Coherent electron cooling

Vladimir N. Litvinenko

C-AD, Brookhaven National Laboratory, Upton, NY, USA

Department of Physics and Astronomy, Stony Brook University

Center for Accelerator Science and Education

Thanks to

Ilan Ben-Zvi, Yue Hao, Vadim Ptitsyn, Gang Wang, Stephen Webb
Brookhaven National Laboratory, Upton, NY 11973, USA

Oleg A. Shevchenko, Nikolay A. Vinokurov
Budker Institute of Nuclear Physics, Novosibirsk, Russia

George I. Bell, David L. Bruhwiler, Andrey Sobol
Tech-X Corp., Boulder, CO 80303, USA

Yaroslav S. Derbenev, Andrew Hutton, Geoff Kraft, Matt Poelker
TJNAF, Newport News, VA, USA

Content

- Why it is needed?
- Classical Coherent Electron Cooling (CeC)
- How to cool transversely
- Theory & Simulations
- Recent advances in CeC
  - Noise reduction in FEL
  - Spin cooling
- Proof of Principle test using R&D ERL
- Q&A

Why to cool hadron beams?

Measure of Collider Performance is the Luminosity

$$\dot{N}_{events} = \sigma_{A\to B} \cdot L$$

$$L = \frac{f_{coll} \cdot N_1 \cdot N_2}{4\pi\beta^* \varepsilon} \cdot g(\beta^*, h, \theta, \sigma_z)$$

Main sources of luminosity limitation

Large or growing emittance
Hour-glass effect
Crossing angle
Beam Intensity & Instabilities
Beam-Beam effects

Why to coherent electron cooling?

- Traditional stochastic cooling does not have enough bandwidth to cool modern-day proton beams
- Efficiency of traditional electron cooling falls as a high power of hadron's energy
- Synchrotron radiation is too fable – event at LHC energy cooling time is more than 10 hours
- Optical stochastic cooling is not suitable for cooling hadrons with large range of energies and has a couple of weak points:
  - Hadron do not like to radiate or absorb photons, the process which OSC uses twice
  - Tunabity and power of laser amplifiers are limited

Examples of hadron beams 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*	-	-	~ 1	*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

Potential increases in luminosities:

RHIC pp ~ 6 fold, eRHIC ~ 50 fold, LHC ~ 2 fold; LHeC ~ 10 fold

Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

$$X=\frac{\varepsilon_x}{\varepsilon_{xo}};\ S=\left(\frac{\sigma_s}{\sigma_{so}}\right)^2=\left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

$$\frac{dX}{dt}=\frac{1}{\tau_{IBS\perp}}\frac{1}{X^{3/2}S^{1/2}}-\frac{\xi_\perp}{\tau_{CeC}}\frac{1}{S};$$

$$\frac{dS}{dt}=\frac{1}{\tau_{IBS//}}\frac{1}{X^{3/2}Y}-\frac{1-2\xi_\perp}{\tau_{CeC}}\frac{1}{X};$$

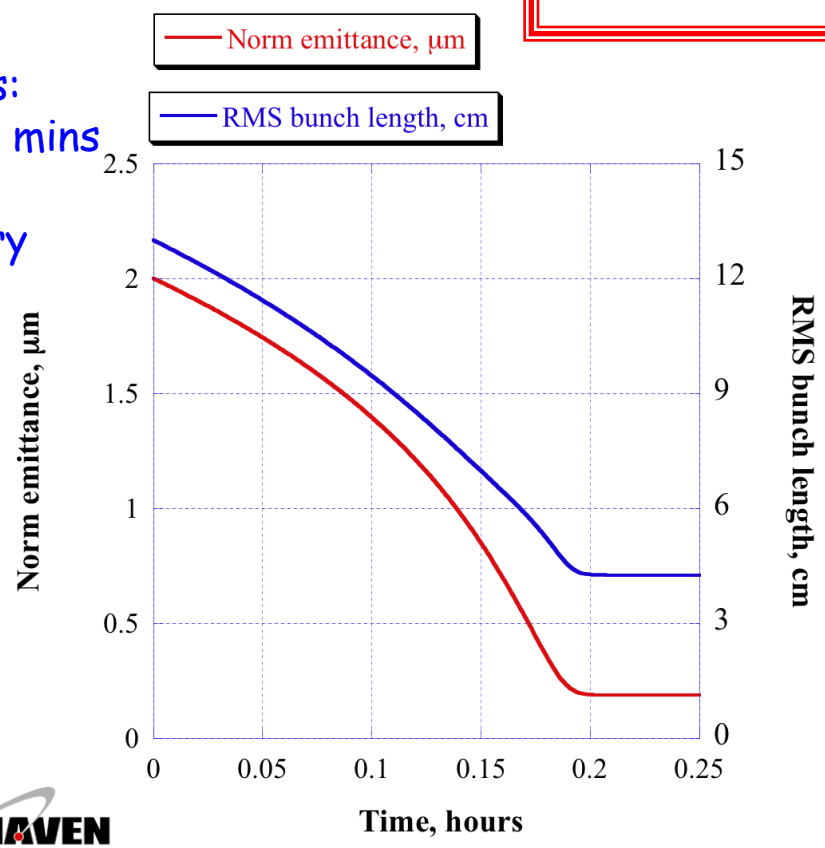
$$X=\frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}}\frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}};\quad S=\frac{\tau_{CeC}}{\tau_{IBS//}}\cdot\sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}}\cdot\sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$

$$\varepsilon_{xn0}=2\,\mu m;\ \sigma_{s0}=13\ cm;\ \sigma_{\delta 0}=4\cdot 10^{-4}$$

$$\tau_{IBS\perp}=4.6\ \ hrs;\ \tau_{IBS//}=1.6\ \ hrs$$

IBS in RHIC for eRHIC, 250 GeV, $N_p=2\cdot 10^{11}$ Beta-cool, ©A.Fedotov

Dynamics: Takes 12 mins to reach stationary point



$$\varepsilon_{xn}=0.2\,\mu m;\ \sigma_s=4.9\ \ \mathrm{cm}$$

This allows

a) keep the luminosity as it is
b) reduce polarized beam current down to 50 mA (10 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing β* from 25 cm down to 5 cm

eRHIC: ERL or ring for electrons?
CeC is the key ingredient

	eRHIC IR2	
	p /A	e
Energy (max), GeV	325/130	20
Number of bunches	166	74 nsec
Bunch intensity (u) , 10^{11}	2.0	0.24
Bunch charge, nC	32	4
Beam current, mA	420	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	1.2	25
Polarization, %	70	80
rms bunch length, cm	4.9	0.2
β^*, cm	5	5
Luminosity, $cm^{-2}s^{-1}$	1.4×10^{34}	

Evolution of beam in LHC at 7 TeV

(assuming nominal LHC bunch intensity 1.15e11 p/bunch and 40% of CeC cooling capability)

$$\frac{\sigma_\varepsilon^2}{\tau_{IBS//}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s} \left\langle \frac{f(\chi_m)}{\beta_y v} \right\rangle; \quad \frac{\varepsilon_x}{\tau_{IBS\perp}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s} \left\langle \frac{H}{\beta_y^{1/2}} f(\chi_m) \right\rangle; \kappa = 1$$

$$f(\chi_m) = \int_{\chi_m}^{\infty} \frac{d\chi}{\chi} \ln\left(\frac{\chi}{\chi_m}\right) e^{-\chi}; \; \chi_m = \frac{r_c m^2 c^4}{b_{\max} \sigma_E^2}; b_{\max} \cong n^{-1/3}; \; r_c = \frac{e^2}{mc^2}; \quad (e \to Ze; m \to Am)$$

J.LeDuff, "Single and Multiple Touschek effects", Proceedings of CERN Accelerator School, Rhodes, Greece, 20 September - 1 October, 1993, Editor: S.Turner, CERN 95-06, 22 November 1995, Vol. II, p. 573

$$X = \frac{\varepsilon_x}{\varepsilon_{xo}}; \; S = \left(\frac{\sigma_s}{\sigma_{so}}\right)^2 = \left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

$$\frac{dX}{dt} = \frac{1}{\tau_{IBS\perp}} \frac{1}{X^{3/2} S^{1/2}} - \frac{\xi_\perp}{\tau_{CeC}} \frac{1}{S};$$

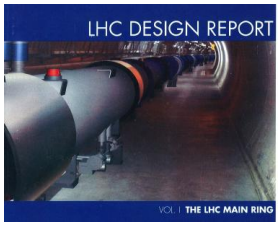
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}} \frac{1}{X^{3/2} S^{1/2}} - \frac{1 - 2\xi_\perp}{\tau_{CeC}} \frac{1}{X};$$

$$\varepsilon_{xn0} = 3.75 \mu m; \; \sigma_{s0} = 7.55 cm$$

$$\tau_{IBS\perp} = 80 \; hrs; \; \tau_{IBS//} = 61 \; hrs$$

IBS rates in LHC from

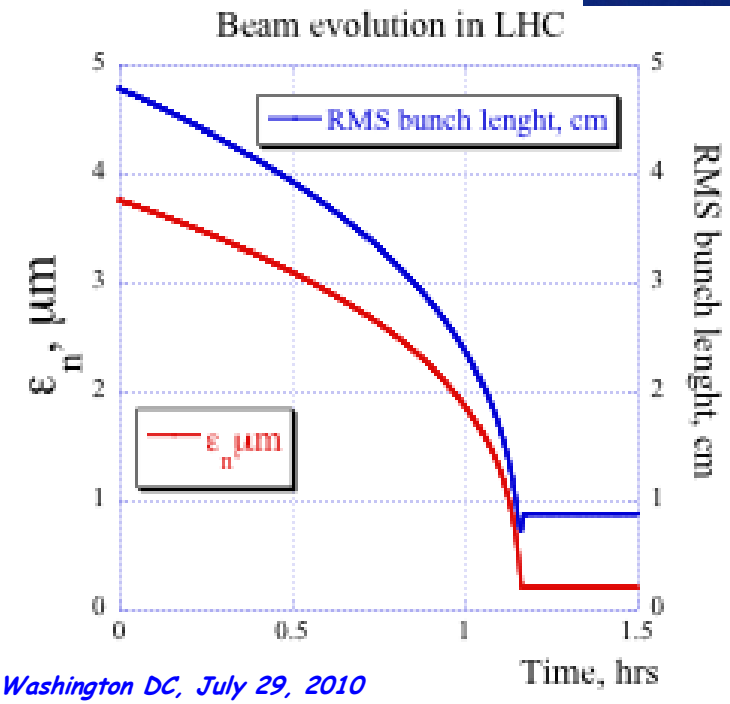
Table 2.2



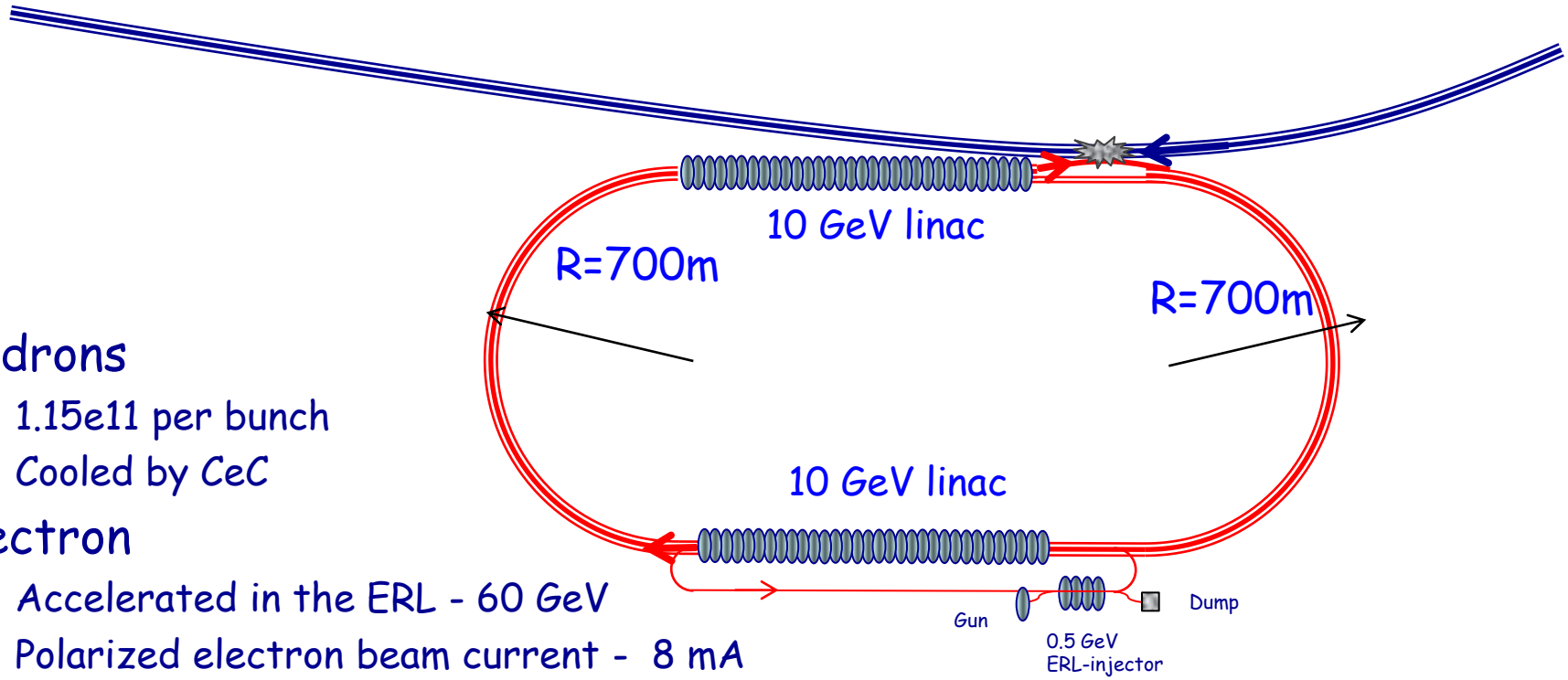
Stationary solution for τ_{CeC} = 0.8 hrs

$$X = \frac{\tau_{CeC}}{\sqrt{\tau_{IBS//} \tau_{IBS\perp}}} \frac{1}{\sqrt{\xi_\perp (1 - 2\xi_\perp)}}; \quad S = \frac{\tau_{CeC}}{\tau_{IBS//}} \cdot \sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}} \cdot \sqrt{\frac{\xi_\perp}{(1 - 2\xi_\perp)^3}}$$

$$\varepsilon_{xn} = 0.19 \mu m; \; \sigma_s = 0.87 \text{ cm}$$



Layout for ERL based LHC



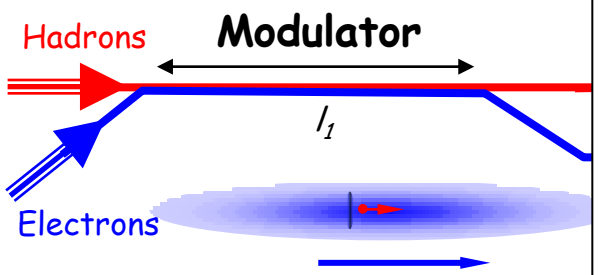
- Hadrons
  - 1.15e11 per bunch
  - Cooled by CeC
- Electron
  - Accelerated in the ERL - 60 GeV
  - Polarized electron beam current - 8 mA
- Number of passes – 3
- AC power consumption – 100 MW
- Crab-crossing
- β^*=12 cm
- $L = 2 \cdot 10^{34}\ cm^{-2}\ sec^{-1}$

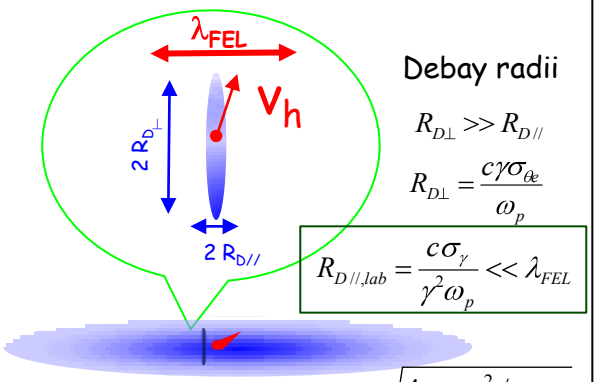
Coherent Electron Cooler

At a half of plasma oscillation

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

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





Debay radii

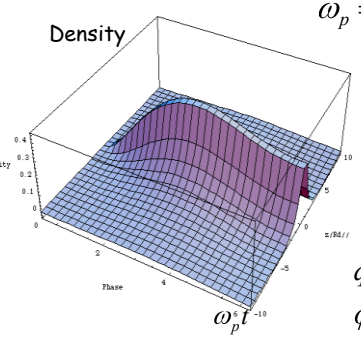
$$R_{D\perp} >> R_{D//}$$

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

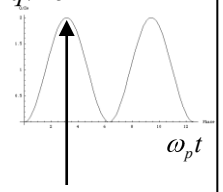
$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_p} << \lambda_{FEL}$$

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

Density



$-q/Ze$



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

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

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

BROOKHAVEN NATIONAL LABORATORY

Analytical formula for damping decrement

$$\langle \zeta_{CeC} \rangle = \zeta \frac{\sigma_{\tau,e}}{\sigma_{\tau,h}} = \kappa \cdot 2G_o \cdot \frac{Z^2}{A} \cdot \frac{r_p \cdot \sigma_{\tau,e}}{\varepsilon_{\perp n}\left(\sigma_\delta \cdot \sigma_{\tau,h}\right)}; \; \kappa \sim 1$$

$$\langle \zeta_{CeC} \rangle \sim \frac{1}{\varepsilon_{long,h}\varepsilon_{trans,h}}$$

Note that damping decrement

a) **Does not depend on the energy of particles !**
b) **Improves as cooling goes on**

It makes it realistic to think about cooling intense proton beam in RHIC & LHC at 100s of GeV and 7 TeV energies
Even though LHC needs one more trick *(back up slides)*

Effects of the surrounding particles

Each charged particle CUAses generation of an electric field wave-packet proportional to its charge and synchronized with its initial position in the bunch

$$\mathbf{E}_{total}(\zeta) = \mathrm{E}_o \cdot \mathrm{Im}\left(X \cdot \sum_{i,hadrons} K(\zeta - \zeta_i) e^{ik(\zeta - \zeta_i)} - \sum_{j,electrons} K(\zeta - \zeta_j) e^{ik(\zeta - \zeta_j)} \right)$$

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

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

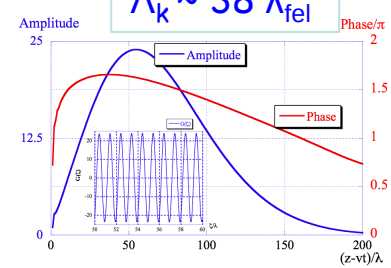
Evolution of the RMS value resembles stochastic cooling!
Best cooling rate achievable is ~ $1/N_{eff}$, N_{eff} is effective number of hadrons in coherent sample ($\Lambda_k = N_c \lambda$)

$$\boxed{\left\langle \delta^2 \right\rangle' = -2\xi \left\langle \delta^2 \right\rangle + D}$$

$$\Lambda_k = \iint |K(z - \zeta)|^2 d\zeta$$

$$N_{eff} \cong N_h \frac{\Lambda_k}{\sqrt{4\pi}\sigma_{z,h}} + \frac{N_e}{X^2} \frac{\Lambda_k}{\sqrt{4\pi}\sigma_{z,e}}$$

$\Lambda_k \sim 38\ \lambda_{fel}$



$$\xi = -g\left\langle \delta_i \mathrm{Im}\left(K(\Delta\zeta_i) e^{ik\Delta\zeta_i}\right)\right\rangle / \left\langle \delta^2 \right\rangle; \quad D = g^2 N_{eff}/2;$$

$$g = G_o \frac{Z^2}{A} \frac{r_p}{\varepsilon_{\perp n}} \left\{ 2f(\varphi_2)(1 - \cos\varphi_1) \frac{l_2}{\beta} \cdot \right\},$$

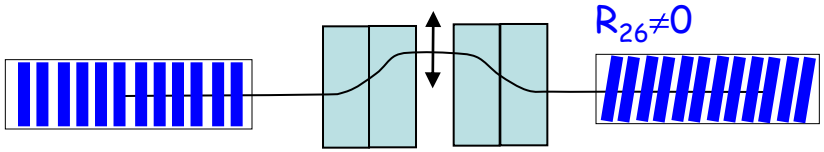
$$\boxed{\xi_{CeC}(\max) = \frac{\Delta}{2\sigma_\gamma} = \frac{2}{N_{eff}} (kD\sigma_\varepsilon) \propto \frac{1}{N_{eff}}}$$

Fortunately, the bandwidth of FELs $\Delta f \sim 10^{13}$-10^{15} Hz is so large that this limitation does not play any practical role in most HE cases

Transverse cooling

- Transverse cooling can be obtained by using coupling with longitudinal motion via transverse dispersion
- Sharing of cooling decrements is similar to sum of decrements theorem for synchrotron radiation damping, i.e. decrement of longitudinal cooling can be split into appropriate portions to cool both transversely and longitudinally: $J_s+J_h+J_v=1$
- Vertical (better to say the second eigen mode) cooling is coming from transverse coupling

Non-achromatic chicane installed at the exit of the FEL before the kicker section turns the wave-fronts of the charged planes in electron beam



$$\delta(ct) = -R_{26}\cdot x$$

$$\Delta\mathbf{E} = -eZ^2\cdot E_o\cdot l_2\cdot \sin\left\{k\left(D\frac{\mathbf{E}-\mathbf{E}_o}{\mathbf{E}_o} + R_{16}x' - R_{26}x + R_{36}y' + R_{46}y\right)\right\};$$

$$\Delta x = -D_x\cdot eZ^2\cdot E_o\cdot L_2\cdot kR_{26}x + \ldots.$$

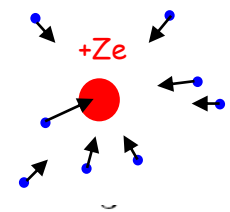
$$\zeta_\perp = J_\perp\zeta_{CeC};\quad \zeta_{//} = (1-2J_\perp)\zeta_{CeC};$$

$$\frac{d\varepsilon_x}{dt} = -\frac{\varepsilon_x}{\tau_{CeC\perp}};\frac{d\sigma_\varepsilon^{\ 2}}{dt} = -\frac{\sigma_\varepsilon^{\ 2}}{\tau_{CeC//}}$$

$$\tau_{CeC\perp} = \frac{1}{2J_\perp\zeta_{CeC}};\ \tau_{CeC\perp} = \frac{1}{2(1-2J_\perp)\zeta_{CeC}};$$

e-Density modulation CUAsed by a hadron (co-moving frame)

Induces charge: $q = -Ze \cdot (1 - \cos\omega_p t)$



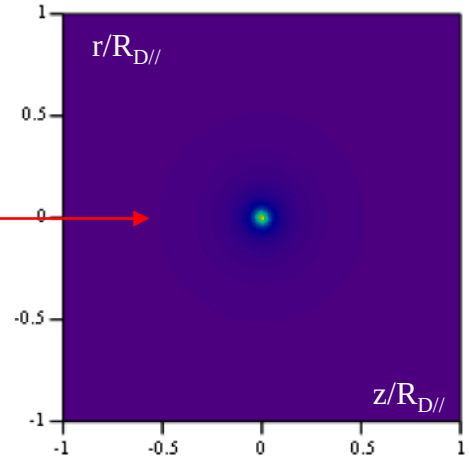
Analytical: for kappa-2 anisotropic electron plasma,

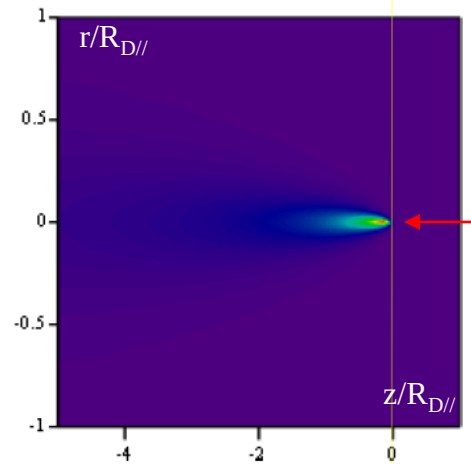
G. Wang and M. Blaskiewicz, Phys Rev E 78, 026413 (2008)

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

Density plots for a quarter of plasma oscillation

Ion rests in c.m.
(0,0) is the location of the ion





Ion moves in c.m. with

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

(0,0) is the location of the ion

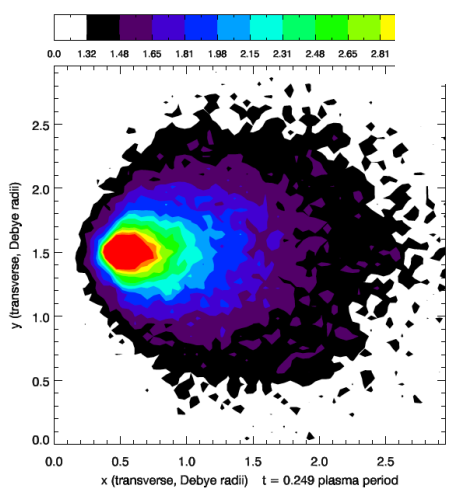


Figure 3: A transverse cross section of the wake behind a gold ion, with the color denoting density enhancement.

Numerical: VORPAL @ TechX)

Parameters of the problem

$$R_{D_\alpha} \propto (|v_\alpha| + \sigma_{v_\alpha})/\omega_p; \quad \alpha = x,y,z$$

$$t = \tau/\omega_p; \quad \vec{v} = \vec{\nu}\sigma_{v_z}; \quad \vec{r} = \vec{\rho}\sigma_{v_z}/\omega_p; \quad \omega_p = \sqrt{\frac{4\pi e^2 n_e}{m}} \qquad s = r_{D_z} = \frac{\sigma_{v_z}}{\omega_p}$$

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

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

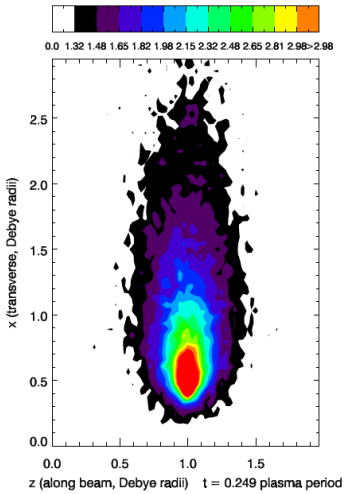
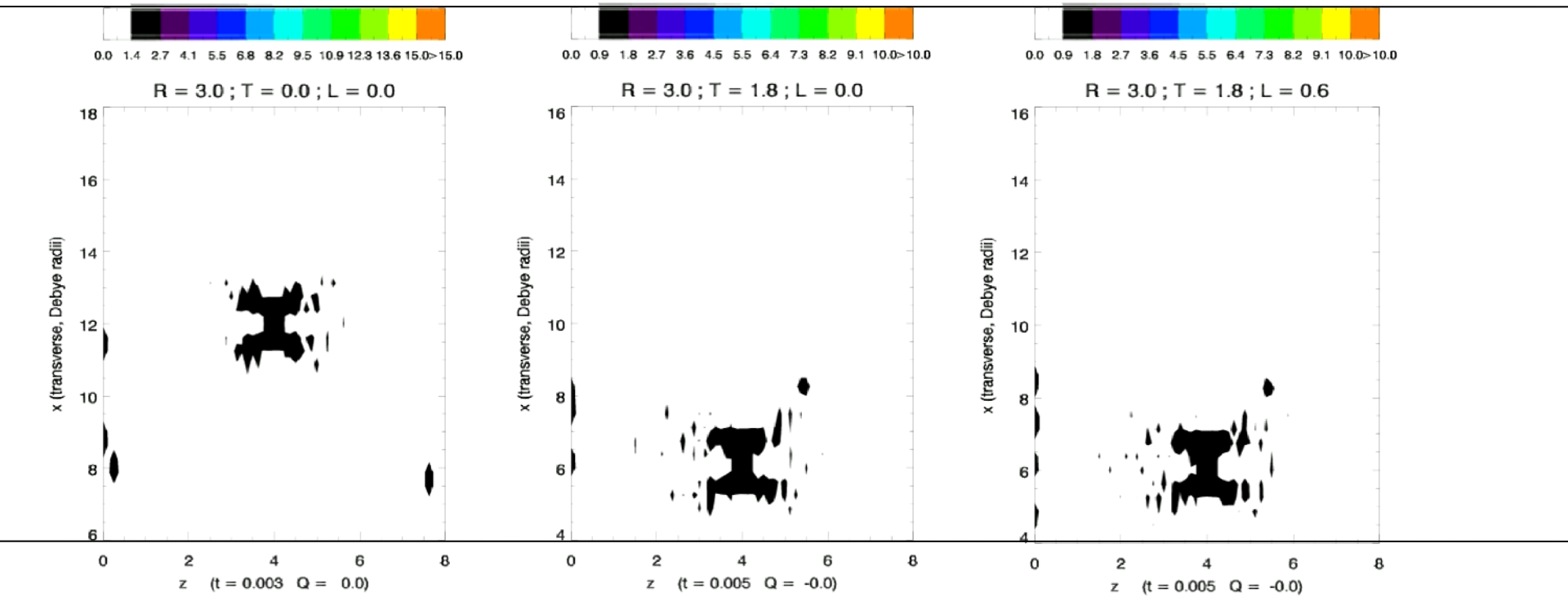
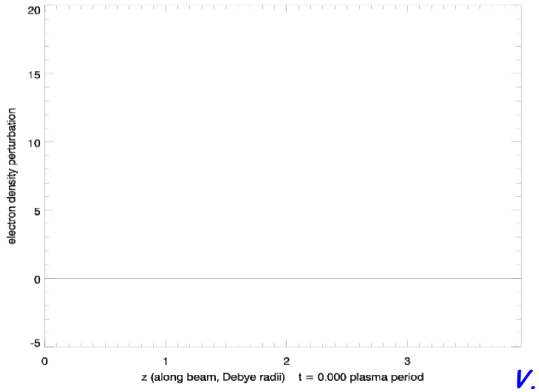


Figure 4: A longitudinal cross section of the wake behind a gold ion, with the color denoting density enhancement.

Numerical simulations (VORPAL @ TechX)
Provides for simulation with arbitrary distributions and finite electron beam size

VORPAL Simulations Relevant to Coherent Electron Cooling, G.I. Bell et al., EPAC'08, (2008)





© TechX

$$R = \frac{\sigma_{v_\perp}}{\sigma_{v_z}};\ T = \frac{V_{hx}}{\sigma_{v_z}};\ L = \frac{V_{hz}}{\sigma_{v_z}}$$

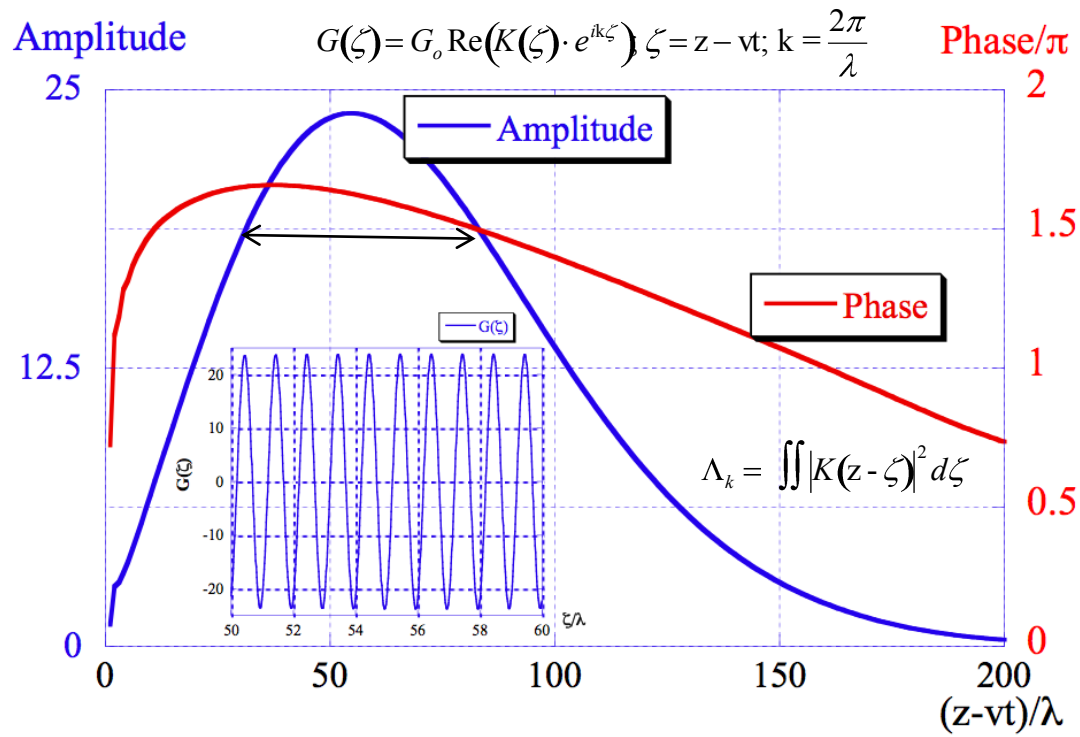
$$q = -Ze \cdot (1 - \cos\omega_p t)$$

3D FEL response calculated Genesis 1.3, confirmed by RON

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

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}.

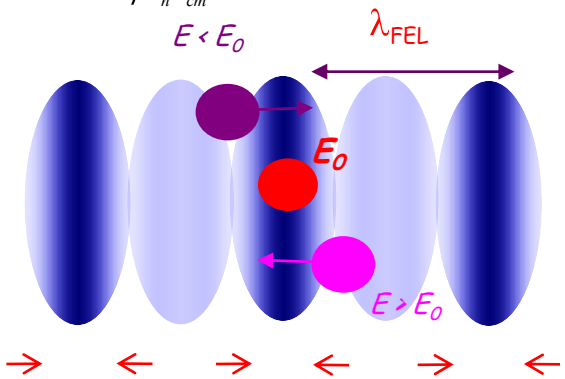


The Kicker

A hadron with central energy (E_o) phased with the hill where longitudinal electric field is zero, a hadron with higher energy ($E > E_o$) arrives earlier and is decelerated, while hadron with lower energy ($E < E_o$) arrives later and is accelerated by the collective field of electrons

Analytical estimation

$$\Delta\varphi = 4\pi\rho \Rightarrow \varphi = -\frac{8G\cdot Ze}{\pi\beta\varepsilon_n k_{cm}}\cdot\cos(k_{cm}z); \quad \vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\frac{8G\cdot Ze}{\pi\beta\varepsilon_n}\cdot\sin(k_{cm}z)$$



Periodical longitudinal electric field

$$\frac{d\mathbf{E}}{dz} = -eE_{peak}\cdot\sin\left\{kD\frac{\mathbf{E}-\mathbf{E}_o}{\mathbf{E}_o}\right\};$$

$$kD\sigma_\delta \sim 1$$

$$\sigma_\delta = \frac{\sigma_{\mathbf{E}}}{\mathbf{E}_o}$$

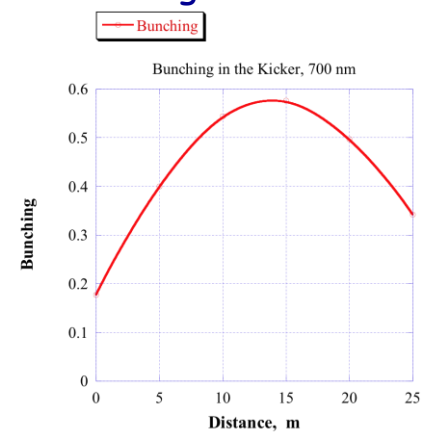
$$\zeta_{CEC} = -\frac{\Delta\mathbf{E}}{\mathbf{E}-\mathbf{E}_o} \approx \frac{e\cdot E_o\cdot l_2}{\gamma_o m_p c^2\cdot\sigma_\varepsilon}\cdot\frac{Z^2}{A}$$

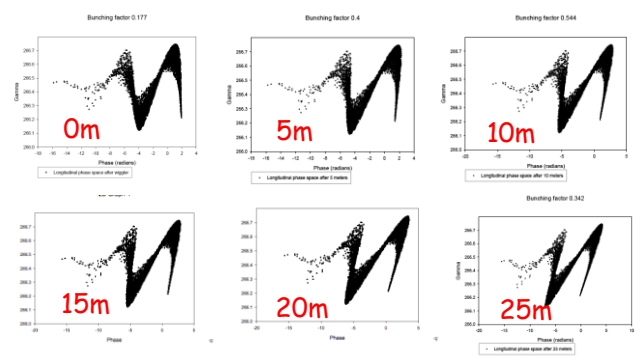
Simulations: only started

Step 1: use 3D FEL code out output + tracking
First simulation indicate that equations on the left significantly underestimate the kick, i.e. the density modulation continues to grow after beam leaves the FEL

Output from Genesis propagated for 25 m

©I.Ben Zvi





Step 2:
use VORPAL with input from Genesis, in preparation

New theoretical developments beyond 1D

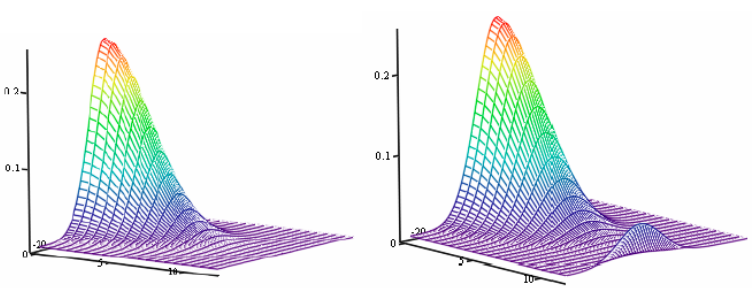
Inserting (8) into (5) generates

$$\frac{\partial}{\partial \hat{z}}\tilde{R}\left(\hat{z},\hat{k}_\perp,\hat{C}\right)=-i\int_0^{\hat{z}} d\hat{z}'(\hat{z}'-\hat{z})\exp\left[i\left(\hat{C}-\hat{k}_\perp^2\right)(\hat{z}'-\hat{z})-\left|\hat{q}(\hat{z}'-\hat{z})\right|\right]\left\{\tilde{R}\left(\hat{z}',\hat{k}_\perp,\hat{C}\right)+i\Lambda_p^2\frac{\partial}{\partial \hat{z}'}\tilde{R}\left(\hat{z}',\hat{k}_\perp,\hat{C}\right)\right\} \quad (9)$$

, which is similar to 1D FEL theory (equation (6.68)~ (6.69) of Gang's thesis) of except that $\hat{C}$ there is replaced by $\hat{C}_{3d}=\hat{C}-\hat{k}_\perp^2$. Thus equation (9) can be reduced to a third order ODE the same way as what is done in 1D FEL theory, i.e.

$$\frac{d^3}{d\hat{z}^3}\tilde{R}(\hat{z})+2\left(i\hat{C}_{3d}+\hat{q}\right)\frac{d^2}{d\hat{z}^2}\tilde{R}(\hat{z})+\left[\hat{\Lambda}_p^2+\left(i\hat{C}_{3d}+\hat{q}\right)^2\right]\frac{d}{d\hat{z}}\tilde{R}(\hat{z})-i\tilde{R}(\hat{z})=0\,. \quad (10)$$

$$\tilde{j}_1(x,y,z,t)=\frac{c^2\Gamma^4\gamma_z^4}{4\pi^3\theta_s\rho}\frac{1}{\xi(z,t)}e^{-i\frac{\hat{x}^2+\hat{y}^2}{4\xi(z,t)}}e^{\pm i(1\pm1)\frac{\pi}{4}}e^{-i\hat{k}_w\xi(z,t)}$$
$$\times\int_{-\infty}^{\infty}\sum_{i=1}^{3}A_i\left(\hat{C}_{3d}\right)\lambda_i\left(\hat{C}_{3d}\right)e^{\lambda_i\left(\hat{C}_{3d}\right)\hat{z}}e^{-i2\gamma_z^2(\hat{z}-c\hat{t})\hat{C}_{3d}}d\hat{C}_{3d}$$



(a) (b)

Figure 8. Comparison of equation (46) with 20 terms expansion and equation (37) by direct integration. (a) calculation done by (37); (b) calculation by (46). For both plots, $\hat{\sigma}_x=2$, $\hat{\sigma}_t=0.1$ and $\xi=0$ are used.

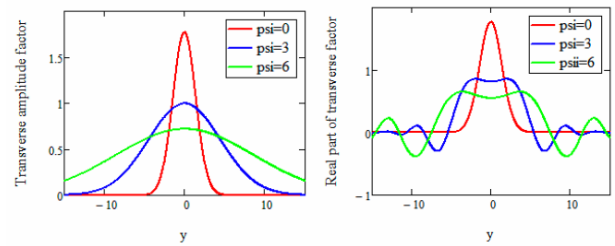
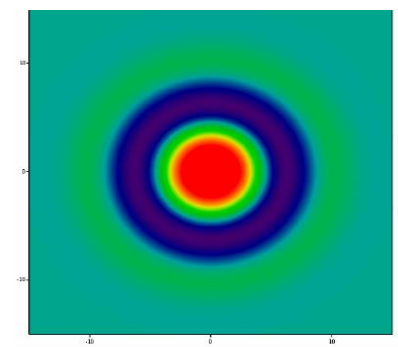


Figure 3. Transverse profile for an initial Gaussian perturbation as calculated from equation (30). The left plot shows the amplitude and the right plot shows the real part.



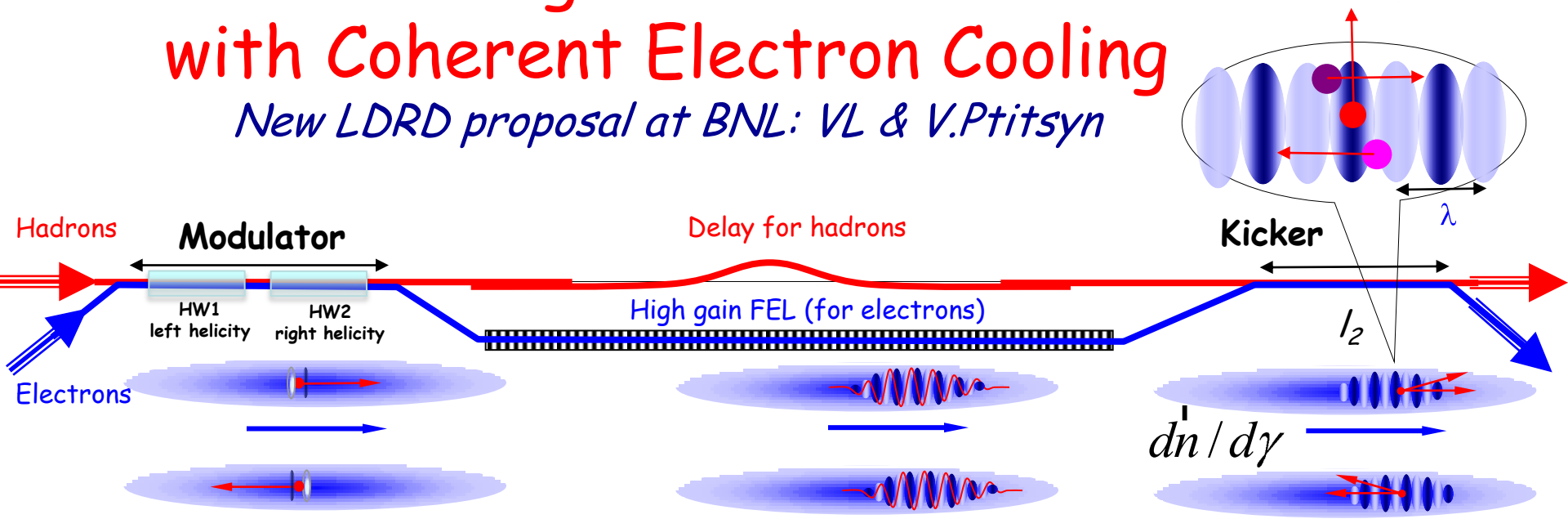
(c)

Figure 2. Amplitude and phase of the growth mode radial distribution factor in eq. (28) for (a) $\hat{C}_0=0$, $\hat{q}=0$, $\hat{\Lambda}_p=0$ and $\hat{z}=6$; (b) $\hat{z}=15$ [1]; (c) plots the real part of the radial distribution for $\hat{z}=15$.

©V.Litvinenko, G.Wang, S.Webb – will be presented in details at FEL'2010

Polarizing Hadron Beams with Coherent Electron Cooling

New LDRD proposal at BNL: VL & V.Ptitsyn



Modulation of the electron beam density around a hadron is CUAsed by value of spin component along the longitudinal axis, z. Hardons with spin projection onto z-axis will attract electrons while traveling through helical wiggler with left helicity and repel them in the helical wiggler with right helicity.

The high gain FEL amplify the imprinted modulation.

Hadrons with z-component of spin will have an energy kick proportional to the value and the sigh if the projection. Placing the kicker in spin dispersion will result in reduction of z-component of the spin and in the increase of the vertical one.

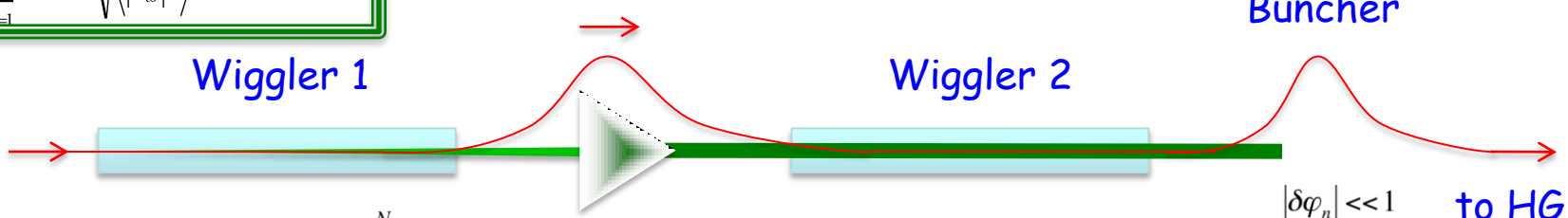
This process will polarize the hadron beam

Shot-Noise Suppressor (in time)

$$\varphi = k_l \cdot c\tau$$

$$h_\omega^o = \sum_{n=1}^{N} e^{i\varphi_n}; \quad \sqrt{\left\langle \left| h_\omega^o \right|^2 \right\rangle} = \sqrt{N}$$

$$\delta\varphi_n = g_o \cdot \mathrm{Im} \sum_{m=1}^{N} e^{i(\varphi_n - \varphi_m)}; \quad g_o = \frac{kD \cdot ea_o L_w \cdot K_w}{2\gamma^2 mc^2}$$



$$|\delta\varphi_n| << 1$$

to HG FEL

$$E = \mathrm{Re}\left(ae^{i\omega t}\right), \quad a = a_o \sum_{n=1}^{N} e^{i\varphi_n}$$

$$\delta E_n = -ea_o L_w \cdot \frac{K_w}{2\gamma} \cdot \mathrm{Im} \sum_{m=1}^{N} e^{i(\varphi_n - \varphi_m)}$$

$$h_\omega = \sum_{n=1}^{N} e^{i(\varphi_n + \delta\varphi_n)} \cong \sum_{n=1}^{N} e^{i\varphi_n}\left(1 + i\delta\varphi_n\right)$$

$$h_\omega = \sum_{n=1}^{N} e^{i\varphi_n} + \frac{g_o}{2} \sum_{n=1}^{N}\sum_{m=1}^{N} e^{i(2\varphi_n - \varphi_m)} - \frac{g_o}{2} \sum_{n=1}^{N}\sum_{m=1}^{N} e^{i\varphi_m} =$$

$$\left(1 - \frac{g_o N}{2}\right) \cdot h_\omega^o + \frac{g_o}{2} \sum_{n=1}^{N}\sum_{m=1}^{N} e^{i(2\varphi_n - \varphi_m)}.$$

$$g_o = 2/N$$

$$h_\omega = \frac{1}{N} \sum_{n=1}^{N}\sum_{m=1}^{N} e^{i(2\varphi_n - \varphi_m)}. \qquad \sqrt{\left\langle \left| h_\omega \right|^2 \right\rangle} = 1$$

Such system will reduce the amplitude of shot-noise by the factor $N^{1/2}$, and the power of short-noise (spontaneous radiation, SASE) by a factor of N.

Proposal to NP DoE, 5 years, $5.9M

PROPOSAL COVER PAGE

Title of Proposal: Coherent Electron Cooling Demonstration Experiment at RHIC

SC Program Announcement Title: Research and Development for Next Generation Nuclear Physics Accelerator Facilities (Program Announcement #10-339)
DOE National Laboratory: Brookhaven National Laboratory
Principal Investigator (PI): Dr. Vladimir Litvinenko
Position Title of Principal Investigator: Senior Physicist
Mailing Address of PI: Brookhaven National Laboratory, P.O. Box 5000, Bldg. 911B, Upton, NY 11973
Telephone Number of PI: (631) 344 2570 / **Fax Number of PI:** (631) 344 5954
Email of PI: vl@bnl.gov

Name of Official 1 Signing for Laboratory: Thomas Roser
Title of Official 1: Collider-Accelerator Department Chair
Telephone of Official 1: (631) 344 7084 / **Fax Number of Official 1:** (631) 344 5954
Email of Official 1: roser@bnl.gov

Name of Official 2Signing for Laboratory: Steve Vigdor
Title of Official 2: Associate Laboratory Director for Nuclear and Particle Physics
Telephone of Official 2: (631) 344 5397 / **Fax Number of Official 2:** (631) 344 5820
Email of Official 2: vigdor@bnl.gov

Requested Funding for Each Year: $1,488K (FY11); $1,446K (FY12); $1,491K (FY13); $1,056K (FY14); $407K (FY15); $5,888K Total Request
Use of Human Subjects in Proposed Project: No
Use of Vertebrate Animals in Proposed Project: No

DOE/Office of Science Program Office: Office of Nuclear Physics
DOE/Office of Science Program Office Technical Contact: Dr. Manouchehr Farkhondeh

Collaborating Institutions:

Institution:	**Thomas Jefferson National Accelerator Facility**
Street Address/City/State/Zip:	12000 Jefferson Ave., Newport News, VA 23606
Co-Principal Investigator:	**Matthew Poelker**
Telephone Number:	757-269-7357
e-mail:	poelker@jlab.org

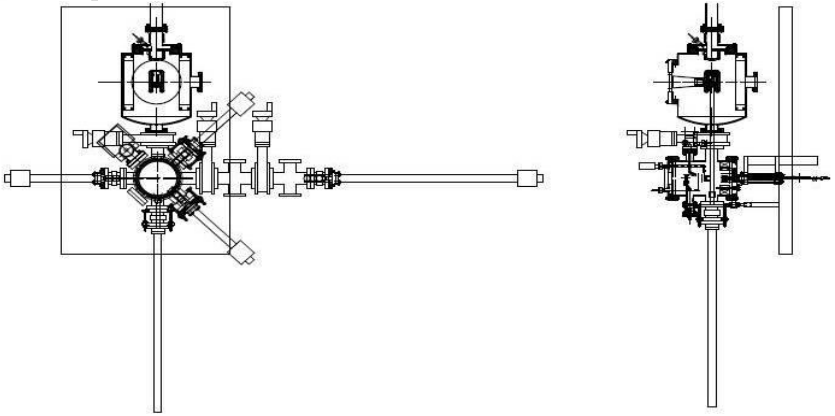
Institution:	**Tech-X Corporation,**
Street Address/City/State/Zip:	5621 Arapahoe Ave, Suite A, Boulder CO 80303
Co-Principal Investigator:	**David Bruhwiler**
Telephone Number:	303-448-0732
e-mail:	bruhwile@txcorp.com

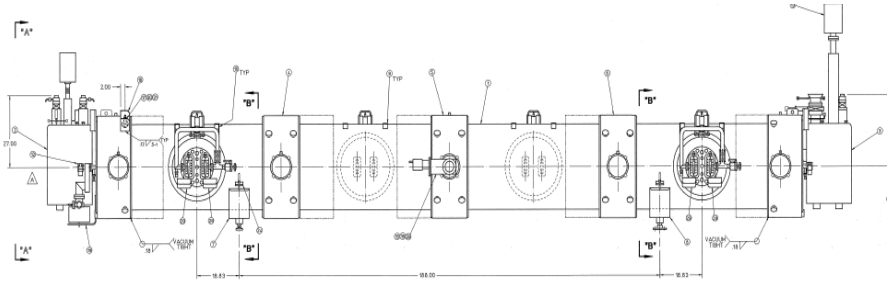
Collaborators budget is included in this proposal. There will be no separate applications from the collaborators.

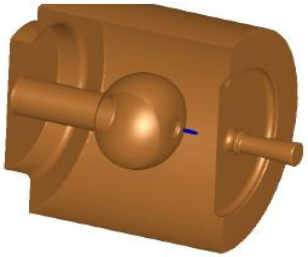
Signature of PI: V. Litvinenko **Date:** 6/7/10
Vladimir Litvinenko

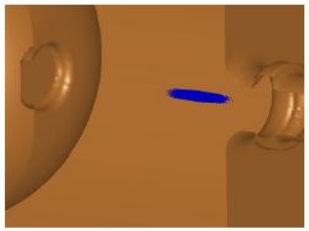
Signature of Official 1: Thomas Roser **Date:** 6/7/10
Thomas Roser

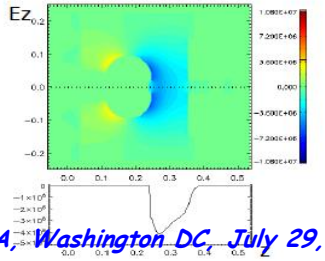
Signature of Official 2: Steven E. Vigdor **Date:** 6/7/10
Steve Vigdor

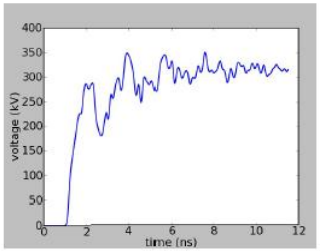




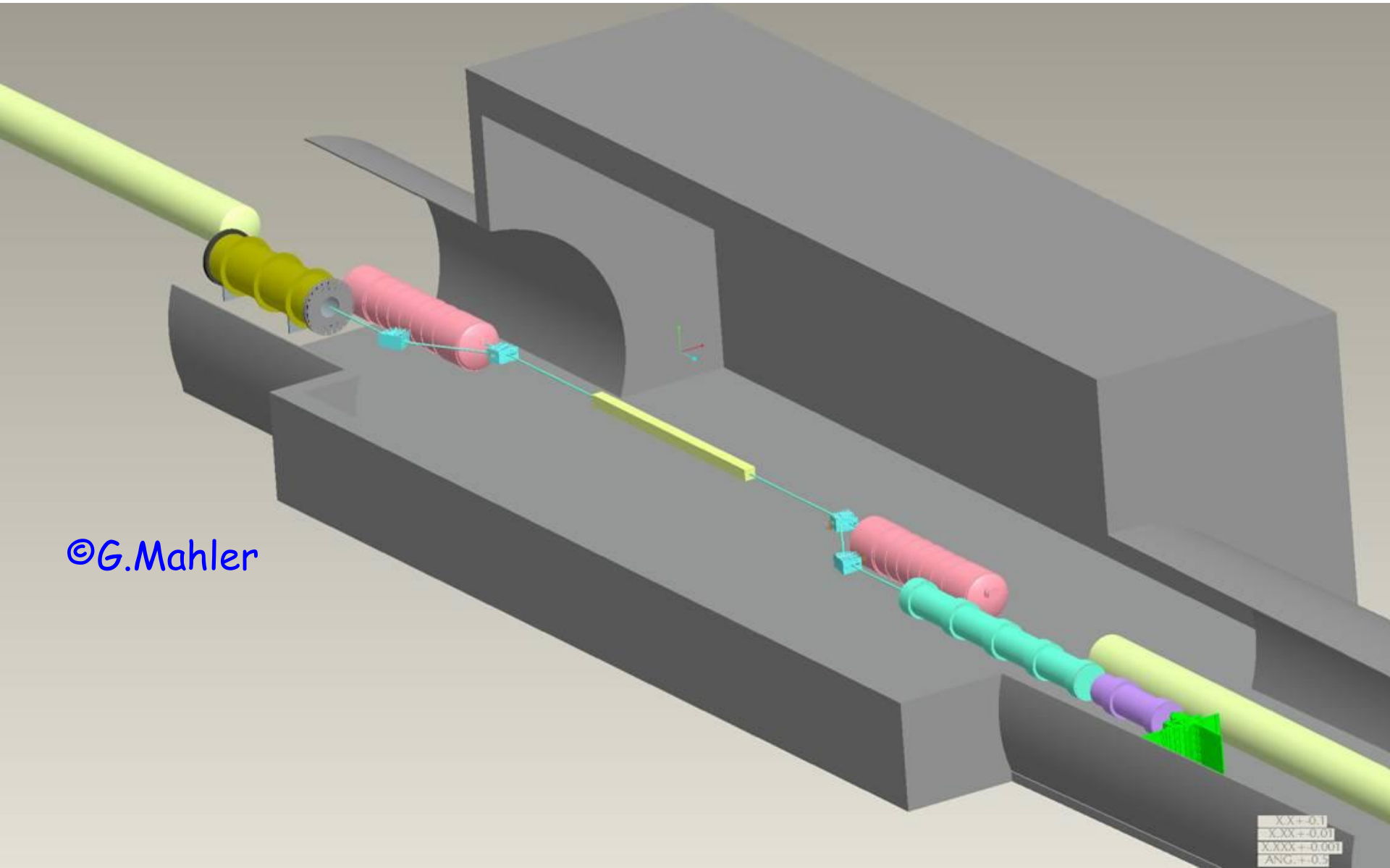








Layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR 2
Collaboration between BNL & JLab



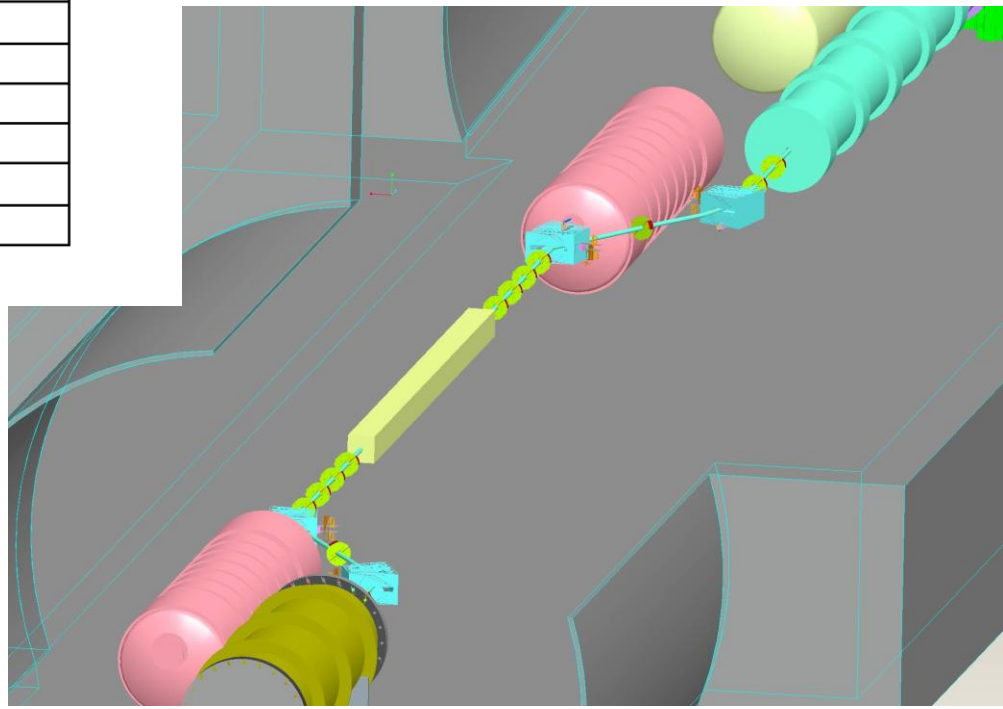
Beam Parameters in CeC

FEL gain set at a realistic value of about 100, local cooling time is estimated at 10.3 seconds, and 20 minutes for cooling entire bunch.

Parameter	**Units**	
Species in RHIC		**Au ions**
Ion's energy	GeV/u	**40**
Electron beam energy	MeV	**21.8**
Rep-rate	kHz	**78.3**
e-beam power	kW	**1.7**
Length of the CeC straight section	m	**14**
Length of the modulator straight section	m	**3**
Length of the kicker straight section	m	**3**
Length of FEL wiggler	m	**7**
Type of wiggler		**Helical**
Wiggler period	cm	**4**
Wiggler parameter, a_w		**0.437**
FEL wavelength	μm	**10**

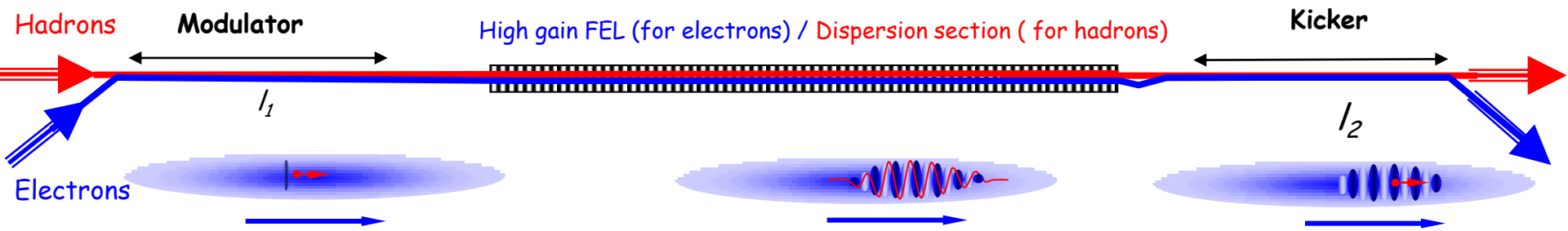
Optics (preliminary)

Parameter	Units	
Ion's energy	GeV/u	**40**
RMS normalized 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, relative		**$3.5x10^{-4}$**
β*	m	**5.5**
s*	m	**0**



Parameter	Units	
Electron beam energy	MeV	**21.8**
Charge per bunch	nC	**0.5-1**
Normalized emittance	mm mrad	**5**
Peak current in FEL	A	**60-100**
RMS energy spread, relative		**$1x10^{-3}$**
Electrons per bunch		**3.1-6.2 $x10^9$**

CeC: Economic option



Electrons

Modulator:region 1
a quarter to a half of plasma oscillation

Amplifier of the e-beam modulation via High Gain FEL and
Longitudinal dispersion for hadrons

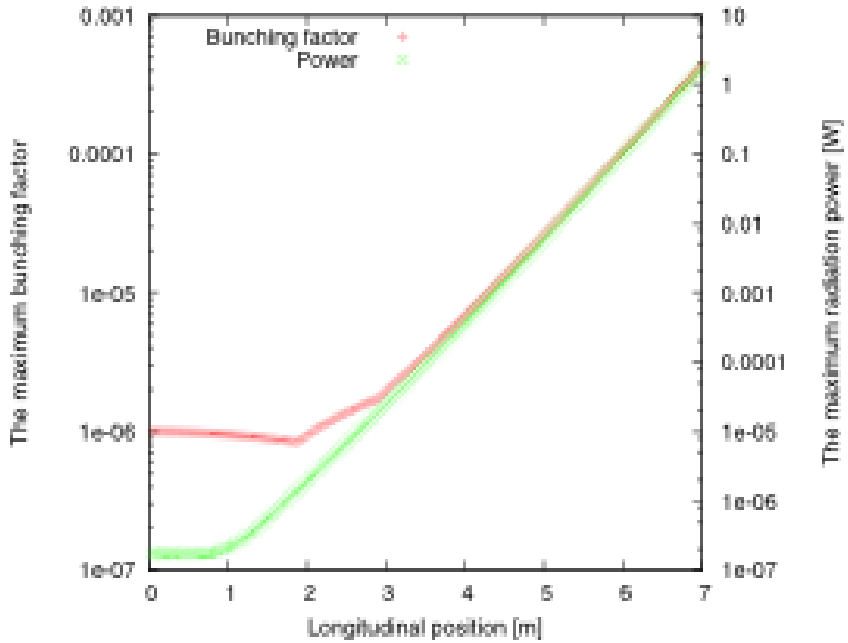
Kicker: region 2

Electron density modulation is amplified in the FEL and made into a train with duration of $N_c \sim L_{gain}/\lambda_w$ alternating hills (high density) and valleys (low density) with period of FEL wavelength λ. Maximum gain for the electron density of HG FEL is ~ 10^3.

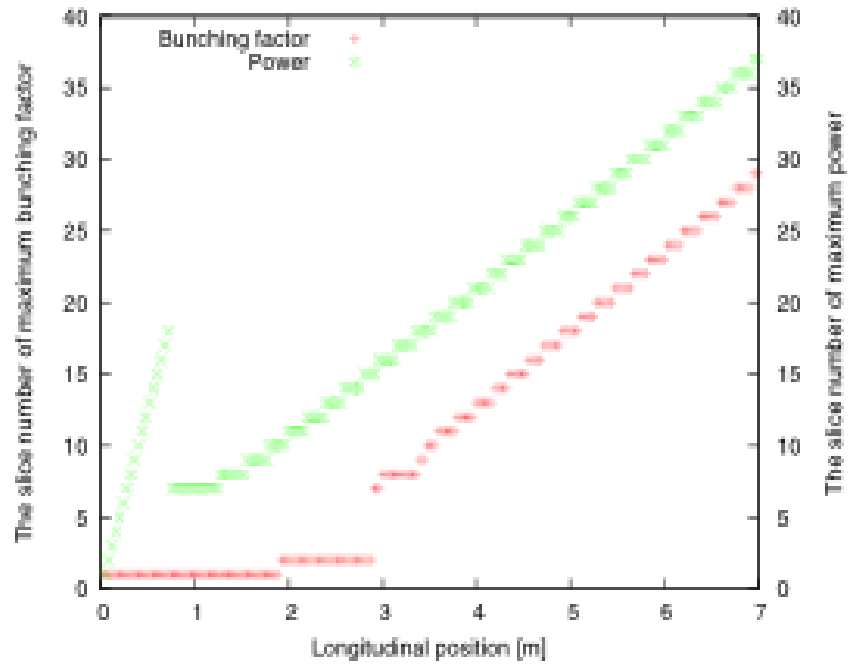
$$v_{group} = (c + 2v_{//})/3 = c\left(1 - \frac{1 + a_w^2}{3\gamma^2}\right) = c\left(1 - \frac{1}{2\gamma^2}\right) + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right) = v_{hadrons} + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right)$$

Economic option requires: $2a_w^2 < 1$!!!

Genesis 3D FEL for CeC PoP



Evolution of the maximum bunching in the e-beam and the FEL power simulated by Genesis.

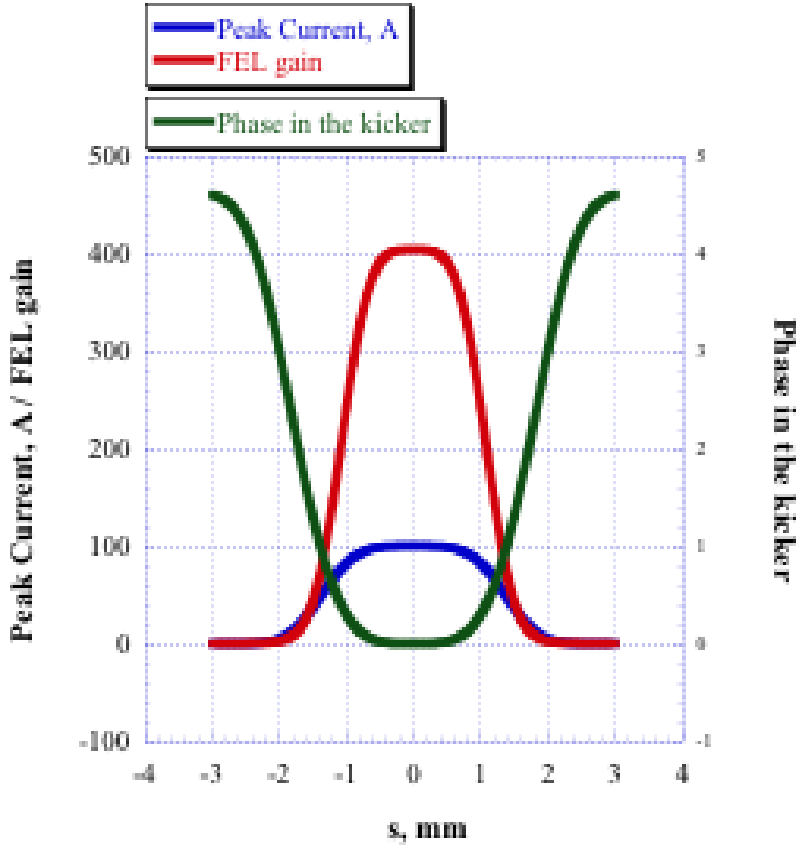


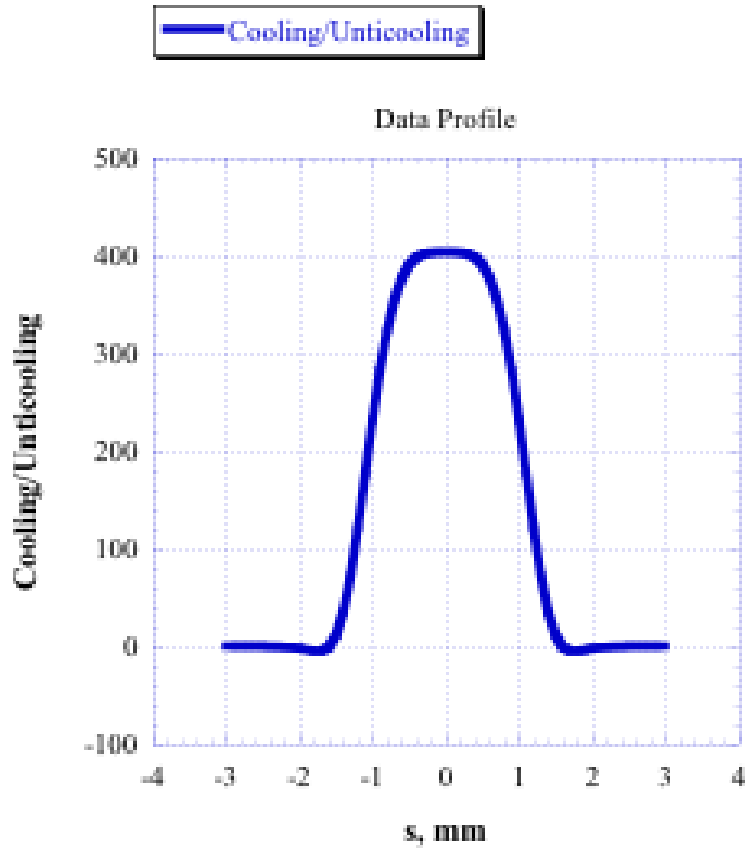
Evolution of the maxima locations in the e-beam bunching and the FEL power simulated by Genesis.

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

©Y.Hao, V. Litvinenko

Profile effect





- The phase velocity in the FEL depends on the peak current through its gain length
- Expected beam-current profile for the beer-can bunch, and corresponding FEL gain (in amplitude) and phase in the kicker. Right graph: The strength of cooling/anti-cooling along the e-bunch.

Conclusions

- Coherent electron cooling has potential of cooling high intensity TeV scale proton and ion beams with reasonable (under an hour) cooling time
- Electron accelerator of choice for such cooler is energy recovery linac (ERL)
- ERL seems to be capable of providing required beam quality for such coolers
- Majority of the technical limitation and requirements on the beam and magnets stability are well within limit of current technology, even though satisfying all of them in nontrivial fit
- We plan a proof of principle experiment of coherent electron cooling with Au ions in RHIC at ~ 40 GeV/n