Coherent electron cooling for LHC

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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 LHC (LHeC) and discuss a proof-of-principle experiment using R&D ERL at RHIC.

Conclusions

- **Coherent electron cooling is very promising method for significant luminosity increase in LHC (and LHeC)**
- **Proof of principle experiment of cooling Au ions in RHIC at ~ 40 GeV/n is feasible with existing R&D ERL**
- Can test conjecture that strong cooling allows for higher beam-beam tune shifts
- **Modest LARP efforts would be critical for CeC PoP experiment and for testing the LHC-specific aspects of coherent electron cooling**

In collaboration with Yaroslav S. Derbenev

Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

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, David Bruhwiler, Dmitry Kayran, Eduard Pozdeyev, Frank Zimmerman, John Jowett

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

Proposed LARP activity will involve BNL, FNAL, Jlab and LBNL in collaboration with LHC AP group

Intro

A bit of history

Principles of Coherent Electron Cooling (CeC)

Analytical estimations

Simulations

CeC at LHC

Proof of Principle test using R&D ERL

LARP

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 ring

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

CERN – Large Hadron Collider (LHC)

Time	2008-
Circumference, [km]	26.7
Energy, [TeV]	7 p 2.75/u Pb
Particles	p-p Pb-Pb
Peak luminosity [$10^{34}cm^{-2}s^{-1}$]	**1 (design)**

e-Cooling at LHC - 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

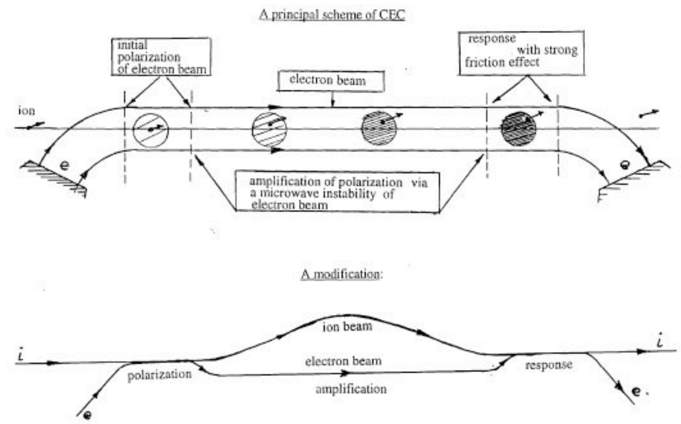
Cooling of hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	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	0.8
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

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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 in last 25 years?

A1. Accelerator technology progressed and

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

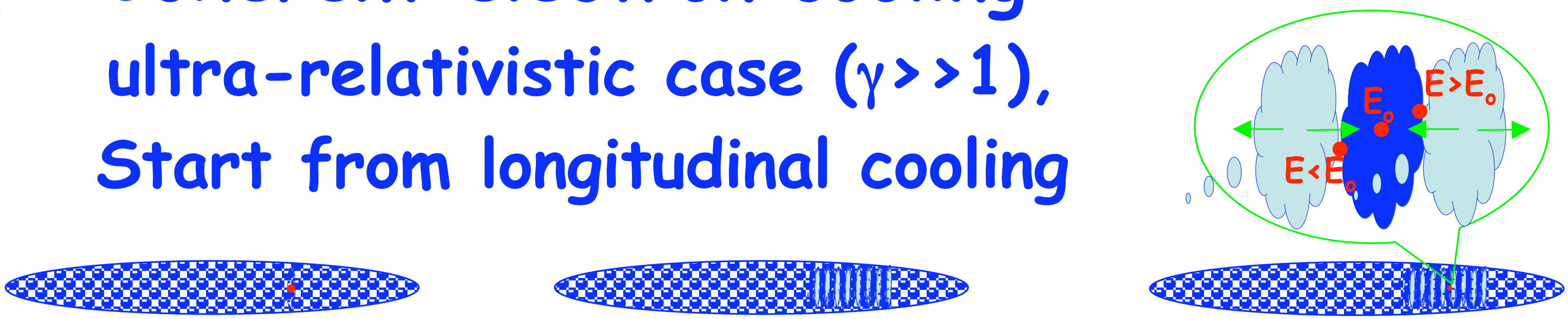
became reality in last decade

A2. A specific scheme and a complete theoretical evaluation (from first principles) had been developed (vl) in 2007/2008

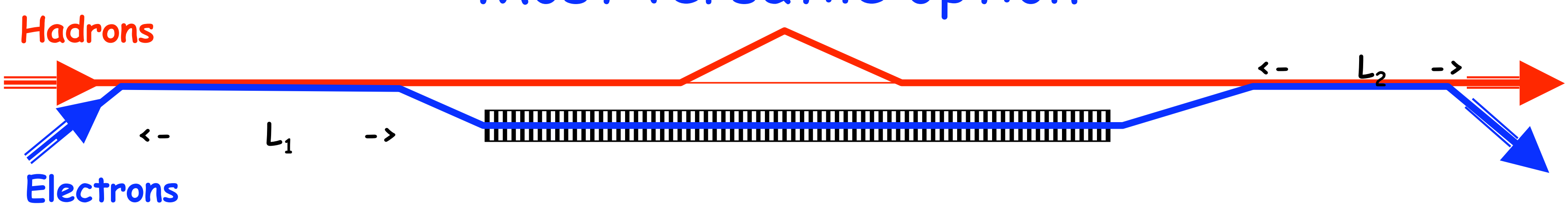
A3. Most important tolerances on e-beam, hadron beam and lattice had been performed

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 test of scrutiny

Coherent electron cooling: ultra-relativistic case ($\gamma >> 1$), Start from longitudinal cooling



Most versatile option



Modulator:region 1
about a quarter of plasma oscillation

Longitudinal dispersion for hadrons

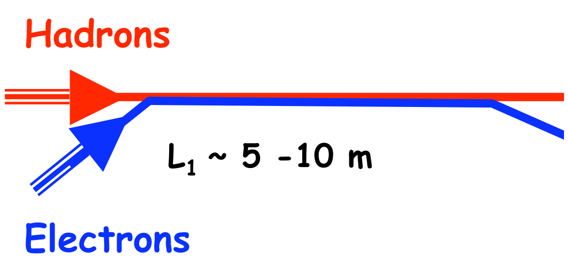
Amplifier of the e-beam modulation via High Gain FEL

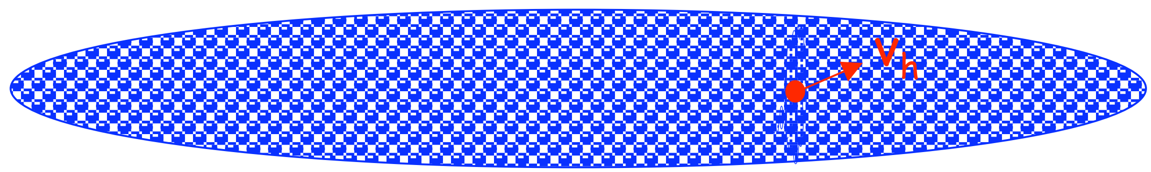
Kicker: region 2

Most economical option

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

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





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

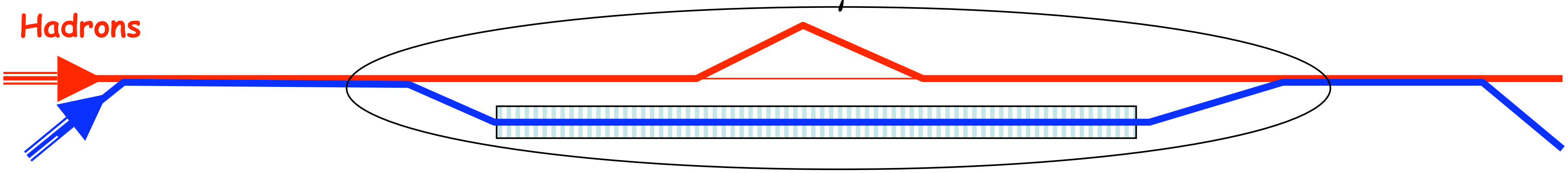
$$r_\perp \propto \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} \qquad r_\perp \sim 0.3mm$$

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: $(T-T_o)\,v_o = -D\,(E-E_o)/E_o$

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

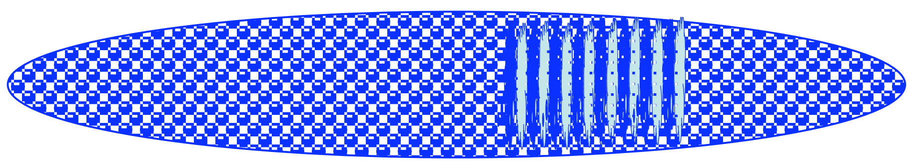
Hadrons



Electrons

Amplifier of the e-beam modulation- a high gain FEL

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



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.

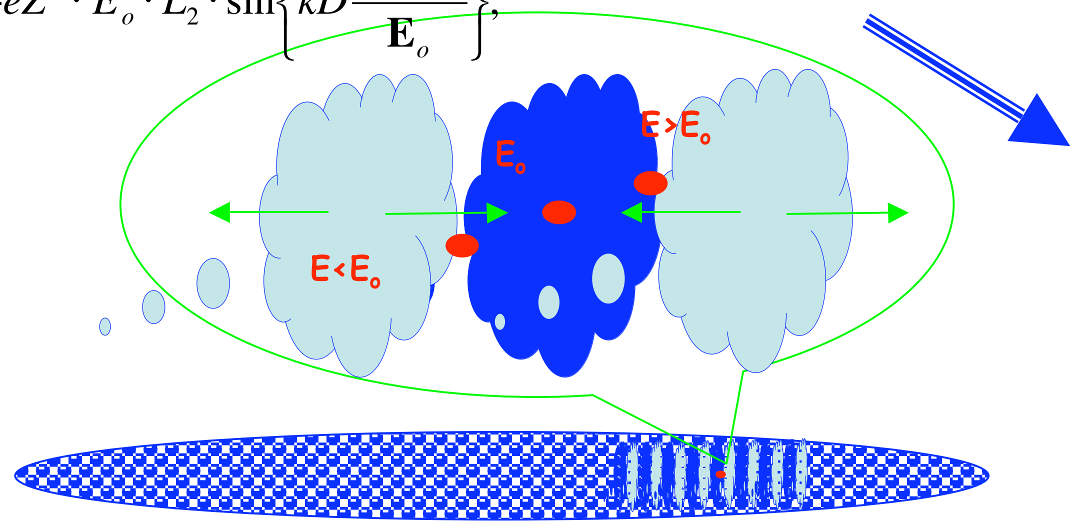
$$v_{group} = (c + 2v_{//})/3 = c\left(1 - \frac{1+a_w^2}{3\gamma^2}\right) = c\left(1 - \frac{1}{2\gamma^2}\right) + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right) = v_{hadrons} + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right)$$

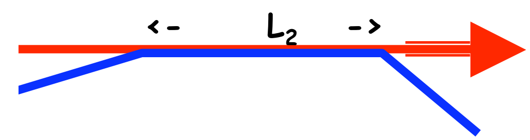
Economic option requires: $2a_w^2 < 1$!!!

Kicker: Interaction region 2

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

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





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

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

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

Analytical formula for damping decrement

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

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

CM frame

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

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

Longitudinal electric field is the same in the lab and CM frames. Locally:

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

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

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

Note that damping decrement:

a) does not depend on the energy of particles !

b) Improves as cooling goes on

$$\langle\zeta_{CEC}\rangle \sim 1/(\varepsilon_{long,h}\varepsilon_{trans,h})$$

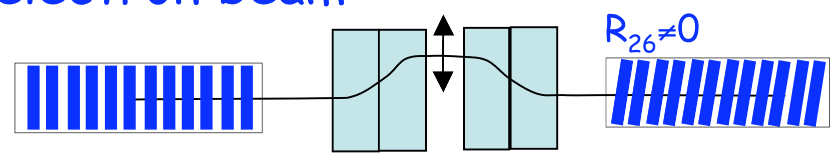
Protons in RHIC !!!

Tevatron ? LHC ?

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:

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

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

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

Evolution of the RMS value resembles stochastic cooling!

Best cooling rate achievable is ~ 1/Ñ, Ñ is effective number of hadrons in coherent sample ($N_c\lambda$)

$$\frac{d\sigma_E^2}{dn} = -2\Delta \frac{kD}{\mathbf{E}_o} \sigma_E^2 + \frac{1}{2}\Delta^2 \tilde{N}$$

$$\Delta = eZ^2 \cdot L_2 \cdot E_o ; \tilde{N} = \tilde{N}_h + \tilde{N}_e / Z^2$$

$$\frac{\sigma_E^2}{\mathbf{E}^2_o} = \frac{1}{4kD} \cdot \frac{\Delta}{\mathbf{E}_o} \cdot \tilde{N}$$

$$J_{CEC} = \frac{\Delta}{2\sigma_E} = \frac{2}{\tilde{N}}\left(kD\sigma_\varepsilon\right) \sim \frac{1}{\tilde{N}}$$

Dimensionless variables are used to clarify the physics

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

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

$$\tau = \omega_p t$$

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

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

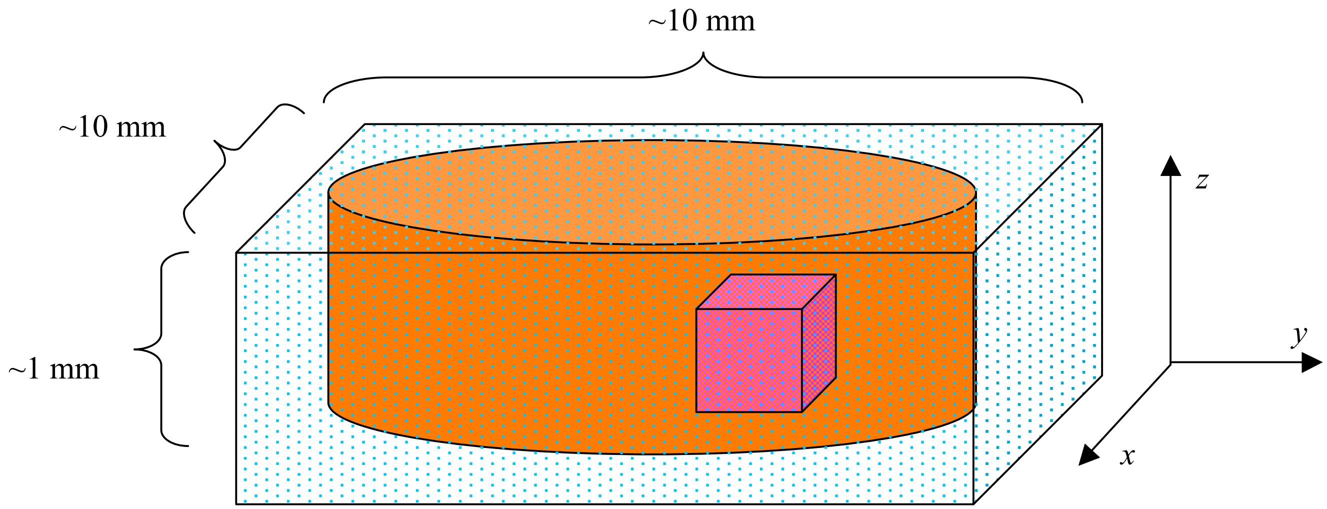
$$\omega_p^2 = \frac{4\pi e^2 n_e}{m}$$

- Four independent parameters to vary:

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

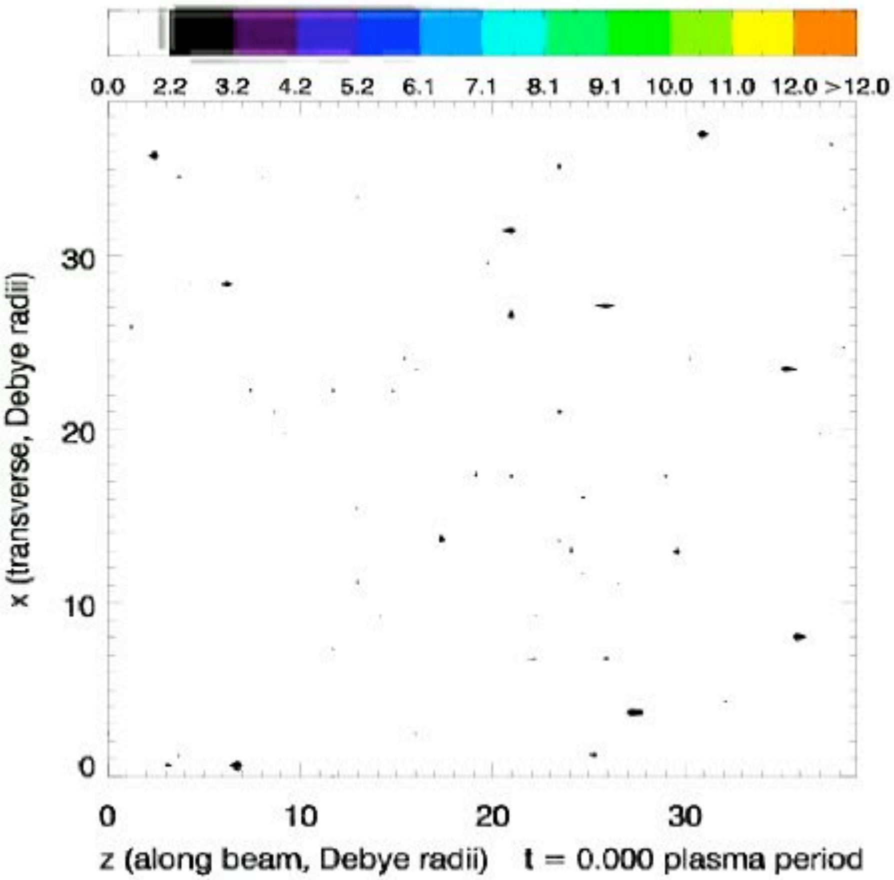
- Initially, we consider the following values:
  - R=3; Z=0., 0.2, 0.6; T=0., 1.8, 5.4

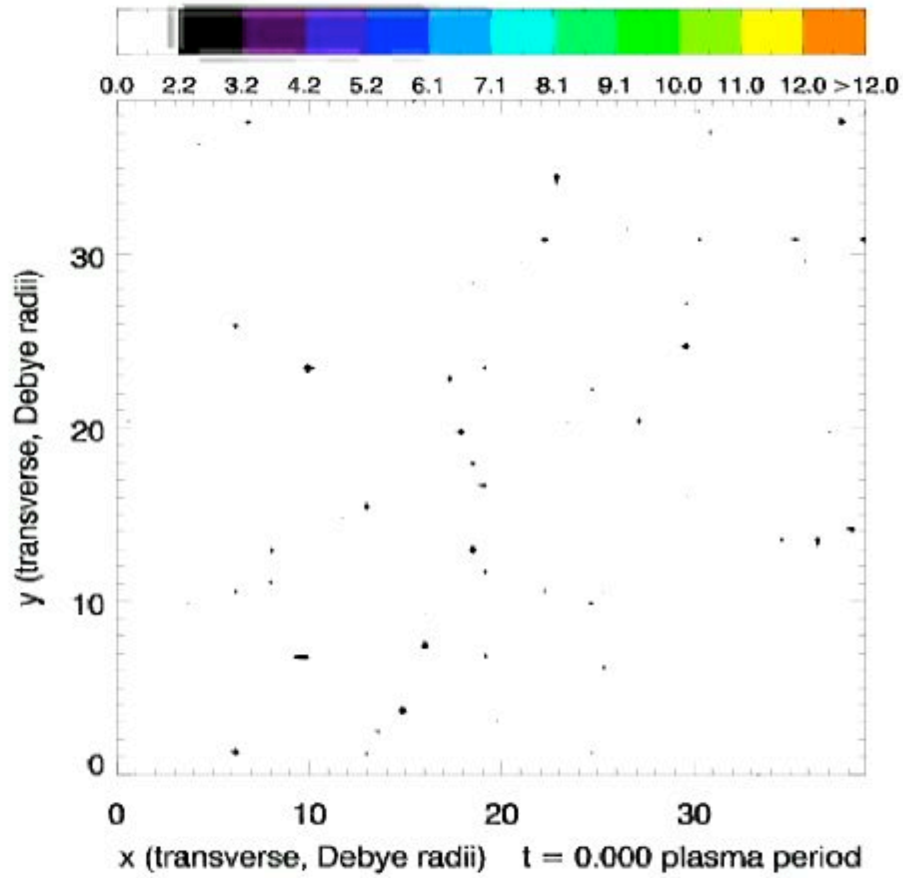
Simulations
Modulator - VORPAL, Kicker - VORPAL
FEL amplifier - Genesis3



- We consider a single ion in a uniform e- distribution
  - electron velocities are Gaussian, separable,asymmetric
  - initial electron density is uniform
  - boundary conditions are periodic (at present)
    - in future, will try to better emulate semi-infinite plasma

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





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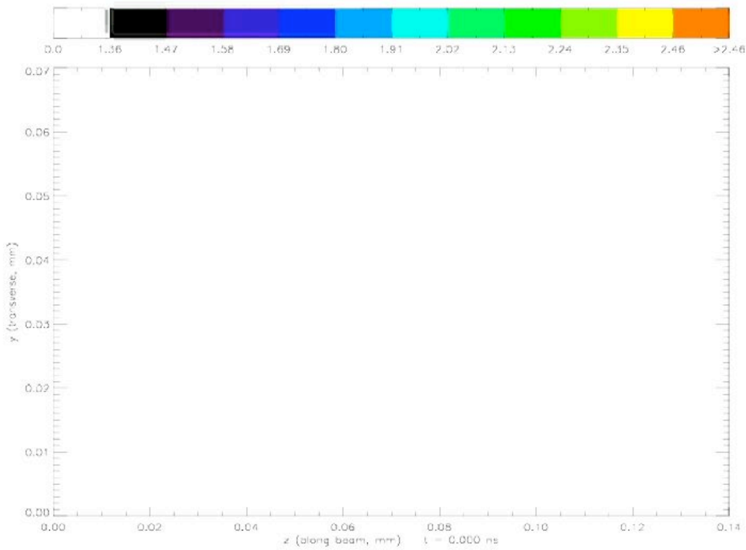
Observables:

example is for F(z)



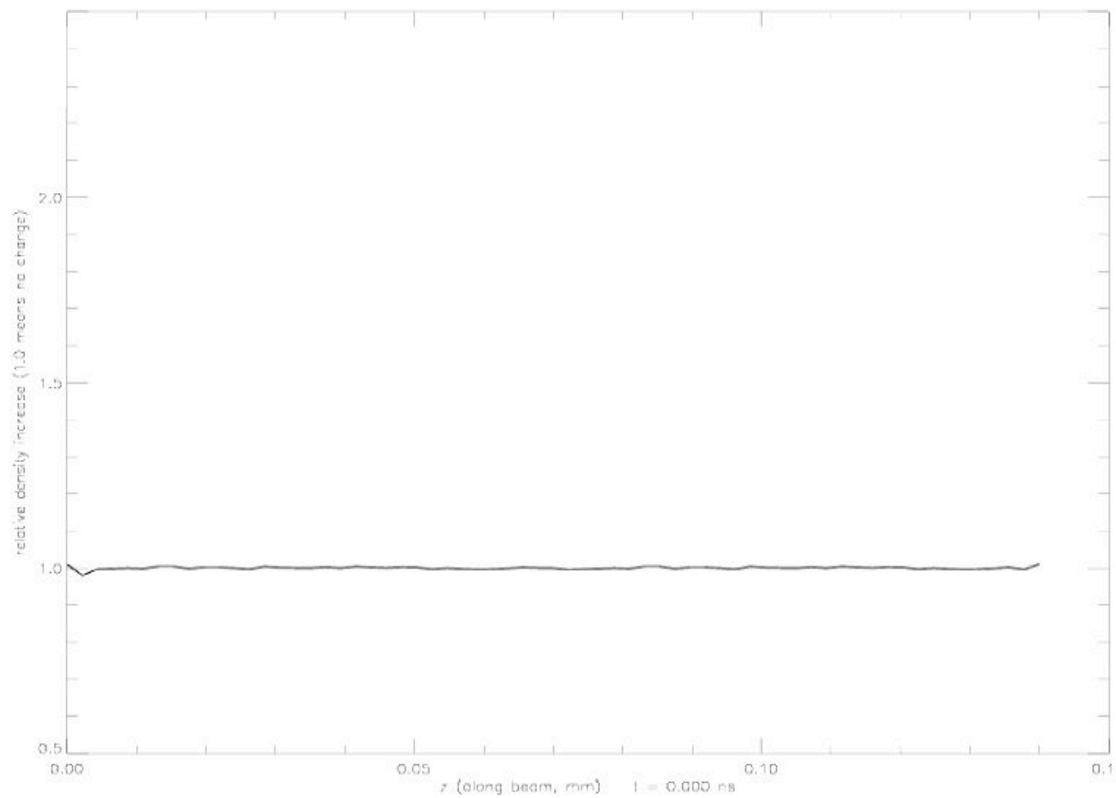
$$F(z) = \int f_e(\vec{\rho} - \hat{z}\cdot Z\tau, \vec{v}, \tau)\, d\vec{v}^3 dxdy$$

$$V_z(z) = \int v_z f_e(\vec{\rho} - \hat{z}\cdot Z\tau, \vec{v}, \tau)\, d\vec{v}^3 dxdy$$

$$F(x) = \int f_e(\vec{\rho} - \hat{x}\cdot T\cdot R\cdot \tau, \vec{v}, \tau)\, d\vec{v}^3 dzdy$$

$$F(y) = \int f_e(\vec{\rho}, \vec{v}, \tau)\, d\vec{v}^3 dzdx$$

$$A(k) = \int F(z)\cdot \exp(ikz)\, dz$$



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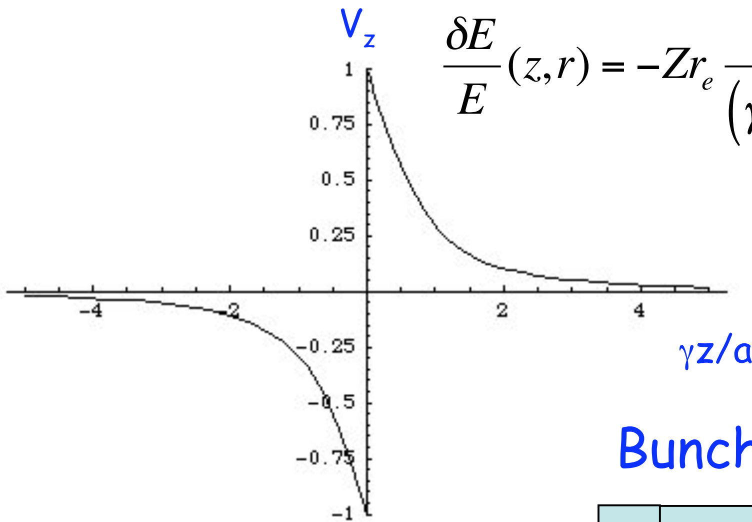
RHIC

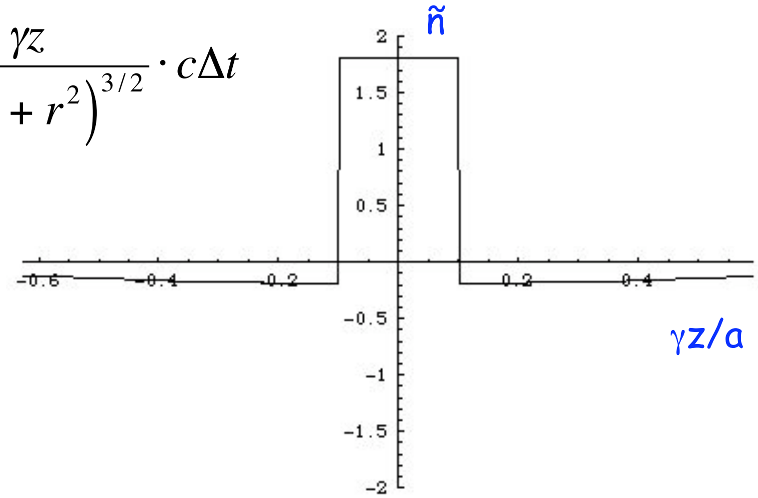
LHC specific issues

- Energy too high and plasma oscillations are **toooooooooooo slow** - plasma period is 6.9 km!!!!
- Charge ~ $(1-\cos(\omega_p t))\sim L_{mod}^2$
- For 100 m modulator $(1-\cos(\omega_p t))\sim 4\ 10^{-3}$ or loss of factor 250 n cooling!
- Is there a way to make ~100 m inot a useful modualator

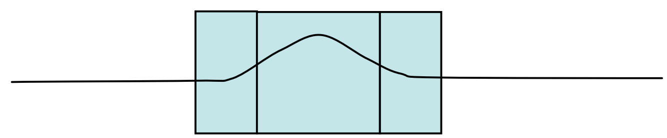
Velocity map & buncher

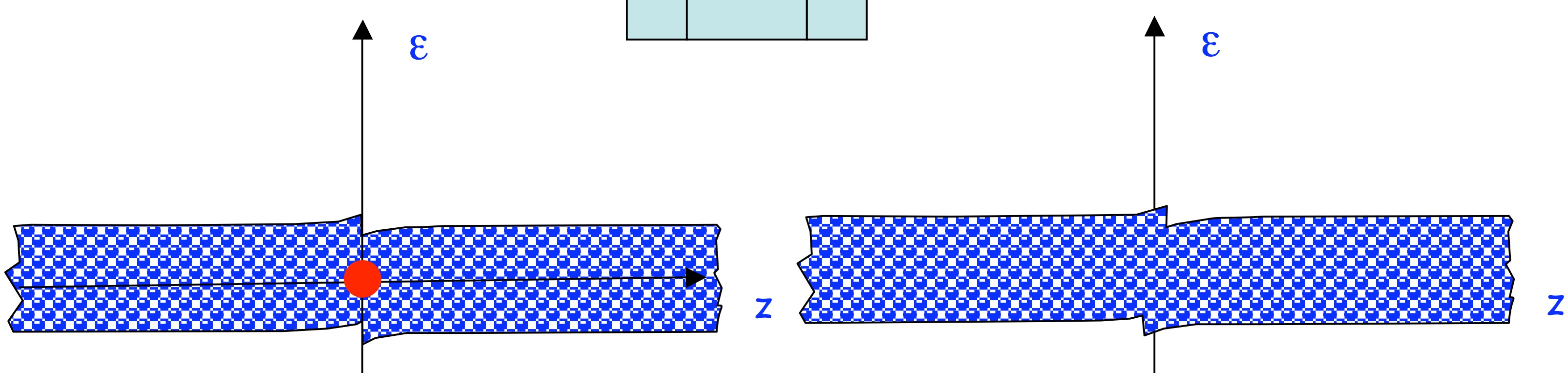


$$\frac{\delta E}{E}(z,r) = -Zr_e \frac{\gamma z}{\left(\gamma^2 z^2 + r^2\right)^{3/2}} \cdot c\Delta t$$



Buncher





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

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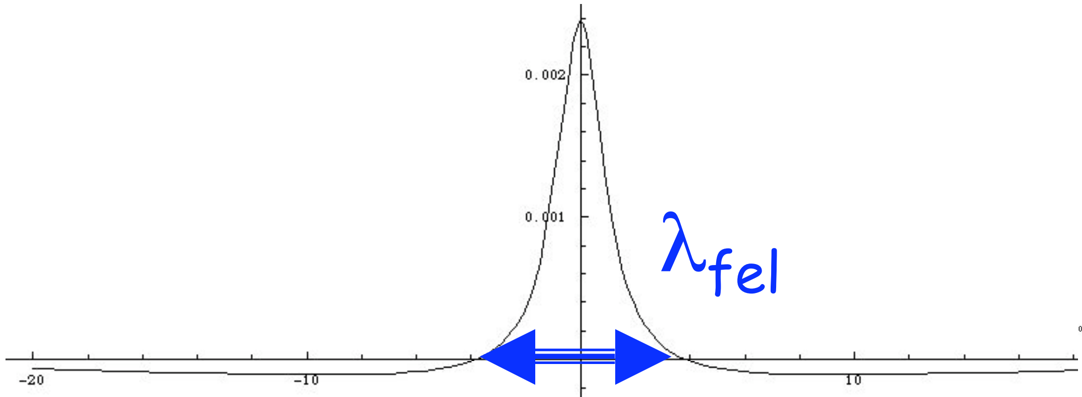
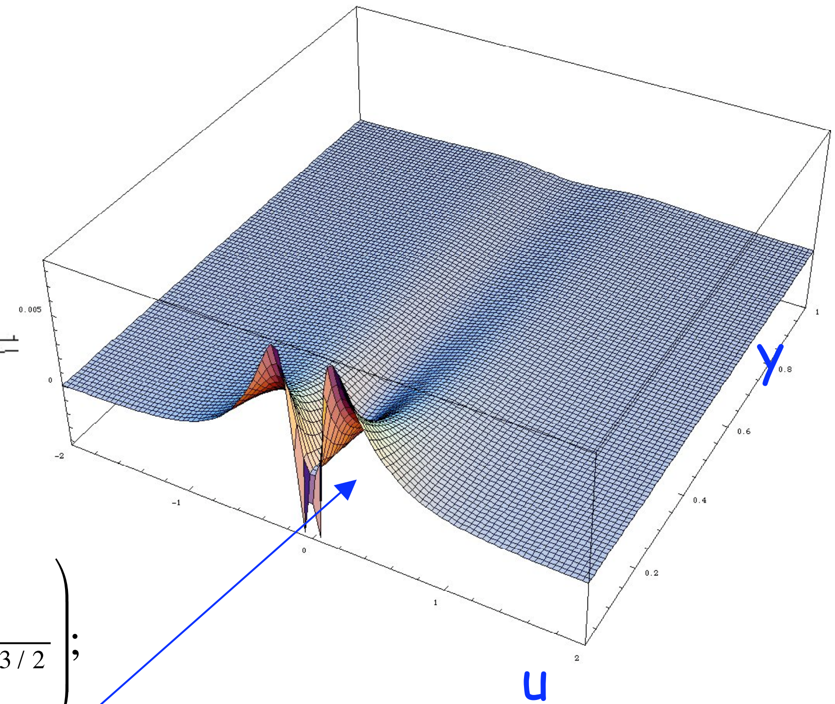
Exact calculations: solving Vlasov equation





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

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

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

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

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

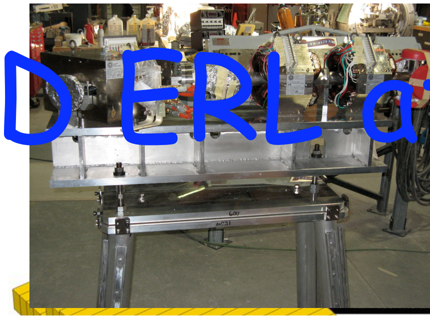
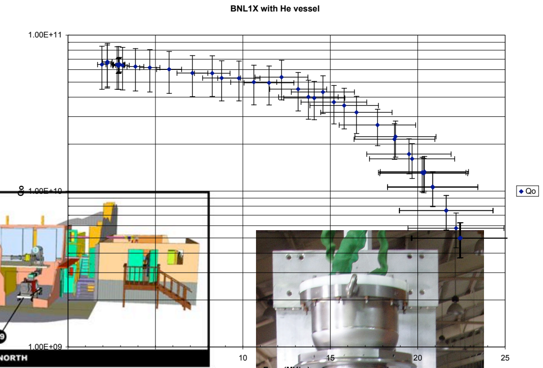
For 7 TeV p in LHC CeC case: My simple "gut-feeling" estimate gave 22.9 boost in the induced charge by a buncher, while exact calculations gave 21.7.

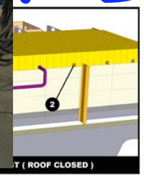
7 TeV protons in LHC: CeC ~200m

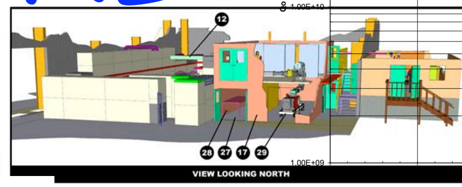
Potential of 4x increase in luminosity

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 Ñ in 10% BW	2 10^6 >> 2.8 10^5	Cooling time, beam	23 minutes

R&D ERL at BNL





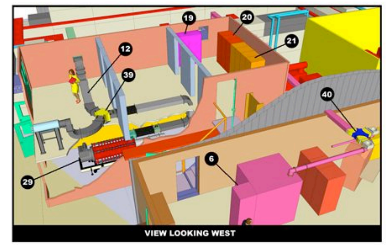
E_{inj} =2.5-.3.5 MeV

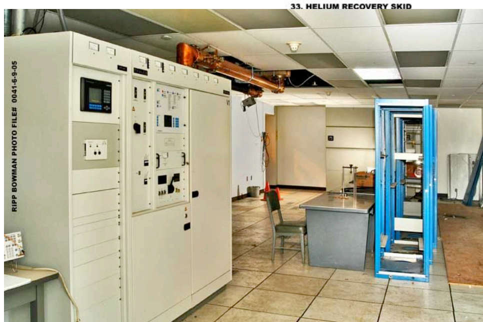
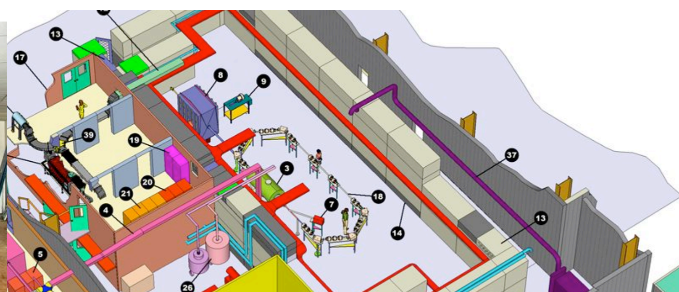
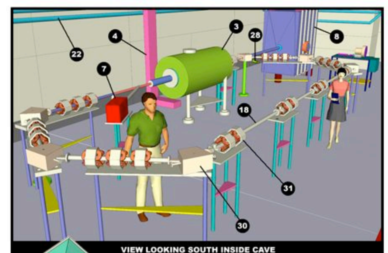
E_{total} = 25 MeV, I_{max} = 0.5 A

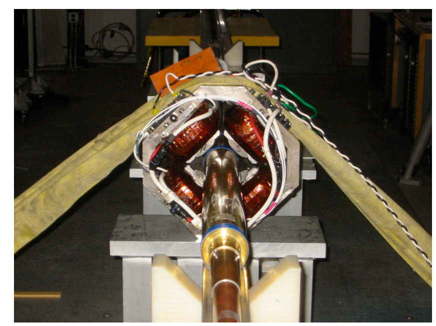
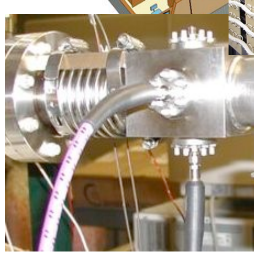
ε_n ~ 2 mm mrad @ 1.4 nC

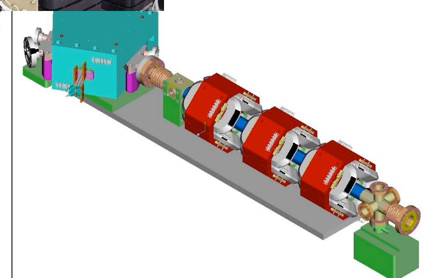
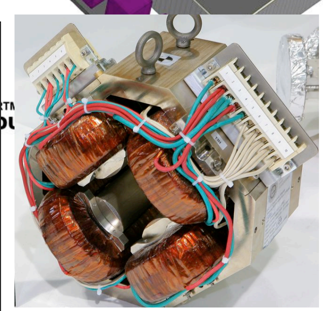
Single Loop, SRF Gun

5 cell SRF linac, 703.75 MHz



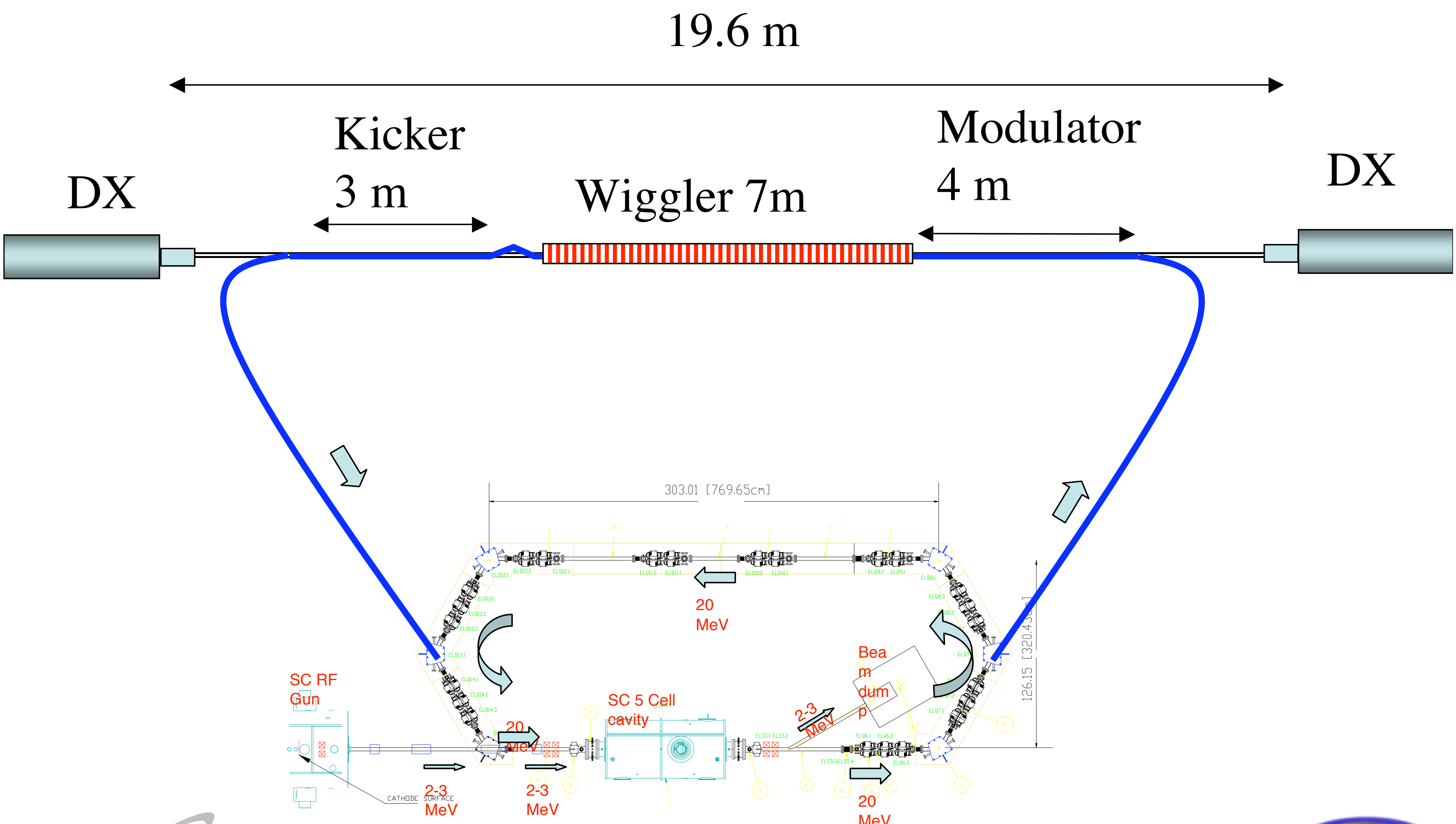



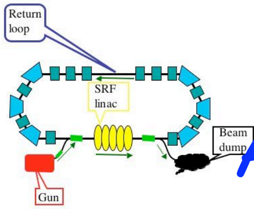
BROOKHAVEN NATIONAL LABORATORY

V.N. Litvinenko, LARP meeting, April 24, 2008

RHIC

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





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**

Timeline
Both eRHIC R&D and LARP

- Complete CeC theory - 2009
- Start R&D ERL operation in Bldg. 912 - 2009
- Complete fist round of CeC simulations - 2009
- **Design CeC PoP system - 2010**
- **Modify and build necessary hardware - 2012**
- LHC CeC simulations - 2012
- **Install R&D ERL at IP2 in RHIC - 2012-2013**
- **CeC PoP experiments - 2013-2014**

Participants in LARP efforts

- **BNL Personnel and tasks:** Vladimir Litvinenko - CeC PoP, theory and experiments; Post-Doc (TBD) – CeC and FEL simulations, Ilan Ben Zvi - SRF and ERL, Dmitry Kayran and Eduard Pozdeyev – R&D ERL and CeC lattice; Dejan Trbojevic and Steven Tepikian– RHIC lattice for CeC PoP; Wuzheng Meng and George Mahler– magnet design; Animesh Jain – magnetic measurements; C-AD engineers and technicians (as needed for specific tasks).
- **SBU Personnel and tasks:** Stephen Webb (graduate student), theory and simulations
- **FNAL Personnel and tasks:** Alexey Burov - theoretical support; Sergei Nagaitsev, Vladimir Shiltsev – participation in the PoP experiment.
- **JLab Personnel and tasks:** Yaroslav Derbenev - theoretical support.
- **LBNL Personnel and tasks:** John Byrd and others – development of the wiggler and the buncher for CeC PoP.

- **CERN liasons:Oliver Bruning, John Jowett, Frank Zimmerman**

Proposed Budget & Goals

MSTC Budget Breakdown:	***K$***
Post doc, Graduate student	160
Other Labor/Materials	315
Travel	25
Total	**500**

- *Cost sharing: This work will be performed as part of eRHIC R&D with expected budget $2M/year (NP DoE) and about 4 FTE efforts from C-AD, BNL. It will take advantage of R&D ERL at BNL with estimated value of $25M. There is possible SBIR support for VORPAL simulations for CeC at Tech X*
- **Ultimate goal of these efforts:**
  1. **Experimental demonstration of coherent electron cooling in CeC PoP at RHIC and test of the LHC specific modes of operation.**
  2. **Conceptual design of the CeC for LHC.**

Conclusions

- **Coherent electron cooling is very promising method for significant luminosity increase in LHC (and LHeC)**
- **Proof of principle experiment of cooling Au ions in RHIC at ~ 40 GeV/n is feasible with existing R&D ERL**
- Can test conjecture that strong cooling allows for higher beam-beam tune shifts
- **Modest LARP efforts would be critical for CeC PoP experiment and for testing the LHC-specific aspects of coherent electron cooling**

2.75 TeV/u Pb ions in LHC

N per bunch	$2\ 10^{11}$	Z, A	82, 207
Energy Au, GeV/n	2750	γ	2940
RMS bunch length, nsec	0.25	Relative energy spread	0.0113%
Emittance norm, μm	3.8	$\beta_{\perp}$, m	47
Energy e^-, MeV	1.503	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	**0.0308**
$\lambda_{D\perp}$, mm	3.7	$\lambda_{D\vert\vert}$, μm	0.17
λ_{FEL}, μm	0.04	λ_w, cm	5
a_w	3.58	L_{Go}, m	1.7
Amplitude gain =250, L_w , m	30.7	L_{G3D}, m	2.35
L_2 (lab frame) ,m	35	Cooling time, local, min	0.5 minutes
$N_{min\ turns}$ or $\tilde{N}$ in 10% BW	$2\ 10^6 \gg 2.8\ 10^5$	Cooling time, beam	3.2 minutes

ERL based LHeC with cooling: 30 x luminosity

	Electrons	Protons
Energy	70 GeV	7 TeV
N per bunch	$0.14\ 10^{11}$	$1.7\ 10^{11}$
Rep rate, MHz	40	
Beam current, mA	90	1090
Norm emittance, μm	3	0.3
β^*, m	0.5	1.3
ξ^* D	12.7 4.56	**0.0057**
Luminosity	**3.77×10^{34} cm^{-2} sec^{-1}**	
Loss for SR, MW	67	Kink Λ=0.93