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Ion acceleration with radiation pressure in quantum electrodynamic regimes

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ABSTRACT

The radiation pressure of next generation high-intensity lasers could efficiently accelerate ions to GeV energies. However, nonlinear quantum-electrodynamic effects play an important role in the interaction of these lasers with matter. We show that these quantum-electrodynamic effects lead to the production of a critical density pair-plasma which completely absorbs the laser pulse and consequently reduces the accelerated ion energy and efficiency by 30-50%.

Keywords: Laser-matter interaction, QED-plasma, Ion acceleration, P.I.C. simulations, Ultra-intense lasers.

1. INTRODUCTION

High-intensity lasers can accelerate ions over much shorter distances than conventional accelerators (microns compared to many metres). Compact ion accelerators based on lasers could have applications in medical physics[1] (radiotherapy) as well as in fundamental physics[2] (hadron interactions). Radiation pressure ion acceleration using next generation lasers (such several of those comprising the soon to be completed Extreme Light Infrastructure[3]) could accelerate ions to GeV energies. However, at the intensities expected to be reached in these laser-matter interactions ($> 10^{23}$ Wcm^{-2}) both relativistic and nonlinear quantum-electrodynamic (QED) effects play a crucial role.[4]

- Relativistic effects modify the target transparency: the density at which the laser is absorbed (critical density) is increased by the Lorentz factor γ_e to which the electrons are accelerated.
- Accelerated electrons start to radiate gamma-ray photons by nonlinear Compton scattering. As such (quantum) radiation reaction[5] affects the electron dynamics, these photons can carry away a substantial fraction of the electron energy leading to laser absorption.[6] These photons can generate electron-positron pairs in the laser-fields[7] which can radiate further photons. A cascade of pair production ensues.

It is known that ions can be accelerated to high energies ($\sim$MeV)[8–10] using ultra-high intensity laser pulses incident on a solid target. Ion acceleration in this regime can be driven by an electrostatic sheath field at the rear surface of the target in a process known as Target Normal Sheath Acceleration (TNSA). This sheath is formed as a result of electrons at the front surface, which are accelerated by the incident laser pulse, setting up a space charge on the rear surface as they escape into the vacuum behind the target.[11] At the intensities expected to be reached by next generation high-intensity lasers ($I \sim 10^{23}$Wcm^{-2}), new acceleration mechanisms become important and TNSA is not expected to give the most favorable scaling of ion energy (for TNSA $\epsilon \propto \sqrt{I}$).[12] An alternative acceleration mechanism, known as radiation pressure acceleration (RPA), uses the momentum exchange between an electromagnetic pulse and the electrons of an opaque target to set up a large space charge which acts to accelerate the remaining ions, resulting in $\epsilon \propto I$. Different regimes of radiation pressure acceleration

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exist, depending on the target thickness compared to the skin depth. The regime where the target is much thicker than the skin depth is known as the 'hole boring' regime , because the intense radiation pressure of the laser must bore a hole into the target material.[13] The regime where the target thickness is of the order of the skin depth or thinner has been named 'light sail' as in this case the whole region of the target within the laser spot is (in principle) accelerated together.[14]

In this paper we use one dimensional particle-in-cell (PIC) simulations to show that QED effects can reduce the energy of ions accelerated by radiation pressure by 50%. We develop a scaling law for the accelerated ion's energy and the efficiency of the acceleration for both hole boring and light sail acceleration, accounting for radiation reaction and pair creation. We show that, in the hole boring scheme, a key role is played by the electron-positron plasma, created by a pair cascade between the laser and the target. This pair plasma can reach the relativistically corrected critical density, i.e. the density at which its dynamics strongly affect the propagation of the laser pulse.[15,16] In fact this pair plasma almost completely absorbs the laser pulse. Consequently, the energy of the accelerated ions could be reduced by $\sim 50\%$. On the contrary, we show that the light sail approach is not affected by QED effects because of the ultra-relativistic target acceleration which curtails all pair production.

2. HOLE BORING

Radiation pressure ion acceleration exploits the exchange of momentum between a relativistic laser pulse and the electrons in a solid target. The resulting acceleration of these electrons leaves a charge separation later creating a large electrostatic field which in turn accelerates the ions in the solid target. The process has been summarized in Fig. 1.

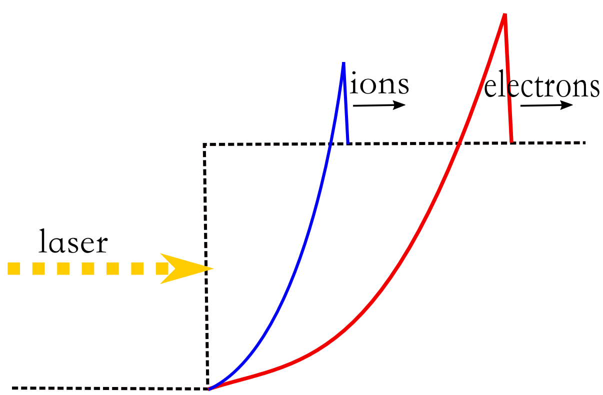

Figure 1. Schematic of hole boring radiation pressure ion acceleration: the electromagnetic momentum carried by the laser (in yellow) pushes the electrons inward (in red) of an opaque target, leaving a charge separation layer and creating an electrostatic field that in turn acts on the ions (in blue) and leads to their acceleration.

2.1 Relativistic classical theory

We present the relativistic classical hole boring scheme as it has been derived in Ref.[13]

The analysis is limited to circularly polarized lasers, in which electron heating is weak.[12] To first approximation, the target acceleration is one dimensional and constant in time, so the system is assumed to be quasi-stationary. Crucially, the derivation of the theory relies on a transformation to the rest frame of the 'hole boring front' as it bores into the target. In this frame, the laser intensity I' is relativistically Doppler shifted. As a function of the laser intensity in the laboratory frame I and of the speed of the hole boring front $\beta_{HB} = v_{HB}/c$ normalized to the speed of light c, it reads

$$I' = I\frac{1-\beta_{HB}}{1+\beta_{HB}}. \tag{1}$$

In the hole boring frame, the laser pulse is partially absorbed and partially reflected (transmission is negligible because of the target thickness), while ions in the target are reflected at the plasma surface. Thus, the longitudinal momentum balance, schematized in Fig. 1, reads

$$\left(\frac{1-\beta_{HB}}{1+\beta_{HB}}\right)\frac{I}{c}\left(1+R'\right)=2\gamma_{HB}^2\rho c^2\beta_{HB}^2, \tag{2}$$

where R' is the reflection coefficient, ρ is the initial target mass density and γ_{HB} is the Lorentz factor. The primed quantities are computed in hole boring (target) instantaneous rest frame, while, when omitted, quantities are computed in the laboratory frame. From Eq. (2), the hole boring velocity and the ion energy in the laboratory frame are respectively[12,13]

$$\beta_{HB}=\frac{\sqrt{\Pi}}{1+\sqrt{\Pi}} \tag{3}$$

and

$$\epsilon=m_i c^2\frac{2\Pi}{1+2\sqrt{\Pi}}, \tag{4}$$

where

$$\Pi=\frac{(1+R')}{2}\frac{I}{\rho c^3}. \tag{5}$$

Finally, it is assumed that, in the absence of QED effects, there is no laser absorption in the hole boring frame, such that $R'=1$.

Hole boring experiments have been performed with gas targets,[18] revealing the right scaling law, and with solid targets.[19–21] The latter is less clear at present,[12] because the electron heating due to the use of linear polarization complicates the picture.

2.2 QED effects

At the intensities accessible by the soon to be completed Extreme Light Infrastructure[22] ($I \gtrsim 10^{23}$ W/cm^2), laser-matter interactions are predicted to reach a new regime inferred to exist in extreme astrophysical environments,[23,24] creating a plasma whose behavior is characterized by the interplay of relativistic plasma kinetics and non-linear quantum electrodynamic (QED) processes.[25] For brevity we describe this new regime as QED-plasma.

The QED processes that mainly can affect the plasma dynamics in the QED-plasma regime are:[25–27]

- gamma-ray emission by electrons and positrons (non-linear Compton scattering), with the resulting radiation-reaction modifying the dynamics;[28]
- pair creation by the emitted gamma-ray photons, in the macroscopic electromagnetic fields (the multi-photon Breit-Wheeler process).

The two processes are shown in Fig. 2.

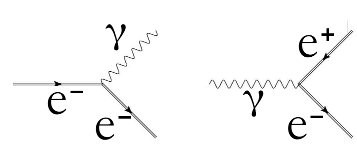

Figure 2. The two main QED processes: non-linear Compton scattering (left) and multi-photon Breit-Wheeler emission (right).

QED effects are parameterized by $\eta=E_0/E_S$, where E_0 is the electric field in the electron instantaneous rest frame, while

$$E_S=\frac{m_e^2c^3}{e\hbar} \tag{6}$$

is the Schwinger field, with m_e a the electron mass, e as the elementary charge and $\hbar$ as the Planck's constant. QED effects are predicted to be important when $\eta>0.1$.[6,29]

2.3 Simulation results

We simulate the effect of QED processes on hole boring ion acceleration using the QED-PIC code EPOCH. The particle-in-cell method uses macro-particles to represent many real particles for computational efficiency. These macro-particles can be used to represent a variety of real particle species including electrons, ions, and eventually positrons and high energy (or hard) photons. Macro-particles move according to kinematic laws and are subjected to the electromagnetic force via a discretized grid, which implies collision-less dynamics. The electromagnetic field is derived from the macro-particle charges and can also include external sources such as a laser field. The evolution of the electromagnetic fields is computed by solving Maxwell's equations on the computational grid.

EPOCH[30] accounts for the QED effects described in the previous section[28] by modeling stochastic electron and hard photon emissions, dependent on specific emission rates.

The following figures show the results of a one dimensional simulation of hole boring ion acceleration in the regime where QED effects are important. The target is initialized as a semi-infinite aluminum slab of electron density $n_0 = 10^{24}$ cm^{-3}. It is illuminated by a circularly polarized 1 μm wavelength laser of intensity 5×10^{24} W/cm^2. The laser temporal profile is flat, with 35 fs of duration. The simulation is performed with 10240 cells in a domain of 20 μm, initialized with 1.31072×10^6 macro-ions and 1.31072×10^6 macro-electrons per cell.

Initially, the simulation shows that the laser accelerates electrons and ions, according to the hole boring scheme dsecribed in Sec. 2.1. Accelerated electrons emit gamma-rays, which in turn emit pairs: a pair cascade occurs. After $t_a \approx 15$ fs, the pair cascade results in the production of an electron-positron pair plasma with density equal to the relativistically corrected critical density for 1μm wavelength light. This plasma, developed between the laser and the aluminum ions, absorbs the laser, reducing the energy of the accelerated ions and the efficiency of the acceleration. This configuration is illustrated in Figure 3, which shows the ion, electron and positron density after 28 fs.

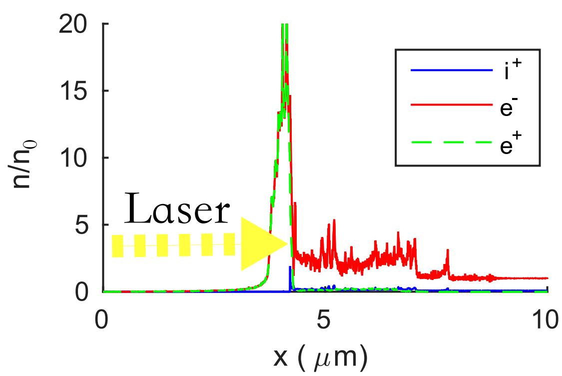

Figure 3. Density profile, normalized to the initial electron density, in the simulation of hole boring ion acceleration, at 28 fs.

By modifying the absorption, the pair plasma generated in front of the target surface reduces the average ion energy. This can be seen in Eq. (4). If we assume that the emitted gamma-ray photons do not contribute to the longitudinal momentum balance, we see that the absorption $A' = 1 - R'$ can decrease the ion energy by 50%.

The average ion energy* is

$$< \epsilon >= \frac{\int d^3x d^3p f \epsilon}{\int d^3x d^3p f}, \tag{7}$$

*The contribution of spatial meshes with average energies below 0.1 GeV has been neglected in order to limit our estimation to accelerated ions only. This does not affect energy and efficiency ratio which remains the same even accounting for all meshes.

where $f(t, \vec{x}, \vec{p})$ is the ion distribution function, ϵ is the ion energy and d^3xd^3v constitutes the phase space volume element. We computed it for two identical simulations, with and without QED effects. Around $t \approx 15$ fs, the two simulations start to diverge significantly. In the QED case, the energy is strongly reduced with respect to the classical case, as predicted by our estimation above. For $t = 35$ fs, the ion energy is reduced to the 67%.

In Fig. 4, the average energy per mesh is plotted at 28 fs. Except for a first peak, related to the first laser-matter interaction, the plot is mainly composed of 'classical' and 'QED-affected' regions, respectively located after and before $x \approx 5$ μm (red and a green squares have been included to emphasize the classical and the QED regime, respectively). The first region, of length $\sim t_a\beta_{HB}c$, is characterized by classical hole boring ion acceleration, since the ions were accelerated before the pair plasma became relativistically overcritical.

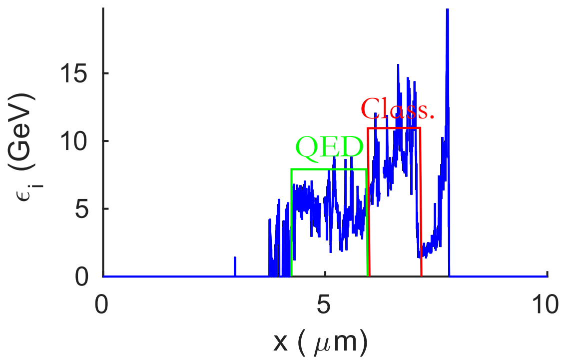

Figure 4. Average ion energy per mesh, as a function of space after 28fs. Red and green squares have been included to emphasize the classical and the QED regime, respectively

3. 'OPTIMAL' LIGHT SAIL

The light sail acceleration mechanism,[14] named as such because it applies to low mass and high surface area targets, applies to targets with a thickness less than the skin depth for a particular wavelength laser. The high surface area to mass ratio means that they acquire a significantly larger boost from the radiation pressure from a given laser pulse when compared to thicker targets.

The one dimensional equation of motion for a moving target in the laboratory frame can be obtained with the help of a Lorentz transformation, similarly to Eq. (2). Neglecting absorption for simplicity and assuming perfect reflection, we obtain

$$\frac{d(\gamma_{LS}\beta_{LS})}{dt} = \left(\frac{1-\beta_{LS}}{1+\beta_{LS}}\right)\frac{2I}{\rho l c^2}, \tag{8}$$

which has the solution[31]

$$\gamma(t) = \sinh(u) + \frac{1}{4\sinh(u)}, \tag{9}$$

with

$$u = \frac{1}{3}\sinh^{-1}\left(3\Omega t + 2\right), \tag{10}$$

γ_{LS} is the Lorentz factor of the target as it is accelerated and

$$\Omega = \frac{Z m_e a_0^2}{m_i \zeta}\frac{2\pi c}{\lambda}. \tag{11}$$

The energy the ions acquire by light sail acceleration (as $t \to \infty$) is

$$\epsilon_{LS} \approx \left(3\Omega t\right)^{1/3} m_i c^2, \tag{12}$$

where Z is the ionization state of ions in the target and $\zeta = \pi n_e l/(n_c \lambda)$ is the transparency threshold. The model predicts ion energy gain at 'optimal' conditions (perfect reflection), which is provided by assuming $\zeta \approx a_0$,[32] where

$$a_0 = 0.6\sqrt{\frac{I\lambda^2}{10^{18}\ \mathrm{W/cm^2}}} \tag{13}$$

is the dimensionless laser intensity for circularly polarized lasers and λ is the laser wavelength, expressed in μm. This approximation suppresses the density dependence.

Light sail experiments[33–36] confirm the expected light sail scaling, but also indicate significant detrimental effects, i.e. the observed ion spectrum is relatively broad, suggesting that transverse inhomogeneity and heating effects need to be reduced.

Light sail ion acceleration is particularly efficient,[14] accelerated targets can easily reach the ultra-relativistic limit (the speed of the target normalized to c is $\beta_{LS} \approx 1$). For this reason, $\eta \propto \sqrt{1-\beta_{LS}^2}$ (because of the Doppler shift[6,37]) is quenched, minimizing QED effects, which become negligible.

4. CONCLUSIONS

In conclusion, we have developed a practical scaling law in order to estimate QED effects on radiation pressure ion acceleration. It shows that pair cascades can modify laser absorption through the creation of an overcritical pair plasma which develops between the laser pulse and the target. This pair plasma absorbs the laser, quenching the radiation pressure accelerating the target. Consequently, for hole boring ion acceleration the average ion energy is reduced by 50%. By contrast, for 'optimal' light sail ion acceleration, the target quickly becomes sufficiently relativistic that pair cascades do not occur and there is no reduction in ion energy or acceleration efficiency.

5. ACKNOWLEDGMENTS

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