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U.S. DEPARTMENT of ENERGY

Space Charge Effects in a Ring-Based Electron Cooler

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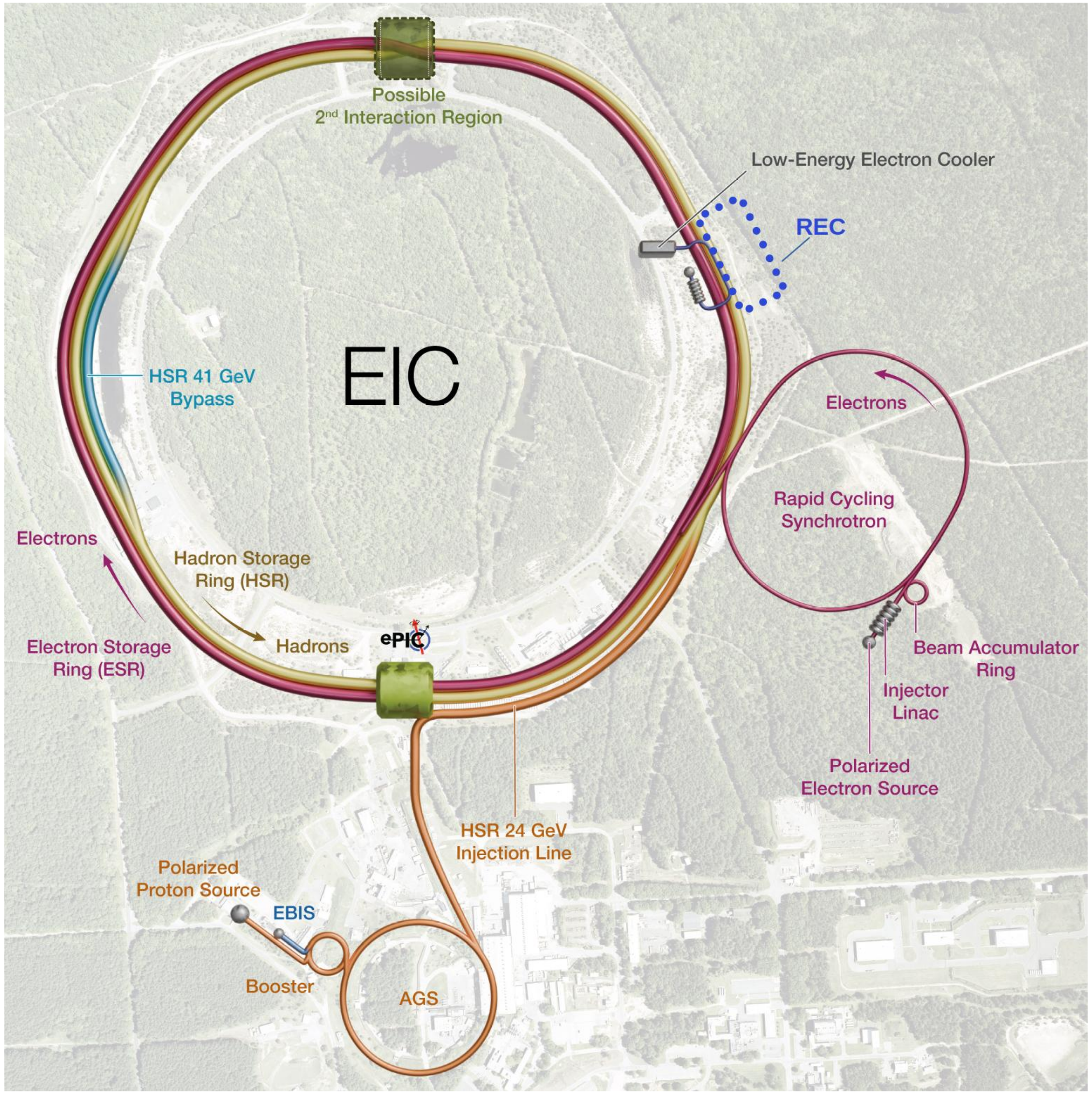
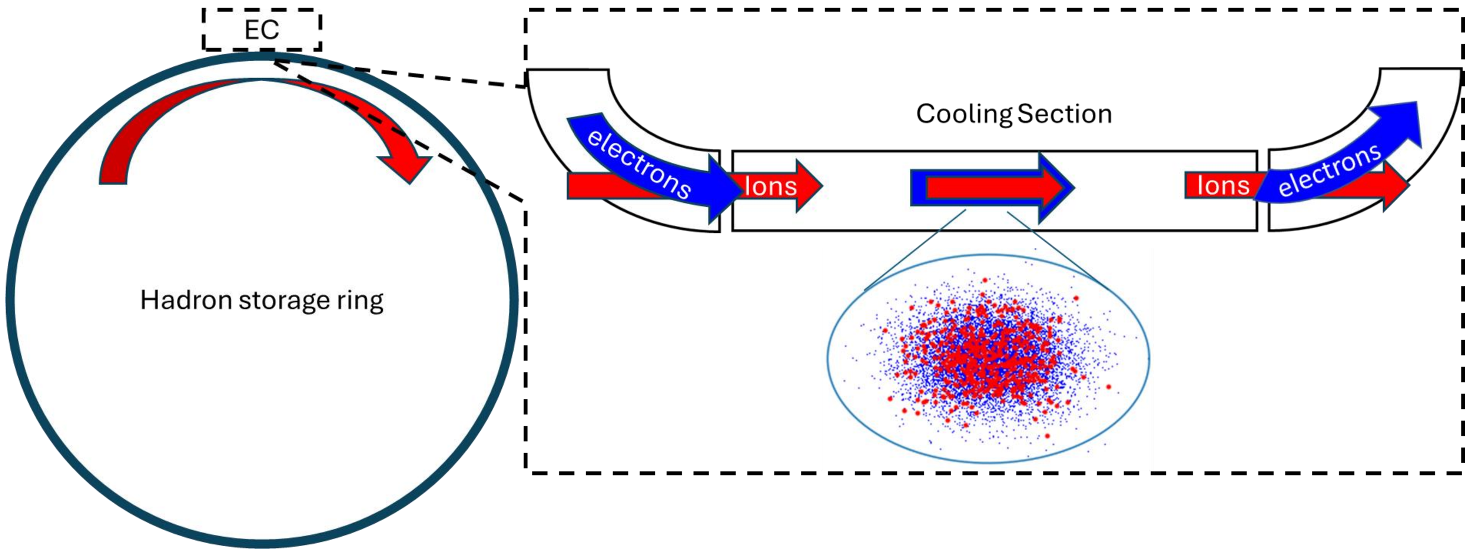
Ring-Based Electron Cooler for EIC



- **Low-Energy Cooling**
  - The Low-Energy Cooler (LEC) cools hadrons at injection energy.
  - The goal is to establish the initial proton parameters by reducing the vertical emittance from ~2 μm to 0.3–0.5 μm (rms normalized).
  - The LEC is an RF-based, single-pass electron cooler.
- **High-Energy Cooling**
  - At the EIC's top proton collision energy, cooling must counteract IBS-driven longitudinal and transverse emittance growth.
  - The cooler must provide $\tau_x = 2$ h and $\tau_z = 3$ h.
  - The cooler must also be compatible with the LEC.

We propose using a Ring Electron Cooler (REC) for high-energy cooling

Reminder: How Electron Cooling Works



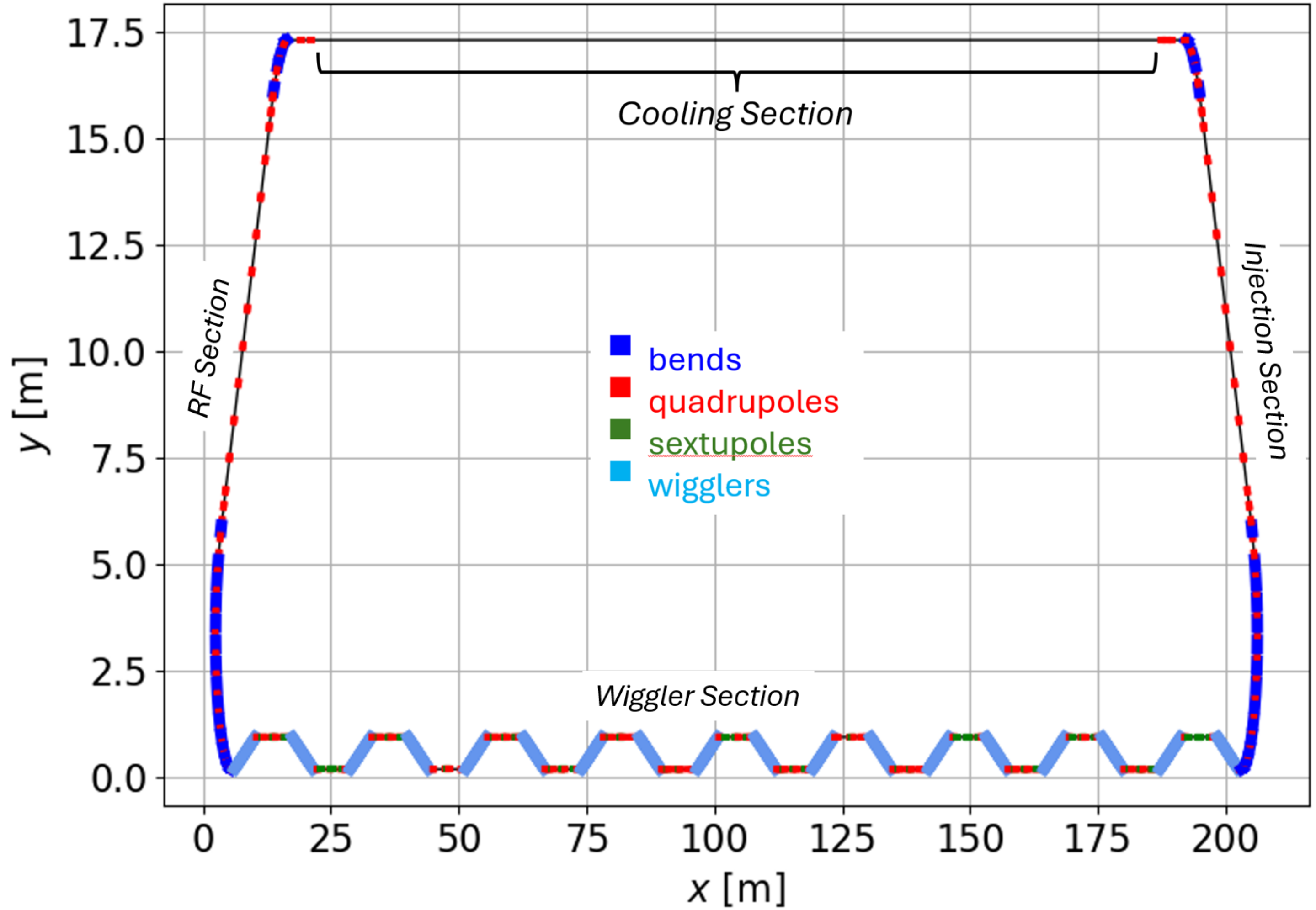
$$m_e \ll m_i$$

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

$$T_e \ll T_i$$

- A hadron bunch and an electron bunch travel together at the same velocity over the cooling section.
- In the co-moving frame, the two bunches can be viewed as a mixture of two gases: ions and electrons.
- Because electrons are much lighter, the electron gas is much colder than the ion gas.
- Heat is transferred from the hadrons to the electrons → electron cooling.

Ring Electron Cooler Concept



- **Our approach: an RF-based, non-magnetized Ring Electron Cooler.**
- Keeping electrons in the storage ring for many turns reduces the required average injector current.
- As the stored electrons cool the hadrons, beam-beam scattering heats the electron bunches.
- The electron emittance also increases due to IBS and other collective effects, including **space charge** and **beam-beam** effects.
- Radiation damping in the wigglers compensates for this emittance growth and maintains the electron emittance.

Cooling rate depends on all three e-bunch emittances

$$\lambda \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A_i m_p} \cdot \frac{1}{\gamma^2} \cdot N_e \cdot \frac{L_{CS}}{C_{ring}} \cdot \frac{1}{\left(\frac{\varepsilon_{ne}}{\beta_e} + \frac{\varepsilon_{ni}}{\beta_i}\right)(\varepsilon_{ne}\beta_e + \varepsilon_{ni}\beta_i)\sqrt{\sigma_{\delta e}^2 + \sigma_{\delta i}^2}\sqrt{\sigma_{ze}^2 + \sigma_{zi}^2}}$$

REC Parameters

Table 1: The REC parameters (electron storage ring)

relativistic γ	293.1
ring circumference [m]	426
cooling section length [m]	170
horizontal dispersion in the CS [m]	1
number of damping wigglers	18
damping wiggler length [m]	4.2
damping wiggler field [T]	2.4
wiggler gap [cm]	2
wiggler period [cm]	23
momentum compaction	$-1.5 \cdot 10^{-3}$
main RF frequency [MHz]	98.6
main RF voltage [kV]	50
2nd harmonic RF voltage [kV]	25
number of bunches	140
number of particles per bunch	$1.3 \cdot 10^{11}$
charge per bunch [nC]	21
peak current [A] (flat top e-bunch)	17.5
average current [A]	2
geometric emittance (x, y) [nm]	7.8, 7.8
CS β-function (x, y) [m]	180, 160
rms relative momentum spread	$9.8 \cdot 10^{-4}$
FWHM bunch length (flat top e-bunch) [cm]	34
tunes (x, y)	60.16, 8.15
space charge tune shift (x, y)	-0.078, -0.115
p-e focusing tune shift (x, y)	0.036, 0.086
radiation damping rate (x, y, z) [s^{-1}]	31, 31, 62
BBS rate (x, y, z) [s^{-1}]	0.8, -0.3, 12
IBS rate (x, y, z) [s^{-1}]	31, 31, 48

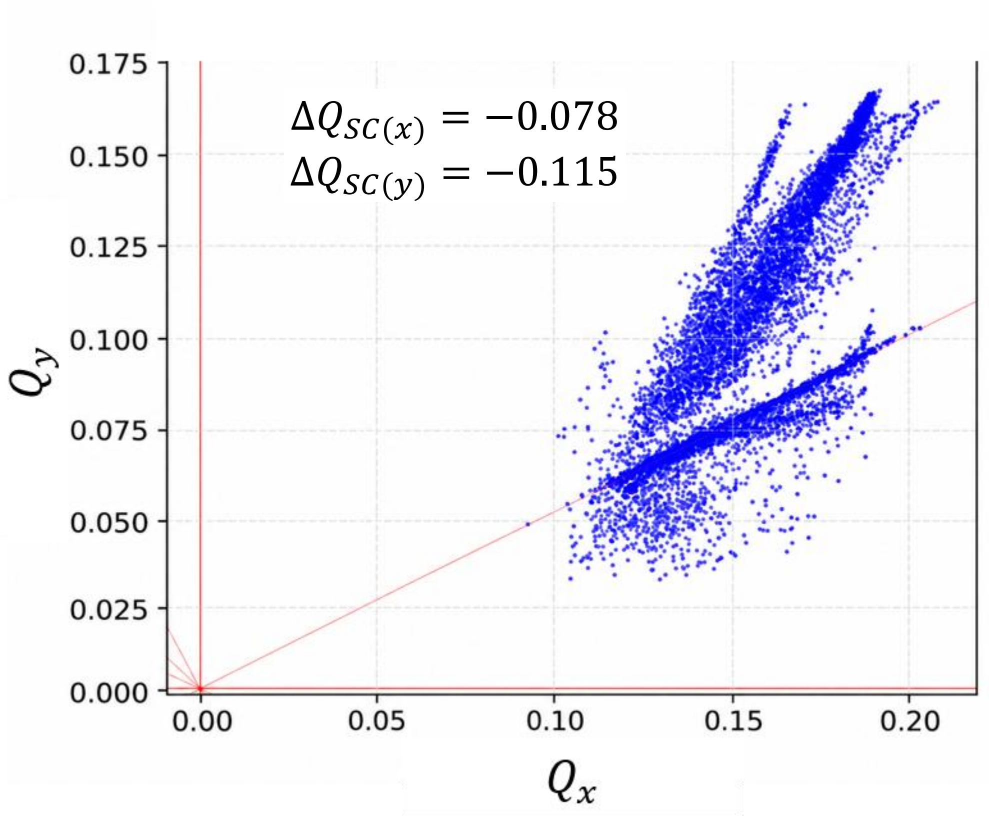
- **Relativistic gamma factor $\gamma = 293.1$**
- 170 m cooling section, compatible with the LEC
- 426 m ring circumference
- 140 electron bunches in the ring
- Each electron bunch makes 9 turns per hadron turn in the HSR
- Electrons are cooled by radiation damping from 18 damping wigglers
- **Electron bunch charge: 21 nC**
- **Electron bunch peak current: 18 A**
- **Proton bunch charge: 11 nC**
- **Proton bunch peak current: 22 A**

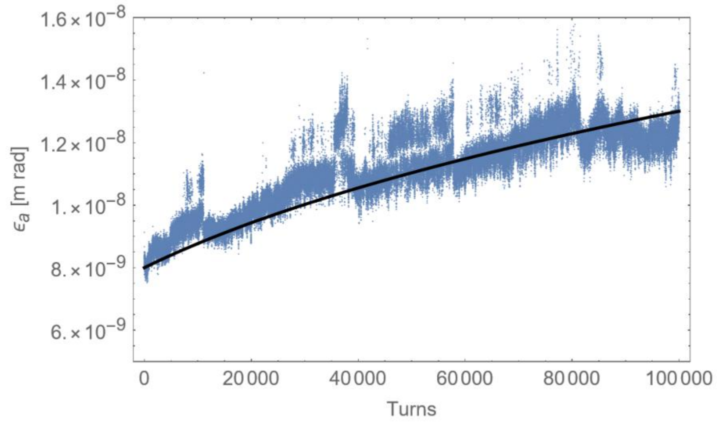
Table 2: The REC parameters (protons in the cooling section)

relativistic γ	293.1
number of particles per bunch	$6.9 \cdot 10^{10}$
geometric emittance (x, y) [nm]	11.3, 1
CS β-function (x, y) [m]	300, 700
rms relative momentum spread	$6 \cdot 10^{-4}$
rms bunch length (Gaussian p-bunch) [cm]	6
horizontal dispersion in the CS [m]	2.1
cooling time (x,y,z) [hrs]	**2, 4, 3**

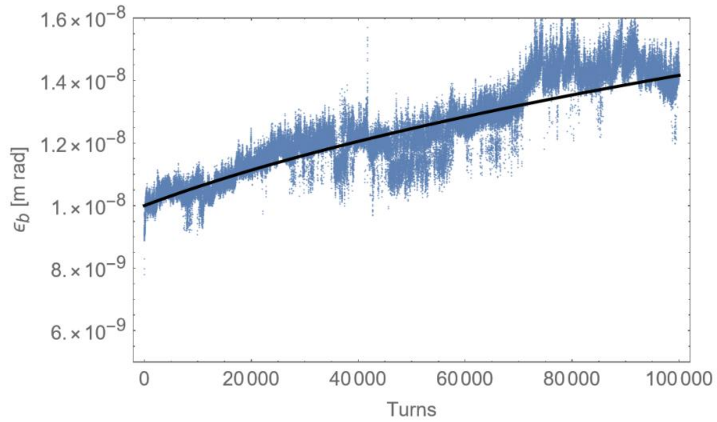
Space Charge in REC

- The space-charge tune spread in the REC bunches is relatively large.
- We track the beam for 10^5 turns, corresponding to more than four damping periods.
- The Bassetti–Erskine model is used to calculate the space-charge force.
- The beam emittance is updated every 1000 turns.





(a) Horizontal



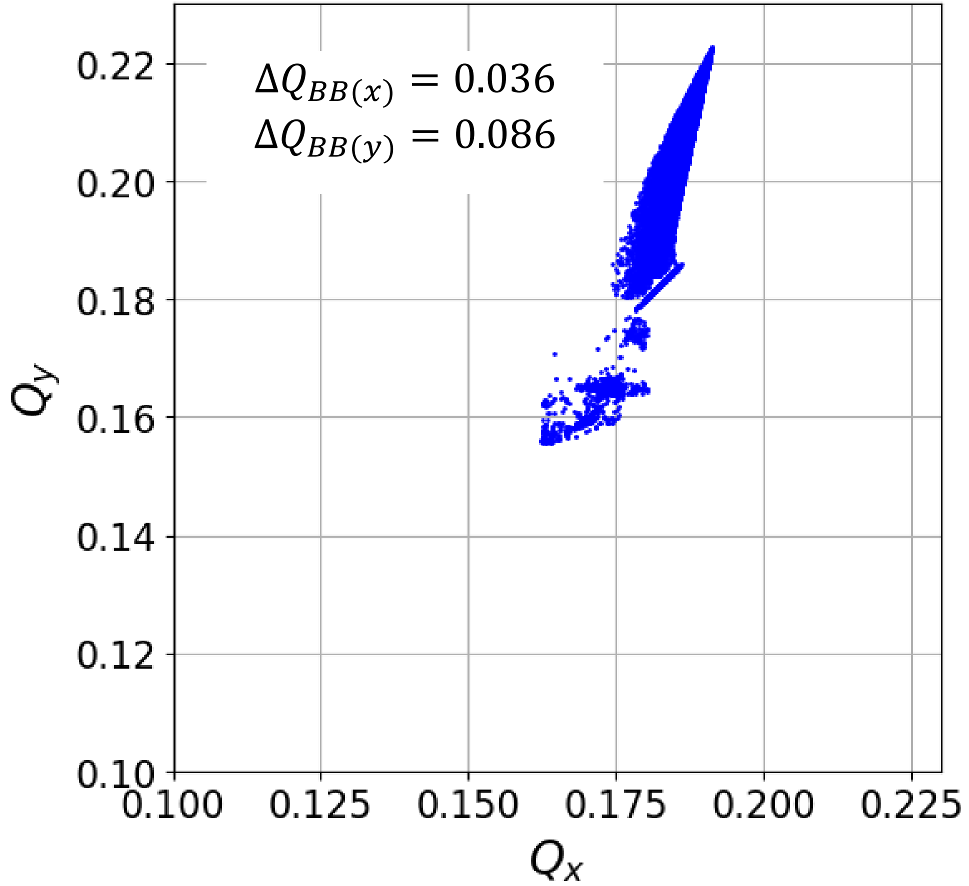
(b) Vertical

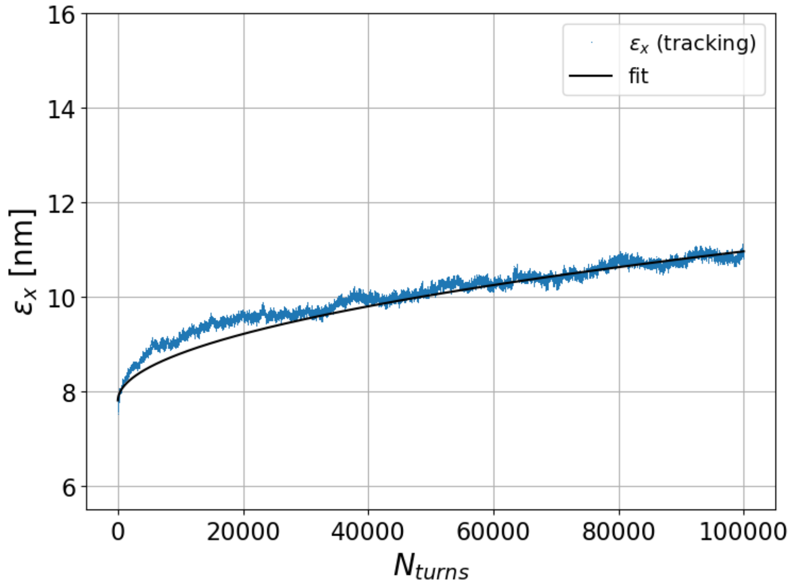
Tracking results give an approximate scaling for the SC-driven short-term emittance-growth rate:

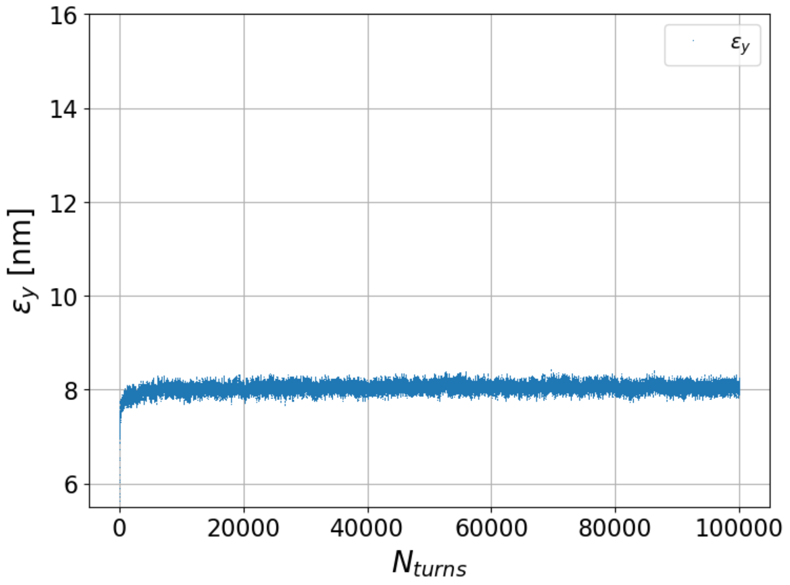
$$\lambda_{SC} = \frac{A_{SC}}{\varepsilon^{3/2}}$$

Beam-Beam Effect in the REC Cooling Section

- In the cooler, the electron and proton bunches co-travel at the same velocity. Therefore, the p–e focusing is reduced by γ^2.
- Nevertheless, the resulting beam-beam effect is non-negligible.
  - We track beam for 10^5 turns
  - A p–e focusing kick is applied on each pass through the cooling section.







Equilibrium Emittance with SC and BB Effects

- To determine the equilibrium emittance in the presence of space-charge (SC) and beam-beam (BB) effects, we find the emittance for which the total growth and damping rates balance
- We solve the following iterative equation:

$$\lambda_{damp}\varepsilon_{n+1} = \big(\lambda_{IBS}(\varepsilon_n) + \lambda_{BBS}(\varepsilon_n) + \lambda_{CS}(\varepsilon_n) + \lambda_{BB}(\varepsilon_n)\big)\varepsilon_n + \lambda_{damp}\varepsilon_{nat}$$

- **We conclude that the SC and BB effects increase the equilibrium emittance by ≈3% from 7.8 nm to 8 nm**

- *Next step:*
  Perform long-term tracking including space charge and beam-beam effects, as well as the intra-beam scattering, beam-beam scattering, and radiation damping in the Ring Electron Cooler.