Direct Measurements of DT Fuel Preheat from Hot Electrons in Direct-Drive Inertial Confinement Fusion

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The generation of hot electrons from laser–plasma interactions has been a longstanding issue for inertial confinement fusion experiments since the early days of the field. Hot-electron preheat increases the entropy (adiabat) of the imploding shell, thereby degrading the final compression and quenching the ignition process. It is one of the major obstacles to ignition via laser direct drive. This summary describes the first direct measurement of the energy deposited by hot electrons into the DT fuel and its spatial distribution within the fuel. All previous attempts to measure preheat assessed only the conversion of laser energy into hot electrons. Since only a small fraction of the total hot-electron energy is deposited into the fuel, previous measurements could not be used to assess fuel preheat and areal-density degradation. This measurement is essential to understanding the effective adiabat (increased by preheat) of the imploding DT shell and the implosion performance. This important issue is addressed by presenting a new technique that can be used to quantify the hot-electron preheat energy deposited into the dense DT fuel for all laser-fusion schemes.

It is shown that, in direct-drive experiments, the hot-electron energy deposited in the DT fuel can be inferred by comparing the hard x-ray signals between a layered DT implosion and its mass-equivalent all-CH implosion irradiated with the same pulse shape. Since the hot-electron source is the same between the two implosions, the difference in hard x-ray signals is proportional to the preheat energy deposited in the DT layer. However, since a significant fraction of the ice layer is ablated during the implosion, it is important to also assess the preheat energy into the unablated fuel, which determines the final areal density. In Fig. 1, the relationship between the degradation in areal density due to preheat is plotted as a function of the preheat energy into the stagnated shell $\left(E_{\text{stag}}^{\text{preheat}}\right)$ normalized to its internal energy (IE_{shell}) for a simulation ensemble of *LILAC* simulations of different targets. Estimating the areal-density degradation due to preheat therefore requires an additional model to describe the spatial distribution of the preheat energy within the fuel.

The spatial distribution of preheat energy was inferred in two experimental campaigns on OMEGA using warm CH targets with Cu-doped plastic payloads of varying thicknesses. The hard x rays from the Cu-doped plastic implosions were used to infer the hot-electron energy deposited in each layer. Post-shot analysis of the hard x-ray signals from these experiments confirmed that the electrons deposit their energy uniformly throughout the unablated mass. Therefore, the energy deposited into the unablated DT can be determined simply by calculating the energy deposited into all of the DT and multiplying by the unablated DT mass ratio. The final results, reported in Table I, show that the preheat analysis presented here explains the observed degradations in areal density with respect to their 1-D simulated values.

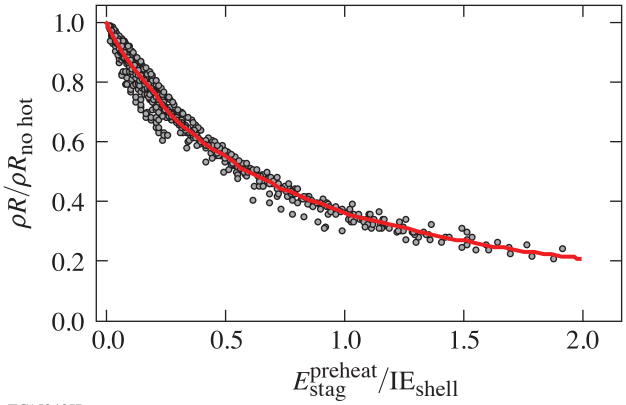

Figure 1
Areal-density degradation versus preheat energy into the stagnated shell preheat $\left(E_{\text{stag}}^{\text{preheat}}\right)$ normalized to the shell internal energy at peak velocity (IE_{shell}) for a large ensemble of *LILAC* simulations with preheat energies ranging from 0 to 100 J and design adiabats between 2 and 5.5. The red curve is the best fit to the simulation data.

Table I: Areal-density (ρR) degradation for OMEGA DT-layered $\alpha \approx 4$ implosions.

Shot number	77064	85784	91830	91834
$E_{\text{DT}}^{\text{preheat}}$ (J)	13.0±4.8	21.5±7.1	48.±11.5	40.5±13.7
$E_{\text{stag}}^{\text{preheat}}$ (J)	4.9±2.1	7.5±2.5	15.0±4.7	11.6±3.9
IE_{shell} (J)	43.0	43.0	48.1	48.0
ρR_{exp} (mg/cm^2)	201±17	154±13	120±9	127±11
$\rho R_{\text{1-D}}$ (mg/cm^2)	225	186	184	188
ρR_{hs} (mg/cm^2)	190±16	156±13	124±15	135±155

The same technique is now being implemented at the National Ignition Facility (NIF) to measure preheat at megajoule laser energies and will be used to assess the viability of direct-drive designs, which may convert more laser energy into hot electrons as the size of the laser facility scales up. Quantifying how preheat scales from OMEGA to the NIF will have important implications for the design of direct-drive implosions on the NIF and the assessment of the next-generation inertial fusion facility. This technique also opens up new research avenues with respect to the design of direct-drive targets on OMEGA and, more specifically, the effects of different pulse shapes, ablator materials, and beam spot sizes on DT fuel preheat.

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