

DESIGN STUDY OF NONLINEAR OPTICS FOR A VERY LOW-EMITTANCE LATTICE OF THE SPRING-8 II

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Abstract

A feasibility of a very low-emittance storage ring has been studied for an upgrade project, SPring-8 II. Its ultimate goal is to provide a superior brilliance for 0.5 ~ 100 keV photons. A sextuple bend lattice with the natural emittance of 70 pmrad at 6 GeV has been examined as the first candidate. The nonlinear optics has been optimized to enlarge the dynamic aperture by correcting nonlinear resonances based on an isolated resonance Hamiltonian. In addition, the optimization with a genetic algorithm has been also examined from the viewpoint of the cross check for the optimization of the nonlinear optics.

INTRODUCTION

In order to advance promising science and to support industrial innovations, an upgrade plan of the SPring-8, the SPring-8 II, has been proposed [1]. In this plan, the emittance of a stored beam is reduced from 3.4 nmrad toward the ultimate goal of 10 pmrad, which corresponds to the diffraction limit for 10 keV photons, to provide a superior brilliance for 0.5 ~ 100 keV photons by $10^2 \sim 10^3$ times higher than the present.

As the first candidate of the SPring-8 II, the feasibility of a sextuple-bend achromat (6BA) lattice has been studied [2, 3]. The main parameters of the latest lattice design are summarized in Table.1. The additional emittance reduction from the natural emittance of 67.5 pm.rad to 10 pm.rad is planned by damping wigglers.

LINEAR OPTICS

The lattice function of the 6BA lattice is shown in Figure 1. In order to maximize the brilliance, the betatron function at the normal straight was set to 1 m in both horizontal and vertical directions for matching the emittance of electrons to the diffraction-limited emittance [4]. Since the dynamic aperture observed at the normal straight having a low-beta value becomes small in proportion to $\beta^{1/2}$, the horizontally high-beta (25 m) section is set at the long straight for beam injection. The damping wigglers are considered to be installed at the low-beta sections of the long straight.

Concerning the latest lattice (as of Sep.21,2011), which means the lattice designed after IPAC'11 [3], the rearrangement of the position of quadrupole and sextupole magnets was performed to effectively correct the linear chromaticity and dominant nonlinear resonances with much lower sextupole magnetic fields than those of Ref. [3]. The maximum sextupole fields could be suppressed from $B'' / B\rho = 834 \text{ m}^{-3}$ to 650 m^{-3} .

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Table 1: Main Parameters of SPring-8 and SPring-8 II (lattice design as of Sep.21,2011)

	SPring-8	SPring-8 II
Beam energy	8 GeV	6 GeV
Stored current	100 mA	300 mA
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)
Momentum compaction α_0	1.68e-4	1.55e-5

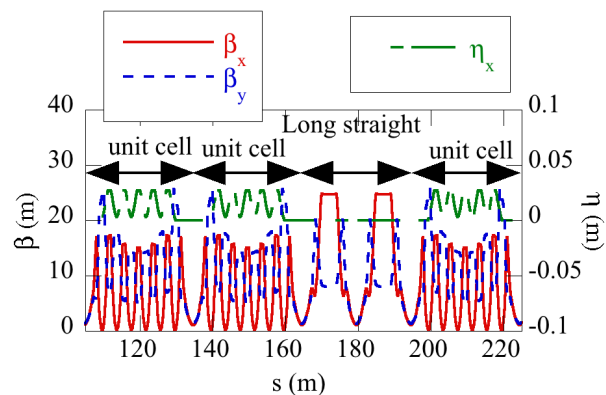


Figure 1: Lattice function of sextuple bend lattice.

NONLINEAR OPTICS OPTIMIZATION BASED ON HAMILTONIAN

The nonlinear optics for the SPring-8 II storage ring has been optimized by a harmonic method based on an isolated resonance Hamiltonian with the (non-)interleaved sextupole magnets [2]. Concerning the nonlinear resonances of $Q_x \sim \text{int.}$, $3 Q_x \sim \text{int.}$ and $Q_x \pm 2 Q_y \sim \text{int.}$ independent of the momentum deviation, where Q_x and Q_y are the horizontal and vertical tunes, respectively, the resonant potential in the isolated resonance Hamiltonian [5] is set to zero by optimizing the sextupole magnetic fields. For off-momentum particles ($2 Q_x \sim \text{int.}$ and $2 Q_y \sim \text{int.}$), quadrupole-induced resonances are cancelled out by superimposing the sextupole-induced resonances with the harmonic method.

In addition, in the latest lattice, the amplitude-dependent tune shift has aggressively been corrected by adding the sextupole magnets as the tuning knob and

numerically searching the expected values with simultaneous equations for the linear chromaticity and nonlinear resonances. The result is shown in Figure 2. The amplitude dependent tune shift of the latest design is drastically suppressed at $|x| \leq 2$ mm, which is the required region for the dynamic aperture in the SPring-8 II.

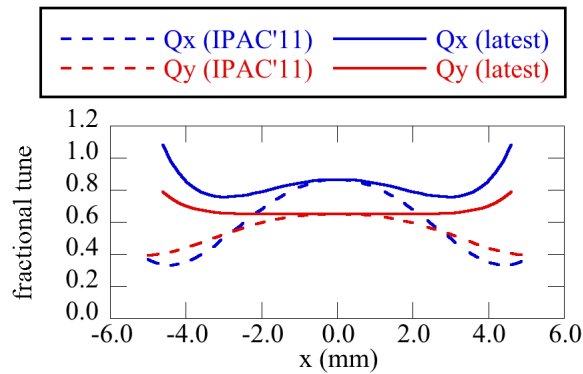


Figure 2: Amplitude dependent tune.

The dynamic aperture for the on-momentum particles at the injection point, where $(\beta_x, \beta_y, \eta) = (24.2 \text{ m}, 7.8 \text{ m}, 0 \text{ m})$, is shown in Figure 3, where the sextupole-alignment errors of $\sigma = 10 \text{ }\mu\text{m}$ were distributed along the ring according to the Gaussian distribution with the cut-off at 2σ . Dynamic aperture calculations were performed by changing the seed for random pattern generation, and the error-induced COD and beta-beat were not corrected for revealing the effects of the correction of the nonlinear resonances. We see that the horizontal dynamic aperture with the error is larger than ± 2 mm, which is the required value from the viewpoint of beam injection. It is noted that the tolerance to the sextupole-alignment errors of $10 \text{ }\mu\text{m}$ in the latest lattice is twice as large as that of Ref. [3]. It is thought that the much weaker sextupole magnetic fields due to the rearrangement of the lattice and the suppression of the amplitude dependent tune shift relax the tolerance to the sextupole-alignment errors.

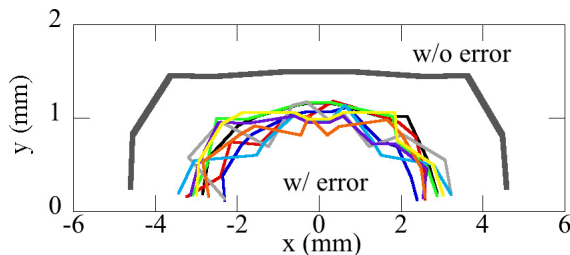


Figure 3: Dynamic aperture at injection point.

The position dependence of the momentum acceptance is shown in Figures 4 as the function of the RF voltage, where Figure 4(a) is the case of the ideal lattice (no errors) and (b) includes the sextupole-alignment errors of $\sigma = 10 \text{ }\mu\text{m}$ with the cut-off at 2σ . In the case of the ideal lattice, the momentum acceptance is saturated at $\delta = \pm 3\%$ over 6.9 MV . This means that the momentum acceptance below 6.9 MV is determined by the RF bucket and that over 6.9 MV is limited by the off-momentum

dynamic aperture. From Figure 4(b) we see that though the alignment errors of $10 \text{ }\mu\text{m}$ are distributed, we still have the momentum acceptance of about $\pm 2\%$ over 4.5 MV .

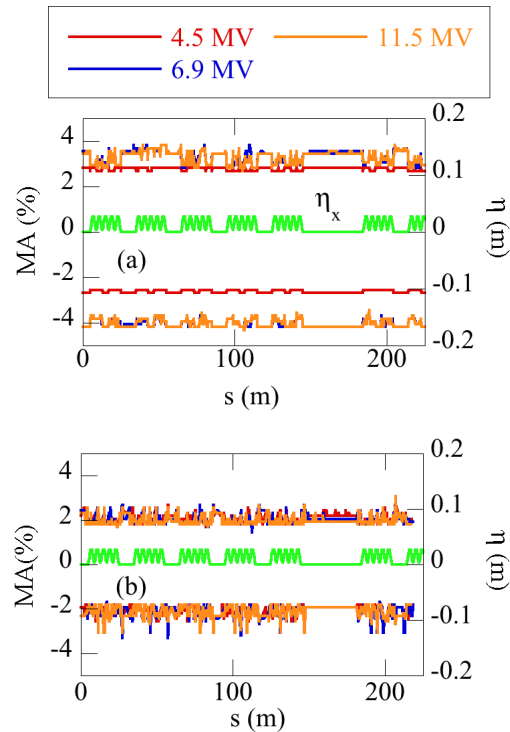


Figure 4: Momentum aperture without error.

So far, the nonlinear optics of the SPring-8 II has been optimized by the harmonic method based on an isolated resonance Hamiltonian. From the viewpoint of the cross check for the optimization of the nonlinear optics, a numerical optimization with a genetic algorithm has been examined for the SBA lattice, which has been developed for optimizing the (non-)linear optics of the present SPring-8 and its justification has been examined experimentally [6]. The sextupole magnetic fields determined from the Hamiltonian were set to the initial values, and new parameters were created by Gaussian random around the initial values. The new sextupole parameters to enlarge the dynamic aperture and to suppress the amplitude-dependent tune shifts were numerically searched with the genetic algorithm. As the conclusion, in the results with the genetic algorithm, the initial value determined by the Hamiltonian itself showed the largest dynamic aperture. It is thought that, when the number of sextupole magnets is more than the degree of freedom to correct the linear chromaticity and nonlinear resonances, where 12 sextupole families are utilized in the SBA lattice, the Hamiltonian can straightforwardly indicate the strict solutions and a genetic algorithm may not be so effective. On the other hand, the (non-)linear optics of the present SPring-8 has been effectively optimized with the genetic algorithm, where 6 sextupole families are implemented in the unit cell and the dominant nonlinear resonances cannot be corrected strictly [6]. It seems that the genetic algorithm should be one of effective

tools for optimizing the (non-)linear optics, not strictly but globally and approximately.

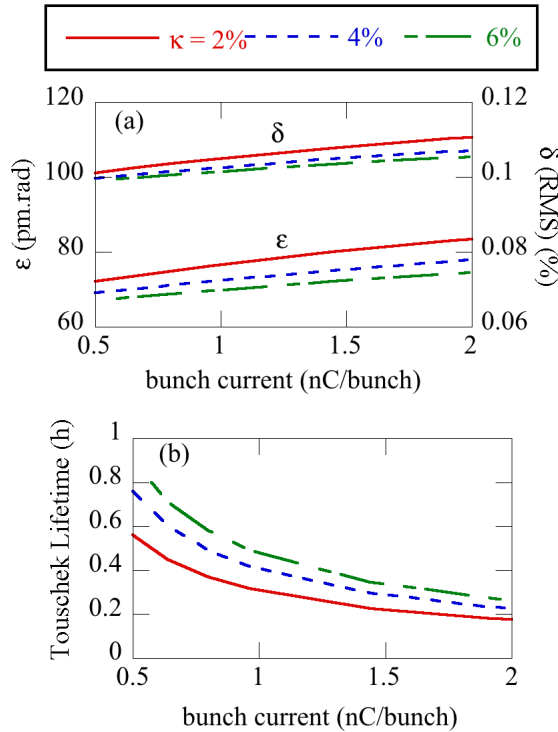


Figure 5: (a) Emittance and momentum deviation with intra-beam scattering effects and (b) Touschek lifetime with SX-alignment errors of $\sigma = 10 \mu\text{m}$ (with the cut-off at 2σ).

INTRABEAM SCATTERING AND BEAM LIFETIME

By using the results of Figure 4(b), the emittance growth due to the intra-beam scattering and the Touschek lifetime were estimated as the function of the coupling factor κ [7, 8]. The emittance growth is shown in Figure 5(a), and the Touschek lifetime is given in Figure 5(b), where the results of intra-beam scattering were used to calculate the Touschek lifetime. Since too high RF voltage causes the bunch shortening and results in the serious emittance growth and lifetime shortening, the RF voltage of 4.5 MV was chosen in the calculations.

Figure 5(a) indicates that the emittance growth with the coupling factor of 2% is less than 20% in the horizontal and longitudinal directions at the bunch charge of 1 nC / bunch, which corresponds to 0.2 mA / bunch.

The lifetime of more than 0.5 hour is required to store the beam current of 300 mA in the ring and to keep the stored current stability of the order of 0.01% when the XFEL (SACLA) linac is used as an injector [1]. It seems that, by controlling the coupling factor, the enough lifetime can be achieved at the required level at the bunch current less than 1 nC / bunch. In order to achieve a longer lifetime at a higher bunch current and/or to suppress the emittance growth by the intra-beam

scattering, a control of bunch length by a higher harmonics RF cavity has been proposed [1].

SUMMARY AND FUTURE OUTLOOK

In designing the SPring-8 II storage ring, the rearrangement of the magnetic position to suppress sextupole magnetic fields and the suppression of the amplitude dependent tune shift were performed. Then the tolerance to the sextupole-alignment errors was relaxed. The additional enlargement of the dynamic aperture and momentum aperture will be studied with the effects of IDs.

From the viewpoint of the cross check for the optimization of the nonlinear optics, the numerical optimization with a genetic algorithm has been examined. It seems that the optimization with the Hamiltonian and / or the genetic algorithm should be properly used depending on the situation, and that the genetic algorithm may not be so effective when the strict solution can be derived by the Hamiltonian.

Recently, a quintuple bend achromat lattice (5BA) has been studied as the second candidate in order to enhance the feasibility of the SPring-8 II, where the natural emittance is 77 pmrad at 4.5 GeV. The (non-)linear optics will be optimized with the Hamiltonian and / or genetic algorithm.

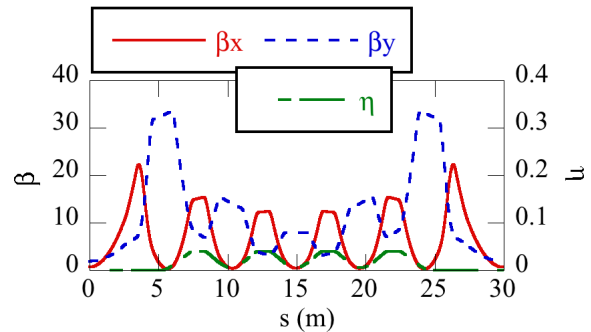


Figure 6: Lattice function of 5BA lattice.

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