Coherent electron cooling – promise and challenges

G. Stupakov
SLAC National Accelerator Laboratory

IAS Program
High Energy Physics
Mini-workshop on Accelerator Physics

January 13-14, 2022

Outline

- Motivation
- Origin and physics of coherent electron cooling (CEC)
- 3 main variants of CEC
- MBEC for the electron-ion collider (EIC)
- Optimized performance and challenges
- Summary

Motivation

Cooling is needed for relativistic hadron beams (electrons are cooled by synchrotron radiation) to counteract the stochastic effects (IBS, noise, wakefields), decrease the beam emittance and keep from growing with time. The two classical cooling techniques—the stochastic cooling and the electron cooling—do not scale well to higher energies and dense beams. New ideas have been proposed to overcome the shortcomings of the classical cooling:

- Coherent electron cooling (CEC)
- Optical stochastic cooling (OSC)

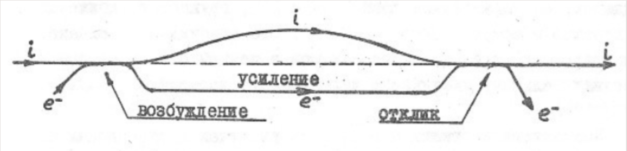
The main advantage of these cooling techniques is that they operate in the range of tens of THz (or higher)—orders of magnitude higher than the conventional stochastic cooling (several GHz).

OCS has been demonstrated in 2021 on IOTA electron machine at Fermilab, USA[1].

[1] J. Jarvis et al. "Experimental Demonstration of Optical Stochastic Cooling", Paper S403, COOL21 (2021).

Coherent electron cooling (CEC)

The concept was invented by Ya. Derbenev in 1980[2] under the name "Enhancement of electron cooling through intrinsic instability of the electron beam".



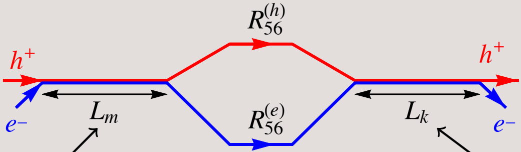
The concept was resurrected in 2009 by V. Litvinenko, Y. Derbenev under the name of Coherent electron Cooling (CeC)[3].

[2] Ya.S. Derbenev, in Proceedings of 7th Conference on Charged Particle Accelerators, Dubna, USSR, 1980, p. 269.

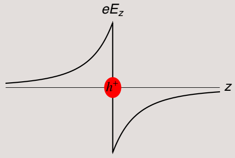
[3] V. Litvinenko, Y. Derbenev, PRL **102**, 114801 (2009).

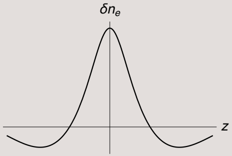
The concept of the generic CEC

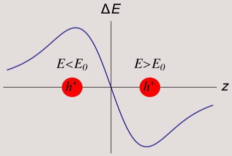
h^+ with $E > E_0$ move forward, $E < E_0$ lag behind



e^- with $E > E_0$ move forward, $E < E_0$ lag behind







The concept of the generic CEC

- In microbunched electron cooling, electrons of the cooler beam with $\gamma_e = \gamma_h = \gamma$ first interact with the ion beam in the modulator.
- The energy perturbations in the electron beam due to the ions are then converted to density modulation in the chicane $R_{56}^{(e)}$.
- The longitudinal electric field of these density perturbations acts back on ions in the kicker.
- High-energy ions passing through $R_{56}^{(h)}$ move ahead and get a negative kick, while low-energy ions move back and get a positive kick.
- Over many passages, this decreases the energy spread of the hadron beam.

CEC needs amplification

Without amplification, the cooling rate is too weak[4]. One needs to amplify the signal in the electron beam (indicated in the original paper by Derbenev).

Three different amplification mechanisms:

- Free electron laser (FEL)[5]. This is a narrow-band amplifier[6].
- Microbunching instability (MBEC)[7] (broadband).
- Plasma-cascade instability[8] (broadband). In principle, does not require separation of the hadron and electron beams between the modulator and the kicker.

---

[4] G. Stupakov, PRAB, **21**, 114402 (2018).

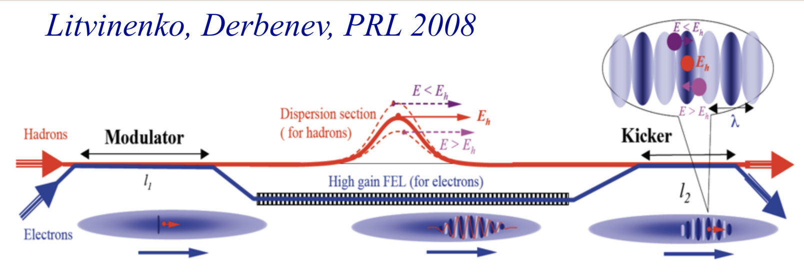
[5] V. Litvinenko, Y. Derbenev, PRL **102**, 114801 (2009).

[6] G. Stupakov, M. Zolotorev. PRL **110**, 269503 (2013).

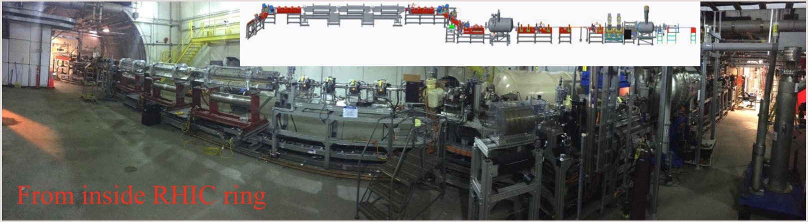
[7] D. Ratner, PRL, **111**, 084802 (2013).

[8] V. Litvinenko et al., arXiv:1902.10846 (2019).

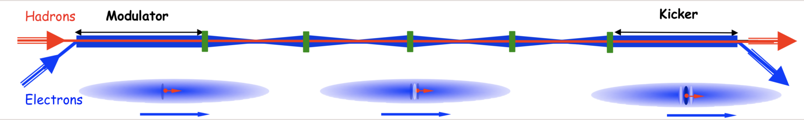
CEC with FEL amplifier



A proof-of-principle experiment has been carried out at RHIC, BNL in 2018, but, the cooling was not observed (large noise in the electron beam).



Plasma cascade amplifier (PCA)[9]

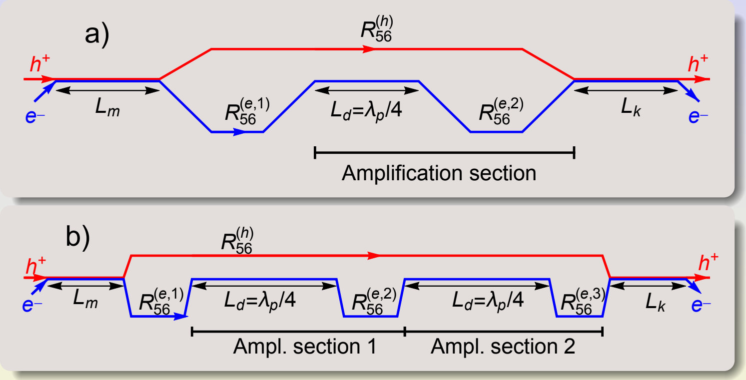


Currently a PCA PoP experiment is being carried out at RHIC at BNL.

[9] V. Litvinenko et al. *"Plasma-Cascade Instability – theory, simulations and experiment"*, arXiv:1902.10846 (2019).

Micro-bunched electron cooling (MBEC)

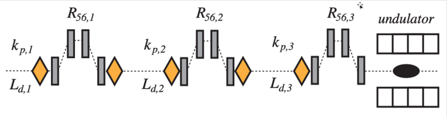
In MBEC the amplification is provided by a sequence of drifts of $\lambda_p/4$ long and chicanes. Here λ_p is the length for one period of plasma oscillations in the beam.



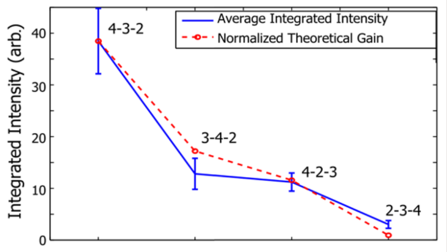
For realistic parameters, one amplification section provides gain $\sim 10 - 20$. The effective bandwidth of this amplifier is tens of THz.

MB amplification was tested experimentally

Micro-bunched amplification is well known in FELs[10]. It has been tested experimentally at NLCTA facility at SLAC[11].



Beam line for the NLCTA experiment. The amplification was inferred from the beam radiation in the undulator



Signal intensity increases when the chicane strength is optimized. Good agreement with theory.

Estimated intensity amplification ~ 3000.

[10] Schneidmiller & Yurkov, PRAB **13**, 110701 (2010); Dohlus et al. PRAB **14**, 090702 (2011).

[11] Marinelli et al. PRL **110**, 264802 (2013)

MBEC cooler for EIC

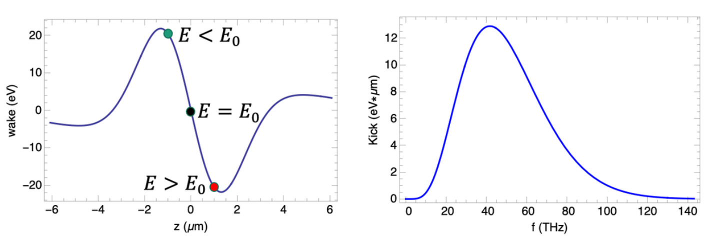
MBEC method has been actively studied over the last several years[12] for cooling hadrons in the EIC.

Proton energy [GeV]	275
Electron energy [MeV]	150
Electron relative energy spread, $(\Delta E/E)_e$	1×10^{-4}
Electron beam charge, Q_e [nC]	1
Electron beam current [A]	0.1
L_m, L_k [m]	39
Amplifier drift length [m]	43

Cooler parameters for the highest proton energy in EIC.

[12] GS and P. Baxevanis, PRAB, **2**2, 034401 (2019); P. Baxevanis and GS, PRAB, **22**, 081003 (2019)); W. Bergan. Paper TUPAB179, IPAC (2021); W. Bergan et al. Paper TUPAB180, IPAC (2021); S. Nagaitsev et al. Paper WEPAB273, IPAC (2021).

How fast cooling can we expect in CEC?



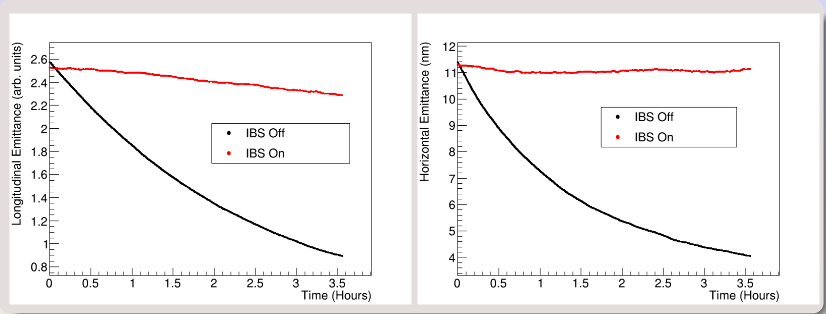
The kick generated by one proton in the kicker section. The frequency bandwidth $\Delta f \approx 40$ THz. In the optimal settings the cooling rate is estimated as

$$\frac{1}{t_c} \sim \frac{\Delta f}{C N_h / \sigma_{z,h}} \approx 0.5 \ \mathrm{min}^{-1}$$

For EIC: $C = 3834$ m, $N_h = 6.9 \times 10^{10}$, $\sigma_{z,h} = 6$ cm.
In reality we calculate the cooling rate $\sim 1 - 2\,\mathrm{h}$ for EIC with 2 amplification sections. It is enough to counteract the IBS in the machine.

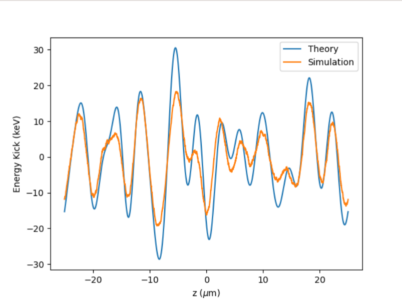
Simulations of cooling time for EIC

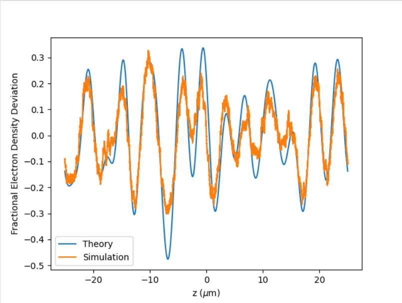
Simulation results of W. Bergan.



Cooling needs a low-noise electron beam. At 275 GeV, increasing the Poisson noise by a factor of 1.5 increases the cooling times to 2 hours horizontally and 3.1 hours longitudinally, close to the IBS limit.

Noise and saturation in the amplifier



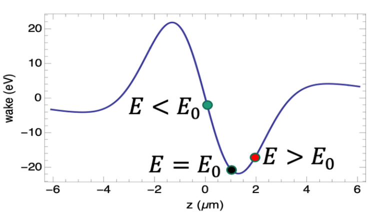


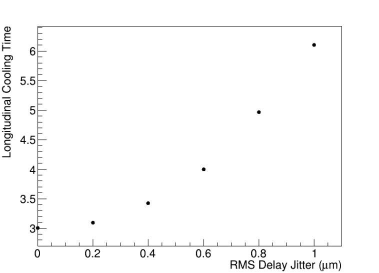
rms kick = 12 keV

$\sqrt{\langle \delta n_e^2 \rangle}/n_0 = 0.18$

This is one of the limitations of the cooling rate. We can achieve cooling time ~ 2 hours with $\sqrt{\langle \delta n_e^2 \rangle}/n_0 = 0.2$.

Effect of unequal path-length of electrons and protons[13]



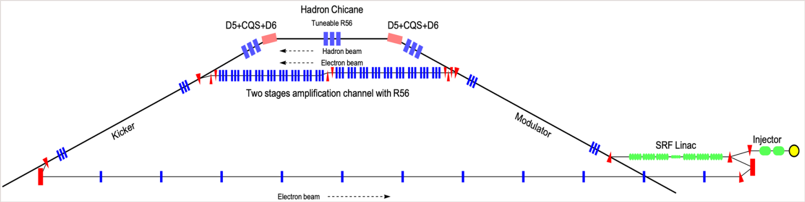


Jitter of the path-length of electrons and ions leads to deterioration of cooling. Simulations show that the rms path length jitter ~ 0.5 μm noticeably increases the cooling time

Contributions to the jitter (E. Wang):
Cooling section electron beamline PS stabilization ~ 3 ppm $\longrightarrow$ longitudinal shift ~ 200 nm
Longitudinal SC $\longrightarrow \sim 56$ nm
CSR wake $\longrightarrow \sim$140 nm.
A feedback system for the path control seems necessary.

13 S. Seletskiy, A. Fedotov, D. Kayran. "Effect of coherent excitation in coherent electron cooler", arXiv:2106.12617 (2021).

MBEC cooler in EIC ring



- 400kV DC gun for 100 mA of beam and 4 MV SRF injector
- Dogleg ERL merger
- 149 MeV Super conducting Energy Recovery LINAC (in existing tunnel)
- e Beam transport to merge hadron beam
- Amplification section with chicanes for electrons
- Hadron chicane (existing magnets) path length matching & R56 adjust
- Return transport of electron beam to ERL
- 2 K He sub cooler station, RF and power infrastructure
- Electron beam instrumentation and diagnostics

Cortesy E. Wang

CEC Challenges

- Needs high-quality electron beam with $\gamma_e = \gamma_i$. High current, small energy spread, small noise in the beam. ERL beyond the state of the art.

- Amplification is limited by the saturation and the noise in the amplifier.

- Large length of the system. The plasma wavelength scales as $\sqrt{\gamma^3/I_e}$, so scaling to higher γ requires a long system. A possible solution - use undulators instead of the drifts[14].

- Path length control for electrons and hadrons with sub-micron accuracy. Require exquisite stability of the system (path length control < 1 μm).

- Theoretical analysis is difficult. Computer simulations involve small spacial scales (~ 1 μm), long times (~ 1 hour), 3D.

[14] GS and A. Zholentz. Paper S803, COOL21 (2021).

Summary

- Compared with conventional coherent cooling, CEC raises the frequency bandwidth of the cooler by several orders of magnitude (from GHz to tens of THz). It has a promise of much faster cooling for medium-energy, dense hadron beams.
- It also introduces a number of challenges, one of which is an exquisite control of the beam path lengths. We hope to overcome these challenges in the MBEC cooler for EIC.
- A proof-of-principle experimental is currently being conducted at RHIC which should demonstrate cooling in PCA-based CEC system.

Acknowledgements

BNL: W. Bergan, E. Wang, M. Blaskiewicz, P. Baxevanis
FNAL: S. Nagaitsev, V. Lebedev
ANL: A. Zholentz