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IMPACT OF COHERENT SYNCHROTRON RADIATION EFFECT ON GENERALIZED LONGITUDINAL STRONG FOCUSING INSERTION UNIT*

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Abstract

The generalized longitudinal strong focusing (GLSF) scheme is a potential approach for a steady-state microbunching (SSMB) storage ring, leveraging the ultra-low vertical emittance in the storage ring. It achieves active vertical-longitudinal coupling through an insertion unit, further compressing bunch length from the hundreds of nanometers scale in the main ring to the nanometers scale, thus emitting coherent radiation. Due to the extremely short bunch length, coherent synchrotron radiation (CSR) effect may significantly impact beam dynamics. We developed a particle tracking program based on one-dimensional CSR model to preliminarily evaluate the influence of CSR effect in the GLSF scheme under current design parameters. Our work contributes to the future optimization of the GLSF scheme.

INTRODUCTION

Steady-state microbunching (SSMB) storage ring [1-4] is a promising solution for high average power and high peak power extreme ultraviolet (EUV) light source. In principle, SSMB storage rings can stably form electron bunches with nanometer-scale lengths per revolution, capable of generating coherent EUV radiation. The generalized longitudinal strong focusing (GLSF) [5] is a possible SSMB scheme. In the GLSF scheme, the main ring is a low-alpha ring, where hundreds of nanometer-scale bunch lengths are achieved using laser modulators with modulation wavelengths much shorter than traditional RF cavities in conventional storage rings. The core of the GLSF scheme is an insertion unit. Through active vertical-longitudinal coupling, this section projects the inherently ultra-low vertical emittance of the storage ring into the longitudinal direction, further compressing the bunches from the main ring to nanometer-scale for radiation generation. To achieve steady-state operation, the latter part of the insertion unit decouples the bunches after radiation emission and returns them to the main ring.

In a typical layout of the GLSF insertion unit, there are four vertically dispersive lattice sections, labeled as part 1-4, along with two laser modulators, MOD1 and MOD2, as illustrated in Fig. 1. Bunch compression is achieved through the combined action of part1, MOD1, and part2. To maintain the steady-state operation, the beam must return to an uncouple and unmodulated state after passing through the whole insertion unit. Therefore, part3 is introduced to form an isochronous and achromatic lattice, together with part2, allowing MOD2 to directly eliminate the modulation caused by MOD1 through an opposite modulation. Finally, part4 clears out any remaining vertical-longitudinal coupling effects. Note that the drastic variations of bunch length occur in part2 and part3.

Coherent synchrotron radiation (CSR) effects become particularly pronounced when short bunches pass through bending magnets, potentially adversely affecting beam quality by increasing beam energy spread and causing transverse emittance dilution. In the GLSF insertion unit, where the bunch length is extremely short and varies significantly, CSR effects may prevent the beam from compressing to the expected length at radiation spot. Additionally, it may also interfere with the cancellation of modulation, thereby disrupting the maintenance of the steady-state operation. To assess the impact of CSR, we have developed a particle tracking program that incorporates CSR effects based on linear beam dynamics. We have evaluated and analyzed the influence of CSR in the GLSF insertion unit using the current design parameters. And we found that the influence is acceptable for a single pass case.

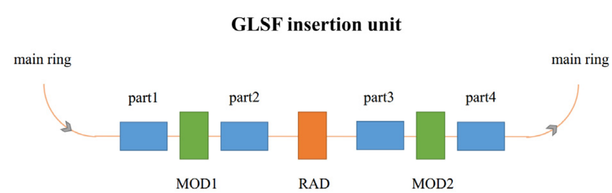

Figure 1: GLSF insertion unit layout.

SIMULATION METHOD

The theory of CSR has been extensively studied. Currently, the most commonly used model in particle tracking programs is the one-dimensional CSR wakefield model, which treats the beam as a thread charge distribution. Murphy et al. [6] have provided a detailed description of the one-dimensional steady-state CSR model. The CSR wake can be expressed as:

$$w(\mu) = \frac{\gamma^4}{3\pi\epsilon_0\rho^2}\phi(\mu), \tag{1}$$

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and

$$\phi(\mu) = \frac{3\,\mathrm{csch}[2\sinh^{-1}\mu]}{4\sqrt{1+\mu^2}}\Big(\frac{3}{\mu} + 3\mu$$
$$-6\cosh\left[\frac{5\sinh^{-1}\mu}{3}\right]\coth[2\sinh^{-1}\mu]$$
$$+5\sinh\left[\frac{5\sinh^{-1}\mu}{3}\right]\Big), \tag{2}$$

where ϵ_0 is the vacuum permittivity, $\mu = \frac{3z\gamma^3}{2\rho} > 0$, z is the distance between particles, γ is the Lorentz factor and ρ is the bending radius of the dipole magnet. When $\mu < 0$, $w(\mu) = 0$.

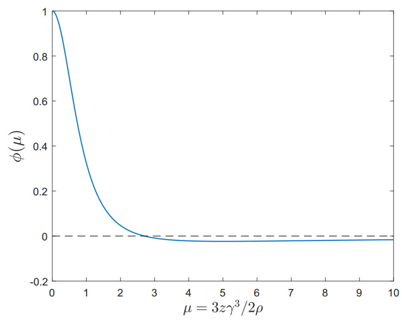

Figure 2: Plot of the function $\phi(\mu)$ versus μ.

The function $\phi(\mu)$ is plotted in Fig. 2. When $\mu \gg 1$, $\phi(\mu) \approx \frac{3}{4\cdot 2^{1/3}}\frac{1}{\mu^{4/3}}$, and

$$w(z) = -\frac{1}{2\cdot 3^{\frac{4}{3}}}\frac{1}{\pi\epsilon_0\rho^{\frac{2}{3}}z^{\frac{4}{3}}}, \tag{3}$$

which is widely used as a 'long-range' approximation. Currently operating accelerator machines generally satisfy this approximation. However, in the GLSF insertion unit, where the bunch length can be as short as nanometers, this approximation does not hold. Therefore, it is necessary to consider the complete CSR wake when analyzing the impact of CSR in the GLSF insertion unit.

When calculating the effect of wakefield on particles within a bunch, the general computational expression is

$$\frac{dE(z)}{ds} = \int_{-\infty}^{z}\lambda(z')w(z-z')dz', \tag{4}$$

where E is the energy of the particle, λ is the density distribution of the bunch, z and z' represent the longitudinal position coordinates of the test particle and the source particle, respectively. The selection of the integration limits is due to the characteristic of the CSR wake. However, since the divergent nature of the CSR wake form, as shown in Eq. (3), directly applying Eq. (4) can not yield a convergent result. Therefore, in practical applications, it is necessary to use integration by parts to rewrite the Eq. (4) as

$$\frac{dE(z)}{ds} = -\lambda(z')S(z-z')|_{-\infty}^{z}$$
$$+\int_{-\infty}^{z}\lambda'(z')S(z-z')dz', \tag{5}$$

where $S(u) = \int_0^u w(x)dx$, and λ' denotes the derivative of the density distribution with respect to the longitudinal position coordinate. Figure 3 shows the plot of $S(u)$. $S(0) = 0$ is a direct result and $S(\infty) = 0$ is determined by the nature of the CSR wake. Therefore, the first term on the right-hand side of the Eq. (5) equals zero. The rate of change of energy in the bunch is thus given by

$$\frac{dE(z)}{ds} = \int_{-\infty}^{z}\lambda'(z')S(z-z')dz'. \tag{6}$$

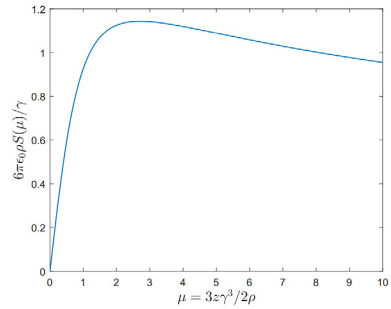

Figure 3: Plot of the function $S(\mu)$ versus μ.

In our program, CSR effect is achieved through the above Eq. (6), and linear dynamics is implemented via the transfer matrix. We have performed a test to validate this CSR algorithm. The test used a Gaussian input bunch with 100000 macroparticles, charge of 1 nC, and a rms bunch length of 50 µm. The bending radius of the dipole magnet was 1.5 m. These parameters are identical to the example given by Saldin et al [7]. The mean energy offset and standard deviation of energy offset of an initial zero energy spread Gaussian bunch after passing through a magnet of length L_b due to CSR can be analytically derived as

$$<\delta> = -0.3505\frac{r_eQL_b}{e\gamma\rho^{\frac{2}{3}}\sigma_z^{\frac{4}{3}}}, \tag{7}$$

and

$$\sigma_\delta = 0.2459\frac{r_eQL_b}{e\gamma\rho^{\frac{2}{3}}\sigma_z^{\frac{4}{3}}}, \tag{8}$$

where r_e is the classical electron radius, Q is the total charge, e is the elementary charge, γ is the Lorentz factor, ρ is the bending radius, and σ_z is the bunch length. Our program reproduced these results accurately, as seen in Fig. 4.

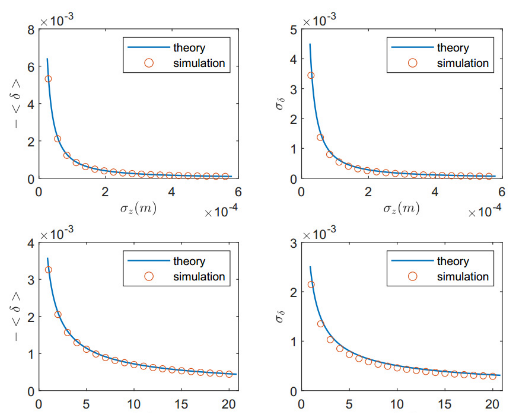

Figure 4: Mean energy offset and standard deviation of energy offset vs rms bunch length and bending magnet radius.

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RESULTS AND DISCUSSION

We generated a Gaussian bunch for tracking, with specific parameters based on the current design as shown in Table 1. Note that the number of particles here represents the actual number of particles. Due to the significant variation of bunch length within the insertion unit, each magnet needs to be sliced sufficiently to achieve convergent simulation results.

Table 1: Beam Parameters of Test Bunch

Parameter	**Value**
Vertical Emittance ϵ_y	1 pm · rad
Bunch Length σ_z	50 nm
Natural Energy Spread σ_δ	2.5×10^{-4}
Number of Particles N	2.2×10^4

There are two parameters of particular interest to our design. One is the bunch length at the radiation spot, which directly affects the final radiation power. Figure 5 shows the longitudinal phase space distribution of the bunch at the radiation spot with and without CSR. The other one is the vertical emittance of the bunch upon exiting the insertion unit, which impacts whether steady-state can be maintained. The vertical phase space distribution of the bunch at the exit of the insertion unit with and without CSR are shown in Fig. 6. Some statistical values are listed in Table 2.

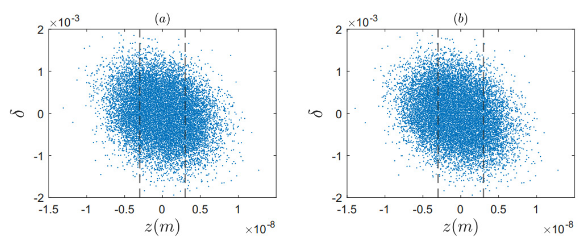

Figure 5: Longitudinal phase space of beam at the radiation spot: (a) with CSR, (b) without CSR.

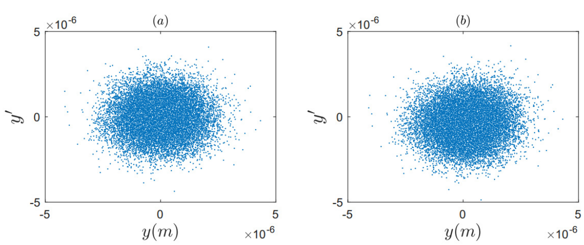

Figure 6: Vertical phase space of beam at the exit of the GLSF insertion unit: (a) with CSR, (b) without CSR.

Table 2: Beam Parameters at Radiation Spot and Exit

Parameter	**Value**
Bunch Length at RAD without CSR σ_{z0}	3.04 nm
Natural Energy Spread at RAD without CSR $\sigma_{\delta 0}$	5.28×10^{-4}
Vertical Emittance at Exit without CSR ϵ_{y0}	1.00 pm · rad
Bunch Length at RAD with CSR σ_z	3.07 nm
Natural Energy Spread at RAD with CSR σ_δ	5.28×10^{-4}
Vertical Emittance at Exit with CSR ϵ_y	1.01 pm · rad

From the simulation results, we can see that, the linear dynamics without considering CSR meets the design requirements. The bunch length at the radiation spot has reached the nanometer scale, and the vertical emittance remains unchanged. When considering CSR, only a slight increase, less than 1%, in both bunch length at radiation spot and vertical emittance at exit is observed. The relatively modest CSR effect can be attributed to two main factors. Firstly, the number of electrons per bunch is actually not very large. Secondly, ultrashort bunch only appears in the two dipoles very close to the radiator. Although the CSR kick is relatively strong there, the dispersion H_y function is still very small, resulting in a not severe impact on vertical emittance. Therefore, we can believe that for the current design parameters, the influence of CSR on the particle dynamics in GLSF insertion unit is acceptable for a single pass case. More indepth study on the multi-pass case and beam equilibrium parameters are ongoing.

Note that here a 1D free space steady-state CSR model is used to give an initial assessment. In fact, the parameters of the bunch do not satisfy the Derbenev criterion, hence a 3D CSR model is needed. We will proceed to evaluate the impact of the higher-dimensional CSR accordingly.

CONCLUSION

We have developed a program to assess the impact of CSR on the beam dynamics in GLSF insertion unit, and we found that under the current design parameters, the effect of CSR is acceptable for a single pass case. We will subsequently utilize more precise CSR model and attempt to conduct theoretical analyses to provide further insights for GLSF insertion unit.

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