FEASIBILITY ANALYSIS OF EMITTANCE PRESERVATION DURING BUNCH COMPRESSION IN THE PRESENCE OF COHERENT SYNCHROTRON RADIATION IN AN ARC*

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Abstract

Electron beam with low transverse emittance, short bunch length and high peak current is the basic requirement in modern high-brightness light sources. However, coherent synchrotron radiation (CSR) will dilute the transverse emittance when the electron beams pass through a magnetic bunch compressor and degrade the performance of the machine. In this paper, based on our CSR point-kick analysis, arc compressors with high compression factor in the presence of CSR effect are studied, both periodic and aperiodic arcs are included. Through analytical and numerical research, an easy optics design technique is introduced to minimize the emittance dilution within these compressors. Taking practical considerations into account, the results of periodic and aperiodic arcs are compared.

INTRODUCTION

In ERL designs, recirculation arcs are often used to compress the bunch length. In order to achieve compression, an ultra-relativistic electron beam with energy chirp passes through the bending system. Since the trajectory is curved, electrons emit coherent synchrotron radiation (CSR) and may induce energy modulation along the bunch and dilutes transverse emittance, leading to degradation of the beam quality [1-3]. To suppress the undesirable emittance growth, several design strategies have been proposed [4-8]. However, most of these designs reach a high compression factor by adopting a low bunch charge. In this paper, the CSR point-kick analysis [8] is reviewed and be applied to an arc compressor consists of symmetric or asymmetric DBAs to achieve emittance preservation with high bunch charge.

POINT-KICK ANALYSIS OF CSR EFFECT

In the “steady-state” approximation for a Gaussian line-charge distribution beam, the CSR-induced rms relative energy spread depends linearly on both L_b and $\rho^{2/3}$ [9-11].

$$\Delta E_{rms} = 0.2459 \frac{eQ\mu_0 c_0^2 L_b}{4\pi\rho^{2/3}\sigma_z^{4/3}}, \quad (1)$$

where e, Q, ρ, σ_z, L_b, μ_0, c_0 represent the charge of a single particle, the bunch charge, the bending radius of the orbit, the rms bunch length, the bending path, the permeability of vacuum, and the speed of light, respectively.

Therefore the CSR effect in a dipole was linearized by assuming $\delta(csr) = kL_b/\rho^{2/3}$, where k depends only on the bunch charge Q and the bunch length σ_z, and is in unit of $m^{1/3}$. In addition, it was shown that the CSR-induced coordinate deviations after a passage through a dipole can be equivalently formulated with a point-kick at the centre of the dipole (see Fig. 1), which is of the form [8]

$$X_k = \begin{pmatrix} \rho^{4/3}k[\theta\cos(\theta/2) - 2\sin(\theta/2)] \\ \sin(\theta/2)(2\delta + \rho^{1/3}k\theta) \end{pmatrix}, \quad (2)$$

where $\delta = \delta_0 + \delta_{csr}$, is the particle energy deviation at the entrance of the dipole, with δ_0 being the initial particle energy deviation and δ_{csr} being that caused by CSR in the upstream path.

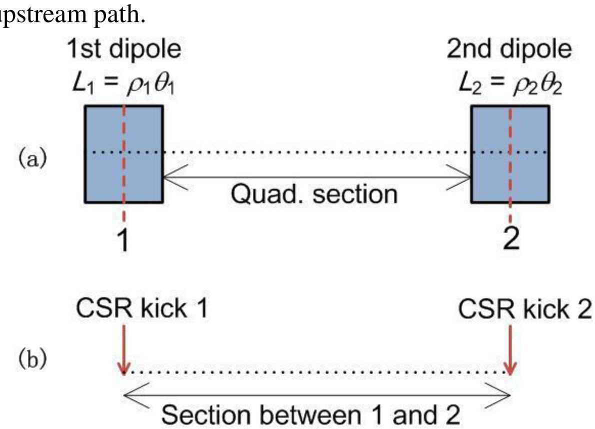

Figure 1: Schematic layout of a two-dipole achromat and physical model for the analysis of the CSR effect with two point kicks. The point 1 and 2 indicate the centres of the first and the second dipole, respectively.

EMITTANCE PRESERVATION OF A CHIRPED BEAM AFTER A DBA

In this section, we will present the derivation of the CSR-minimization condition for a DBA with symmetric layout. As sketched in Fig. 1, the bending angles of the first and the second dipole are denoted by θ, the bending radii of these dipoles are the same, denoted by ρ. According to the point-kick analysis, CSR kicks occur at the centres of the two dipoles (denoted by 1, 2, in Fig. 1), and between the adjacent kicks only one 2-by-2 transfer matrix of the horizontal betatron motion is considered. For simplicity, it is assumed that the initial particle coordinates relative to the reference trajectory are $X_0 = (x_0, x_0')^\dagger = (0, 0)^\dagger$ and the energy deviation is $\delta = 0$. According to Eq. (2), the coordinates remain zero until the particle

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experiences the CSR-kick at point 1, where the particle coordinates are given by

$$X_1 = \begin{pmatrix} -\rho^{4/3} k_1 r \\ S\rho^{1/3} k_1 \theta \end{pmatrix}, \tag{3}$$

where $r = 2\sin(\theta/2) - \theta\cos(\theta/2)$, and $S = \sin(\theta/2)$. Since the DBA satisfied the achromat condition, the transport matrix can be expressed as

$$M_{12} = \begin{pmatrix} -1 & 0 \\ m_{21} & -1 \end{pmatrix}. \tag{4}$$

After passing through the section between point 1 and 2, the particle experiences the second kick. Note that due to energy chirp, as S. Di Mitri mentioned before [7], the bunch length of the beam is compressed and the coefficient $k_2 = g_n^{4/3} k_1$, where g_n is the compression factor in the nth DBA. Finally, the CSR-induced particle coordinate deviations at point 2 are (the energy spread δ grows to $k_1\rho^{1/3}\theta$ at point 2)

$$X_2 = \begin{pmatrix} -\rho^{4/3} k_1 r (g_n^{4/3} - 1) \\ \rho^{1/3} k_1 [m_{21}\theta\rho C + (\theta + g_n^{4/3}\theta - 2m_{21}\rho) S] \end{pmatrix}, \tag{5}$$

where $C = \cos(\theta/2)$. The final geometric emittance (the geometric emittance at the end of the DBA) in presence of the CSR effect can be estimated by

$$\begin{aligned} \varepsilon^2 &= \varepsilon_0^{\,2} + \varepsilon_0 \cdot d\varepsilon, \\ d\varepsilon &= \gamma_2 x_{2,rms}^2 + 2\alpha_2 x_{2,rms} x'_{2,rms} + \beta_2 x'^2_{2,rms}. \end{aligned} \tag{6}$$

where ε_0 is the unperturbed geometric emittance and α_2, β_2, γ_2 are the C-S parameters at the centre of the second dipole of the DBA. To achieve minimum emittance growth, the matrix element m_{21} can be solved by differentiating Eq. (6) with respect to m_{21},

$$m_{21} = \frac{\alpha_2 (1 - g_n^{4/3})}{\beta_1} + \frac{6(1 + g_n^{4/3})}{L_b}. \tag{7}$$

With $m_{21} = (\alpha_2 - \alpha_1)/\beta_1$, from which the linear CSR-suppression condition can be obtained,

$$\alpha_2 = \frac{L_b \alpha_1 + 6\beta_1 (1 + g_n^{4/3})}{L_b g_n^{4/3}}. \tag{8}$$

In the particular case with $\alpha_2 = -\alpha_1$, Eq. (8) turns to be[12]

$$\beta_1 / \alpha_1 = -L_b / 6. \tag{9}$$

where in Eqs. (8) ~ (9) only the first significant terms with respect to θ are kept. These two equations are the CSR suppression condition of aperiodic and periodic arc.

ARC COMPRESSOR

The compression arc can be consists of several identical or distinct DBAs, and the total compression factor is defined as $C_0 = 1 / (1+hR_{56})$ in first order, where h and R_{56} are the bunch energy chirp and the z-δ correlation term of transport matrix, respectively. To minimize the CSR-induced emittance growth after the arc, one should choose the proper initial C-S parameters, which satisfying Eq. (8) or (9). To contrast, the dependency of the emittance growth $\Delta\varepsilon_n$ on different lattices are investigated with ELEGANT simulations, the initial beam distribution in phase space is generated accordingly to match the optics. Now consider a 180° arc compressor made of 6 DBA which satisfying the conditions deduced above, some parameters of the lattice and the beam are listed in Table. 1 and R_{56} of the arc is 0.128m. To achieve a total compression factor $C_0 = 50$, one need the energy chirp h = -7.6 m^{-1} at the entrance of the arc. The bunch charge in the simulations are 500 pC. The dipole bending radius and bending angle are 2 m and 15 degrees, respectively. All the simulation parameters can be seen from Table. 1.

We establish four different optics to compare the CSR suppression efficiency. The first design is made of six identical DBAs with the C-S parameters $\beta_0(i)$ = 11.4 m, $\alpha_0(i)$ = 5.9 and $\beta_f(i)$ = 11.4 m, $\alpha_f(i)$ = -5.9, i = 1,2…6, which satisfying Eq. (9). The second design is different from the first one just in the last DBA, which has $\beta_0(6)$ = 5.4 m, $\alpha_0(6)$ = 1.3 and $\beta_f(6)$ = 12.7 m, $\alpha_f(6)$ = -6.5. The correlated C-S parameters in point 1 and 2 in the last DBA are $\beta_1(6) = \beta_2(6)$ = 2 m, $\alpha_1(6)$ = 0 and $\alpha_2(6)$ =2.41, satisfying Eq. (8) with g_6 = 9.2. The third design is also satisfying Eq. (8), each DBA is distinct, only has the same $\beta_1(i) = \beta_2(i)$ = 2 m and $\alpha_1(i)$ = 0. The forth design is periodic but not satisfying the CSR suppression condition, the C-S parameters are $\beta_0(i)$ = 14.0 m, $\alpha_0(i)$ = 3.5 and $\beta_f(i)$ = 14.0 m, $\alpha_f(i)$ = -3.5, i = 1,2…6. These four lattices are shown in Fig. 2.

Table 1: Summary of the Simulation Parameters

Parameter	Value	Units
Bunch charge	500	pC
Normalized emittance	1	μm.rad
Beam energy	4	GeV
Energy spread	0.03	%
Initial bunch length	1	mm
Dipole bending radius	2	m
Dipole bending angle	15	degree
Final bunch length	20	μm

Simulation results are shown in Fig. 3. Each point in Fig. 3 represents the ε_n after every DBA. It can be seen that with the previous three designs, CSR induced emittance growth can be suppressed since Eq. (8) or Eq. (9) can be satisfied, and the final normalized emittance are all

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around 1.68 μm. To contrast, with the forth design, the final normalized emittance grows to 1.99 μm, which is larger than the previous three designs. It is worth mentioning that in our simulations, the final emittance increases with increasing the final β function at the end of the arc. Thus, in our designs, all final β function at the end of the arc are close to 13 m. Results show that the suppression condtions Eqs. (8) and (9) lead to smaller emittance growth, however, the emittance growth in the last DBA is still very large. This is because in our rough model, the bunch length does not change in the dipole, which means that our model requires short bending magnets, and the arc should consist of more cells to avoid large compression factor in the last cell.

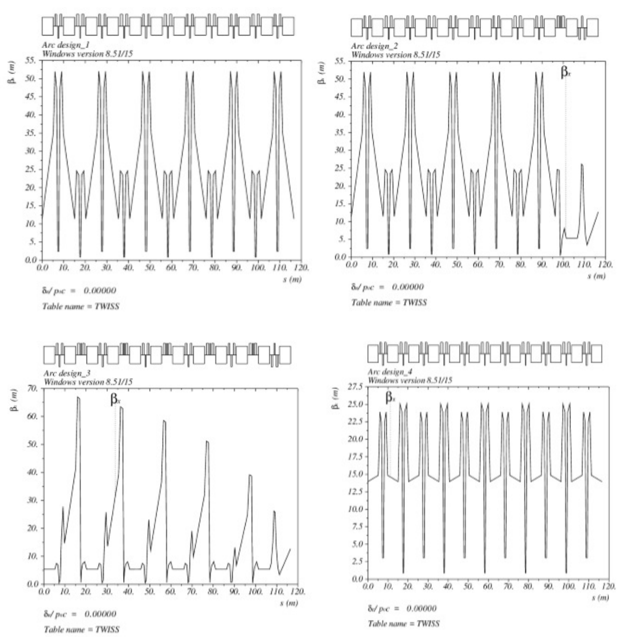

Figure 2: The four different lattices of the arc compressor.

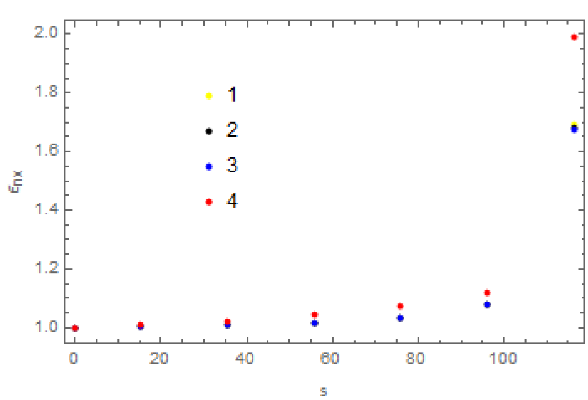

Figure 3: Final normalized emittance in four lattices.

DISCUSSIONS

By adopting a few modifications on the point-kick analysis, we have derived the generic condition for minimizing the CSR kicks in a linear regime. This condition provide a new way to suppress the CSR-induced growth emittance in an arc compressor made of identical or different DBAs with the beam of high bunch charge. It is worth mentioning that the final emittance growth depends on β_f, the beta function at the centre of dipole should be cautiously tuned for both emittance preservation and optics, and maybe the asymmetric design can be applied more widely. We hope that our results provide guidance on gauging the trade-off between tolerable emittance growth and the optimum lattice design.

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