Measurement of laser ablation using X-ray laser transmission

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Introduction

Laser ablation rates are determined by the rate of energy absorption and transport within a laser-produced plasma[1]. Absorption of the incident laser energy predominantly occurs by resonance absorption or by inverse bremsstrahlung[2]. An experiment is described using an X-ray laser to probe the solid thickness of a laser-irradiated solid target enabling the rate of laser ablation to be measured.

Measurements of laser ablation rates are particularly important in laser fusion, where the outer surface of a target wall is ablated and results in the implosion of the target. Knowledge of the rate of mass ablation from the target surface is necessary in order to determine the hydrodynamic efficiency of the target wall implosion[3]. Laser ablation rate measurements are also important in the production of X-ray lasers and in material coating and cutting through laser ablation.

Experiment details

The experiment used the Vulcan laser in target area west at the Central Laser Facility to pump an X-ray laser and to irradiate a sample target. A 4d – 4p Ni-like Ag X-ray laser was pumped using two overlapping pulses irradiating a solid silver slab target. An initial pre-pulse was used to create a pre-plasma on the target. The pre-pulse had an energy of ≈10 J in 290 ps and was focussed to a line of dimension ≈75 μm × 5 mm on the target, at an irradiance of approximately 8×10^{12} Wcm^{-2}. The main CPA pulse contained approximately 35 J in 750 fs, resulting in an irradiance of ≈3×10^{15} Wcm^{-2} in the line focus. The pre-pulse was frequency doubled to 527 nm whilst the CPA pulse remained at its original wavelength of 1.053 μm.

A sample target was ablated using a third beam of the 1.053 μm Vulcan laser. The beam contained ≈20 J in 290 ps and was focussed to a spot ≈0.5 mm × 1.0 mm on target. The sample targets consisted of a thickness of 50 nm of Fe supported on a 0.1 μm layer of CH placed on circular copper mounts placed onto fingers, which were in turn mounted onto a solid piece of aluminium to allow a number of targets to be irradiated without breaking vacuum.

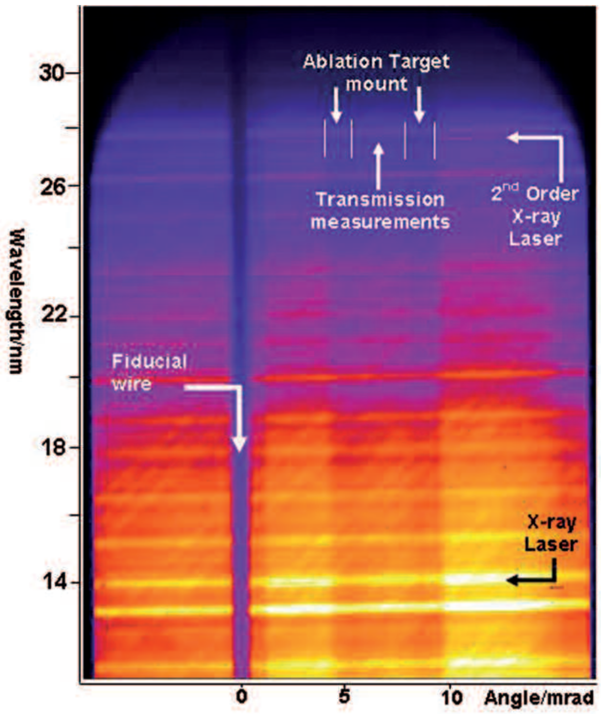

Figure 1. Flat-field spectrometer image showing out-of-focus self emission from the ablation target plasma around the transmitted first order 13.9 nm lasing line. The ablation target attenuates at 6 – 9 mrad angles to the X-ray laser target surface enabling a transmission measurement through the target. The time separation between the arrival of the peak of the ablating beam on the sample target and the peak of the X-ray laser is ≈100 ps.

Figure 1 shows a typical image from a flat-field spectrometer employed to record the transmission of the X-ray laser at 45° to the target normal through the sample target. The 13.9 nm lasing lines in both first and second order are highlighted in the image. Around the position of the first order lasing line, a large amount of self emission from the heating of the ablation target is visible. Lineouts are taken of the X-ray laser in second order to measure the transmission through the ablation target (figure 2). Interpolations of the X-ray laser output either side of the ablation target need to be made to obtain the intensity of the X-ray laser without the target in order to calculate the transmission of the X-ray laser through the ablation target. This leads to errors in the transmission measurements of approximately 20 %.

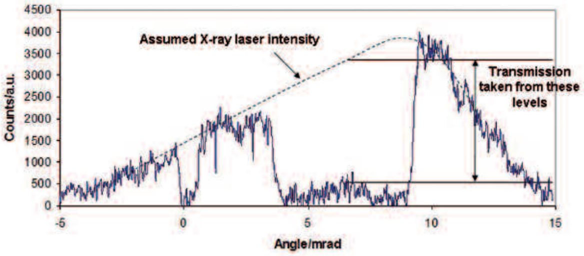

Figure 2. Lineout of the second order X-ray laser transmission from the image in figure 1 showing where the transmission measurements are taken from and the assumptions made for the X-ray laser intensity.

Figure 2 shows a lineout of the second order X-ray lasing line from figure 1, indicating the levels at which transmission measurements are taken. The transmission through the target from this image is calculated to be 0.17 ± 0.03.

A self-regulating model[4] of laser ablation can be used to theoretically calculate the X-ray laser transmission through the target and to give a value to the absorption of the infrared laser in interacting with the target. The self-regulating model applies where inverse bremsstrahlung is considered to be the heating source driving the expansion of a plasma plume. It is so called as the optical depth in the plasma for absorption of the heating beam must be approximately unity[5]. Previous measurements by the York group have shown that the self-regulating model applies for experiments with longer heating pulse duration (≈500 ps)[6].

The absorbed laser intensity at the target is needed in the self-regulating model. We use that the absorbed laser irradiance $I_a = AI$ where I is the irradiance on target of the heating beam and A represents the fraction of the irradiance absorbed by the target. The self-regulating model expression[5] to calculate the mass ablation rate dm/dt (g cm^{-2} s^{-1}) is given by

$$\frac{dm}{dt} \approx 1.06\times10^{-5}\,\frac{A_m^{7/8}}{Z^{9/8}}\,\frac{I_a^{1/2}}{\lambda^{1/2}t^{1/4}} \qquad (1)$$

where A_m is the mass number of the target material, Z is the average charge of the plasma, λ is the wavelength of the heating beam laser (in µm) and t is the time from the start of the laser pulse. For calculations using the self-regulating model, Ne-like ionisation $Z = 16$ is assumed as crystal spectrometer measurements indicate this level of ionisation. From equation (1) it is possible to calculate the rate of mass ablation from the target as a function of time and from there calculate the transmission of the X-ray laser through the target using the knowledge of the mass of target remaining.[7]

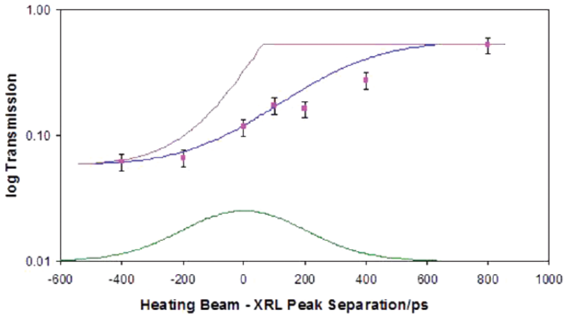

Figure 3. Experimental (■) values for the transmission of the X-ray laser through the target as a function of time relative to the ablating laser pulse are compared with the self-regulating model for a value of laser absorption A = 0.01 (—) and A = 0.05 (—). The Gaussian curve (—) is added to display the ablating beam intensity variation as a function of time.

Ablation rate measurements

Figure 3 shows a plot of the transmission of the X-ray laser through the target as a function of time for both the experimental data and using the self-regulating model. For these measurements, it is assumed that the CH layer retains the value of transmission at its solid, non-ablated density. Two curves for the model are plotted. The curve which most closely matches the data uses a value for the absorption of the laser of A = 0.01 and the second curve is for a value of A = 0.05, as used in previous experiments[6].

Measurements of the ablation rate were attempted with a much larger focus of the heating beam of ≈2 mm × 5 mm. The two data points taken for this focal spot size are shown in figure 4. The irradiance on the targets is ≈1×10^{12} Wcm^{-2}, which is an order of magnitude lower than the previous measurements. The self-regulating model of transmission at this lower irradiance with A = 0.01 is superimposed in figure 4. There is an approximate agreement of the experimental data points with the model, but the amount of target material ablated is small.

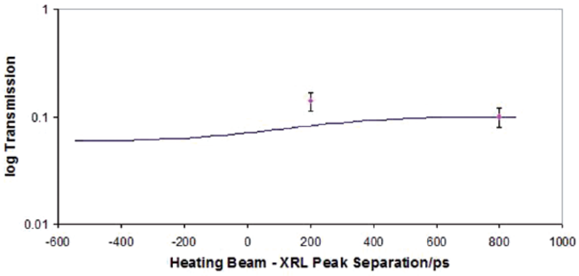

Figure 4. Transmission measurements through the target measured experimentally (◆) for low heating laser irradiance of ≈1×10^{12} Wcm^{-2} and compared to the self-regulating model (—) for this irradiance at the target and for the same value of A = 0.01 as is used in figure 3.

Conclusions

The measurements of laser ablation were the first taken using a CPA pumped X-ray laser as a direct probe measurement for ablation and provided more accurate measurements of the temporal evolution of the ablation of plasma material from a target than previous experiments[6]. However the absorption of laser intensity was found to be low with $A = 0.01$ by comparing experimental transmission to a self-regulating model, as opposed to $A = 0.3$, the expected value for absorption at laser intensities of $\approx 1 \times 10^{13} - 1 \times 10^{14}$ Wcm^{-2} at an incident wavelength of ~1 µm[8]. The absorption, A, measured with the technique represents the fraction of energy transferred to thermal plasma. Energy transferred to superthermal electrons or transported laterally does not contribute to ablation and so is not measured. This may explain why the measured value of absorption is low compared to other measurements.

References

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