A Suite of Neutron Time-of-Flight Detectors to Measure Hot-Spot Motion in Direct-Drive Inertial Confinement Fusion Experiments on OMEGA

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In direct-drive inertial confinement fusion (ICF) experiments, a capsule filled with a deuterium–tritium (DT) gas surrounded by a cryogenic DT fuel layer is illuminated by high-power lasers designed to symmetrically compress the target to generate a hot fusing plasma. In experiments where 3-D perturbations exist due to sources such as laser beam pointing errors, laser beam power imbalance, target nonuniformities, or target offsets, the capsule will be compressed asymmetrically. Asymmetric compression of ICF targets reduces the implosion performance by generating residual kinetic energy (RKE) in the target that could have otherwise been used to generate a hotter and denser plasma.[1] Signatures of RKE include a complex flow structure within the fusing hot spot and an asymmetric dense fuel layer. Measuring these signatures of RKE can provide insights into the sources of asymmetries and strategies to improve implosion performance.

Neutron spectroscopy is a particularly useful tool for diagnosing asymmetric compression of ICF targets because neutrons are generated within the fusing plasma and scatter while exiting through the dense fuel layer. This results in the primary unscattered neutron energy spectrum containing information on the state of the fusing hot spot from which they were generated, while the scattered neutron spectrum contains information about the dense fuel layer. In particular, if a collective motion of the hot spot is present in an ICF hot spot, the primary neutron energy spectrum will be Doppler shifted by the hot-spot velocity and will affect measurements the neutron energy spectrum made along various lines of sight differently.[2]

If the neutron velocity is measured along a direction $\hat{d}$, the neutron velocity measured along that line of sight (LOS) is given by

$$v = \langle v_{\text{iso}} \rangle + \langle \vec{u} \cdot \hat{d} \rangle, \tag{1}$$

where v_{iso} is the isotropic neutron velocity, $\vec{u}$ is the hot-spot velocity, and a bracket indicates a neutron-averaged quantity. The isotropic neutron velocity is the sum of the zero-temperature neutron velocity (51,233 km/s for DT neutrons) and the Gamow velocity shift,[3] which is a function of ion temperature and can be written as $v_{\text{iso}} = v_0 + v_{\text{th}}\,(T_{\text{i}})$. By combining multiple measurements of the neutron velocity along different LOS's, the hot-spot velocity $\vec{u}$ and Gamow velocity shift can be determined directly.

To make this measurement, a suite of six neutron time-of-flight detectors has been built and calibrated to measure the primary DT neutron energy spectrum along multiple quasi-orthogonal LOS's on the OMEGA laser. The six detectors, positioned along five LOS's on OMEGA, are shown in Fig. 1 and use either a single detector or a dual collinear or antipodal configuration. The detectors use different technologies including a scintillator coupled to a photomultiplier tube (PMT) detector, a chemical-vapor–deposition diamond-based detector, or a PMT-based detector. By combining the neutron velocity measurements made by each of these detectors, the neutron-averaged hot-spot velocity present in a cryogenic laser-direct-drive implosion has been measured for the first time on OMEGA.

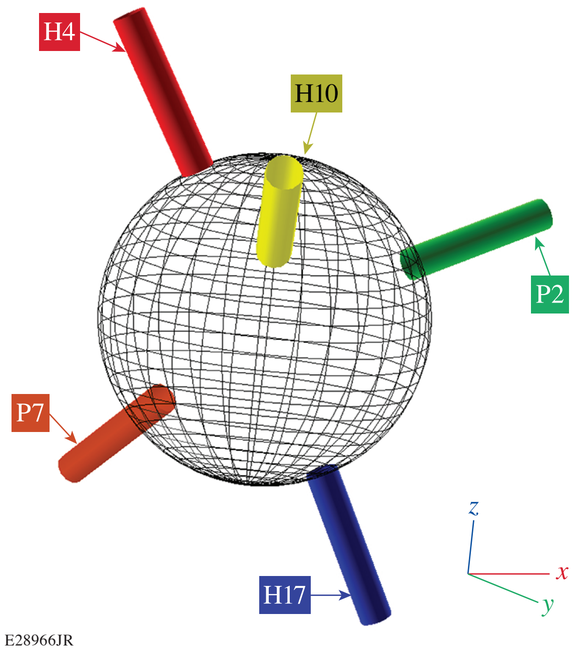

Figure 1
The four axes used on the OMEGA laser for reconstruction of the neutron-averaged hot-spot velocity. The target chamber is represented as a mesh grid, while the five detector LOS's are indicated with cylinders

To validate the velocity measurements made by this detector suite, a set of experiments with large and small target offsets has been studied. Radiation-hydrodynamic simulations predict that if a large target offset is present in direct-drive implosions, a large hot-spot velocity will be observed in the direction of the offset, while zero flow will be observed in the absence of an offset. Measurements of the hot-spot velocity have been made for experiments with both large and small offsets. In experiments with large 52.0-μm and 34.4-μm initial target offsets, large hot-spot velocity magnitudes of 148.9 and 163.7 km/s were measured and the direction was consistent with the initial target offset. In a similar experiment with only a 1.0-μm offset, the hot-spot velocity magnitude was measured to be 60.4 km/s. The presence of a small hot-spot velocity for the zero-offset experiment suggests the presence of a small low-mode asymmetry in either the target or laser system. Despite this, the inferred neutron-averaged hot-spot velocity for targets with large offsets was aligned with the initial target offset directions, consistent with simulation predictions. A summary of these measurements is shown in Fig. 2.

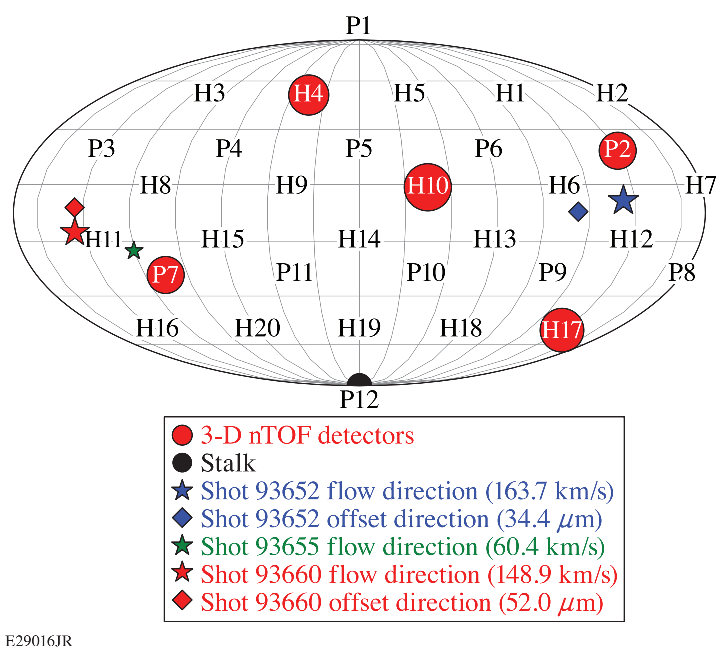

Figure 2
A Mollweide projection of the OMEGA target chamber coordinate system with the neutron-averaged hot-spot velocity reconstruction (stars) inferred from three cryogenic experiments along with their initial target offset direction (diamonds). Two experiments had large target offsets of 34.4 μm with a 52.0-μm offset, while the third had only a 1-μm offset and is not shown. The size of the stars is proportional to the magnitude of the velocity reconstruction. Also shown in red are the ports of LOS's used in the reconstruction.

With the completion of this new diagnostic suite, greater insights into the 3-D behavior of cryogenic experiments will be gained. In particular, the hot-spot velocity measurement will be the primary diagnostic signature of mode-1 asymmetries present in our experiments. These measurements can be used to constrain simulation results and will guide the search for unknown sources of mode-1 asymmetries. Future work will extend this detector suite to include the two measurements of the D–D fusion neutron spectrum that are available on OMEGA.

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