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Nonlinear Thomson scattering with strong radiation damping

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Abstract. With the advent of high-intensity short pulse lasers it has become possible to achieve extremely high intensities. When such laser pulses interact with plasmas or high-energy electron beams, radiation damping, which is usually small, can become large. We examine the effects of radiation damping on the backscattered Thomson radiation numerically and analytically. Using parameters comparable to the laser and microtron at the Advanced Photon Research Center we find that the overall spectrum is down-shifted and that the overall amplitude of the radiation is smaller than in the case with no damping.

1. Introduction

Since the development of chirped pulse amplification (CPA), laser irradiance has increased dramatically [1]. At irradiances above $5 \times 10^{22}\,\mathrm{W\,cm^{-2}}$ it has been shown via simulation that the effects of radiation damping can become very large [2]. Such irradiances have been nearly achieved by focusing 45-TW 30-fs laser pulses to very small spot sizes [3]. By focusing petawatt level lasers via this technique to small spot sizes, irradiances of $10^{23}\,\mathrm{W\,cm^{-2}}$ or more could be achieved [4]. In addition, much higher irradiances reaching the vacuum breakdown limit, $10^{29}\ \mathrm{W\,cm^{-2}}$, could be achieved via counter-propagating laser pulses [5] or via ultra-short pulses of relativistically strong electromagnetic waves reflected back at a plasma–vacuum interface [6]. Since laser irradiances are now reaching levels where the radiation damping can become large, we study this problem numerically. In particular, we examine the interaction of a 150 MeV electron with a high irradiance laser and examine the effects on the backscattered radiation.

2. Radiation damping

When an electron is accelerated, it radiates with the exception of uniform acceleration [7]. Under most circumstances the amount of radiation emitted is small and has a small effect on the motion of the electron. However, under the extreme

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accelerations encountered in the interaction with an extremely high irradiance laser pulse, the electron emits large amounts of radiation and the electron dynamics can be substantially altered. Equations describing the dynamics of electrons with radiation damping in the relativistic regime were first derived by Dirac in 1938 [8]. However, if the equations are integrated forward in time, there is an exponential blowup in the energy of the electron even if there is no electromagnetic field present. This has to do with assigning a finite mass to the point-like electron which has an infinite electromagnetic 'intrinsic mass' [9]. Due to problems with the numerical integration of these equations a perturbative form is used [9]:

$$\frac{d\gamma\boldsymbol{\beta}}{dt} = \frac{e}{mc}\left(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}\right) + \frac{2e^2}{3mc^2}\mathbf{g}_0 \tag{2.1}$$

where

$$\mathbf{g}_0 = \frac{e}{mc^2}\gamma\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\boldsymbol{\nabla}\right)\left(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}\right) + \left(\frac{e}{mc^2}\right)^2 c\left[\left(\boldsymbol{\beta}\cdot\mathbf{E}\right)\mathbf{E} + \left(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}\right)\times\mathbf{B}\right]$$

$$-\left(\frac{e}{mc^2}\right)^2\gamma^2 c\boldsymbol{\beta}\left[\left(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}\right)^2 - \left(\boldsymbol{\beta}\cdot\mathbf{E}\right)^2\right], \tag{2.2}$$

$\boldsymbol{\beta} = \mathbf{v}/c$, $\mathbf{v}$ is the velocity of the electron, $\gamma = 1/\sqrt{1-\beta^2}$, $\mathbf{E}$ is the electric field, and $\mathbf{B}$ is the magnetic field. This system of first-order differential equations has been shown to be valid in the regime where damping is strong and up to the classical limit for wavelengths as short as $\lambda_0 \sim \lambda_C$ where λ_0 is the laser wavelength and λ_C is the Compton wavelength $\lambda_C = h/m_e c$ [10].

3. Results

We calculated the interaction of a single 150 MeV electron counter-streaming with a linearly polarized Gaussian laser pulse of the form $\mathbf{E}(\mathbf{x},t) = \hat{z}E_0 h(\phi)\sin(\phi)$, where $h(\phi) = \exp[-(\phi/\omega_0\tau)^2]$, $\phi = \omega_0(t - x/c)$, ω_0 is the laser frequency, τ is the laser pulse duration, and E_0 is the peak laser amplitude. We advance the electron using the equations of motion including radiation damping and numerically integrate them using an adaptive Runge–Kutte scheme [11].

We calculated the case for $a_0 = 30$ with a pulse length of 30 fs where $a_0 \equiv eE_0/mc\omega_0$. The electron lost about 20% of its initial energy after passing through the laser pulse. In order to calculate the spectra we use the formula [12]:

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty}\left[\frac{\hat{n}\times\left[\left(\hat{n}-\boldsymbol{\beta}\right)\times\dot{\boldsymbol{\beta}}\right]}{\left(1-\boldsymbol{\beta}\cdot\hat{n}\right)^3}\right]_{\mathrm{ret}} e^{i\omega t}\,dt\right|^2 \tag{3.1}$$

where $\hat{n}$ is the unit normal vector in the direction of radiation emission, $\dot{\boldsymbol{\beta}} = \dot{\mathbf{v}}/c$, and ret refers to the retarded time, t', evaluated at $t' + R(t')/c = t$ where $R(t')$ is the distance of the electron from the observation point. Since the points used to calculate the spectra are unevenly distributed in time, we use the method developed to calculate the spectra for unevenly sampled data [11, 13, 14].

In Fig. 1 we show the calculated spectra. The difference in amplitudes of the peak in the spectra are clearly different between the damping (solid black line) and non-damping case (dashed grey line). Also the position of the peak has become clearly different. The overall spectral frequency is down-shifted and the amplitude is smaller. This down-shift comes from the average energy loss of the electron as it

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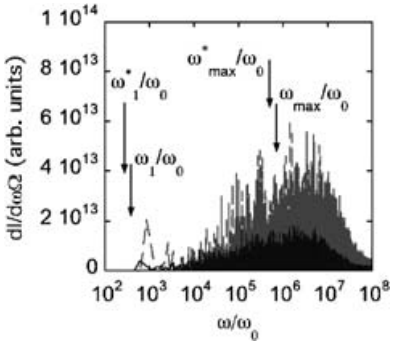


Figure 1. Power spectrum for $a_0 = 30$. The dashed grey line is for electron motion without damping and the solid black line is with damping. The arrows indicate the theoretical prediction for the first harmonic without, ω_1/ω_0, and with damping, ω_1^*/ω_0, and the peak of the spectrum without, $\omega_{\max}/\omega_0$, and with damping, $\omega_{\max}^*/\omega_0$.

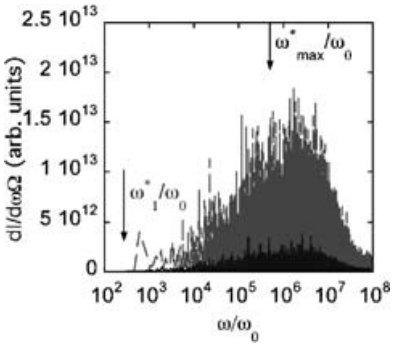


Figure 2. Power spectrum for $a_0 = 30$. The dashed red line is for electron motion a pulse of 30 fs and the solid blue line is for 300 fs. The arrows indicate the theoretical prediction for the first harmonic with damping, ω_1^*/ω_0, and the peak of the spectrum with damping, $\omega_{\max}^*/\omega_0$.

traverses the laser pulse. The arrows indicate the theoretical prediction for the first harmonic without, ω_1/ω_0, and with damping, ω_1^*/ω_0, and the peak of the spectrum without, $\omega_{\max}\omega_0$, and with damping, $\omega_{\max}^*/\omega_0$ [15]. The theoretical predictions are calculated for a circularly polarized plane wave including estimates of the average energy loss during the interaction with the laser pulse (details can be found in [15]). The theoretical prediction of the peak in the spectra agrees fairly well with the numerical results. The smaller overall amplitude of the spectra is also due to the electron's energy loss, since the spectra are very sensitive to the electron's energy. In the case with no damping the electron loses no energy and continues to radiate at the initial energy whereas with damping the electron radiates while continually losing energy. Figure 2 compares the case of a 30-fs and 300-fs pulse with $a_0 = 30$. The spectrum is further reduced. The electron has lost 77.6% of its energy. Again, the theoretical prediction is in fairly good agreement with the numerical results.

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4. Conclusion

In summary we have found that radiation damping can have a significant effect on the backscattered radiation emitted from a 150 MeV electron counter-propagating with a high irradiance laser pulse. The overall spectra are down-shifted in frequency and lower in intensity from the cases including no damping. This has been found to be the result of the overall loss of energy of the electron as it traverses the laser pulse. In addition, these effects are accentuated as the laser pulse becomes longer. This is due to the additional loss of energy for longer pulses. In future work we will address the issue of multi-electron interaction with the laser pulse, as well as examine the interaction in the quantum regime.

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