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SIMULATION STUDIES OF BEAM COMMISSIONING AND EXPECTED PERFORMANCE OF THE SPRING-8-II STORAGE RING

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Abstract

In the SPring-8 upgrade project, the 5-bend achromat lattice is adopted for achieving a very low emittance of 157 pm.rad at 6 GeV. Since the dynamic aperture (DA) and the beam performance become sensitive against errors, we carried out tracking simulations to evaluate the tolerance of machine imperfections. It is found that the first-turn-steering (FTS) with the use of single-pass BPM's is indispensable for accumulating the beam and by performing the orbit and optics corrections, we can finally achieve an emittance value of 160 ~ 180 pm.rad, being close to the design value. We also found that a naive application of the SVD algorithm to orbit corrections yields unwanted local bumps between BPM's and this deteriorates the vertical emittance. A possible scheme to avoid such local bumps by effectively interpolating the measured orbit is also discussed.

INTRODUCTION

In order to provide highly brilliant and highly coherent X-rays, an upgrade plan of the SPring-8, the SPring-8 II, has been proposed [1]. The main parameters are listed in Table. 1. For achieving a very low emittance of 157 pm.rad at 6 GeV, the 5-bend achromat (5BA) lattice is adopted in the SPring-8-II (see Fig. 1) [2]. The emittance will further be reduced to about 100 pm.rad with the help of the radiation damping effect by insertion devices.

Table 1: Main Parameters of SPring-8 and SPring-8-II

	SPring-8	SPring-8-II
Energy	8 GeV	6 GeV
Lattice Type	Double bend	5 bend achromat
Emittance	2.4 nm.rad (natural)	150 pm.rad (natural) 100 pm.rad (with rad. damping)
Tune	(41.14, 19.35)	(108.10, 44.58)
Nat. Chrom.	(-117, -47)	(-143, -147)
(β_x, β_y, D) at Straight	(31.2 m, 5.0 m, 0.15 m)	(5.5 m, 2.2 m, 0.00 m)

At the SPring-8-II, the following scenario is scheduled for the beam commissioning: (1) On-axis injection with the FTS method for accumulating low current beam. (2) Rough orbit correction and beam-based calibration of BPM's. (3) Off-axis injection for accumulating high current beam. (4) Fine corrections of COD and lattice functions.

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In the MBA lattice, strong quadrupole and sextupole magnets are generally used, and in the SPring-8-II 5BA lattice the quadrupole and sextupole field strength is as strong as 2.7 m^{-2} and 135 m^{-3}, respectively. These strong fields can cause intolerable COD and/or emittance growth due to the machine imperfections such as the misalignment, magnetic field errors and the offset of BPM's. We then carried out simulation studies for confirming the above commissioning scenario and for estimating the achievable beam performance under realistic machine conditions by using the 6D symplectic code CETRA [3].

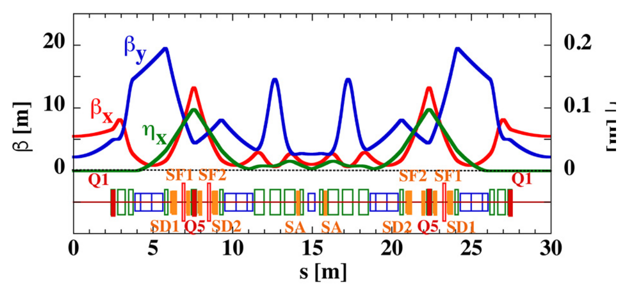

Figure 1: Lattice functions of SPring-8-II.

SIMULATION CONDITIONS

In the unit cell there are 8 horizontal and 8 vertical steering magnets and 7 BPM's for the COD correction. The steering magnets are combined with quadrupole and sextupole magnets indicated in Fig. 1 as Q1, SD1, SD2 and SA and their maximum kick angle is 0.25mrad (0.1mrad for SA). The BPM's are located near Q1, SD1, SD2 and upper SA. Quadrupole and sextupole magnets are connected in series to each family's power supply but upper Q5 has an additional auxiliary power supply for correcting the beta function and the horizontal dispersion function. One skew quadrupole is near upper SD1 for correcting the vertical dispersion function.

In the simulation, the tolerable misalignment between girders in the transverse direction was set to ±90um (given by Gaussian random of σ = 45 μm with 2σ cut) and that between magnets inside a girder was ±15um, whose accuracies can be achieved by the vibrating wire method as discussed in Ref. [1]. These longitudinal position errors were not included. In addition to the transverse position errors, (1) the magnetic field errors were distributed with σ = 5.0e-4 (2σ cut, the same hereinafter), (2) the tilt errors with σ = 0.1 mrad for bends, σ = 0.2 mrad for quadrupoles and σ = 0.5 mrad for sextupoles, and (3) the BPM offsets with σ = 100 μm at low beam currents before beam-based calibration of BPM's and σ = 10 μm after the calibration.

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FIRST TURN STEERING SCHEME

The strong quadrupole and sextupole magnets are used in the 5BA lattice, so that the impact of these misalignment is not negligible. This means that, at the first stage of the beam commissioning, the beam cannot be stored without the help of steering magnets. For storing the beam, the FTS method will be adopted with the use of single-pass BPM's. The procedures are as follows: (1) calculate the response matrix between the single particle trajectory at the BPM's, not the COD, and the kick of the steering magnets, and (2) correct the injection oscillation by using this response matrix with the SVD method.

The results are shown in Fig. 2, where the initial position and angle errors of the injected beam were taken into account shot-by-shot by randomly distributing the errors with σ = 100 μm and 10μrad in the transverse direction and σ = 0.1% in the longitudinal ($\Delta p / p$) direction. In addition, the BPM offset was set to σ = 100 μm at this time. When the initial steering kicks are set to be zero, the beam is lost within the first turn. By applying the FTS method, the amplitude of the injection oscillation is damped and the beam survives until the second turn. The electron can be stored after repeating the second correction. The on-momentum DA after the FTS corrections is shown in Fig. 3, where the nominal COD correction was not yet applied here. Since for the off-axis injection the beam is injected at around x = -2 mm, we can expect from Fig. 3 that a high current beam can be accumulated in the ring with the nominal off-axis injection scheme.

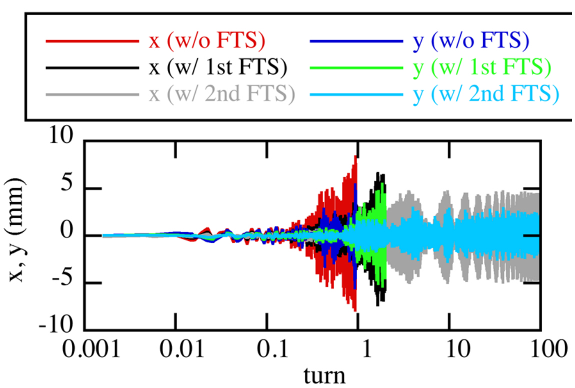

Figure 2: Trajectory of injected beam.

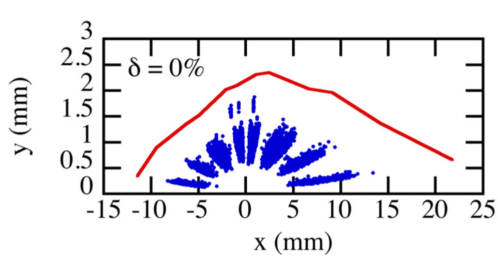

Figure 3: On-momentum DA (red) without error and (blue) with machine imperfections after FTS method.

EXPECTED BEAM PERFORMANCES

We then carried out simulation studies for checking achievable beam performances by preparing 625 ring models with machine imperfections mentioned before and doing fine corrections of COD, tunes, lattice functions, etc. The BPM's are assumed to be well calibrated by using a stored beam and in simulations we distributed random offset values with σ = 10 μm.

After the fine corrections, the remanent of the COD becomes about 30 μm (RMS) in both horizontal and vertical under the limitation of kick angle as mentioned before. We plotted the evaluated emittance in Fig.4. The achievable horizontal emittance is 160 ~ 180 pm.rad and its median is 163 pm.rad, and the median of the beta-modulation is 1.9 % and that of the dispersion-modulation is 3.1 mm. The medians of the emittance, the beta-modulation and the dispersion-modulation in the vertical are 0.45 pm.rad, 2.4 % and 0.7 mm, respectively. For achieving the emittance of Fig. 4, the required strength of the auxiliary quadrupole is 0.0021 m^{-1} (RMS) and that of the skew quadrupole is 0.0019 m^{-1} (RMS), both being sufficiently weak and less than a few percent of main quadrupole strengths. The vertical emittance in Fig.4 is small enough from a viewpoint of the Touschek beam lifetime, so that the required strength of skew quadrupole magnets can be relaxed from that of Fig. 5.

The on-momentum dynamic aperture after the fine corrections is shown in Fig. 6. In comparison with Fig. 3, the stable area is clearly enlarged.

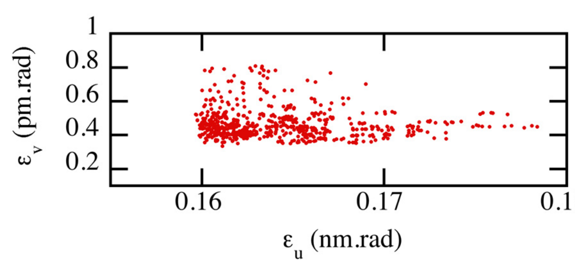

Figure 4: Emittance with machine imperfections.

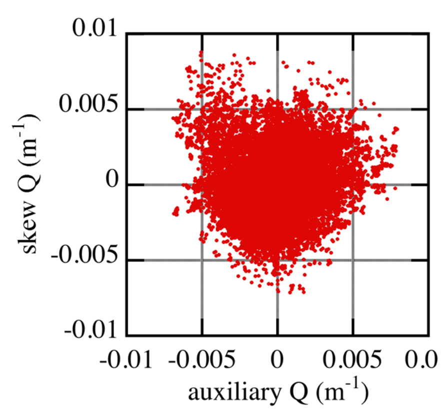

Figure 5: The auxiliary and the skew quadrupole fields.

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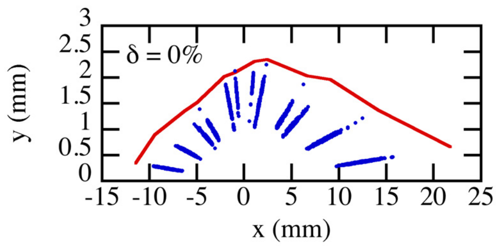

Figure 6: On-momentum DA after fine corrections.

A NEW COD CORRECTION SCHEME WITH VIRTUAL BPM'S

In some cases of the above simulations, we observed an unexpected emittance growth in the vertical direction. This was observed even when magnetic field errors, the BPM offset and sextupole fields were set to zero (see Fig. 7, where the COD induced by the misalignment of quadrupole magnets was corrected with SVD and the emittance was calculated). A typical COD in this case is shown in Fig. 8. The COD measured by BPM's at discrete positions was well corrected but unwanted local bumps were induced between some BPM's. The vertical dispersion function was generated by these local bumps since the beam passes through the off-center of the quadrupole magnets, and then the unexpected emittance growth was induced in the vertical direction.

Though such local bumps might be suppressed if we increase the number of BPM's and steering magnets, it will be difficult to find enough spaces for installing these in the MBA type storage rings. So, for avoiding these local bumps between the BPM's without increasing the number, we adopt the following new scheme of COD correction: (1) Measure COD when roughly corrected by steering magnets with SVD. (2) Estimate the natural COD (i.e. COD w/o steering magnets) by using the information of measured COD at BPM's, used steering kicks and the response matrix given by the ideal design lattice (RMDL). (3) Distribute an adequate number of dipole error kicks in the ring to simulate the estimated natural COD. The strength of these error kicks are calculated by using the RMDL analytically. (4) By using the RMDL, the actually used steering kicks and the evaluated error kicks of (3), calculate the COD between BPM's analytically. We call this process here the observation of COD by virtual BPM's. (5) Correct this interpolated COD using the position data at actual and virtual BPM's by the steering magnets with the RMDL.

We applied the above new scheme firstly to a 3GeV storage ring of SLiT-J [4] where the ring is constructed with 16 unit cells and has a simpler lattice structure than SPring-8-II. Such a ring with a simpler structure will be beneficial for gaining insights into the new scheme and improving it. The result is shown in Fig. 9. By applying COD corrections naively to the SLiT-J storage ring, unwanted local bumps are created between BPM's as shown by the red curve and the vertical emittance was as large as 20.6pm.rad. With our new scheme of COD correction, these local bumps are clearly suppressed as shown by the blue curve and the vertical emittance is decreased to 14.0 pm.rad without skew quadrupole magnets. Further investigations for improving the scheme are going to be done and the new scheme will be tested by applying to the SPring-8-II storage ring.

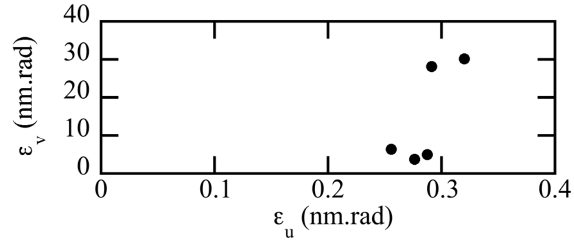

Figure 7: Emittance growth in the vertical due to misalignment of quadrupoles.

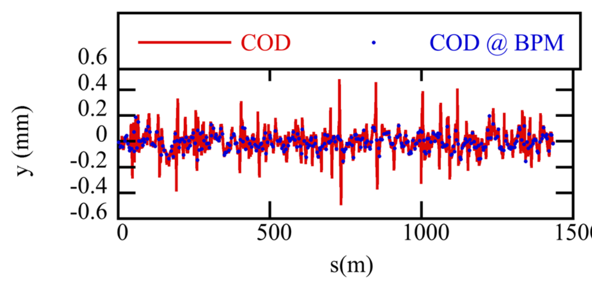

Figure 8: Continuous COD and sampled one by BPM.

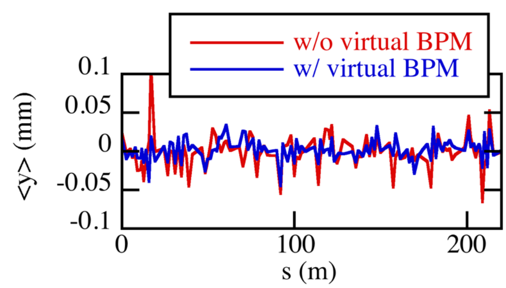

Figure 9: COD after correcting with virtual BPM.

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