A DESIGN APPROACH OF THE BEAM OPTICS IN THE COMPLEX STORAGE RING

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Abstract

Beam optics design is a crucial issue in modern synchrotron radiation facility. A design approach of the beam optics is presented here. It provides much convenience for effectively exploring achievable linear optics and globally investigating flexibility of a complex lattice with super-periodicity. Low-α_C optics is emphasized, and the SSRF storage ring is taken as a test lattice.

INTRODUCTION

In modern synchrotron radiation facility, providing very high brightness photon, a compact and complex strong focusing structure is required to reach a low beam emittance and save much circumference of the ring for insertion devices. Double Bend Achromatic (DBA) cell and Triplet Bend Achromatic (TBA) cell are usually used to obtain a small beam cross section [1, 2]. Multi-objective genetic algorithm has been introduced in the linear optics design. Its application in a TBA-based hybrid lattice with six quadrupole families obtained very interesting results [3, 4], and showed its broad prospects in the complex lattice.

If the multi-objective genetic algorithm is applied to find the stable linear optics in the SSRF-like lattices with super-periods, most of the results will lose periodicity in the standard cells due to mismatch of the matching cell. It is possible to restore the periodicity of this mismatched optics with a fitting algorithm based on gradient information, but the efforts are not paid by any objective beam parameter due to the large adjustment. So, it would be improved to be competent in this kind of complex lattice.

We adopt a matching method of fractional steps [5] to explore achievable linear beam optics in the SSRF-like lattice. The first step is to replace the matching cell with the standard cell, and thus the complex lattice becomes a perfectly cell-periodic lattice. The multi-objective genetic algorithm is applied in this cell-periodic lattice to result in a lot of stable linear optics and do a global investigation. The second step is to find matching cell setting by converging optical parameters of the matching point to the ones of standard cell. The third step is to recover the super-periodicity of the lattice with the resulted standard cell setting and the associated matching cell setting.

SSRF STORAGE RING

The SSRF storage ring consists of 20 DBA cells, forming four super-periods. Fig. 1 shows the lattice layout and the nominal linear optics in one fold of the ring. The lines from A to B and from C to D are two half-DBA cells that connect to be the matching cell. All the quadrupoles in the matching cells are classified into five families (QL1, QL2, QL3, QL4, and QL5). The line from B to C includes three DBA standard cells and two half-DBA standard cells, where all the quadrupoles are classified into another five families (Q1, Q2, Q3, Q4, and Q5). Point B and C that locate in the center of SF (focusing sextupole for chromaticity correction) are the matching points. If we replace the matching cells with the standard cells, the lattice becomes perfectively 20-periodic, the circumference of the ring becomes 406.6 m from 432 m, and only five quadrupole families are included. We firstly explore the stable linear optics of the new lattice, where the global beam parameters are emphatically considered, and then find the matching cell's settings to recover the four-super-periodic lattice.

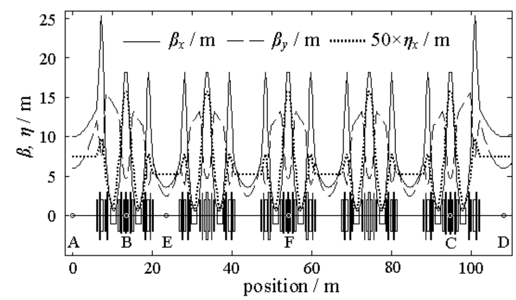

Fig. 1: Lattice layout and nominal linear optics in one fold of the SSRF storage ring

GLOBAL INVESTIGATION

The first generation of genetic algorithm obtained a lot of stable linear solutions by random setting of the quadrupole strengths. It is in fact feasible to do one-turn tracking in one cell, and then scale the beam parameters (such as the tune and the chromaticity) by the number of the periodicity to be the ones of the whole ring. It can save much tracking time. All the settings are within hardware restriction and maintain individual polarizations of quadurpoles (Q1, Q3, and Q4 are defocusing, Q2 and Q5 are focusing). Large size of the first generation is beneficial to global investigation of all the linear optics in this given lattice. Fig. 2 plots some beam parameters of all these stable linear optics as a function of the horizontal tune, including the natural emittance, the momentum compaction factor, and the natural horizontal chromaticity.

When the horizontal tune is larger than 20, the decrease of the natural emittance is very few, but with an enormous increase of the natural horizontal chromaticity. This is the reason why most of the third generation light source storage rings are set by a horizontal phase advance slightly larger than 2π in one DBA cell. The low-α_C optics is expected to be obtained in the tune ranges from 10 to 20 and from 20 to 30.

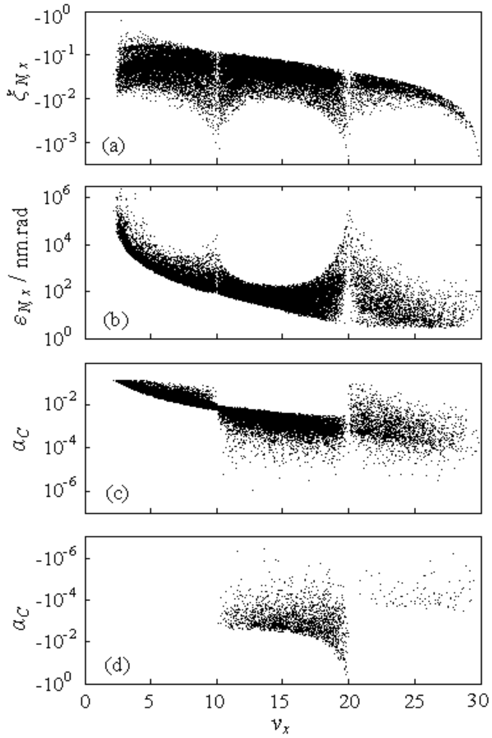

Fig. 2: Beam parameters as a function of the horizontal tune, (a) is the natural horizontal chromaticity, (b) is the natural emittance, (c) is positive values of the momentum compaction factor, and (d) is negative ones

LOW-ALPHA OPTICS DESIGN

Linear optics

It is well-known that the low-α_C will be reached by decreasing the dispersion in the straight section. Unfortunately, the α_C increases with the reduction of the dispersion in the straight section while maintaining other optical parameters as the nominal optics (its tune is 22.22 (H), 11.29(V)) in the SSRF storage ring. It is one of the motivations of this job how to comprehend its mechanism and adjust other parameters.

The process is started with the first generation shown in Fig. 2. The low-α_C settings are selected out generation by generation. Three kinds of low-α_C optics that are expected by theory are found out, shown as Fig. 3. Table 1 summarizes the beam parameters of the ring.

It is realized that Case (i) and Case (ii) shown in Fig. 3 are obtained only with the horizontal tune from 10 to 20, and Case (iii) only form 20 to 30. The linear structural resonance Q_x=20 is a critical line. The reason is that Case (i) and (ii) need weaker focusing, while Case (iii) needs stronger focusing. The negative-α_C modes have the same distribution in the horizontal tune as the low-α_C modes.

Table 1. Main parameters of the three low-α_C modes in the SSRF 20-cell-periodic lattice

Parameter	Case i	Case ii	Case iii
ν_x, ν_y	17.06, 8.17	18.46, 8.11	24.89, 11.83
$\varepsilon_{N,x}$ / nm.rad	55.4	84.0	12.2
ξ_x, ξ_y	-27.4, -14.2	-26.9, -19.5	-67.8, -25.2
α_C	3.92×10^{-6}	8.39×10^{-6}	5.88×10^{-6}

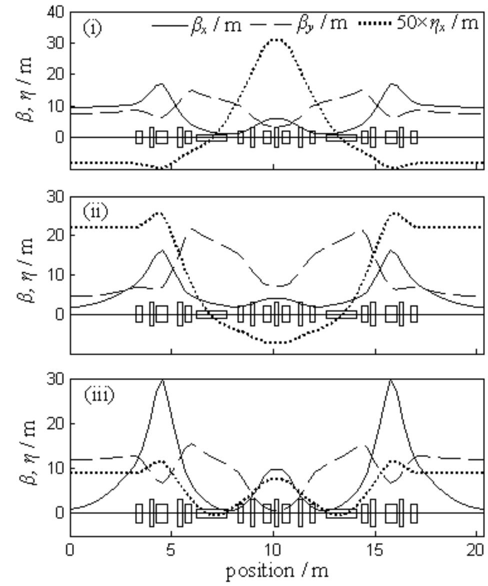

Fig. 3: Three low-α_C optics in one cell of the SSRF 20-cell-periodic lattice.

Case (i) is the common mode that is extensively adopted in the third generation light sources. It can be smoothly adjusted down to a negative α_C by decreasing the dispersion in the straight section. Because of the higher dispersion in the arc cell, the natural chromaticity can be easily corrected by the sextupoles located in the arc cell. The momentum compaction factor of Case (ii) can be smoothly adjusted down to a negative value by increasing the dispersion in the straight section. The chromaticity correction can be fulfilled by the harmonic sextupoles. In Case (iii), the low momentum compaction factor is obtained, with a not too large natural emittance. However, because of the larger natural chromaticity and the lower dispersion distributing along the ring, the chromaticity correction is impractical with the current sextupole hardware. Case (i) is used to be the standard cell setting, and its associated matching cell setting is to be found out by converging optical function (β_x, β_y, and η_x) at the matching point to be 6.0847, 3.5122, and 0.6154 m respectively. The results are plotted in Fig. 4 (a). Fig. 4 (b) plots the optics in one fold of the SSRF storage ring after being added with the standard cell and the matching cell setting, where a little disturbance is observed. Fig. 4 (c) plots the periodicity-restored optics. Table 2 summarizes the beam parameters of the ring.

Table 2. Main parameters of the low-α_C mode of the SSRF storage ring.

Parameter	Value
Circumference / m	432.0
Beam energy / GeV	3.5
Tune ν_x, ν_y	17.37, 8.23
Emittance / (nm.rad)	59.2
Natural chromaticity ξ_x, ξ_y	-28.13, -15.04
Momentum compaction factor	4.46×10^{-6}
Energy loss per turn / MeV	1.435
RMS energy spread	9.85×10^{-4}
Damping times τ_x, τ_y, τ_s / ms	7.02, 7.02, 3.51

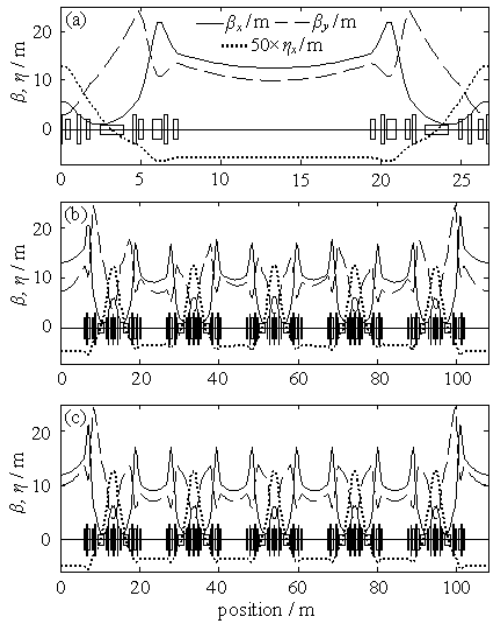

Fig. 4: Linear optics design of the low-α_C optics in the SSRF storage ring.

Nonlinear optimization

A successful suppression for the 2nd order α_C is expected to obtain a large energy acceptance, but here we used a more direct method to enlarge the energy acceptance and the dynamic aperture simultaneously. The solution are also improved generation by generation with the method of multi-objective genetic algorithm. The energy acceptance size, its linearity, and the horizontal dynamic aperture size are taken as the objective functions. Becauese the low-positive-α_C optics has three stable points in the longitudinal phase space, the α_C is adjuested to a low-negative value, which can have one stable point. A good result is plot in Fig. 5 and Fig.6. More details of the nonlinear optimization can be found in Ref. [6].

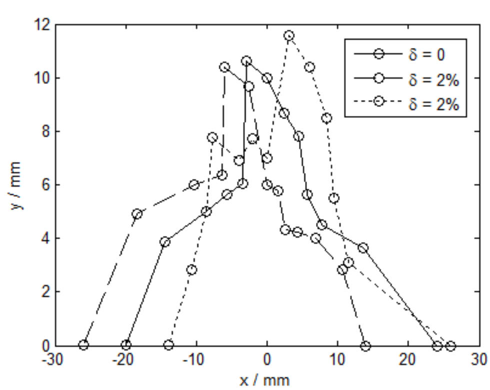

Fig. 5: Dynamic aperture (injection point) of the SSRF storage ring with a low-negative α_C optics

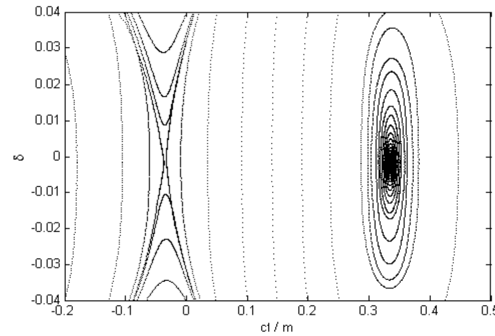

Fig. 6: Longitudinal phase map of the SSRF storage ring with a low-negative α_C optics

OTHER OPTICS FOR SSRF

It is revealed from the global investigation that the SSRF storage ring can reach low emittance as 5 nm.rad or so, when the horizontal tune is slightly larger than 20. Its identified optics can be easily obtained with the above design process. Two operation modes have been reported in Reference [7]. The ultra-low emittance is 2.5 nm.rad with the beam energy of 3.5 GeV, resulting from the exploring. Unfortunately, it is impractical because of the strong nonlinearity and the difficulty of chromaticity correction with current hard-ware. If the horizontal tune is set to 15 or so, the nonlinearity is very weak. The dynamic aperture will be large enough for injection without any harmonic compensation. This concept is beneficial for the commissioning of a new machine. The negative-α_C optics can be obtained by increasing (Case-ii-based) or decreasing (Case-i-based) the dispersion in the straight section.

CONCLUSIONS

The design strategy, combining the matching method of fractional steps, the multi-objective genetic algorithm, and the fitting algorithm based on gradient information, is applied in the SSRF storage ring. Global investigation for the linear optics in the SSRF storage ring has been done, and the results show a great flexibility. Three kinds of low-α_C optics are obtained in the SSRF storage ring, and two of them, with horizontal tune from 15 to 20, are feasible.

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