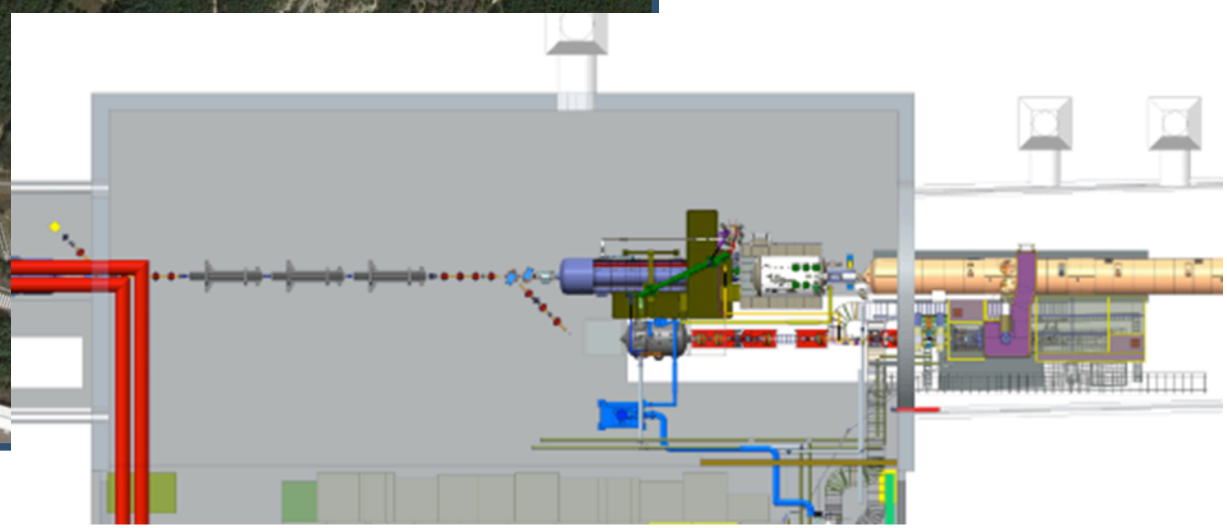


VORPAL prediction of the coherent kicker electric field E_k due to e-density perturbation from modulator, amplified in the FEL.

Simulations by Tech-X

Location – RHIC 02:00 Region



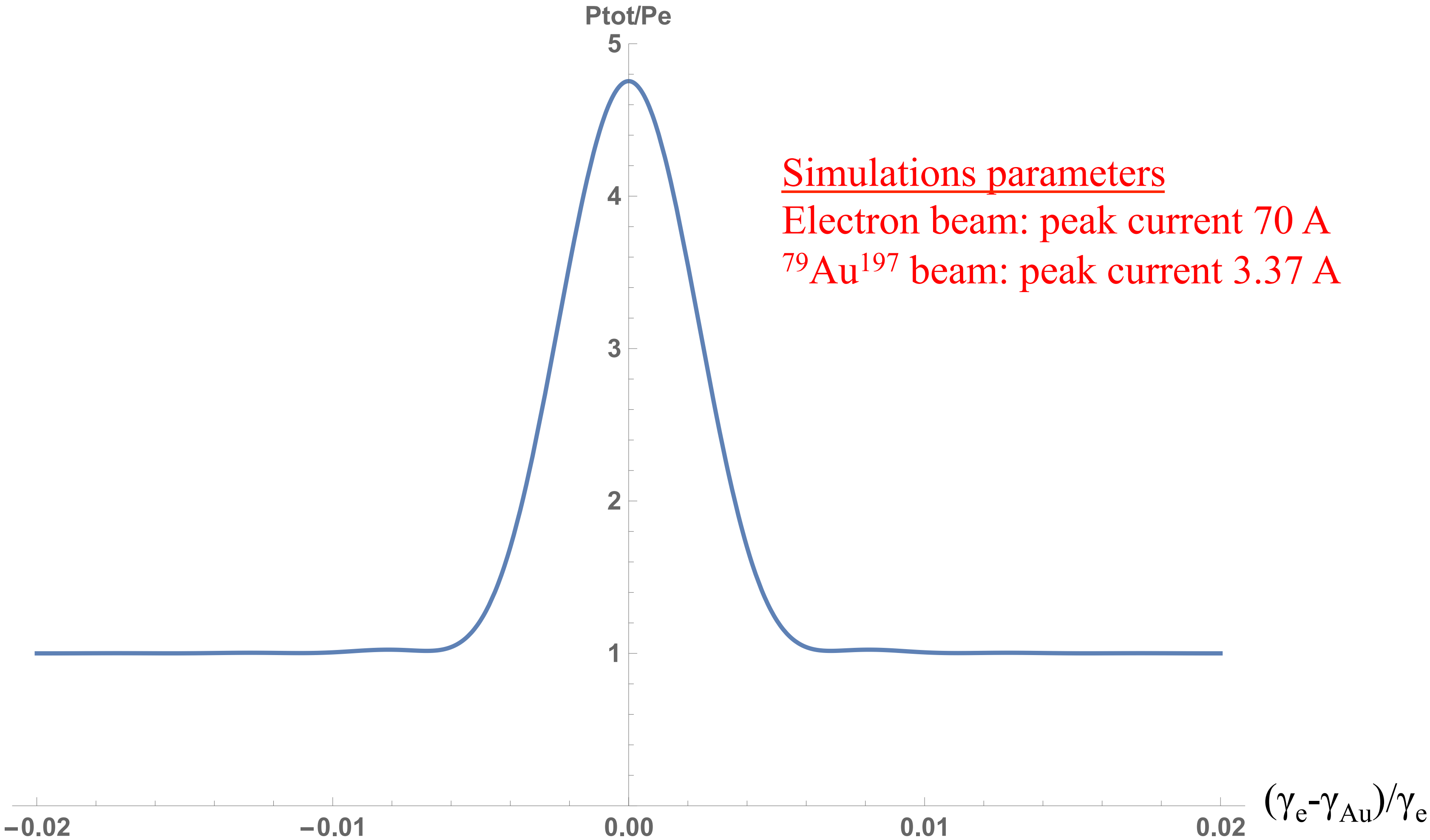


Main Accelerator Parameters

Electron Beam	
RMS Energy Spread	$\leq 1\times10^{-3}$
Normalized Emittance	$\leq$ 5 µm·rad
Peak Current	60-100 A
FEL	
Wiggler Length	3×2.5 m
Wiggler Period	40 mm
Wiggler Strength, a_w	0.5 +0.05/-0.1
FEL Wavelength	13.6 µm

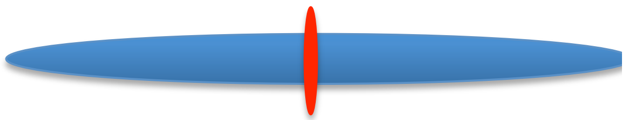
Parameter	**Value**
Species in RHIC	Au^{+79} ions, 40 GeV/u
Relativistic factor	42.96
Number of particles in bucket	10^9
Electron energy	21.95 MeV
Charge per e-bunch	0.5-5 nC
Rep-rate	78.17 kHz
Average e-beam current	0.39 mA
Electron beam power	8.6 kW

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

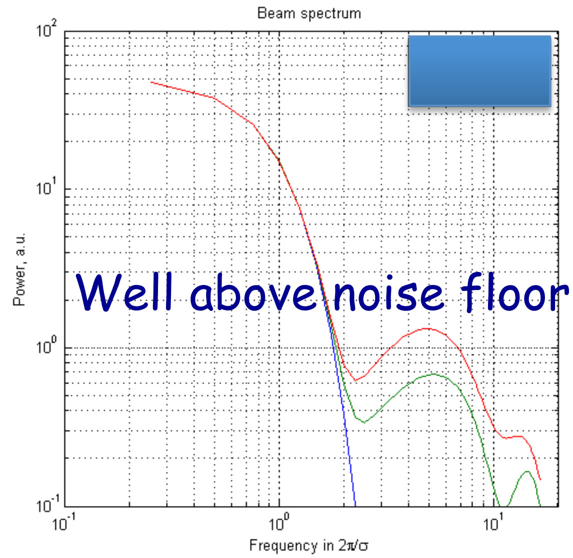


Anticipated Beam Dynamics

Electron bunch – 10 psec

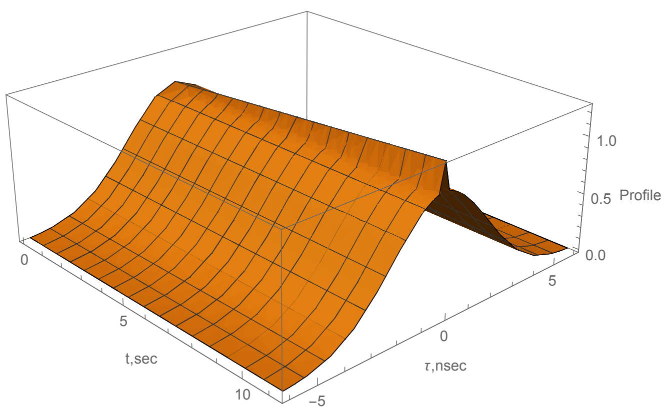


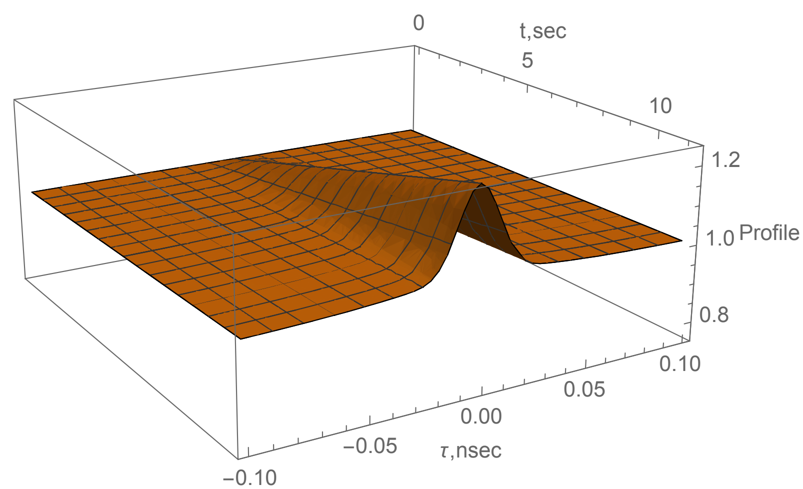
Ion bunch – 2 nsec



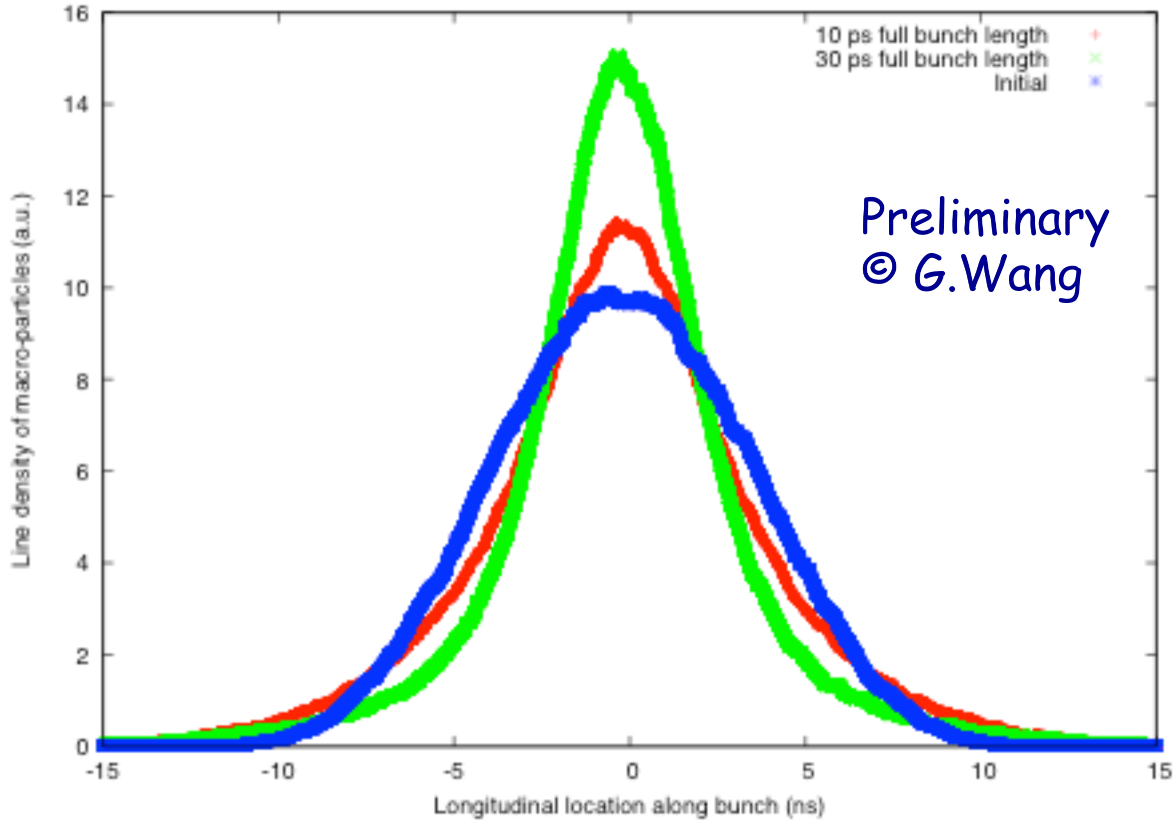
r.m.s. length of the cooled part 80-120 ps. The cooling effects can 2 GHz (or more) bandwidth using spectrum analyzer or digital scope

Simulated beam profile evolution with CeC PoP parameters



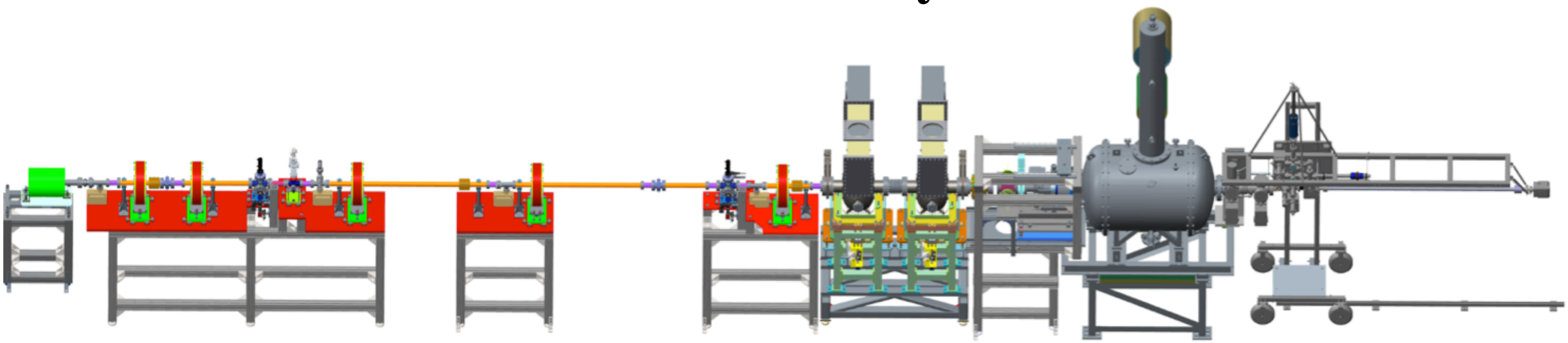


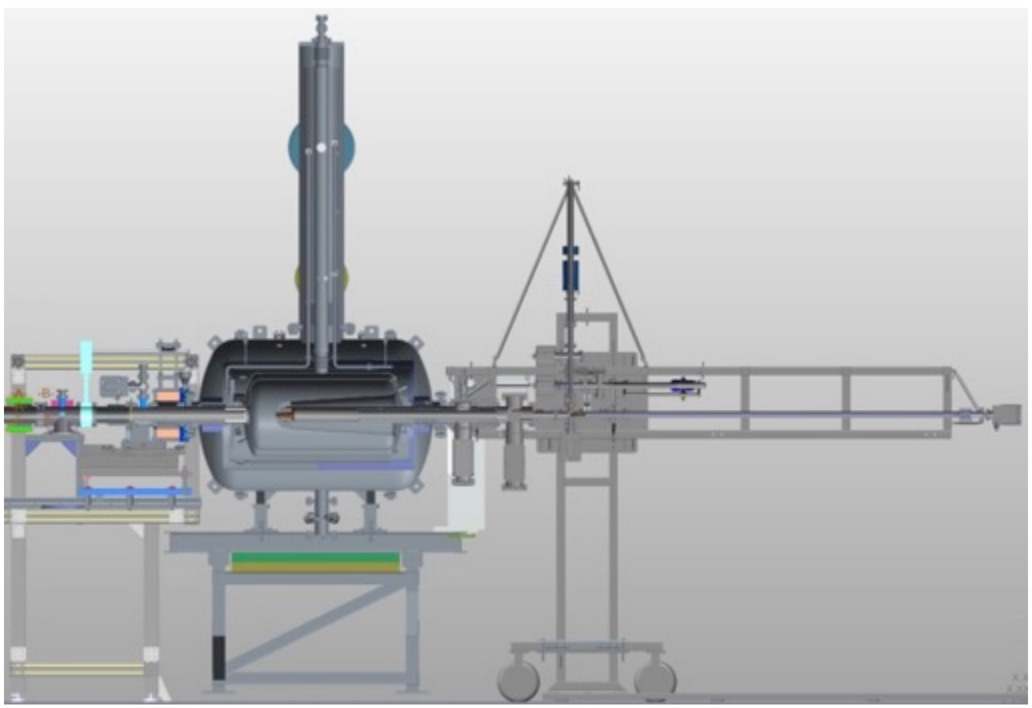
Cooling full bunch
Self-consistent simulations



Plot shows evolution of Au ion bunch profile after 40 mins of CeC using 1 nC (10 psec long) and 3 nC (30 psec long) electron bunches.

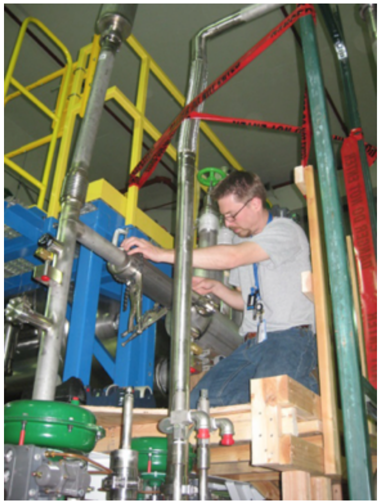
CeC PoP Phase I Layout

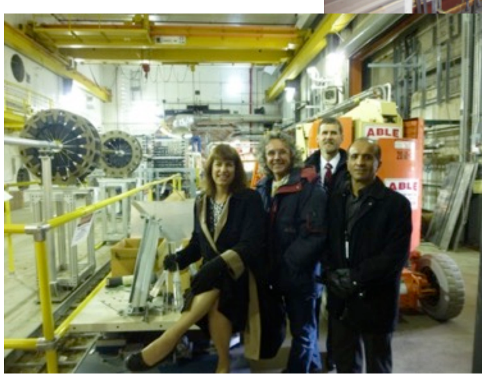




- 112 MHz SRF Gun, Support Systems, and Cathode
- Two 500 MHz NC cavities
- Beamline, diagnostics and low-power beam dump

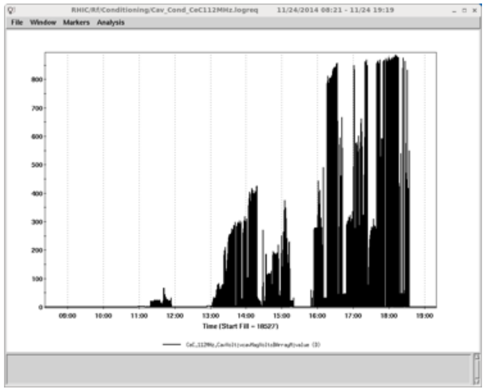
Phase I: Low energy beam-line

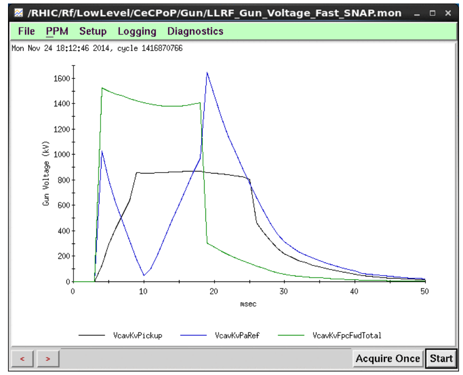


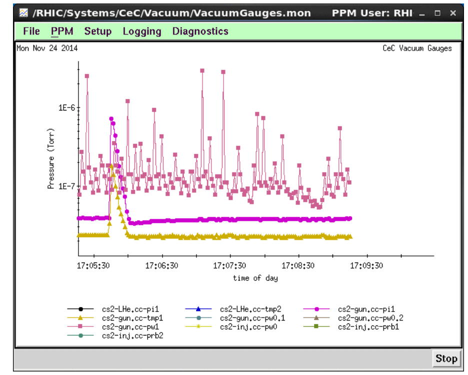


Coherent electron *Cooling* PoP

Conditioning of 112 MHz SRF Gun: Nov-Dec 2014





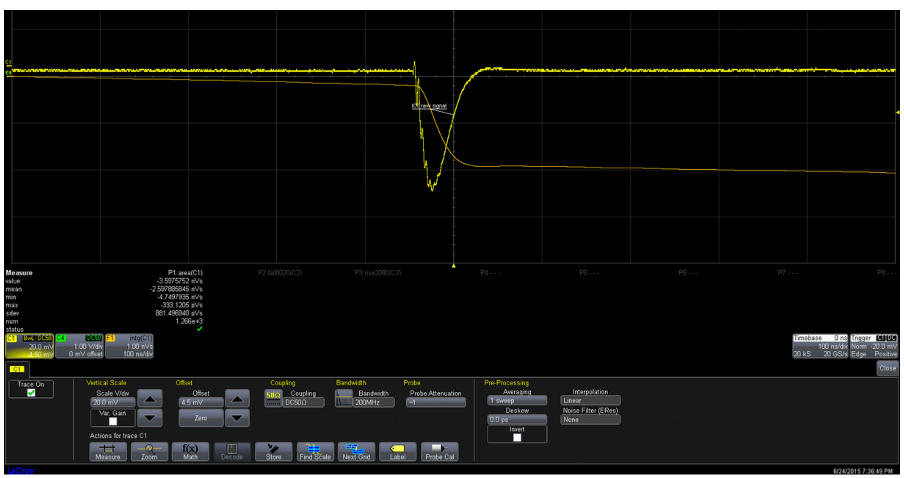


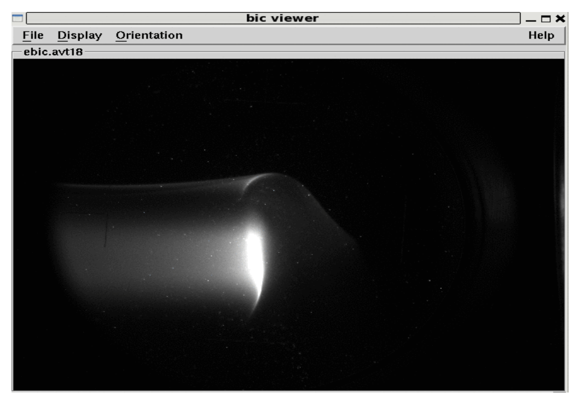
Record beam parameters from CW SRF 112 MHz gun – June 2015

1.6-1.7 MeV (kinetic energy) e-Beam with 3 nC in CW mode

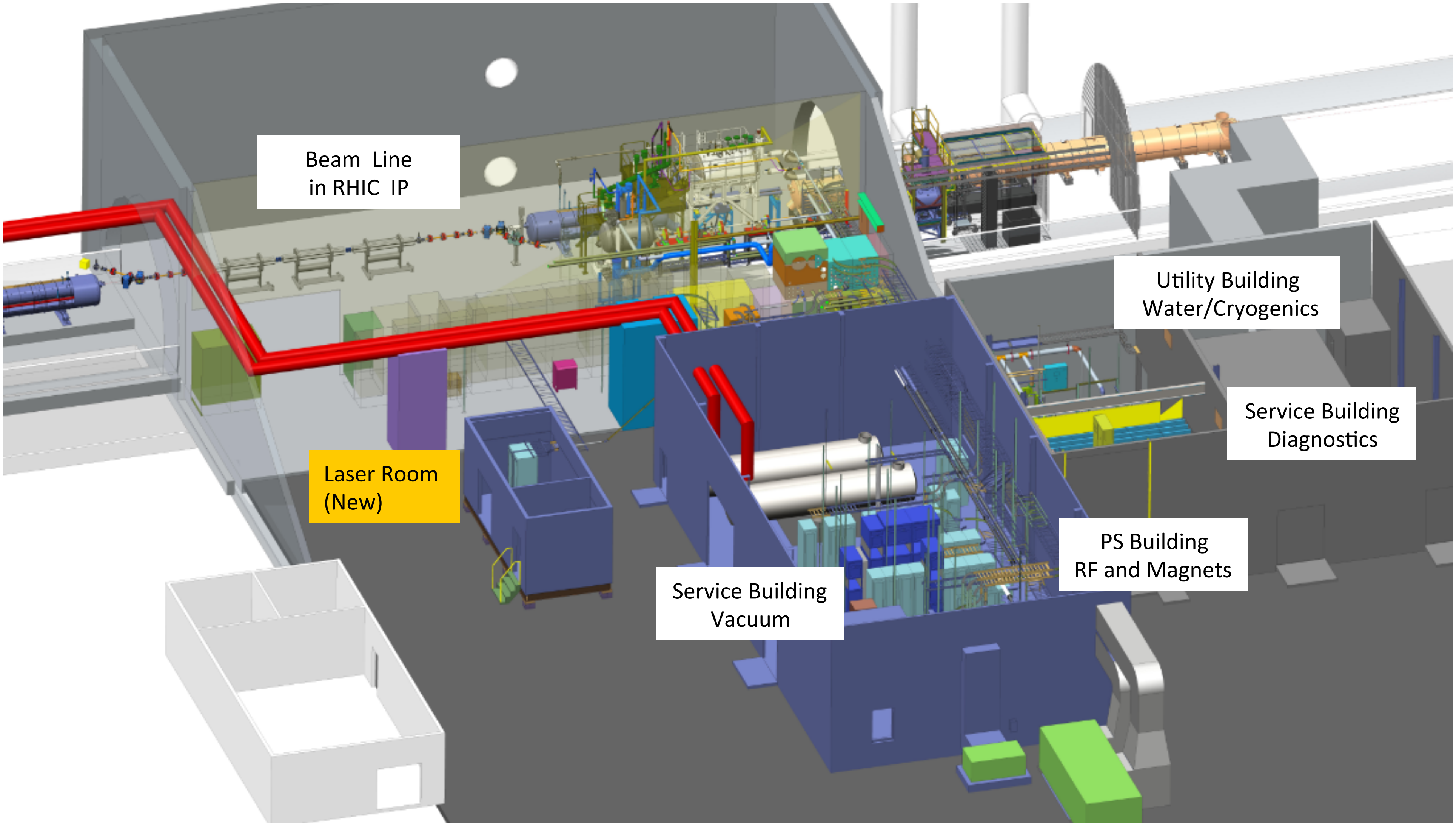
2 MeV in pulse mode

20 MV/m at photocathode

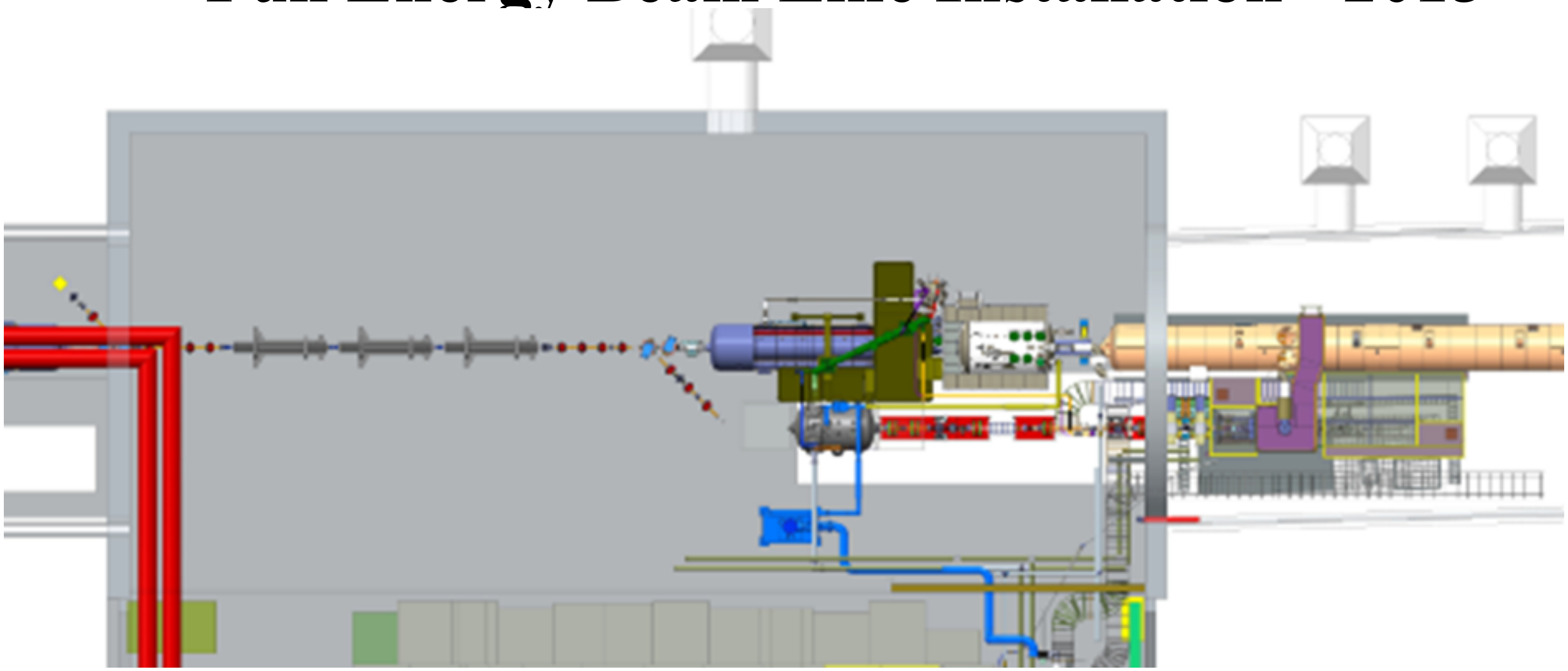




CeC PoP Final Configuration



Full Energy Beam Line Installation - 2015

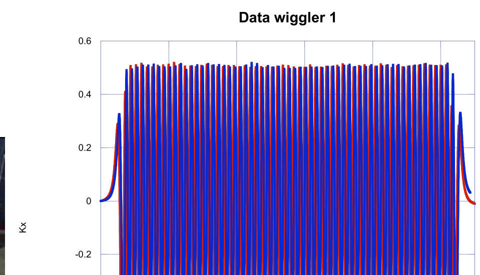


- Install 704 MHz Systems and supporting cryogenic system
- Install Wiggler Magnets
- Install RHIC beam line components: dipoles, quads, correctors, vacuum
- Install beam diagnostics
- Modify and install RHIC DX-DO chamber for FEL light diagnostics
- Move CeC beam dump line to final location

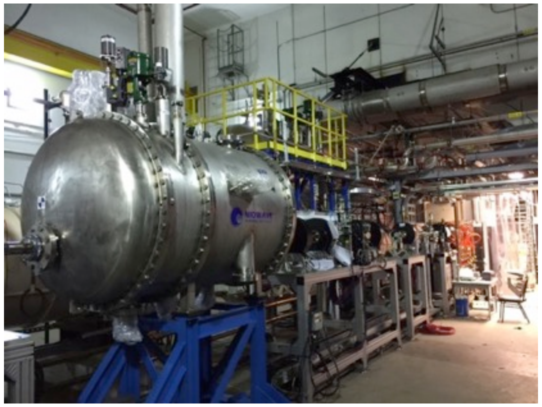
Key deliveries

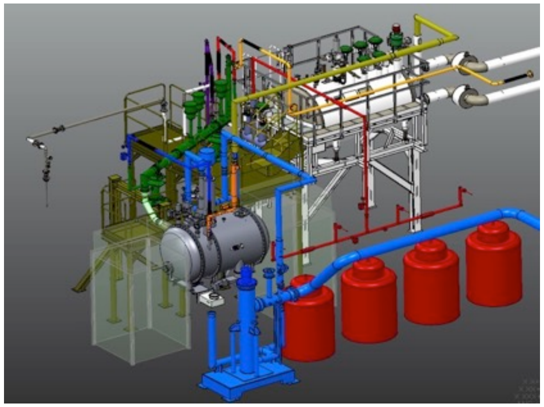
704 MHz SRF linac from Niowave

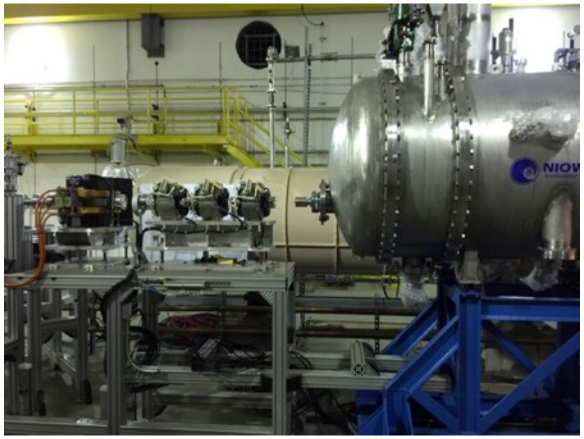
Three helical wiggler from BINP (Novosibirsk)



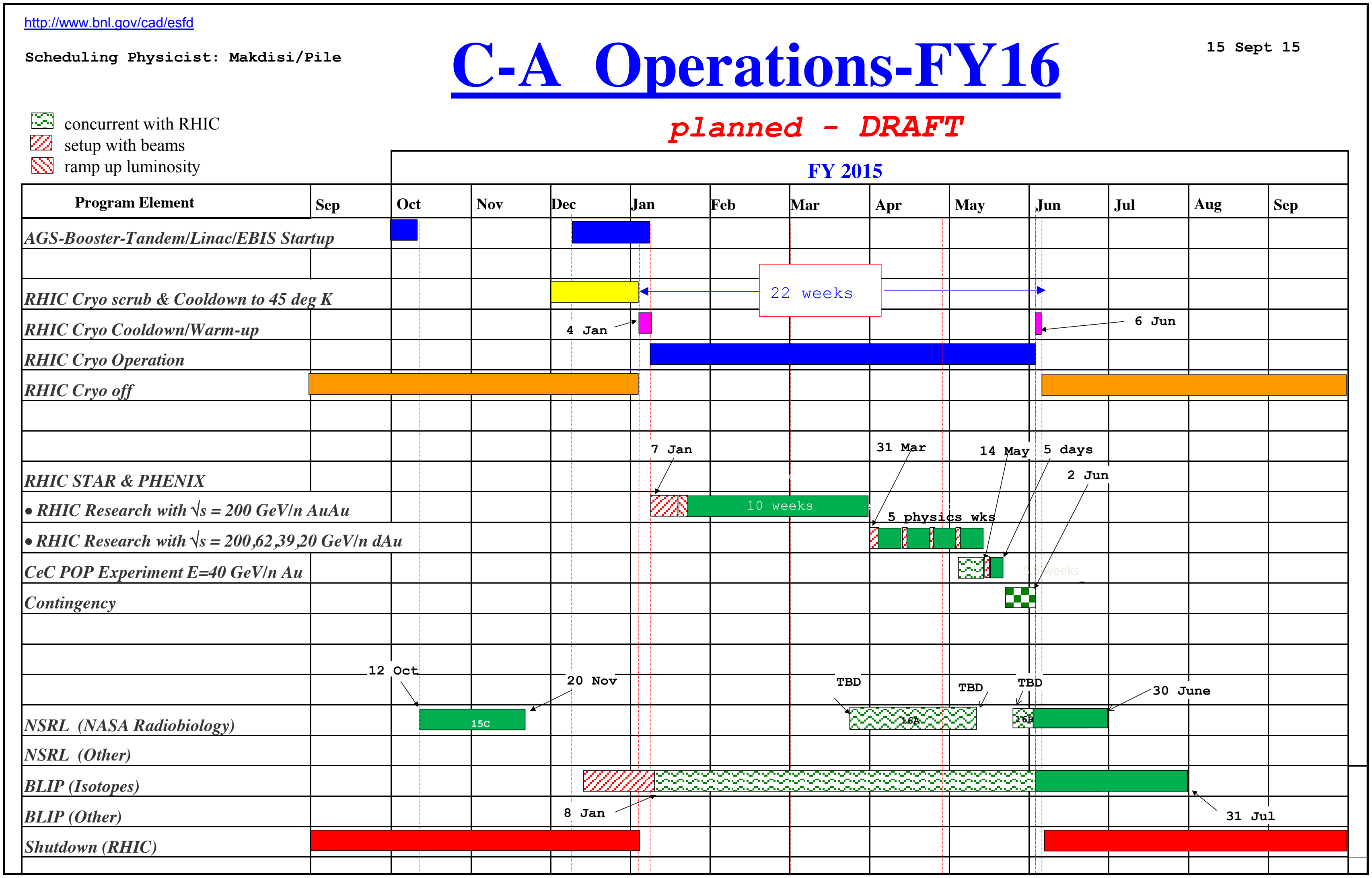
We are on the move with rest of the CeC PoP







CeC experiment is now a part of RHIC Run-16 plan



Plans

- We plan to finish installation of complete CeC PoP system before start of RHIC rung in January 2015
- We plan step-by-step commissioning of the CeC systems, initially in background, and later in a dedicated mode of operation.
- The ambitious goal is to detect fist cooling during Run 16
  - – this requires commissioning of the 22 MeV SRF accelerator, transport system, diagnostics, attainment of design electron beam parameters, demonstration of FEL HG amplifier, development of RHIC ramp, and finally full synchronization and alignment of electron and ion beams...
- Our goal is to use RHIC run 17 for detailed characterization of CeC
  - and, if time allows, for testing elements of advanced CeC (micro-bunching amplifier)

Summary

- Progress continues with the component installation and commissioning of CeC proof-of-principle experiment
- Our super-conducting 112 MHz gun generated photo-emitted CW electron beam with record parameters: 1.7 MeV , 3 nC per punch
- Critical deliveries (704 MHz SRF linac and three helical wiggler) had been made
- Installation of the complete CeC system is in progress
- CeC experiment is highest R&D priority of C-AD and is now elevated to the status of RHIC experiment
- We plan to commission CeC during RHIC Run 16 and to evaluate its performance during RHIC Run 17.

People involved with CeC PoP at BNL

V. Litvinenko, I. Pinayev J. Tuozzolo, J. Skaritka, Y. Hao, Y. Jing, G.Wang, D. Kayran, B. Xiao, B. Sheehy, E. Wang, T. Rao, Z. Altinbas, S.A. Belomestnykh, K.A. Brown, J.C. Brutus, A.J. Curcio, L. DeSanto, C. Folz, D.M. Gassner, C. Ho, R.L. Hulsart, M. Ilardo, J.P. Jamilkowski, F.X. Karl, N. Laloudakis, R.F. Lambiase, G.J. Mahler, M. Mapes, W. Meng, R.J. Michnoff, T.A. Miller, M.G. Minty, G. Nayara, P. Orfin, F. Randazzo, , J. Sandberg, K.S. Smith, L. Snydstrup, A.N. Steszyn, R. Than, C. Theisen, R.J. Todd, D. Weiss, M. Wilinski, A. ZaltsmanR. Kellerman, T. Xin, D. Ravikumar, Y. Wu

(*and we definitely missed somebody!*)

BACK-UP

Schedule

Construction

CeC PoP experiment is a DOE NP competitive R&D project –
we are submitting quarterly progress and budget reports

x - a milestone, X – major milestone

Delivery of 704 MHz linac to BNL	✓	30-Jul-15
Assembling and tuning helical wigglers	2/3 done	1-Oct-15
Installing/plumbing the 704 MHz in RHIC tunnel	x	15-Nov-15
Install helical wigglers in RHIC tunnel	x	01-Dec-15
CW laser is commissioned	x	01-Dec-15
Beam diagnostics is intalled		15-Dec-15
Optical diagnostics is installed		15-Dec-15
Complete CeC beam-line	**X**	**15-Dec-15**

Schedule for RHIC run 16

(dates are tentative and are adjusted to the preliminary RHIC Run 16schedule)

Commissioning	Milestones	End date	
SRF cavities cold	x	15-Jan-16	Has to be synchronized with RHIC run
Complete cavity conditioning	**X**	**20-Feb-16**	
Generating first beam	**X**	**10-Mar-16**	
Measuring beam parameters	X	1-Apr-16	
Propagate beam to the beam dump	x	20-April-16	
Test co-propagation with ion beam	**X**	**1-May-16**	
Demonstrate FEL amplification	**X**	**15-May-16**	
First cooling attempt	**X**	**02-Jun-16**	Dedicated 5 days of running

Schedule - demonstration

(dates are tentative and will be adjusted to RHIC Run 17)

Making necessary up-grades/ improvements	01-Jul-16	31-Dec-16	Improving and updating diagnostics, optical system, as well as installing buncher for ACeC test
SRF cavities cold	x	15-Feb-17	Has to be synchronized with RHIC run
Complete cavity conditioning	**X**	**01-Mar-17**	
Recreating operational conditions	**X**	**21-Mar-17**	
Start CeC PoP experiments (using APEX shifts)	**X**	**07-Apr-17**	
Demonstrate microbunching amplification (ACeC)	x	30-May-17	if time allows
Demonstrate CeC PoP cooling	**X**	**30-Jun-17**	
CeC cooling experiments end	**X**	**30-Jun-17**	Dates have to be adjusted to the end of the RHIC run

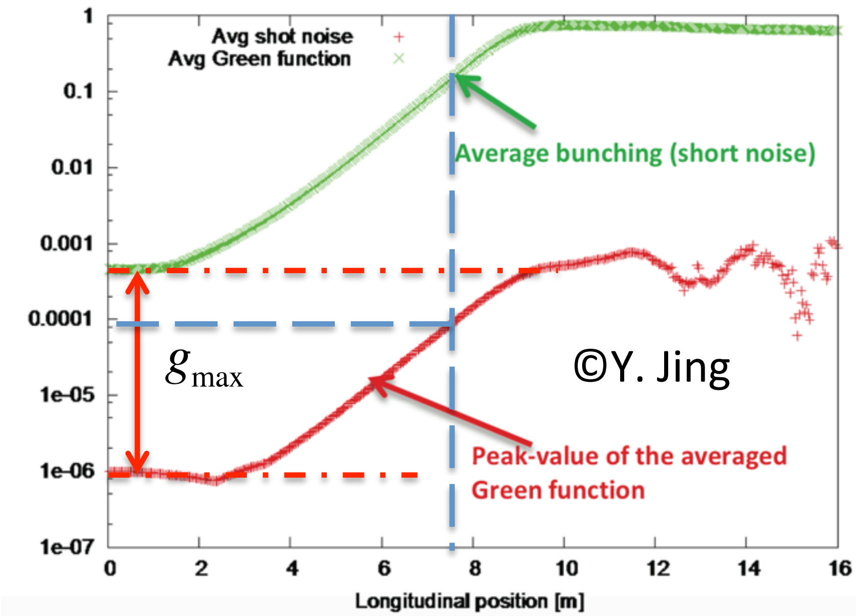
FEL amplifier simulation II:

With shot noise from electrons:

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

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

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

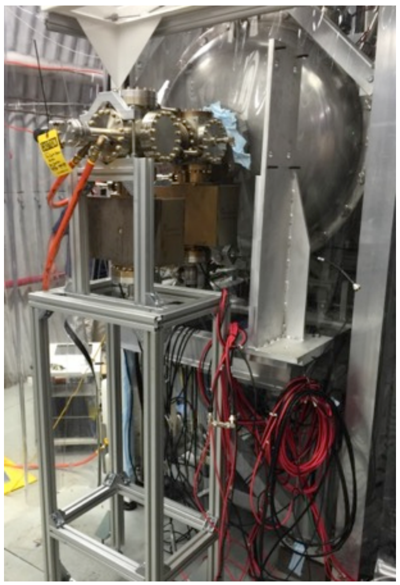


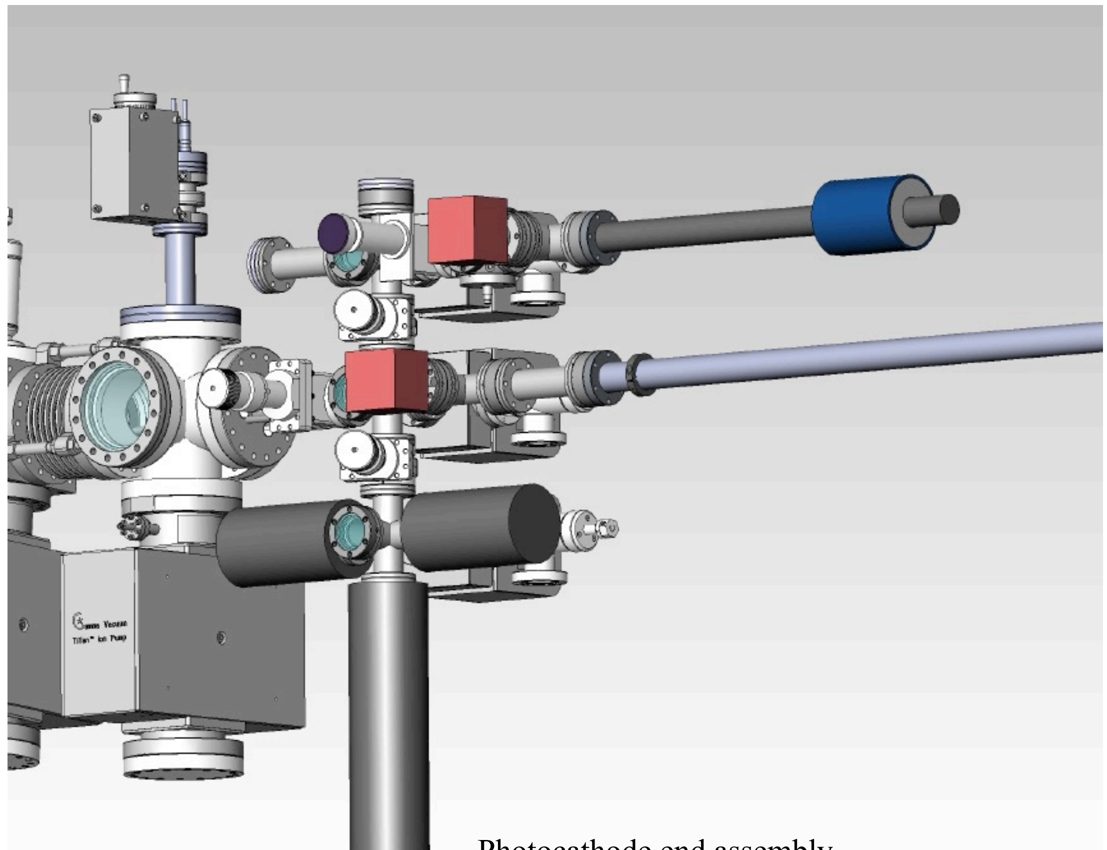
3D Genesis simulation shows that the maximal gain in bunching factor is 409, which agrees with our estimation.

Cathode Deposition and Transfer

We are modifying the cathode deposition system to avoid coverage of the cathode sides with photo-emissive material and for “Serial” production of the cathodes for operation

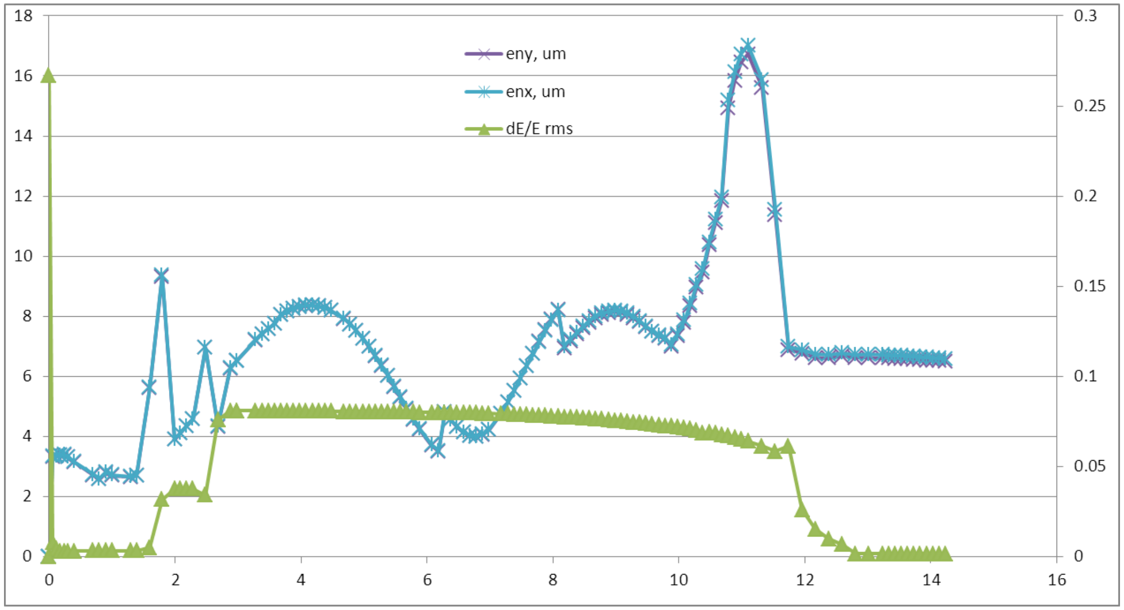
We also up-dating the cathode transfer system in the 112 MHz SRF gun into a robust and reliable UHV system





Photocathode end assembly

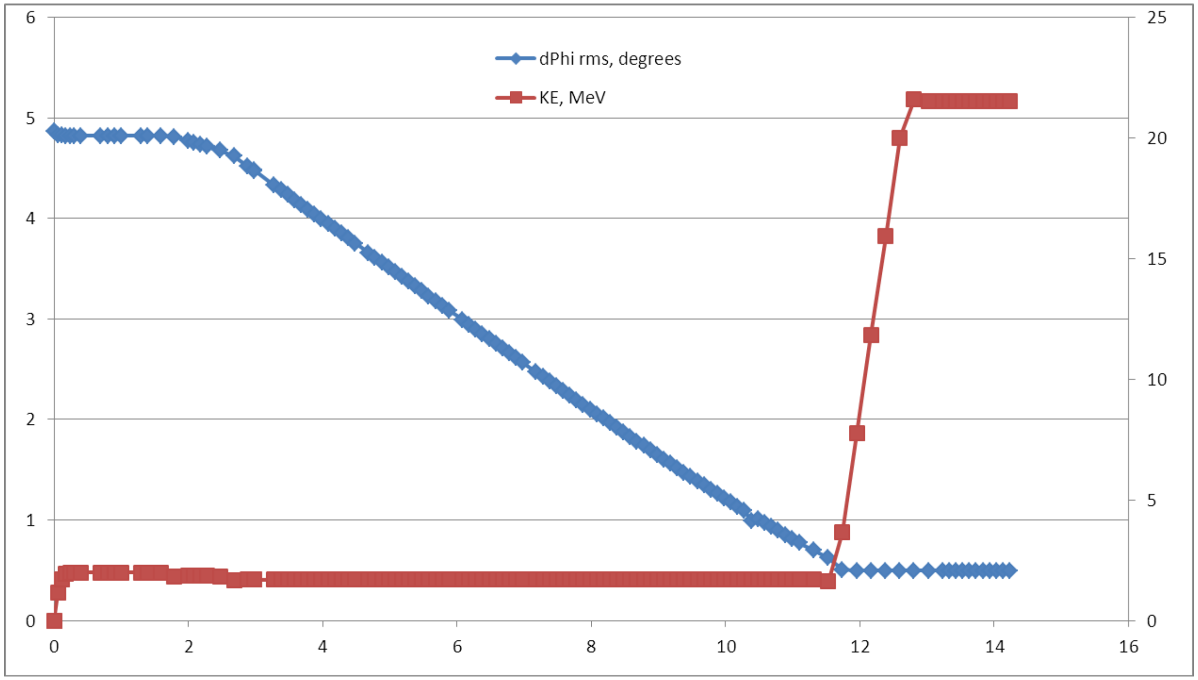
Expected Electron Beam Parameters



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



Field Reduction due to Finite Transverse Modulation Size

$$\rho(\vec{r}) = \rho_o(r)\cdot\cos(kz);$$

$$\Delta\varphi = -4\pi\rho \Rightarrow \varphi(\vec{r}) = \varphi_o(r)\cdot\cos(kz);$$

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\varphi_o}{dr}\right) - k^2\varphi_o = 4\pi\rho_o(r)$$

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

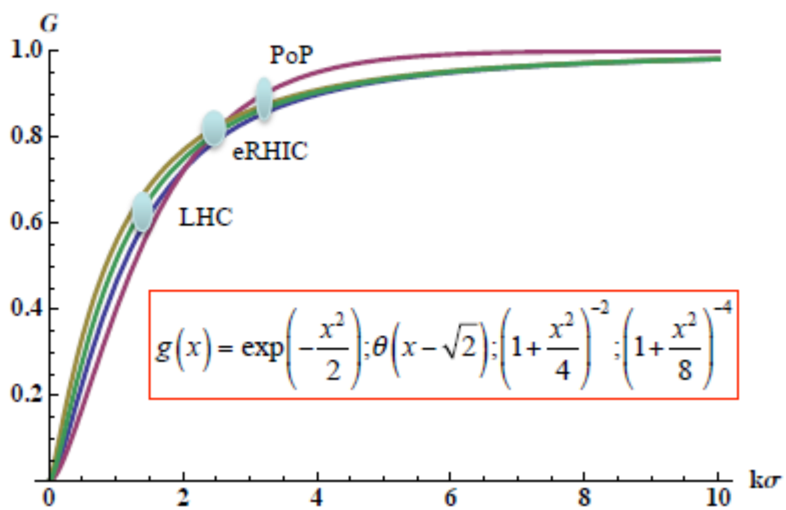
$$E_{zo}(r=0) \propto -\frac{4\pi\tilde{q}}{\sigma^2}G(k_{cm}\sigma)$$

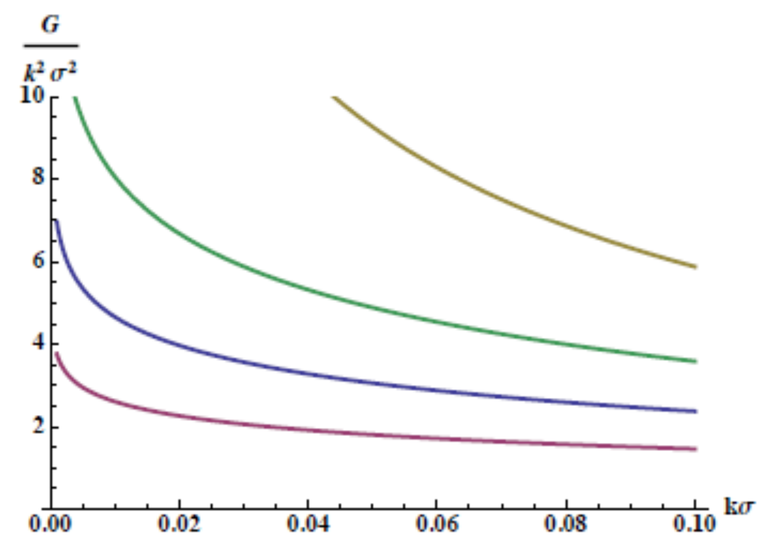
$$\varphi(\vec{r}) = -4\pi\cos(kz)\left\{I_0(kr)\int_r^\infty \xi K_0(k\xi)\cdot\rho_o(\xi)d\xi + K_0(kr)\int_0^r \xi I_0(k\xi)\cdot\rho_o(\xi)d\xi\right\}$$

$$E_z = -\frac{\partial\varphi}{\partial z} = -4\pi k\sin(kz)\left\{I_0(kr)\int_r^\infty \xi K_0(k\xi)\cdot\rho_o(\xi)d\xi + K_0(kr)\int_0^r \xi I_0(k\xi)\cdot\rho_o(\xi)d\xi\right\}$$

$$E_r = -\frac{\partial\varphi}{\partial r} = 4\pi k\cos(kz)\left\{I_1(kr)\int_r^\infty \xi K_0(k\xi)\cdot\rho_o(\xi)d\xi - K_1(kr)\int_0^r \xi I_0(k\xi)\cdot\rho_o(\xi)d\xi\right\}$$

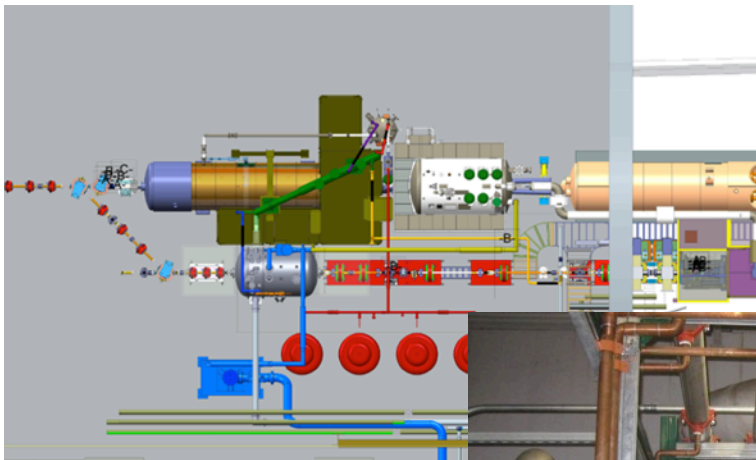
$$k_{cm}\sigma_\perp = \frac{k_o}{\gamma_o}\sqrt{\frac{\beta_\perp\varepsilon_{n\perp}}{\gamma_o}} = \sqrt{\gamma_o}\sqrt{\beta_\perp\varepsilon_{n\perp}}\,\frac{k_w}{2(1+a_w^2)}$$

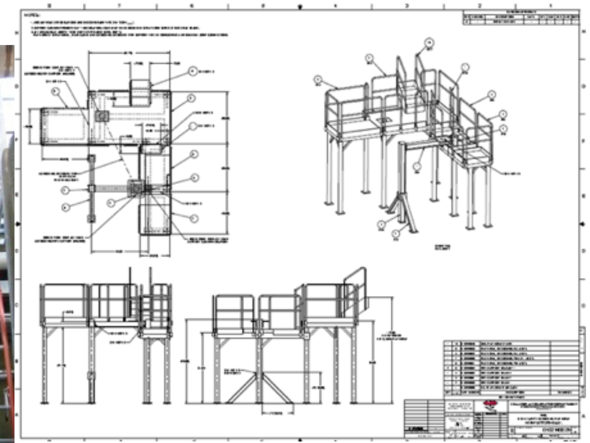


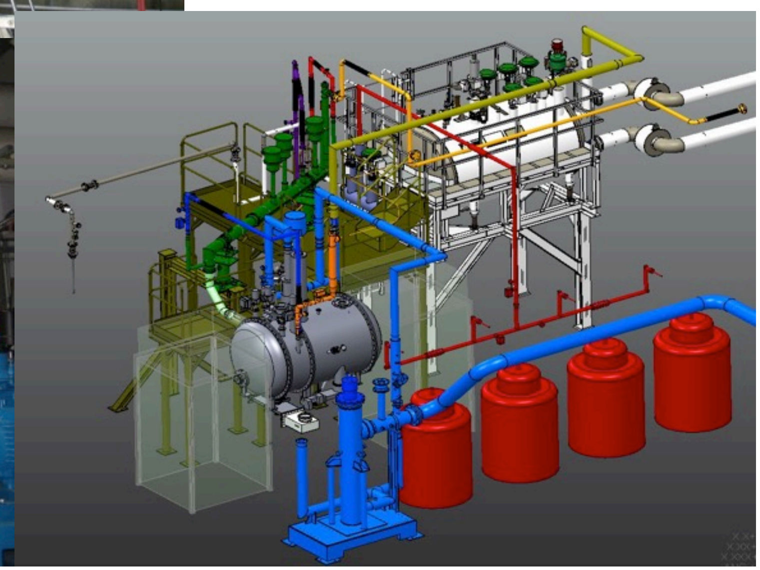


Phase 3 - 704 MHz Cryogenics

- Integration with LEReC supply and return requirements complete
- All components ordered: VJP (green monster), heater return (blue), cooldown return (lime green to QHS heater), heater skid.
- Warm return vacuum header installation
- 704 MHz scaffold order

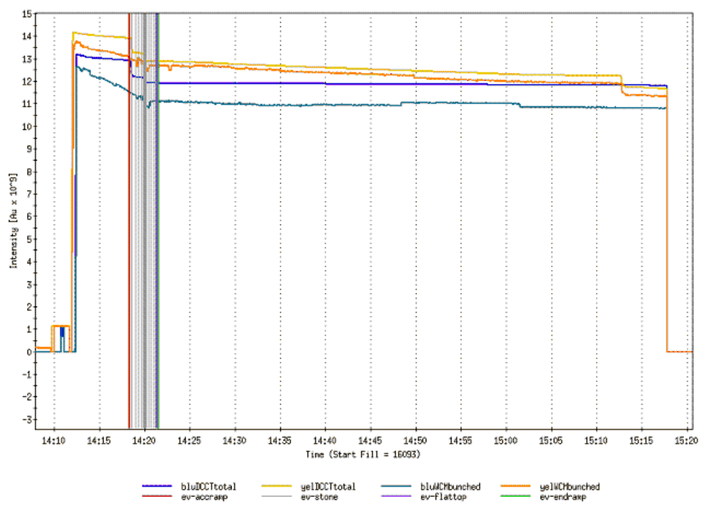






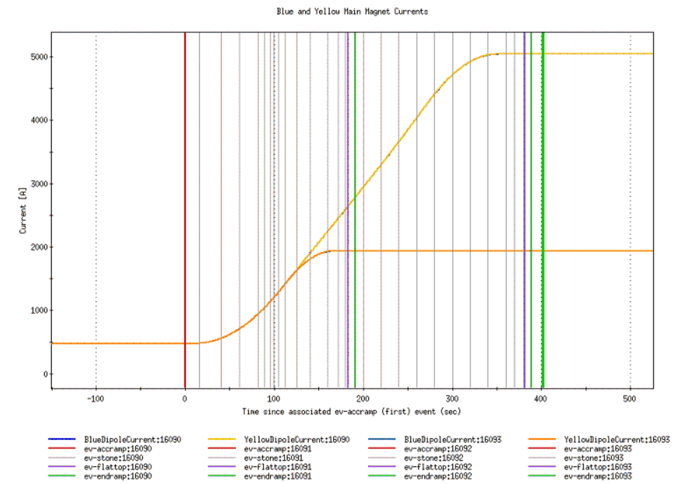
CeC PoP RHIC Ramp Development

Ramp : beam intensity

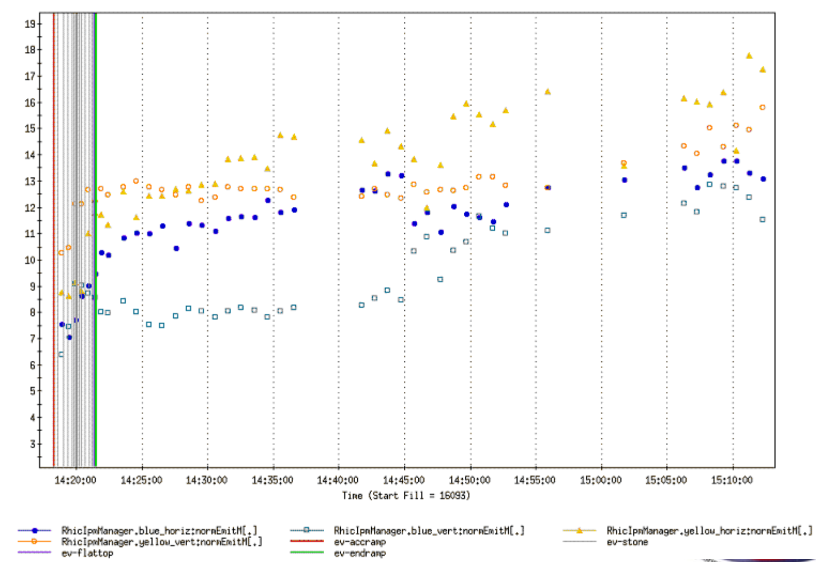


APEX on RUN 11: 2pm-4pm, June 20th, 2011 Fill: 16093

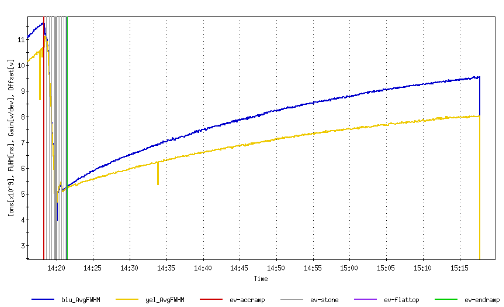
Ramp : Magnets currents

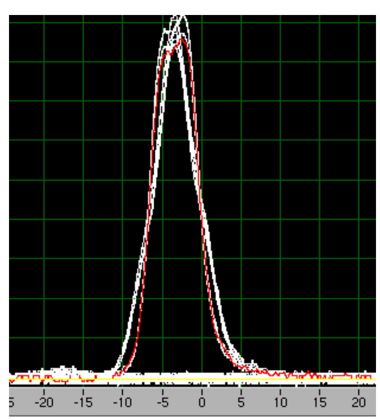


Emittance growth at 40 GeV

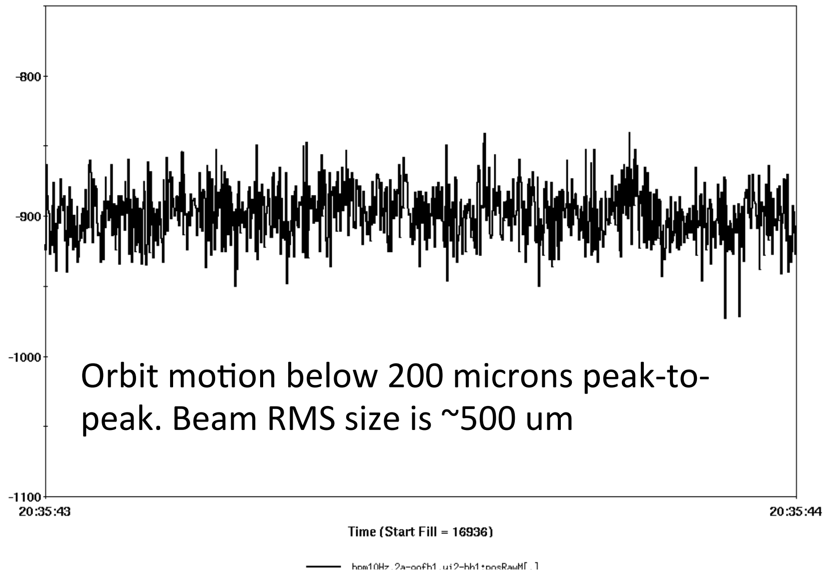


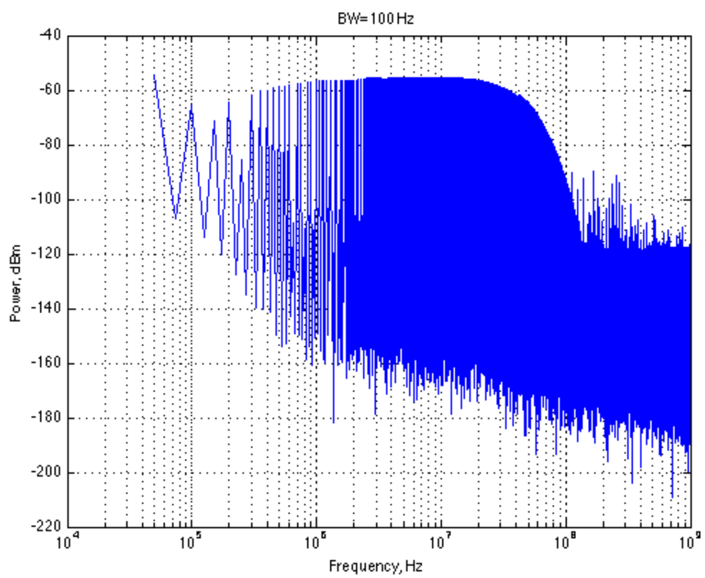
Bunch length and profiles at 40 GeV

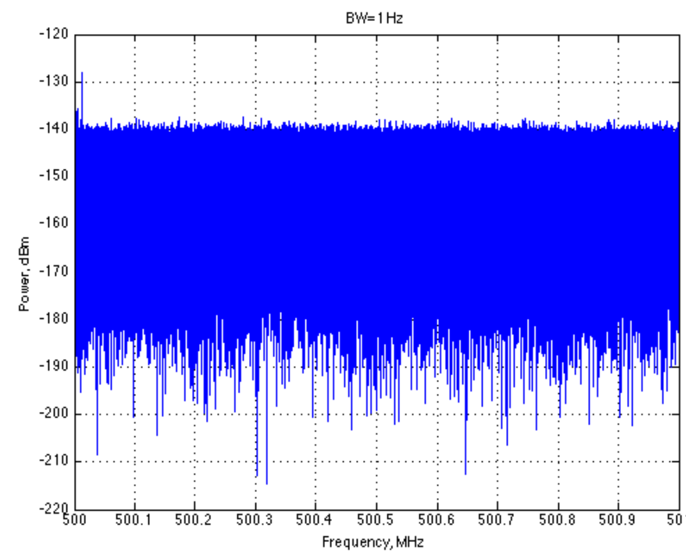




Ion Beam Parameters Characterization







Noise floor is 80 dB below the signal at revolution frequency.