Effect of laser intensity and pulse shape on the spectra and the angular distribution of nonlinear Thomson scattering*

Yuelin Li and Stephen V. Milton
Argonne National Laboratory, 9700S. Cass Ave., Argonne, IL 60439
(630) 252-7863, ylli@aps.anl.gov

Abstract: The radiation spectra and angular distribution of free electrons irradiated by intense, ultrafast laser pulses are numerically studied, revealing their dependences on the laser intensity and pulse shape.

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1. Introduction

Nonlinear Thomson scattering of intense laser radiation has been studied theoretically [1,2] and predicts generation of radiation at the harmonics of the laser frequency. For electrons initially at rest, the harmonics peak at

$$\omega_n = \frac{n\omega_0}{1+(a/2)^2(1-\cos\theta)}, \tag{1}$$

with the harmonic number n up to a critical value of $n_c \sim a^3$. Here θ is the angle from the laser propagation direction and a is the normalized laser strength. For a constant a, Eq. (1) indicates no harmonic overlap, and the theory holds accurately.

In reality, a changes due to the finite rising and falling time of the laser pulse, hence the harmonic spectrum is not only red shifted but also broadened. For large enough a, this results in the overlap of harmonics, a situation not treated in the theory but which may be important for interpreting experimental results such as those in ref. [3,4].

In this paper we perform a preliminary set of numerical simulations on the radiation properties of a free electron in a strong laser field using realistic laser fields, concentrating on the spectral and angular distribution of the harmonics.

2. Formula and results

We start by numerically solving the Lorentz equation using the laser field given by the angular spectrum representation [5], characterized by the beam waist w_0, the wavelength, and the pulse shape, for which we use $a=a_0\cos^2[\pi(t-z/c)/2\tau]$. Here τ is the pulse duration. Quasi-flat-top pulses are approximated with a plateau sandwiched between the $\cos^2$ edges. The angular spectrum distribution is calculated using the Lienard-Wiechert potentials [6],

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int \mathbf{n}\times(\mathbf{n}\times\boldsymbol{\beta})e^{i\omega(t-\mathbf{n}\cdot\mathbf{r}/c)}dt\right|^2. \tag{2}$$

Here $\mathbf{n}=\mathbf{e}_x\sin\theta\cos\phi+\mathbf{e}_y\sin\theta\sin\phi+\mathbf{e}_z\cos\theta$, with ϕ the azimuthal angle. The laser is linearly polarized in the ϕ=0 plane and propagates along the z direction. The electron is initially at rest at the laser focus position.

Figure 1 (a-d) shows the spectra at θ=0, 30, 60, and 90° for an electron irradiated by an 800-nm laser pulse with a_0=3, τ=20 fs, showing red shift and spectral broadening as θ increases. At θ=90°, overlapping of the harmonics is evident, in contrast to the quasi-flat-topped pulse (80 fs pulse with 60 fs flat) case where the harmonics are well separated even at θ=90° [Fig. 1 (e)]. This varying a effect is more pronounced for large a at high harmonic numbers, resulting in the generation of a super X-ray continuum [4], recently termed 'laser Larmor X-ray radiation' [7].

In Fig. 2, normalized azimuthal distributions for the second and the third harmonics are depicted for three laser pulses at θ=60 and 90°. The radiation patterns at θ=60° are very similar, demonstrating quadrupole and sextapole characteristics. However, at θ=90°, the radiation patterns are very different and are clearly pulse shape- and intensity-related. The left-right asymmetry of the pattern is due to the asymmetric electron motion, evidenced by net transverse momentum gain at the end of the laser pulse.

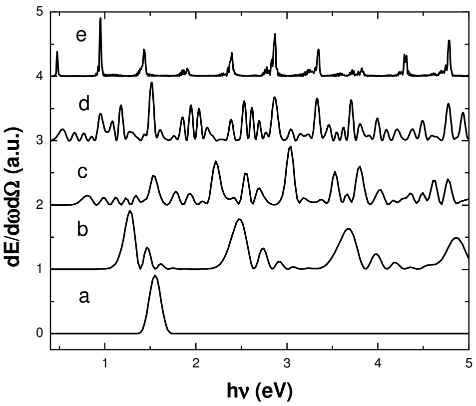

Fig. 1. Spectra of single electron irradiated by (a)-(d) 20-fs laser pulse with a_0=3 for ϕ=40° at θ=0, 30, 60, and 90°, and (e) with quasi-flat-top 80-fs pulse with a_0=3 for ϕ=40° at θ= 90°.

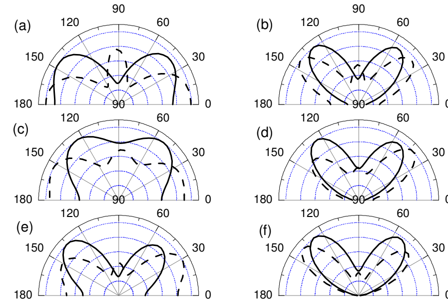

Fig. 2. Radiation pattern of the second (solid) and third (dashed) harmonics at θ=90 (left panels) and 60° (right panels) for (a)-(b) 80-fs quasi-flat-top pulse a_0=3, (c)-(d) 20-fs pulse with a_0=3 and (e-f) 20-fs pulse with a_0=2.

3. Conclusions

We show that the spectra and the radiation pattern of nonlinear Thomson scattering are dependent on the laser pulse shape and intensity, an effect important for interpreting relevant experimental results. Future investigation should include effects of the electron initial position and velocity distribution to elucidate the effect at a macroscopic level.

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4. References

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