Heating in wire-like target using laser-generated fast electrons and the theory of angular rarefaction

Contact: raba500@york.ac.uk

R. A. B. Alraddadi, N. C. Woolsey, J. Pasley
York Plasma Institute,
Department of Physics,
University of York,
York, YO10 5DD, UK

A. P. L. Robinson
Plasma Physics Group,
Central Laser Facility,
STFC Rutherford-Appleton Lab,
Harwell Oxford,
OX11 0QX, UK

1 Introduction

The creation of warm and hot dense plasma with a high degree of uniformity in temperature and density is one of the current aims of ultra- intense laser- plasma experiments. This uniformity is an important requirement in order to enable high quality high energy density plasma experiments to explore material properties such as opacity and equation of state [1]. Uniform isochoric heating is also needed for hydrodynamic experiments. In all cases, it is necessary to design the size of target to meet the requirements of a specific experiments and this is especially the case in the longitudinal direction.

Uniformity of heating in solid targets by laser-generated fast electrons should be distinguished in two directions; the transverse direction and the longitudinal direction (denoted w and L, respectively in Figure 1). The transverse direction (z) is where fast electrons move out of the beam axis. The longitudinal direction (x) is where the fast electrons move along of the beam axis. Heating in the transverse direction is known to be limited by the Weibel-like filaments instability [2] and transverse spreading of the fast electrons. Heating in the longitudinal direction is known to be limited by electric field inhibition [3] and by transverse spreading of the fast electrons which reduces the fast electron current density. The transverse spreading of the fast electrons in targets increases with the increasing width and thickness. Good transverse confinement can be obtaining electrostatically by making the target width and thickness comparable to the laser spot size, i.e. wire-like. Also, the fast electron transverse confinement can be obtained using structured resistive guiding [4-5]. These solutions mitigate the spreading of the fast electrons. It is thought that controlling the transverse spreading of the fast electrons in this way will lead to much better heating especially with reducing the target length to encourage fast electron refluxing [6].

In this article, we show that uniform heating is difficult to obtain even when these conditions for target design are met. We, also, propose another previously unidentified effect that impairs the uniformity of heating along the beam direction.

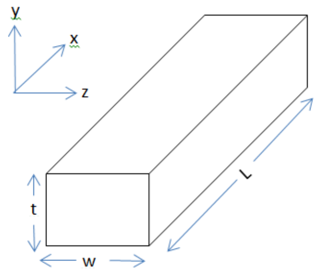

Figure 1: Target geometry, w refers to the width, t to the thickness and L to the length.

2 Controlling the transverse spreading of fast electrons

Consider a target as a wire in terms of geometry where both the width and thickness are of a comparable size to the laser spot. Simulations were performed using the 3D particle hybrid code ZEPHYROS [7 - 8]. Two different wire-like targets of Al are used as summarized in Table 1. The cell size in these simulations was 1 μm in each direction. The beam irradiation intensity was 1.27×10^{20} Wcm^{-2} and a pulse duration of 3 ps. It is assumed 30 % of the laser energy coupled to the fast electrons. A Gaussian function with FWHM of 5 μm defines the fast electron transverse profile. The fast electron angular distribution is a uniform over a solid angle define by the half-angle of divergence θ_d. The fast electron angular distribution is a uniform over a solid angle which is define by the half-angle of divergence θ_d. The energy distribution of the fast electrons is of the form $f(E) = exp[-E/T_f]$, where $T_f = 0.6T_{pond}$ is the fast electron temperature obtained from Wilks' ponderomotive scaling [9] and $T_f =$ 2.7 MeV. The minimum mean free path was taken as $5r_s$, where r_s is the interatomic spacing. The background temperature was set initially to 1 eV everywhere. The resistivity is described by the reduced Lee and More's model [10]. The main parameters, which are varied in the simulations, are summarized in Table 1.

Table 1: Table of simulation parameters

Target	target dimension (μm) ($w \times t \times L$)	θ_d (degree)
A	$27 \times 27 \times 200$	60
B	$15 \times 15 \times 200$	60
C	$27 \times 27 \times 200$	50

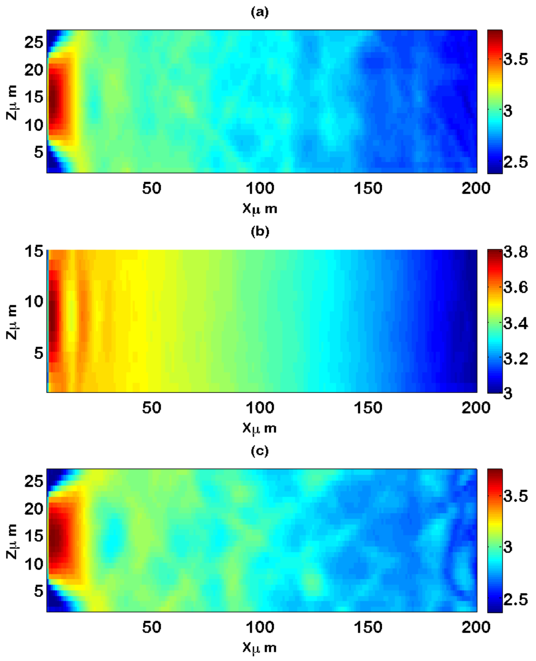

Figure 2: Plots of background temperature (eV) $\log_{10}$ in z-y midplane at 3.3 ps (a) target A, (b) target B and (c) target C. The horizontal (x) and vertical (z) axis are defined in Fig. 1

Targets A and B were used to explore the idea of fast electron transverse confinement. The ratio between the laser spot and the transverse width in these two targets is 1:3 and 2:3, respectively. Figures 2(a) and 2(b) show the background temperature plots in the mid y-z plane at 3.3 ps. The temperature is shown in a logarithmic scale. As shown, although the spreading of the fast electrons has been controlled, there is a clear non-uniform heating along of the beam axis (x-axis in Fig. 1) in A and B target geometries. One of reasons for this non-uniformity is the electric field inhibition proposed by Bell *et al.* [3]. This theory shows that the growth of an intense electric field would tend to confine a large number of the fast electrons near to the absorption region. This retards the fast electron beam, limiting penetration and target heating.

In addition, the fast electron half-angle divergence still has a role in heating even with a constrained target. This is can be seen in Figure 2(c) in the comparison with Figure 1(a) where the only difference between the two targets is the half divergence angle of 10°. It is clear that the heating uniformity along x-axis is different even with the same target dimensions. This suggests that there is another process, which is impairing the heating along of the x-axis due to the difference in divergence angle. We have named this effect angular rarefaction. This new term refers to the decay in the fast electron density due to angular spread. In the next section, we will explain this effect and show how will influence heating uniformity.

3 Theory of angular rarefaction

It has been experimentally shown that the fast electron source size is several times the laser spot size [11 -12]. The fast electrons have a significant angular spread which is characterized by a divergence angle θ_d. We have found that this angular spread of the fast electrons produces a longitudinal velocity spread $c\ cos\theta_d$ where c is the speed of light and because of this the fast electrons bunch is dispersed which we call "angular rarefaction". This effect has influence on the longitudinal heating uniformity for the following reasons:

Target heating is Ohmic heating via the return current. We take into consideration the rarefaction α induced by the angular spread of the fast electrons. This rarefaction increases with fast electron beam duration τ to $\alpha\tau$ where $\alpha > 1$ and it will decrease the fast electron density n_f according to flux conservation ($n_f \to n_f/\alpha$). Thus, the Ohmic-heating rate in the case of fixed resistivity becomes,

$$P_\Omega = \frac{\eta e^2 c^2 n^2}{\alpha^2} \tag{1}$$

where η is the resistivity, e is the electron charge, n_f is the fast electrons beam density. This implies that the rarefaction has a quadratic effect on the heating power. The change in the background energy density due to this effect is,

$$\Delta U_b = P_\Omega \tau = \frac{\eta e^2 c^2 n^2 \tau}{\alpha} \tag{2}$$

So the angular rarefaction increases the electron beam duration. However, due to the quadratic effect on heating rate, the overall heating falls linearly with rarefaction α. At a given time, we can estimate that the rarefaction as,

$$\alpha = 1 + \frac{t}{\tau}(1 - cos\theta_d) \tag{3}$$

and the rarefaction at a given distance where the divergence θ_d is small (and thus the rarefaction is slow) as,

$$\alpha = 1 + \frac{x}{c\tau}(1 - cos\theta_d) \tag{4}$$

From here the scale of fast electron penetration due to rarefaction is,

$$L \approx \frac{c\tau}{1 - cos\theta_d} \tag{5}$$

Thus, the scale of fast electron penetration is large if the divergence of the beam θ_d is small and the pulse duration determines the depth of the beam propagation.

To test this theory numerically, we performed a simulation in the case of small angular divergence 30° and short pulse duration 100 fs. The rest of the simulation parameters are as described in the previous section and the wire-like target has a geometry of $27 \times 27 \times 200\ \mu$m.

Figure 3 shows a time sequence plots of fast electron density.This figure shows a clear increase in the duration of electron beam lengths due to the fast electron spatial dispersion or angular rarefaction α. The quick decline in the fast electron density explains that the role of θ_d in producing longitudinal fast electron velocity spread. The rarefaction of fast electrons affects the heating uniformity as parameterised by equation (1).

The scale of fast electron penetration suggested in equation (5) can be seen in Figures 2(a) and 2(c). In these two figures the fast electrons flow further along the x-axis with lower divergence angle θ_d of the beam.

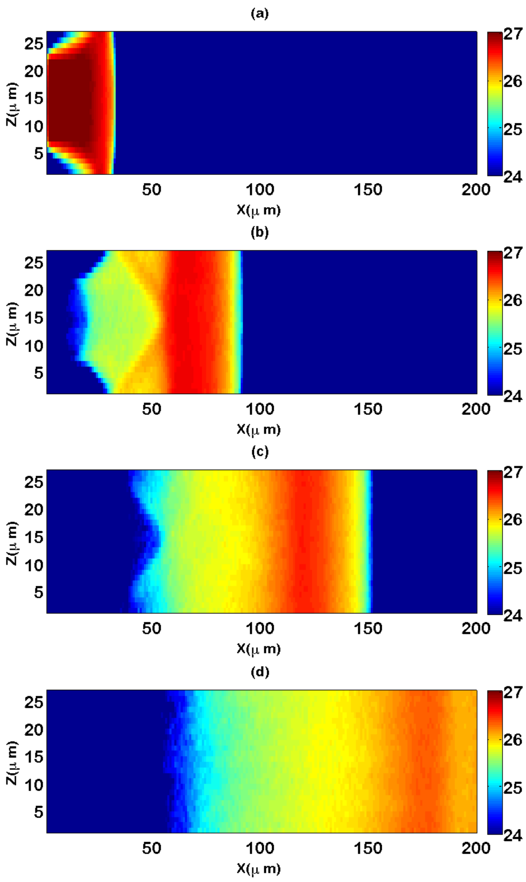

Figure 3: log_{10} fast electron density (in m^{-3}) (a) 100 fs (b) 300 fs (c) 500 fs and (d) 700 fs respectively in the mid y-z plane of simulation box. The x, y and z axis are defined in Fig 1.

4 Conclusion

We have shown the difficulty of obtaining uniform isochoric heating even in the case of excellent fast electron transverse confinement. Also, we have demonstrated the newly effect of angular rarefaction which impairs the uniformity of heating. The term "angular rarefaction" refers to the decay in fast electron penetration in the longitudinal direction due to the electron divergence. We found that fast electron divergence produces a longitudinal velocity spread that disperses fast electrons bunches. Currently, we are working to determine the importance of this newly effect in comparison with electric field inhibition.

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