Analysis of Core Asymmetries in Inertial Confinement Fusion Implosions Using Three-Dimensional Hot-Spot Reconstruction

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Three-dimensional effects play a crucial role during the hot-spot formation in inertial confinement fusion implosions. To characterize effects of low modes on hot-spot formations, a data-analysis technique for 3-D hot-spot reconstruction from experimental observables was developed. In summary, the effective flow direction, governed by the maximum eigenvalue in the velocity variance of apparent ion temperatures, was found to agree with the measured hot-spot flows for implosions dominated by mode $\ell = 1$. Asymmetries in areal-density (ρR) measurements were found to be characterized by a unique cosine variation along the hot-spot flow axis. A 3-D hot-spot x-ray emission tomography method was developed to reconstruct the 3-D hot-spot plasma emissivity using a generalized spherical-harmonic Gaussian function. The mapping between the projections from the 3-D hot-spot emission model and the measured x-ray images along multiple views is obtained by a gradient descent optimization algorithm.

Spherically symmetric flows,[1,2] turbulences,[3] and 3-D flows[4] are sources of velocity variances in neutron velocity spectra. Non-stagnating hot-spot flows kinematically boost the velocity of neutrons, produced from deuterium (D) and tritium (T) nuclear fusion reactions. The hot-spot residual fluid motion modifies the neutron velocity distribution so that the width of a neutron velocity spectrum is broadened according to a unique function of the velocity variance $\sigma = \text{var}\left[v_{\text{flow}} \cdot d_{\text{LOS}}\right]$, where v_{flow} is the hot-spot flow velocity measured in the laboratory frame and d_{LOS} is the line of sight (LOS) unit vector, pointing from the target chamber center to the position of a detector. The velocity variance is a measurement for the hot-spot flow residual kinetic energy (RKE) since it measures the square of hot-spot flow velocity fluctuations. It contains six independent components $\sigma_{ij} = \left\langle\left(v_i - \bar{v}_i\right)\cdot\left(v_j - \bar{v}_j\right)\right\rangle$, including three directional variances with $i = j$ and three covariances with $i \neq j$. Indices i and j go from 1 to 3, representing x, y, and z Cartesian coordinates, respectively. Since covariances are unchanged upon exchanging i and j indices, the velocity variance matrix is Hermitian. This implies that σ is diagonalizable with real eigenvalues λ_i, which are the components of the hot-spot RKE along three orthonormal eigenvector directions e_i. This behavior is consistent with the fact that the trace of σ, the total hot-spot residual kinetic energy, is invariant under the special orthogonal SO(3) transformation in the 3-D Euclidean space. Hence, an apparent ion temperature measured at a given LOS is related to the hot-spot RKE's along the three eigenvector directions through the SO(3) transformation

$$T_{\text{LOS}} = T_{\text{thermal}} + M_{\text{DT}} \sum_{i=1}^{3} \lambda_i \left\langle d_{\text{LOS}} \middle| e_i \right\rangle^2, \tag{1}$$

where T_{thermal} is the ion thermal temperature in the center of mass frame of D–T nuclear reactions, and the bracket notation represents the inner product between the LOS unit vector and the ith eigenvector. Equation (1) is a generalized result to explain variations in apparent ion temperatures nonrelativistically. When implosions are dominated by mode 1, Eq. (1) implies a cosine-square variation along the eigenvector direction with the maximum eigenvalue, i.e., the hot-spot RKE of the jet. The extrapolation for the cosine-square variation in OMEGA ion-temperature measurements using Eq. (1) is illustrated in Fig. 1(a). When implosions contain mode 2, the difference between eigenvalues parallel $\lambda_{\parallel}$ and perpendicular $\lambda_{\perp}$ to the rotational axis implies a nonvanishing ion-temperature asymmetry. Even the measured hot-spot flow velocity is zero since symmetric mode-2 hot-spot flows do not change the first moment of neutron velocity spectra. This phenomenon is illustrated by Fig. 1(b). A good agreement between the trend of experimental data and *DEC3D* simulations with a uniform 2% initial velocity perturbation of mode 2 on varying mode-1 perturbations is obtained. A semi-analytic model is derived to explain the mode-1 ρR degradation. Both 4π averaged and variations in ρR are found to be a function of the ion-temperature ratio $R_T = T_{\max}/T_{\min}$,

$$\frac{(\rho R)\mathrm{LOS}}{(\rho R)\mathrm{1\text{-}D}} = R_T^{\alpha} + \sqrt{R_T^{2\alpha} - R_T^{2\beta}}\,\cos\theta_{\mathrm{LOS\text{-}flow}}\,, \tag{2}$$

where $\alpha = -0.3$ and $\beta = -0.47$ are parameters obtained from *DEC3D* mode-1 simulations, and $\theta_{\mathrm{LOS-flow}}$ is the inclination angle between the LOS and the measured hot-spot flow vectors. The extrapolation for the mode-1 angular-dependence in areal density measurements is illustrated by Fig. 1(c). The 3-D kernel as stated by Eq. (2) is shown to accurately fit the H10 ρR measurements. A 3-D x-ray emission tomography method was devised to reconstruct arbitrary hot-spot shapes using a generalized spherical harmonic Gaussian function,

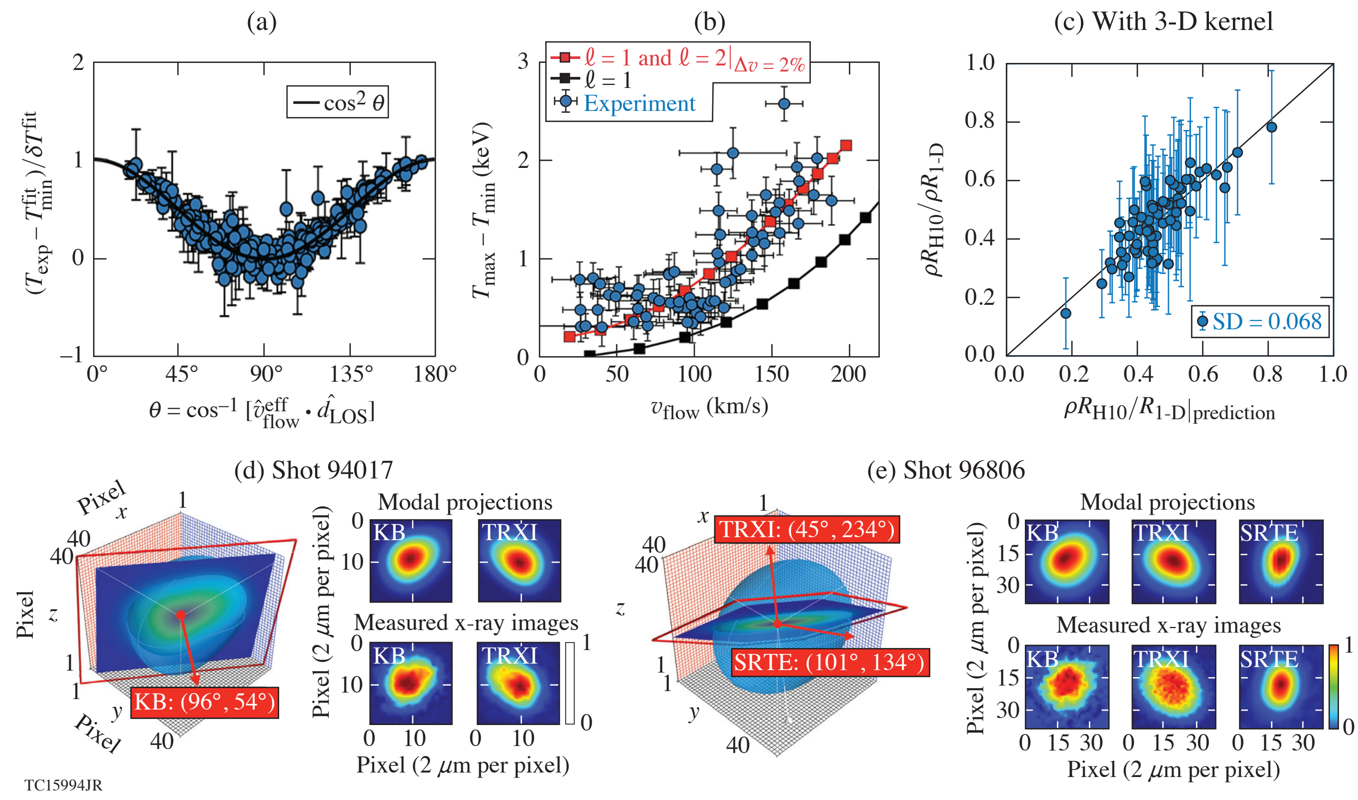

Figure 1
Analysis of core asymmetries in OMEGA implosion experiments. (a) The extrapolation for the cosine-square variation in ion-temperature measurements using Eq. (1). (b) The reconstruction for the trend of T_{i} and flow relation using *DEC3D* simulations. (c) The extrapolation for the mode-1 angular-dependence in areal density measurements using the 3-D kernel in Eq. (2). [(d),(e)] Three-dimensional hot-spot reconstructions for shots 94017 and 96806 using the generalized spherical-harmonic Gaussian model in Eq. (3). SD: standard deviation; KB: Kirkpatrick–Baez; TRXI: time-resolved x-ray imager; SRTE: spatially resolved x-ray imager.

$$\ln \varepsilon_{\nu} = \sum_{n=0}^{\infty} \sigma_n R^n \left[1 + \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} \sum_{k=0}^{\infty} A_{\ell mk} R^k Y_{\ell m}(\theta,\phi)\right]^n. \tag{3}$$

Expansion coefficients in Eq. (3) are determined by minimizing the root-mean-square deviations between modal projections and measured x-ray images measured at multiple views using the gradient descent optimization algorithm. Three-dimensional hot-spot reconstructions are illustrated in Fig. 1(d) and 1(e). The mode-1 skew signature and the mode-2 ellipticity are well reconstructed for shots 94017 and 96806, respectively.

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