Beam-beam effects in EIC electron coolers

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Presented at ICFA workshop: Beam-Beam Effects in Circular Colliders BB24
September 2-5, 2024

Beam-beam in Electron Ion Collider (EIC)

- There is the **beam-beam effect from the colliding beams**
- Also, EIC employs cooling of hadrons, both at the injection energy (pre-cooler) and at the top energy (high energy cooler).
- In the coolers bunches of electrons co-travel with hadrons. The focusing effect from electrons on hadrons (and vice-versa for a proposed ring cooler) is non-negligible.
- There is the **beam-beam effect in the pre-cooler**
- There is the **beam-beam effect in the high energy cooler**

Why does Electron Ion Collider need coolers?

- We need to achieve and maintain optimal hadron emittances at the collision energy

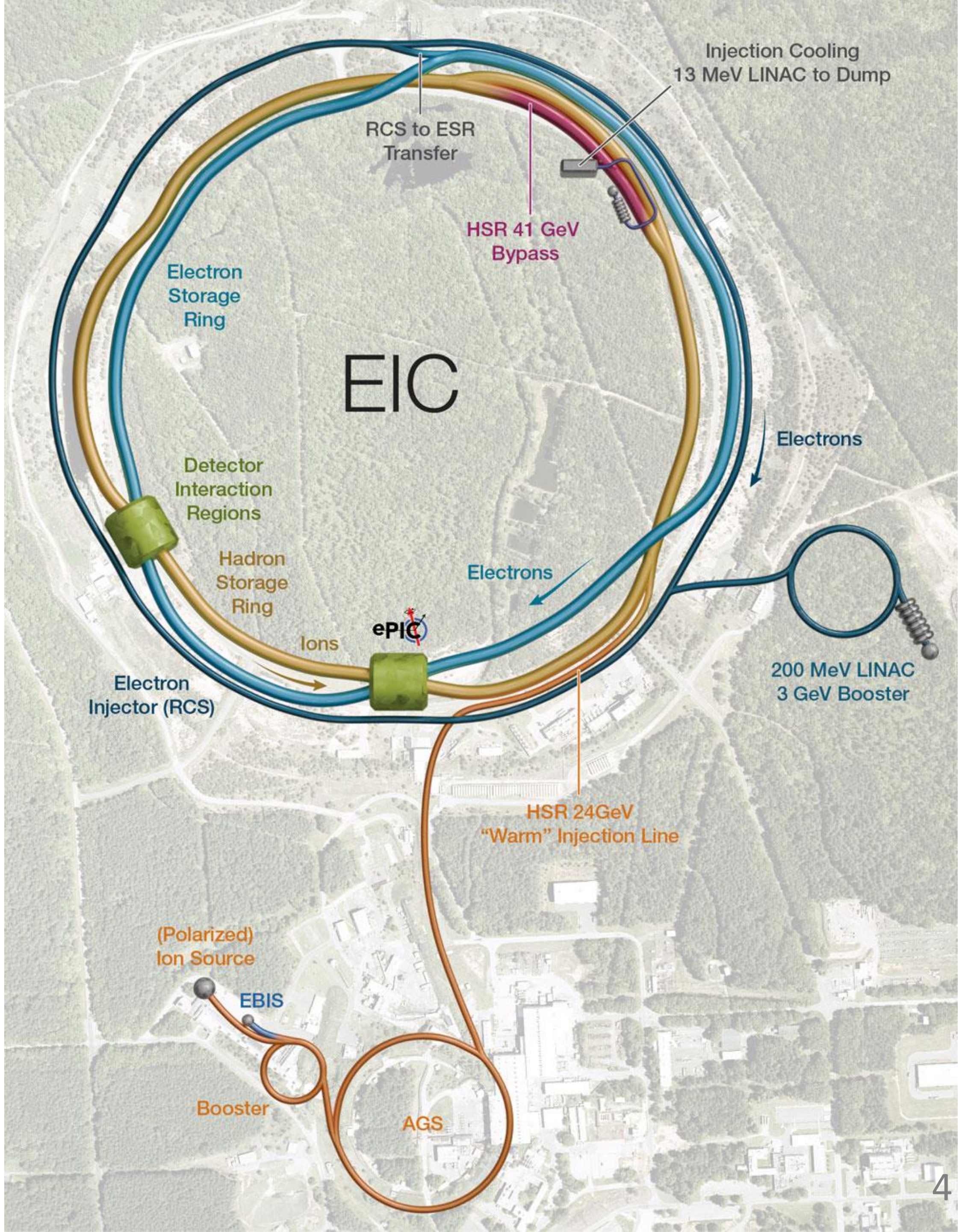
Table 1 Main parameters for the electron-proton operation in high divergence operation mode.

Parameter		Units	p+	e-	p+	e-	p+	e-	p+	e-	p+	e-
Energy		GeV	275	18	275	10	100	10	100	5	41	5
CM energy		GeV	141		105		63.2		44.7		28.6	
Bunch intensity		10^{10}	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
Number of bunches		-	290		1160		1160		1160		1160	
RMS normalized emittance	H	μm	5.2	845	3.3	391	3.2	391	2.7	196	1.9	196
	V		0.47	71	0.3	26	0.29	26	0.25	18	0.45	34
RMS emittance	H	nm	18	24.0	11.3	20	30	20	26	20	44	20
	V		1.6	2.0	1.0	1.3	2.7	1.3	2.3	1.8	10	3.5
RMS longitudinal emittance		10^{-3} eV·s	36		36		21		21		11	53/42
RMS bunch length		cm	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS fractional momentum spread		10^{-4}	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Longitudinal IBS time		hrs	2		2.9		2.5		3.1		3.8	
Transverse IBS time	H	hrs	2		2		2.0		2.0		3.4	
	V		Lrg		Lrg		4.0		4.0		2.1	

- We must cool a hadron bunch at injection energy ($\gamma \approx 25$) to obtain the required emittances
- We must cool hadrons at top energy to counteract an IBS-driven heating

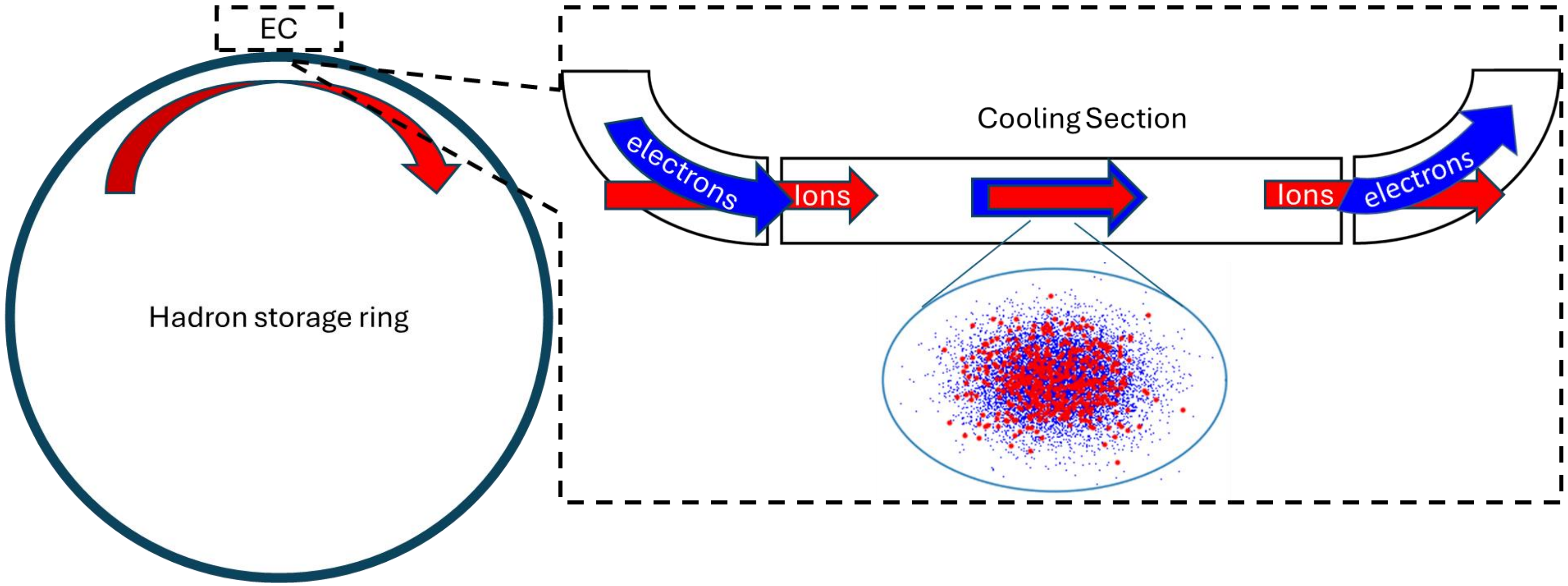
EIC layout

- Two coolers are needed:
  - The pre-cooler (injection energy cooler) – a single pass electron cooler
  - The high energy cooler - one of the possible options for it is to use a ring electron cooler (multi-pass electron cooler)
- Both coolers must share the same cooling section ($L \approx 170$ m)



How electron cooling works

- Mix a hadron bunch with an electron bunch traveling with the same velocity and let the two bunches travel together over some length (for us $L = 170$ m). You will notice that the emittances of hadrons get reduced. Why?
- In the co-moving frame, the mixture of two bunches looks like a mixture of two gases – a gas of ions and a gas of electrons
- Electrons are much lighter; hence, the gas of electrons is much colder than the gas of ions. Heat transfer ≡ Electron Cooling

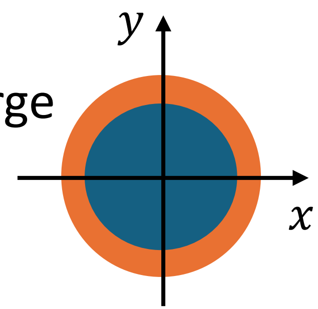


$$m_e \ll m_i$$

$$T = \frac{m\bar{v}^2}{3k_B}$$

$$T_e \ll T_i$$

Beam-beam effect in electron coolers



- Consider two co-traveling bunches of type 1 and type 2 particles. Assume that the bunches are oppositely charged and assume that both bunches are circularly symmetric. Then the space charge effect from bunch 1 on a particle of bunch 2 is:

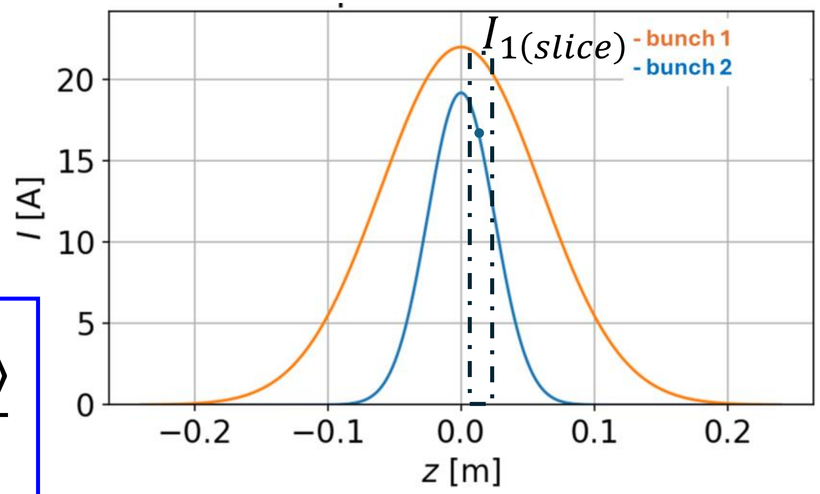
$$x'' = -\frac{2}{\gamma^3} \cdot \frac{I_{1(slice)}}{I_A} \cdot Z_2 \cdot \frac{m_e}{m_2} \cdot \frac{\left(1 - e^{-\frac{x^2+y^2}{2\sigma_1^2}}\right)}{x^2 + y^2} x$$

- In linear approximation:

$$x'' = -\frac{1}{\gamma^3} \cdot \frac{I_{1(slice)}}{I_A} \cdot Z_2 \cdot \frac{m_e}{m_2} \cdot \frac{x}{\sigma_1^2}$$

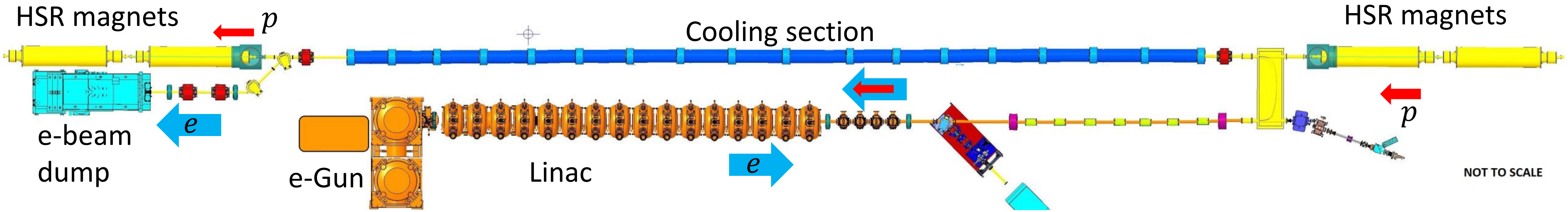
- The maximum tune shift:

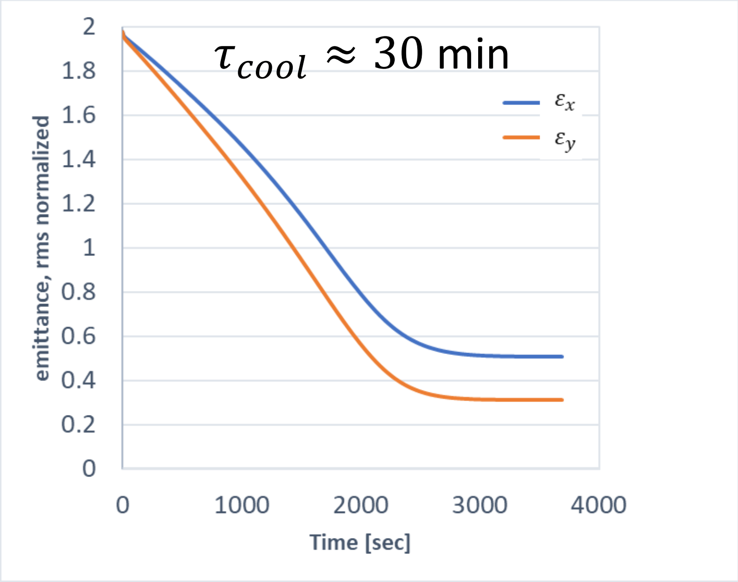
$$\max(\Delta\nu_{12}) = \frac{1}{4\pi\gamma^3} \cdot \frac{I_{1(peak)}}{I_A} \cdot Z_2 \cdot \frac{m_e}{m_2} \cdot \frac{L_{CS}\langle\beta_{2(CS)}\rangle}{\sigma_1^2}$$



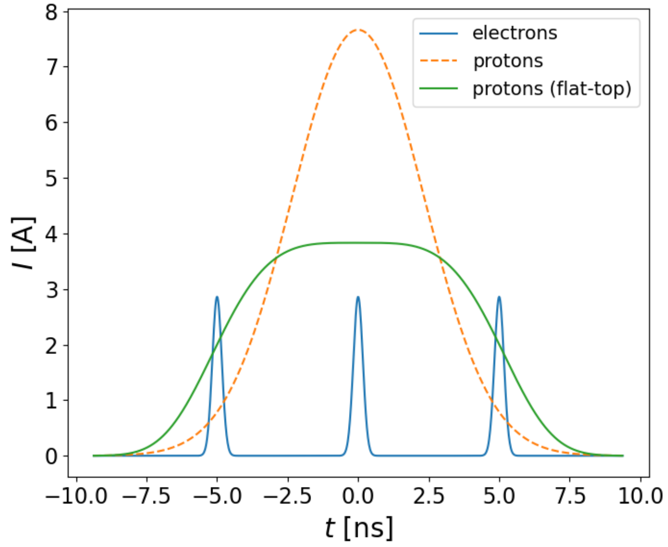
- The bunches are co-traveling; hence, the space charge effect is reduced by γ^2, yet the cooling section length L_{CS} is 170 m.
- On a single pass through the CS each particle interacts with a slice of the other bunch. A nonuniform longitudinal distribution will cause periodic modulation of the turn-by-turn focusing kick.

Beam-beam effect in EIC pre-cooler



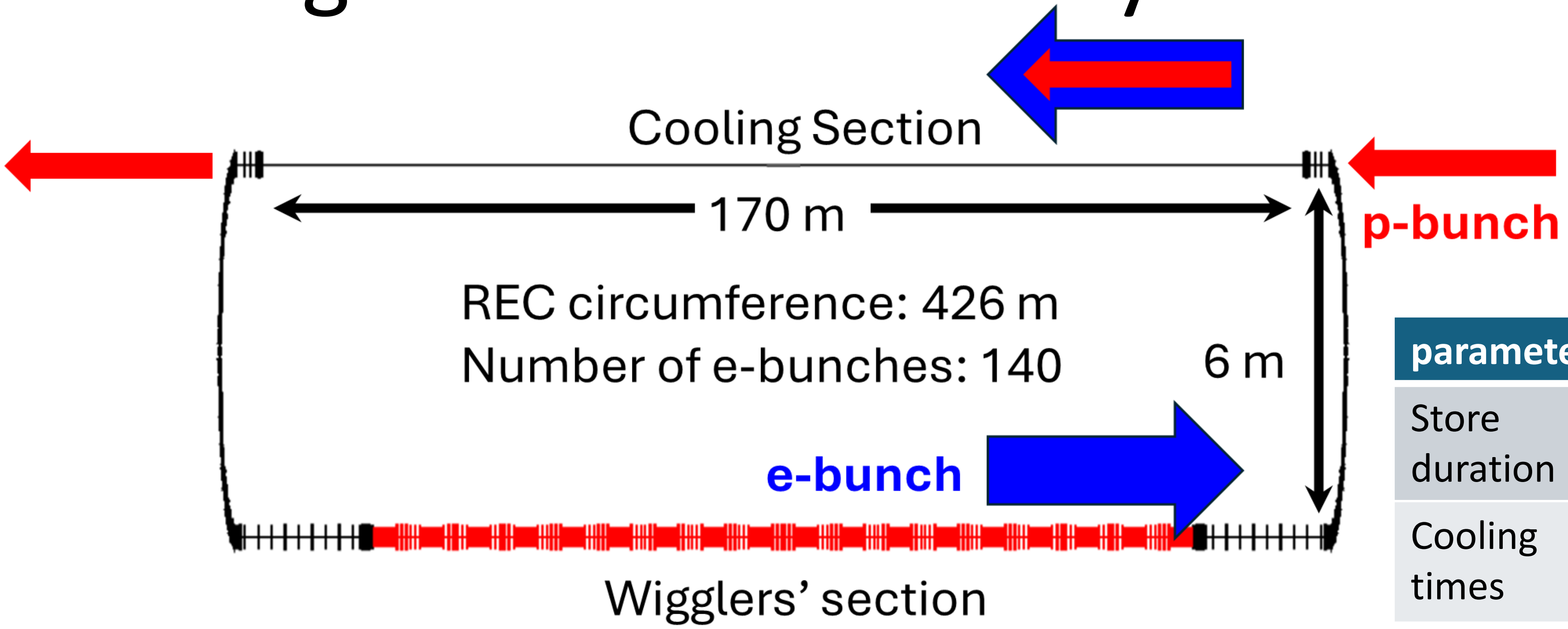


parameter	electrons	protons
γ	25.4	
L_{CS} [m]	170	
ε_n [μm]	1.5	2
β_{CS} [m]	150	150
Q_b [nC]	1.2×3	45
σ_z [cm]	5	70



$$\Delta\nu_{ep} = 1.3 \cdot 10^{-3}$$

Ring Electron Cooler layout



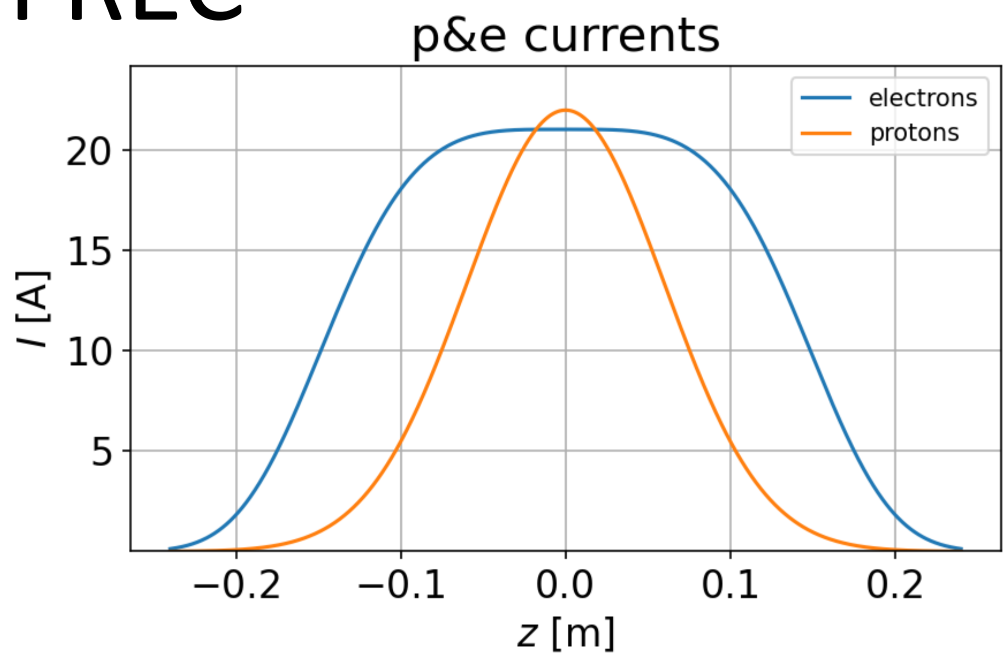
parameter	electrons	protons
Store duration	3 s	24 h
Cooling times	$\tau_{x,y} = 0.033$ s $\tau_z = 0.017$ s	$\tau_x = 2$ h $\tau_z = 3$ h

- The Ring Electron Cooler (REC) must counteract IBS-driven heating of protons at the collision energy ($\gamma = 293$). The required cooling times for 275 GeV protons are 2 hrs horizontal and 3 hrs longitudinal.
- The REC reutilizes electron bunches for several million turns. Damping wigglers are used in the REC to counteract electrons' emittance growth from IBS, BBS and quantum excitations.

- **Since there are two rings to consider (HSR and REC), both the electron-proton and proton-electron beam-beam effects become important.**

Beam-beam effects in REC

parameter	electrons	protons
γ	293	
L_{CS} [m]	170	
ε_x [nm]	9	11.3
ε_y [nm]	9	1
$\beta_{x(CS)}$ [m]	150	350
$\beta_{y(CS)}$ [m]	150	650
Q_b [nC]	22	11
σ_z [cm]		6
L_z (FWHM) [cm]	32	



$$\Delta\nu_{ep(x)} = 1 \cdot 10^{-4}$$
$$\Delta\nu_{ep(y)} = 1.7 \cdot 10^{-4}$$

For comparison:
$\xi_p = 12 \cdot 10^{-3}$

$$\Delta\nu_{pe(x,y)} = \frac{I_p \beta_{eCS(x,y)} L_{CS}}{2\pi I_a \gamma^3 \sigma_{p(x,y)} (\sigma_{px} + \sigma_{py})}$$

$$\Delta\nu_{pe(x)} = 0.04$$
$$\Delta\nu_{pe(y)} = 0.1$$

Tracking electrons in REC

- Considering the central slice of a p-bunch ($\max I_p$):

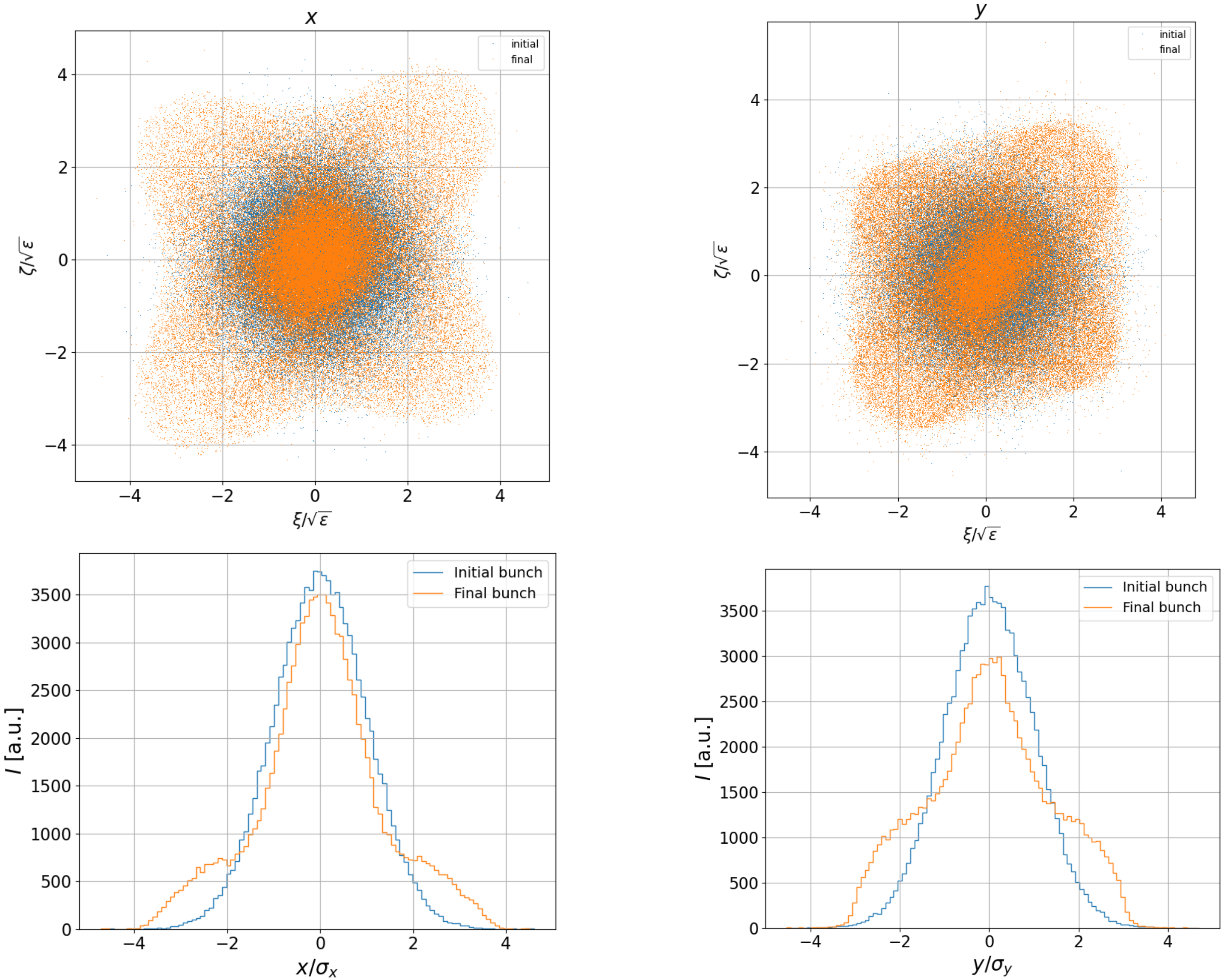
$$\delta\theta_x = \frac{K_p}{2} L_{CS} x I_x; \quad \delta\theta_y = \frac{K_p}{2} L_{CS} y I_y; \quad K_p = \frac{2 I_p}{I_A \gamma^3 \beta^3} \qquad (1)$$

$$I_x = \int_0^\infty \frac{\exp\left(-\frac{x^2}{2(\sigma_x^2+q)} - \frac{y^2}{2(\sigma_y^2+q)}\right)}{(\sigma_x^2+q)^{\frac{3}{2}}(\sigma_y^2+q)^{\frac{1}{2}}} dq\,; \quad I_y = \int_0^\infty \frac{\exp\left(-\frac{x^2}{2(\sigma_x^2+q)} - \frac{y^2}{2(\sigma_y^2+q)}\right)}{(\sigma_x^2+q)^{\frac{1}{2}}(\sigma_y^2+q)^{\frac{3}{2}}} dq$$

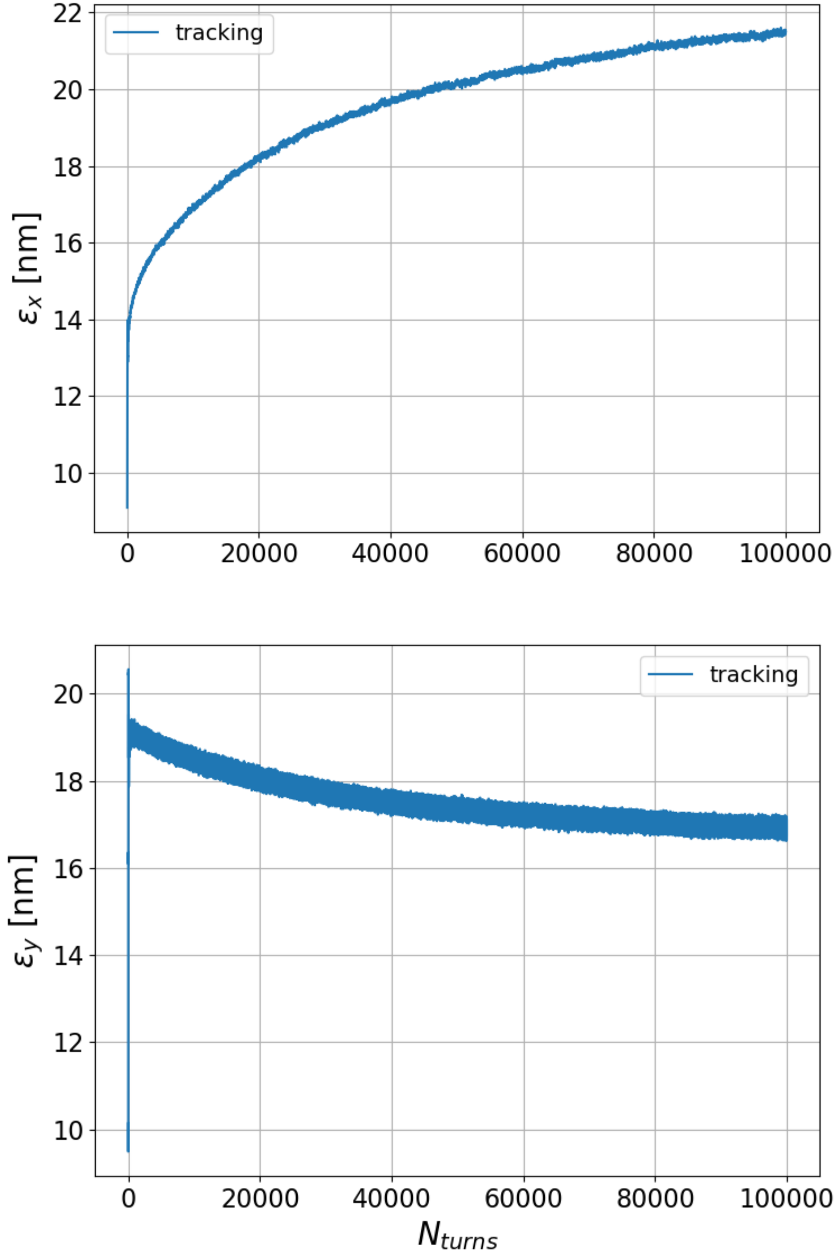
$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix} = M_x \begin{pmatrix} x_n \\ x'_n + \delta\theta_x(x_n, y_n) \end{pmatrix} \qquad \begin{pmatrix} y_{n+1} \\ y'_{n+1} \end{pmatrix} = M_y \begin{pmatrix} y_n \\ y'_n + \delta\theta_y(x_n, y_n) \end{pmatrix}$$

REC working point choice (I)

We started with $\nu_x = 0.23, \nu_y = 0.21$

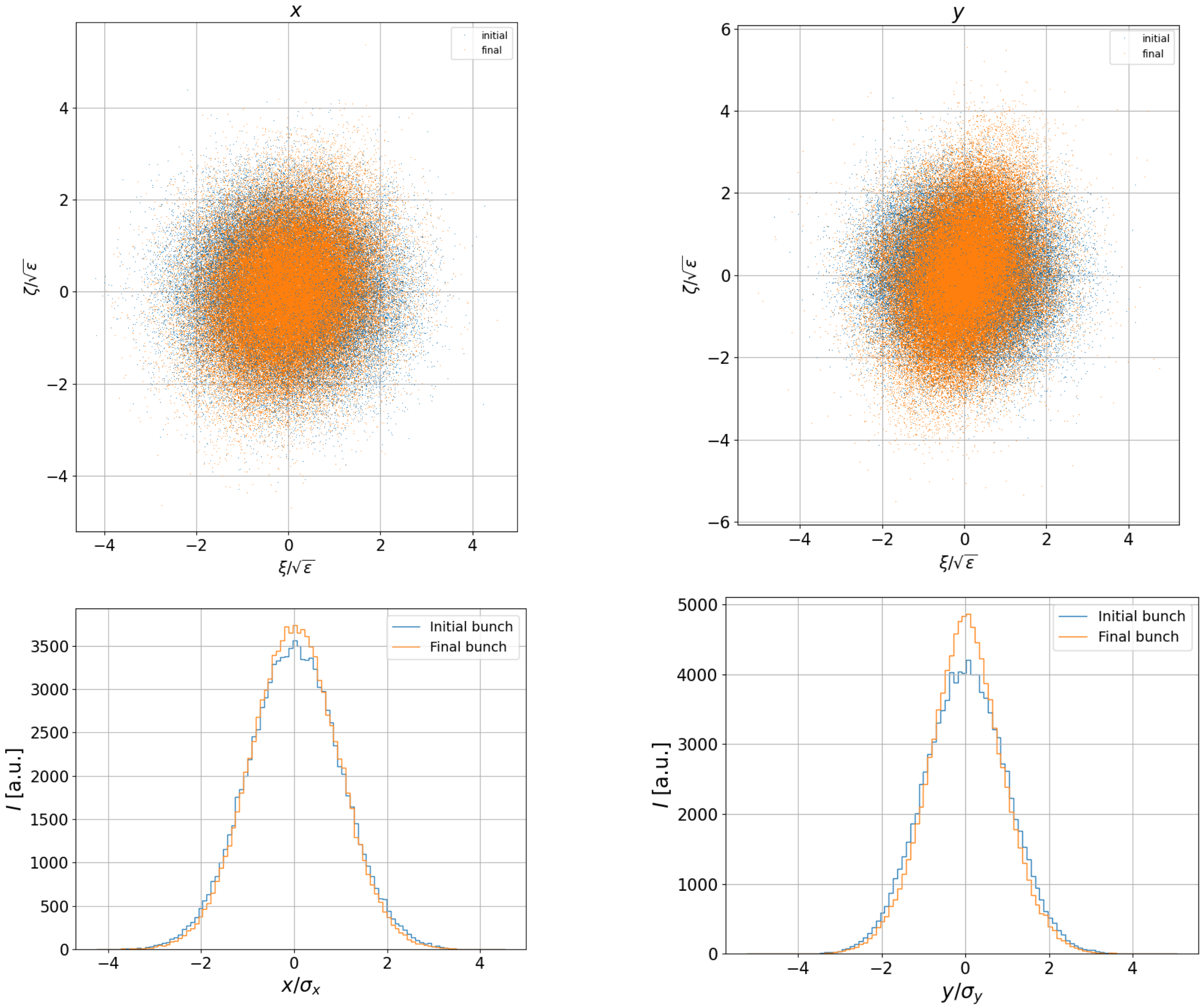


tracking 100k particles

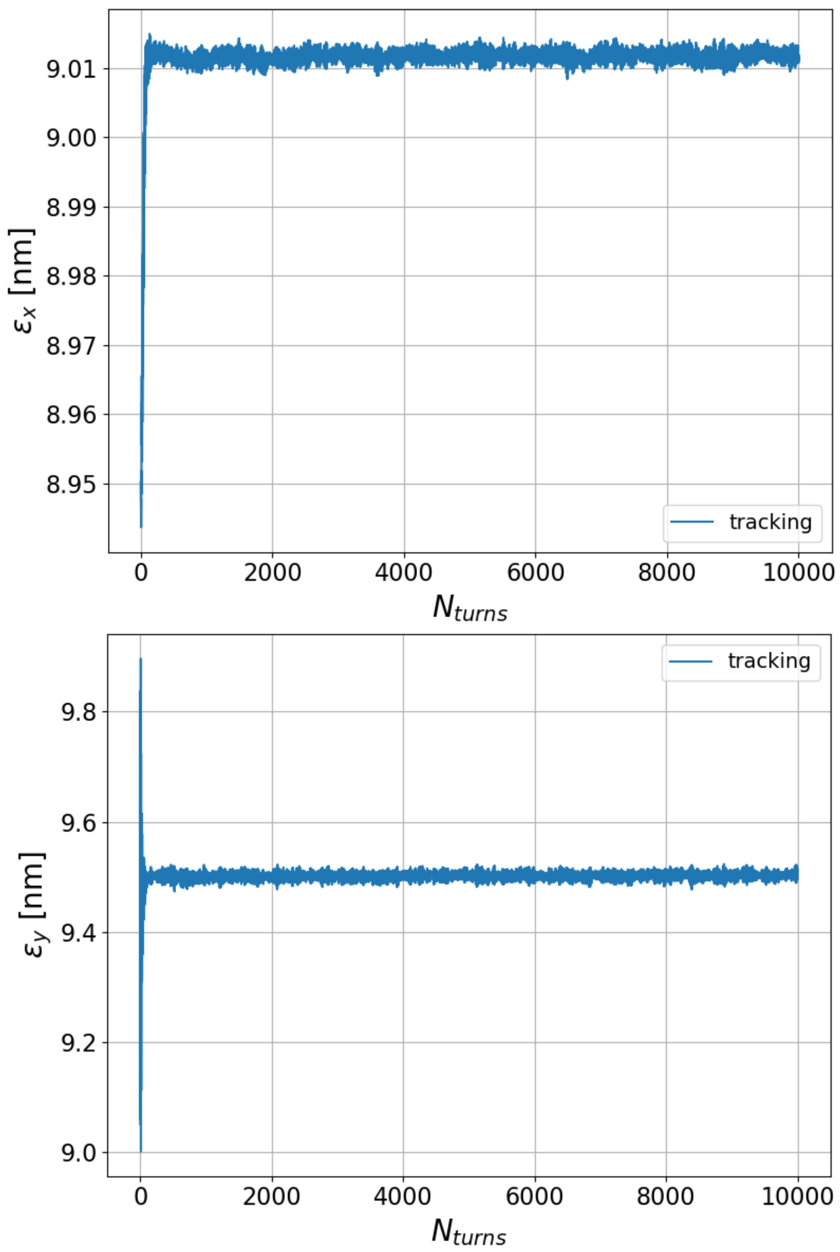


REC working point choice (II)

Adjusting the working point to $\nu_x = 0.13, \nu_y = 0.09$, allowed us to keep good emittance, and we got a halo under control.



tracking 100k particles



Relative trajectory stability (I)

- To estimate requirements to a stability of e- and p- trajectories in the CS with respect to each other we simulate kicks in Eq. (1) as:

$$\delta\theta_x = \frac{K_p}{2} L_{CS}(x + \Delta x) I_x; \quad \delta\theta_y = \frac{K_p}{2} L_{CS}(y + \Delta y) I_y$$

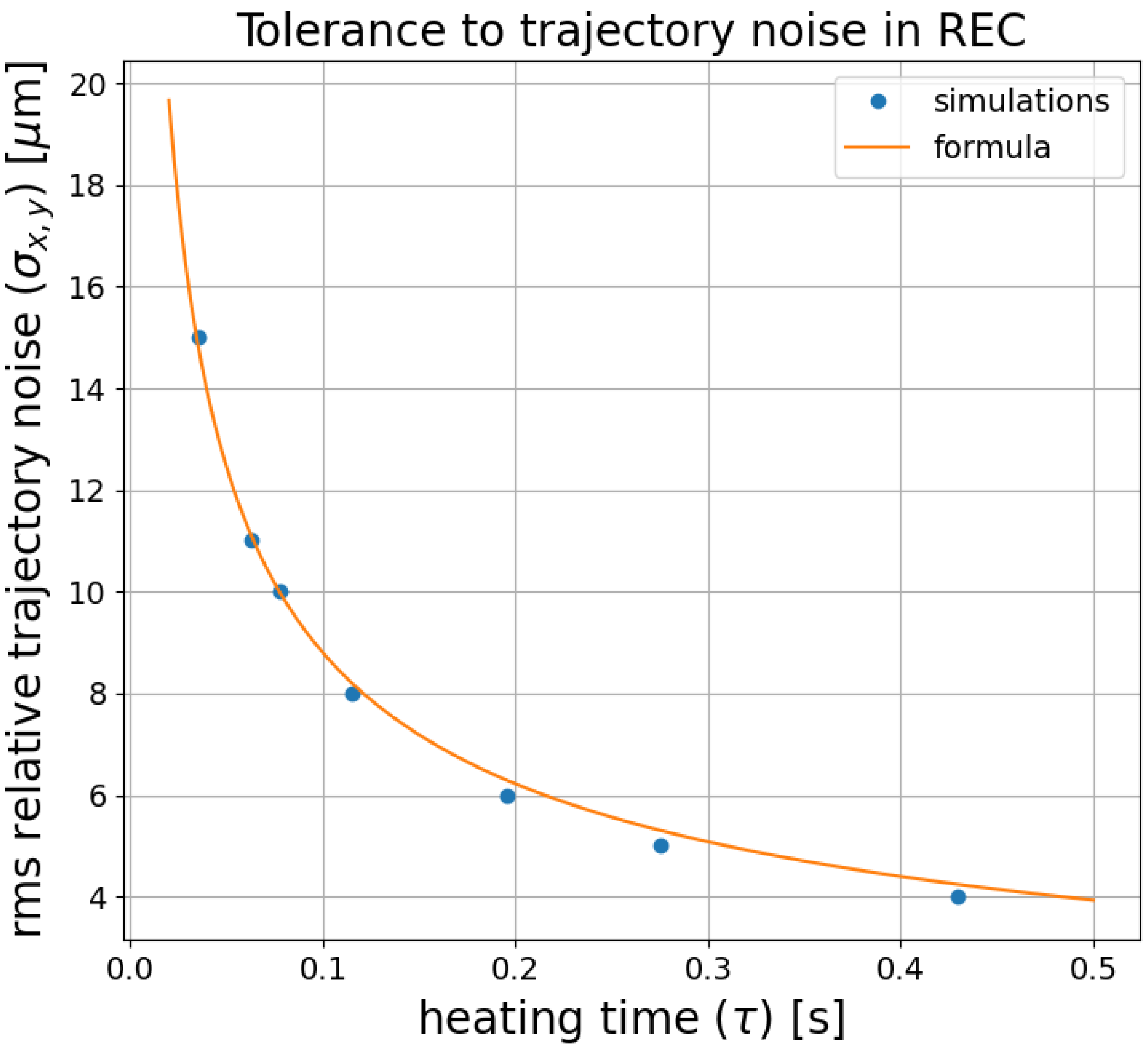
where displacements Δx and Δy are varying on each turn and are randomly distributed with σ_x, σ_y

- A quick estimate (overestimate) for the resulting emittance growth can be obtained from a “random walk-emittance dilution” model assuming a linear p-e kick:

$$\varepsilon = \varepsilon_0 + \frac{\pi}{8} \beta_{e(CS)} \sigma^2_{\theta(noise)} \cdot N_{turns}$$

$$\sigma_{\theta(noise)} = \frac{4\pi\Delta\nu_{pe}}{\beta_{eCS}} \sigma_{(noise)}$$

Relative trajectory stability (II)



An analytic formula (with a fudge-factor n=0.4) is a good match for heating times obtained from tracking

$$\sigma_{(noise)} = \sqrt{\frac{\varepsilon_e \beta_e T_{rev}}{2\pi^3 \Delta\nu_{pe}^2 \cdot \tau \cdot n}}$$

n accounts for the difference between an actual non-linear space charge and a model linear SC and depends on parameters of both bunches.

If we want the noise driven heating time (τ) to be an order of magnitude smaller than the transverse damping time, then the requirement to noise is $\boldsymbol{\sigma_{(noise)} \leq}$ **5 $\boldsymbol{\mu}$m**

Conclusion

- It is proposed to use electron coolers at EIC both at the injection and at the top energy to achieve and maintain the required hadron parameters.
- In electron coolers the electron and hadron beams are co-traveling in the common section with the same velocity. Although the beam-beam effect is suppressed by γ^2, the cooling section can be long, and the resulting effect can be substantial.
- We started considering the effect of proton focusing on electron’s dynamics in the EIC Ring Electron Cooler
  - A “single slice” p-e focusing was included into simulations
  - Requirements to stability of beam trajectories with respect to each other were derived
  - We are working on including longitudinal dynamics into the simulations
  - Studying of beam-beam in combination with the self-SC, IBS and radiation damping effects is planned