PROGRESS WITH FEL-BASED COHERENT ELECTRON COOLING

Vladimir Litvinenko, Ilan Ben Zvi, Michael Blaskiewicz, Yue Hao, Dmitry Kayran, Eduard Pozdeyev, Gang Wang

Brookhaven National Laboratory, Upton, NY 11973, USA

BROOKHAVEN NATIONAL LABORATORY

Oleg A. Shevchenko, N.A. Vinokurov

Budker Institute of Nuclear Physics, Novosibirsk, Russia

Yaroslav S. Derbenev, TJNAF, Newport News, VA, USA

Jefferson Lab

Sven Reiche, *UCLA, Los Angelis, CA, USA*

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pbpl Particle Beam Physics Laboratory

RHIC

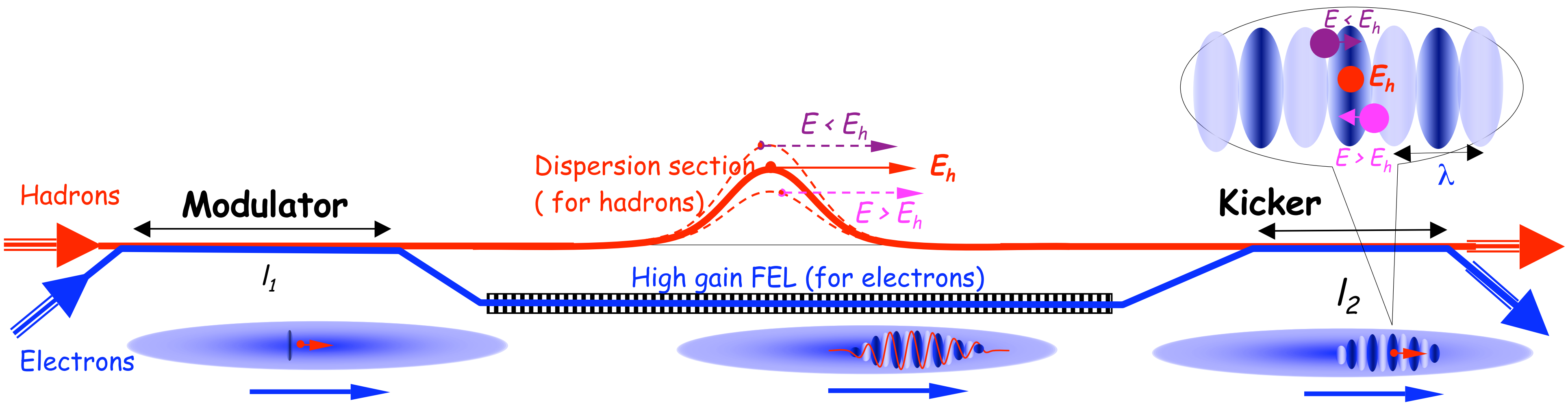
Content

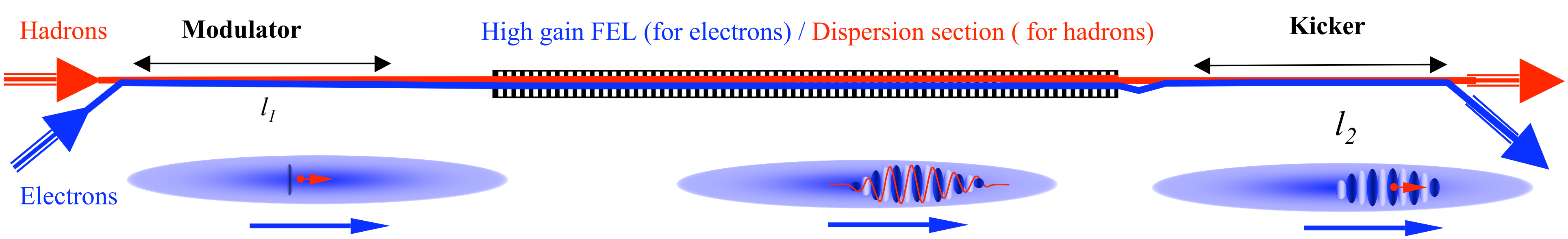
* What is Coherent electron Cooling?
* Why it is needed?
* Our plan of the comprehensive studies
* Progress with Modulator, FEL, Kicker, PoP
* Conclusions

Cooling intense high-energy hadron beams remains a major challenge for accelerator physics. Synchrotron radiation is too feeble, while efficiency of two other cooling methods falls rapidly either at high bunch intensities (i.e. stochastic cooling of protons) or at high energies (i.e. e-cooling). Possibility of coherent electron cooling based on high-gain FEL and ERL was presented at last FEL conference [1]. This scheme promises significant increases in luminosities of modern high-energy hadron and electron-hadron colliders, such as LHC and eRHIC. In this talk we present progress in development of this concept, results of analytical and numerical evaluation of the concept as well our prediction for LHC and RHIC. We also present layout for proof-of-principle experiment at RHIC using existing R&D ERL. In this paper we report on the progress in the development of the scheme of coherent electron cooling (CeC) since a specific scheme and its theoretical evaluation were proposed about an year ago [1].

[1] V.N. Litvinenko, Y.S. Derbenev, Proc. of FEL'07 Conference, Novosibirsk, Russia, August 27-31, 2007, p.268
http://accelconf.web.cern.ch/accelconf/f07

Coherent Electron Cooling





Decrements for hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, hrs	Trad. Electron cooling hrs	Coherent Electron Cooling, hrs 1D/3D
RHIC PoP	*Au*	*40*	-	-	-	*0.02/0.06*
eRHIC	Au	130	~1	20,961 ∞	~ 1	0.015/0.05
eRHIC	**p**	**325**	**~100**	**40,246 ∞**	**> 30**	**0.1/0.3**
LHC	p	7,000	~ 1,000	13/26	∞ ∞	0.3/<1

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Comprehensive studies

Analytical, Numerical and Computer Tools to:

1. find reaction *(distortion of the distribution function of electrons)* on a presence of moving hadron inside an electron beam

$$\frac{\partial f_e}{\partial t} + \frac{\partial f_e}{\partial \vec{v}} \cdot \frac{e\vec{E}}{m} + \frac{\partial f_e}{\partial \vec{r}} \cdot \vec{v} = 0; \quad \vec{r}_h(t) \cong \vec{r}_o + \vec{v}_h t;$$

$$\left(\vec{\nabla} \cdot \vec{E}\right) = 4\pi e n_e \left(\frac{Z}{n_e} \delta\left(\vec{r} - \vec{r}_h(t)\right) - \int f_e d\vec{v}^3 \right).$$

$$f \Rightarrow f_o + \delta f$$

2a. Find how an arbitrary δf is amplified in high-gain FEL

$$f_{exit}(\vec{r}_\perp, \vec{p}, t) = f_{o\ exit}(\vec{r}_\perp, \vec{p}) + \int K\left(\vec{r}_\perp, \vec{p}, \vec{r}_{\perp 1}, \vec{p}_1, t - t_1\right) \cdot \delta f(\vec{r}_1, \vec{p}_1, t_1) \cdot d\vec{r}_{\perp 1} d\vec{p}_1 dt_1$$

2b. Design cost effective lattice for hadrons + coupling

3. Find how the amplified reaction of the e-beam acts on the hadron (including coupling to transverse motion)

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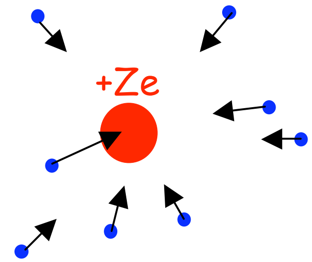
Modulator

Dimensionless equations of motion



$$\frac{\partial f_e}{\partial t} + \frac{\partial f_e}{\partial \vec{\mathrm{v}}}\cdot\frac{e\vec{E}}{m} + \frac{\partial f_e}{\partial \vec{r}}\cdot\vec{\mathrm{v}} = 0;\quad \vec{r}_h(t) \cong \vec{r}_o + \vec{\mathrm{v}}_{\mathrm{h}} t;$$

$$\left(\vec{\nabla}\cdot\vec{E}\right) = 4\pi e n_e\left(\frac{Z}{n_e}\delta\left(\vec{r}-\vec{r}_h(t)\right) - \int f_e d\vec{\mathrm{v}}^3\right).$$

$\Rightarrow$

$$\frac{\partial f_e}{\partial \tau} + \frac{\partial f_e}{\partial \vec{v}}\cdot\vec{g} + \frac{\partial f_e}{\partial \vec{\rho}}\cdot\vec{v} = 0;\ \vec{g} = \frac{e\vec{E}}{m\omega_p^{\,2} s};$$

$$\left(\vec{\nabla}_n\cdot\vec{g}\right) = \frac{Z}{s^3 n_e}\delta\left(\vec{\rho}-\vec{\rho}_i(t)\right) - \int f_e d\vec{v}^3;\quad \vec{\nabla}_n \equiv \partial_{\vec{\rho}}.$$

$$t = \tau/\omega_p;\quad \vec{\mathrm{v}} = \vec{v}\sigma_{\mathrm{v}_z};\quad \vec{r} = \vec{\rho}\sigma_{\mathrm{v}_z}/\omega_p;\ \omega_p^2 = \frac{4\pi e^2 n_e}{m}$$

$$s = r_{D_z} = \sigma_{\mathrm{v}_z}/\omega_p$$

Parameters of the problem

$$\mathrm{R} = \frac{\sigma_{v_\perp}}{\sigma_{v_z}};\ \mathrm{T} = \frac{\mathrm{v_{hx}}}{\sigma_{v_z}};\ \mathrm{L} = \frac{\mathrm{v_{hz}}}{\sigma_{v_z}};\ \xi = \frac{Z}{4\pi n_e R^2 s^3};$$

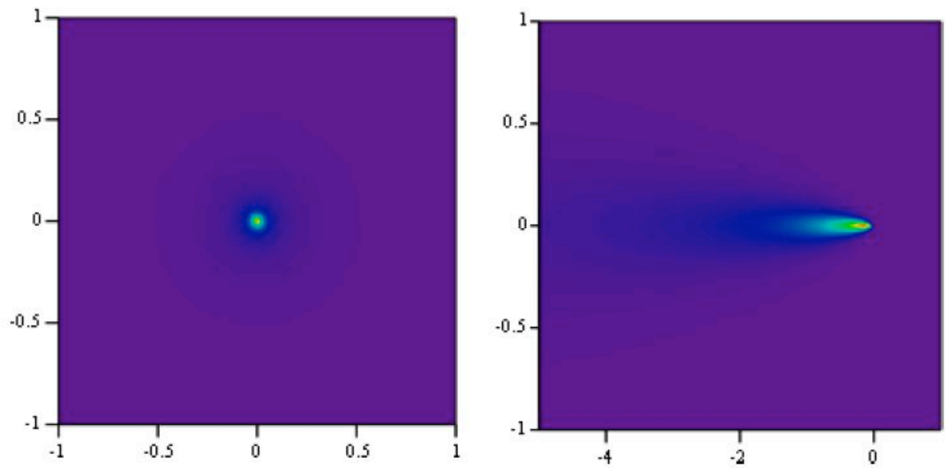
$$\mathrm{A} = \frac{a}{s};\ \mathrm{X} = \frac{\mathrm{x_{ho}}}{a};\mathrm{Y} = \frac{\mathrm{y_{ho}}}{a}.$$

Perturbation caused by a hadron (co-moving frame)

Analytical: for Lorentzian electron plasma, *G. Wang and M. Blaskiewicz, Phys Rev E 78, 026413 (2008)*

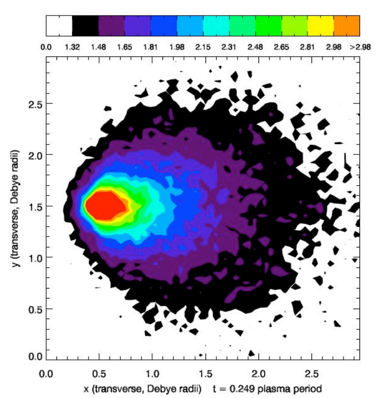
$$\tilde{n}(\vec{r},t) = \frac{Z n_o \omega_p^3}{\pi^2 \sigma_{vx}\sigma_{vy}\sigma_{vz}} \int_0^{\omega_p t} \tau \sin\tau \left(\tau^2 + \left(\frac{x - v_{hx}\tau/\omega_p}{r_{Dx}}\right)^2 + \left(\frac{y - v_{hy}\tau/\omega_p}{r_{Dy}}\right)^2 + \left(\frac{z - v_{hz}\tau/\omega_p}{r_{Dz}}\right)^2\right)^{-2} d\tau$$

Ion at rest



$$v_{hz} = 10\sigma_{vz}$$

Numerical (VORPAL @ TechX)



$$F(z) = \int f_e(\vec{\rho} - \hat{z}\cdot Z\tau, \vec{v}, \tau) d\vec{v}^3 dxdy \approx const + \int \tilde{f}(\vec{\rho} - Z\tau, \vec{v}, \tau) d\vec{v}^3 dxdy$$
$$V_z(z) = \int v_z f_e(\vec{\rho} - \hat{z}\cdot Z\tau, \vec{v}, \tau) d\vec{v}^3 dxdy$$
$$F(x) = \int f_e(\vec{\rho} - \hat{x}\cdot T\cdot R\cdot \tau, \vec{v}, \tau) d\vec{v}^3 dzdy$$
$$F(y) = \int f_e(\vec{\rho}, \vec{v}, \tau) d\vec{v}^3 dzdx$$

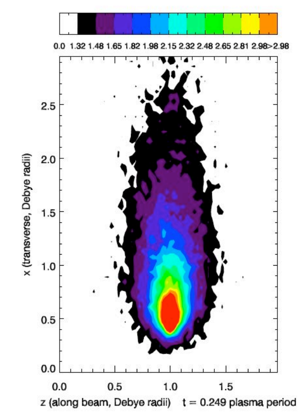


Figure 3: A transverse cross section of the wake behind a gold ion, with the color denoting density enhancement.

Figure 4: A longitudinal cross section of the wake behind a gold ion, with the color denoting density enhancement.

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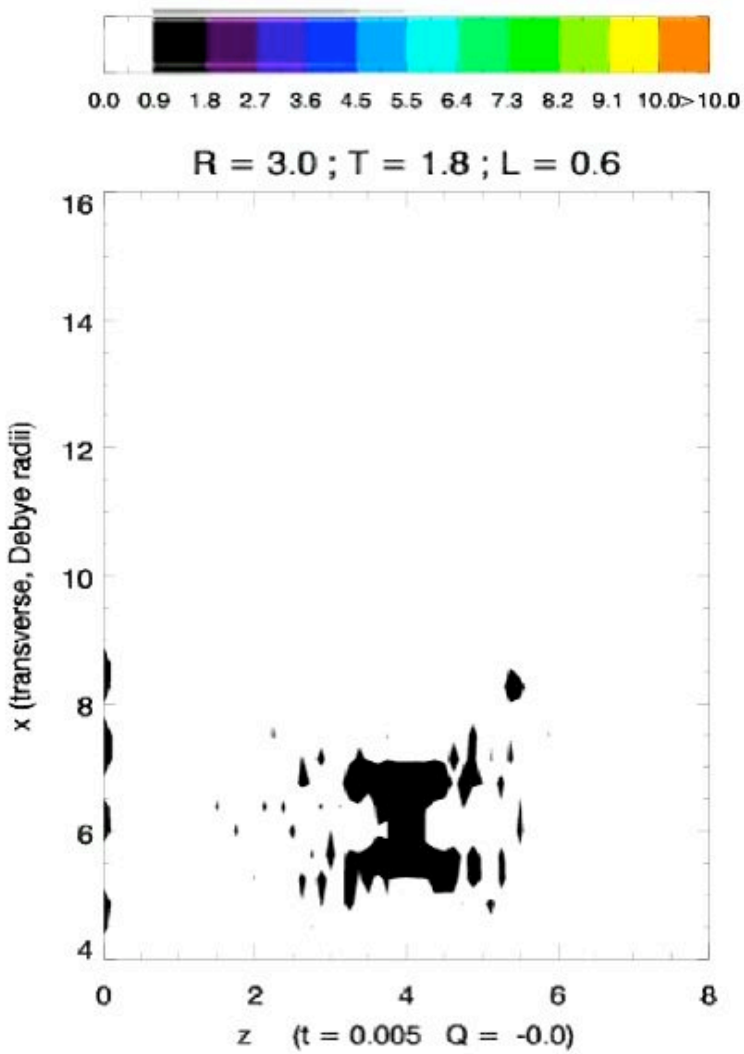
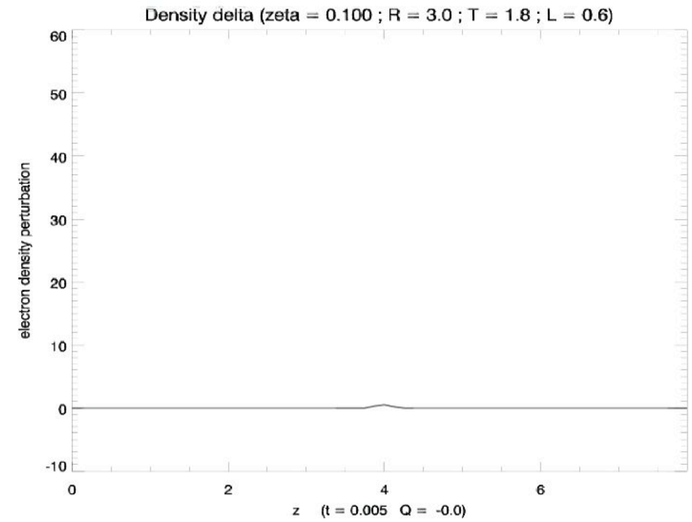
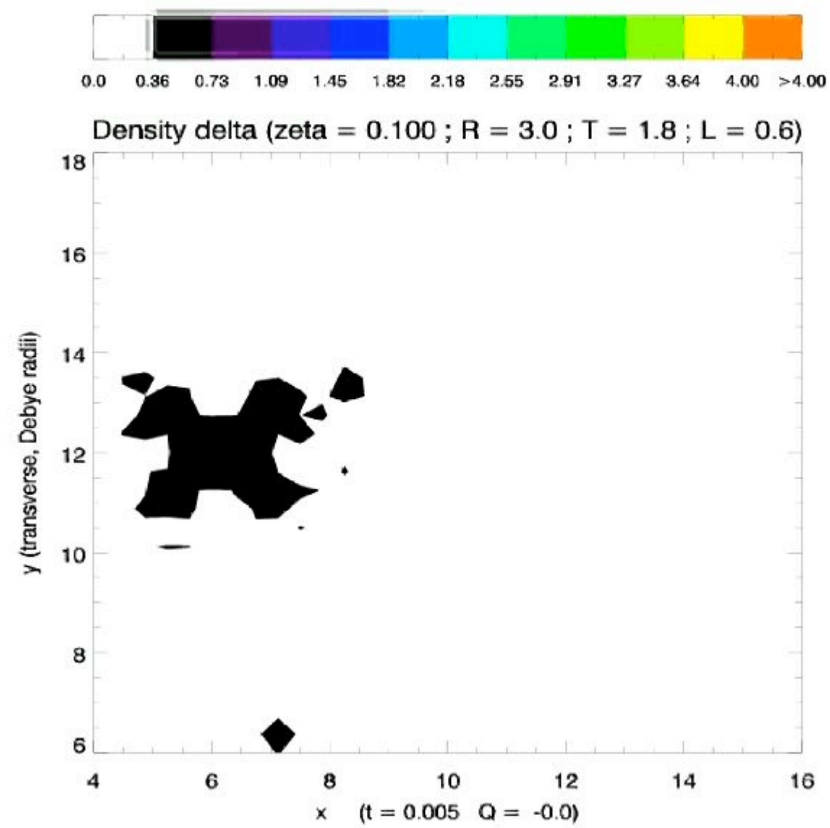
VORPAL @ TechX



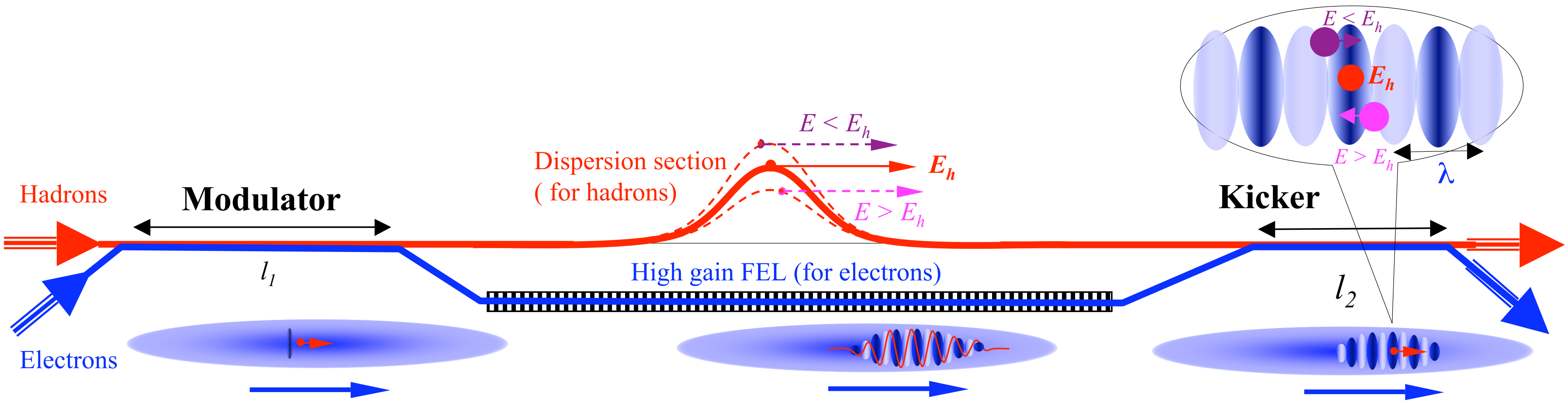




CeC: FEL response

$$f_{input}(\vec{r}_\perp,\vec{p},t) = f_{o\ input}(\vec{r}_\perp,\vec{p}) + \delta f(\vec{r}_\perp,\vec{p},t)$$

$$f_{exit}(\vec{r}_\perp,\vec{p},t) = f_{o\ exit}(\vec{r}_\perp,\vec{p}) + \int K\left(\vec{r}_\perp,\vec{p},\vec{r}_{\perp 1},\vec{p}_1,t-t_1\right)\cdot \delta f(\vec{r}_1,\vec{p}_1,t_1)\cdot d\vec{r}_{\perp 1} d\vec{p}_1 dt_1$$



1D FEL response

$$\rho_{exit}(t;z) = \rho_o + \int G(\tau;z)\cdot \delta\rho(t-\tau;0)\cdot d\tau$$

$$G(\tau;z) = \mathrm{Re}\left(\tilde{G}_z(\tau)e^{i\omega_o\tau}\right) \qquad \omega_0 = \frac{2\pi c}{\lambda_o};$$

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FEL's Green Function

1D - analytical approach $G(\tau;z) = \mathrm{Re}\left(\tilde{G}_z(\tau)e^{i\omega_o\tau}\right)$

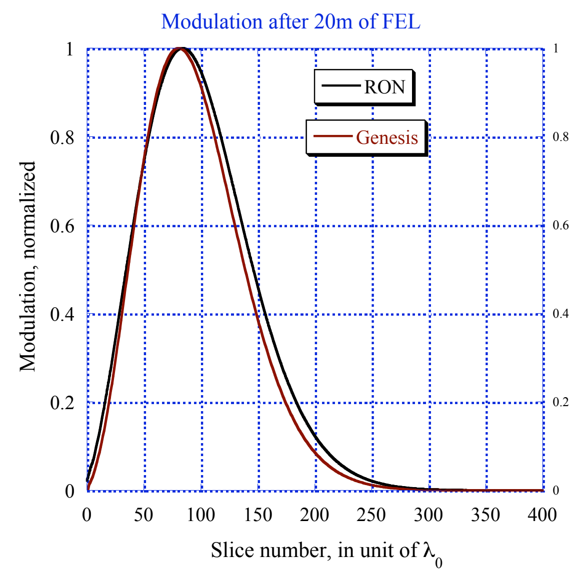
3D - 3D FEL codes RON and Genesis 1.3

FEL parameters for Genesis 1.3 and RON simulations

FEL gain length: 1 m (power), 2m (amplitude)

Main FEL parameters for eRHIC with 250 GeV protons

Energy, MeV	136.2	γ	266.45
Peak current, A	100	λ_o, nm	700
Bunchlength, psec	50	λ_w, cm	5
Emittance, norm	5 mm mrad	a_w	0.994
Energy spread	0.03%	Wiggler	Helical



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Response - 1D FEL

Assume the 1D energy distribution is Lorentzian

$$F(\hat{P}) = \frac{1}{\pi \hat{q}} \frac{1}{1 + \frac{\hat{P}^2}{\hat{q}^2}} \qquad \hat{P} = \frac{\Delta E}{\rho E_0}$$

$$\rho = \gamma_z^2 \Gamma c / \omega \approx 2 \times 10^{-3}$$

Evolution of a specific frequency component is determined by the following ODE

$$\frac{d^3}{d\hat{z}^3}\hat{\tilde{E}}(\hat{z}) + 2\left(\hat{q} + i\hat{C}\right)\frac{d^2}{d\hat{z}^2}\hat{\tilde{E}}(\hat{z}) + \left[\hat{\Lambda}_p^2 + \left(\hat{q} + i\hat{C}\right)^2\right]\frac{d}{d\hat{z}}\hat{\tilde{E}}(\hat{z}) - i\hat{\tilde{E}}(\hat{z}) = 0$$

$$\frac{d}{dz}\tilde{E}(z) = -\frac{\theta_s}{2\varepsilon_0 c}\hat{\tilde{j}}_1(z)$$

$$\Gamma = \left[\frac{\pi j_0 \theta_s^2 \omega}{c \gamma_z^2 \gamma I_A}\right]^{\frac{1}{3}} \approx 1 m^{-1}$$

$$\tilde{E}(\hat{z}) = A_1 e^{\lambda_1 \hat{z}} + A_2 e^{\lambda_2 \hat{z}} + A_3 e^{\lambda_3 \hat{z}}$$

$$I_A = 17 KA$$

$$\tilde{j}_1(z) = -\left(\frac{\theta_s}{2\varepsilon_0 c}\right)^{-1}\left[A_1\lambda_1 e^{\lambda_1 \hat{z}} + A_2\lambda_2 e^{\lambda_2 \hat{z}} + A_3\lambda_3 e^{\lambda_3 \hat{z}}\right]$$

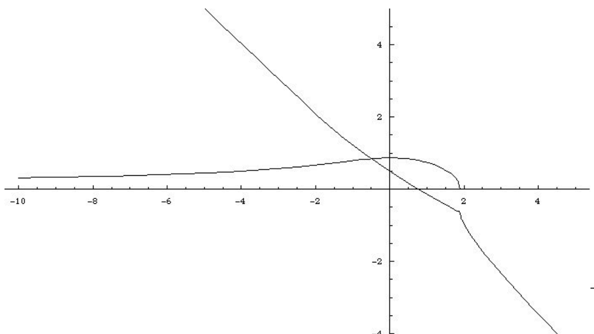
E.L.Saldin, E.A.Schneidmiller, M.V.Yurkov, The Physics of Free Electron Lasers, Springer, 1999

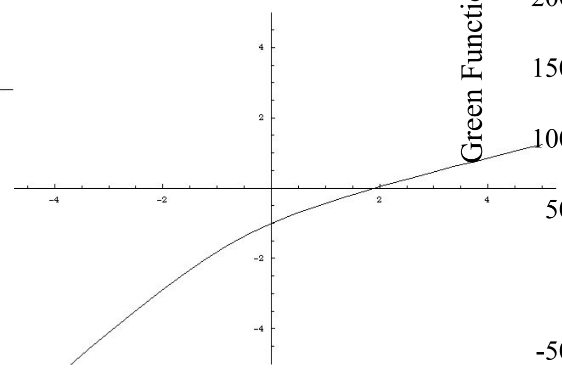
Response - 1D FEL after 10 gain lengths

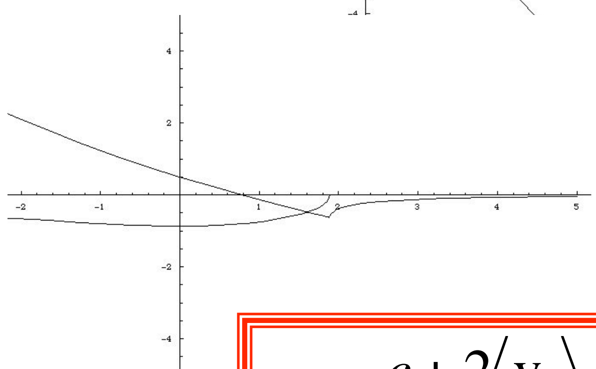
$$\left\{\left\{x\to\frac{1}{3}\left(-2\,i\,c-\frac{2^{1/3}c^2}{\left(27\,i-2\,i\,c^3+3\sqrt{3}\sqrt{-27+4c^3}\right)^{1/3}}+\frac{\left(27\,i-2\,i\,c^3+3\sqrt{3}\sqrt{-27+4c^3}\right)^{1/3}}{2^{1/3}}\right)\right\},\right.$$

$$\left\{x\to-\frac{2\,i\,c}{3}+\frac{\left(1+i\sqrt{3}\right)c^2}{3\,2^{2/3}\left(27\,i-2\,i\,c^3+3\sqrt{3}\sqrt{-27+4c^3}\right)^{1/3}}-\frac{\left(1-i\sqrt{3}\right)\left(27\,i-2\,i\,c^3+3\sqrt{3}\sqrt{-27+4c^3}\right)^{1/3}}{6\,2^{1/3}}\right\},$$

$$\left.\left\{x\to-\frac{2\,i\,c}{3}+\frac{\left(1-i\sqrt{3}\right)c^2}{3\,2^{2/3}\left(27\,i-2\,i\,c^3+3\sqrt{3}\sqrt{-27+4c^3}\right)^{1/3}}-\frac{\left(1+i\sqrt{3}\right)\left(27\,i-2\,i\,c^3+3\sqrt{3}\sqrt{-27+4c^3}\right)^{1/3}}{6\,2^{1/3}}\right\}\right\}$$

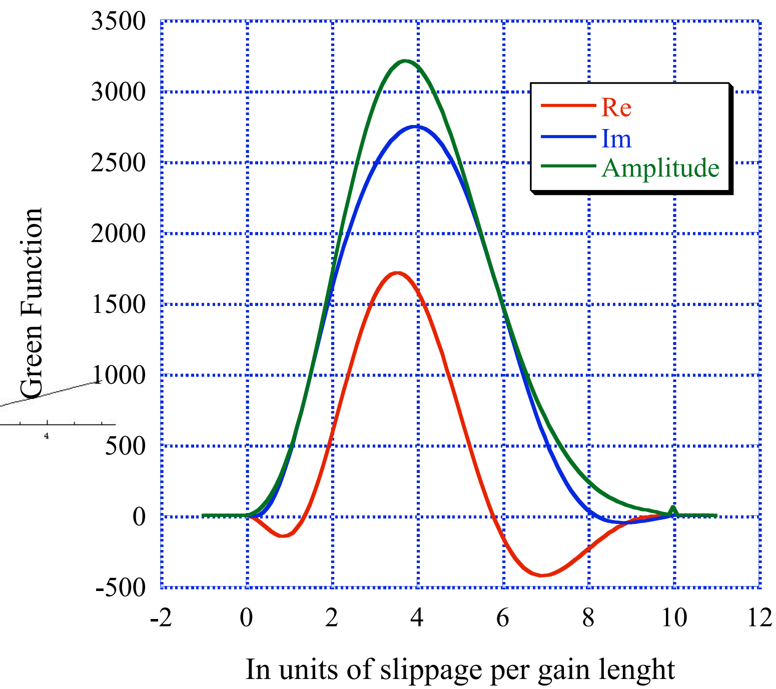






$$v_g=\frac{c+2\langle v_z\rangle}{3}=c\left(1-\frac{1+a_w^2}{3\gamma_o^2}\right)$$

Green-function envelope (Abs, Re and Im)



Maximum located at 3.744 slippage units,
(i.e. just a bit further that expected 3 and 1/3)
The Green function (with oscillations) had
effective RMS length of 1.48 slippage units.

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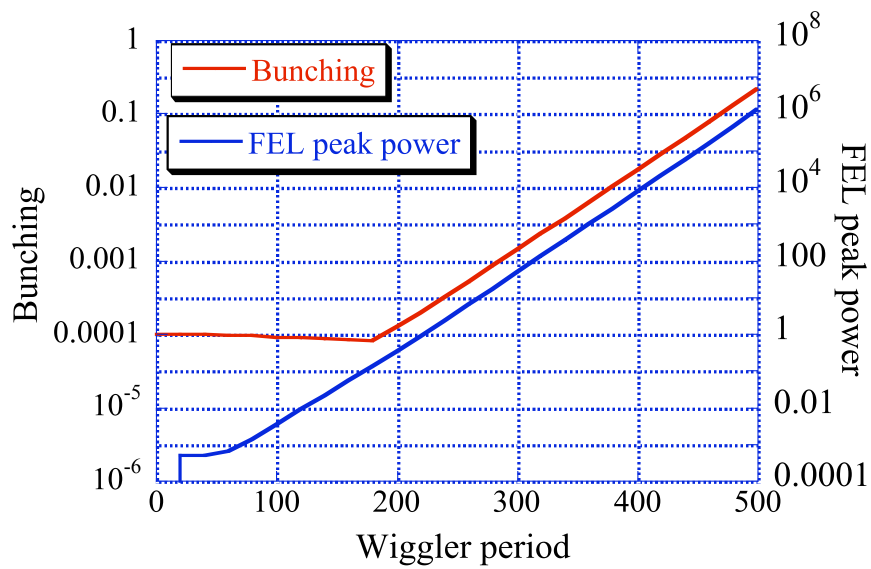
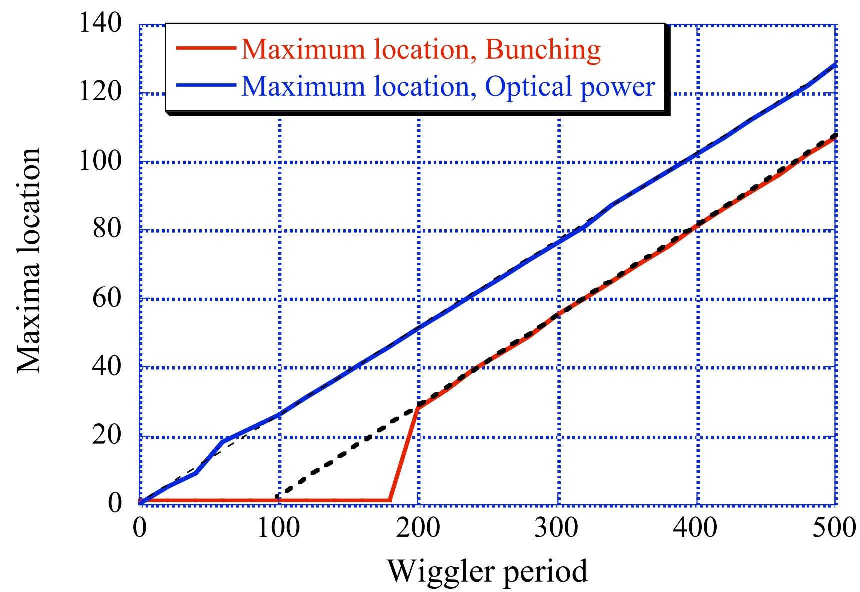
Genesis: 3D FEL





Evolution of the maximum bunching in the e-beam and the FEL power simulated by Genesis.
The location of the maxima, both for the optical power and the bunching progresses with a lower speed compared with prediction by 1D theory,
i.e. electrons carry ~75% for the "information"

Evolution of the maxima locations in the e-beam bunching and the FEL power simulated by Genesis.
Gain length for the optical power is 1 m (20 periods) and for the amplitude/modulation is 2m (40 periods)

$$v_g \cong \frac{c + 3\langle v_z \rangle}{4} = c\left(1 - \frac{3}{8}\frac{1 + a_w^2}{\gamma_o^2}\right)$$

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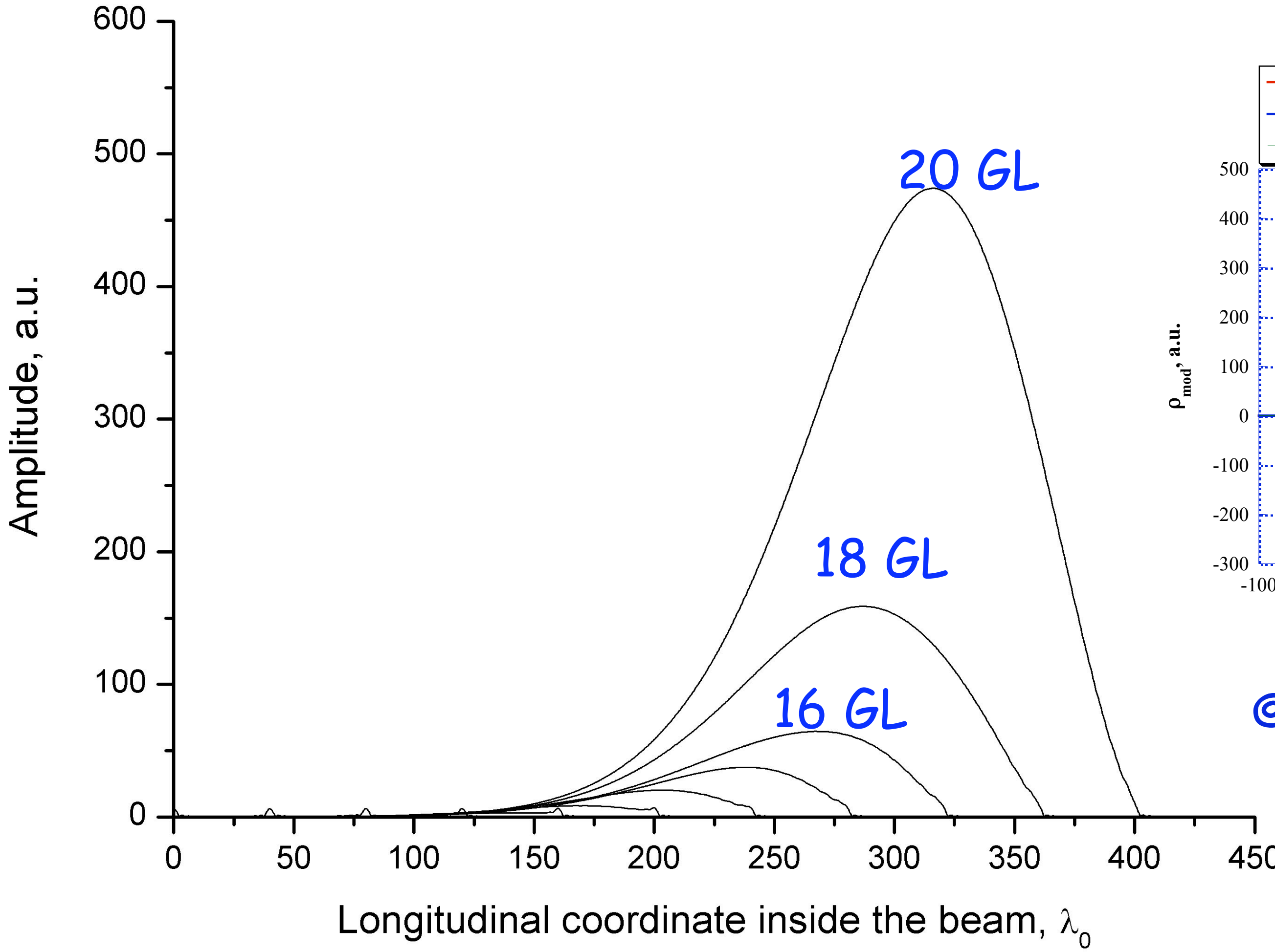
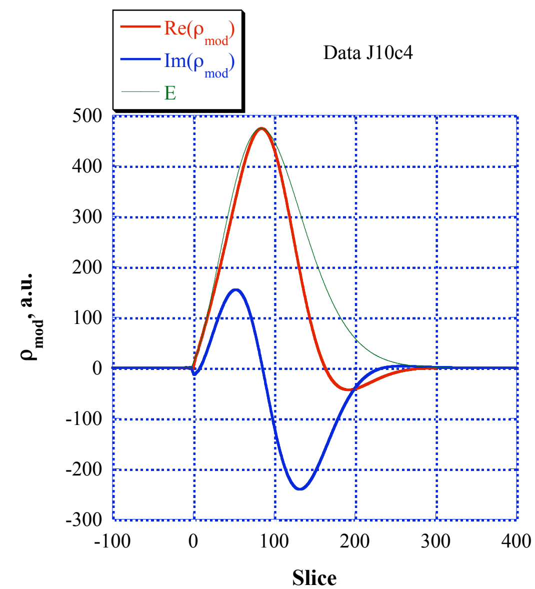
3D FEL, RON code

RHIC 250 GeV, FEL @ 0.7 μm, gain length - 40 periods (amplitude). 20 (power)





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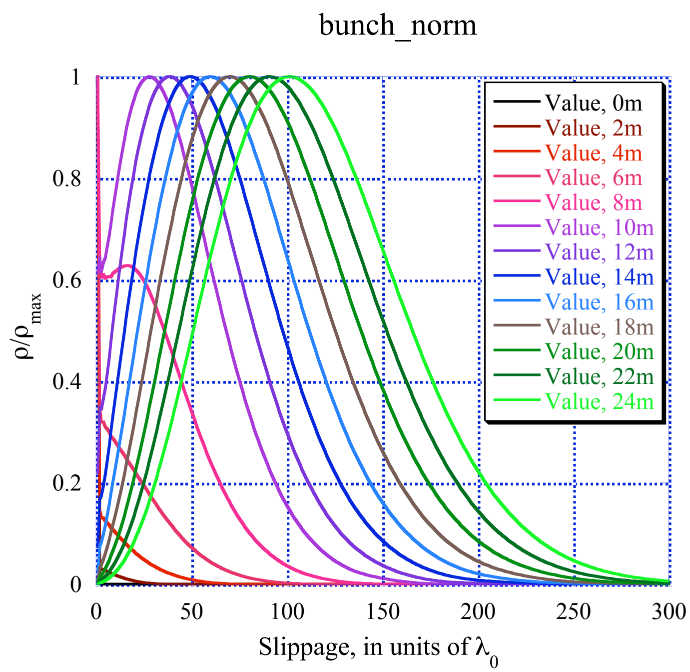
Genesis: 3D FEL



Evolution of the normalized bunching envelope

The Green function (with oscillations) after 10 gain-lengths had also smaller effective RMS length [1] of 0.96 slippage units (i.e. about 38 optical wavelengths, or 27 microns

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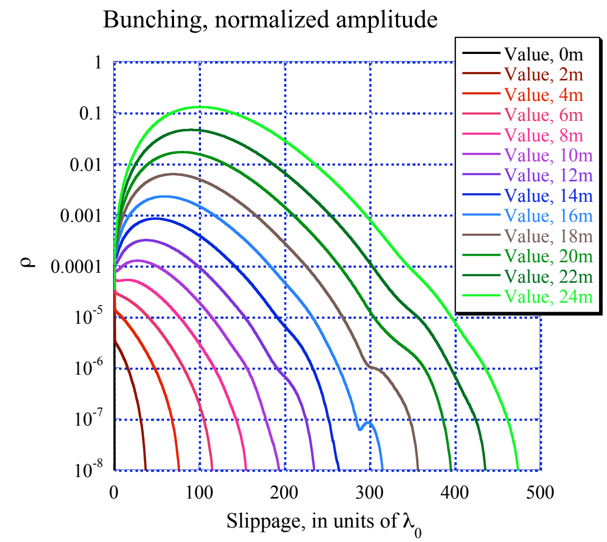
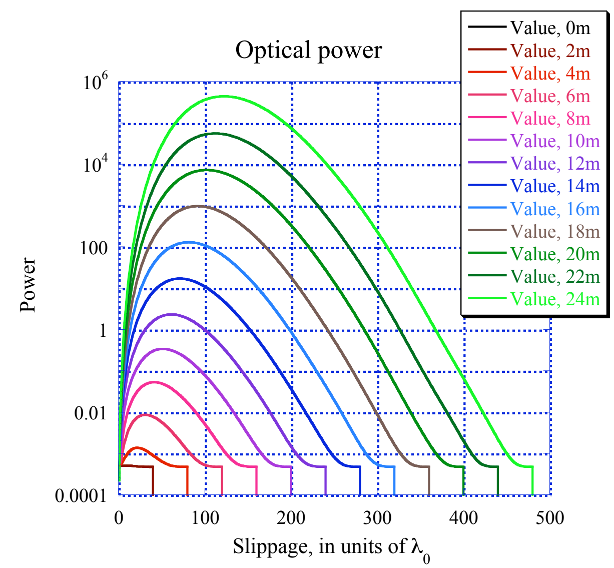
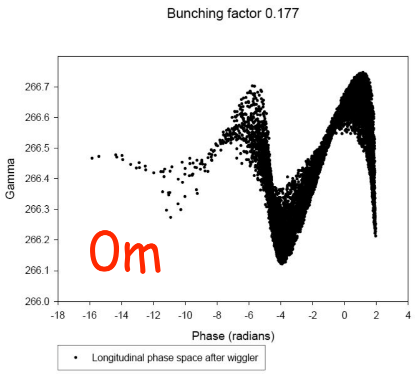
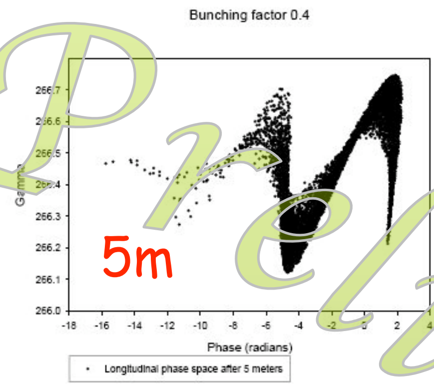


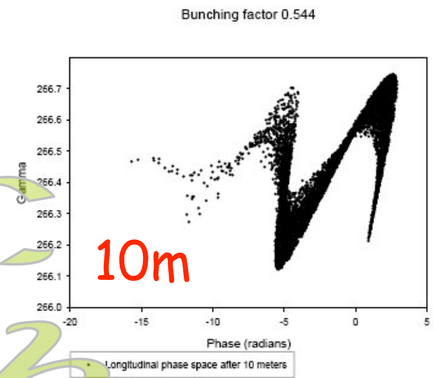


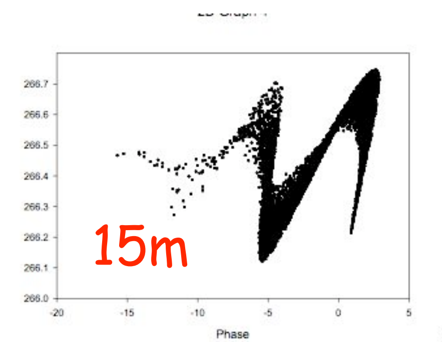
Evolution of the bunching and optical power envelopes (vertical scale is logarithmic)

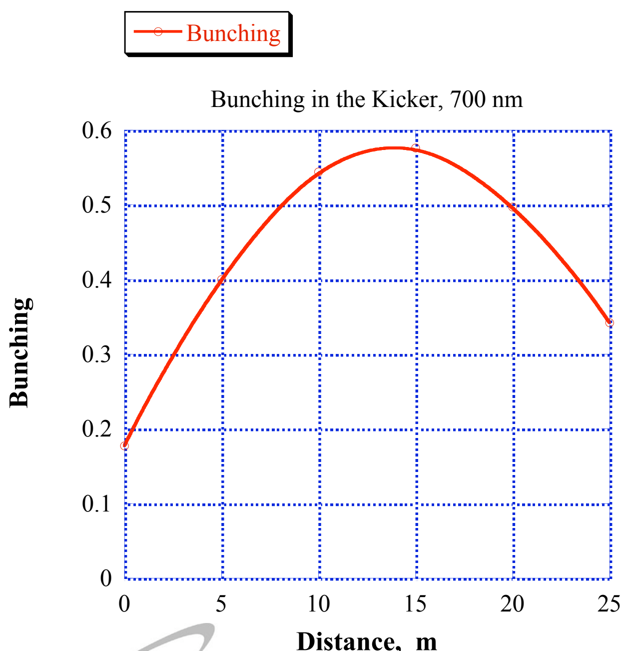
Kicker: output from Genesis propagated for 25 m

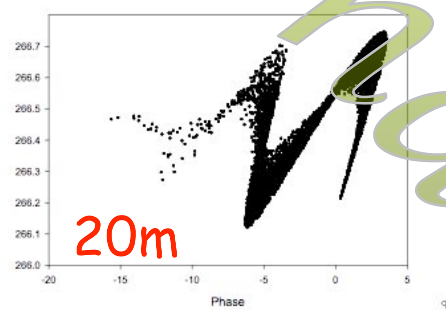


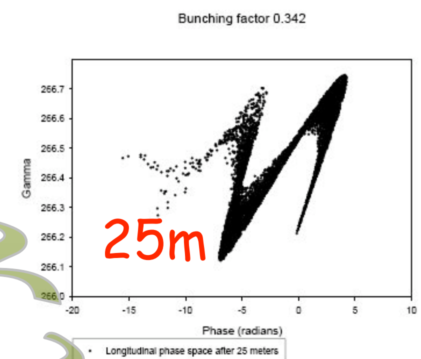












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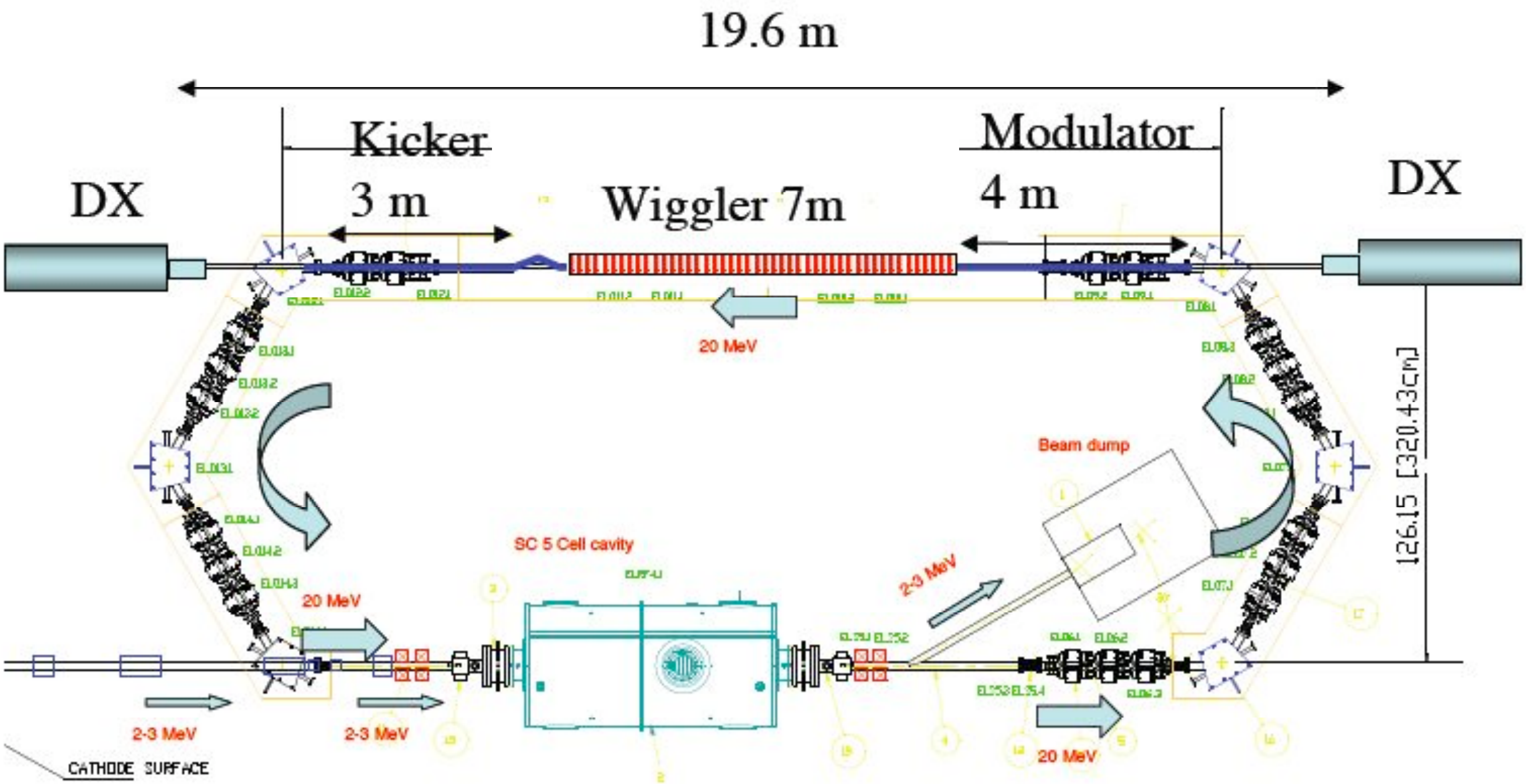
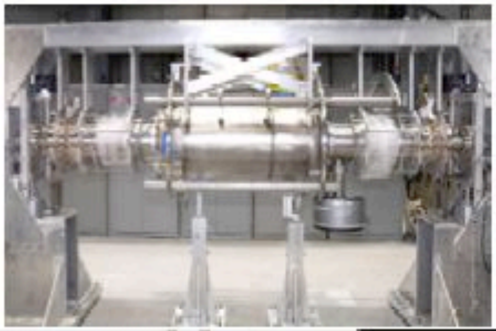
IR-2 layout for Coherent Electron Cooling proof-of-principle experiment

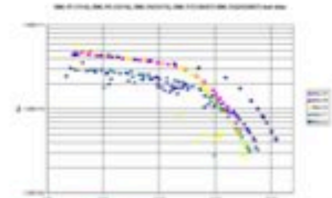


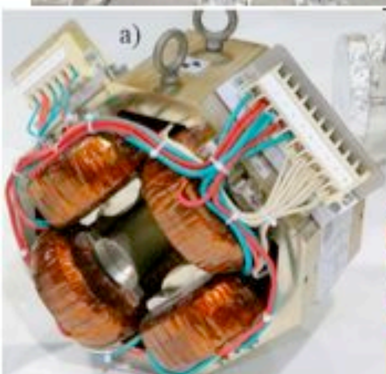
Conclusions

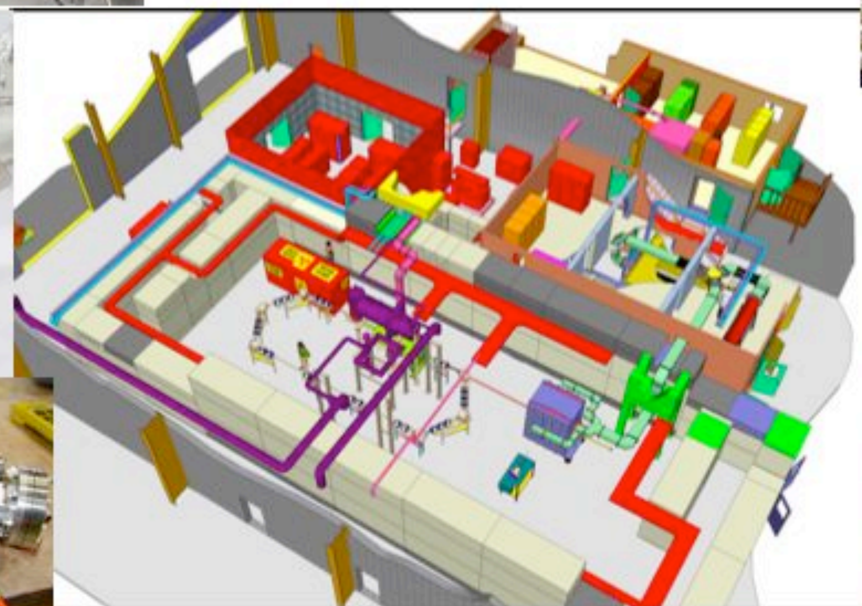
- These initial studies did not find any phenomena, which challenges the concept of CeC
- Our initial CeC estimations passed the test
- At the same time, we found a number of new and interesting details to pursue further
- Future studies will refine the model and improve the quality of predictions
- We plan to test validity of the concept experimentally in Proof-of-Principle experiment using BNL's R&D ERL installed in one of available IPs at RHIC



R&D ERL Commissioning start 2009







Response - 1D FEL; z=13m

Effect of energy spread and space charge

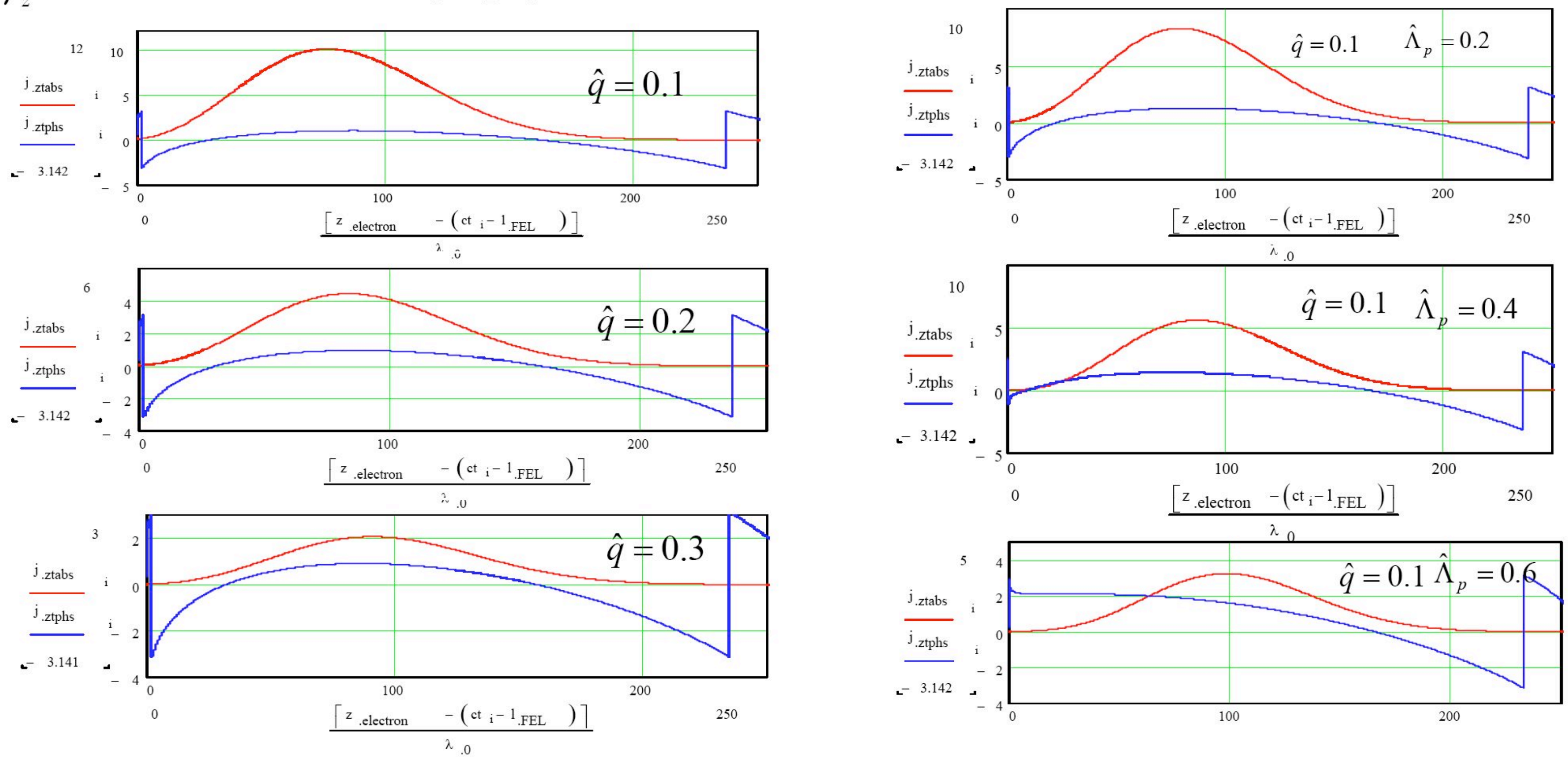
Red - amplitude, Blue - phase

$$\hat{\Lambda}_p = l_{gain}\left[\frac{4\pi j_0}{\gamma_z^2 \gamma I_A}\right]^{1/2} \approx 0.2$$

@

$$I_{peak} = 100A$$

$$\rho = \gamma_z^2 \Gamma c / \omega \approx 2\times 10^{-3} \qquad q = \hat{q}\times\rho$$



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