Coherent electron cooling for hadron colliders

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Cooling intense high-energy hadron beams remains a major challenge for accelerator physics. Synchrotron radiation is too feeble, while efficiency of two other cooling methods falls rapidly either at high bunch intensities (i.e. stochastic cooling of protons) or at high energies (i.e. e-cooling). Possibility of coherent electron cooling using instabilities in electron beam was discussed by Derbenev since early 1980's .

The scheme presented in this talk -with cooling times under an hour for 7 TeV protons in LHC - is a first specific scheme with complete theoretical evaluation of its performance. The scheme is based present-day accelerator technology - a high-gain free-electron laser driven by an energy recovery linac. I will present some numerical examples for RHIC, eRHIc and LHC (LHeC) and discuss a proof-of-principle experiment using R&D ERL at RHIC.

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In collaboration with Yaroslav S. Derbenev
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Jefferson Lab

First paper: Vladimir N. Litvinenko, Yaroslav S. Derbenev, Free-Electron Lasers and High-Energy Electron Cooling, Proc. of 29th International Free Electron Laser Conference, Novosibirsk, Russia, August 2008,
http://accelconf.web.cern.ch/AccelConf/f07/HTML/AUTHOR.HTM **pp. 268-275**
http://ssrc.inp.nsk.su/FEL07/proceedings.html

Inputs from George Bell, Ilan Ben-Zvi, Michael Blaskiewicz, David Bruhwiler, John Jowett, Dmitry Kayran, Eduard Pozdeyev, Gang Wang, Frank Zimmerman

Collaboration on Coherent Electron Cooling includes scientists from BNL, Jlab, BINP (Novosibirsk), FNAL, Dubna, UCLA, TechX, LBNL… open for others: http://www.bnl.gov/cad/ecooling/cec.asp

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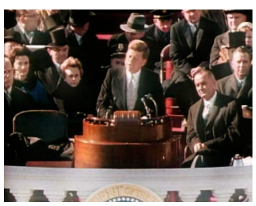
A bit of history

Principles of Coherent Electron Cooling (CeC)

Analytical estimations, Simulations

Proof of Principle test using R&D ERL



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

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

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

Measure of Performance
Luminosity

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

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

Main sources of luminosity limitation

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

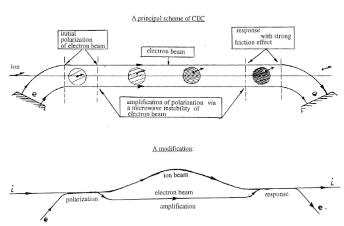
Cooling of hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, hrs	Trad. Electron cooling hrs	**Coherent Electron Cooling hrs**
RHIC PoP	**Au**	**40**	**-**	**-**	**-**	**0.04**
RHIC	Au	100	~1	20,961 ∞	~ 1	**0.03**
RHIC	**p**	**250**	**~100**	**40,246 ∞**	**> 30**	**0.4**
LHC	**p**	**7,000**	**~ 1,000**	**13/26**	**∞ ∞**	**<1**
LHC	Pb	2.75	?	~10	∞	**0.15**

History

possibility of 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 ....



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.

Q: What changed?

A1. Accelerator technology progressed in last 25 years and

- energy recovery linacs with high quality e-beam
- high gain amplification in FELs at μm and nm wavelengths

became reality in last decade

A2. A specific scheme with a complete theoretical evaluation had been developed (vl/yd) in 2007/2008

A3. Checks of most important tolerances on e-beam, hadron beam and lattice had been performed

A4. The scheme had been presented at major international forums (FEL'07 and COOL'07), at major accelerator labs (BNL, CERN, BINP, Jlab…) and passed fist tests of scrutiny

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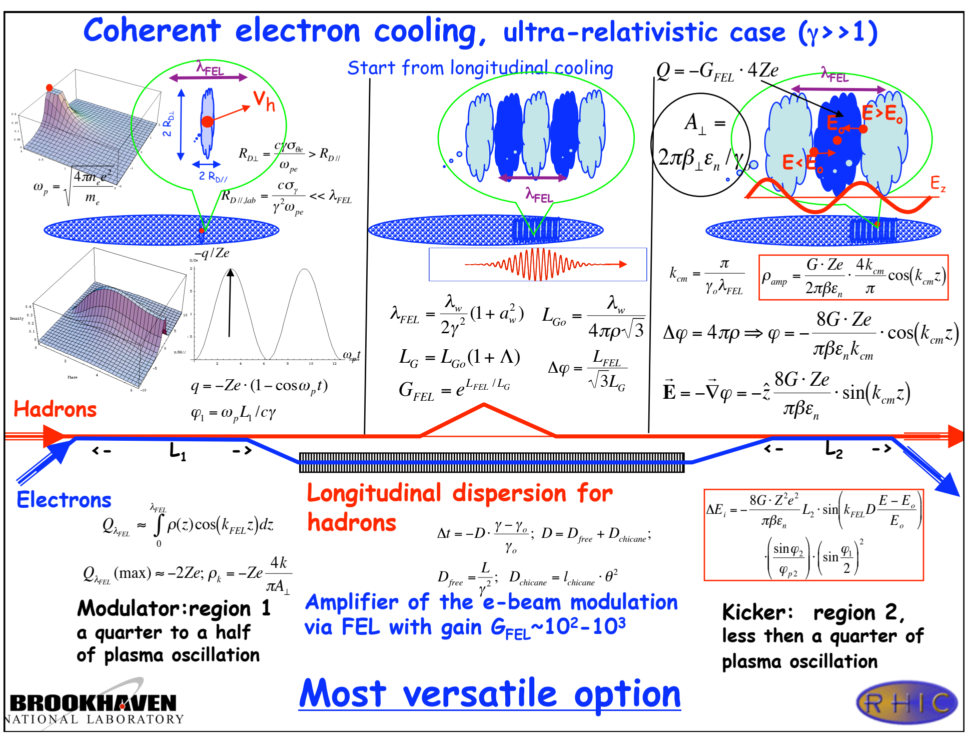
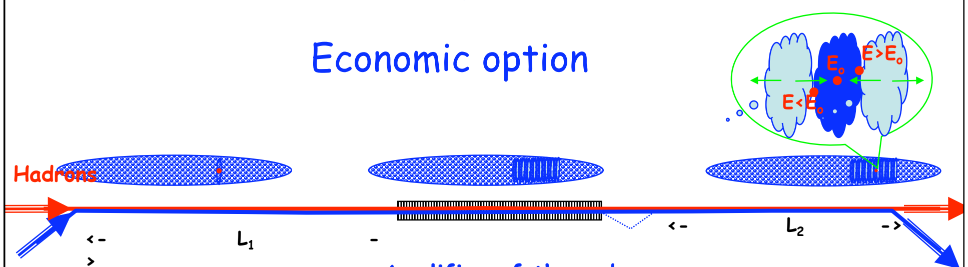


Coherent electron cooling, ultra-relativistic case ($\gamma >> 1$)

Economic option



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

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

Kicker: region 2

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

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

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

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Analytical formula for damping decrement

- 1/2 of plasma oscillation in the modulator creates a pancake of electrons with the charge -2Ze
- electron clamp is well within $\Delta z \sim \lambda_{FEL}/2\pi$
- gain in SASE FEL is $G \sim 10^2$-10^3
- electron beam is wider than $2\gamma_o\lambda_{FEL}$ - it is 1D field
- Length of the region 2 is ~ beta-function

$$\varepsilon = a \cdot \sin\Omega_s t$$

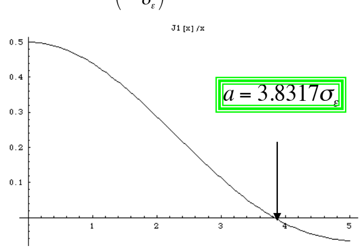
$$\left\langle \varepsilon^2 \right\rangle' = -\left\langle 2A \cdot a^2 \cdot \cos^2\Omega_s t \cdot \sin\left(\frac{a}{\sigma_\varepsilon} \cdot \chi \cdot \sin\Omega_s t\right)\right\rangle$$

$$= -2A \cdot \left\langle \varepsilon^2 \right\rangle \cdot J_1\left(\chi \cdot \frac{a}{\sigma_\varepsilon}\right)$$

$$\zeta = -\frac{\Delta E_i}{E - E_o} = A \cdot \frac{L_2}{\beta} \cdot \chi \cdot \mathrm{sinc}(\varphi_3) \cdot \mathrm{sinc}\varphi_2 \cdot \left(\sin\frac{\varphi_1}{2}\right)^2$$

$$A = \frac{8G}{\pi} \cdot \frac{Z^2}{A} \cdot \frac{r_p}{\varepsilon_{n,h}\sigma_\varepsilon}; \quad \chi = k_{FEL} D \cdot \sigma_\varepsilon;$$

$$\mathrm{sinc}(\varphi) = \sin(\varphi)/x; \; \varphi_3 = k_{FEL} D\varepsilon; \; \varepsilon = \frac{E - E_o}{E_o}$$



$$a = 3.8317\sigma_\varepsilon$$

$$\chi = 1$$

$$\frac{L_2}{\beta} \cdot \chi \cdot \mathrm{sinc}(\varphi_3) \cdot \mathrm{sinc}\varphi_2 \cdot \left(\sin\frac{\varphi_1}{2}\right)^2 \sim 1$$

Beam-Average decrement;

$$\int \frac{2J_1(x)}{x} e^{-x^2/2} dx = 0.889$$

$$\left\langle \zeta_{CeC} \right\rangle = \zeta \frac{\sigma_{\tau,e}}{\sigma_{\tau,h}} = \kappa \cdot \frac{8G}{\pi} \cdot \frac{Z^2}{A} \cdot \frac{r_p \cdot \sigma_{\tau,e}}{\varepsilon_{n,h}\left(\sigma_\varepsilon \cdot \sigma_{\tau,h}\right)}; \; \kappa \sim 1$$

ε_L

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

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Analytical formula for damping decrement

$$\langle \zeta_{CeC} \rangle = \zeta \frac{\sigma_{\tau,e}}{\sigma_{\tau,h}} = \kappa \cdot \frac{8G}{\pi} \cdot \frac{Z^2}{A} \cdot \frac{r_p \cdot \sigma_{\tau,e}}{\varepsilon_{n,h} \left(\sigma_\varepsilon \cdot \sigma_{\tau,h} \right)}; \ \kappa \sim 1$$

Note that damping decrement:

a) does not depend on the energy of particles !

b) Improves as cooling goes on

Protons in RHIC !!!

Tevatron ? LHC ?

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

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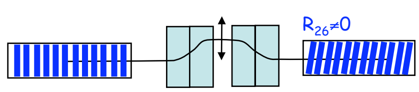
Transverse cooling

- 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: $J_s+J_h+J_v=J_{CEC}$
- Vertical (better to say the second eigen mode) cooling is coming from transverse coupling

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



$$\delta z = -R_{26} \cdot x$$

$$\Delta \mathbf{E} = -eZ^2 \cdot E_o \cdot L_2 \cdot$$

$$\sin\left\{ k\left(D\frac{\mathbf{E}-\mathbf{E}_o}{\mathbf{E}_o} + R_{16}x' - R_{26}x + R_{36}y' + R_{46}y \right) \right\};$$

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

Example:

$$J_\perp \propto \frac{D\sigma_\varepsilon}{\sigma_\perp} J_{CeC} \quad when \quad kR_{26}\sigma_\perp \sim 1$$

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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

$$\mathbf{E}_{total} = \sum_{i,hadrons} Z \cdot \mathbf{E}(v_o t - z + z_j) \cdot \sin k(v_o t - z + z_i) - \sum_{j,electrons} \mathbf{E}(v_o t - z + z_j) \cdot \sin k(v_o t - z + z_j)$$

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

$$\frac{d\sigma_\gamma^2}{dn} = -2\Delta \frac{kD}{\gamma_o}\sigma_\gamma^2 + \frac{1}{2}\Delta^2 \tilde{N}$$

$$\Delta = eZ^2 \cdot L_2 \cdot \mathbf{E} / Mc^2; \quad \tilde{N} = \tilde{N}_h + \tilde{N}_e / Z^2$$

$$\frac{\sigma_\gamma^2}{\gamma_o^2} = \frac{1}{4kD} \cdot \frac{\Delta}{\gamma_o} \cdot \tilde{N}$$

$$J_{CeC}(\max) = \frac{\Delta}{2\sigma_\gamma} = \frac{2}{\tilde{N}}(kD\sigma_\varepsilon) \sim \frac{1}{\tilde{N}}$$

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Dimensionless variables can be usedused to clarify the physics

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

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

$$\tau = \omega_p t$$

$$\vec{\mathrm{v}} = \vec{v}\sigma_{\mathrm{v}_z}$$

$$\vec{r} = \vec{\rho}\sigma_{\mathrm{v}_z} / \omega_p$$

$$\omega_p^2 = \frac{4\pi e^2 n_e}{m}$$

- Four independent parameters to vary:

$$R = \frac{\sigma_{\mathrm{v}_{//}}}{\sigma_{\mathrm{v}_\perp}} \qquad Z = \frac{\mathrm{v}_{iz}}{\sigma_{\mathrm{v}_\perp}} \qquad T = \frac{\mathrm{v}_{ix}}{\sigma_{\mathrm{v}_\perp}} \qquad \zeta = \frac{Z}{R^2 s^3 n_e}; \quad s = \mathrm{v}_z / \omega_p$$

- Four approaches for modulator and kicker: first-principles, analytical (**talk by G.Wang follows**), numerical (integration of various types) and direct molecular dynamics (VORPAL)
- FELs - 1D theory is completely analytical, 3D - simulations with code GENESIS

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Linearized Vlasov equations

$$f = F(\vec v) + \tilde f; \quad |\tilde f| \ll |F|$$

$$\partial_t \tilde f(\vec k,\vec v,t) + i(\vec k\cdot\vec v)\tilde f(\vec k,\vec v,t) - \frac{e n_e}{m}\vec E(\vec k,t)\cdot\partial_{\vec v}F(\vec v) = 0$$

$$\varphi(\vec k,t) = \frac{4\pi e}{k^2}\left(Z\cdot e^{i\vec k\cdot(\vec r_o+\vec v_i t)} - \int \tilde f(\vec k,\vec v,t)\,d\vec v\right)$$

$$\vec E(\vec k,t) = -\frac{4\pi i e\vec k}{k^2}\left(Z\cdot e^{i\vec k\cdot(\vec r_o+\vec v_i t)} - \int \tilde f(\vec k,\vec v,t)\,d\vec v\right)$$

$$g(\vec k,\omega) = \int \frac{\frac{\vec k}{k^2}}{\omega+(\vec k\cdot\vec v)+i\varepsilon}\cdot\partial_{\vec v}F(\vec v)\,dv^3$$

$$\tilde\rho(\vec k,\omega) = -\omega_p^2\left(Z\cdot\delta(\omega-\vec k\vec v_i)e^{i\vec k\cdot\vec r_o} - \tilde\rho(\vec k,\omega)\right)\cdot g(\vec k,\omega);$$

$$\tilde\rho(\vec k,\omega)\left(1-\omega_p^2 g(\vec k,\omega)\right) = -\omega_p^2 Z\cdot\delta(\omega-\vec k\vec v_i)e^{i\vec k\cdot\vec r_o}g(\vec k,\omega)$$

$$\tilde\rho(\vec k,\omega) = \frac{-\omega_p^2 Z\cdot\delta(\omega-\vec k\vec v_i)e^{i\vec k\cdot\vec r_o}g(\vec k,\omega)}{1-\omega_p^2 g(\vec k,\omega)}$$

More in next talk

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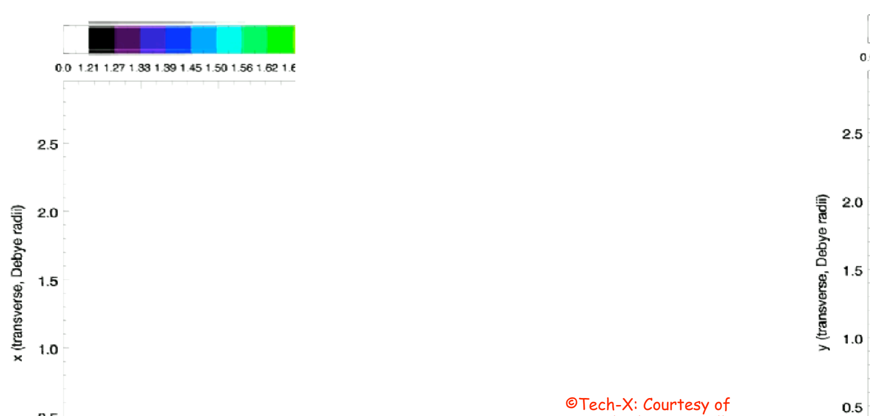
R=3; Z=0; T=0 - Asymmetry of electron velocity distribution → pancake-shaped wake



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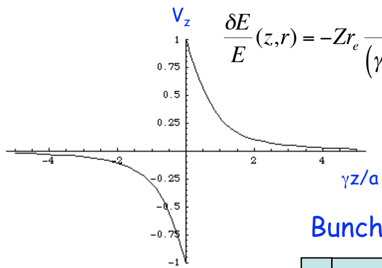
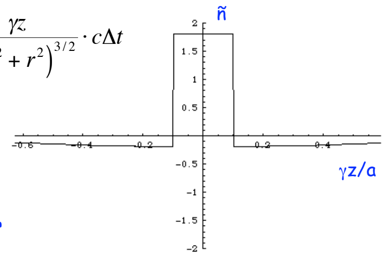
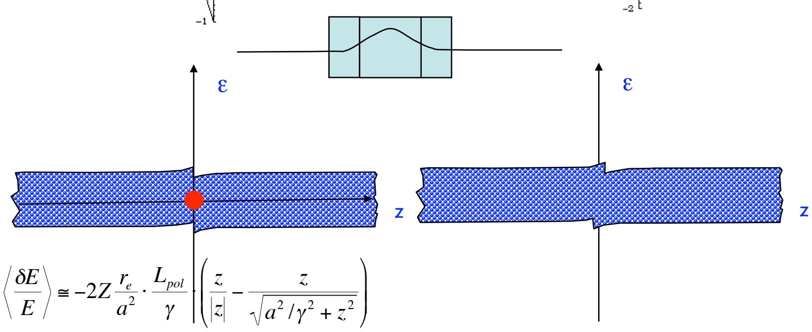
Velocity map & buncher (γ>1000)

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





Buncher



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

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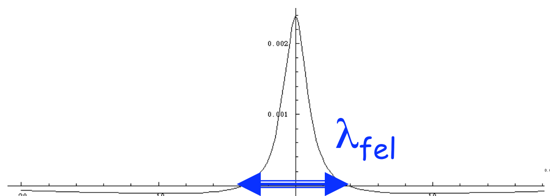
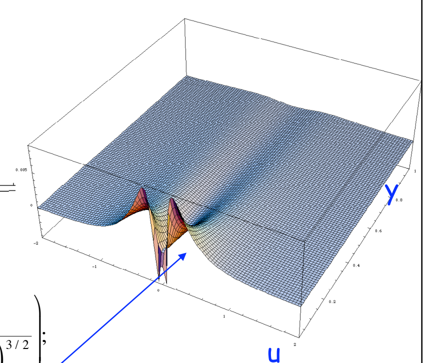
Exact calculations: solving Vlasov equation





$$f_o(r,\vec{p}_\perp,z,\gamma) = \frac{\theta(r-a)}{a^2/2}\cdot\frac{\theta(z-l_z)}{l_z}\cdot\frac{1}{\sqrt{2\pi}\sigma_\gamma}e^{-\frac{(\gamma-\gamma_o)^2}{2\sigma_\gamma^2}}\cdot g(\vec{p}_\perp)$$

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

$$l_z\rho(z) = \Phi(s) = \frac{1}{\kappa^2\sqrt{2\pi}}\int_0^{\kappa^2}dy\int_{-L/2}^{L/2}\left[\exp\left\{-\frac{1}{2}\left(s-u\left(1-\frac{G}{\left(y+u^2\right)^{3/2}}\right)\right)^2\right\} - \exp\left\{-\frac{(s-u)^2}{2}\right\}\right]du;$$

$$G = Z\frac{r_e L_{\mathrm{mod}}|D|}{\left(\gamma_o\sigma_{p_1}|D|\right)^3};\ \kappa = \frac{a}{\gamma_o\sigma_{p_1}|D|};\ L = \frac{l_z}{\sigma_{p_1}|D|}$$

$$u = \frac{x_1}{\sigma_{p_1}|D|};\ s = \frac{z}{\sigma_{p_1}|D|};\ y = \frac{r^2}{\left(\gamma_o\sigma_{p_1}|D|\right)^2}$$

For 7 TeV p in LHC CeC case: My simple "gut-feeling" estimate gave 22.9 boost in the induced charge by a buncher, while exact calculations gave 21.7.

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250 GeV polarized protons in RHIC, L_{cooler} fits in IR

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**

Not optimized!

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Au ions in RHIC with 100 GeV/n, L_{cooler} ~ 20 m

N per bunch	2 10^9	Z, A	79, 197
Energy Au, GeV/n	100	γ	106.58
RMS bunch length, nsec	1	Relative energy spread	0.1%
Emittance norm, μm	2.5	$\beta_{\perp}$, m	5
Energy e^-, MeV	54.5	Peak current, A	50
Charge per bunch, nC	5	Bunch length, nsec	0.1
Emittance norm, μm	3	Relative energy spread	0.1%
$\beta_{\perp}$, m	10	L_1 (lab frame) ,m	8.5
ω_{pe}, CM, Hz	5.9 10^9	Number of plasma oscillations	0.25
$\lambda_{D\perp}$, μm	78	$\lambda_{D\|\|}$, μm	0.75
λ_{FEL}, μm	**3**	**λ_w, cm**	**5**
a_w	**0.603**	**L_{Go}, m**	**0.5**
Amplitude gain =200, L_w , m	**8.11 (-> 9)**	**L_{G3D}, m**	**0.77**
L_2 (lab frame) ,m	5	**Cooling time, local, minimum**	**0.08 minutes**
$N_{min\ turns}$ or Ñ in 5% BW	6 10^5> 2 10^5	**Cooling time, beam, min**	**1.93 minutes**

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7 TeV protons in LHC: CeC ~200m
Potential of 4x increase in luminosity

N per bunch	1.4 10^{11}	Z, A	1, 1
Energy Au, GeV/n	7000	γ	7460
RMS bunch length, nsec	0.25	Relative energy spread	0.0113%
Emittance norm, μm	3.8	$\beta_{\perp}$, m	47
Energy e^-, MeV	3,812	Peak current, A	100
Charge per bunch, nC	5	Bunch length, nsec	0.05
Emittance norm, μm	3	Relative energy spread	0.01%
$\beta_{\perp}$, m	59	L_1 (lab frame) ,m	**70**
ω_{pe}, CM, Hz	2.44 10^9	Number of plasma oscillations	**0.0121**
$\lambda_{D\perp}$, mm	3.7	$\lambda_{D\|\|}$, μm	0.17
λ_{FEL}, μm	**0.01**	**λ_w, cm**	**5**
a_w	**4.61**	**L_{Go}, m**	**2.7**
Amplitude gain =1000, L_w , m	**61.8**	**L_{G3D}, m**	**3.9**
L_2 (lab frame) ,m	**35**	**Cooling time, local, min**	**3 minutes**
$N_{min\ turns}$ or $\tilde{N}$ in 10% BW	2 10^6 >> 2.8 10^5	**Cooling time, beam**	**23 minutes**

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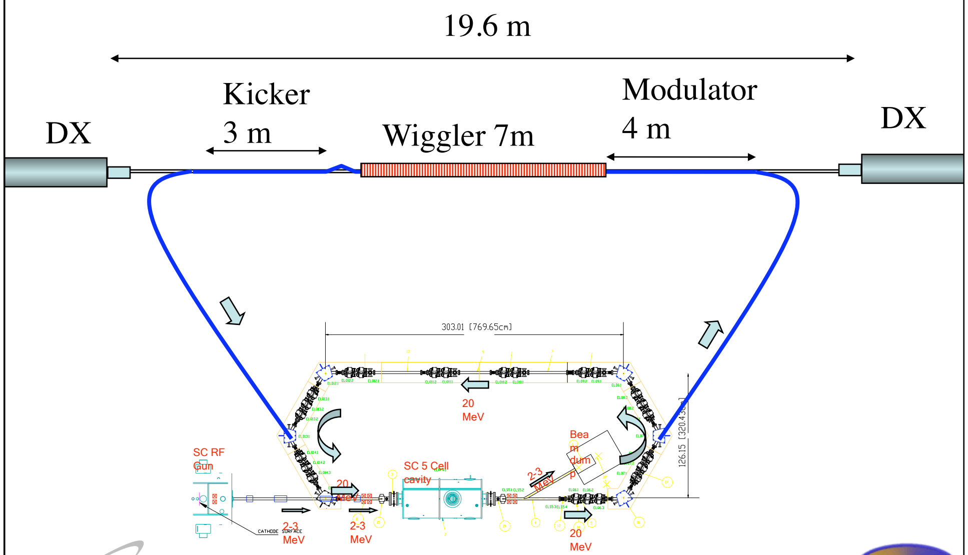
IR-2 layout for Coherent Electron Cooling proof-of-principle experiment



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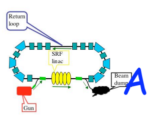

PoP test using BNL R&D ERL: Au ions in RHIC with 40 GeV/n, L_{cooler} = 14 m

N per bunch	1 10^9	Z, A	79, 197
Energy Au, GeV/n	40	γ	42.63
RMS bunch length, nsec	3.2	Relative energy spread	0.037%
Emittance norm, μm	2.5	$\beta_\perp$, m*	8
Energy e^-, MeV	21.79	Peak current, A	60
Charge per bunch, nC	5 (or 4 x 1.4)	Bunch length, RMS, psec	83
Emittance norm, μm	5 (4)	Relative energy spread	0.15%
$\beta_\perp$, m	5	L_1 (lab frame) ,m	4
ω_{pe}, CM, Hz	5.03 10^9	Number of plasma oscillations	0.256
$\lambda_{D\perp}$, μm	611	$\lambda_{D\|\|}$, μm	3.3
λ_{FEL}, μm	**18**	**λ_w, cm**	**5**
a_w	**0.555**	**L_{Go}, m**	**0.67**
Amplitude gain =150, L_w , m	**6.75 (7)**	**L_{G3D}, m**	**1.35**
L_2 (lab frame) ,m	**3**	**Cooling time, local, minimum**	**0.05 minutes**
N_{turns}, Ñ, 5% BW	8 10^6, 6 10^4	**Cooling time, beam, min**	**2.6 minutes**

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Conclusions

- **Coherent electron cooling is very promising method for significant luminosity increase and is a key for high luminosity eRHIC, LHC (and LHeC)**
- **Proof of principle experiment of cooling Au ions in RHIC at ~ 40 GeV/n is feasible with existing R&D ERL**
- We can test conjecture that strong cooling allows for higher beam-beam tune shifts

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