Control of Wire Heating with Resistively Guided Fast Electrons through an Inverse Conical Taper

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The heating of a solid wire embedded in a solid substrate (of lower Z material) by relativistic electrons generated by ultra-intense laser irradiation is considered. Previously it has been noted that the initial angular distribution of the fast electrons is a highly important factor in the efficacy of the heating. We show, using 3D numerical simulations, that the addition of an inverse conical taper at the front of the wire can considerably improve the heating of the wire due to the reduction of the angular spread of the fast electrons which is caused by transport through the inverse conical taper.

I. INTRODUCTION

In this paper we consider the heating of a solid wire embedded in a lower-Z substrate by laser-generated fast electrons. In a number of previous studies it has been noted that the strong enhancement of magnetic field generation at the wire-substrate interface due to the resistivity gradient there leads to highly effective guiding and confinement of the fast electrons in the wire. Schemes which exploit the enhanced generation of magnetic fields where fast electron flows intersect resistivity gradients have been proposed for the Fast Ignition (FI) variant of Inertial Confinement Fusion (ICF).

Fast electron heating has already been used as a tool for studying the fundamental physics of warm and hot dense matter, and such controlled fast electron transport and heating may be useful for laser-driven x-ray production and for rapid heating of solid density materials for radiation hydrodynamics studies. It should also be noted that the role of resistivity gradients has been noted in other studies not specifically related to either specially engineered targets, or controlling resistive guiding.

Recently the authors carried out a systematic study of this configuration, which aimed to build on earlier work. In this recent study the importance of the laser wavelength, laser intensity, laser pulse duration, wire radius to laser spot radius ratio, materials, and fast electron angular distribution were all examined. Of all of these parameters most can be controlled experimentally, with the notable exception of the fast electron angular distribution. There is not yet a comprehensive theoretical understanding of the origins of the angular distribution of the fast electrons (despite extensive theoretical efforts, e.g.), nor is there a clear understanding of how to control it, even in a purely theoretical context.

Even if there is not a clear approach to changing the fast electron angular distribution in terms of the laser-plasma interaction, there may be a chance of controlling it through transport effects. To do this we propose using the conical guide structure that we first studied in a recent paper. Instead of coupling the inverse conical taper to a homogeneous target, we now couple it to a straight wire of constant radius. We refer to this combined structure as a wire with an inverse conical taper, and an illustration of the concept is given in figure 1 for the purpose of avoiding confusion. The conical guide element does not focus the fast electrons, instead it reduces the angular distribution of the fast electrons (in momentum space) at the expense of the fast electron beam expanding radially (in real space). Despite having to accept some radial expansion of the fast electron beam, and a corresponding fall in fast electron density, we show, using 3D hybrid simulations, that the use of this inverse conical taper on the embedded wire leads to a substantial improvement in heating of the wire.

II. THEORY

In this section we will summarize the key concept underlying the conical guide that was presented in. Consider what happens when a particle travelling at some angle, \( \theta \), to the \( x \)-axis impinges on a oblique, reflecting
wall that lies at angle $\alpha$ to the $x$-axis. This problem can be solved using elementary geometrical techniques. Alternatively one can use the vector law of specular reflection,

$$v = u - 2(u \cdot n)n,$$

and along with trigonometric identities one will determine that the angle of the reflected particles (with respect to the $x$-axis) is

$$\theta' = 2\alpha - \theta.$$  

Therefore if we consider a population of particles the effect of a conical inverse taper (which acts as a rigid reflecting wall) will be to produce an overall reduction in the angular spread. This comes at the expense of the beam increasing in radius and undergoing some longitudinal dispersion. If we now apply this to the case of fast electron transport, the boundary between the guide element and substrate has already been shown to act as a rigid reflector to a reasonable approximation, and where it does not those electrons escape the guide element and are lost (therefore being of no further concern). The inverse conical taper should therefore be beneficial, as it has previously been shown that better wire heating is obtained with fast electrons which are injected with a lower divergence angle. There are, however, the issues of beam expansion, longitudinal dispersion, and annular transport that need to be addressed.

Furthermore it should be noted that the argument presented above applies to a single bounce. We might imagine employing a long, low $\alpha$ inverse taper or a short, higher $\alpha$ inverse taper. Using the former configuration would appear to be better as given a distribution of angles, we know that the proportion of fast electrons that will undergo at least one bounce from the inverse taper is,

$$P_1 = \int_0^{\pi/2} \int_0^{\pi/2} g(\theta) \sin \theta d\theta d\theta,$$

where $g(\theta)$ is the angular distribution of the fast electrons. This implies that choosing a low $\alpha$ configuration means that a greater proportion of the population will have their angle reduced slowly over a few bounces. In a high $\alpha$ configuration, only the high angle electrons will be affected by a single bounce. High angle electrons will have their divergence angle reduced in the low $\alpha$ configuration too, albeit more bounces will be required. Clearly it is difficult to make simple estimates, hence the need to employ numerical simulation, and the results of a such a study will be reported in the following section.

### III. SIMULATIONS

#### A. Set-Up

Simulations were performed using the 3D particle hybrid code ZEPHYROS. The 'standard' run used was set up as follows: A $200 \times 200 \times 200$ grid was used with a 1$\mu$m cell size in each direction. The target consisted of a CH$_2$ substrate of 50$\mu$m thickness, within which a aluminium guide element was embedded. The guide element had the form of a wire with an inverse conical taper, and was collinear with the $x$-axis and centred on $y=z=100\mu$m. The initial radius of the inverse tapered segment was always 5 $\mu$m, and this increased over a distance, $d_{cone}$ up to 10 $\mu$m. For $x > d_{cone}$ the radius of the embedded wire was held constant at 10 $\mu$m. The half-angle of the inverse conical taper is therefore given by $\tan \alpha = 5/d_{cone}[\mu\text{m}]$. The background temperature was initially set to 1eV. The background resistivity was described by the model which closely follows Lee and More, but with the minimum electron mean free path taken to be $5r_s$, where $r_s$ is the interatomic spacing. The background fluid equation of state was based on the Thomas-Fermi model (this includes the ionization state). The temporal profile of the injected fast electron beam is a top-hat function of $\tau_L=1$ ps duration, and the transverse profile was also a top-hat of 5 $\mu$m radius. The injected fast electron beam models irradiation at an intensity of $I_L=1 \times 10^{20}\text{Wcm}^{-2}$, with the assumption of 30% conversion efficiency. The fast electron angular distribution was chosen to be a $\cos^2 \theta$ distribution thoughout. The fast electron temperature used was set according to the Ponderomotive Scaling proposed by Wilks,

$$T_f = 0.511 \left[ 1 + \frac{I_L \lambda_L^2}{1.38 \times 10^{18} \text{Wcm}^{-2}} - 1 \right] \text{MeV. (4)}$$

A total of eight simulations were carried out, and they are labelled A–H. Irradiation at wavelengths of $\lambda_L=1\mu$m or $\lambda_L=0.5\mu$m, were modelled in two different subsets, namely A–D (1 micron) and E–H (0.5 microns). Runs B and F were comparator runs in which a straight wire (of radius 10 $\mu$m) was used with no inverse taper. We have tabulated the details of each simulation in Table I, including the cone half-angle, $\alpha$.

#### B. Results

The principal results of these simulations are encapsulated in figure 2 where we plot the background electron temperature in electron-Volts at 1.5 ps in runs A–D, and

| Simulation | $d_{cone}$ ($\mu$m) | Wavelength ($\mu$m) | $\alpha^\circ$ |
|------------|---------------------|-------------------|----------------|
| A          | 57                  | 1                 | 5              |
| B          | n/a                 | 1                 | 0              |
| C          | 28                  | 1                 | 10             |
| D          | 100                 | 1                 | 2.9            |
| E          | 57                  | 0.5               | 5              |
| F          | n/a                 | 0.5               | 0              |
| G          | 28                  | 0.5               | 10             |
| H          | 100                 | 0.5               | 2.9            |
3 where the same plots are shown for runs E–H. Recall that runs B and F are the ‘comparator’ runs in which the wire has a constant radius of 10µm. It is clear from these figures that the runs that employ a low α inverse taper (i.e. A,D,E, and H) produce much better heating than both the comparator runs (B and F) and the high α runs (C and G).

FIG. 2. Plots of background electron temperature in eV at 1.5 ps in runs A–D.

FIG. 3. Plots of background electron temperature in eV at 1.5 ps in runs E–H.

This can seen in a more quantitative fashion if one compares the simulation results at 1.5 ps in terms of the average temperature in the region defined by $x > x_0$ and $r < 10 \mu$m (where $r$ is the radial distance from $y = z = 100 \mu$m). This was computed for each simulation and the results are tabulated in table II for $x_0 = 30$, 50, and 100 µm.

| Simulation | $T$ (eV) | $T$ (eV) | $T$ (eV) |
|------------|----------|----------|----------|
|            | $(x_0 = 30 \mu m)$ | $(x_0 = 50 \mu m)$ | $(x_0 = 100 \mu m)$ |
| A          | 158.6    | 145.4    | 114.5    |
| B          | 69.3     | 52.8     | 16.4     |
| C          | 102.6    | 80.9     | 34.7     |
| D          | 139.6    | 124.9    | 98.2     |
| E          | 483.8    | 453.1    | 378.3    |
| F          | 320.7    | 272.8    | 148.9    |
| G          | 431.3    | 384.7    | 260.4    |
| H          | 451.3    | 420.9    | 352.4    |

Table II shows that whatever volume is considered the low α inverse conical taper targets (A,D,E, and H) produce better heating in terms of the volume-averaged temperature than the straight wires and the high α inverse conical tapers (C and G). The biggest advantage occurs for $\lambda_L = 1 \mu$m and $x_0 > 100 \mu$m where a low α inverse conical taper can improve the volume average temperature by more than a factor of 5 compared to the straight wire. The advantage in terms of volume-averaged temperature is more pronounced in the case of the 1 micron wavelength simulations than the 0.5 micron wavelength simulations. The stronger heating in the 0.5 micron simulations was noted and explained in previous work. Yet another way to view the data in figures 2 and 3 in more detail is to look at line-outs of the background electron temperature along the $y = z = 100 \mu$m line. This is shown in figure 4. From this perspective it can be seen that the low α inverse conical tapers (A and D) produce substantially better heating all along this line, however the heating at depth (>100µm) is very much enhanced in runs A and D.
In addition to looking at heating in terms of spatial averages or line-outs, one can see from figures 2 and 3 that the heating in the radial direction of the wire is much more even in the case of the low $\alpha$ inverse conical tapers (A,D,E, and H) than either the reference wires (B and F), or the high $\alpha$ inverse conical tapers. The high $\alpha$ inverse conical tapers (C and G) in particular seem to produce an annular transport pattern that leads to heating the outer surface of the wire. In some cases this may be a sought-after effect, but in terms of attempting to produce as uniform heating as possible this is clearly not desirable. Having considered the background electron heating from several perspectives, we would argue that it is clearly the case that the low $\alpha$ inverse conical taper targets lead to substantially better heating of the wire.

We attribute the clear improvement in heating to the reduction in the angular spread of the fast electron beam by the inverse conical taper, which our original paper on the inverse conical taper concept was primarily concerned with. In our study of the embedded wire configuration we had previously identified the fast electron angular spread as an important factor, which much better heating being obtained with a lower angular spread. This is due to the improvement in confinement of fast electrons in the wire that comes from having a lower angular spread at injection. Although the result presented here might be suspected or inferred from our previous work, here we have presented actual numerical simulations which verify this inference.

IV. CONCLUSIONS

In this paper we have investigated the effect of adding an inverse conical taper onto an embedded wire target. These embedded wire targets have previously been shown to strongly confine and guide fast electrons due to the enhanced growth of magnetic field at the interfacial resistivity gradient. In previous work the authors had studied the heating of embedded wire targets and found that reducing the angular spread of the fast electron source would lead to enhanced wire heating. As it is not clear how to achieve this through manipulating the laser-target interaction, the inverse conical taper was considered, as in previous work we had shown that a conical guide target could reduce the angular spread of fast electrons purely by exploiting the geometry of specular reflection.

Three dimensional hybrid simulations were carried out to evaluate the potential of these embedded wires with inverse conical tapers as compared to an embedded wire of constant radius. The simulation results clearly show that the addition of an inverse conical taper can substantially enhance the heating of the wire, particularly the heating very far from the fast electron source. Furthermore we conjectured that low $\alpha$ (low angle), long inverse conical tapers would be preferable to high $\alpha$ (high angle) inverse conical tapers. The numerical simulations confirmed this conjecture, producing better heating as well as producing a uniform fill in the radial direction, whereas the high $\alpha$ cases produced an annular transport pattern.

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