Hot dense matter creation in short-pulse laser interaction with tamped foils

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Introduction

The possibility of producing hot dense matter has important applications for the understanding of transport processes in inertial confinement fusion (ICF)[1] and laboratory astrophysics experiments[2]. While the success of ICF requires the correct solution of a complex interaction between laser coupling, equation-of-state, and particle transport problems, the possibility of experimentally recreating conditions found during the ignition phase in a simplified geometry is extremely appealing.

In this paper we will show that hot dense plasma conditions found during ICF ignition experiments can be reproduced by illuminating a tamped foil with a high intensity laser. We will show that temperatures on the order of kiloelectronvolts at solid densities can be achieved under controlled conditions during the experiment. Hydrodynamic tamping by surface coatings allows to reach higher density regimes by enabling the diagnosis of matter that has not yet begun to decompress, thus opening the possibility of directly investigating strongly coupled systems[3]. Our experimental diagnostics is based on K-shell spectroscopy coupled to x-ray imaging techniques. Such techniques have recently become prevalent in the diagnosis of hot dense matter[4]. By looking at the presence, and relative strengths, of lines associated with different ionization states, spectroscopy provides considerable insight into plasma conditions. At the same time, curved crystal imaging techniques allow for the spatial resolution of different regions of the target, both allowing for comparison of heating processes with the results of Particle-In-Cell (PIC) and hybrid simulation codes.

Experiment

The experiment described in this paper was carried out in Target Area West of the Vulcan laser facility at the Rutherford Appleton Laboratory (UK). We have irradiated tamped solid foils, using the chirped pulse amplified (CPA) arm of the Vulcan laser delivering ~85 J of 1.053 µm light in either 1.5 or 10 ps pulse length. The beam was focused down to a 10 µm diameter spot by a f/3 parabola. Focused intensities were on the order of 3×10^{19} W/cm^2. The targets (see Fig. 1), consisting of a square 5 µm thick Ti sandwiched on each by either 1 µm Al or 2 µm CH, were mounted such that their normal was 30° from the laser axis, to prevent back reflections onto the laser system. Two target sizes were used, 250×250 µm^2 or 1×1 mm^2 squares. The targets were formed by coating the tamper onto the surface of the Titanium foil such that no glue was used between the layers.

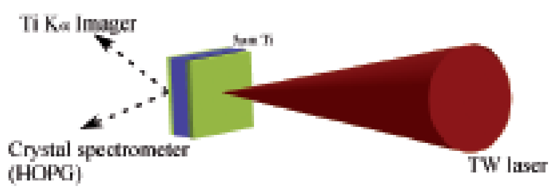

Figure 1. Experimental setup.

A flat highly oriented pyrolytic graphite (HOPG) crystal[5] coupled to a FujiFilm image plate detector[6] viewed the back emission from the target in the 4-6 keV region. A spherical quartz crystal, also coupled to an image plate detector, was used to spatially image the narrowband 4.51 K-α Ti emission[7] from the rear surface of the target.

Results and Discussion

The measured Ti K-shell emission from the Al-tamped target is shown in Fig. 2. The units of intensity have been linearized to units of PSL[8], where PSL represents radiation dose stored in the image plate. It is worth noting that the presence of He-like lines indicates temperatures >300 eV.

Since the short pulse duration was much less than that over which significant hydrodynamic motion, changes in density during the interaction can be reasonably ignored. However, given the targets were only a few microns in thickness, the role of a pre-pulse (i.e., the presence of pedestal and nanosecond laser emission ahead of the primary pulse) in determining the target conditions was expected to be significant. The pre-pulse was measured to be ~106 times less intense than the primary pulse with a flat-top duration of 0.5 ns.

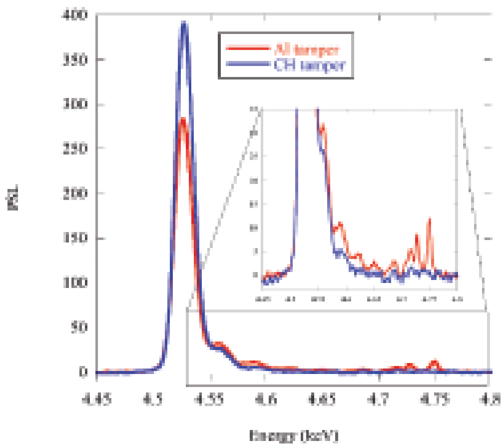

Figure 2. Experimental spectra showing various K-shell ionization states (from cold Kα at 4.51 keV to He-like 4.75 keV) resulting from the target tamped with 1 µm Al and from the 2 µm CH tamped target. Both targets were 250×250 µm² in size. The laser pulse length was 1.5 ps.

The prepulse interacts with the Al or CH layer and launches a shock wave that propagates through the target thus causing the densities to rise above those for solid titanium (Fig. 3). The tamping layers were designed to limit expansion of the Titanium after the shock passes, but some hydrodynamic motion of this central region was expected. HELIOS[9], a 1-D radiation-hydrodynamics code was used to estimate the conditions at the moment of the short pulse interaction. Fig. 3 shows that the bulk of the Titanium is compressed to approximately 6 g/cc.

When the main short-pulse arrives, hot electrons are generated at, or around, the critical surface. From the simulation we see that the critical surface is situated around 15 µm away from the ablation front at the moment the peak of the pulse reaches the target. The beam of hot electrons produced by the short pulse is expected to be contained within a 15° cone[10].

To estimate the temperatures to which the plasma was heated by the hot electrons, the experimental spectra have been compared to the predictions of SCRAM a collisional-radiative atomic physics package[11], showing that electron temperature in excess of 1 keV are consistent with the appearance of the He-α line. Our spectra calculations have simplified the pre-plasma conditions by describing the target as two slabs of differing density – one to mimic the compressed / solid density region, and the other to the decompressed portion. The two densities employed were 6 and 2 g/cc respectively. As shown in Fig. 2, the Ti He-α from the rear surface was observed only with Al tamper and none with the CH tamper. This suggests lower peak temperatures obtained with CH tamper, indicating a less efficient coupling of the electron beam onto the solid Ti. Due to the presence of the prepulse, the front, Al or CH layer is heated up to 20-60 eV (see Fig. 2), thus destroying, when the main short-pulse arrives, any possible difference in hot electron transport due to conduction/valence band or solid state effects.

Spatially resolved K-α images of both Al and CH tamped targets are shown in Fig. 4. Since the K-α emission is directly proportional to the hot electron number, these

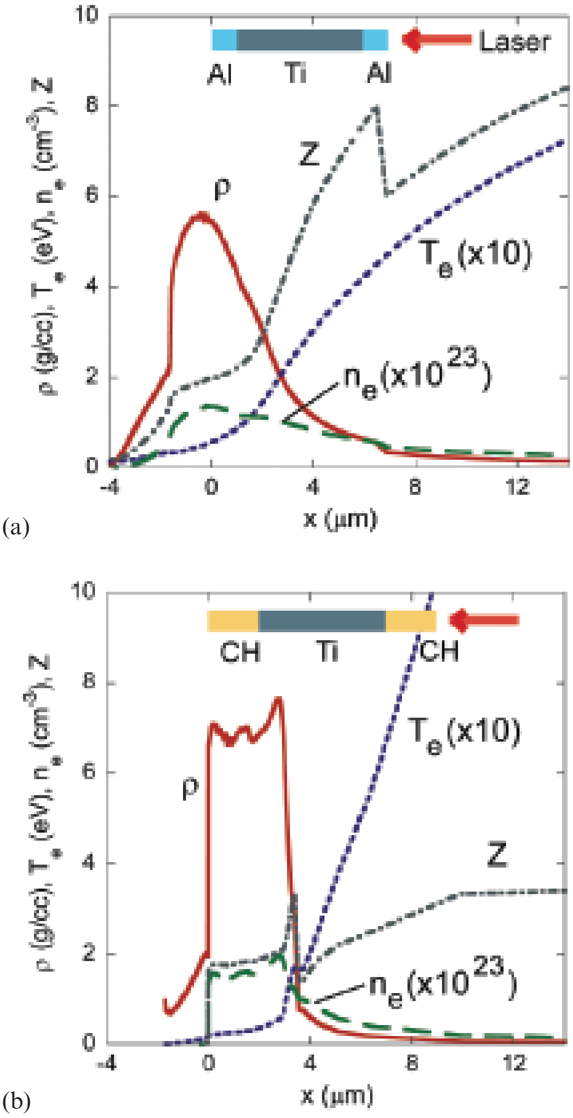

Figure 3. Simulation results of plasma condition of Al tamped target (a) and CH tamped target (b), arising from the 30 TW/cm² pre-pulse just before the arrival of the main short-pulse.

images are indicative of the hot electron spreading at the rear surface. The measurement indicates that in the case of CH tamped target the hot electrons distribute of a much larger volume, probably as a result of filamentation instabilities[12], and consequently the specific energy deposited is significantly lower. We argue that this could explain the missing He-α emission from CH tamped targets. Comparisons with the predictions of PIC and hybrid codes will be essential to determine the physical mechanism of electron transport behind the observed differences in the electron spatial distribution at the rear of the target. Also, measurements taken with different target size (1×1 mm²) showed that either 1 or 2 µm Al tamper does not affect the size of the hot spot.

There was, however, with both Al and CH tampers, Ti K-shell emission from various ionization states, appearing as side peaks blue shifted from the primary cold K-α line. This thus indicates that the temperature within the target varied considerably. The comparison done with the

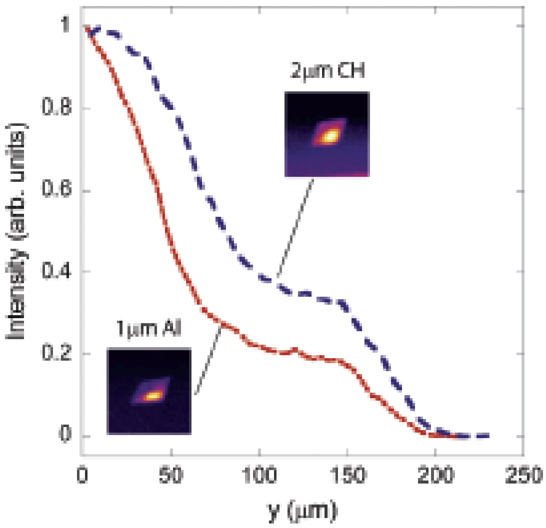

Figure 4. Measured spatial distribution of the K-α emission from the rear of 250×250 μm² targets. The line profiles correspond to the spatial distribution of the hot spot intensity. The laser pulse length was 1.5 ps.

SCRAM code suggests average temperature ~125eV, in agreement with previous work[3].

Summary

We have successfully created a dense Ti plasma, with density ~6 g/cc and temperature above 1 keV. These conditions can be used to develop a test bed platform to study EOS and transport problems that are relevant to both ICF and laboratory astrophysics experiments.

Acknowledgements

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