Optics for the lattice of the compact storage ring for a Compton X-ray source*

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Abstract We present two types of optics for the lattice of a compact storage ring for a Compton X-ray source. The optics design for different operation modes of the storage ring are discussed in detail. For the pulse mode optics, an IBS-suppression scheme is applied to optimize the optics for lower IBS emittance growth rate; as for the steady mode, the method to control momentum compact factor is adopted [Gladkikh P, Phys. Rev. ST Accel. Beams 8, 050702] to obtain stability of the electron beam.

Key words lattice, beam dynamics, Compton scattering, x-ray source

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1 Introduction

There is growing interest in developing x-ray source based upon Compton scattering. The basic principle is Compton scattering off a low energy electron beam with an intense laser pulse to produce the desired photon spectrum. The idea of utilizing the laser-electron storage ring (LESR) for the purpose of increasing frequency and luminosity of hard x-ray photon was proposed in 1998[1], in which the electron beam is stored in a storage ring while the laser pulse is stored in an optical cavity. For its compactness and low construction cost, this scheme is an alternative proposal to the traditional synchrotron radiation source.

There are two main operation modes for the LESR: the pulse mode[2] and the steady mode[3]. In the pulse mode, the electrons are stored only for a short period of time before they are dumped. Due to the relatively low energy utilized in this scheme, the strong effect of Intra-beam scattering (IBS) would increase the transverse emittance in a short period of time, which leads to reduction in intensity. Hence, in this operation mode, the x-ray source generates scattered photon with pulse nature. In the steady mode, electrons are stored for a long period of time, and the equilibrium parameters of the electron beam are achieved. Therefore, the total x-ray photon yield is stable in the steady mode.

The average parameters of the electron beam differ greatly from each other. We utilize injected electron beam with electron energy 50 MeV, pulse length 10 ps, and RMS energy spread 0.2%, which is generated by a low emittance RF photocathode, to interact with laser photon with the wavelength 800 nm and stored laser energy 1mJ. For the pulse mode, the transverse emittance right before the beam is dumped is 2.2×10^{-7}m·rad; and the energy spread is 0.3%. As for the steady mode, the equilibrium transverse emittance is 1.2×10^{-6}m·rad, and the equilibrium energy spread is 1%[4].

2 LESR lattice

2.1 Requirements of the LESR lattice

There are some requirements in common for both schemes of the LESR lattice. First of all, beta function should be small at the Interaction Point (IP)

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to enhance the total yield of the scattered photons, which can be accomplished by quadrupoles quadruplets. For the large natural chromaticities brought in by the low beta insertion, strong sextupoles are introduced to correct them. Consequently, the dynamic aperture (DA) has to be enhanced by means of harmonic sextupoles.

2.1.1 Pulse mode optics

The dominant factor in the pulse mode is the IBS effect. By strengthening the quadropules strength, we minimize the average value of the auxiliary function $\mathcal{H}_x$ and beta function to minimize the IBS effect and space charge tune shift. Moreover, most parts of the ring should be dispersion-free to place the RF cavity, injection system, and IP. Consequently, the momentum compaction factor α is relatively large for such an optics design. It is quite inflexible due to the compactness of the design. The momentum acceptance

$$\sigma_{\rm RF} \approx \sqrt{\frac{2\ eV_{\rm RF}}{\pi\alpha h E_{\rm e}}} \tag{1}$$

and beam length

$$\sigma_{\rm s} \propto \sqrt{\frac{\alpha h}{V_{\rm RF}|\cos\phi|}} \tag{2}$$

usually prefer small α. Nevertheless, since the energy spread is quite small during the whole storage period in the pulse mode, the relatively large α is tolerable for stable motion of the electron.

2.1.2 Steady mode optics

In the steady mode, since IBS effect would eventually be counter-balanced by the damping effect of Compton scattering (CS) and synchrotron radiation, the main dynamic features are determined by CS. Therefore, off-momentum DA is crucial since the equilibrium RMS energy spread is relatively large due to CS. As is evident from Eq. (1), α should be small to achieve large momentum acceptance. There are several means to change the first order compaction factor α_1, e.g. dispersion manipulation[3] and combined function damping wigglers[6]. However, the small α_1 may give rise to the second-order compaction factor α_2. We know that for the crucial quadratic compaction factor[3]

$$\alpha_{\rm c} = \sqrt{\frac{E_0\omega_{\rm RF}T_0|\alpha_1|^3}{12\ eV_{\rm RF}\left[-\cos\phi_{\rm s}+\left(\pi/2-\phi_{\rm s}\sin\phi_{\rm s}\right)\right]}}, \tag{3}$$

when $|\alpha_2| > \alpha_{\rm c}$, the momentum acceptance is determined by

$$\sigma_{\rm RF} = \left|\frac{3\alpha_1}{2\alpha_2}\right|. \tag{4}$$

Hence, the momentum acceptance becomes quite small for large α_2. As a result, α_2 has to be suppressed as well.

Aside from the compaction factor, second-order dispersion becomes a significant term in $D = D_1 + D_2\delta + \ldots$ for the reason of the large energy spread. The closed orbit would enhance for the off-momentum particle. Following the approaches by Piwinski[7], the horizontal invariant change of an electron can be described as

$$dJ_x = -\frac{2x}{\beta_x^2}D\frac{\Delta P_s}{P} + D^2\left(\frac{\Delta P_s}{P}\right)^2 + 2x'\frac{\Delta P_x}{P} + \left(\frac{\Delta P_x}{P}\right)^2. \tag{5}$$

It is evident from Eq. (5) that the majority of the emittance growth at the IP is attributable to the term $D^2\left(\Delta P_s/P\right)^2$. Hence, the first and second-dispersions should both be suppressed at the IP.

3 Optics for the LESR lattice

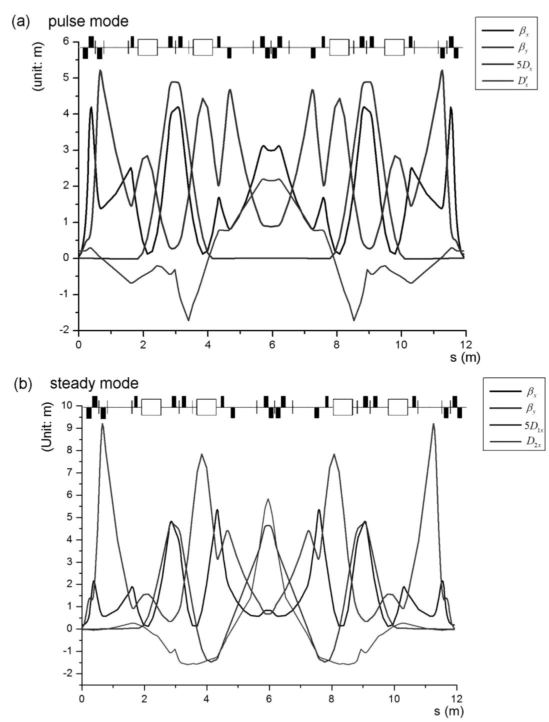

Fig. 1. The twiss function for the optics. (a) is the pulse mode and (b) is the steady mode. The circumference of the ring is C =11.918 m.

For the LESR lattice[8], we present the optics for the pulse mode and the steady mode in Fig. 1. For the pulse mode, both long straight sections are dispersion-free and we enhanced the betatron tune to achieve lower tune shift and H_x[5]. As a result, we successfully reduce 25% of the original IBS growth rate in Ref. [8]. The on-momentum DA is 3 mm at the IP.

As for the steady mode, the compaction factor is adjusted by the dispersive long straight section[3]. For this optics, α_1 is 7×10^{-3}, and α_2 is 3×10^{-3}. We suppress the first and second-order dispersion at the IP [cf. Fig. 1(b)]. We likewise suppress the first and second-order chromaticities at the IP.

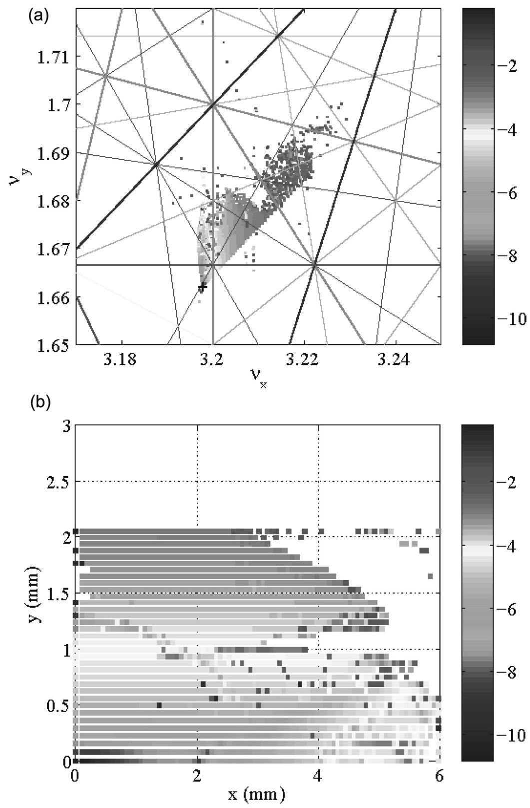

Fig. 2. The dynamics in the steady mode optics is greatly influenced by the node (3.211,1.685), which limits the vertical DA. Moreover, the 5th order resonance may be further excited by the magnet errors. Nevertheless, the DA horizontal size is sufficient for the steady mode.

The working point of the steady mode is $(Q_x,Q_y) = (3.197,1.662)$, which is close to the 5 th order resonance. Hence, we calculate the frequency map[9] of this optics, as is shown in Fig. 2. The vertical DA is greatly decreased by the node (3.211,1.685) [cf. Fig. 2(a)]. Furthermore, the node (3.200,1.680) is attributable to the white tongue at y=1 mm. The 5 th resonance may be strengthened by magnet errors, which will further reduce the vertical direction of the DA. We drop the point at the upper-right side of the 5th resonance $3n_x+2n_y=13$ since it is impossible for the particle to get across the resonance line without beam loss. The horizontal DA is about 6mm and we have witnessed no distinct resonance [cf. Fig. 2(b)]. Since the horizontal emittance is much large than it is in the pulse mode, a robust DA with large horizontal size would benefit the stability of the particle.

Other parameters of the two optics are listed in Table 1.

Table 1. Parameters of the optics.

parameters	pulse	steady
tunes		
horizontal	2.87	3.197
vertical	1.69	1.662
beta function at IP		
horizontal, cm	4.9	17.5
vertical, cm	11.5	3.0
compaction factor (linear)	0.081	0.007
energy acceptance	3.4%	⩾8%
horizontal beam size at IP/μm	104*	452
natural chromaticity		
horizontal	-6.06	-6.49
vertical	-4.09	-6.14

4 Summary

Two types of optics for the lattice of the LESR are designed according to the requirements for the pulse mode and the steady mode. For the pulse mode, the IBS suppression is of prior importance; as for the steady mode, small momentum compaction factor is essential to keep long-term stable motion of the electron beam in the LESR.

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