Microbunched Electron Cooling (MBEC) for future electron-ion colliders

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Electron-ion collider in the US

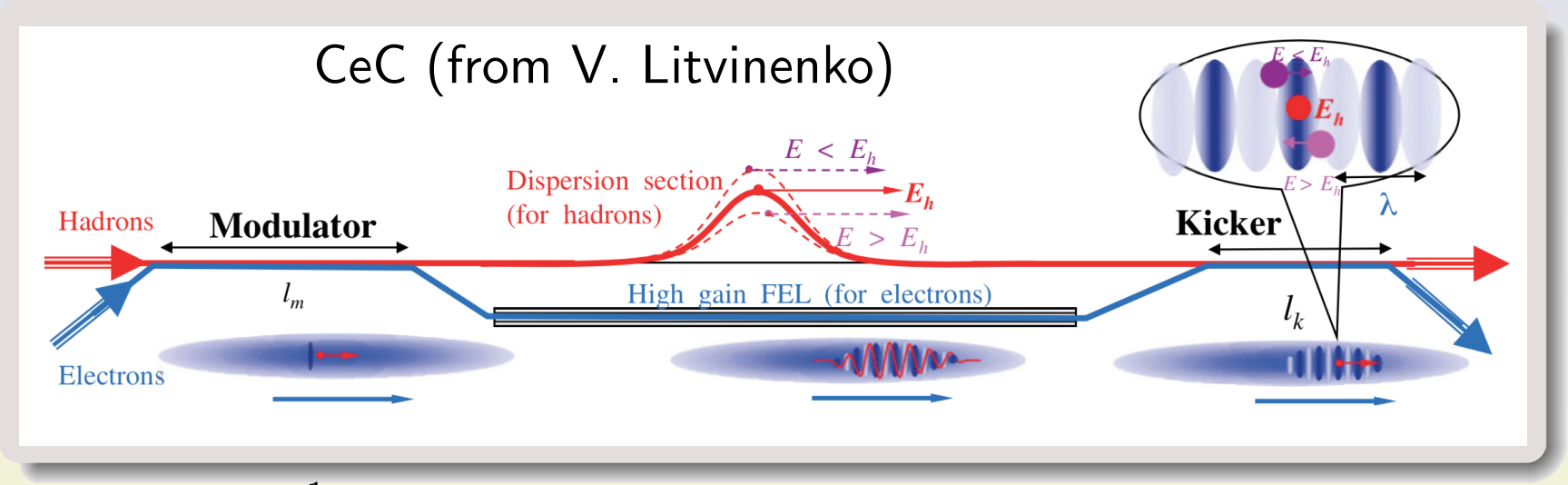
There are two proposals in the US of electron-ion colliders (EIC): eRHIC at BNL and MEIC (aka JLEIC) at JLab. Both projects require cooling of hadrons to overcome IBS and to deliver the highest luminosity to the experiment.

eRHIC maximum luminosity parameters

Parameter	proton	electron
Energy [GeV]	275	10
Ring circumference [m]	3434	
Number of bunches	1320	
Beam current [A]	1	2.5
Bunch length, $\sigma_{z,h}$, [cm]	5	1.9
IBS growth time [h]	≈ 2	
Luminosity [10^{34} cm^{-2} s^{-1}]	1.05	

Cooling options for EIC

- Stochastic cooling — too slow for EIC parameters
- Conventional electron cooling (adopted for JLEIC)
- Optical stochastic cooling (requires long SC wigglers with multi-T fields)
- Coherent electron cooling (CeC) with an FEL amplifier



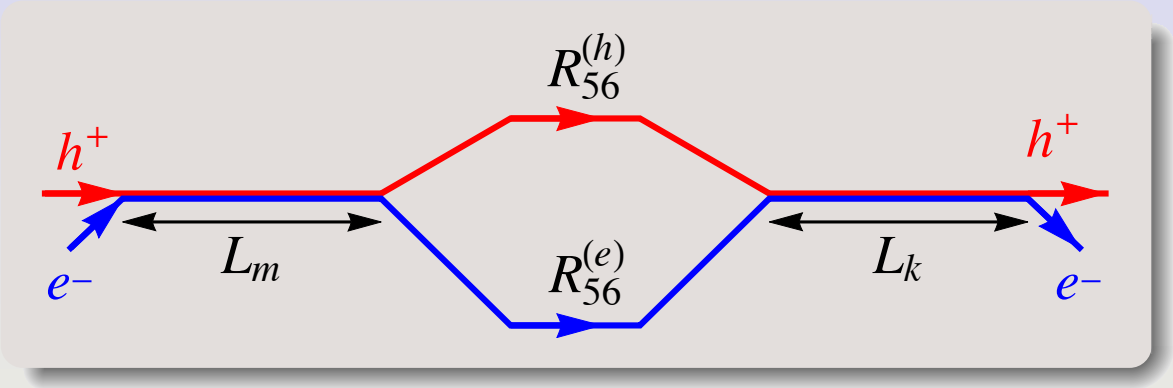
Proposed in Ref.[1]. An FEL is a narrow-band amplifier and the gain is limited by the saturation effects.

[1] Derbenev, AIP Conf. Proc. **253**, 103 (1992); Litvinenko, Derbenev. PRL, **102**, 114801 (2009).

Microbunched electron cooling (MBEC)

- Microbunched coherent electron cooling (MBEC). Adopted for eRHIC.

Proposed in Ref.[2].



In microbunched electron cooling electrons of the cooler beam with $\gamma_e = \gamma_h$ first interact with the hadron beam in the modulator. The energy perturbations in the electron beam due to hadrons 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.

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

Representative set of parameters for eRHIC MBEC

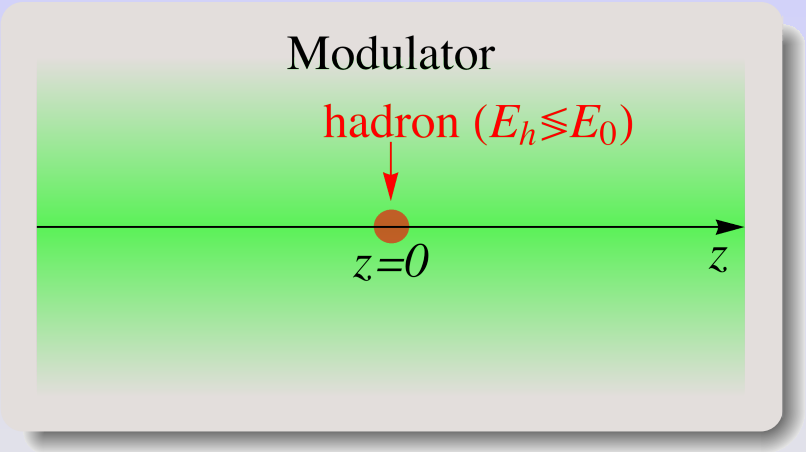
In numerical estimates I assume the following set of parameters for the hadron and electron cooler beams:

Proton energy [GeV]	275
Proton relative energy spread, $\sigma_{\eta h}$	5.8×10^{-4}
Electron energy [MeV]	150
Electron relative energy spread, $\sigma_{\eta e}$	1×10^{-4}
Electron beam charge [nC]	1
Electron beam peak current [A]	30
Repetition rate [MHz]	112
RMS beam size in mod. and kicker, Σ, [mm]	0.7
L_m, L_k [m]	40

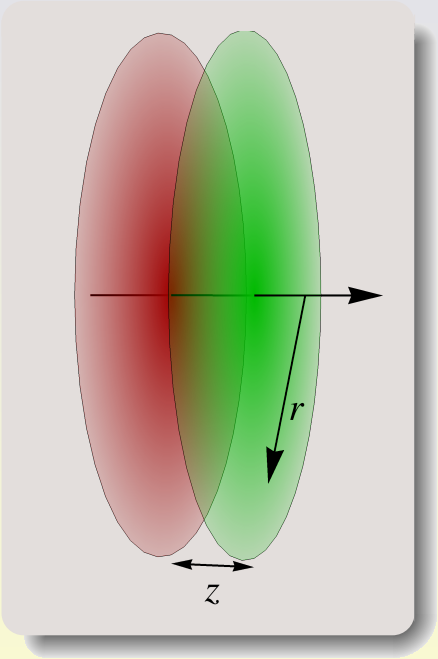
The electron bunch length, $\sigma_{ze} \approx 4$ mm, is much shorter than the proton bunch length, $\sigma_{ze} \lesssim \sigma_{zh} = 5$ cm.

The cooler-beam current is ~ 100 mA.

How the MBEC cooling rate scales with beam parameters?

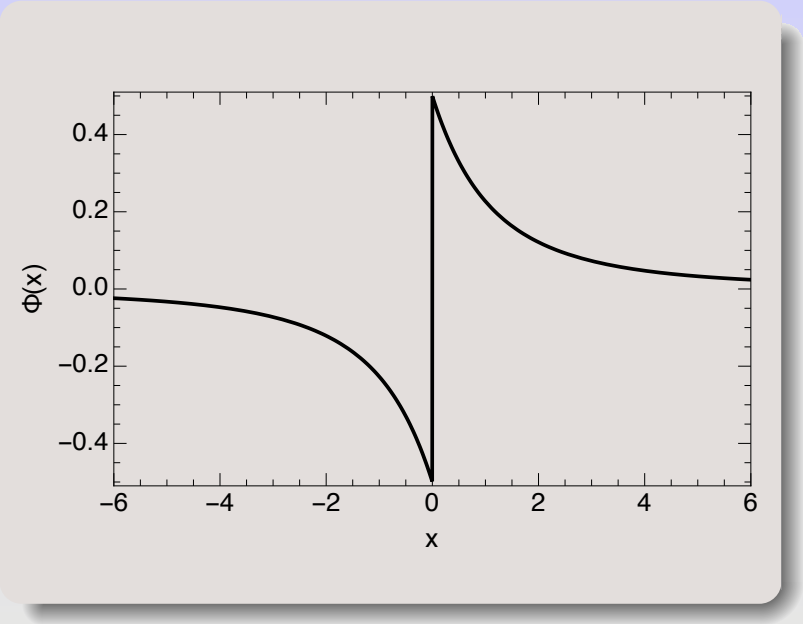


A hadron in the modulator interacts with the nearby electrons and changes their energy.



Each hadron and electron are treated as infinitely thin slices of charge Ze or $-e$ respectively with a Gaussian transversed charge distribution over the surface of the slice, $\sim (Ze/2\pi\Sigma^2)e^{-r^2/2\Sigma^2}$ (this is justifiable if hadrons and electron execute several betatron oscillations during interaction). Here Σ is the rms transverse size of the beam.

1D Model of hadron-electron interaction



The interaction force of two slices

$$F_z(z) = -\frac{Ze^2}{\Sigma^2}\Phi\left(\frac{z\gamma}{\Sigma}\right)$$

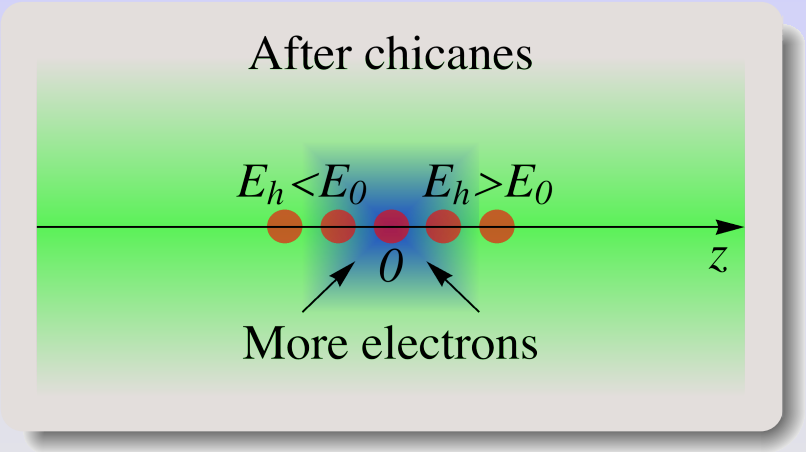
The interaction force extends over the distance $\Delta z_{\rm int} \sim \Sigma/\gamma \approx 2.4\,\mu$m. The number of electrons within $\Delta z_{\rm int}$ is $N_e \sim 1.5 \times 10^6$.

We neglect the longitudinal shift of the particles on the length L_m, L_k. The electrons within the distance $\sim \Delta z_{\rm int}$ change their energy by $\delta E = F_z(z) L_m$,

$$\delta\eta_e = \frac{\delta E}{\gamma m_e c^2} \sim \frac{Ze^2 L_m}{\Sigma^2 \gamma m_e c^2} \sim 10^{-9}$$

In absolute units $\delta E \sim 0.15$ eV. Electrons are decelerated ahead of the hadron and accelerated behind the it.

Passage through the chicanes



Due to the interaction with the hadron, electrons ahead of the hadron (with smaller energy) will shift less, and electrons behind the hadron (with higher energy) shift more by $\delta z \sim R_{56}^{(e)} \delta\eta_e$. The optimal value $R_{56}^{(e)} \sim \Delta z_{\rm int}/\sigma_{\eta e}$ (larger $R_{56}^{(e)}$ smears out perturbations on the scale $\Delta z_{\rm int}$).

This will cause a density perturbation

$$\delta n_e \sim \frac{\delta z}{\Delta z_{\rm int}} n_e \sim \frac{\delta\eta_e}{\sigma_{\eta e}} n_e \sim 10^{-5} n_e$$

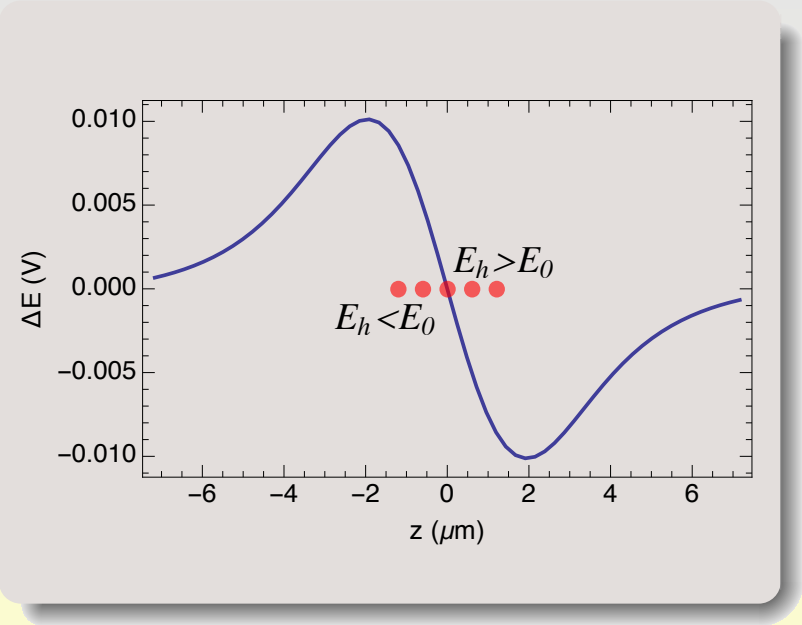
where n_e is the number of electrons (slices) per unit length. For our parameters the excess of electrons created by one hadron is $\delta n_e \Delta z_{\rm int} \sim 1.5$.

The kicker

The excess of electrons creates the longitudinal electric field

$$\mathcal{E}_z \sim \frac{e}{\Sigma^2}\delta n_e \Delta z_{\rm int} \sim e\frac{\delta\eta_e}{\sigma_{\eta e}}\frac{n_e}{\Sigma\gamma}$$

and this field changes the hadron energy by $\Delta E = Ze\mathcal{E}_z L_k$ in the kicker. Hadrons are shifted by $R_{56}^{(h)}\eta_h$ with the higher energy than the nominal one slipping ahead and the lower energy lagging behind.



The cooling time (in revolution periods)

$$N_c \sim \frac{\sigma_{\eta h}}{\Delta E/E_h} \sim 7.4 \times 10^8$$

This formula has the right scaling with the beam parameters. More accurate calculations (see below) give the cooling time ~ 50 h.

Theoretical analysis (SLAC-PUB-17208)

In this analysis I used the Vlasov equation to track the dynamics of microscopic 1D fluctuations in the electron and hadron beams during their interaction and propagation through the system.

Assumptions:

- 1D model: hadrons and electrons are treated as infinitely thin slices of charge Ze ($-e$ for electrons) with a Gaussian transverse charge distribution (round beams).
- Perfect overlap of the electron and hadron beams in the modulator and the kicker.
- Particles (slices) do not shift relative to each longitudinally during the interaction in the modulator and the kicker.
- Chicanes shift particles in the longitudinal direction by $R_{56}\eta$.
- There is a perfect mixing in the hadron beam on the scale Δz_{int} during one revolution in the ring.
- I calculate the cooling time for the longitudinal energy spread.

Kinetic equation for F_h

Evolution of the energy distribution function of hadrons $F_h(\eta, t)$ in the ring over many passages through the cooling system

$$\frac{\partial F_h}{\partial t} = \frac{1}{2t_{\rm cool}} \frac{\partial(\eta F_h)}{\partial \eta} + D \frac{\partial^2 F_h}{\partial^2 \eta}$$

Multiplying this equation by η^2 and integrating it over η we obtain

$$\frac{d\sigma_h^2}{dt} = -\frac{\sigma_h^2}{t_{\rm cool}} + 2D$$

The cooling time depends on $R_{56}^{(e)}$ and $R_{56}^{(h)}$. The optimal values are: $R_{56}^{(e)} = 0.6\Sigma/\sigma_{\eta e}\gamma$, $R_{56}^{(h)} = 0.6\Sigma/\sigma_{\eta h}\gamma$, with

$$N_{\rm cool}^{-1} \equiv \left(\frac{t_{\rm cool}}{T}\right)^{-1} = \frac{0.1}{\sigma_h \sigma_e} \frac{1}{\gamma^3} \frac{I_e}{I_A} \frac{r_h L_m L_k}{\Sigma^3}$$

(T is the revolution period).

Cooling rate

The electron beam overlaps only with a small fraction of the hadron beam. Over many revolutions, hadrons move longitudinally due to the synchrotron oscillations. One needs to average the cooling rate over the length of the electron bunch,

$$N_{\mathrm{cool}}^{-1} = \frac{0.1}{\sigma_h \sigma_e} \frac{1}{\gamma^3} \frac{c Q_e}{\sqrt{2\pi}\sigma_{zh} I_A} \frac{r_h L_m L_k}{\Sigma^3}$$

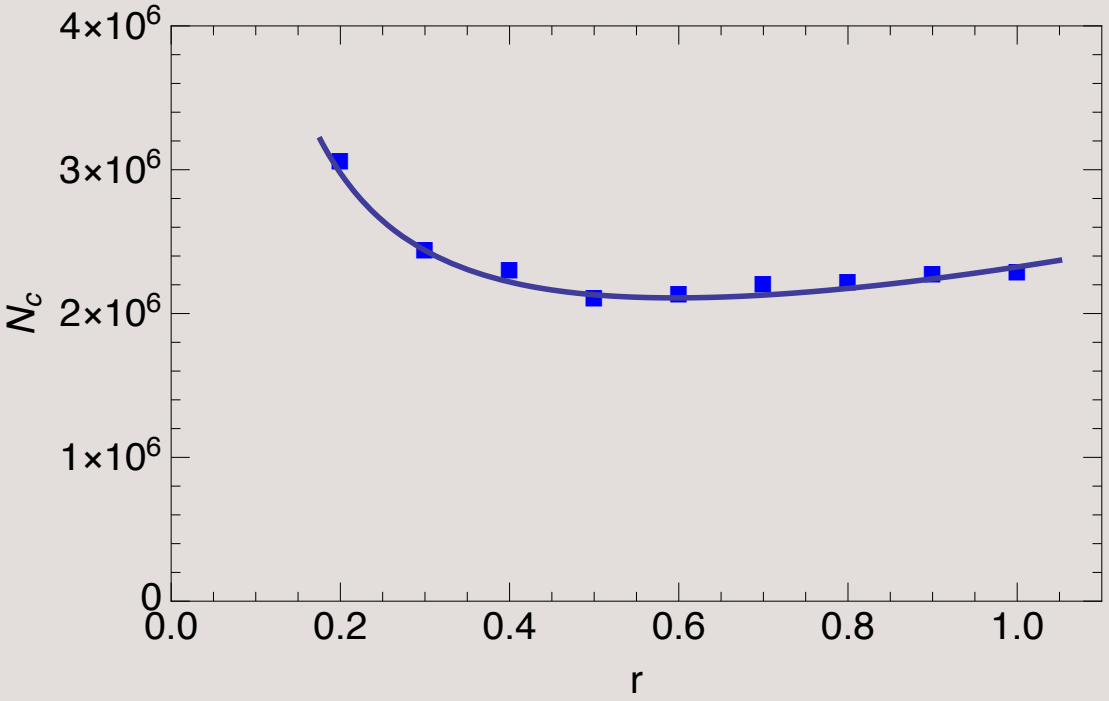
the cooling time is

$$T_{\mathrm{cool}} \approx 52 \ \mathrm{h}$$

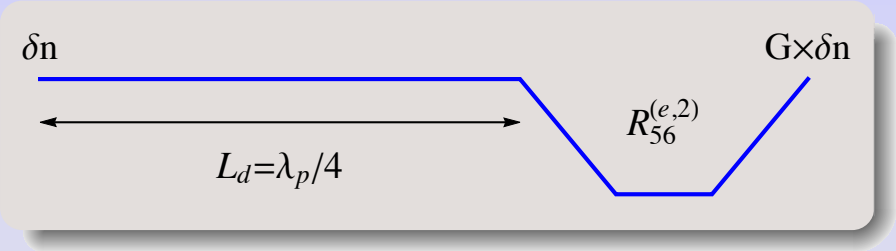
The cooling rate increases for smaller Σ, but we cannot focus both (hadron and electron) beams in the modulator and the kicker. [Currently, it is assumed that these are drifts.]

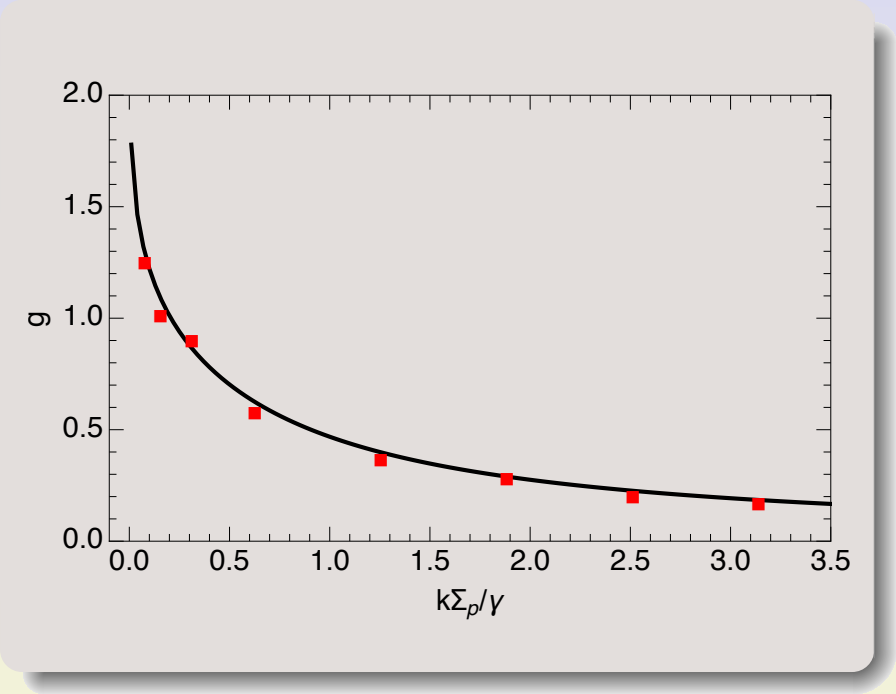
Numerical simulations

We used $N_e = 10^4$ electron macroparticles and the length of the "electron bunch" $\Delta z = 20\Sigma/\gamma$. The averaging was done over $M = 5 \times 10^6$ runs. The plot of the simulated cooling times as a function of the dimensionless chicane strength $r = R_{56}^{(h)}\sigma_{\eta h}\gamma/\Sigma = R_{56}^{(e)}\sigma_{\eta e}\gamma/\Sigma$. Our choice of parameters can be interpreted as if each macroparticle has a charge of approximately $36e$.



Amplification of microbunching in the electron beam[3]





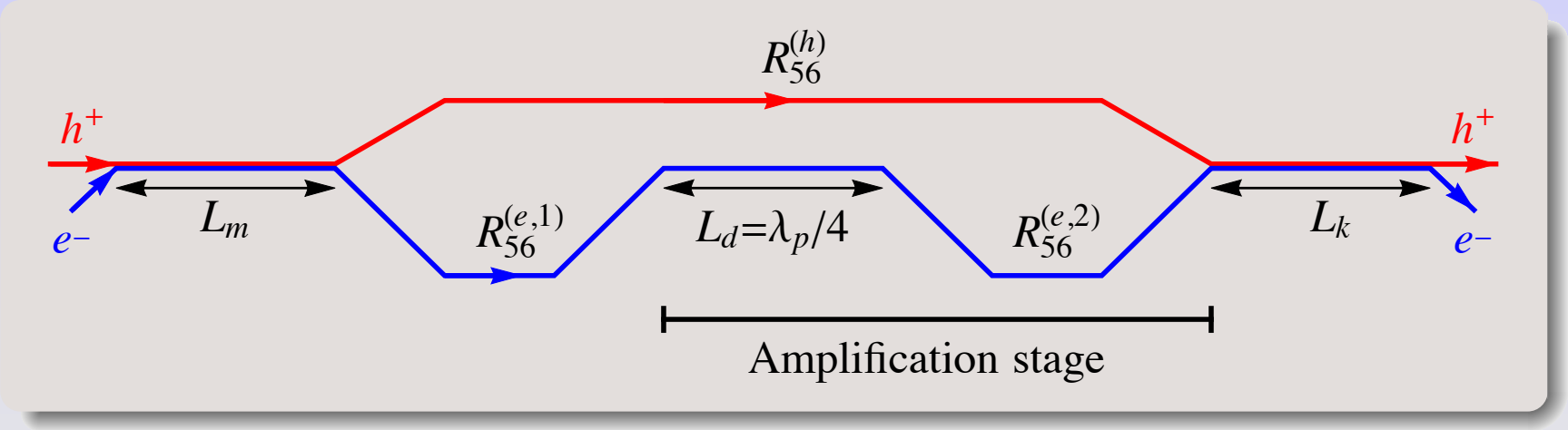
In 1D model, the amplification factor $G(k)$ is derived theoretically. For the optimized chicane strength (note the minus sign in G—this is for $R_{56}^{(e,2)} > 0$),

$$G(k) = -\frac{1}{\sigma_{he}}\sqrt{\frac{I_e}{I_A\gamma}}\, g\left(\frac{k\Sigma_p}{\gamma}\right)$$

Note the broadband character of the amplification factor.
We also simulated g solving equations of motion for electrons in the drift with account of the Coulomb interactions.
Red dots—the result of simulations.

[3] Schneidmiller and Yurkov, PRSTAB **13**, 110701 (2010); Dohlus, Schneidmiller and Yurkov, PRSTAB **14** 090702 (2011); Marinelli et al., PRL **110**, 264802 (2013).

MBEC amplification using plasma oscillations[4]



Analytic theory predicts for the amplification factor for the beam current I_e (assuming $\Sigma_p = 0.1$ mm, $\Sigma_p/\Sigma = 0.17$)

$$G \approx 0.9 \frac{1}{\sigma_{he}} \sqrt{\frac{I_e}{\gamma I_A}}$$

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

MBEC amplification using plasma oscillations

Using $I_e \approx 30$ A and eRHIC parameters we obtain

$$G \approx 22$$

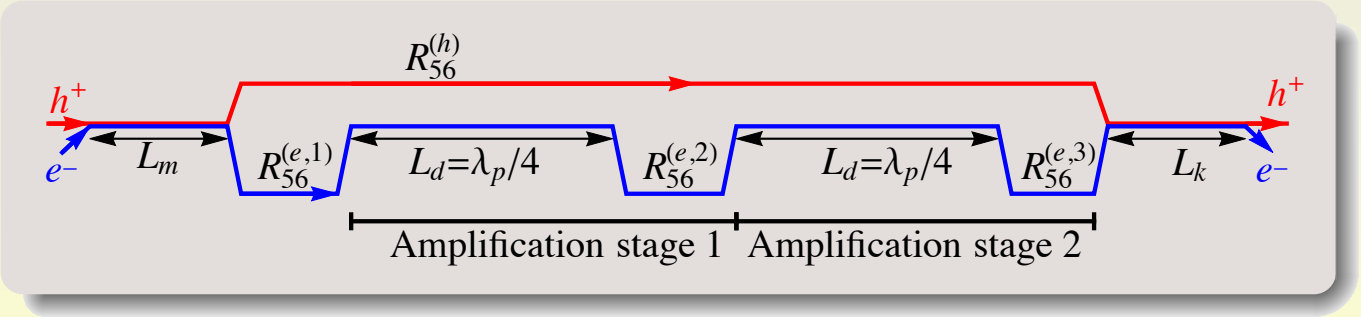
and the cooling time

$$T_{\mathrm{cool}} \approx 2.4 \ \mathrm{h}$$

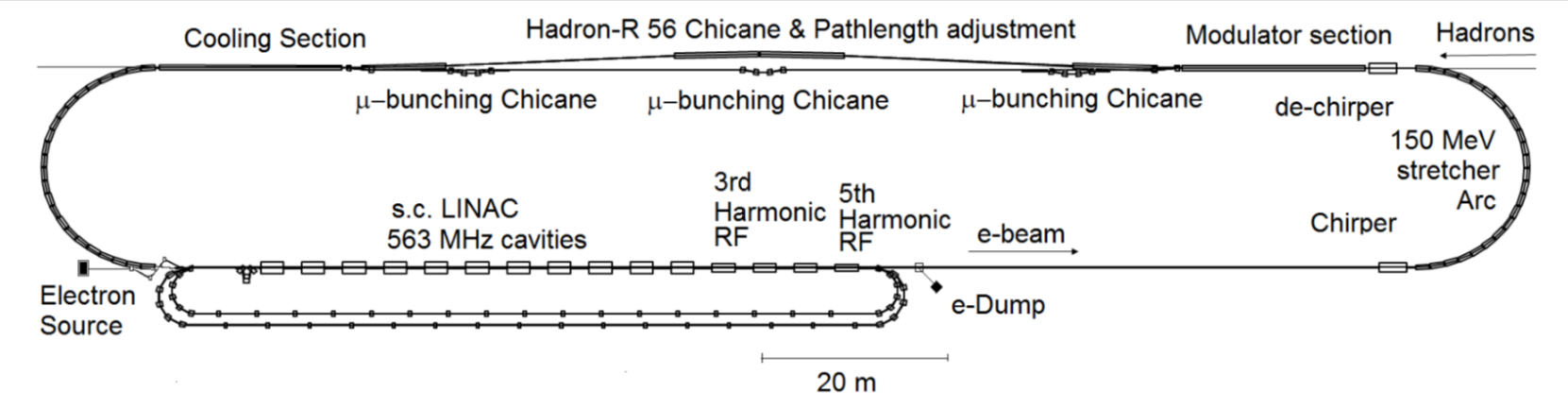
For the quarter of plasma period we have

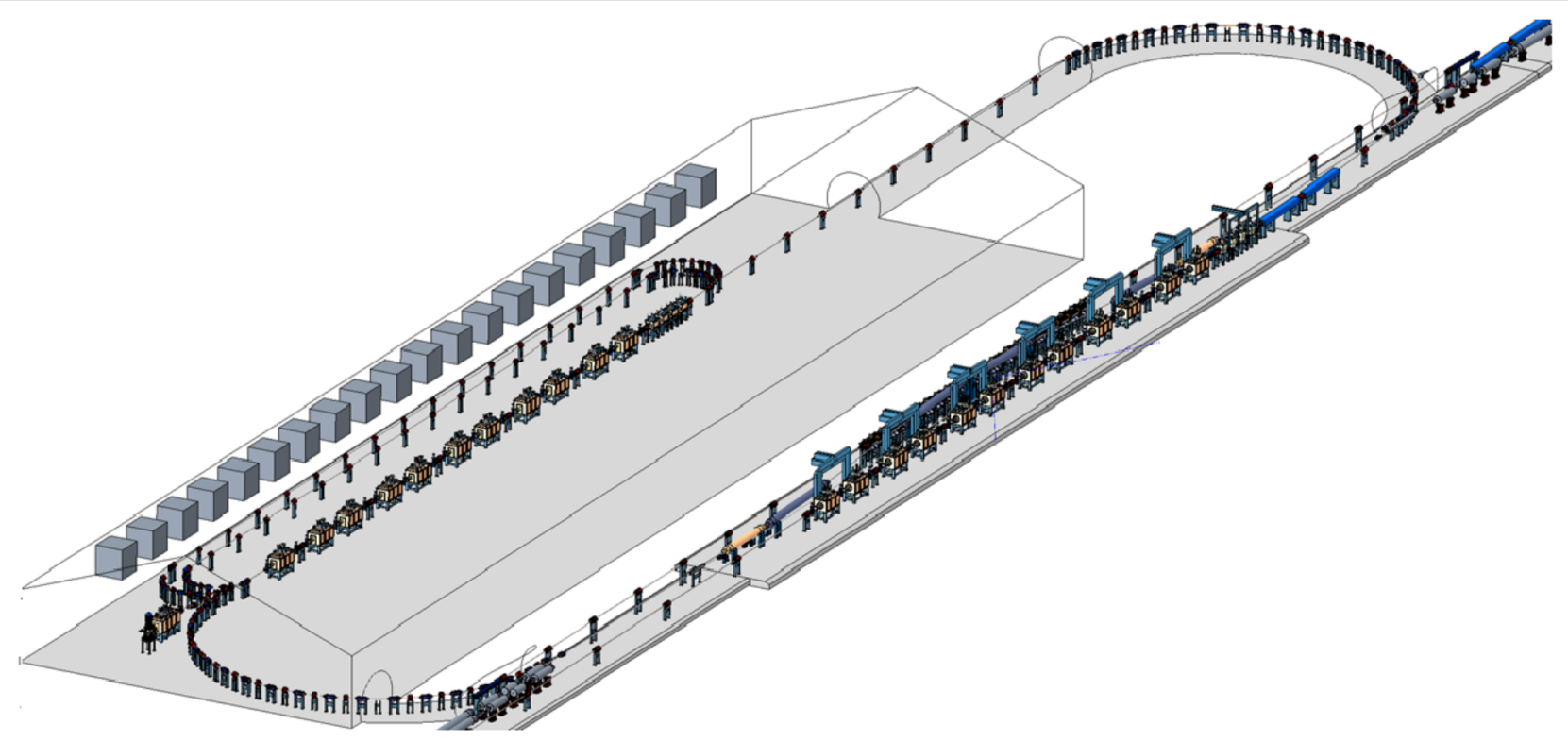
$$\frac{1}{4}\lambda_p \approx 14.5 \ \mathrm{m}$$

Two stages of plasma amplification should be enough for eRHIC.



Sketch of MBEC cooler for eRHIC from pre-CDR





Summary

- 1D model of MBEC is developed and a simple formula for the cooling rate is derived, which shows that the cooling rate for eRHIC is too low without amplification. Analytical formulas are benchmarked against simulations with a new matlab code.
- The cooling rate amplification in $\frac{1}{4}\lambda_p$ drift+chicane is studied both analytically and numerically.
- Parameters for a MBEC cooler in eRHIC are proposed that, with two amplification stages, should provide the cooling time below 2h

Future plans

- Cooling of transverse degrees of freedom
- Effects not covered by 1D model (e.g., non-axisymmetric beam, 3D Coulomb interaction of particles, etc.)
- Realistic magnetic lattice and nonlinear lattice effects
- ...