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GINGER SIMULATIONS OF SHORT-PULSE EFFECTS IN THE LEUTL FEL *

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Abstract

While the long-pulse, coasting beam model is often used in analysis and simulation of self-amplified spontaneous emission (SASE) free-electron lasers (FELs), many current SASE demonstration experiments employ relatively short electron bunches whose pulse length is on the order of the radiation slippage length. In particular, the low-energy undulator test line (LEUTL) FEL at the Advanced Photon Source has recently lased and nominally saturated in both visible and near-ultraviolet wavelength regions with a sub-ps pulse length that is somewhat shorter than the total slippage length in the 22-m undulator system. In this paper we explore several characteristics of the short pulse regime for SASE FELs with the multidimensional, time-dependent simulation code GINGER, concentrating on making a direct comparison with the experimental results from LEUTL. Items of interest include the radiation gain length, pulse energy, saturation position, and spectral bandwidth. We address the importance of short-pulse effects when scaling the LEUTL results to proposed x-ray FELs and also briefly discuss the possible importance of coherent spontaneous emission at startup.

1 INTRODUCTION

Intense experimental efforts [1, 2, 3] are currently underway to characterize the performance of free-electron lasers (FEL) based on self-amplified spontaneous emission (SASE), a leading candidate as a fourth-generation light source [4]. Comparison of these experimental results with SASE theories and simulation codes is a critical element for the eventual realization of an x-ray FEL facility.

In a high-gain FEL, both resonance and gain result when the undulator radiation slips one radiation wavelength, λ_r , ahead of the electron bunch per each undulator period, λ_u , traversed. The electron beam density becomes modulated longitudinally with a periodicity λ_r , while the emitted radiation grows exponentially with the undulator distance, z , until power saturation is eventually reached. In a SASE FEL, the initial radiation is spontaneous emission from the random “shot-noise” bunching on the electron beam when it enters the undulator. When the electron bunch length is much longer than the total slippage length, $l_s (\equiv N_u \lambda_r$, where N_u is the number of undulator periods traversed by the electrons), the electron beam-radiation interaction remains longitudinally localized in the electron

bunch. Hence, the FEL performance is only sensitive to the peak current (ratio of charge over bunch length), not to the bunch length itself. This will be the case for the proposed x-ray FELs [4], where the electron bunch length is hundreds of thousands of the x-ray wavelengths long while the total slippage length is a few thousand wavelengths.

However, for many current SASE demonstration experiments that lase at visible or longer wavelengths, the electron bunch length is comparable to the total slippage length of the radiation. In this case, a significant fraction of the radiation slips ahead of the electron bunch, stops interacting with the beam, and propagates as in free space. The beam-radiation interaction is also very non-uniform longitudinally across the electron bunch because the trailing part of the bunch experiences a less amplified radiation field than does the leading part. The short-pulse regime has been investigated previously [5, 6, 7] using a 1-D approximation and a rectangular bunch profile. Here we study short pulse effects for SASE FELs using the FEL simulation code GINGER [8] and semi-analytic models, with the goal of direct comparison to recent SASE FEL experiments on the low-energy undulator test line (LEUTL) at Argonne.

2 CODE DESCRIPTION

GINGER is a multidimensional [3D macroparticle, 2D ($r-z$) radiation], time-dependent code originally written in the mid-1980s to study sideband growth in single-pass FEL amplifiers. GINGER utilizes the KMR [9] wiggler-period-averaged electron-radiation interaction equations and the slowly-varying envelope approximation (SVEA) in both time and space for radiation propagation. For time-dependent (i.e., polychromatic) simulations, GINGER in effect follows a narrow bandwidth of frequencies centered around a central wavelength λ_0 ; however, the code itself operates purely in the time domain and all frequency analysis is done later by a postprocessor code. Both the electron and radiation pulses are represented by uniformly separated slices in time. Due to reasons of memory and message-passing optimization, slippage is applied at discrete z -locations, whose spacing generally is much smaller than the radiation power gain length, L_G . This ensures that the effective frequency bandwidth around λ_0 is much greater than the FEL’s gain bandwidth.

Code modifications now permit GINGER to model short-pulse effects for both amplifier and oscillator configurations, and to run effectively on massively parallel processor hardware. Since the random shot-noise bunching in the SASE process gives rise to the statistical fluctuations in the output radiation energy, all the simulation results presented

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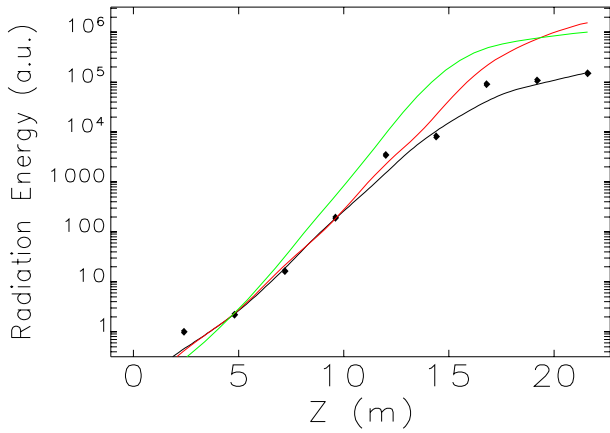


Figure 1: Comparison between the LEUTL FEL 530-nm experimental data [1] (*black dots*), two long-pulse GINGER simulations with initial σ_E of 0.35% (*green line*) and 0.4% (*red line*), and a short-pulse ($\tau_b = 0.2$ ps) GINGER simulation with initial $\sigma_E = 0.35\%$ (*black line*).

in the following section are quantities averaged over a significant number (8–50) of GINGER runs initialized with different random number seeds. Furthermore, for simplicity, all these runs ignored the presence of the LEUTL diagnostic drift sections because these should have negligible effects upon the FEL performance.

3 NUMERICAL ANALYSIS

The LEUTL FEL utilizes a high brightness, rf-linac-produced electron beam and was designed to investigate the SASE process at wavelengths ranging from 600 nm (visible) down to 100 nm (vacuum ultraviolet). A detailed description of the experimental facility and results obtained can be found in Ref. [1] and references therein. Here we focus on one experimental run that showed exponential gain and saturation at $\lambda_r = 530$ nm. The nominal electron beam energy, $E_0 = 217$ MeV. An upstream bunch compression system compressed the electron beam to an rms bunch length, $l_b = 60 \mu\text{m}$ (or an rms pulse duration $\tau_b \equiv l_b/c = 0.2$ ps), resulting in a peak current, $I_0 = 600$ A. The total length of the LEUTL undulator system (ignoring diagnostic drift sections) was $9 \times 2.4 \text{ m} = 21.6$ m, which together with the 0.033-m undulator period results in a total slippage length, $l_s = 350 \mu\text{m}$ (≈ 1.2 ps). The measured rms normalized energy spread, $\sigma_E = 0.4\%$, and the rms normalized transverse emittance, $\varepsilon_n = 9$ mm-mrad.

Figure 1 shows the measured average radiation energy (uncalibrated in absolute value) along the undulator distance, z (reproduced from Ref. [1]), as well as three GINGER SASE simulations with different electron beam properties. Since the measurements were made over a wide wavelength band and a relatively large-opening angle, the first experimental data point (at $z = 2.4$ m) contains mostly spontaneous radiation. As in Ref. [1], we normalized all the immediately following simulation results to the *second* experimental data point, where the coherent, expo-

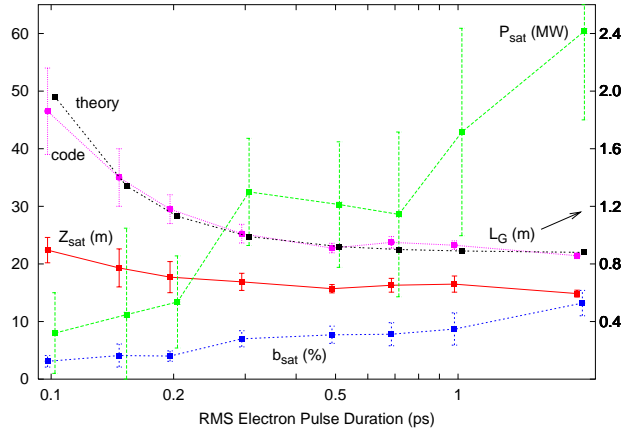


Figure 2: Plot of various output diagnostics from GINGER code scans versus pulse duration for beam parameters corresponding to the LEUTL experiment. The points at the extreme right correspond to infinite pulse length. The error bars correspond to the run-to-run standard deviations.

entially growing FEL radiation should be dominant. The red curve corresponds to the simulation results for a long, constant-current pulse ($l_b \geq 5l_s$) using the experimentally measured beam parameters for I_0 , E_0 , σ_E , and ε_n , and periodic boundary conditions (BC) in time, thus neglecting any short-pulse effects. The predicted power fits the exponential growth rate of the measured radiation energy ($L_G = 1.2$ m), but fails to model well either the saturation point in z or the saturation level. By contrast, a short-pulse GINGER simulation (black curve) of a Gaussian-profile electron bunch with an rms pulse duration of 0.2 ps, together with a slightly reduced initial energy spread ($\sigma_E = 0.35\%$) instead of the quoted experimental value of 0.4% (such an adjustment is within the 0.1% resolution limit of the beam spectrometer), fits both the exponential growth length and the saturation behavior of the experimental data extremely well. For direct comparison with the short-pulse 0.2-ps case, Fig. 1 also shows a periodic BC simulation with the rms energy spread decreased to 0.35% (green curve). Although the saturation point in z now agrees more closely to the data than did the other long-pulse simulation, the gain length is 20% too short and the saturation level remains an order of magnitude too great.

To examine the sensitivity of the FEL output to pulse length, we performed an extensive series of GINGER SASE runs adopting the LEUTL parameters of the previous paragraph but varying the rms electron pulse duration, τ_b , from 0.1 ps up to 1.0 ps. (This procedure cannot be implemented in the LEUTL experiment because most beam parameters change with the bunch length accordingly.) To characterize the SASE FEL saturation, we define the saturation distance, Z_{sat} , as the z location of minimum rms spectral bandwidth. This minimum occurs because the radiation spectrum undergoes a gain-narrowing process in the exponential growth regime [10], which reverses in the saturation regime where the spectrum begins to broaden due to the appearance of synchrotron sidebands [9, 11]. Fig. 2

plots several output parameters for these runs such as the exponential gain length, L_G ; the saturation distance, Z_{sat} ; the saturated power, P_{sat} , defined as $W(Z_{sat})/(\sqrt{2\pi}\tau_b)$, where W is the radiation pulse energy; and the current-weighted bunching fraction, b_{sat} , at saturation. For comparison, the long-pulse limit obtained from periodic BC runs with $l_b \geq 4l_s$ is also included in Fig. 2. One sees a clear trend of decreasing L_G and Z_{sat} and increasing P_{sat} and b_{sat} as the pulse length increases. With the exception of the two shortest-pulse runs (0.1 ps and 0.15 ps), Z_{sat} and L_G appear quite insensitive to the bunch length variation. Furthermore, the minimum relative rms bandwidth of the radiation pulse evaluated at Z_{sat} is around 0.3% for $\tau_b \geq 0.2$ ps, increasing to 0.4% for the shortest pulses, values significantly above the Fourier-transform-limited bandwidth corresponding to τ_b .

The observed gain length dependence upon the electron bunch length can be modeled through an effective current “seen” by the radiation field as it slips through the electron bunch. It has been shown that the high-gain FEL dispersion relation for a coasting beam can be generalized to a bunched beam with a weighting factor on the peak current [6, 7]. For the Gaussian current profile, the effective current can be defined as

$$I_{eff}(\tau_b) \equiv I_0 \int_{-\tau_s/2}^{\tau_s/2} \exp\left(-\frac{t^2}{2\tau_b^2}\right) \frac{dt}{\tau_s}, \quad (1)$$

where τ_s is the relevant slippage time in the exponential growth regime. For $\tau_b > \tau_s$, $I_{eff} \approx I_0$. For $\tau_b < \tau_s$, $I_{eff} < I_0$. Empirically, we find that $\tau_s = 0.5$ ps (or approximately the slippage time corresponding to 10 m of exponential growth) gives a reasonable estimation of the effective current. As shown in the black curve marked “theory” in Fig. 2, the power gain length obtained from Xie’s fitting formula [12] with I_{eff} defined as above reproduces the simulation results (the purple curve marked “code”).

4 COHERENT SPONTANEOUS EMISSION

Coherent spontaneous emission (CSE) can be important at FEL startup if the electron-bunch spectrum contains significant frequency components within the gain bandwidth around the resonant frequency ($\omega_r \equiv 2\pi c/\lambda_r$). As is true for shot-noise startup, CSE will grow exponentially with z in a high-gain FEL. GINGER does not presently model any CSE, due in part to sampling limitations in the time domain [7]. Without an absolute energy measurement of the radiation energy, we cannot rule out a CSE contribution in the LEUTL FEL. However, for a true Gaussian current profile, CSE is significant only when the rms bunch length, l_b , is comparable to $\lambda_r \approx 0.5 \mu\text{m}$. For a less smooth current profile, $I_b(t)$, it can be shown that the shot-noise bunching should dominate coherent bunching so long as

$$N_b \ll (\omega_r \delta T)^{2m} (\omega_r T_b)^2, \quad (2)$$

where N_b is the total number of beam electrons, T_b is the effective pulse duration, m corresponds to the derivative number for which there is a sharp discontinuity in $I_b(t)$, and $c\delta T$ is the scale length for this discontinuity. Ref. [13] suggested $m = 2$ may apply, in which case the inequality is satisfied for LEUTL parameters when $c\delta T \geq 0.5 \mu\text{m}$; even when there is a first-derivative discontinuity (i.e., $m = 1$), the inequality remains good for $c\delta T \geq 2.0 \mu\text{m}$. It is unlikely that significant discontinuities exist within the LEUTL beam with so short a scale length [14].

5 CONCLUSIONS

Our GINGER simulation results indicate that the LEUTL FEL 530-nm experimental results were not seriously affected by short-pulse effects. Although the effective energy extraction efficiency might be a factor of about 5 smaller than would be true for a long pulse, the increase in gain length was only about 20% and the position of power saturation was barely changed. An effective current as defined in Eq. (1) is proposed to model the gain length dependence on the bunch length. CSE was likely to be small at startup relative to shot-noise excitation in view of Eq. (2). Consequently, we believe the LEUTL results should be scalable to even shorter wavelengths, where the ratio of slippage length to pulse length should be much smaller.

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