Microbunched Coherent Electron Cooling for the Electron-Ion Collider (EIC) project

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BROOKHAVEN NATIONAL LABORATORY

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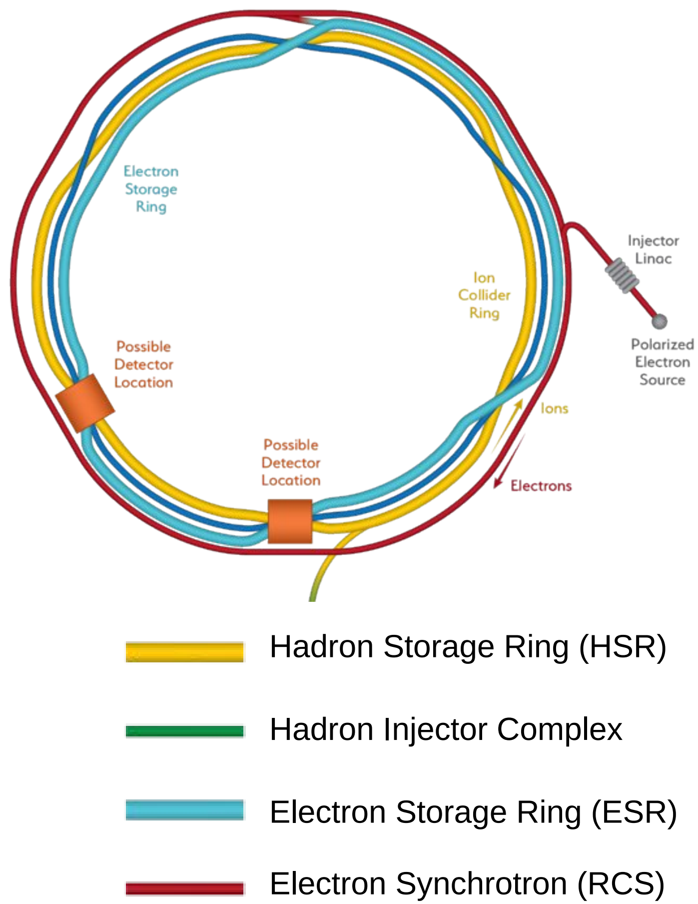
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- EIC and the need of the strong hadron cooling
- Variants of the coherent electron cooling, MBEC
- Theoretical analysis and optimization of the EIC cooler for EIC
  - The quasi-1D model
  - Computer code and simulations
  - Saturation of the amplifier
  - Dynamics of cooling
  - Path length jitter
  - 3D effects
- Summary

EIC design overview



Design based on **existing RHIC Complex**

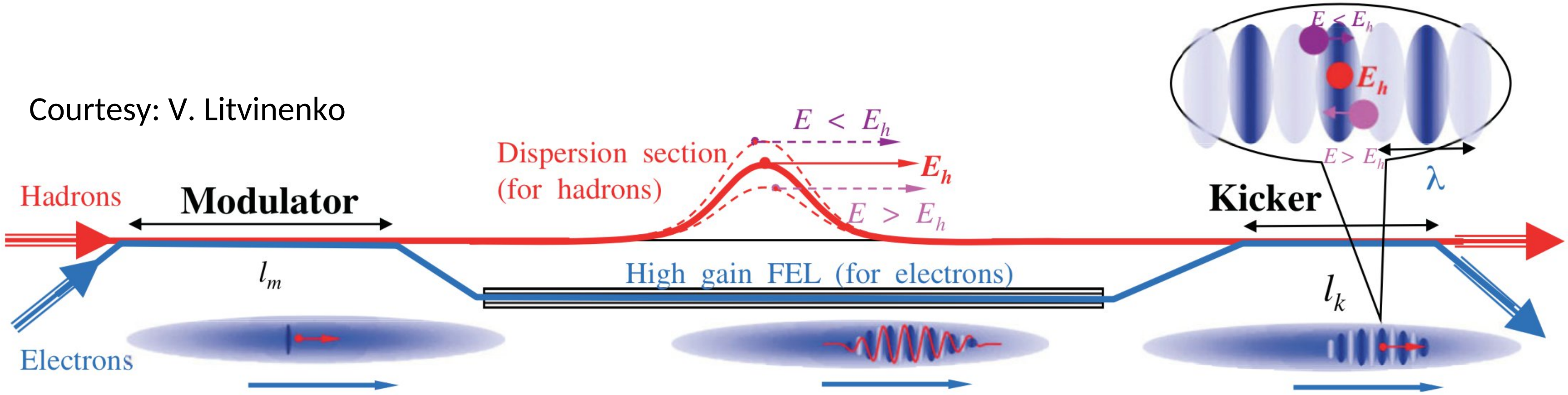
- **Electron storage ring 2.5–18 GeV** (**new**)
  - 1160 bunches
  - Large beam current, 2.5 A
- **Hadron storage ring 40-275 GeV**

(RHIC Yellow, exists with sufficient magnet strength)

  - 1160 bunches, 1A beam current (3xRHIC)
  - Bright vertical beam emittance 1.5 nm
  - Strong cooling (coherent electron cooling, hadron bunch IBS growth times ~2h)

The Concept of Coherent electron Cooling (CeC)

Courtesy: V. Litvinenko

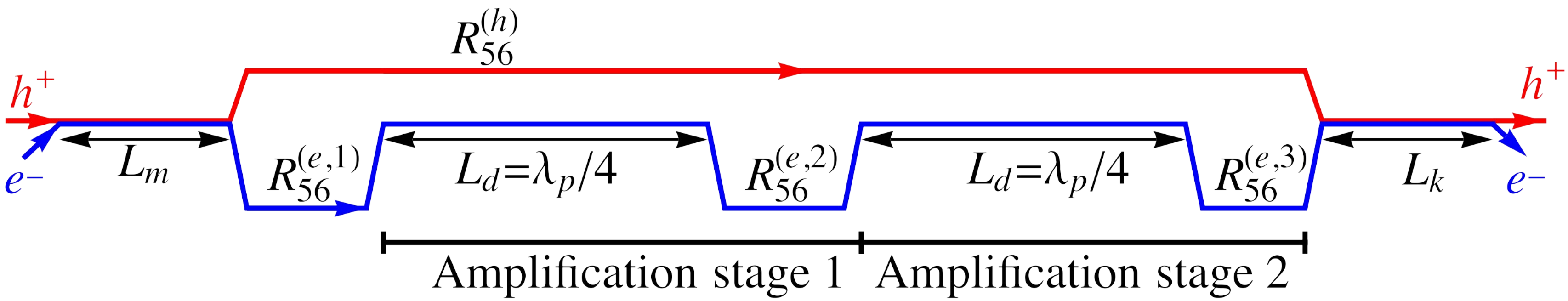


Coherent electron cooling is a variant of the stochastic cooling with the operational frequency range raised from ~GHz to tens of THz. (Derbenev, AIP Conf. Proc. **253**, 103 (1992); Litvinenko, Derbenev. PRL, **102**, 114801 (2009)).

The pickup and the kicker are implemented via the Coulomb interaction of the hadrons and electrons, $g_e = g_h$. The signal (imprint in the e-beam) is amplified via a controlled e-beam instability.

MBEC cooling is selected for EIC

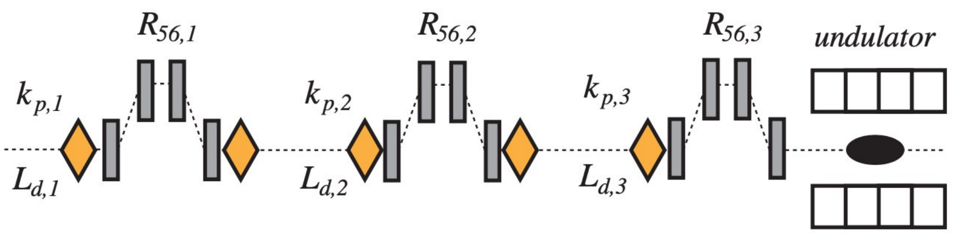
Micro-bunched electron cooling (MBEC) was proposed by D. Ratner (PRL, **111**, 084802 (2013)). It has an advantage of *broad-band amplification* (in contrast to the FEL).



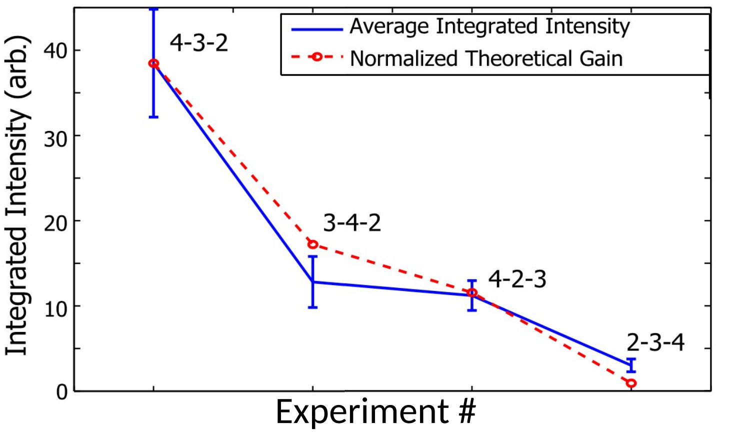
One stage of amplification is achieved through a combination of a drift of length=$\frac{1}{4}$ plasma oscillation length followed by a chicane. For the nominal EIC parameters, one stage amplification gain $G \approx \frac{1}{\Delta E/E}\sqrt{\frac{I_e}{I_A\gamma}} \approx 10$–$20$.

MB amplification was tested experimentally

Micro-bunched amplification is well known in FELs (Schneidmiller&Yurkov PRAB **13**, 110701 (2010); Dohlus et al. PRAB **14**, 090702 (2011)). It has been tested experimentally at NLCTA facility at SLAC (Marinelli et al. PRL **110**, 264802 (2013)).



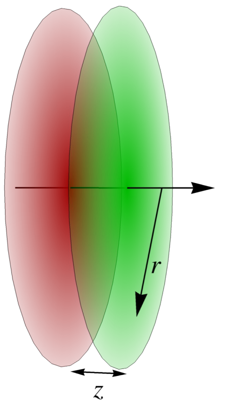
Beam line for the NLCTA experiment. The amplification was inferred from the beam radiation in the undulator

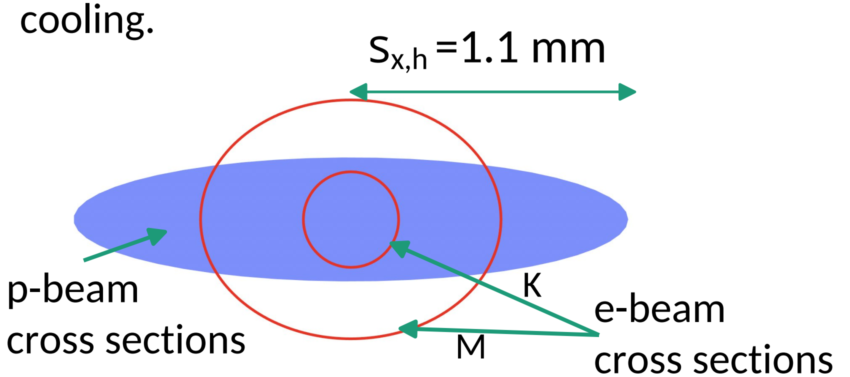


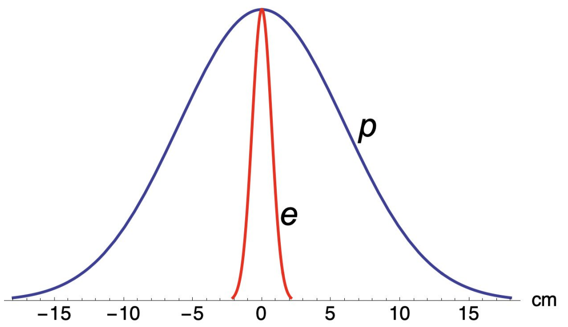
Signal intensity increases when the chicane strength is optimized. Good agreement with theory.

Theoretical studies of MBEC

MBEC for EIC parameters has been studied theoretically in detail over the last ~3 years by GS and P. Baxevanis (PRAB, **21**, 114402 (2018); PRAB, **22**, 034401 (2019); PRAB, **22**, 081003 (2019)). A *quasi-1D* model was used to simplify analysis – p- and e-point charges are replaced by elliptical slices with 2D Gaussian distribution of charge over the surface of the slice. With the horizontal dispersion D in the modulator and kicker this model predicts both the longitudinal and horizontal cooling.



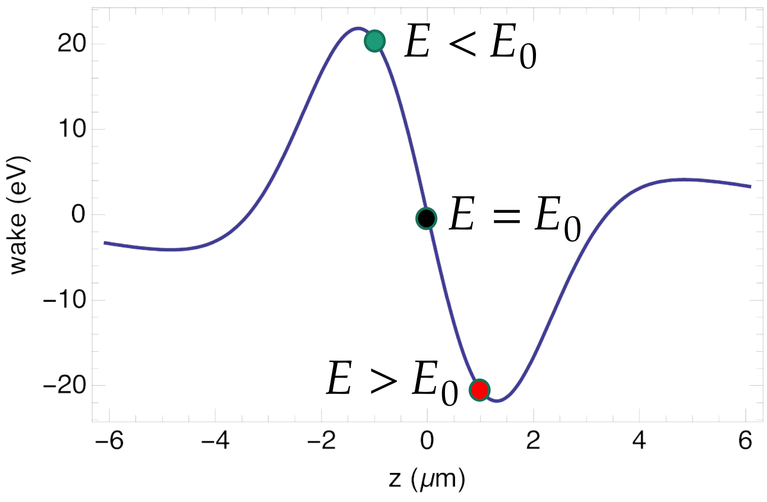


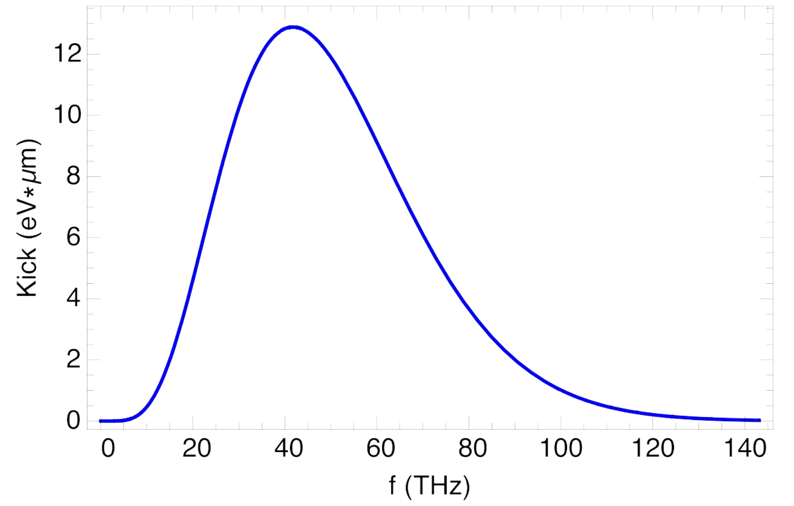


Gaussian charge distribution with different s_x and s_y corresponding to the nominal *x* and *y* proton beam emittance in EIC.

The electron bunch length is shorter than the hadron one. Hadrons with large synchrotron amplitudes spend a fraction of time inside the electron beam.

Energy kick (wake) in the kicker section





The kick generated by one proton in the kicker section. The longitudinal scale of the wake is $z{\sim}3\mu$m, corresponding to the frequency bandwidth $\Delta f{\sim}c/\pi z \approx 40$ THz. In the *optimal* settings the cooling rate is estimated as

$$\frac{1}{t_c} \sim \frac{\Delta f}{CNh/\sigma_z} \sim 0.5\ \mathrm{min}^{-1}$$

$\Delta f = 40$ THz, C =3834 m, Nh=6.9×10^{10}, σ_z=6 cm

Cooling time and energy diffusion

Using this wake, we can calculate the cooling time and the diffusion coefficients due to the noise in the hadron and electron beams.

$$\frac{d\langle\Delta E^2\rangle}{dt} = -\frac{d\langle\Delta E^2\rangle}{t_{\parallel}} + D_{\Delta E}$$

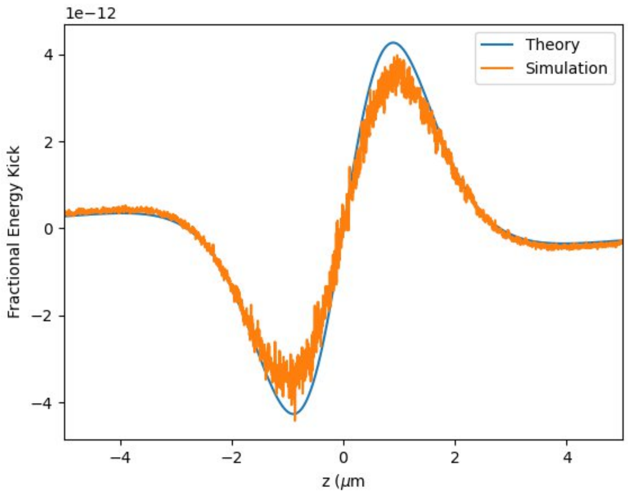
$$\frac{d\epsilon_x}{dt} = -\frac{\epsilon_x}{t_{\perp}} + D_{\epsilon}$$

Contributions to the diffusion terms D_{DE} and D_{e} come from the noise in the hadron beam, noise in the electron beam, and IBS.

We derived analytical expressions for $t_{\parallel}$ and $t_{\perp}$ and carried out initial optimization of the parameters of the cooler. Further optimization was based on computer simulations.

Computer simulations of MBEC

W. Bergan (BNL) wrote (in C++/Python) a cloud-in-cell computer code that simulates the cooling process through macro-particle tracking*. First, a small fraction (~50 μm) of the two beams is simulated to find the wake. This wake is then used to calculate the cooling over many (~10^9) passages through the cooling section.

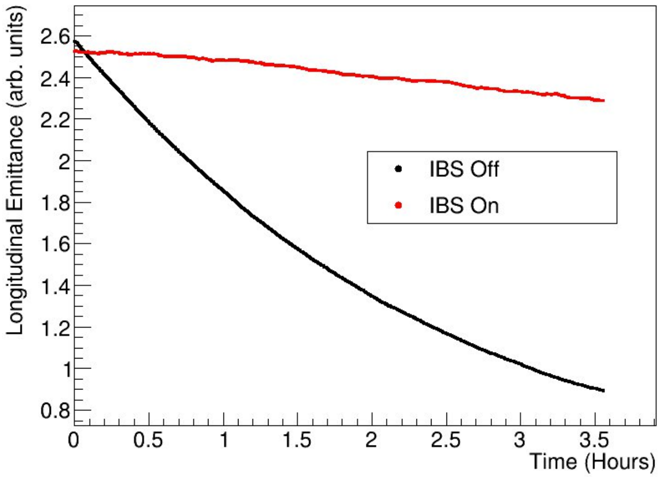


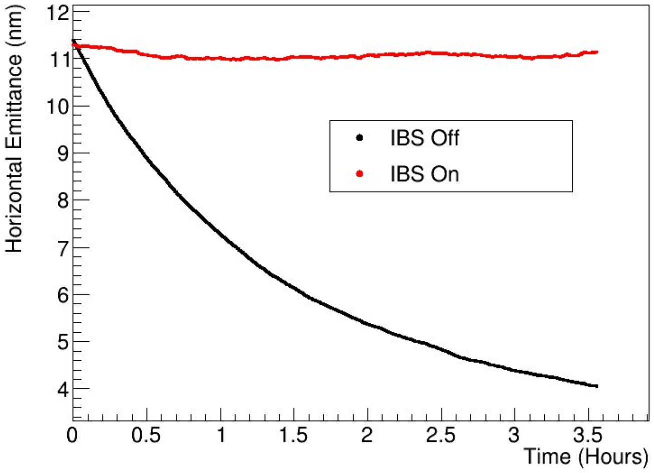
Wake for the case of one amplifier for 275 GeV protons, both from the linear theory and the average of 10 runs of the simulation. Good agreement is observed.

- Synchrotron motion of the ions is included.
- The code allows the horizontal dispersion D (and D') in the modulator and kicker and simulates horizontal cooling of hadrons together with the longitudinal cooling.
- It includes diffusion due to the noise in the hadron and electron beams, and IBS.
- The cooling time is averaged over the longitudinal distribution of the e-bunch

*) W. Bergan. Paper TUPAB179, IPAC 2021; W. Bergan et al. Paper TUPAB180, IPAC 2021.

Simulations of cooling time for EIC





Cooling needs a low-noise electron beam

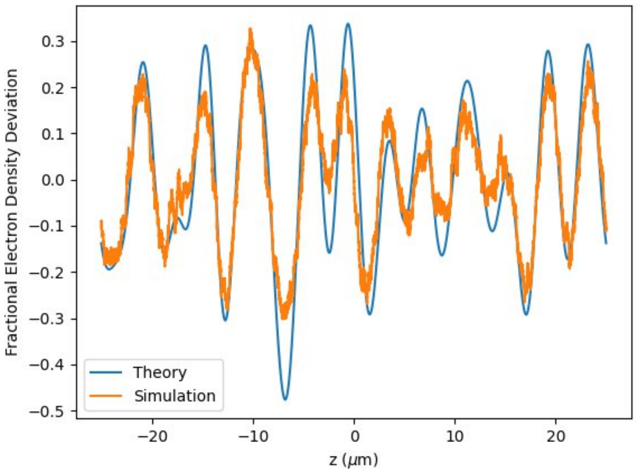
At 275 GeV, increasing the Poisson noise by a factor of 1.5 increases the cooling times to 2 hours horizontally and 3.1 hours longitudinally, close to the IBS limit. At 100 GeV, the noise in the electron beam is limited to 3 times the Poisson random noise.

EIC SHC parameters

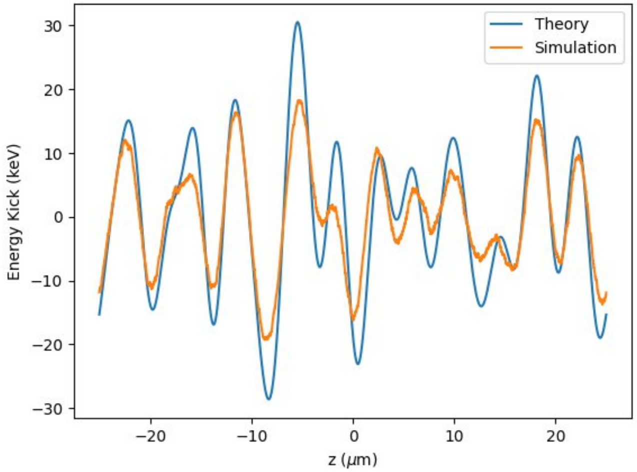
Case	**100 GeV**	**275 GeV**
Proton Bunch Length (cm)	7	6
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	14	7
Electron Fractional Energy Spread	1e-4	1e-4
Modulator/Kicker Length (m)	39 / 39	39 / 39
Amplifier Drift Lengths (m)	43	43
Proton Horizontal Dispersion in Modulator & Kicker (m)	1.108	1.36
Horizontal / Longitudinal IBS Times (hours)	2.0 / 2.5	2.0 / 2.9
Horizontal / Longitudinal Cooling Times (hours)	1.8 / 2.3	1.9 / 3.0

Saturation of the amplifier

In theory we assume a linear amplifier, but simulations show that nonlinear effects are important due to a relatively large value of $\sqrt{<\delta n_e{}^2>}/n_0$ in the kicker.



$\sqrt{<\delta n_e{}^2>}/n_0$=0.18



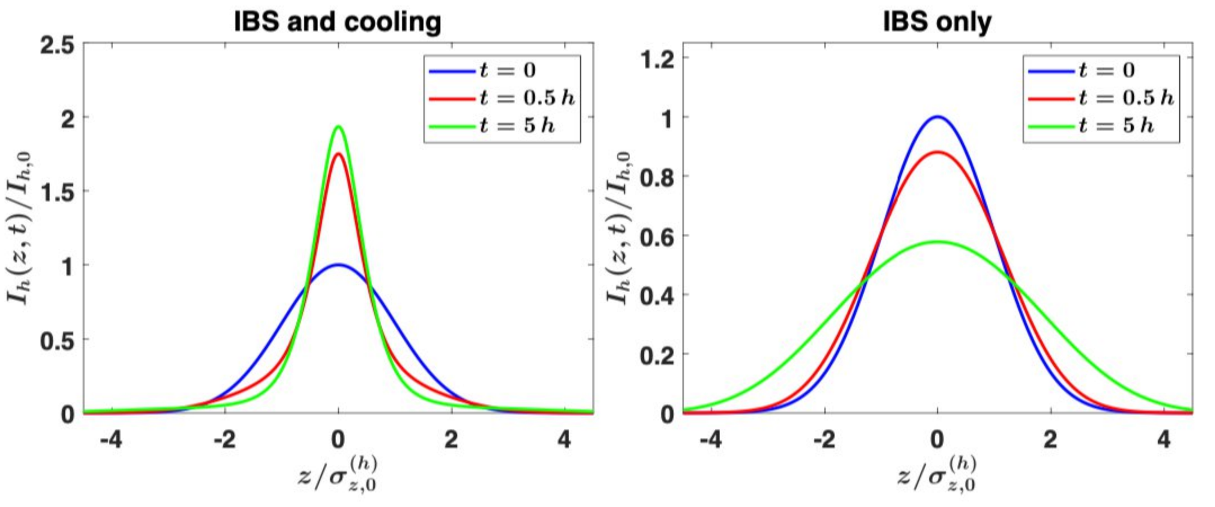
Rms kick=12 keV

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

Dynamics of cooling

Time evolution of the energy distribution function F_h of hadrons is governed by the Fokker-Planck equation* (J is the longitudinal action for synchrotron oscillations)

$$\frac{\partial F_h}{\partial t} = \frac{\partial}{\partial J}\left(\sqrt{J}\nu(J)F_h\right) + \frac{\partial}{\partial J}\left(D(J)J\frac{\partial F_h}{\partial J}\right)$$

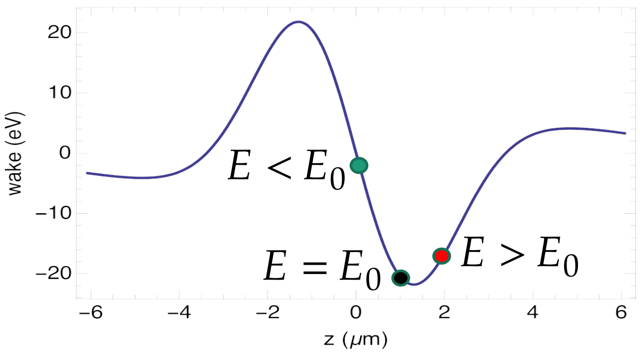


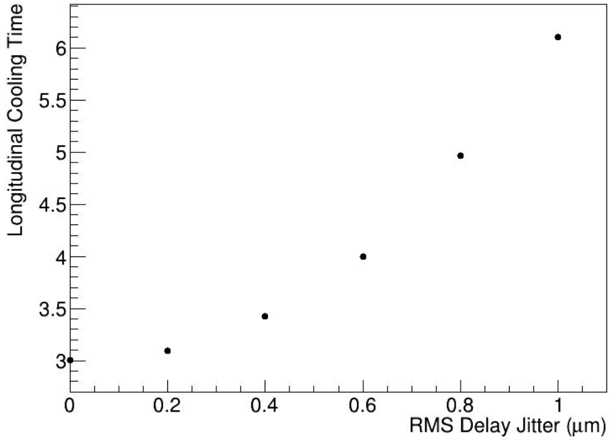
The hadron longitudinal distribution becomes narrower when the energy spread decreases due to cooling.

Without cooling the hadron bunch length increases.

*) P. Baxevanis, G. Stupakov, PRAB, **23**, 111001 (2020)); S. Nagaitsev et al., WEPAB273, IPAC 2021.

Effect of unequal path-length of electrons and protons





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

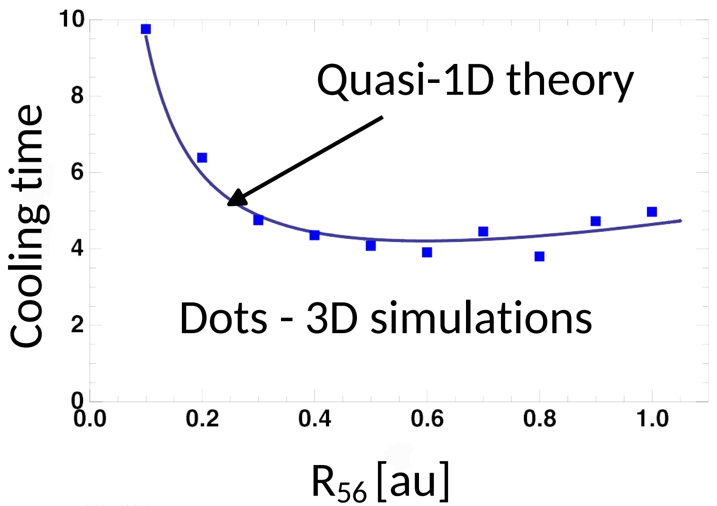
Contributions to the jitter:

- Cooling section electron beamline PS stabilization ~ 3 ppm → longitudinal shift ~200nm
- Longitudinal SC → ~56 nm
- CSR wake → ~140nm
- Hadron chicane contribution is being studied.

A feedback system for the path control seems necessary.

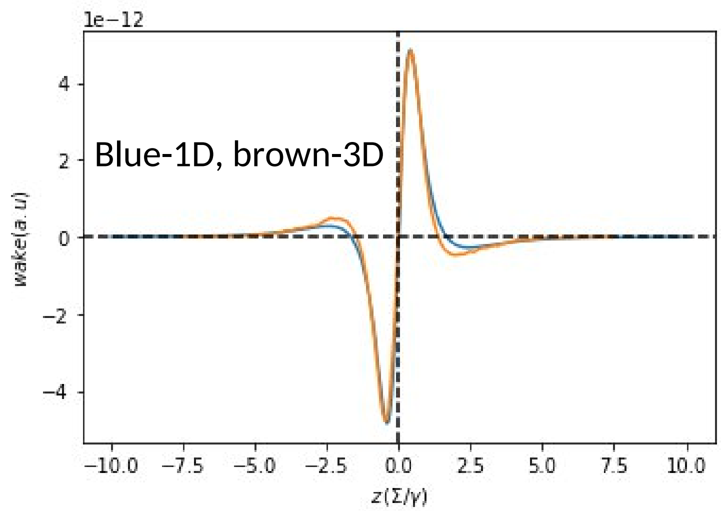
*) S. Seletskiy, A. Fedotov, D. Kayran. “Effect of coherent excitation in coherent electron cooler”, arXiv:2106.12617 (2021).

3D effects in MBEC



3D effects have been studied analytically* in the case when there is no amplification. In this case, the results agree well with the quasi-1D model. No unexpected surprises found in 3D.

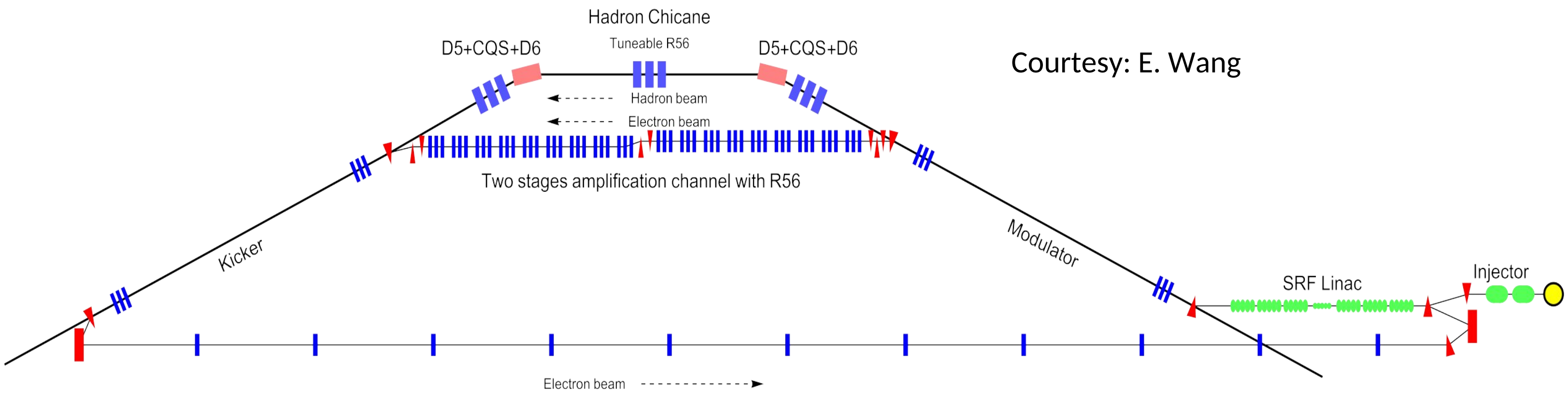
*) G. Stupakov and P. Baxevanis, IPAC 2019, p. 814, 2019.



P. Baxevanis is developing 3D MBEC code**. Here is the comparison of 1D and 3D wakes in MBEC with one amplification section.

**)P. Baxevanis, Preprint EIC-ADD-TN-021, BNL, 2021.

EIC Strong Hadron Cooling Facility



Courtesy: E. Wang

- 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 & R_{56} adjust
- Return transport of electron beam to ERL
- 2 K He sub cooler station, RF and power infrastructure
- Electron beam instrumentation and diagnostics

Summary

- We have a reasonably good understanding of the MBEC physics and various limitations it imposes on cooling time.
- We keep developing computational tools for calculation and optimization of the cooling rate. A consistent set of parameters is worked out that can serve as a basis for the design of the SHC for the EIC.
- SHC requires a high-quality (low noise with small energy spread) electron beam, and averaged current 0.1 A.
- The beams' path-length should be kept constant <0.5 μm.

Acknowledgements

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ANL: A. Zholentz