Shrinking the Angular Distribution of Fast Electrons via Wires with an Inverse Conical Taper

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Abstract
We report on our recent studies of targets that exploit resistivity gradients to guide fast electrons and which incorporate an inverse conical taper. This perhaps the simplest geometry that is interesting in terms of its ability to reduce the angular spread of the fast electrons. We also show how this can be applied to wire heating and the remarkable improvement that including even a slight inverse conical taper can yield.

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1. Introduction

In this report we provide a summary of work [1, 2] that we have carried out in the last period on controlling fast electron beams using magnetic fields that are resistively self-generated, primarily at resistivity gradients engineered by target construction. This area of study is important for advancing the Fast Ignition variant of ICF, as well as developing fast electron heating as a tool for HEDP, and advancing x-ray generation from fast electrons in solid targets.

The motivation behind this work was to find the most simple geometry in which we could reduce the transverse angular distribution of a fast electron beam. Previously we had considered semi-ellipsoidal targets which are relatively complex. A conical structure is sufficient to shrink the transverse angular distribution, but a conical structure will not have the focussing properties that the ellipsoidal configuration has. Despite the lack of a focussing capability, the ability to shrink the transverse angular distribution in a relatively simple configuration is of quite considerable interest due to the implications this has for target heating and x-ray generation.

2. Core Idea

Why would a conical configuration shrink the transverse angular distribution of a fast electron beam? The configuration that we are considering is a wire with a truncated inverse conical taper, with the fast electron source located at the tip, so that the radius of the cone expands as the fast electrons propagate down the cone. This is shown in figure 1 below.

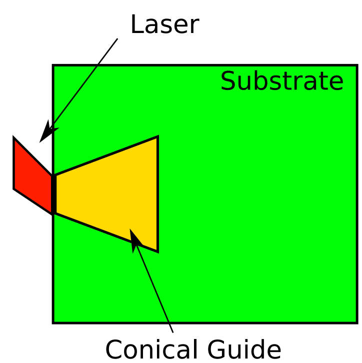

Figure 1. Schematic plot of Wire with Inverse Conical Taper

Suppose that a flow of fast electrons leads to sufficiently strong growth of azimuthal magnetic field around the conical structure such that the magnetic field becomes specularly reflecting to all fast electrons. The fast electrons will effectively undergo reflections from an oblique plane, and, as figure 2 shows,

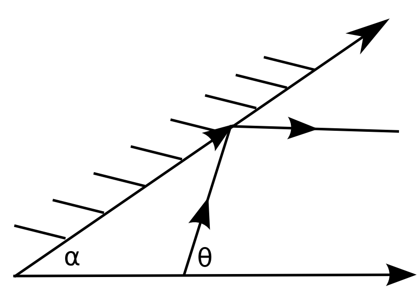

Figure 2. Schematic plot of reflection from oblique plane.

this implies that the fast electron's angle with respect to the guide axis will be reduced. The angle after a single collision can be deduced from the vectorial law of specular reflection,

$$\mathbf{v} = \mathbf{u} - 2(\mathbf{u}.\hat{\mathbf{n}})\hat{\mathbf{n}}, \tag{1}$$

where $\mathbf{v}$ is the reflected velocity vector, $\mathbf{u}$ is the incident velocity vector, and $\hat{\mathbf{n}}$ is the unit normal to the reflecting plane. It can also be deduced by treating the problem as a plane geometry problem, either way the result is that the propagation angle (with respect to the guide axis) after a single collision is,

$$\theta' = 2\alpha - \theta, \tag{2}$$

where θ' is the post-reflection angle, θ is the initial angle, and α is the half-angle that the conical guide subtends. So each collision reduces the propagation by twice the angle the cone walls make to the propagation axis. This means that quite a gentle inverse taper (say 5-10°) could be highly effective provided that the fast electron can make a few reflections before it leaves the conical guide.

3. Key Findings from Numerical Studies

We have carried out a number of simulations to study the wire with an inverse conical taper using the ZEPHYROS 3D particle-based hybrid code which has been used in a number of previous studies. The precise simulation parameters used in these different studies has varied, and the details can be found in the relevant publications [1, 2]. In most simulations we have used a 200×200×200 domain with either a 0.5 or 1 μm cell spacing in each direction. We have used either a carbon or aluminium guide element embedded in a CH substrate. The fast electron injection was set up to model 10^{20}Wcm^{-2} irradiation at 0.5–1 μm wavelength for around 1 ps. Often a $\cos^2\theta$ distribution was used as the angular distribution. In some other cases we used a uniform angular distribution up to a cut-off at 50° half-angle.

3.1 Reduction of Angular Distribution

In figure 3 we show a set of angular distributions of fast electrons from a set of simulations reported in [1]. The runs (A and B) with small gradient (5° and 10°) inverse conical tapers should be compared to runs E and F (straight wire and plain CH).

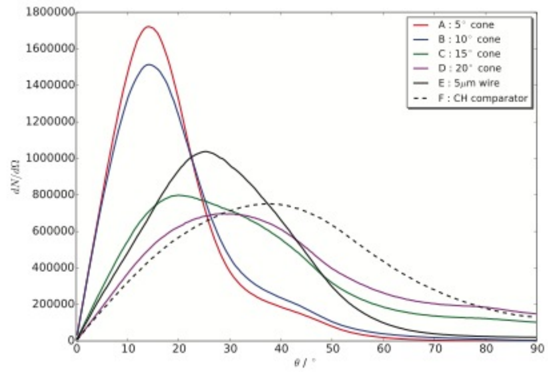

Figure 3. Angular distribution of fast electrons from different simulations in [1]. Legend indicates type of guide element used in each simulation. Distributions are calculated at 3 ps (substantially after end of injection).

It is very clear from this comparison that the inverse conical taper can drastically reduce the angular distribution of the fast electron beam, as we predicted based on assuming specular reflection. The reduction in the angular spread in the straight wire can be attributed to escaping electrons. These escaping electrons will leave the wire but experience some reduction in divergence in doing so. In terms of the average angle, when a a $\cos^2\theta$ distribution was used the average angle at late time was about 24.1-27.2° which should be compared to 38.2° for the injected distribution, and 35.8° for the straight wire simulation. We can therefore see that the reduction in angular spread in the small gradient inverse conical tapers is really quite substantial.

3.2 Effect on Wire Heating

In figure 4 we present some results reported in [2]. These are simulations done with different wire targets with/without conical tapers. Runs A,C, D have inverse conical tapers with half-angles of 5,10, and 2.9 degrees respectively. Run B has no inverse tapering, i.e. it is just a 'straight' wire. In all other respects the simulations are carried out under the same conditions — fast electron injection, material resistivity, etc.

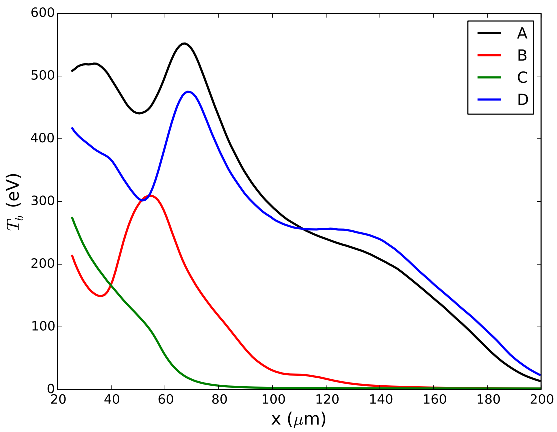

Figure 4. Lineouts (along guide axis) of background electron temperature (eV) in simulations with different wire targets with/without inverse conical tapers.

Figure 4 shows that there are very substantial differences in wire heating which depend purely on the wire geometry. The low-angle inverse conical tapers are vastly better at heating deep down the wire than either the straight wire or the wire with a large angle inverse conical taper. We attribute this to the reduction in angular spread making it much easier to confine more fast electrons in the wire. The large angle inverse conical taper (run C) is subject to an annular transport pattern occuring, which means one should be careful about interpreting figure 4 in this respect. Nonetheless the ability of the inverse conical taper to affect the wire heating is remarkable and is clearly demonstrated by these simulations.

4. Conclusions

In this brief report we have highlighted some of the principal results from a study of targets exploiting guiding based on resistivity gradients that incorporate an inverse conical taper. We have shown that this geometry has a strong ability to shrink the angular distribution and to improve the heating of the wire.

5. Acknowledgements

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References

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[2] A.P.L.Robinson, H.Schmitz, J.S.Green, C.P.Ridgers, N.Booth, and J.Pasley. Control of wire heating with resistively guided fast electrons through an inverse conical taper. *Phys.Plasmas*, 22:043118, 2015.