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Accelerated Thin Foil Targets

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Measurement by XUV laser radiography of hydrodynamic perturbations in laser accelerated thin foil targets

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Abstract

A novel diagnostic application of XUV lasers has been developed for the study of the hydrodynamic imprinting of laser speckle pattern on directly driven laser fusion targets. A neon-like Yttrium laser operating at 15.5 nm is used to probe thin foils of Si irradiated with an SSD smoothed laser at 0.35 μm wavelength and $6 \times 10^{12} \text{ W cm}^{-2}$ intensity, simulating the initial phase of irradiation a laser fusion capsule. Measurements of the perturbations in target opacity are made by XUV radiography through the foil. The magnitude and Fourier composition of the perturbations has been determined both before and after Rayleigh Taylor growth showing the mode spectra of both the initial imprint and the subsequent RT growth.

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Introduction and relevance to directly driven laser fusion

Progress towards ignition of inertially confined fusion in laser driven implosions has two major branches, termed indirect and direct drive. Indirect drive uses laser irradiation of the interior wall of a hohlraum target to generate thermal soft X-rays which provide very uniform intensity at the surface of a spherical capsule containing an inner layer of solid deuterium-tritium fusion fuel. Direct drive irradiates the spherical capsule with multiple laser beams using optical techniques to smooth the radiation pattern on the target. Both approaches require a pulse shape for the drive which begins with a low intensity foot of typically 10 ns duration followed by a circa one hundred fold increase in intensity to a main drive phase of a few nanoseconds duration. For direct drive the preferred wavelength is as short as possible dictated by plasma instabilities in the main drive phase. With a glass laser this means in practice the third harmonic at 0.35 micron. The intensity in the foot of the pulse is typically 10^{13} Wcm^{-2} and in the main drive phase more than 10^{15} Wcm^{-2} .

The optical smoothing methods rely on producing focused beam patterns which have smooth Fraunhofer envelopes within which there is a temporally fluctuating laser speckle pattern. The time averaged uniformity of the radiation thus improves with time. The net radiation field can be computed as the linear superposition of all the contributing sources and, while this calculation is complex in its details it is conceptually straight forward.

A most important issue for direct drive is the hydrodynamic response of the target to the radiation pattern. Numerical modelling suggests that the first nanosecond of irradiation in the foot of the drive pulse plays a key role. The thermal conduction layer between the region of absorption of the laser light and the location of the peak drive pressure at the ablation front develops from zero thickness to a significant near steady state magnitude in about 1 ns. Transverse perturbations of energy flow with a scale length comparable to the thickness of the conduction zone are very effectively smoothed by the diffusive nature of heat conduction and the smoothing therefore affects progressively longer scale length perturbations as the conduction zone widens with time. After about a nanosecond the growth of perturbations becomes independent of the driving source

and predominantly due to other processes multiplying the instantaneous amplitude, particularly the Rayleigh Taylor instability. The end result is that the speckle pattern creates the seed hydrodynamic perturbations of the target which are then multiplied in amplitude. This process is often termed imprinting. The duration of the imprint phase is less than the transit time of the shock front through the shell. Once the shock breaks out strong acceleration occurs and RT growth of perturbations is totally dominant.

The imprinted disturbance includes rippling of the ablation surface, variations in mass per unit area of the shell due to transverse flow, spatial variations in shocked material density and rippling of the shock front driven into the shell. Of these the most important is the rippling of the ablation surface which later grows by RT instability, but the different perturbations are intimately connected and measurement of one allows inference of another. The design of ignition targets by numerical modelling necessarily includes modelling of imprint. This modelling is however of unproven accuracy and requires approximations such as limiting the perturbations to one transverse dimension. Full 3D modelling is not possible with current codes and there remains significant uncertainty about the detailed behaviour of imprint.

Both experimentally and in the design of ignition targets the aim is to minimize imprinting by maximizing the optical smoothing. It is important also to quantify it in order to assess whether or not the imploding shell will break up before the implosion is complete.

Measurement is difficult because the imprinted amplitudes are small, typically less than 100 nm surface perturbations. A novel approach which we have developed uses the high absorption coefficient for XUV radiation to reveal such small thickness perturbations by transmission radiography and the high brightness of an XUV laser to allow transmission radiography of a foil target with an attenuation factor as high as 10^4 .

The experimental system

The experiments were conducted at the two beam target irradiation facility which is part of the 10 beam Nova laser, see figure 1.

Figure1

One beam of Nova (labeled 27) operating at 2.0 kJ energy at the second harmonic wavelength of 530 nm in a 600 ps square pulse served as the Yttrium laser driver. It was focused at $f/4$ to a 3 cm line on a thin foil target comprised of a 100 nm CH substrate and 200 nm Y coating. The output of the Y laser at 15.5 nm was a pulse of 70 to 100 ps duration and approximately 30 MW power in a beam of 10 mrad divergence [1]. Multilayer mirrors (Si/Mo) of 60% reflectivity at normal incidence and 35% reflectivity at 45 degrees were used in the radiography system. Following the beam to the top of figure 1, Mirror 1 was planar and mirror 2, the condensing optic, was spherical with 1 m radius. A plane 2.2 cm from the laser output was imaged at 0.8x magnification by mirror 2 onto the Si sample. Mirror 3, planar, redirected the beam and mirror 4, the imaging optic, was spherical of 50 cm radius and positioned to project a 26x magnified image. The mirror apertures were 2cm. Astigmatism in the image was minimized by operating mirror 4 at 1.5 degrees off normal incidence. Mirror 5 provided screening against broad band thermal XUV emission and a 100 nm Al foil at the CCD detector protected against stray laser light. The radiographic image was

recorded on a Peltier cooled back thinned XUV CCD camera with 1024 x1024 pixels of 16 bit resolution and 24 micron size .

The second beam of Nova (labeled 26) was operated at the third harmonic wavelength of 351 nm to provide focused intensity of $6 \times 10^{12} \text{ W cm}^{-2}$ in a 1mm diameter focal spot . The focusing lens was f/4 and the beam diameter 70 cm . A random phase plate with hexagonal elements of diameter 2 mm controlled the spot diameter . The beam had smoothing by spectral dispersion (SSD) and the bandwidth from the oscillator was broadened by cross phase modulation (XPM) and dispersed with a diffraction grating giving 1.7 mrad/cm^{-1} in the output. beam at 351 nm . The maximum bandwidth at 351 nm was limited by the third harmonic conversion to 0.5 THz, giving an asymptotic smoothing limit of 10% [2]. The UV drive was monitored via an on line diagnostic station using a small fraction of the power to provide a time integrated image of the focal plane speckle pattern, a measure of the spectral bandwidth , the pulse energy and the pulse duration . Streak cameras in the Nova system monitored the relative timing of the two beams used for the experiment and this timing was adjustable with a precision of 10 ps .

The UV beam irradiated the main target which was a Si foil of 3 micron thickness .The Si absorption coefficient at 15.5 nm (in the L transmission window) is 2.14 / micron , giving 24% intensity change for a 0.1 micron thickness change. The smoothed signal level at the CCD was typically 5000 counts so that thickness changes of 0.1 micron give signals well above the statistical noise level.

The output of the Yttrium laser was monitored as a time integrated image of the beam pattern on a second XUV CCD camera and as a streaked image of a section of the beam, both using the emission from the other end of the laser as illustrated in figure 1 . (In long pulse ASE mode the laser emits a similar beam in both directions). These diagnostics gave the duration of the pulse (70 to 100 ps) and enabled estimation of the typically 20% increase in opacity of the shocked target from the change in the ratio of the intensities in the radiograph and monitor channels for shocked and unshocked targets.

Tests with an un-irradiated Si foil target having a lithographically formed pattern of rectangular grooves 5 micron wide and 0.24 micron deep showed that the system correctly recorded the depth of the grooves and could resolve features of micron scale [3].

Experimental results with SSD smoothed UV irradiation

For irradiated targets the X-ray laser pulse was timed to arrive 200 ps after the start of UV irradiation of the foil. This time corresponded to the time of shock breakout at the rear of the foil. Acceleration of the whole foil begins after shock break out and RT growth dominates over imprinting after this time. The shock transit time studied here is less than the 1 ns duration attributed to the imprint phase in an ignition target, but measurement over a 200 ps interval covers a significant fraction of the imprint because the rate of imprint accumulation falls off with time due to the combined effects of increasing thermal smoothing and greater time averaged uniformity. The drive pulse was approximately square and its duration was chosen so it continued to the end of the XUV laser probing. Where later probe time was used to study RT growth the duration of the drive pulse was correspondingly lengthened.

The radiographs were produced with a typically 300 micron diameter region illuminated by the XUV laser within the 1 mm zone of uniform drive. Sections 100 micron square cut from the images are shown in figure 2 for 3 cases of increasing SSD bandwidth.

The images were processed by fitting a smooth 2D function and subtracting the logarithm of the smooth fit from the variable signal level to give a variation in opacity. The RMS variation was obtained from the array of values and is noted in figure 2. Of particular interest is the Fourier composition of the imprint. This is shown in figure 3 in the form of the image of the fast Fourier transform. The 2D power spectrum of the imprint is obtained by summing the power of individual modes in annular zones in the 2D transforms and is shown in figure 4. The square root of the power spectrum gives the RMS opacity variation per mode.

Figure 2 *Sections of radiographs labeled with the infrared bandwidth and RMS opacity variation .*

Figure 3 *Fourier transforms of the images in figure 2. The maximum spatial frequency in the transforms corresponds to 2 micron wavelength .*

Figure 4 *Power spectra of opacity for the three cases shown in figures 2 and 3*

The results show in figure 2 a 2 fold reduction in RMS variation in opacity with increasing bandwidth. Notable in the Fourier transforms in figure 3 is the narrowing of the spectrum along the direction of SSD dispersion and the broader angularly symmetric spectrum in the case of static speckle. The power spectra in figure 4 have components out as far as 2 micron wavelength which is the Nyquist limit due to the pixel size of the data .

Figure 5 shows how RT growth over an additional 400 ps affects the radiographic image and in figure 6 the corresponding power spectrum shows an elegant demonstration of the high frequency cut off of RT growth at wavelengths below 3 micron and the peaking of the growth at about 10 micron.

10 Å at shock breakout
RMS: 0.18 (25062014)

100 μm

10 Å delayed 400 ps
RMS: 0.55 (25062112)

Figure 5 *Radiographs at shock break -out and after RT growth*

Figure 6 *Power spectra of opacity from figure 5*

Comparison with optical speckle patterns

It is instructive to analyze the optical speckle pattern and the corresponding radiographs in the same way. This was done here by processing digitized photographic images of the focal plane speckle patterns. The images of the 2D Fourier transforms of the speckle pattern and corresponding radiograph in figure 7 are striking in the similarity which they show even down to reproduction in the imprint of the unexpected bi-directional feature of the optical transform.

Figure 7 Comparison of Fourier transforms of the UV speckle pattern and XUV radiograph for 4A infrared bandwidth (there is a left to right symmetry switch between the two plots). The scale circles indicate a spatial wavelength of 2.5 microns.

Discussion

The similarity of the optical and imprint transforms in figure 7 is suggestive of linearity in the imprint process. In this connection the criterion for onset of non linearity in a continuum of modes developed by Haan [4] has been used to verify that the imprint

developed by Haan [4] has been used to verify that the imprint remains well within linear limits in these measurements. Linearity is helpful in permitting the use of an imprint efficiency which is the ratio of the imprint amplitude (RMS per mode) to the speckle fluctuation fraction (RMS per mode). This efficiency is obtained as the square root of the ratio of the corresponding 2D power spectra. Using the spectrum of linear imprint efficiency the linear imprint for any specified optical power spectrum can be inferred. This enables projections to interesting cases such as targets designed for ignition.

The opacity variations determined here can be converted to equivalent thickness variations or surface ripple amplitude using the absorption coefficient. An approximate approach is to assume that the length variations are at the solid density with the medium having the normal solid absorption coefficient. On this basis the RMS variations are 0.18, 0.10 and 0.08 micron in the three images recorded in figure 2. The delayed measurement in figure 5 has variation of 0.26 micron RMS.

Analysis of the results shown here is the subject of more detailed current study and the preliminary discussion here is only indicative of the way analysis is being made.

Conclusions

An XUV laser has been used to measure imprint under conditions relevant to directly driven fusion. The effect of RT growth of the imprinted seed amplitudes has been observed and the mode spectrum of RT growth determined showing a cut off and a peak. More detailed analysis of these data and direct comparison with modelling is in progress.

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