Using ERLs for Coherent electron Cooling

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Motivation

- Traditional stochastic cooling does not have sufficient bandwidth to cool intense proton beams (~3×10^{11} p/nsec) and can not provide two orders of density increase for heavy ion beams
- Efficiency of traditional electron cooling falls as as high power of hadron's energy
- Synchrotron radiation is rather fable due to the heavy masses. For the same reason optical stochastic cooling is not suitable

Species	Energy, GeV/u	Stochastic cooling, hrs	Electron Cooling, hrs	CeC, hrs 1D/3D
Au	130	1	1	0.015/0.3
p	325	100	> 30	0.3/1

Coherent Electron Cooling (CeC)

At a half of plasma oscillation

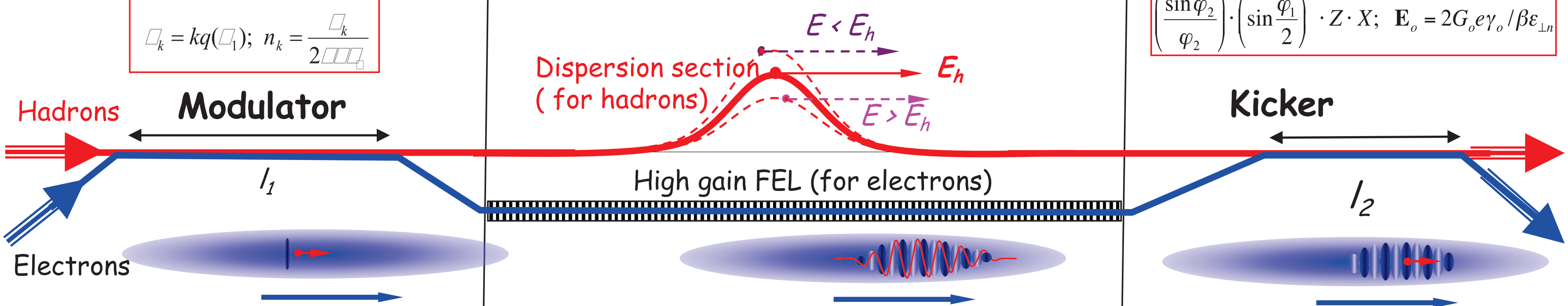
$$q_{\lambda FEL} \cong \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

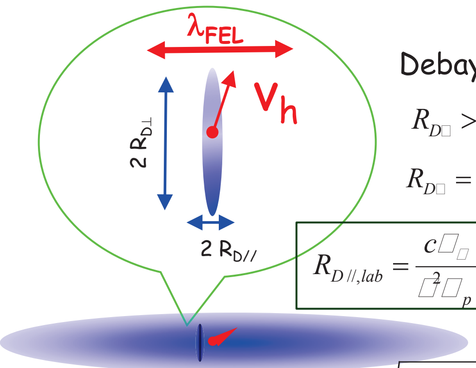
$$\rho_k = kq(\varphi_1); \quad n_k = \frac{\rho_k}{2\pi \ldots}$$

Dispersion

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

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





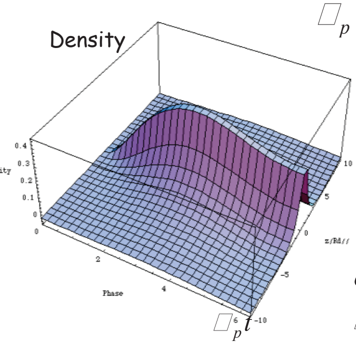
Debay radii

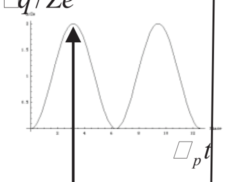
$R_{D\perp} >> R_{D//}$

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

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

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



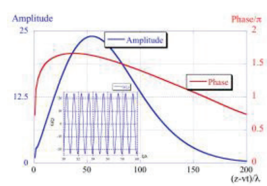


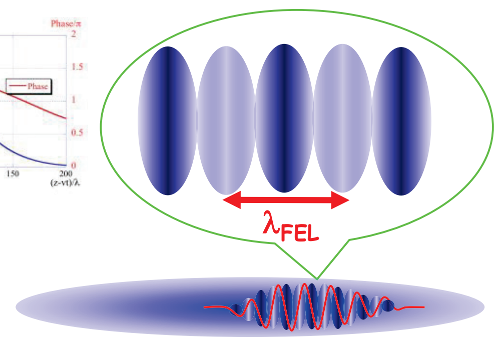
$$q = -Ze\times(1-\cos\varphi_1)$$

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

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

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





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

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

$$L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$

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

Coherent Electron Cooling

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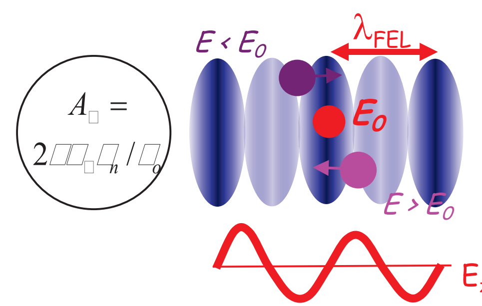
(Received 24 September 2008; published 16 March 2009)



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

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

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

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

$$\mathbf{E}_o = 2G_o\gamma_o\frac{e}{\beta\varepsilon_n}$$

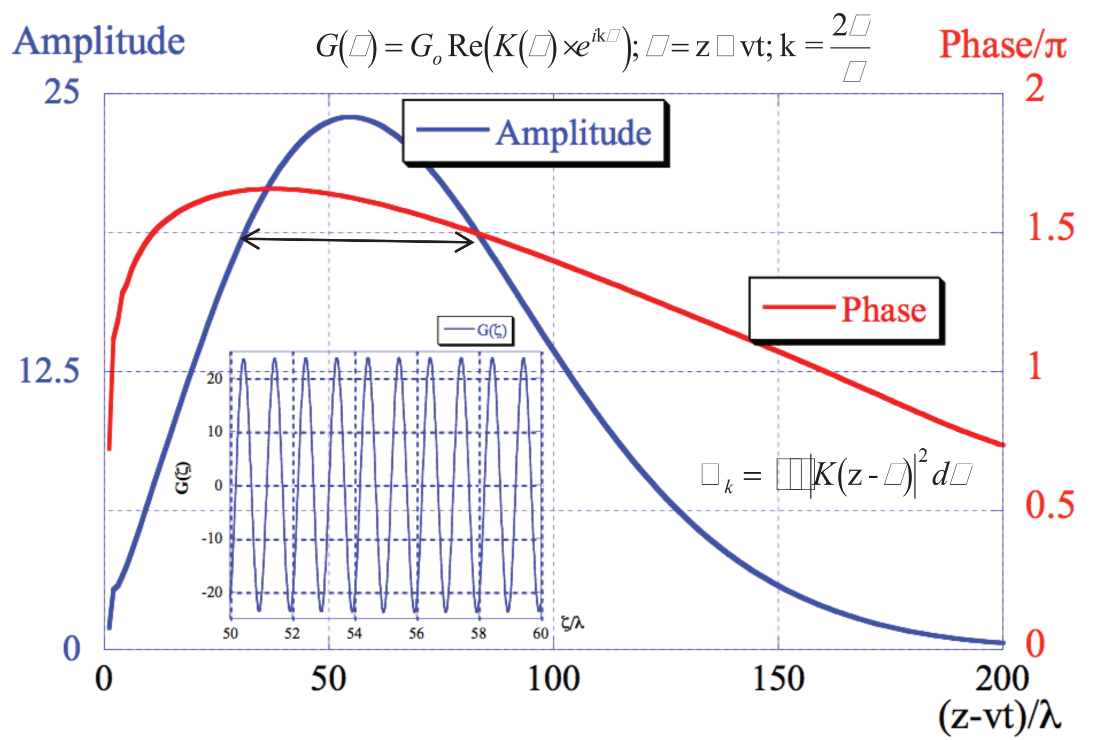
$$X = q/e \cong Z(1-\cos\varphi_1) \sim Z$$

3D FEL response
calculated Genesis 1.3, confirmed by RON

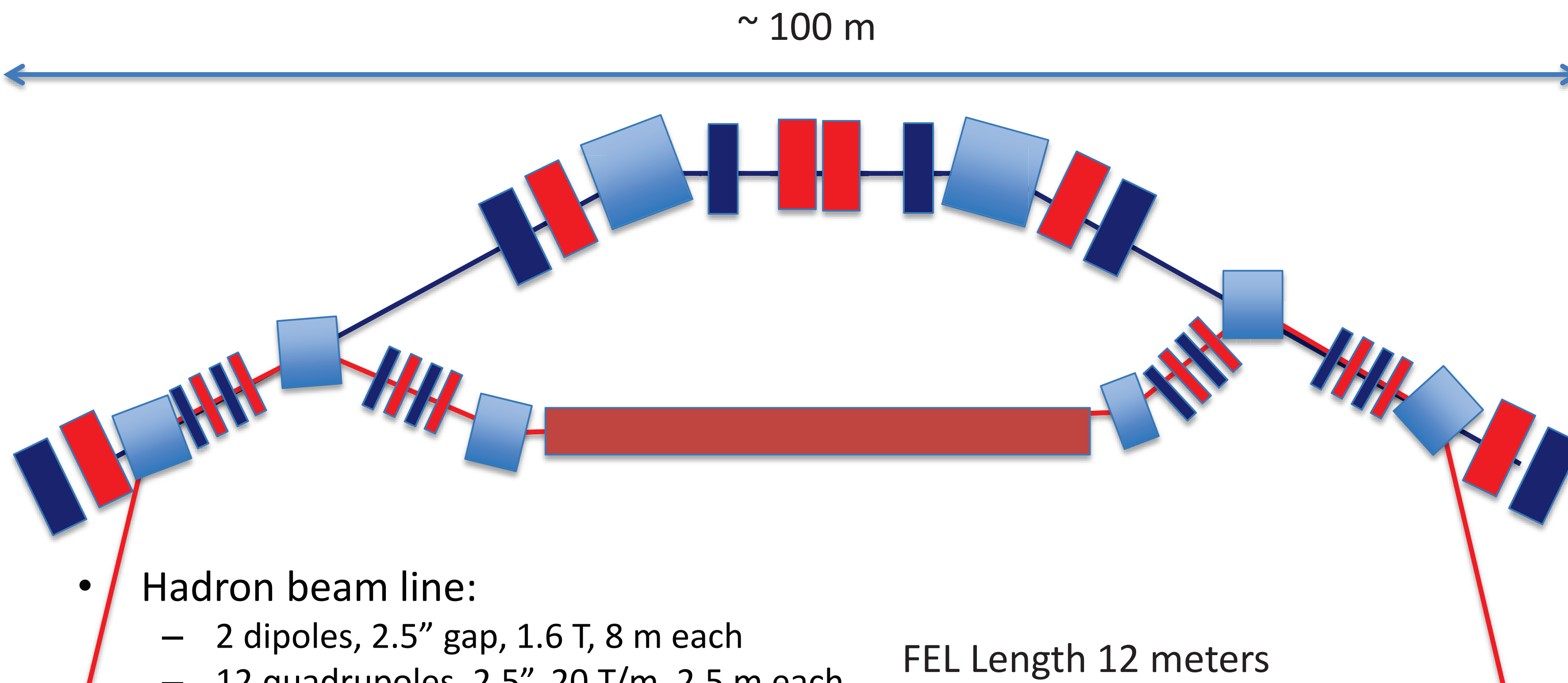
Main FEL parameters for eRHIC with 250 GeV protons

Energy, MeV	136.2	□	266.45
Peak current, A	100	$□_o$, nm	700
Bunchlength, psec	50	$□_w$, cm	5
Emittance, norm	5 mm mrad	a_w	0.994
Energy spread	0.03%	Wiggler	Helical

The amplitude (**blue line**) and the phase (**red line**, in the units of π) of the FEL gain envelope after 7.5 gain-lengths (300 period). Total slippage in the FEL is 300λ, λ=0.5 μm. A clip shows the central part of the full gain function for the range of ζ={50λ, 60λ}.



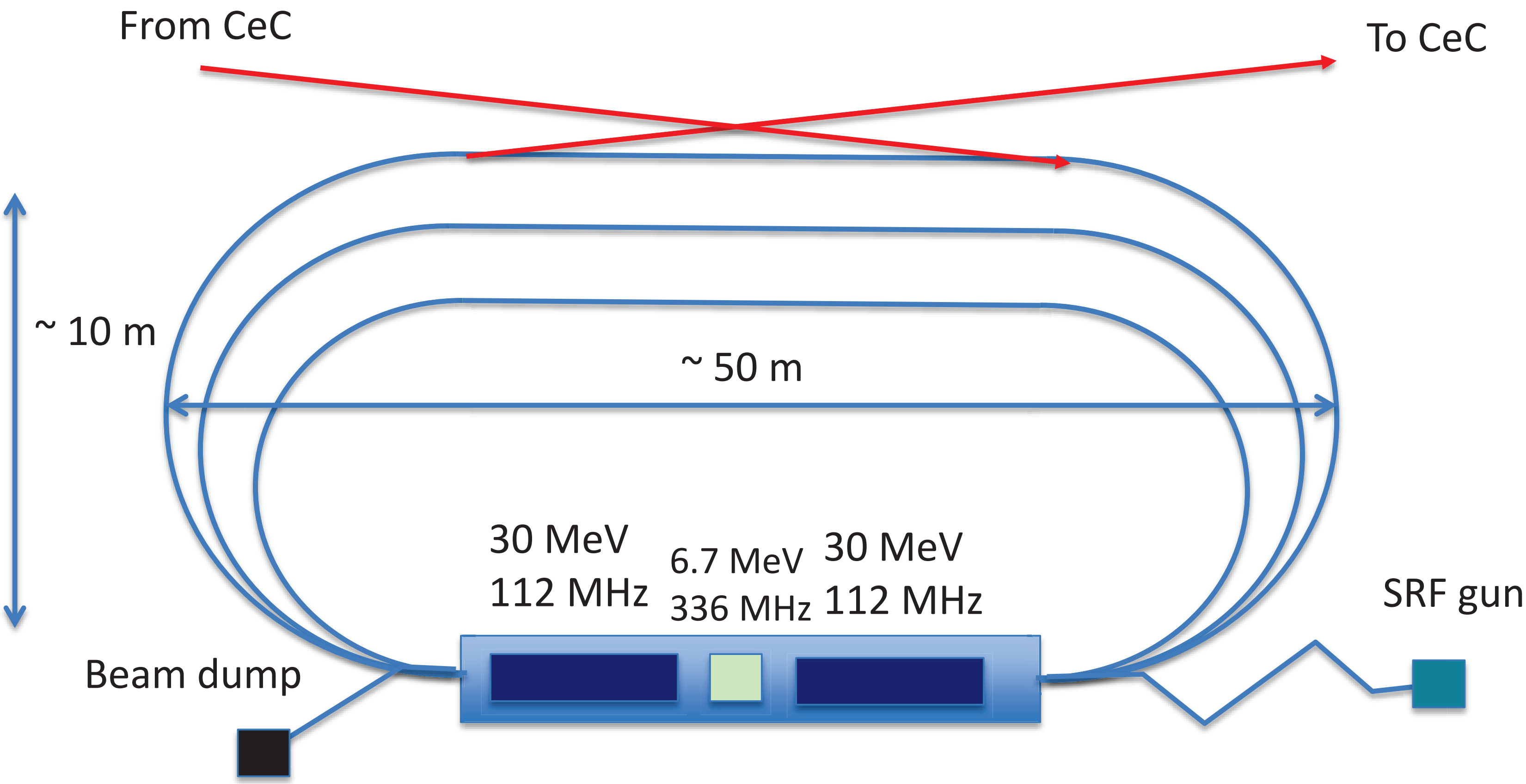
eRHIC CeC Layout



- Hadron beam line:
  - 2 dipoles, 2.5” gap, 1.6 T, 8 m each
  - 12 quadrupoles, 2.5”, 20 T/m, 2.5 m each
  - 20 dipole trims: 10A, 20 V
- Electron beam line
  - 6 dipoles, 2.5” gap, 0.3 T, 0.4 m each
  - 16 quadrupoles, 2.5”, 7 T/m, 0.3 m each
  - FEL: period 4 cm, length 12 m
  - 30 dipole trims: 1A, 10 V

FEL Length 12 meters
Kicker – 20 m
Modulator – 20 m
FEL wavelength 0.56-14 μ (50-250GeV)
Delay in FEL 0.185-1.1 mm

Possible ERL Configuration



ERL Beam Parameters

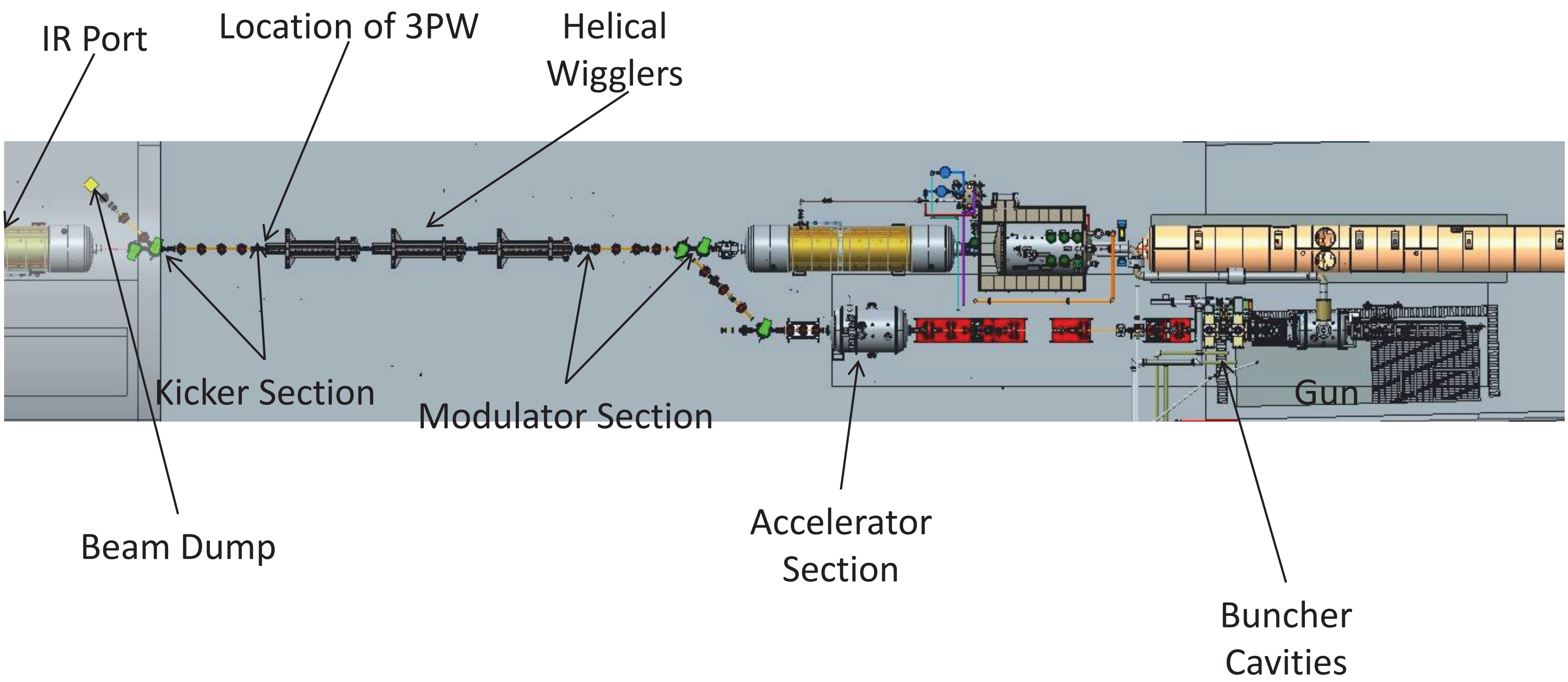
Parameter	Value
Electron beam energy	25-140 MeV
Electron beam current	50 mA
Bunch charge	5 nC
Repetition rate	9.38 MHz
Bunch length	0.2 nsec
Normalized emittance	< 3 mm mrad
Relative energy spread	$<10^{-4}$

CeC PoP experiment

Main parameters for the CeC experiment with $^{197}Au^{79}$ ions

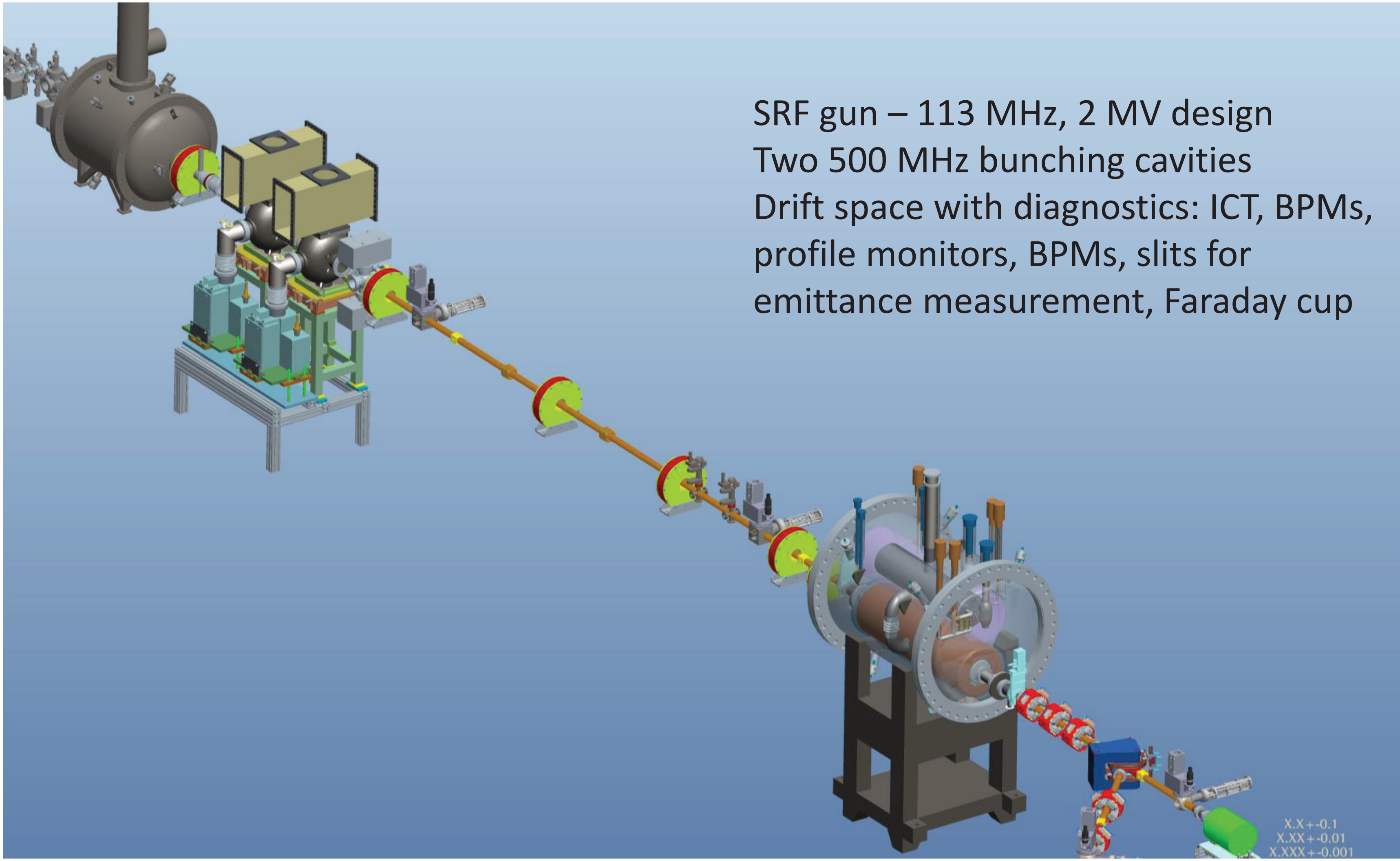
Parameter	*Units*	
Ion's energy	GeV/u	40
RMS norm. emittance, x,y	mm mrad	2
Ion per bunch		$1x10^{9}$
Longitudinal emittance	eV sec	0.5
RMS bunch-length	nsec	1.5
RMS momentum spread		$3.5x10^{-4}$
□*	m	5.5
Rep-rate	kHz	78.3
Electron beam energy	MeV	21.8
Charge per bunch	nC	0.5-2
RMS normalized emittance	mm mrad	5
Peak current in FEL	A	60-100
RMS energy spread		$1x10^{-3}$
Electrons per bunch	$x10^{9}$	3.1-12.4
Electrons beam current	µA	160
e-beam power	kW	3.5
Length of the CeC	m	14
Length of FEL wiggler	m	3x2.5
Type of wiggler		Helical
Wiggler period	cm	5
Wiggler parameter, a_w		0.5
FEL wavelength	□m	13

Layout of CeC experiment in IP2

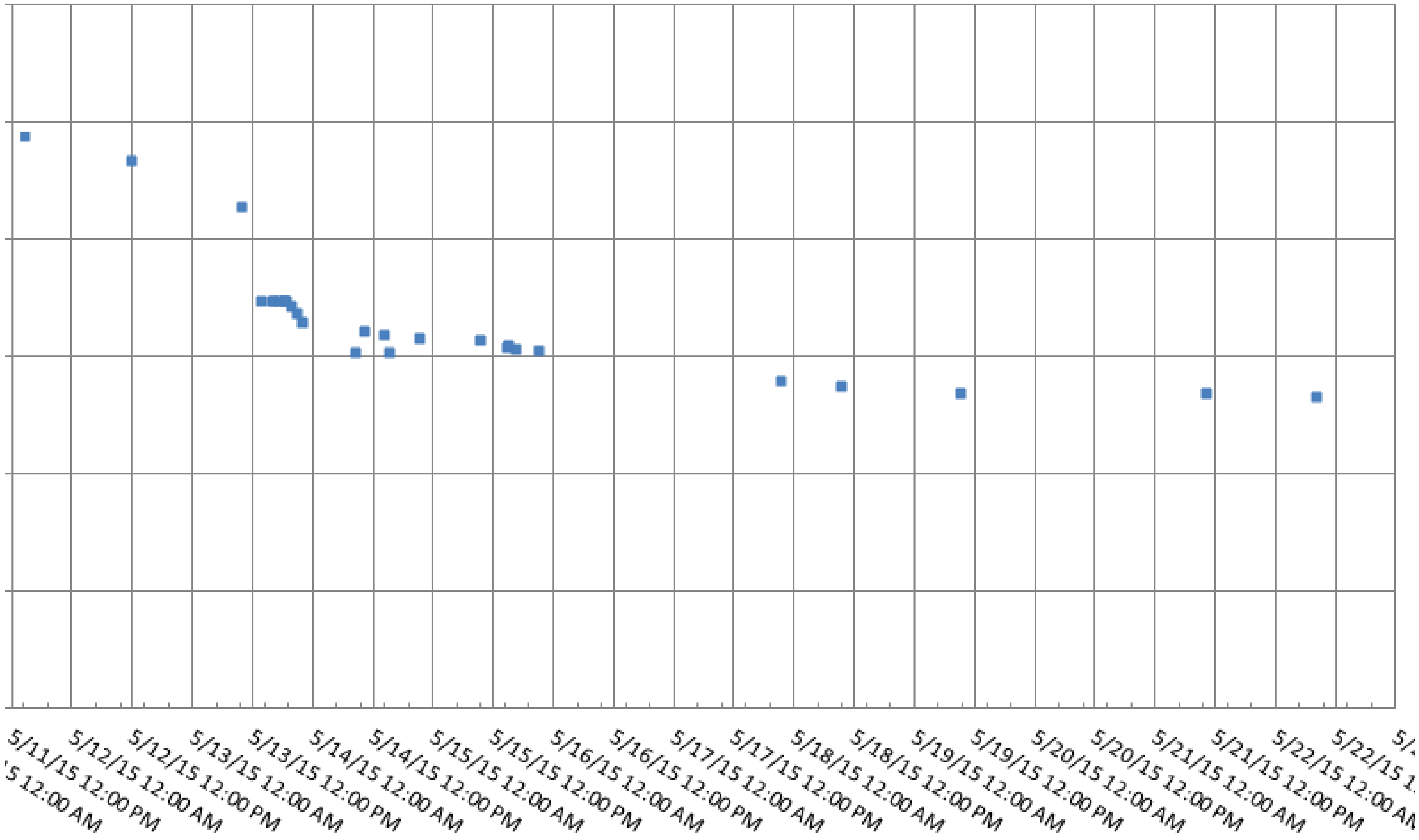


Injector Section

SRF gun – 113 MHz, 2 MV design
Two 500 MHz bunching cavities
Drift space with diagnostics: ICT, BPMs, profile monitors, BPMs, slits for emittance measurement, Faraday cup



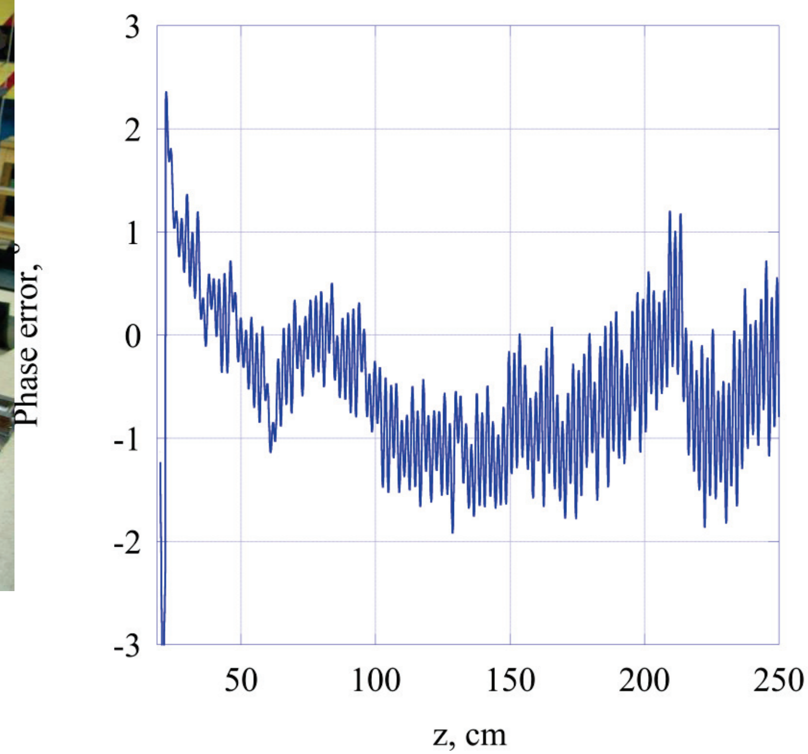
Photocathode



Accelerator Cavity

- 704 MHz frequency
- 20 MV accelerating voltage
- Ready to be shipped next week

Helical Wigglers



All three wiggler were delivered to BNL. We are waiting for magnetic measurement equipment to be shipped and perform measurements on site prior installation.

Summary

- Coherent electron cooling is of critical importance for the eRHIC
- High requirements on the beam quality and high electron beam power dictate usage of energy recovery linac
- Base parameters of the electron beam design are defined but the final design depends on the findings of the proof-of-principle experiment, which is progressing at RHIC