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Effect of reentrant cone geometry on energy transport in intense laser-plasma interactions


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The energy transport in cone-guided low-Z targets has been studied for laser intensities on target of 2.5 \times 10^{20} W cm^{-2}. Extreme ultraviolet (XUV) imaging and transverse optical shadowgraphy of the rear surfaces of slab and cone-slab targets show that the cone geometry strongly influences the observed transport patterns. The XUV intensity showed an average spot size of 65 \pm 10 \mu m for slab targets. The cone slabs showed a reduced spot size of 44 \pm 10 \mu m. The shadowgraphy for the aforementioned shots demonstrate the same behavior. The transverse size of the expansion pattern was 357 \pm 32 \mu m for the slabs and reduced to 210 \pm 30 \mu m. A transport model was constructed which showed that the change in transport pattern is due to suppression of refluxing electrons in the material surrounding the cone.

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The cone-guided fast ignition inertial fusion concept uses a hollow gold cone to keep a channel clear from plasma generated in the compression of a deuterium-tritium fuel-filled capsule to high density. At peak compression, a PW laser pulse is then focused into the cone tip and generates copious numbers of hot electrons that travel into the dense fuel and deposit their energy. Ideally the electron beam must be collimated so that all the useful energy can reach the fuel and deposit their energy. Ideally the electron beam must be collimated so that all the useful energy can reach the fuel and deposit their energy. Ultimately, it is possible to guide and collimate MeV electrons without an attached hollow Au cone, there was a lateral spreading of the fast electron beam (as measured by imaging a Cu \(\text{K}\alpha\) emission region) in the case of cone-attached geometry. On the other hand, Kodama et al. [6] showed that, by irradiating a solid 200-\mu m-thick Al slab and a solid cone (30° full angle) attached to 10 \mu m foil, the optical thermal emission (which is directly proportional to the black-body temperature) increased by more than a factor of three in the case of the solid cone slab.

Here we employ targets to show that reentrant cone geometry strongly influences the observed transport pattern in absence of electron refluxing. It is thought that the extra material surrounding the cone suppresses refluxing of the hot electrons inside the target, thus reducing the heated area at the back surface. This experiment is highly relevant to fast ignition since refluxing is not important for transport in that case. A two-dimensional (2D) refluxing model reproduced the size and temperature of the heated region. In the case of these targets, there was no need to invoke “guiding” in order to explain these results.

In this Rapid Communication, the targets were irradiated with petawatt laser pulses from the Vulcan laser facility [7]. The targets were designed to eliminate the vacuum region on the outside of the cone. This is more similar to the intended situation in fast ignition inertial fusion where plasma formed on the outside of the cone supplies the return current, allowing the fast electron beam to more freely propagate.

Diagnosing the physics of the laser interaction inside of the cone is difficult due to the closed geometry. To overcome this limitation, a comparison of energy transport from a cone-slab geometry to planar slab geometry was made, as
The thickness of the interaction region in both target types were substantial energy in the wings out to 60 Å.

Fujifilm BAS-MS imaging plates were placed at distances of 12.5 and 25 cm from the interaction region, respectively. The cone tip width was 30 µm. The average peak counts number was 12. Interferograms show a cutoff density of 5 × 10^{19} cm^{-3}.

Shadowgraphs of the slab and cone-slab interactions are presented in Figs. 2(a) and 2(b). The shadowgraph of slab without cone geometry shows regular expansion pattern of transverse size 357 ± 30 µm. The shadowgraph of cone-slab geometry shows a smaller transverse region of expansion of size (average) 210 ± 30 µm although the longitudinal extent is approximately the same as the slab.

XUV images at 256 eV were obtained for targets with and without CH cones attached (see Figs. 3(c) and 3(a), respectively). When plane slabs were irradiated both at 0° and at 43° there was a clear ring structure visible in the heated region on the rear surface. The full width half maximum (FWHM) of a lineout of intensity through the center of the image in the vertical direction was an average of 65 ± 10 µm. When the cone slabs were irradiated the ring structure disappeared and instead the arbitrary intensity peaked on axis with an average FWHM of 44 ± 10 µm. The average peak counts (which is proportional to maximum temperature [12]) for the slab with no CH cone was 2 × 10^{13} and with CH cone 2.5 × 10^{13}, which is not a significant difference.

The lateral decrease in size seen in the shadowgrams is in agreement with the XUV data. Since the peak counts in the slab and the cone-slab case are similar, this agrees well with the similar longitudinal extent of the expansion in both cases observed in the shadowgraphy.

X-ray emission spectra were obtained for these shots. An example is shown in Fig. 4. The measured x-ray spectra show Ly-α, He-α, He-β, and He-γ Al resonance emission lines. The spectra were analyzed using a model that combines collisional-radiative atomic kinetics with spectroscopic quality radiation transport and Stark line-broadening effects.
EFFECT OF REENTRANT CONE GEOMETRY ON ENERGY... PHYSICAL REVIEW E 80, 045401(R) (2009)

FIG. 3. XUV images of 4 μm/0.2 μm/4 μm CH/Al/CH slab targets without (a) and with (c) a plastic guide cone attached. Figures (b) and (d) are the lineouts taken from the images.

...and with experimental data it was possible to estimate typical values of plasma conditions present during the observed line emission. Previous work shows that time integrated measurements can provide similar temperature information to time resolved [14].

The calculated spectra were normalized to the He-α resonance line and temperature and density were chosen to match the intensity of the Ly-α line. Based on this analysis, it was possible to infer characteristic temperature and density conditions of 610±50 eV and 1×10^{24} el./cc with the cone attached to the target and 790±50 eV and 7×10^{23} el./cc without the cone. In these calculations it was not possible to simultaneously reproduce the satellite emission lines on the red wings of the He-α and Ly-α lines. This can be attributed to the fact that the measured spectra are space and time integrated. The He-β and He-γ line were also not reproduced using this method alone. More detailed atomic physics calculations were required to reproduce these lines and are not discussed here. This will be the subject of a future publication. The difference in temperature between the two target types could arise due to the fact that there is simply more material to heat in the case of the reentrant cone geometry. Having more material also changes refluxing of fast electrons and therefore the heating of the target. In thin targets electrons can make many passes before the end of the laser pulse. However, the reentrant cone geometry has a large amount of material either side of the interaction region which would prevent refluxing.

The unusual ring structure observed in Fig. 3(a) is unlikely to be the beam hollowing [15]. This is because the rapid rise in temperature reduces the resistivity. In the case of resistivity decreasing with temperature the hollowing effect is counteracted. A similar ring structure has been observed in soft x-ray images of buried layer targets previously published by Koch et al. [16]. From their detailed discussion, they suggest that it is a Weibel-like instability driven development of an annular pattern. This could be on explanation for the ring structure observed here in this work. The transport pattern behavior with and without cone geometry was repeatable for all shots using such targets. The Annular/ring structures were consistent both within this experiment and on subsequent experiments using the same laser with similar targets.

In order to assess the effect of refluxing electrons on the heating pattern on the target’s rear surface we have constructed a simple 2D model which assumes, for simplicity, that the laser-produced fast electrons propagate out of the absorption region in a conical beam. We assume that the beam propagates ballistically out of the absorption region and is specularly reflected at the rear surface. The reflected backward propagating beam can then be allowed to specularly reflect at the target front surface and propagate back through the target with a reduced current density. This process may be repeated an arbitrary number of times to include the effect of multiple beam refluxing.

Each successive (Nth) beam can be thought of as propagating from the origin of its own spherical coordinate system (r_N, θ_N, ϕ), with θ as the polar angle and azimuthal symmetry is assumed. If ϕ is the beam divergence angle, then the current density of the Nth beam will be:

\[ j_N = j_0 \left( \frac{R}{r_N} \right)^2 U(\phi - \theta_N), \]

where U is the unit step function and J_N is a normalization integral. R is the distance from the beam focal point to the beam edge on the front surface.

The total current density along the rear surface \( j_r \) =∑_N j_N \sin θ can be found by summing the above equation over N. The factor of 2 in the expression for \( j_r \) arises because the transverse components of the reflected and incident electron fluxes are in the same direction (while the longitudinal fluxes are antiparallel and therefore cancel at the rear surface).
If we next assume that the dominant heating mechanism of the background electrons is joule heating by the resistively-induced electric field due to the net beam current, then the temperature on the rear surface will be given by the solution to the simple energy equation $\frac{\partial T_e}{\partial t} = -\nabla \cdot (\eta(T_e) \nabla T_e)$, where $n_e$ is the electron density, $T_e$ is the electron temperature, and $\mathbf{E} = \eta(T_e) \mathbf{j}$, with $\eta(T_e)$ as the resistivity. Since the target is initially cold, Spitzer resistivity does not apply and we use the hybrid resistivity described in [17] to obtain a numerical solution to the above equation. It was assumed that: the initial beam radius was 5 $\mu$m; the beam divergence angle was 60°; the current density at the target front surface due to laser-accelerated fast electrons was $=4 \times 10^{16}$ A m$^{-2}$; the beam duration was 500 fs and the target was composed of 8- $\mu$m-thick solid CH with an average ionization of $Z = 3.5$. The solution is plotted in Fig. 5, which shows two cases: the first assumes the beam undergoes ten successive forward-and-backward passes through the target, which represents the case of a thin isolated target; the second assumes only a single forward-and-backward pass, which represents the cone target, which is able to absorb any electrons passing back to the front surface. The two different heating patterns in Fig. 5 match aspects of the experimental observations: the cone target has a somewhat lower peak temperature and limited radial extent, while the isolated target shows a higher peak temperature and significantly wider radial extent because the multiple refluxing leads to more heating over an extended area. Thus, this model suggests that the reason for the reduced temperature and radial extent of the heating pattern on the rear surface of cone targets is due to the absorption by the cone material of refluxing fast electrons, which prevents multiple refluxes. This situation is much closer to the transport physics of fast ignition cone-shell implosions. In conclusion, for these specific target geometries the data can be explained completely by changes in refluxing of the fast electron beam. Despite the fact that the energy of the laser was contained within a 60 $\mu$m spot (including the wings) and the tip of the cone was 30 $\mu$m (conditions conducive to guiding according to theory), there was no reason to invoke guiding of the electron beam due to self-generated magnetic and electric fields.

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