Knock-on Deuterion Imaging of the Hot Spot and Compressed Fuel in Direct-Drive Cryogenic ICF Implosions

Reconstructed images:

- \( E > 10 \text{ MeV}: \) Hot-spot
- \( E < 3 \text{ MeV}: \) Cold fuel

Hans Rinderknecht, UR LLE
ICF: Neutron Diagnostics, GO11.9

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- Elastically-scattered \( (n,d) \) deuterons constrain ICF fuel conditions at stagnation:
  - High-energy (> 10 MeV) images are equivalent to neutron images
  - Low-energy (< 6 MeV) images contain information about the surrounding cold fuel
- A KoDI system has been implemented at the OMEGA-60 laser system
- Significant differences are observed between the high- and low-energy deuteron images, consistent with a large mode-1 perturbation of the implosion

KoDI imaging will be used on up to 5 lines of sight to obtain 3D hotspot and \( \rho R \) images on OMEGA ICF implosions.

Related talks:
J. Kunimune, GO11.10 (next): “Reconstruction and analysis of knock-on deuteron images of direct-drive ICF implosions at OMEGA”
O. Mannion, KI02.1: “Mitigation of mode-one asymmetry in laser-direct-drive inertial confinement fusion implosions”
Collaborators


LLLE

J. Kunimune, P. Adrian, M. Gatu Johnson, J. Frenje, F. Seguin MIT

B. Bachmann, LLNL
Three-dimensional perturbations are now thought to significantly distort inertial-confinement fusion implosions at stagnation.

3-D ASTER simulation of hot-spot flow velocity ($v_f$) at stagnation (arrows indicate direction)

Equatorial plane

3-D x-ray images of hot spot (arrow indicates flow direction from 3-D nuclear)

Measurements

Simulations

3-D signature of hot-spot flow velocity inferred from 4 NTOF lines of sight*

We need a diagnostic to measure detailed 3D fuel $\rho R$ distributions.

Elastic $(n,d)$ scattering creates deuterons with energy in range $0–12.4$ MeV, depending on the scattering angle $\theta$.

- **Forward scatter:** $> 12$ MeV
- **Side scatter:** $< 6$ MeV

**Deuteron yield scales with $\rho R$:**

$$Y_D \approx 7.7 \times 10^{11} \left( \frac{\rho R}{100 \text{mg/cm}^2} \right) \left( \frac{Y_N}{10^{14}} \right)$$
A Knock-on Deuteron Imager (KoDI) provides information on both hotspot size and converged fuel shape.

High-energy deuterons are forward-scattered, encoding the shape of neutron emission.

- Synthetic images: $\rho R = 100 \text{ mg/cm}^2$
- Deuterons: $\sigma = 10.1 \mu\text{m}$
- Neutrons: $\sigma = 9.3 \mu\text{m}$
A Knock-on Deuteron Imager (KoDI) provides information on both hotspot size and converged fuel shape.

High-energy deuterons are forward-scattered, encoding the shape of neutron emission.

Low-energy deuterons are a combination of side-scattered and ranged-down deuterons. They include information about the surrounding dense fuel.

With OMEGA yields, a resolution of < 10 μm is expected.
The Knock-on Deuteron Imager (KoDI) is a high magnification (~35×) penumbral imager for charged particles and x-rays on cryogenic ICF experiments. The diagnostic is based on the Particle Core Imaging System (PCIS), with a new detector location.
Deuteron energy is selected using differential filtering in the detector pack and track diameter in the CR-39

1. **Tantalum filters** stop deuterons below 2 MeV and 10 MeV, respectively.

2. **Track diameter in CR-39** is a monotonic function of deuteron energy.*

Tantalum filters:
- 125 μm (half)
- 10 μm (full)

* B. Lahmann, RSI 91, 053502 (2020)
The penumbral projections are summed to increase statistics and the source is reconstructed using a maximum likelihood method.

Fit to 50% contour:
- $P_0$: 34.4 μm
- $P_1/P_0$: 5.6%
- $P_2/P_0$: 14.0%
- $P_3/P_0$: 0.3%
- $P_4/P_0$: 7.3%

Fit to 17% contour:
- $P_0$: 54.5 μm
- $P_1/P_0$: 3.8%
- $P_2/P_0$: 6.2%
- $P_3/P_0$: 3.6%
- $P_4/P_0$: 7.0%

Different diameter cuts in the CR-39 data provide varying energy images

Reconstructions:

- **5.6 – 7.1 MeV*:**
  - $\chi^2_{\text{red}} = 1.27$

- **3.4 – 4.3 MeV*:**
  - $\chi^2_{\text{red}} = 1.23$

- **2.7 – 3.4 MeV*:**
  - $\chi^2_{\text{red}} = 1.11$

- **2 – 2.7 MeV*:**
  - $\chi^2_{\text{red}} = 1.03$

*approximate deuteron energy ranges
Different diameter cuts in the CR-39 data provide varying energy images

Reconstructions:

5.6 – 7.1 MeV*

3.4 – 4.3 MeV*

2.7 – 3.4 MeV*

2 – 2.7 MeV*

*approximate deuteron energy ranges

Offset direction of low-energy images is opposite the direction of hot-spot velocity.

Arrow: direction of neutron-inferred hotspot velocity (O. Mannion)
Different diameter cuts in the CR-39 data provide varying energy images

Reconstructions:

- **5.6 – 7.1 MeV**
  - Arrow: direction of neutron-inferred hotspot velocity (O. Mannion)
  - Offset direction of low-energy images is opposite the direction of hot-spot velocity.
  
  This is the expected direction, if it were caused by a large mode-1 in the fuel mass

- **3.4 – 4.3 MeV**
  - ASTER* simulation at peak neutron production

- **2.7 – 3.4 MeV**

- **2 – 2.7 MeV**

\[ \chi^2_{\text{red}} = 1.27 \]
\[ \chi^2_{\text{red}} = 1.23 \]
\[ \chi^2_{\text{red}} = 1.11 \]
\[ \chi^2_{\text{red}} = 1.03 \]

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*approximate* deuteron energy ranges

The upgraded hardware is compatible with 5 of 6 TIMs, enabling imaging and reconstruction of nearly the full 3D fuel layer.

Three sets of PCIS hardware exist, which can measure up to ~75% of the sphere. The five available TIMs will detect ~93%.*

<table>
<thead>
<tr>
<th>Shot Type</th>
<th>TIM 1</th>
<th>TIM 2</th>
<th>TIM 3</th>
<th>TIM 4</th>
<th>TIM 6</th>
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<tbody>
<tr>
<td>Warm</td>
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<td>40x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryo</td>
<td>35x</td>
<td>18.75x</td>
<td>24.7x</td>
<td>35x</td>
<td>35x</td>
</tr>
</tbody>
</table>

*assuming 2 MeV deuterons → 67° scattering angle
Summary

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