Influence of the radiation reaction on plasma dynamics in the context of ultra-relativistic laser plasma interaction

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Several laser systems operating in the petawatt and multipetawatt regimes will soon be available in Europe [1]. Extreme light interaction with plasmas on these forthcoming laser facilities will be characterized by a copious emission of high-energy photons (in the hard X-ray and γ-domains) due to strongly accelerated/decelerated electrons. At laser intensities beyond 10^{22} W/cm^2, a non-negligible part of the incident laser power is radiated away, and the back-reaction effect of photon emission on the electron dynamics has to be accounted for. The importance of taking into account radiation losses under these conditions was demonstrated in Refs. [5, 6]. To account for this force, the incoherent radiation emission and its back-reaction effect via the so-called self-force have been introduced in the particle-in-cell (PIC) code PICLS [2] using the model proposed by Sokolov [3].

In this work, we analyze the changes in the plasma dynamics due to the self-force acting on electrons. In our simulations, incoherent radiation emission is computed assuming synchrotron radiation emission by the macroparticles, which requires the emitted photon wavelength to be much shorter than the characteristic distance between electrons in the plasma. This condition can be rewritten as a condition on the critical frequency ω_{cr} of the continuous radiation emitted by a macroparticle: $\omega_{cr} \gg c n_e^{1/3}$ where $\omega_{cr} = \frac{3}{2}\gamma_e^3 |\mathbf{p}_e \times \mathbf{F}_{Le}|/p_e^2$. This condition limits the applicability of our model to relativistic electrons only and to the most energetic part of the photon spectrum (beyond a few keV typically). Moreover, we will restrict our study to the limits of classical electrodynamics and we assume the plasma to be transparent to the high-energy photons.

We consider a circularly polarized laser pulse with vector potential $A(t,x) \sim a(t)\,\mathrm{Re}\{(\hat{\mathbf{y}} + i\hat{\mathbf{z}})\, e^{i(kx-\omega t)}\}$ and wavelength $\lambda_L = 1$ μm. The laser pulse has a trapezoidal temporal profile with the intensity increasing/decreasing linearly over one laser period (T_L), and a 16 T_L-long plateau at maximal amplitude $a(t) = a_0 = 180$. Each plasma cell has the size $\lambda_L/100$ and contains 30 macro-particles for each species. The laser pulse is normally incident onto an overdense deuterium plasma located at $x = 0$ and reaches the target at time $t = 0$. In what follows, we discuss two examples: a semi-infinite plasma and a thin (0.3 μm-thick) plasma slab, both simulated using the 1D3V code PICLS.

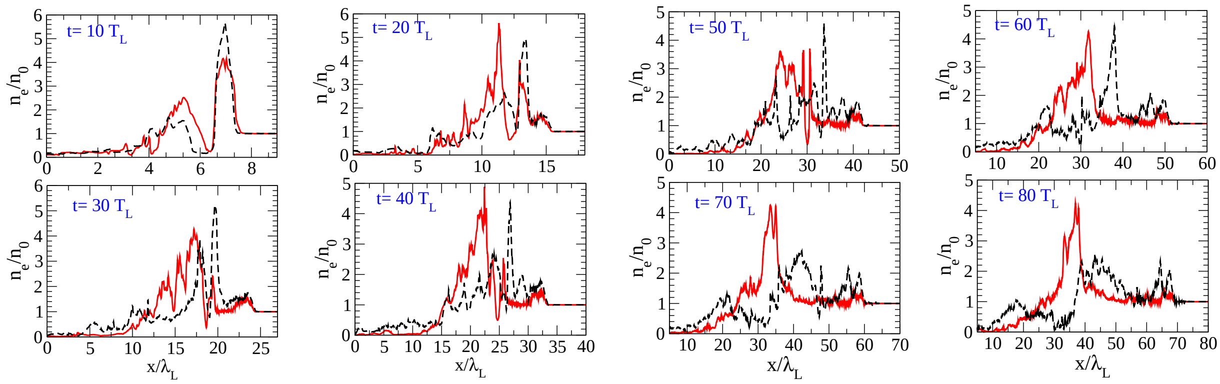

Figure 1: Semi-infinite target. Evolution of the electron density versus time in the induced transparency case. In red: with radiation losses. In dashed black: without radiation losses.

Let us first consider the case of a semi-infinite target with electron density n_e= 10 n_c where n_c= $m_e\omega_L^2\varepsilon_0/e^2$ is the critical frequency. Figure 1 shows the spatial distribution of the electron density for the cases with and without radiation losses. The radiation back-reaction clearly improves the stability of the shock-like compressed structure visible in Fig. 1. Moreover, the radiation back-reaction force reduces the propagation velocity of this shock-like structure and a better shapes for the electron profile. This can be seen in Fig. 1 from t = 70 T_L onward: the electron bunch density is higher when accounting for radiation losses. A similar feature has previously been discussed in the case of laser-driven hole-boring [5]. It follows from the cooling effect on escaping electrons that are strongly slowed down by radiation losses.

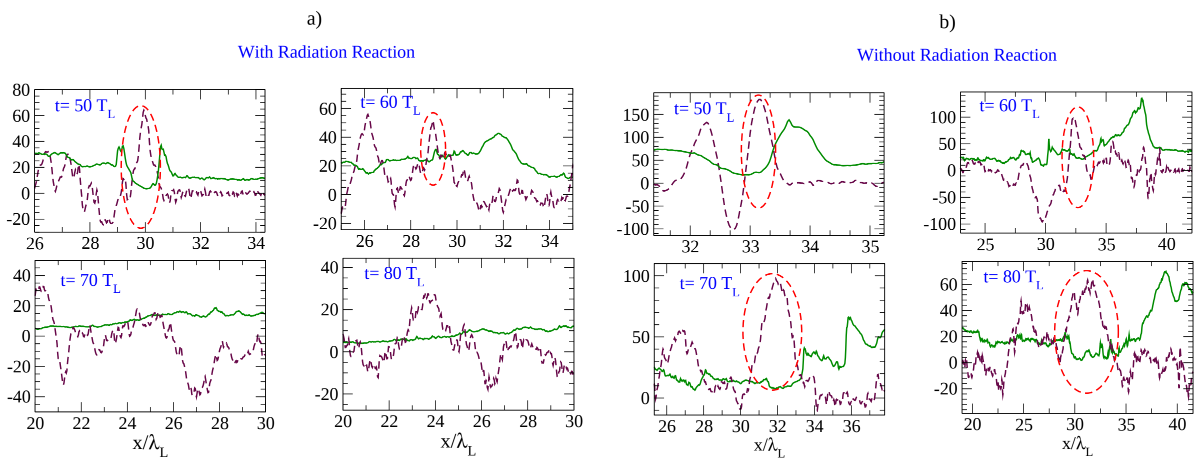

Figure 2: Time evolution of the soliton mode. In dashed maroon: y component of the electric field. In green: electron density normailzed by initial density ($\times$10) (a), ($\times$30) (b).

It is found in our simulations with an overdense plasma that part of the incident laser pulse penetrates through the piston and propagates deeper intothe plasma in a form of soliton. Figure 2 shows such a soliton mode propagating through the plasma without spreading. The electromagnetic field of this solition is trapped in the electron density hole. Without radiation losses, Fig. 2-b, this mode is stable. However when taking into account radiation losses, in Figure 2-a this mode is unstable and disappears after several tens of lasers periods.

Let us now consider a second regime of interaction where the laser pulse interacts with a 0.3 μm-thick target with electron density n_e= 100 n_c. Simulation results in Fig. 3 show that, in this regime, most of the electrons and ions are pushed in front of the laser pulse. The main electron bunch is very close to the main ion bunch inducing a constant accelerating field. This structure leads to light-sail acceleration [7] of the whole target. Accounting for the radiation back-reaction force allows to cool down electrons and in turn compresses the electron bunch. As a result, 70 % of the electron population is located in the compressed electron bunch when radiation losses are accounted for, whereas only 50 % of the total number of electrons are located in the compressed electron layer when radiation losses are neglected. This results in a net increase of the order of 50 % of the maximal density of the compressed electron layer, and in turn, to a larger number of accelerated ions.

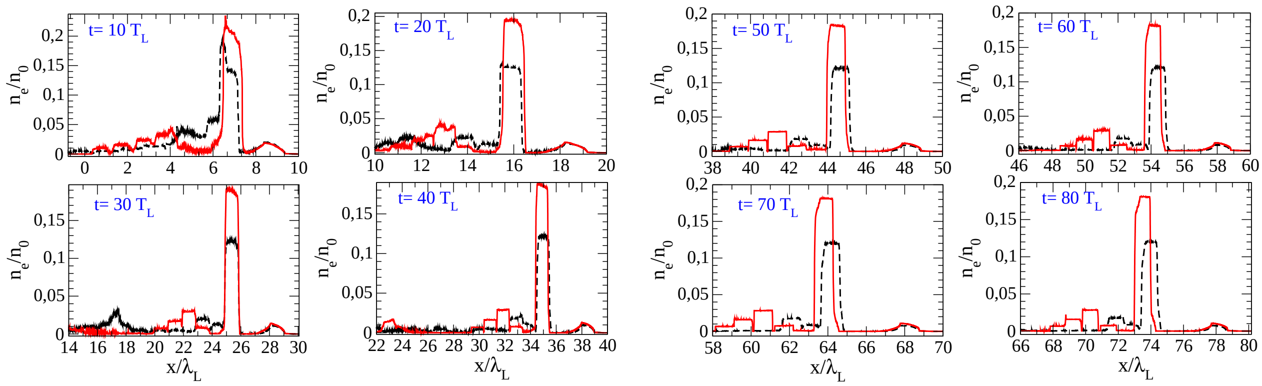

Figure 3: Thin target: several snap-shots of the electron density distribution in the light sail regime. In red: with radiation losses. In dashed black: without radiation losses.

Figure 4 shows the electrostatic field at the rear-side of the target. This constant charge separation field is generated by the small and fastest part of the electron bunch. This field creates a fast ion bunch which separates from the main one visible as seen in Fig. 4. When taking into account radiation reaction, the longitudinal field is inscreased by 40 %, improving the ion energy spectrum for the most energetic part as can be seen in panel c.

These two examples show that the effect of radiation reaction force on strongly accelerated/decelerated electrons can modify the overall plasma dynamics. In the case of the semi-infinite plasma, the radiation back-reaction improves the stability of the electrostatic shock

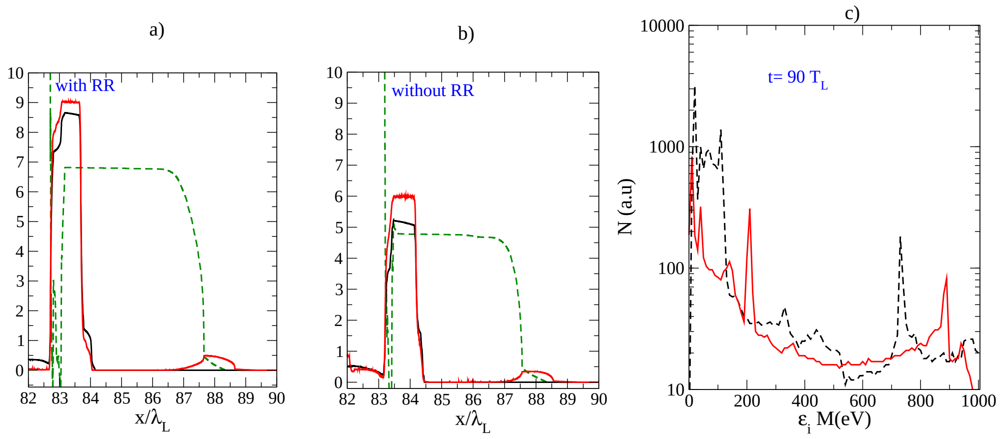

Figure 4: Thin target. (a) and (b); In dashed green: longitudinal field. In black: Ion density normalized by initial density ($\times 50$). In red: electron density normalized by initial density ($\times 50$). Ion energy spectrum (c). In red: with radiation losses. In dashed black: without radiation losses.

launched into the plasma by the strong radiation pressure. The generation of soliton structures is also observed to be strongly affected by radiation losses in this regime. In the case of light-sail acceleration of thin targets, the density of the compressed electron bunch is increased so that more ions can be accelerated. This analysis of the influence of the radiation back-reaction on plasma dynamics may be used to prepare designing new diagnostics for future ultra-high intensity experimental campaigns. They can also help us assessing the importance of radiation losses on laser ion acceleration in the ultra high laser intensity regime.

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