TECHNIQUE FOR THE GENERATION OF ATTOSECOND X-RAY PULSES USING AN FEL*

G. Penn, A.A. Zholents, LBNL, Berkeley, CA 94720, USA

Abstract

We describe a technique for the generation of an isolated burst of X-ray radiation with a duration of ~ 100 attoseconds in a free electron laser (FEL) employing self-amplified spontaneous emission. Our scheme relies on an initial interaction of the electron beam with an ultra-short laser pulse in a one-period wiggler followed by compression in a dispersive section. The result of this interaction is to create a sub-femtosecond slice of the electron beam with enhanced growth rates for FEL amplification. After many gain lengths through the FEL undulator, the X-ray output from this slice dominates the radiation of the entire bunch. We consider the impact of various effects on the efficiency of this technique. Different configurations are considered in order to realize various timing structures for the resulting radiation.

INTRODUCTION

There has been a great deal of recent research towards developing the means to produce attosecond X-ray pulses from free electron lasers (FELs) [1, 2, 3, 4, 5]. Here, we present simulation results for a scheme which employs laser seeds to perturb the electron beam and produce short X-ray pulses, thus taking advantage of the synchronization and phase control of which lasers are capable. By varying the laser profile, the timing structure of the output radiation can be modified, and optimized for particular applications.

We consider the use of a laser seed at UV wavelengths to modulate the energy of the electrons. This is achieved by overlapping the laser and electrons within a short undulator tuned for that specific wavelength, according to the resonance condition $\lambda_r = \lambda_w(1 + K^2/2 + (\gamma\phi)^2)/2\gamma^2$. Here, λ_r is the resonant laser wavelength, λ_w is the undulator period, $K = eB_0\lambda_w/2\pi mc$ is the wiggler parameter, γ is the electron beam relativistic factor, and ϕ is the angle of the seed laser with respect to the electron beam.

The electron beam is then passed through a dispersive section which converts the energy modulation into microbunching with an increased energy spread. Because of the short length scales for the microbunch, the required dispersion is small. The electron beam is then passed through a long undulator tuned to produce X-ray radiation through the self-amplified spontaneous emission (SASE) process [6]. These microbunches have strongly enhanced peak current compared to the original electron beam; even with the increased energy spread, the microbunches produce strongly enhanced power levels of radiation.

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SIMULATION METHODS

The scheme considered here has been simulated using a combination of an analytic model for the modulating undulators, and the FEL code GENESIS [7] for the X-ray output. This is required because most FEL codes require the laser seed (and electron beam properties) to vary slowly on the scale length of the resonant wavelength, and we are considering laser pulses with carrier envelopes that span only a few laser periods.

The model used for the modulating undulators is as follows [8, 9]:

$$\begin{aligned}\frac{\mathrm{d}\gamma(\hat{s})}{\mathrm{d}\hat{z}} \;=\;& \sqrt{16\pi\frac{A}{\tau P_0}N\xi}\;[J_0(\xi/2) - J_1(\xi/2)] \\ &\times \cos\left[2\pi\nu\hat{z} + \arctan(q\hat{z}) - 2\pi N\hat{s} - \frac{\pi}{2}\right] \\ &\times \sqrt{\frac{q}{1+(q\hat{z})^2}}\; e^{-(\hat{z}-\hat{s})^2/2\sigma_s^2}, \qquad (1)\end{aligned}$$

where A is the laser pulse energy; $\xi = K^2/(2 + K^2)$; J_0, J_1 are zero and first order Bessel functions of the first kind; $P_0 = I_A mc^2/e \simeq 8.7 \times 10^9$ W where I_A is the Alfvén current; N is the number of wiggler periods and we use N=1; $q = N\lambda_w/Z_R$ where Z_R is the Rayleigh length. The scaled coordinates are $\hat{z} = z/(N\lambda_w)$ where z is the coordinate along the wiggler, and $\hat{s} = s/(N\lambda)$ where s is the coordinate along the electron beam; also, $\sigma_s = \sqrt{2}c\tau/(2.35\,N\lambda)$ where τ is the duration of the laser pulse in terms of FWHM of intensity. The wiggler detuning parameter $\nu = N(\lambda_r - \lambda)/\lambda$. Here, the size of the electron beam and the displacements caused by the undulator motion are treated as small in comparison to the laser spot size. For a short undulator, the dependence of the interaction on electron energy is also very weak on the scale of typical beam energy spreads. The evolution of the ponderomotive phase across the undulator is also unimportant. To make efficient use of the seed laser, we choose to set the values $q = 4$ and $\nu = -0.5$.

The resulting, modulated beam is then passed through a chicane to generate dispersion, so that higher energy particles move towards the head of the electron beam. This yields a bunched beam which enters the FEL. The bunched beam is divided into time slices and simulated in the FEL using GENESIS in multi-slice mode with shot noise.

MODULATED BEAMS

We adopt parameters loosely based on the design report for the Linc Coherent Light Source (LCLS)[10], in order to take advantage of prior design work on this SASE FEL. Thus, the average beam current is 3.4 kA, the beam energy is 14.3 GeV, the energy spread is 1.1 MeV, the normalized emittance is 1.2 μm, and the average beta function is 18 m. The undulator period is 3 cm, and the output radiation has wavelength 0.15 nm.

We consider three examples where the peak current is enhanced prior to the FEL, as well as simulating the SASE performance of the unmodified beam. In the first example, a single-period undulator with length 70 cm is used for the energy modulation. In this undulator, the electron beam overlaps with a continuous 1200 nm seed laser to generate an energy modulation of ± 7 MeV. The laser power required is approximately 18 GW. After passing through a dispersive section with dispersion parameter $R_{56} = 425$ μm, the electron beam forms microbunches separated by 4 fs, each having a peak current of approximately 20 kA, with a FWHM of roughly 0.35 fs.

The second example is similar to the first, except an extremely short laser seed pulse is used. The power profile is Gaussian with FWHM of 7.5 fs (1.9 laser periods). This pulse duration corresponds to a frequency bandwidth of 24% FWHM, which is pushing the limits of current laser technology. The laser phase is locked to the laser envelope so that the electric field is zero at the center of the envelope. The resulting central microbunch has a peak current of 19 kA, similar to the first example. The two closest microbunches have peak current of 11 kA and FWHM of 0.55 fs, while the rest of the electron beam is largely unperturbed.

The short laser seed pulse described above produces a well-defined current spike with sub-femtosecond duration. The two additional current spikes, though smaller in magnitude, are sufficiently large that they also yield enhanced SASE radiation. Because of this, the radiation output tends to come in three short bursts. Producing a single electron microbunch with sufficient contrast from the rest of the beam would require an even shorter laser pulse, with a larger bandwidth than is currently available.

One method to obtain more contrast between microbunches is to add a second energy modulation stage, before the dispersive section. The two modulations add to each other independently, and if the two laser seeds are at different wavelengths the total modulation of the beam will have a higher effective bandwidth. Here, we consider a 1200 nm seed laser generating a ± 4 MeV energy modulation, and a second, 1600 nm seed laser generating a ± 3 MeV energy modulation. Both seed lasers have FWHM in intensity of 1.9 times their respective wavelengths. Both undulators are single period and 70 cm in length, but tuned to be resonant at 1200 and 1600 nm respectively. An example of this scheme is analyzed in more detail in Ref. [11]. The peak current of the central microbunch is 19 kA, but the peakc current of the adjacent microbunches is only 6.5 kA. The longitudinal phase space after the chicane is shown in Figure 1. The current profile for all three cases is shown in Figure 2.

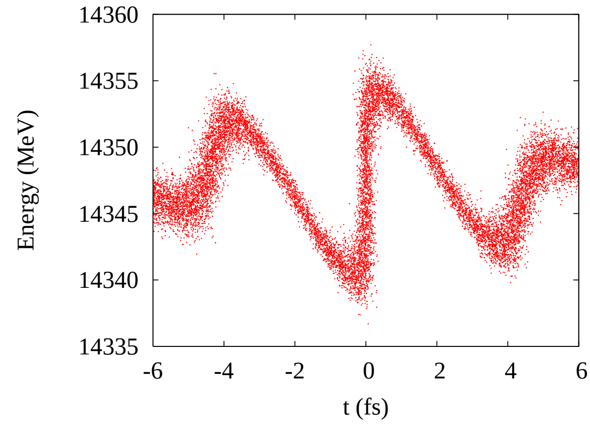

Figure 1: Longitudinal phase space distribution for electron beam after two energy modulation sections followed by a dispersive section.

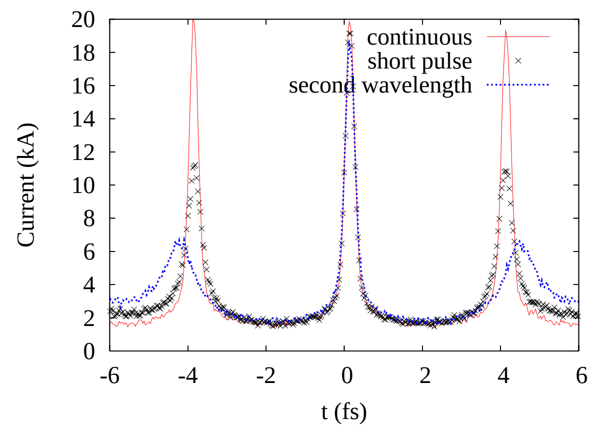

Figure 2: Current profile for three methods of modifying an initial, 3.4 kA electron beam using seed lasers.

RESULTS

The SASE output from after 50 m of FEL are shown in Figure 3. Note that bunch-to-bunch fluctuations are expected due to the growth from shot noise. When a single, short laser pulse is used, the three central microbunches produce similar amounts of X-ray output, at ≈ 2.5 μJ. With two modulating sections, the central microbunch produces of order 10 μJ, and each side bunch produces ≈ 1 μJ.

After 50 m, the average output power from an unperturbed beam is 0.05 GW. By comparison, the time-averaged power produced when using a continuous 1200 nm laser seed is 1.4 GW. Although the background power does not reach saturation until roughly 100 m, for FELs which cannot be made long enough to reach saturation this is an alternative method to increase the total photon yield [5].

In Figure 4, the energy from a single attosecond pulse is shown as a function of distance along the FEL, and compared to background levels from 100 fs of electron beam. Specifically, the core pulse from the example with two

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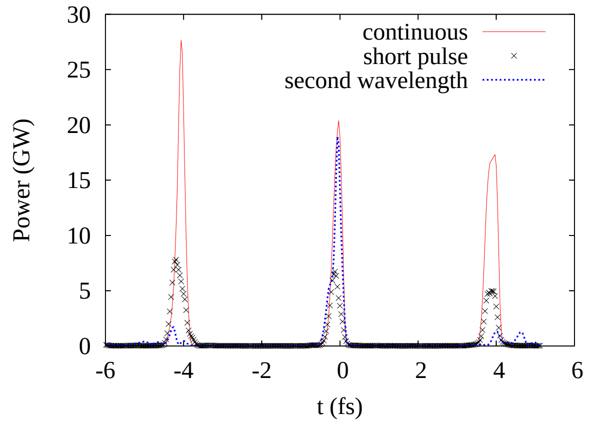

Figure 3: Output power after 50 m for three methods of modifying an initial, 3.4 kA electron beam using seed lasers.

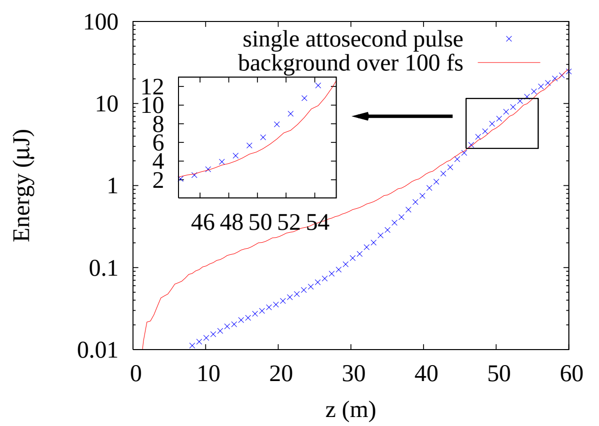

Figure 4: Energy for one attosecond X-ray pulse compared with background energy integrated over 100 fs.

modulators is used. After 50 m, the signal to background level is roughly 1:1.

CONCLUSIONS

Three examples of SASE performance for electron beams which interact with seed lasers have been simulated. The seed laser wavelength is in the UV range and generates sub-femtosecond microbunches. The enhanced current of the microbunch reduces the gain length for SASE. The duration of the microbunch affects performance because the radiation field slips relative to the microbunch, possibly terminating the exponential gain before saturation is reached. This pushes the design towards seeds laser with longer wavelengths.

The time structure of the output radiation can be controlled through the time structure of the seed laser. We have described the short-pulse examples as having a laser phase which is locked to the power envelope. However, sensitivity to this phase primarily occurs when trying to obtain a single microbunch, as in the third example, where the relative phase between the two laser seeds must be accurate of the order of 100 microradians. This level of control over phase-locking falls within current technological limits.

The final example yields a single, isolated attosecond X-ray pulse with very strong contrast compared to the other microbunches. After 50 m of FEL, of order 10 μJ of energy is contained within this pulse, although this will be subject to the statistical fluctuations inherent in the SASE process. For typical electron beams, the background from the unaffected portion of the beam will be the main competing effect. For a 100 fs long electron beam, the energy in the background SASE radiation is comparable to the energy in the 250 attosecond long pulse.

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