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A STORAGE RING DESIGN FOR STEADY-STATE MICROBUNCHING TO GENERATE COHERENT EUV LIGHT SOURCE

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Abstract

The proposal of Steady State Microbunching (SSMB) makes it available to generate high average power coherent radiation, especially has the potential to generate kW level of EUV source for lithography. In order to achieve and maintain SSMB, we propose several concepts. One is that a very short electron bunch below 100 nm is stored in the ring, inserting a strong focusing part to compress the bunch to ~3 nm, then radiating coherently, which is called longitudinal strong focusing (LSF) scheme. We have optimized the candidate lattice to achieve the very short electron bunch storage and microbunching for electron beam. The tracking results show the equilibrium length of the electron bunch is about 400 nm and no particles lose after 4.3 damping time while only single-particle effect is considered. More optimization and some new design based on the simulation results are still implementing.

INTRODUCTION

Because of the limitation of electron beam size in the traditional storage ring based synchrotron facilities, the average power of the incoherent radiation from this kind of facility will still be low although with extremely high repetition rate. On the other hand, the linac based FEL facilities can't generate high average power radiation due to the low repetition rate. The SSMB makes it achievable to radiate coherently in storage ring with high repetition rate, in other words, high average power radiation is available.

To achieve SSMB, several schemes have been proposed and pushed by our collaboration team in recent time, including longitudinal strong focusing (LSF) [1], reversible seeding[2], and hybrid scheme. Among those schemes, the LSF scheme requires that the storage ring can stably store the electron beam with a bunch length under 100 nm.

Based on the conventional formula by Sands[3], the length of electron bunch is determined by momentum compaction factor of the storage ring and RF parameters.

$$\sigma_s = \sigma_\delta L \frac{\alpha_c}{2\pi\nu_s}, \tag{1}$$

where α_c is momentum compaction factor, L is the circumference of the storage ring, σ_δ is equilibrium rms energy spread, ν_s is synchrotron tune.

According to eq.1, a storage ring with low momentum compaction factor on the magnitude of 1×10^{-6} or lower is needed to match our requirements. On the other hand, the second order momentum compaction factor may dominate the longitudinal dynamics and reduce the RF bucket area if not been optimized properly in the low momentum compaction factor storage ring [4].

The bunch length formula from Sands neglects the part of path length fluctuation from photon emission, which associates with local momentum compaction factor, or partial alpha [1]. The bunch length formula by taking account this effect in is [5]

$$\sigma_s = \sigma_\delta L \sqrt{(\frac{\alpha_c}{2\pi\nu_s})^2 + I_{\bar{\alpha}}}, \tag{2}$$

where $I_{\bar{\alpha}}$ is the variance of partial alpha. So the partial alpha of the storage ring should also be minimized to prevent the bunch length increasing.

The isochronous cell scheme has been proposed by our team to design the SSMB lattice [6]. We adopt that lattice in this paper and make some improvement in terms of slight adjustment of momentum compaction factor, minimizing second order momentum compaction factor, and dynamic aperture optimization. Then we do some single-particle simulation based on this lattice. The simulation results will show some direction for further lattice optimization.

LATTICE PARAMETERS

The lattice layout can refer to [6]. There are two dispersion free straight sections and two arc sections, and 6 isochronous cells in per arc section. The twiss function of one isochronous cell is shown in Fig.1. The integration of $\int_0^{L_b} \frac{\eta_x(s)}{\rho} ds$ will be 0 through the dipole in the isochronous cell, where L_b is the dipole length. So the momentum compaction factor of the whole ring could be very small. Three families of sextupoles named S1, S2, S3 are introduced to minimize the chromaticity and second order momentum compaction factor. The ring parameters are listed in Table.1.

The second order compaction factor has been optimized and the relation $\alpha_c > 10\alpha_{c2}\sigma_\delta$ is satisfied by referring to Table.1, so the longitudinal dynamics is still dominant by α_c. The bunch length induced by partial alpha is related with $\sqrt{I_{\bar{\alpha}}}$, the value will be ~ 300 *nm*. The equilibrium bunch length of this lattice will not be shorter than 300 *nm*, we will do some single-particle simulation based on this lattice later to check the partial alpha theory and get some guideline on the next step optimizaion.

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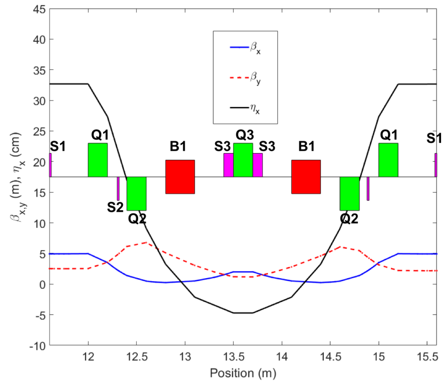

Figure 1: Twiss function of one isochronous cell in the lattice.

Table 1: Ring Parameters

Ring Parameters	**Values**
Circumference	94.4 m
Tunes(x/y)	13.22/3.48
Chrom.(x/y)	0.657/0.987
α_c	2.73×10^{-7}
α_{c2}	3.45×10^{-5}
$\sqrt{I_{\tilde{a}}}$	1.1×10^{-5}
Energy Spread σ_δ	2.97×10^{-4}
Energy Loss Per Turn	1.736 keV
Natural emittance	1.67 nm
Hor./Ver Damping Time	145/145 ms
Long. Damping Time	72.5 ms

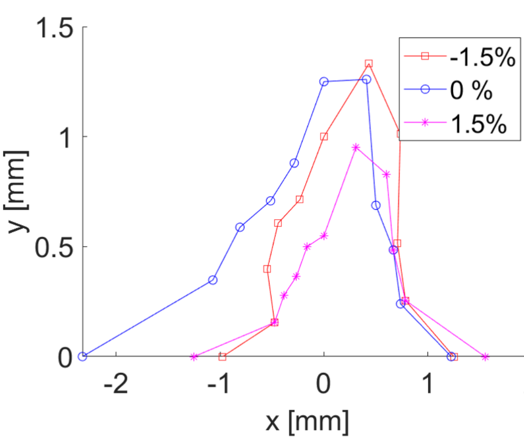

Figure 2: Dynamic aperture of the lattice.

DYNAMIC APERTURE

The dynamic aperture is optimized by inserting two families of harmonic sextupoles at the dispersion free locations. Taking the diffusion rate as objective, we scan the strengths of the two families sextupoles to get an optimal solution. Dynamic aperture is about 2 mm in horizontal direction and 1 mm in vertical direction as shown in Fig.2.

Table 2: RF Settings for Tracking in the Lattice

RF wavelength	$\lambda = 3\ \mu m$	$\lambda = 5\ \mu m$
RF Voltage V	120 kV	100 kV
Half bucket height δ_{rf}	2.09×10^{-3}	2.45×10^{-3}
Synchrotron tune ν_s	0.045	0.032
Bunch length $\sigma_{s,sands}$	134.48 nm	190.21 nm
RF Voltage V	250 kV	150 kV
Half bucket height δ_{rf}	3.03×10^{-3}	3.02×10^{-3}
Synchrotron tune ν_s	0.065	0.039
Bunch length $\sigma_{s,sands}$	93.17 nm	155.29 nm

SIMULATION

We have set up several simulations for this lattice, while only single-particle effects are considered in terms of synchrotron radiation, quantum excitation, and the nonlinear effects in this lattice. We choose different RF cavity wavelength and voltage to study the effects that dominant the particle loss for single particle. Four sets of parameters are chosen and listed in Table.2.

The four settings are labeled as C1 through C4: *i)* RF wavelength and voltage are 3 μm and 120 kV respectively (C1); *ii)* RF wavelength and voltage are 3 μm and 250 kV respectively (C2); *iii)* RF wavelength and voltage are 5 μm and 100 kV respectively (C3); *iv)* RF wavelength and voltage are 5 μm and 150 kV respectively (C4).

The Pelegant[7] will track 200 macro-particles for 1 million turns (4.3 damping time) for all the four different settings based on the lattice. It is single particle trcking so there is no space charge effect, no coherent synchrotron radiation effect, and no intra-beam scattering effect. The lattice error is not included in this simulation too.

We record the phase space coordinates of electrons every 1000 turns during simulation, and collect the data from latest 50 recording points (the latest 50 thousands turns, if no particle lose, there will be 10000 particles in total) to calculate the rms bunch length, energy spread, and horizontal emittance for electron bunch.

Simulation Results

After tracking for 1 million turns, the survived particles are collected in a file, the lost conditions are summarized in Table.3. It is obvious that the particles can't be stored in the ring if we set the RF wavelength at 3 μm, because the rms bunch length induced by the partial alpha is larger than 300 *nm*, which means the distribution length will be larger than 1.8 μm, while the phase stable area of the 3 μm RF is smaller than 1.5 μm, so most particles will lose during tracking. As for 5 μm RF, all the particles can stay in the phase stable area and simulation results show that no particle lose for RF settings C3 and C4.

Comparing the lost conditions for C1 and C2, the particles can survive more with the setting of C1. That is because the larger RF voltage in setting C2 will give a larger kick to the

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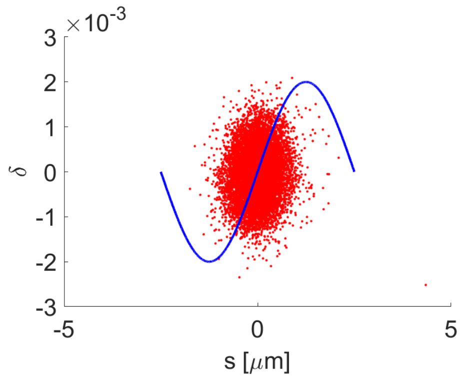
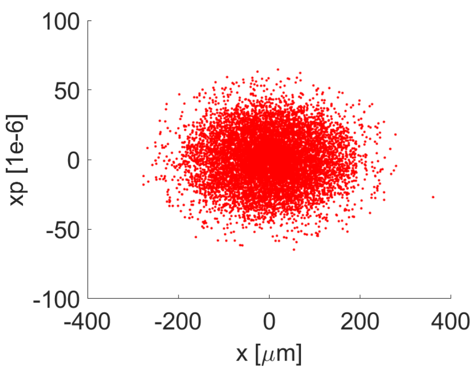
particle while it go through the RF cavity. The larger kick make it more likely to escape from the RF bucket.

Table 3: Lost Conditions for All the Four Settings

RF settings	lost condition
C1	79 survived over 200 particles
C2	5 survived over 200 particles
C3	200 survived over 200 particles
C4	200 survived over 200 particles



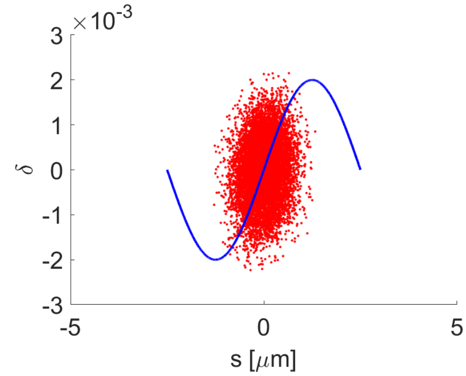
(a)



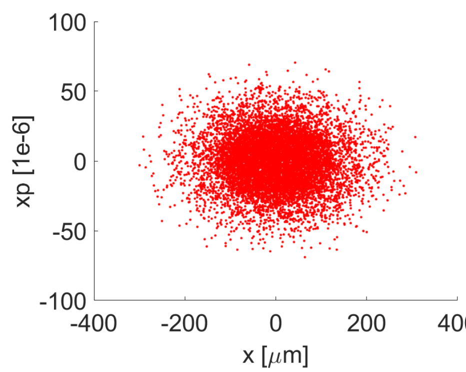
(b)

Figure 3: Longitudinal and horizontal distributions of the survived particles for setting C3. (a) is longitudinal distribution and (b) is horizontal distribution.

The longitudinal and horizontal distribution of the survived particles in setting C3 and C4 have been plotted in Fig.3 and Fig.4. As mentioned above, the data from latest 50 thousands turns with the interval of 1000 turns are used in the plot. The rms bunch length and energy spread calculated from the data in the plot for setting C3 is σ_s = 400.7 *nm* and $\sigma_\delta = 5.92{\times}10^{-4}$, as for the bunch length from Sands formula is $\sigma_{s,sands}$ = 190.21 *nm*, so the bunch length from partial alpha is $\sigma_{s,\sqrt{I_{\bar{a}}}}$ = 352.67 *nm*. For setting C4, σ_s = 373.3 *nm* and $\sigma_\delta = 6.83 \times 10^{-4}$, as for the bunch length from Sands formula is $\sigma_{s,sands}$ = 155.29 *nm*, so $\sigma_{s,\sqrt{I_{\bar{a}}}}$ = 339.46 *nm*. The difference of $\sigma_{s,\sqrt{I_{\bar{a}}}}$ between the two settings C3 and C4 is about 3%.



(a)



(b)

Figure 4: Longitudinal and horizontal distributions of the survived particles for setting C4. (a) is longitudinal distribution and (b) is horizontal distribution.

CONCLUSION

The lattice based on isochronous cell has been optimized for SSMB project. The second order compaction factor and dynamic aperture are optimized within requirements. The simulation of single particle tracking has shown that the bunch length of electron stored in this lattice will be ~ 400 *nm* due to the limitation of large partial alpha. A new lattice with designed value of $\sqrt{I_{\bar{a}}}$ to 1×10^{-6} has also been designed and the single particle tracking is performing. The new lattice will store the electron bunch with rms bunch length of ~ 40 *nm*.

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