ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-MOPB039

LOW-ALPHA STORAGE RING DESIGN FOR STEADY-STATE MICROBUNCHING TO GENERATE EUV RADIATION

Zhilong Pan*, Chuanxiang Tang, Xiujie Deng, Wenhui Huang, Alex Chao, Zizheng Li
Tsinghua University, Beijing, China

Abstract

A new concept is proposed to minimize the longitudinal emittance of a low momentum compaction factor (low-alpha) storage ring which has the capability to stably store sub-femtosecond electron bunches for the first time. This storage ring is designed for steady-state microbunching (SSMB) to generate kW EUV radiation with level average power, combined with a carefully designed insertion device in which the electron bunches are compressed to nm-long at radiator [1]. The proposed design approach can be applied to any quasi-isochronous storage rings to yield very high power radiation due to longitudinal coherence of the radiation. We obtain an optimal lattice design by minimizing global and local momentum compaction factors simultaneously. Nonlinear dynamics and IBS effect are discussed in this lattice, as there are many differences for them in traditional rings and SSMB ring.

INTRODUCTION

SSMB, is a new concept, by subtly manipulating the longitudinal phase space of electron bunches in storage rings, to maintain micro-bunches stably [2]. while bunches with nm-level length are maintained and radiate in super high repetition frequency, the EUV radiation with ~ kW average power could be produced, with a wide variety of applications in high-volume chip manufacturing [3] and many advanced science researches, such as high energy resolution in angle-resolved photon-emission spectroscopy [4]. There are many progresses in SSMB research recent years, such as the successful proof of principle experiment [5], several proposed schemes to generate kW average power EUV radiation based on SSMB [6, 7]. Among the proposed schemes, a SSMB storage ring in which electron bunches with a bunch length of less than 100 nm should be stored is essential. In normal storage rings, the achieved bunch length of stored electron bunches is on the magnitude of mm or larger. One important reason is that radio-frequency (RF) cavity whose wavelength is on the magnitude of meter is used to focus the bunch in longitudinal phase space. In SSMB rings, RF will replaced by laser modulator (LM), with a modulation wavelength of micron-meter. Another issue is low-alpha mode operation of storage rings, M. Sands's formula breaks down as the global alpha of storage ring reaches the minimum limit as many literature pointed out [8, 9]. The underlying physics behind the breakdown is statistical property of radiation excitation, and it can also be defined as partial alpha effects. That is to say, the local alpha all along the ring should be minimized in lattice design. We introduce the method to minimize local alpha in SSMB storage ring lattice design and give the ring design results first. Based on the ring, we discuss the difference of nonlinear dynamics and IBS between SSMB ring and normal ring. Conclusion is given at the end.

* panzl@mail.tsinghua.edu.cn

SSMB RING LATTICE DESIGN

Design Concept

The SSMB ring, as we mentioned above, should be a low-alpha ring, but also be a low local alpha ring. If we define a point for bunch length observation, then the bunch length contribution from local alpha ($\widetilde{\alpha_c}$) should be the variation of all the alpha (defined as $I_{\widetilde{\alpha_c}}$) from any radiation point to observation point, written as

$$\widetilde{\alpha_{c,s_r}} = \frac{1}{C}\int_{s_r}^{s_0} \frac{\eta(s)}{\rho} ds. \qquad (1)$$

Where s_r is radiation point, s_0 is observation point, η is dispersion function, ρ is bending radius, C is the total length from s_r to s_0. To minimize $I_{\widetilde{\alpha_{c,s_r}}}$, each local $\widetilde{\alpha_{c,s_r}}$ should be minimized. A straightforward idea is to make the momentum compaction in each dipole be zero and decrease the bending angle of each dipole simultaneously.

Figure 1: Layout of main cell. The red rectangle represents dipole, green rectangles represent quadrupoles, rose red rectangles represent sextupoles.

Here, we give an instance of lattice design to illustrate the idea above. The basic structure used to achieve the idea is shown in Fig. 1, called main cell. The whole ring will be mainly constructed by main cell. To explain more detailed, we can assuming the ring is consist of several super period, for example, two. And each super period will be constructed by several main cell and match cell as shown in Fig. 2.

Figure 2: Sketch of super period constitution.

Looking back on the main cell, one objective is making the integration $\int_0^{C_1} \frac{\eta(s)}{\rho} ds$ be zero, while C_1 is the total length of main cell. As Fig. 2 shows, the main cell is periodically arranged. If there is, for example, 7 main cell in a super cell, then the tunes of main cell should better be set as $\nu_x = \frac{i}{7}$ and $\nu_y = \frac{j}{7}$ which is benefit for nonlinear dynamics, while i and j are integers less than 7.

ISBN: 978-3-95450-265-3
doi:10.18429/JACoW-SAP2023-MOPB039

Ring Lattice Layout and Parameters

Here, the ring lattice layout is shown in Fig. 3. It is consisted of two super periods, and 12 main cell in each super period.

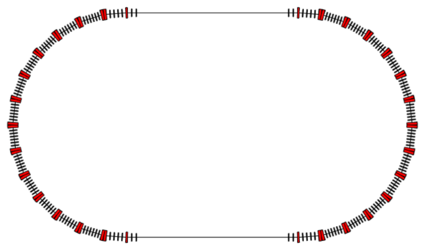

Figure 3: The layout of ring lattice.

And the twiss functions of the ring is shown in Fig. 4.

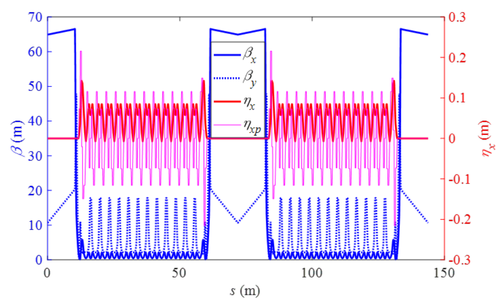

Figure 4: The twiss functions of the ring.

The lattice arrangement and twiss functions of main cell is shown in Fig. 5.

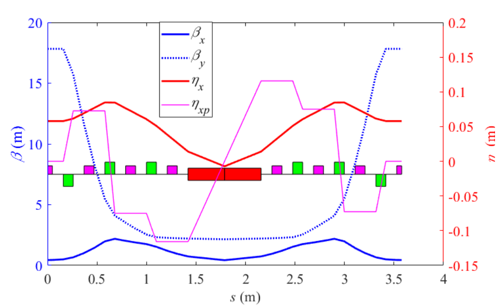

Figure 5: Lattice arrangement and twiss functions of main cell. The red represents dipoles, the green represents quadrupole, the rose red represent sextupole.

The main parameters of the ring are listed in Table 1. The bunch length is calculated by SLIM formula [10], while local momentum compaction is self-consistently considered. The damping time of the ring is a little bit large, more optimization is needed by decreasing bending radius or adding damping wigglers.

Longitudinal dynamics in SSMB ring should be carefully studied, as LM is used as the longitudinal focusing element. The bucket height is only 6.4×10^{-4} with the parameters of Table 1, the quantum lifetime then will be very small if no additional trapping element is used. A barrier bucket or an additional RF could be the potential choice. The detailed study is on-going.

Table 1: Ring Parameters

Parameters	**Value**	**Units**
Circumference	143.78	m
Beam energy	400	MeV
Tunes x/y	18.58/7.11	/
Phase slippage factor	2.69e-6	/
2nd order phase slippage factor	1.23e-4	/
Natural emittance	281.7	pm
LM wavelength	1	µm
LM voltage	100	kV
Energy spread	2.23×10^{-4}	/
Bunch length at straight	91.4	nm
Damping times (x/y/z)	542.2/542.4/271.1	ms
Energy loss per turn	0.71	keV

NONLINEAR DYNAMICS

As the LM bucket width is on the magnitude of micronmeter, extra attention is needed in transverse-longitudinal (T-L) coupling non-linearity in SSMB rings. The particles with a transverse size will move in different path with reference particle and result in the path length deviation. In normal storage rings, this path length deviation is typically less small than the RF wavelength and can be easily hold by the phase stability principle. While in SSMB ring, the path length deviation from T-L coupling is very likely larger than the laser wavelength (µm) without careful optimization, so the particle will jump between different LM buckets making the phase stability break down.

Here, we briefly discuss T-L coupling to make it more clear for SSMB ring optimization. The particle motion in storage ring can be described by Hamiltonian. We define the hamiltonian by H, given as (under 3rd order, longitudinal Hamiltonian is not included)

$$H(J_x, J_y, \delta) = \mu_x J_x + \mu_y J_y + h_{11001} J_x \delta + h_{00111} J_y \delta + |h_{20001}| J_x \delta e^{-2\phi_x j} + |h_{00201}| J_y \delta e^{-2\phi_y j}, \tag{2}$$

where J_x and J_y represent the action of the particle in x and y direction respectively. μ_x and μ_y are betatron phase advance in x and y direction respectively. δ is relative energy deviation, ϕ_x and ϕ_y are betatron phase. The last four terms describe the T-L coupling at dispersion free location, and h_{11001}, h_{00111} h_{20001} h_{00201} determine the strength of T-L coupling.

In Hamiltonian system, the path length deviation per turn for a particle can be expressed as (we only talk the contribution from low order T-L coupling here)

$$\Delta z = \frac{\partial H}{\partial \delta} = h_{11001} J_x + h_{00111} J_y + |h_{20001}| J_x e^{-2\phi_x j} + |h_{00201}| J_y e^{-2\phi_y j}, \tag{3}$$

ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-MOPB039

Eq. (3) says the path length deviation per turn is related to transverse action and some coefficients. The first two terms h_{11001} and h_{00111} are independent with betatron phase, which means it will not vary turn by turn. The last two terms consist betatron phase, which means the path length deviation per turn will oscillate with betatron phase. Let $h_{20001} = |h_{20001}|e^{-2\phi_x j}$ and $h_{00201} = |h_{00201}|e^{-2\phi_y j}$.

Comparing the definition of chromaticity, we can get

$$\begin{aligned} h_{11001} &= 2\pi\xi_x \\ h_{00111} &= 2\pi\xi_y. \end{aligned} \tag{4}$$

Without special design, the magnitude of $|h_{20001}|$ and $|h_{00201}|$ will be 10 or larger. When injection, the action of injected particle could be 1×10^{-7} m (with 1 mm size and ~ 10 m beta function), then the path length deviation will oscillate with a amplitude of $A_x = |h20001|J_x \sim 10*10^{-7} \sim$ 1 µm. As we mentioned above, the LM bucket width is 1 µm, the T-L coupling will result in that a particle with large transverse action is very likely to jump to adjacent LM bucket and make the longtudinal motion unstable.

We have done preliminary optimization for those T-L coupling terms, and the dynamic aperture (DA) of the ring is shown in Fig. 6.

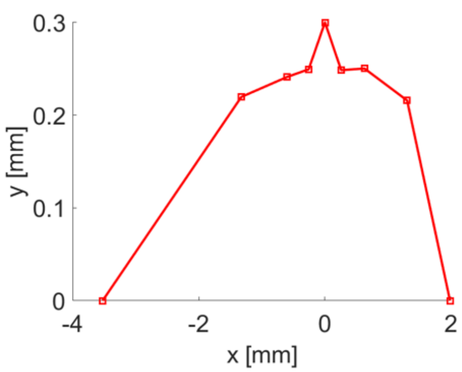

Figure 6: DA of ring, after 20000 turns tracking.

INTRA-BEAM SCATTERING

Intra-beam scattering (IBS) is coulomb scattering effect due to space charge inside the beam of charged particles. IBS will induce increase of beam emittance in low energy electron storage rings. In normal rings, the bunch length of electron bunch can be regarded as constant around the ring. But it varies dramatically in SSMB ring, as shown in Fig. 7. So the widely used formulas for IBS growth rate calculation is not suitable anymore in SSMB ring.

The IBS growth rate derived by Bjorken and Mtingwa [11] is

$$\begin{aligned} \frac{1}{T_i} = 4\pi A(log)\left\langle \int_0^\infty \frac{d\lambda\lambda^{1/2}}{[det(L+\lambda I)]^{1/2}} \right. \\ \left. \left\{ TrL^{(i)}Tr(\frac{1}{L+\lambda I}) - 3TrL^{(i)}(\frac{1}{L+\lambda I}) \right\} \right\rangle. \end{aligned} \tag{5}$$

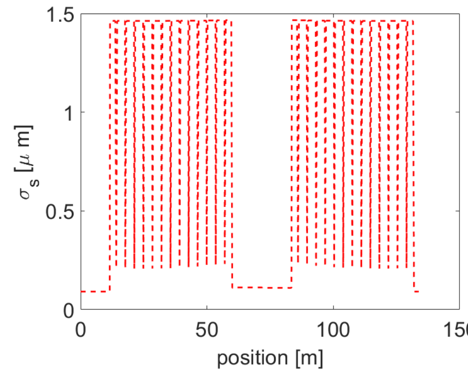

Figure 7: Bunch length of electron bunch vs observation point in SSMB ring.

The i represent three different directions, x, y, s, and $L = L^{(x)} + L^{(y)} + L^{(s)}$. In SSMB ring, the $L^{(s)}$ should be replaced as

$$\begin{aligned} L^{(s)} &= \frac{\gamma^2}{\sigma_p^2}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ \Rightarrow L^{(s)} &= \begin{bmatrix} \frac{\gamma_s\eta^2}{\epsilon_s} & 0 & -\gamma\frac{\alpha_s\eta}{\epsilon_s} \\ 0 & 0 & 0 \\ -\gamma\frac{\alpha_s\eta}{\epsilon_s} & 0 & \frac{\gamma^2\beta_s}{\epsilon_s} \end{bmatrix} \end{aligned} \tag{6}$$

We adopt the correction and calculate the equilibrium beam emittance considering the IBS effect at selected beam current, and the results fit well with SAD in which any coupling situation can be handled for IBS calculation.

CONCLUSION

In this paper, a SSMB ring who can store the electron bunches with very short bunch length under 100 nm has been designed. A method to minimize the local momentum compaction effect is proposed. We also talk about the nonlinear dynamics in this ring, and give a preliminary thoughts to enlarge the DA. The IBS calculation could be a little bit different with in the normal ring. We clarify where the difference comes from and make some correction on widely used IBS growth rate formulas.

REFERENCES

[1] Z. Li, X. Deng, Z. Pan, C. Tang, and A. Chao, “Generalized longitudinal strong focusing: A ring-based beam manipulation technique,” SAP, Sichuan, China, 2023, paper MOPB037, this conference.

[2] D. F. Ratner and A. W. Chao, “Steady-state microbunching in a storage ring for generating coherent radiation,” *Physical review letters*, vol. 105, no. 15, p. 154 801, 2010.

[3] V. Bakshi, “Euv lithography,” 2009.

[4] A. Damascelli, Z. Hussain, and Z.-X. Shen, “Angle-resolved photoemission studies of the cuprate superconductors,” *Reviews of modern physics*, vol. 75, no. 2, p. 473, 2003.

ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-MOPB039

[5] X. Deng *et al.*, “Experimental demonstration of the mechanism of steady-state microbunching,” *Nature*, vol. 590, no. 7847, pp. 576–579, 2021.

[6] Y. Zhang *et al.*, “Ultralow longitudinal emittance storage rings,” *Physical Review Accelerators and Beams*, vol. 24, no. 9, p. 090 701, 2021.

[7] B. Jiang *et al.*, “A synchrotron-based kilowatt-level radiation source for euv lithography,” *Scientific Reports*, vol. 12, no. 1, p. 3325, 2022.

[8] Y. Shoji, H. Tanaka, M. Takao, and K. Soutome, “Longitudinal radiation excitation in an electron storage ring,” *Physical Review E*, vol. 54, no. 5, R4556, 1996.

[9] X. Deng *et al.*, “Breakdown of classical bunch length and energy spread formula in a quasi-isochronous electron storage ring,” *Physical Review Accelerators and Beams*, vol. 26, no. 5, p. 054 001, 2023.

[10] A. Chao, “Slim—a formalism for linear coupled systems,” *Chinese Physics C*, vol. 33, no. S2, pp. 115–120, 2009.

[11] J. D. Bjorken and S. K. Mtingwa, “Intrabeam scattering,” *Part. Accel.*, vol. 13, no. FERMILAB-PUB-82-47-THY, pp. 115–143, 1982.