NON-LINEAR OPTIMIZATION OF STORAGE RING LATTICE FOR THE SPring-8 UPGRADE

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Abstract

A lattice of a newly designed 6GeV electron storage ring for the SPring-8 upgrade project is of a 5-bend achromat type. The betatron phase between the two dispersion arcs is set to $(2n+1)\pi$ to suppress harmful effects of chromaticity-correcting sextupoles, By detuning this phase, optimizing sextupole strengths in a cell and introducing octupoles, we can obtain a sufficient dynamic aperture for beam injection even for the symmetry-broken ring having four long straight sections and a high-beta injection section. However, the off-momentum behavior such as the non-linear chromaticity needs to be optimized to achieve a target momentum acceptance of 3% or larger. We hence extended the excitation pattern of sextupoles from one unit cell to plural cells to increase the number of tuning knobs. By this scheme we succeeded in suppressing the lowest order coefficients of amplitude-dependent tune shift and the second order chromaticities at the same time. Results of the optimization will be presented together with a problem still remained.

INTRODUCTION

A project of upgrading the SPring-8 facility is ongoing to convert the present storage ring to a high-coherence hard X-ray source (SPring-8-II) [1, 2]. The present ring has a lattice structure of the double-bend (DB) type and the natural emittance is 6.6nmrad for achromat optics and 2.4nmrad for non-achromat optics at the beam energy of 8GeV. The upgrade project aims at reducing the emittance by a factor of more than 10, and we plan to change the lattice type to a multi-bend one. Since the project is not a green field build, there are some constraints, which are important from a viewpoint of lattice designing, that the present machine tunnel must be reused and the X-ray source point of insertion device beamlines must be kept unchanged. To make the project feasible we also impose that quadrupole and sextupole magnets must have moderate strengths so that they can be built with a conventional method. Under these constraints we tested several kinds of multi-bend lattice and adopted a 5-bend achromat design as a new lattice. In designing this lattice we introduced a bending magnet with longitudinal gradient [3] in the arc section to reduce the emittance as much as possible: a bending magnet in the arc was divided into three segments and the strength of each segment was optimized to achieve a lower emittance value.

Since the emittance is proportional to the square of the energy, we can further reduce the emittance by lowering the beam energy from 8GeV to 6GeV. The shift of synchrotron radiation spectrum to lower energy regions can be compensated by shortening a period length of undulators. Lowering the operation energy also has a merit that the energy loss by bending magnets is reduced from a present value of 9MeV/turn to 3MeV/turn. This enhances the damping effect by insertion devices and it is expected that the actual emittance in user operation is reduced by more than 20~30% from a design value.

At present the arrangement of main magnets in a unit cell is almost fixed, and linear and especially non-linear optimization is ongoing to obtain better stability of both on- and off-momentum particles, i.e. a wider dynamic aperture (DA) for higher efficiencies of beam injection and a larger momentum acceptance (MA) for longer beam lifetime. In what follows we describe our design of linear optics and the present status of non-linear optimization. The effectiveness of a method of extending sextupole excitation pattern from one unit cell to plural cells will be discussed.

LINEAR OPTICS DESIGN

In Fig. 1 we show a unit cell structure of the 5-bend achromat lattice. There are two "dispersion bumps" in a cell and sextupole magnets are placed only inside these arcs for correcting the natural chromaticities. The betatron phase difference between the two arcs $\Delta\psi^{(arc)}$ is basically set to $(2n+1)\pi$ to cancel dominant effects of non-linear kicks due to sextupoles [4–6]. This new type of multi-bend lattice was first proposed by the ESRF [7, 8]. In our lattice, some concepts of the ESRF design were incorporated and some were not to fit into the SPring-8 case.

For example, we have chosen a 5-bend structure and not a 7-bend one. The number of bending magnets was determined by considering a balance between a figure of merit (light source performance) and technological feasibility. Since the space is limited, the 7-bend structure inevitably requires that some bending magnets must be of a combined-function type with strong (de-)focusing. We have checked that in such a ring, misalignment of strong combined magnets of the order of 100μm easily generates a vertical emittance of 50pmrad [9] and a final performance will become comparable to the 5-bend lattice which can be built with conventional magnets.

Since the present ring has four long straight sections (LSS's) and the machine tunnel will be reused, the new

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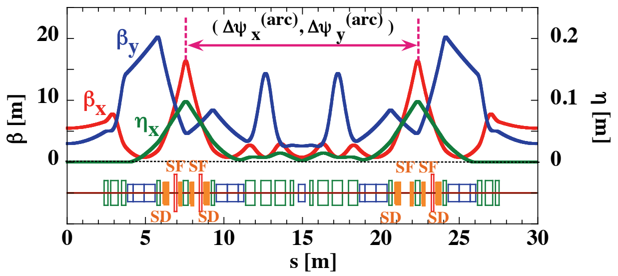

Figure 1: A unit cell of the 5-bend achromat lattice. The β_x and β_y are the horizontal and vertical betatron functions and η_x is the dispersion function. The arrangement of bending, quadrupole, sextupole and octupole magnets is shown by the blue, green, orange (solid) and red boxes, respectively.

ring also has to have LSS's at the same place (by a geometrical reason). For the LSS we have tentatively chosen a simple lattice structure made by only quadrupole magnets. The betatron phase is matched as $(\Delta\psi_x, \Delta\psi_y) = (2\pi, 2\pi)$ to keep the symmetry of ring for on-momentum particles. The local chromaticity of the LSS section is suppressed to $(\Delta\xi_x, \Delta\xi_y) = (-0.86, -1.71)$ not to deteriorate the off-momentum acceptance.

For beam injection we modified the structure of two unit cells located upstream and downstream of the injection point. The horizontal betatron function takes a large value of 30m at the injection point. To keep the dynamical stability, we put a constraint on the betatron phase over the two cells as $(\Delta\psi_x, \Delta\psi_y) = (9\pi, 4\pi)$.

In Table 1 we list machine parameters. For comparison, parameters of the present ring are also shown. A design value of the natural emittance is 140pmrad and in user operation it will be reduced to about 100pmrad by the damping effect of undulators. The betatron functions at straight sections are lowered to β_x=5.5m and β_y=3.0m to obtain higher brilliance and coherence.

Table 1: Machine Parameters

	New Ring	Present Ring
Lattice Type	5-BA	DB
Energy [GeV]	6	8
Circ. [m]	1435.45	1435.95
Nat. Emittance [nmrad]	0.14	6.6 (Achromat) 2.4 (Non-Achr.)
Tune (ν_x, ν_y)	(109.14, 42.34)	(40.15, 18.35) A (41.14, 19.35) NA
Nat. Chrom. (ξ_x, ξ_y)	(-155, -146)	(-90, -41) A (-117, -47) NA
Beta at Straight (β_x, β_y)	(5.5, 3.0)	(24.4, 5.8) A (31.2, 5.0) NA
Mom. Compct.	3.32e-5	1.46e-4 A 1.60e-4 NA
Ene. Spread [%]	0.093	0.109

NON-LINEAR OPTIMIZATION

Sextupole Optimization in Unit of One Cell

Though the phase matching between arcs (interleaved-sextupole scheme) works to a certain extent, the cancellation is not perfect and we need to make additional tuning for controlling non-linearity of the lattice.[*] In optimizing sextupole strengths we first assumed that the periodicity of sextupole potential is the same as that of linear optics. In this case the main knobs to control the non-linearity are strengths of sextuoples and auxiliary octupoles within a cell, the betatron phase difference between the arcs $(\Delta\psi_x^{(arc)}, \Delta\psi_y^{(arc)})$ and the betatron tune per unit cell. We then tried to suppress the coefficients of amplitude-dependent tune shifts (ADTS) in the lowest order of sextupole perturbation [10] to enlarge the on-momentum DA: $\Delta\nu_x = \alpha_{xx}J_x + \alpha_{xy}J_y, \Delta\nu_y = \alpha_{yx}J_x + \alpha_{yy}J_y$, where $\alpha_{yx} = \alpha_{xy}$ and J_z is the action variable (z=x or y) and can be written as $J_z = z^2/(2\beta_z)$ at the center of straight sections with $z' = 0$. Since the number of tuning knob is not so many, we have broken a symmetry of excitation pattern of sextupoles in a cell. For example, sextupoles shown in Fig. 1 are excited in such a way as [SD1-SF-SF-SD2, SD2-SF-SF-SD1].

Figures 2 show an example of response of the lowest-order coefficients of ADTS to $(\Delta\psi_x^{(arc)}, \Delta\psi_y^{(arc)})$ and to sextupole strengths. In these calculations we first set a base design of linear optics and sextupole strengths and then calculated the coefficients by changing $(\Delta\psi_x^{(arc)}, \Delta\psi_y^{(arc)})$ by hand. A point on each curve indicates that the corresponding coefficient α_{ij} becomes zero at that phase condition. Though this is not a fully consistent calculation, it works to estimate the next target point in an iteration procedure.

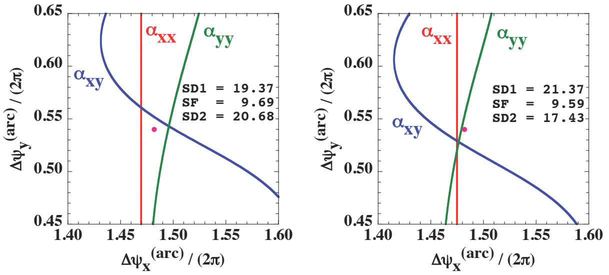

Figure 2: Response of ADTS. The coefficient α_{ij} vanishes on each curve. A dot near the center corresponds to a base design of linear optics. The sextupole strength is $B''L/[B\rho]/2$ in units of m^{-2}.

After some iteration procedures we obtained a candidate set of linear optics and sextupole strengths for a unit cell. We then added three families of octupole magnets as an auxiliary knob and made a final tuning for a whole ring by taking account of ADTS and the excitation strength of non-linear resonances due to sextupoles and octupoles. An example of such optimization results is shown in Figs. 3 [1].

For the beam injection we are planning to use SACLA as a high-quality beam injector [2], and we checked by com-

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[*] In calculations of this section slightly different versions of lattice from Fig.1 are used but main conclusions are not affected by this.

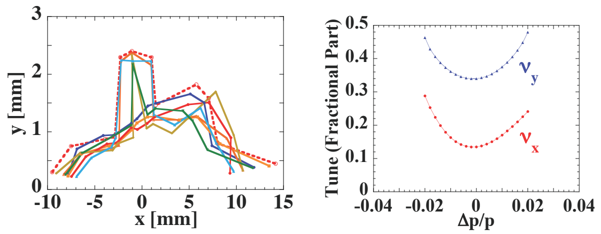

Figure 3: Left: The dynamic aperture for on-momentum electrons calculated at the injection point where β_x = 30m and β_y = 3m. The dashed line is for the ideal ring, and the solid lines are for the ring with sextupole alignment errors of 25μm in rms. The beam is injected at around x=-3mm. Right: The energy dependence of the betatron tunes.

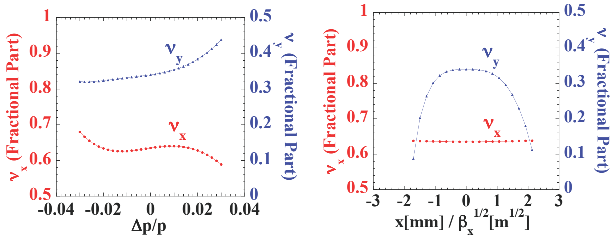

Figure 4: The energy dependence (right) and the horizontal amplitude-dependence (left) of the betatron tunes for the ring constructed by 42 cells. Sextupoles are excited in a 3-cell periodicity and auxiliary weak octupoles are used.

puter simulations that the DA as shown in Fig. 3 (left) is sufficient for carrying out beam commissioning and successive beam tuning: We could obtain a sufficient DA for the symmetry-broken ring having four LSS's and a high-beta injection section and found no obstacles to the beam commissioning. However, the off-momentum behavior such as the non-linear chromaticity still needs to be optimized, since the average value of MA is about 2%. This causes shortening of beam lifetime and will affect the stability and flexibility of machine operation. One reason for this is a large second order chromaticity as shown in Fig. 3 (right). To enlarge MA as much as 3% (or more) we must control and limit the tune footprint due to energy deviation.

Optimization over Plural Cells

To this end we tried to extended the periodicity of sextupole excitation pattern from one unit cell to plural cells. By this extension we can increase the number of available knobs to control the lattice non-linearity [11, 12]. We examined the efficiency of this method by changing the periodicity of sextupole excitation pattern from 1 cell to 2, 3 and 4 cells. For each trial pattern, sextupole strengths were fitted to suppress the second-order chromaticities [13] in addition to the lowest-order coefficients of ADTS. The most efficient pattern we found up to now is a 3-cell periodicity as [S1-S2-S2-S3, S3-S2-S2-S1] [S4-S5-S5-S6, S6-S5-S5-S4] [S1-S2-S2-S3, S3-S2-S2-S1]. By combining with a tuning knob of ($\Delta\psi_x^{(\mathrm{arc})}$, $\Delta\psi_y^{(\mathrm{arc})}$) as shown in Fig. 2, we can find in an iterative way a set of sextupole excitation pattern which suppresses the lowest-order coefficients of ADTS and the second-order chromaticities at the same time. Figures 4 illustrate such an example. In this calculation the ring constructed by 42 normal cells was used (without LSS's and the injection section), since we should suppress non-linear terms firstly for a periodic cell structure and then consider the whole ring with broken symmetry.

As seen from Figs.4 the second order chromaticity is well suppressed. However, the vertical tune decreases rapidly for large horizontal amplitudes and this seems to limit the dynamic aperture. This tendency is observed in all of our optimization calculations and will suggest that we need to include not only the lowest order terms but also higher order terms in the optimization procedure in a comprehensive manner. The development of such an optimization scheme is our next target and studies are ongoing.

SUMMARY

In this paper we presented a design of linear optics of the SPring-8-II storage ring and discussed the optimization of sextupole strengths for suppressing the ADTS and chromaticities. We extended the excitation pattern of sextupoles to plural cells and found that a 3-cell periodicity is most efficient in our case. Though we succeeded in suppressing the lowest order coefficients of ADTS and the second order chromaticities, it seems that higher order contributions to ADTS has become predominant. We are now developing an optimization scheme that can treat such contributions.

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