Proof-of-principle Experiment for FEL-based Coherent Electron Cooling

Vladimir N. Litvinenko for CeC collaboration

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

Collaboration of BNL, Jlab, Tech-X, BNL, Daresbury Lab

Sergei Belomestnykh, Ilan Ben-Zvi, Jean Clifford Brutus, Alexei Fedotov, Yue Hao, Dmitry Kayran, Vladimir N. Litvinenko, George Mahler, Aljosa Marusic, Wuzheng Meng, Gary McIntyre, Michiko Minty, Vadim Ptitsyn, Igor Pinayev, Triveni Rao, Thomas Roser, Brian Sheehy, Steven Tepikian, Yatming Than, Dejan Trbojevic, Joseph Tuozzolo, Gang Wang, Vitaly Yakimenko, *Brookhaven National Laboratory, Upton, NY 11973, USA*

Matt Poelker, Andrew Hutton, Geoffrey Kraft, Robert Rimmer, *TJNAF, Newport News, VA, USA*

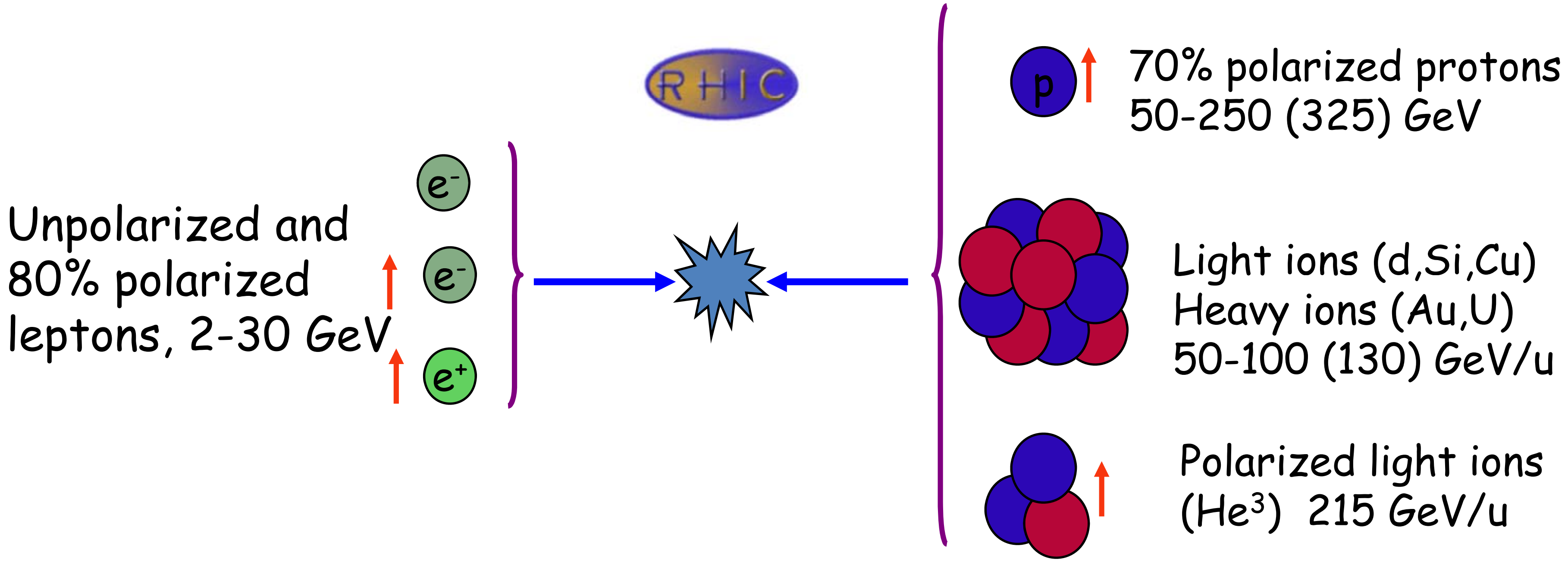
David L. Bruhwiler, Dan T. Abell, Chet Nieter, Vahid Ranjbar, Brian T. Schwartz
Tech-X Corp., Boulder, CO 80303, USA

Pavel Vobly, Mikhail Kholopov, Oleg Shevchenko
Budker Institute of Nuclear Physics, Novosibirsk, 6300090, Russia

Peter Mcintosh Alan Wheelhouse
STFC, Daresbury Lab, Daresbury, Warrington, Cheshire, UK, WA4 4AD

eRHIC: QCD Facility at BNL

Add electron accelerator to the existing $2B RHIC



Unpolarized and
80% polarized
leptons, 2-30 GeV

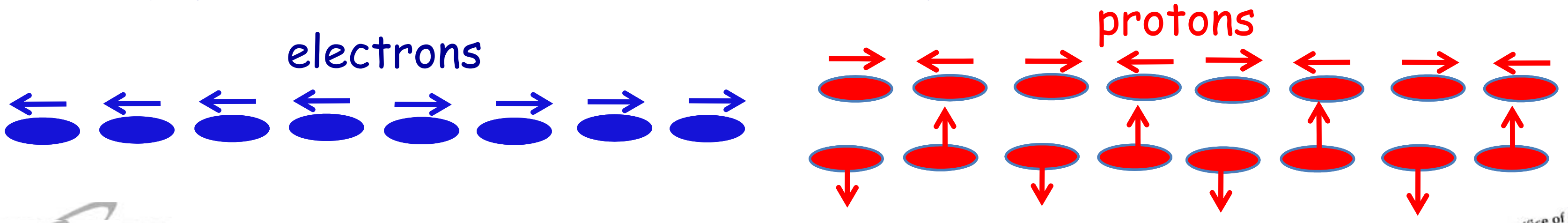
70% polarized protons
50-250 (325) GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 (130) GeV/u

Polarized light ions
(He^3) 215 GeV/u

Center of mass energy range: 20-200 GeV

Any polarization direction in lepton-hadrons collisions



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Exploring Nuclear Matter - Quarks to Stars

Why coherent electron cooling at RHIC?

- Traditional stochastic cooling does not have enough bandwidth to cool modern-day proton beams (~ 3 10^{11} / nsec)
- And can not provide two orders of density increase for heavy ion beams
- Efficiency of traditional electron cooling falls as a high power of hadron's energy
- Synchrotron radiation is too fable - no need to mention
- 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
    - Tunability 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 polarized pp ~ 6 fold, eRHIC ~ 50 fold, LHC ~ 2 fold

Coherent Electron Cooling (CeC)

At a half of plasma oscillation

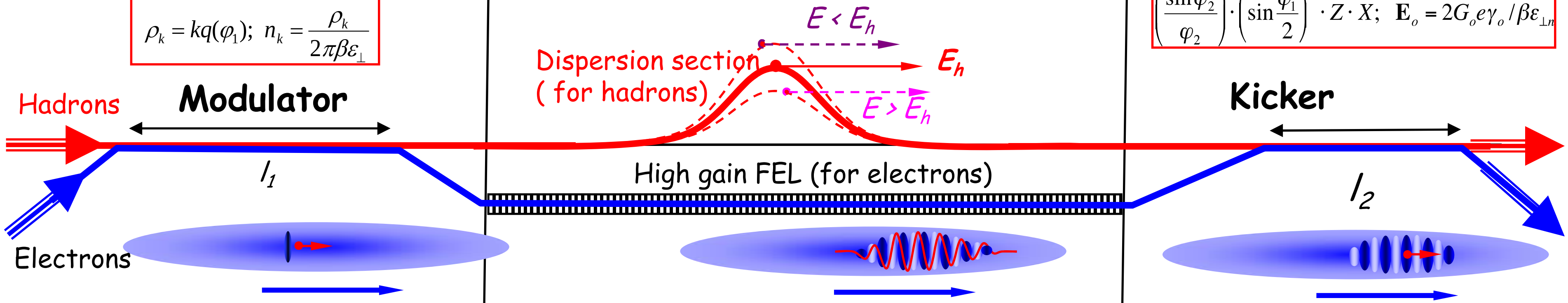
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

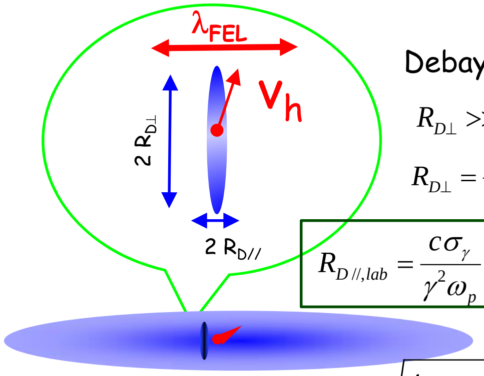
$$\rho_k = kq(\varphi_1);\ \ n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

Dispersion

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

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





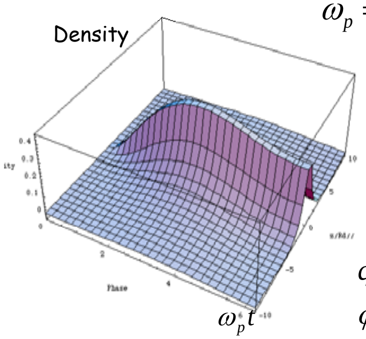
Debay radii

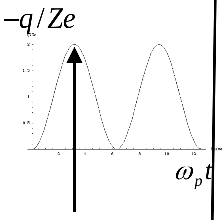
$$R_{D\perp} >> R_{D//}$$

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

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

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





$$q = -Ze\cdot(1-\cos\varphi_1)$$
$$\varphi_1 = \omega_p l_1/c\gamma$$
$$q_{peak} = -2Ze$$

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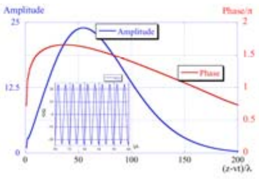
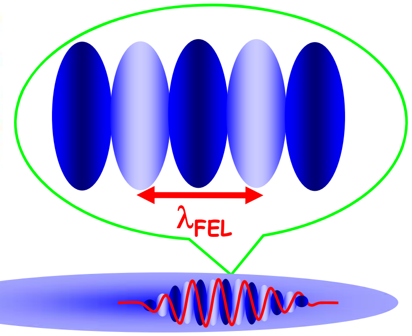
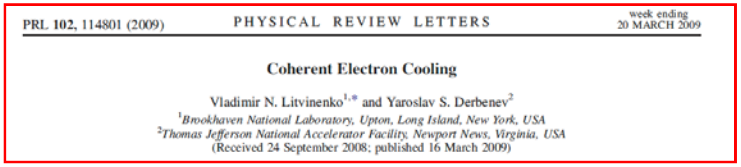
Amplifier of the e-beam modulation in an FEL with gain G_{FEL}~10^2-10^3





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

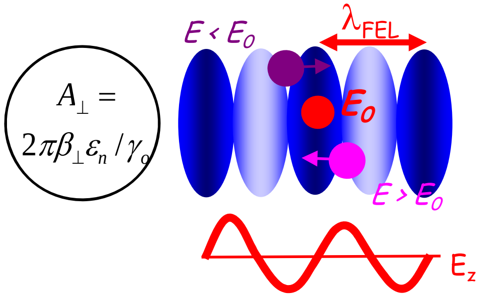
$$L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$


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

Coherent Electron Cooling

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

[1]*Brookhaven National Laboratory, Upton, Long Island, New York, USA*
[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA*
(Received 24 September 2008; published 16 March 2009)



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

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

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

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

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

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

Analytical Studies and Simulations

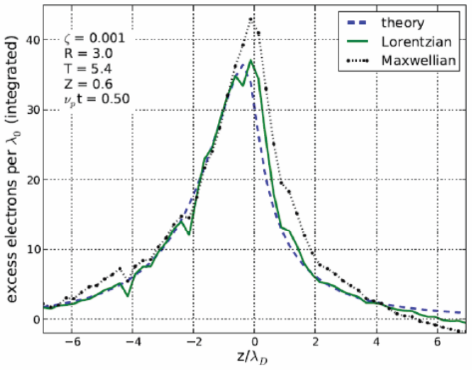
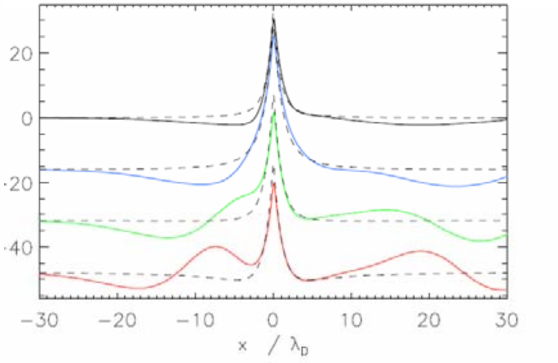
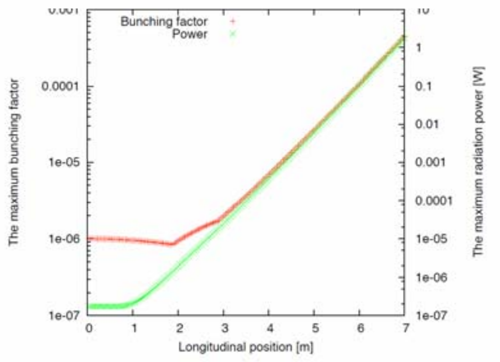


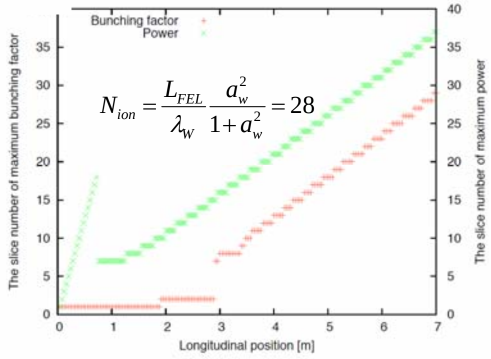
Figure 3: Longitudinal charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

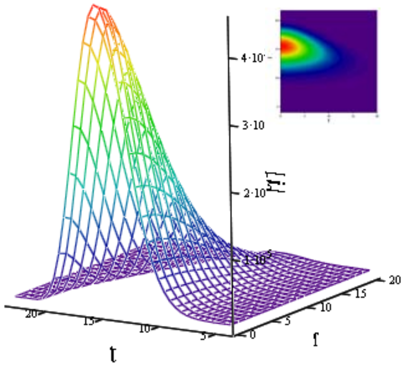


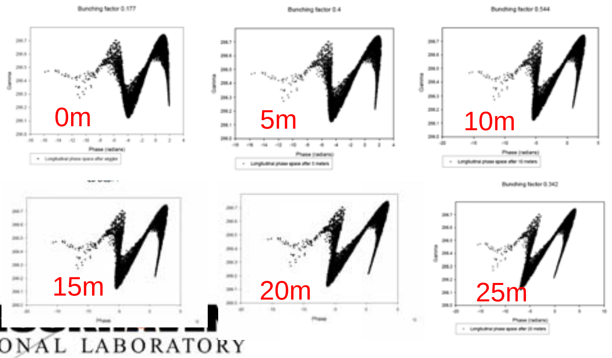
- Modulator: VORPAL simulation has been validated by analytical model and progresses have been made recently towards simulations with more realistic beam profile.

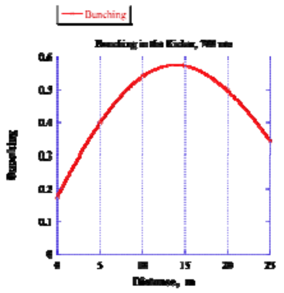
- FEL amplifier: we use Genesis to simulate the evolution of electron density modulation. Efforts have been made to correctly taken into account shot noises. We are also developing analytical tool to better understand underlying physics and scaling law.

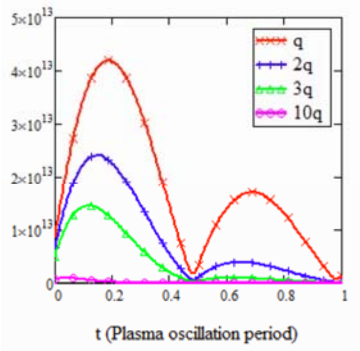








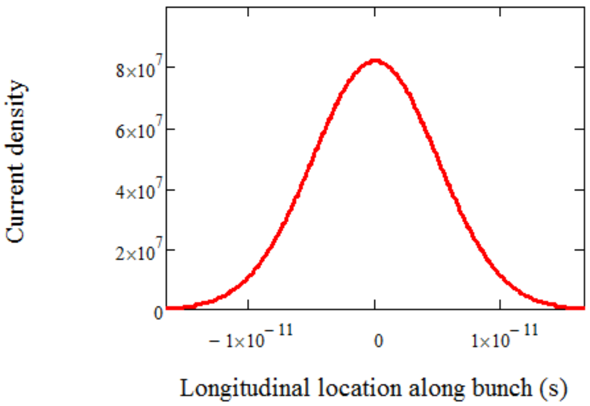




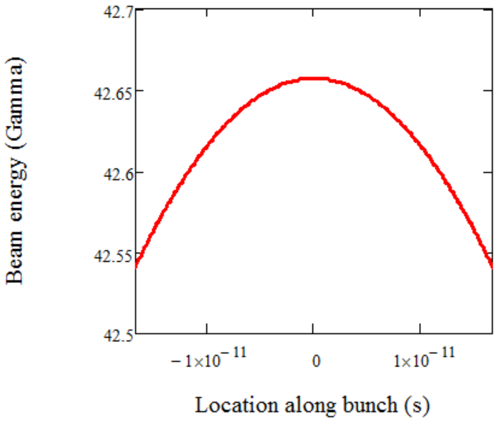
- Kicker: analytical model has been developed. Preliminary simulation qualitatively agrees with analytical model. VORPAL simulation is under way with space charge effect and Landau damping taken into account.

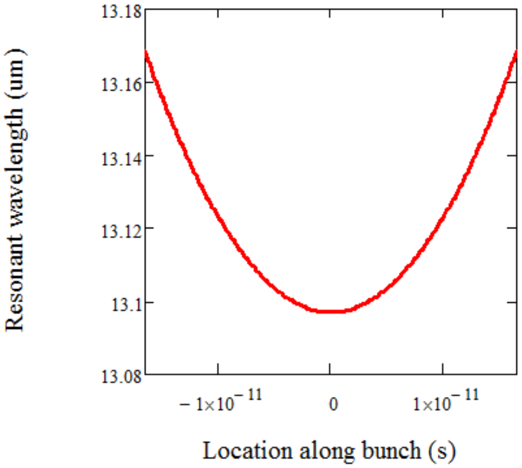
Beam conditioning for realistic beams – recent discovery

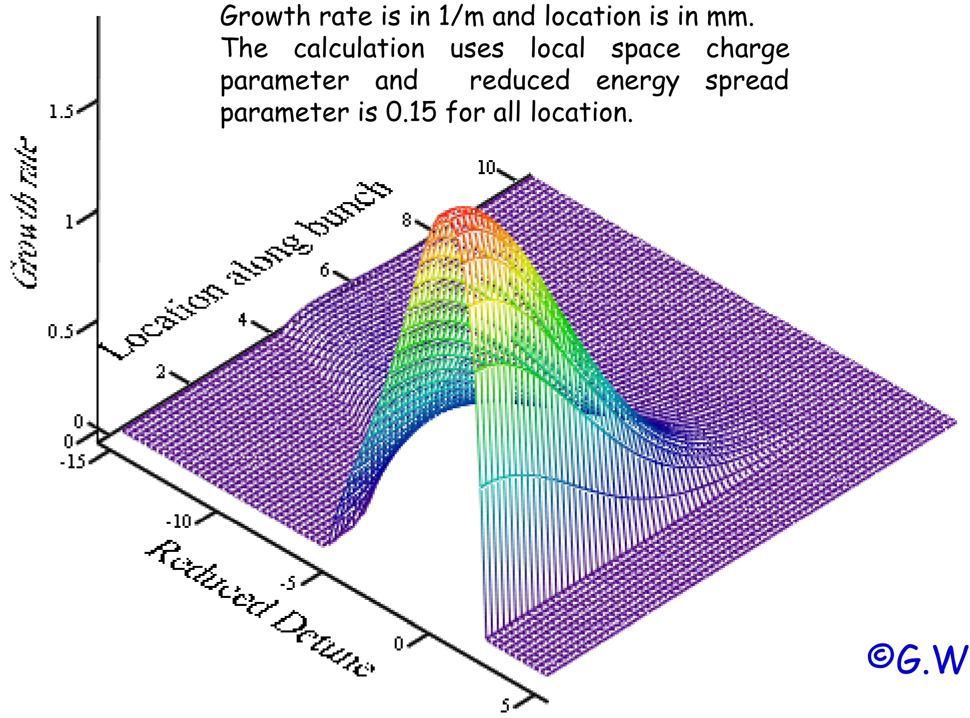
Electron beam density in A/m^2



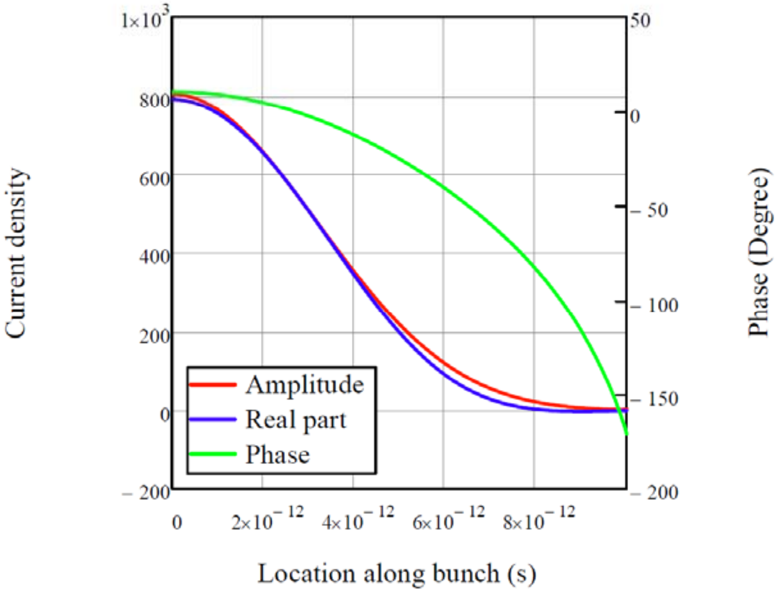
Unperturbed electron energy







Growth rate is in 1/m and location is in mm. The calculation uses local space charge parameter and reduced energy spread parameter is 0.15 for all location.



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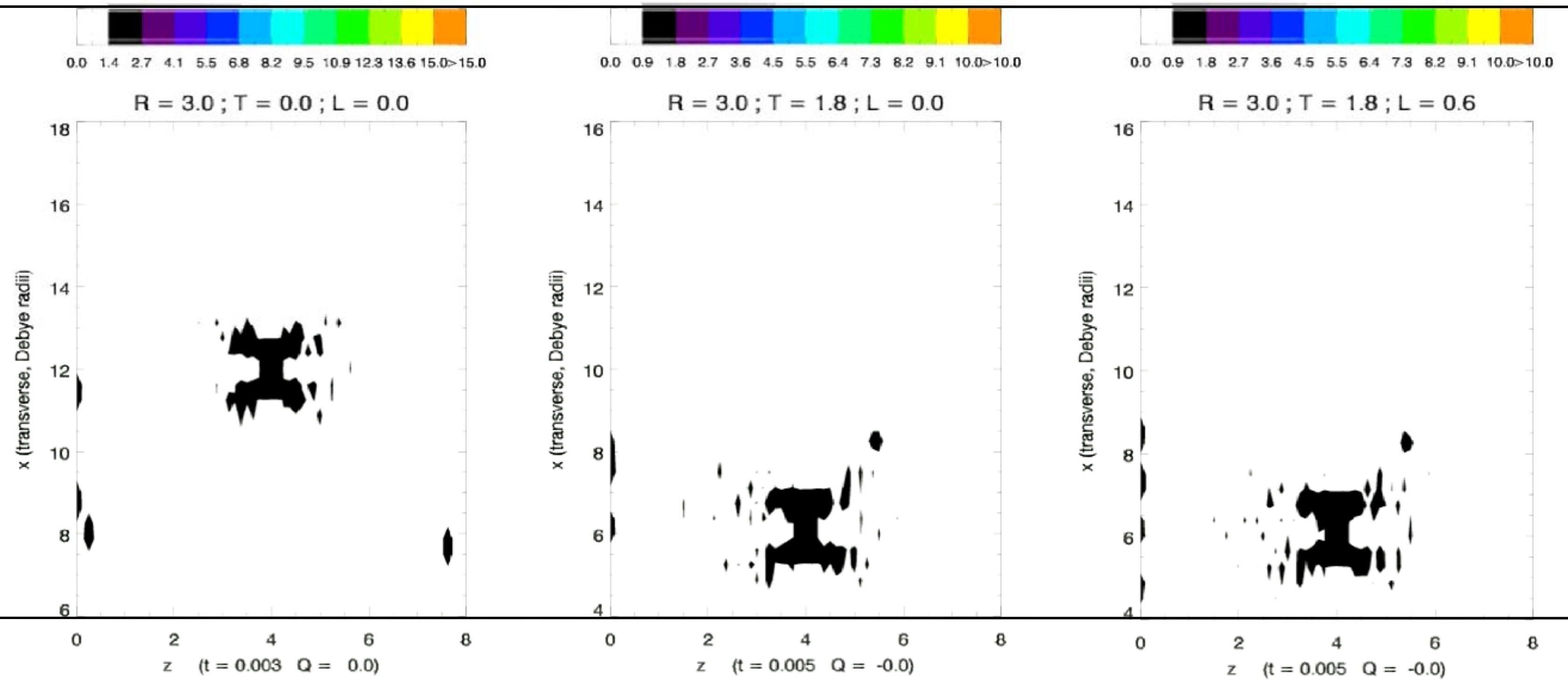
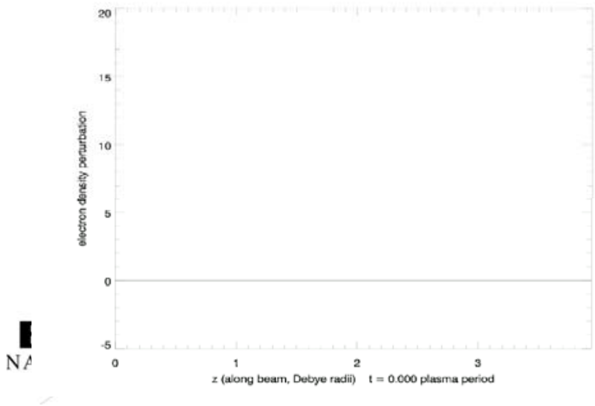
Numerical simulations (VORPAL @ TechX)
Provides for simulation with arbitrary distributions and finite electron beam size

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





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

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

Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

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

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

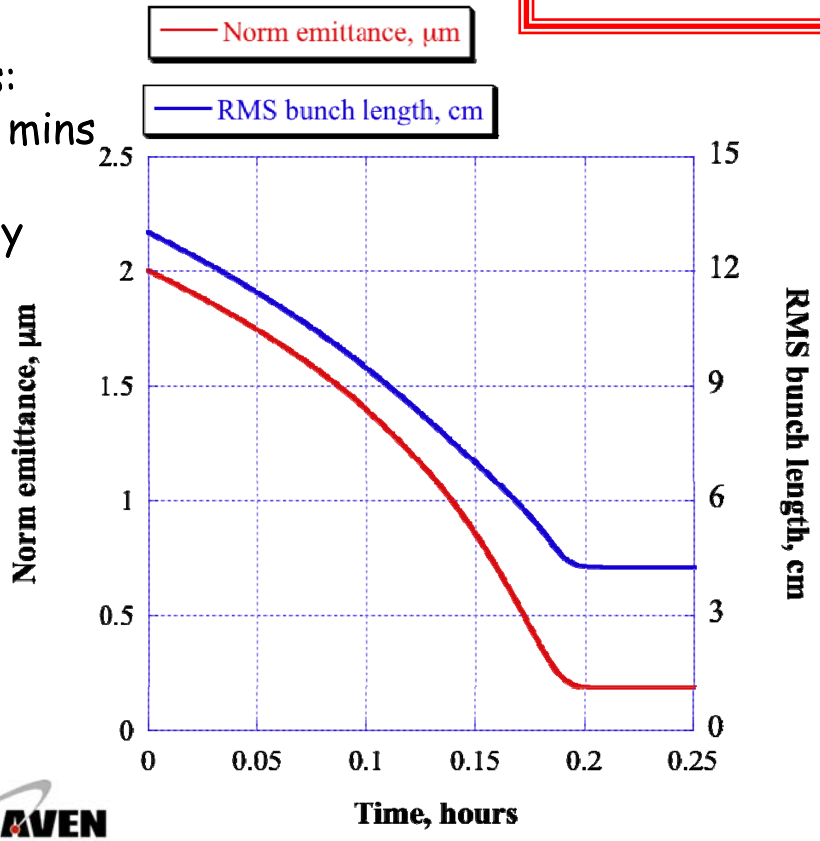
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}}\frac{1}{X^{3/2}Y} - \frac{1-2\xi_\perp}{\tau_{CeC}}\frac{1}{X};$$

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

$$\varepsilon_{xn0} = 2\,\mu m;\ \sigma_{s0} = 13\ cm;\ \sigma_{\delta 0} = 4\cdot 10^{-4}$$
$$\tau_{IBS\perp} = 4.6\ \ hrs;\ \tau_{IBS//} = 1.6\ \ hrs$$

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



$$\varepsilon_{x\,n} = 0.2\,\mu m;\ \sigma_s = 4.9\ \ \text{cm}$$

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

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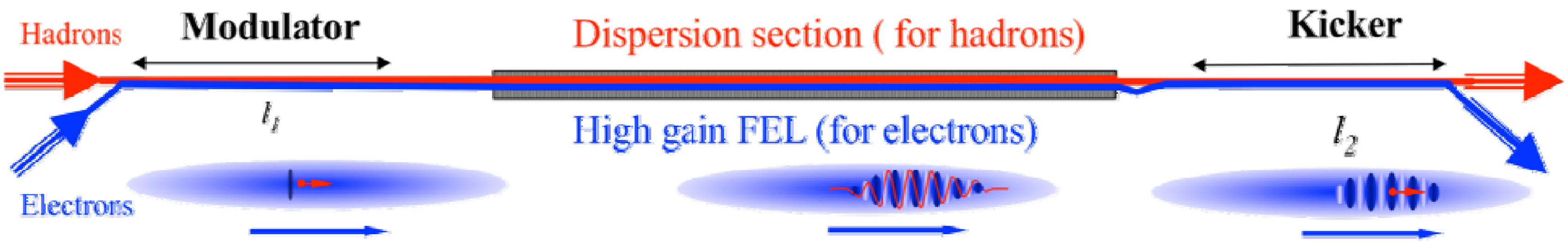
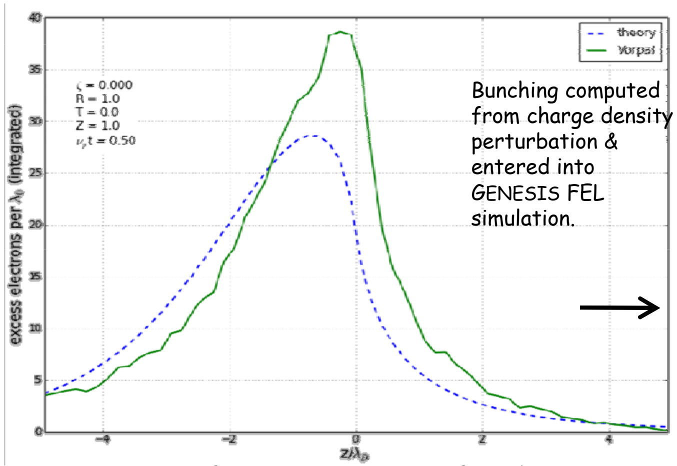
VORPAL & GENESIS simulate performance of the novel Coherent *e-* Cooling concept to increase luminosity of future hadron colliders

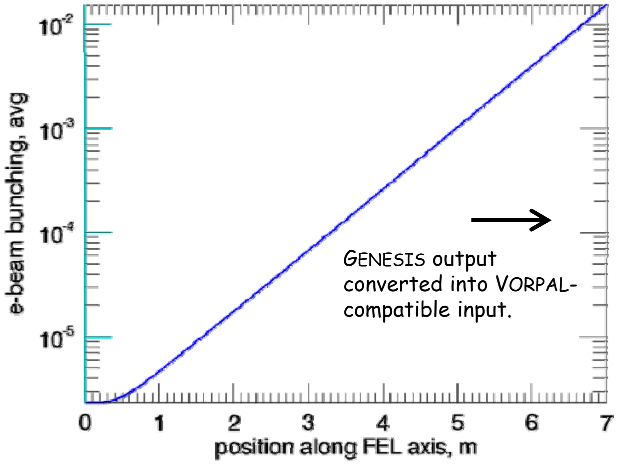


Param.'s from 40 GeV proof-of-principle exp. at BNL



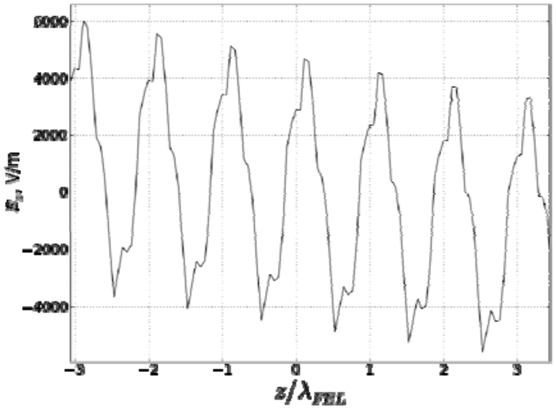
Bunching computed from charge density perturbation & entered into GENESIS FEL simulation.

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 output converted into VORPAL-compatible input.

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



VORPAL prediction of the coherent kicker electric fields E^c due to e- density perturb. from modulator, amplified in the FEL.

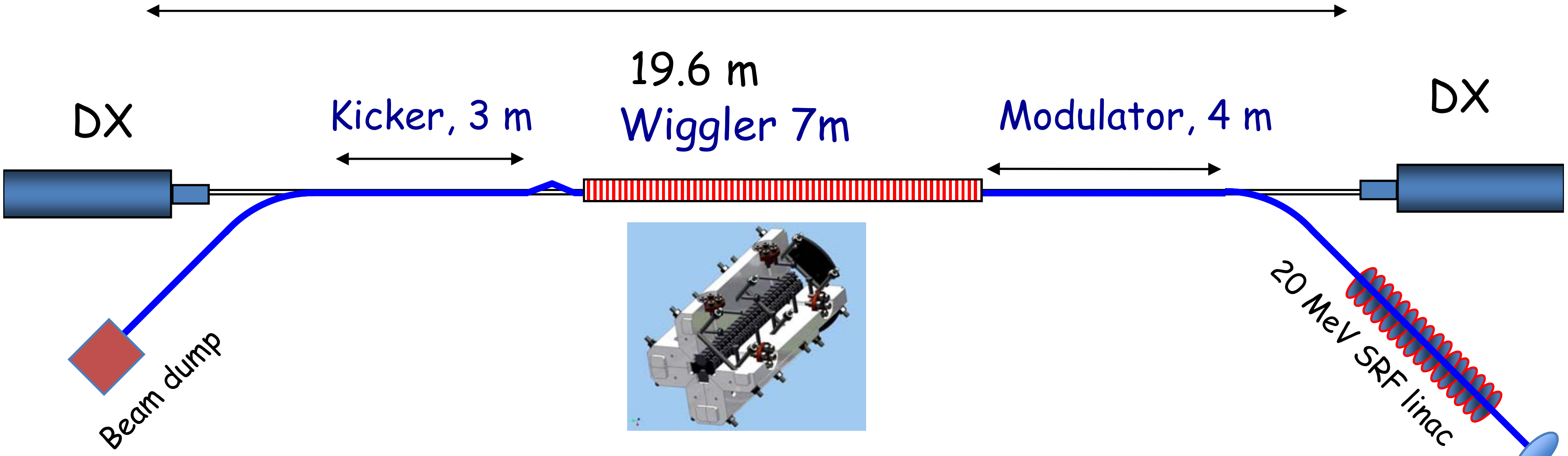
The cooling time for a CeC system in a hadron collider depends on many factors [1,2], like coherent energy correction per pass, shot noise effects, etc. which are computed using the parallel VORPAL framework and the FEL code Genesis.

[1] Litvinenko & Derbenev, "Coherent Electron Cooling," PRL (2009).

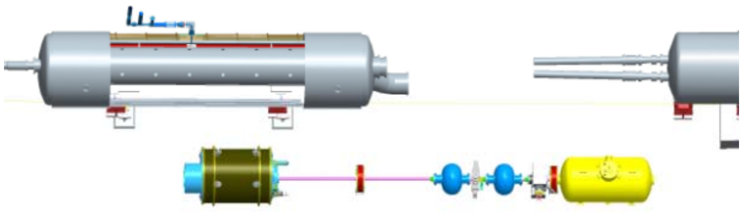
[2] Mohl, "The status of stochastic cooling," Nucl. Instr. Meth. A (1997).

Coherent Electron Cooling demonstration experiment at RHIC IR2

Goal – cool a single 40 GeV/u Au ion bunch in RHIC

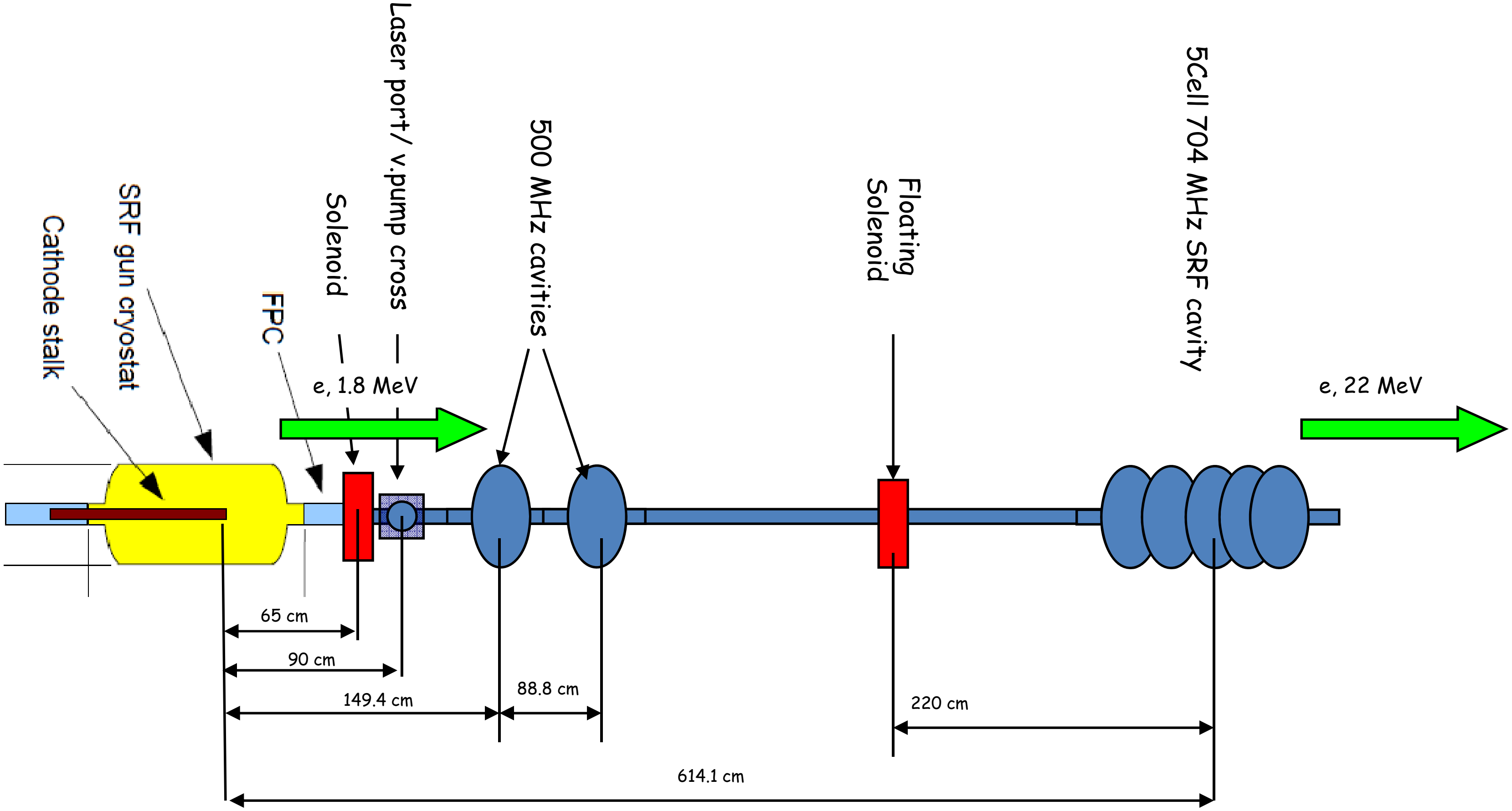


Parameter	
Species in RHIC	Au ions, 40 GeV/u
Electron energy	21.8 MeV
Charge per bunch	1 nC
Train	1 bunches
Rep-rate	78.3 kHz
e-beam current	0.078 mA
e-beam power	1.7 kW



Supported by DoE NP office, started designs and prototyping, experiments planed for 2014-15

Coherent electron cooling experiment: accelerator layout



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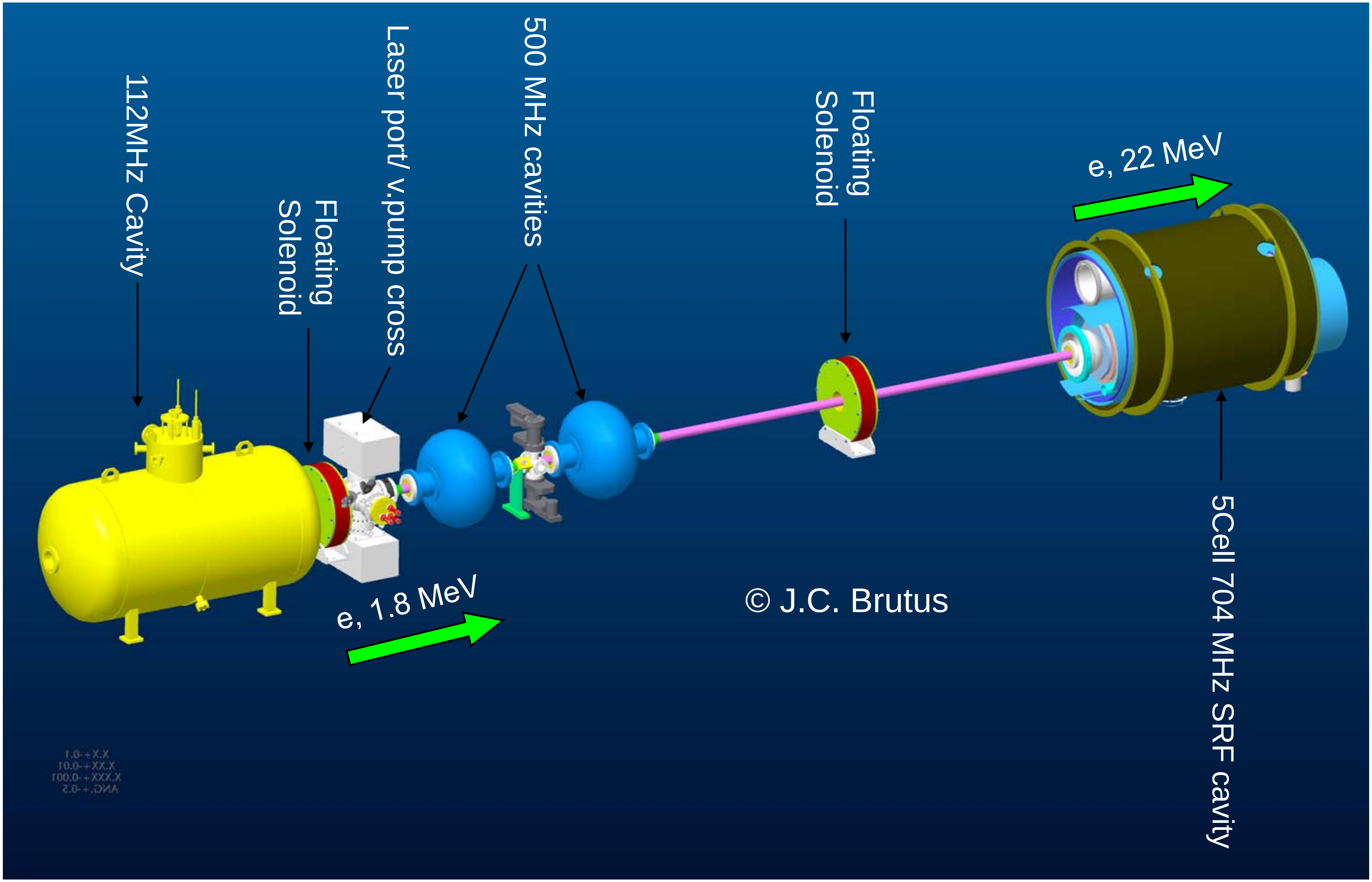
Coherent electron cooling experiment: accelerator 3-D layout



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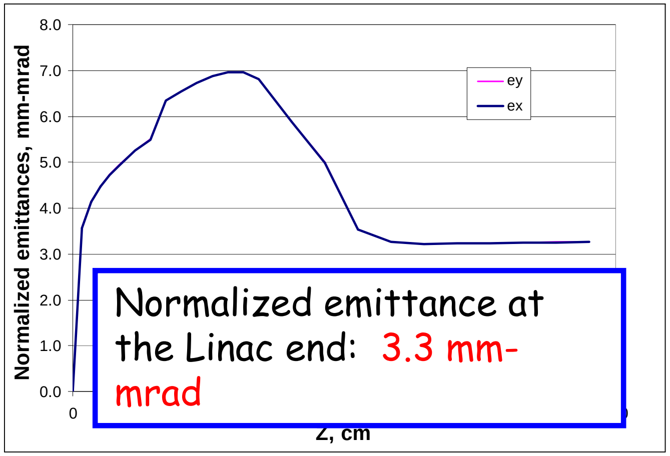
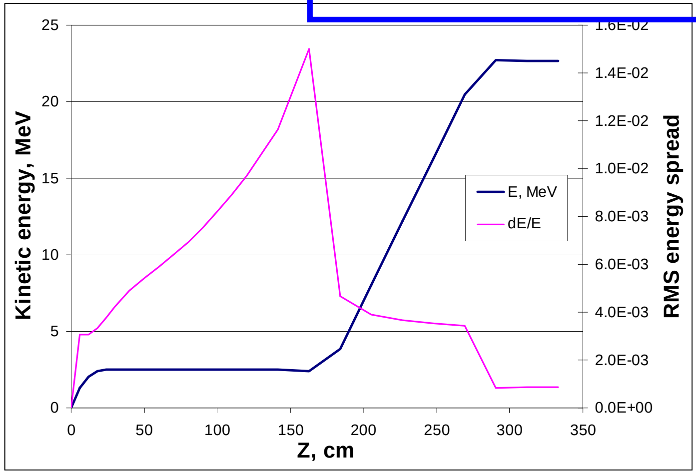
Preliminary simulations



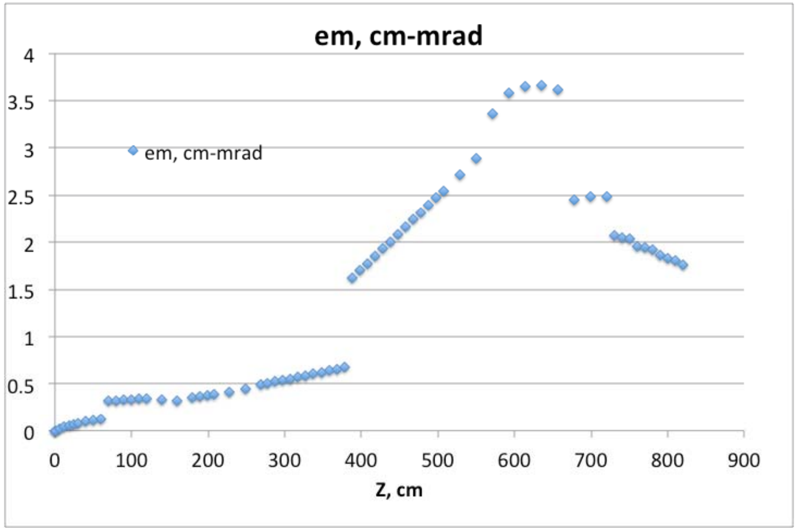
Normalized emittance at the Linac end: 3.3 mm-mrad

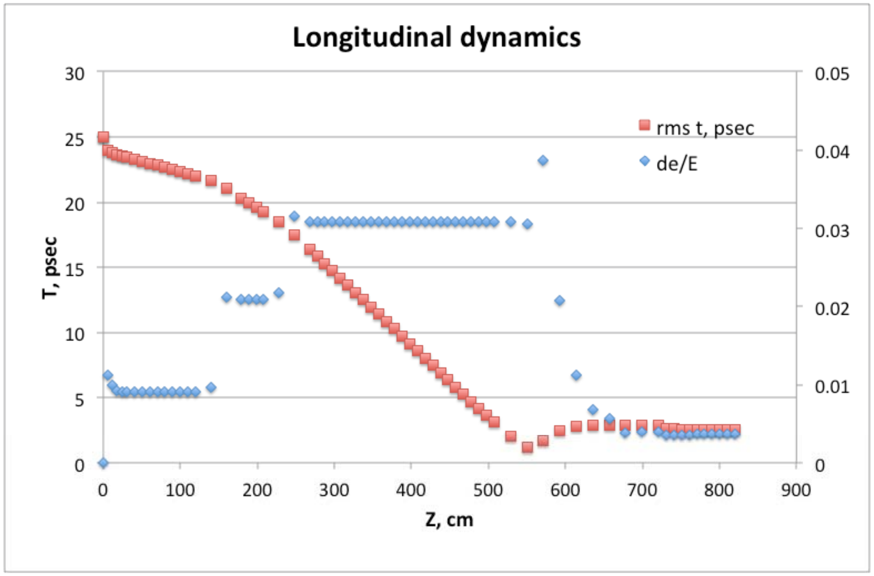
Without Buncher cavities



RMS energy spread at the Linac end: 9×10^{-4}

With Buncher cavities

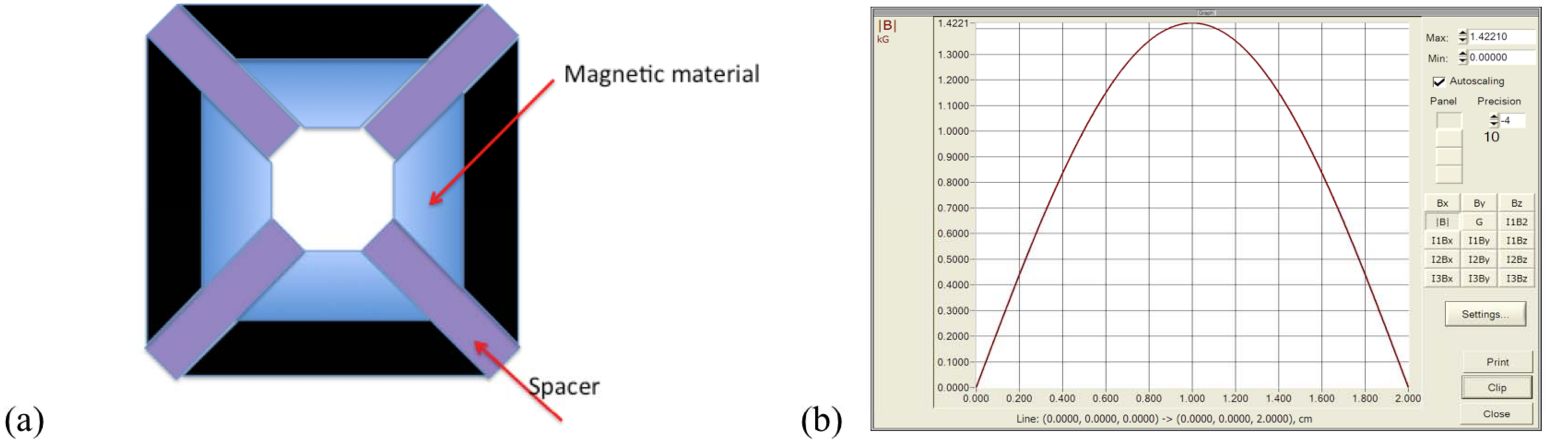




Helical Wiggler: prototyping at BINP

Table 1. Main parameters for the CeC demonstration experiment

Parameter	**Units**	
Electron beam energy	MeV	**21.8**
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**



Max: 1.42210

Min: 0.00000

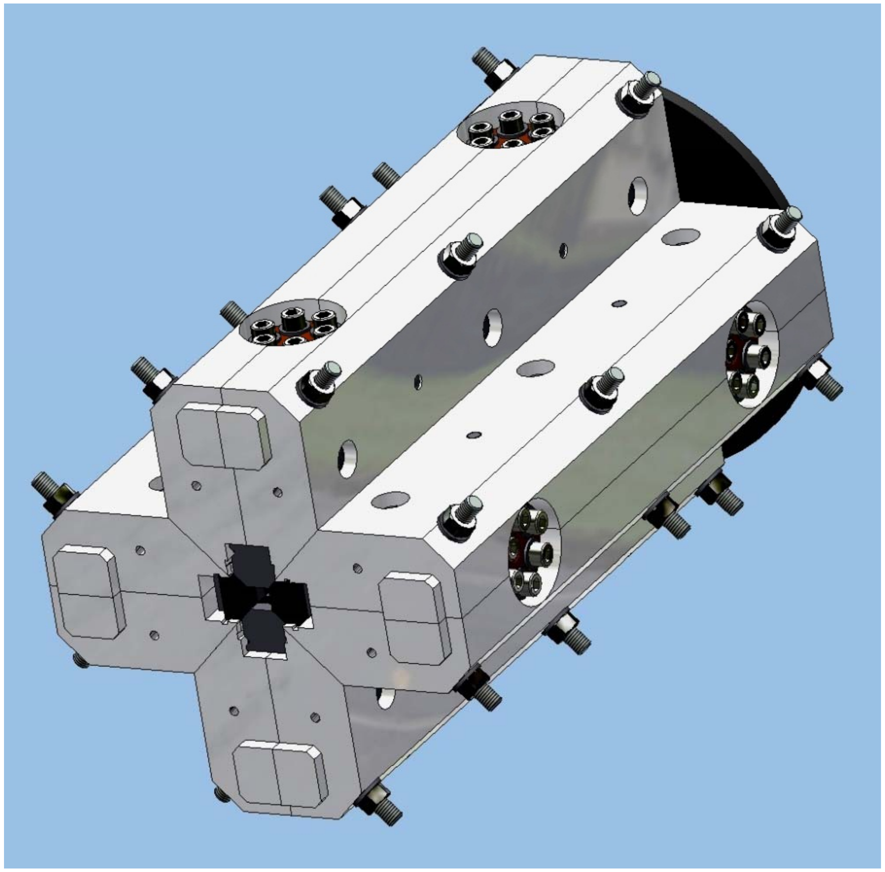
☑ Autoscaling

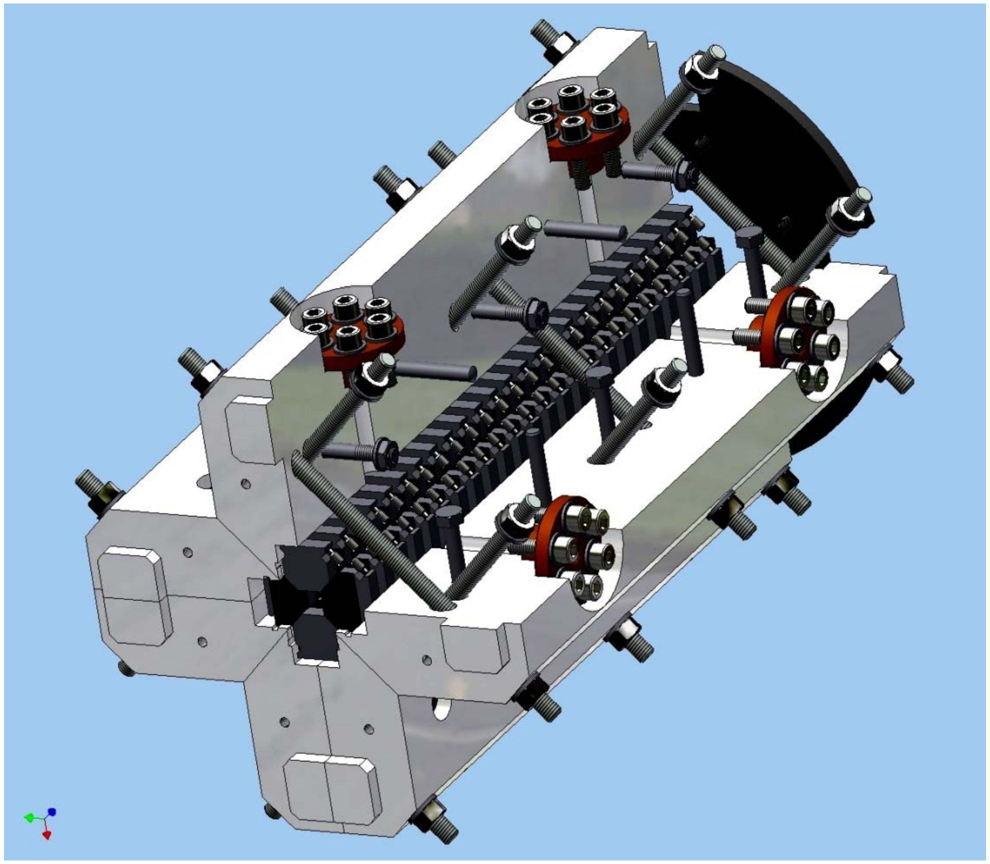
Precision: -4

Line: (0.0000, 0.0000, 0.0000) -> (0.0000, 0.0000, 2.0000), cm

Fig. 2. Left (a) shows the wiggler cross-section (b) wiggler’s filed from 3D simulations.

Design of helical undulator





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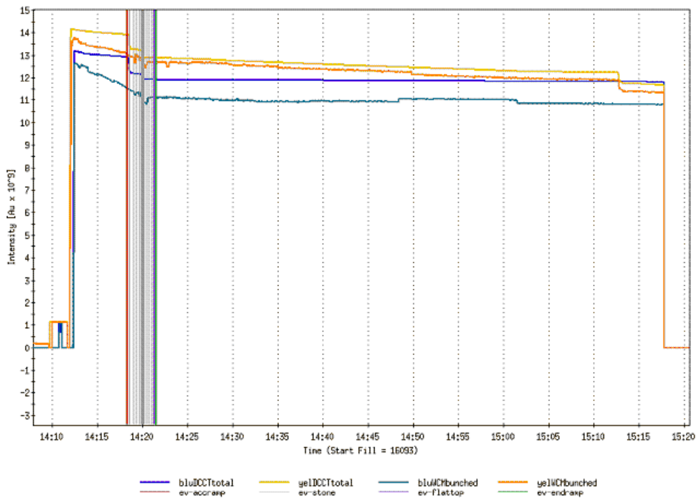
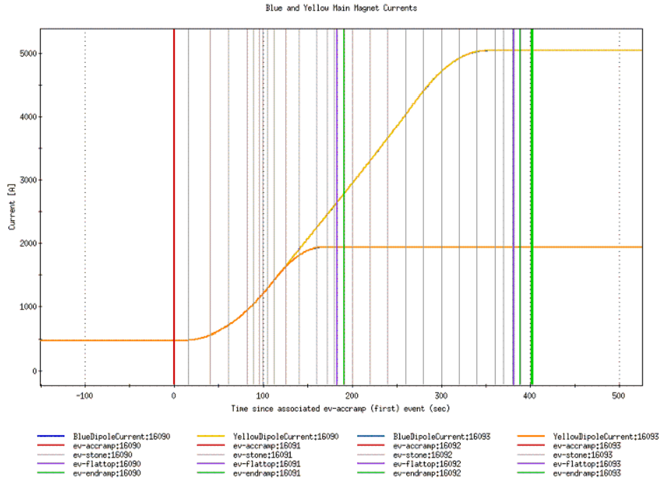
CeC PoP RHIC lattice and ramp development

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

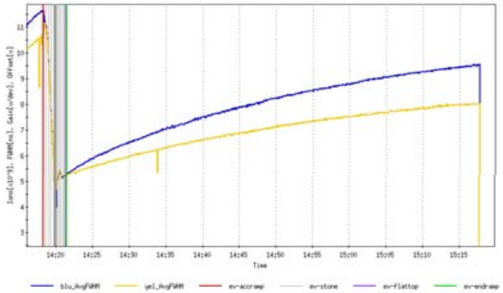
Ramp : beam intensity

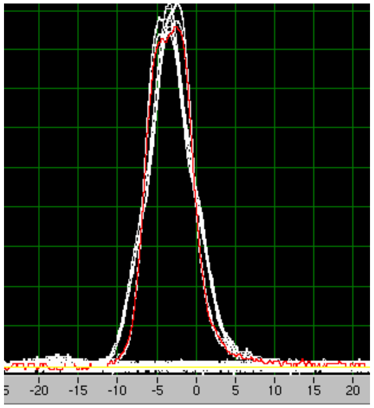


Ramp : Magnets currents

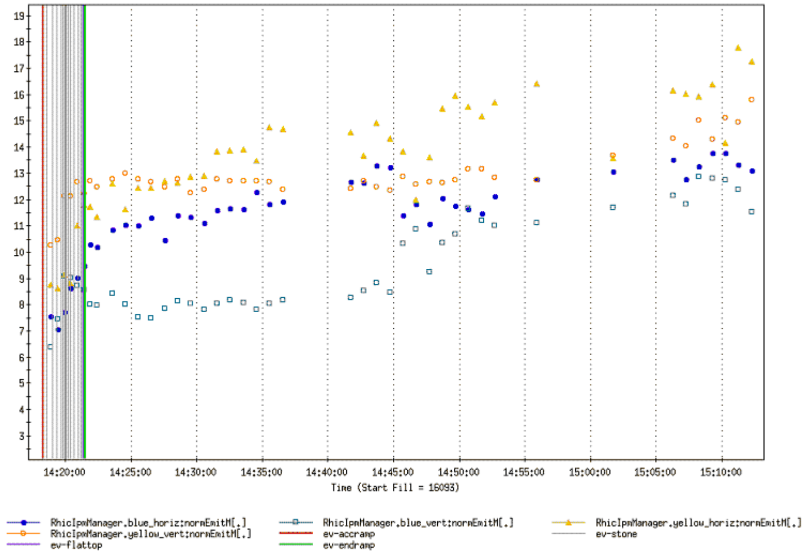


Bunch length and profiles at 40 GeV





Emittance growth at 40 GeV



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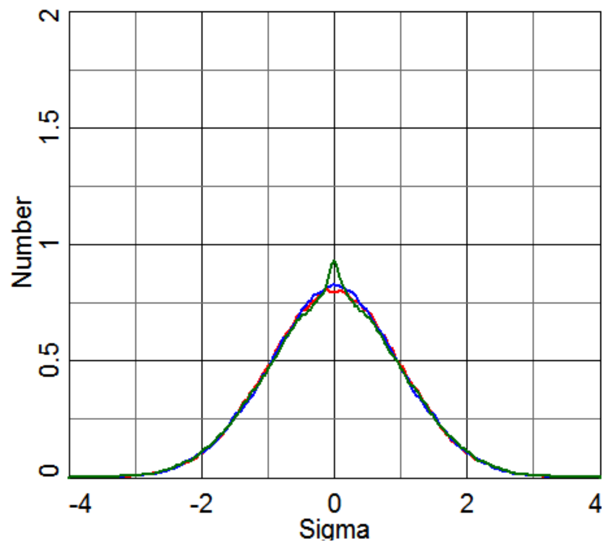
Anticipated beam dynamics

Electron bunch
– 10 psec

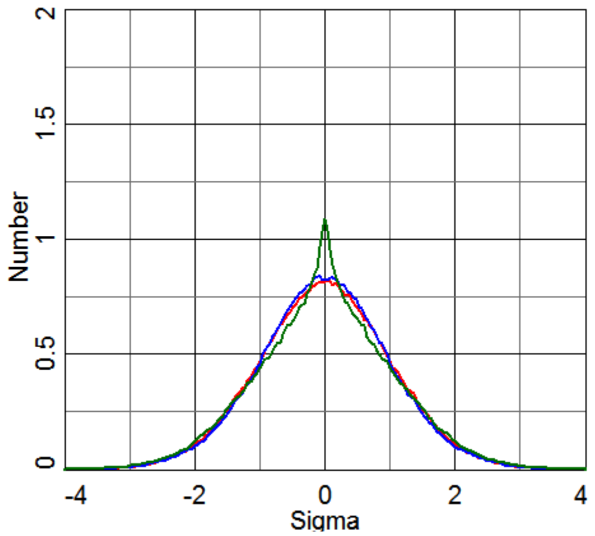
Ion bunch – 2nsec

For demonstration only:
detailed simulations will be done using complete CeC package

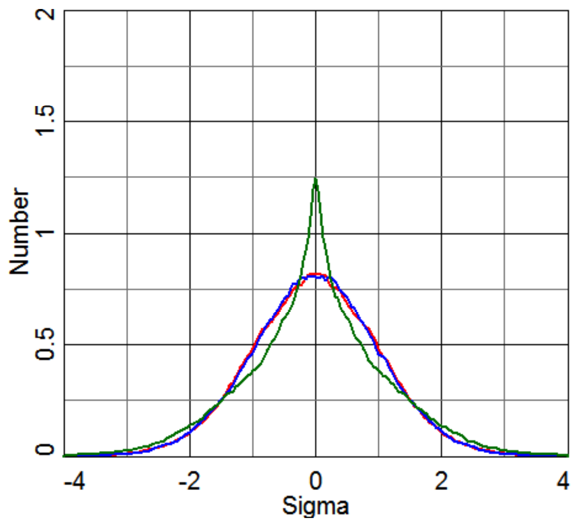
After 60 sec



After 250 sec



After 650 sec

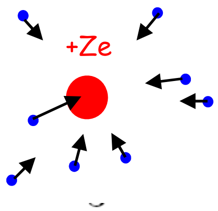


Conclusions

- Coherent electron cooling is of critical importance for eRHIC. 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
- Both theory and simulation tools for CeC are progressing – we expect first start-to-end simulation package in 2012
- Design and procurements of $2.2M cryogenic system for CeC experiment started. 112 MHz SRF gun design is in progress.
- Demonstration coherent electron cooling experiment project using Au ions in RHIC at ~ 40 GeV/n started in FY11.
- Experiments planned to start in 2014 and conducted for two-three years

Theory and modeling of CeC

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

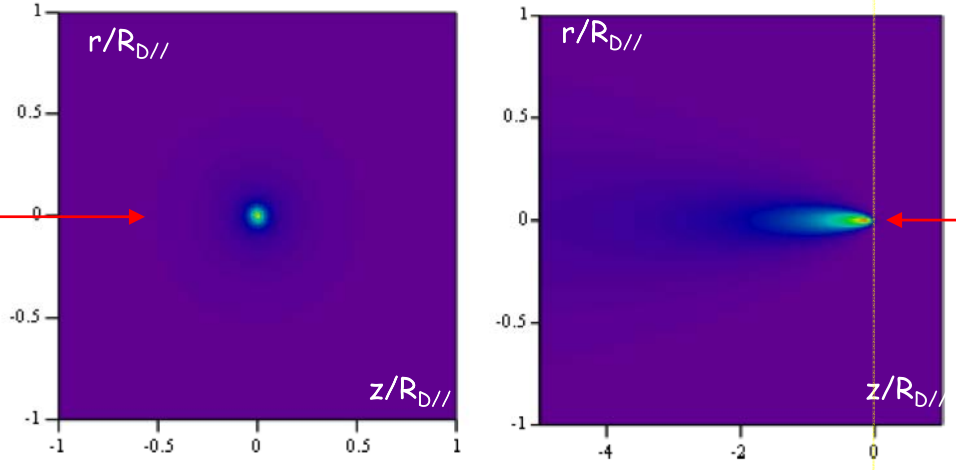


Analytical: for kappa-2 anisotropic electron plasma,
G. Wang and M. Blaskiewicz, Phys Rev E 78, 026413 (2008)

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

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

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

(0,0) is the location of the ion

Numerical: VORPAL @ TechX)

Parameters of the problem

$$\mathrm{R}_{D_\alpha} \propto \left(|\mathrm{v}_\alpha| + \sigma_{\mathrm{v}_\alpha}\right)/\omega_p; \quad \alpha = x,y,z$$

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

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

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

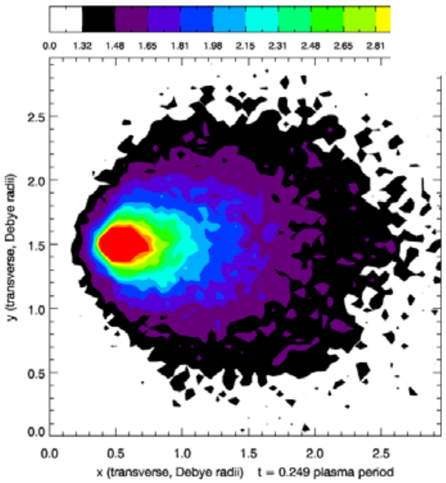


Figure 3: A transverse cross section of the wake behind a gold ion, with the color denoting density enhancement.

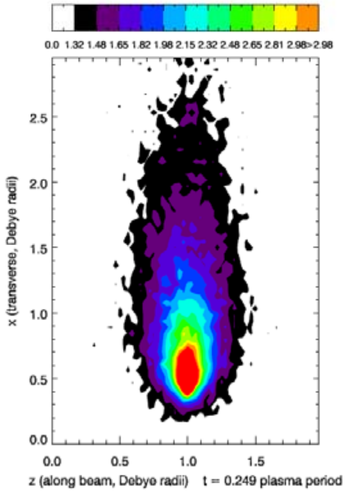
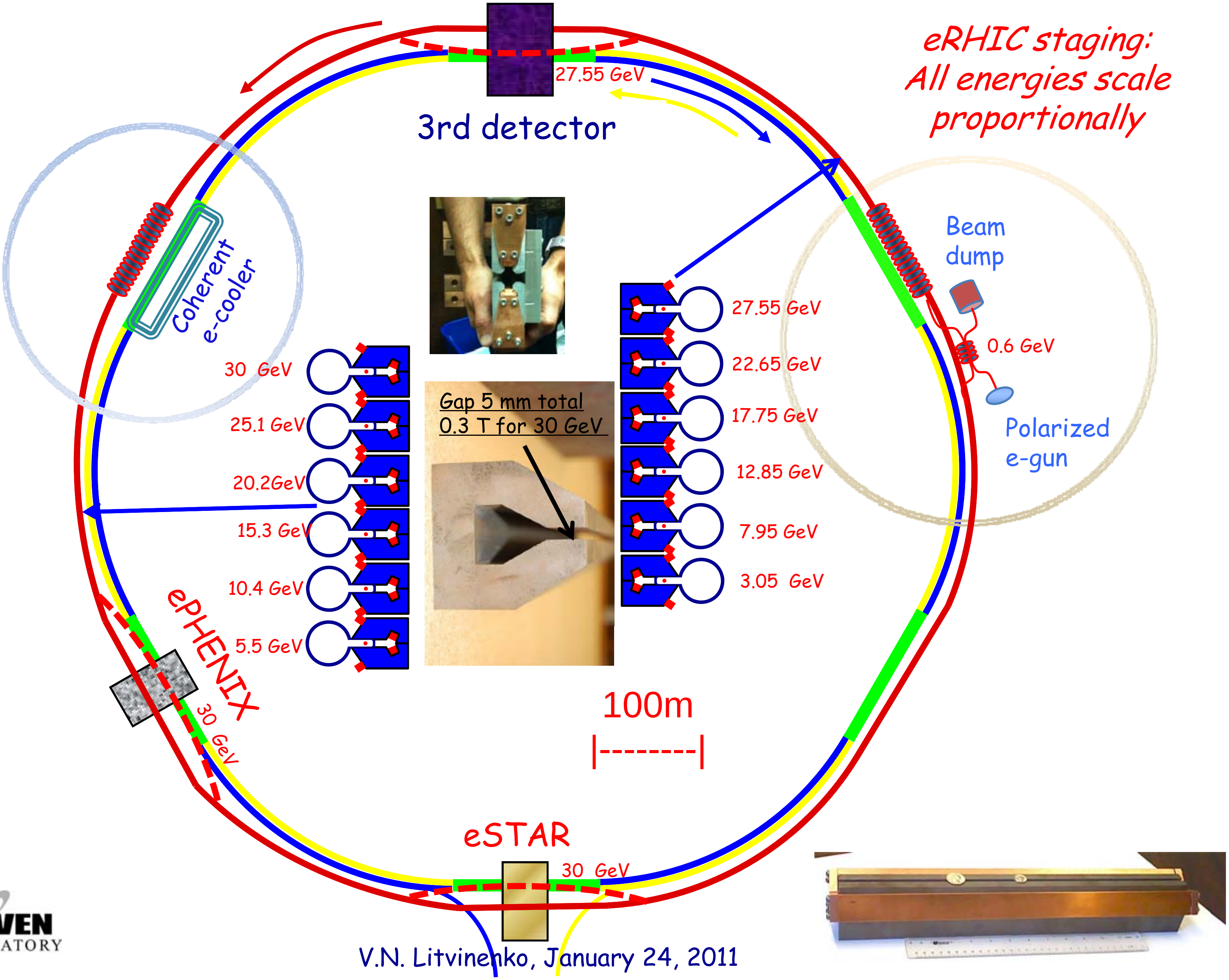


Figure 4: A longitudinal cross section of the wake behind a gold ion, with the color denoting density enhancement.

eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u

eRHIC staging: All energies scale proportionally



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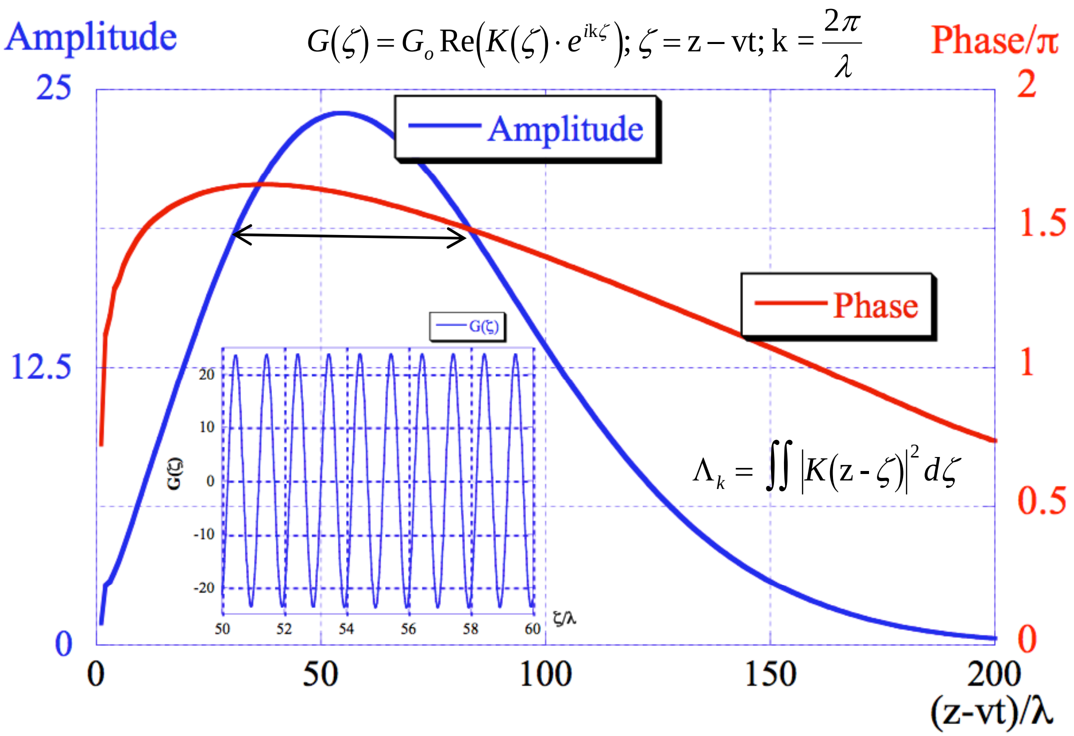
V.N. Litvinenko, January 24, 2011

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

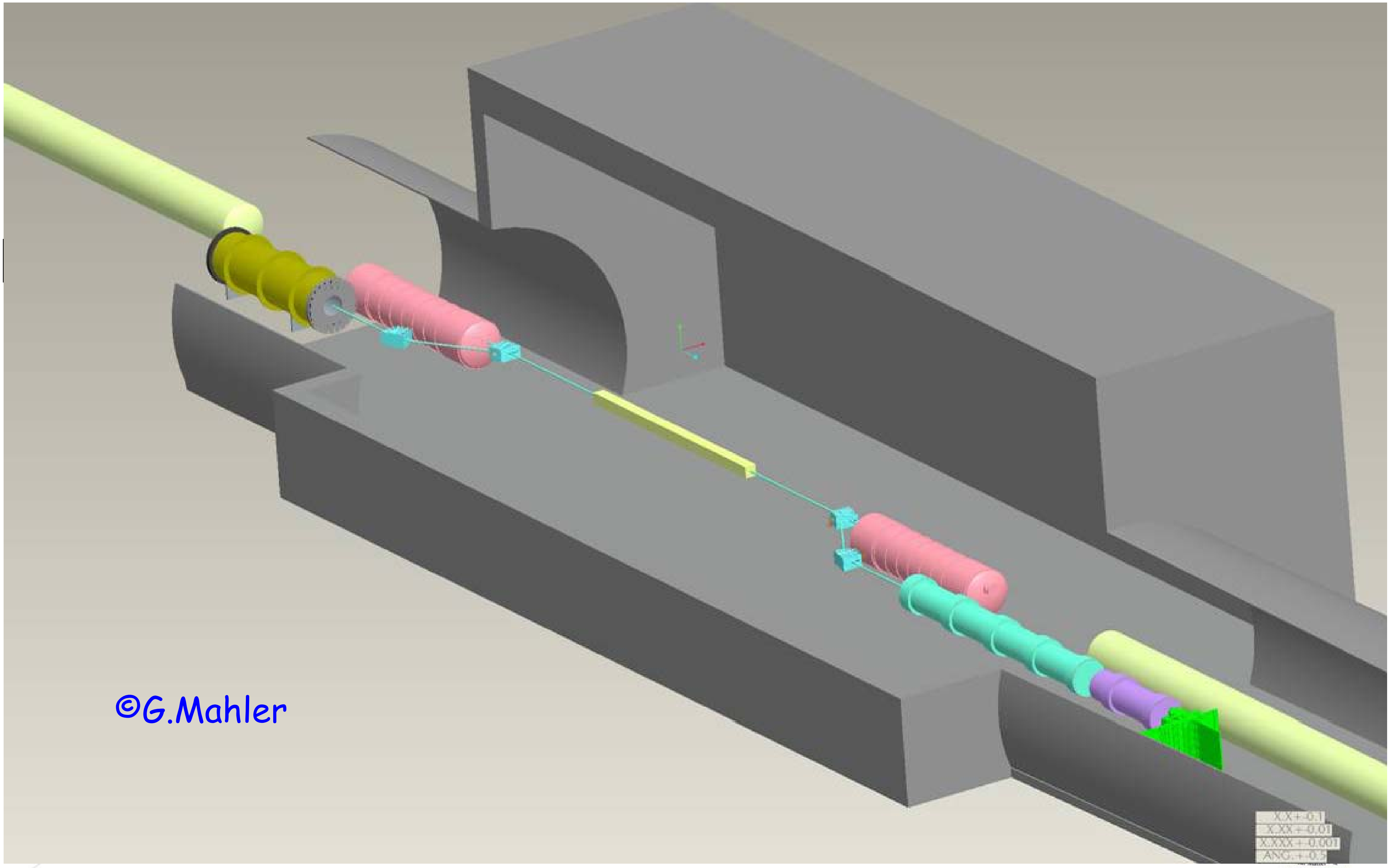
The amplitude (**blue line**) and the phase (**red line**, in the units of π) of the FEL gain envelope after 7.5 gain-lengths (300 period). Total slippage in the FEL is 300λ, $\lambda=0.5\ \mu$m. A clip shows the central part of the full gain function for the range of $\zeta=\{50\lambda, 60\lambda\}$.



$$G(\zeta) = G_o \operatorname{Re}\left(K(\zeta)\cdot e^{ik\zeta}\right);\ \zeta = z - vt;\ k = \frac{2\pi}{\lambda}$$

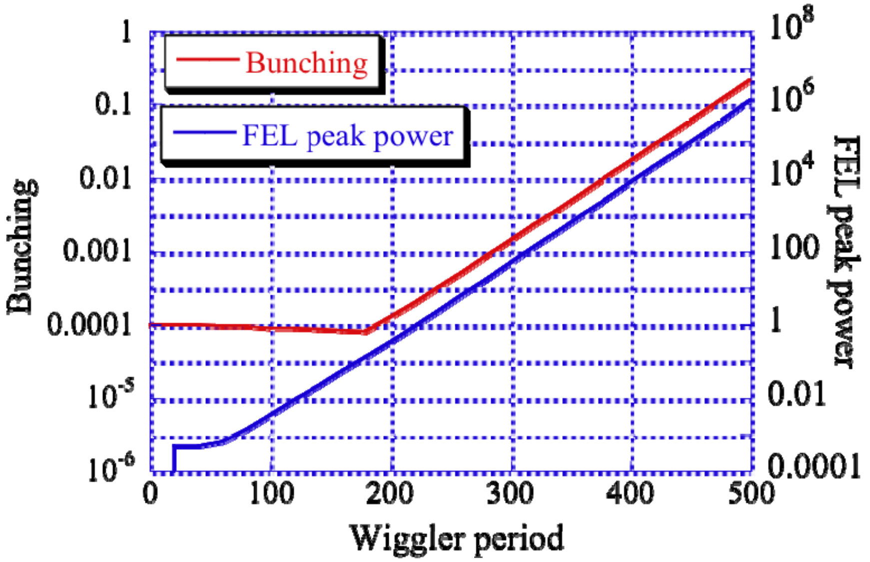
$$\Lambda_k = \iint \left|K(z-\zeta)\right|^2 d\zeta$$

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

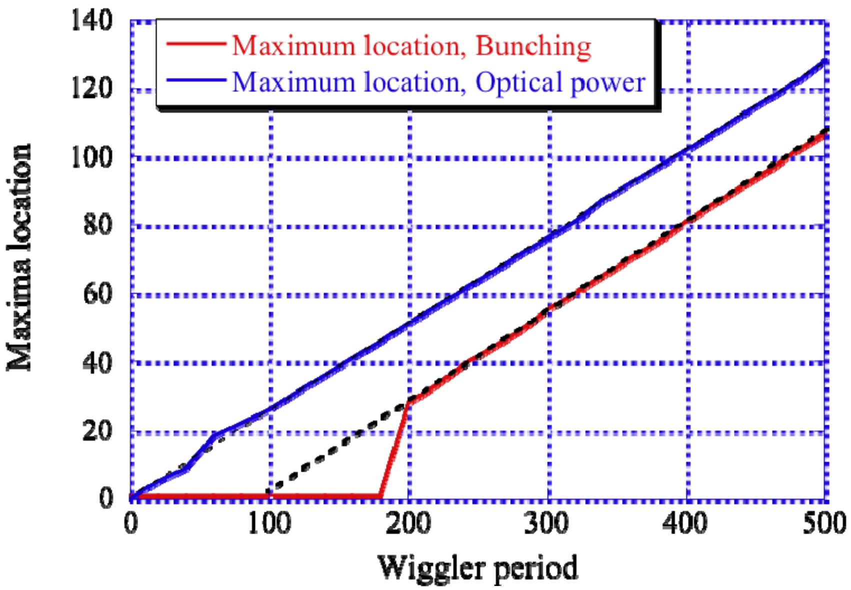


©G.Mahler

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)

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

©Y.Hao, V.Litvinenko

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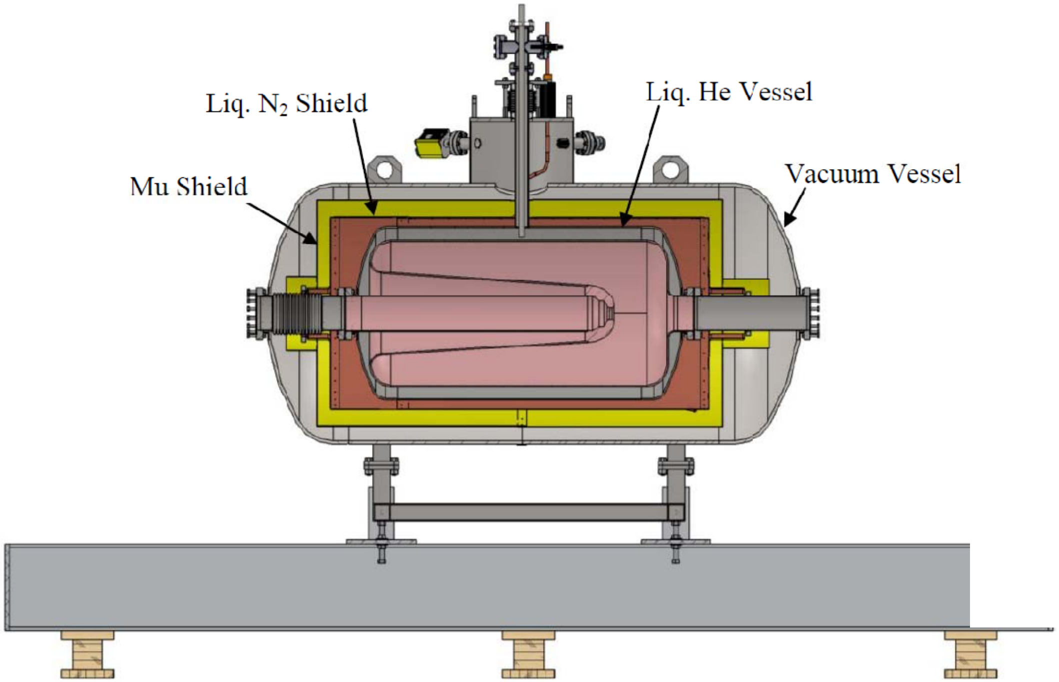
112 MHz SRF gun



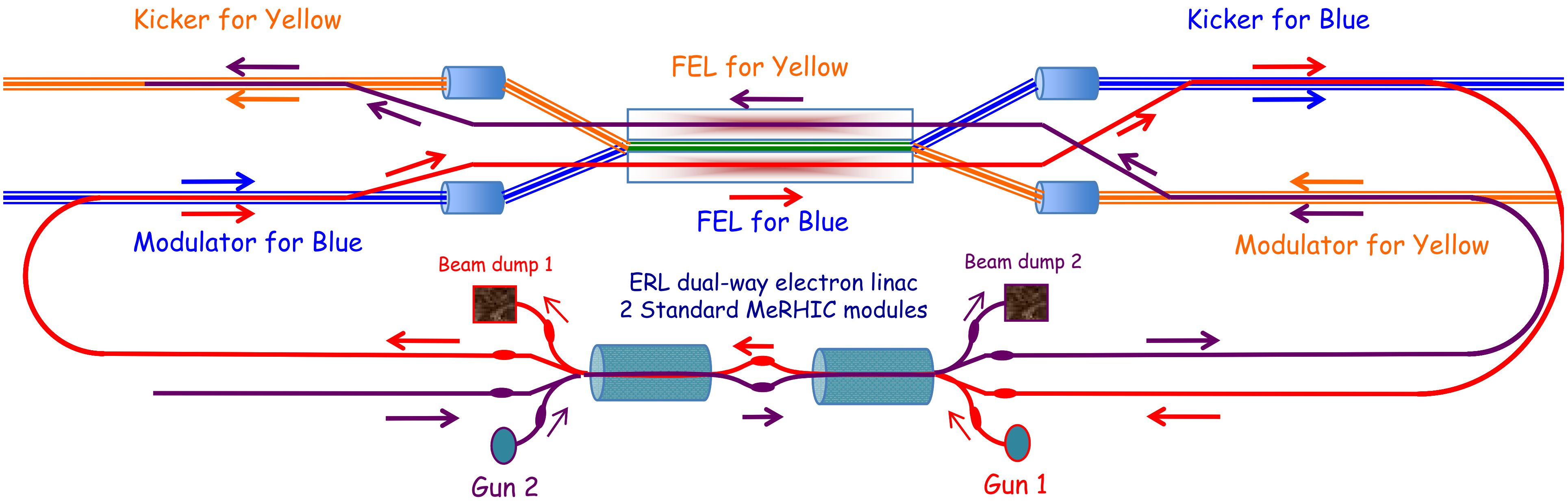
Courtesy of NIOWAVE

The SRF cavity has been built and tested under SBIR

To make the cavity an electron gun some modifications is under way:

1. Cathode insertion/locked mechanism
2. More powerful fundamental power coupling
3. Fundamental frequency tuner

One possible layout in RHIC IP of CeC driven by a single linac


Kicker for Yellow

Kicker for Blue

FEL for Yellow

FEL for Blue

Modulator for Blue

Modulator for Yellow

Beam dump 1

Beam dump 2

ERL dual-way electron linac
2 Standard MeRHIC modules

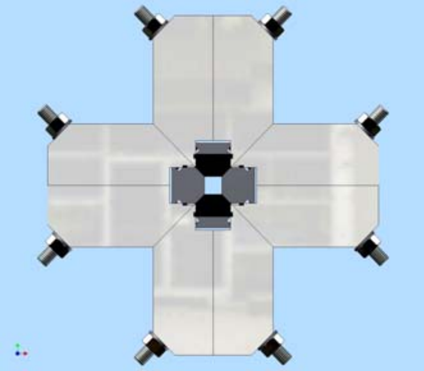
Gun 2

Gun 1

E_p, GeV	γ	E_e, MeV
100	106.58	54.46
250	**266.45**	**136.15**
325	346.38	177.00

Helical Wiggler: prototyping at BINP

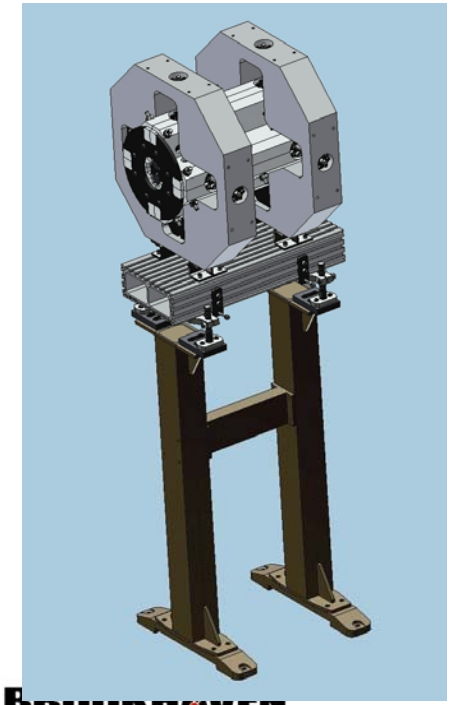
Courtesy to P.Vobly and M.Kholopov

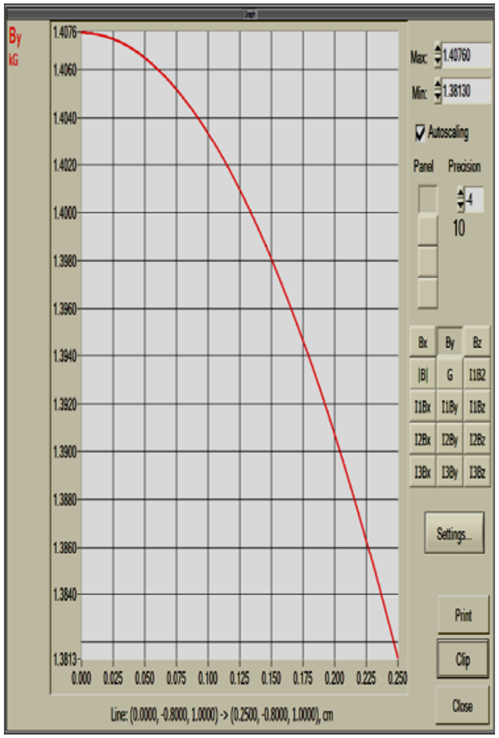


At present next stages of work has been done:

1. Magnetic and force calculation
2. Design of helical undulator prototype
3. Preliminary undulator drawings

After BNL approval of helical undulator design it’s necessary to order permanent magnets and start detailed designing.





Max: 1.40760

Min: 1.38130

☑ Autoscaling

Precision: 4

10

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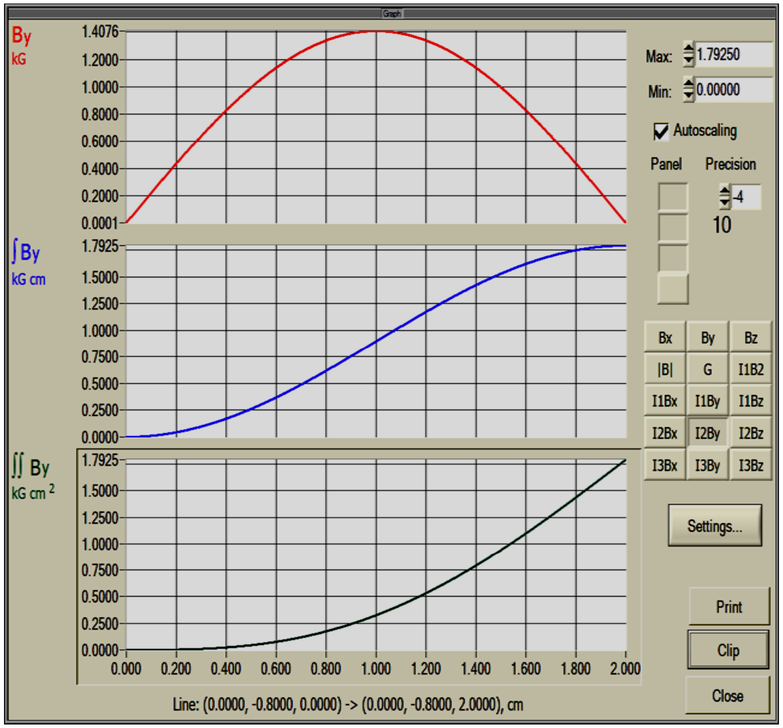

Max: 1.79250

Min: 0.00000

☑ Autoscaling

Precision: -4

10

Line: (0.0000, -0.8000, 0.0000) -> (0.0000, -0.8000, 2.0000), cm

Coherent Electron Cooling Demonstration Experiment

Vladimir N. Litvinenko for CeC collaboration
C-AD, Brookhaven National Laboratory, Upton, NY, USA

Collaboration of BNL, Jlab, Tech-X, BNL, Daresbury Lab

Sergei Belomestnykh, Ilan Ben-Zvi, Jean Clifford Brutus, Alexei Fedotov, Yue Hao, Dmitry Kayran, Vladimir N. Litvinenko, George Mahler, Aljosa Marusic, Wuzheng Meng, Gary McIntyre, Michiko Minty, Vadim Ptitsyn, Igor Pinayev, Triveni Rao, Thomas Roser, Brian Sheehy, Steven Tepikian, Yatming Than, Dejan Trbojevic, Joseph Tuozzolo, Gang Wang, Vitaly Yakimenko, *Brookhaven National Laboratory, Upton, NY 11973, USA*

Matt Poelker, Andrew Hutton, Geoffrey Kraft, Robert Rimmer, *TJNAF, Newport News, VA, USA*

David L. Bruhwiler, Dan T. Abell, Chet Nieter, Vahid Ranjbar, Brian T. Schwartz
Tech-X Corp., Boulder, CO 80303, USA

Pavel Vobly, Mikhail Kholopov, Oleg Shevchenko
Budker Institute of Nuclear Physics, Novosibirsk, 6300090, Russia

Peter Mcintosh Alan Wheelhouse
STFC, Daresbury Lab, Daresbury, Warrington, Cheshire, UK, WA4 4AD