Evaluating the Residual Kinetic Energy in Direct-Drive Cryogenic Implosions on OMEGA

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62nd Annual Meeting of the American Physical Society Division of Plasma Physics
Memphis, TN November 9-13 2020 (virtual)
Summary

Efficient conversion of the shell kinetic energy to the internal hot-spot energy is an essential requirement in ICF fusion implosions

- The spectral moments of the neutron distribution emitted from a fusing deuterium-tritium (DT) plasma is used to interpret the hot-spot velocity and temperature of the reactants.

- An isotropic and anisotropic flow can introduce additional broadening of the second moment on the energy distribution of fusion-produced neutrons.

- Hot-spot residual kinetic energy (RKE) from the presence of anisotropc flow is observed with increasing hot-spot velocity (> 100km/s).

*K. Woo et al., Phys. Plasmas 27, 062702 (2020).*
Collaborators


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Two different mechanisms can introduce broadening on the energy distribution of fusion-produced neutrons used to infer the temperature of the reactants.

Anisotropic Flow \textsuperscript{*} (LOS)

Isotropic Flow

Anisotropic and isotropic flows are a signature of hot-spot residual kinetic energy (RKE) and can be determined since they have a different effect on the DT and DD ion temperatures.

A 1-D model with a temperature profile from hydrodynamic simulations* can be used to calculate the DT and DD neutron-averaged ion temperature. The DT and DD reactants have different sensitivities with respect to the temperature profile of the hot spot.

A generalized forward-fit technique is used to infer the spectral moments of the peak distributions from a neutron-time-of-flight (nTOF) diagnostic

- The forward-fit approach uses a semi-relativistic energy distribution $dN/dE^*$. 
  \[ \frac{dN}{dE} = I_0 \exp \left( -\frac{2E}{\sigma^2} (\sqrt{E} - \sqrt{E})^2 \right), \]

- The line-of-sight $S(E)_{\text{los}}$ attenuation and non-linear light output $S(E)_{\text{nlo}}$ were modeled using a neutron transport code (MCNP).

- An energy dependent response function $R(E,t)^{**}$ is required for a more accurate interpretation of the time-of-flight signal in region around the DD peak distribution**.

  \[ I(t) = c \left[ S(E)_{\text{los}}S(E)_{\text{nlo}} \frac{dN}{dE} \frac{dt}{dt} \right] \otimes R(E, t) \]

The hot-spot velocity is inferred using 5 different lines-of-sight.

Two highly-collimated line-of-sight allows for accurate measurements of the primary DT and DD neutron distributions.

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Residual kinetic energy (RKE)\(^*\) from the presence of isotropic and anisotropic flows can be inferred with the ion temperature from separate lines-of-sight.

Unconverted hot-spot kinetic energy does not contribute to the thermal energy of the system.

This effect will manifest itself into the additional broadening of the neutron velocity distribution (RKE \(\equiv M_{DT} \sigma_{1,2}^2\)) where 1,2 is the LOS.

\[
\begin{bmatrix}
T_1^{DT} \\
T_1^{DD} \\
T_2^{DT} \\
T_2^{DD}
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & 1 & 0 \\
\alpha & 0.8 & 0.8 & 0 \\
1 & 1 & 0 & 1 \\
\alpha & 0.8 & 0 & 0.8
\end{bmatrix}
\begin{bmatrix}
T_{th} \\
M_{DT} \sigma_{iso}^2 \\
M_{DT} (\sigma_{aniso}^2)_1 \\
M_{DT} (\sigma_{aniso}^2)_2
\end{bmatrix}
\]

\[\alpha = T_{DD}^{th}/T_{DT}^{th}\]

The observation of large differences in the ion temperatures along separate line-of-sight indicates that RKE is likely due to low-mode asymmetries. The difference in the ion temperature along two different line-of-sight is produced from anisotropic flows in the hot-spot.

\[
\frac{T_{1}^{DT} - T_{2}^{DT}}{T_{1}^{DD} - T_{2}^{DD}} = \frac{M_{DT}(\sigma_{1}^{2} - \sigma_{2}^{2})}{0.8M_{DT}(\sigma_{1}^{2} - \sigma_{2}^{2})}
\]

This implies,

\[
T_{1}^{DT} - T_{2}^{DT} > T_{1}^{DD} - T_{2}^{DD}
\]
The residual kinetic energy due to anisotropic flows from two separate line-of-sight increases with the flow velocity of the hot-spot.

These results indicate a significant anisotropic flow is observed in OMEGA cryogenic DT implosions.
A limit on the thermal temperature will require all of the available DT and DD ion temperature and hot-spot flow experimental values.

A more generalize formalization using all available measurements can be used to monitor the entire system.

2nd Moment

\[ T_{los}^{DT} = T_{th} + M_{DT} Var[\hat{v} \cdot \hat{d}_{los}] \]

\[ T_{los}^{DD} = \alpha T_{th} + 0.8 M_{DT} Var[\hat{v} \cdot \hat{d}_{los}] \]

1st Moment

\[ \Delta V_{los} = 7.35 T_{keV} + (\hat{v}_{km/s} \cdot \hat{d}_{los})^{*} \]

\[ \begin{align*}
T_{los}^{DT} &= 6 \text{ lines-of-sight (P2,P4,P7,H4,H10,H17)} \\
T_{los}^{DD} &= 2 \text{ lines-of-sight (P7, H10)} \\
\Delta V_{los} &= 5 \text{ lines-of-sight (P2,P7,H4,H10,H17)}
\end{align*} \]

O. Mannion, Session KI02: Invited: Inertial Confinement Fusion
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