Poster ID :61The 2025 International Workshop on the High Energy Circular Electron Positron Collider (CEPC2025), GuangZhou, China, Nov 5-10, 2025

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SAD-Based Particle Tracking Simulation of Injection Efficiency and Beam Loss in SuperKEKB LER

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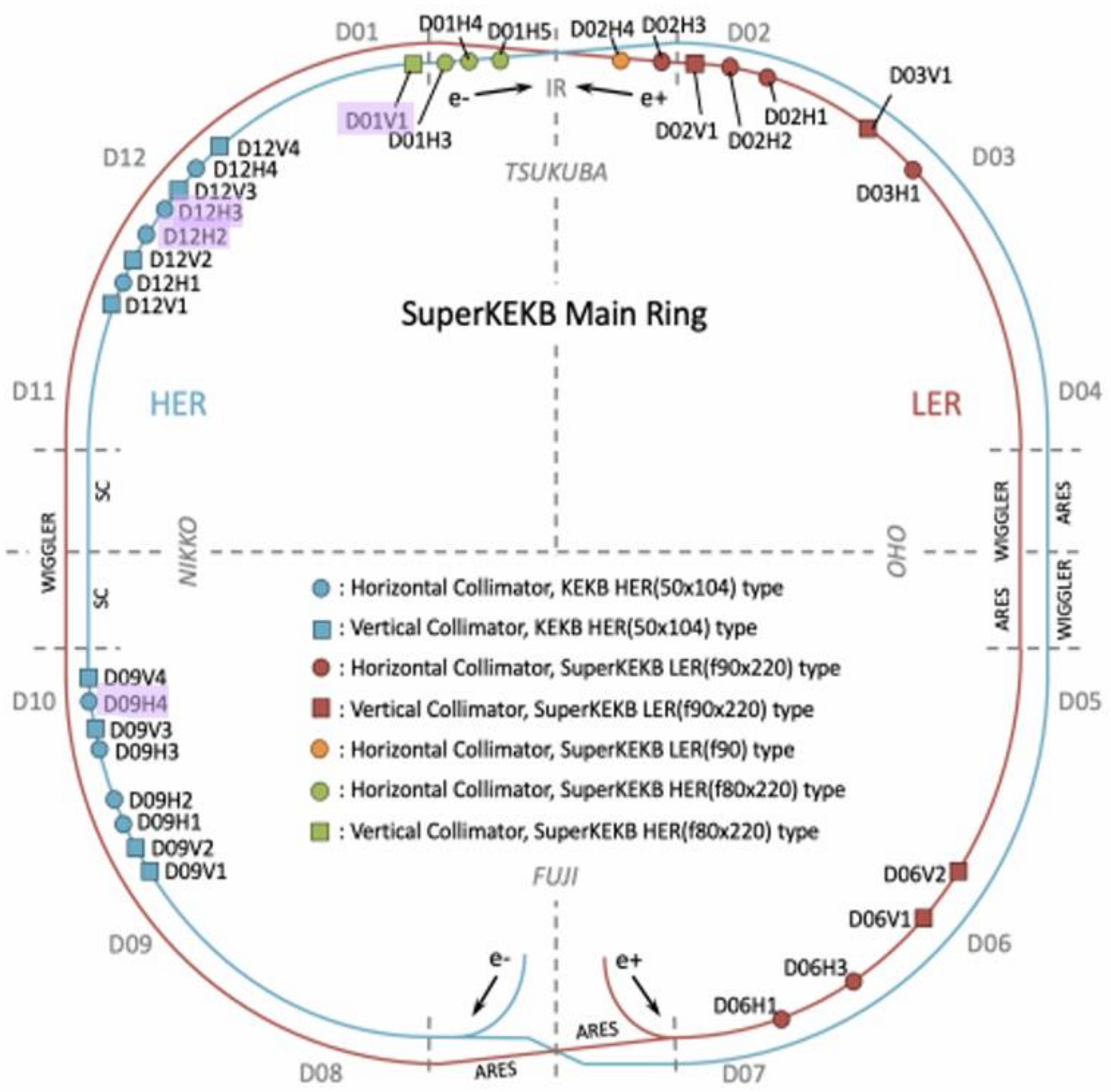
Abstract

This study employs the SAD program to perform particle tracking simulations of the multi-turn injection process in the SuperKEKB Low-Energy Ring (LER). By tracking large numbers of particles, we quantitatively analyze the beam loss distribution and identify the primary sources of particle loss during injection. The results provide a detailed understanding of the factors limiting the injection efficiency and offer insights for optimizing the injection parameters to mitigate beam loss.

Introduction

Particle colliders, such as SuperKEKB, push the frontiers of high-energy physics by pursuing unprecedented luminosities. This endeavor critically depends on the efficient and continuous injection of particle beams to replenish those lost due to collisions and other effects. In this study, we employ the SAD (Strategic Accelerator Design) program to perform high-fidelity, multi-turn particle tracking simulations of the injection process into the SuperKEKB LER. The primary objectives are to quantitatively analyze the beam loss distribution around the ring and pinpoint the key factors limiting the injection efficiency.



The SuperKEKB Main Ring

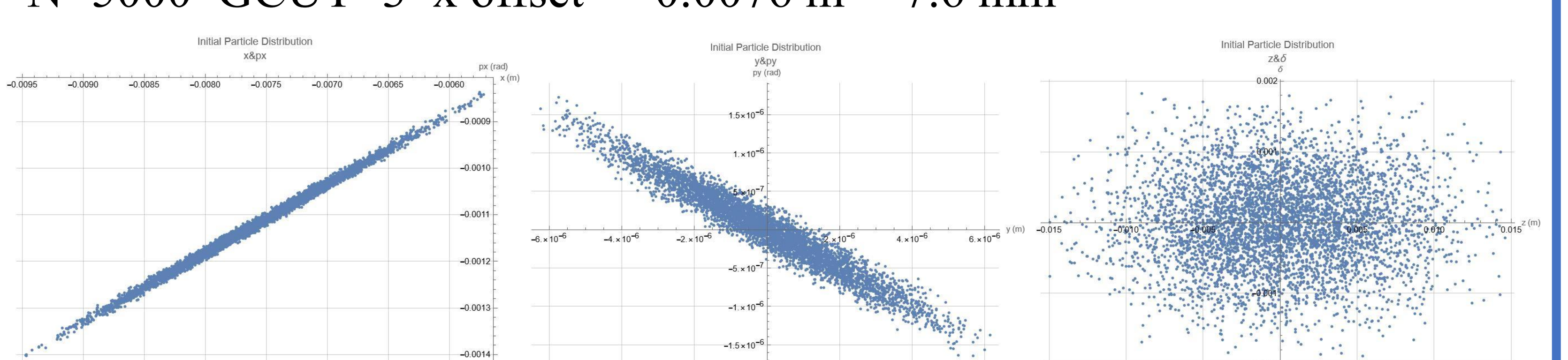
Simulation Setup

- To accurately simulate beam loss and particle tracking in the SuperKEKB LER, a detailed aperture model is implemented in SAD, defining collimator aperture.

```
APERT  AQC1LC  =(AX =.01 AY =.0135 DY =.0015 )
       AQC1LO  =(AX =.013     AY =.0135 DY =.0015 )
       AQC2LC  =(AX =.035     AY =.035  DY =.0015 )
       AQC2LO  =(AX =.035     AY =.035  DY =.0015 )
       PMD06H1 =(AX =1    AY =1 )
       FPMD06H2=(AX =1    AY =1 )
       PMD06H3 =(DX1 =.00992  DX2 =-.01015  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       FPMD06H4=(DX1 =.00996  DX2 =-.00994  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       PMD06V1 =(DX1 =.05     DX2 =-.05     DY1 =.00246  DY2 =-.00222  AX =1    AY =1 )
       PMD06V2 =(DX1 =.05     DX2 =-.05     DY1 =.00209  DY2 =-.00328  AX =1    AY =1 )
       PMD03H1 =(DX1 =.00997  DX2 =-.01003  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       FPMD03H2=(AX =1    AY =1 )
       PMD03V1 =(AX =1    AY =1 )
       FPMD03V2=(AX =1    AY =1 )
       PMD02H1 =(DX1 =.00788  DX2 =-.00790  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       PMD02H2 =(DX1 =.01037  DX2 =-.01081  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       PMD02V1 =(DX1 =.05     DX2 =-.05     DY1 =.00063  DY2 =-.00147  AX =1    AY =1 )
       PMD02H3 =(DX1 =.01481  DX2 =-.01474  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       PMD02H4 =(DX1 =.00745  DX2 =-.00742  DY1 =.05      DY2 =-.05      AX =1    AY =1 )
       AQC2RO  =(AX =.035     AY =.035  DY =.001 )
       AQC2RC  =(AX =.035     AY =.035  DY =.001 )
       AQC1RO  =(AX =.013     AY =.0135 DY =.001 )
       AQC1RC  =(AX =.01 AY =.0135 DY =.001 )
```

Collimator Aperture

- The number of initial particles is 5,000, and the particle distribution adopts Gaussian distribution (with a value of three times σ).
  N=5000 GCUT=3 x offset = -0.0076 m= -7.6 mm

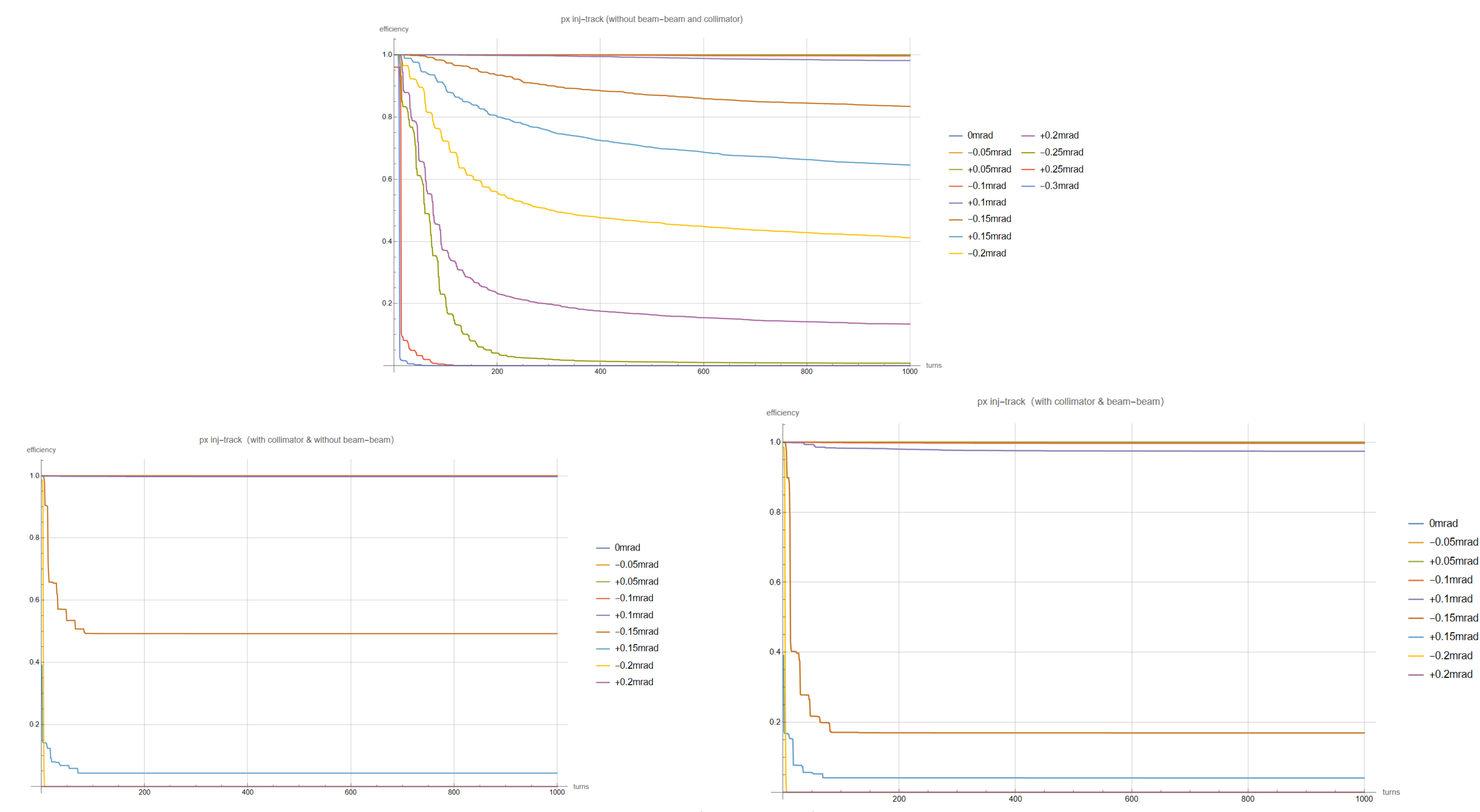


Initial Particle Distribution

Injection simulation of LER

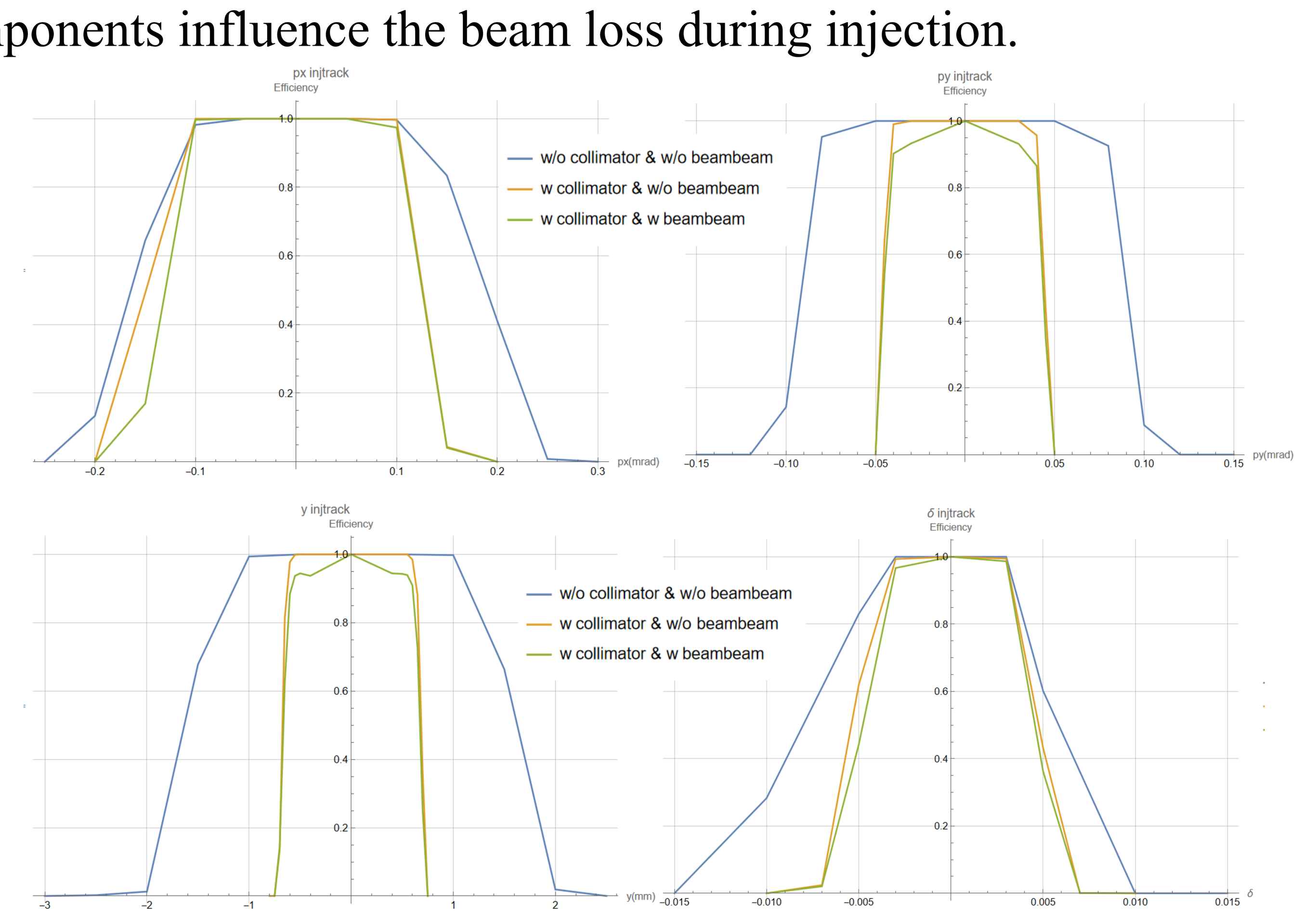
Track 5000 particles 1000 turns

The comparative analysis reveals that collimators significantly accelerate initial particle loss by defining strict machine acceptance, while the inclusion of beam-beam interactions further exacerbates particle loss, particularly for beams with larger horizontal emittance.



Px Inj-track

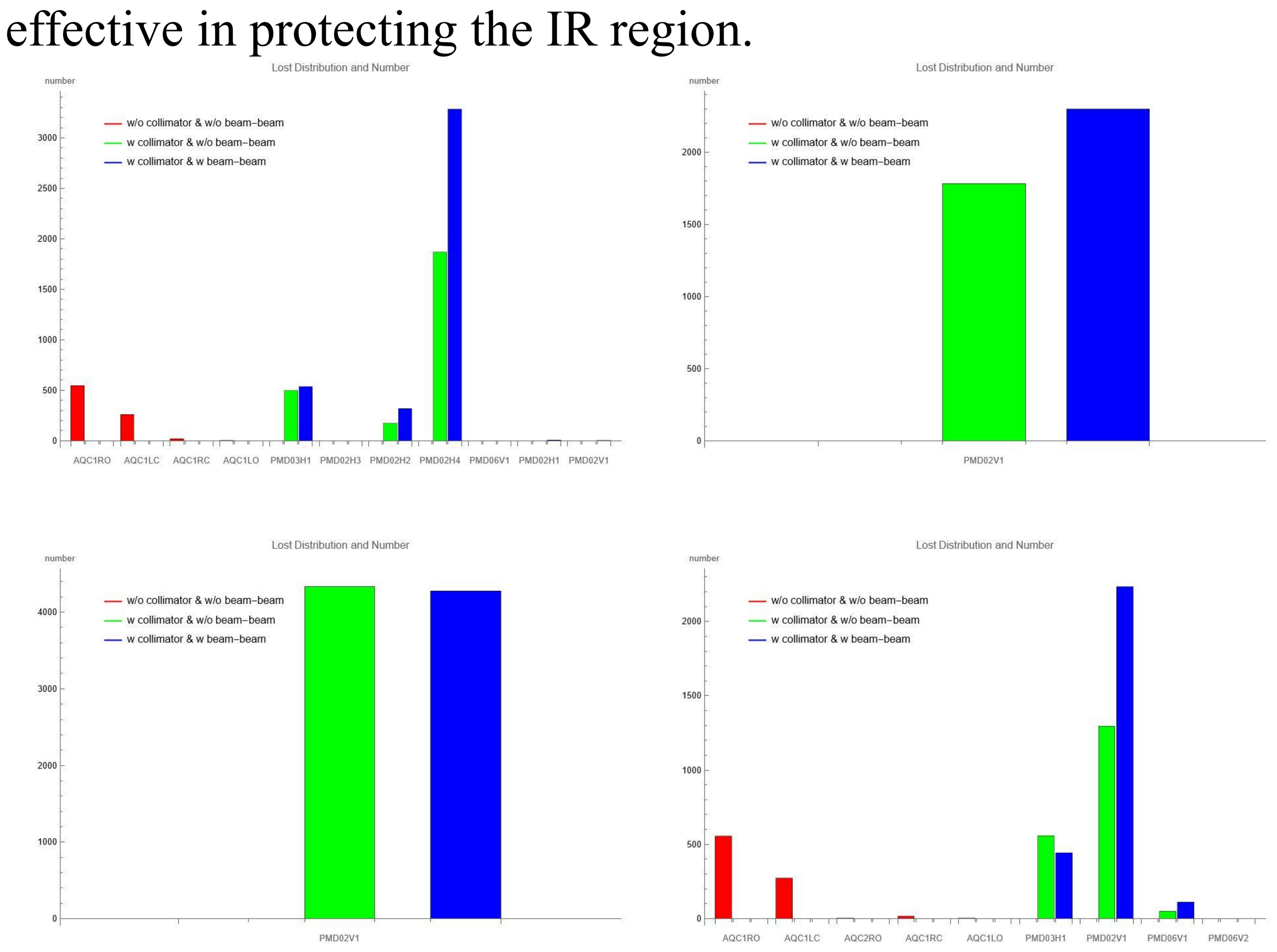
For all parameters (p_x, p_y, y, δ), efficiency peaks at *"optimal" values* (e.g., p_x=0, p_y=0, y=0, δ=0) and decreases with deviation. Collimators and beam-beam interactions (seen in *green*/*orange* curves) narrow the "range of high efficiency" — this reflects how these components influence the beam loss during injection.



Integrated with Collimator & Beam-Beam Comparison

Beam Loss Distribution

With collimators in place, the majority of beam loss occurs at the PMD02V1 and PMD02H4; without collimators, the majority of beam loss occurs at the AQC1RO and AQC1LC. We can see the collimators are effective in protecting the IR region.



Beam Loss Distribution & Number