Study of Electron Transverse Emittance Mismatch in the EIC Swap-Out Injection Scheme

Derong Xu

November 8, 2024

Abstract

This study examines the effect of electron emittance mismatch on proton emittance growth in the EIC swap-out injection. Strong-strong simulations show negligible growth for electron charge of 7 and 14 nC, but significant growth at 28 nC when electron emittance is much smaller than design values.

1 Introduction

The Electron-Ion Collider (EIC) is designed to achieve a high peak luminosity of 10^{34} cm^{-2}s^{-1} through collisions of polarized electron and proton beams. The Electron Storage Ring (ESR) is expected to deliver high-charge electron bunches of up to 28 nC. The ESR lattice is engineered to provide a dynamic aperture of 10σ in all three planes. Due to the limited polarization lifetime, frequent electron bunch replacement is required. The swap-out injection scheme offers an efficient solution to meet these demands, while accommodating the small dynamic aperture. The Rapid Cycling Synchrotron (RCS) is responsible for electron accumulation, acceleration, and injection to the ESR.

However, the design emittances of the RCS and ESR differ significantly. In the RCS, the vertical emittance is nearly zero to suppress vertical intrinsic spin resonances. In contrast, the ESR maintains a finite vertical emittance to match the proton beam size at the interaction point (IP). Although the electron beam can be manipulated during transport from the RCS to the ESR, maintaining precise control over the resulting emittance is challenging. This emittance mismatch during electron injection can lead to proton emittance growth.

An alternative injection scheme involves injecting electron bunches directly from the LINAC into the ESR, eliminating the need for the RCS. This approach meets the Phase I goals, where the ESR only needs to provide 5/10 GeV electron bunches with a maximum charge of 7 nC [1] . In Phase II, where a 28 nC electron bunch is required, multiple electron bunches can be injected into the same ESR bucket. Off-momentum injection can be employed to minimize electron emittance blow-up, making this accumulation scheme feasible. Our previous study indicates that the accumulation scheme is a viable option [2].

The electron bunch from the LINAC also differs from the ESR design value. In this note, we apply the strong-strong simulation method to study proton emittance growth during the swap-out injection for electron bunch charges of 7, 14, and 28 nC, respectively. The electron injection emittance spans a wide range to account for both LINAC and RCS cases. The accumulation scenario with significant emittance mismatch will be revisited in future studies.

2 Method

To model the distribution evolution of both the electron and proton beams, a self-consistent simulation is required. Accordingly, we employ the strong-strong simulation method. The beam parameters used in the simulation are presented in Table 1.

The horizontal emittance of the electron beam is scanned from 5 nm to 23 nm in steps of 2 nm. The vertical emittance is scanned from 0.5 nm to 5.0 nm, with a step size of 0.5 nm. The injected electron bunches are assumed to match the ESR optics, and their initial beam sizes are determined based on the scanned emittance and beam optics. The initial proton beam follows a perfect Gaussian

Table 1: Beam parameters used in strong-strong simulation. The columns “Proton design” and “Electron design” are directly taken from EIC-CDR [3]. The “Electron input” is what we actually use in the simulation. Without beam-beam interaction, the electron beam parameters will evolve toward the “Electron design” parameter. “H” stands for horizontal and “V” denotes vertical below. Parameters marked in red as “TBD” indicate values that were scanned during the simulation.

Parameter	Unit	Proton design	Electron design	Electron input
Circumference	m	3834	3834	3834
Energy	GeV	275	10	10
Particles per bunch	10^{11}	0.688	1.72	1.72
Half crossing angle	mrad	12.5	12.5	12.5
Crab cavity frequency	MHz	200.0/400.0	400.0	400.0
β_x^*/β_y^*	cm	80.0/7.20	55.0/5.60	55.0/5.60
RMS emittance (H/V)	nm · rad	11.3/1.00	20.4/1.6	TBD
RMS bunch size (H/V)	μm	95.0/8.5	106/9.5	TBD
RMS bunch length	cm	6.0	0.7	0.09
RMS energy spread	10^{-4}	6.6	5.5	20.0
Transverse fractional tune (H/V)	-	0.228/0.210	0.08/0.14	0.08/0.14
Synchrotron tune	-	-0.010	-0.069	-0.069
Transverse damping time	turns	∞	4000	4000
Longitudinal damping time	turns	∞	2000	2000
Chromaticity (H/V)	-	2/2	1/1	1/1

Table 2: Model parameters during the strong-strong simulation

Model parameter	Proton beam	Electron beam
Number of macro particles	$512,000$	$1,280,000$
Number of longitudinal slices	11	11
Number of transverse grids	64×64	

distribution and begins interacting with the electron beam from the 1st turn. After $50,000$ turns, the electron bunch is swapped out and replaced with a fresh one, allowing the HSR bunch to continue interaction with the newly injected electron bunch.

The strong-strong simulation is influenced by numerical noise, which varies based on the model parameters. The chosen model parameters are listed in Table 2. The ratio of macro particles is set equal to the ratio of bunch intensities, following our previous study. To reduce computation time, we also reduce the number of longitudinal slices and transverse grids.

3 Result

A typical tracking result is shown in Figure 1. At 50,000-th turns, following the replacement of the electron bunch, a slight jump in the proton vertical emittance is observed. This emittance jump must be carefully controlled to remain small; otherwise, the flat hadron beam profile may be compromised. More tracking results are available at Github repository.

Figure 2 presents the proton horizontal and vertical emittance jumps for varying initial electron emittances and electron charges. Different colors represent the percentage increase in emittance per injection. The emittance increase is calculated as follows:

(1) The tracking data between 40,000 and 41,000 turns are averaged to obtain ϵ_1

(2) The tracking data between 90,000 and 91,000 turns are averaged to obtain ϵ_2

(3) The relative emittance growth per injection is normalized using

$$\frac{\Delta\epsilon}{\epsilon_0} = \frac{\epsilon_2 - \epsilon_1}{\epsilon_0}$$

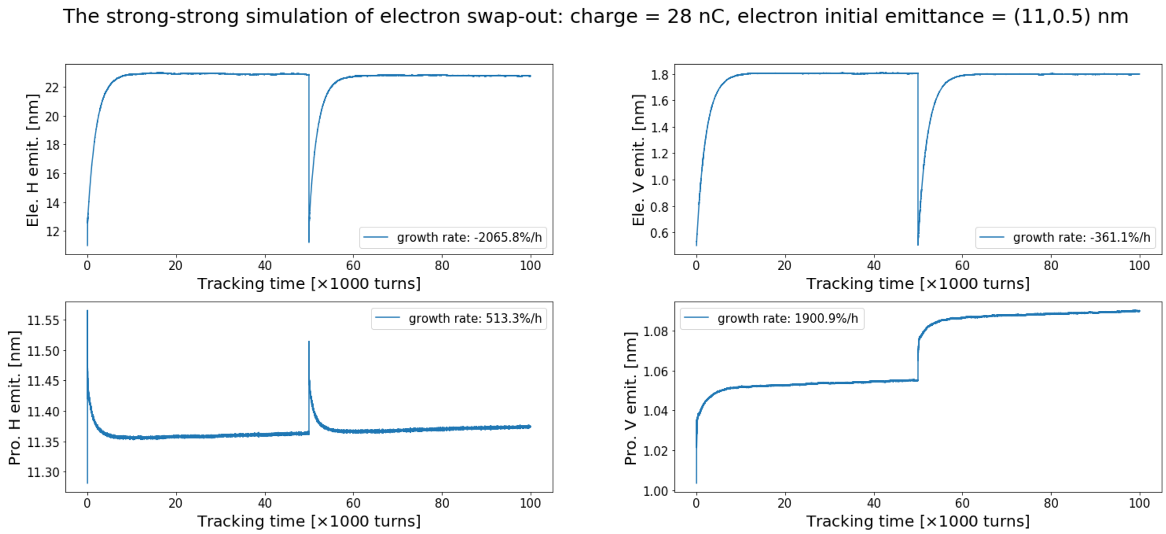

Figure 1: Electron (top) and proton (bottom) emittance evolution in strong-strong simulation.

Table 3: Model parameter B in Figure 4.

Model parameter	Proton beam	Electron beam
Number of macro particles	$1,024,000$	$2,560,000$
Number of longitudinal slices	15	15
Number of transverse grids	128×128	

where ϵ_0 is the proton design value shown in Table 1.

From Figure 2, it is evident that the emittance jump is negligible for electron charges of 7 nC or 14 nC. However, for 28 nC, with smaller injected emittances (e.g. $\epsilon_x = 5$ nm, $\epsilon_y = 0.5$ nm), the vertical emittance jump reaches as high as 9.2% per injection, which is unacceptably large. Increasing the injected horizontal or vertical electron emittance helps reduce the emittance jump. When the injected electron emittance is matched to the design values ($\epsilon_x \sim 20$ nm, $\epsilon_y \sim 2$ nm), the proton emittance jump is minimized.

4 Discussion

In addition to the emittance jump observed during the swap-out process, there is a gradual vertical emittance decrease at 7 nC or 14 nC. This behavior contrasts with the case of 28 nC, where both horizontal and vertical growth rates are positive.

Figure 3 compares the emittance tracking result for different electron charge. The emittance growth rate is fitted by last 30% tracking data, which is $30,000$ turns. As shown in this figure, the proton vertical growth rate is negative for 7 nC or 14 nC.

One possible explanation is that the beam-beam kick is too weak, and the tracking duration is not long enough for the proton beam distribution to reach equilibrium. Another factor could be that the growth rate in the simulation is sensitive to the model parameters, as we also observed in a previous study regarding the impact of numerical noise on proton emittance growth in strong-strong simulations [4].

Figure 4 presents the strong-strong tracking results using different model parameters. The beam parameters are set according to the EIC design values listed in Table 1. Models A, B, and C are detailed in Tables 2, ,3, and 4, respectively. The results clearly demonstrate that the proton growth rate in strong-strong simulations is dependent on the model parameters, with the vertical growth rates varying from negative to positive.

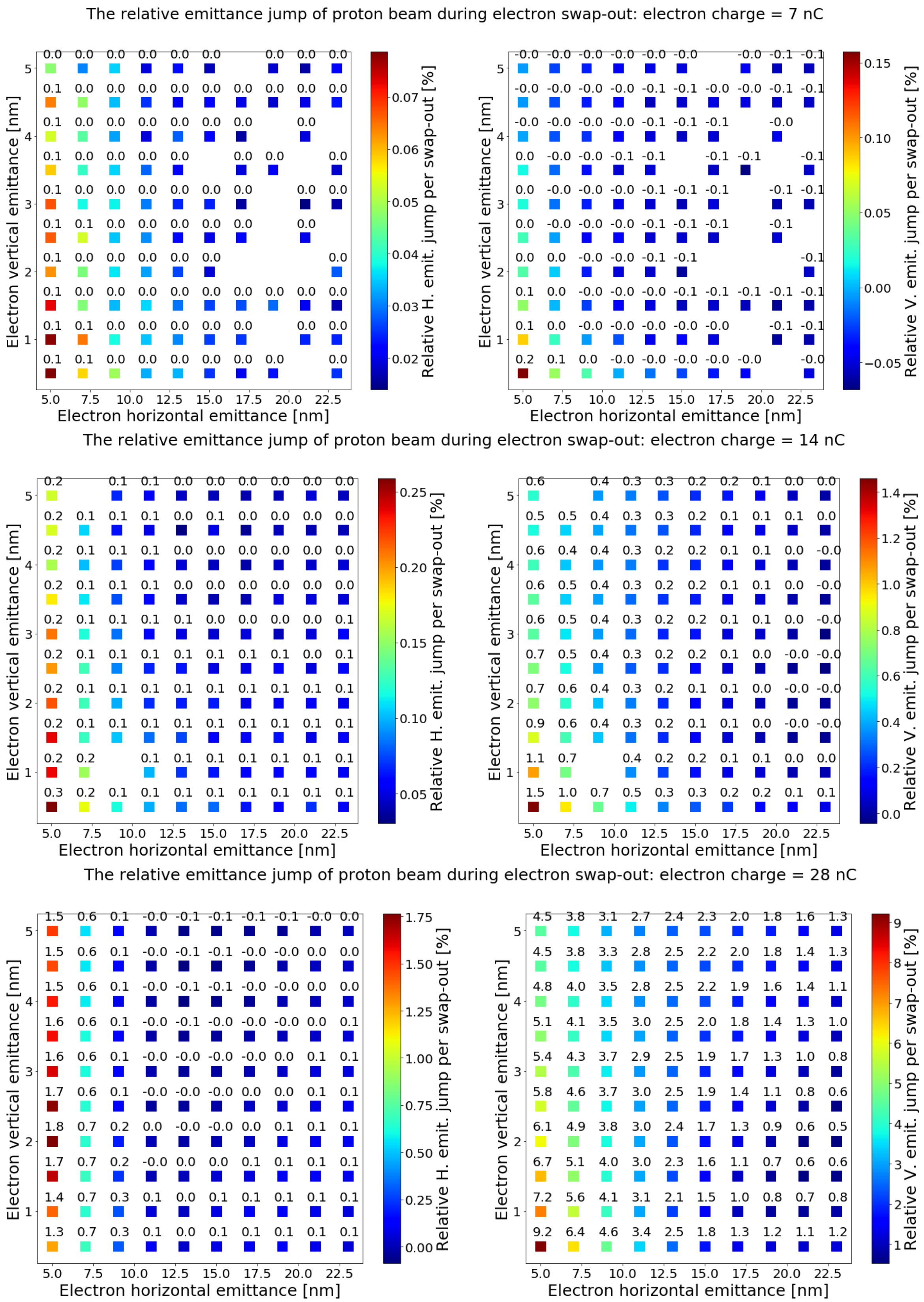

Figure 2: Relative proton emittance growth per injection. Empty blocks indicate that the simulation was terminated accidentally, resulting in insufficient tracking data.

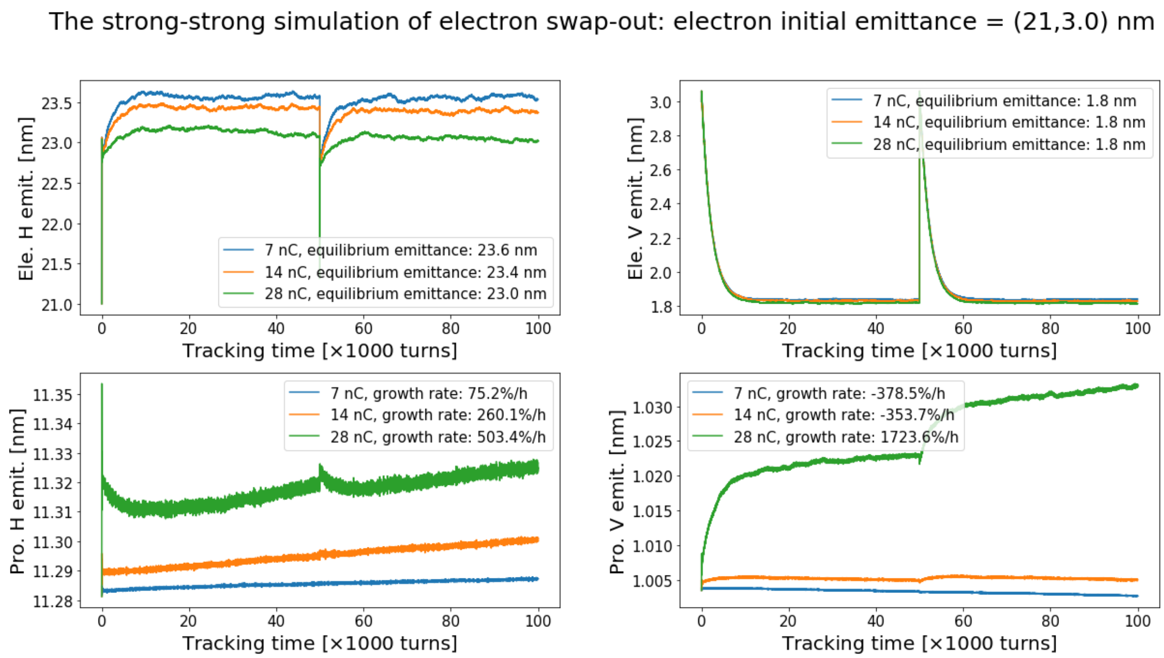

Figure 3: The vertical emittance growth rate of proton beam are negative for 7 nC or 14 nC.

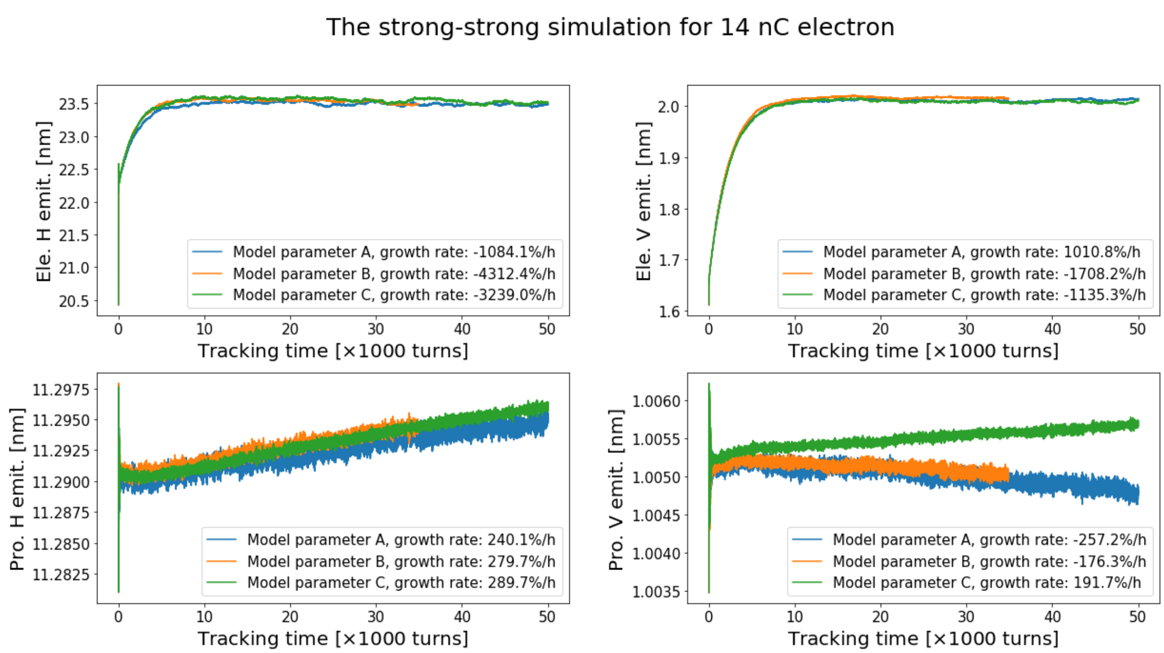

Figure 4: The vertical emittance growth rate in strong-strong simulation depends on model parameters. Models A, B, and C are detailed in Tables 2, ,3, and 4, respectively.

Table 4: Model parameter C in Figure 4.

Model parameter	Proton beam	Electron beam
Number of macro particles	$2,048,000$	$1,024,000$
Number of longitudinal slices	7	21
Number of transverse grids	128×128	

5 Summary

Proton emittance growth in the EIC swap-out injection is small for 7 and 14 nC but large for 28 nC when the electron emittance is mismatched. Matching the emittance to the ESR design reduces this growth. The growth rate also depends on the model parameters but is less relevant to this study.

References

[1] S. Nagaitsev. Project overview — phasing approach, Sept. 16 - 18 2024. EIC Machine Advisory Committee Meeting.

[2] D. Xu et al. Advancing electron injection dynamics and mitigation approaches in the electron-ion collider's swap-out injection scheme. In *Proc. IPAC'24*, number 15 in IPAC'24 - 15th International Particle Accelerator Conference, pages 230–233. JACoW Publishing, Geneva, Switzerland, 05 2024.

[3] Ferdinand Willeke and J Beebe-Wang. Electron ion collider conceptual design report 2021. Technical report, Brookhaven National Lab.(BNL), Upton, NY (United States); Thomas Jefferson . . . , 2021.

[4] Derong Xu. Convergence of strong-strong beam-beam simulations for EIC, Nov. 29 2022. EIC beam physics workshop.