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Modelling of radiation losses for ion acceleration at ultra-high laser intensities

Remi Capdessus[a], Emmanuel d'Humières and Vladimir Tikhonchuk

CELIA (Centre Lasers Intenses et Applications), University Bordeaux-CNRS-CEA, 33400 Talence, France

Abstract. Radiation losses of charged particles can become important in ultra high intensity laser plasma interaction. This process is described by the radiation back reaction term in the electron equation of motion. This term is implemented in the relativistic particle-in-cell code by using a renormalized Lorentz-Abraham-Dirac model. In the hole boring regime case of laser ion acceleration it is shown that radiation losses results in a decrease of the piston velocity.

1. INTRODUCTION

One of the important applications of ultra intense laser pulses is acceleration of charged particles to extremely high energies. Due to recent developments in laser technology, intensities could soon reach 10^{24} W/cm^2. New physical processes are expected under theses conditions such as emission of high energy photons, action of radiation on electron, electron-positron pair production, acceleration of ions (or protons) to relativistic energies, etc [1]. Our numerical and theoretical approach is classical. The effect of radiation losses as a friction force is implemented in the equation of motion. The electric field in the rest frame of the electron is supposed to be smaller than the Schwinger field, which is defined by the condition that the electron gains a relativistic energy on the Compton length. We define the Schwinger field

$$E_S = m_e^2 c^3 / e\hbar,$$

and we introduce the dimensionless parameter $\chi = E/E_S$, which should be small, $\chi \ll 1$, in the domain where classical electrodynamics apply. For lasers, the Schwinger field corresponds to the intensity $I_S = \frac{1}{2}\epsilon_0 c E_S^2$ of about 10^{29} W/cm^2. Due to the relativistic effect [2] the domain of applicability of the classical electrodynamics is limited by the condition $a_L \lesssim (m_e c^2/\hbar\omega_L)^{1/2} \simeq 440$ corresponding to the laser intensities of about 4.2×10^{23} W/cm^2. In this domain Landau and Lifshitz (LL) have proposed a simplified, divergence-free version of the Lorentz-Abraham-Dirac (LAD) equation. An improvement of the LL equation was proposed recently [3]. This renormalized LAD equation accounts for the modification of the electron orbit under the action of the self force. Although still limited by the condition of the classical approach, $\chi_e < 1$ [3], this approach is more accurate than the LL equation and it is also better suited for numerical implementation in particle-in-cell (PIC) codes. In this paper, we implemented the Sokolov model in the one dimensional (1D) relativistic PIC code PICLS [4] and applied it for several typical problems of laser plasma interaction. The theoretical approach is discussed briefly in Sec. 2.

[a]e-mail: capdessus@celia.u-bordeaux1.fr

2. THEORETICAL APPROACH

Charged particles in the presence of a strong electromagnetic field are emitting high frequency radiation. Its intensity, $I = 2\,q^2 w^2/3\,c^3$ is given by the Larmor formula, where q is the particle charge, $\mathbf{w} = (m\gamma)^{-1}[\mathbf{f}_L - (\mathbf{f}_L \cdot \beta)\beta]$ is the acceleration by the Lorentz force

$$\mathbf{f}_L = q\ (\mathbf{E} + \beta_e \times \mathbf{B})$$

where γ is the relativistic factor and $\beta = \mathbf{v}/c$ is the dimensionless particle velocity. The electrons as light particles are responsible for the radiation. In the relativistic case, it is concentrated around a cone with an angle $\sim 1/\gamma$. This radiation takes away from the electron and laser field the momentum and the energy that need to be accounted for in the electron equation of motion. We use Sokolov model [3] describing the electron dynamic by the following system of equations:

$$\frac{d\mathbf{p}_e}{dt} = \mathbf{f}_L - e\,\delta\beta_e \times \mathbf{B} - \gamma_e^2(\mathbf{f}_L \cdot \delta\beta_e)\beta_e, \tag{1}$$

$$\frac{d\mathbf{x}_e}{dt} = (\beta_e + \delta\beta_e)c, \quad \delta\beta_e = \frac{\tau_0}{m_e c}\frac{\mathbf{f}_L - \beta_e(\beta_e \cdot \mathbf{f}_L)}{1 + \tau_0(\beta_e \cdot \mathbf{f}_L)/m_e c}\,. \tag{2}$$

The radiation losses are represented by two terms in the right hand side in Eq. (1). The term $\mathbf{f_R} = \gamma_e^2(\mathbf{f}_L \cdot \delta\beta_e)\beta_e$ can be identified as a friction force as it is directed in the sense opposite to the particle velocity. The dimensionless velocity perturbation due to the radiation losses $\delta\beta_e$ induces the deviation of the electron momentum and can be thought as a modification of the cyclotron frequency. However, this second term in the right hand side of Eq. (1) is very small of the order of $1/\gamma_e^2 \ll 1$ compared to the radiation force term in the ultra relativistic case.

The radiation reaction enters explicitly only in the electron equation of motion. The ion motion is affected implicitly by electron density redistribution and modification of the electric field. Consequently, the ion equation of motion has a standard form:

$$\frac{d\mathbf{p}_i}{dt} = \frac{Ze}{m_i}(\mathbf{E} + \beta_i \times \mathbf{B})\,.$$

In Ref. [2], it was shown that radiation losses could have an influence on the dynamics of charged particles, for laser intensities more than 10^{22} W/cm^2.

In the particle-in-cell method, the plasma is represented as an ensemble of macro particles moving in a continuous phase space. The moments of the particle distribution such as density and current are computed at each time step on the Eulerian (stationary) grid. The self-force is implemented in the one-dimensional (1D) version of the code PICLS [4]. This code is developed for modeling of laser-plasma interaction at relativistic intensities. It is known that the grid size should be smaller than the Debye length in order to avoid numerical heating of plasma particles.The radiation losses are implemented at the first sub-step while solving the equations of motion of electrons. More information about the numerical scheme and in particular about implementation of the self force can be found in Ref. [2].

3. EFFECT OF RADIATION LOSSES ON THE SHOCK VELOCITY IN THE HOLE BORING REGIME

We investigated the effect of radiation losses in the hole boring regime of laser ion acceleration. We consider a laser field interacting with a thick and diluted target. Laser parameters are the following: $\lambda_0 = 0.8\,\mu$m, $I_0 = 8 \times 10^{22}$ W/cm^2, circular polarization, a trapezoidal temporal profile with a linear front during one laser period and a constant section of 16 laser periods (T_0). The plasma parameters are the following: the ion to electron mass ratio $m_i/m_e = 3680$, ion charge $Z = 1$, electron density $n_e = 10\,n_c$, and temperature $T_e = 5.11$ keV, the layer of thickness $l = 100\,\lambda_L$ surrounded by vacuum. At $t = 0$ the laser pulse penetrates the plasma layer.

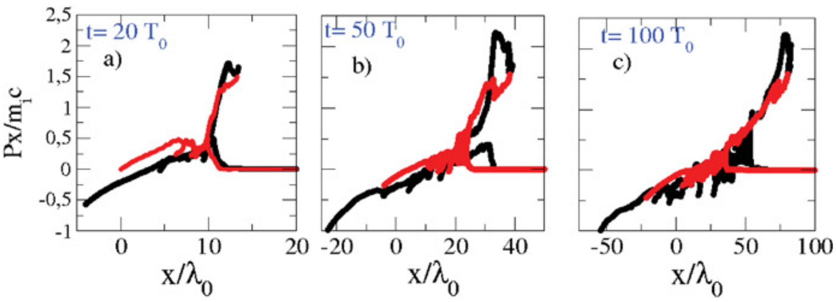

Figure 1. Evolution of ion phase space over time. In red: with radiation losses. In black: without radiation losses.

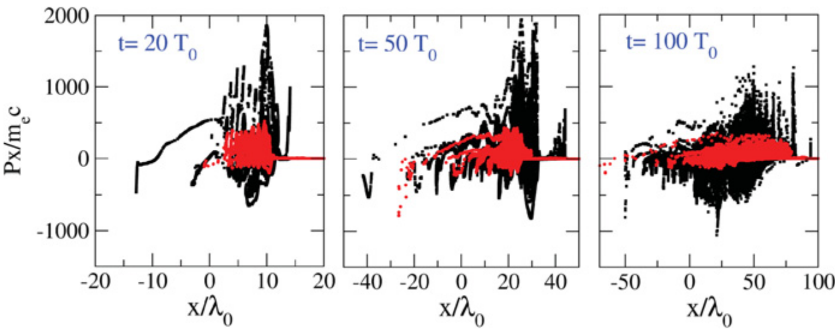

Figure 2. Evolution of electron phase space over time. In red: with radiation losses. In black: without radiation losses.

Figure 1 shows the evolution of the ion phase space at three different times. Furthermore, we can see in the figure 3-c that the shock velocity is modified due to radiation losses. This can be explained as follow. At the beginning of the interaction between the laser field and the target, the laser field interacts with electrons. Almost electrons are pushed in front of the laser field by the ponderomotrice force, creating thus a charge separation field. At $t = 20T_0$, by comparing the corresponding panels in figures 3 and 4, we note that radiation losses involve a strong cooling of the electron bunch. This cooling can be clearly seen in the electron phase in figure 2. Without taking into account radiation losses the maximum electron energy is around 800 MeV whereas with radiation losses maximum electron energy is of the order of 250 MeV for $t = 20T_0$. Radiation losses imply a stronger density jump for the shock as we can see in figures 3 and 4. In other words radiation losses stabilize the structure of the shock. Furthemore, the radiation losses deacrease the shock velocity. In figure 3 one can see that the electron bunch is more compressed when the self-force is taken into account in the equation of motion of electrons. Radiation losses result in a reduction of the electron phase space volume [5]. One can estimate the shock velocity by: $v_b \approx \frac{1}{2} a_L c \sqrt{m_e n_c / m_i n_i}$ without radiation losses [6]. The shock velocity is inversely proportionnal to the root of the ion density. According to figure 3 the ion density is not the same when the radiation losses are taken into account. At the point of the shock, the ion density is higher with radiation losses. So it implies a decrease of the shock velocity according to the previous expression. That is consistent with the physical arguments mentioned above. In fact, in order to obtain a correct expression of the shock velocity, high energy photons generated by accelerated electron at the front of the shock should be taken into account in the equation of balance [7]. Moreover, this reduction of the shock velocity implies a higher reflectivity of the laser from the plasma. Indeed, knowing the shock velocity, the reflection coefficient of the laser light in the laboratory frame writes: $(1 - \beta_b)/(1 + \beta_b)$ and

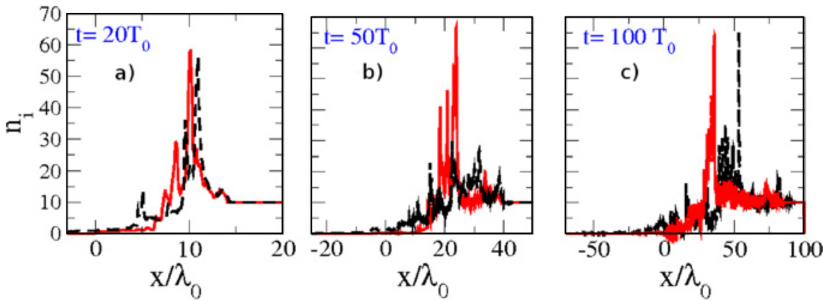

Figure 3. Ion density at several times. In red: with radiation losses. In black: without radiation losses.

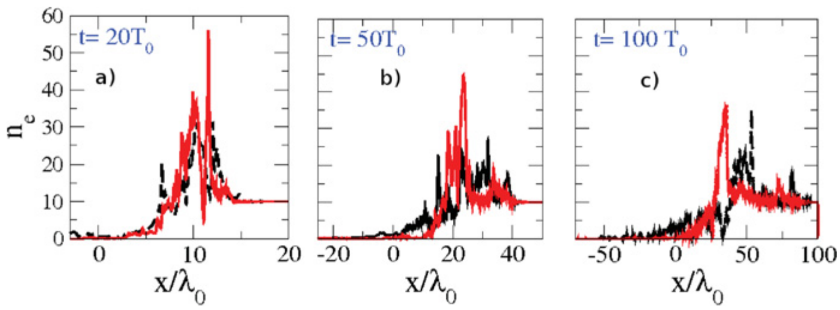

Figure 4. Electron density at several times. In red: with radiation losses. In black: without radiation losses.

the energetic efficiency of the laser driven ion acceleration: $1 - R = (2\beta_b)/(1 + \beta_b)$. This expression confirms that radiation losses lead to a less efficient ion acceleration.

4. CONCLUSIONS

The hole boring case regime has been studied for a diluted and thick target irradiated by an ultra-high laser intensity using Particle-In-Cell simulation including a model of radiation losses. Taking into account the electron self-force implies a decrease of the shock velocity. Strong electron cooling at the front of the shock has consequence, preventing electrons to escape the shock zone. So propagation of the shock is more stable. Radiation losses therefore lead to an increase of the reflection coefficient of the laser light on the plasma and to a decrease of ion acceleration efficiency in this regime.

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