Radiation Reaction Effects in Relativistic Laser-Produced Plasmas

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Introduction

At the extremely high laser intensities expected in next-generation experiments, electrons can become ultrarelativistic within a fraction of wave period experiencing superstrong accelerations. At these intensities radiation reaction (RR) effects become increasingly important as RR can be the dominant force acting on electrons [1]. It may be then necessary to include RR effects to describe the foreseen laser-plasma interaction regimes at such extreme intensities. One prominent example is Radiation Pressure Acceleration (RPA) in the "radiation-dominated" or "Laser Piston" (LP) regime [2] where relativistic ion energies may be obtained. In fact, previous particle-in-cell (PIC) simulations [3] showed that RR effects become important at intensities exceeding $5\times10^{22}\,\mathrm{W\,cm^{-2}}$ and increase nonlinearly with the laser intensity. Recent studies for thick targets in the hole boring regime [4] and ultrathin plasma slabs [5] pointed out the RR ability to impede the electron backward motion through the laser pulse cooling the electrons and enhancing the ion bunching.

In the present contribution, we investigate the RR effects in the interaction of a super-intense laser pulse with a thin foil in the RPA regime by PIC simulations both for linear and circular polarization. In particular, we check the RR ability to reduce the electron heating which is responsible of the broadening of both the electron and ion spectrum.

The Radiation Reaction force

The RR force basically describes the back-action on a single particle by its self-generated electromagnetic fields. The inclusion of the RR force in the dynamics of a plasma accounts for the incoherent emission of high frequency radiation by ultrarelativistic electrons. We assume that the incoherent radiation does not interact again with the plasma since its frequency is much higher than the plasma frequency and the plasma is transparent to it.

Our approach is based on the Landau-Lifshitz (LL) equation [1] which is free from known problems of other approaches such as, e.g., runaway solutions [6]. In order to highlight the relevant quantities, we normalize time in units of ω^{-1}, space in units of $c\omega^{-1}$, momenta in units of mc and fields in units of $m\omega c/|e|$ where ω is the laser frequency. The full three-dimensional

LL equation is

$$\begin{aligned}\frac{d\mathbf{p}}{dt} &= -\Big(\mathbf{E}+\mathbf{v}\times\mathbf{B}\Big) \\ &- \left(\frac{4}{3}\pi\frac{r_e}{\lambda}\right)\gamma\Big[\Big(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\Big)\mathbf{E}+\mathbf{v}\times\Big(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\Big)\mathbf{B}\Big] \\ &+ \left(\frac{4}{3}\pi\frac{r_e}{\lambda}\right)\Big[\Big(\mathbf{E}+\mathbf{v}\times\mathbf{B}\Big)\times\mathbf{B}+\Big(\mathbf{v}\cdot\mathbf{E}\Big)\mathbf{E}\Big] \\ &- \left(\frac{4}{3}\pi\frac{r_e}{\lambda}\right)\gamma^2\Big[\Big(\mathbf{E}+\mathbf{v}\times\mathbf{B}\Big)^2-\Big(\mathbf{v}\cdot\mathbf{E}\Big)^2\Big]\mathbf{v} \qquad (1)\end{aligned}$$

where $r_e \equiv e^2/mc^2$ is the classical electron radius, λ is the laser wavelength and $4\pi r_e/3 \approx 1.18\times10^{-8}\,\mu$m. The exact solution for the motion of an electron in a plane wave [7] was used as a benchmark and reference case for the numerical algorithm. Our numerical approach was tested for a range of intensities from $10^{22}\,\mathrm{W\,cm^{-2}}$ up to $10^{24}\,\mathrm{W\,cm^{-2}}$ with good agreement between analytical and numerical predictions.

The PIC simulations

We performed 1D3V PIC simulations with a plasma slab of protons with initial plasma density $n_0 = 100n_c$ and thickness $l = 1\lambda$. The laser pulse fields rise as a $\sin^2$ function for one cycle, remain constant for five cycles then fall as a $\sin^2$ function for one cycle with a laser wavelength $\lambda = 0.8\,\mu$m. According to [2], RPA dominates for both circular polarization (CP) and linear polarization (LP) when the laser intensity $I \gtrsim 10^{23}\,\mathrm{W\,cm^{-2}}$. In our case the chosen laser intensity were $I = 2.33\times10^{23}\,\mathrm{W\,cm^{-2}}$, $I = 5.5\times10^{23}\,\mathrm{W\,cm^{-2}}$ and $I = 10^{24}\,\mathrm{W\,cm^{-2}}$ both for CP and LP.

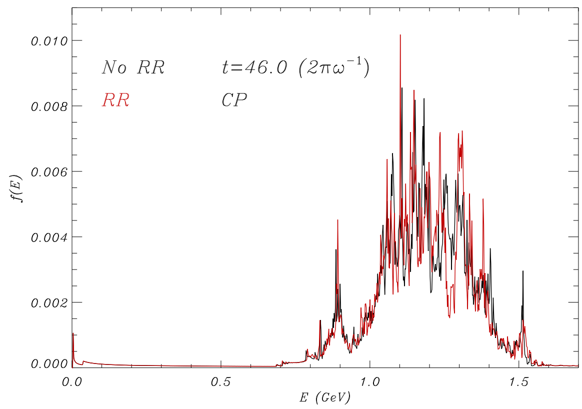

Figure 1: Ion energy spectrum at $t = 46\,(2\pi\omega^{-1})$ with (red) and without (black) RR for CP and $I = 2.33\times10^{23}\,\mathrm{W\,cm^{-2}}$.

In the CP case, we found that RR effects on the ion spectrum are completely negligible (Fig. 1) even for $I = 10^{24}\,\mathrm{W\,cm^{-2}}$ if the laser pulse does not break through the foil. This can be explained noticing that in this case the laser pulse penetrates into the foil for a tiny fraction of the order of $\lambda/20$ i.e. the fields in the plasma are much smaller than the fields in vacuum and the RR force (1) is vary small compared to the Lorentz force. These results are in agreement with previous studies which found significant RR effects for CP when the laser pulse is transmitted through the plasma foil [5].

In the LP case the foil is accelerated by radiation pressure too but unlike CP the laser pulse does penetrate up to a fraction of the order of $\lambda/4$ on the front surface of the foil. Electrons on the front surface therefore move in a strong electromagnetic field of the same order of the vacuum fields. In this case the RR force reaches values comparable with the Lorentz force and RR clearly affects the spectrum (Fig. 2). The deep penetration of the laser pulse in the LP case may be explained by the strong longitudinal oscillatory motion due to the $\mathbf{J}\times\mathbf{B}$ force which allows the electrons to move inside the foil. Anyway, a significant fraction of hot electrons is produced by the $\mathbf{J}\times\mathbf{B}$ oscillations both with and without RR. The thermal expansion of the hot electrons increasingly broaden the ion energy spectrum after the acceleration stage and eventually the energy spread is very large (Fig. 3).

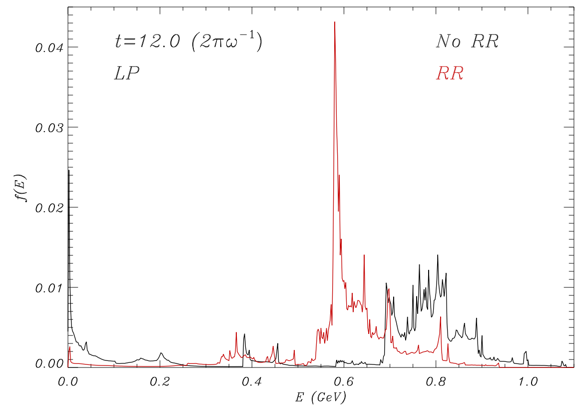

Figure 2: Ion energy spectrum at $t = 12\,(2\pi\omega^{-1})$ with (red) and without (black) RR for LP and $I = 2.33\times 10^{23}\,\mathrm{W\,cm^{-2}}$.

Conclusion

In conclusion, we performed PIC simulations in the RPA regime checking the influence of RR effects. For CP, we found that RR effects become important only for non optimal regimes for ion acceleration i.e. when the laser pulse breaks through the foil. For LP, we found that RR effects are important during the laser-foil interaction improving the quality of the ion spectrum and leading to a reduction of the maximum achievable ion energy. However, after the laser-foil interaction stage, hot electrons broaden the ion spectrum and eventually the energy spread is very large both with and without RR.

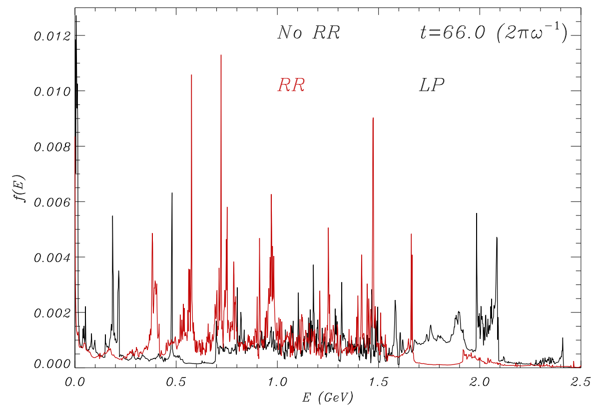

Figure 3: Ion energy spectrum at $t = 66\,(2\pi\omega^{-1})$ with (red) and without (black) RR for LP and $I = 2.33\times 10^{23}\,\mathrm{W\,cm^{-2}}$.

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