Electron-positron pair modification of the hole-boring scenario in intense laser-solid interactions

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Introduction

It has been predicted that experiments using optical laser pulses of intensity between 10^{23} and $10^{24}\,\mathrm{W\,cm^{-2}}$ will be able to initiate non-linear electromagnetic cascades that produce large numbers of electron-positron pairs and an intense flux of high-energy gamma-rays [1, 2]. Recently, a set-up favourable for such cascades has been investigated in which the beam is incident on an overdense foil [3]. In the "hole-boring" scenario that describes this interaction, the laser beam evacuates a cylindrical channel by driving a working surface or "front" into the target. At $10^{23}\,\mathrm{W\,cm^{-2}}$, PIC-QED simulations show that pairs are created primarily at the working surface [3], where they do not initiate a cascade. However, they also accumulate in the evacuated channel, where they scatter photons out of the incoming beam. Here we use exact solutions to a cold, two-fluid (electron and positron) model including classical radiation reaction in the Landau-Lifshitz approximation, to investigate the influence of these pairs on the threshold for a non-linear cascade in the channel.

Hole-boring front

The hole-boring front sweeps up ions and electrons as it advances into the solid by building a charge-separated region containing a strong, longitudinal electric field. In the simplest picture, these particles are reflected elastically [4, 5]. At the same time, in the frame in which the front is at rest (the "HB-frame") the circularly polarized laser is perfectly reflected, i.e., the reflectivity in this frame is $R' = 1$. In a stationary solution, the speed of advance of the front into the solid, $c\beta_{\rm f}$, is found by equating the pressure exerted by the laser with that exerted by the target particles: $\beta_{\rm f} = \sqrt{X}/\left(1+\sqrt{X}\right)$, where $X = I/\left(\rho c^3\right)$ is the ratio of the energy density of the incident laser beam, I/c, to the rest-mass energy density of the target ρc^2. This gives a reflectivity $R = \left(1+2\sqrt{X}\right)^{-2}$ in the lab. frame. However, if pairs are present in the channel, they dissipate some of the laser energy into high-frequency photons, implying $R' < 1$. In this case, the advance speed and lab. frame reflectivity are given by making the replacement $X \to \xi = X\left(1+R'\right)/2$ in the above expressions.

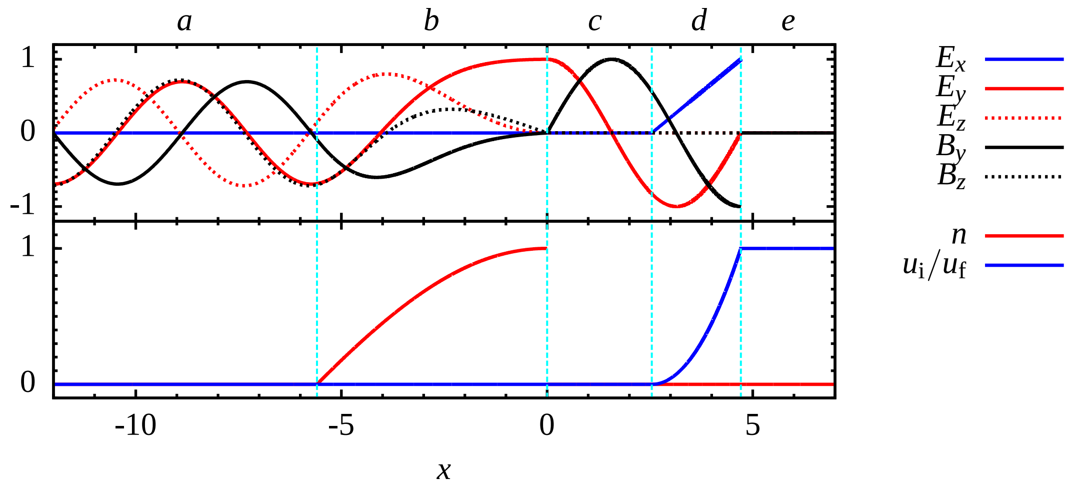

Figure 1: Field and density profiles for the pair front and ion sheath: region a: the vacuum channel; region b: the pair front; region c: the vacuum gap; region d: the ion sheath; region e: the target, containing reflected ions and electrons. n is the density of pairs in the cushion, normalised to the critical density, u_i is the speed of the swept-up and reflected ions in the ion sheath, which reaches a maximum of u_f. The parameters are for an aluminium target, a laser wavelength of $1\,\mu$m and an intensity of $10^{23}\,\mathrm{W\,cm^{-2}}$.

Pair cushions

In the absence of pairs, the channel ahead of the front contains a vacuum standing wave as seen in the HB-frame, in which the electric and magnetic fields rotate together, remaining everywhere parallel, and have magnitudes that are constant in time, but vary with position x. A small amount of pair plasma introduced into this wave will, in general, experience a time-dependent force in the x direction, which cannot be balanced by pressure terms in the model we adopt. However, at both the electric nodes and the magnetic nodes, this force vanishes, and a stationary solution with pairs is possible. At an electric node, the electrons and positrons that form part of a stationary solution must be completely cold and, therefore, have no effect on the wave. But at the magnetic nodes they perform circular trajectories in opposite senses — a situation analysed in the test-particle case by [1].

The radiation reaction force experienced by particles in a “cushion” of pairs inserted near a magnetic node (region b in Fig. 1) causes energy to be removed from the beam and converted into high frequency photons. The Poynting flux is, therefore, not divergence-free in the interior of the cushion, and the electric and magnetic fields are no longer parallel. This reduces the flux incident on the hole-boring front, and, in turn, the speed of the front with respect to the lab. frame, until perfect reflection of the incident flux is again established. Thus, the Poynting flux vanishes at the hole-boring front, and between it and the nearest boundary of the pair cushion, leading to a vacuum gap (region c in Fig. 1) between the target and the pair cushion .

In the cushion, the electric field, provides both the centripetal force needed for a circular trajectory, and the force required to compensate radiation losses. But the particle trajectory remains in the *y*-*z*-plane only if the magnetic field either vanishes, or is parallel to the velocity vector. Thus, in a self-consistent solution, the Poynting flux in the cushion vanishes only at a magnetic node, and such a point is, therefore, the only possible location of the edge of the cushion closest to the hole-boring front. On the other hand, the front itself, consisting of an ion sheath (region *d* in Fig. 1) and a mirror (the interface between regions *d* and *e*) is located at or close to a node of the *electric* field in this wave. As a result, stationary solutions must contain a vacuum gap separating the pair cushion from the hole-boring front.

The boundary of the pair cushion that is closer to the laser is not subject to such a restriction, since it does not have to match a vacuum wave of vanishing Poynting flux. Instead, its location is determined by the total number of pairs per unit area contained in the cushion. This fixes the fraction of the incident flux that is re-radiated as high frequency photons, and, hence the magnitude of the reflected wave that propagates back towards the laser. Within the cushion, the density decreases monotonically towards the laser, and drops discontinuously to zero at the cushion edge. The maximum permitted cushion size, and, therefore, the maximum number of pairs allowed by a self-consistent, stationary solution is achieved when the density discontinuity at this edge vanishes. This is the configuration shown in Fig. 1. The reflectivity R' varies between 1 (no pairs) and R'_{min} for a maximal cushion. We show elsewhere [6] that Maxwell's equations and the cold two-fluid equations are solved by a single quadrature, from which R'_{min} can be obtained.

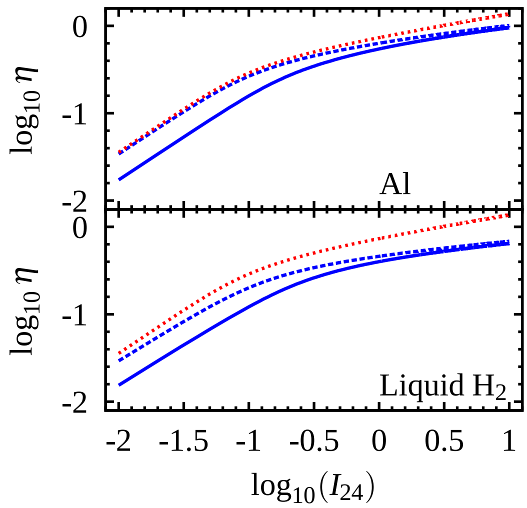

Figure 2: η for electrons and positrons in the channel for vacuum conditions (blue dashed lines) and for a maximal pair cushion (blue solid lines), against laser intensity for a liquid hydrogen target (bottom) and an aluminium target (top). The laser intensity is $I_{24} \times 10^{24}\,\mathrm{W\,cm^{-2}}$, wavelength $1\,\mu$m. For comparison, η as given by [1] for counter-propagating beams ($R = 1$) is also shown (red lines).

A non-linear pair cascade will occur when a sufficiently large volume is occupied by electrons and/or positrons that are capable of initiating pair creation in a region in which the pairs themselves subsequently achieve this capability. The relevant dimensionless QED parameter is the electric field measured in the particle rest-frame in units of the critical field

$E_c = 1.3 \times 10^{18}\,\mathrm{V\,m^{-1}}$, denoted here by η. For an electron trajectory in counter-propagating vacuum waves, this is computed in [1]. These authors also estimate that a plasma of linear dimension equal to the laser wavelength should reach threshold when $\eta \approx 1$.

In the current scenario, pairs created in regions *a* through *e* in Fig. 1 will be reaccelerated, the most favourable locations being close to the magnetic nodes in regions *b* and *c*. For trajectories at these points, the parameter η is plotted in Fig 2. Target recoil increases the laser intensity needed to reach threshold for a non-linear pair cascade, an effect which is stronger for lighter targets, as can be seen by comparing liquid hydrogen with aluminium. The idealized, counter-propagating case [1], plotted as η_{BK}, corresponds to $R = 1$, i.e., the limit of a infinitely dense target. If pairs accumulate in a pair cushion, the value of η is reduced. However, even with the maximum number of pairs that can be accommodated in a stationary cushion, this is only a small effect at intensities above $I_{24} = 1$, where the cascade is expected to occur. Therefore, it is unlikely to have a substantial effect on the threshold.

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