

SIMULATED COMMISSIONING AND LATTICE ROBUSTNESS STUDIES FOR BESSY III

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Abstract

BESSY III will be a fourth-generation synchrotron light source that aims to deliver diffraction-limited, extremely brilliant soft X-rays, with the goal of becoming a key instrument for discoveries in materials and energy research. During the current design phase, extensive simulation studies are being performed to evaluate and improve the robustness and reliability of the candidate storage ring lattice.

The robustness analysis allows a direct comparison of the expected lattice performance and sensitivity with that of other fourth-generation facilities under realistic error conditions. Building on this, the simulated commissioning process aims to recover optimal machine performance by mitigating the impact of imperfections originating from magnet misalignments and magnetic field errors. This work quantifies the achievable performance of the machine by simulating the full commissioning sequence, including beam-transmission optimisation, sextupole ramp-up, RF-cavity correction, beam-based alignment (BBA), orbit correction, and LOCO-based optics correction. After carrying out the lattice correction, the off-axis injection possibility and the Touschek lifetime are evaluated.

Although the preliminary results provide essential feedback for defining the commissioning strategy and enhancing the overall resilience of the BESSY III lattice design, they do not yet include the complete error set.

INTRODUCTION

BESSY III will be a fourth-generation light source (4GLS) storage ring. It is currently being designed at Helmholtz-Zentrum Berlin. Like other ultralow-emittance rings, its strong focusing optics make it inherently sensitive to magnetic misalignments and field errors, making a detailed commissioning simulation essential during the design phase. This work builds on methods developed for similar facilities [1–4], extending them to the specific BESSY III lattice and error model.

The design energy of the storage ring is 2.5 GeV, with a target emittance of 98 pm-rad. The ring consists of 16 periodic arcs and an injection straight section. It contains 192 BPMs, 144 units of each vertical and horizontal corrector magnets, and skew quadrupole components added to selected sextupoles for coupling correction. The linear optics and the lattice layout for one of the 16 identical arcs of the BESSY III lattice can be seen in Fig. 1.

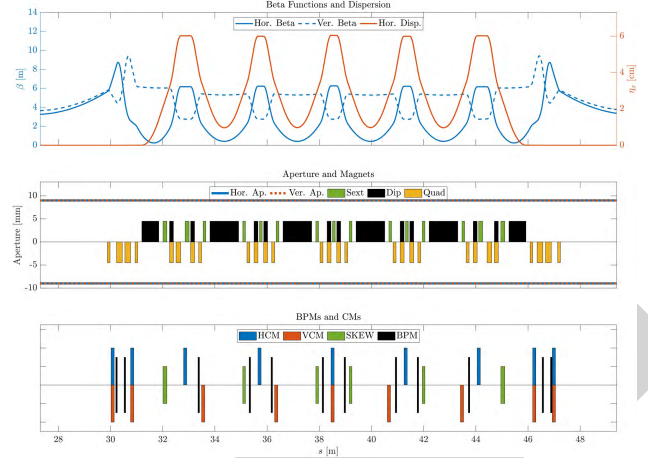


Figure 1: Optics and lattice layout of a BESSY III arc.

ERROR MODEL

The tolerance set employed in this study is divided into four groups: magnet errors, BPM diagnostic errors, RF cavity errors, and injection errors. Key RMS values are listed in Tables 1, 2, and 3.

Table 1: Magnet Errors

Error Type	RMS Value
Offset (x, y, z)	30 μm
Roll for long bends	180 μrad (z), 60 μrad (x,y)
Roll for short magnets	180 μrad (z), 400 μrad (x,y)
Calibration (steering magnets)	5%
Calibration (all other magnets)	0.1%

Table 2: BPM and RF Cavity Errors

Error Type	RMS Value	Error Type	RMS Value
BPM offset	500 μm	BPM noise (CO)	1 μm
BPM roll	180 μrad	RF frequency error	100 Hz
BPM calibration	5%	RF voltage error	5 kV
BPM noise (TbT)	10 μm	RF phase error	90°

Table 3: Injection Errors

Coordinate Units	x μm	x' μrad	y μm	y' μrad	δp %	Phase °
Systematic	100	10	100	10	1	0
Random	0	10	0	0	0.1	0.1

All the errors in this study have been truncated at 2σ . Girder and support structure errors are not included because the final girder layout has not been decided yet. Therefore, misalignment errors for both magnets and BPMs are referred

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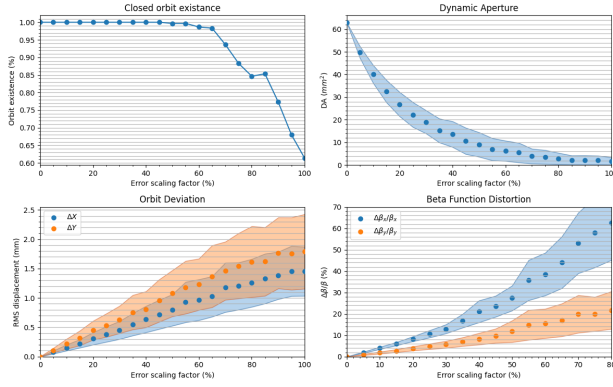


Figure 2: Close orbit existence, DA, RMS orbit displacement, and beta-beating for BESSY III as a function of error scale, averaged over 300 error seeds. Shaded regions represent RMS spread. Simulations include physical apertures.

to the absolute reference frame of the ring in the tunnel. BPM offsets are defined as before the beam-based alignment. A relative circumference error of 10^{-6} is included. Multipole errors of the magnets are not considered in this study.

ROBUSTNESS ANALYSIS

Before any correction is applied, a robustness study characterises how the lattice performance degrades as a function of error magnitude. All error distributions are scaled uniformly from 0% to 100% of their nominal values. At each scaling level, 300 random error seeds are generated. For each one, the existence of a closed orbit is verified using the `findorbit6` function of the Accelerator Toolbox (AT) for MATLAB. If a stable orbit is found, the dynamic aperture (DA), the uncorrected orbit displacement, and the beta-beating are computed at every element in the ring.

The averaged results for 300 lattice realisations show the dynamic aperture shrinking progressively as errors increase, with the orbit becoming unstable for ~40% of seeds at full error level. The robustness results serve as a benchmark for comparison with other 4GLS facilities [1, 3, 4], and confirm that the error set adopted here represents a realistic and challenging commissioning scenario. As can be observed in Fig. 2, the DA drops to zero when the errors are at 100%, thus the only option is to inject the beam on-axis to correct the machine.

SIMULATED COMMISSIONING CHAIN

The correction chain follows a procedure that mirrors the approaches described in the commissioning studies for the Petra IV storage ring, ALS-U accumulator and storage rings, and Argonne storage ring [1–4]. A beam with transverse emittances of $[\varepsilon_x, \varepsilon_y] = [5.0, 0.5]$ nmrad (from the BESSY III booster) is injected on-axis by a dipolar kick in the injection straight, including injection errors. Elliptic physical apertures of [20, 9] mm radii are used in the injection straight, [5, 9] mm for the injection septum, and [9, 9] mm in the rest of the ring. The commissioning chain is

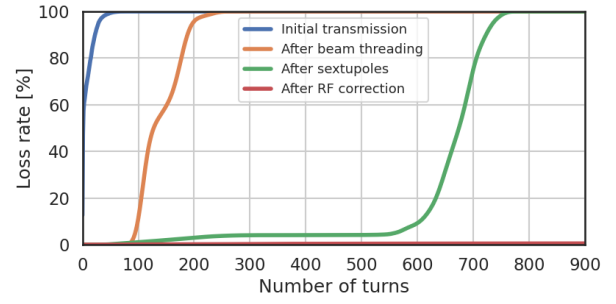


Figure 3: Mean particle loss rate for on-axis injected beams after each commissioning step until beam capture.

simulated using the Simulated Commissioning (SC) toolkit for MATLAB [5].

Initial on-axis injection: In the initial state (sextupoles and RF off), the on-axis injected particle bunch survives at least one turn in 92% of machine realisations; however, the beam is typically lost within the first few turns due to uncorrected orbit distortions and only 38% of seeds show more than 60% particle transmission after 5 turns. The particle loss rate per turn at this point can be seen in Fig. 3.

Beam threading: An iterative, feedback-based single-turn trajectory correction is applied using BPM readings. Once a full single-turn transmission is established, a beam threading procedure extends this to two turns by appending second-turn BPM readings to the first-turn reference. After the threading is performed, all machine realisations show beam survival well beyond 100 turns, limited primarily by the large natural chromaticities ($\xi_x \approx -90$, $\xi_y \approx -35$).

Sextupole ramp up: The sextupoles are then ramped to their design strengths in 10% relative steps, with trajectory feedback applied after each step. This procedure extends the beam survival to more than 500 turns and simultaneously reduces decoherence from chromaticity, which improves turn-by-turn BPM resolution.

RF correction: After the sextupoles are at design strength, the RF phase and frequency are corrected using turn-by-turn (TbT) horizontal BPM data, which reflects energy changes via dispersion. The RF phase is scanned over $\pm\pi$ in steps, and a sine fit to the mean horizontal TbT BPM variation identifies the synchronous phase. The RF frequency is then corrected similarly, using a linear fit over a ± 1 kHz range evaluated over 130 turns. Both corrections are iterated three times. Final mean errors after correction are 0.14° in phase and 5×10^{-4} in relative momentum offset.

Basic optics correction: A brief tune scan over two quadrupole families is performed to increase transmission to over 80% after 500 turns in the ~2% of realisations that still require optics adjustment. After RF correction and the tune scan, the losses for on-axis injection are well below 1% on average for two radiation damping times (see Fig. 3); the beam can be considered captured in all cases.

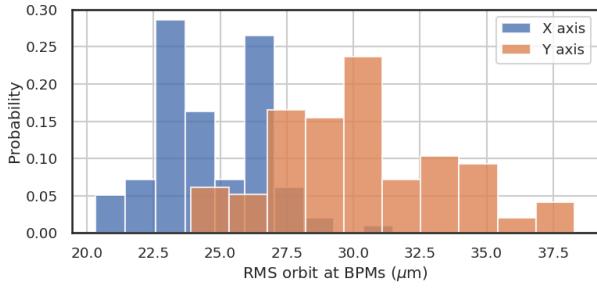


Figure 4: Orbit RMS values for 100 error seeds.

Beam-Based Alignment (BBA): Beam-based alignment measures and corrects BPM zero-position offsets with respect to the magnetic centres of nearby quadrupole or sextupole magnets. BPMs are paired to the nearest suitable magnet to minimise phase advance. The orbit is perturbed using a CM, and for each beam position, the strength of the paired magnet is varied; the zero-crossing of the resulting orbit-change versus BPM-position fit identifies the BPM offset. Operator intervention is modelled to handle BPMs where the automated procedure fails, sampling the resulting offset from a Gaussian distribution consistent with successfully corrected BPMs.

Orbit correction: The study of orbit correction for BESSY III under simplified assumptions was presented in [6]. Here, BBA and orbit correction are iterated several times alternately. After two BBA-orbit correction iterations, RMS BPM offsets (relative to the ideal beam axis) are reduced from approximately 440 μm initially to below 50 μm in both planes (Table 4). The final orbit RMS values for 100 error seeds are shown in Fig. 4. For subsequent large-scale simulations, a pseudo-BBA approach is used, sampling post-BBA BPM offsets from a Gaussian with 50 μm RMS (truncated at 2σ) to reduce computational cost.

Table 4: RMS BPM Offset vs. Number of BBA Iterations

Plane	Initial	1×BBA	2×BBA	3×BBA
Horizontal	442 μm	79 μm	50 μm	48 μm
Vertical	440 μm	63 μm	48 μm	48 μm

Linear Optics Correction: After the orbit is brought to the "golden orbit" following BBA and orbit correction, a Linear Optics from Closed Orbit (LOCO) correction is applied. LOCO fits the measured orbit response matrix (ORM) to a model ORM, yielding a calibrated model of the ring. Corrections are applied iteratively over ten steps, progressively including: separate-function quadrupole strengths for beta and horizontal dispersion correction; BPM and CM gain calibration; reverse-bend quadrupoles; and sextupole strengths for chromaticity correction to reach the design value of $[\xi_x, \xi_y] = [1, 1]$. The Levenberg–Marquardt solver is used for all fits.

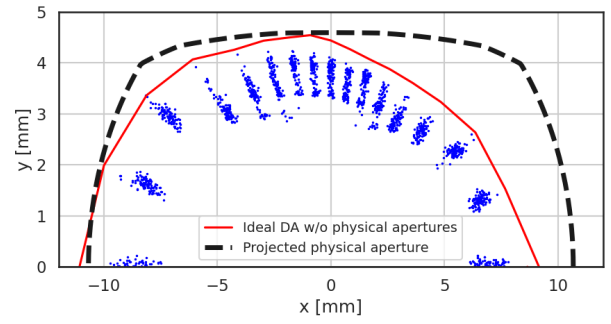


Figure 5: Dynamic aperture at the nonlinear kicker (NLK) for the ideal ring case (red), for each of the 100 machine realisations after LOCO (blue dots), and the projected physical aperture without insertion devices (dashed black line).

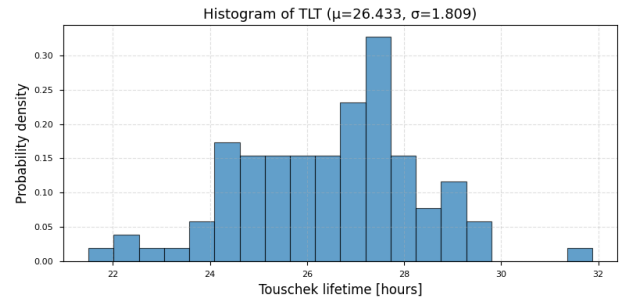


Figure 6: Touschek lifetime for 100 machine realisations calculated using the Fast Touschek Tracking method [7] after correction, including the physical apertures. The Touschek lifetime for the ideal lattice obtained by FTT is 28.74 hours.

RESULTS

Over 100 machine realisations, the commissioning chain reduces beta-beating in both planes to below 2% and dispersion-beating (both planes) to below 1 mm in all cases. The final horizontal emittance of the accelerator is always below 98.3 pm rad. Dynamic aperture and local momentum acceptance are also substantially recovered after correction, leading to the possibility of performing off-axis transparent injection during user operations [8], and Touschek lifetimes with a mean value of 26 hours as shown in Fig. 5 and Fig. 6.

CONCLUSION

A full simulated commissioning chain for the BESSY III storage ring has been developed and validated over 100 machine realisations with a realistic error model. The procedure, including trajectory correction, sextupole ramp-up, RF correction, BBA, orbit correction, and LOCO, reliably delivers beam capture, sub-50 μm BPM alignment, sub-2% beta-beating, Touschek lifetimes over 20 hours, and enables off-axis injection. These results demonstrate that the BESSY III lattice and associated correction hardware are adequate for commissioning under realistic imperfection conditions. Future work will include girder layout studies, off-axis injection efficiency studies, sensitivity studies of hardware tolerances, and optimisation of nonlinear optics [9].

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