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Modelling K shell spectra from short pulse heated buried microdot targets

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ABSTRACT

K shell X-ray emission measurements have been used to diagnose plasma conditions in short-pulse heated buried microdot targets on the Orion high power laser. These experiments have been used to validate simulations of short pulse laser-solid interaction that combine hybrid PIC modelling of the laser absorption with radiation-hydrodynamics simulations including an electron transport model. Comparison of these simulations with streaked K shell spectroscopy show the importance of including radial gradients in fitting the spectra. An example is presented of the emission of sulphur from a 50 μm diameter microdot sample buried in a plastic foil. Previously agreement between simulation and experiment was obtained only by treating the absorbed energy, electron temperature and beam divergence as fitting parameters. The good agreement obtained in this work used the measured laser energy and laser pulse length and calculated the laser-solid target interaction from first principles.

1. Introduction

Experiments to study dense, high temperature, plasma properties have been conducted over many years using short-pulse high-contrast sub-picosecond laser pulses to heat sample layers buried in low Z tamper foils [1–7]. Though these measurements of dense plasma properties such as ionization potential depression [8,9] and line-widths [4,10] have yielded useful data, the laser-solid target interaction is still not fully understood. To address this there has been an effort to improve the computational models of the laser-target interaction by simultaneously using both the experimental data and the simulation predictions.

Experiments on the UK HELEN laser at AWE showed the importance of the density gradient encountered by the peak intensity short pulse and the effect of pre-pulse irradiation in decoupling the laser energy from the heating of the bulk of the solid target [11]. The modelling of these experiments treated the fraction of the laser energy absorbed into electrons, the mean energy per particle (or the hot electron temperature) and forward directed electron beam divergence as free parameters. These values were altered so that the predicted time history of the plasma conditions matched those of K-shell emission measurements inferred by matching spectra from simulation and experiment. Building on this work, experiments at AWE on the Orion laser [12], used 0.7 ps, 100 J laser pulses in second harmonic to confirm the HELEN results at higher energy. This paper presents the progress made in calculations of the solid-laser interaction and the heating of buried layer targets from first principles by comparison with sulphur K-shell emission experiments.

Previous attempts to model the laser-solid interaction problem from first principles using hybrid-PIC models coupled to radiation-hydrodynamics modelling overestimated the degree of heating from first harmonic light, underestimated that produced by second harmonic, and failed to model the effect of the pre-pulse and associated density gradient on the heating of solid targets. These models have been refined by comparison with the results from buried layer experiments [13] and have in turn helped to establish the effect of radial gradients in the interpretation of emitted spectra. In recent work agreement with experimental electron temperatures, pulse durations and temperature profiles has been obtained with the AWE codes using the experimentally measured laser energy and laser pulse duration. The fraction of laser energy absorbed, the mean energy per particle in the electron distribution and the electron

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beam divergence are no longer fitting parameters but are calculated from first principles.

2. Experimental method

On the Orion laser system one of the short pulse laser beams can be converted to second harmonic (2ω, 0.53 μm) but this can only be done at sub-aperture because the type 1 KDP conversion crystal has to be thin enough (~2 mm maximum) to prevent back-conversion of the 0.7 ps pulse. The diameter of the beam that can be converted is therefore limited by the structural strength of the conversion crystal. In this work the beam diameter was reduced to 30 cm from the 60 cm full beam diameter because this is the diameter of the KDP crystal that can be safely handled without breaking. The reduced beam diameter, along with losses due to the conversion, limited the second harmonic energy to 100 J for the experiments reported here. However, recently an option has been implemented to split the beam and pass it through two square KDP crystals stacked vertically. This allows the conversion of a larger portion of the beam and the energy in second harmonic to be increased to over 200 J. Converting to second harmonic, and subsequent reflection from four mirrors to reject any residual unconverted 1.06 μm light, reduces pre-pulse levels by many orders of magnitude and sharpens up the leading edge of the pulse which results in more efficient heating of the sample foil [9,11]. The targets used in the experiments described here are microdots encased in parylene N type plastic foils (C_8H_8). A schematic of the sample is shown in Fig. 1. The microdot sample is typically 50 μm in diameter and buried in parylene N which, on the front side irradiated with the laser, is 4 μm thick and 3 μm on the rear. The foil is positioned so that the laser passes through the hole in the 80 μm thick plastic washer to irradiate the sample foil. The hole is 1 mm in diameter and the outer washer diameter is typically 2 mm. The laser beam is defocused to the diameter of the microdot or slightly larger. The spot size is limited by the irradiance required to heat the volume of plastic substrates and the sample to the required high temperature.

The thickness of the parylene N coatings were chosen based on radiation-hydrodynamics simulations and trials where the duration of the emitted x-ray pulse was measured with an X-ray streak camera with picosecond temporal resolution. The plastic is selected to be thick enough that the rarefaction wave from the outer target surface does not reach the buried microdot until after the duration of the emitted x-ray pulse from the sample. This ensures that the sample stays at high density throughout the spectral measurement. The plastic must also be thin enough so that the laser energy is sufficient to heat the plastic overcoat and sample to high temperature and to ensure that the sample is heated as uniformly as possible over its entire diameter. In the experiments described, the laser irradiance is typically 5×10^{18} W/cm^2. The microdot sample was a sulphide containing an areal density of sulphur of 24 μg/cm^2 on average. Each microdot was characterized using Rutherford backscattering for thickness, composition and areal density [14] and also white light interferometry for thickness. Further cross checks were performed on witness slides using energy dispersive and wavelength dispersive spectroscopy to check sample composition. A variation of up to 40% was observed from the characterization which resulted in some sample rejection so that shots in a sequence would use almost identical samples. In addition a significant degree of oxidation was observed, typically around 30%. This was shown to be through the whole sample thickness, the RBS technique allowing sample assay layer by layer through the sample by tuning the He ion beam energy. These data, along with the thickness measurements, showed a reduction of a factor of two in the sample density compared to the nominal value at solid.

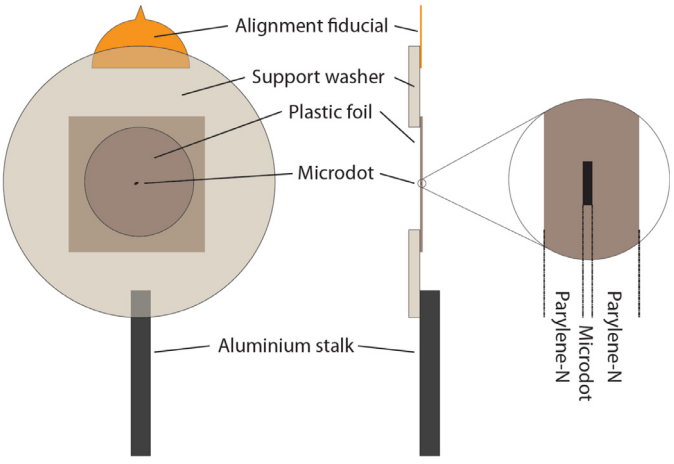

Fig. 1. A schematic of buried microdot targets used at Orion. The microdot diameter is 50 μm.

The sulphur K shell emission from the heated microdot was measured using an Axis-photonique x-ray streak camera [15] with picosecond resolution coupled to an x-ray crystal spectrometer using a convex cylindrically bent CsAP crystal. The streak camera used a caesium iodide photocathode. The spectra were also recorded time-integrated using crystal spectrometers recording onto BAS-TR Fuji image plate [16]. The emitting area of the microdot was measured with two instruments on two lines of sight. These were an x-ray pinhole camera with a 5 μm diameter pinhole recording onto BAS-TR image plate with eight times magnification viewing 50° to the target normal and a Kirkpatrick-Baez microscope [17] also recording onto TR image plate with a magnification of ten times viewing 21° to the target normal. These measurements checked the uniformity of the microdot heating and monitored any structure that may have been imprinted by laser beam spatial structure.

The streaked spectral range was limited to the line transitions from the 1 s2 p–1 s^2 and 2 p–1 s lines of He-like and H-like sulphur and the ratio of these transitions was used to infer the time dependent electron temperature during the x-ray pulse. The atomic kinetics and spectral synthesis code FLYCHK [18] was used to compare synthetic spectra to the lineouts of the streak spectra to establish the temperature time history. Fig. 2 shows the streaked sulphur results from the x-ray streak camera for different incidence irradiance resulting in different peak electron temperatures.

In addition to temporal measurements a slit imaging crystal spectrometer was fielded to record spatially resolved spectra across the focal spot. Results from the microdot targets ranging from 50–100 μm micron diameter showed the temperature across the laser spot diameter and the rapid fall off at the edges of the spot [19]. The data also showed a 20–30 μm diameter emitting area even when the beam was fired at best focus, which was measured at an equivalent plane focal spot monitor as 10–15 μm, showing that there was significant enlargement of the x-ray emitting area compared to the laser spot at the highest irradiances. However, for a defocused beam, 50 μm FWHM spot, the x-ray emitting area corresponded closely to the laser spot. This effect was replicated in the simulations with the increase in the x-ray emitting area diameter compared to the focused laser spot attributed to electrons refluxing laterally between the fields produced at the sample-tamper boundaries by fast electron transport during the laser pulse.

3. Data analysis and modelling

Previous modelling of buried layer targets used a Gaussian time-dependent energy deposition over the duration of the laser pulse input to a radiation-hydrodynamics model to produce a time history of the sample conditions. The energy deposited was treated as a free