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INERTIAL CONFINEMENT FUSION RESEARCH AT THE SERC CENTRAL LASER FACILITY, UNITED KINGDOM

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Abstract

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The paper reviews experimental and theoretical work relevant to inertial confinement fusion which was carried out in connection with the high power laser programme at the SERC Central Laser Facility. The main effort of recent research concentrated on studies with improved laser illumination uniformity generated by various optical smoothing techniques. It was observed that non-uniformities are produced at the ablation front caused by the initial laser imprint on the cold target surface at the beginning of the laser pulse even when optically smoothed laser beams were used whereas uniform plasmas were generated with soft X ray irradiation. To combat the initial imprint problem, a novel indirect/direct drive scheme is proposed in which the target is irradiated with intense soft X ray radiation ahead of the optical laser pulse. The soft X ray radiation is generated by irradiating a converter foil with optical laser light. The interaction, transport and hydrodynamic efficiency of intense soft X ray pulses are studied in thin foil targets. The propagation of a supersonic ionization front produced by soft X ray heating is investigated in low density foam targets. The effects of various beam smoothing techniques on the Rayleigh–Taylor instability are studied, and the first experimental observations of mode coagulation are made in which short wavelength modes couple into long wavelength ones. The growth of the Rayleigh–Taylor instability in the deceleration phase is calculated with a 3-D hydrodynamics code.

Uniformity of illumination to a very high degree ($<1\%$) is essential for the direct drive laser fusion scheme. Small perturbations on the laser beams, for example, may grow because of self-focusing and filamentation, resulting in localized heating of the target and causing non-uniformities in the ablation pressure that drives the implosion. The non-uniformities may also be a seed for hydrodynamic instabilities such as the Rayleigh–Taylor instability which can lead to a breakup of the imploding target shell during the acceleration phase at the ablation surface and/or during the deceleration phase at the inner surface of the fuel shell. For these reasons various beam smoothing techniques were recently developed to improve the spatial intensity profile of the laser beams. We report here on some physics issues which are critical for the direct drive approach. In particular, the effects of various laser beam smoothing techniques on several physical processes were investigated. It was observed that the initial laser imprint on the cold target surface at the beginning of the pulse produces considerable density perturbations at the ablation surface. The find a solution to this startup phase is one of the key issues for the direct drive approach. A novel indirect/direct drive scheme is proposed as a possible solution.

The levels of parametric instabilities including laser beam filamentation, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) were studied in large underdense preformed plasmas for either coherent laser light or optical beams smoothed by random phase plate (RPP) arrays or the induced spatial incoherence (ISI) technique. Millimetre sized cylindrical underdense high temperature plasmas were produced by irradiating thin foil targets with a number of laser beams in a line focus geometry. A separate laser beam delayed between 1 and 3 ns interacted axially with the preformed plasma [1, 2]. The focal spot profiles of the interaction pulse were calculated with an interference code and compared to either time integrated or framed equivalent focal spot images. Direct experimental evidence was obtained that SRS is predominantly generated in laser filaments [3]. The 'anomalous' SRS spectral features so commonly reported in time resolved studies are shown to be characteristic emission of SRS from filaments. The effectiveness of the ISI in suppressing SBS was to be strongly dependent on the laser wavelength and intensity for the interaction regime investigated. Significantly higher levels of SBS were recorded for infrared ($\lambda_0 = 1.05\ \mu\text{m}$) as opposed to green ($\lambda_0 = 0.53\ \mu\text{m}$) laser wavelength interactions. A correlation can be made between the SBS level and the strength of the filamentation instability. In addition, the first observations of the occurrence of thermal whole beam self-focusing with ISI laser light were obtained [4]. Side on X ray pinhole imaging with a multiframe camera was used to record the propagation characteristics of the interaction beam through the preformed plasma. The self-focusing growth length was measured directly.

The uniformity of the overdense plasma of laser irradiated targets was investigated by using a novel time resolved X ray imaging technique with submicron spatial resolution [5, 6]. Two-dimensional spatially resolved images show that laser beam non-uniformities imprint themselves onto the cold target surface at the beginning of the laser pulse, generating considerable density perturbations which persist throughout and after the laser pulse with no evidence of smoothing [7]. This imprint phenomenon is interpreted in terms of poor thermal smoothing under the conditions prevailing at the beginning of the laser pulse. On the other hand, it was observed that the plasma blowoff is uniform when the targets are irradiated with intense soft X ray pulses. The plasma production was characterized interferometrically with the use of an optical probe beam with a wavelength of 350 nm. Electron density profiles were obtained for soft X ray heated thin wire targets during and after the pulse, allowing the distance of the critical density for an infrared laser beam (n_q

$= 1 \times 10^{21}$ cm^{-3}) to be determined at several times. The efficiency of thermal smoothing was investigated by interacting an infrared laser beam with a uniform plasma produced by an X ray pulse. A periodic structure was imposed on the beam with wavelengths between 15 and 50 μm and an intensity modulation of 2:1. It was observed, by using side on soft X ray radiography, that the ablation surface was uniform within the sensitivity of the imaging system when the distance between critical and ablation surfaces was larger than the imposed periodic structure on the laser beam. The production of uniform plasmas with soft X rays and the process of thermal smoothing are utilized in the indirect/direct drive approach. The scheme was tested by irradiating thin foil targets with a soft X ray pulse followed by an SSD/RPP smoothed optical pulse. No breakup of the accelerating foil was observed which is in sharp contrast with results in which the foil was driven directly with either an SSD/RPP or an ISI/RPP optical pulse. In this case a periodic breakup with a wavelength consistent with the initial imprint structure was observed.

The interaction, heating and dynamics of low Z foil targets irradiated with intense, approximately Planckian, soft X ray pulses have been investigated. These studies are not only intrinsically interesting but are also important for the indirect/direct drive approach. The soft X ray pulses, generated from separate laser irradiated converters consisting of 1 μm thick CH which is overcoated with 750 Å of gold, were used to irradiate planar plastic foils. The global transport of soft X ray radiation through thin foil low atomic number targets was studied by using time resolved X ray ultraviolet (XUV) spectroscopy [8]. The X ray heating was investigated by measuring the temperature histories of chlorinated tracer layers buried at

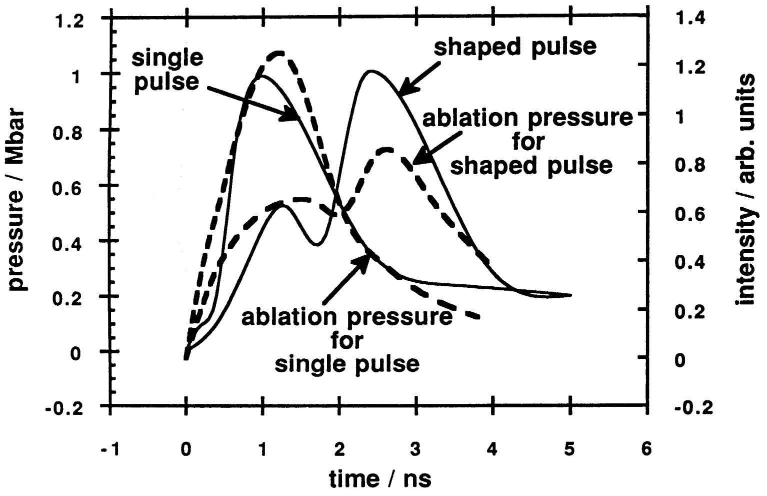

FIG. 1. Radiation hydrodynamic simulations showing that the ablation pressure strongly depends on the shape of the soft X ray pulse.

different depths in the targets. The temperature diagnostic was a novel time resolved XUV absorption spectroscopy technique using chlorine L-shell transitions. The temporal temperature profiles were reasonably well reproduced by radiation hydrodynamic simulations [9]. The dynamics of accelerated targets were diagnosed by using a high resolution soft X ray imaging system. A long pulse backlighter was used, and the rear surface of the accelerating foil target was time resolved with an X ray streak camera. The probe wavelength was about 60 Å. Similar results were obtained on targets driven by optical smoothed laser radiation. The experimental results were simulated with a radiation hydrocode which showed good agreement [10]. In addition, thin foil targets were driven either with shaped soft X ray or optical pulses or a combination thereof. It was observed that the efficiency of the soft X ray drive was significantly reduced later in the shaped pulse, owing to absorption of radiation in the plasma blowoff. These results are in distinct contrast to similar targets which were driven with shaped optical laser radiation. Figure 1 presents hydrodynamic simulations showing the ablation pressure for targets driven by a single 1 ns (full width at half maximum, FWHM) and a shaped soft X ray pulse, respectively. Evidently, the ablation pressure generated by the latter part of the shaped soft X ray pulse is significantly lower than the pressure produced by a single pulse with a similar incident X ray flux.

The propagation of an ionization front produced by soft X ray heating was observed in cylindrical foam targets with a density between 30 and 50 mg/cm^3. The position of the ionization front was observed either in absorption or emission at various times during and after the pulse using a 2-D soft X ray imaging technique with a probe wave of about 50 Å. In absorption, the heated material becomes transparent to the probe beam whereas the cold material ahead of the front is opaque. The use of low density foam attached to the outside of the fusion target may be another solution to the initial laser imprint problem.

Growth rates of the Rayleigh–Taylor instability were measured in thin foil targets with imposed sinusoidal modulations irradiated by optically smoothed laser beams. A hybrid optical smoothing scheme utilizing ISI and RPP was used. The enhancement in the modulation depth during acceleration was observed with time resolved transmission radiography using a soft X ray backlighting source. The wavenumber dependence and non-linearity of the Rayleigh–Taylor growth were investigated by using a range of modulation periodicities and depths. The measurements were compared with 2-D hydrocode simulations [11, 12]. The effects on the Rayleigh–Taylor instability and the secular target breakup were studied by using different illumination schemes including coherent, ISI/RPP smoothed green and soft X ray radiation. Side on images with a probe wavelength of about 50 Å were obtained for various targets with modulation wavelengths between 20 and 50 μm. Figure 2 shows a series of images of targets which were irradiated with the three different illumination schemes. Targets with a 50 μm periodicity were used for this study. As can be seen the target driven with coherent laser beams shows both Rayleigh–Taylor growth and target breakup caused by non-uniformities in the laser

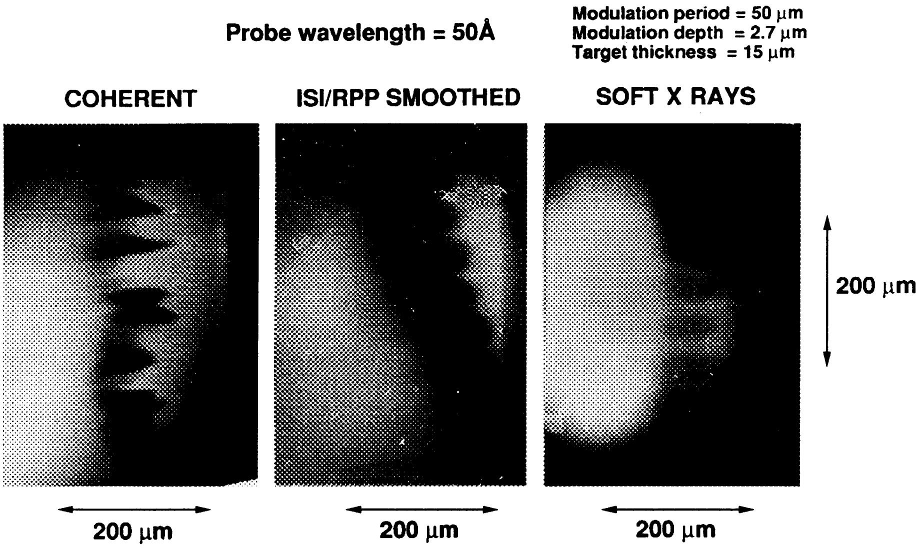

FIG. 2. Side on soft X ray radiographs of premodulated CH foil targets driven by coherent, ISI/RPP smoothed laser beams and soft X ray radiation. The frames were recorded 3 ns after the start of the driving 1 ns pulse.

illumination. The target driven by ISI/RPP smoothed irradiation was accelerated more uniformly, showing bubble and spike formation. It moved furthest at the centre of the beam where the laser intensity was highest. The third image taken on a target which was driven entirely uniformly by an intense soft X ray pulse clearly shows the target breakup caused solely by the Rayleigh–Taylor instability. Again bubble and spike formation is observed. In addition, the first measurements of the Rayleigh–Taylor instability at short wavelength were obtained. Thin foil targets with a modulation periodicity of 2.6 μm and an initial amplitude of 0.2 μm were driven by ISI/RPP irradiation. Side on images recorded 3 ns after the start of a 2 ns laser pulse show that the target is broken up with wavelengths between 5 and 50 μm. The longer wavelengths are seen on the part of the target which was driven furthest caused by the most intense part of the laser beam (which had a Gaussian spatial profile). These observations indicate that the short wavelength modes couple into longer perturbations.

Three dimensional simulations of the Rayleigh–Taylor instability in the deceleration phase of ICF implosions have shown that (a) non-linear growth is about 25% faster in 3-D than in 2-D; (b) growth is faster for thin shells; and (c) shell integrity is increased by driving the target more strongly under the beams than at the beam intersections. Two topologically non-linear modes are apparent in 3-D, the spike valley and the bubble ridge, their occurrence depending on the initial conditions [13].

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DISCUSSION

L.J. DHARESHWAR: In earlier work, you reported on plasma jets which had no relevance to laser beam uniformity. Have you done any recent conclusive experiments on the role these jets play in the ablative acceleration physics?

O. WILLI: We have seen that the initial laser non-uniformities of the laser beam imprint themselves on the cold target surface. We have not yet carried out experiments which show that the plasma jets occur at the ablation surface.

L.J. DHARESHWAR: In our work, we have observed that plasma jetting is pronounced for gold targets. In your opinion, would these plasma jets have a detrimental effect on indirect drive schemes where gold converters are being used?

O. WILLI: We have only used converter foils to generate soft X rays. We have not yet investigated the gold foil, and we have no experimental data on plasma jets in the indirect drive scheme.