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Intrabeam Scattering in an X-ray FEL Driver*

Z. Huang
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

Intrabeam scattering (IBS) of a high-brightness electron beam in an x-ray free-electron laser (FEL) driver is studied. Such a beam is much "colder" in the longitudinal direction than in transverse ones. As a result, the beam energy spread is increased with negligible change of transverse emittances. We estimate the IBS induced energy spread in the Linac Coherent Light Source and evaluate its effects on FEL and CSR microbunching instabilities.

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1 Introduction

In an x-ray free-electron laser (FEL) driver [1, 2], high-brightness electron beams are generated from an rf photocathode gun with a small emittance and a small energy spread, accelerated by a normal conducting or a superconducting linear accelerator to a desired energy, while the bunch length is compressed by magnetic compressors at a few selected locations along the linac. In this note, we study intrabeam scattering (IBS) in such an accelerator system and apply the result to the Linac Coherent Light Source (LCLS).

2 Intrabeam Scattering in a Linac

Intrabeam scattering [3] is due to multiple Coulomb scattering and will redistribute the beam momenta in an approach to "thermal" equilibrium. In the electron's comoving frame, the rms horizontal, vertical, and longitudinal velocities (normalized to the speed of light c) are giving by

$$\gamma\sigma_{x'}, \quad \gamma\sigma_{y'}, \quad \sigma_\delta \tag{1}$$

respectively, where γ is the electron energy in units of the rest energy (mc^2), $\sigma_{x',y'}$ is the rms transverse angular divergence, and σ_δ is the rms fractional energy spread. Beams in accelerators are generally much "colder" longitudinally than in transverse directions as

$$\sigma_{x',y'} \gg \sigma_\delta/\gamma. \tag{2}$$

This condition is certainly satisfied in a x-ray FEL driver from the injector to the end of the linac. Thus, "heat" is transferred from the transverse degrees of freedom to the longitudinal one. Applying Piwinski's IBS formula for the instantaneous growth rate of the beam energy spread in the absence of synchrotron motion [3], we have

$$\frac{1}{\tau_\delta} = \frac{2r_e^2 cN_b}{64\pi^2\beta^3\gamma^2\varepsilon_x^n\varepsilon_y^n\sigma_z\sigma_\delta} f\left(\frac{\sigma_\delta}{\gamma\sigma_{x'}}, \frac{\sigma_\delta}{\gamma\sigma_{y'}}, 2\sigma_\delta\beta\sqrt{\frac{\sigma_y}{r_e}}\right). \tag{3}$$

Here r_e is the classical electron radius, βc is the electron velocity, N_b is the number of electrons in the beam, $\varepsilon_{x,y}^n$ is the normalized transverse emittance, σ_z is the rms bunch length, and the function f takes a simple form [4]

$$f(a, a, q) \approx \frac{4\pi^2}{a}\left(2\ln\frac{q}{2a} - 0.5775\right) \quad \text{when} \quad a \ll 1. \tag{4}$$

We take a transversely round beam (i.e., $\sigma_{x'} = \sigma_{y'}$ and $\sigma_x = \sigma_y$) and set $\beta \approx 1$ to obtain

$$\frac{1}{\tau_\delta} \approx \frac{r_e^2 cN_b}{8\sigma_x\varepsilon_x^n\sigma_z\sigma_\gamma^2} \ln\left(\frac{\Delta\gamma_{max}}{\Delta\gamma_{min}}\right), \tag{5}$$

where $\sigma_\gamma = \gamma\sigma_\delta$ is the rms energy spread in units of mc^2. The argument of the Coulomb logorithm is written in the form of $\Delta\gamma_{max}/\Delta\gamma_{min}$, where

$$\Delta\gamma_{max} \sim \gamma^2\sigma_{x'}, \quad \Delta\gamma_{min} \sim r_e/(\sigma_x\sigma_{x'}) \tag{6}$$

are the maximum and the minimum energy exchange in γ due to a single scattering event [3]. Following an argument made in Ref. [5], the IBS energy distribution has a nearly gaussian core (due to soft scatterings) with a long tail (due to hard scatterings). Since we are mostly interested in the energy spread of the gaussian core, we cut off the contribution of the tail by limiting the maximum energy transfer to $\Delta\gamma_c = \gamma \times 10^{-5}$, In this case, we change the Coulomb log to

$$\ln \frac{\gamma \times 10^{-5}}{r_e/(\sigma_x \sigma_{x'})} = \ln \frac{\varepsilon_x^n \times 10^{-5}}{r_e} \approx 8.2 \tag{7}$$

for $\varepsilon_x^n = 1$ μm. Although the cutoff is somewhat arbitrary, its influence on the result is weak (e.g., the Coulomb logrithm is about 16 without any cutoff). Thus, the change of the energy spread due to IBS is

$$\frac{1}{\sigma_\gamma} \frac{d\sigma_\gamma}{dt} \equiv \frac{1}{\tau_\delta} \approx \frac{r_e^2 c N_b}{\sigma_x \varepsilon_x^n \sigma_z \sigma_\gamma^2} \tag{8}$$

and is almost energy-independent (although σ_x is somewhat energy dependent). For simplicity, we use the average beam size $\langle\sigma_x\rangle$ and assume that σ_z changes suddenly in the middle of the bunch compressor (i.e., σ_z is piecewise constant). Integrating Eq. (8) yields

$$\sigma_\gamma^2 = (\sigma_{\gamma 0}^2) + \frac{2 r_e^2 N_b}{\langle\sigma_x\rangle \varepsilon_x^n \sigma_z} \Delta s, \tag{9}$$

where Δs is the distance tranversed prior to the bunch length being suddenly changed at a bunch compressor. Note that the IBS induced energy spread is uncorrelated and contributes to the increase of the incoherent energy spread.

Since the "heat" is transferred from the transverse degrees of freedom to the longitudinal one, the transverse emittances are slightly reduced at a rate $\sigma_\delta^2/(\gamma\sigma_{x'})^2$ times the longitudinal one given by Eq. (3) [3]. At dispersive locations (such as in bunch compressors), the IBS induced energy change can lead to the emittance growth. However, the magnitudes of these transverse IBS effects are extremely small for an x-ray FEL driver.

3 Numerical Examples

To estimate the IBS induced energy spread in the LCLS, we take $N_b = 6.2 \times 10^9$ for 1 nC charge, $\varepsilon_x^n = 1$ μm, $\langle\sigma_x\rangle \approx 100$ μm throughout the accelerator. The rms bunch length $\sigma_z = 830$ μm before the first bunch compressor, and the PARMELA simulation indicates an initial incoherent enersy spread $(\sigma_\gamma^2)_0 \approx 0.006$ at the exit of the gun [1]. Applying Eq. (9), we obtain $\sigma_\gamma \approx 0.009$ at $\Delta s = 40$ m (the location of the first bunch compressor). After the first bunch compressor $\sigma_z = 190$ μm and $\sigma_\gamma \approx 0.04$ due to the longitudinal phase space exchange. Since $\Delta s = 400 - 40 = 360$ m prior to the second bunch compressor, we apply Eq. (9) between the two bunch compressors to obtain the incoherent energy spread $\sigma_\gamma = 0.06$ at the second compressor, which is about 7×10^{-6} fractional energy spread at 4.5 GeV and more than two times larger than the energy spread without IBS (3×10^{-6} prior to BC2 [1]). At the end of the linac, the energy spread is further increased to about 2×10^{-5} at 14.3 GeV. Integrating Eq. (8) numerically with a $s-$depedendent σ_x yields very similar results [6].

The incoherent energy spread is an important parameter in instability processes. Since the FEL scaling parameter ρ is on the order of 10^{-4} for the LCLS and is much larger than the IBS induced energy spread, we do not expect the IBS to affect the FEL operation. However, the induced energy spread is comparable to the intrinsic energy spread at two bunch compressors and may mitigate the microbunching instability induced by the coherent synchrotron radiation at these bunch compressors. We evaluate the gain of CSR microbunching in the LCLS bend systems using the method of Ref. [7] and the energy spread calculated above. Figure 1 show that the gain is reduced when the IBS induced energy spread is taken into account, but the reduction is not as significant as the inclusion of a damping wiggler that increase the energy spread at the entrance of BC2 to 3×10^{-5} [1].

4 Acknowledgment

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References

[1] Linac Coherent Light Source Conceptual Design Report, http://www-ssrl.slac.stanford.edu/lcls/CDR/ (2002).

[2] TESLA Techinical Design Report, DESY TESLA-FEL 2001-05 (2001).

[3] A. Piwinski, Intrabeam Scattering, in CERN Accelerator School, 1991, p.226.

[4] A. Piwinski, Intrabeam Scattering with Vertical Dispersion, Proc. of 1983 SSC Workshop, p.59. Ann Arbor, MI (1983).

[5] T. Raubenheimer, Particle Accelerator **45**, 111 (1994).

[6] P. Emma, (private communications).

[7] Z. Huang, M. Borland, P. Emma and K.-J. Kim, to be published in Proc. of the 24th International Free Electron Laser Conference and 9th FEL Users Workshop (Argonne, Illinois, 2002), SLAC-PUB-9538.

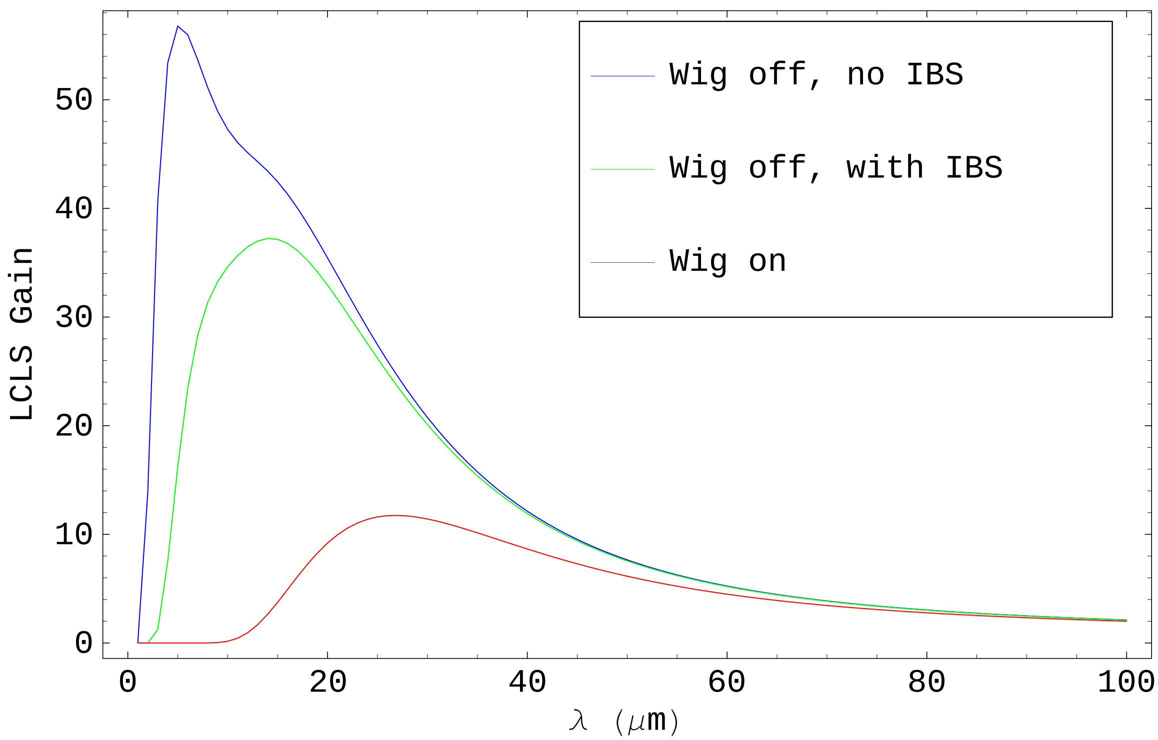

Figure 1: Total gain of the entire LCLS bend system as a function of the modulation wavelength at the exit of BC1.