MODELLING OPTICS AND BEAM-BEAM EFFECTS OF SuperKEKB WITH Xsuite[*,†]

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Abstract

SuperKEKB, located at KEK, is a second generation B-factory, providing beam to the Belle-II experiment. Optics design and simulation of SuperKEKB were previously performed using the optics code SAD, developed at KEK. In this paper, we present a new model of SuperKEKB using the tracking code Xsuite, developed at CERN. An alternative strategy for modelling the interaction region, with controllable final focus quadrupoles, has been adopted. Optics comparisons between the new Xsuite model and existing SAD model, as well as tracking simulations including beam-beam modelling are presented.

INTRODUCTION

SuperKEKB is an electron-positron collider located at KEK, Japan [1, 2]. A second generation B factory, SuperKEKB operates with a 10.58 GeV centre-of-mass energy targetting the $\Upsilon\ (4s)$ meson resonance. The BELLE-II experiment uses these collisions to study the physics of B mesons [3]. SuperKEKB holds the record for instantaneous luminosity at $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ achieved in December 2024 [4].

SuperKEKB is an asymmetric, double ring collider. The High Energy Ring (HER) stores 7 GeV electrons for collision with 4 GeV positrons stored in the Low Energy Ring (LER). To achieve high luminosity, high current operation (> 1 A) the nano-beam collision scheme [5], and the crab-waist scheme with a large full crossing angle of 83 mrad are employed.

The design and operation of SuperKEKB is based on SAD (Strategic Accelerator Design) [6]. SAD is a FORTRAN based computer program for accelerator design, developed at KEK since 1986 and used at SuperKEKB, J-PARC, ATF and more.

Xsuite

Xsuite, developed at CERN since 2021, is a set of python packages for modelling particle accelerators [7]. The different packages allow multi-physics simulations, from lattice tracking to beam-beam simulation and more. Xsuite has been benchmarked at CERN accelerators including tests during Machine Development periods at the LHC [8].

Motivation

The wide range of tools available across the Xsuite packages allows for a wide range of studies at SuperKEKB. An Xsuite model of SuperKEKB also offers a benchmark against SAD simulations. As upgrades are studied, Xsuite can be an alternative tool for BELLE-II and KEK collaborators.

Furthermore, there are strong synergies between SuperKEKB studies and Future Circular Lepton Collider (FCC-ee) studies. The current FCC-ee design also employs the nano-beam scheme, crab-waist scheme and a large crossing angle of 30 mrad [9–11]. FCC-ee's Global Hybrid Correction (GHC) optics [12] are also developed using SAD. For FCC-ee studies, it is crucial to benchmark the CERN tools at existing lepton collider facilities, and SuperKEKB offers an excellent opportunity for that.

LATTICE CONVERSION PROCESS

The conversion of the SuperKEKB lattices from SAD to Xsuite is non-trivial. For the initial stage of the conversion process, a SAD to Xsuite converter (SAD2XS) is in active development [13]. The SAD2XS converter has been successfully demonstrated on FCC-ee and J-PARC Main Ring lattices. Due to specific challenges of the SuperKEKB lattices a multi-stage conversion process is required.

The key challenges relate to the import of the Interaction Region (IR) and differences in fringe modelling between SAD and Xsuite [14]. The IRs of the SAD lattices are represented by alternating solenoid and multipole slices extending ±4 m from the Interaction Point in the beam-line reference frame. Strengths are derived from a 3D model of the IR [15] using Ansys [16]. The fringes account for the other discrepancies in the optics outside of the IR.

Global Transformations

Global transformations are also required to convert the lattices to Xsuite. Both LER and HER lattices were natively stored in SAD as clockwise positron rings. In the Xsuite models, the element orders, bend angles and species matches the order of the real machines. This process was complicated by differences in reference systems between SAD and Xsuite; both codes use right handed coordinate systems, SAD choosing to fix s along and x outwards, while Xsuite fixes s along and y upwards.

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Optics Matching Approach

To account for modelling differences the optics must be rematched. Re-matching is performed using the Xtrack module. It is not possible to match all Twiss parameters at all s positions, so key optical properties are selected to be maintained during re-matching.

Re-matching begins with a periodic match of the arc cell. All other sections (arc mid cells, straight sections) are then matched to these boundaries. During matching, other key parameters are also maintained, such as sextupole pair phase advances and IP parameters.

Bend magnets are not re-matched to avoid altering the geometry of the ring. Wiggler magnets are rematched to correct the energy loss, and therefore emittances, in the rings. The target values for matching are extracted from a twiss of the target lattice in SAD. Strength changes of magnets are minimised.

Lattice Models

Two different approaches to modelling the optics of SuperKEKB are in development.

One approach imports the full multipole expanded IR from SAD. Significant restructuring of the IR elements is required due to code differences. A survey showing the layout around the IR in this model is shown in Fig. 1.

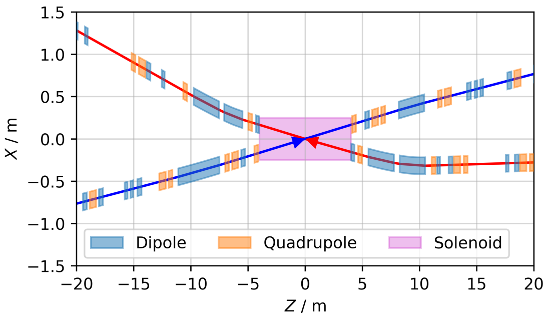

Figure 1: Survey of the SuperKEKB IR showing dipole, quadrupole and solenoid elements. The LER (e^+) beam-line is shown in red and the HER (e^-) is shown in blue.

The alternative approach is to reconstruct the IR with thick Final Focus Quadrupoles (FFQs). This approach enables the creation of a no-solenoid lattice. Then, solenoid components can be overlayed to produce a solenoid optics, while maintaining direct access to the strengths, rotations and offsets of the FFQs. This makes certain studies, such as offset studies, more accessible.

To achieve these new optics, the lattice is imported using SAD2XS. The IR elements are then replaced with thick FFQs and the lattice is rematched (without skew quadrupoles or IR bends). The thick FFQ elements are then sliced ± 4 m from the IP and replaced with solenoid elements. Reference frame transformations are applied such that, in this model, the solenoid is represented in its reference frame. The FFQs are then represented by offset and rotated multipoles within the solenoid elements. The solenoid profile is from measured data at BELLE-II [17].

OPTICS COMPARISONS

Optics benchmarks between SAD and Xsuite have been performed across both models. Some optics discrepancies are observed due to the re-matching process. For comparison, the import process including the import of the SAD IR multipoles is presented.

Solenoid

The solenoid is a defining aspect of the SuperKEKB lattice models and the performance of the real machine. Furthermore, as the structure of the elements defining this region differ between SAD and XSuite, the optics in the solenoid is being strictly benchmarked. A key parameter in the benchmarking process is the orbit. Excellent agreement between SAD and Xsuite has been observed. A comparison for the LER is presented in Fig. 2.

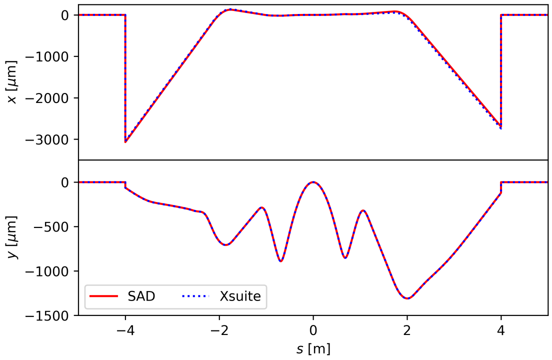

Figure 2: Comparison of the orbit in the solenoid region for the LER. Excellent agreement is seen between SAD and Xsuite in both the horizontal and vertical planes.

Linear Optics

The re-matching process focusses on the linear optics functions of the lattice. As such, there is overall excellent agreement. The parameters matched include: beta function, alpha functions, dispersions and phases. These aspects are not always equally weighted, for example the optical functions at the IPs have significantly stricter tolerances. A comparison of some key linear optics parameters is shown in Fig. 3. The linear optics are seen to agree in both ‘4d’ and ‘6d’ tracking modes. To achieve ‘6d’ tracking additional zeta shift elements are required. This is due to the difference in modelling of RF cavities between SAD and Xsuite; SAD uses harmonic cavities and a frequency shift while Xsuite cavities use frequencies and lags. The use of zeta shifts enables the lags to be set to 180 degrees in the nominal case without radiation.

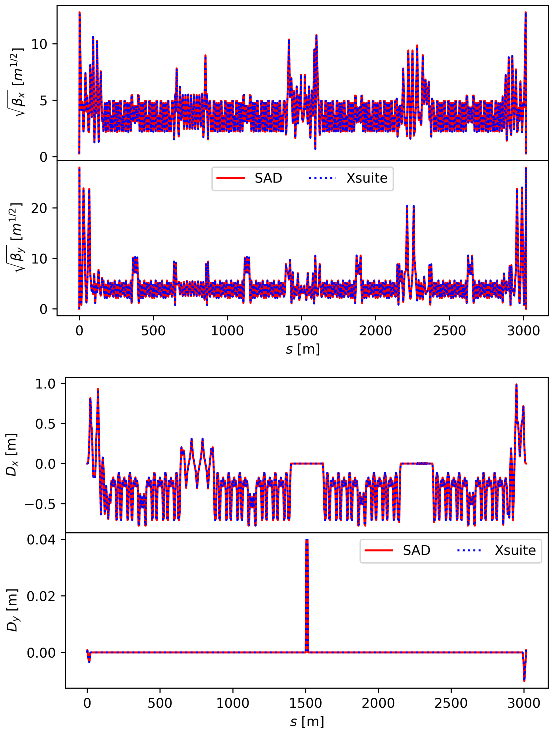

Figure 3: Comparison of beta functions and horizontal dispersions along the full ring for the LER. Excellent agreement is seen between SAD and Xsuite.

Non-Linear Optics

Non-linear behaviour is also under study. IR multipoles contribute significantly to the chromatic properties of the lattices. In the models where the IR is replaced, the chromaticity of the machine must be rematched by scaling all focussing and defocussing sextupoles. When importing the IR multipoles from SAD, the chromaticity has not been rematched as there is good natural agreement.

The chromatic functions for this import method for the LER are shown in Fig. 4. Good agreement is observed. The minor discrepancies may arise due to the optics re-matching process; there are slightly different beta functions at the sextupoles resulting in slightly different chromatic properties.

BEAM-BEAM MODELLING

Beam-beam installation is enabled by the Xfields module. Beam-beam modelling has been tested in weak-strong (WS) configuration, though Strong-Strong and Particle In Cell methods are also available.

To benchmark the beam-beam elements, the beam-beam tune shift is studied. The shift is computed using a Twiss with and without a scaled down beam-beam element. This is then compared with the analytic formula for the beam-beam parameter of a flat beam with a large crossing angle [18],

$$\Delta\nu_{y,bb} \sim \xi_{bb}^{(\pm)} = \frac{N^{(\mp)} r_e}{2\pi\gamma^{\pm}} \frac{\beta_y^*}{\sigma_y^* \sigma_x^* \sqrt{1+\theta_P^2}} \qquad (1)$$

and strong agreement has been found, shown in Table 1.

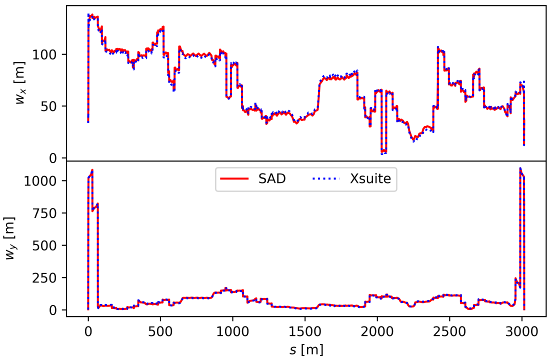

Figure 4: Comparison of the chromatic functions along the full ring for the LER. Very good agreement is seen between SAD and Xsuite. In this lattice, the sextupole strengths have not been rematched.

Table 1: Comparison of Xsuite measured beam-beam tune shifts with those calculated using Eq. (1). A linear rescaling of factor 100 is applied to the bunch intensity for the Twiss.

Parameter	Unit	LER		HER	
N. Hor. Emit.	μm rad	31.4		62.9	
N. Ver. Emit.	μm rad	0.362		0.633	
RMS Bunch Len.	mm	4.60		5.10	
Bunch Intensity	10^{10}	3.69		3.07	
Tune Shift (Eq.)	10^{-3}	3.12	38.5	1.97	29.3
Tune Shift (Tw.)	10^{-3}	3.13	39.6	1.96	29.4
Rel. Difference	%	0.18	2.87	-0.31	0.35

Multi-turn tracking with beam-beam is also possible, and studies are underway. Studies including the interplay with other effects are also underway, including radiation and space-charge.

CONCLUSION

Working optics models of the SuperKEKB LER and HER have been achieved in Xsuite opening the possibility for many novel combined effect studies. Studies are already underway for the SuperKEKB beam backgrounds [19].

Benchmarks are promising, but further work is ongoing. Some differences are expected to remain due to the re-matching process but the lattices appear performant for studies.

The challenges of the conversion process have resulted in the development of tools that have enabled the conversion of other lattices, such as the J-PARC Main Ring.

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