Impact on the magnetic compressor due to CSR *

LIU Chu-Yu(刘初玉)[1)] WANG Fang(王芳) WANG Er-Dong(王尔东) QUAN Sheng-Wen(全胜文) HAO Jian-Kui(郝建奎) LU Xiang-Yang(鲁向阳) ZHANG Bao-Cheng(张保澄) ZHAO Kui(赵夔)

(MOE Key Laboratory of Heavy Ion Physics, Institute of Heavy Ion Physics, Peking University, Beijing 100871, China)

Abstract When an electron bunch is compressed in a chicane compressor, the CSR (coherent synchrotron radiation) will induce energy redistribution along the bunch. Such energy redistribution will affect the longitudinal emittance as a direct consequence. It will also excite betatron oscillation due to the chromatic transfer functions, and hence a transverse emittance change. So, it is indispensable for us to find a way to alleviate the CSR-caused emittance dilution and the bad result of chicane compressor in PKU-FEL.

Key words coherent synchrotron radiation, magnetic compressor, energy spread, emittance

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1 Introduction

Peking University IR-FEL (Infrared Free Electron Laser) Facility[1] is supported by 973 projects. It is composed of four parts: the DC-SC (direct current and superconducting) photo-injector[2], the 2×9 cell 1.3 GHz main accelerator, the chicane compressor[3] and the wiggler. To get a short saturation length and high luminosity FEL laser, a high luminosity electron source is needed. For the presence of space charge effect, usually, a low peak current electron beam is produced from the source first, then it is accelerated to relativistic energy, with manipulation of the phase space in the following transport line, finally we get a short electron beam and a high peak current. Chicane compressor is used in several labs to achieve short bunch[4—6]. Fig. 1 shows the schematic plot of chicane compressor at Peking University.

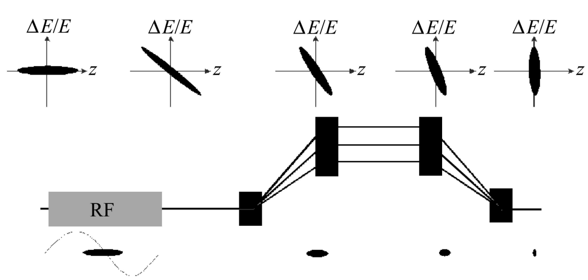

Fig. 1. The schematic of magnetic compressor in PKU-FEL.

Before the chicane, the electron bunch has high energy in the rear and low energy in the head. In the chicane, low energy electrons will take a longer trajectory so that the bunch length gets compressed. Table 1 shows the optimized parameters of chicane compressor.

Table 1. Parameters of the magnetic compressor in PKU-FEL.

parameter	value	unit
$B_{\max}$	0.1873	T
bend angle	12—22	degrees
bend effective length	20	cm
drift length between magnets 1—2 and 3—4	40	cm
drift length between magnets 2—3	20	cm
magnet gap	2.4	cm
good field of magnets 2—3	14	cm
good field of magnets 1—4	6	cm
field uniformity	0.1%	
stability of power supply	0.05%	

2 Energy spread

To analyze the CSR effects, we use one dimensional "steady model"[7]. The charge distribution is described by a linear Gaussian function

$$\lambda(s)=\frac{N}{\sqrt{2\pi}\sigma_s}\mathrm{e}^{-s^2/2\sigma_s^2}\ , \qquad (1)$$

The power loss due to CSR in different positions is

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1) E-mail: unco@pku.edu.cn

$$\frac{\mathrm{d}\varepsilon}{c\mathrm{d}t}=\frac{2Ne^2}{\sqrt{2\pi}(3\rho^2\sigma_s^4)^{1/3}}F\left(\frac{s}{\sigma_s}\right). \tag{2}$$

Here F is the form factor of CSR

$$F(\xi)=-\int_{-\infty}^{\xi}\frac{\mathrm{d}\xi'}{(\xi-\xi')^{1/3}}\frac{\mathrm{d}}{\mathrm{d}\xi'}\mathrm{e}^{-\xi'^2/2}\ , \tag{3}$$

N is the number of electrons of the bunch; ρ is the radius of the electron trajectory; s is longiludinal coordinate; σ_s is the rms bunch length. It is obvious that the CSR effect becomes stronger when the bunch length gets shorter. With the CSR effect, the bunch will gain energy in the head ($F>0$) and lose energy in the middle and tail ($F<0$)[8]. It is clear from the CSR wake potential of electron bunch shown in Fig. 2 in which the horizontal axis represents the displacement from the beam center in unit of longitudinal sigma of the bunch.

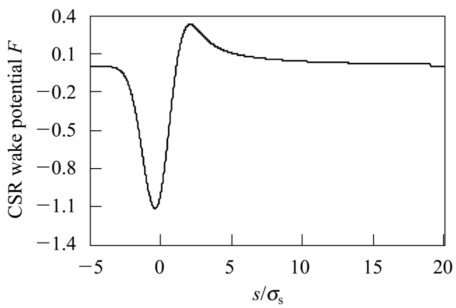

Fig. 2. CSR wake potential of electron bunch.

Before entering the chicane, the bunch is accelerated off-crest in the RF module so that the near linear chirp with the high energy tail and the low energy head is induced. When compressed in the chicane, the low energy head will gain energy but the high energy tail will lose energy, and its energy spread will become smaller due to the CSR effect!

With the simulation using ELEGANT[9], we can see the energy spread change in the chicane compressor in Fig. 3: The energy spread changes from 4.80‰ to 4.74‰. This is consistent with the result: The energy spread becomes smaller due to the CSR effect in the chicane compressor. The FEL lasing process will benefit from it in some sense since the low energy spread is desirable.

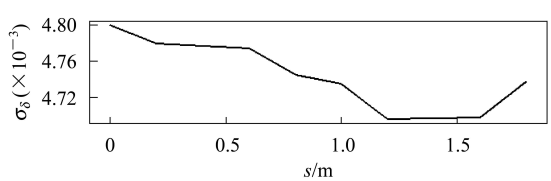

Fig. 3. Change of energy in the magnetic compressor.

3 Transversal emittance

For the edge field of dipole and without normal incidence of electron beam, the symmetric four-dipole chicane is not achromatic. The initial energy spread and the change due to CSR will affect the transversal emittance through chromatic equations[10]: $\partial x/\partial\delta=R_{16}$, $\partial x'/\partial\delta=R_{26}$, the result is emittance dilution. The transversal emittance after compression should be

$$\varepsilon^2\approx\varepsilon_0^2+\varepsilon_0\frac{1}{\beta}\left[\langle\Delta x^2\rangle+\left(\alpha\langle\Delta x^2\rangle^{\frac{1}{2}}+\beta\langle\Delta x'^2\rangle^{\frac{1}{2}}\right)^2\right], \tag{4}$$

Here,

$$\langle\Delta x^2\rangle=\left(\int R_{16}\frac{\mathrm{d}\sigma_\delta}{\mathrm{d}s}\mathrm{d}s\right)^2,\quad \langle\Delta x'^2\rangle=\left(\int R_{26}\frac{\mathrm{d}\sigma_\delta}{\mathrm{d}s}\mathrm{d}s\right)^2.$$

σ_δ is the relative energy spread, ε_0 is the initial emittance, α and β are the twiss parameters after chicane.

The emittance change is shown in Fig. 4 also using ELEGANT. The emittance in x and y direction will both increase after the beam compressed in chicane compressor. It is a little hard to tell the difference of emittance in x before and after compressor due to the bigger scale of Fig. 4(a). Exact values of emittance will be given next.

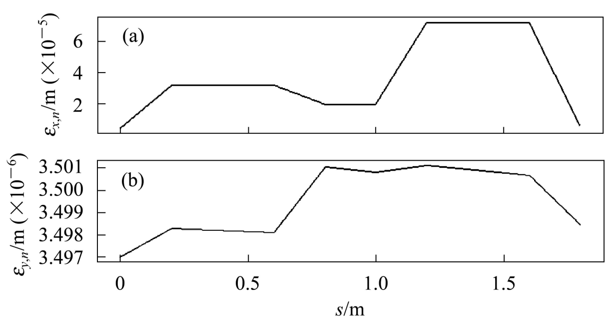

Fig. 4. Change of ε_x (a) and ε_y (b) in the magnetic compressor.

The CSR effect was considered in those simulations. Also simulations without CSR were done to check how much the impact was. The comparison with and without CSR is shown in Table 2. The emittance in x will increase dramatically with CSR because chicane compressor is in x plane. The relative emittance change reaches up to 14.2%. Once the emittance causes any trouble on lasing, lots of attention should be paid to the CSR effect in the chicane.

Table 2. Emittance with and without CSR.

property	initial beam	final beam (CSR OFF)	final beam (CSR ON)
emit, x	4.424 mm·mrad	4.424 mm·mrad	5.407 mm·mrad
emit, y	3.497 mm·mrad	3.503 mm·mrad	3.498 mm·mrad

4 Impact on compression

The energy redistribution during the chicane will destroy the linear chirp of the bunch, and cause distortion in the longitudinal phase space. With simulation, the bunch length will be compressed from 1.770 mm (5.9 ps) to 0.0956 mm (319 fs) without CSR and to 0.0975 mm (325 fs) with CSR.

5 Suppression of CSR

The radiation from electron bunch going through dipole comprises incoherent and coherent synchrotron radiation. If $\lambda < \sigma_s$, it's incoherent radiation; $\lambda > \sigma_s$, it's coherent radiation. Choosing a right size for the vacuum chamber is the way to suppress coherent radiation. With the shielding of chamber, strong radiation only remains in a certain wavelength range $\sigma_s < \lambda < \lambda_c$. λ_c is the characteristic wavelength, radiation beyond it will be considerably reduced[11]. $\lambda_c = 2h\left(\frac{h}{\rho}\right)^{1/2}$, h is the height of vacuum chamber. Considering the dispersion of electron bunch in the chamber and emittance dilution in the chicane, we decide the height of chamber to be $h = 1.8$ cm, then $\lambda_c = 6.50$ cm (R=0.553 m). The bunch quality will be kept acceptable for lasing.

6 Conclusion

With the simulation of ELEGANT, we know that the main cause of emittance dilution in chicane is the CSR effect which will affect the compression result also. Suppressing CSR should always be in mind when designing the chamber.

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