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Approaching radiation dominant regime in interaction of short, PW-class laser pulses with dense plasma

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Exploring of high energy-density matter requires powerful x-ray sources that can produce and probe exotic material states with high densities in radiation dominant regime. Such x-ray source can be generated with use of PW-class lasers. Numerical simulations of the radiation sources based on such plasma are of particular interest. A simulation has to include the radiation field to provide general characteristics of plasma. Utmost question here is how to calculate the radiation field. Whether it require a quantum approach or the classical approach is enough. Here we study non-linear cascade scattering of intense, tightly focused laser pulses by relativistic electrons, which is typical for a relativistic plasma, numerically in the classical approximation including radiation damping for the quantum parameter $<\hbar\omega_{x\text{-ray}}>/\varepsilon<1$ and an arbitrary radiation parameter χ.

1. Introduction

Radiation dominant regime in laser induced plasma is known as that regime where the radiation intensity dominates standard collisional atomic processes, thereby creating exotic states of matter; it can be reached for far lower intensities than those required for the radiation dominant regime. Plasma produced by XFEL radiation is a typical sample of radiation dominant regime. PW-class lasers with a flux density of 10^{21} W/cm^2 or more already exist. They are generally much less expensive and more compact than XFEL facilities. On the other hand, PW-class lasers can provide a much higher X-ray intensity. Presently, laser intensities are approaching a threshold where the radiation becomes dominant [1]. Therefore, this radiation dominant regime has become an object of detailed study both experimentally and theoretically. So far, ab initio simulations of the radiation even from a classical relativistic plasma standpoint are impossible due to the requirements of extremely high spatial and temporal resolution. Non-linear and quantum radiation effects in the interaction of relativistic electron beams and intense laser pulses occur at relatively smaller, accessible laser intensities. Their experimental and numerical study could result in the development of the necessary radiation models.

In contrast to cyclotron radiation, the laser light scattering process is always a free-free electron transition and may proceed differently depending on the field and electron energies. At low laser pulse intensities and high electron energies there is the well-known Compton scattering which is determined only by the quantum parameter: $\nu=2\gamma_0\hbar\omega_0/mc^2$. At high intensities the 'quantum' scattering is usually characterized by the parameter:

$$\chi = (\hbar\omega_0\gamma / mc^2)\sqrt{(\tilde{\tilde{\vec{E}}} + \vec{v}\times\tilde{\tilde{\vec{B}}}/c)^2 - (\vec{v}\cdot\tilde{\tilde{\vec{E}}}/c)^2}$$

[2], where $\vec{E}$ and $\vec{B}$ are normalized. For χ>>1 the scattering probability, P, differs from the classical one as ~$P_{\text{classical}}(\chi)\chi^{-1/3}$ [2]. Parameter c can be presented as in a form $\chi=(\hbar\omega_0/mc^2)Q$, where Q is the squre root of radiation parameter. To reach the limit χ>>1 one has to use very short wave length radiation or to work in the strong radiation regime, Q>>1. However in the latter case the radiation damping may drastically change the physical picture.

2. Numerical Simulation

A 6-th order Runge-Kutta method is used to solve the equations of motion for an electron. To correctly include the ponderomotive force, we use the parabolic approximation for the focused laser field. To calculate the spectrum (for the intensity), we exploit the well-known equation for the Lienard-Wiechert potentials. The spectral resolution is given by the number of spectral points, M, where M=2000 with the maximum frequency

$\omega_{x\text{-ray}}^{max}=(5/10)a_0\omega_0(4\gamma_0^2)$. This choice cannot provide enough resolution at lower frequencies. However, it is good enough to describe the spectra of the highest harmonics, which are necessary to estimate the contribution of quantum effects to the total amount of radiation losses.

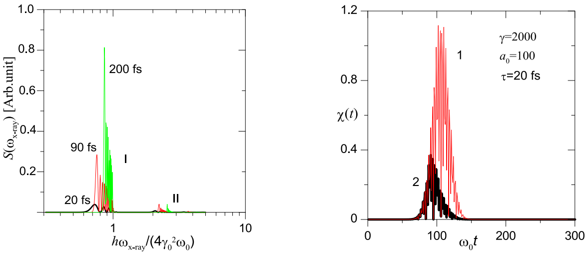

Fig. 1 (a) Spectra of backward scattering (θ=π) at a_0=1 for Gaussian pulses of duration 20, 90, and 200 fs; head-on collision at γ=200. (I) are the fundamental harmonics, (II)- the third harmonics [even harmonics for the linear polarized laser pulse vanish]. Radiation damping is included.(b)Time evolution of the χ parameter for an electron γ=2000 without (1) (red curve) and with (2) (black curve) radiation damping in a 20 fs Gaussian pulse with a_0=100; head-on collision.

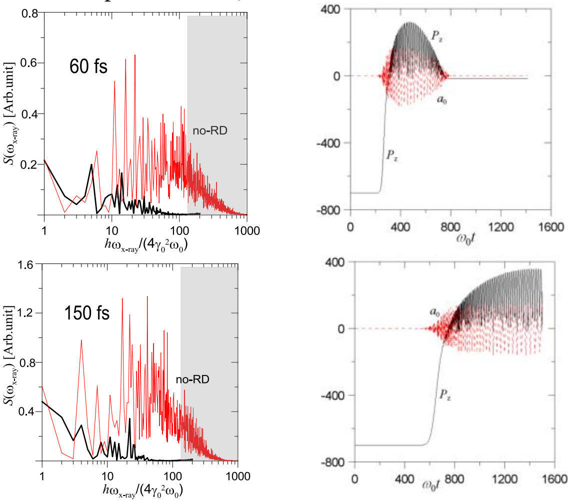

Fig.2 Spectra of backward scattering (θ=π) with a_0=200 Gaussian pulses of duration 60 fs (a) and 150 fs (c) for a head-on collision, γ=700, with (red) and without (black) radiation damping. (b),(d) show the pulse field, $a_0(t)$ (red), seen by the electron during the interaction and the longitudinal momentum (black), P_z, of that electron

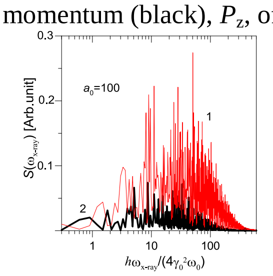

Fig. 3 Spectra of backward scattering (θ=π) in the two pulse scheme (1) (red curve) for the time delay 45 fs as in Fig.7 (2) [both pulses have a_0=100, τ=10 fs, the scattered pulse is focused to w_0=5 μm, the driving pulse is a plane wave] and with only the scattered pulse (2) (black curve).

Results of simulation, partially presented in Fig.1-3 (see also [3]) show that the radiation damping lessens the quantum effects in the "classical" Compton scattering. Parameter c is usually less then unity due to strong radiation.

3. Summary

We have restricted our calculations to the regime where the radiation is strong, but the emission is located in the classical part of radiation spectrum, $<h\Omega_{x\text{-ray}}>< mc^2(\gamma\text{-}1)$. Our results have shown that, nowadays, the classical method still allows a self-consistent analysis of the interaction of relativistic particles with an intense laser field including the ponderomotive side scattering and electron vacuum acceleration. It has been shown that the classical approach remains valid at much higher laser intensities and particle energies due to the effect of the radiation damping resulting in much lower frequencies of emitted x-rays. The parameter χ remains much less than unity due to the radiation damping even for GeV level electrons with laser intensities ~10^{23}-10^{24} W/cm^2. In the case of plasma produced by intense short laser pulses, the 'quantum' condition is even softer, because plasma electrons acquire their energy from the laser pulses starting from the 'classical' regime. It has been demonstrated that an experimental realization of the scattering by relativistic electrons at $a_{0C}\geq 100$ is impossible due to the radiation damping and ponderomotive side-scattering. Even high energy electrons lose their energy far before the maximum of the laser field is reached. The 'two pulse scheme' with a co-propagating laser pulse as an electron booster is proposed to solve the problem of non-linear Compton scattering at high a_{0C}. The ponderomotive acceleration of electrons can over-come the radiation damping of electrons with energy lower than 1GeV with a practical intensity of the boosting laser pulse and an intensity of the scattered laser pulse exceeding a_{0C}=100. At higher energies the necessary intensities increase as a_{0D}~ γ_0^2. Moreover for this case, a comprehensive quantum analysis requires more sophisticated approaches that have yet to be developed.

References

[1] J. Colgan, J. Abdallah, A.Y. Faenov, *et al.*, *Phys. Rev. Letters* **110**, 125001(2013)

[2] A. I. Nikishov and V. I. Ritus, Sov. Phys. JETP **19**, 529 (1964); ibid **19**, 1191 (1964)

[3] A. Zhidkov, *et al.*, Phys. Rev. ST **17**, 054001 (2014)