LATTICE DESIGN OF A VERY LOW-EMITTANCE STORAGE RING FOR SPRING-8-II

Y. Shimosaki[#], K. Soutome, J. Schimizu, K. Kaneki, M. Takao, T. Nakamura and H. Ohkuma
JASRI / SPring-8, Hyogo, Japan.

Abstract

Beam dynamic issues for the sextuple-bend lattice (the natural emittance of 70 pmrad at 6 GeV) have been examined for an upgrade project of the SPring-8, the SPring-8-II, to enlarge dynamic aperture. The lattice design for the coming upgrade of SPring-8 is presented in detail.

INTRODUCTION OF SPRING-8 II

The SPring-8 is the electron storage ring for the third generation type synchrotron radiation facilities in Hyogo, Japan. The brilliant hard X-ray radiation has been provided for more than 10 years.

The design study for an upgrade project of the SPring-8, the SPring-8-II, is in progress [1-4]. Its ultimate goal is to provide a superior brilliance of photons by $10^2 \sim 10^3$ times higher than the present by reducing emittance of electrons until a diffraction limit in 2019 [1].

The emittance reduction by a multi-bend lattice on the low energy operation has been examined step by step, such as a double bend lattice (natural emittance of 2000 pm.rad at 6 GeV), a triple-bend lattice (400 pm.rad) and a quadruple-bend lattice (170 pm.rad) [5]. For an additional emittance reduction, the feasibility of a sextuple-bend achromat (6BA) lattice has been studied as the first candidate [1-4]. The main parameters are listed in Table.1. The additional emittance reduction from the natural emittance of 67.5 pm.rad to 10 pm.rad is planed by damping wigglers, which is the diffraction limit for 10 keV photons.

Table 1: Main Parameters of SPring-8 and SPring-8 II (lattice_ver: Aug.10,2011).

	SPring-8	SPring-8 II
Beam energy	8 GeV	6 GeV
Stored current	100 mA	300 mA
Lattice	Double bend	Sextuple bend achromat (6BA)
Natural emittance (0 current)	3400 pm.rad	67.5 pm.rad
σ_E / E (0 current)	0.109 %	0.096 %
Tune (Q_x, Q_y)	(40.14, 18.35)	(141.865, 36.65)
Natural chromaticity	(-88, -42)	(-475, -191)

* #shimosaki@spring8.or.jp

The lattice function of the 6BA lattice is shown in Fig.1. The ring is consisted of 44 unit cells and 4 long straights. The injection point is planed at the long straight as shown in Fig.1, at which the high-beta of 25 m is set for enlarging the dynamic aperture in the horizontal. Moreover, the low-beta of 1 m is set for the optimum photon brilliance by matching the emittance of electrons to the diffraction-limited emittance at the nominal straight in the horizontal and the vertical [6].

From the viewpoint of the stable user operation at the SPring-8 II, the off-axis injection is indispensable not only for the top-up operation but also for the nominal injection. The off-axis injection scheme by the quadruplole electric kicker has been proposed [2]. In the case of the SPring-8 II, the dynamic aperture of ±2 mm in the horizontal is required at the injection point.

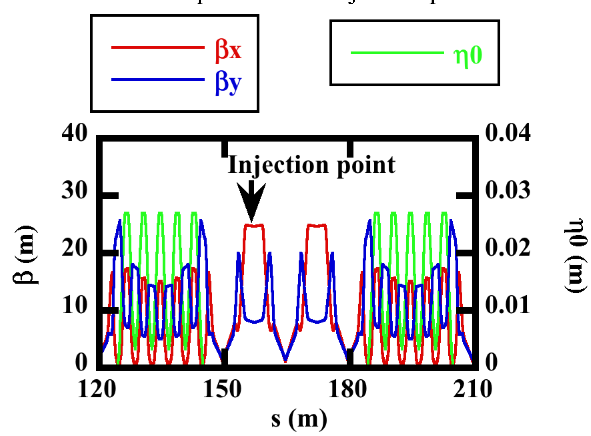

Figure 1: Lattice function of SPring-8 II.

STRATEGY OF LATTICE DESIGN

In general, the dynamic aperture of a low emittance lattice shrinks because of nonlinear phenomena induced by quadrupole magnetic fields (Qs) and sextupole magnetic field (Sxs) [5]. In the case of the SPring-8 II, 12 sextupole families are installed, and the strong Sx of $B''L / B\rho = 114$ m^{-2} is required to correct the large natural chromaticity listed in Table.1; in the case of the SPring-8 on the 6 GeV operation, the Sx of 0.3 m^{-2} is utilized. In addition, the alignment error of the Sx induces the Q field error ($\Delta Q / Q$ is about 10^{-3} m^{-1} with the Sx-alignment error of $\sigma = 10$ μm, where $Q = B'L / B\rho$ is the nominal Q's kick and $\Delta Q = 2\sigma B''L / B\rho$ is one induced by the Sx-alignment error), which also results in the shrinking of the dynamic aperture.

In order to enlarging the dynamic aperture until the required value, we have studied the nonlinear dynamic phenomena and have taken the countermeasures on 3 steps of "design of linear optics", "tune selection" and "design of nonlinear optics" in the lattice design.

In designing the linear optics, we have set the first priority to design the lattice as low natural chromaticity as possible. The strength of the Sx becomes smaller as the natural chromaticity is lower, which results in the smaller nonlinear forces and the lower Q field error by the Sx-alignment error mentioned above. The unit cell of the 6BA lattice is consisted of 4 minimum emittance parts and 2 matching parts [7]. The position and strength of the bending and quadrupole magnets have been determined for each part with this concept.

Concerning the tune selection, we have taken not only to avoid the strong resonances but also to adjust the betatron phase advance to provide nearly *-I* transformation for (non-) interleaves Sx into account [6]. The non-interleaved Sx is locally set inside the unit cell in the horizontal. Concerning the interleaved Sx, the phase advance is adjusted every 4 cells in the horizontal and every 2 cells in the vertical within the tolerance of the natural chromaticity growth and the natural emittance growth by changing the tune.

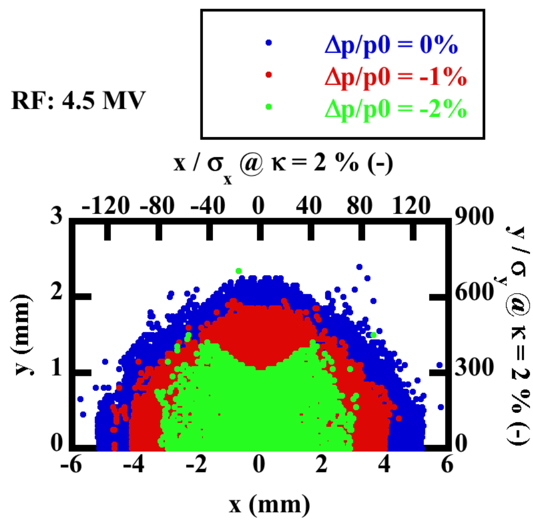

Figure 2: Dynamic aperture without error at injection point.

The nonlinear optics for the SPring-8 II has been optimized by 5 processes. (1) Nonlinear resonances independent on $\Delta p/p$ induced by the Sxs, such as $Q_x \sim$ int., $3Q_x \sim$ int., and $Q_x \pm 2Q_y \sim$ int., are corrected by the harmonic method: the amplitude of the resonant potential in the isolated resonance Hamiltonian [8] is Fourier analyzed, and the dominant term is set to zero by optimizing the Sxs. (2) Nonlinear resonances of $2Q_x \sim$ int. and $2Q_y \sim$ int. are induced by the Qs and Sxs for off-momentum particles. The Q-induced resonances are cancelled out by the Sx-induced resonances with the harmonic method. (3) (Non-)interleaved Sxs are utilized for suppressing the higher order resonances for on-momentum particles. (4) The momentum-dependent tune shift is suppressed under the process (2) because the off-momentum beta-beat also is suppressed by this correction [7]. Additional correction of the momentum-dependent tune shift is expected by the correction of the second-order dispersion function [9, 10]. The second-order dispersion can be corrected by the harmonic method same as the COD correction because of the closed form. (5) The amplitude-dependent tune shift can be corrected by adding the arbitrary Sxs as the knob, and numerically searching the expected values by changing the knobs with the processes (1), (2) and (4).

The strength of the Sx is determined by the simultaneous equations derived by the processes (1) and (2), and if required, (4) and (5). The latter means that the strength of the Sx for the processes (4) and (5) tend to become strong and the dynamic aperture may be small.

LATEST LATTICE

The lattice of the SPring-8 II has been designing by iterating the above steps, where 12 sextupole families have been optimized with PATRASH [8], and the tracking has been performed by CETRA [11] and ELEGANT [12]. Concerning the latest lattice design (lattice_ver: Aug.10,2011), the parameters of the linear optics are listed in Table.1, and the lattice function is shown in Fig.1.

The dynamic aperture for the ideal lattice (no error) at the injection point (bottom and left axes) is shown in Fig. 2, in which the upper and the right axes are the normalized coordinates by the r.m.s. beam size with the coupling factor of 2 %. The RF voltage of 4.5 MV and the radiation damping by bending magnet (power loss is 4 MeV) were included. Fig.2 indicates that the dynamic aperture for the on-momentum is enlarged beyond 100 σ_x in the horizontal.

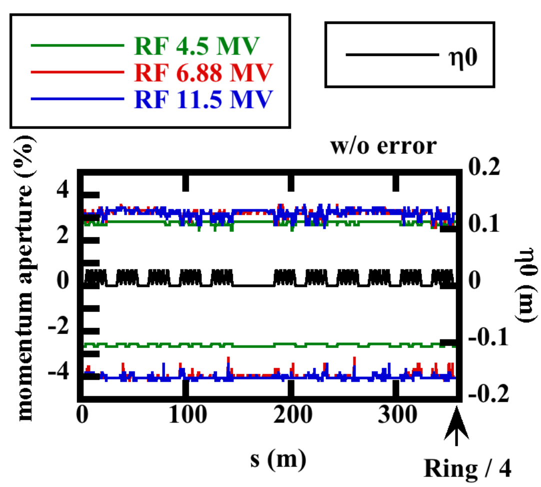

Figure 3: Momentum aperture without error.

The momentum aperture as the function of the RF voltage without the error is shown in Fig.3. The momentum acceptance is saturated over 6.88 MV, which means the momentum aperture is decided by the off-momentum dynamic aperture. The evaluated momentum acceptance for the ideal lattice is about $\Delta p/p = \pm 3$ %.

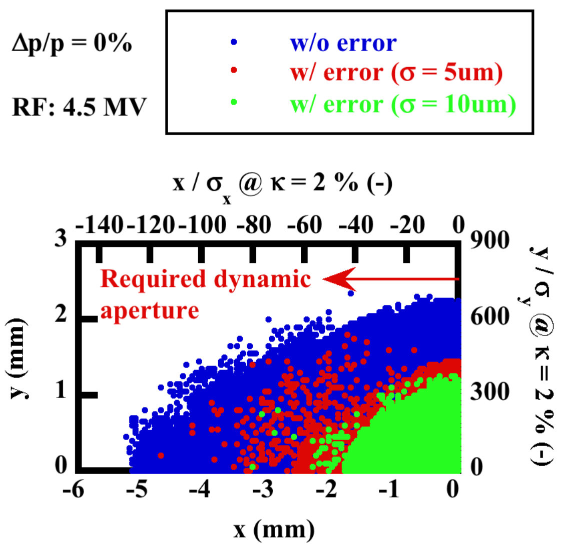

Figure 4: Dynamic aperture for on-momentum particles with Sx-alignment error at injection point.

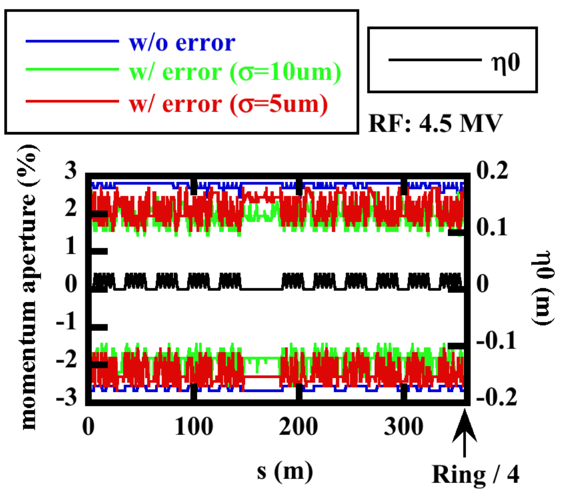

Figure 5: Momentum aperture with Sx-alignment error.

The Sx-alignment error induces the Q field error, which results in the serious shrinking of the dynamic aperture, that is zero aperture, if the optimization of the nonlinear optics is not sufficient. For revealing the effect of the optimization, the dynamic aperture and the momentum aperture were calculated with the Sx-alignment error, where the error-induced COD and beta-beat were not corrected. The Sx-alignment error was distributed along the ring by the Gaussian random with 2 σ cut. The dynamic aperture for the on-momentum particles is shown in Fig. 4 and the momentum aperture is shown in Fig.5. In this random pattern, the dynamic aperture with the error of σ = 5 μm is remained until the required dynamic aperture of ±2 mm (~50 σ_x), even though the strong Sx of $B''L$ / $B\rho$ = 114 m^{-2} is utilized. Concerning the observed shrinking of the dynamic aperture, it is thought from the frequency map analysis that the resonance of 2 Q_x ~ int. and Q_x + 2 Q_y ~ int. dependent on the amplitude-dependent tune shift is strengthened by the alignment error and the shrinking is caused. As shown in Fig.5, the momentum aperture with the error of σ = 5 μm is about $\Delta p/p$ = ±2 % on the RF voltage of 4.5 MV in this pattern. In this case, the Touschek lifetime with the intra-beam scattering effect [13] is estimated as 0.57 h for the electron beam of 0.1 mA / bunch (0.48 nC / bunch), against 0.5 h of the required lifetime from the injection [2].

SUMMARY

The design study for the SPring-8-II is in progress. We have plotted the strategy of the lattice design for enlarging the dynamic aperture on 3 steps of "design of linear optics", "tune selection" and "design of nonlinear optics" in the lattice design. Concerning the design of nonlinear optics, the harmonic method with the (non-)interleaved sextupole has been adopted for correcting nonlinear resonance independent on $\Delta p/p$, that for the off-momentum and the higher order resonance for the on-momentum.

Even though the strong Sx of $B''L$ / $B\rho$ = 114 m^{-2} is utilized, the dynamic aperture for the on-momentum was enlarged to 5 mm (120 σ_x) without the error and to 2.5 mm (60 σ_x) with the Sx-alignment error of σ = 5 μm (Gaussian Random, 2 σ cut), and the momentum acceptance was $\Delta p/p$ = ±3 % without the error and ±2 % with the same error.

The additional enlargement of the dynamic aperture and the momentum aperture, effects of IDs, and the correction scheme of errors will be studied in detail.

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