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SIMULATED COMMISSIONING FOR DIAMOND-II STORAGE RING FROM ON-AXIS TO OFF-AXIS INJECTION

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Abstract

The Diamond-II storage ring commissioning simulations have continued based on the previous results where on-axis injected beams are captured. The next goal is to enlarge the dynamic aperture so that off-axis injection can be achieved. The procedures include beam based alignment, beta-beating correction and linear optics correction. Details of the implementations are discussed and the simulation results are presented. In the end, we are able to reach off-axis injection which allows accumulation.

INTRODUCTION

The Diamond-II project [1] features a storage ring using a modified hybrid six-bend achromat lattice. The parameters of the current baseline lattice are listed in Table 1.

Table 1: Diamond-II Storage Ring Parameters

Parameter	Value	Unit
Energy	3.5	GeV
Circumference	560.56	m
Number of Straight Sections	48	
Betatron Tune (H/V)	54.14 / 20.24	
Natural Chromaticity (H/V)	-68 / -89	
Damping Partition (J_x)	1.88	
Natural Emittance	162	pm-rad
Momentum Compaction Factor	1.03	10^{-4}
Energy Loss Per Turn (w/o IDs)	723	keV
Rad. Damping Time (H/V/L)	9.7 / 18.1 / 16.0	ms
Natural Energy Spread†	9.4	10^{-4}
Natural Bunch Length†	3.5	mm
Synchrotron Tune†	0.0025	
Beta Functions (H/V)‡	8.44 / 3.41	m

† Estimated with only main RF total voltage = 1.42 MV
‡ At long straight centres

The general commissioning strategies and some preliminary simulation results were presented in the previous study [2], including initial estimates for storage ring error tolerances. Since that time, prototyping and alignment trials have begun, ensuring all sources of error are minimised within the practical engineering constraints. As such, the error specifications continue to evolve.

In the follow-up study [3], the revised error tolerances are given and some alternative methods for early-stage commissioning are discussed. Initial commissioning stages were simulated for 200 random machines, up to the phase when an on-axis injected beam is captured. The demonstrated dynamic apertures, estimated by particle tracking with more than one synchrotron period, are large enough to capture on-axis injected beams efficiently.

At this stage the beam current will be low (< 1 mA), but sufficient to detect a closed orbit and betatron tunes. In addition, the RF frequencies and phases are already adjusted to minimise the synchrotron oscillation of the captured beam.

In this paper the plans for the subsequent commissioning will be discussed, together with some details of the implementation and simulation results.

COMMISSIONING RECIPES AND SIMULATIONS

The next goal of commissioning is to enlarge the dynamic aperture to switch from on-axis injection to off-axis injection for accumulation. The current subsequent commissioning recipes are as follows.

1. Very first time closed orbit correction and chromaticity correction,
2. Set up ab-initio BPM offsets,
3. Preliminary beam based alignment (BBA),
4. Preliminary beta-beating correction (BBC),
5. Integer tune correction,
6. Further iterations of BBA and linear optics correction.

During the course of commissioning a tune scan can always be performed to ensure a good beam transmission whenever needed. The tune response matrix used is constructed from the ideal lattice with 7 families of quadrupoles (excluding strong quadrupoles). Some of the commissioning procedures are detailed as follows.

First Closed Orbit Correction

The Tikhonov parameter [4] used to regularise the corrector strengths is set very weak ($\alpha = 1000$). As shown in Fig. 1, the rms BPM readouts are slightly improved to a few hundreds μm and an extreme case is fixed.

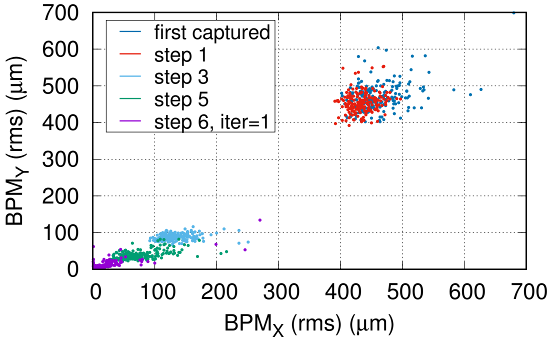

Figure 1: RMS BPM readouts at different steps.

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Initial BPM Offsets and BBA

The BPM signals are weak and noisy because the intensity of captured beam is very low at this moment. We have to assign ab-initio BPM offsets to improve the closed orbit correction targets. The orbits with small quadrupole and corrector variations can be measured in order to find the most probable values of the BPM-to-quad offsets by numerical fitting. These offset values are the update values to be added to the original BPM offsets (which are initially zeros). The found values may contain some false results and extreme outliers. To reduce the harm caused by them, we can scale the updated values down by a factor and set a cap to limit the maximum change.

The closed orbits established in the first step are fragile, as any large changes of correctors may easily cause the loss of stable conditions. Therefore this step will be carried out based on the same closed orbit, i.e. no orbit corrections are applied.

After this step, the beams are still at the same position but the BPM readouts are different because the BPM offsets are changed closer to the adjacent quadrupole centres. Once these ab-initio values of BPM offsets are assigned, we can then proceed to further BPM offset refinements with frequent applications of closed orbit corrections in the first BBA routine. The BPMs have been grouped into 48 subsets based on the girders they sit on. All the subsets are visited once. The resulting rms BPM readouts are brought down from around 450 µm to 150 µm, as Fig. 1 shows.

Beta-beating Correction

The linear optics correction can be carried out by Linear Optics from Closed Orbits (LOCO) [5] by fitting the closed orbit response matrix. However, there are some disadvantages to use this method with the on-axis injection. First of all, the accuracy of closed orbit response matrix is poor because of the large BPM noise at low current. Secondly, the measurement speed is slow due to the repetitive shot-by-shot injection. Lastly, the first LOCO solutions are not unique and depend strongly on the arbitrary choice of singular values [6]. A few trials will be needed to get a solution.

Instead, we can perform a preliminary beta-beating correction on the average beta functions. The only requirement is a beam with sufficient number of revolutions for good tune measurements. As long as the tune resolution is sufficient, the average beta function in a quadrupole can be estimated by the ratio of the tune changes and the field gradient changes $\bar{\beta}_i = 4\pi\Delta Q/(\Delta k_1 L)_i$. The corresponding beta-beating response matrix R (length weighed) is defined as

$$\frac{\bar{\beta}_i - \bar{\beta}_{0,i}}{\bar{\beta}_{0,i}} = \sum_j R_{ij}\Delta k_j,$$

where $\bar{\beta}_0$ can be calculated by the ideal model simulation. The beta-beating is then corrected by the pseudo inverse of R derived by the SVD method.

There are in total 300 pure quadrupoles therefore the dimension of R is 600 × 300. It takes 90,000 bi-directional quadrupole variations to complete the R measurement. It is more time consuming than the closed orbit response matrix measurement but the problem of noisy BPM can be avoided.

Figure 2 shows the BBC results for all 200 cases simulated. The vertical beta-beatings correspond to quadrupole indices from 301 to 600. From this step on the quadrupole setpoints grouped in families are split into 300 individual setpoints.

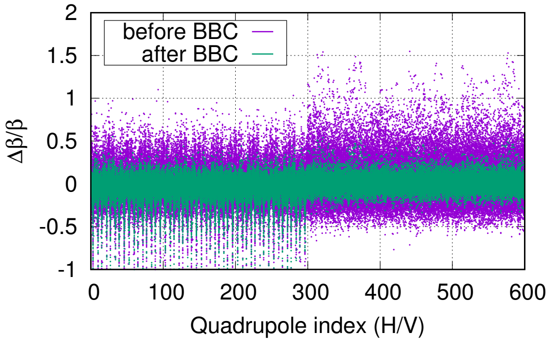

Figure 2: Beta beating improvement (200 seeds).

There are some caveats about this method. If the beta function variation in a quadrupole is large, this method may not be very effective.

Integer Tune Correction

Up to the BBC step some betatron tunes may be above the half-integer or have incorrect integer tune. The next step is to adjust the full tune to be in the correct half-integer tune window. In the simulation, it's easier to get the full tune as the phase advances can be calculated. However, in the control room, the un-corrected linear coupling and above half-integer tunes can cause the tune confusion therefore human supervision and intervention are always needed. In general the integer part of the betatron tune can be derived by counting the number of betatron oscillations. Meanwhile the fractional part of the betatron tune can be judged by observing the movement of the FFT spectrum peaks with some quadrupole change tests. In practice, trial-and-error can resolve this issue.

Figure 3 shows the tune distribution for 200-seed simulations. The corrected results are shown in the green dots.

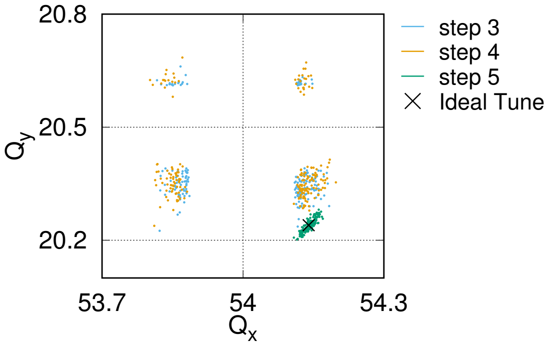

Figure 3: Full tunes at different commissioning states for 200 seeds simulations.

Some other facts are observed:

- Only about 50% of simulated seeds are in the correct half-integer tune window before correction.
- Uncorrected vertical tunes tend to be higher.
- The integer tunes do not change in the previous BBC procedure.
- The rms BPM readings do not change much in the previous BBC procedure.
- The dynamic aperture, shown by the green line in Fig. 4 (step 5), is significantly improved after the tune is adjusted.

After this step off-axis injection should be possible. If the beam can be accumulated, it will be very beneficial for the following commissioning steps in terms of BPM noise and commissioning time. LOCO can be carried out to have better linear optics corrections.

Further Corrections

We have investigated applying the LOCO for the first time at this stage but it only gets marginal improvement on dynamic apertures. A lesson learnt is the importance of improving BPM-to-quad alignment again before the application of the first LOCO for better results. Ideally we want the ability to carry out closed orbit corrections with strong corrector regularisation.

Further simulations are carried out for the second BBA and the first LOCO with all 300 independently powered quadrupoles. In the end, 95% of all generated random machines are successfully simulated and the resulting mean dynamic apertures are shown by the purple line in Fig. 4 (step 6). The chance of off-axis injection for beam accumulation is further increased.

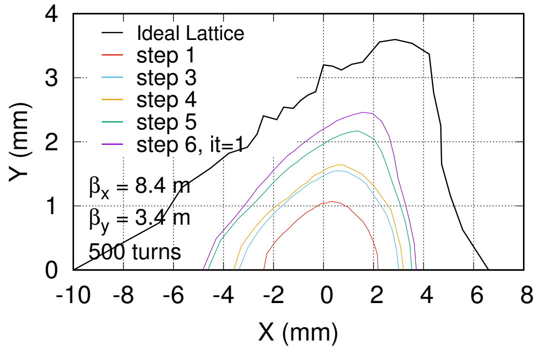

Figure 4: The average dynamic apertures at different commissioning states.

In some exceptional cases the BBA procedure results in non-converging BPM readings. These can be resolved by more careful tune control and iterative BBA. A robust BBA method is still under development. To further enlarge the dynamic aperture to improve the injection efficiency, more iterations of BBA and linear optics corrections by LOCO are necessary.

SUMMARY

The commissioning plans from on-axis to off-axis injection are outlined and the detailed procedures are explained in this study. The actual commissioning plan may still be evolving but here are some lessons we have learnt so far:

- The trick to find and set the ab-initio BPM offsets with the same closed orbit.
- Carrying out the first optics correction based on tune measurements.
- The impact of integer tune correction on dynamic apertures.
- Good BPM-to-quad alignment is essential for LOCO.

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