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Coherent Synchrotron Radiation as a Diagnostic Tool for the LCLS Longitudinal Feedback System*

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Abstract

The Linac Coherent Light Source (LCLS) will be the world's first x-ray free-electron laser (FEL). To ensure the vitality of FEL lasing, a longitudinal feedback system is required together with other diagnostics. In this paper, we study the possibility of using Coherent Synchrotron Radiation (CSR) from the chicane as a diagnostic tool for bunch length feedback. Studies show that CSR is a good candidate, even for a non-Gaussian, double-horn longitudinal charge distribution as in the LCLS. We further check the possibility for detecting possible microbunching.

Introduction

LCLS operation will rely heavily on a longitudinal feedback system to maintain the peak current [1], where we plan to use Coherent Synchrotron Radiation (CSR) from the two chicanes as a relative bunch length monitor. According to the LCLS design report, the rms bunch length at the first bunch compressor (BC1) is 190 μm; at the second (BC2) it is 21 μm. Hence, for such a short bunch length, CSR is substantial, and therefore very attractive as a bunch length monitor. In this paper, we study this possibility.

For a group of N_e electrons, the energy emitted per unit frequency and solid angle is

$$\frac{d^2\mathcal{I}}{d\omega d\Omega} = N_e^2|F|^2\frac{d^2\mathcal{I}_0}{d\omega d\Omega}, \tag{1}$$

where $d^2\mathcal{I}_0/(d\omega d\Omega)$ is the radiation produced by a single electron, and $|F|^2$ is the coherent enhancement factor [2], which is defined as

$$|F|^2 = \left|\int n(z)\, e^{-ikz}dz\right|^2. \tag{2}$$

In the above expression, we have assumed a line charge, *i.e.*, zero transverse dimension, and $n(z)$ is the longitudinal density distribution. If $n(z)$ is Gaussian, we have $F = \exp(-k^2\sigma_z^2/2) = \exp(-2\pi^2\sigma_z^2/\lambda^2)$. Hence, it explicitly shows that only long wavelength radiation, roughly speaking, for $\lambda > 2\pi\sigma_z$, is coherently enhanced.

Longitudinal Distribution and Spectrum

In the LCLS case, the longitudinal distribution after BC1 is parabolic. Hence, for a CSR detector at BC1, one may take the Gaussian coherent enhancement factor, or work out for a parabolic distribution. However, when the electron bunch with parabolic distribution passes the LINAC after BC1, due to the LINAC wakefield, a nonlinear curvature is developed along the electron bunch as shown in Fig. 1. The dashed line stands for the linear chirp induced by the LINAC RF between BC1 and BC2. Adding the residual chirp from the LINAC before BC1, it becomes the long-dashed line. Finally, the longitudinal wakefield of 330 meters of accelerating structures induces a nonlinear curvature to become the solid curve. After compression, the longitudinal distribution becomes a double-horn structure. For the LCLS nominal parameters, the longitudinal distribution is shown in Fig. 2. Because of this, we would expect high frequency content in the bunch spectrum. As a comparison, we show the bunch spectrum for a Gaussian and a step function distribution, but with the same rms bunch length in Fig. 3. However, we see clearly that if we stay within the low frequency region, say less that 4 THz, all the distribution functions have reasonably similar bunch spectra. For the purpose of a longitudinal feedback system, one prefers to stay in the low frequency regime where details of the bunch structure will not influence the measurement.

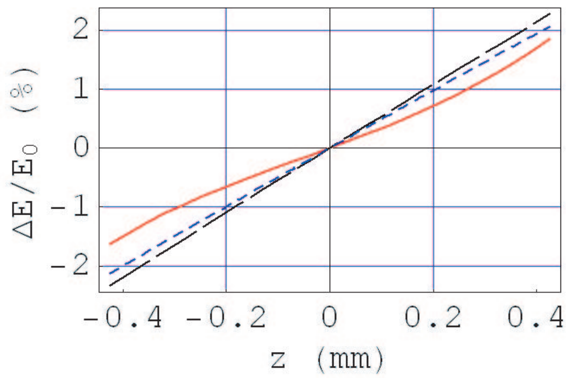

Figure 1: Bunch longitudinal phase space before BC2.

CSR Energy Spectrum

The single electron radiation spectrum is very broad. For fixed bandwidth in wavelength, *i.e.*, fixed $\Delta\lambda$, the spectrum increases with frequency at a power of $7/3$ until it reaches a critical wavelength [3, 4], $\lambda_c[\AA] = 18.64/(B_0[\mathrm{T}]E^2[\mathrm{GeV}])$. In our case, at energy $E = 4.54$ GeV, and assuming a magnetic field $B_0 = 1$ Tesla, we have $\lambda_c \approx 1$ Å. The incoherent synchrotron radiation (ISR) power (P_{isr}) per milliradian of horizontal arc (θ) and integrated over all vertical angles is proportional to the number of electrons and is given by [3, 4]

$$P_{isr}(\lambda)\left[\frac{\mathrm{W}}{\mathrm{rad}\theta\mathrm{-m}}\right] = \frac{8.42\times10^{-9}\rho^{1/3}I}{\lambda^{7/3}}, \tag{3}$$

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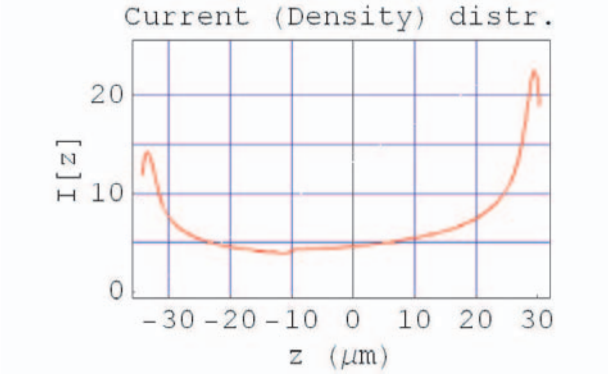

Figure 2: Bunch longitudinal distribution after BC2.

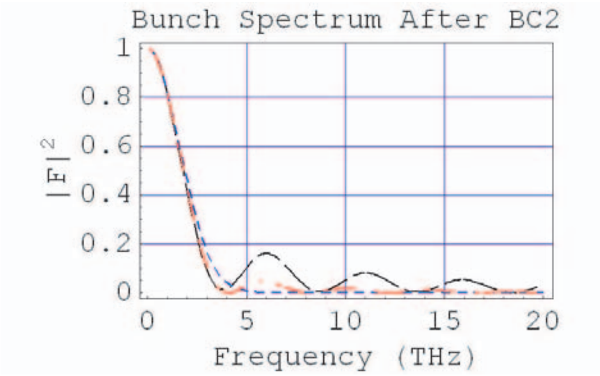

Figure 3: Bunch spectrum after BC2. Long dashed curve (black) is for the double-horn distribution; dashed curve (blue) is for a Gaussian distribution, and dash-dotted (red) is for a step function.

for $\lambda \ll \lambda_c$. Notice that this power spectrum is derived from Eq. (9) of Ref. [3] for 1 % bandwidth in wavelength. Caution should be taken when this is not precise enough. Given the ISR power spectrum in Eq. (3), the coherent synchrotron radiation power spectrum is then

$$P_{csr}(\lambda)\,[W/(\mathrm{rad}\theta - \mathrm{m})] = N\,|F|^2\,P_{isr}(\lambda). \quad (4)$$

Notice that the P_{isr} is expressed in current I, hence, there is only $N|F|^2$ enhancement, but not N^2 as one may expect. Experimentally, one will measure the radiation energy rather than the power, hence we write

$$\mathcal{E}_{csr}(\lambda)\,[J/(\mathrm{rad}\theta - \mathrm{m})] = \frac{2\sqrt{3}\sigma_z}{c} N\,|F|^2\,P_{isr}(\lambda). \quad (5)$$

For BC1 and BC2 in LCLS, we have the parameters in Table 1. Should we take typical wavelength of $\lambda_0 = 2\pi\sigma_z$, the correspond frequency f_0 is also shown in Table 1.

Now, let us look at the CSR energy spectrum for the double-horn bunch after BC2. We assume that the detector has a bandwidth of $\Delta\lambda/\lambda = 1\%$, and the horizontal bending angle $\theta = 1$ mrad. The detected CSR energy as a function of detector central response frequency is shown in Fig. 4. As a comparison, again, we use Gaussian and step function distributions with the same rms bunch length. It is clearly shown that the double-horn introduces radiation at high frequency. Hence, if we have a detector receiving all the radiation, then this high frequency content will smear out the bunch length information. Therefore, a filter is needed if we want to extract the rms bunch length. The general strategy is then to stay in the low frequency regime, where a Gaussian distribution gives a reasonable representation of the double-horn distribution.

Table 1: Nominal parameters for LCLS BC1 and BC2.

	ρ (m)	σ_z (mm)	λ_0 (mm)	f_0 (THz)	I (A)
BC1	2.4	0.19	1.2	0.25	400
BC2	14.5	0.021	0.13	2.3	3400

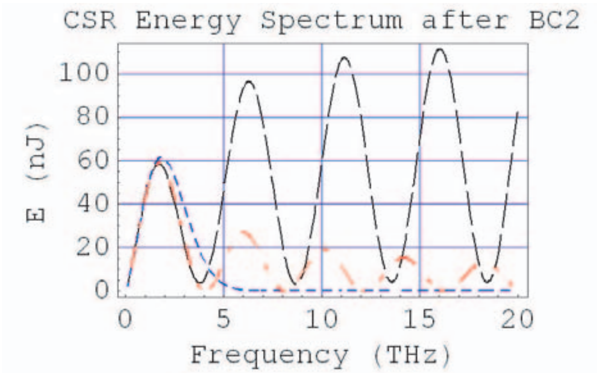

Figure 4: CSR energy spectrum as a function of frequency after BC2. Curves have the same meaning as in Fig. 3.

Detector

For a detector with fixed bandwidth $\Delta\lambda$ in wavelength, the detected CSR energy is then

$$\mathcal{E}_{det}(\lambda)\,[J/(\mathrm{rad}\theta)] = \int_{\lambda-\frac{\Delta\lambda}{2}}^{\lambda+\frac{\Delta\lambda}{2}} d\lambda \mathcal{E}_{csr}(\lambda). \quad (6)$$

For a Gaussian distribution, according to $\mathcal{E}_{csr}$ given in Eq. (5), and P_{isr} in Eq. (3), we have

$$\mathcal{E}_{det}(\lambda,\Delta\lambda)\,[J/(\mathrm{rad}\theta)] = \frac{3.63\times 10^{-10} N^2 e \rho^{1/3}}{\sigma_z^{4/3}} \times\left\{\Gamma\left[\frac{2}{3}, \frac{4\pi^2\sigma_z^2}{(\lambda+\frac{\Delta\lambda}{2})^2}\right] - \Gamma\left[\frac{2}{3}, \frac{4\pi^2\sigma_z^2}{(\lambda-\frac{\Delta\lambda}{2})^2}\right]\right\}, \quad (7)$$

where $\Gamma(a,x) \equiv \int_x^\infty t^{a-1}e^{-t}dt$ is the "upper" incomplete Gamma function.

In the following, we assume the horizontal bending angle to be $\theta = 1$ mrad, and a detector with the central response wavelength at $\lambda_0 = 0.3$ mm, and bandwidth of

10%, *i.e.*, $\Delta\lambda = 30\ \mu$m. The corresponding frequency is $f \in [0.95, 1.05]$ THz. As shown in Fig. 5, we find that, given this detector, the CSR energy of the realistic bunch distribution is well approximated by that of a Gaussian bunch. This ensures that we can use the simple expression in Eq. (7) in our longitudinal feedback system. Indeed, it works well [1].

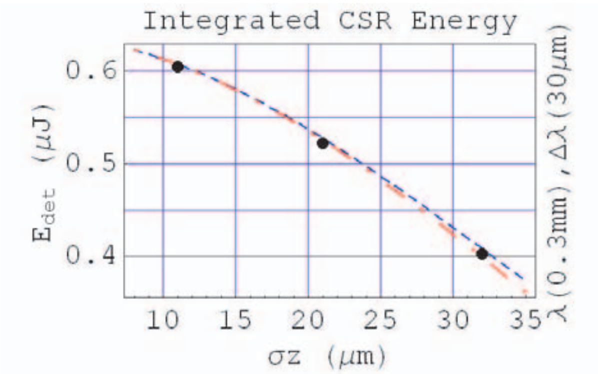

Figure 5: Detected CSR energy as a function of bunch length. The dot (black) is for the double-horn distribution, and the curves have the same meaning as in Fig. 3.

Microbunching

Besides the bunch length monitor needed for the longitudinal feedback system, CSR is also a good candidate for detecting microbunching [5]. However, due to the double-horn structure after BC2 as shown in Fig. 2, the microbunching information can be smeared out. Assuming an initial microbunching with $0.5-$mm wavelength, and after compression through BC1 and BC2, the wavelength is compressed to about $500/40 = 12.5\ \mu$m, which corresponds to a signal at about 24 THz. If we assume a $20-\%$ amplitude modulation, the corresponding CSR spectrum is shown in Fig. 6. One may argue that it is still detectable, even though the double-horn complicates the situation. However, it is a better idea to detect microbunching at BC1, since at BC1 the bunch distribution is mostly parabolic and any small microbunching will show up more clearly. As an example, assuming the same initial microbunching wavelength at 0.5 mm, after BC1 compression the wavelength becomes $500/4 = 125\ \mu$m (frequency at 2.4 THz). Now assuming that at that stage there is only 5% amplitude modulation, we find the CSR spectrum shows the structure even more explicitly, as in Fig. 7. Hence, BC1 is a better place to detect microbunching.

Discussion

Based on the study in this paper, CSR is a good candidate for a relative bunch length monitor, even though after BC2 the longitudinal distribution becomes a double-horn. However, this double-horn structure will smear out any microbunching information, hence BC1 turns out to be a better place to detect microbunching.

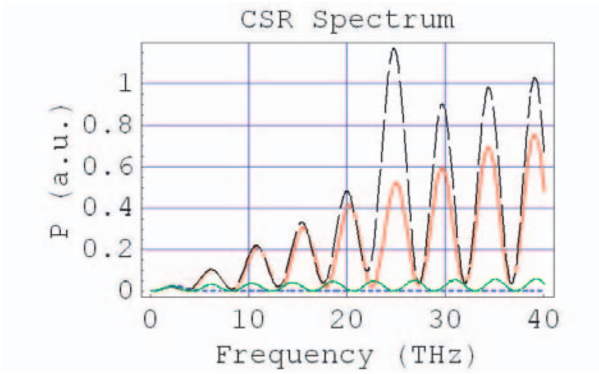

Figure 6: CSR spectrum with $20-\%$ amplitude modulation after BC2. The long-dashed curve (black) is for the double-horn with $20-\%$ modulation; the solid (red) is for the double-horn without modulation; the dashed (blue) is for a Gaussian; and the dotted (green) is for a step function.

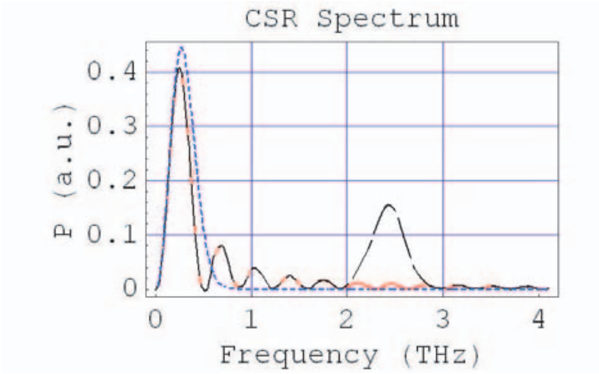

Figure 7: CSR spectrum with $5-\%$ amplitude modulation after BC1. The long-dashed curve (black) is for the parabolic distribution with $5-\%$ modulation; the solid (red) is for the parabolic distribution without modulation; the dashed (blue) is for a Gaussian.

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