Measurements of the Effect of Laser Beam Smoothing on Direct-Drive Inertial-Confinement-Fusion Capsule Implosions

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We present measurements of the effect of various levels of laser beam smoothing on both burnthrough time and the neutron yield in layered, deuterium-filled imploding microballoons. Burnthrough times are found to improve as smoothing is increased. This effect is believed to result from a reduction in the seeding of the Rayleigh-Taylor (RT) instability with increasing smoothing. The results are in agreement with simulations that model the development of the RT instability from initial perturbation spectra consistent with measured changes in uniformity. The neutron yields are also observed to increase in the presence of smoothing, but are much less sensitive to uniformity changes than the burnthrough rates.

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Drive uniformity is crucial to the success of inertial confinement fusion (ICF) [1]. One potentially serious consequence of drive nonuniformity in ICF capsule implosions is the development of a fluid instability analogous to the classical Rayleigh-Taylor (RT) instability [2,3], which can adversely affect target performance through mixing. Such mixing was assumed to be responsible for the discrepancy between the experimental and simulation results of the burnthrough experiments reported in Ref. [4]. In those experiments, the laser irradiated a spherical target that consisted of a glass shell or a solid glass sphere overcoated with a parylene $[(CH)_x]$ layer, in which one or more thin signature layers of moderate to high-Z material were embedded for the purpose of diagnosing the penetration of the heat front. A different type of burnthrough experiment carried out to study RT mixing in planar targets has been reported [5], but these experiments did not address the effect of beam smoothing. Two potential regions for growth of the RT instability exist in burnthrough targets, one at the ablation surface and one at the parylene–signature-layer interface. Under current laser conditions, the instability grows from initial perturbations created mainly by the laser illumination nonuniformity, although normal target fabrication imperfections also play a minor role in initializing the instability. As laser uniformity improvements continue to be made, the contribution of these target imperfections will become more significant.

A primary result of the analysis in Ref. [4] was that the timing of the burnthrough was correlated with the illumination nonuniformity; i.e., improving the uniformity results in an increased burnthrough time. For similar shell drive conditions (acceleration, mass density scale length, and Atwood number), the RT growth rates should be similar and the rms amplitude of the instability should depend on the initial perturbation as long as the instability has not saturated. Thus, a conclusion of Ref. [4] was that the effectiveness of new methods developed to improve the laser illumination could be tested by measuring the burnthrough time in burnthrough targets, along with other observables affected by mixing such as neutron yield and fuel density.

In this paper, we present results of burnthrough experiments on D_2-filled imploding targets undertaken to study the effect of smoothing on both the burnthrough time and the neutron yield. The smoothing technique implemented on the 24-beam OMEGA laser of the University of Rochester includes the use of distributed phase plates (DPP's) [6,7] and of smoothing by spectral dispersion (SSD) [8]. In the SSD technique, as currently installed on OMEGA, a spectrally dispersed broad-bandwidth phase-modulated laser pulse is produced by an electrooptic phase modulator and a pair of transmission gratings. When this pulse is focused onto a target through a DPP and lens, the instantaneous speckle pattern formed on the target by the DPP varies rapidly as the redshifted and blueshifted components cycle across the beam, resulting in a time-averaged far-field profile that is extremely uniform. The larger the bandwidth, the more rapidly one would expect the structure to change in time and achieve a given level of smoothing. This is illustrated in Figs. 1(a) and 1(b) where we have plotted the predicted rms on-target nonuniformity as a function of averaging time for two different bandwidths, $\Delta\lambda = 5\times10^{-5}\lambda$ and $\Delta\lambda = 3\times10^{-4}\lambda$, where $\Delta\lambda$ is given by the FWHM of the spectral envelope in the pulse. (For the purpose of quantifying the on-target nonuniformity, the beam intensity distributions are decomposed into Legendre modes and superimposed on the target surface.) In the case of Figs. 1(a) and 1(b) the initial l-mode spectrum was the same in each case and was derived from measured beam far-field profiles. The effect of thermal smoothing, which can be obtained from hydrocode simulations, has been conservatively included by multiplying the amplitude of each l mode by a factor $\exp(-0.01l)$, in accordance with the "cloudy-day" model [9]. It can be seen by comparing the two figures that the overall level of nonuniformity is expected to fall both more quickly and to a lower asymptotic value in the higher bandwidth case than in the lower. This effect is much more pronounced for the higher l

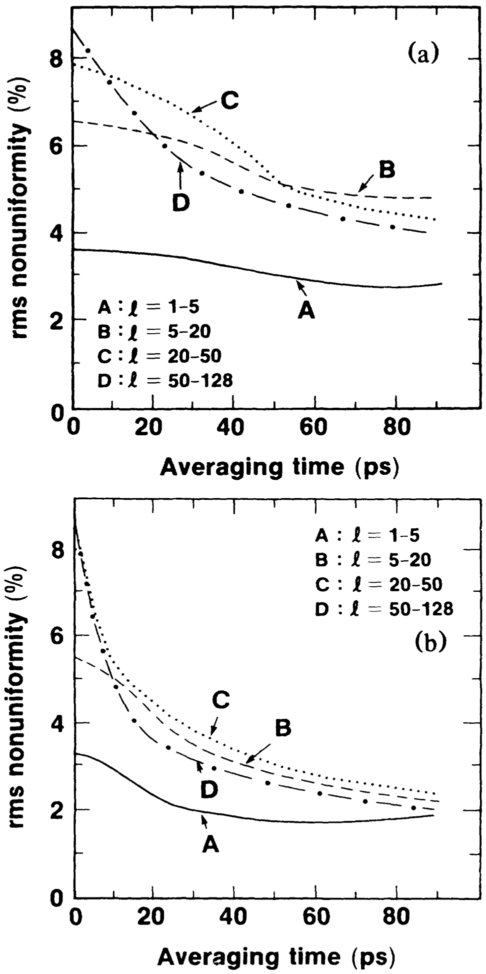

FIG. 1. Illumination rms nonuniformity on target for various l-mode ranges as a function of averaging time for SSD bandwidths of (a) $\Delta\lambda/\lambda = 5\times10^{-5}$ and (b) $\Delta\lambda/\lambda = 3\times10^{-4}$. The modulation frequency was 8 GHz.

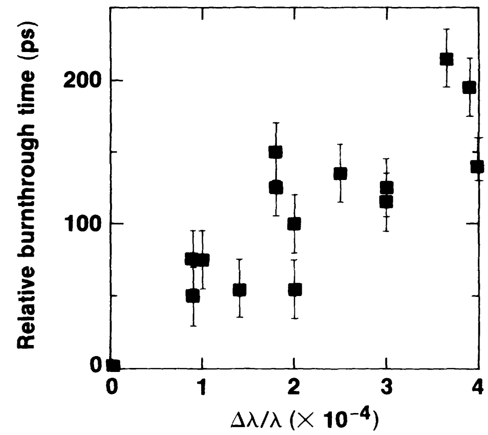

FIG. 2. Relative burnthrough times plotted as a function of SSD bandwidth. For each sequence of shots, the zero-bandwidth case has been normalized to 0 ps to allow a comparison to be made.

modes, which are predicted to be the more destructive ones in terms of causing early burnthrough [4]. We observe that increasing the SSD bandwidth from zero to $\Delta\lambda = 4\times10^{-4}\lambda$ increases the burnthrough time by about 200 ps. Simulations carried out on the one-dimensional code LILAC and a mixing model postprocessor confirm that these improvements can be attributed to a decrease, as a result of SSD, in the amplitude of the initial perturbations which seed the RT instability.

The experiments were carried out on the OMEGA laser system at 351 nm with 600-ps FWHM Gaussian pulses at peak intensities of about $(8\text{–}9)\times10^{14}$ W/cm^2 and with values for the SSD bandwidth in the range $\Delta\lambda = (0\text{–}4)\times10^{-4}\lambda$. In all cases the SSD modulation frequency was 8.74 GHz. Different bandwidths were obtained by varying the power to the phase modulator. The targets consisted of 3-μm-thick glass shells, with diameters ranging from 260 to 270 μm, filled with 50 atm of D_2 and coated with 6 μm of parylene. A barrier layer, consisting of 0.1 μm of Al, was deposited on the targets to prevent shinethrough [10] of the early part of the laser pulse into the target before formation of the critical surface. X-ray emission from the barrier layers also served as a timing marker since a fiducial beam was not available for these experiments. Illumination uniformity and absorption were optimized by choosing targets with diameters about a factor of 1.28 smaller than the diameter of the first zero of the DPP envelope (387 μm).

Measurements of the temporal emission of the Al and Si H-like and He-like lines were provided by SPEAXS [11], a time-resolving x-ray spectrometer in which an elliptically curved pentaerythritol (PET) crystal analyzer is used to disperse the x-ray spectrum (1.5–2.5-keV range) onto the slit of an x-ray streak camera. Neutron yields from the D-D fusion reactions were measured using silver activation and a set of scintillator-photomultiplier pairs [12,13]. Laser absorption was measured by an array of plasma calorimeters. Since no absolute laser timing fiducial was available during these experiments we have defined the burnthrough time as the temporal difference between the onset of the Al and Si emission. (The onset is defined as the time at which the emission reaches $\frac{1}{10}$ of its maximum value.) Data recorded on previous experiments, when a timing fiducial was present, indicated that the Al onset time is $\sim$600 ps before the peak of the laser pulse.

Figure 2 shows the measured relative burnthrough times for several series of target shots with SSD bandwidths in the range $\Delta\lambda = (0\text{–}4)\times10^{-4}\lambda$. For the purposes of comparing data from several different shot series, each with slightly different initial conditions, the burnthrough time at zero bandwidth has been defined as 0 ps for each series. Actual zero-bandwidth time delays were $\sim$550 ps between Al and Si emission; i.e., Si onset times were $\sim$50 ps before peak laser power. There are two things to note from Fig. 2. First, for all shot series, we have always seen an improvement in burnthrough time when SSD bandwidth is present, compared to zero-bandwidth shots. Second, the burnthrough times continue to improve as SSD bandwidth is increased, with up to a 200-ps improvement at the maximum measured bandwidth of $4\times10^{-4}\lambda$. Figure 3 shows the measured neutron yield, expressed as a fraction of the one-dimensional yield predicted by LILAC, as a function of SSD bandwidth. In this case there is a noticeable and consistent improvement when bandwidth is present, compared to the no-SSD shots. However, there is not as clear a trend of improving yield with increasing bandwidth as with the burnthrough times, indicating that the neutron yield is not as sensitive an indicator of illumination uniformity as the burnthrough measurement. This is consistent with the idea that the burnthrough time is sensitive to instabilities that develop during the acceleration phase of the implosion. On the other hand, the neutron yield, which occurs much later during the implosion, can be affected by many more physical processes, including additional fluid instabilities that can develop during the deceleration phase. It should also be pointed out that even at a bandwidth of $4\times10^{-4}\lambda$ we observe burnthrough into the glass layer shortly after the peak of the laser pulse, indicating that there still exist substantial perturbations in the target.

The effect of SSD on the burnthrough time is analyzed theoretically with the one-dimensional hydrodynamic code LILAC and a postprocessor that models qualitatively the evolution of the RT instability and calculates a mixing thickness [4]. The model is qualitative in the sense that it assumes that the initial surface perturbation spectrum on the target is proportional to the illumination nonuniformity spectrum and that the mixing thickness is defined as the rms of the mode amplitudes at the ablation surface rather than obtained from a realistic mixing model. Both issues are complex and are the subject of further investigation. The mixing thickness at the ablation surface is calculated using a multimode analysis [14] in which each mode of an initial perturbation spectrum is evolved exponentially with the ablatively stabilized growth rate [15] $\gamma=0.9\sqrt{ka}-3kV_a$, where k is the unstable mode wave number, a is the acceleration, and V_a is the ablation velocity. (For these types of targets, the mixing at the glass/parylene interface is smaller than that at the ablation surface and is, therefore, neglected in the analysis.) Burnthrough time is defined in the model as the time at which the mixing thickness is larger than the distance between the 200-eV isotherm and the glass/parylene interface. Further details on the model can be found in Ref. [4]. The initial perturbation spectra, shown in Fig. 4, were constructed to approximate the measured irradiation uniformity on target [16] as follows:

$$A_{lm}(t=0)=\xi_0[\exp(-S_1 l)+R_2\exp(-S_2 l)]\ \mu\text{m/mode}$$

for $l<35$ and $A_{l,m}=A_{35,m}$ for $35<l<64$, where ξ_0 is the initial perturbation in microns, $S_1=0.13$, $S_2=-0.039$ for zero bandwidth, $S_1=0.20$, $S_2=0.0$ for full bandwidth, and $R_2=\exp[(S_2-S_1)l_0]$, with $l_0=17$. (The modes are assumed to be symmetric in the azimuthal direction.) For $l>64$, the measured spectra were extended to $l=200$ by assuming the same 1% thermal smoothing as in Fig. 1. The value of ξ_0 is normalized to the burnthrough time for the zero-bandwidth case.

The effect of SSD on the burnthrough times can be observed in simulations of the targets described above. Using the zero-bandwidth spectrum in Fig. 4 (curve a), a value for $\xi_0=350$ Å gives a burnthrough time of about -65 ps with respect to the peak of the laser pulse, approximately the time measured in the experiment. Using the maximum-bandwidth spectrum in Fig. 4 (curve b) and the same value for ξ_0 gives a burnthrough time of

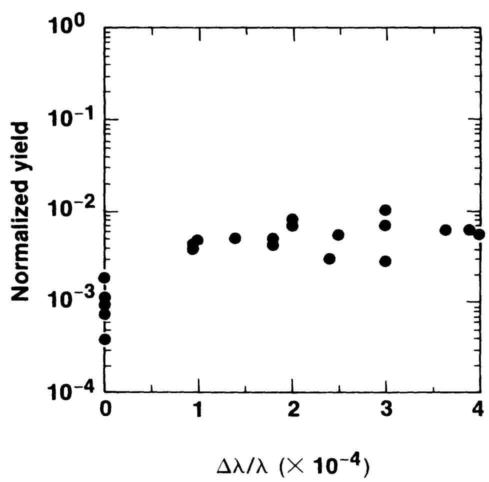

FIG. 3. Normalized neutron yields for the data in Fig. 2 plotted as a function of SSD bandwidth. The normalized yield is expressed in terms of the ratio of the measured yield to the one-dimensional yield predicted by LILAC.

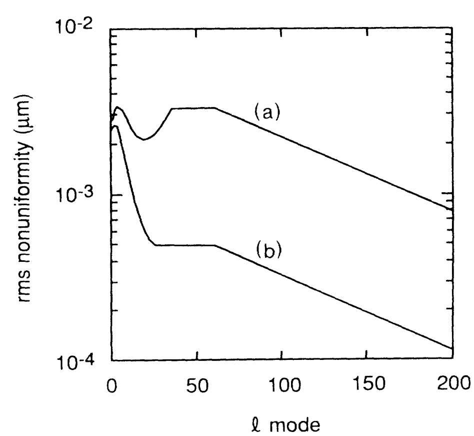

FIG. 4. l-mode distribution of the initial perturbation used in the model to estimate the mixing region thickness. Curve a is for zero bandwidth and curve b is for the maximum-bandwidth case ($\Delta\lambda/\lambda=4\times10^{-4}$).

+95 ps. Thus, when SSD is added to the mixing model by changing the initial spectrum, while keeping the initial perturbation amplitude constant, the burnthrough time is advanced by 160 ps. This value agrees reasonably well with the 200-ps time delay between the zero-bandwidth and the maximum-bandwidth burnthrough times measured in the experiment. Therefore, within the limitations of the mixing model, we have shown qualitatively that improving the illumination uniformity with SSD in the mixing model, through the reduction in the amplitude of modes $l > 10$, accounts for the observed increase in the burnthrough time.

In summary, we have investigated the effect of the drive uniformity improvements resulting from SSD in burnthrough experiments. We had shown in previous work that the burnthrough time is a measure of the evolution of the Rayleigh-Taylor instability at the ablation surface and the glass/parylene interface. Since the evolution does not saturate, it depends on the initial perturbation and should, therefore, be sensitive to the level of illumination nonuniformity. The measured burnthrough times show continued improvement as the SSD bandwidth is increased from zero up to $\Delta\lambda = 4\times 10^{-4}\lambda$, consistent with continually improving uniformity. The neutron yields show an immediate improvement with a small amount of SSD bandwidth present, but do not show a strong bandwidth dependence beyond that. The measured improvements in burnthrough times can be qualitatively reproduced by a postprocessor to the one-dimensional code LILAC that models the evolution of the RT instability, and which includes initial perturbation spectra consistent with the measured change in uniformity.

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