The role of fast-electron preheating in low-adiabat cryogenic implosions on OMEGA

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Abstract. The compression in direct-drive, low-adiabat spherical implosions was studied using cryogenic D_2 targets on the 60-beam, 351-nm OMEGA laser in the range of laser intensities from ~3 × 10^{14} to ~1.5 × 10^{15} W/cm^2. The neutron-burn–averaged areal densities decreased as the laser intensity increased. This decrease in areal density is highly correlated with the increased hard-x-ray signals, caused by hot electrons generated by the two-plasmon-decay instability. The areal-density reduction up to ~2, observed in the experiments, requires a preheat energy of ~60 J (~0.3% of total laser energy), which is consistent with the estimated preheat levels inferred from the hard-x-ray signal levels. Mitigating the generation of fast-electrons results in high areal densities which are close to the 1D predictions.

The baseline direct-drive-ignition target design [1] for the NIF uses a cryogenic deuterium–tritium (DT) shell imploded with a total energy up to 1.5 MJ. To achieve the high areal densities (ρR) required for ignition and gain requires laser pulse shapes that drive the capsule on a low-adiabat (α) since $\rho R \sim 1/\alpha^{0.6}$ [2]. Here α = P(Mb)/2.3ρ (g/cc)$^{5/3}$ is the ratio of the pressure to the Fermi pressure [3]. The goal of the OMEGA cryogenic-implosion program is to validate the predicted performance of low-adiabat implosions. The cryogenic target experiments described here use low-adiabat laser pulses, D_2 fuel as a surrogate to DT, and peak laser intensities varying from 2.5 × 10^{14} to 1.5 × 10^{15} W/cm^2. Figure 1 shows the measured ρR as a function of the predicted ρR for implosions done at high laser intensities (~10^{15} W/cm^2). As the adiabat decreases, the measured ρR does not rise as expected, saturating at ~100 mg/cm^2, and a degradation of up to a factor of 2 to 3 from 1-D predictions is observed at the lowest adiabats. Based on the analysis of the data, it was concluded that the most likely explanation of the observed ρR degradation is hot-electron preheating during the peak of the laser intensity. The long mean-free-path hot electrons are produced by laser–plasma instabilities such as the two-plasmon-decay (TPD), and raise the adiabat by depositing their energy in the cold shell. Experiments carried out on OMEGA using CH and cryogenic targets [4,5] showed a clear

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signature of hot electrons preheating at T_{hot} > 50 KeV at intensities above ~5 × 10^{14} W/cm^2, through the hard-x-ray (HXR) signal, which was correlated with the 3/2ω-emission signature of the TPD.

The target heating required for such a severe ρR degradation can be estimated using the scaling [2] $\rho R \sim \alpha^{(-0.6)}$. A decrease in ρR of about 2 requires an increase in α by a factor of about 3. For a typical α ~ 3 implosion, this means an increase in the shell temperature from about 25 eV to 50 eV, requiring a preheat energy of the order of 60 J, or 0.3% of the incident laser energy. The hot-electron generation by TPD depends strongly on laser intensity, plasma-scale length, temperature, and composition [4,5]. For long-pulse implosions the threshold intensity for the TPD instability can be as low as ~2 × 10^{14} W/cm^2.

In the work described here, direct-drive implosions of ~860-μm-diam targets with ~95-μm-thick inner D_2-ice layer and outer 4-μm-thick plastic CD overcoat were carried out using the 351-nm, 60-beam OMEGA Laser System. The targets were imploded with shaped, high-compression pulses with peak intensities from ~3 × 10^{14} to ~1.5 × 10^{15} W/cm^2, energies from 13 kJ to 25 kJ, and adiabats from 1.3 to 3. Those shots produced measurable areal-density and hot-electron-preheat data. The areal densities predicted by the 1-D code *LILAC* ranged from ~140 to ~200 mg/cm^2. The measured HXR signals (with photon energies of >40 keV) generated by hot electrons are shown in Fig. 2 together with the measured hot-electron temperatures as a function of laser intensity. The HXR signal steeply rises with intensities in the range of ~3 × 10^{14} to ~5 × 10^{14} W/cm^2 and it saturates above ~10^{15} W/cm^2. The hot-electron temperature increases monotonically from 50 to 170 keV. The HXR signal occurred at the last ~600 ps of the laser drive, indicating that most hot electrons generated late in the laser pulse, when the CD was already ablated away and the laser was mainly interacting with the deuterium plasma.

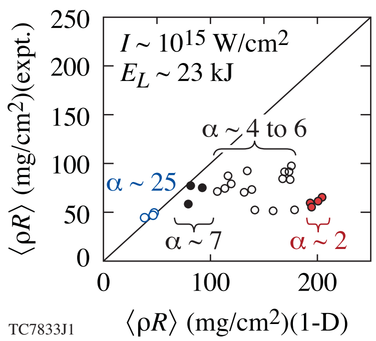

Figure 1. Measured ρR versus the predicted value for cryogenic implosions at high intensity (~10^{15} W/cm^2) and energy (~23 kJ).

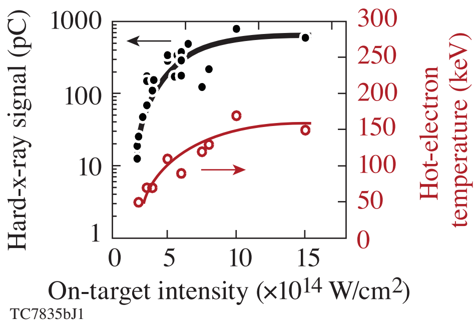

Figure 2. Measured hard-x-ray signal and hot-electron temperature versus laser intensity.

The measured areal density is plotted as a function of laser intensity, shown by diamonds and triangles, in Fig. 3(a) together with the HXR signals. The diamonds represent data measured from the spectra of secondary protons [6] created near peak burn, while triangles represent data measured from x-ray spectra [7] near peak x-ray production (close to peak burn). While HXR signals and hot-electron temperature monotonically increase with the laser intensity, the ρR decreases. The predicted peak-burn areal density varies from ~140 to ~200 mg/cm^2. Figure 3(b) shows the dependence of the measured ρR normalized with the 1-D prediction as a function of the laser intensity using the same data as in Fig. 3(a). As seen in Figs. 3(a) and 3(b), this degradation strongly correlates with the increase in the HXR signals. The highest compression in low-adiabat implosions was achieved at low intensities of ~3 × 10^{14} W/cm^2 with areal densities of the order of 150 mg/cm^2 and their values close to 1-D predictions.

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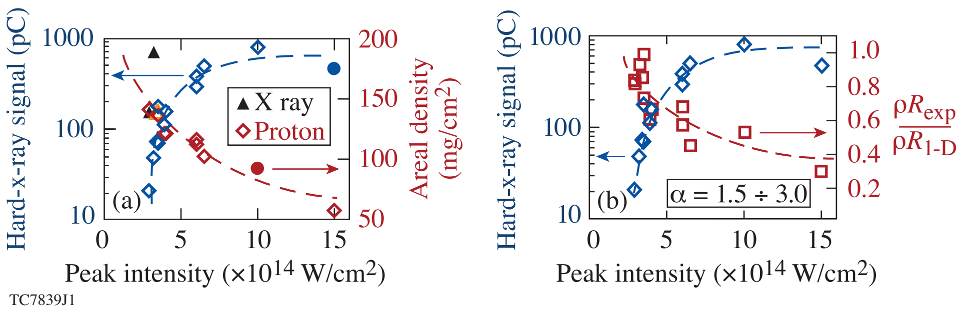

Figure 3. (a) Measured peak-burn areal density and hard-x-ray signal as a function of peak intensity for low-α implosions.(b) ρR over 1-D prediction and hard-x-ray signal as a function of peak intensity.

A simple estimate of the areal-density degradation $\rho R_{\text{exp}}/\rho R_{1\text{-D}}$ of the cold-shell is carried out by treating the plasma as an ideal gas and assuming uniform deposition of the preheat energy H_s (in J) over the unablated shell (about 50% of the initial mass). Such a model yields a ρR degradation:

$$\rho R_{\text{exp}}/\rho R_{1\text{-D}} \approx 1\Big/\left[1+0.012\,H_s\Big/\left(0.5\alpha^{3/5}I_{15}^{4/15}\right)\right], \tag{1}$$

where I_{15} is the intensity in 10^{15} W/cm^2. Figure 4 compares Eq. (1) with 1-D simulations results including fast-electron transport for several cryogenic implosions. Figure 4(a) shows that ~70 J are needed to degrade ρR by a factor of about 2 and that the results are in good agreement with Eq. (1) [see Fig. 4(b)].

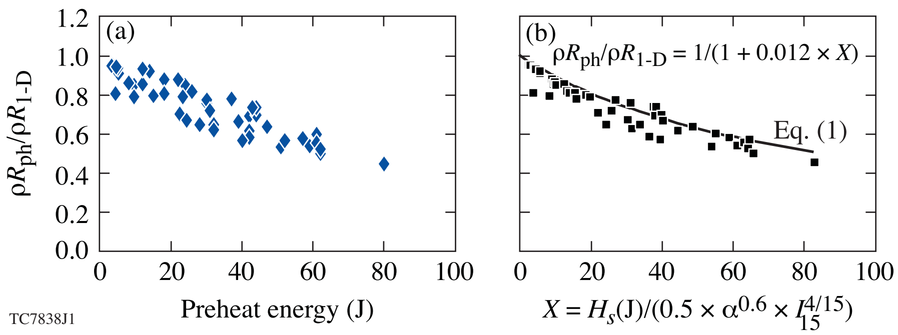

Figure 4. (a) ρR degradation versus preheat energy in dense D_2 shell from simulations. (b) The fit of areal-density degradation from the simulations [shown in (a)] to the theoretical prediction of Eq. (1).

Equation (1) is now used to estimate the amount of preheat energy H_s necessary to degrade the observed compression performance $\rho R_{\text{exp}}/\rho R_{1\text{-D}}$ as in Fig. 3. Figure 5(a) plots this estimate as a function of peak laser intensity (black dots). The required preheat energy needed to reduce the 1-D ρR to the experimental values are highly correlated with the HXR signals for the same shots (red dots).

The preheat energy is inferred from the HXR signals as shown in Ref. 5. This HXR signal comes from ablated CD and D_2 and from the cold-shell D_2. Based on simulations, at the end of the laser drive about 1/2 of the total target mass is in the cold D_2 shell, 1/4 in the ablated D_2, and 1/4 is in the ablated CD. Since fast electrons with $E > 50$ keV have a mean free path greater than the shell thickness during the laser pulse the preheating per unit mass at $T_{\text{hot}} \gtrsim 100$ keV is about constant. Assuming that the HXR-emission rate in CD is higher by about a factor of 3 than that in D_2 (due to Z dependence), one can estimate that about 1/2 of the HXR's are produced in the D_2, while only ~2/3 of the HXR's from the D_2 are produced in cold-shell D_2 (i.e., 1/3 of the total HXR's are produced in the dense D_2 layer).

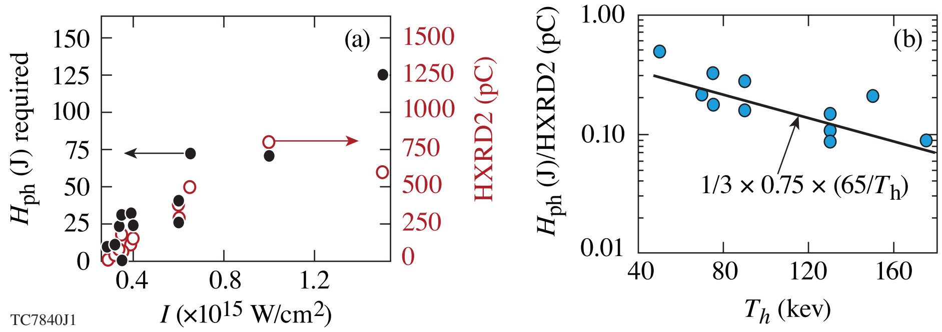

Figure 5. (a) Preheat energy required to explain the observed ρR degradation shown in Fig. 3(b), using Eq. (1), and HXR signal as a function of intensity. (b) The ratio of the required preheat energy in (a) to the HXRD signal (>40 keV) and estimated ratio (black line) based on Ref. 5 as a function of T_{hot}.

The correspondence between the HXR signal in pC and the energy deposited in pure D_2 is given in Ref. 5 and can be approximated as E_{dep}(J)/HXRD(pC) ~ 0.75 × [65/T_{hot} (KeV)]. If 1/3 of the total HXR's are produced in the dense D_2 layer, the preheat energy deposited in the dense D_2 layer is E_{dep}(J) ~ 1/3 × 0.75 × [65/T_{hot} (KeV)] × HXR D_2(pC). This estimation is compared in Fig. 5(b) with the ratio of H_s(J)/HXRD(pC) for the implosions shown in Fig. 5(a). Even though the total uncertainty of the estimated electron preheating, due to uncertainties in the electron transport and the HXR production models as well as the uncertainty in the absolute calibration of the HXR detector, is estimated to be within a factor ~2. The strong correlation of the performance degradation with the HXR signal together with the quantitative agreement of the preheat estimates with the theoretical predictions, suggests that hot-electron preheat is the major factor causing the compression degradation of cryogenic D_2 implosions. It was also observed that the HXR is greatly reduced in CD ablators (~5 to 10 times lower) with respect to D_2 ablators at intensities of 5 × 10^{14} W/cm^2. Such intensities have been recently used to implode cryogenic shells with a thicker CD ablator (~10 μm) without producing high-HXR signals (since the ablator material was CD throughout the implosion process), resulting in an areal density of ~200 mg/cm^2, close to 1-D predictions [8]. In conclusion, preheating by hot electrons generated by TPD instability plays an important role in the compression degradation of low-adiabat cryogenic D_2 implosions. Mitigating the fast-electron generation from TPD results in high areal densities that are close to 1-D predictions.

Acknowledgment
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References
[1] McKenty P W *et al.*, 2001 *Phys. Plasmas* **8** 2315
[2] Zhou C D and Betti R 2007 *Phys. Plasmas* **14** 072703
[3] Lindl J D *et al.*, Phys. Plasmas **11**, 339 (2004)
[4] Stoeckl C *et al.*, 2003 *Phys. Rev. Lett.* **90** 235002
[5] Yaakobi B *et al.*, 2005 *Phys. Plasmas* **12** 092703
[6] Séguin F H *et al.*, 2003 *Rev. Sci. Instrum.* **74** 975
[7] Yaakobi B, Epstein R and Marshall F J 1991 *Phys. Rev. A* **44** 8429
[8] Harding D R *et al*. Cryogenic target implosion experiments on OMEGA this proceedings; Goncharov V N *et al*. Modeling high-compression, direct-drive, ICF experiments this proceedings