Measurements of Low-Mode Asymmetries in the Areal Density of Laser-Direct-Drive Deuterium–Tritium Cryogenic Implosions on OMEGA Using Neutron Spectroscopy

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The OMEGA laser is used to study direct-drive inertial confinement fusion (ICF) by symmetrically irradiating a thin shell target with nominally identical laser beams. The shell is comprised of an outer plastic ablator (<10 μm) and a layer of cryogenic deuterium–tritium (DT) ice (~50 μm) encapsulating a vapor region DT gas. In these target designs, the incident laser ablates the thin shell, which then launches one or multiple shocks through the remaining converging shell and into the vapor region. The shock-transit stage of the implosion is followed by a deceleration phase, where the kinetic energy of the converging shell is converted to the internal energy of the hot spot. To achieve conditions relevant for ignition implosion designs, the hot-spot size must exceed the mean free path of the fusing ions and alpha particles in order to remain confined in the dense plasma. This requirement is essential to maximize the energy deposition of the alpha particle in the hot spot and surrounding dense fuel. Targets that are not compressed symmetrically will be unable to fully convert their shell kinetic energy to hot-spot thermal energy.

Areal density is one of the key parameters that determines the confinement time in ICF experiments, and low-mode asymmetries in the compressed fuel are detrimental to the implosion performance. The energy spectra from scattering of the primary DT neutrons off the compressed cold fuel assembly are used to investigate low-mode nonuniformities in direct-drive cryogenic DT implosions. For spherically symmetric implosions, the shape of the energy spectrum is primarily determined by the elastic and inelastic scattering cross sections for both neutron–deuterium (nD) and neutron–tritium (nT) kinematic interactions given by

$$\frac{\mathrm{d}N}{\mathrm{d}E} = Y_\mathrm{n}\left\{\left[\mathrm{DT} + \frac{1}{2}\frac{f_\mathrm{d}}{f_\mathrm{t}}\frac{\langle\sigma\nu_\mathrm{dd}\rangle}{\langle\sigma\nu_\mathrm{dt}\rangle}\mathrm{DD} + \frac{f_\mathrm{t}}{f_\mathrm{d}}\frac{\langle\sigma\nu_\mathrm{tt}\rangle}{\langle\sigma\nu_\mathrm{dt}\rangle}\mathrm{TT}\right]\right.$$

$$\left. + \rho L N_\mathrm{a}\left[\frac{\left(\mathrm{d}\sigma_\mathrm{nD}/\mathrm{d}E\right)f_\mathrm{d} + \left(\mathrm{d}\sigma_\mathrm{nT}/\mathrm{d}E\right)f_\mathrm{t}}{f_\mathrm{d}m_\mathrm{d} + f_\mathrm{t}m_\mathrm{t}} + \frac{\left(\mathrm{d}\sigma^\mathrm{d}_{\sigma_\mathrm{n2n}}/\mathrm{d}E\right)f_\mathrm{d}}{f_\mathrm{d}m_\mathrm{d} + f_\mathrm{t}m_\mathrm{t}} + \frac{\left(\mathrm{d}\sigma^\mathrm{t}_{\sigma_\mathrm{n2n}}/\mathrm{d}E\right)f_\mathrm{t}}{f_\mathrm{d}m_\mathrm{d} + f_\mathrm{t}m_\mathrm{t}}\right]\right\},$$

where Y_n is the primary DT yield, f_d and f_t are the fuel fraction of the fuel, and $\langle\sigma\nu\rangle$ is the reactivity rate with the associated fusing pair of ions. In the above expression DT, DD, and TT represent the shape of the primary neutron energy spectra for each reaction. The differential and double-differential cross-sections require a term to better describe this variation in the cold fuel, assuming a low-mode (ℓ = 1) distribution as given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} = \int\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)\left(1+\frac{\Delta\rho L}{\rho L} * \cos\theta\right)\mathrm{d}E,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{n,2n}}}{\mathrm{d}E} = \int 2\pi\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}E\mathrm{d}\Omega}\right)\left(1+\frac{\Delta\rho L}{\rho L} * \cos\theta\right)\mathrm{d}\cos\theta.$$

Experimental observations shown in Fig. 1 of the low-mode variations cold fuel assembly ($\rho L_0 + \rho L_1$) show good agreement with this recently developed model, indicating a departure from a spherical symmetry of the compressed DT fuel assembly.

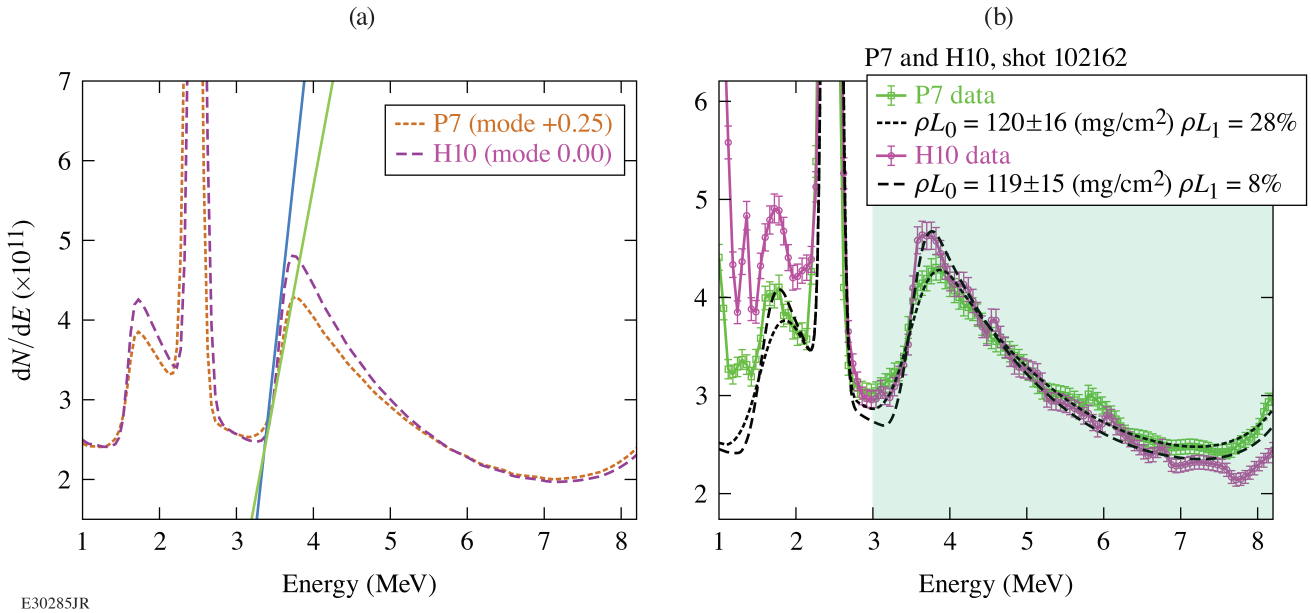

Figure 1
(a) An example of a cryogenic implosion with a significant mode 1 that shows qualitative agreement with the broadening of the kinematic edge due to the anisotropy of the cold fuel depending on the spectrometer's line of sight as predicted by the model. (b) A model illustrates the broadening of the kinematic edge due to the anisotropy of the cold fuel depending on the spectrometer's line of sight. Straight lines tangent to the nT edges are included to emphasize the difference in slopes. An example of a cryogenic implosion with a significant mode 1 shows qualitative agreement with the broadening of the kinematic edge due to the anisotropy of the cold fuel depending on the spectrometers line of sight as predicted by the model.

Another key signature in the presence of a low-mode variation is the broadening of the kinematic end point due to anisotropy of the dense fuel conditions has been observed. Recent theoretical[1] and experimental[2] studies have showed that the neutron-backscatter edge presents a novel measurement of the hydrodynamic conditions at stagnation. The spectral shape of the edge is determined by the velocity distribution of the scattering ions. When there is a large mode-1 variation in areal density, hydrodynamic models predict that the higher areal density side will decelerate slower than the lower areal density side.[3] The lower areal density side will therefore exhibit a larger variation in scattering ion velocities and consequently will produce a broader backscatter edge; the opposite is true for the higher areal density side.

More-recent hydrodynamics simulations of OMEGA implosions perturbed by a mode 1 were post-processed with a neutron transport code to obtain synthetic spectra on the P7 and H10 OMEGA lines of sight showing the anisotropic edge broadening. This anisotropy has been predicted in simulation to appear (Fig. 1) in the backscatter edge shape along different lines of sight. Measurements on the broadening of the kinematic edges show qualitative agreement with the anisotropy of the dense fuel conditions from separate lines of sight given by the model prediction. The anisotropy is also correlated with the observed mode-1 areal-density asymmetry. The P7 line of sight observes a positive mode-1 areal-density asymmetry and therefore backscatter occurs in a lower areal-density region for this line of sight.

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