Interaction of high intensity laser pulses with pre-formed plasma in fast ignition targets

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Abstract. Two-dimensional PIC simulations of the interaction of a high intensity, short pulse laser with planar foil targets preceded by a pre-formed density ramp have been performed. We observe a trend towards hot electron sources with higher characteristic energies and larger divergence angles in targets with longer pre-plasma scale lengths. We also present the results of simulations of cone geometry targets containing pre-formed plasma, and examine the case of a misfire involving the incident laser being offset from the central cone axis. The resultant hot electron populations produced in the presence of both short and long scale length pre-plasmas suggest that beam accuracy may be critical when scaling to a full fast ignition facility.

1. Introduction
The fast ignition approach to inertial confinement fusion (ICF) [1] commonly uses a short pulse laser to accelerate electrons, which deliver their energy to the core of a compressed fusion capsule. The requirements for ignition of the fuel capsule place constraints on the divergence angle, energy and duration of the hot electron beam. Recent studies [2, 3] of cone-guided fast ignition targets [4] suggest that plasma filling of the cone tip due to a pre-pulse will have a significant impact on the production of hot electrons. Some advanced fast ignition target designs include a low density foam lining in the cone [5] to create a controlled pre-plasma in an attempt to maximise the absorption of incident light and the production of energetic electrons.

Using the particle-in-cell code, EPOCH1, we have studied the effect of varying the pre-plasma scale length on hot electron production for the case of a high density foil with a long scale length, low density pre-plasma. We have considered foils at normal and oblique incidence, in order to represent the cone tip and walls. We also present the results for 2D cone geometry targets. All simulations were performed without collisions.

2. Planar foil simulations
The simulated targets consisted of a 25 µm thick, high density \(n_e = 5 \times 10^{28} \text{ m}^{-3}\), high Z plasma with a front surface pre-plasma of exponential density scale length 5 or 50 µm. Initial temperatures of 1 keV in the pre-plasma and 100 eV in the foil were used. The density and temperature profiles were based on 1D simulations of a 1 ns pre-pulse with an intensity contrast

1 EPOCH has been developed under EPSRC S&I funding at the University of Warwick, and its continuing development is funded under an EPSRC CCP at three UK universities.
ratio of $10^6$ performed using AWE’s hydro-code, NYM [6]. Targets were simulated at 0 and 70° (equivalent to a 20° half-angle cone) to the laser axis respectively, at both pre-plasma scale lengths. The ions were assigned mass and charge values of $40m_p$ and $20e$ respectively. The incident short pulse laser was modelled as a 0.5 ps FWHM top-hat pulse with a short rise time, focused to a 10 µm diameter spot and peak intensity of $Iλ^2 = 10^{20}$ Wcm$^{-2}$µm$^2$ for $λ = 1054$ nm.

Hot electrons produced by the laser interaction with the pre-plasma region were recorded by particle probes placed at a plane 10 µm into the high density foil region. The energy spectra of the electrons recorded by the particle probes are shown in figure 1a. By fitting an exponential to the high energy tails of the electron distributions, it was possible to estimate the characteristic hot electron energy, $T_h$. The values of $T_h$, fraction of laser energy absorbed into hot electrons detected by the probes, and their mean direction of motion (relative to the laser axis) for each simulated case are given in table 1.

Table 1: Table of the values of $T_h$ for each scale length ($L$) and angle of incidence ($θ$) case. Also tabulated are the fraction of laser energy absorbed into hot electrons detected by the probe plane, and their mean direction of motion ($⟨φ⟩$). Note, the ideal value of $T_h$ is 1–5 MeV [1, 8].

| $L$ (µm) | $θ$ (°) | $T_h$ (MeV) | Abs. frac. | $⟨φ⟩$ |
|---------|---------|-------------|------------|-------|
| 5       | 0       | 5.3         | 18%        | −1.2° |
| 5       | 70      | 7.6         | 19%        | 50.6° |
| 50      | 0       | 25.4        | 35%        | −4.6° |
| 50      | 70      | 37.0        | 36%        | 58.3° |

The presence of a long scale length pre-plasma resulted in a higher maximum electron energy, and an increase in $T_h$. At oblique incidence the laser effectively encounters a longer scale length pre-plasma. Thus moving away from normal incidence continued the trend towards higher peak electron energies, higher $T_h$ and more energy absorbed from the laser overall. The increase in $T_h$ with pre-plasma scale length may be linked to the production of small numbers of very high energy electrons in the low density channel ($n_e < 10^{26}$ m$^{-3}$) formed by the laser pulse, analogous to the laser wakefield accelerator [9, 10].

The hot electron divergence angles (defined as the standard deviation in their direction of motion) showed a noticeable increase in the normal incidence, long scale length results, as shown by figure 1b. This may have been due to the onset of plasma instabilities such as laser filamentation [11]. Any filaments produced in the oblique incidence case were refracted away from the foil, and thus similar divergence angles to the short scale length cases were recorded by the probes.

3. Cone target simulations

The interaction of the laser pulse with the cone tip was predicted to yield similar results to the normal incidence, planar targets. However, the laser missing the cone tip and striking the side of the cone may result in further interaction events occurring elsewhere within the cone. Therefore, to investigate the potentially detrimental impact of such a misfire in the presence of a pre-plasma, the central axis of the laser pulse was deliberately offset from the cone axis by 25 µm. The 2D cone geometry targets were simulated as having a thickness of 25 µm, inner tip diameter of 30 µm and a 20° half-angle. Exponential density profiles, of scale lengths 5 and 2

Note that we avoid comparison with the ponderomotive energy (3.9 MeV) due to ambiguities over factors such as the range of energies over which to calculate $T_h$ [7].
Multiple interactions were observed in the presence of a short scale length pre-plasma. The reflection of the laser pulse from the upper wall, cone tip and lower wall is visible in the magnetic field ($B_z$) plot, figure 2a. This behaviour produced multiple hot electron sources, each directed away from the expected position of the assembled fuel (see table 2). In the long scale length case, however, the laser pulse was refracted in the cone tip (as shown in figure 2b). The refraction of the laser resulted in a larger and higher energy, single hot electron source with a greater divergence angle than any of the individual short scale length sources. The mean directions of motion and divergence angles recorded by the particle probes are given in table 2. Using the combined energy and angular distribution data, the fraction of electron energy which could potentially be deposited in the assembled fuel ($E \leq 100\text{ MeV}$ and $-45^\circ \leq \phi \leq 45^\circ$) for the short and long scale length cases was calculated to be 56% and 42% of the total forward travelling electron energy respectively.

Figure 1: (Colour online) Data recorded by the particle probes for 5 (red) and 50 (blue) micron scale length pre-plasmas at 0 (solid) and 70 (dashed) degrees to the incident laser.

50 $\mu$m, were added to the front (inside) of the cones. The laser parameters were unchanged from the planar foil simulations.

Figure 2: (Colour online) Z-component of the magnetic field ($B_z$), taken at $t = 1.25\text{ ps}$, from simulations of a laser offset $25\text{ $\mu$m}$ from the cone tip.
Table 2: Table of the mean angle of motion \( \langle \phi \rangle \) of the hot electrons passing through each of the cone walls for the short and long scale length cases, relative to the laser axis. The divergence half-angles are given in parentheses.

| Probe position | \( \langle \phi \rangle \) for \( L = 5 \mu m \) | \( \langle \phi \rangle \) for \( L = 50 \mu m \) |
|----------------|-----------------------------------------------|-----------------------------------------------|
| Upper wall     | 47.8° (42.7°)                                | 40.8° (28.1°)                                 |
| Cone tip       | −22.3° (25.3°)                               | −23.2° (22.8°)                                |
| Lower wall     | −93.9° (27.7°)                               | −80.5° (36.7°)                                |

4. Conclusion

For the purposes of hot electron generation in the cone-guided fast ignition approach to ICF, the presence of a pre-plasma within the cone appears to be undesirable. In the case of a long scale length pre-plasma, the laser pulse must propagate through a large region of low density plasma. The interaction of a short pulse laser with underdense \( (n_e < n_c) \) plasma is known to produce highly energetic electrons [9, 10] which have a much greater stopping distance than is suitable for fast ignition. A long scale length pre-plasma allows more energy to be coupled to the hot electrons overall. However, reducing the extent of the pre-plasma (possibly via pre-pulse mitigation techniques) is more likely to yield hot electron populations with energy distributions more suitable for fast ignition purposes. The presence of a shorter scale length pre-plasma also appears to reduce the divergence of the hot electrons. This may be due to the conditions being less suitable for the growth of instabilities such as laser filamentation [11] and Raman scattering [12].

When the full cone geometry is taken into consideration (in 2D), a cone wall interaction has a detrimental effect on the hot electron population. A short scale length pre-plasma leads to multiple interactions as the laser is reflected from the cone surfaces, producing multiple hot electron sources with few electrons directed towards the assembled fuel (56% of the forward travelling electron energy). Increasing the pre-plasma scale length, however, causes the laser pulse to refract in the cone tip, producing a single, large, highly divergent source of hot electrons (with 42% of the forward travelling electron energy directed towards the assembled fuel).

Further PIC simulations at a range of beam offsets and angles are required to better characterise the potential impact of a misfire. Full 3D runs will also be required to determine if these effects remain the same in a full 3D geometry.

We have found that neither of the cone geometry cases considered are desirable for fast ignition. Thus we conclude that ensuring a consistently high degree of beam accuracy may prove to be a critical factor in the design of a high repetition rate fast ignition facility.

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