Reconstructing Three-Dimensional Asymmetries in Laser-Direct-Drive Implosions on OMEGA

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Neutron spectroscopy is a key diagnostic tool in inertial confinement fusion experiments. The primary fusion neutron energy spectrum is used to infer the fusion yield, hot-spot apparent ion temperature, and hot-spot velocity, while the scattered neutron energy spectrum is used to infer the areal density of the compressed DT fuel. These measurements are key to understanding and identifying sources of 3-D asymmetries and the effect that these asymmetries have on target performance.

Over the past decade, a suite of neutron spectrometers have been fielded to measure the neutron energy spectrum emitted in laser-direct-drive implosions on the OMEGA laser. The detectors have been strategically positioned around the OMEGA target chamber such that each detector provides unique data that can be used to reconstruct the 3-D conditions of the compressed target. The current detector suite on OMEGA consists of neutron time-of-flight (nTOF)[1] detectors positioned along seven different lines of sight (LOS's),[2] a magnetic recoil spectrometer (MRS),[3] and two charged-particle spectrometers (CPS's).[4] The configuration of the nTOF and charged-particle spectrometers around the OMEGA target chamber is shown in Fig. 1. Measurements of the neutron energy spectrum are made using the nTOF and MRS detectors, while measurements of the knock-on deuteron spectrum are made with the CPS detectors.

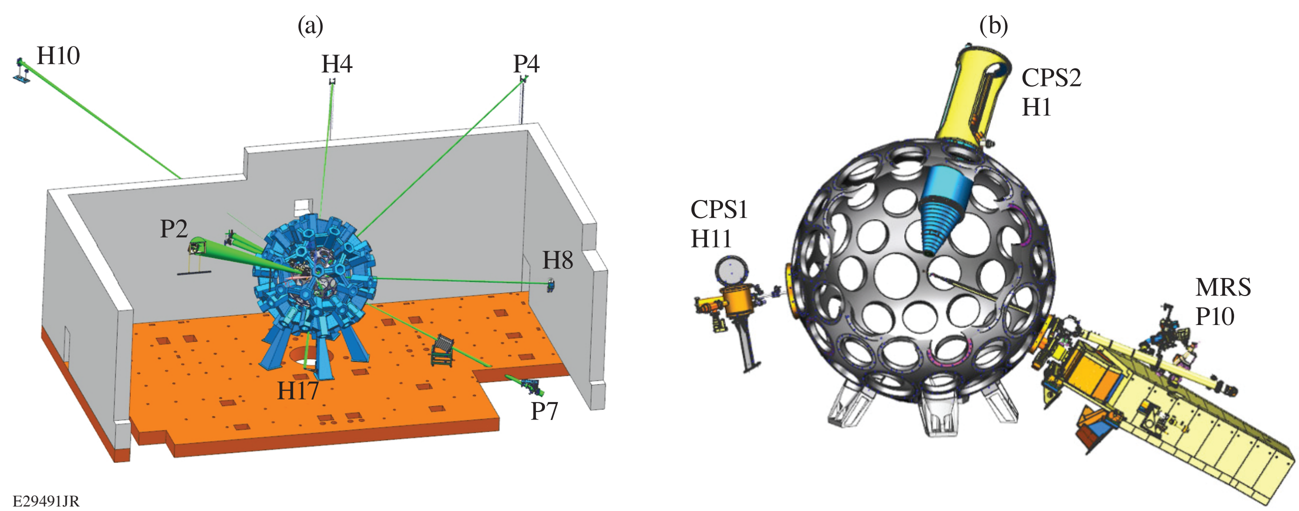

Figure 1
The lines of sight along which (a) nTOF detectors and (b) charged-particle spectrometers are fielded on OMEGA.

The neutron spectrometers on OMEGA measure either the fusion yield, apparent ion temperature, hot-spot velocity, or the areal density along a particular direction of the target. To make use of these individual LOS measurements, 3-D reconstruction algorithms have been developed[5] that combine the individual measurements into a holistic 3-D view of the hot spot and dense fuel conditions. In this work, models for the hot-spot velocity, apparent ion temperature,[6] and areal density[7] are used to fit the measured values along each LOS. Once the optimal parameters are found in each model, the results can be used to gain a greater understanding of the implosion symmetry.

The reconstruction algorithms that have been developed were applied to OMEGA shot 94660. This shot was known to have a large mode-one drive asymmetry due to anomalous laser beam-pointing errors.[8] This experiment is therefore a good candidate for testing these reconstruction algorithms since the asymmetries in the hot spot and DT fuel are exacerbated, in a known direction, and can be resolved with the current measurement uncertainties. Three-dimensional radiation-hydrodynamic simulations predict that experiments with large mode-one drive asymmetries will have large hot-spot flow velocities (>100 km/s) in the direction of the mode-one drive asymmetry.[8] Additionally, simulations predict that a large apparent ion temperature (>1.0-keV) asymmetry and areal-density asymmetry will be present and aligned with the hot-spot velocity and mode-one direction.[8–10] Therefore, we can use these experimental results to check if the reconstruction techniques are consistent with the expectation from radiation-hydrodynamic simulations.

The hot-spot velocity reconstruction for this experiment had a magnitude of 155±11 km/s. The direction of the velocity was $\theta = 74\pm6°$ and $\phi = 139\pm5°$ in the OMEGA coordinate system. This direction was nearly aligned with the direction of the known mode-one drive asymmetry,[8] $(\theta,\phi) = (51°,122°)$. The mode-one drive-asymmetry direction was determined using a hard sphere laser illumination calculation using the measured beam pointing, target offset, and laser energies on the experiment.[6]

The apparent ion temperature reconstruction was performed for this shot, and the velocity variances and covariances were determined. The square root of the reconstructed velocity covariance matrix elements were large (>100 km/s), indicating large residual motion within the hot spot. The magnitude of these values is consistent with those found in highly perturbed radiation-hydrodynamic simulations.[11] The principle eigenvector of the flow velocity's covariance matrix is along the direction $(\theta,\phi) = (53°,135°)$ and represents the direction of maximum flow-velocity variance. This direction is consistent with the direction of the hot-spot velocity reconstruction. The apparent ion temperature reconstruction is shown in Fig. 2.

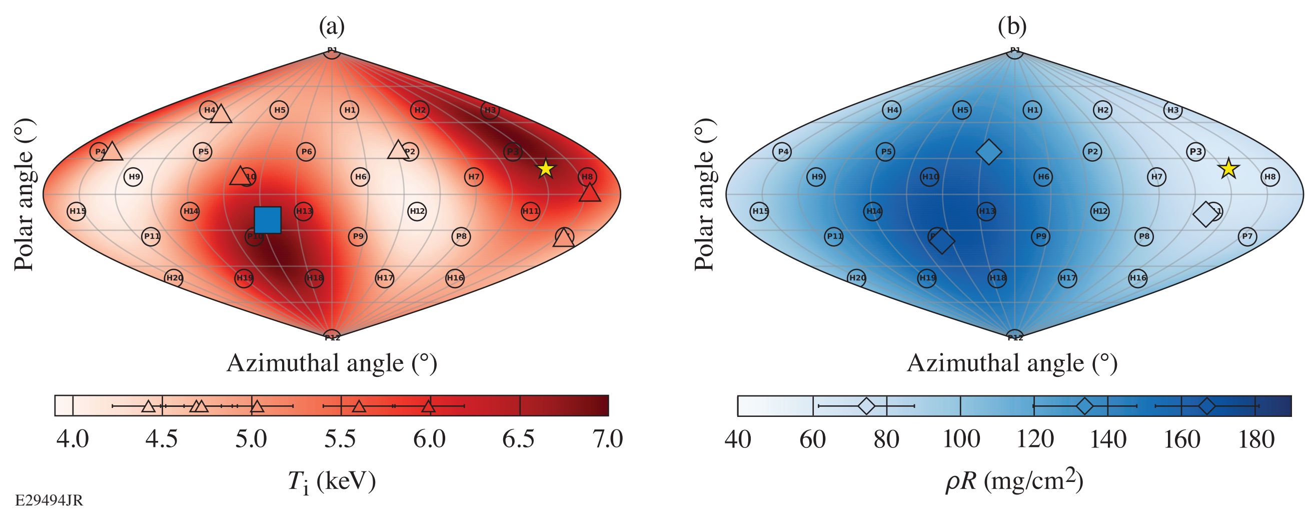

Figure 2
(a) A sinusoidal projection of the OMEGA target chamber's coordinate system showing the reconstructed hot-spot velocity direction (yellow star), the antipodal direction of the hot-spot velocity (blue square), the measured DT apparent ion temperatures (triangles), and the apparent ion temperature reconstruction (red color map) for shot 94660. (b) A sinusoidal projection of the OMEGA target chamber's coordinate system showing the reconstructed hot-spot velocity (yellow star), measured areal densities (diamonds), and areal-density reconstruction (blue color map) for shot 94660.

The areal-density reconstruction has been performed for shot 94660 and the average areal density and areal-density variation were determined. Due to the limitations of the current detector suite, a mode-one areal-density model was used, and the direction of the asymmetry was assumed to be along the direction of the hot-spot velocity. From the reconstruction, the average 4π areal density was inferred to be ρR_0 = 115±9 mg/cm^2, while the variation in the areal density was found to be $\Delta\rho R$ = 54±12 mg/cm^2. The areal-density reconstruction is shown in Fig. 2, where we see that the areal-density measurements are consistent with the apparent ion temperature and hot-spot velocity data.

The techniques described in this work can now be used to diagnose low-mode asymmetries in laser-direct-drive implosions on OMEGA. Future work will focus on extending these reconstructions by incorporating more measurements. In particular, recent theoretical work[11] has demonstrated that if the DD apparent ion temperature measurements are included in the apparent ion temperature reconstruction, the thermal ion temperature can be inferred. A more-general areal-density reconstruction will be developed so that the direction of the areal-density asymmetry need not be assumed along the direction of the hot-spot velocity. This will require the inclusion of more areal-density measurements. Additional areal-density measurements can be obtained from measurements of the knock-on deuteron spectrum measured by the CPS detectors already fielded on OMEGA (see Fig. 1) but will require that a more-advanced analysis of the knock-on deuteron spectrum be developed that can be used at an areal density >100 mg/cm^2.

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