SUPERKEKB BEAM TRANSPORT TRACKING AND DYNAMIC APERTURE COMPARISON AS AN APPROXIMATION FOR INJECTION EFFICIENCY*

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Abstract

A new Energy Compression System (ECS), consisting of four RF cavities, was installed in the SuperKEKB electron transfer line (BTe) during the 2025 summer shutdown. Optimising BTe performance using full multi-turn injection simulations is computationally demanding. To accelerate this process, we compare the beam tracked through BTe, including the ECS, to the dynamic aperture of the High-Energy Ring lattice obtained from Xsuite simulations. The SAD lattices were converted to Xsuite and benchmarked to ensure consistency between the two frameworks. A fast, first order-estimate of the injection efficiency is obtained by comparing the action amplitudes of particles tracked through BTe with computed main ring dynamic apertures and septum positions. The injection efficiency is then optimised by varying ECS parameters. Radiation effects and a tapering can be optionally included. Different injection schemes are supported within the same framework. Together, these elements enable rapid optimisation of the ECS parameters with significantly reduced computational cost.

INTRODUCTION

SuperKEKB is an asymmetric, double ring electron-positron collider located at KEK, Japan [1, 2]. Electrons at 7 GeV are stored in the High Energy Ring (HER) for collision with 4 GeV positrons stored in the Low Energy Ring (LER). SuperKEKB holds the record for instantaneous luminosity at $5.24 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, achieved in March 2026 [3]. To achieve high luminosity, SuperKEKB employs the nano-beam collision scheme [4], the crab-waist scheme [5] with a large full crossing angle of 83 mrad, and high operational beam currents exceeding 1 A. To facilitate such high current operation, top up injection [6] is required with high injection frequency and efficiency.

Beam generation and preparation are provided by KEK's injector complex [7, 8]. Positrons are injected into the LER from the beam transport line BTp while electrons are injected into the HER from the beam transport line BTe. These transport lines feature complex geometries, descending by ~7 m over their 500 m extent.

BTe Upgrade

In the summer of 2025, the BTe was upgraded to include a new Energy Compression System (ECS), which was first implemented during the 2025c operation period. The ECS is composed of four Radio Frequency (RF) cavities operating with a single frequency, voltage and lag. The RF frequency is nominally 2.856 GHz with a maximum voltage of 25 MV per cavity.

The ECS operates by combining RF cavities with dispersive optics to remove correlated energy spread and rotate the longitudinal phase space, thereby minimising the energy spread σ_δ. This not only allows the transported beam to better satisfy the stringent energy acceptance and matching requirements for injection into HER but also enables maximising of both injection efficiency and beam quality.

MODELLING KEK'S BT TRANSPORT LINES

The design and operation of SuperKEKB's BT lines are performed using SAD (Strategic Accelerator Design) [9], a FORTRAN based tool developed at KEK since 1986. For the studies presented here it was chosen to use Xsuite [10], a set of python packages for modelling particle accelerators developed at CERN since 2021. Following recent successful modelling of the LER and HER with Xsuite [11] it was a natural choice to expand to modelling the BT lines with Xsuite as well. Furthermore, the same strong synergies between SuperKEKB studies and Future Circular Lepton Collider (FCC-ee) [12, 13] studies extend to their respective transport lines and allows for crucial benchmarking of these tools on existing lepton colliders. The conversion of the BT lattices from SAD to Xsuite was performed using the SAD to Xsuite converter (SAD2XS) [14].

Apertures were not included in the SAD models of the BT lines but have been incorporated for all elements in the Xsuite model, with the following specifications: 47 mm diameter round cross-section at drifts and quadrupoles and 30 mm height and 50 mm width rectangular cross-section at dipoles.

Benchmarking

Prior to performing any ECS studies, the Xsuite lattice models were benchmarked against the SAD models. The first aspects benchmarked were the orbits and linear optics, computed in both 4D and 6D configurations. Excel-

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lent agreement (up to numerical precision) was observed across the board, an example is shown in Fig. 1. Following the benchmarking of optics calculations, particle tracking was performed. To facilitate comparison, Gaussian bunches were initialised at the start of the transport line and tracked to the injection point, where they were compared. Excellent agreement was observed in the tracked distributions, as demonstrated in Fig. 2. This further indicates that lattice non-linearities are also consistent between the two models.

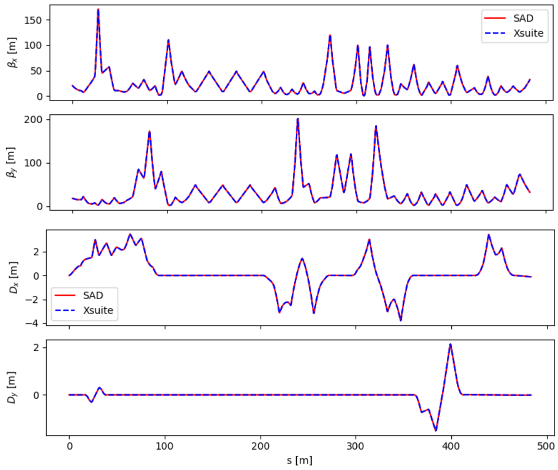

Figure 1: Comparison of horizontal and vertical Twiss beta and dispersion functions between SAD and Xsuite for BTe.

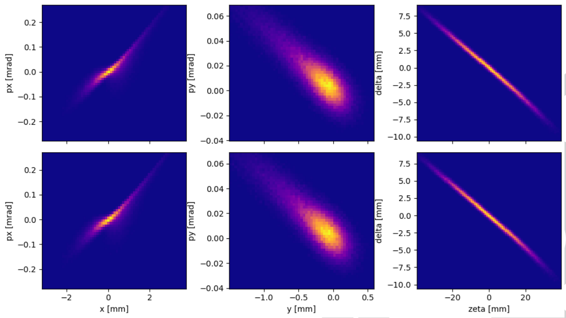

Figure 2: Comparison of horizontal, vertical and longitudinal particle distributions between SAD (top) and Xsuite (bottom) for Gaussian input beams tracked through BTe.

INJECTION EFFICIENCY ESTIMATION METHODOLOGY

Using the lattice models of the BT lines along with the LER and HER, full injection simulations can be performed with various ECS settings. However, such simulations are computationally demanding (taking several hours, to days), as they require tracking thousands of turns in the main rings, which consist of thousands of magnetic elements and apertures [15].

For ECS optimisation, the optics of the main rings are assumed to remain constant. This allows particle tracking to be performed solely through the BT lines, which contain fewer elements and involve only a single pass, making the process faster (a few minutes) and more computationally efficient.

To approximate an injection efficiency from the tracked particles, a realistic distribution from the LINAC [16] is transported through the transfer line and projected onto the ring's dynamic aperture (DA), and septum acceptance. These projections are performed using the known reference frame transformations between the BTs and ring injection points. By counting the number of particles within all acceptances, a survival fraction, and thus an approximate injection efficiency, can be determined

Dynamic Aperture Computation The DA of the main rings is a complex 3D object in action-amplitude space. To map this object in full 3D with high granularity is unfeasible due to the large number of required particle turns. Instead, three representative slices are computed along the XY, ZX, and ZY planes.

Each plane is computed by tracking grids of particles with different action amplitudes, starting at the injection point, through the Xsuite HER lattice for four phases (0, $\pi/4$, $\pi/2$, and $3\pi/4$). Particles are tracked for 6000 turns with mean synchrotron radiation, corresponding to approximately three longitudinal damping times. As this DA corresponds to an ideal machine without errors or imperfections, we adopt a conservative criterion: particles must survive all turns for all phases to be considered within the DA.

The action amplitude A_a for each plane $a = x, y, z$ is defined as

$$A_a = \sqrt{\frac{2 \cdot J_a}{\varepsilon_a}}, \tag{1}$$

where J_a is the particle action and ε_a is the corresponding emittance. The emittance values used for the results presented here are obtained from tracking with quantum synchrotron radiation. This provides a normalised measure of the particle's motion relative to the beam size.

This process was repeated for various different optics configurations. When using squeezed optics, it is noted that the acceptance in the vertical plane is stringent.

Septum Aperture Particle losses on the septum represent a key limitation for injection efficiency. Operational experience shows that radiation monitors detect increased losses when the BT lines are not optimally tuned.

Due to the septum's complex geometry, its aperture is not included in the lattice model. Instead, a stand alone check is performed on the tracked particle distributions; any particle that would intercept the septum is deemed lost.

Injection Scheme During the 2025c operation period, SuperKEKB demonstrated operation with electron synchrotron injection in addition to the previous betatron injection mode [17]. This model was designed to provide flexibility for studying both injection approaches, as well as potential hybrid schemes. As optimisation of the ECS system was carried out during the synchrotron injection tests the presented ECS values are based on synchrotron injection optics in the HER.

Model Assumptions The following key assumptions are made:

- The DA is unaffected by the injection orbit bump.
- The injection orbit bump is correctly tuned to match the target δ and the ring dispersion values.
- The septum position is known to a precision of 100 µm.
- All ECS RF cavities share the same power converter settings.
- The injection point markers in the BT lattice models and main ring lattice models are at the same longitudinal position (at the edge of the septum).
- Injection angles and offsets are purely horizontal.

An example set of checks, showing the LINAC distribution tracked to the injection point, overlaid on the XY, ZX, and ZY dynamic apertures, and checked against the septum cut is shown in Fig. 3. This example considers the HER with $\beta^*_{x,y}$ = (200 mm, 8 mm) synchrotron injection optics with a 0.6 % energy offset from BTe and an optimised ECS. Losses are primarily observed in the vertical plane A_y. Injection efficiencies of ~70 % showed good agreement with full tracking simulations and measurements [18].

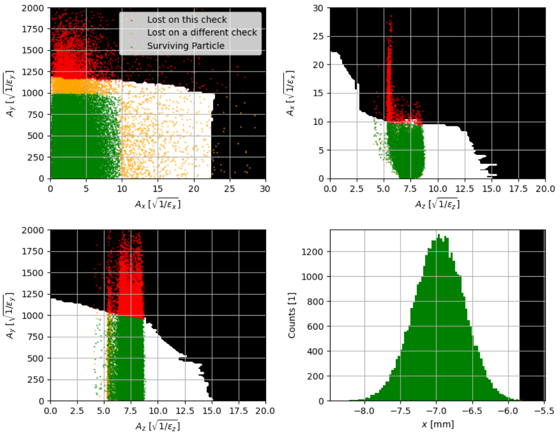

Figure 3: Dynamic aperture checks for the XY, ZX and ZY planes as well as septum (bottom right) checks for an example injection efficiency estimation. Particles lost on a check are marked in red, particles lost on a different check are marked in orange, and surviving particles satisfying all four requirements are marked in green.

ECS OPTIMISATION

Optimisation of the BTe ECS was carried out in two stages. In the first stage, only the RF lag was optimised and the RF voltage was kept at 18 MV. In the second stage, both the cavity lag and the RF voltage were optimised through a two-dimensional study. It is noted here that there is a clear increase in injection efficiency, across several optics and injection configurations, when the ECS is turned on. In both cases, the optimisation target was to maximise the surviving fraction of particles within the DA and septum acceptance checks.

The lag of 180 deg corresponds to the zero crossing phase in Xsuite. The cavity lag was optimised using Brent's algorithm [19] as implemented in SciPy's [20] “‘optimize.minimize_scalar”’ function. The optimisation steps are presented in Fig. 4 with an optimal lag just below 180 deg.

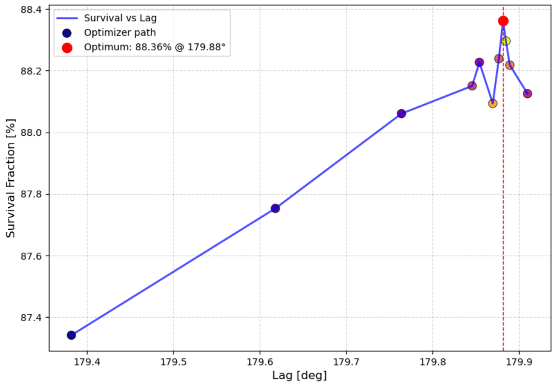

Figure 4: Optimisation of ECS RF cavity lag with survival fraction estimated from tracking.

The 2D optimisation was performed using the stochastic differential evolution method, in particular the algorithm of Storn and Price [21] as implemented in SciPy's “‘optimize.differential_evolution”’ function. The optimisation steps are presented in Fig. 5 where an optimal lag just above 180 deg is observed, with no observed dependence on voltage.

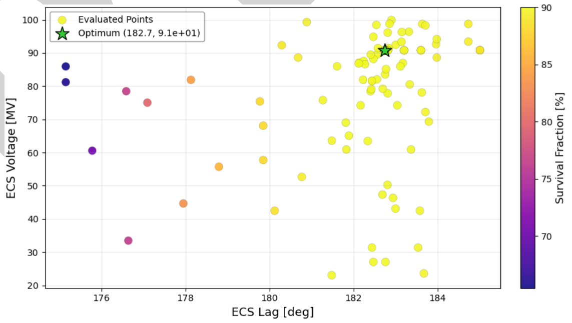

Figure 5: Optimisation of ECS RF cavity lag and RF voltage with survival fraction estimated from tracking.

CONCLUSIONS AND OUTLOOK

Xsuite models of KEK's BTe and BTp lines have been converted and benchmarked. The newly installed Energy Compression System has been optimised to maximise injection efficiency. This approach, relying on dynamic aperture, septum position, and particle tracking in BTe, is far more computationally efficient than full multi-turn simulations, and the predicted optimal values agree with control room observations and full tracking results.

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