Inferring Thermal Ion Temperature and Residual Kinetic Energy from Nuclear Measurements in Inertial Confinement Fusion Implosions

K. M. Woo,[1,2] R. Betti,[1,2,3] O. M. Mannion,[1,2] C. J. Forrest,[1] J. P. Knauer,[1] V. N. Goncharov,[1] P. B. Radha,[1] D. Patel,[1,3] V. Gopalaswamy,[1,3] and V. Yu. Glebov[1]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Department of Physics & Astronomy, University of Rochester
[3]Department of Mechanical Engineering, University of Rochester

In inertial confinement fusion (ICF) implosion experiments, the presence of residual anisotropic fluid motion within the stagnating hot spot leads to significant variations in ion-temperature measurements using neutron time-of-flight detectors along different lines of sight (LOS's). The minimum of measured ion temperatures is typically used as representative of the thermal temperature. In the presence of isotropic flows, however, even the minimum DT neutron-inferred ion temperature can be well above the plasma thermal temperature. Consequently, apparent ion temperatures, which are inferred from the width of neutron energy spectra,[1] are larger than the real thermal ion temperature. This leads to underestimating the inferred hot-spot pressures used as a metric to measure ICF implosion performance.

The influence of 3-D flow effects on apparent ion temperatures is governed by the properties of velocity variance, contributed by both isotropic and anisotropic flows. To describe this phenomenon, the method of velocity variance decomposition[2] is applied. The fluid velocity vector and the LOS unit vector are substituted into the velocity variance, followed by an expansion into six components. The resulting apparent ion temperatures can be rewritten as

$$T_{\mathrm{i}}^{\mathrm{inferred}} = T_{\mathrm{i}}^{\mathrm{thermal}} + M_{\mathrm{DT}} \sum_{i,j=1}^{3} g_i g_j \sigma_{ij}. \tag{1}$$

Here M_{DT} is the DT total reactant mass. The indices 1, 2, and 3 correspond to Cartesian coordinates x, y, and z, respectively; $\hat{e}_i$ is an orthonormal unit vector. Three geometrical factors—$g_1 = \sin\theta\cos\phi$, $g_2 = \sin\theta\sin\phi$, and $g_3 = \cos\theta$—specify the polar θ and azimuthal ϕ angles for a given LOS. The six components of the fluid velocity variance $\sigma_{ij} = \langle \Delta v_i \Delta v_j \rangle$ measure the flow structure within the hot spot, where $\Delta v_i = v_i - \langle v_i \rangle$ is the velocity fluctuation along the ith direction with respect to the mean velocity $\langle v_i \rangle$. The covariances σ_{12}, σ_{23}, and σ_{31} measure the degree of azimuthal asymmetry. The directional variances σ_{11}, σ_{22}, and σ_{33} are proportional to the nontranslational component of the hot-spot fluid kinetic energy, i.e., $\sigma_{ii} = \langle \Delta v_i^2 \rangle$.

Equation (1) describes the nonrelativistic, 3-D hot-spot flow asymmetry on neutron-inferred ion-temperature measurements. The variation in ion-temperature measurements along different LOS's is uniquely governed by the content of the fluid (residual) kinetic energy (RKE) and the properties of the hot-spot flow structure. For turbulent flows, the vanishing covariances lead to apparent ion temperatures inflated uniformly in 4π caused by the isotropic hot-spot fluid kinetic energies from the radial component of the flows. The 4π minimum of the velocity variance is the fundamental isotropic source contributed by fluid properties that causes the minimum apparent ion temperatures above the real thermal ion temperatures. Equation (1) reveals that the solution for the real thermal ion temperature can be derived by performing DD and DT ion-temperature measurements at a given set of LOS's to form an invertible matrix.

Figure 1(a) shows the strong correlation between the D–T experimental yields and the derived DD minimum ion temperatures in the OMEGA implosion database. The strong dependence on the DD minimum ion temperatures leads to yields that scale with ion temperatures $\sim T^{3.96}$ close to the power of 4. The minimum of DD ion temperature is closer to the real thermal ion temperature because the DD total fusion reactant mass $M_{DD} \simeq 0.8 M_{DT}$ is smaller than that of DT's, resulting in a smaller contribution of isotropic flows in T_{min}^{DD}. Consider a simultaneous ion-temperature measurement for DD and DT along the same single LOS: $T_{LOS}^{DT} = T_{min}^{DT} + M_{DT}\sigma_{aniso}^{DT}$ and $T_{LOS}^{DD} = T_{min}^{DD} + M_{DD}\sigma_{aniso}^{DD}$; the minimum DD ion temperature can be derived by removing the common part of the anisotropic velocity variance σ_{aniso}.

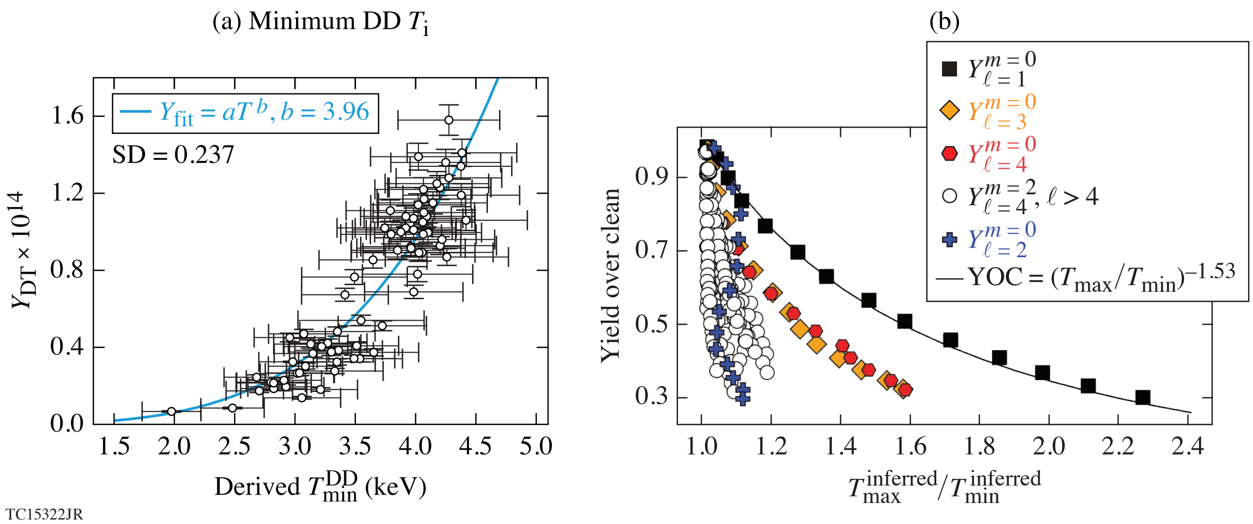

Figure 1
(a) Comparison between the experimental D–T yields with the derived DD minimum ion temperatures. (b) Comparison between the simulated YOC with the ratio of the inferred maximum to the inferred minimum ion temperatures for single modes $\ell = 1$ to 10.

Figure 1(b) compares the yield-over-clean (YOC) with the ratio of the inferred maximum to the inferred minimum ion temperatures for single modes $\ell = 1$ to 10. The YOC is shown to be less sensitive with increasing Legendre mode numbers. A good agreement is observed between the yield degradation and the analytic curve: YOC $\simeq \left(T_{max}/T_{min}\right)^{-1.53}$, derived using Eq. (1). This result explains the effect of mode-1 ion-temperature asymmetries in terms of residual kinetic energies: $\left(T_{max}/T_{min}\right)_{\ell=1} = 1 + 4\text{RKE}/(1\text{–RKE})$, where RKE is given by the ratio of the difference of fluid kinetic energies at stagnations between 3-D and 1-D to the maximum 1-D in-flight fluid kinetic energy.

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