Coherent electron cooling - perfect tool for EIC

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And so, my fellow Americans, ask not what your country can do for you; ask what you can do for your country.

Measure of Performance

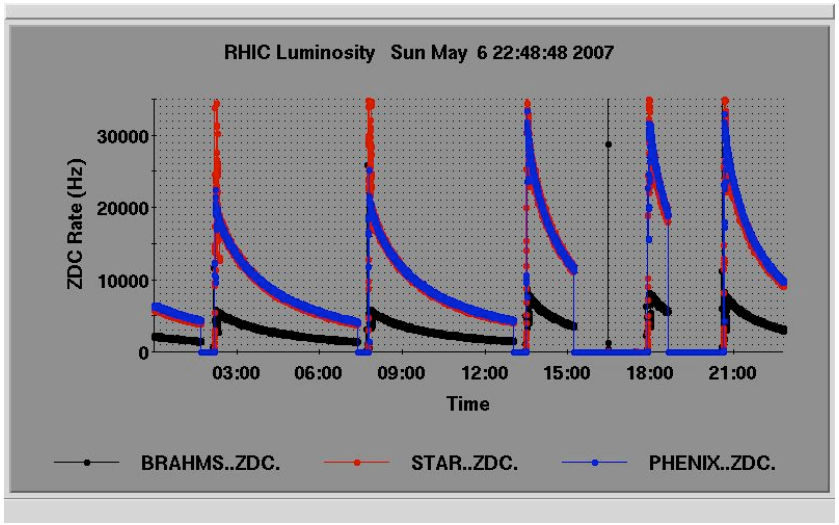
In Colliders - Luminosity

$$\dot{N}_{events} = \sigma_{A \to B} \cdot L \qquad L = \frac{f_{coll} \cdot N_1 \cdot N_2}{4\pi\beta^* \varepsilon}$$

Main sources of luminosity reduction
emittance growth and loss of particles

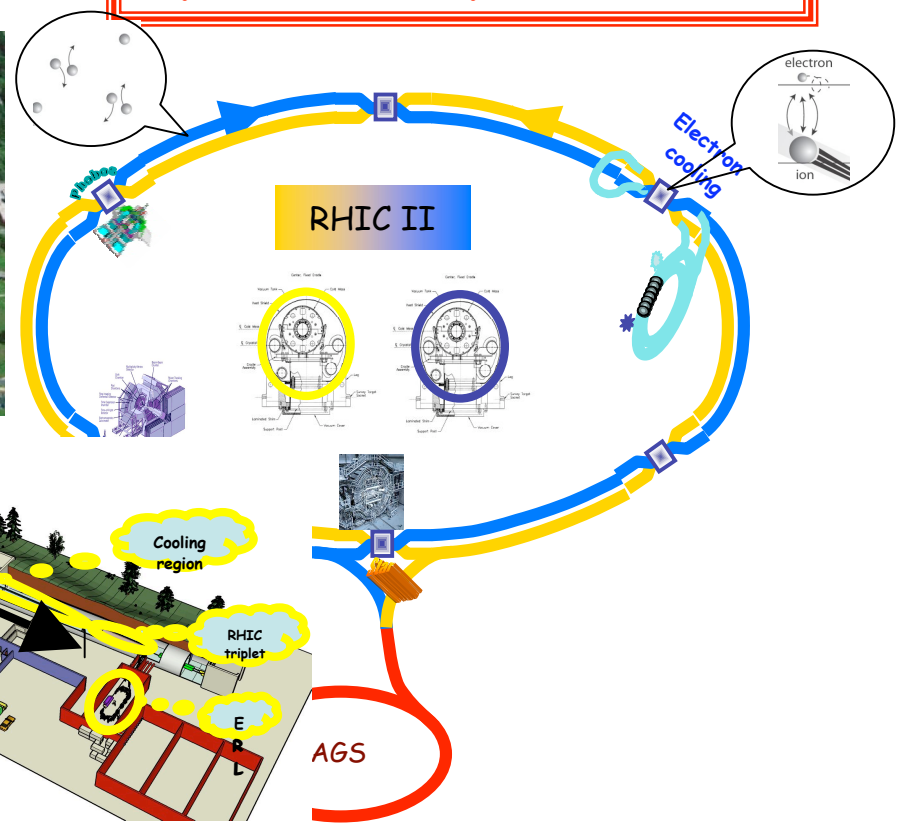
from the talk at International FEL conference, Novosibirsk, Russia, August, 2007

And so, my fellow FELers, ask not what storage ring can do for FELs;
Ask what FELs can do for your storage rings!



C-AD at BNL: home of RHIC and eRHIC

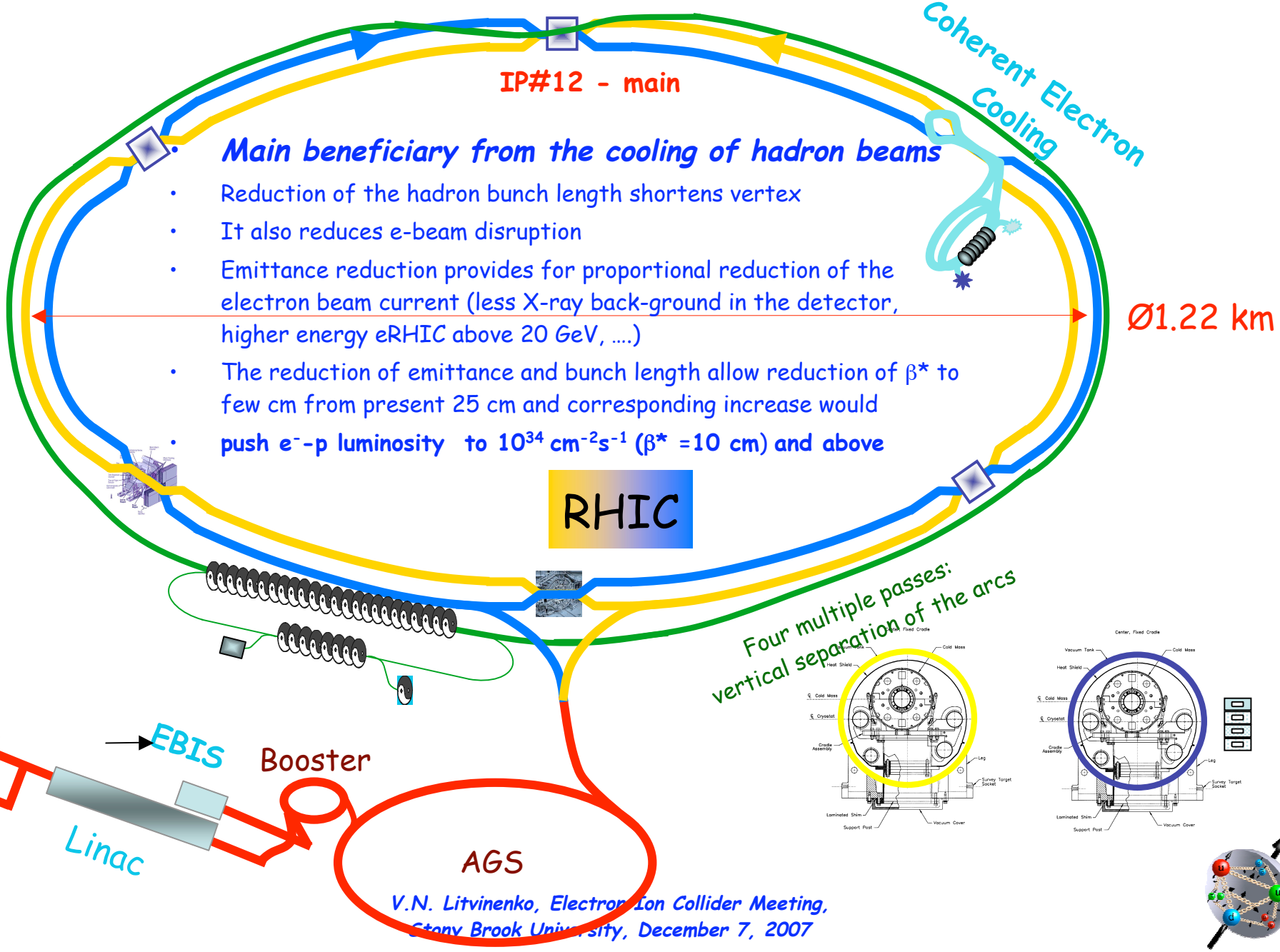
Traditional e-Cooling efficiency falls as $\gamma^{-7/2}$ and $\sim Z^2/A$
Very hihg energies and protons are problematic!



100 m at IP2 between triplets is sufficient for cooling

V.N. Litvinenko, Electron Ion Collider Meeting,
Stony Brook University, December 7, 2007

eRHIC based on 5-20$^+$ GeV ERL



- ***Main beneficiary from the cooling of hadron beams***
  - Reduction of the hadron bunch length shortens vertex
  - It also reduces e-beam disruption
  - Emittance reduction provides for proportional reduction of the electron beam current (less X-ray back-ground in the detector, higher energy eRHIC above 20 GeV, ...)
  - The reduction of emittance and bunch length allow reduction of β^* to few cm from present 25 cm and corresponding increase would
  - **push e^--p luminosity to 10^{34} cm^{-2}s^{-1} (β^* =10 cm) and above**

CERN: home of LHC & LHeC

Circumference [km]	26.7
Energy [GeV]	**7000 p** **580000 Pb** **70 e**
Particles	p-p Pb-Pb p-e, Pb-e
Peak luminosity [$10^{30}cm^{-2}s^{-1}$]	**10000 (design)**

Cooling LHC & LHeC - is it possible to even dream about?
It is just 10^{10} times harder that cooling antiprotons in Fermilab recycler; 10^{8} times harder than cooling Au ions in RHIC

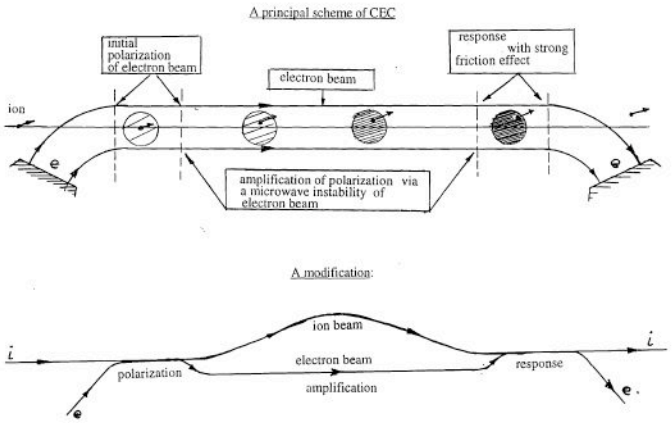
Cooling of hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	Synchrotron radiation, hrs	Electron cooling, hrs	CEC, hrs
RHIC	Au	100	20,961 ∞	~ 1	0.03
RHIC	protons	250	40,246 ∞	> 30	0.8
LHC	protons	450	48,489 ∞	> 1,600	0.95
LHC	protons	7,000	13/26	∞ ∞	< 2

History of idea:

coherent electron cooling was suggested by Yaroslav Derbenev about 26 years ago

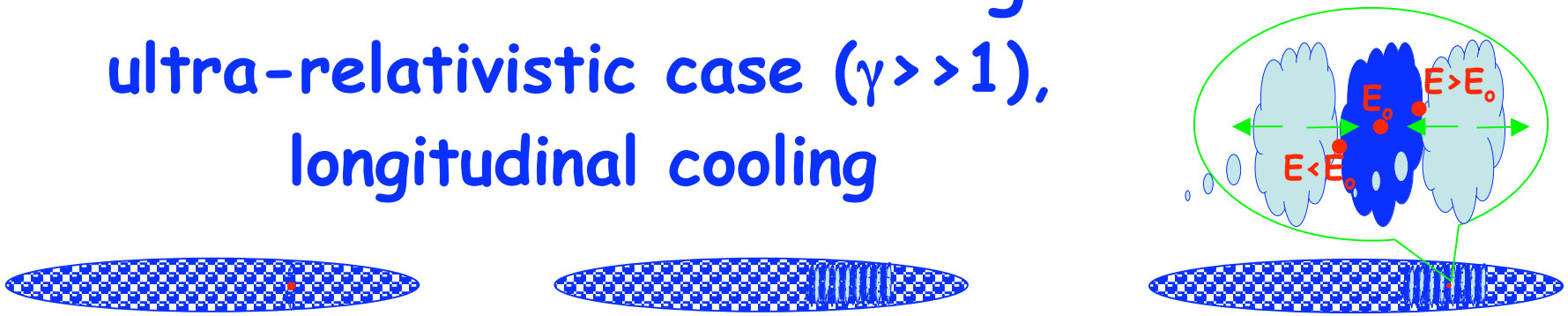
- Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980)
- Coherent electron cooling, Ya. S. Derbenev, Randall Laboratory of Physics, University of Michigan, MI, USA, UM HE 91-28, August 7, 1991
- Ya.S.Derbenev, Electron-stochastic cooling, DESY , Hamburg,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



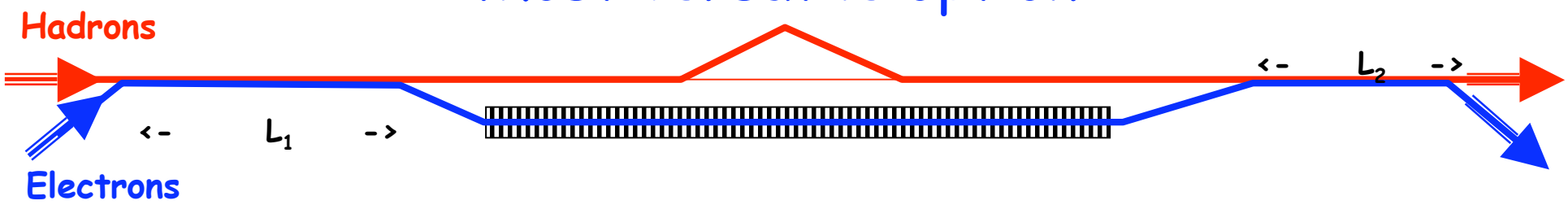
Q: What changed in last 25 years?

A: Accelerator technology caught up with the idea
- high gain amplification at optical (μm and nm) wavelengths became reality

Coherent electron cooling: ultra-relativistic case (γ>>1), longitudinal cooling



Most versatile option

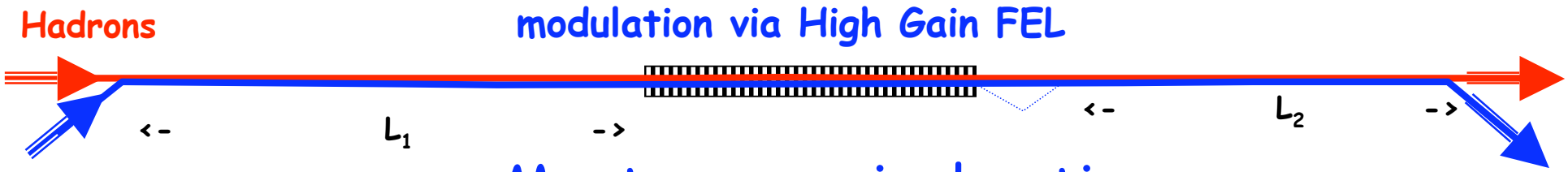


Modulator:region 1
about a quarter of plasma oscillation

Longitudinal dispersion for hadrons

Amplifier of the e-beam modulation via High Gain FEL

Kicker: region 2



Most economical option

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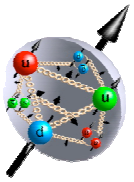
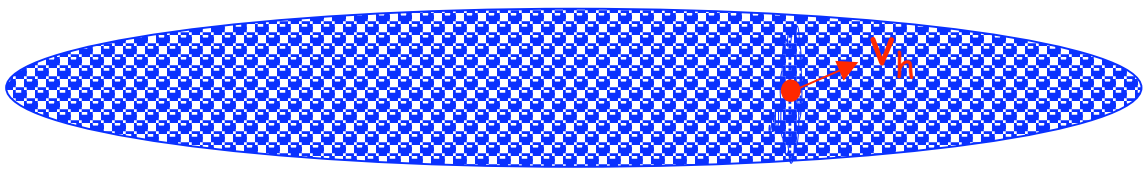
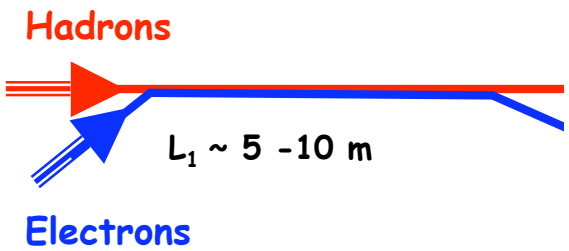


Modulator: Interaction region 1
Length: about a quarter of plasma oscillation

$$\omega_{pe} = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

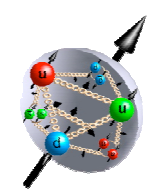




$$r_{//,lab} \propto \frac{c\sigma_\gamma}{\gamma^2 \omega_{pe}} \qquad r_{//,lab}(.1\%) \propto 7 \cdot 10^{-5}[m]/\gamma$$

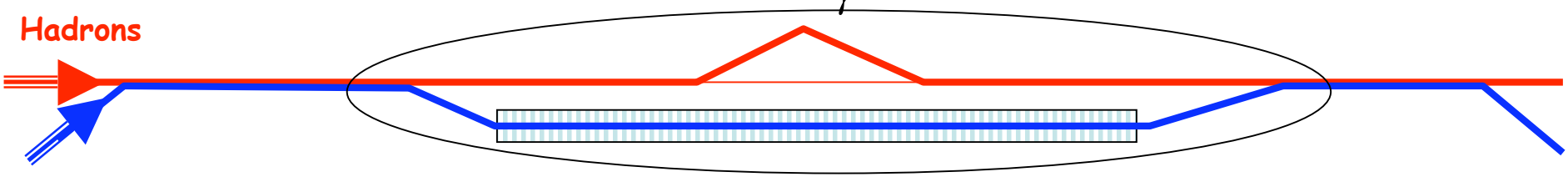
$$r_\perp \propto \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} \qquad r_\perp \sim 0.3mm$$

Each hadron generates modulation in the electron density with total charge of about minus charge of the hadron, Z



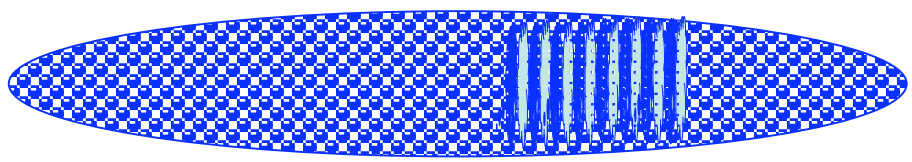
Longitudinal dispersion for hadrons, time of flight depends on its energy: $(T-T_o)\, v_o = -D\,(E-E_o)/E_o$

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



Amplifier of the e-beam modulation- high gain FEL

$$\lambda = \frac{\lambda_w}{2\gamma^2}(1+a_w^2) \qquad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}} \qquad L_G = L_{Go}(1+\Lambda)$$



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. Maximum gain for the electron density of HG FEL is ~ 10^3.

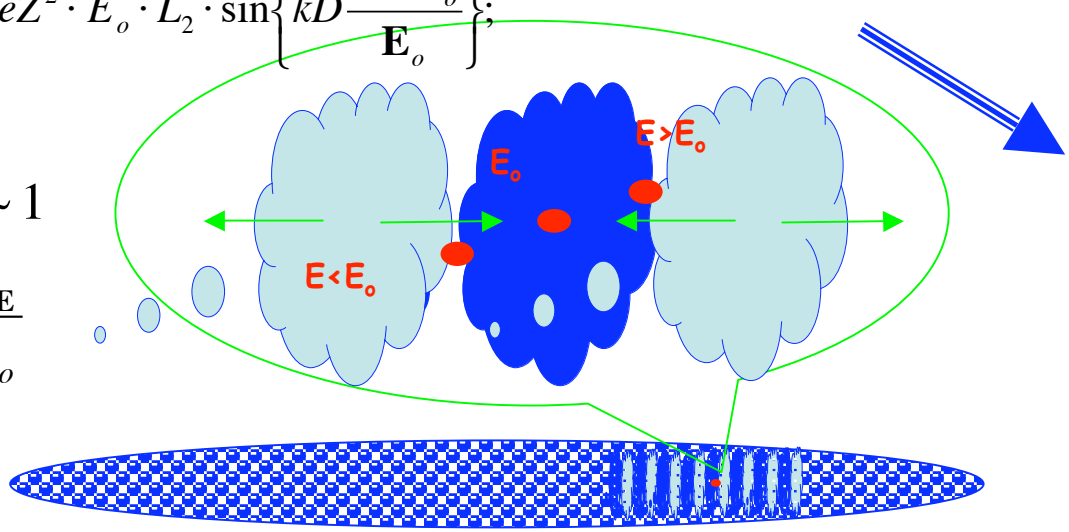
$$v_{group} = (c+2v_{//})/3 = c\left(1-\frac{1+a_w^2}{3\gamma^2}\right) = c\left(1-\frac{1}{2\gamma^2}\right) + \frac{c}{3\gamma^2}\left(1-2a_w^2\right) = v_{hadrons} + \frac{c}{3\gamma^2}\left(1-2a_w^2\right)$$

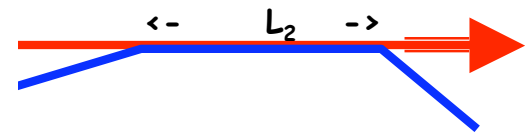
A hadron with central energy (E_o) phased with the hill where longitudinal electric field is zero, a hadron with higher energy ($E>E_o$) arrives earlier and is decelerated, while hadron with lower energy ($E<E_o$) arrives later and is accelerated by the collective field of electrons

$$\Delta \mathbf{E} = -eZ^2 \cdot E_o \cdot L_2 \cdot \sin\left\{ kD \frac{\mathbf{E} - \mathbf{E}_o}{\mathbf{E}_o} \right\};$$

$$kD\sigma_\varepsilon \sim 1$$

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





$$\zeta_{CEC} = -\frac{\Delta \mathbf{E}}{\mathbf{E} - \mathbf{E}_o} \approx \frac{e \cdot E_o \cdot L_2}{\gamma_o m_p c^2 \cdot \sigma_\varepsilon} \cdot \frac{Z^2}{A}$$

Estimation of damping decrement

- 1/4 of plasma oscillation in region 1 with a clamp of electrons with the charge -Ze is formed
- longitudinal extend of the electron clamp is well within $\lambda_o/2\pi$
- gain in SASE FEL* is G ~ 10^3
- electron beam is wider than $2\gamma_o\lambda_o$ - it is 1D field
- Length of the region 2 is equal to beta-function

After the FEL charge modulation is -G*Ze

$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$

i.e. the charge density in CM frame can be written as

$$\rho = \frac{k}{2\gamma_o}\frac{G\cdot Z\cdot e}{A_\perp}\cdot\sin\left(kz/2\gamma_o\right)$$

CM frame

$$divE \cong kE_z/2\gamma_o = 4\pi\rho;$$

$$E_z = Z\cdot E_o\cdot\sin\left(kz/2\gamma_o\right); \quad E_o = \frac{2G\cdot e}{\beta_\perp\varepsilon_n}\gamma_o$$

Longitudinal electric field is the same in the lab and CM frames

$$\zeta_{CEC} = 2G\cdot\frac{r_p}{\sigma_\varepsilon\varepsilon_n}\cdot\frac{L_2}{\beta_\perp}\cdot\frac{Z^2}{A}$$

Electron bunches are usually much shorter that the hadron bunches and cooling time for the entire bunch is proportional to the bunch-lengths ratios

$$\zeta_{bunch} = \zeta_{CEC}\frac{\sigma_{\tau,e}}{\sigma_{\tau,h}}$$

Note that damping decrement does not depend on the energy of particles ! p in RHIC? Tevatron ? LHC ?

250 GeV polarized protons in RHIC, L_{cooler} ~ 60m

N per bunch	$2\ 10^{11}$	Z, A	1, 1
Energy Au, GeV/n	250	γ	266.45
RMS bunch length, nsec	1	Relative energy spread	0.04%
Emittance norm, μm	2.5	$\beta_\perp$, m	10
Energy e^-, MeV	136.16	Peak current, A	100
Charge per bunch, nC	5	Bunch length, nsec	0.2
Emittance norm, μm	3	Relative energy spread	0.04%
$\beta_\perp$, m	10	L_1 (lab frame) ,m	30
ω_{pe}, CM, Hz	$4.19\ 10^9$	Number of plasma oscillations	0.25
$\lambda_{D\perp}$, μm	1004	$\lambda_{D\|\|}$, μm	0.17
λ_{FEL}, μm	**0.5**	**λ_w, cm**	**5**
a_w	**0.648**	**L_{Go}, m**	**0.87**
Amplitude gain =100, L_w , m	**13 (-> 15)**	**L_{G3D}, m**	**1.22**
L_2 (lab frame) ,m	10	**Cooling time, local, min**	**1.96**
$N_{min\ turns}$ or Ñ in 10% BW	$6.7\ 10^6 > 5.9\ 10^6$	**Cooling time, beam, min**	**49.2**

Conclusions

- Coherent electron cooling is very promising method for high energy hadron and lepton-hadron colliders
- It takes full advantage of high gain FELs based on high brightness ERLs
- Proof of principle experiment of cooling Au ions in RHIC at ~ 40 GeV/n is feasible with existing R&D ERL
- Cooling 100 GeV/n ions and 250 GeV protons in RHIC seems to be straight forward
- Cooling protons in LCH at 7 TeV seems to be possible, but may require slightly more elaborate scheme