Azimuthal Drive Asymmetry in Inertial Confinement Fusion Implosions at the National Ignition Facility

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The large radial convergence required for hot-spot ignition places demanding requirements on the symmetry of implosions. Asymmetric convergence of an inertial confinement fusion (ICF) implosion is predicted to generate unstagnated flows in the converged fuel and hot spot, which limits the maximum hot-spot pressure and reduces confinement time.[1] An offset drive illuminating one side of a capsule more brightly than the opposite can produce a net velocity in the fusing hot spot and significant asymmetry in fuel assembly.[2] Hot-spot flows have been measured using time-resolved x-ray pinhole cameras,[3] but the accuracy of this technique is limited by the small number of diagnostic views. Asymmetry in the assembled fuel has been suggested by trends in hot-spot areal density, ion temperature, and pressure,[4] and from significant variations of scattered neutron flux with line of sight observed on some implosions.[5] In this work, nuclear diagnostics were found to present a strong signature of a systematic mode-1 drive asymmetry in the cryogenic implosion campaigns performed at the National Ignition Facility (NIF) from 2016–2018. The observed asymmetry limits the performance of the present ICF implosions and must be corrected if ignition is to be achieved.

Flows in the hot-spot plasma are diagnosed by measuring the Doppler shift of the fusion neutrons. A neutron-averaged flow velocity projected along each of four neutron time-of-flight detector lines of sight is obtained by measuring the shift in mean neutron energy relative to the expected value.[6] The mean hot-spot velocity magnitude and direction are obtained from these measurements, as shown in Fig. 1(a) for 44 shots performed during 2016–2018. For implosions in which significant velocity was inferred ($v > 30$ km/s, a typical value for the measurement uncertainty), the hot spots are observed to flow toward one hemisphere (approximately $-20° < \phi < 160°$). This data set includes experiments that use a variety of laser pulse shapes and ablators, including shots from the high-density carbon (HDC), "Bigfoot" (high-adiabat HDC), and CH campaigns.[7] It is worth noting the magnitude of the velocities observed: many of the implosions presented velocities in excess of 20% of the implosion velocity (typically 350 to 420 km/s), representing significant perturbations to the implosions' uniformity.

The areal density (ρR) of the assembled fuel is diagnosed by a suite of neutron activation diagnostics on over 20 lines of sight. Activation of Zr-90 atoms records the fluence of unscattered neutrons above 12 MeV, which is inversely proportional to ρR after correcting for the effects of the Doppler shift on the measurement.[8] If scattered neutrons are assumed to be lost from detection, the variation in areal density ($\Delta\rho R$) can be calculated from the variation in activation A relative to the mean value $\langle A \rangle$ as

$$\Delta\rho R \approx -\frac{M_{\rm DT}}{\sigma_{\rm DT}} \ln\left(\frac{A}{\langle A \rangle}\right) \sim -\ln\left(\frac{A}{\langle A \rangle}\right) 4.64 \text{ g/cm}^2. \tag{1}$$

Performing the activation analysis for the 2016–2018 NIF cryogenic experiments produces a similar pattern to that observed in the velocity data. The inferred areal-density asymmetry [from Eq. (1)] normalized to the average areal density is plotted in Fig. 1(b) compared with the measured hot-spot velocity. The magnitudes of the two signatures are observed to scale linearly across the entire data set: a best-fit slope of 39% ρR mode-1 asymmetry per 100-km/s hot-spot velocity matches the data with a reduced

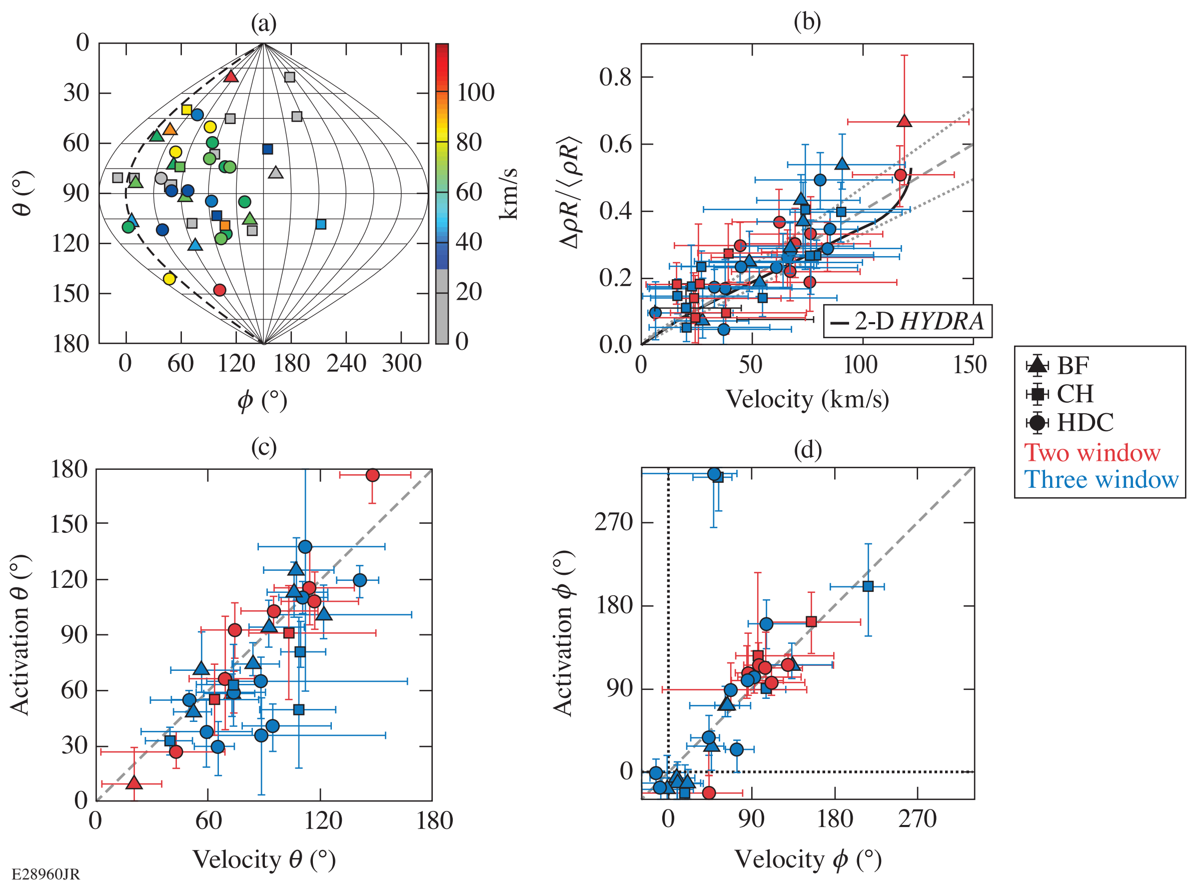

Figure 1
(a) The measured hot-spot velocity for 43 implosions performed on the NIF from 2016–2018. Most shots in the data set (32) present significant hot-spot velocity ($v > 30$ km/s) clustering in one hemisphere. (b) Mode-1 variation in areal density ($\Delta\rho R/\rho R$) compared with measured hot-spot velocity (km/s). Areal-density variation scales linearly with velocity, in agreement with a 2-D *HYDRA* model including mode-1 drive asymmetry (black line). [(c),(d)] The inferred (θ, ϕ) direction of maximum activation (minimum ρR) compared with hot-spot velocity. Implosions with two-window hohlraums (red symbols) cluster toward $\phi = 94°\pm35°$, whereas those with three-window hohlraums (blue symbols) cluster toward $\phi = 58°\pm53°$.

χ^2 metric of 0.3. Moreover, the direction of high activation (low areal density) was found to match the direction of the hot-spot velocity, as shown in Figs. 1(c) and 1(d). The hypothesis that the (θ, ϕ) directions of the hot-spot velocity and activation mode-1 are the same is supported with reduced χ^2 values of 0.7 and 0.6, respectively. (These low values of the reduced χ^2 metric suggest that the measurement uncertainties are likely overestimated.) The comparison of the azimuthal angle in Fig. 1(d) clearly shows the clustering of data points into the range $-20° \lesssim \phi \lesssim 160°$. The implosions used hohlraums with diagnostic windows (regions of the hohlraum wall with thinner gold layers) toward $\phi = 78°$ and $99°$ ["two-window" (red)] and with an additional window toward $\phi = 314°$ ["three-window" (blue)], which cluster toward different directions. The two-window hohlraums are observed to produce hot-spot velocities on average in the direction $\phi = 94°\pm35°$, whereas three-window hohlraums produce velocities toward $\phi = 58°\pm53°$. These values are consistent with the average of the window directions in each design, suggesting the windows contribute to the observed trend.

These observations together strongly indicate the presence of an unexpected systematic implosion asymmetry in NIF cryogenic implosions over the past three years. Spears *et al.*[2] performed 2-D simulations of indirectly driven implosions with an imposed mode-1 asymmetry in the radiation intensity that produced a trend consistent with our observations. While this work was motivated by the possibility of pole-to-pole asymmetry, the result does not consider hohlraum geometry and is generally applicable to radiation asymmetry in arbitrary directions. The drive asymmetry accelerated the capsule away from the direction with higher radiation flux, producing a neutron-weighted hot-spot velocity in that direction that scaled with the flux asymmetry and covered the range we observed (≤120 km/s). Areal density also increased in the direction of peak intensity and decreased in the opposite direction. A prediction of the scaling between neutron-inferred hot-spot velocity and areal-density asymmetry magnitude [black line in Fig. 1(b)] agrees with the data.

The hohlraum windows can plausibly create such a mode-1 radiation asymmetry. Figure 2 shows a calculation of the reduction in radiation flux onto a capsule inside a three-window hohlraum, assuming complete radiation loss at the windows, performed using the view factor code VisRAD.[9] Up to 6.2% radiation deficit toward the windows is predicted in this limiting case: significantly larger than the asymmetry needed to explain the most extreme velocities. In experiments, thinner gold layers and gaps approaching half the window area will reduce local radiation power by some fraction of this amount, inducing velocity and higher activation in the average direction of the windows. This hypothesis matches the observed data trends with hohlraum window design. Together, these observations provide strong evidence that a systematic, azimuthally directed mode-1 drive asymmetry of up to ±2% in radiation intensity is present in this series of implosions. Detailed models are in development to more quantitatively assess window radiation losses, including the effects of window architecture and ablation dynamics.[10,11]

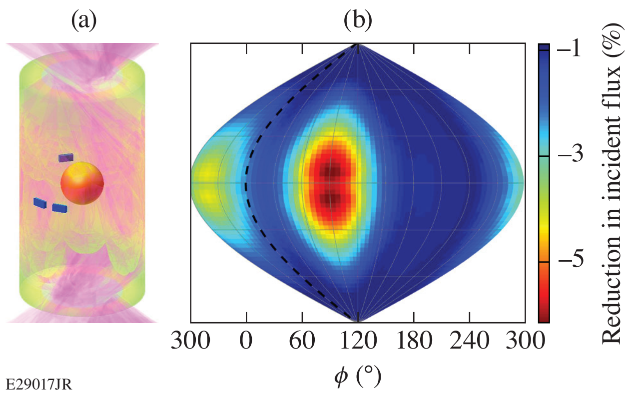

Figure 2
(a) Model of the capsule in a laser-irradiated hohlraum from view angle (65°, 120°). Size and position of diagnostic windows are shown in blue. (b) Calculated reduction of radiation flux on the capsule in a three-window hohlraum, assuming complete radiation loss through windows.

Such an asymmetry represents a dominant degradation mechanism for the implosions: a 3-D model predicts that the implosion asymmetry reduced the yield by 5× for a representative shot in this data set.[1] Investigation of asymmetry sources, including hohlraum windows, laser delivery, capsule and ice-thickness variations, and target alignment is ongoing to improve implosion symmetry control and performance.

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