Microbunched Coherent Electron Cooling for Future Hadron Colliders

Gennady Stupakov
SLAC National Accelerator Laboratory, Menlo Park, CA 94025

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State of the art

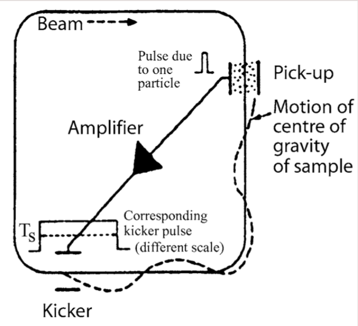
In electron circular accelerators there is a strong cooling mechanism through incoherent synchrotron radiation. It naturally cools the longitudinal degree of freedom, and through the horizontal-longitudinal coupling cools the beam in the horizontal direction. The equilibrium beam emittance is determined by the beam energy and properties of the lattice in the ring.

Radiation cooling for protons is typically weak for hadrons, due to their large mass. There are two well developed conventional cooling techniques for hadrons[1]:

- Stochastic cooling
- Electron cooling

[1] See more details in: S. Nagaitsev, "Review of Recent Advances in Cooling Techniques" at NAPAC 2019.

Stochastic cooling



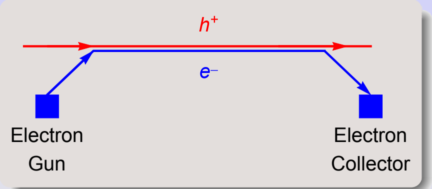
The optimized cooling rate

$$\frac{1}{\epsilon}\frac{d\epsilon}{dt} = -\frac{1}{2TN_{\mathrm{sample}}}$$

where T is the revolution period.

For coasting beam, N_{sample} is the number of particles in the duration of the kick, $N_{\mathrm{sample}} \approx N(\Delta T_{\mathrm{kick}})/T \approx N/TW$, where W is the amplifier bandwidth. Typically, for conventional stochastic cooling, $W \sim$ several GHz. Faster cooling corresponds to a broader bandwidth.

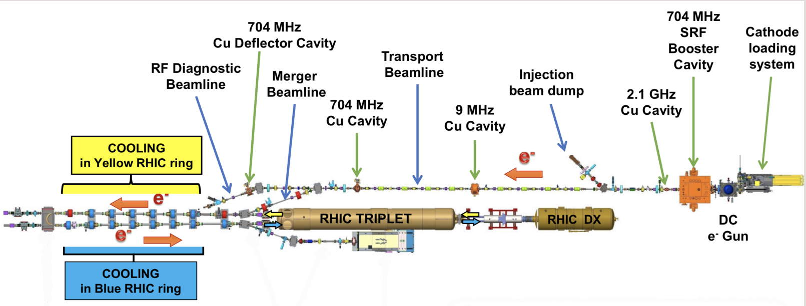
Electron cooling



Electron beam with $\gamma_e = \gamma_h$.
Friction force in the beam frame

$$\boldsymbol{F}(\boldsymbol{v}) = 4\pi\Lambda n_e m_e (Z r_e c^2)^2 \times \int_{-\infty}^{\infty} f(\boldsymbol{v}_e) \frac{\boldsymbol{v}_e - \boldsymbol{v}}{|\boldsymbol{v}_e - \boldsymbol{v}|^3} d^3 v_e$$

Low-Energy RHIC electron Cooler (LEReC) at BNL, $E_e = 1.6 - 2.6$ MeV.



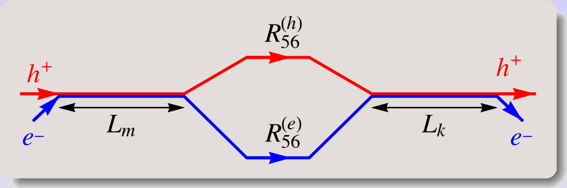
The challenge

Designs of electron-ion colliders require cooling of proton beams at 100-300 GeV with the cooling times ~ 1 hour.

• Traditional dc electron cooling schemes are not scalable to energies above > 10 GeV
• Conventional stochastic cooling is too slow for bunched protons (not enough bandwidth)

During the last decade several new concepts of the hadron cooling were proposed that have a promise of much faster cooling rates. They use a mechanism of the *coherent* cooling and seem capable to satisfy the needs of the future EIC.

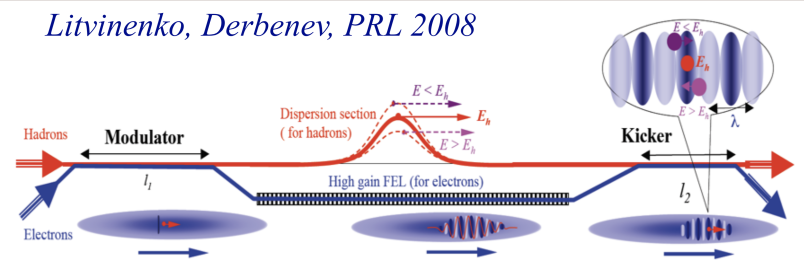
Concept of generic Coherent electron Cooling (CeC)



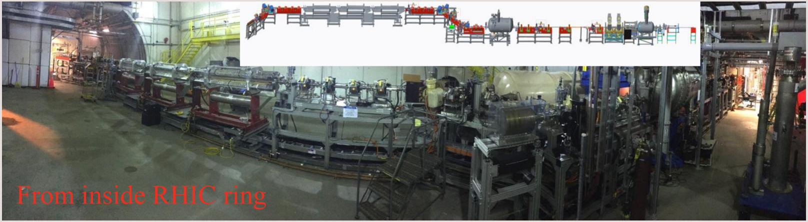
Electrons of the cooler beam with $\gamma_e = \gamma_h$ first interact with the hadron beam in a short modulator where their energy is perturbed by hadrons. The energy perturbations in the electron beam are then converted to density modulation in the chicane $R_{56}^{(e)}$. The longitudinal electric field of these density perturbations acts back on hadrons in the kicker. High-energy hadrons passing through $R_{56}^{(h)}$ move ahead and get a negative kick, low-energy move back and get a positive kick. Over many passages, this decreases the energy spread of the hadron beam.

This scheme is typically too weak to provide an adequate cooling and should be supplemented by an amplification of the signal in the electron beam.

CeC with FEL amplifier

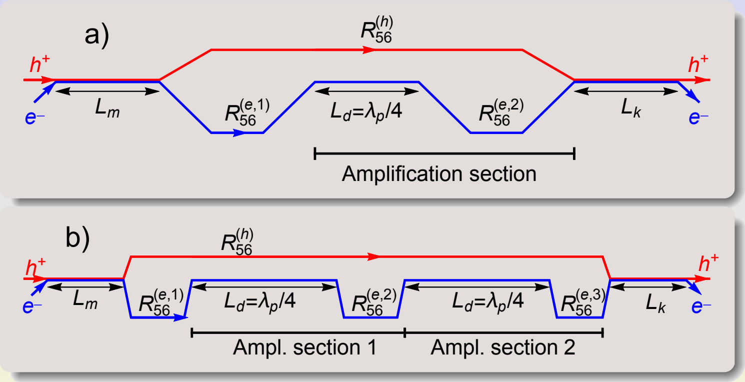


A proof-of-principle experiment was conducted at BNL, however, the cooling was not observed (because of the large noise in the electron beam).



Microbunched electron cooling (MBEC)[2].

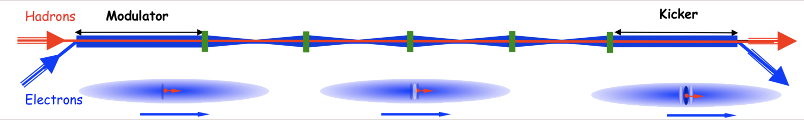
In MBEC the amplification is provided by a sequence of drifts of $\lambda_p/4$ long and chicanes.



The main advantage of MBEC is its broadband amplification as compared to the narrow-band FEL CeC. The effective bandwidth of this amplifier is tens of THz.

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

Plasma cascade amplifier (PCA)[3]



This is also a broadband amplifier. PCA PoP experiment is being prepared at BNL.

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

Theoretical studies of MBEC at SLAC, 1D model

• Longitudinal cooling rate for the generic CeC [G. Stupakov, PRAB, **21**, 114402 (2018)]

$$N_c^{-1} \equiv \frac{T}{t_c} \approx \frac{0.3}{\sigma_{\eta h}\sigma_{\eta e}} \frac{1}{\gamma^3} \frac{Q_e c/\sigma_{zh}}{\sqrt{2\pi} I_A} \frac{r_h L_m L_k}{\Sigma_x^3}$$

• Microbunched electron cooling with amplification cascades [G. Stupakov, P. Baxevanis, PRAB, **22**, 034401, 2019]

• Transverse MBEC cooling [P. Baxevanis and G. Stupakov, PRAB **22**, 081003 (2019)].

• Diffusion and nonlinear plasma effects in microbunched electron cooling [P. Baxevanis and G. Stupakov, NAPAC19, WEPLH17, 2019].

Theoretical formulas are benchmarked against 1D computer simulations.

Representative set of parameters for eRHIC MBEC

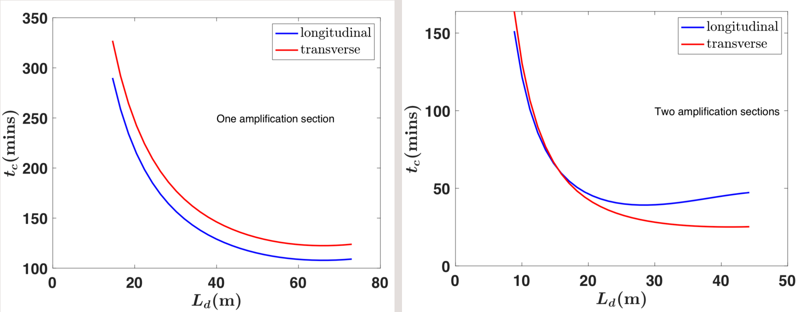
Proton energy [GeV]	275
Proton relative energy spread, $\sigma_{\eta h}$	4.6×10^{-4}
Electron energy [MeV]	150
Electron relative energy spread, $\sigma_{\eta e}$	1×10^{-4}
Electron beam charge, Q_e [nC]	1
Electron beam peak current [A]	30
Repetition rate [MHz]	112
RMS beam size in mod. and kicker, Σ_x, [mm]	0.7
L_m, L_k [m]	40

The electron bunch length, $\sigma_{ze} \approx 4$ mm, is much shorter than the proton bunch length, $\sigma_{ze} \lesssim \sigma_{zh} = 5$ cm.

The cooler-beam current is ~ 100 mA.

The cooling rate without amplification is $13.6\,\mathrm{h}$.

Optimization of the cooling rate with account of noise in the beam



- What is the desirable outcome? What are the potential impacts?

We need to achieve good understanding of the mechanism of the coherent cooling with different amplification methods, evaluate the challenges, work out scaling relations and optimize the design of CeC cooler. We need to develop software for more realistic simulations of CeC.

A success of this program would give a tool for cooling relativistic hadron beams that is orders of magnitude faster than the conventional methods.

- How does it fit into the GARD ABP missions?

It is a part of *"Advance physics of accelerators and beams to enable future accelerators"*.

- How can it fail? What can go wrong with this idea?

One of the challenges of this approach is to generate a relativistic beam with minimal internal noise (no fluctuations above the shot noise), and a small energy spread. [The first experiment at BNL failed to demonstrate the cooling because of the large noise in the beam.] This cooling method would need an ERL (the estimated electron current ~ 100 mA).

- Is it testable? What facility?

Experimental test requires a facility with a hadron and high-current electron beam. PoP experiment of PCA concept is being planned at RHIC. One can think about partial tests that do not involve the hadron beam (minimizing the noise in the electron beam, testing the beam as amplification medium). Such experiments (using only the electron beam) can be carried out at FAST (FNAL). Another experiment is being planned at ANL (A. Zholents).

- Which Grand Challenges is this proposal/idea addressing?

> **Grand challenge #2 (beam quality):** How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?

- Describe potential synergies and connections to other GARD thrusts and other SC offices.

Critical for the high luminosity program at EIC (Office of Nuclear Physics).

• Who is working on this now? Collaborations? Are current facilities adequate? What's available now?

In addition to the CeC PoP experiment and supporting theoretical activity at BNL (headed by V. Litvinenko) there is a 2-year (mid 2018 – mid 2020) collaboration (ANL, BNL, JLAB, SLAC) effort titled "*Strong hadron cooling with micro-bunched electron beams*", funded by NP.