

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

Shotky-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)

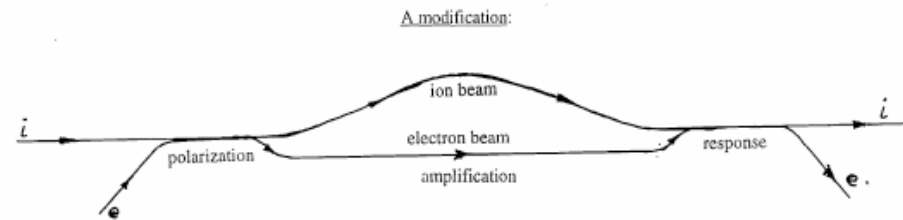
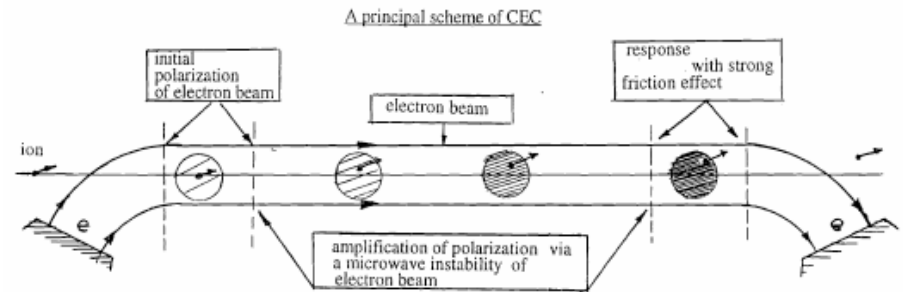
Precise phasing required

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:

$$n = n_0 + \tilde{n}; \quad \ddot{\tilde{n}} + \omega_e^2 \tilde{n} = -\omega_e^2 Z e \delta(\vec{r} - \vec{v}t)$$

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

$$v \gg v_e = \sqrt{T_e / m}$$

<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 ρ :

$$\frac{v_e}{\omega_e} \equiv \rho_D < \rho \leq \rho_{sh} \equiv \frac{v}{\omega_e} \quad \text{-area of collective response}$$

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 $G \leq n_0 \rho_{sh}^3 \quad (\cong 10^6)!$

- 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...)

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

- The momentum transfer is then

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

- 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 parametric plasma resonance $\ddot{\tilde{n}} + \omega_e^2(t)\tilde{n} = 0$

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

Possible way:

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

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

- After q periods: $\frac{\tilde{n}_q}{\tilde{n}_0} = \left(\frac{r_2}{r_1}\right)^q$

Correction: 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

$$\theta_0 := \frac{B_u / B_s}{\kappa_u \hat{\lambda}_c - 1} \quad \hat{\lambda}_c = p / eB_s$$

- The angle grows with energy at $\kappa_u \hat{\lambda}_c < 1$

- Translation velocity:

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

decreases with energy at

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

Coulomb instability:

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

Microwave electron instabilities -3

FEL instability

• Undulator period $2\pi\hat{\lambda}_u$

• 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

$$l_G \approx l_e \left(\frac{\hat{\lambda}_u}{l_e \gamma^2 \theta_u^2} \right)^{1/3} \quad \text{at} \quad \sqrt{\hat{\lambda}_u l_G} \leq \gamma r$$

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

Limitations of CEC due to ion interactions

- **Conventional stochastic cooling limit:**

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

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

Reduction of mixing limit by a factor of

$$\left[\frac{\mathcal{N}_{\perp}}{\min(\rho_{sh}, \sigma_{\perp})} \right]^2$$

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 yields $G_{max} \approx \frac{m_i}{m_e}$

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: $\omega = k / \beta c$ $k \geq 1 / \sigma_{\perp}$

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:

$$\Gamma_{\max}^2 \cong \frac{e^2 n_e \rho_{sh}^2}{T_{ez}} = \frac{m}{M} \frac{T_i}{T_{ez}}; \quad G_{\max} \cong \frac{T_i}{T_{ez}} \quad (\Rightarrow 10^7 - 10^9)$$

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

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

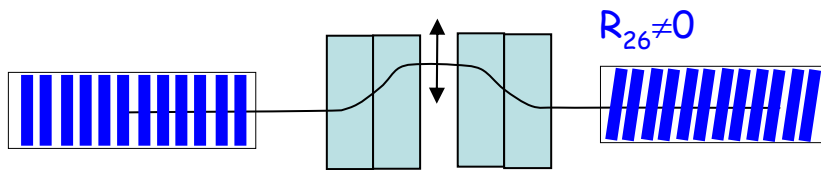
Maximum gain for real i-beam:

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

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

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 FEL Conference

August 26-31, 2007, BINP, Novosibirsk

FELs and HEEC

Content

And so, my fellow FELers, ask not
what storage ring can do for FELs:

Ask what FELs can do
for your storage rings!

Vladimir Litvinenko

29th International FEL Conference

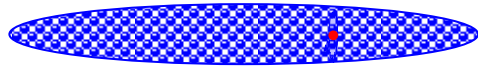
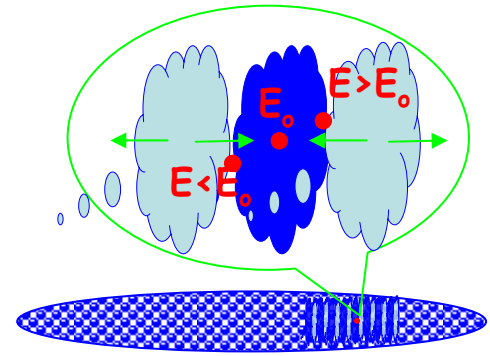
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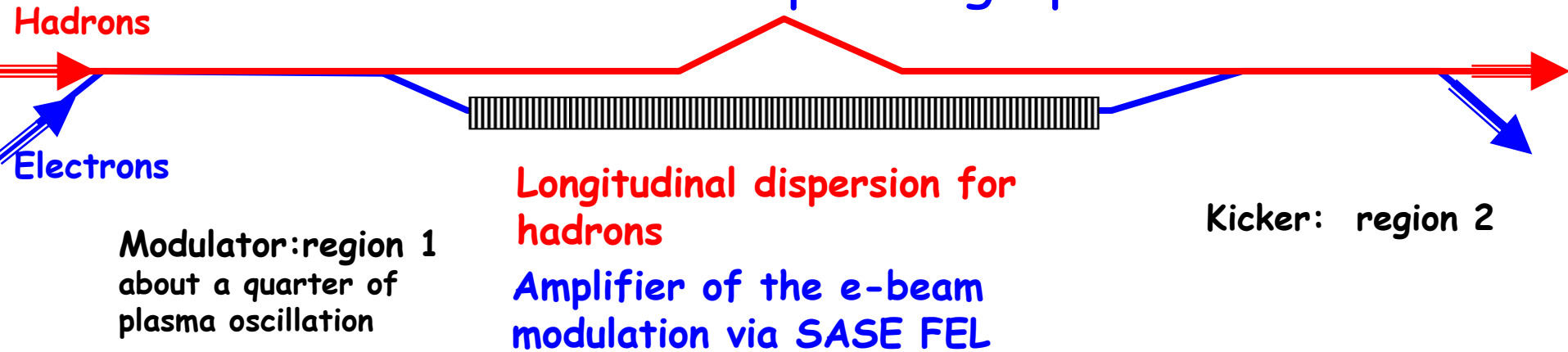
And so, my fellow Americans,
ask not what your country
can do for you;
ask what you can do
for your country.

CEC on SASE FEL

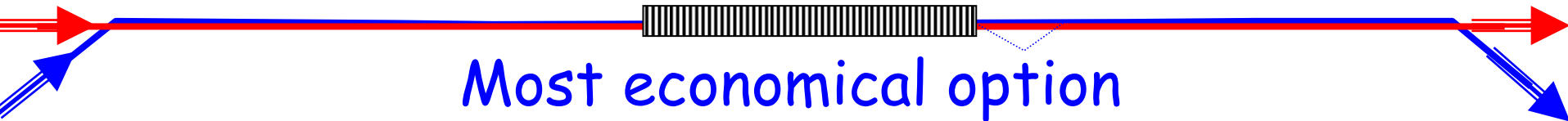
ultra-relativistic case ($\gamma \gg 1$),
longitudinal cooling



Most versatile phasing option



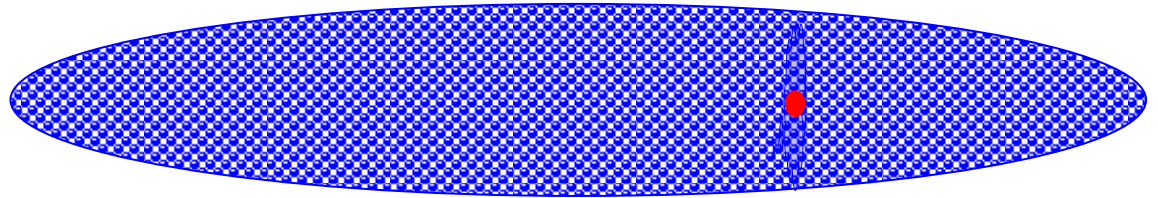
Most economical option



CEC on FEL

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

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

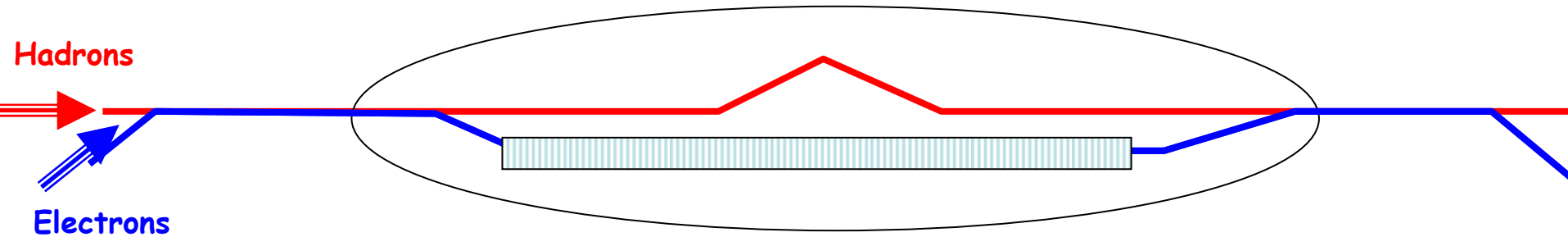


Each hadron generates modulation in the electron density with total charge of about minus charge of the hadron, **Z**

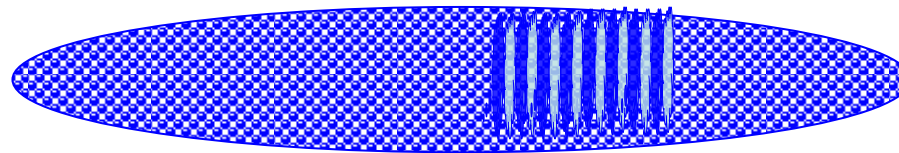
CEC on FEL

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

$$(T-T_0) v_0 = -D (E-E_0)/E_0$$



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

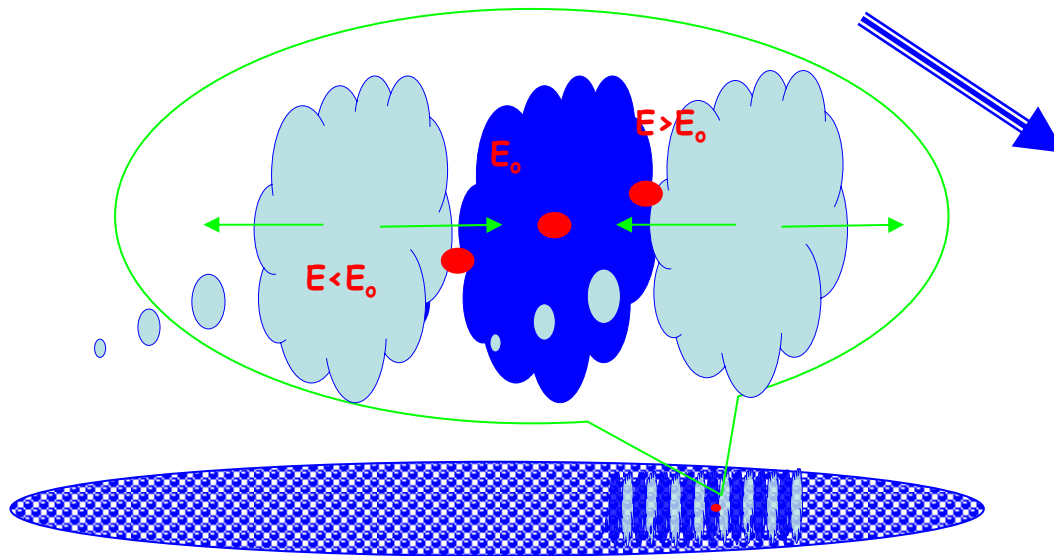
$$\lambda_0 = \lambda_w (1 + a_w^2) / 2\gamma^2 ; N_c \sim L_{\text{gain}} / \lambda_w$$

Maximum gain of the electron density of SASE FEL is $\sim 10^3$.

CEC on FEL

Kicker: Interaction region 2

A hadron with central energy (E_0) phased with the hill where longitudinal electric field is zero, a hadron with higher energy ($E > E_0$) arrives earlier and is decelerated, while hadron with lower energy ($E < E_0$) 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...