

## Implosion Experiments using Glass Ablators for Direct-Drive Inertial Confinement Fusion

V. A. Smalyuk, R. Betti,\* J. A. Delettrez, V. Yu. Glebov, D. D. Meyerhofer,\* P. B. Radha, S. P. Regan, T. C. Sangster, J. Sanz,† W. Seka, C. Stoeckl, and B. Yaakobi

*Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623-1299, USA*

J. A. Frenje, C. K. Li, R. D. Petrasso,‡ and F. H. Séguin

*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

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Direct-drive implosions with 20- $\mu\text{m}$ -thick glass shells were conducted on the Omega Laser Facility to test the performance of high- $Z$  glass abulators for direct-drive, inertial confinement fusion. The x-ray signal caused by hot electrons generated by two-plasmon-decay instability was reduced by more than  $\sim 40\times$  and hot-electron temperature by  $\sim 2\times$  in the glass compared to plastic abulators at ignition-relevant drive intensities of  $\sim 1 \times 10^{15} \text{ W/cm}^2$ , suggesting reduced target preheat. The measured absorption and compression were close to 1D predictions. The measured soft x-ray production in the spectral range of  $\sim 2$  to 4 keV was  $\sim 2\times$  to  $3\times$  lower than 1D predictions, indicating that the shell preheat caused by soft x-rays is less than predicted. A direct-drive-ignition design based on glass abulators is introduced.

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The goal of inertial confinement fusion (ICF) [1,2] is to implode a spherical target to achieve high compression of the fuel and high temperature in the hot spot to trigger ignition and maximize the thermonuclear energy gain. To achieve high compression, the shell entropy and temperature must remain low because it is easier to compress the fuel at a low temperature than at a high temperature [2]. The entropy is defined [3] by adiabat  $\alpha = P(\text{Mb})/[2.2\rho(\text{g/cc})^{5/3}]$ , the ratio of the plasma pressure to the Fermi pressure of a fully degenerate electron gas [3]. In direct-drive spherical implosions, the target is driven by direct illumination with overlapped laser beams. To ignite DT fuel on the National Ignition Facility (NIF) [2] with a laser energy of  $E_L = 1.5 \text{ MJ}$  and to achieve a gain of  $\sim 40$  to 50 will require high fuel compression with a total target areal density ( $\rho R$ ) of  $\sim 1500 \text{ mg/cm}^2$  [4]. As shown in Ref. [3],  $\rho R(\text{mg/cm}^2) \approx 2600 E_L(\text{MJ})^{1/3} \alpha^{-0.6}$  so high areal densities require low-adiabat,  $\alpha \leq 3$  implosions. The fuel adiabat is determined by shocks launched at the beginning of the implosion [2]. The shock waves must be precisely tuned to set the inner portion of the shell on a low adiabat. Adiabat control is critical to achieving the desired  $\rho R$  at peak compression [1,2]. Shock mistiming was an important cause of  $\rho R$  degradation in direct-drive, cryogenic implosions on OMEGA and a subject of intensive research [5,6]. Another area of concern to ICF is the unstable growth of target modulations caused by hydrodynamic instabilities [1,2]. While the areal densities at peak compression have been shown to be relatively insensitive to hydrodynamic instabilities, the fusion neutron yields are very sensitive [7]. Shell preheat, another source of compression degradation, is caused by hot electrons generated by two-plasmon-decay (TPD) instability [8,9]. This preheat was shown to be virulent in DT and  $D_2$

abulators [6,10] and was reduced by using plastic abulators [6,11]. The highest ignition-relevant areal densities with a shell  $\rho R$  of  $\sim 200 \text{ mg/cm}^2$  were achieved in cryogenic  $D_2$ -ice implosions with plastic abulators, when the hot-electron preheat was suppressed, at a moderate laser-drive peak intensity of  $\sim 5 \times 10^{14} \text{ W/cm}^2$  and a laser energy of  $\sim 16 \text{ kJ}$  on OMEGA [11]. Because of the moderate laser-drive intensity, the implosion velocity of  $\sim 2.4 \times 10^7 \text{ cm/s}$  was lower than required for ignition on the NIF ( $3.5$  to  $4 \times 10^7 \text{ cm/s}$ ) [4]. Increasing the peak intensity to  $\sim 1 \times 10^{15} \text{ W/cm}^2$  allows the implosion velocity to be raised to levels required for ignition, but hard x-ray signals, associated with TPD hot electrons, increase with laser intensity [6,10,11]. Current hot-electron preheat estimates in plastic-ablator OMEGA implosions (with the estimated cold-shell preheat energy fraction of  $\sim 0.1\%$  of the total laser energy) may not preclude achieving ignition-relevant compression (with a shell  $\rho R$  of  $\sim 200 \text{ mg/cm}^2$ ) at high peak intensities of  $\sim 1 \times 10^{15} \text{ W/cm}^2$  and a slightly lower initial shell adiabat of  $\alpha \sim 2$  [6]. The longer plasma scale lengths in the larger NIF targets make them potentially more susceptible to hot-electron production than OMEGA targets [10]. While the very complex nature of nonlinear TPD instability makes it difficult to reliably predict hot-electron preheat, it is important to explore new abulators that mitigate hot-electron preheat compared to plastic abulators. Based on the reduced preheat levels measured in plastic (CH) with respect to  $D_2$  abulators, it is plausible to expect further preheat mitigation in higher- $Z$  abulators such as doped plastic, glass, or others. Plastic abulators with 5% by atom of Si dopant were studied [12] for this purpose, but the preheat reduction was insignificant at peak intensities of  $\sim 1 \times 10^{15} \text{ W/cm}^2$ . This Letter presents the first experimental results using a glass ( $\text{SiO}_2$ ) abulators that show

significant hot-electron-preheat reduction at peak intensities of  $\sim 1 \times 10^{15}$  W/cm<sup>2</sup>. A direct-drive-ignition design based on the glass ablator is introduced. The first results show that there is a scientific basis to develop this concept further, and to understand all other aspects of ignition design including setting appropriate adiabat, mitigating hydroinstabilities, understanding laser-plasma interactions, etc.

Spherical 20- $\mu$ m-thick glass shells with  $\sim 860$ - $\mu$ m-initial-diam, filled with 20 arm of  $D_2$  gas, were imploded on the 351-nm, 60-beam Omega Laser System [13]. The targets were driven by two shaped pulses at peak laser intensities of  $\sim 5 \times 10^{14}$  and  $\sim 1 \times 10^{15}$  W/cm<sup>2</sup>. The on-target energies were  $\sim 21$  kJ in midintensity implosions and  $\sim 26$  kJ in high-intensity implosions. All of the experiments used distributed phase plates (DPP's) [14] and polarization smoothing (PS) [15], using birefringent wedges. The goal of these experiments was to measure target performance with glass ablators, hard x-ray signals produced by hot electrons from TPD instability in glass implosions and to compare them with those from plastic implosions. A secondary goal was to measure soft x-ray production in the plasma corona (in the photon-energy range from 1 to 6 keV) and compare them with 1D predictions. The soft x rays in this photon-energy range are a potential source of fuel preheat in high-Z ablators because their production is stronger than in low-Z ablators. The hard x-ray signals (with photon energies of  $>40$  keV) generated by hot electrons from TPD instability were measured by the hard x-ray (HXR) detector [16]. The HXR detector has four channels that measure x rays  $>20$ ,  $>40$ ,  $>60$ , and  $>80$  keV, respectively. The soft x-ray signals were measured by the Dante detector [17] with 8 channels in the photon-energy range from 1 to 6 keV. The target areal density at peak compression was used as a diagnostic of preheating by comparing the measured  $\rho R$  with its predicted value. The burn-averaged areal densities were inferred from the spectra of secondary protons [18] created by fusion reactions near peak burn. The 20- $\mu$ m-thick targets kept the shell convergence ratio (the ratio of the initial inner shell radius to that at peak compression) low, about  $\sim 8$ , so the effects of hydrodynamic

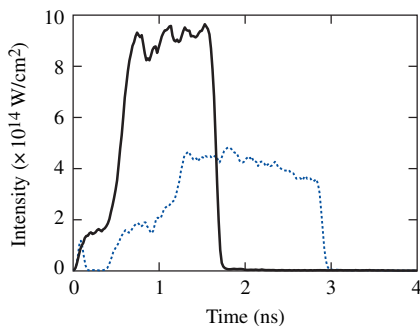


FIG. 1 (color online). Pulse shapes used in mid- and high-intensity glass implosions.

modulation growth on areal density were minimized. The predicted areal densities, based on the 1D hydrodynamic code LILAC [19], including radiation transport, were in the range of  $\sim 150$  to  $170$  mg/cm<sup>2</sup>. Areal density at peak compression only weakly depends on drive energy or peak laser intensity while it strongly depends on shell adiabat set by the shocks at the beginning of the drive.

Figure 1 shows the pulse shapes used in mid- and high-intensity glass-target implosions. The hard x-ray signals caused by hot electrons were reduced by  $\sim 40\times$  in the glass implosions compared to plastic implosions at highest laser energies. The measured hot-electron temperatures were reduced in glass to  $35 \pm 5$  keV versus  $75 \pm 10$  keV in plastic. Based on preheat model in Ref. [20], the preheat in glass ablators was reduced more than an order of magnitude compared to plastic ablators at ignition-relevant intensity  $\sim 1 \times 10^{15}$  W/cm<sup>2</sup>. In addition, increased electron scattering in high-Z ablators reduced the number of hot electrons reaching and preheating the inner shell compared to low-Z ablators [20]. There was no hard x-ray signal detected in low-energy glass implosions. The possible explanations of reduced preheat in high-Z ablators are (1) higher TPD thresholds and decreased growth rates caused by increased collisional plasma wave damping, and (2) saturation at lower laser intensities caused by decreased damping of the ion waves that can saturate the TPD via Langmuir decay instability [21]. The measured and predicted [19] soft x-ray emissions are shown in Fig. 2(a), at peak laser power (1.5 ns) when the emission is the strongest, for one of the high-intensity implosions. The measured x-ray radiation is  $\sim 2\times$  to  $3\times$  lower than predicted in the energy range of 1 to 6 keV—a range critical to soft x-ray preheat of the bulk of the target. The

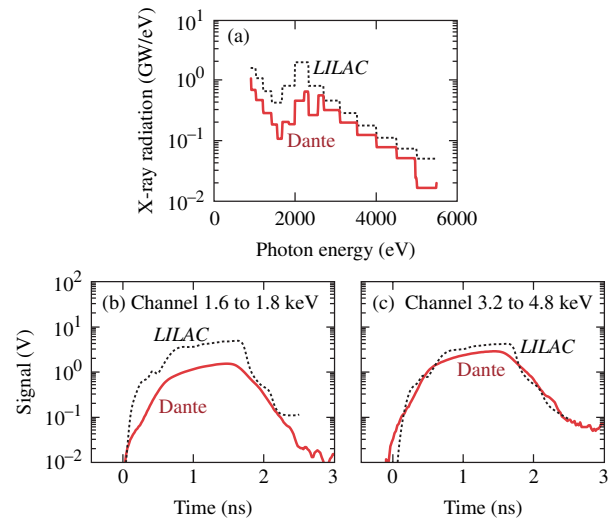


FIG. 2 (color online). (a) The measured and predicted spectra of soft x-ray emission at 1.5 ns for one of the high-intensity implosions. Comparison of measured and predicted x-ray signals in two channels with photon energies of (b) 1.6 to 1.8 keV and (c) 3.2 to 4.8 keV.

spectra were constructed using 8 channels of the x-ray detector Dante [17] covering the x-ray energy range from  $\sim 1$  to 6 keV in these experiments [22]. Figure 2 compares measured and predicted x-ray Dante signals in two representative channels with photon energies from 1.6 to 1.8 keV [Fig. 2(b)] and 3.2 to 4.8 keV [Fig. 2(c)]. The measured emission does not exceed predicted levels implying that the glass capsules are not being excessively preheated by soft x rays, compared to 1D simulations. This result is important because it validates the LILAC predictions [19] that the fuel will not be preheated by the soft x rays in an ignition design with glass ablators for the NIF-like energies as discussed later. Figure 3(a) shows the measured versus predicted peak-burn areal densities for both midintensity (triangles) and high-intensity (diamonds) implosions. The triangle data point was integrated over three shots to improve signal-to-noise ratio in low-yield, midintensity implosions. Preheating can significantly reduce shell areal density by many times. Our measurements show that when preheating is mitigated, measured areal density can be within  $\sim 16\%$  of predicted. This indicates that the inner shell is not preheated by hot electrons or soft x-rays. The  $\sim 16\%$  deviation, while tolerable in ignition designs, indicates that other physics (most probably shock timing, which sets up the shell adiabat) should be further addressed in future experiments. Radiation-hydrodynamic physics in LILAC included self-opacity effects in  $\text{SiO}_2$  layer, but the observed difference in soft x-ray emission between experimental measurements indicates that the radiation transport modeling may also have to be improved in LILAC. Figure 3(b) shows that

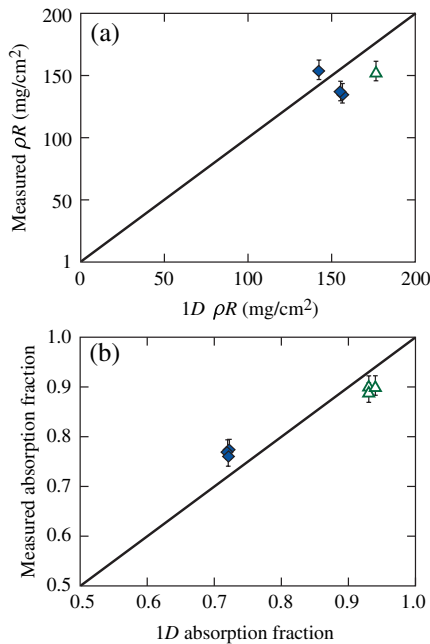


FIG. 3 (color online). Measured versus predicted (a) peak-burn areal densities and (b) laser-absorption fractions for midintensity (triangles) and high-intensity (diamonds) implosions.

measured laser-absorption fractions are in good agreement with the simulated values for both types of implosions. The absorption fractions in glass ablators are  $\sim 10\%$  higher than those in plastic ablators at ignition-relevant intensities caused by higher  $Z$  in the corona.

Based on these results from OMEGA glass-shell implosions an ignition design for the NIF based on a glass ablator is introduced. Figure 4(a) shows the drive pulse shape and a target schematic. The 1600- $\mu\text{m}$ -radius target has a 35- $\mu\text{m}$ -thick outer glass-ablator shell enclosing a 80- $\mu\text{m}$ -thick DT-fuel shell. The target is driven by a shaped, 10-ns pulse with a total laser energy of 1.5 MJ and a peak intensity of  $\sim 8.7 \times 10^{14}$  W/cm<sup>2</sup>. The predicted gain of this 1D ignition design is 27. Figure 4(b) compares the density profiles of ignition designs with all-DT (dashed curve) [4] and glass-ablator (solid curve) targets taken near the end of their acceleration phases at the same distance traveled. The profile of the glass-ablator design shows a double ablation front [23]: the outer front is driven by the electron conduction (the same mechanism that drives all-DT and plastic targets), the inner ablation front is driven by the x rays generated in plasma corona and

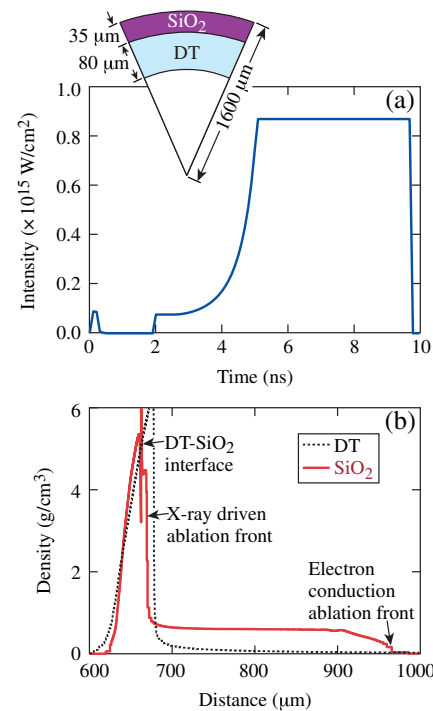


FIG. 4 (color online). (a) The schematic of the glass-ablator ignition target with a radius of 1600  $\mu\text{m}$ , a 35- $\mu\text{m}$ -thick outer glass-ablator shell followed by an 80- $\mu\text{m}$ -thick DT-ice shell. The target is driven by a 10-ns pulse with a total laser energy of 1.5 MJ and a peak intensity of  $\sim 8.7 \times 10^{14}$  W/cm<sup>2</sup>. The predicted gain in this 1D ignition design is 27. (b) Comparison of the density profiles of ignition designs with all-DT (dashed curve) and glass-ablator (solid curve) targets taken near the end of their acceleration phases. The profile of the glass-ablator design shows a double ablation front.

absorbed within a glass ablator. As a result of this double ablation front [23], the glass-ablator target is  $\sim 5\times$  thicker (calculated from electron-conduction ablation surface to back surface of the shell) than a DT target during its acceleration phase, making it more robust with respect to hydrodynamic instabilities. These predictions will be tested in future OMEGA experiments. While the hot-electron preheat was reduced in glass ablaters on OMEGA, experiments with larger plasma scale lengths need to be conducted in the future to test hot-electron preheat in conditions closer to NIF-scale targets.

In conclusion, direct-drive implosions with 20- $\mu\text{m}$ -thick glass shells were performed on the 351-nm OMEGA Laser Facility to test the performance of the high-Z ablator concept for direct-drive ICF. The shell preheat caused by hot electrons generated by two-plasmon decay (TPD) instability was reduced by more than an order of magnitude and hot-electron temperature by  $\sim 2\times$  in the glass compared to plastic ablaters at an ignition-relevant drive intensity of  $\sim 1 \times 10^{15} \text{ W/cm}^2$ . The measured absorption and compression were close to 1D predictions, while the measured soft x-ray production was  $\sim 2\times$  to  $3\times$  times lower than 1D predictions in the spectral range of  $\sim 2$  to 4 keV, relevant to soft x-ray preheat. A direct-drive-ignition design based on the glass ablator was described.

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\*Also at Departments of Mechanical Engineering and Physics & Astronomy, University of Rochester, Rochester, NY, USA.

<sup>†</sup>Also at ETSI Aeronauticos, Universidad Politecnica de Madrid 28040, Spain.

<sup>‡</sup>Visiting scientist from Laboratory for Laser Energetics, University of Rochester, Rochester, NY, USA.

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