DESIGN AND COMMISSIONING OF THE VERY LOW EMITTANCE OPTICS IN THE SSRF STORAGE RING

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Abstract

In synchrotron radiation light sources, there are continuous efforts to lower emittance and thus increase photon brightness. A systematic analysis method based on Multi-Objective Genetic Algorithm (MOGA) is applied to explore the very low effective emittance optics for Shanghai Synchrotron Radiation Facility (SSRF). Results of design and commissioning of this kind of optics are presented, including 3.5GeV and 3.0GeV beam energy.

INTRODUCTION

When photon diffraction emittance is small enough, photon brightness is inverse proportional to the beam effective emittances. In Tanaka's paper [1], the horizontal effective emittance is derived as:

$$\varepsilon_{x,eff}(s) = \sqrt{\varepsilon_x^2 + H(s)\delta_E^2\varepsilon_x}\ ,$$

where ε_x is the natural emittance, δ_E is the energy spread, and

$$H(s) = \gamma_x\eta_x^2 + 2\alpha_x\eta_x\eta_x' + \beta_x\eta_x'^2\ .$$

The Theoretical Minimum horizontal Effective Emittance (TMEE) of the Double Bend Achromatic (DBA) structure is derived as:

$$\varepsilon_{x,eff.\min.} \approx \frac{1}{2}\varepsilon_{x,achro.\min.},$$

where $\varepsilon_{x,\ achro.\ min.}$ is the well-known DBA's achromatic Theoretical Minimum Emittance (TME), which is 4.5 nm.rad in the 3.5 GeV storage ring of SSRF. So, TMEE of the SSRF storage ring is about 2.25 nm.rad.

SSRF has been operated for users' experiments since May 2009 [2, 3]. Fig. 1 plots the nominal operation optics, and Table 1 summarizes the main parameters in the storage ring, including the designed ones and the measured ones. Since the nominal optics has been well operated, we are also interested in how much the available lowest emittance is, not only TME or TMEE.

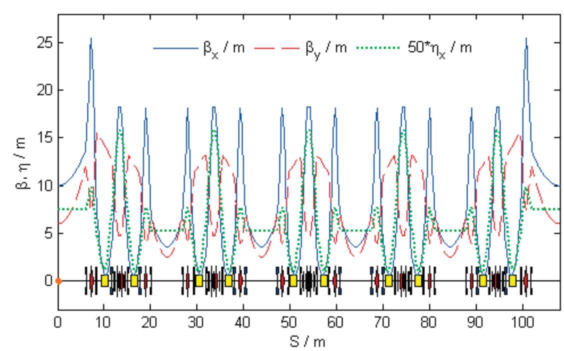

Figure 1: Nominal linear optics in SSRF.

It is desired to do a systematic analysis, which seems to be a tedious process. Multi-Objective Genetic Algorithm (MOGA) are developed or applied in ALS in

Table 1: Beam Parameters of the SSRF Storage Ring

Parameter / unit	Design value	Measured value
Beam energy / GeV	3.50	3.50±0.02
Beam current / mA	200~300	210 (operation current) 300 (achievable)
Tune (H, V)	22.22, 11.29	22.220, 11.290 (±0.002)
Natural emittance / nm.rad	3.89	3.8±0.2
Coupling	1%	0.3%
Natural chromaticity (H, V)	-55.7, -17.9	-55.8, -17.9 (LOCO model) -50, -15 (direct measurement)
Corrected chromaticity (H, V)	---------	1.5, 0.5
RMS energy spread	9.845×10^{-4}	0.001
Energy loss per turn / MeV	1.435 (without ID)	~1.45 (without ID)
Momentum compaction factor	4.27×10^{-4}	$(4.2\pm0.2)\times10^{-4}$
RF voltage / MV	4.0	>4.3
RF frequency / MHz	499.654	499.654 (depend on machine conditions)
Synchrotron frequency	0.0072 (V_{RF}=4.0MV)	0.0075±0.0002
Natural bunch length / ps	13	14±2
Injection efficiency	---------	>95%
Beam lifetime / hrs	>10	17.0 (0.3% coupling, 210 mA)

ISBN 978-3-95450-115-1

order to find lower emittance optics for its upgrade [4, 5]. Its application has shown the possibility of the systematic analysis for the lattice design. Ref. [6] has developed MOGA's application in the SSRF-liked lattice with super-period. Here, we introduce how to explore the available lowest emittance optics for the SSRF storage ring with this method, and the design results and the machine experience are presented.

SYSTEMATIC ANALYSIS

Pareto optimal front is defined as a collection of all the optimal solutions without any tradeoff between some parameters conflicting with each other. Finding the Pareto optimal front is a crucial step for the optics optimization. The horizontal tune and the beam emittance are a pair of typically conflicting parameters in the lattice. The natural horizontal chromaticity has a roughly proportional relationship with the tune.

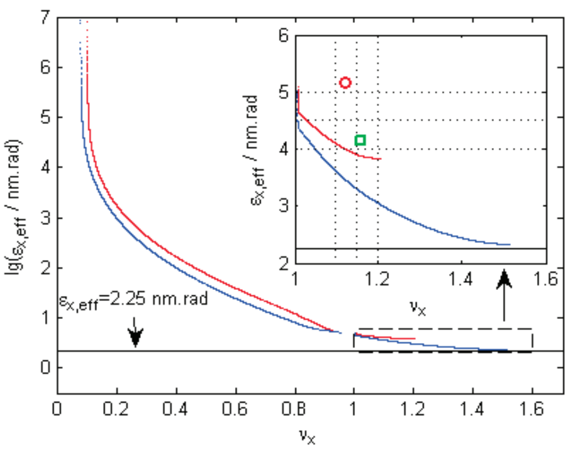

Figure 2: Optimal front of the beam emittance vs the horizontal tune per cell.

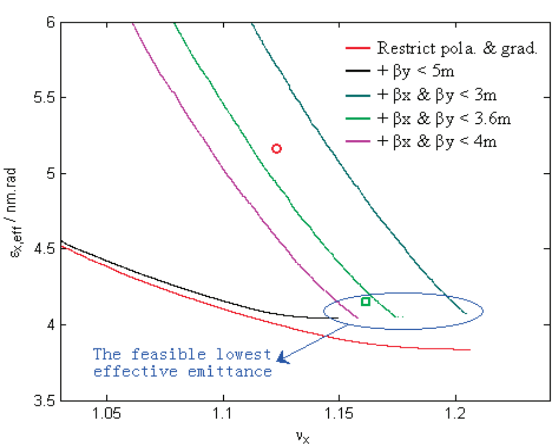

Figure 3: Optimal front of the effective emittance with beta function restrictions.

Fig. 2 plots the Pareto front between the horizontal tune and the horizontal effective emittance, including with and without current hardware constraints of the quadrupoles (nominal polarizations and maximum gradients). The effective emittance reaches TMEE at the horizontal tune per cell of 1.5, without any hardware constraint, shown as blue line, while it reaches a minimum value at the horizontal tune per cell of 1.2 with constraints, shown as red line.

Unfortunately, all the solutions in this red line have a very high vertical beta function. They are unreasonable for the users' requirements or unfeasible in the machine experience. Fig. 3 plots different Pareto optimal fronts with different beta function restrictions, including the cases less than 3 m, 3.6 m, and 4.0 m. The optimal solution with lowest effective emittance can be selected out from these results.

DESIGN OF THE VERY LOW EMITTANCE OPTICS

A very low effective emittance optics is selected and has been recovered to super-period solution. This optics is plotted as green square and the nominal one as red circle in Fig.2 and Fig.3. The natural emittance and the effective emittance in the standard straight section are less than the nominal one by about one unit, so the photon brightness will increase by 20%~40%. Fig. 4 plots its linear optics in one super-period, and the lattice parameters are summarized in Table 2. However, its linear optics is unique with smaller beta functions in the center of the long straight section. These smaller beta functions must lead to very small dynamic apertures restricted by the physical apertures. It is imposed by the maximum gradients of the quadrupoles, and has few improvements.

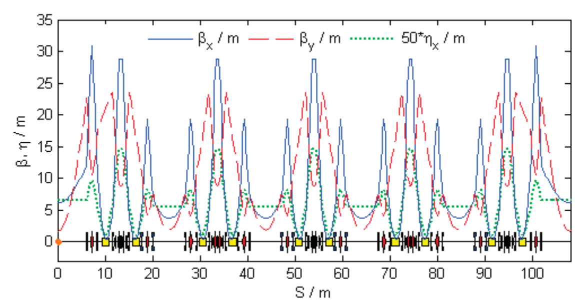

Figure 4: Linear optics in one super-period of the very low effective emittance optics.

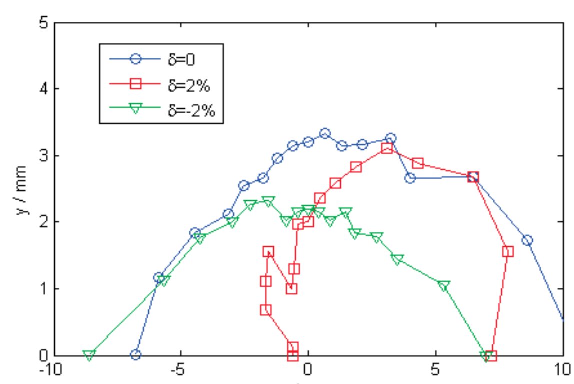

Figure 5: Dynamic apertures of the very low emittance optics, including on- and off-momentum particle.

Table 2: Beam Parameters of the Very Low Emittance Optics

Parameter	Design	Measurement	Measurement
Beam energy / GeV	3.5 (3.0)	3.50±0.02	2.99±0.02
Tune (H, V)	23.31, 11.23	23.31, 11.24	23.31, 11.23
Natural emittance / nm.rad	2.88 (2.12)	2.9±0.2	2.0±0.3
Natural chromaticity (H, V)	-74.5, -26.7	-67, -23	-67, -24
Corrected chromaticity (H, V)	------	2.0, 3.0	3.0, 4.0
RF voltage / MV	4.0	>4.3	>4.3
Momentum compaction factor	4.13×10^{-4}	$(4.2\pm0.2)\times10^{-4}$	$(3.9\pm0.3)\times10^{-4}$
Longitudinal tune	0.0074 (0.0079)	0.0074±0.0002	0.0078±0.0003
Coupling	------	0.5%	0.4%
Beam current / mA	------	210	210
Beam lifetime / hrs	------	15.0	8.5
Injection efficiency	------	~50%	~50%
RMS beta beatings (H, V)	------	0.7%, 0.8%	0.6%, 0.8%

Nonlinear optimization in much stronger focusing optics is very difficult, in addition to lower beta function in the injection point. We have applied several optimization methods, but the optimal result is dispiriting. Dynamic aperture of on-momentum particle is about 7 mm, and the energy acceptance is about 2% in this optics, of which the simulation includes radiation damping, cavity compensate, and physical aperture of the vacuum chamber. Fig. 5 plots the dynamics apertures of on- and off-momentum particle. The beam injection difficulty would be foreseen.

COMMISSIONING OF THE VERY LOW EMITTANCE OPTICS

At the first test of this very low emittance optics in the machine, the injection is very difficult. After lowering the excited current of the second septum, a few electrons are much reluctantly injected into the storage ring. Combining the adjustments of the high energy transport line (optics matching) and the sextupoles in the ring (dynamic aperture optimization), the injection efficiency is improved. It finally reaches about 50%. The beam current is also accumulated to 210 mA. Effects of the linear optics correction, the orbit correction, and the orbit stability etc. are very similar with the nominal optics. In order to suppress the beam blow-up, the chromaticities are corrected to a higher value (2 and 3) in both transverse planes than the nominal ones. This is the main difference between this very low emittance optics and nominal one, expect for injection efficiency and beam lifetime. The measured beam parameters are also summarized in Table 2, which shows a good agreement.

When the beam energy is reduced to 3.0 GeV, the natural emittance of this optics is reduced to 2.1 nm.rad. We also tested this optics on this energy. With the corrected results and the experience on the beam energy of 3.5 GeV, the commissioning on 3.0GeV seems to be easier. The beam current reaches 210 mA, and it has a good growth potential, with the restrictions of RF hardware. The measured beam parameters are summarized in Table 2.

Beam lifetime and injection efficiency of this low emittance optics are lower than the nominal mode. This shorter beam lifetime is available and acceptable in TOP-UP injection. Safety problem of the low injection efficiency will be solved by scraping halo of the beam in the high energy transport line with the scrapers. There is no intrinsic issue to operate in SSRF.

CONCLUSIONS

The very low effective emittance optics of SSRF is found out by the method of MOGA. The effective emittance in the standard straight section and the natural emittance are decreased by one unit with respect to the nominal one, when the beam energy is 3.5 GeV, and it is reduced to about 2.1nm.rad on the beam energy of 3.0 GeV. Commissioning of this optics is carefully carried out in SSRF, and the results are satisfying. Some work improving injection will be done before this optics is routinely operated in SSRF.

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ISBN 978-3-95450-115-1