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Abstract

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Abstract

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INTRODUCTION

Magnetic bunch compressors are designed to increase the peak current while maintaining the small emittance for the electron beam necessary to drive an x-ray free-electron laser (FEL) [1, 2]. Recent simulation studies [3] and theoretical investigations [4, 5, 6] have shown that such a bend system is subject to a microbunching instability driven by coherent synchrotron radiation (CSR) and hence can be very sensitive to any density or energy modulation of the incoming beam distribution. Multiple stage compressions are often employed in x-ray FELs to partially offset the effect of rf phase jitters and to reach a peak current of a few kA. In this case, both density and energy modulations induced in the first-stage compressor can be further amplified in the next-stage compressor, leading to a large gain in overall modulation amplitudes [6, 7]. In this paper, we show that in an S-band linac such as the Stanford linear accelerator, the geometric wakefield of the accelerating structures can also induce significant energy modulation and enhance the CSR microbunching in the subsequent bunch compressor. We determine the total gain in density modulation for the Linac Coherent Light Source (LCLS) [1] and compare with numerical simulations that model the entire accelerator system.

CSR MICROBUNCHING

A magnetic bunch compressor introduces a linear path length dependence on the electron energy (characterized by the momentum compaction factor R_{56}). An incoming electron beam with an energy chirp will be compressed if the tail of the bunch catches up the head by going through a shorter trajectory. CSR emitted by a very short bunch in the bends of a compressor can interact with the bunch itself and increase both correlated energy spread and projected emittances in the bending plane [8]. Furthermore, if the longitudinal density of the bunch is not smooth but is modulated at a wavelength $\lambda = 2\pi/k$ that is much smaller than the bunch length, CSR will be emitted at the same wavelength and induce energy modulation. Such energy modulation can be turned into additional density modulation through R_{56} of the compressor, leading to a microbunching instability. This process can also be initiated by energy modulation of the incoming beam. If this effect is large, both the "sliced" energy spread and the "sliced" emittance on the scale of the wavelength will be increased, directly affecting the FEL performance which depends critically on these "sliced" quantities.

Given the electron distribution function $f(\mathbf{X};s)$ in the horizontal and longitudinal phase space denoted by $\mathbf{X} \equiv (x, x', z, \delta \equiv \Delta\gamma/\gamma)$, we can quantify both density and energy modulations by

$$
\begin{aligned}
b(k;s) &= \frac{1}{N}\int d\mathbf{X} e^{-ikz} f(\mathbf{X};s)\,, \\
p(k;s) &= \frac{1}{N}\int d\mathbf{X} e^{-ikz} \delta f(\mathbf{X};s)\,,
\end{aligned} \tag{1}
$$

where $N = \int d\mathbf{X} f(\mathbf{X};s)$ is the total number of electrons. Considering the evolution of the distribution function in the presence of CSR, one can show that the bunching spectrum $b(k;s)$ is governed by an integral equation [5, 6]

$$
\begin{aligned}
b[k(s);s] = [b_0(k_0) - ik(s)R_{56}(s)p_0(k_0)]\,L(0,s) + ik(s) \\
\times \int_0^s d\tau R_{56}(\tau \to s)\frac{I(\tau)}{\gamma I_A} Z[k(\tau);\tau] b[k(\tau);\tau] L(\tau,s)\,,
\end{aligned} \tag{2}
$$

where $b_0(k_0)$ and $p_0(k_0)$ are the initial density and energy spectra, respectively, $I(\tau)$ is the peak current at τ, $I_A \approx 17$ kA is the Alfven current, $Z(k;s) = (1.63 + 0.94i)k^{1/3}/R(s)^{2/3}$ is the steady-state CSR impedance for a bending radius $R(s)$ [9], $L(\tau, s)$ denotes Landau damping from τ to s due to the beam emittance and energy spread. The integral equation can be solved numerically [5] or analytically for a typical bunch compressor chicane [6] to obtain $b(k;s)$. The energy modulation spectrum is then

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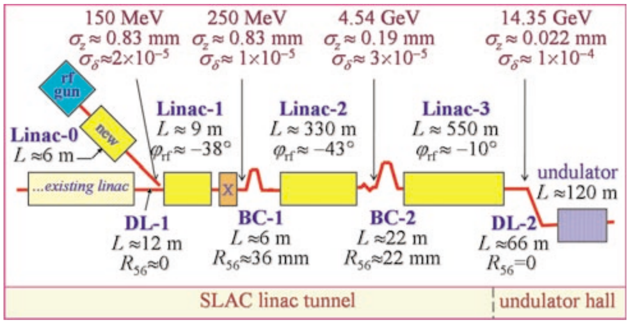

Figure 1: Layout of the LCLS accelerator system.

determined by [6]

$$p[k(s);s] = p_0(k_0)L(0,s) - \int_0^s d\tau \frac{I(\tau)}{\gamma I_A} Z[k(\tau),\tau] \times b[k(\tau),\tau]L(\tau,s)\,. \quad (3)$$

We note that Eqs. (2) and (3) can be used not only for a bunch compressor but also for any beam transport system with a given impedance.

In Ref. [7], the analytical solutions of Eqs. (2) and (3) are applied to study the gain of density modulation for the LCLS bend systems (see Fig. 1). The results agree reasonably well with tracking studies of these bend systems. Furthermore, `elegant` simulations of the entire accelerator system show a peak gain almost a factor of 2 larger than the gain of just these bend systems. In what follows, we extend this study to consider wakefield in the accelerator that can enhance CSR microbunching.

LINAC WAKEFIELD AND IMPEDANCE

As was pointed out in Refs. [4, 6], wakefield upstream of a bunch compressor can accumulate energy modulation for a density-modulated beam and induce additional density modulation in the bunch compressor. For a periodic, cylindrically symmetric accelerating structure such as the SLAC S-band linac, Gluckstern has derived the high-frequency behavior of the longitudinal impedance as [10]

$$Z_{\rm L}(k) \approx \frac{4i}{ka^2}\left[1+(1+i)\frac{\alpha L}{a}\left(\frac{\pi}{kg}\right)^{1/2}\right]^{-1}, \quad (4)$$

where a is the average iris radius, L is the cell (period) length, g is the gap distance between irises and is comparable to L in normal structures, and the parameter α is a function of g/L and is about 0.5 for $g/L \sim 1$. Fourier transformation of Eq. (4) yields a very short-range wakefield $W(z)$ (valid for $z < 100\ \mu$m). A wakefield fitting formula valid for a larger distance (up to a few mm) is given by [11]

$$W(z) = \frac{Z_0 c}{\pi a^2}\exp\left(-\sqrt{\frac{z}{z_0}}\right), \quad (5)$$

where $Z_0 = 377\ \Omega$ and $z_0 \approx 0.41 a^{1.8} g^{1.6}/L^{2.4}$. Eqs. (4) and (5) are steady-state solutions of a periodic accelerating structure and can be applied to a linac longer than the catch up distance $\alpha k a^2$ [10, 11]. For the SLAC linac, $a = 11.6$ mm, $L = 3.5$ cm, $g = 2.9$ cm, and $z_0 \approx 1.32$ mm, and the catch up distance varies from a few meters to a few hundred meters for $\lambda = 100\ \mu$m down to 1 μm, the wavelength range of interest for CSR microbunching.

Equation (4) indicates that the linac impedance decreases with λ. Let us compare magnitudes of the leading term of the linac impedance with the steady-state CSR impedance, say, at $\lambda = 100\ \mu$m:

$$|Z_{\rm L}| \sim \frac{4}{ka^2} \approx 0.5\,{\rm m}^{-1}\,,\ |Z_{\rm CSR}| \sim \frac{k^{1/3}}{R^{2/3}} \approx 9\,{\rm m}^{-1} \quad (6)$$

for $a = 11.6$ mm and $R = 10$ m. We see that the wakefield effect per unit length is much smaller than the CSR effect at these short modulation wavelengths. However, the net effect of the impedance on a beam is integrated over the interaction distance. For CSR, the interaction distance is the total length of dipoles and is on the order of a few meters. For the linac wakefield, the interaction distance is the total length of the linac and is on the order of a few hundred meters. Thus, the net effect of CSR and linac impedances on the microbunching instability can be comparable for the LCLS. Since $R_{56} \approx 0$ in the linac, and the Landau damping due to beam emittance and energy spread is negligible, Eqs. (2) and (3) reduce to

$$\begin{aligned} b[k(s);s] &= b_0(k_0)\,, \\ \gamma(s)p[k(s);s] &= \gamma_0 p_0(k_0) - \frac{I}{I_A}Z_{\rm L}(k_0)b_0(k_0)s\,. \end{aligned} \quad (7)$$

Here we have multiplied Eq. (3) by γ on both sides to include the adiabatic damping due to acceleration.

LCLS TOTAL GAIN

We can now evaluate the amplification of a small current modulation in the initial beam distribution through the entire LCLS accelerator by taking into account both CSR and wakefield effects. Here we take the normalized emittance at 1 μm and keep track of the change of the incoherent energy spread σ_δ due to acceleration and compression (see Fig. 1). The peak currents are obtained by assuming a 1-nC Gaussian bunch with rms bunch lengths σ_z given in Fig. 1 at various stages of compression. We also use the steady-state CSR impedance and the high-frequency linac impedance (i.e., Eq. (4)) for simplicity. First, we calculate the induced density and energy modulations in DL-1 and BC-1 through the analytical solutions of Eqs. (2) and (3) as was done in Ref. [7]. For the given density modulation at the exit of BC-1, the linac wakefield induces additional energy modulation through Eq. (7) in Linac-2 (its effect in Linac-0 and Linac-1 is negligible). Finally, Eq. (2) is again applied to BC-2 to calculate the final density modulation amplified from both density and energy modulations at the entrance of BC-2. Two cases are considered: (1) the incoherent energy spread at the entrance of BC-2 (at 4.54 GeV) is 3×10^{-6} without the superconducting wiggler; (2) the incoherent energy spread at the entrance of BC-2 is increased to 3×10^{-5} by the superconducting wiggler as indicated in Fig. 1. Since $R_{56}\approx 0$ in DL-2, the density modulation after BC-2 is unchanged, and its ratio to the initial density modulation is defined as the total gain. In Fig. 2, we show the total gain as a function of the initial modulation wavelength with and without the damping wiggler. For comparison, we also plot `elegant` simulation results from Ref. [7]. Note that `elegant` uses the transient CSR model [12] and Eq. (5) for the linac wakefield. Nonlinearities in the machine lattice are also included. While theory predicts that the modulation wavelength should compress according to the bunch length compression (by about a factor of 38 after BC-2), simulation shows less wavelength compression than expected. Nevertheless, we see that the gain calculation including the linac wakefield agrees roughly with the `elegant` results. The peak gain is increased by about a factor of 2 compared to previous studies that did not take into account the linac wakefield [7].

It is very important to design the LCLS to have a low gain in CSR microbunching. Typical drive laser of the photocathade rf gun can have structures on the order of a few hundred femtosecond. Suppose such structures cause 1% density modulation of electron beam at $\lambda = 60$ μm in the injector, a total gain close to 100 (in the absence of the damping wiggler, see Fig. 2) implies nearly 100% final density modulation at $\lambda_f \approx 60/38 \approx 1.6$ μm. When the density modulation is close to 100% or $|b_f|\approx 1$, nonlinear effects of CSR instability can significantly increase the incoherent energy spread and sliced emittance on the scale of the modulation wavelength, which is not treated in the present linear theory. Furthermore, we can estimate the induced energy modulation by the linac impedance in Linac-3 and the CSR impedance in DL-2 for the given b_f:

$$\Delta p_f \approx \left|\frac{I_f}{\gamma_f I_A}\left[Z_{\rm L}L_{\rm Linac3}+Z_{\rm CSR}L_{\rm DL2}\right]b_f\right|, \qquad (8)$$

where $L_{\rm Linac3}\approx 550$ m is the length of Linac-3 and $L_{\rm DL2}=4\times 2.62$ m ≈ 10.5 m is the total dipole length in DL-2. For $\lambda_f = 1.6$ μm, $I_f\approx 5$ kA, $\gamma_f\approx 28077$, $|b_f|\approx 1$, and the bending radius of DL-2 dipoles $R=231$ m, we have the final energy modulation $\Delta p_f\approx 9\times10^{-4}$, almost a factor of 2 larger than the FEL parameter $\rho\approx 5\times10^{-4}$ for the LCLS [1]. In such cases, the high gain in the absence of the damping wiggler would mean that the FEL may not reach saturation for a 100-m undulator.

CONCLUSION

We have extended previous studies of CSR microbunching instability to include the effect of geometric wakefield in the accelerator. Using the analytical model for the high-frequency, periodic accelerating structure and the analytical solutions of the integral equation for the CSR instability in a bunch compressor chicane, we have evaluated the total gain of density modulation in the LCLS accelerator system and found the linac wakefield can increase the gain by about a factor of 2. The gain in shorter wavelength modulations may be more detrimental to the FEL performance and can be strongly suppressed by the damping wiggler incorporated in the LCLS design.

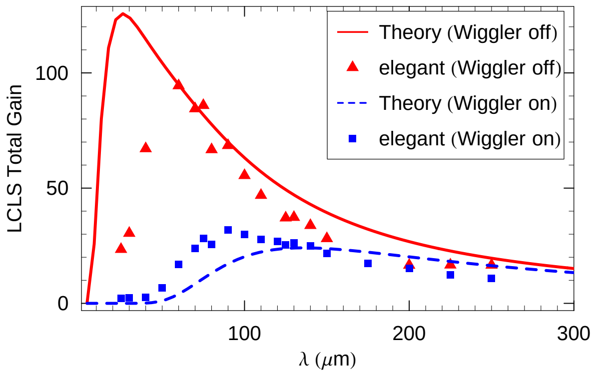

Figure 2: LCLS total gain of density modulation as a function of the initial modulation wavelength.

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