Effect of cone-guiding on energy transport in plastic targets containing an Al signature layer

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Introduction

The effect of the target geometry on fast electron energy transport in intense laser-plasma interactions is a topic of intense study and interest at the present time[1]. The cone-guided fast ignition concept uses a hollow gold cone to keep a channel clear from plasma generated in the compression of the deuterium-tritium fuel so that a multi-PW laser pulse can be focused at the cone tip. The laser-plasma interaction there generates copious numbers of hot electrons which subsequently travel into the dense fuel and deposit their energy via classical and collective stopping processes. In addition, it has been shown that, using cone-fiber geometry, it is possible to guide and collimate MeV electrons along a thin carbon fiber plasma, thereby generating (potentially) Gbar plasma pressures for equation of state studies[2].

The success of these cone-guided experiments at Osaka University has prompted a theoretical study into the effects of the target geometry. Sentoku *et al*., for example, used a three-dimensional particle-in-cell code and showed that the laser light can be focused to a greater intensity, provided that the tip width is the same size as the laser focal spot[3]. The resulting hot electrons converge to the tip due to surface electron flow guided by magnetic and electric fields.

In this report, novel targets were irradiated with petawatt laser pulses from the Vulcan laser facility to measure the effect of the cone geometry on energy transport inside the target. A comparison of energy transport from cone-slab geometry to plane-slab geometry was made using Al X-ray spectroscopy of a buried signature layer and XUV imaging of the rear surface of the irradiated targets. It was found that, by adding a cone, the transport pattern changed from being annular in structure in slab geometry to being circular when the cone was added. The background electron temperature derived from Al X-ray emission spectroscopy decreased with the addition of the cone, although the absolute XUV emission brightness remained the same between the two cases, suggesting that the heating was more long lived in the cone-attached case. Equally important, it was found, for the first time, that the Al He-β, and He-γ emission lines in both cases were much brighter than expected when compared with collisional-radiative atomic physics models where the electron thermal distribution is assumed to be Maxwellian. A new atomic physics model has been constructed that is able to qualitatively reproduce the enhanced emission of these resonance lines.

The Vulcan petawatt laser delivered up to 300 J of $\lambda = 1.05$ µm light on to target in a pulse duration of 700 fs. The laser was focused on to target using an F/3 off axis parabolic mirror to a spot size of 7 µm diameter. Approximately 30% of the energy was contained within the central focal spot giving peak intensities up to 5×10^{20} Wcm^{-2}. The ASE of the laser was 5×10^{-8}, 1.5 nanoseconds ahead of the interaction pulse. The laser was incident on to target at an angle of 43° and for the cone geometry the laser was incident normally to the tip surface. Buried layer targets consisted of 4 µm CH, 0.2 µm Al, 4 µm CH. A number of targets had CH cones of 40° flare angle attached to the front surface. The cone tip width was 30 µm, i.e. much larger than the laser focal spot size of 7 µm.

A CsAP conically curved X-ray crystal spectrometer was used to record x-ray spectra from the heated Al layer[4]. The spectrometer operated in the wavelength range 6.2 to 8.4 Angstroms. The center of the crystal and the imaging plane were placed at distances of 12.5 cm and 25 cm from the interaction point, respectively. Fujifilm BAS imaging plates were used to record the spectra as this has a approximately flat spectral response over this range. The image plates were read using a Fuji Film BAS 180II reader [5]. The heated region at the rear surface was imaged using XUV radiation emitted at 68 eV and 256 eV. The radiation was focused using spherical multilayer mirror onto a Princeton Instruments 16-bit charge coupled device (CCD) camera. The magnification was 12 and the spatial resolution was 10 µm.

XUV images were obtained for targets with and without CH cones attached. When plane slabs were irradiated both normally and at 43° there was a clear ring structure visible in the heating pattern on the rear surface. The full width half maximum (FWHM) of a line-out through the center of the image in the vertical direction was an average of 70 µm. When the cone/slabs were irradiated the ring structure disappeared.

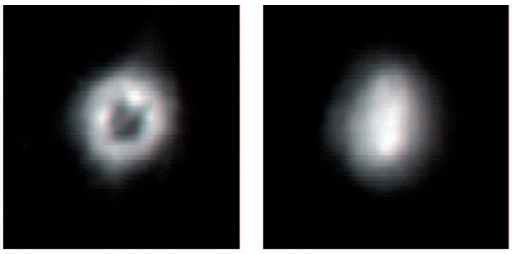

Figure 1. Rear surface imaging at 256 eV of a plane CH/Al/CH foil irradiated slab (left) and a plastic cone-attached CH/Al/CH slab (right).

Aluminum spectra were obtained for these shots. 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[6]. By calculating synthetic spectra for single temperature and electron density and comparing with experimental data it was possible to estimate typical values of plasma conditions present during the observed line emission. The results of this analysis are shown in Figures 2 and 3.

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 eV and 1×10^{24} cm^{-3} with the cone attached to the target and 790 eV and 7×10^{23} cm^{-3} 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.

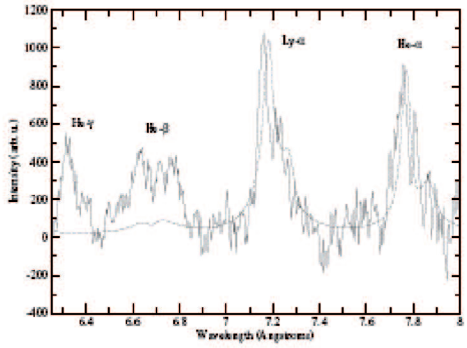

Figure 2. Comparison of measured and calculated spectra for target with a cone guide attached. The fitted temperature is 790 eV.

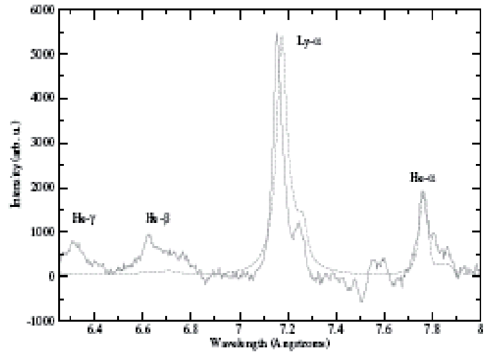

Figure 3. Comparison of measured and calculated spectra for the free standing target with no cone guide attached. The fitted temperature is 610 eV.

The same argument cannot be used to address the discrepancy between the calculated and observed intensities of the He-β and He-γ spectral features; regardless of the selected single temperature and density conditions, the He-β and He-γ lines never become stronger than the He-α line. This behaviour was seen in previous experiments in which the high electron densities result in a broadening of these two lines which strongly reduces their peak intensities. In the experiment reported here, the laser intensities are two to three orders of magnitude higher which opens the possibility of additional effects leading to the strongly enhanced He-β and He-γ lines.

The non-local thermodynamic equilibrium (non-LTE) code GALAXY was used to investigate the Li-like hollow ions of the type *2l 2l' 2l''*, *2l 2l' 3l''*, and *2l 2l' 4l''*, as possible channels through which the upper levels of He-β and He-γ lines could obtain additional population [7]. However, the overall population distribution remain essentially the same and therefore a development of a new spectral model that can account for possible new physics at higher laser intensities is therefore warranted.

To this end, a collisional-radiative atomic kinetics model has been constructed that considers the effects of both the Li-like hollow atom states and nonthermal electron distributions[8]. It is proposed that these bound states, in conjunction with nonthermal electron distributions, could serve as a conduit to observed enhanced emission of He-β and He-γ lines.

The effects of self-absorption have also been included in the calculation of the spectra[9]. As has been shown before, opacity effects can significantly reduce intensities of these lines even in much thinner Al layers (25 nm) than used in present experiments (200 nm)[6]. Strong self-absorption in the He-α line reduces its intensity to the point that the He-β line intensity becomes comparable to it, which is similar to the trends seen in the experiment. The He-γ is also enhanced when compared to the He-α line.

The atomic structure and process data were calculated with the Flexible Atomic Code (FAC). Al ions from fully-stripped through the Li-like are included in the model. The H-like ion contains excited states up to $n=5$, in the He-like ion all states with n up to 5 for both electrons (i.e. both singly and doubly-excited states). The same $n=5$ limit is applied to all three electrons in the Li-like ion, which therefore include doubly and triply excited ("hollow atom") states.

The code qualitatively reproduces the observed spectra, with the assumptions of steady-state conditions with a "cold" electron temperature of 100 eV, an electron density of 1×10^{22} cm^{-3}, and without a "hot" 800 eV electron component.

Further analysis is underway, in particular a more precise calculation of the return current distribution using Vlasov-Fokker-Planck methods[10].

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