Advanced Cooling Concepts for Future Electron-Ion Colliders

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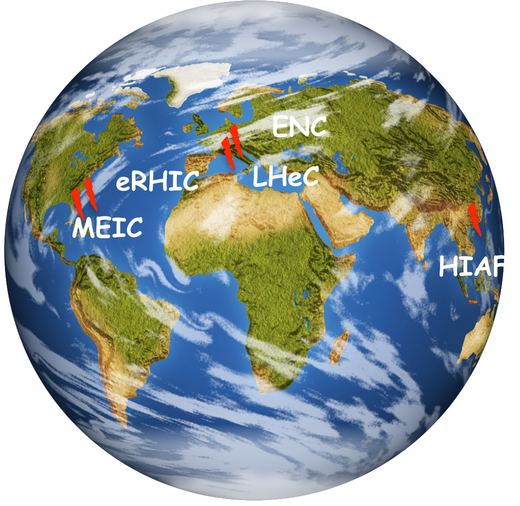
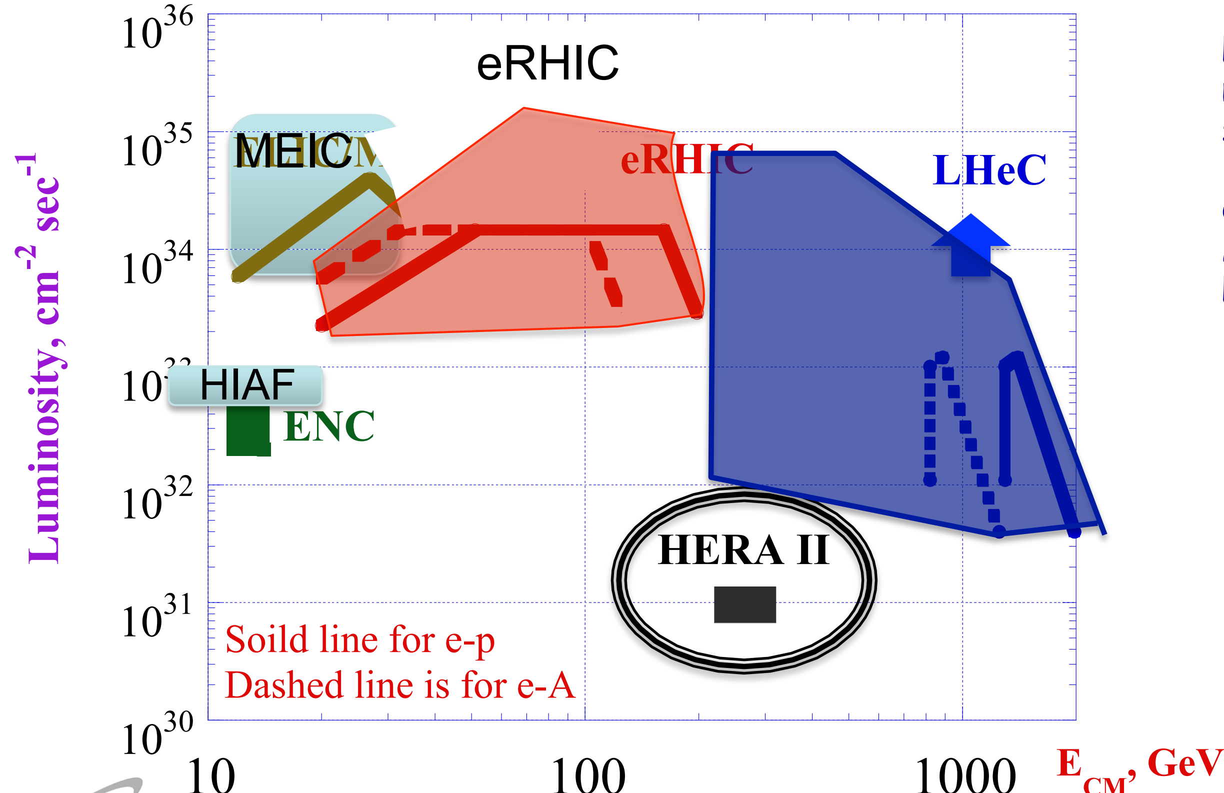
Future electron-hadron colliders



$$E_{CM} \cong \sqrt{4 E_e E_h}$$

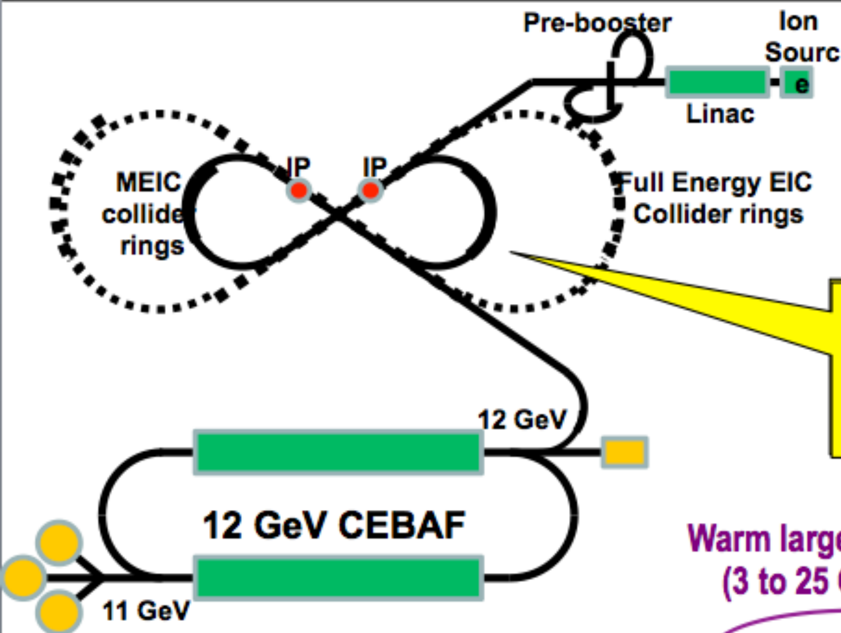


Luminosity in e-A case is per nucleon, i.e. it is the RHIC style "equivalent e-p luminosity"

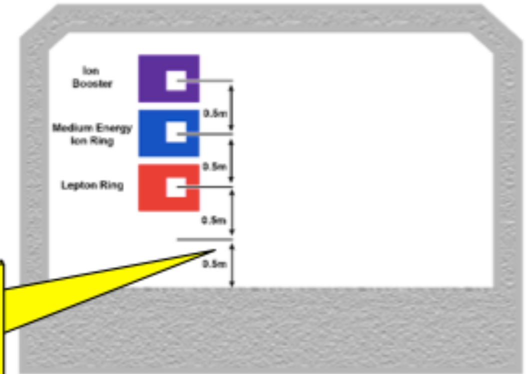
China is currently considering a MEIC-type low energy EIC in Lanzhou, Gansu.

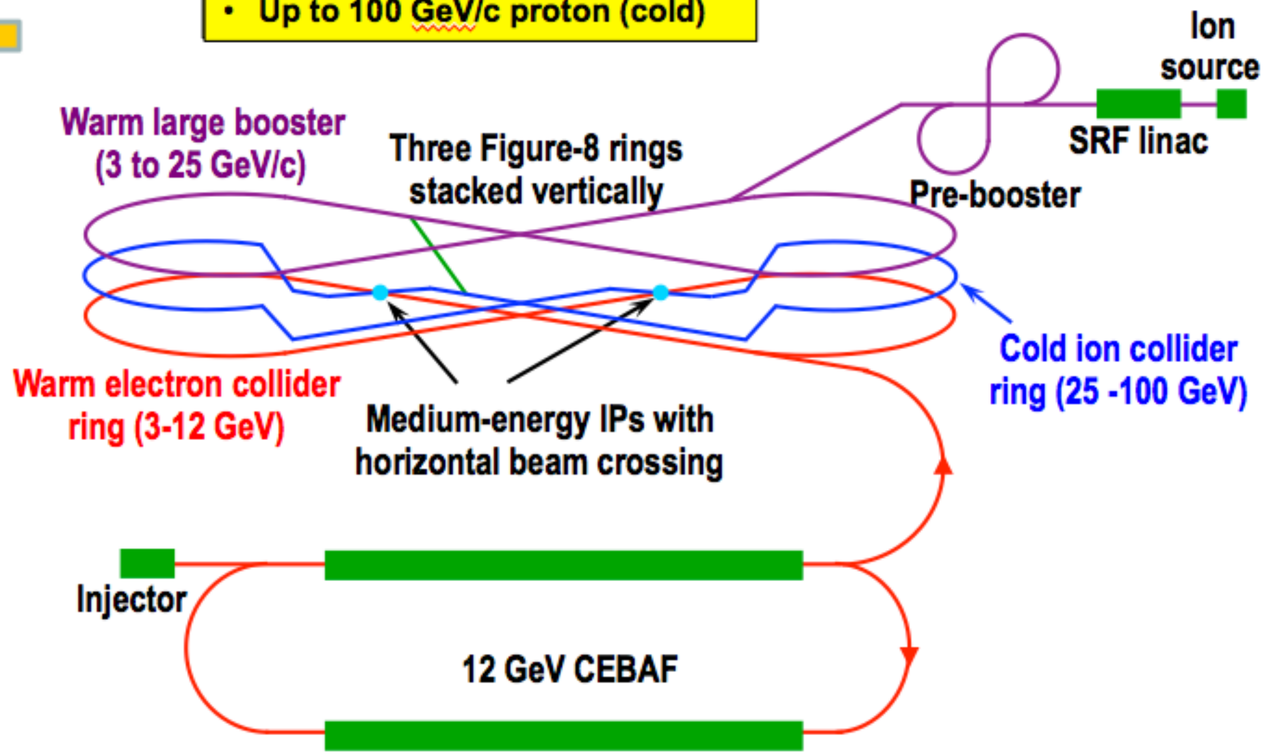
- Materials on MEIC are prepared by Y. Derbenev (Jlab)

MEIC Layout



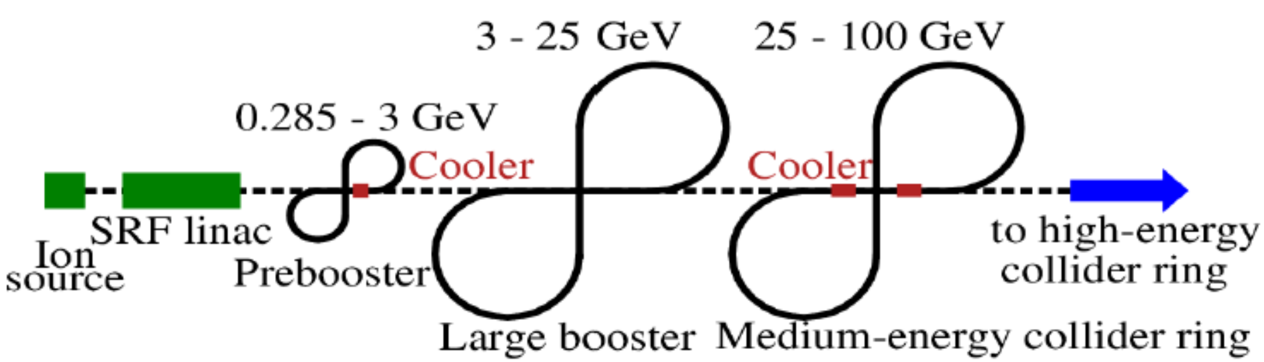
Three compact rings:
- 3 to 12 GeV electron
- Up to 25 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)





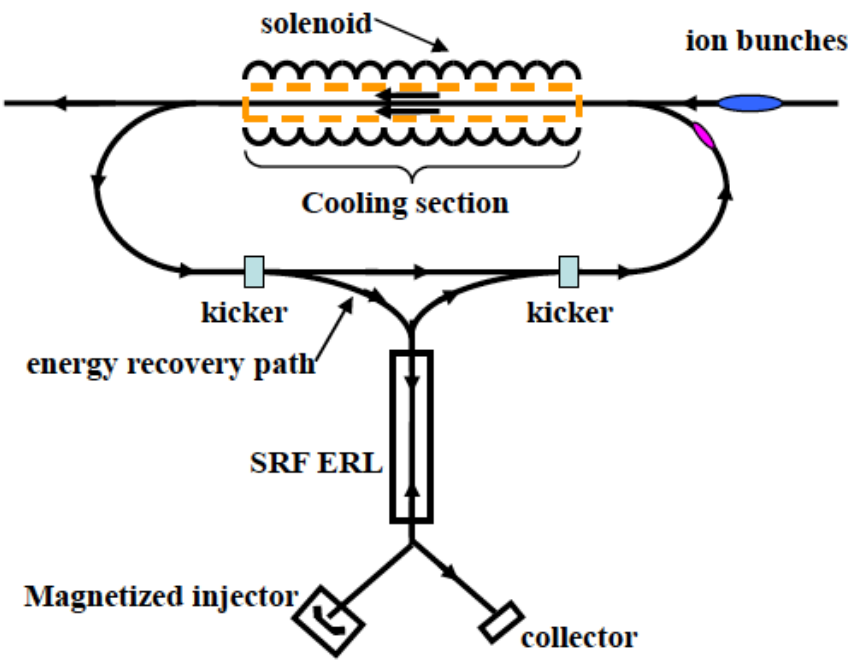
Electron Cooling for MEIC

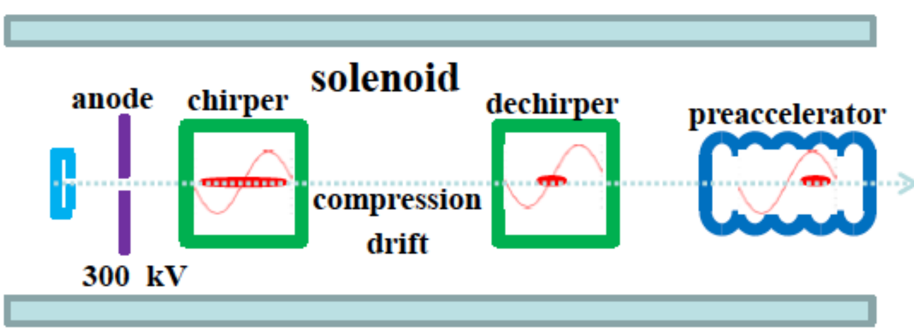
- MEIC design adopts traditional electron cooling.
- Cooling time is proportional to beam energy and 6D emittance: $\tau \propto \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4d}$
- Multi-phased scheme takes advantages of high electron cooling efficiency at low energy and/or small 6D emittance.
  1. Low energy DC cooling at the pre-booster (3 GeV/u)
  2. Bunched electron beam cooling for coasting ion beam at the injection energy (25 GeV/u) of the collider ring
  3. Bunched electron beam cooling for bunched ion beam at the collision energy (up to 100 GeV/u) of the collider ring



MEIC ion complex

ERL-based Circulated Magnetized HEEC





Magnetized injector for SRF ERL

- Magnetized (2KG) grid-operated DC gun: 300 KV, 30 mA; 1-2 ns, 2nC, 15-50 MHz
- Magnetized Compressor-preaccelerator : 5 MeV, 2 cm bunches
- 5 to 55 -140 MeV, 500 MHz SRF ERL
- Post-ERL 1.5 GHz SRF beam monochromator
- Circulator-cooler ring with 2T solenoid: 0.75 or 1.5 GHz bunch rep. rate, up to 3A
- Beam-beam kicker: similar source (higher charge/bunch) + DC energy recovery)

SRF ERL

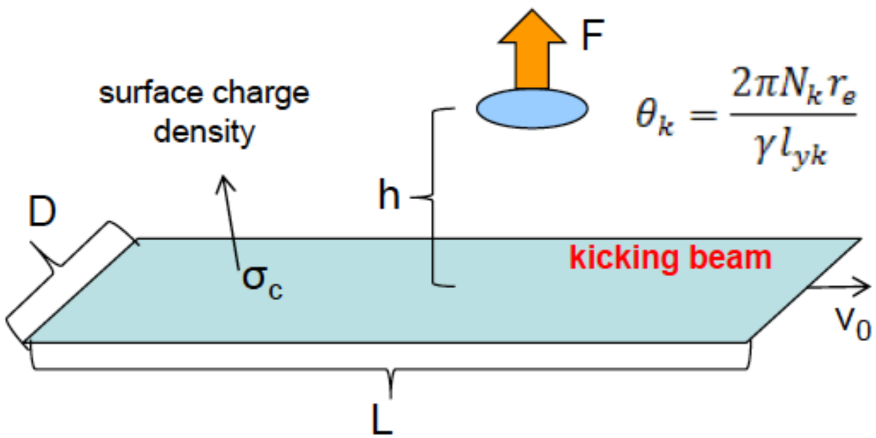
- Frequency 500 MHz
- (assume rep. rate in CCR 1.5 GHz)
- Voltage 36 MV
- Beam energy spread $5\cdot 10^{-3}$

Post-ERL energy corrector

- Frequency 1.5 GHz
- Voltage 4 MV
- Residual energy spread $5\cdot 10^{-5}$

Beam-beam Kicker

Ejection/injection of cooling bunches in the horizontal plane by kicks in x-direction



$$\theta_k = \frac{2\pi N_k r_e}{\gamma l_{yk}}$$

Circulating beam energy	MeV	33
Kicking beam energy	MeV	~0.3
Repetition frequency	MHz	5 -15
Kicking angle θ_k	mrad	0.7
K- bunch length	cm	15-30
K- bunch width l_{yk}	cm	0.5
K-bunch charge $N_k e$	nC	2

- Both beams magnetized
- Both beams should be flattened in the kick sections to have a small horizontal size while relatively large the vertical sizes
- A short (1~ 3 cm) target electron bunch passes through a long (10 - 20 cm) low-energy flat bunch at a very close distance, receiving a transverse kick θ_k :

Obtaining flat beams in the kick sections

- *Round-to-flat beam transformation* for cooling beam
- A **flat kicker beam** can be produced utilizing a grid-operated DC (thermionic) electron gun with a round magnetized cathode. **While maintaining the beam in solenoid, impose a constant quadrupole field** that causes beam shrinking in one plane while enlarging in the other plane.

Why Magnetized Electron Cooler?

- At cathode immersed in solenoid, the gun generates almost parallel (laminar) beam state of a **large** size (Larmor circles are very small compared to beam size)
- Such state is then transplanted to the solenoid in cooling section (while preserving the magnetic flux across the beam area)
- The solenoid field can be controlled to make e-beam size matching properly the ion beam size

Magnetization results in the following critical advantages

(compared to a non-magnetized gun):

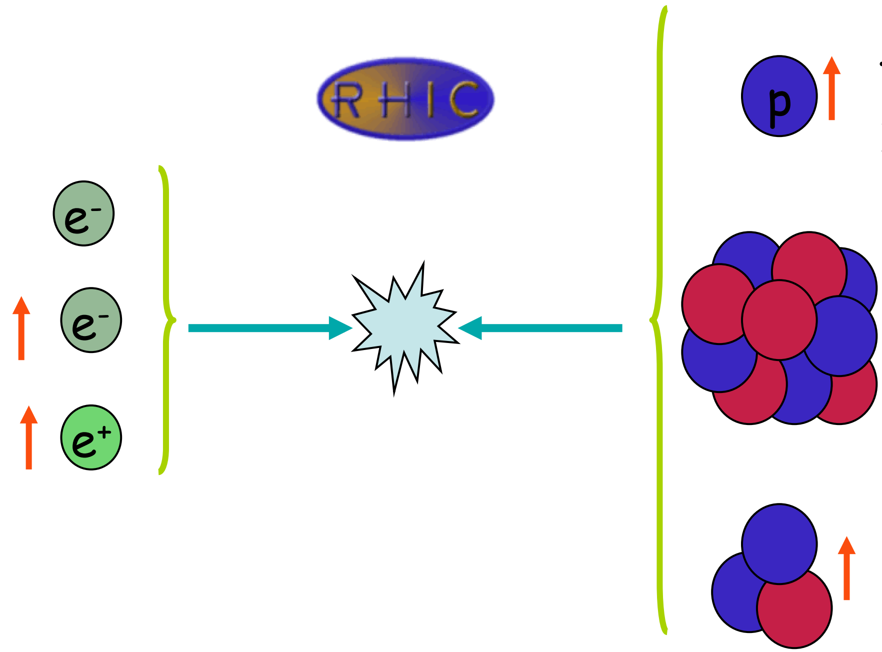
- **Tremendous reduction (by two orders of value) of the regional and global Space Charge very bad impact to dynamics in CCR**

  (tune shift, micro-bunching)
- **Strong mitigation (suppression) of CSR microbunching/ energy spread growth**
- **Suppression of very bad impacts of high electron transverse velocity spread and short-wave misalignments to cooling rates (thanks to ion collisions with "frozen" electrons)**

eRHIC: QCD Facility at BNL

Add electron accelerator to the existing $2B RHIC

Unpolarized and 80% polarized leptons, 5-21.2 GeV

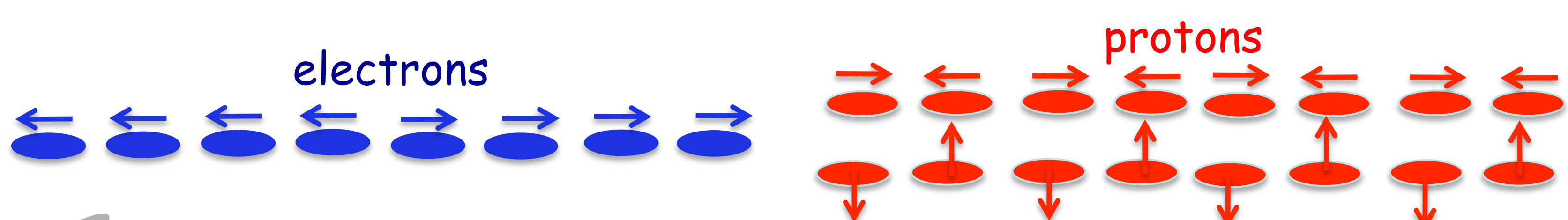


70% polarized protons
100-250 GeV

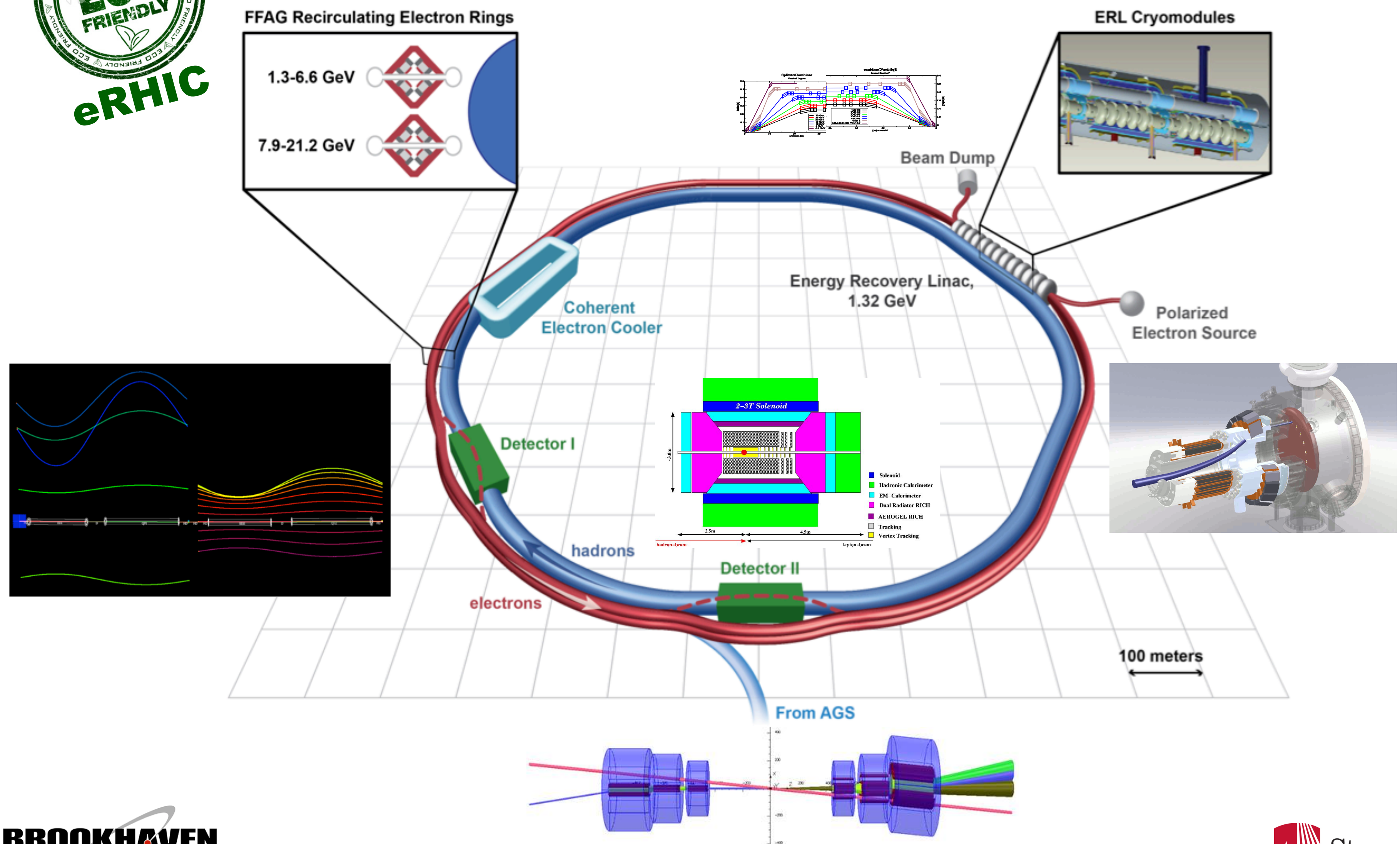
Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

Polarized light ions (He^3) 167 GeV/u

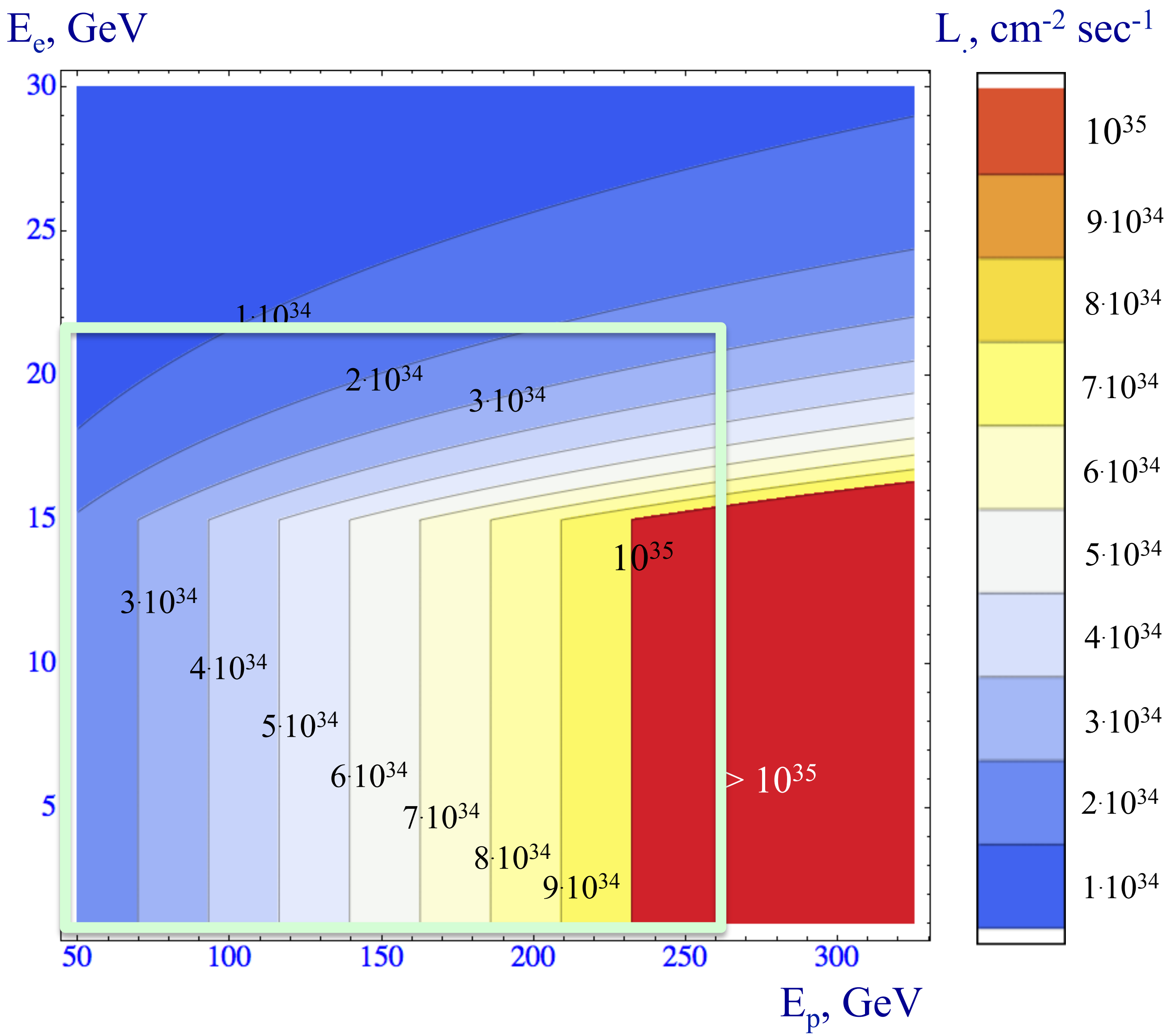
Center of mass energy range: 30-145 GeV
Any polarization direction in lepton-hadrons collisions



eRHIC with 21.2 GeV ERL



Ultimate eRHIC luminosity as function of beam energies



The box shows eRHIC reach in energy with current FFAG arc design from day one

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Luminosities at top hadron beam energy

	e	p	$^2He^3$	$^{79}Au^{197}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	**0.33**	**0.3-3**	**0.6-6**	**0.6-6**
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms normalized emittance, 10^{-6} m		**0.27**	**0.20**	**0.20**
Electron rms normalized emittance, 10^{-6} m		31.6	34.7	57.9
β^*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Electron beam disruption		2.8-28	5.2-52	1.9-19
Space charge parameter		0.006	0.016	0.016
rms bunch length, cm	0.4	**5**	**5**	**5**
Polarization, %	70	70	70	none
Peak luminosity, 10^{33} cm^{-2}s^{-1}		1.5-145	2.8-28	1.7-17

Cooling hadron beam transversely to 1/10th of the longitudinal and transverse emittances is the key for attaining high luminosity in eRHIC

Why Coherent electron Cooling?

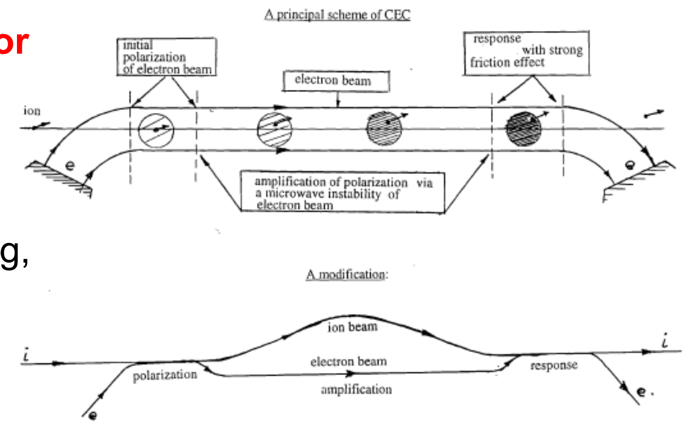
IBS time for EIC hadron beam is measured in minutes or even in seconds with energy span of at least facto of 5

- no other technique is capable of doing the job

Machine		Energy GeV/n	Stochastic Cooling, hrs	SR, hrs	e-cooling hrs	CeC estmates
RHIC CeC PoP	*Au*	*40*	-	-	~ 1	*4 sec - local* *12 min - bunch*
eRHIC	p	325	~100	∞	~ 30	~start at 0.1hr and improves
LHC	p	7,000	~ 1,000	13/26	∞	~ start at 1 hr and improves

Yaroslav Derbenev Started Discussing Possibility of Coherent electron Cooling (CeC) 34 years ago

- **Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980)**
- **Coherent electron cooling**, Ya. S. Derbenev, University of Michigan, MI, USA, UM HE 91-28, August 7, 1991
- Ya.S.Derbenev, Electron-stochastic cooling, DESY , Hamburg, Germany, 1995 ……….



UM HE 91-28

August 7, 1991

COHERENT ELECTRON COOLING

1. Physics of the method in general

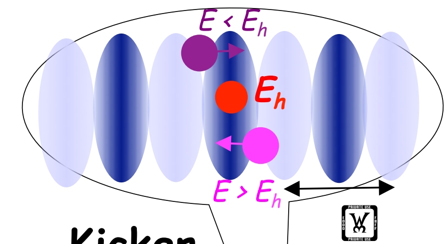
Ya. S. Derbenev
Randall Laboratory of Physics, University of Michigan
Ann Arbor, Michigan 48109-1120 USA

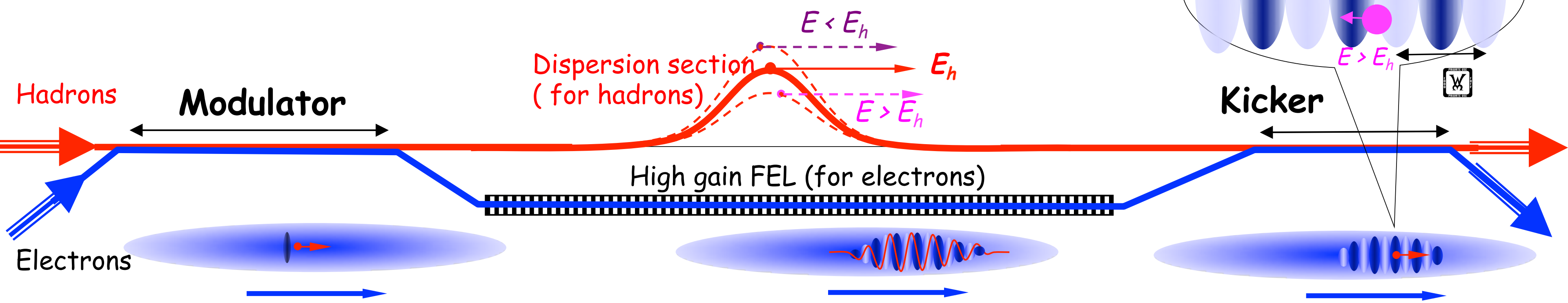
Conclusion

The method considered above combines principles of electron and stochastic cooling and microwave amplification. Such an unification promises to frequently increase the cooling rate and stacking of high-temperature, intensive heavy particle beams. Certainly, for the whole understanding of new possibilities thorough theoretical study is required of all principle properties and other factors of the method.

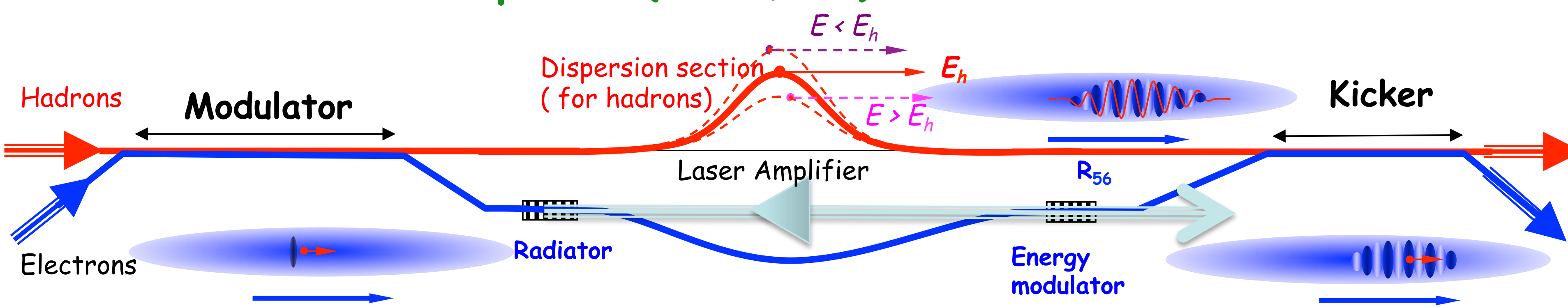
Coherent Electron Cooling Schemes

Classic – FEL amplifier (2006, PRL VL & YD)

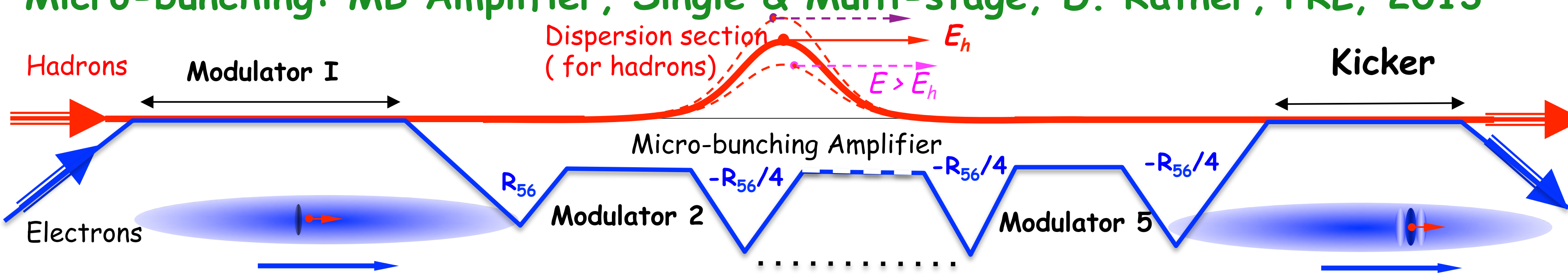




Blended – laser amplifier (2007, VL)



Enhanced bunching: single stage - VL, FEL 2007
Micro-bunching: MB Amplifier, Single & Multi-stage, D. Ratner, PRL, 2013

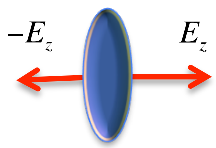


Why Coherent Electron Cooling ?

$$\gamma = E_p / m_p c^2$$

- Has potential of a rather large bandwidth W ~ 10^{13} -10^{17} Hz
- Electrons are easy to manipulate, force to radiate, bunch etc.
- **THE MOST IMPORTANT: Longitudinal electric field of bunched electron clamp is very effective way of cooling high energy hadrons – see the example below**

  - Let's assume that as result of CeC interaction a proton induced a density clamp (pancake) in the e-beam with charge of one electron



$$\boxed{q = -e}$$

$$E_z = -2\pi \frac{e}{A}; \quad A = 2\pi \frac{\beta \cdot \varepsilon_n}{\gamma} - beam\ area$$

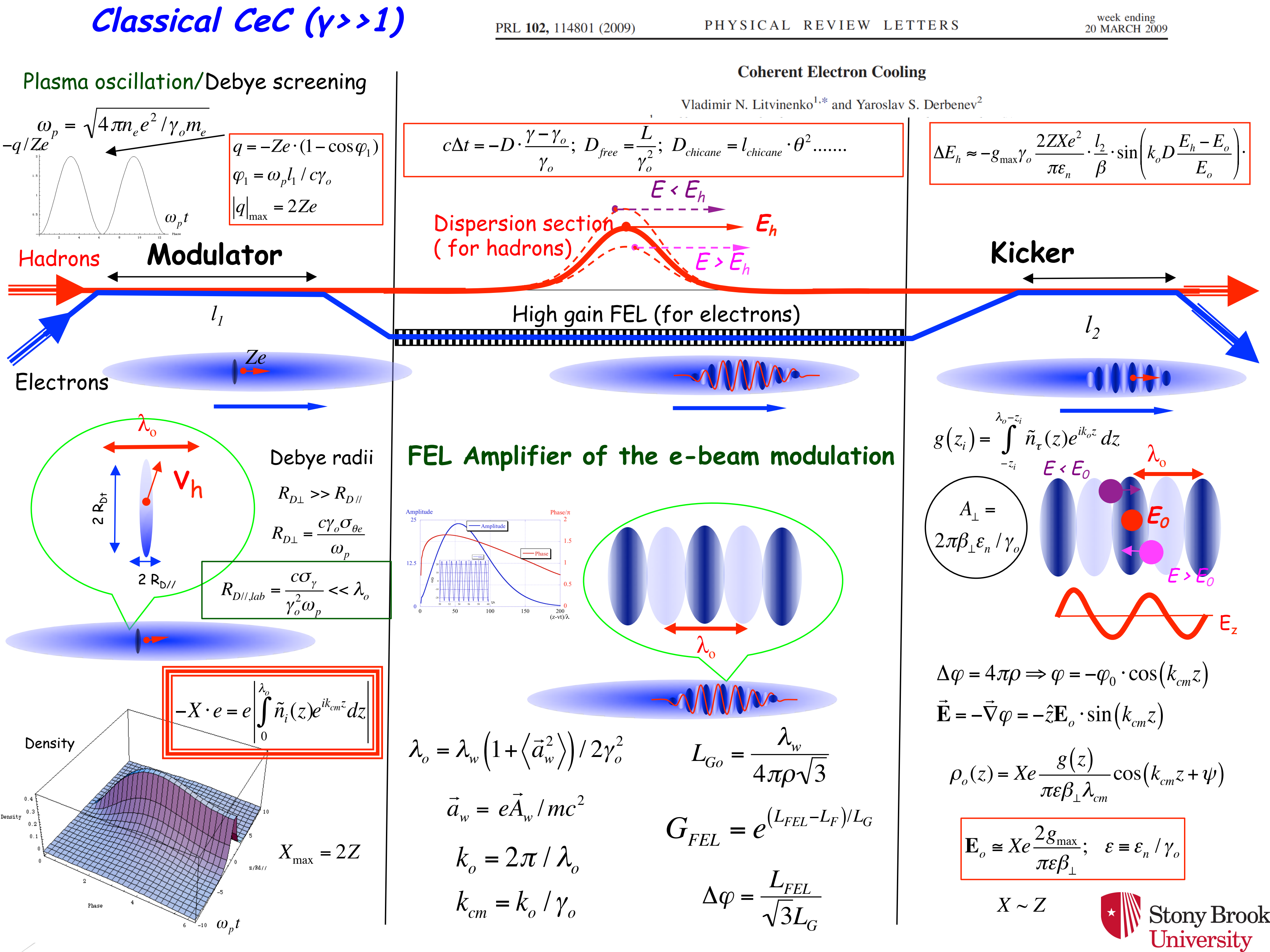
  - Longitudinal electric field induced by this charge (from the Gauss law)
  - The proton energy change in the kicker with length $L = \beta$

$$\boxed{\frac{\Delta E}{E} \sim \frac{eE_z L}{\gamma m_p c^2} = -\frac{r_p}{\varepsilon_n};}$$

  - And cooling time will be $\boxed{\tau \approx \frac{1}{f_o} \frac{\sigma_E}{E} \frac{\varepsilon_n}{r_p}; f_o - revolution\ \ frequency}$

Putting parameters for 250 GeV RHIC proton beam: normalized RMS emittance of 2 mm mrad and relative energy spread of 2 x10^{-4} we get cooling time of 0.93 hours! In eRHIC with normalized RMS emittance of 0.2 mm mrad, without any gain the cooling time is 5.6 mins for protons and 25 sec for 100 GeV/u gold ions. For protons in LHC it would be under 7 hours. Gain ~ 10 puts it under an hour.

The CeC based on the longitudinal electric field is very effective, especially when compared with using transverse fields!



Classical CeC (γ>>1)
PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009
Coherent Electron Cooling
Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]
Plasma oscillation/Debye screening
$\omega_p = \sqrt{4\pi n_e e^2/\gamma_o m_e}$
$-q/Ze$
$\omega_p t$
$q = -Ze\cdot(1-\cos\varphi_1)$
$\varphi_1 = \omega_p l_1 / c\gamma_o$
$|q|_{max} = 2Ze$
$c\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D_{free} = \frac{L}{\gamma_o^2};\ D_{chicane} = l_{chicane}\cdot\theta^2.......$
$\Delta E_h \approx -g_{max}\gamma_o \frac{2ZXe^2}{\pi\varepsilon_n}\cdot\frac{l_2}{\beta}\cdot\sin\left(k_o D\frac{E_h-E_o}{E_o}\right)\cdot$
E < Eh
Eh
E > Eh
Dispersion section
(for hadrons)
Hadrons
Modulator
Kicker
l_1
High gain FEL (for electrons)
l_2
Ze
Electrons
λ_o
V_h
$2 R_{D\perp}$
$2 R_{D//}$
Debye radii
$R_{D\perp} >> R_{D//}$
$R_{D\perp} = \frac{c\gamma_o\sigma_{\theta e}}{\omega_p}$
$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma_o^2\omega_p} << \lambda_o$
FEL Amplifier of the e-beam modulation
$g(z_i) = \int_{-z_i}^{\lambda_o - z_i} \tilde{n}_\tau(z) e^{ik_o z} dz$
λ_o
E < Eo
Eo
E > Eo
$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$
E_z
$-X\cdot e = e\left|\int_0^{\lambda_o} \tilde{n}_i(z)e^{ik_{cm}z}dz\right|$
Density
$X_{max} = 2Z$
$\omega_p t$
$\lambda_o = \lambda_w\left(1+\langle\vec{a}_w^2\rangle\right)/2\gamma_o^2$
$\vec{a}_w = e\vec{A}_w/mc^2$
$k_o = 2\pi/\lambda_o$
$k_{cm} = k_o/\gamma_o$
$L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$
$G_{FEL} = e^{(L_{FEL}-L_F)/L_G}$
$\Delta\varphi = \frac{L_{FEL}}{\sqrt{3}L_G}$
$\Delta\varphi = 4\pi\rho \Rightarrow \varphi = -\varphi_0\cdot\cos(k_{cm}z)$
$\vec{E} = -\vec{\nabla}\varphi = -\hat{z}\mathbf{E}_o\cdot\sin(k_{cm}z)$
$\rho_o(z) = Xe\frac{g(z)}{\pi\varepsilon\beta_\perp\lambda_{cm}}\cos(k_{cm}z+\psi)$
$\mathbf{E}_o \cong Xe\frac{2g_{max}}{\pi\varepsilon\beta_\perp};\quad \varepsilon\equiv\varepsilon_n/\gamma_o$
$X \sim Z$
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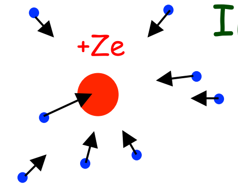
Density modulation caused by a hadron (co-moving frame)

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

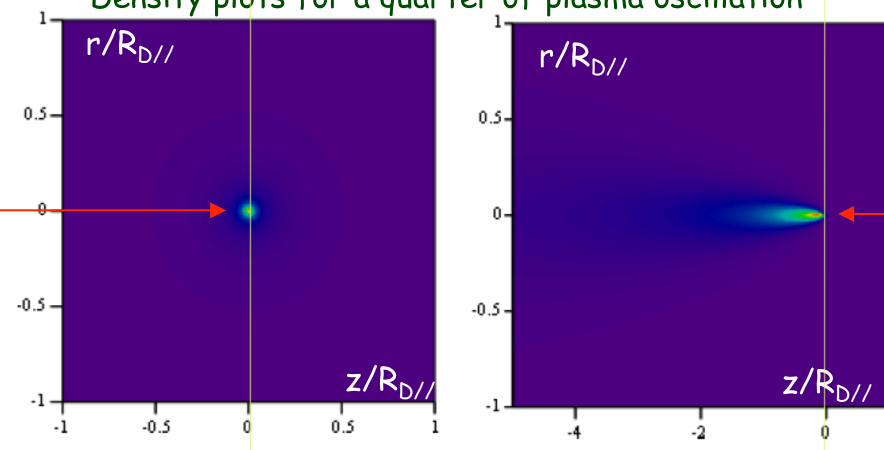
$$\tilde{n}(\vec{r},t) = \frac{Zn_o\omega_p^3}{\pi^2\sigma_{vx}\sigma_{vy}\sigma_{vz}}\int_0^{\omega_p t}\tau\sin\tau\left(\tau^2+\left(\frac{x - v_{hx}\tau/\omega_p}{r_{Dx}}\right)^2+\left(\frac{y - v_{hy}\tau/\omega_p}{r_{Dy}}\right)^2+\left(\frac{z - v_{hz}\tau/\omega_p}{r_{Dz}}\right)^2\right)^{-2}d\tau$$

Induces charge



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

Density plots for a quarter of plasma oscillation

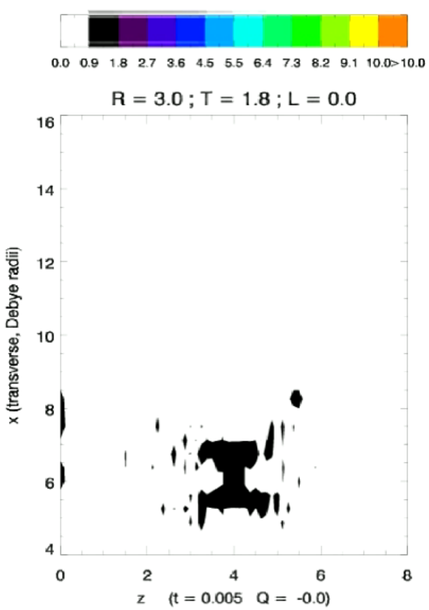


Ion rests in c.m.
(0,0) is the location of the ion

Ion moves in c.m. with

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

(0,0) is the location of the ion



Numerical: VORPAL @ TechX)

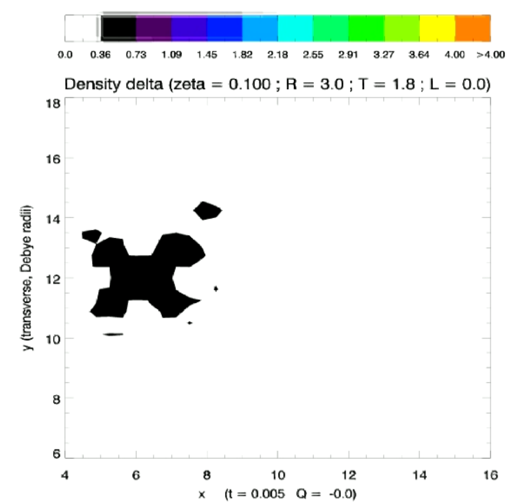
Parameters of the problem

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

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

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

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



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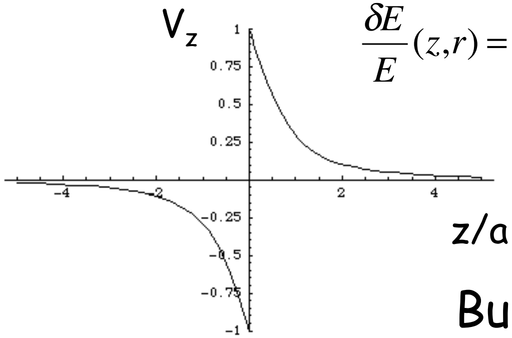
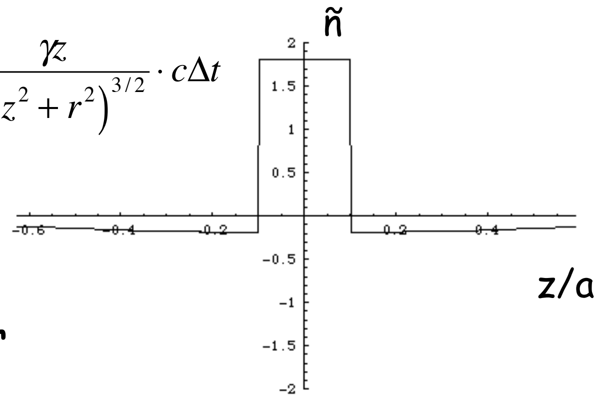
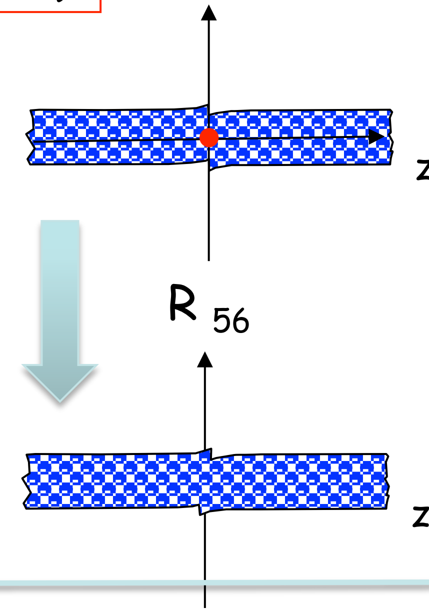
Bunching for high energy beams ($\omega_p t << 1$)



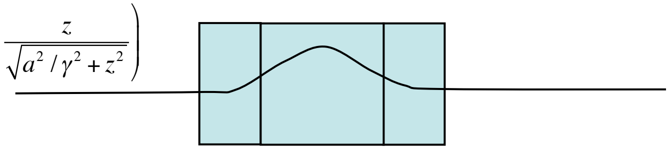
$$\frac{\delta E}{E}(z,r) = -Zr_e \frac{\gamma z}{\left(\gamma^2 z^2 + r^2\right)^{3/2}} \cdot c\Delta t$$



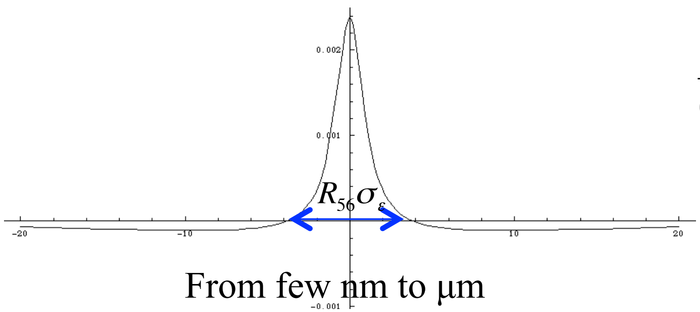


Buncher

$$\left\langle \frac{\delta E}{E} \right\rangle \cong -2Z\frac{r_e}{a^2} \cdot \frac{L_{pol}}{\gamma} \cdot \left(\frac{z}{|z|} - \frac{z}{\sqrt{a^2/\gamma^2 + z^2}} \right)$$



Exact calculations: solving Vlasov equation

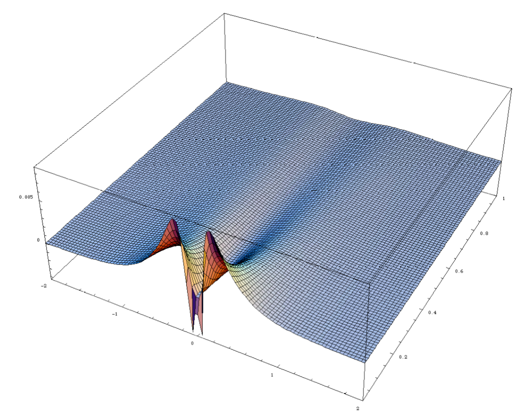


From few nm to μm

$$\frac{\gamma_o z_i}{\left(r_i^2 + \gamma_o^2 z_i^2\right)^{3/2}}; \; z = z_i + R_{56}\left(\frac{\delta\gamma_i}{\gamma_o} - A\frac{\gamma_o z_i}{\left(r_i^2 + \gamma_o^2 z_i^2\right)^{3/2}} \right);$$

$$\Omega = \frac{Zr_e L}{\beta_o^2 R_{56}^2 \gamma_o^3 \sigma_\varepsilon^3}$$

$$N_e \approx 4\pi Z n_o \frac{r_e L |R_{56}|}{\beta_o^2 \gamma_o}$$



$$\tilde{\rho}(z \cdot R_{56}\sigma_\varepsilon) = \pi c_o \cdot \int_0^\infty Y\, dY \cdot \left\{ \frac{Erf\left(\frac{Y - \Omega Y^{-2} + z}{\sqrt{2}}\right) + Erf\left(\frac{Y - \Omega Y^{-2} - z}{\sqrt{2}}\right)}{1 - \Omega Y^{-3}} - Erf\left(\frac{Y+z}{\sqrt{2}}\right) - Erf\left(\frac{Y-z}{\sqrt{2}}\right) \right\};$$

For 7 TeV p in LHC CeC case: Simple “gut-feeling” estimate gave 22.9 boost in the induced charge by a buncher, while exact calculations gave 21.7. Maximum bunching depends on the e-beam quality

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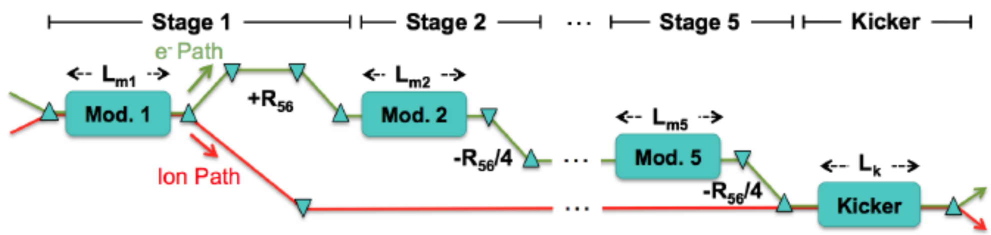
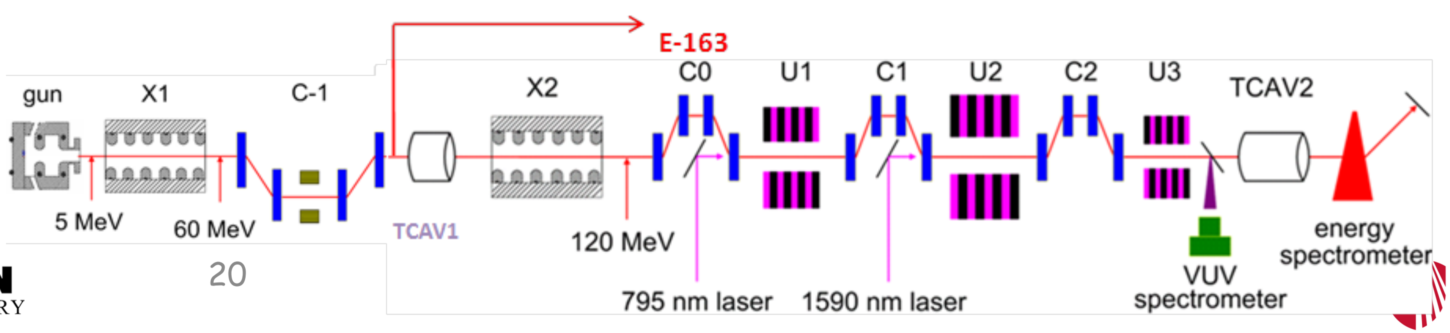
More details on micro-bunching amplification in CeC in next talk by D. Ratner



Today 1:45 pm

WG5 - San Martin Room

Relativistic Effects in (micro)bunching: What are limits of amplification?

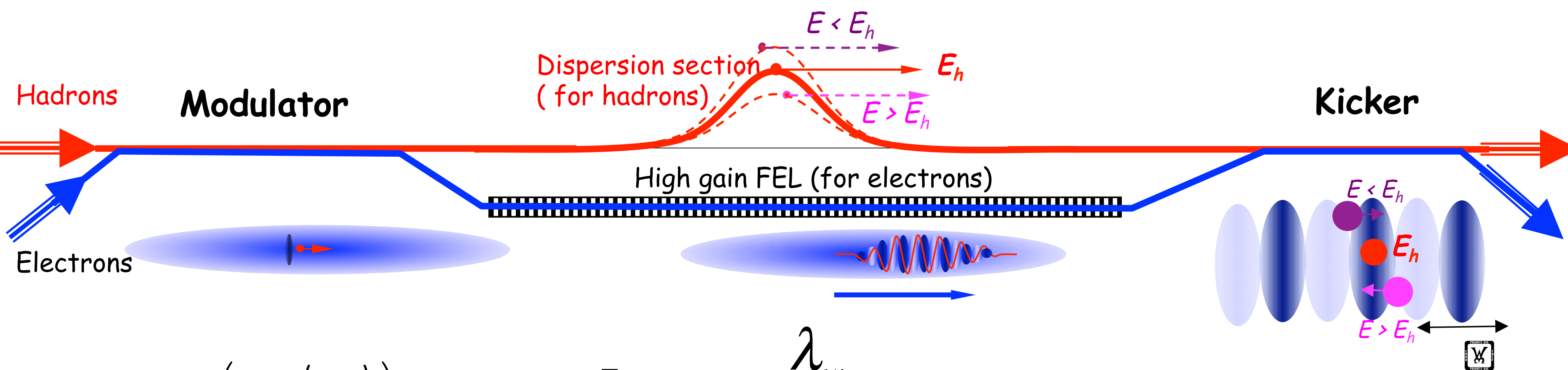


CeC Parameters
Modulator

Parameter	CeC PoP	eRHIC	LHC
Spices	Au	p	p
Particles per bunch	10^9	$2x10^{11}$	$1.7x10^{11}$
Energy GeV/u	40	250	7,000
RMS ε_n, mm mrad	2.5	0.2	3
RMS energy spread	$3.7\ x10^{-4}$	10^{-4}	10^{-4}
RMS bunch length, nsec	3.5	0.27	1
e-beam energy MeV	21.8	136.2	3812
Peak current	75	50	30
RMS ε_n, mm mrad	5	1	1
RMS energy spread	$1\ 10^{-4}$	$5\ 10^{-5}$	$2\ 10^{-5}$
RMS bunch length, nsec	0.05	0.27	1
Modulator length, m	**3**	**10**	**100**
Plasma phase advance, rad	**1.7**	**2.14**	**0.06**
Buncher	**None**	**None**	**Yes**
Induced charge, e	**88.1**	**1.54**	**2**

Central Section of CeC

$$D = D_{free} + D_{chicane};\; D_{free} = \frac{L}{\gamma^2};\;\; D_{chicane} = l_{chicane} \cdot \theta^2$$



$$\lambda_o = \lambda_w \left(1 + \left\langle \vec{a}_w^{\,2} \right\rangle\right) / 2\gamma_o^2 \qquad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}} \qquad L_G = L_{Go}(1+\Lambda)$$

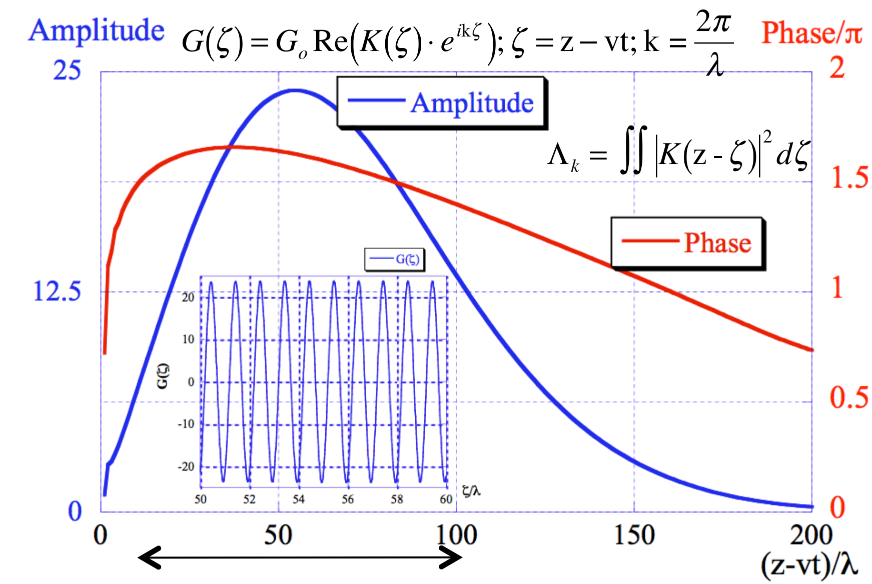
Electron density modulation is amplified in the FEL and made into a train with duration of $N_c \sim L_{gain}/\lambda_w$ alternating hills (high density) and valleys (low density) with period of FEL wavelength λ_o. Maximum gain for the electron density of High Gain FEL depends on the e-beam parameters.

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

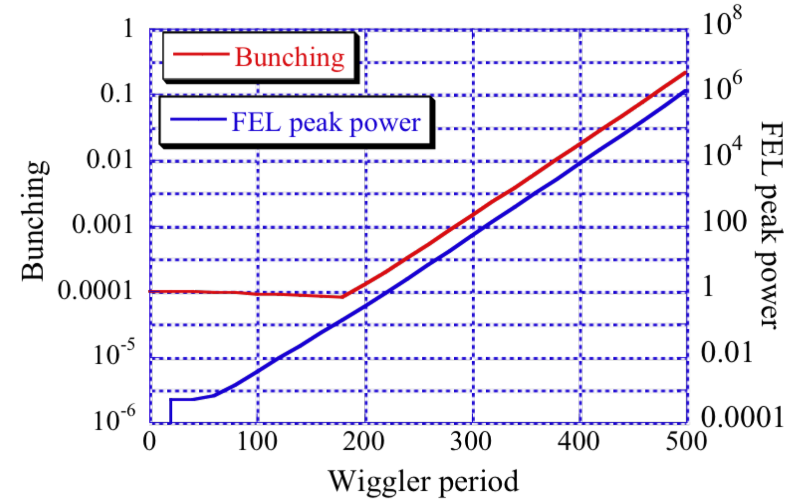
3D FEL response on δ-like perturbation: Green function calculated Genesis 1.3, confirmed by RON

Example for 250 GeV protons

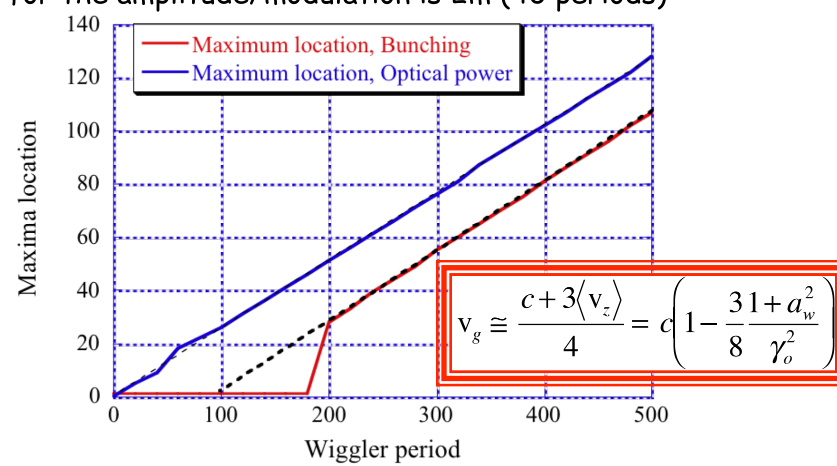
Energy, MeV	136.2	γ	266.45
Peak current, A	100	λ_o, nm	700
Bunchlength, psec	50	λ_w, cm	5
Emittance, norm	5 mm mrad	a_w	0.994
Energy spread	0.03%	Wiggler	Helical



The amplitude (**blue line**) and the phase (**red line** in the units of λ) of the FEL gain envelope (Green function) after 7.5 gain-lengths (300 period). Total slippage in the FEL is 300λ, λ=0.7 µm. A clip shows the central part of the full gain function for the range of ζ={50λ, 60λ}.



Evolution of 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)



Propagation of the maximum of the bunching wave-packet and the FEL power simulated by Genesis, e.g. moving with group velocities. 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". There is also a delay for bunching!

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Saturation

A collective instability in electron beam, including FEL or micro-bunching, is described by set of Vlasov-Maxwell equations

$$\frac{df}{dt} \equiv \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \vec{q}}\frac{\partial H}{\partial \vec{P}} - \frac{\partial f}{\partial \vec{P}}\frac{\partial H}{\partial \vec{q}} = 0 \qquad \frac{\partial F^{ik}}{\partial x^k} = -\frac{4\pi}{c} j^i$$

Maxwell equations a linear by definition, while Vlasov equation is not!
Hence, a model-independent estimate for maximum gain using definition of saturation when the e-beam density perturbation is in order of the initial beam density

$$\boxed{\frac{\delta n}{n} \sim 1}$$

The rest is a trivial (here I show 1D version) using Green-function

$$\delta n = \delta(z - z_o) \longrightarrow n(\tau) = n_o + \delta(z - z_o) + G_\tau(z - z_o), \; G_\tau(z) = \operatorname{Re} G_o(z) e^{ik_o z}$$

And assuming uncorrelated shot noise

$$n_o(0,z) = \sum_{i=1}^{N} \delta(z - z_i) \qquad \lambda_o \equiv 2\pi / k_o \qquad g(z_i) = \int_{-z_i}^{\lambda_o - z_i} G_\tau(z) e^{ik_o z}\, dz;$$

$$\boxed{\left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle \sim 1} \Longrightarrow g_{\max} \le \sqrt{\frac{I_p \cdot \lambda_o}{ec \cdot M_c}} \propto \sqrt{\frac{\delta\omega}{\omega}}$$

$$\Lambda_k = \frac{\iint \left| G(\zeta) \right|^2 d\zeta}{\left| G(\zeta) \right|^2_{\max}}; M_c = \frac{\Lambda_k}{\lambda_o}$$

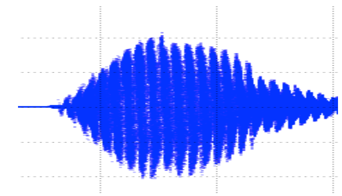
$$g_{\max} \sim 144 \cdot \sqrt{\frac{I_p[A] \cdot \lambda_o[\mu m]}{M_c}}$$

$$I_p = 10A, \; \lambda_o = 0.7\mu m; \; M_c = 38$$
$$g_{\max} \sim 62, \quad \Delta f \sim 10^{13} \; Hz$$

In excellent agreement with 3D FEL Genesis simulations

Full picture: Practical limitation

$$G(z) = \mathrm{Re}\left(g(z)\cdot e^{ikz}\right)$$



$$\int_{-\infty}^{\infty} \left|g(z)\right|^2 dz = g_{\max}^2 M_c \lambda_o$$

$$\boxed{N_e \cdot b = \sum_{i,z_i\in\{0,\lambda_o\}} e^{ik_o z_i} + g(z_i)\sum_{i=1}^{N_e} e^{ik_o z_i} + Xg(z_j)\sum_{j=1}^{N_i} e^{ik_o z_j}}$$

$$|b|^2 \sim 1$$

$X \sim 2 \;\; for \;\; protons$

$X \sim 150 \;\; for \;\; heavy \;\; ions$

$$N_e = \frac{\lambda_o I_e}{ec}; N_h = \frac{\lambda_o I_h}{eZc}$$

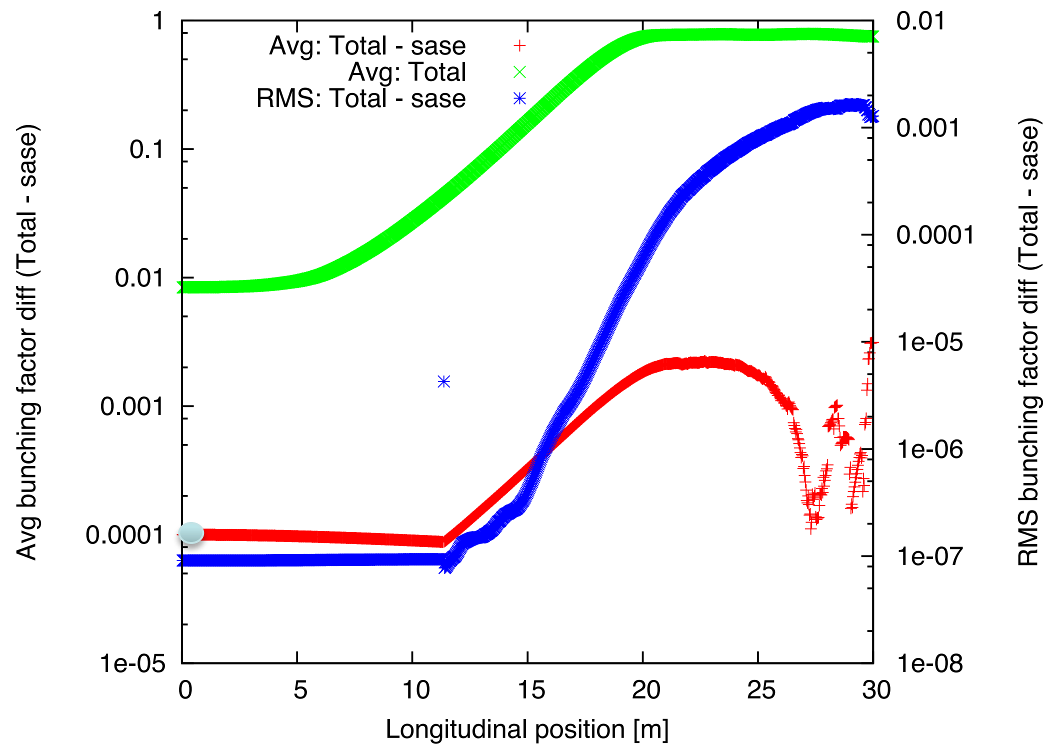
$$1 + g_{\max}^2 M_c \left(1 + X^2 \cdot \frac{N_h}{N_e}\right) \le N_e$$

$$\boxed{g_{\max} \le 144 \cdot \sqrt{\frac{I_{pe}[A]\cdot\lambda_o[\mu m]}{M_c\left(1+\frac{X^2}{Z}\cdot\frac{I_h}{I_e}\right)}}}$$

While there are ideas of reducing noise in electron beam, presence of short noise in hadron beam is the key feature of any stochastic cooling which can not be eliminated.

Comparing with simulation using Genesis (one example of RHIC 250 GeV p)

E_e	136 MeV
I_{peak}	10 A
ε_n	1 mm mrad
E spread	$1.5\ 10^{-5}$
λ_w	3 cm
a_w	1
λ_{fel}	422 nm
Nc	78
Δf	$1.4\ 10^{13}$ Hz
g_{max} (est)	33
g_{max} (sim)	27



Comparison was done for 3 cases:
CeC PoP (40 GeV/u), eRHIC (250 GeV), LHC (7 TeV)

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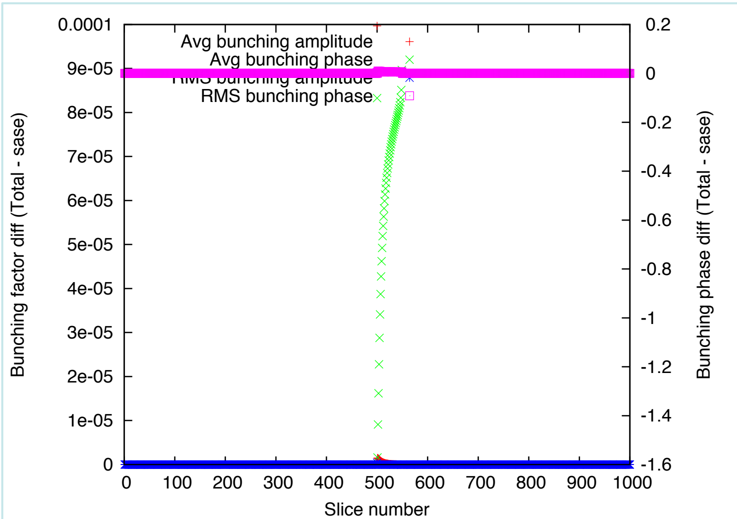
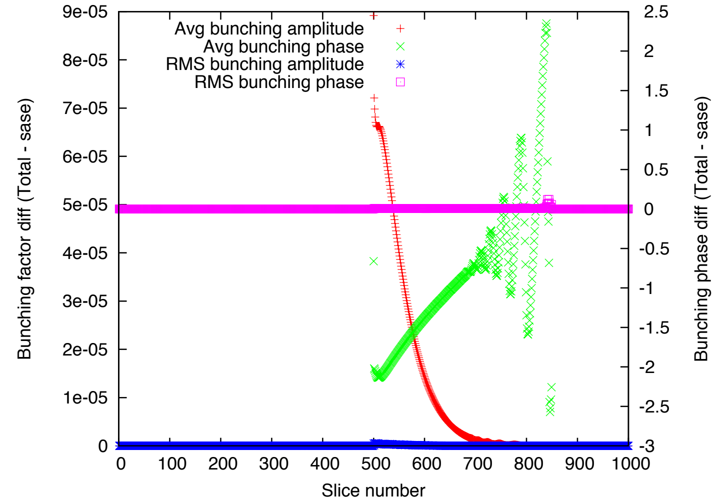
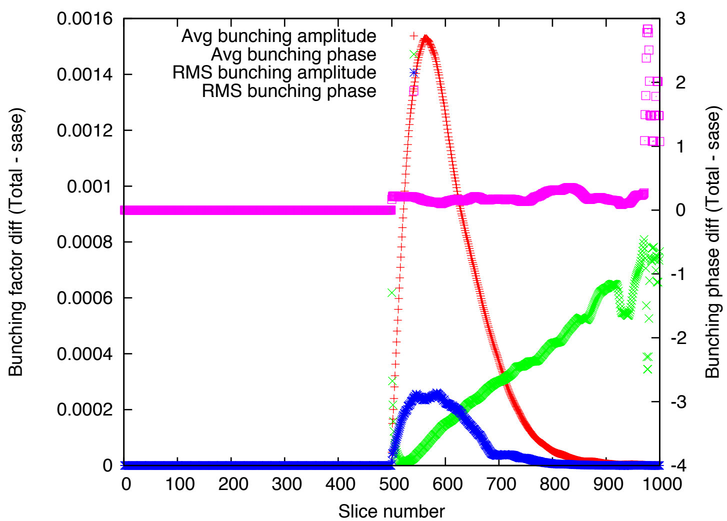
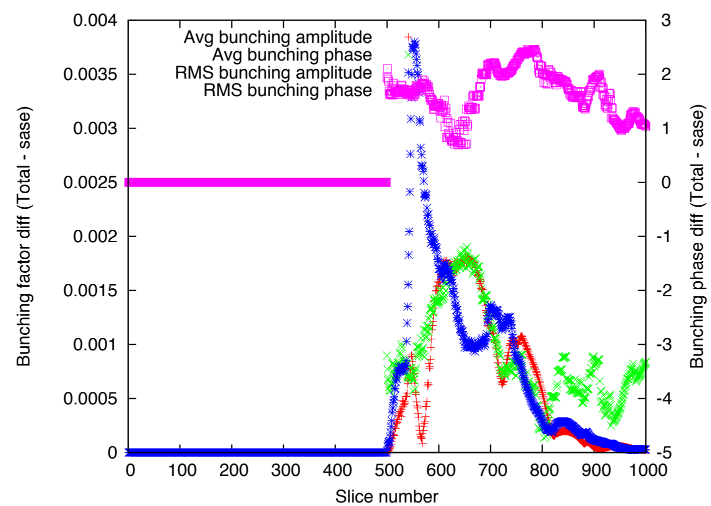
Comparing with simulation using Genesis (one example of RHIC 250 GeV p)









CeC Parameters: FEL amplifier

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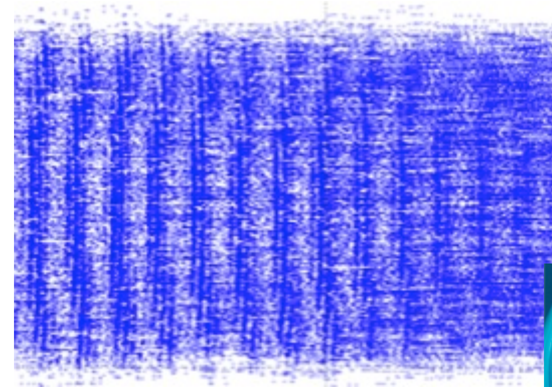
RMS bunch length, nsec	0.05	0.27	1
λ_w, cm	**4**	**3**	**10**
λ_o, nm	**13,755**	**423**	**91**
a_w	**0.5**	**1**	**10**
g_{max}	**650**	**44**	**17**
$g_{\ required}$	**100**	**3**	**8.5**
FEL length, m	**7.5**	**9**	**100**
Bandwidth, Hz	**$6.2\ 10^{11}$**	**$1.1\ 10^{13}$**	**$2.4\ 10^{13}$**

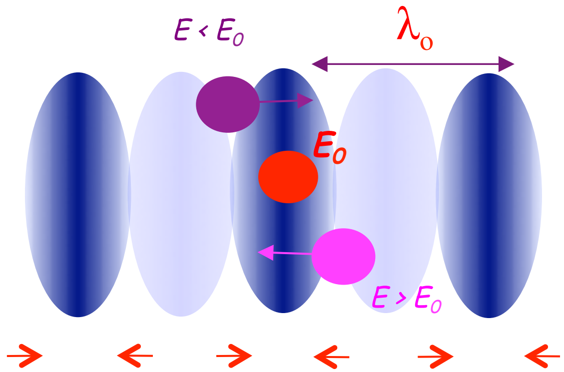
The Kicker

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

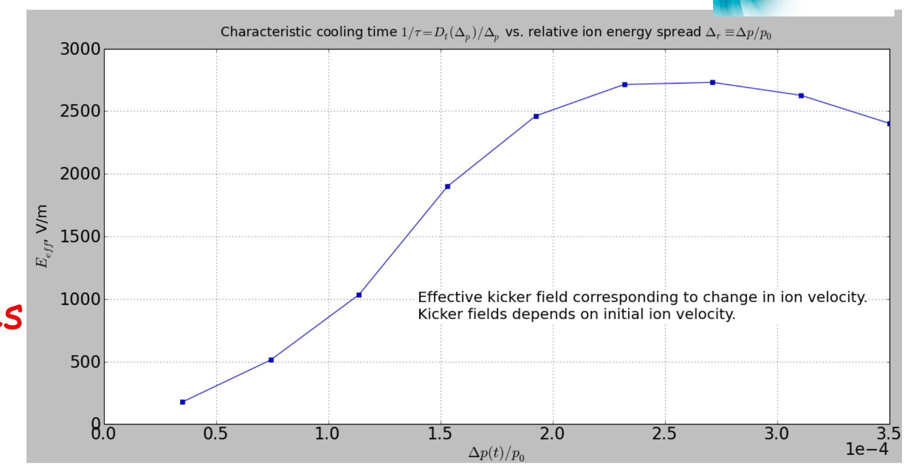


Analytical estimation

$$\Delta\varphi = 4\pi\rho \Rightarrow \mathbf{E}_z = -\mathbf{E}_o \sin k_o (z - \mathrm{v}t);\;\; \mathbf{E}_o \cong Xe\frac{2g_{\max}}{\pi\varepsilon_n\beta}\gamma_o;$$



Periodical longitudinal electric field
The same value in the co-moving and lab- frames



$$\frac{d\mathbf{E}}{dz} \cong -eE_o \cdot \sin\left\{k_o \cdot D\frac{\mathbf{E} - \mathbf{E}_o}{\mathbf{E}_o}\right\};$$

$$\boxed{\zeta_{CEC} = -\frac{\Delta\mathbf{E}}{\mathbf{E} - \mathbf{E}_o} \approx g_{\max}\frac{2}{\pi}\frac{Z^2}{A}\cdot\frac{r_p}{\varepsilon_n \cdot \sigma_\varepsilon}\cdot\chi\frac{l_2}{\beta_\perp}\frac{X}{Z};}$$

$$\chi = k_o D\sigma_\varepsilon \sim 1, \quad \frac{l_2}{\beta_\perp} \sim 1, \quad \frac{X}{Z} \sim 1.$$

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

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Transverse size effects

$$\rho(\vec{r}) = \rho_o(r)\cdot\cos(kz);$$

$$\Delta\varphi = 4\pi\rho \Rightarrow \varphi(\vec{r}) = \varphi_o(r)\cdot\cos(kz);$$

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\varphi_o}{dr}\right) - k^2\varphi_o = 4\pi\rho_o(r)$$

$$\varphi(\vec{r}) = -4\pi\cos(kz)\left\{I_0(kr)\int_r^\infty \xi K_0(k\xi)\cdot\rho_o(\xi)\,d\xi + K_0(kr)\int_0^r \xi I_0(k\xi)\cdot\rho_o(\xi)\,d\xi\right\}$$

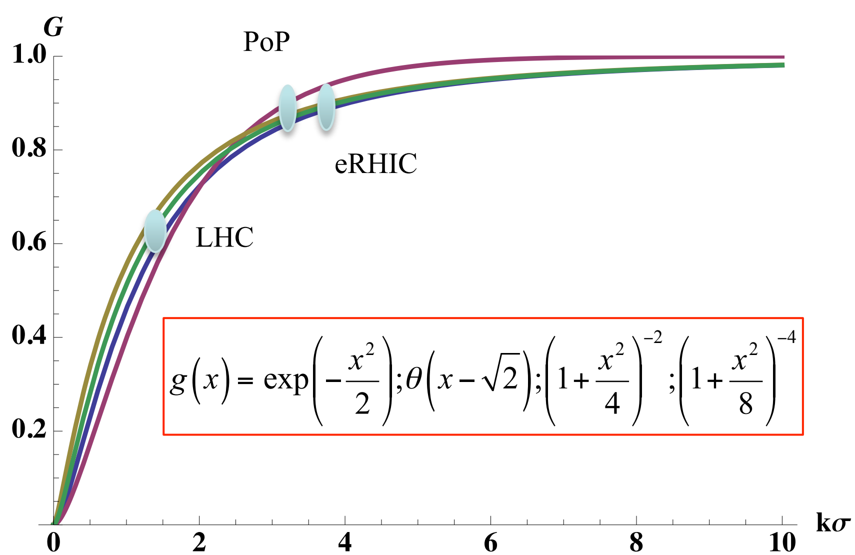
$$E_z = -\frac{\partial\varphi}{\partial z} = -4\pi k\sin(kz)\left\{I_0(kr)\int_r^\infty \xi K_0(k\xi)\cdot\rho_o(\xi)\,d\xi + K_0(kr)\int_0^r \xi I_0(k\xi)\cdot\rho_o(\xi)\,d\xi\right\}$$

$$E_r = -\frac{\partial\varphi}{\partial r} = 4\pi k\cos(kz)\left\{I_1(kr)\int_r^\infty \xi K_0(k\xi)\cdot\rho_o(\xi)\,d\xi - K_1(kr)\int_0^r \xi I_0(k\xi)\cdot\rho_o(\xi)\,d\xi\right\}$$

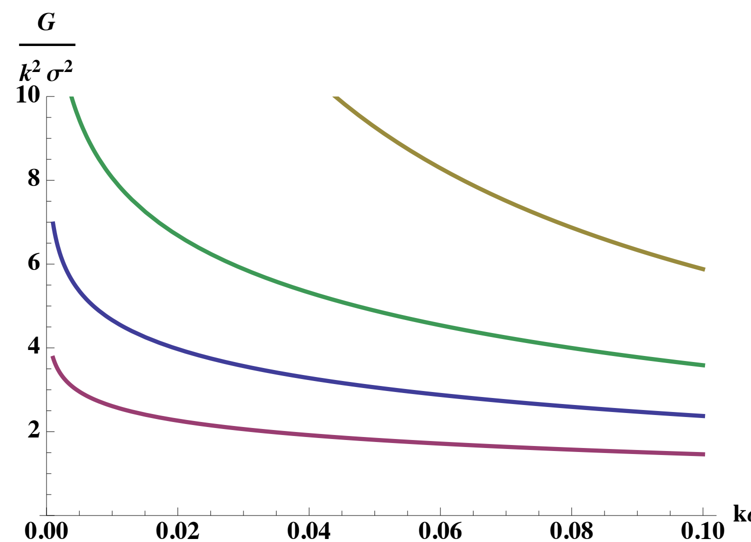
$$\rho(r) = \rho(0)\cdot g(r/\sigma)$$

$$E_{zo}(r=0) \propto -\frac{4\pi\tilde{q}}{\sigma^2}G(k_{cm}\sigma)$$

$$\boxed{k_{cm}\sigma_\perp = \frac{k_o}{\gamma_o}\sqrt{\frac{\beta_\perp\varepsilon_{n\perp}}{\gamma_o}} = \sqrt{\gamma_o}\sqrt{\beta_\perp\varepsilon_{n\perp}}\,\frac{k_w}{2(1+a_w^2)}}$$



$$\boxed{g(x) = \exp\left(-\frac{x^2}{2}\right);\theta\left(x-\sqrt{2}\right);\left(1+\frac{x^2}{4}\right)^{-2};\left(1+\frac{x^2}{8}\right)^{-4}}$$



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CeC Parameters: Kicker

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RMS energy spread	$1\ 10^{-4}$	$5\ 10^{-5}$	$2\ 10^{-5}$
RMS bunch length, nsec	0.05	0.27	1
Licker length, m	**3**	**10**	**100**
Plasma phase advance, rad	**1.69**	**1.4**	**0.06**
$k_o \sigma_r / \gamma$	**3.18**	**3.94**	**1.32**
$D \cdot k_o \sigma_\varepsilon$	**0.74**	**1**	**1**

Effects of the surrounding particles

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

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

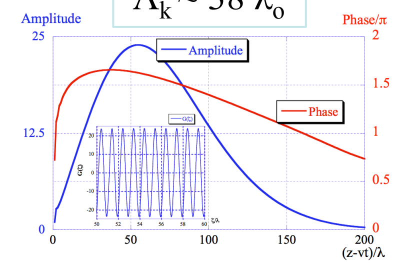
Evolution of the RMS value resembles stochastic cooling!

Best cooling rate achievable is $\sim 1/N_{eff}$, N_{eff} is effective number of hadrons in coherent sample ($\Lambda_k = M_c$)

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

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

$\Lambda_k \sim 38\, \lambda_o$



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

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

$$g \cong g_{\max} \frac{Z \cdot X}{A} \frac{2r_p}{\pi \varepsilon_{\perp n}} f(\varphi_2) \cdot \frac{l_2}{\beta_\perp},$$

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

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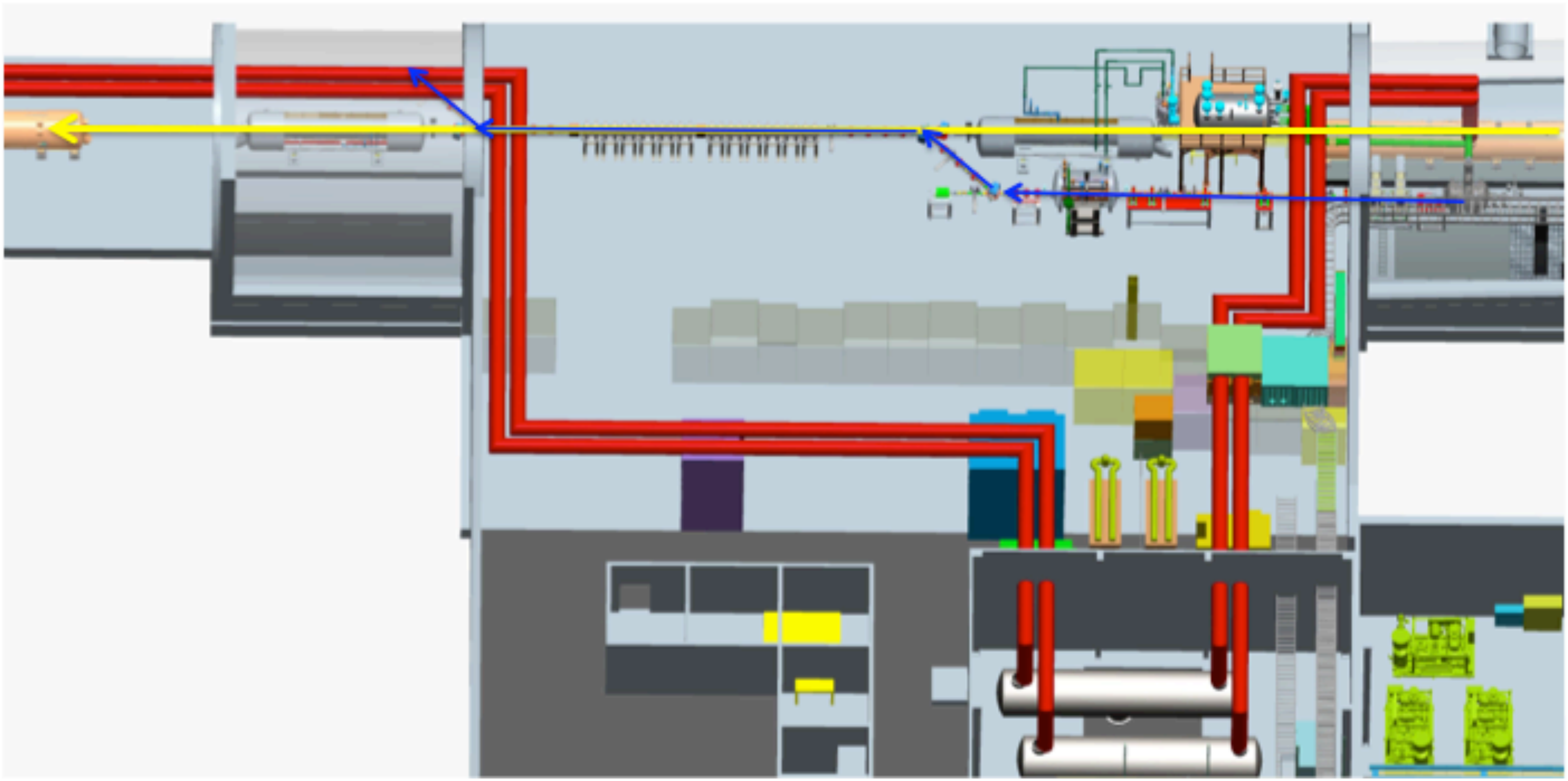
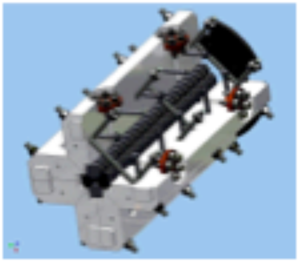
CeC Proof-of-Principle Experiment
40 GeV/u Au ions cooled by 22 MeV electrons

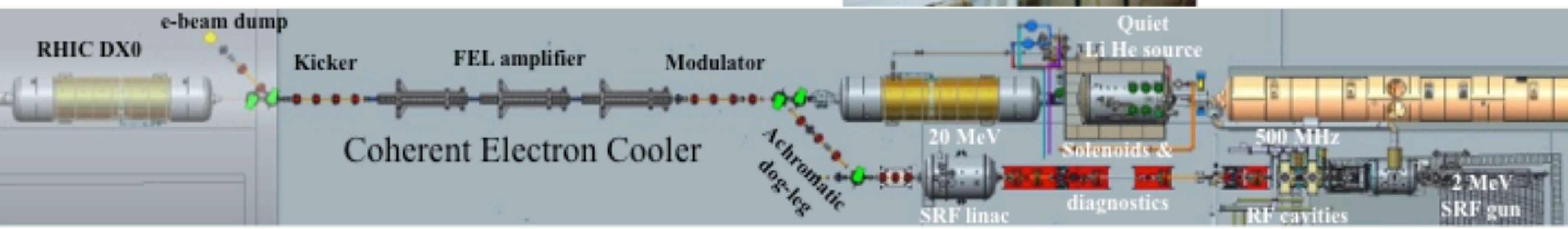


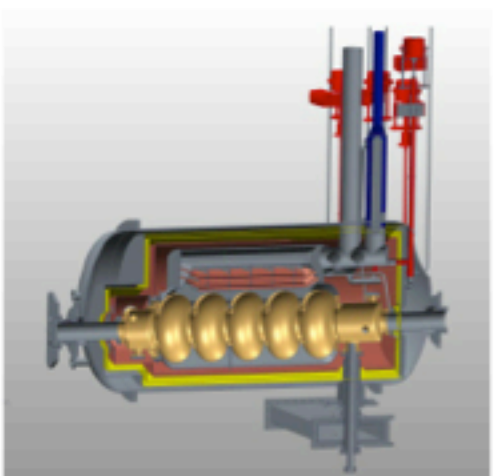
Under contraction

To test FEL & MBI based CeC

Installing CeC equipment in RHIC tunnel

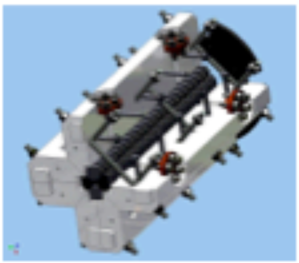


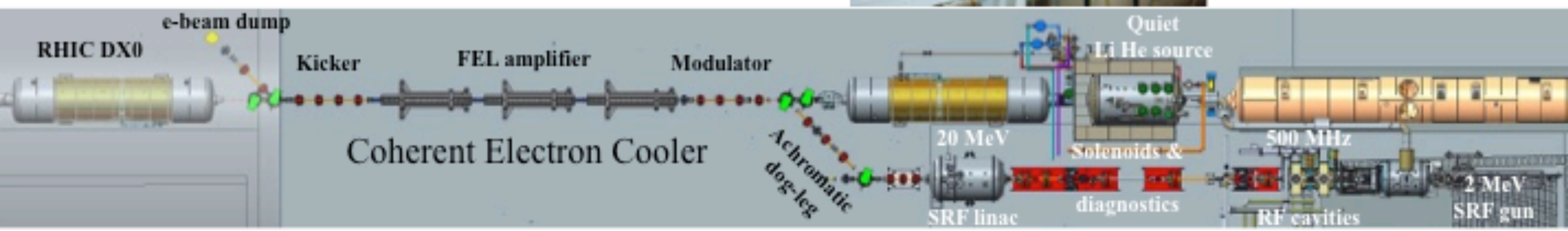


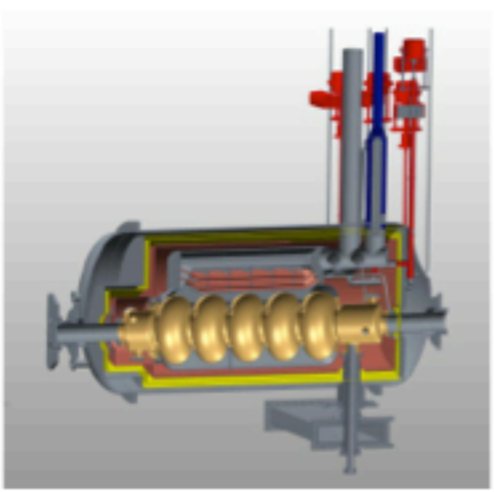


Will also use it to test eRHIC beam-beam effects

Installing CeC equipment in RHIC tunnel







Will also use it to test eRHIC beam-beam effects

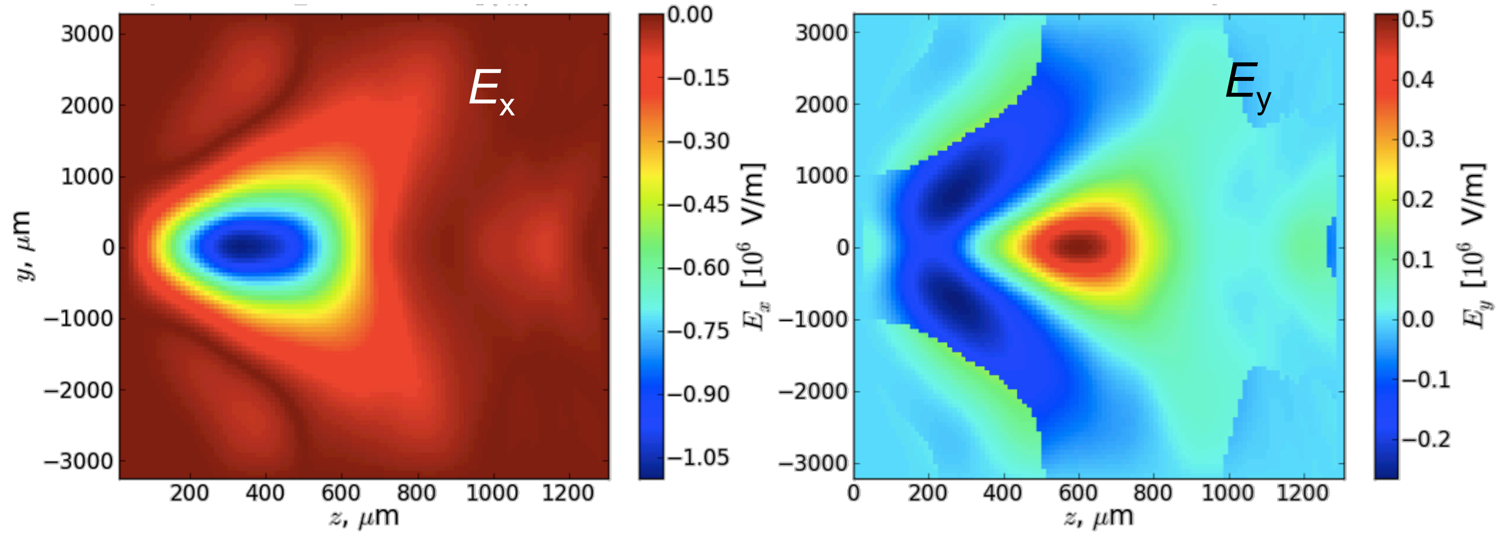
Conclusions

- At the moment there are two methods promising cooling of dense high-energy hadron beams – optical stochastic and coherent electron cooling
- In my opinion the later is more versatile and promises to deliver bandwidth exceeding that of optical stochastic cooling by orders of magnitude
- Test of the coherent electron cooling (with both FEL and micro-bunching amplification) is under preparation at BNL with possible start of experiments in 2016
- There is a lot of other fascinating (and frequently very tough problem) things we found working on *CeC* – too much to discuss in a single talk - they can be found in our 30+ publications.

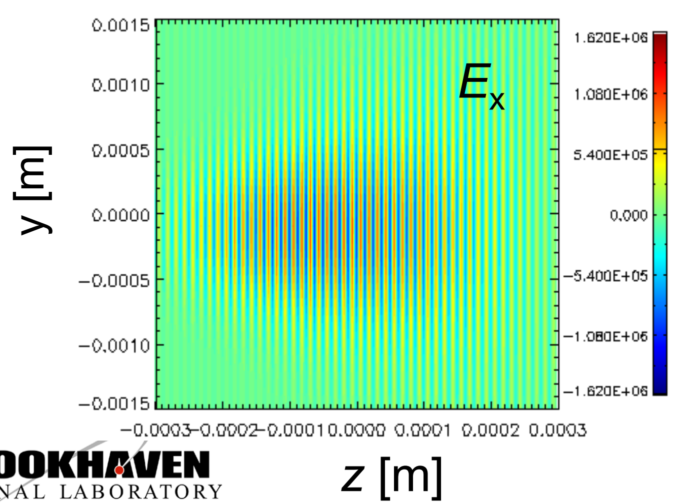
Thank you for attention!

FEL electric fields can be coupled correctly from GENESIS to VORPAL in the lab frame

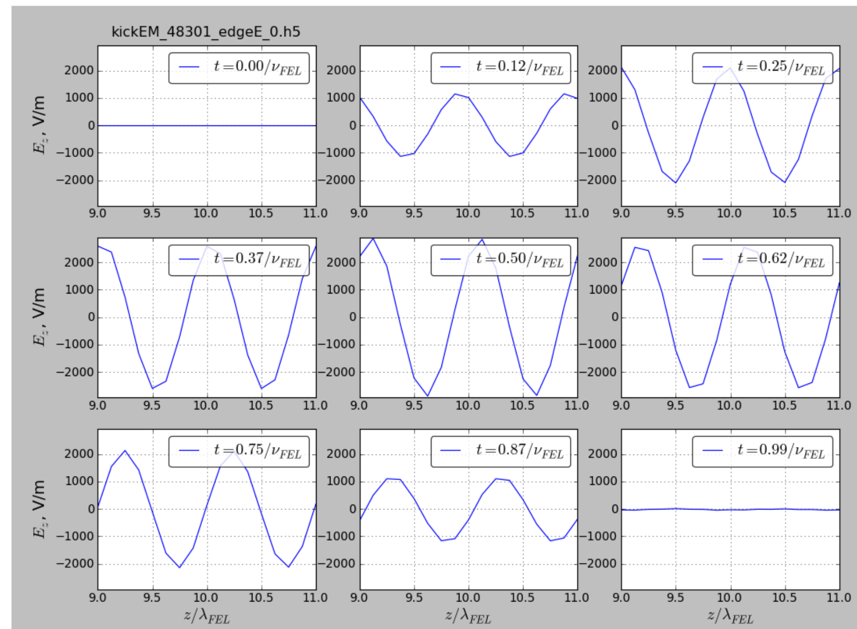
GENESIS output:



GENESIS outputs only E_x & E_y envelopes for FEL field. In VORPAL, fast oscillations are added; then E_z evolves self-consistently:



Longitudinal E-field



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Coherent Electron Cooling vs. IBS at 250 GeV

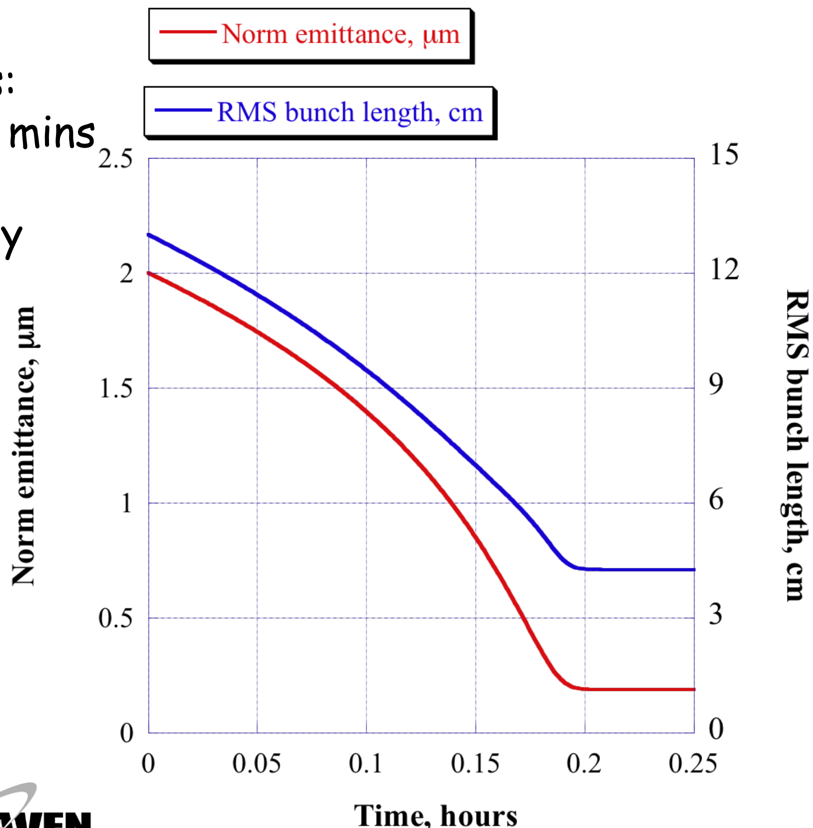
$$X = \frac{\varepsilon_x}{\varepsilon_{xo}};\ S = \left(\frac{\sigma_s}{\sigma_{so}}\right)^2 = \left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

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

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

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

Dynamics: Takes 12 mins to reach stationary point



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

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

IBS rate in RHIC p at 250 GeV, $N_p = 2 \cdot 10^{11}$
Using Beta-cool by A.Fedotov

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

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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
- Estimates for required R_{26} and D:

$$R_{26e} \sim 10^{-3};\ D_{zh} \sim \frac{\lambda_o}{2\pi\sigma_{\delta h}}$$

$$D \sim \frac{2}{3R_{26e}} \cdot \frac{\lambda_o}{2\pi\sigma_{\delta h}} \sim 10^2 \cdot \frac{\lambda_o}{\sigma_{\delta h}} \sim 10^5 \lambda_o$$

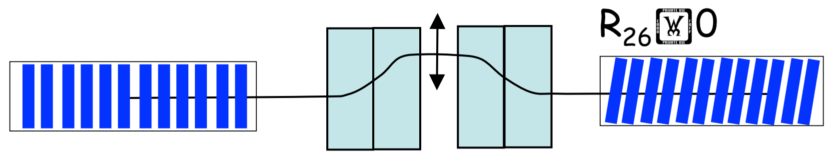
- CeC PoP

$$\lambda_{FEL} \sim 10^{-5} \Rightarrow D_{xh} \sim 1m$$

- eRHIC

$$\lambda_{FEL} \sim 0.5 \cdot 10^{-6} \Rightarrow D_{xh} \sim 0.05m$$

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



$$\delta\left(ct_e\right) = -R_{e26} \cdot x$$

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

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

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

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

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

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IBS in EIC

eRHIC: p, 250 GeV

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

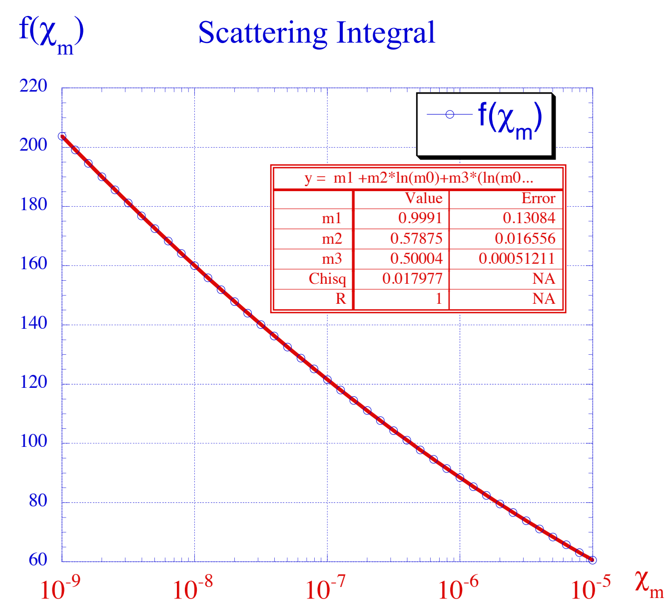
IBS rate in RHIC p at 250 GeV, $N_p=2\cdot 10^{11}$
Using Beta-cool by A.Fedotov

$$\varepsilon_{xn} = 0.2\,\mu m;\ \sigma_s = 4.9\ \text{cm}$$
$$\tau_{IBS\perp} = 0.3\min;\ \tau_{IBS//} = 1\min$$

eRHIC: $^{79}Au^{197}$, 100 GeV/u

$$\varepsilon_{xn} = 0.2\,\mu m;\ \sigma_s = 4.9\ \text{cm}$$
$$\tau_{IBS\perp} = 0.4\sec;\ \tau_{IBS//} = 1.3\sec$$

$$\frac{d}{dt}\sigma_\delta^2 = D_{\delta\,IBS} + D_{\delta\,cool} - \xi_s\sigma_\delta^2;\ \ \delta = \frac{E-E_0}{E_0};$$
$$\frac{d}{dt}\varepsilon_x = \langle H\cdot D_{\delta\,IBS}\rangle - \langle H\cdot D_{\delta\,cool}\rangle - \xi_x\varepsilon_x$$
$$H = \frac{1}{\beta_x}\left[\eta_x^2 + (\beta_x\eta_x' - \beta_x'\eta_x/2)^2\right],$$
$$D_{\delta\,IBS} = \frac{N_e r_e^2 c}{2^5\pi\gamma^3\varepsilon_x\sqrt{\varepsilon_y\beta_y(s)}\sigma_s} f(\chi_m(s));\ \ f(\chi_m) = \int_{\chi_m}^{\infty}\frac{d\chi}{\chi}\ln\left(\frac{\chi}{\chi_m}\right)e^{-\chi};$$
$$\chi_m = \frac{r_e m^2 c^4}{b_{\max}\Delta E_{acc}^2};\ b_{\max} \cong n^{-1/3},$$



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Advances in Coherent Electron Cooling

V.N.Litvinenko, G.Wang, G.I.Bell, D.L.Bruhwiler, A.Elizarov, Y.Hao, Y.Jing D.Kayran, I.V.Pogorelov, D.Ratner, B.T.Schwartz, O. Shevchenko, A.Sobol, S.D.Webb

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SLAC National Accelerator Laboratory, Menlo Park, CA USA

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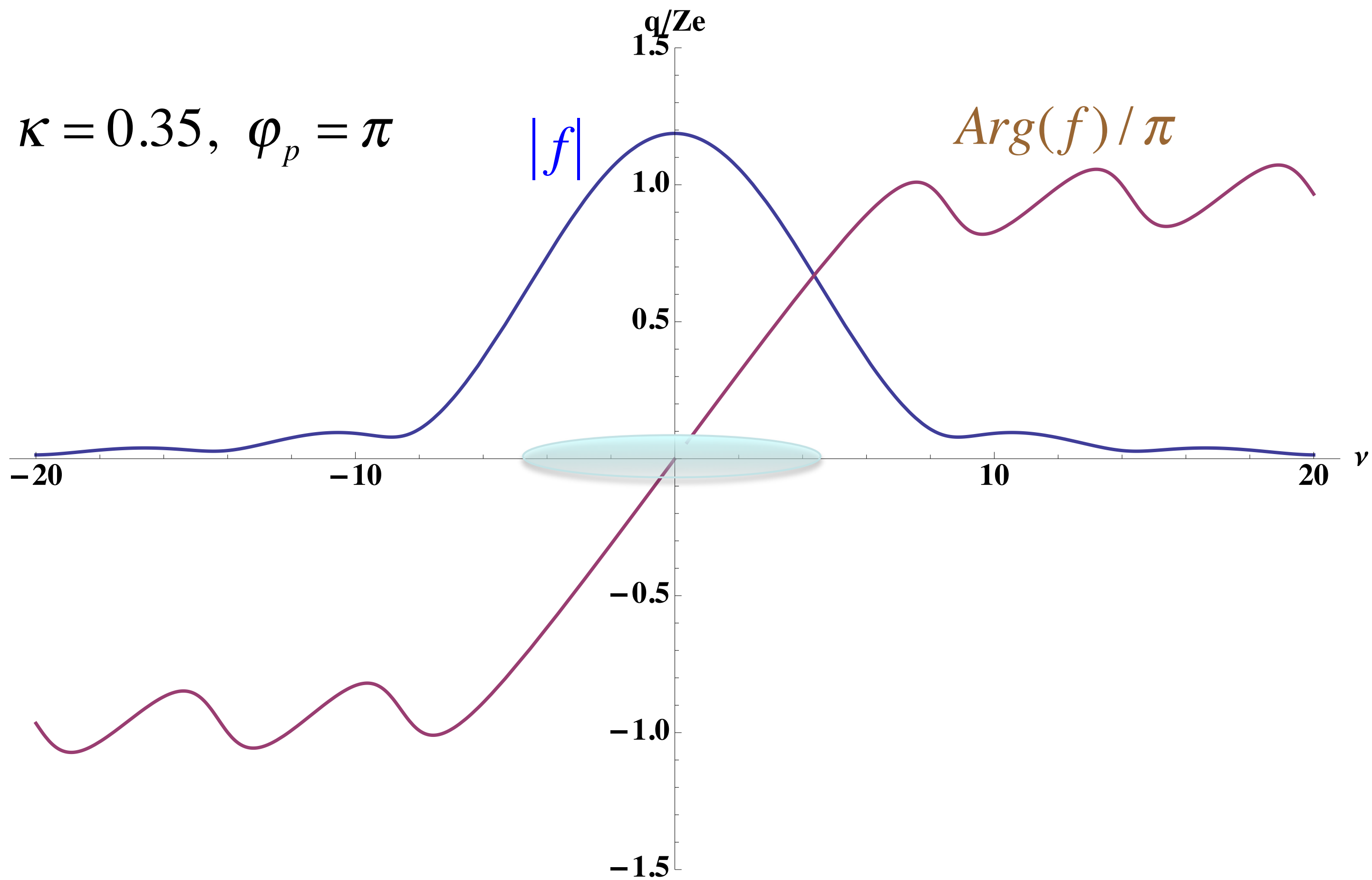
Input to FEL amplifier
Moving Ion

$$\nu = \delta\gamma_i / \sigma_{\gamma_e}$$

$$\gamma_i \neq \langle \gamma_e \rangle = \gamma_o$$



Challenges for the Theory

- Screening of hadron in a non-uniform/various density e-beam
  - Finding cases where analytical solutions are tractable
  - Developing exact self-consistent theoretical solutions with numerical evaluation (Laplace/Fourier transforms)
- Matching group and phase velocities of the wave-packet of the density modulation through the e-bunch
- Nonlinearity of FEL requires detailed studies
- Analytical solution for hadron beam dynamics with CeC and IBS is also need to cross-check the simulations

Challenges on simulations

- While modulator/kicker VORPAL simulations for a uniform constant density e-beam are well under control, finite beam size and alternative focusing are needed for dynamics in modulator/kicker
- Start-to-end simulations for e-beam, including space charge effects, are needed
- New FEL code, naturally connected to VORPAL, is needed (EVOLUTION vs. GENESIS)
- Inclusion of the CeC cooling in one of the cooling codes (like Betacool) is needed

- Other CeC schemes differ for the classical option by the amplification mechanism, but otherwise have similar features:
  - In the modulator hadrons imprint their "image" into the electron beam
  - In an amplifier this image is amplified
  - The hadrons go through a dispersion section with an appropriate delay
  - In the kicker the energy of the hadrons is corrected by self-induced electric field in the electron beam

- In the case, the blended scheme with a laser amplifier would have similar bandwidth as a visible FEL ~ 10^{14} Hz .
  - The amplifier can be less expensive (no need for a long FEL wiggler).
  - At the same time, it would require a larger delay of the hadron beam (since the cm-scale light delays in windows and laser amplifier media) and it could be significantly more expensive (read elaborate) hadron lattice to achieve require R_{56}.
- The buncher/micro modulator scheme most likely would have largest bandwidth of ~ 10^{17} Hz and could be considered also for cooling muon beams

Ultimate case: 7 TeV LHC p

- γ=7460.52
- Peak current: 30 A
- Norm emittance 1 mm mrad
- RMS energy spread 2.5e-5
- λw=10 cm
- $a_w = 10$
- λo=90.73 nm
- Mc = 140

My simple formula gives

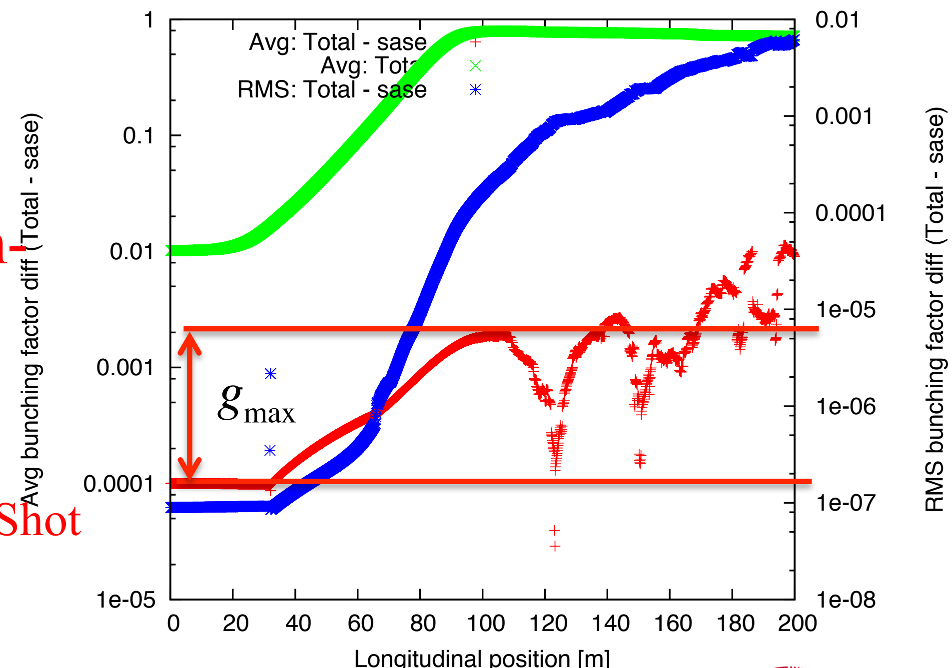
$$g_{\max} \sim 144 \cdot \sqrt{\frac{I_p[A] \cdot \lambda_o[\mu m]}{M_c}} = 20$$

3D Genesis 1.3 simulations; Green-function saturates at $g_{\max}$ =18.7

32 random shot-noise seeds

Green function is the averaged difference (not RMS!) between the resulting bunching from (Shot Noise +δ-function) minus from (Shot Noise)

We plan to use – g= 8.5!

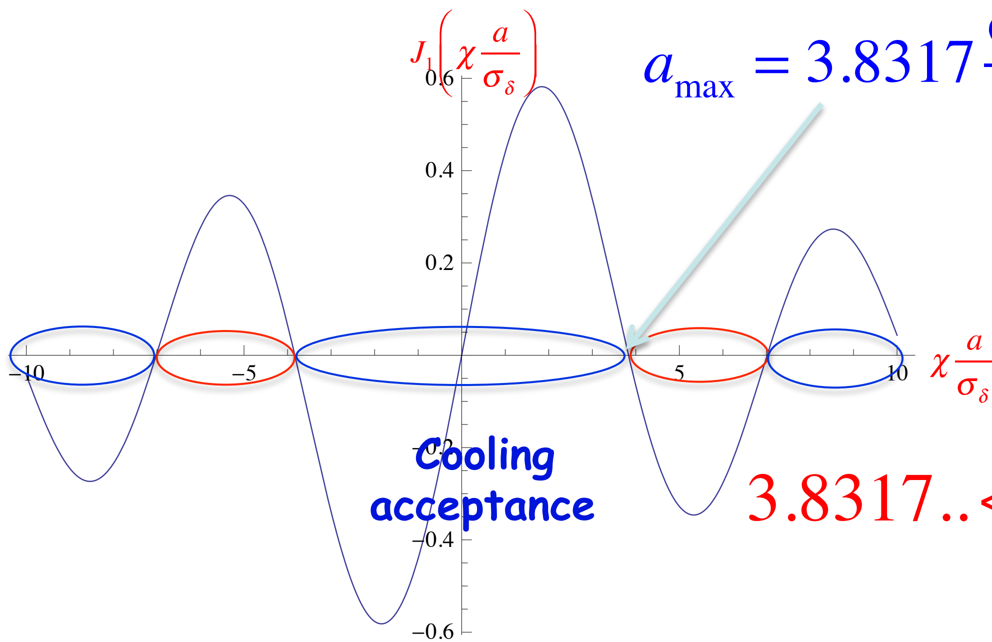


Synchrotron Oscillations

$$\frac{d\delta}{dn} = -\zeta\sigma_{\delta h}\cdot\sin\left\{\chi\frac{\delta}{\sigma_{\delta h}}\right\};\ \chi = k_{fel}D_{zh}\sigma_{\sigma h}$$

$$\delta = a\cdot\cos(\omega_s n+\phi)$$

$$\left\langle\frac{a'}{\sigma_{\delta h}}\right\rangle = \zeta\cdot J_1\left(\chi\frac{a}{\sigma_{\delta h}}\right)$$



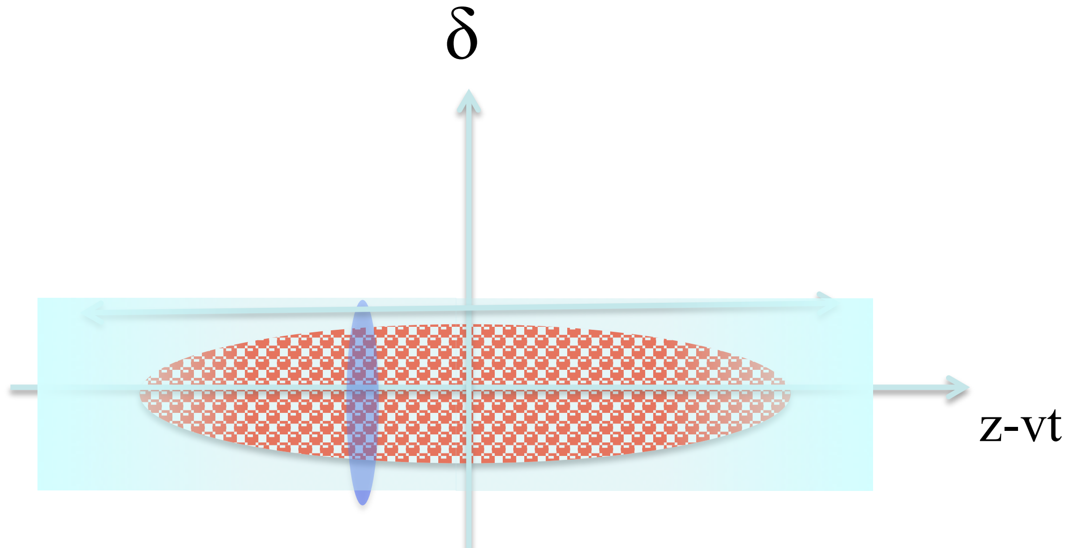
$$a_{\max} = 3.8317\frac{\sigma_{\delta h}}{\chi}$$

$$3.8317.. < \chi\cdot\frac{a}{\sigma_{\delta h}} < 7.0...$$

Painting

- It is natural that e-bunches are many-fold shorter than the hadron bunches
- Since cooling is slow process taking millions of turns, a slow modulating the phase locking between the electron accelerator and the hadron ring RF system will allow to cover the entire hadron bunch
- Choosing an appropriate phase variation function, we can en
- e that beam is not overcooled and that the local cooling is proportional to the local diffusion

$$\left\langle \zeta_{CeC}(z) \right\rangle \sim \mathbf{D}_{IBS}(z)$$



$$\left\langle \zeta_{CeC} \right\rangle \approx \zeta \cdot \frac{\sigma_{z,e}}{\sigma_{z,h}}$$

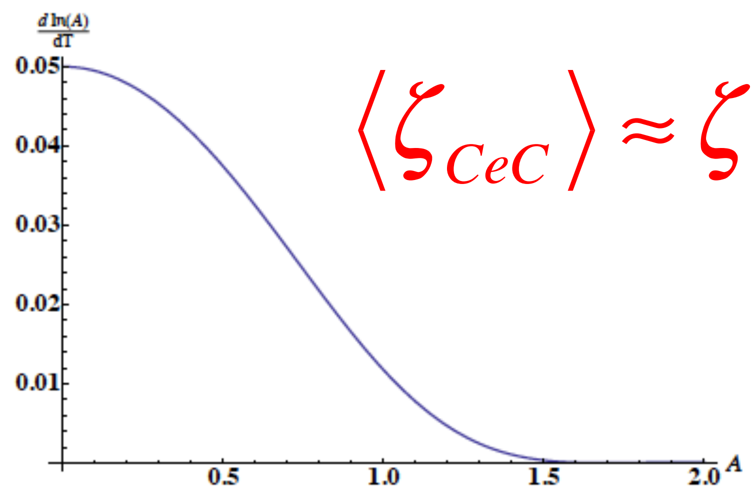


Figure 1: Cooling rate for the given set of parameters with painting at width $3\sigma_z$

Details are in S.Webb, Gang Wang , V. N. Litvinenko, PAC'11 (2011) p. 232

Distribution of the decrements

$$X = \frac{1}{2}\sum_{k=1}^{3}\left(a_k Y_k(s) e^{i\psi_k} + c.c.\right);\ \ Y_j^{*T} S Y_k = 2i\delta_{jk}; Y_j^T S Y_k = 0;\ S = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & \sigma \end{bmatrix}; \sigma = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

$$\delta X = -\xi \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \delta + k_x x \end{bmatrix} = -\xi K \cdot X = -\xi \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ k_x & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \frac{1}{2}\sum_{k=1}^{3}\left(a_k Y_k(s) e^{i\psi_k} + c.c.\right);$$

$$\delta a_k = -\xi \frac{e^{-i\psi_k}}{2i} Y_k^{*T} S K \cdot \sum_{j=1}^{3}\left(a_j Y_j(s) e^{i\psi_j} + c.c.\right);$$

$$\xi_k = \frac{\langle \delta a_k \rangle}{a_k} = -\xi \frac{Y_k^{*T} S K Y_k}{2i}; \qquad 2 \cdot \sum_{k=1}^{3} \xi_k = \xi \cdot Tr(K) = \xi;$$

$$\xi_k = \frac{\xi}{2i} \cdot Y_k^{5*}\left(k_x Y_k^1 + Y_k^6\right)$$

$$X^T = \{x, x', y, y', -c\tau, \delta\}$$

$$k_x = \frac{R_{52e}}{D_{zh}}$$

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Distribution of the decrements

$$Q_s << Q_{1,2}$$

$$Y_{k=1,2} \cong \begin{pmatrix} Y_{k1} \\ Y_{k2} \\ Y_{k3} \\ Y_{k4} \\ Y_{k5} \\ 0 \end{pmatrix} = \begin{pmatrix} Z_k \\ -Z_k^T SD \\ 0 \end{pmatrix}; Y_3 \cong \frac{1}{\sqrt{\Omega}} \begin{pmatrix} D_x \\ D'_x \\ D_y \\ D'_y \\ i\Omega \\ 1 \end{pmatrix};$$

$$\xi_k = \frac{\xi}{2i} \cdot Y_k^{*5} \left(k_x Y_k^1 + Y_k^6 \right)$$

$$\xi_s = \frac{\xi}{2} \left(k_x D_x + 1 \right);$$

$$\xi_{k=1,2} = -\frac{\xi}{2i} \cdot \left(Z_k^{*T} SD \right) \cdot k_x Z_k^1$$

$$\xi_1 + \xi_2 = -k_x D_x \frac{\xi}{2}$$

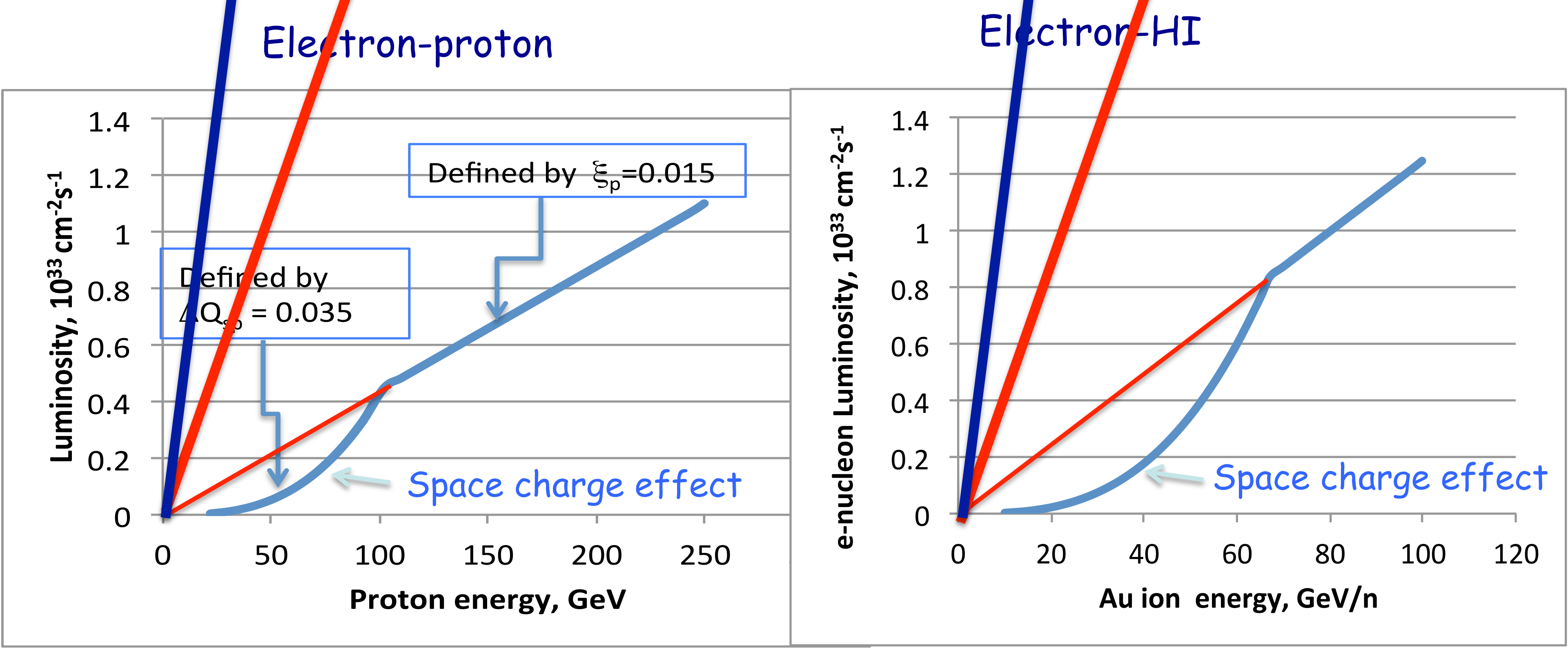
Uncoupled case

$$\xi_y = 0; \quad \operatorname{Re} \xi_x = -\frac{\xi}{2} \cdot R_{52e} \frac{D_{xh}}{D_{zh}}; \quad \operatorname{Re} \xi_s = \frac{\xi}{2} \cdot \left(1 - R_{52e} \frac{D_{xh}}{D_{zh}} \right)$$

Developments

- Optimization of the CeC process revealed a contra-intuitive trend
  - For a fixed charge per e-bunch (a reasonable assumption)
  - It is the best to stretch the e-bunch to cover the duration of the hadron bunch
  - If plasma oscillations are too slow or length of the modulator becomes excessive – use a buncher to generate the density modulation
  - The maximum possible density modulation is inversely proportional to a local energy spread

Luminosity depends on the hadron beam energy



The electron energy is 15.9 GeV or below; 40% at 21.1 GeV

Going on the red curve requires space charge effect compensators – one of future AIPs

Luminosity enhancement – in contrast with energy increases - can be done without interapting physics program

IBS

$$\varepsilon_x = \tau_x \cdot \left(D_{ibs} + D_{cool}\right);$$

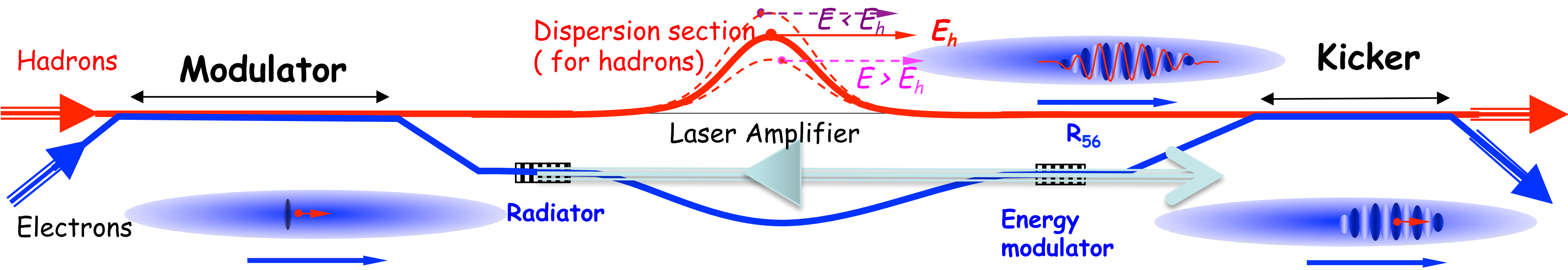
$$D_{ibs} = \frac{N_e r_c{}^2 c}{2^5 \pi \gamma^3 \varepsilon_x \sqrt{\varepsilon_y} \sigma_s} \left\langle \frac{f\left(\chi_m(s)\right) H(s)}{\sqrt{\beta_y(s)}} \right\rangle_s ; r_c = \frac{Z^2 e^2}{Am}$$

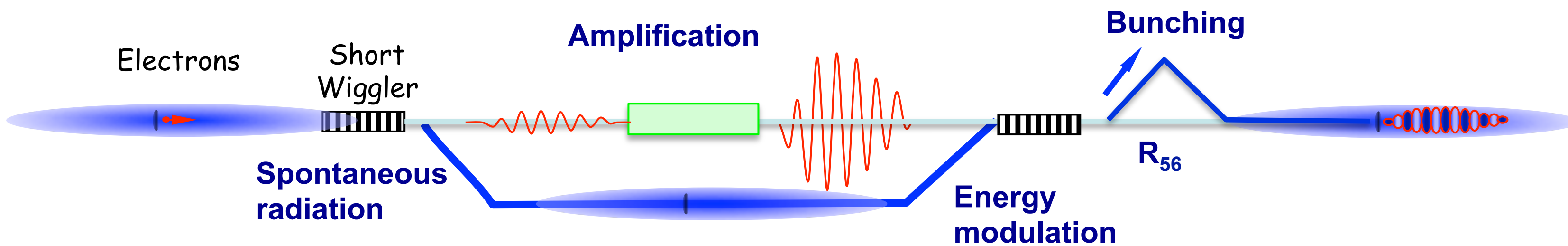
$$f\left(\chi_m\right) = \int_{\chi_m}^{\infty} \frac{d\chi}{\chi} \ln\left(\frac{\chi}{\chi_m}\right) e^{-\chi};$$

$$\chi_m = \frac{r_e m^2 c^4}{b_{\max} \sigma_E{}^2}; b_{\max} \cong n^{-1/3}$$

Coherent Electron Cooling Schemes

Blended – laser amplifier (2007, VL)



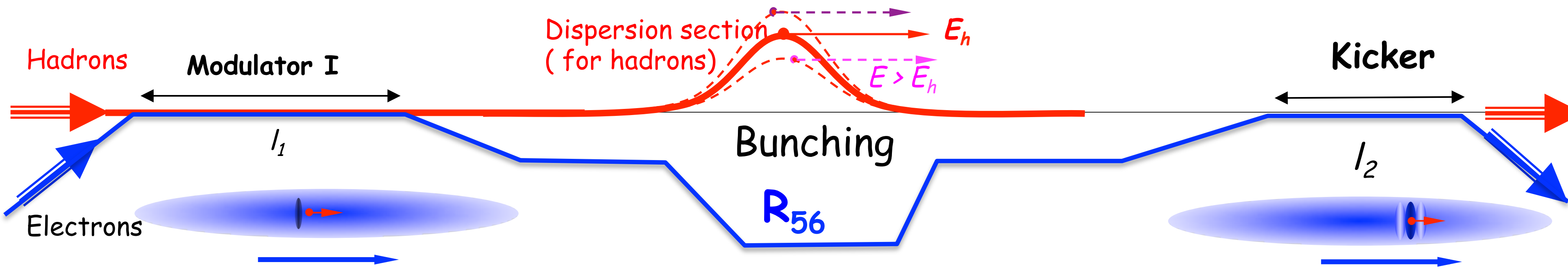


- Main advantage: most likely cheaper than FEL (much shorter wigglers). Power requirements for the amplifier are very low (in watts)
- Main disadvantage: longer delay (windows plus active media) for hadrons. Will need active reduction of longitudinal dispersion
- Note: since electrons radiate with the light, the resonant conditions with the amplifier wavelength can be maintained by changing Kw

$$\lambda_o = \lambda_w \left(1 + \frac{K_w^2}{2}\right) / 2\gamma_o^2$$

Coherent Electron Cooling Schemes

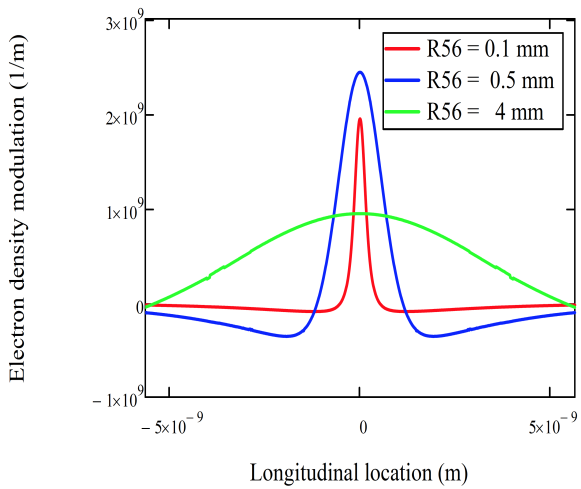
Enhanced bunching: single stage - VL, FEL 2007
Micro-bunching: Multi-stage 2013, D. Ratner,



Enhanced e-cooling

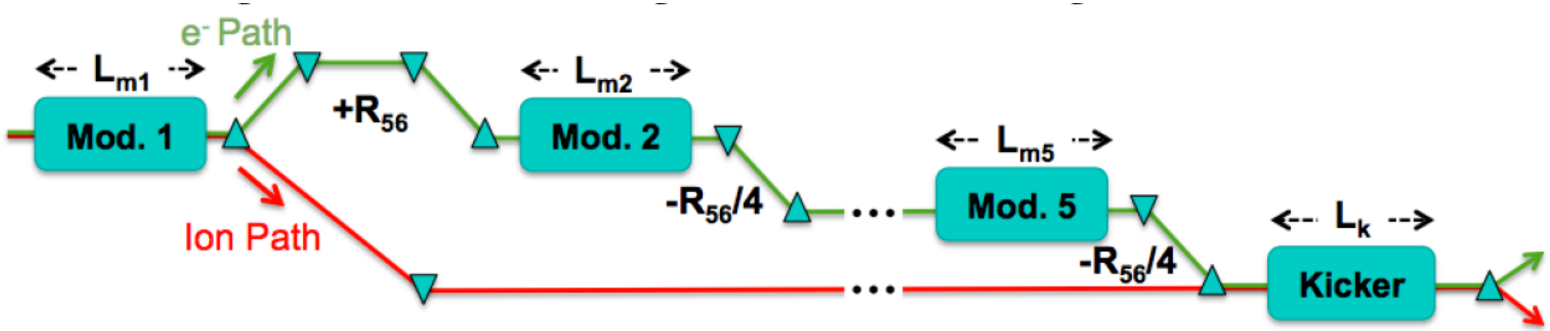
γ	7461	R_{56} (mm)	0.5
$\varepsilon_{n,rms}$ (μm)	0.5	Bunch length (full,cm)	1.5
Q_e (nC)	0.5	$\Delta\gamma/\gamma$, rms	1E-6
I_{peak} (A)	10	Beam width, rms (μm)	30
β (m)	13	Plasma phase advances (rad)	0.064
L_{mod} (m)	25	Back ground line density (1/m)	2.1E11

Table 1: parameters applied in generating Fig. 1-6.



Coherent Electron Cooling with Micro-bunching amplifier

D. Ratner, Physical Review Letters **111** (2013),084802.



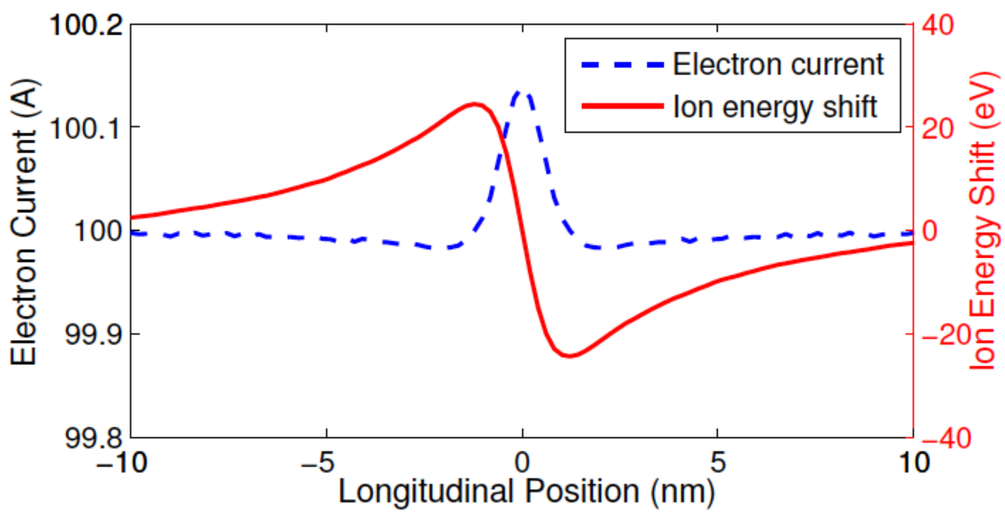


FIG. 4. The blue dashed line shows the final electron current from a fluid model without shot noise for LHC-like parameters of Table I . The corresponding ion energy shift (solid red line) has a maximum kick of around 25 eV per pass.

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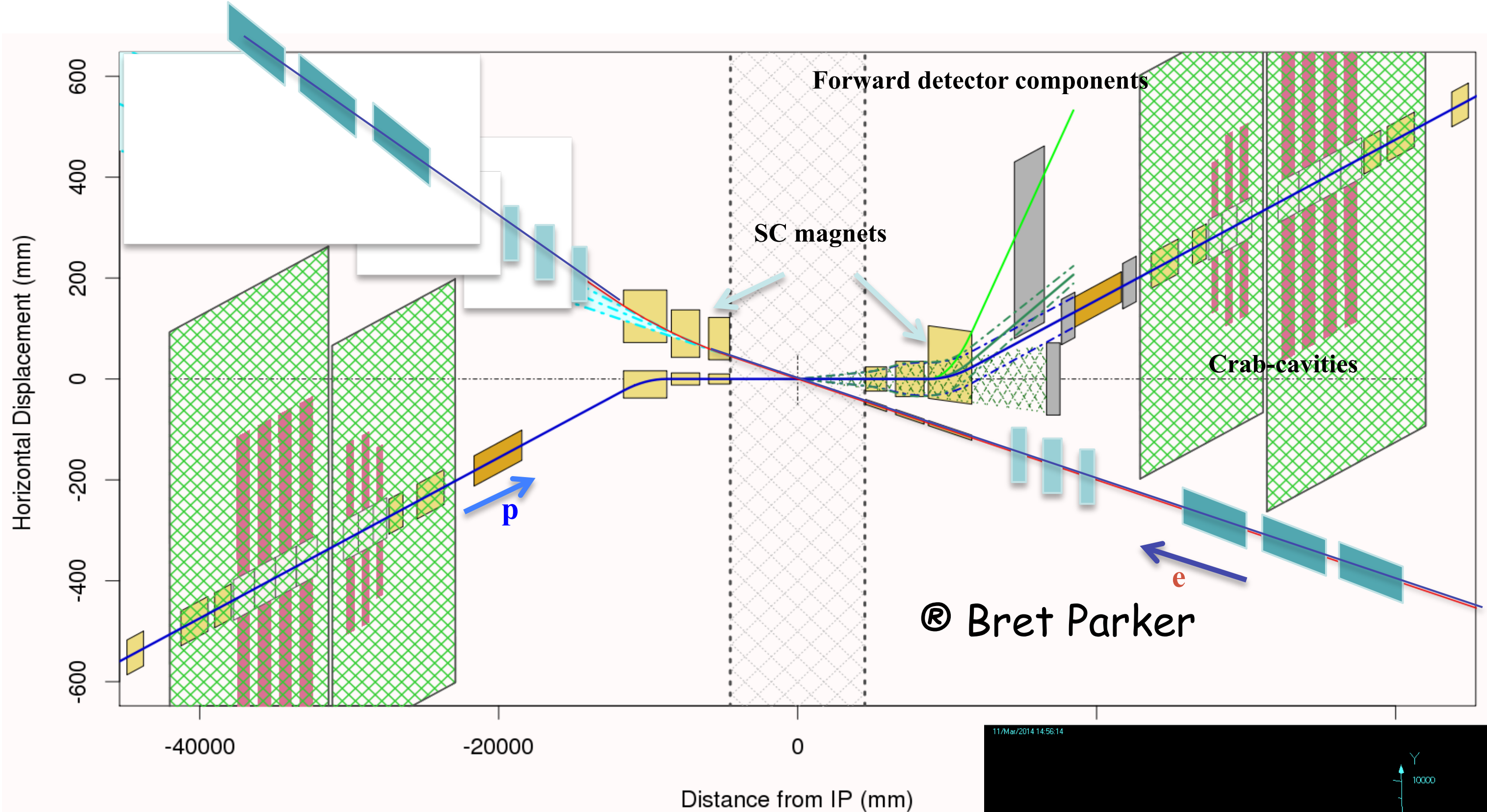
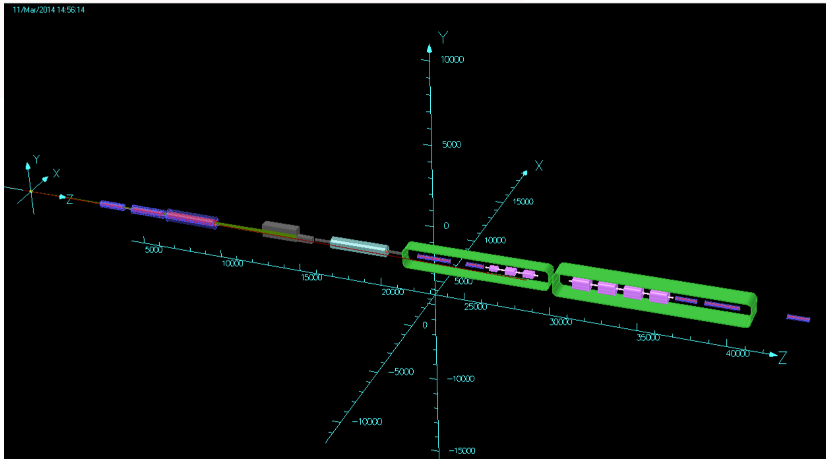
Interaction Region with β* = 5 cm





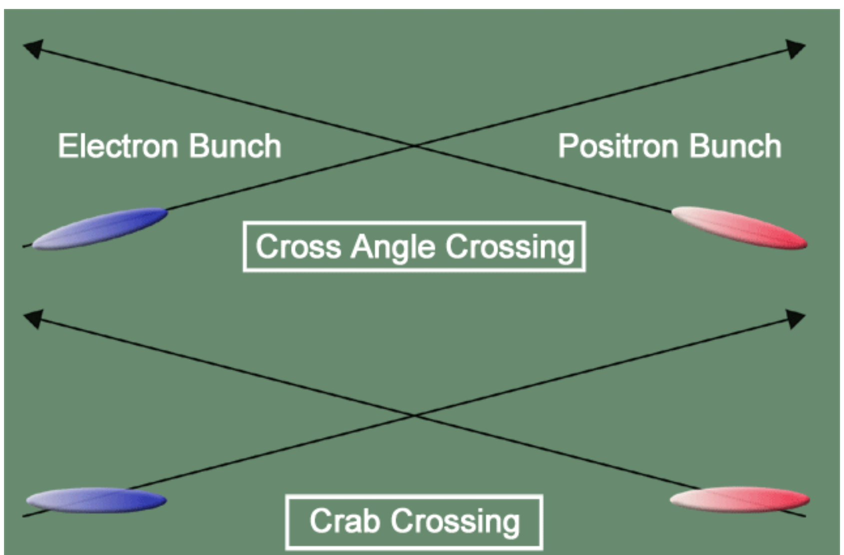
We are bending electron beam gently towards the IR and use 10 mrad crossing angle to separate the beam without bending electron beam ....

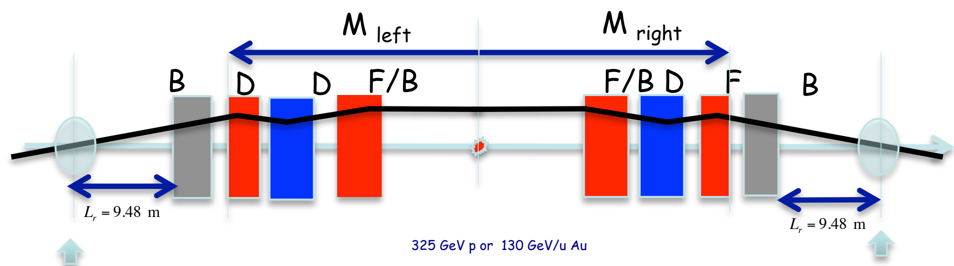
*15-fold reduction compared with RHIC

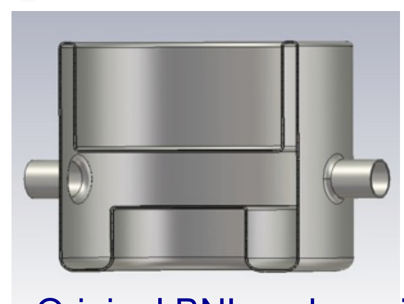
Why crab-crossing?

- We have to separate colliding beams.
- To avoid synchrotron radiation by 30 GeV electrons in the IR – one of serious backgrounds at HERA, we can not use separating dipoles.
- To separate beams without applying magnetic field, we need a crossing angle
- This also allows bringing the hadron triplet closer to the IR – hence lower β*
- Crossing angle reduces luminosity ~100-fold
- The crabbing (tail up, nose up) is needed to restore luminosity

Idea Introduced by R. B. Palmer SLAC PUB 4832







Original BNL crab-cavity design (I. Ben-Zvi)

Courtesy of I. Ben-Zvi, S. Belomestnykh, D. Trbojevic and Q. Wu