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EARLY COMMISSIONING SIMULATION OF THE DIAMOND STORAGE RING UPGRADE

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Abstract

A low beam emittance lattice has been designed for upgrade of the Diamond storage ring. Due to the use of strong focusing elements and rather small vacuum chamber and considering the required short dark time, commissioning of the designed storage ring becomes very challenging. This paper briefly explains the progress of early commissioning simulations of the storage ring, gives the required engineering tolerances, presents the first simulation results and discusses the non-linear beam dynamics (NLBD) issues after successful commissioning with and without insertion devices (IDs).

INTRODUCTION

The Diamond Light Source (DLS) has started to study the feasibility of replacing the existing electron storage ring with a low beam emittance ring called Diamond-II. A careful lattice design and non-linear beam dynamics optimization have been carried out to achieve the desired storage ring specifications with large dynamic and momentum apertures, enabling efficient injection of the incoming beams [1]. The proposed lattice has a six-fold symmetry. It is based on three unit cells (UC) and two matching cells (MC) at the start and end of a super period. It provides the natural beam emittance of 160 pm, around 17 times smaller than the present Diamond ring within circumference of 560.57 m.

The required small emittance is achieved using stronger quadrupole magnets which inevitably results in a larger natural chromaticity and then strong sextupoles are employed to control the NLBD issues. Misalignments of the strong quadrupoles produce large orbit or trajectory offsets along the ring and due to the use of strong sextupoles, this leads to large optics and coupling errors. However, fine tuning of the orbit and optics require a circulating beam with sufficient current which has to be first established. In addition, consideration of the desired short dark time in the project schedule reveals that the alignment and commissioning of the storage ring are expected to be very challenging.

In this paper, we have addressed the rapid commissioning simulation challenges to find out what are the required engineering tolerances and to understand how the machine operation would be in the presence of the realistic errors in the ring. The impact of the realistic distribution of the elements errors on the performance of the ring has been assessed by means of a statistical analysis of the closed orbit, linear optics and of the key performance parameters of the NLBD.

COMMISSIONING PROCEDURE

The ultimate aim of the simulation is to model the actual commissioning of the machine including all expected errors. Therefore, our simulation procedure closely follows the steps which will be performed within the real commissioning. It consists of the following steps; (1) impose the errors for all the ring elements according to Table 1, (2) establish the first and many turn trajectory correction until the closed orbit is found, (3) perform global closed orbit correction down to reasonable level, (4) correct the optics and linear coupling errors [2-4]. All simulations of the lattice imperfections and the commissioning strategies were made using AT [5] and ELEGANT [6] codes.

In order to correct the trajectory/orbit and the optics and to control the coupling, a set of beam position monitors (BPMs), combined horizontal and vertical correctors (HVCORs) and skew quadrupoles (SQUADs) have been distributed along the cell, as shown in Fig. 1.

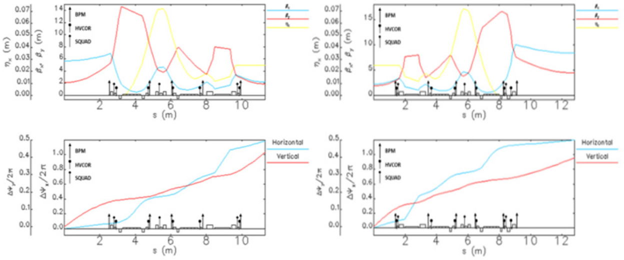

Figure 1: Distribution of BPMs, HVCORs and SQUADs with respect to normalized phase advance in half UC (left) and MC (right).

The position of such corrector elements was carefully chosen to provide a sufficiently dense sampling of the phase advance along the cell, so that an effective orbit correction can be achieved, reducing the orbit close to zero at the BPMs without correctors fighting each other and effectively controlling the coupling. There are 252 BPMs, 252 HVCORs and 144 SQUADs in total for the whole ring. For precise orbit control at the IDs, BPMs are placed at either end of the straight sections. A group of 240 correctors is embedded in the sextupoles by means of additional windings, while the remaining 12 will be standalone correctors combining both horizontal and vertical correction. All the 144 skew quadrupoles have been considered as additional windings inside the sextupoles. Two thirds of the skew quadrupoles (96 SQUADs) are positioned in locations of non-zero dispersion while the remaining third (48 SQUADs) are located in the dispersion-free straights.

To start the simulation of the commissioning steps, relatively large initial errors according to Table 1 have been

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randomly imposed to the lattice elements for 100 seeds using a Gaussian distribution with 2σ cut-off. The errors include transverse misalignment and fractional strength of the ring elements. The longitudinal misalignment and jitter of the incoming beam have not yet been considered. Distribution of the elements errors along the ring for one arbitrary seeds is displayed in Fig. 2.

Table 1: The Errors Used in Commissioning Simulation

Girder offset/roll [μm/ μrad]	150/150
Dipole offset/roll in girder [μm/ μrad]	50/100
Quad., Sext., Oct. offset in girder [μm]	25
BPM offset/roll in girder [μm/ μrad]	100/100
Dipole strength error	5E-4
Quad., Sext., Oct. strength error	1E-3

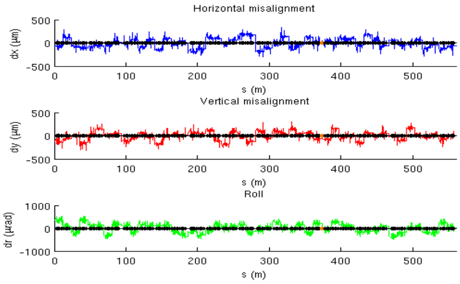

Figure 2: Distribution of the girder and elements alignment errors in the ring for an arbitrary seed.

Trajectory Correction

After generating the errors, the transverse trajectory has been corrected based on the response matrix method and SVD algorithm with the goal of closing the first turn. In order to correct the trajectory in the ring, the response of horizontal/vertical trajectory is measured at the BPMs by changing the horizontal/vertical correctors' strength. The sextupole magnets have been switched off in this step to increase the likelihood of beam transfer and to follow more realistically the actual commissioning procedure. The distorted and corrected trajectories along the ring and corresponding corrector strengths are displayed in Fig. 3 for all 100 error seeds.

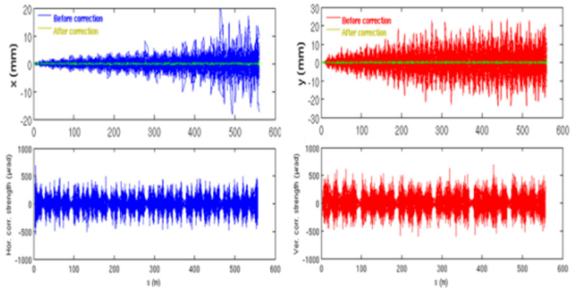

Figure 3: Transverse trajectory of the beam before and after correction (top) and corresponding corrector's strength (bottom).

It is assumed that x0=y0=0, x0'=y0'=0 as initial conditions. The maximum value of the correctors over 100 seeds is less than 0.7 mrad.

Orbit Correction

The first turn trajectory correction provides corrector settings that are used as a starting point for the subsequent orbit correction. First we compute the orbit with sextupoles on and then a global closed orbit correction is performed based on the orbit response matrix method. It is assumed that the preliminary BPM calibration and quadrupole centering (also known as beam-based alignment (BBA)) has been done. The closed orbit along the ring before and after correction and corresponding corrector strengths are is displayed in Fig. 4 for all machine ensembles. In this step, 8% of the machine samples are lost and for the remaining 92%, the closed orbit is found.

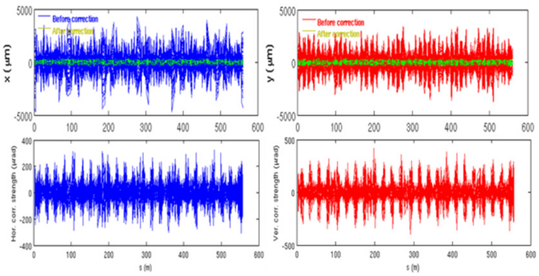

Figure 4: Closed orbit before and after the correction (top) and corresponding corrector's strength (bottom).

The rms x/y value of the corrected orbit over all elements of the machine is less than 50 μm, while at the BPMs the orbit is virtually corrected to zero. The rms corrector strength is below 100 μrad. It is assumed that $x_0=y_0=0$, $x_0'=y_0'=0$ as initial conditions. The maximum value of the correctors over 100 seeds is less than 0.7 mrad.

Optics Correction

Once the orbit is corrected, we proceed with the correction of the linear optics. Several alternative methods of correction have been tested and in what follows we present an example of the application of the well-known LOCO (Linear Optics from Closed Orbit) package [7]. The applicability of these techniques is enabled by having independent power supplies on all the focusing elements. LOCO provides the corrections required to the gradients of the normal and skew quadrupoles. The application of LOCO has been tested in a simple case where we assign well defined errors to a subset of elements to check the ability of LOCO to pinpoint where the errors are. This analysis identified degeneracy in the LOCO matrix, producing quadrupole corrections fighting each other as is the case of the pair of quads in the dispersion bump. As a result such quadrupoles are now locked together in the LOCO error fit procedure. A typical example of the optic correction with LOCO is described in Fig. 5. The results reveal that the peak-to-peak of the uncorrected beta-beat is within ±15% and can be corrected to below ±1.5% in both planes with quadrupole strength variations well below ±1%.

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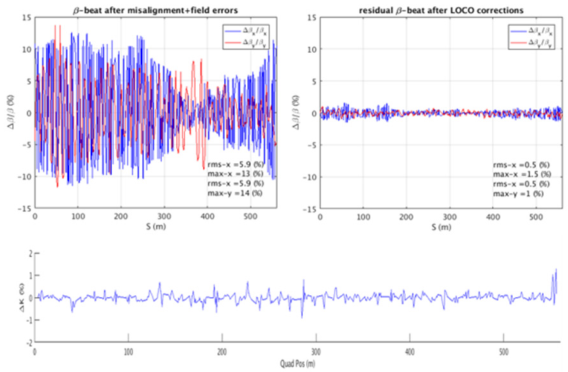

Figure 5: The beta-beat before and after correction (top) and random quadruple gradient error (in %) reconstructed with LOCO (bottom).

Vertical Dispersion and Coupling Corrections

Vertical dispersion and linear coupling have to be corrected in order to control the vertical emittance. It is likely that operations will aim at providing a small vertical emittance in the single digit pm, provided that the impact on the Touschek lifetime is manageable. Taking as an example 8 pm, as in our present lattice, this value corresponds to a coupling ratio of 5% in Diamond-II. After the orbit and beta-beat corrections, the emittance ratio k = εy/εx averaged over 30 seeds is 12.3% corresponding to a vertical emittance of 19.4 pm. A full LOCO correction reduces the coupling to k = 0.6% corresponding to a vertical emittance of ~1pm and brings the vertical dispersion to below a millimetre. The maximum strength of skew quadrupole was 0.05 m^{-2} which corresponds to a gradient of 0.58 Tm^{-1}, comparable to that used in Diamond.

IMPACT OF IMPERFECTIONS ON NLBD

With the successful correction of the orbit, optics and coupling, we turn now to the analysis of the impact of the errors on the non-linear beam dynamics to complete the commissioning simulations. Particle tracking has been carried out for 30 random error seeds and the non-linear beam dynamics has been investigated. The 6D on-energy and 4D off-energy dynamic aperture (DA) are displayed in Fig. 6. The on-energy DA is on average ±6 mm in the horizontal and ±2 mm in the vertical planes which is sufficient for off axis injection [8]. However, the real momentum aperture is ±2.5% in the long straight sections. The 4D on/off-energy DA and corresponding frequency map analysis (FMA) for one arbitrary seed of errors are shown in Fig. 7.

A more realistic case was simulated including all IDs and the errors. The perturbation to the optics function is within ±10% in the horizontal plane and ±15% in the vertical plane, the last one mostly dominated by the effect of the two wigglers I12 (4.2 T) and I15 (3.5T).

The beta beating and linear optics were fully corrected with LOCO. Figure 8 shows the DA and the FMA and corresponding beta-beating after applying LOCO correction to the machine with all IDs and errors for an example of one error seed. It should be mentioned that the vertical emittance in Fig. 8 is corrected to less than 1 pm.

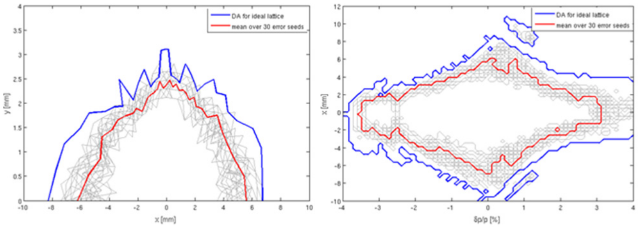

Figure 6: On-energy DA including RF cavity (left) and 4D off-energy DA (right) after commissioning of the ring.

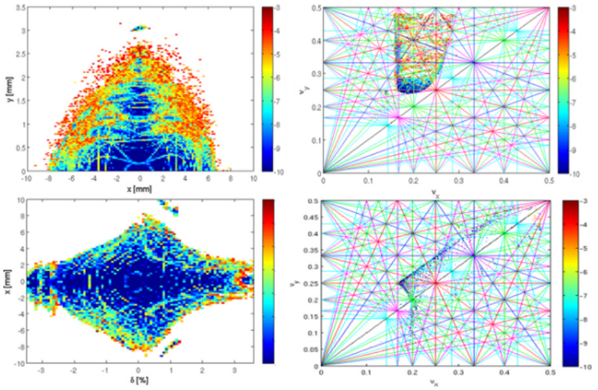

Figure 7: The on-energy (top) and off-energy (bottom) DA after commissioning of the ring. Corresponding FMA are given in the right hand side plots.

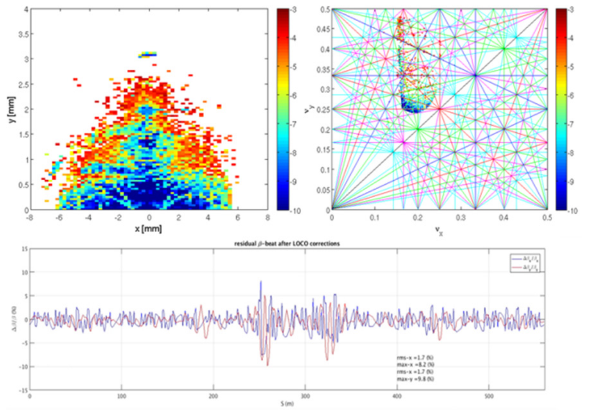

Figure 8: The DA (top-left) and FMA (top-right) and corresponding corrected beta-beating (bottom).

CONCLUSION

The commissioning simulation and error analysis has been done for the proposed Diamond-II storage ring lattice. LOCO has been successfully tested and the results reveal that the peak-to peak beta-beat can be corrected to the level of ±1.5%. The NLBD results reveal that off-axis injection is feasible. Adding the physical aperture, development of the correction tools to deal with few seeds that no closed orbit could be found, adding energy errors, using larger BPM offset, introducing an effective way of controlling the coupling to the desired level and tracking a bunch of particles would be the next steps.

REFERENCES

[1] Diamond conceptual design report, 2019.

[2] V. Sajaev and M. Borland, “Commissioning Simulations for the APS Upgrade Lattice”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 553-555, `doi:10.18429/JACoW-IPAC2015-MOPMA010`

[3] T. Hellert *et al.*, “Simulation of Trajectory Correction in Early Commissioning of the Advanced Light Source Upgrade”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 4256-4258, `doi:10.18429/JACoW-IPAC2018-THPMF078`

[4] S. M. Liuzzo, N. Carmignani, L. Farvacque, and B. Nash, “Lattice Tuning and Error Setting in Accelerator Toolbox”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3067-3070, `doi:10.18429/JACoW-IPAC2017-WEPIK061`

[5] A. Terebilo, *Accelerator toolbox for MATLAB*, in Proc. Workshop on Performance Issues at Synchrotron Light Sources Berkeley, California, October 2-4, 2000.

[6] J. Safranek, Experimental determination of storage ring optics using closed orbit response measurements”, *Nucl. Inst. and Meth.*, A388, 1997, pp. 27-36.

[7] M. Borland, *Elegant: a flexible sdds-compliant code for accelerator simulation*, Advanced Photon Source, Argonne National Laboratory, USA, Report No. LS-287, 2000.

[8] I. P. S. Martin, R. Bartolini, H. Ghasem, J. P. Kennedy, and B. Singh, “Injection Studies for the Proposed Diamond-II Storage Ring”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper WEPMP043, this conference.