# Coherent Electron Cooling

## Use of an Electron Beam
## for
## Stochastic Cooling

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# Outline

Principal idea

Polarization of electron plasma (beam) by a fast ion

Potentially possible amplification

Region of amplification

Limitation of cooling rate due to ion shielding

Arrangements for microwave instabilities in e-beam

Shottky-noise limitation and suppression of noise

Limitation due to non-linear saturation

Phasing

CEC on FEL  (preliminary estimates)

Conclusions and outlook

# History of idea (1980-91-95-2007)

## **Coherent electron cooling (CEC)** was proposed 27 years ago

- General idea: amplify response of e-beam to an ion by a micro-wave instability of the beam
- A few instabilities have been shown
- CEC advantages/disadvantages compared to:

EC : Gain in cooling rate

Complicate BT

SC : Very large FB (30 GHz – optics)

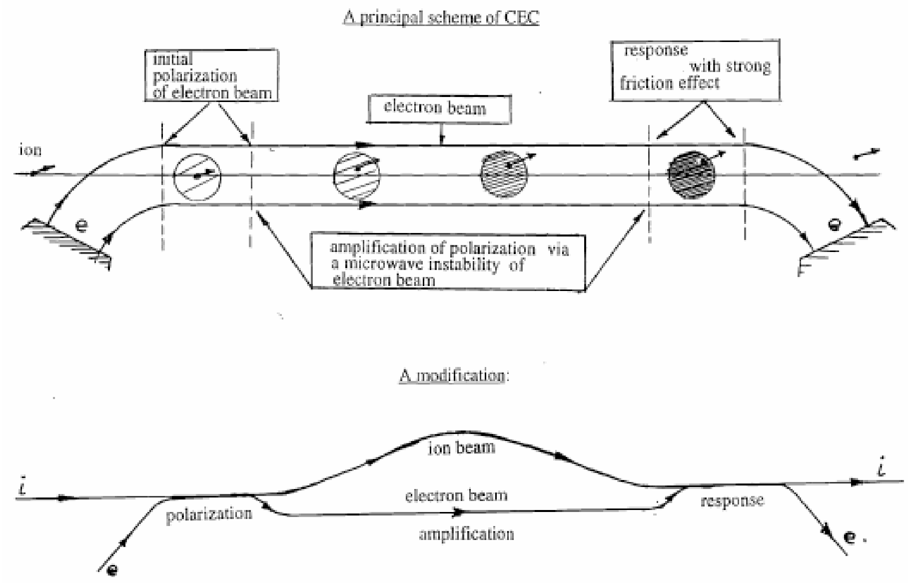
Precise phasing required

OSC : Effective in a wide energy range

Small signal delay

Intense e-beam required

Signal gain is limited




What changed in last 10 years?

- **Relativistic DC EC realized (FNAL)**
- **ERL realized (JLab)**
- **SASE FEL realized (UCLA - DESY)**
- **ERL-based HEEC on the way (BNL)**

**And more…**

# Fast ion wake in electron gas

Fast ion produces polarization of e-gas:

$$\omega_e^2 = 4\pi n_0 e^2 / m$$

$$\upsilon >> \upsilon_e = \sqrt{T_e / m}$$

$$n = n_0 + \tilde{n}; \qquad \ddot{\tilde{n}} + \omega_e^2 \tilde{n} = -\omega_e^2 Ze\delta(\vec{r} - \vec{\upsilon}t)$$

<In magnetized beam: $T_e \Rightarrow T_{ez} \approx e^2 n_0^{1/3} \approx 10^{-4} eV$ >

Ion interacts with charge image spread over distances $\rho$ :

$$\frac{\upsilon_e}{\omega_e} \equiv \rho_D < \rho \le \rho_{sh} \equiv \frac{\upsilon}{\omega_e}$$

-area of collective response

In stable plasma, ion receives drag force $F_0 = \frac{(Ze)^2}{\rho_{sh}^2} \int \frac{d\rho}{\rho}$

Polarization is small: $\frac{\tilde{n}}{n_0} \approx \frac{\delta\rho}{\rho_{sh}} \approx \frac{1}{n_0 \rho_{sh}^3}$

Thus, there is an enhancement potential $G \le n_0 \rho_{sh}^3 \qquad (\cong 10^6)!$

- A micro-wave instability is called…
- E-beam should be cool enough…
- Phasing is required…

# Maximum CEC rate

- **Maximum field initiated by a single ion (after amplification at absence of friends…)**

$$\mathrm{E} \Rightarrow 4\pi n_0 e \rho_{sh} = 4\pi n_0 e \upsilon / \omega_e$$

- The momentum transfer is then

$$\Delta p_{\perp} = F \cdot \tau \cong Ze^2 4\pi n_0 / \omega_e^2 = Zm_e \upsilon = \frac{Z}{A} \frac{m_e}{m_p} p_{\perp}$$

- And, the cooling time then would be

$$\tau_c \cong \frac{A}{Z} \frac{m_p}{m_e} \frac{1}{f_0}$$

# Microwave electron instabilities -1

**Introduce** <u>parametric plasma resonance</u> $\ddot{\tilde{n}} + \omega_e^2(t)\tilde{n} = 0$

- Change electron density up and down every 90 degree of plasma phase advance

Possible way:

- E-beam in modulated solenoid: $\omega_e^2(s) = \dfrac{4J/J_A}{\gamma \upsilon r^2(s)};$ $\quad r(s) = r_1 \leftrightarrow r_2;\quad r_2 > r_1$

- Start at $\dot{\tilde{n}} = 0$, then after each single period: $\dfrac{\tilde{n}_{k+1}}{\tilde{n}_k} = -\dfrac{\omega_{e1}}{\omega_{e2}} = -\dfrac{r_2}{r_1};$

- After q periods: $\dfrac{\tilde{n}_q}{\tilde{n}_0} = \left(\dfrac{r_2}{r_r}\right)^q$

<u>Correction:</u> magnetized plasma is non-isotropic: $\omega_e \Rightarrow \omega_e \times \cos\theta$

# Microwave electron instabilities-2

- **Negative longitudinal mass instability**

## An example:

**e-beam in solenoid with helical undulator, period** $2\pi / \kappa_u$

- **Beam angle**

$$\theta_0 \approx \frac{B_u / B_s}{\kappa_u ƛ_c - 1} \qquad ƛ_c = p / eB_s$$

- **The angle grows with energy at** $\kappa_u ƛ_c < 1$
- **Translation velocity:**

$$\upsilon_z^2 = 1 - \frac{1}{\gamma^2} - \theta_0^2;$$

**decreases with energy at**

$$\frac{1}{\mu} \equiv \frac{d\upsilon_z}{d\gamma} = \frac{1}{\gamma^3} - \frac{1}{2}\frac{d\theta_0^2}{d\gamma} < 0$$

Coulomb instability:

$$\Lambda = \sqrt{\frac{4\pi n e^2}{-\mu c^2}}$$

# Microwave electron instabilities -3

## FEL instability

•Undulator period $2\pi\lambdabar_u$

•Radiation wave length $$\lambda = \frac{1}{2}\lambda_u\left(\frac{1}{\gamma^2} + \theta_u^2\right)$$

•Plasma beat wave length $$l_e = \frac{\gamma r}{2}\sqrt{\frac{\gamma J_A}{J(1+\gamma^2\theta_u^2)}}$$

•SASE gain length $$l_G \approx l_e\left(\frac{\lambdabar_u}{l_e\gamma^2\theta_u^2}\right)^{1/3}$$ at $$\sqrt{\lambdabar_u l_G} \le \gamma r$$

•Optimal arrangement: $$\lambdabar_u \approx \gamma r \min\left(1, \frac{l_e}{l_c}\right)$$

# Limitations of CEC due to ion interactions

- **Conventional stochastic cooling limit:**

$$(\tau_c)_{\min} \geq \frac{N_{\Delta\varphi}\Delta\varphi}{2\pi\Delta f_0} = \frac{(J_{peak}/e)}{(\Delta\omega)^2}\frac{f_0}{\Delta f_0} \qquad \Delta\omega = 2\pi\Delta f \leq \frac{c}{l_\perp}$$

•CEC: $$\Delta\omega = \frac{\gamma\beta c}{\min(\rho_{sh}, \sigma_\perp)}$$

Reduction of mixing limit by a factor of $[\frac{\gamma l_\perp}{\min(\rho_{sh}, \sigma_\perp)}]^2$

# Schottky noise limitation of CEC

- **Normal Schottky impact:**

$$\dot{T}_{scat} \approx -\frac{m_e}{m_i}\dot{T}_{cool}$$

Rates gain in CEC: $\dot{T}_{cool} \rightarrow \times G$ $\dot{T}_{scat} \rightarrow \times G^2$

It yelds $G_{\max} \approx \frac{m_i}{m_e}$

Suppressed Schottky noise: $\dot{T}_{scatt} \rightarrow \times \Gamma^{-2}$

Then $G_{\max} \Rightarrow \frac{m_i}{m_e}\Gamma^2$

# Suppression of Schottky noise

- **Frequency range:** $\omega = k/\beta c$ $\qquad k \geq 1/\sigma_\perp$

Possible ways:

•3/2 e-gun regime: $\Gamma^2 \approx (eU/T_{cath})^{1/2}$

•Adiabatic acceleration (more suppression)

;

•Thermal relaxation along a low energy drift (most effective, in principle)

•Fast acceleration case: implement plasma gymnastics to compensate for instability mode (not effective in case of FEL amplification}

An “absolute” suppression limit:

$$\Gamma^2_{\max} \cong \frac{e^2 n_e \rho^2{}_{sh}}{\mathrm{T}_{ez}} = \frac{m}{M}\frac{\mathrm{T}_i}{\mathrm{T}_{ez}}; \qquad G_{\max} \cong \frac{\mathrm{T}_i}{\mathrm{T}_{ez}} \qquad (\Rightarrow 10^7 - 10^9)$$

# Gain limitation due to non-linear saturation

## Maximum gain for an absolute cooled e-beam:

$$G_1 \cong (n_e \sigma^3 / \gamma) \approx N_e \frac{\sigma_\perp}{\gamma \sigma_z}$$

Maximum gain for a real e-beam

$$G_2 \cong \Gamma (n_e \sigma^3 / \gamma)^{1/2} \qquad (\Gamma < \sqrt{n_e \sigma^3 / \gamma})$$

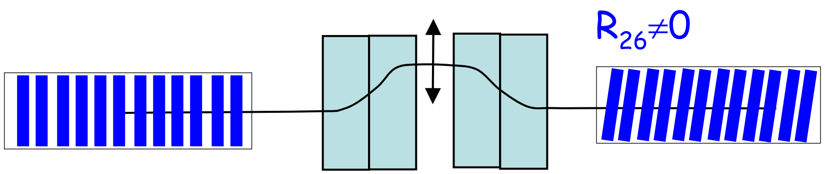
Maximum gain for real i-beam:

$$G_3 \cong (n_e \sigma^3 / \gamma) / (n_i \sigma^3 / \gamma)^{1/2}$$

Max. gain, at all: $G \le \min(G_2, G_3, \Gamma^2 \frac{m_p}{m_e}) \quad (\cong 10^3 - 10^4)$

# Transverse vs longitudinal CEC

- **Due to beam transport conditions and nature of microwave instabilities, transverse e-polarization is low compared to the longitudinal one. Therefore, the transverse drag force is small compared to the longitudinal one**
- **Solution in general: arrange for dispersive cooling**
- **Method : ion dispersion + tilt of electron ellipsoids**




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

•An alternative option: create transverse gradient of electron energy, by introducing the gradient SRF (no bend required…)

# CEC phasing

- The "good mixing" in CEC is extraordinary good (super-large frequency bandwidth!)
- The "bad mixing" for non-bent ion beam is not bad…

$$\Delta s = \frac{\Delta\gamma}{\gamma^3} l \cong \frac{\lambda}{4}\frac{4l}{\lambda_u}\frac{\Delta\gamma}{\gamma} < \frac{\lambda}{4}$$

- However, the e-beam response experiences some delay (necessary for amplification)
- The most advantageous way to compensate for delay time seems to be:

Increase (or modulate) electron energy

- In case of CEC on FEL, the "light"overtakes the ion…

Optimal phasing needs more study

# FELs and high-energy electron cooling

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*29th International FELConference*

*August 26-31, 2007, BINP, Novosibirsk*

# Content

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

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

*Vladimilr Litvinenko*
*29th International FEL Conference*
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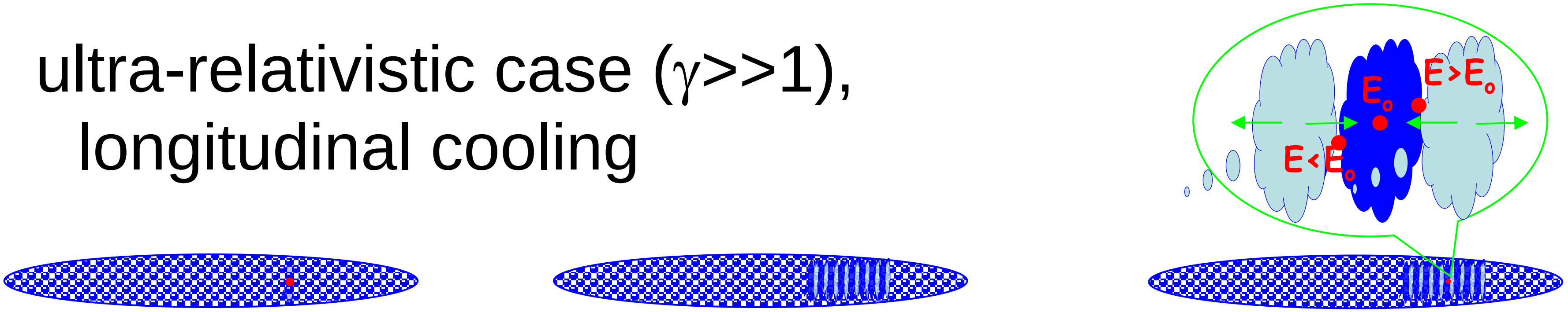
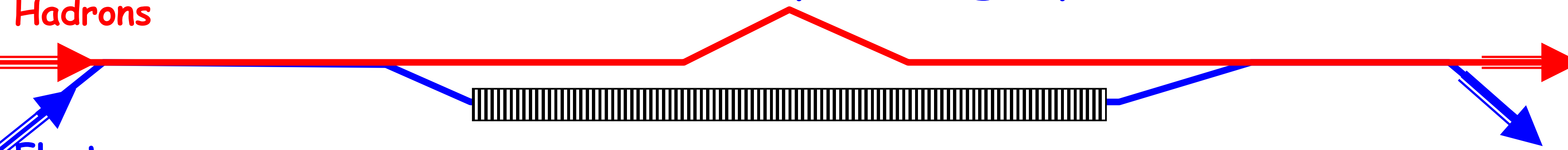
# CEC on SASE FEL

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




## Most versatile phasing option

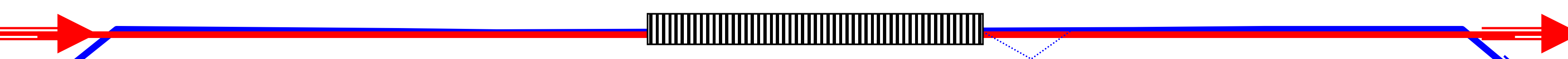



**Modulator:region 1**
about a quarter of
plasma oscillation

Longitudinal dispersion for hadrons

Amplifier of the e-beam modulation via SASE FEL

**Kicker: region 2**

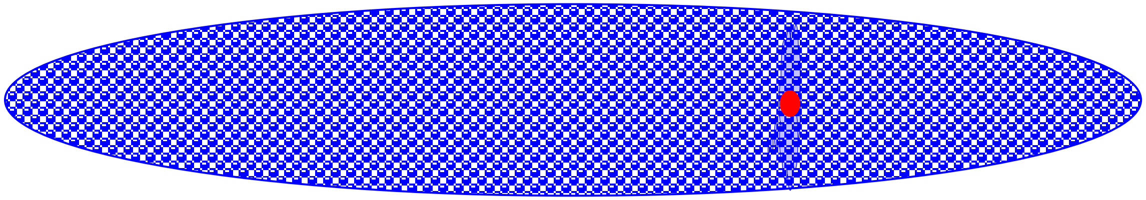


## Most economical option

# CEC on FEL

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

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

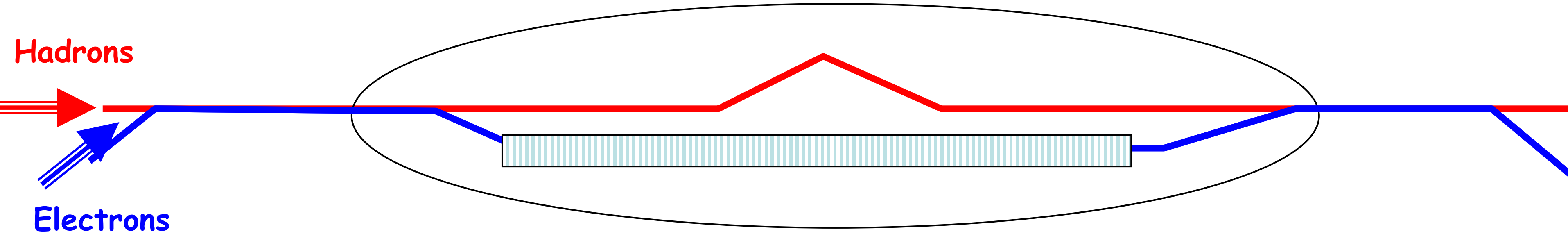


**Each hadron generates modulation in the electron density with total charge of about minus charge of the hadron, Z**

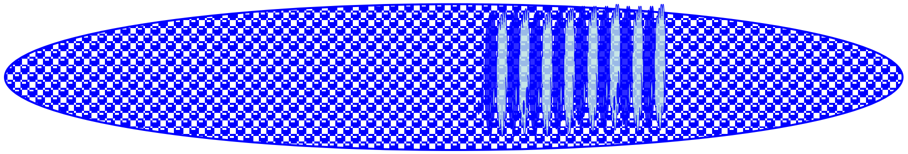
# CEC on FEL

**Longitudinal dispersion for hadrons, time of flight depends on its energy:**

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




**Amplifier of the e-beam modulation- SASE FEL**



**Electron density modulation is amplified in SASE FEL and made into a train with duration of N alternating hills (high density) and valleys (low density) with period of FEL wavelength**

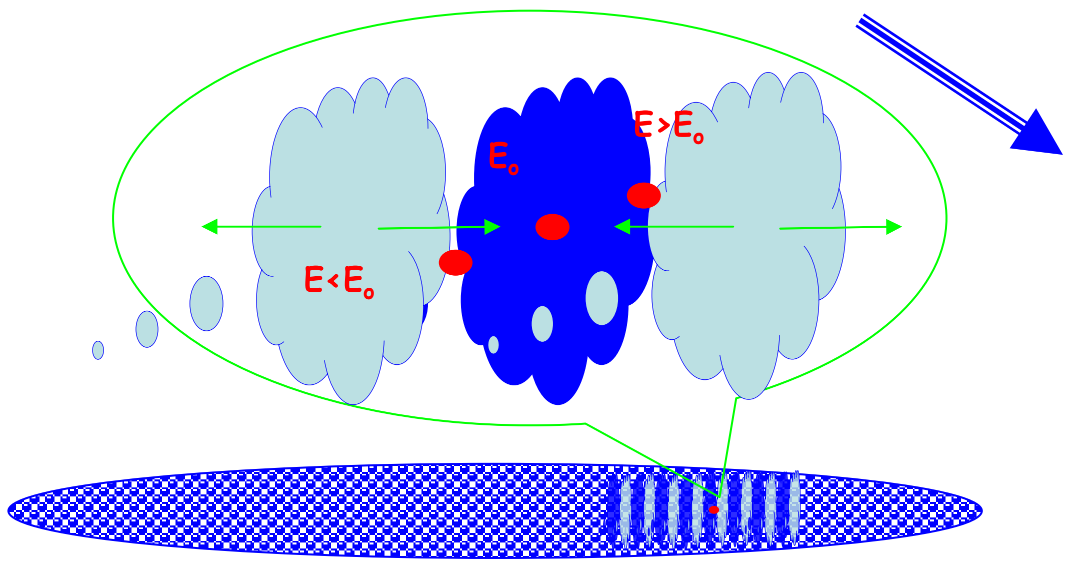
$\lambda_o=\lambda_w(1+a_w^2)/2\gamma^2$ ; $N_c \sim L_{gain}/\lambda_w$

**Maximum gain of the electron density of SASE FEL is ~ $10^3$.**

# CEC on FEL

**Kicker: Interaction region 2**

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



# Cooling of hadron beams

| 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 |

# Conclusions

- **Coherent electron cooling seems to be a promising method to enhance the capabilities of electron/stochastic cooling. It might find important applications in a wide energy range of hadron beams in accelerators**
- **At high energies, it might take 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 (oper. starts in 2009)**
- **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 (buncher, etc.)**
- **Question of possible short-noise suppression in electron beam is very interesting and should be further studies**

# Afterwards

**It seems we see the prairie, but**

**was the horse laying there?**

A comprehensive study to follow…