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COMMISSIONING SIMULATIONS FOR THE DIAMOND-II UPGRADE

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Abstract

The Diamond-II [1,2] storage ring, compared to Diamond, improves the natural emittance from 2.7 nm to 160 pm and the beam energy from 3 to 3.5 GeV. The number of straight sections is also doubled from 24 to 48 thanks to the modified hybrid six-bend-achromat lattice. To reduce the impact on the existing science program, the dark time period must be minimised. To assist in this aim, storage ring commissioning simulations have been carried out to predict and resolve possible issues. These studies include beam commissioning starting from on-axis first-turn beam threading up to beam based alignment and full linear optics correction with stored beam. The linear optics corrections with insertion devices are also included. The machine characterisations at different stages are compared. Considerations on realistic chamber limitations, error definitions and some commissioning strategies are also discussed.

INTRODUCTION

To predict and resolve possible problems during the storage ring commissioning, start-to-end beam commissioning simulations have been carried out. The simulations help to validate the specification and error tolerances defined for the machine components. The code Simulated Commissioning toolkit [3] based on the Accelerator Toolbox [4] which is well integrated with Matlab Middle Layer [5] scripts is chosen for the simulation. The commissioning of the storage ring can be divided into different phases:

1. Achieve a stored beam, starting with beam-threading and on-axis injection,
2. Achieve beam accumulation with off-axis injection,
3. Correct the linear optics, optimise the injection efficiency and the beam lifetime,
4. Commissioning of all insertion devices (IDs), harmonic cavity, etc.

The commissioning is simulated from the beam threading step to linear optics correction including all ID effects. Forty random machines are simulated to get the statistics.

The structure of this paper is organised as follows. Firstly, the error sources are defined. Then the early stage commissioning procedures including the beam threading and the RF tuning are described. Next is the linear lattice correction including the coupling correction and the alleviating of beta-beating caused by IDs. Finally a short conclusion is given.

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ERROR DEFINITIONS

The error tolerences are developed in consultation with the Diamond-II Magnet and Engineering groups. They are tabulated in Table 1 and listed in Table 2. The systematic and random multipolar field errors are included up to 15-th order [1]. All the errors used here are populated in a normal distribution with truncation at two standard deviations.

Table 1: Magnet and Girder Errors

Element	Misalignment		Relative Field	
	Offset (μm)	Roll (μrad)	Main Field (%)	Secondary Field (%)
Girder	150/150§	150		
DL Magnet†	100	100	0.05	
Gradient Dipole	50	100	0.05	0.10
Anti-bend Quad	35	100	0.05	0.10
Pure Quad	35	100	0.10	
Sextupole	35	100	0.10	
Octupole	35	100	0.10	
CM	150	150	0.10	
CM‡				0.10
Skew Quad‡				0.50

§ Independent offsets at each end of the girder
† Longitudinal varying dipole
‡ Embedded in sextupole trim coils

Table 2: BPM, RF and Other Error Sources

BPM Errors		
Initial Offsets	500	μm
Roll	10	mrad
Calibration	5	%
Noise (Turn-by-Turn)	60	μm
Noise (Closed Orbit)	1	μm
RF Errors		
Frequency	100	Hz
Voltage	0.5	%
Phase Offset	90	°
Injected Beam Jitter		
Transverse Displacement	100	μm
Transverse Divergency	10	μrad
Energy Deviation	0.1	%
Phase Shifts	0.1	°
Other Errors		
Circumference	1	μm
Injection Pulsed Magnet Jitter	0.024	%

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Aside from these errors, the additional field errors induced by the correctors in the sextupoles are also included in the commissioning studies. The lowest order components, being normal and skew decapolar terms, are linearly proportional to the corrector strengths with a factor of 1.35×10^7. No errors are included in the ID kick-maps [6].

Realistic physical aperture limits are imposed by the round chambers of 20 mm inner diameter in general and the narrow-gap vacuum chambers in some straights since some IDs will be in place on day one of commissioning [1]. All collimators are left open until the commissioning of IDs.

COMMISSIONING SIMULATIONS

Beam Threading and RF Tuning

In the beam threading process the sextupoles are turned off to avoid extra sources of errors. During this step the orbit correction is iteratively applied to globally flatten the trajectory. The threading is then progressively extended from one-turn to multi-turns, during which the trajectory correction gradually improves. After multi-turn threading is achieved, the sextupoles are ramped to full strength in multiple steps. Some additional dipole errors are introduced during this process so further global orbit corrections are applied as required. The orbit tuning is continued until the beam survives a few hundred turns and the betatron tune can be detected. A simple quadrupole scan then can be performed using the beam transmission rate or the injection efficiency as an objective.

The next step is to turn on the main RF cavities leaving the harmonic cavity off. The applied RF errors result in a mismatch in the longitudinal phase space, so the RF phase and frequency are adjusted at this stage to remove the unwanted synchrotron oscillations.

The beam-based RF tuning procedures to find and set the optimal phase and frequency are applied iteratively until the beam is centred in the real RF bucket. After this process is complete, another quadrupole scan is performed followed by chromaticity adjustment to maximise the beam survival time. Up to here the first phase beam commissioning is complete.

Moving Towards Off-axis Injection

From this moment we are entering the second phase where we switch from on-axis to off-axis injection for beam accumulation.

The commissioning procedure in this phase comprises iteratively applying closed orbit corrections, tune correction, beam-based alignment (BBA), and the linear optics correction by Linear Optics from Closed Orbits (LOCO) [7]. The closed orbit correction convergence is controlled by the α parameter in the Tikhonov regularisation [8], which is a parameter used to regularise the corrector strengths.

The BBA follows a procedure modified from the one in used at Diamond, which is originally developed at the ALS [9]. To reduce the commissioning time, the BPMs have been grouped into 48 subsets based on the girders they sit on. During the commissioning the BBA process visit all groups three times.

The commissioning steps are listed and elaborated below.

1. First Tuning
   This is an optional intervention step in case of the low beam transmission at the end of Phase 1. Some interventions, for example, further quadrupole scans or a simplified LOCO correction using a reduced number of quadrupole families can be applied to improve the dynamic aperture (DA). Out of the 40 random machines simulated only one special case needs manual intervention.

2. First BBA
   This is a coarse BBA step performed with relaxed corrector strengths ($\alpha = 50$). A subsequent orbit correction sequence is launched with descending α until the maximum corrector strength reaches 0.5 mrad. Figure 1 shows the improvement of orbits as the BBA progresses.

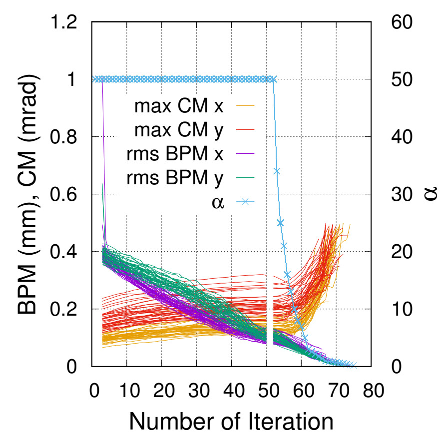

Figure 1: The change of the closed orbits and corrector strengths in the first BBA step. Before the iteration number 50, the BPM reading values decrease as the new BPM offsets are updated closer toward quad centres. After that, the BPM readings continue to decrease but the corrector strengths begin to increase rapidly in line with the decreasing α.

3. First LOCO
   The goal of this step is to provide a coarse linear lattice correction. For this, LOCO is configured to use just the pure quadrupoles magnets.

4. Second BBA and LOCO
   We then refine the BBA measurements by launching the BBA procedure again with smaller α and the CM strength limit 0.7 mrad. This is the preparation for the next LOCO with the dispersion included in the response matrix measurement.

After this stage the DA is large enough for off-axis injection [10]. We are now ready to move on to the next phase.

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Coupling Correction

In the third phase of commissioning, the goal is to establish the nominal machine optics and thereby improve the injection efficiency and beam lifetime. The first objective is to further correct the linear optics including the coupling. Therefore, all skew quadrupoles are now used. The rest of the field gradient tuning knobs (in strong gradient dipoles and anti-bend quadrupoles) are also used. The simulation is extended to a third iteration of BBA and LOCO.

In summary, the DAs and their improvements at each LOCO step are shown in Figure 2. The average rms beta-beating is controlled to 1.0% horizontally and 1.7% vertically, as shown in the top plot of Figure 3.

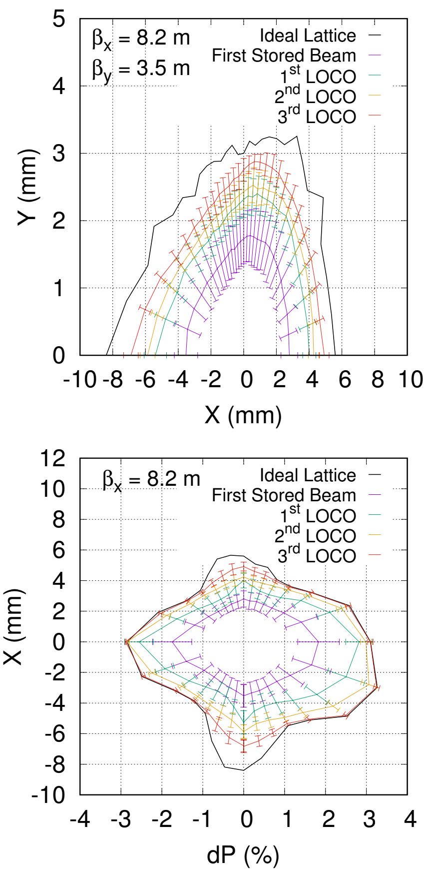

Figure 2: The on- and off-momentum dynamic apertures at different commissioning stages. The averages are connected by solid lines and the error bars are shown in dashes.

By controlling the vertical emittance to 8 pm−rad, which is the diffraction limit of 10 keV photons, the average Touschek lifetime (estimated at 0.6 nC bunch current and neglecting collective effects) is brought back to 2.25 hours, close to the 2.4 hours derived from the ideal lattice.

Insertion Device Commissioning

After the nominal machine optics without ID have been reached, we can move on to the commissioning of the IDs. Here we focus on the commissioning step to alleviate the beta-beating induced by all IDs. Further in-depth studies of ID impacts are described in [11].

Multiple LOCO steps are applied to recover the linear optics to the ideal case. The first LOCO step is a coarse correction by 6 families of quadrupoles, while the rest of the LOCO steps perform fine-corrections using all possible tuning knobs. As a result, the mean rms beta-beating at BPMs of all these 40 random machines can be controlled to the values 1.5% horizontally and 2.6 % vertically. The distributions of the RMS beta-beating at different commissioning stages are shown in the bottom plot of Figure 3.

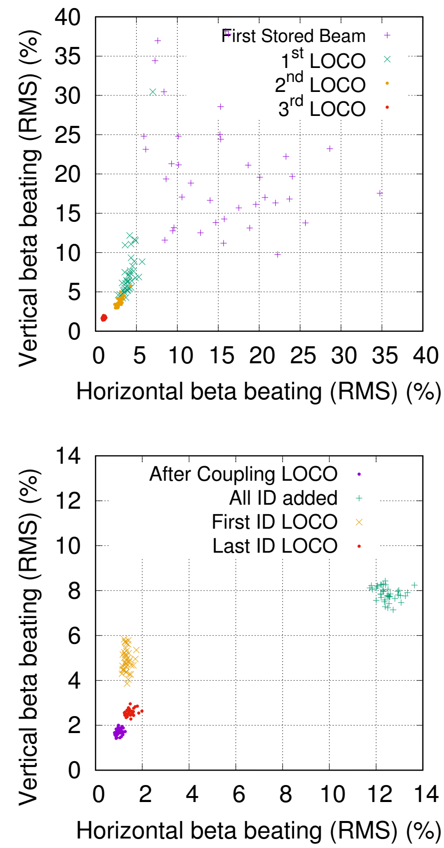

Figure 3: The distributions of the rms beta-beating at different stages. (Top: without ID. Bottom: with ID)

CONCLUSION

With reasonable error definitions, the start-to-end storage ring commissioning simulations of 40 random machines are carried out with mature techniques that have been used for decades in the synchrotron light source community. The performance of the storage ring is restored close to the ideal values. This gives us good confidence for the future commissioning of Diamond-II storage ring.

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