EPJ Web of Conferences **59**, 04003 (2013)
DOI: 10.1051/epjconf/20135904003

Bump evolution driven by the x-ray ablation Richtmyer-Meshkov effect in plastic inertial confinement fusion Ablators

Eric Loomis[1,a], Dave Braun[2], Steven H. Batha[1] and Otto L. Landen[2]

[1]*Los Alamos National Laboratory, Los Alamos, NM 87544, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

Abstract. Growth of hydrodynamic instabilities at the interfaces of inertial confinement fusion capsules (ICF) due to ablator and fuel non-uniformities are a primary concern for the ICF program. Recently, observed jetting and parasitic mix into the fuel were attributed to isolated defects on the outer surface of the capsule. Strategies for mitigation of these defects exist, however, they require reduced uncertainties in Equation of State (EOS) models prior to invoking them. In light of this, we have begun a campaign to measure the growth of isolated defects (bumps) due to x-ray ablation Richtmyer-Meshkov in plastic ablators to validate these models. Experiments used hohlraums with radiation temperatures near 70 eV driven by 15 beams from the Omega laser (Laboratory for Laser Energetics, University of Rochester, NY), which sent a $\sim$1.25 Mbar shock into a planar CH target placed over one laser entrance hole. Targets consisted of 2-D arrays of quasi-gaussian bumps (10 microns tall, 34 microns FWHM) deposited on the surface facing into the hohlraum. On-axis radiography with a saran (Cl $He_\alpha - 2.76$ keV) backlighter was used to measure bump evolution prior to shock breakout. Shock speed measurements were also performed to determine target conditions. Simulations using the LEOS 5310 and SESAME 7592 models required the simulated laser power be turned down to 80 and 88%, respectively to match observed shock speeds. Both LEOS 5310 and SESAME 7592 simulations agreed with measured bump areal densities out to 6 ns where ablative RM oscillations were observed in previous laser-driven experiments, but did not occur in the x-ray driven case. The QEOS model, conversely, over predicted shock speeds and under predicted areal density in the bump.

1. INTRODUCTION

Achieving energy gain through thermonuclear ignition and burn from indirect drive inertial confinement fusion (ICF) is a profoundly difficult task requiring a near perfect chain of events to occur in just 20 ns. The primary physics issues affecting the probability of ignition include implosion velocity, fuel entropy, hot spot radius (perturbed), and mix mass. With computationally validated scaling laws [1] these parameters give an indication of how close to ignition one is in a given implosion. If the fuel is assembled to the right conditions allowing the cryogenic deuterium-tritium (DT) fuel to heat up and sustain a burn wave from alpha particle deposition then a monumental step towards fusion energy will have been attained.

The hydrodynamic perturbation of the capsule that sets the stage for late time mixing of capsule material into the fuel is inherently a three-dimensional problem in most cases and arguably possesses the greatest uncertainties. The increasing implosion velocity and hence decrease in ablator mass remaining at ignition-relevant conditions has resulted in the appearance of ablator material jets penetrating the fuel caused by the 1000-fold Rayleigh-Taylor (RT) growth of isolated defects originally on the capsule outer

[a]e-mail: loomis@lanl.gov

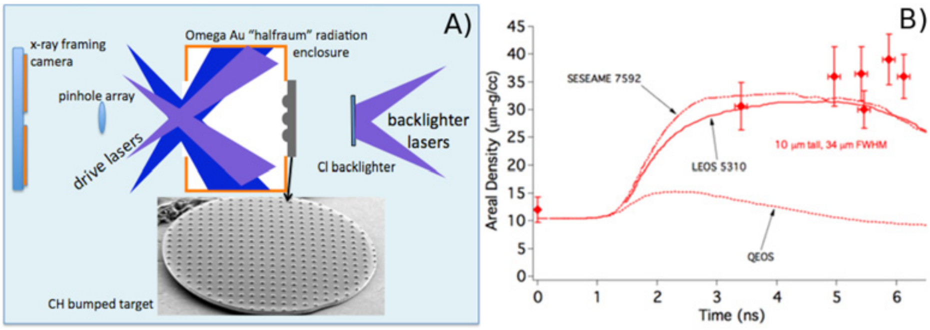

Figure 1. A) Experimental configuration for measuring isolated mass perturbation growth at the Omega laser. Shock speed measurements used identical drive conditions. B) Measured and simulated bump areal density evolution using extended 5 ns laser drive pulse.

surface [2]. High-mode growth of these isolated defects are currently the subject of intense scrutiny from a target fabrication standpoint as well as from the point of view of experimental diagnosis and mitigation. One option for mitigation lies at the heart of the research described in this paper, which is based on the occurrence of decaying oscillations of ablation surface perturbations prior to capsule acceleration referred to as ablative Richtmyer-Meshkov (RM) [3].

Depending on the oscillation frequency of perturbations being indirectly driven by x-ray ablation it is possible to adjust the foot of the ignition pulse so that the perturbation amplitude is minimum at the onset of ablative RT. Before designing methods that use ablative RM as a mitigation strategy, uncertainties in the equation of state (EOS) models must first be resolved. That is the goal of the present experiments described in the next section. In the sections that follow we also discuss differences in x-ray vs. laser-driven ablative RM through numerical simulations of single mode perturbation evolution.

2. MEASUREMENTS OF BUMP AREAL DENSITY EVOLUTION

Experiments at the OMEGA Laser used large diameter (3.6 mm) Au "halfraums" irradiated by fifteen beams pointing symmetrically around the H3-H18 experimental axis in two clusters at 60° and 48° angles to the halfraum axis. Pulse durations for the two beam clusters were each 2.5 ns in which the six low angle beams were delayed by 2.5 ns to the nine high angle beams in order to create and enclose a soft x-ray reservoir heating and driving the areal density evolution of an array of surface bumps on a polystyrene (CH) ablator for over 5 ns. Lasers entered the 2.2 mm long halfraum through a 2.4 mm diameter laser entrance hole (LEH) on the H3 side with a peak power of 900 GW that decreased to 40% by the end of the 5 ns pulse. The CH package was attached over another hole identical to, but opposite the LEH (see Fig. 1 A)). Beam spatial profiles were controlled using distributed phase plate (DPP) focusing optics (700 μm SG4 spot size) resulting in NIC-like first shock laser intensities and M-band preheat levels.

Areal density variations produced by the evolving bumps were measured using on-axis x-ray radiography. Six beams irradiated a saran backlighter on the H18 side of the halfraum at an angle of 23° placed 4 mm from the target. The Cl He$_\alpha$ emission from the saran was recorded by a two-strip x-ray framing camera in H3 after imaging the target using a pinhole array set at 21.5x magnification. Contrast in the recorded images was due to contributions from the rippled shock front as well as the ablation surface profile. The rippled shock is expected to decay rapidly, however, and oscillates at a much faster frequency given by u_s/λ where u_s is the shock speed and λ is the perturbation wavelength [4]. Comparisons to measured areal densities were made with the two-dimensional (axisymmetric) radiation

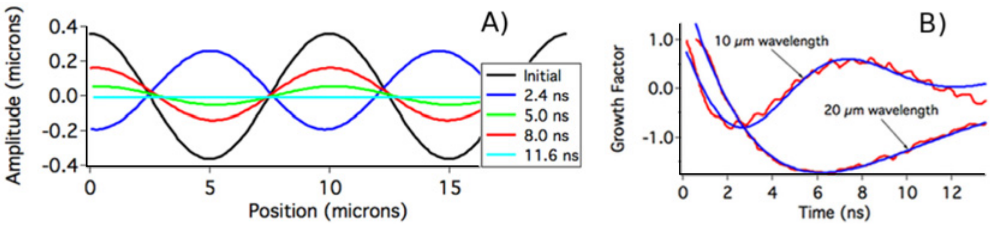

Figure 2. Simulations for short wavelength sinusoid perturbations. A) Ablation surface profiles for a 10 μm wavelength sinusoid using 70 eV drive and B) single mode simulations of growth factor in areal density where the blue curves represent fits to the 10 and 20 μm wavelength perturbations.

hydrodynamics code Lasnex [5]. Details of the analysis procedure for extracting areal densities as well as of the simulations are given in ref. [6].

Experiments using identical drive conditions, but with stepped plastic targets in place of bumped targets established target conditions by measuring shock speed with the OMEGA Active Shock Breakout (ASBO) diagnostic. Laser power in the simulations were adjusted to match the measured shock speeds prior to performing full simulations of the evolving bumps.

3. RESULTS AND DISCUSSION

Figure 1 B) shows the measured and simulated areal densities for 10 μm tall, 34 μm FWHM bumps for the drive conditions described above. The laser power in the simulations were adjusted to 88%, 80%, and 60% for SESAME 7592, LEOS 5310, and QEOS, respectively to match the measured shock velocity of $\sim$15 μm/ns. The bump areal density evolution is characterized by an early time increase from lateral compression of the bump raising its density on-axis as a converging shock first transits the bump [6]. The SESAME and LEOS 5310 models show good agreement with the data, however, QEOS is far below the data due to its lower compressibility. The differences in compressibility along the Hugoniots and isentropes between QEOS and LEOS 5310 does not alone explain the large differences in early time growth factors observed in the simulations and data. If, however, we take into account the converging shock effects in Guderley's formulation [7, 8] then we see that the shock pressure immediately behind the shock front continues to increase as the center of the bump is approached due to convergence effects. This increasing pressure represents higher states along the Hugoniot and likely is more pronounced for more compressible materials. Behind the converging shock adiabatic compression takes place so that each point in the flow follows a different isentrope starting from the pressure and density of the shock at that point. The increasing shock strength due to convergence in more compressible materials leads to greater separation in achievable density between the two different EOS as the converging shock propagates through the bump.

Neither the data or simulations show evidence of ablative RM oscillations occurring out to 6 ns even though Aglitskiy et al. [9] observed them previously in direct laser ablation experiments. The likely cause of this lower oscillation frequency in the current experiments is due to a much lower contribution from "dynamic overpressure" stabilization [3].

To further study oscillation frequencies in x-ray driven ablative RM single mode simulations were performed for the conditions in our OMEGA experiments. Figure 2 B) shows the growth factors (GF) in areal density for 10 and 20 μm wavelength (0.3 μm amplitude) sinusoid perturbations on plastic ablators. The solid blue curves in B) represent the fit to the simulated red curves using a functional form given by

$$GF(t) = \exp(-t/\tau)(A \sin \omega t + B \cos \omega t) \tag{1}$$

where τ is the decay constant and ω is the oscillation frequency. The 10 μm wavelength perturbation shows $\omega = 0.66\,\text{ns}^{-1}$ with a decay constant of 5.3 ns. If the "overpressure" was dominant one would expect an oscillation frequency scaling with the wave number k in units of μm^{-1} as 7k ns^{-1} (the prefactor has units μm/ns) for our experimental conditions [6] although this simulation suggests a scaling of $\sim$k ns^{-1}.

Figure 2 A) shows the evolution of the 95% density contour at the ablation surface for the 10 μm wavelength sinusoid for comparison with the areal density evolution of Fig. 2 B). Ablation surface profiles were extracted near the nodes (5 and 11.6 ns) and anti-nodes (2.4 and 8 ns) of the ablation surface oscillation history. Figure 2 demonstrates that there are slight discrepancies between node and anti-node times at the ablation surface when compared to areal density oscillations since the areal density perturbation includes effects of the rippled shock, which is also oscillating at a different frequency. These discrepancies result in only a small difference in inferred oscillation frequency of the ablation surface profile when measuring the areal density profile.

4. CONCLUSIONS

The growth of isolated defects on the outer surface of plastic ICF ablators during the shock transit (ablative RM) stage of the implosion sets the initial conditions for ablative RT growth once the capsule begins to accelerate. Minimizing the bump amplitudes is therefore important to prevent late time mixing into the hot spot. By adjusting the foot of the ignition pulse it is conceivable that specific unstable high frequency modes can be minimized near the time of shock breakout and capsule acceleration. This first requires gaining a better understanding of ablative RM in the x-ray driven regime.

On-axis x-ray radiography of halfraum driven gaussian bumps showed that simulations using the LEOS 5310 and SESAME 7592 models predict well the ablative RM growth of wide bumps out to 6 ns whereas the QEOS model substantially under predicted areal density growth. The laser power in these simulations were first adjusted to match measured shock speeds. The LEOS 5310 and SESAME 7592 simulations were adjusted to 80% and 88%, respectively relative to the laser power in the experiments.

Single mode simulations showed that the predicted oscillation frequency scaling with wave number was about 7x less than that predicted by theory assuming a dominant "dynamic overpressure" stabilizing mechanism. This suggests that the "dynamic overpressure" is not dominant for x-ray driven ablation.

This work was performed under the auspices of the US Department of Energy for the National Ignition Campaign. We would like to thank the Laboratory for Laser Energetics at the University of Rochester and General Atomics (Abbas Nikroo, Annette Greenwood, Mike Farrell, Noel Alfonso, Kari Moreno) for manufacturing bump and step experimental packages. We also thank Los Alamos National Laboratory Target Fabrication (Derek Schmidt, James Williams, Kimberly Defriend Obrey, and Deanna Capelli MST-7) for target fabrication and metrology as well as Scott Evans, Tom Sedillo, and Joe Cowan (P-24) for diagnostic support. Thanks to John Kline (LANL) for performing Dante analysis.

References

[1] D.S. Clark, S.W. Haan, J.D. Salmonson, Phys. Plasmas **15**, 056305 (2008)
[2] B.A. Hammel, S.W. Haan, D.S. Clark, M.J. Edwards, S.H. Langer, M.M. Marinak, M.V. Patel, J.D. Salmonson, H.A. Scott, High Energy Density Physics **6**, 171-178 (2010)
[3] V.N. Goncharov, O.V. Gotchev, E. Vianello, T.R. Boehly, J.P. Knauer, P.W. McKenty, P.B. Radha, S.P. Regan, T.C. Sangster, S. Skupsky, V.A. Smalyuk, R. Betti, R.L. McCrory, D.D. Meyerhofer, C. Cherfils-Clerouin, Phys. Plasmas **13**, 012702 (2006)

[4] P.M. Celliers, D.J. Erskine, C.M. Sorce, D.G. Braun, O.L. Landen, G.W. Collins, Rev. Sci. Inst. **81**, 035101 (2010)
[5] G.B. Zimmerman and W.L. Kruer, Comments Plasma Phys. Controlled Fusion **2**, 51-61 (1975)
[6] E.N. Loomis, D. Braun, S.H. Batha, C. Sorce, O.L. Landen, Phys. Plasmas **18**, 092702 (2011)
[7] S. Atzeni and J. Meyer-Ter-Vehn, *The Physics of Inertial Fusion* (Oxford Science Publication), 170-190 (Oxford 2004)
[8] R.A. Axford, Laser and Particle Beams **18**, 93-100 (2000)
[9] Y. Aglitskiy, A.L. Velikovich, M. Karasik, V. Serlin, C.J. Pawley, A.J. Schmitt, S.P. Obenschain, A.N. Mostovych, J.H. Gardner, N. Metzler, Phys. Rev. Letts. **87**, 265001 (2001)