ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP036

# EMITTANCE MISMATCHING OF ELECTRON INJECTION FOR THE ELECTRON STORAGE RING OF THE ELECTRON-ION COLLIDER*

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*Abstract*

The Electron-Ion Collider (EIC), to be constructed at Brookhaven National Laboratory, will collide polarized high-energy electron beams with polarized proton and ion beams, achieving peak luminosities of up to $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the center-of-mass energy range of 20-140 GeV. The EIC consists of two storage rings: the Hadron Storage Ring (HSR) and the Electron Storage Ring (ESR). Due to the short polarization lifetime of the electron beam, a swap-out injection scheme is adopted for the ESR. In this article, we estimate the injection emittance mismatch tolerances for electron bunches transferred from the Rapid Cycling Synchrotron (RCS) into the ESR. These studies are based on strong-strong beam-beam simulations. The resulting tolerances for injection emittance mismatch in the ESR are presented.

## INTRODUCTION

There are several collision modes involving highly polarized electrons colliding with protons or ions in the EIC [1,2]. In this article, we study the emittance mismatch during electron bunch injection from the Rapid Cycling Synchrotron (RCS) into the Electron Storage Ring (ESR). The electron beam energies in the ESR can be 5 GeV, 10 GeV, or 18 GeV. To maintain an average polarization above 70%, electron bunches must be periodically swapped out and replaced with freshly polarized bunches. For instance, at 18 GeV, the electron bunch must be replaced approximately every three minutes.

In contrast, proton bunches remain in the Hadron Storage Ring (HSR) for the entire physics store, which can last several hours. A key concern is the potential increase in proton emittance during the repeated electron bunch swap-out process, particularly due to injection emittance mismatch between the RCS and ESR. Since the injected electron bunch collides with the circulating proton bunch immediately upon injection, any mismatch can lead to proton emittance growth. The emittance of the injected electron bunch is mainly determined by the linac performance and synchrotron radiation damping in the RCS.

In the following sections, we perform strong-strong beam-beam simulations [3] to study the impact of electron injection emittance mismatch during the swap-out process. Our goal is to limit the proton emittance growth from each individual electron bunch injection to less than 1%, ensuring that the cumulative emittance increase remains below 20% over a typical 9-hour store. Based on this criterion, we determine the acceptable tolerances for injection emittance mismatch.

* Work supported by the U.S. Department of Energy, Office of Science under contracts DE-SC0012704 and DE-AC05-06OR23177
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Table 1: Electron Beam Design Parameters for the ESR

| Emittances | 5 GeV | 10 GeV | 18 GeV |
|---|---|---|---|
| $\epsilon_x$ (nm) | 20 | 20 | 24 |
| $\epsilon_y$ (nm) | 1.8 | 1.1 | 2.0 |
| Bunch length (cm) | 0.7 | 0.7 | 0.9 |
| RMS $dp/p_0$ ($10^{-4}$) | 6.8 | 5.8 | 10.9 |
| $\epsilon_L$ ($10^{-4}$ eVs) | 0.8 | 1.35 | 5.8 |

Table 2: Equilibrium Electron Parameters for the RCS

| Emittances | 5 GeV | 10 GeV | 18 GeV |
|---|---|---|---|
| $\epsilon_x$ (nm) | 3.87 | 15.51 | 50.2 |
| $\epsilon_y$ (nm) | ~ 0 | ~ 0 | ~ 0 |
| Bunch length (cm) | (0.46) | (1.08) | (1.33) |
| RMS $dp/p_0$ ($10^{-4}$) | 4.49 | 8.96 | 16.1 |
| $\epsilon_L$ ($10^{-4}$ eVs) | (0.35) | (3.22) | (12.65) |

## EMITTANCE MISMATCH

In this article, we focus on three electron–proton collision modes: (1) 5 GeV electrons colliding with 100 GeV protons, (2) 10 GeV electrons with 275 GeV protons, and (3) 18 GeV electrons with 275 GeV protons. Table 1 lists the main design parameters for the electron bunches in the ESR. The design parameters for the latter two collision modes are already well optimized. However, for the first mode between 5 GeV electrons and 100 GeV protons, we must reduce the electron bunch intensity by 30% from the value presented in the EIC Conceptual Design Report (CDR) in order to stabilize the proton beam under beam-beam interaction. The proton beam-beam parameters for the three collision modes are approximately 0.01, 0.012, and 0.004, respectively.

The original plan was to place the RCS inside the RHIC tunnel, sharing the same space with both the HSR and ESR. However, due to extremely tight installation constraints, it was recently decided to relocate the RCS outside of the RHIC tunnel [2]. Based on preliminary calculations, Table 2 lists the electron emittances, bunch lengths, and relative momentum spreads $(\delta p/p_0)_{\mathrm{rms}}$ at the three extraction energies [4]. The values for bunch length and longitudinal emittance listed in brackets are derived from the calculated momentum spread, assuming matched longitudinal phase space profiles between the RCS and ESR.

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Comparing Table 2 with Table 1, the RCS longitudinal emittance at 5 GeV is approximately half that of the ESR. At the other two energies, the longitudinal emittances from the RCS are about twice the ESR's design values. The design horizontal emittance for the ESR is around 20 nm at all three electron energies. In contrast, the estimated horizontal emittances from the RCS are approximately 4 nm, 15 nm, 15 nm at 5 GeV, 10 GeV, and 18 GeV, respectively. At 5 GeV, the RCS horizontal emittance is about five times smaller than the ESR design value, while at 18 GeV, it is roughly twice as large. The ESR's vertical emittance is designed to be 1-2 nm, whereas the vertical emittance from the RCS is negligible.

## SIMULATION OF LONGITUDINAL EMITTANCE MISMATCH

We first study the impact of longitudinal emittance mismatch during electron injection from the RCS into the ESR. In this study, we assume that the transverse emittances are matched, and we vary only the longitudinal emittance. During the scan, both the bunch length and momentum spread are scaled by the same factor to preserve the longitudinal phase space shape of the injected electron bunch relative to that of the ESR. The injected longitudinal emittances from the RCS are set to 1/3, 1/2, 1, 2, and 3 times the ESR design values for all three collision modes.

As an example, Figure 1 shows the evolution of the electron bunch length after injection into the ESR at an electron energy of 5 GeV. As mentioned earlier, the injected electron bunch begins colliding with the circulating proton bunch immediately after injection. Synchrotron radiation damping and quantum excitation are included in the simulation. From the plot, the electron bunch length converges to the ESR design value within approximately two longitudinal damping periods, or about 4000 turns.

Figure 2 shows the corresponding evolution of the proton vertical beam size. Across the five initial longitudinal emittance values, there is little difference in the proton vertical beam size evolution during the first 4000 turns. The beam size growth observed after this period is attributed to numerical noise in the strong–strong beam-beam simulation [5]. The simulation results indicate that the proton beam is tolerant to the range of longitudinal emittance mismatches studied.

## SIMULATION OF HORIZONTAL EMITTANCE MISMATCH

Next, we simulate the effects of horizontal emittance mismatch during electron injection. For all three collision modes, we scan five values of the injected horizontal emittance: 4 nm, 10 nm, 24 nm, 35 nm, and 50 nm, while assuming perfect matching in both longitudinal and vertical emittances. It takes approximately 10,000 turns for the injected electron bunch to damp to the ESR design emittance through synchrotron radiation.

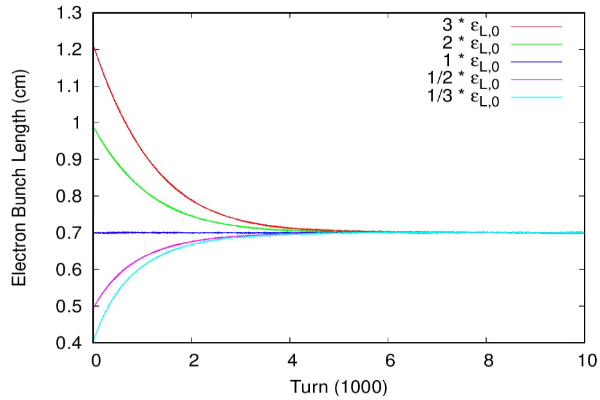


Figure 1: The evolution of electron bunches with longitudinal emittance mis-match. The collision mdoe between 5 GeV electrons and 100 GeV protons is used.

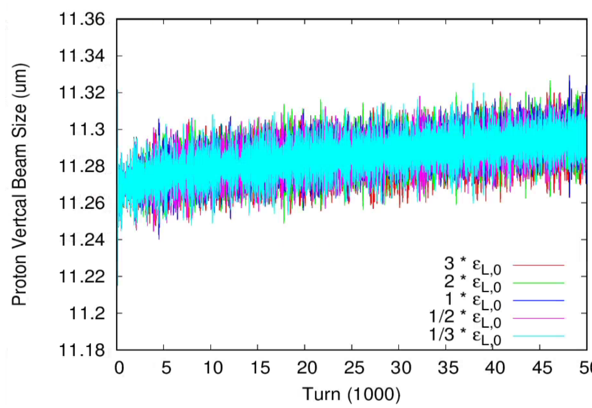


Figure 2: The evolution of proton vertical beam size with longitudinal emittance mis-match. The collision mdoe between 5 GeV electrons and 100 GeV protons is used.

Figure 3 shows the evolution of the proton horizontal and vertical beam sizes for the collision mode involving 5 GeV electrons and 100 GeV protons. From the results, injected horizontal emittances of 4 nm and 10 nm are not acceptable, as they cause more than a 1% increase in proton vertical emittance or more than a 0.5% increase in vertical beam size after a single electron bunch injection. In contrast, larger injection emittances of 35 nm and 50 nm are acceptable. A similar conclusion applies to the collision mode between 10 GeV electrons and 275 GeV protons. For the 18 GeV electron and 275 GeV proton collision mode, all simulated injection horizontal emittances are acceptable, due to the relatively small proton beam-beam parameter of 0.003.

Figure 4 shows the proton vertical emittance at turn 10,000 as a function of the injected electron horizontal emittance for the 5 GeV electron and 100 GeV proton collision mode. Based on this plot, we recommend that the injected horizontal emittance be greater than 15 nm. Injection emittances larger than the ESR design value are acceptable.

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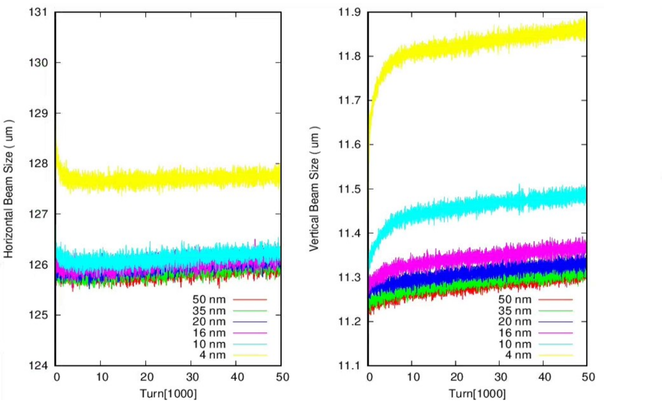


Figure 3: Evolution of proton transverse beam sizes with horizontal emittance mismatching for the collision mode between 5 GeV electrons and 100 GeV protons.

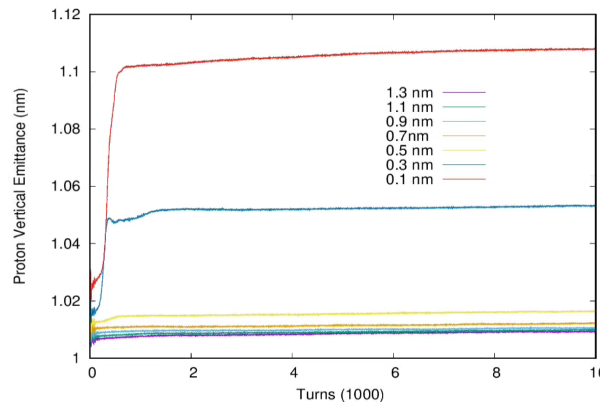


Figure 5: Evolution of proton vertical beam sizes with five different electron vertical injection emittances for the collision mode between 10 GeV electrons and 275 GeV protons.

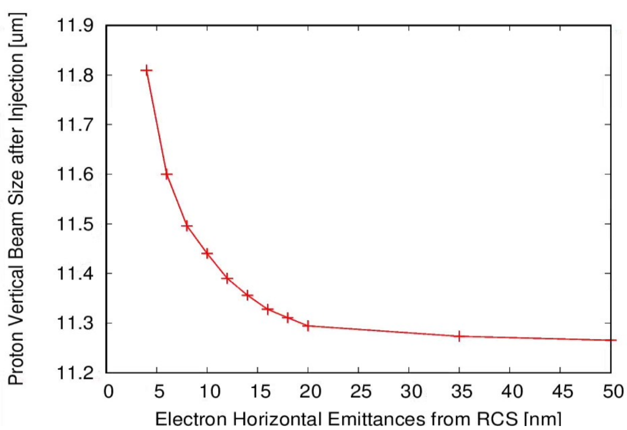


Figure 4: Proton vertical beam size as function of electron injection horizontal emittance for the collision mode with 5 GeV electrons and 100 GeV protons.

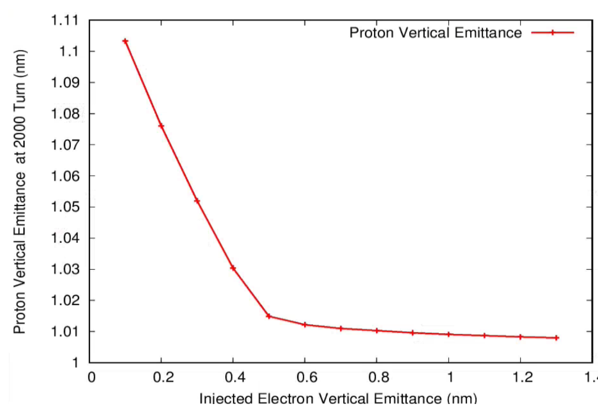


Figure 6: Proton vertical beam size as a function of electron vertical injection emittance for the collision mode between 10 GeV electrons and 275 GeV protons.

## VERTICAL EMITTANCE MISMATCH

The vertical emittance of electrons injected from the RCS is negligible compared to that of the ESR. The ESR design vertical emittances are 1.8 nm, 1.1 nm, and 2 nm for 5 GeV, 10 GeV, and 18 GeV electron beams, respectively. In our simulation study, we scan the incoming RCS electron vertical emittance from 0.1 nm to 2 nm to assess the impact on proton beam stability.

As an example, Figure 5 shows the evolution of the proton vertical beam size for the collision mode between 10 GeV electrons and 275 GeV protons. The injected electron vertical emittance is scanned from 1.3 nm down to 0.1 nm in steps of 0.1 nm. From the results, a significant increase in the proton vertical beam size occurs when the injected electron vertical emittance is smaller than 0.5 nm.

Figure 6 shows the proton vertical emittance at turn 10,000 after injection as a function of the injected electron vertical emittance. To limit the proton vertical emittance increase to less than 1% per injection, the injected electron vertical emittance must be greater than 0.8 nm. From the perspective of beam-beam interaction, injected vertical emittances larger than the ESR design values are acceptable.

For the collision mode between 18 GeV electrons and 275 GeV protons, the electron vertical injection emittances should be larger than 0.2 nm, due to the relatively small proton beam-beam parameter. Similarly, for the collision mode between 5 GeV electrons and 100 GeV protons, injected vertical emittances greater than 0.5 nm are acceptable.

## SUMMARY

In this article, we performed strong–strong beam-beam simulations to study the impact and tolerances of electron injection emittance mismatch from the RCS to the ESR. Our results show that longitudinal emittance mismatch has a negligible effect on proton emittance growth. To limit the proton vertical emittance increase to less than 1% per injection, the injected electron horizontal emittance should be greater than 15 nm, and the vertical emittance should be greater than 0.8 nm for the most critical collision modes.

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