Coherent Electron Cooling in Run 16

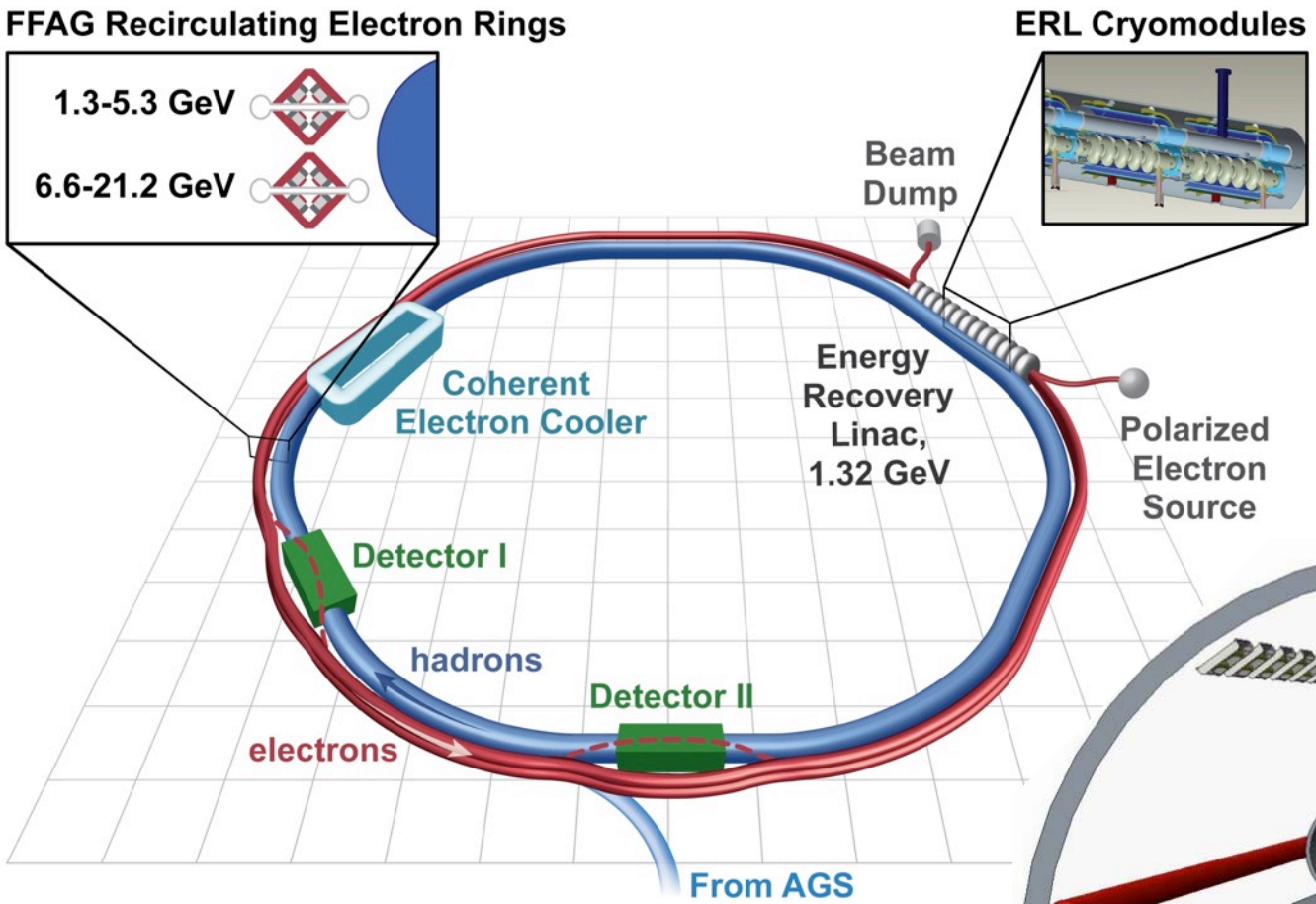
VN. Litvinenko, I. Pinayev, J. Tuozzolo

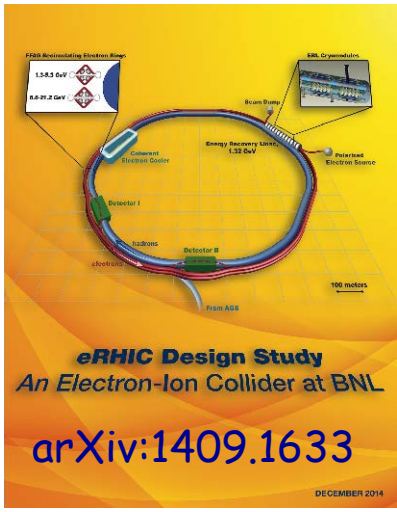
RSC meeting

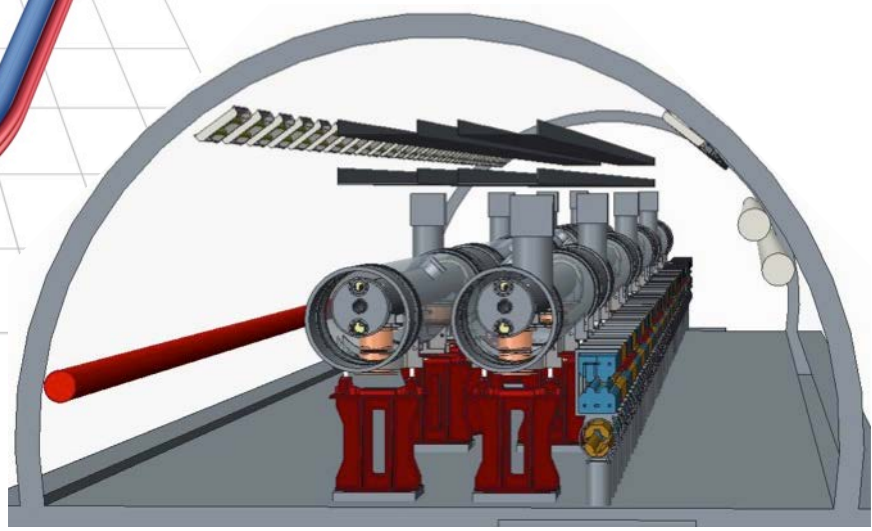
November 13, 2015

eRHIC design

Highly advanced and energy efficient accelerator

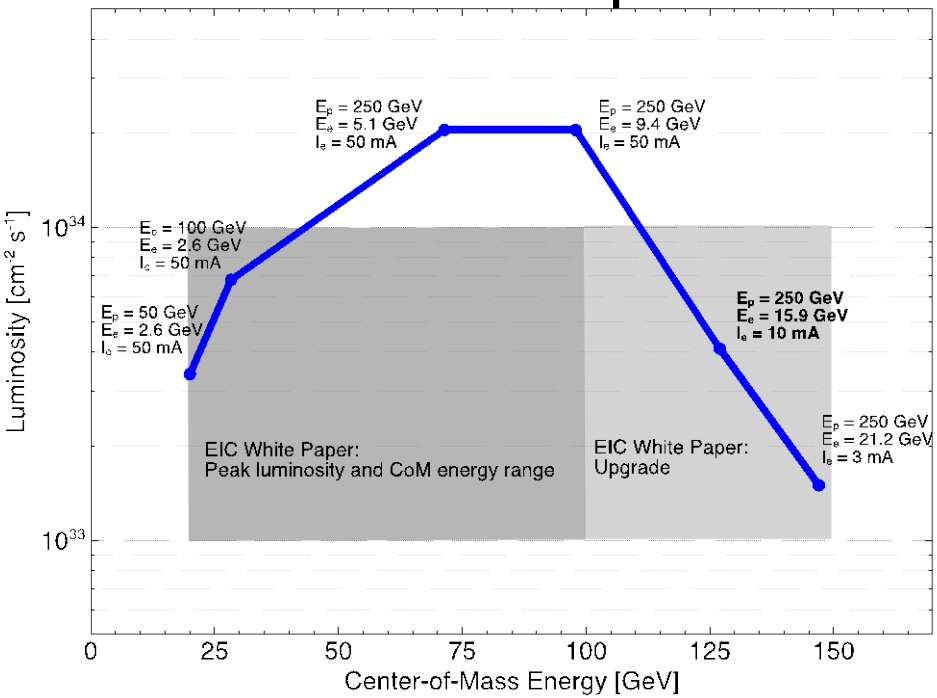


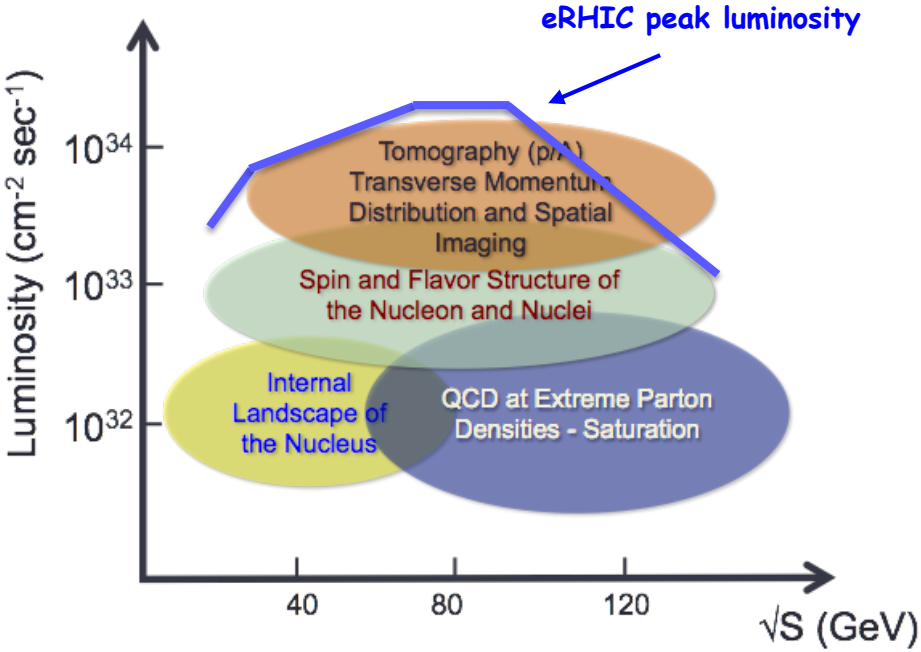




- 4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e↑ on 250 GeV p↑)

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

"Classical: Coherent electron Cooling scheme

At a half of plasma oscillation

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

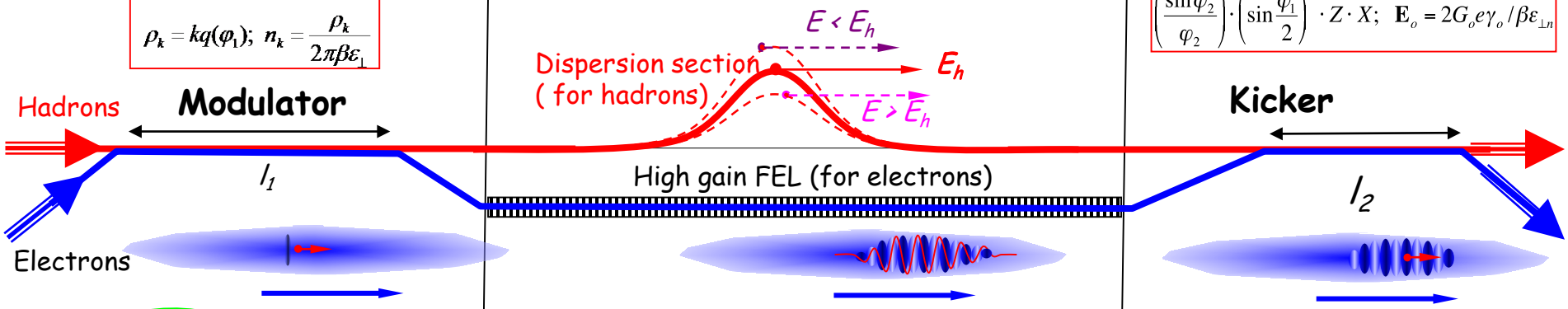
$$\rho_k = kq(\varphi_1);\ n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

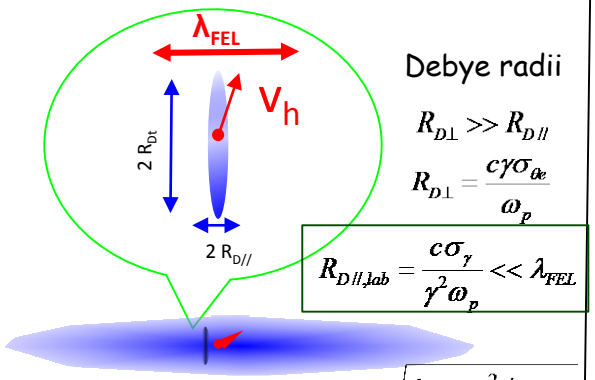
Dispersion

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

$$\Delta E_h = -e\cdot \mathbf{E}_o \cdot l_2 \cdot \sin\left(k_{FEL} D \frac{E-E_o}{E_o}\right)\cdot$$

$$\left(\frac{\sin\varphi_2}{\varphi_2}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2\cdot Z\cdot X;\ \ \mathbf{E}_o = 2G_o e\gamma_o/\beta\varepsilon_{\perp n}$$





Debye radii

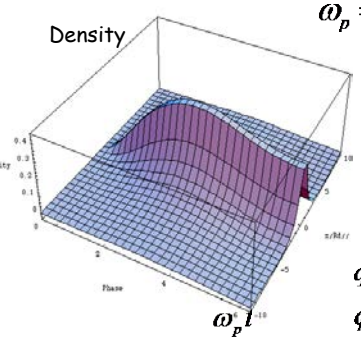
$$R_{D\perp} >> R_{D//}$$

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

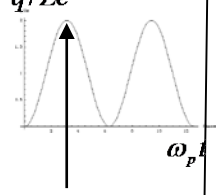
$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_p} << \lambda_{FEL}$$

$$\omega_p = \sqrt{4\pi n_e e^2/\gamma_o m_e}$$

Density



$-q/Ze$

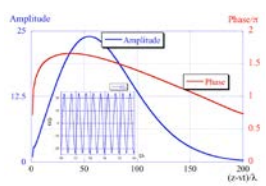


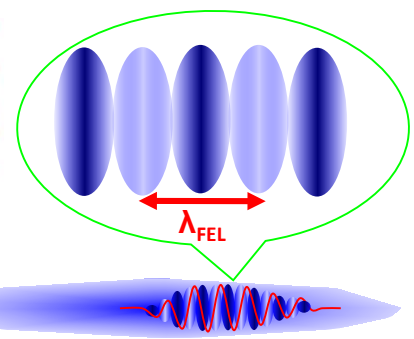
$$q = -Ze\cdot(1-\cos\varphi_1)$$

$$\varphi_1 = \omega_p l_1/c\gamma$$

$$q_{peak} = -2Ze$$

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





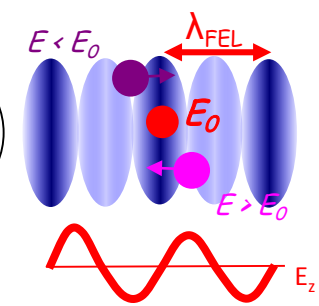
$$\lambda_{fel} = \lambda_w\left(1+\langle\vec{a}_w^2\rangle\right)/2\gamma_o^2$$

$$\vec{a}_w = e\vec{A}_w/mc^2$$

$$L_G = L_{Go}(1+\Lambda)$$

$$G_{FEL} = e^{L_{FEL}/L_G}$$

$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$



$$k_{FEL} = 2\pi/\lambda_{FEL};\ k_{cm} = k_{FEL}/2\gamma_o$$

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

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

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

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

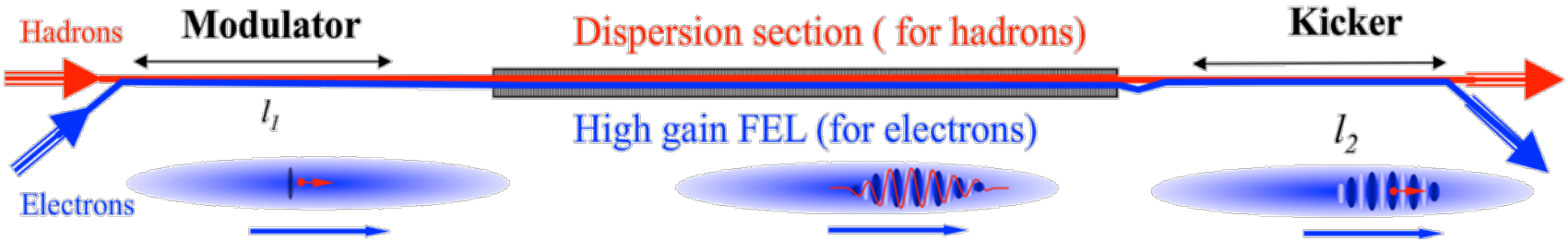
$$X = q/e \cong Z(1-\cos\varphi_1) \sim Z$$

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

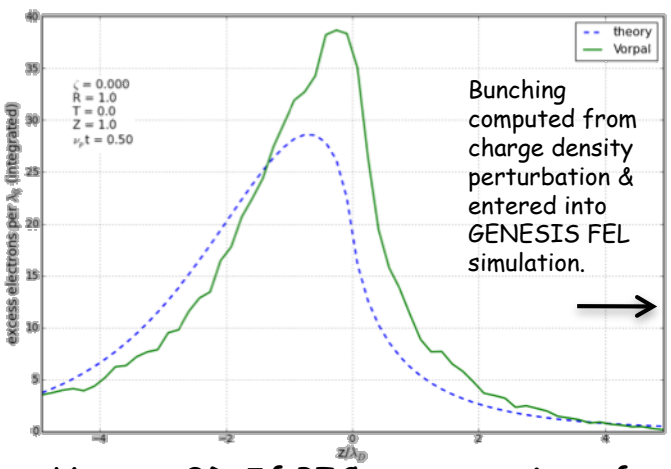
Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

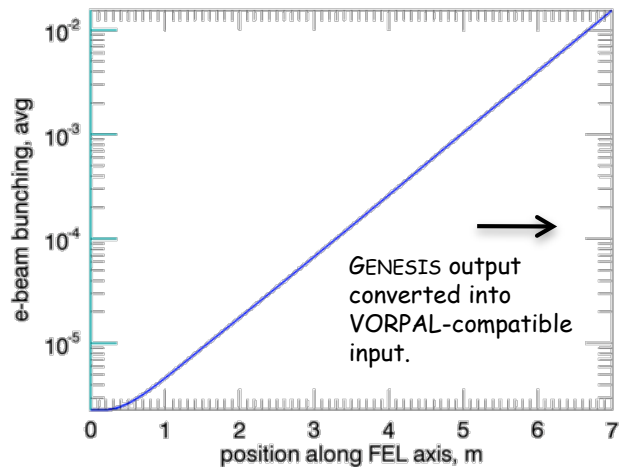
Our PoP is based on an economic version of CeC: it limits strength of the wiggler a_w to about 0.5 **but it is very cost effective**



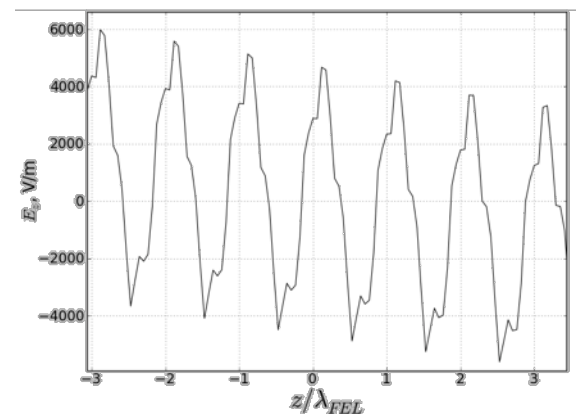
Param.' s from 40 GeV proof-of-principle exp. at BNL



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



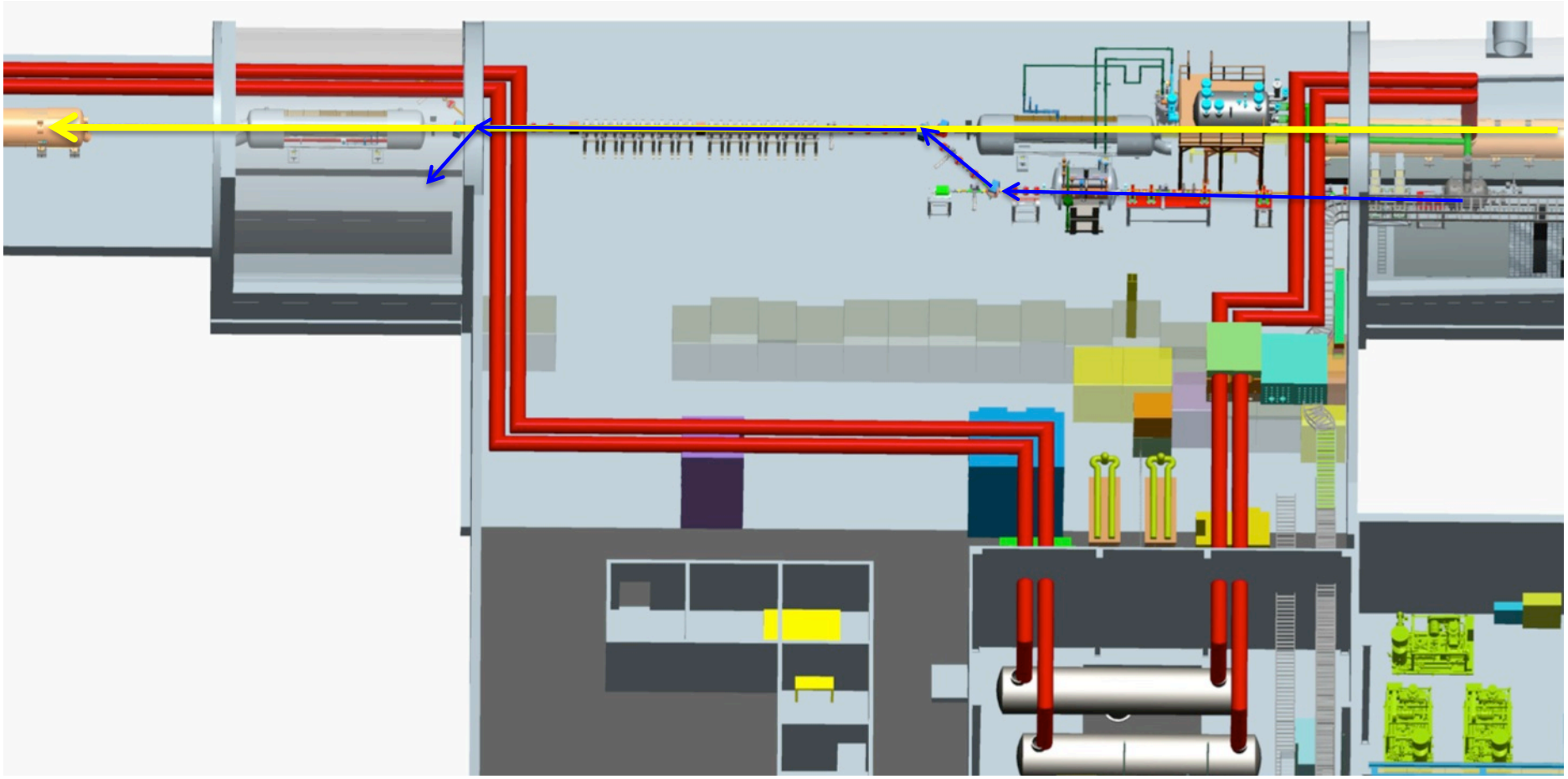
GENESIS parallel computation of electron beam bunching in free electron laser (FEL) shows amplification of modulator signal.



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

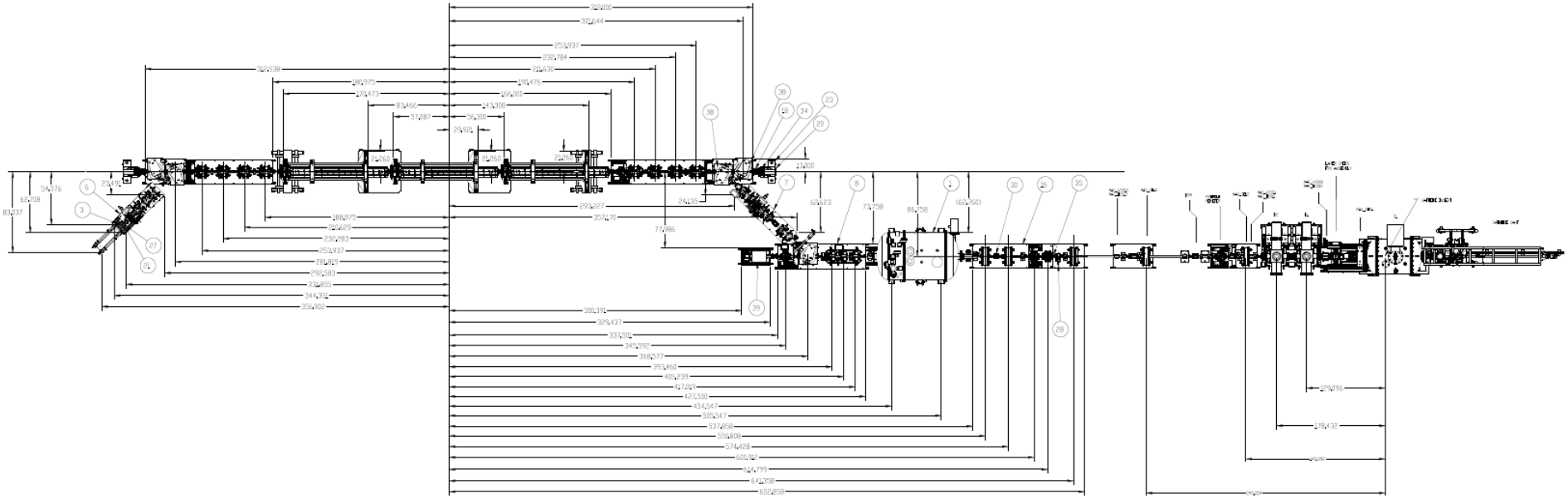
Simulations by Tech-X

CeC Proof-of-Principle Experiment



Coherent electron *Cooling* PoP

The complete system



Main Beam Parameters for CeC Experiment

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

Electron Beam and FEL Parameters
for CeC PoP experiment

Electron Beam	
RMS Energy Spread	$\leq 1\times10^{-3}$
Normalized Emittance	≤ 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

Table of matching energies

Electron Beam, MeV	Ion beam, GeV
10	18.5
15	27.8
20	37
21.95	**40**
25	46.3

Integrated Beam Time

Month	Hours @ 1 W	Hours @ 6 kW	Note
January	0	0	Start-up, RF conditioning
February	320	0	To low power dump
March	350	0	To high power dump
April	325	25	To high power dump
May	300	50	Commissioning
June	250	100	Commissioning, experiment

Estimate is based on 5 working days per week, 2 shifts per day. It does not account for down time and cathode lifetime.

March 24, 2014

The beam dump location will move and any potential change in external radiation levels must be examined.

In progress

The 500 MHz buncher cavities will use two contactors in series as critical devices. The contactors are in the process of being purchased. It was requested that if possible that the purchase order be changed so that safety contactors from different manufacturers could be used.

Adopted for 112 and 500 MHz

ATS-RHIC-May 15, 2014-RHIC-(C. Naylor& D. Beavis) Modify IR2 sweep procedure.

Will be done after installation is complete

The committee requires that the operation of CeCPoP with beam will only be conducted with the MCR manned so that alarms can be proper response to alarms.

ATS-RHIC-CEC-May 15, 2104-(Beavis&Pinayev)

All operation conduct of the CeC PoP will be performed from MCR with the MCR manned

A series of radiation surveys must be conducted and if beam operations occur then a set of surveys and fault studies must be conducted with beam.

ATS-RHIC-CEC-May 15, 2104-(Beavis&Pinayev)

The radiation survey were scheduled but were not conducted due to the limited cathode lifetime. We plan conduct surveys during Run16.

ATS-RHIC-CEC-May 15, 2104-(Beavis&Pinayev) Prepare RSC Check-off list

The list was prepared and signed off. For the Run16 similar list will be prepared.

September 16, 2015

A profile monitor exists in the beam transport that is common with the RHIC beam. **If this intrusive instrumentation moves off the out switches the beam permit shall be pulled. (Ck-CeCPoP-A. Drees & I. Pinavey-952)**

Independent dry contact switch will be provided to RHC Beam Permit.

With the dipoles in series the most likely faults are a turn-to-turn short in one magnet or mistakenly placing a magnet in the wrong polarity by reversing the cables during installation or maintenance. The power supply in unipolar. This will be examined at the next meeting. **(Ck-CeCPoP-J. Tuozzolo&I. Pinavey-953)**

A turn-to-turn short reduces field in a dipole by 1.2% (2 coils with 42 turns each). Bending angle for electrons is 45 degrees and for the hadrons is at least 2000 times less. Estimate on the hadron beam kick due to the fault is at microradian level and does not gives any hazard. The electron beam will be lost completely.

After installation and/or maintenance work on the dipoles the polarity check will be performed.

Radiation measurements and beam fault studies should be part of this planning.**(CK-electrons-CeCPoP-Pinayev-968)**

The radiation measurements as well beam fault studies are included in the test/commissioning plans

October 16, 2015

The Project needs to provide an estimate of the total beam used in the IR so that external radiation and environmental issues can be addressed. These issues typically deal with integrated beam rather than just instantaneous. **(CK-electrons-CeCPoP-Pinayev&Beavis-967).**

We have the following estimates for maximal integrated operation times:

- January - none
- February – 300 hours of 1 W beam (2 and 22 MeV) into the low power dump
- March – 350 hours of 1 W (22 MeV) beam into the high power dump
- April – 325 hours of 1 W (22 MeV) beam into the high power dump and 25 hours of 6 kW beam
- May – 300 hours of 1 W (22 MeV) beam into the high power dump and 50 hours of 6 kW beam
- June – 250 hours of 1 W (22 MeV) beam into the high power dump and 100 hours of 6 kW beam

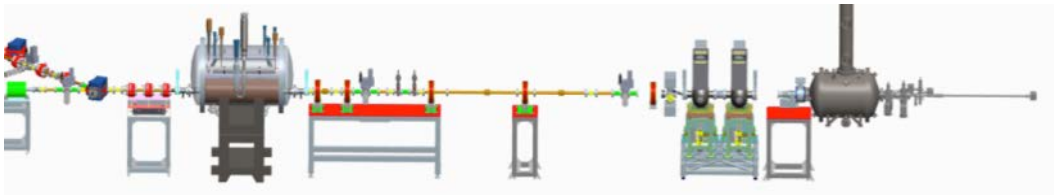
Examine the penetrations for under bending last dipole, beam aimed down the tunnel from the first dipole, and that the shielding policy is met for full beam fault in the IR. **(CK-electrons-CeCPoP-Pinayev&beavis-969)**

Low Power Beam Test

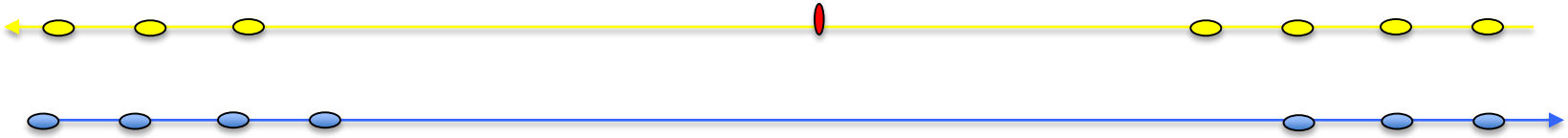
- Low power beam testing will be conducted at low repetition rate (around 1 Hz) and bunch charge not exceeding 10 nC (typically 3 nC).
- There will be three modes of operation:
  - electron beam is steered to low power dump (dipole PS is off), no interaction with hadron beams
  - electron beam is propagated to the high power beam dump but no interaction with hadron beams (see slide later)
  - dedicated CeC mode, no beam in the “blue” ring, 40 GeV/u gold ions in the “yellow” ring (6 or 12 bunches with 10^9 hadrons per bunch). Electrons and ions in a single bunch do interact.
- Test objectives:
  - verify equipment operation (beam transport, RF, diagnostics)
  - verify energy match of the ion and electron beam

How do we operate I

- Commissioning of CeC accelerator till the IP2
  - Parallel to RHIC operation, except occasional requests for access



- Propagating electron beam through the IP2 to the dump at low rep-rate, tune FEL amplification
  - Parallel to RHIC operation: electron bunches passing through the IP2 during Blue abort gap and between 2 yellow bunches



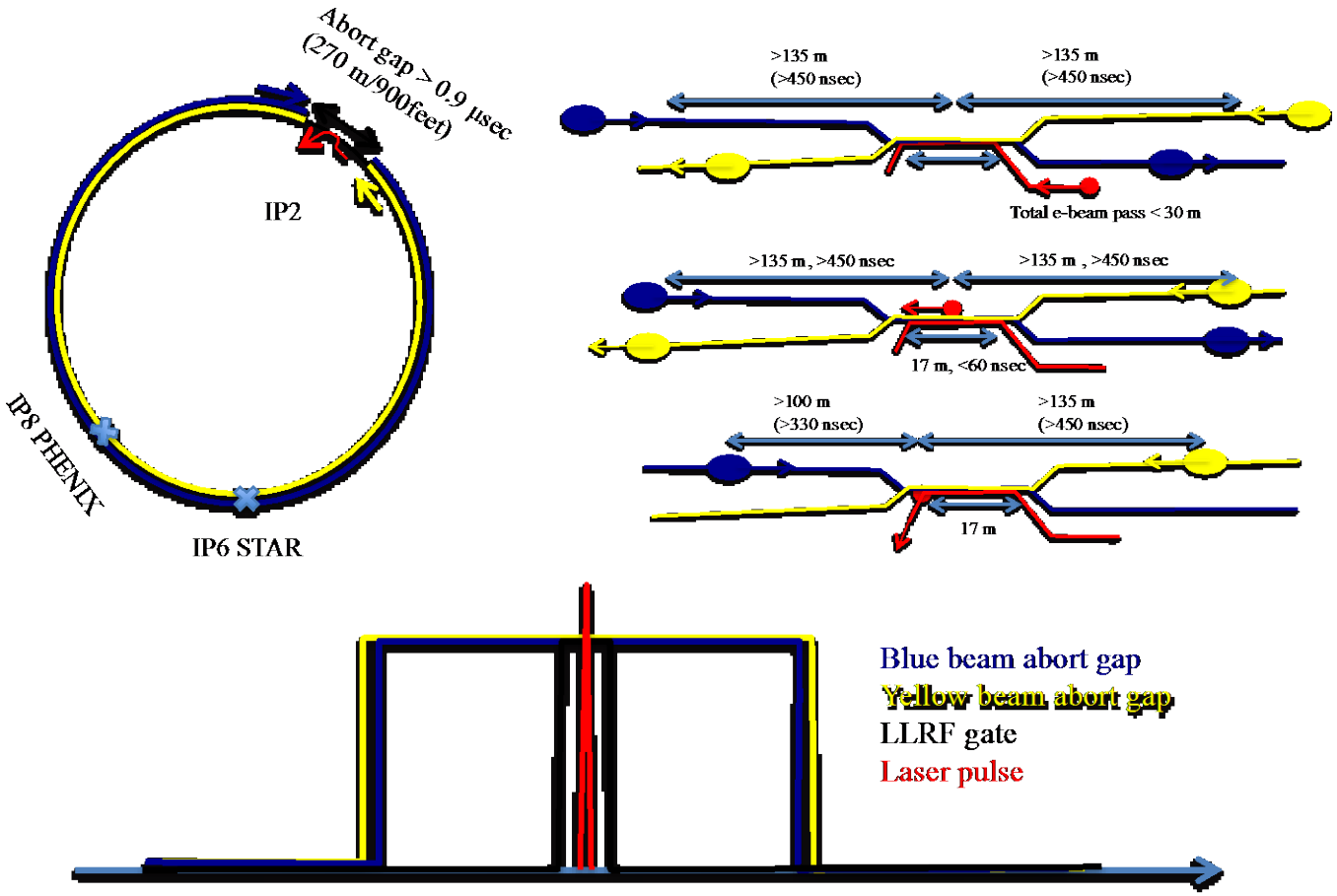
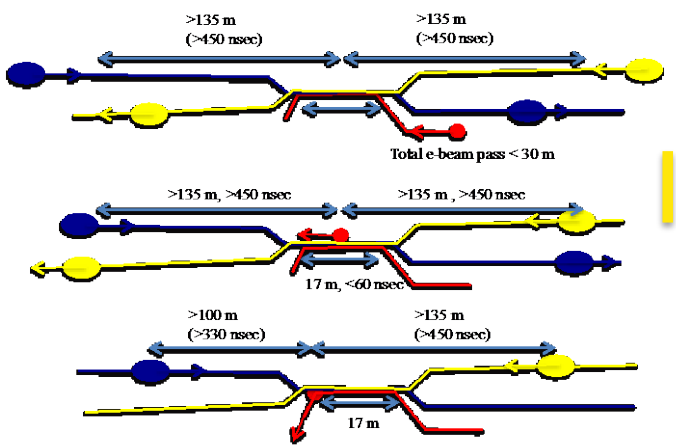
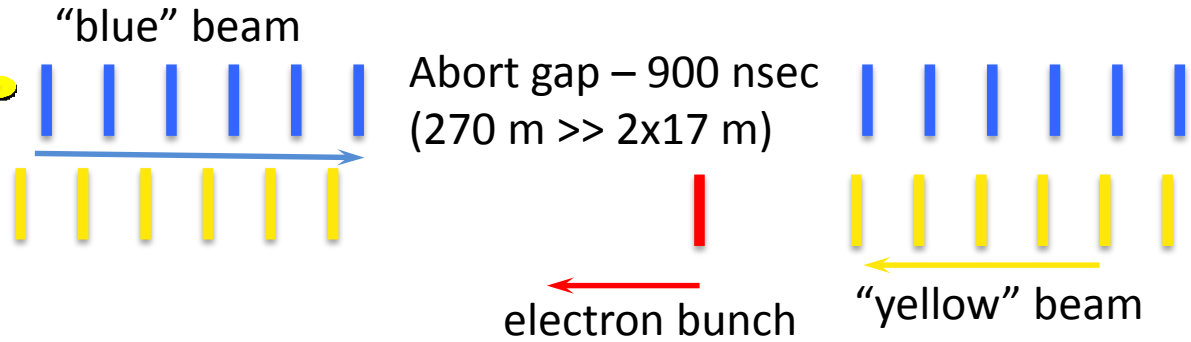


Figure 3 In RHIC, colliding hadron beams have an abort gap that is typically 1 microsecond long but always longer than 0.9 microseconds. By design, these abort gaps always overlap at IP8 and IP2. It provides a long period when there are zero hadrons in the 19-m long straight section common for yellow and blue hadron beam and CeC's electron beam. CeC Pop Experiment will use 200 nsec of this gap to propagate electron beam in the common section. The gate window for this propagation will be opened by the RHIC/CeC low-level RF system.

Avoiding Collision/Interaction of Electron and Hadron Bunches





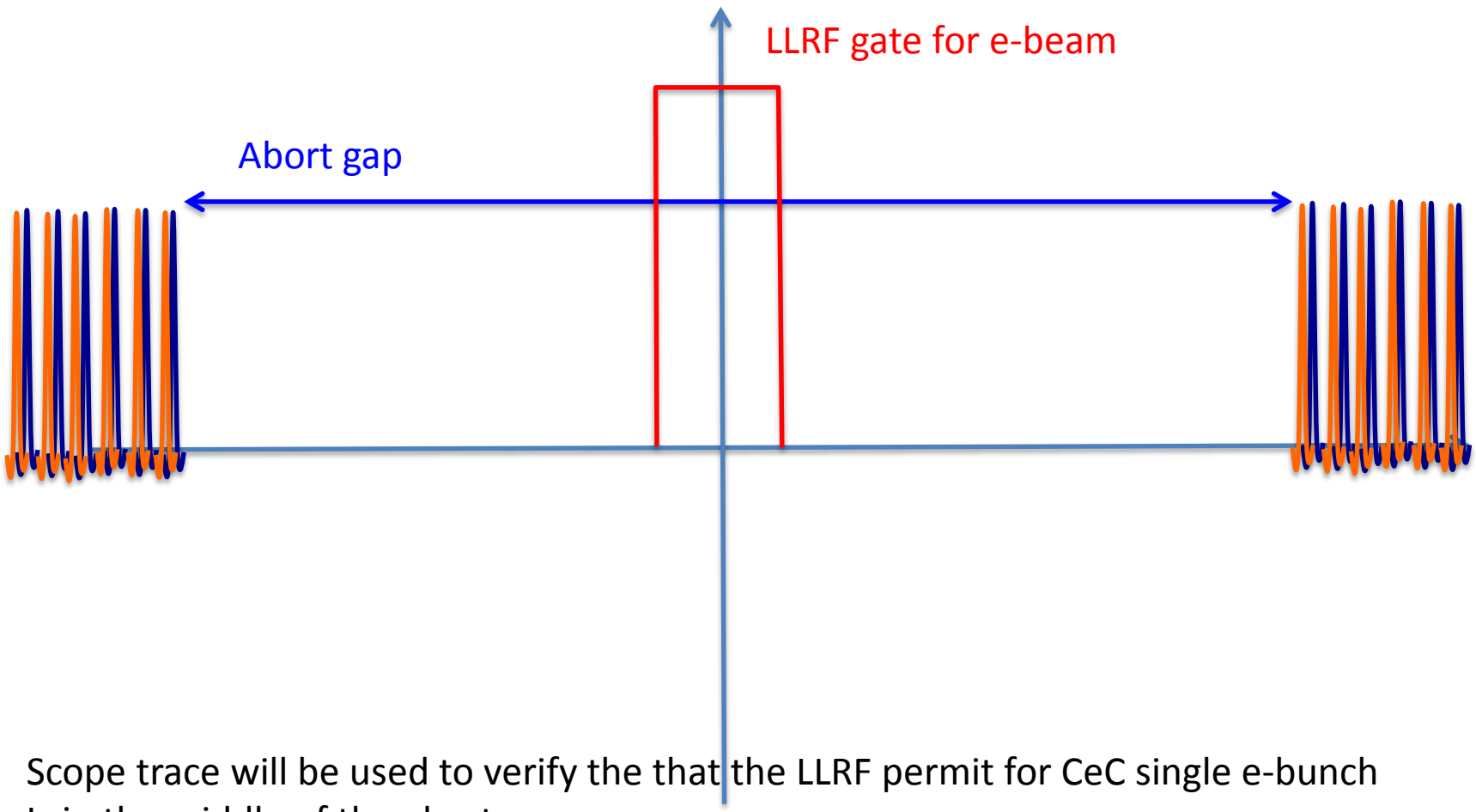
The electron beam will be separated in time domain from the circulating hadron beams:

a) it will propagate in the same direction between "yellow" bunches (107 nsec separation)

b) it will propagate through 17 m common section when abort gap of the "blue" beam is present

The laser trigger is generated by the low level RF system synchronized with RHIC. We can verify the proper operation of the timing system by observing electron bunch and hadron beam signals induced on the BPM electrodes. Initially it will be done without beam steering to the common section and later will be confirmed at APEX session.

Scope trace from IR2 BMP and LLRF permit



Scope trace will be used to verify the that the LLRF permit for CeC single e-bunch
Is in the middle of the abort gap

Fault studies

- We will confirm that a collision of hadron beam circulating in Blue RHIC ring with a single electron bunch from CeC accelerator does not affect hadron beam
- While this is understood theoretically, we plan to demonstrate it experimentally during one of APEX studies
- We will intentionally inject 6 bunches of hadrons in Blue RHIC ring and will collide a single bunch of electrons with one of the hadron bunches. Five other bunches will be used for comparison
- The fact of the collision of electron beam with hadron beam will be observed by a significant modification of the electron beam profile at the profile monitor in front of the full power beam dump

Commissioning Plan for CeC System

- Initial low power commissioning goal is generate, accelerate measure beam parameters
- After measuring beam parameters electron beam will be transported to the high power dump without interacting with the hadrons beam. The goal is to establish electron trajectory, commission balance of beam diagnostics (BPMs, transmission measurement, IR diagnostics), and prepare for high power commissioning. Some fault studies can be conducted at this stage.
- High power commissioning will be performed by gradually increasing electron bunch repetition rate aiming at commissioning high power operation of all systems (mainly RF, high power beam dump and machine protection system).

Schedule for RHIC Run 16

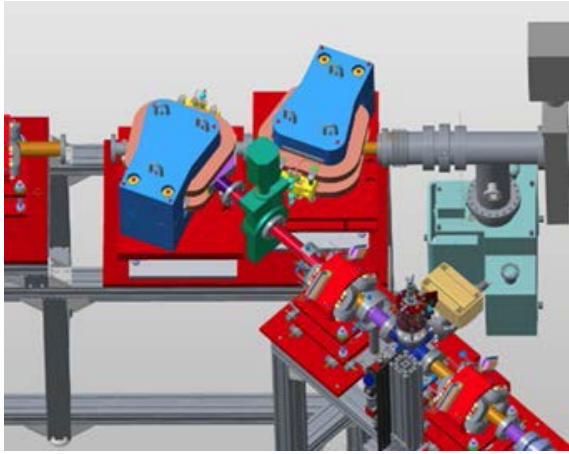
Milestones	**Date**	**Note**
SRF cavities cold	15-Feb-16	Has to be synchronized with RHIC run
Complete cavity conditioning	**15-Mar-16**	
Generate first beam	**01-Apr-16**	Assuming that SRF gun is working with photocathode pack
Measure beam parameters	15-Apr-16	
Propagate beam to the high power beam dump	01-May-16	
Test co-propagation with ion beam	**15-May-16**	
Demonstrate FEL amplification	**01-Jun-16**	
First cooling attempt	**01-Jul-16**	Dedicated 5 days of running, dates have to be adjusted to the end of the RHIC run

How do we operate II

- Operating CeC beam at full power, developing CeC RHIC ramp, co-propagating ion and electron beams
  - As dedicated APEX experiments
- Demonstration of cooling, tuning the systems
  - May try as a dedicated APEX experiment
  - Use short dedicated RHIC run for full access and to characterize the CeC

Dipole Fault Scenarios

- Dipole PS failure
  - should not affect the hadrons beams (one supply for all dipoles, polarity will be checked by two independent tests and the cables will be tagged)
  - electron beam will be steered towards low power beam dump
  - CeC MPS should drop electron beam permit (current below certain level, beam position out of the range, transmission is zero)
- Short coil in the dipole
  - should not affect the hadron beam (approximately 1 microradian kick)
  - electron beam will be lost on the vacuum chamber with shallow (~10 mrad) incident angle
  - CeC MPS should drop electron beam permit (beam position out of the range, transmission is zero)



Quadrupole and Trim Faults

- Should not affect the hadrons beam, too weak
- The electron beam will be lost on vacuum chamber most likely defocused (quadrupole) or at shallow incident angle (trim)
- The unlikely fault of the last two quadrupoles PS (in front of high power beam dump) is handled by CeC MPS, dropping the electron beam permit if currents are out of the pre-defined window. The short in the coil will cause slight change in the beam size inside the dump.

RF System Faults

- Change in the phase and/or filed amplitude in either one of the three RF system will cause change electron beam energy and relative energy spread. The electron beam will be lost most likely in the dogleg.
- MPS protection system should drop the electron beam permit (zero transmission, beam position out of range)

Lost Synchronization with RHIC

- Electrons can interact with hadron beam
- Should not affect noticeably hadron beam
  - electron bunch charge is substantially less of the hadrons (12.6 nC), which are colliding with revolution frequency
  - electrons will be unable to perturb the same hadron bunch continuously due to the difference in the relativistic factors (electron bunch repetition rate differs from RHIC revolution frequency)
- Trajectory of electron beam most likely will be distorted, and it will be over-focused
- MPS will drop electron beam permit if orbit deviation or e-beam losses exceed the safe level

Potential to drill a hole in vacuum chamber

- At full power of 8.5 kW focused into a small sub-mm spot electron beam can, in principle, drill a hole in a wall of vacuum chamber
- To avoid any possibility of such scenario, we plan to do the following:
  - Establish the beam trajectory through the center of the vacuum chambers (within a mm accuracy) using low power (1W) beam;
  - Set the limits for the trajectory deviation in all of our BPM electronics to few mm
  - Gradually increase the rep-rate and the beam power
  - If trajectory deviates in any of the BPMs beyond the set range, MPS will stop the beam. We should not that the change of the trajectory can not happen instantaneously, because magnets have time constants of many milliseconds as well as the SRF system has long filling/detuning time.
  - If by some reasons, beam is strongly defocused but stays on the design orbit, it can reach the walls of the vacuum chamber which is 10s of mm (typically ~ 1”) away from the orbit. But this beam will be completely defocused (~2” is diameter) and could not burn a hole in vacuum chamber. Than the MPS protection system (both the beam loss and radiation detection) will have ample time to shut down the beam.

Back-up slides

Plan for CeC System Low Power Test

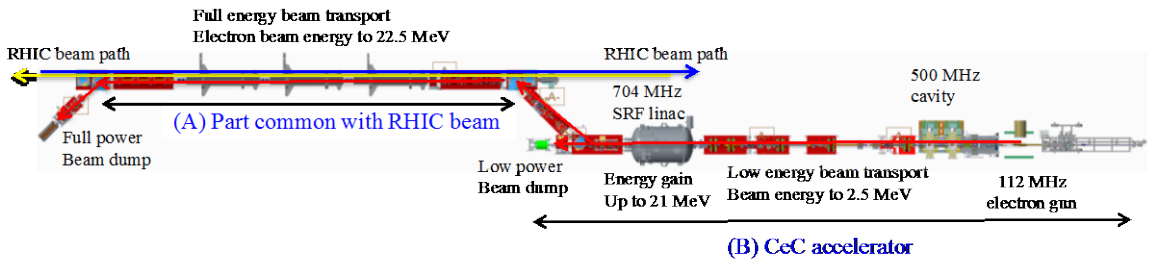


Figure 1. Layout of CeC system: (A) part common with RHIC beam; (B) CeC accelerator. Electron pulses will be generated in a 2-MeV 112-MHz SRF gun and then pass through two 300-kV 500-MHz bunching cavities and transported to the 704-MHz SRF linac for acceleration to full energy up to 25 MeV. The beam will be delivered to the RSC approved dump. Shielding and access controls have been designed for the future full power mode up to 8000 watts. Beam power in the low power test mode is less than 1 watt.

Table 1: Range of the CeC PoP Experiment Parameters in Two Modes

	Low Power Test Mode	
	Low Power Beam Dump at (B)	RSC Approved Low Power Dump at (A)
Beam energy, MeV		
Nominal	1.5 MeV – 22 MeV	20 - 22 MeV
Allowable range	< 25 MeV	< 25 MeV
Beam current	< 1 μA	< 4 μA
Beam power, W	< 1	< 1

The steps of the bringing up the CeC experimental system will include

(a) installation of the equipment;
(b) conditioning of sub-systems;
(c) testing of the systems with low power electron beam

(a) C-AD plans to complete the installation of the equipment before the start of RHIC Run 16. Sub-systems, that do not generate radiation hazards will be tested after the routine industrial safety hazards have been reviewed, field inspected, and authorized to operate by the C-AD Accelerator Systems Safety Review Committee. This could occur prior to the start of the RHIC run. Such system include: water, AC power, environmental controls, equipment controls, power supplies, magnets, vacuum system and diagnostic instrumentation. The laser delivery system would be commissioned inside the dedicated trailer and its delivery to the SRF gun will be tested when the area is secured according the laser safety requirements. Laser operators will be qualified to a BNL approved Laser SOP.

(a) Two of three CeC's RF accelerators are super-conducting (one operating at 2K and the other at 4K) and require liquid He to operate. The liquid He will be provided by RHIC's cryogenic facility or using He Dewars. Conditioning of CeC's three RF systems (112 MHz SRF gun, two 500 MHz bunching cavities and 704 MHz SRF linac) will generate X-rays and will be conducted within the RHIC tunnel radiation enclosure after a sweep is complete and when an approved RSC check-off list has been completed. Completion of functionality tests for the PASS system is documented on the RSC check-off list. Interlocks will block this system from being turned on if PASS is not active. Radiation absorbed dose rates up to 5 rad in an hour are expected in the vicinity of RF cavities during their conditioning.

(a) Low power beam testing will be conducted at low repetition rate (typically 1Hz) and bunch charge not exceeding 10 nC (typically 3 nC). The low power beam testing will be conducted without interacting with or operating with RHIC hadron beam. Test electron beam at 1 W cannot change the orbit of the rigid RHIC ion beams. Low power beam testing will happen in four distinctive modes:

Mode I: Beam will be accelerated in CeC accelerator and delivered to the low power dump. Energy of the beam will not exceed 25 MeV and the beam power will not exceed 1 W. This mode can be operated any time the IP2 PASS system is activated and CeC systems (including MPS) are operational. During measuring beam parameters we will intercept electron beam with beam-profile or pepper-pot screens. We plan to beam current < 5 nA and beam power < 0.125 W for such measurements. We will use the CeC bending magnet to measure and to calibrate beam energy. Prior to using this mode, we will use one of the APEX sessions to prove experimentally that turning on and changing current in the CeC dipole magnets does not affect both blue and yellow hadron beam in RHIC. This feature is provided by use of compensating dipoles (see Figure 2) installed in the hadron beam pass, which are identical to those bending electron beam, but opposite in sign. All CeC dipoles are powered in series providing full transparency for hadron beams. The loss monitors around the ring will be documented during these tests and the results sent to the C-AD RSC for review.

CeC dipoles should affect RHIC beam at injection energy, which is when RHIC ion beams are most vulnerable. The orbit variation outside IP2 area caused by the CeC dipoles should not exceed $1/10^{th}$ of the hadron beam size. An official record of these results will be provided to the C-AD Chair and the C-AD RSC for review.

In addition, the energy measurements will be conducted with a closed vacuum valve in the dog-leg (see Figure 2) intercepting the beam and preventing it from propagating into RHIC.

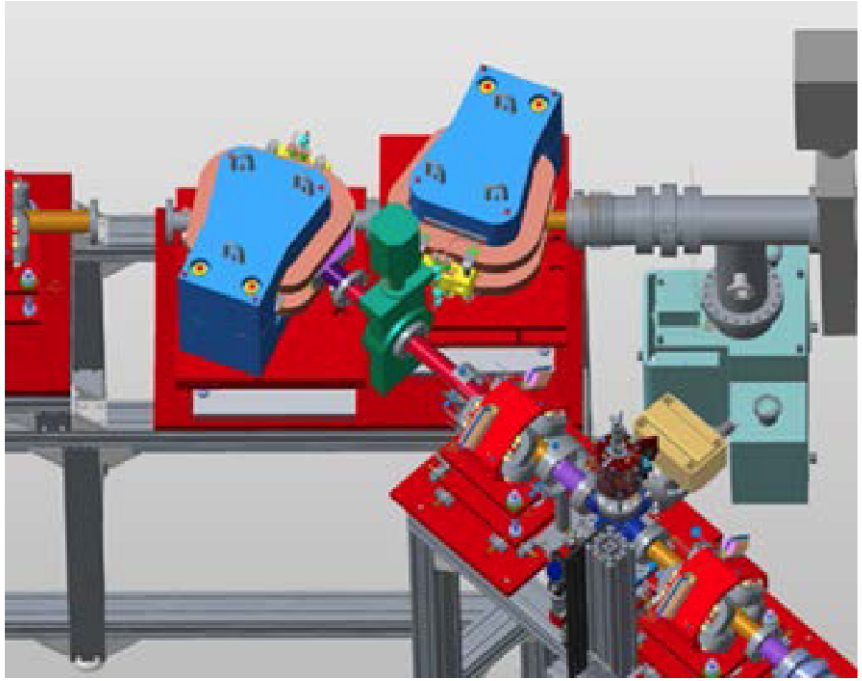


Figure 2. End of the CeC system dog-leg after which electron and ion beams merge. A pair of identical dipoles with opposite field direction is fed in series and provides zero field integral (null-angle) for the hadron beams circulating in RHIC. The bilaterally symmetric pair of dipoles is installed at the electron beam exit to the Low Power Dump. The vacuum valve (green) separating the CeC accelerator from RHIC vacuum pipe will be closed when CeC is in Modes I and II.

Mode II: Parallel to the RHIC collider operation and transparent for RHIC beams. In this mode CeC Pop physicists will propagate electron beam to the RSC Approved Low Power Beam Dump at the end of the transport and guarantee that electron beam does not interact with either yellow or blue hadron beam circulating in RHIC. This feature will be provided by low-level RF system, which controls CeC PoP Experiment laser permits. Specifically, RHIC beam pattern has an abort gap of at least 0.9 μsec (270 m) long. In the middle of this gap, the low-level RF system will provide a time window allowing generation of CeC laser pulse – see Figure 3. In this configuration, electron beam will travel at the same velocity close to that of the hadron beam and propagate through the IP2 without any interaction with hadron beams circulating in RHIC beam. We will have a dedicated APEX session to test that, indeed, the electron beam generated by such scheme passes through the IP2 common section in the middle of the abort gap and within ± 100 nsec from its center. This will be verified by observation of the signals from IP2 common beam-position monitors using a digital oscilloscope. When this mode is verified, we will make an official record of these results and provide them to the RSC Chair.

Mode III: Dedicated CeC mode. This mode will be exercised either during dedicated APEX session or during dedicated CeC RHIC time. In this mode we will operate CeC accelerator simultaneously with ion beam circulating in Yellow RHIC ring. Hadron beam in Blue ring will be prohibited using established RHIC procedures. We will operate Yellow ring with 6 to 12 ion bunches with nominal intensity not exceeding 10^9 ions per bunch and total intensity of $12x10^9$ ions. This mode had been established for APEX sessions at RHIC and is within RHIC beam safety analysis where one complete RHIC fill (111 ion bunches; $5x10^{11}$ Au ions or equivalent) was treated as a point loss. This mode will be used for establishing reliable propagation of the electron beam through the common section and establishing that the ion beam imprints its shot noise structure into the electron beam.

There is a single intercepting beam profile monitor installed in the common section. It is prevented from being inserted by a tagged mechanical lock. This lock can be removed and the beam profile monitor could be inserted to tracing electron beam. Such operation will be following a dedicated administrative procedure of removing the lock for the test and then installing it back, prior to any injection of hadron beam into RHIC.

The only hadrons, which can collide with electron beam, will be de-bunched hadrons (lost from the main bunch train) and spread nearly-evenly around RHIC circumference. The amount of such hadrons is strictly controlled during RHIC operation, mostly because of the background they provide to the detectors and also to avoid "dirty" beam dumps. Large numbers of hadrons in the abort gap is defeating the entire purpose of the abort gap. Thus, the total population of de-trapped hadrons is kept well under 1% of the total beam (< 3x1011 protons or 2x109 ions), using when necessary a abort gap cleaning devise (ARTUS). Only a small portion of these ions (34 m out of 3.8 km, < 1%) can collide with a single electron bunch.

Hence, the worst-case scenario, which assumes the CeC electron bunch disrupts the de-bunched hadrons,, could not cause loss of more than 3x109 protons or 2x107 ions per electron bunch. Finally, the chronic losses could not exceed the rate of populating the abort gap with de-bunched hadrons. That rate cannot exceed the total loss from the hadron beams during regular RHIC operation, whose lifetime is from 3 to 10 hours. Hence, the chronic loss would not exceed that already occurring in RHIC during standard operations.

In addition, the test 25 MeV electron beam at 1 W power level cannot change the orbit or stability of the 10-250 GeV RHIC hadron beams, should they inadvertently occupy the same space.

Mode IV. Full power operation of the CeC system will be allowed with and without interacting with the RHIC beam (e.g. cooling). We will operate Yellow ring with six to twelve ion bunches with nominal intensity not exceeding 10^9 ions per bunch and total intensity of 12×10^9 ions. Beam energy for the full power operation will bellow 25 MeV with power at the dump not to exceed 8 kW.