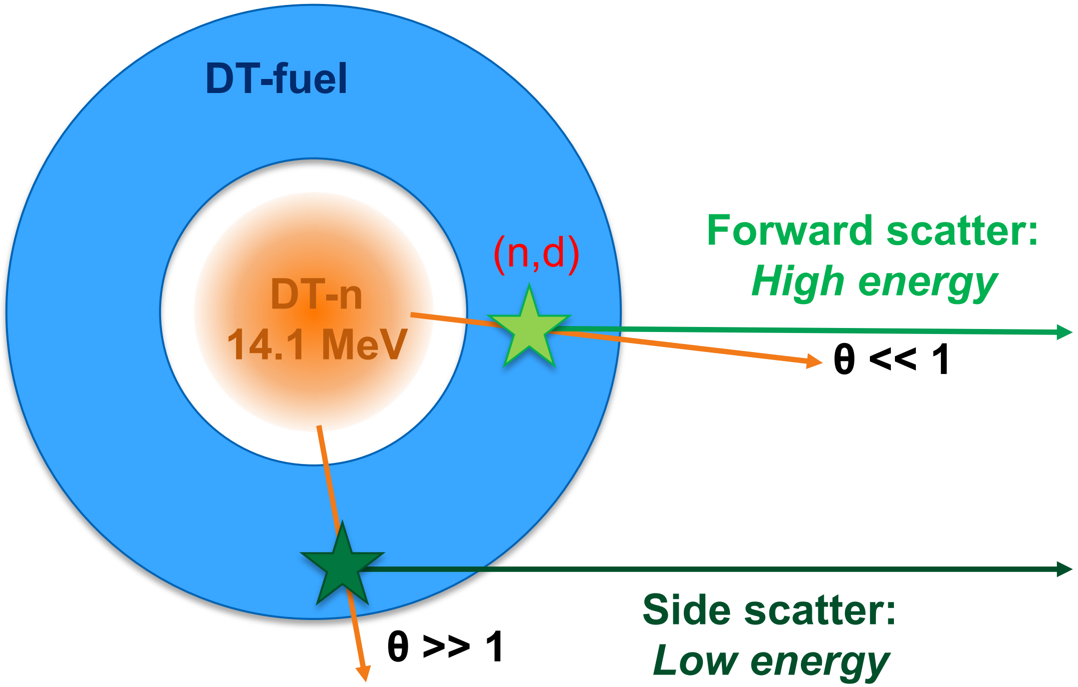
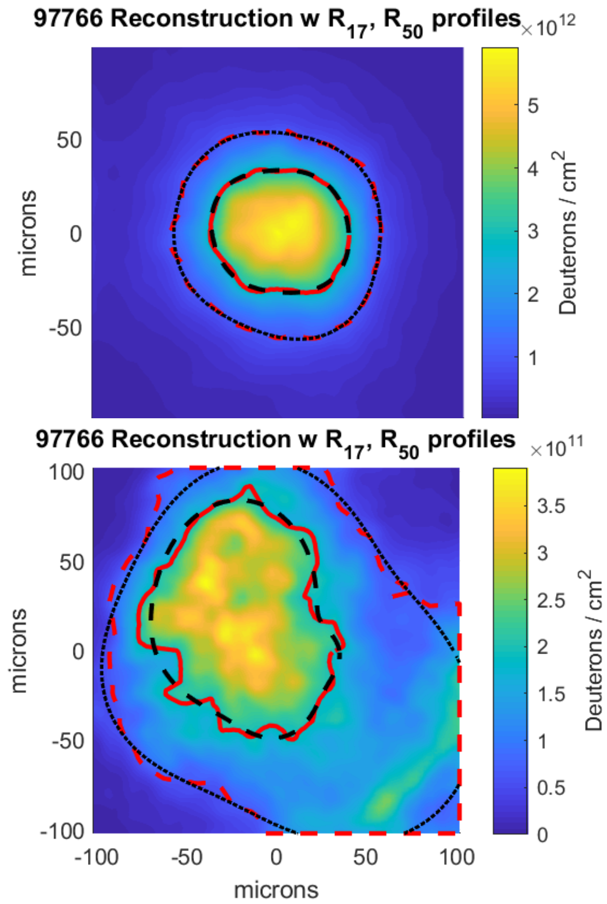
Knock-on Deuteron Imaging of the Hot Spot and Compressed Fuel in Direct-Drive Cryogenic ICF Implosions





Reconstructed images:

E > 10 MeV:
Hot-spot

E < 3 MeV:
Cold fuel

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

62nd Annual Meeting of the APS-DPP
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Summary

Hot-spot and cold-fuel images have been recorded using Knock-on Deuteron Imaging (KoDI) at OMEGA

- **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 ρR 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

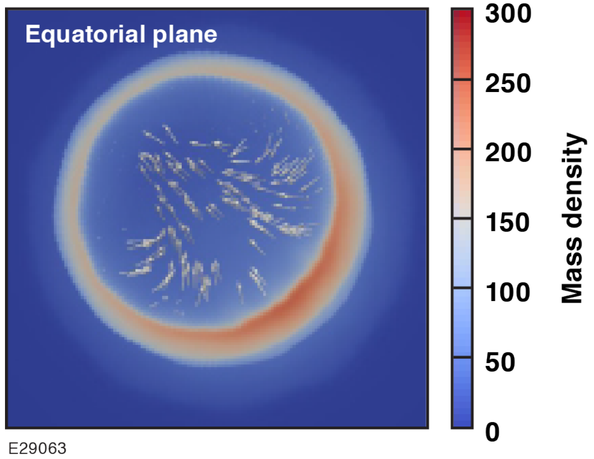
Hans Rinderknecht, J. Knauer, W. Theobald, R. Fairbanks, B. Brannon, V. Kobilansky, R. Peck, J. Armstrong, M. Weisbeck, J. Brown, P. B. Radha, S. Regan
LLE

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

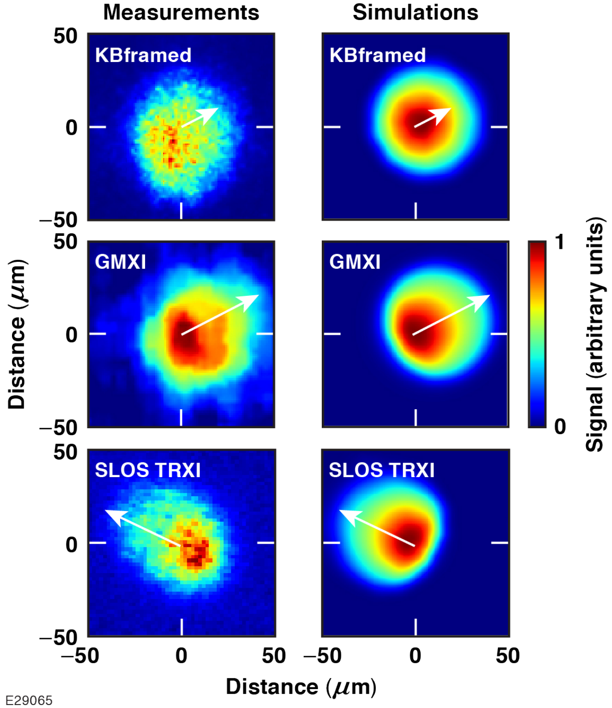
B. Bachmann, *LLNL*

Three-dimensional perturbations are now thought to significantly distort inertial-confinement fusion implosions at stagnation

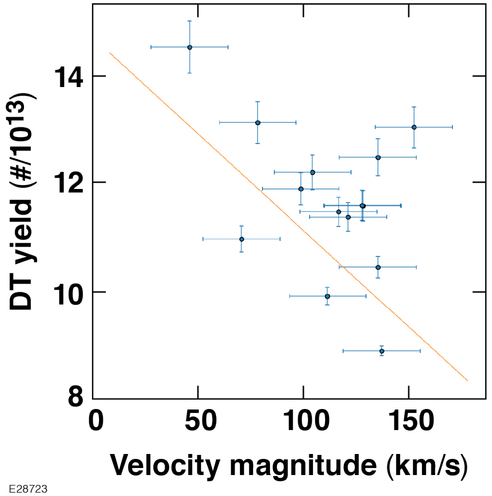
3-D *ASTER* simulation of hot-spot flow velocity (v_f) at stagnation (arrows indicate direction)

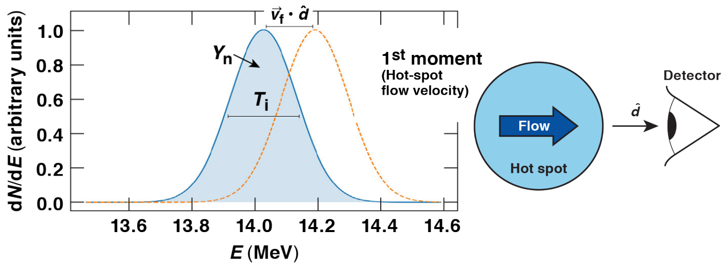


3-D x-ray images of hot spot (arrow indicates flow direction from 3-D nuclear)



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

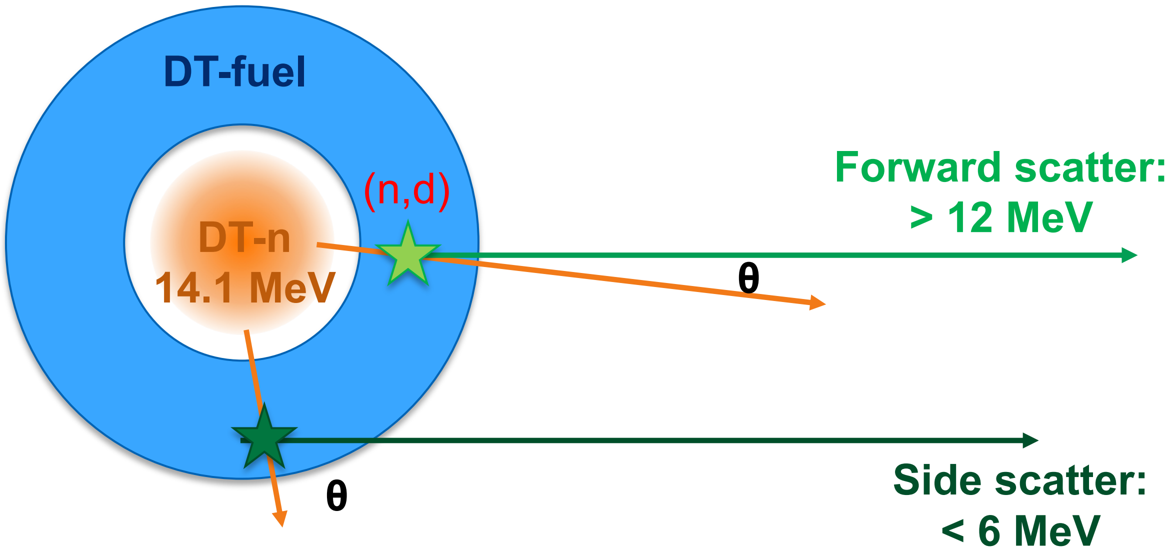


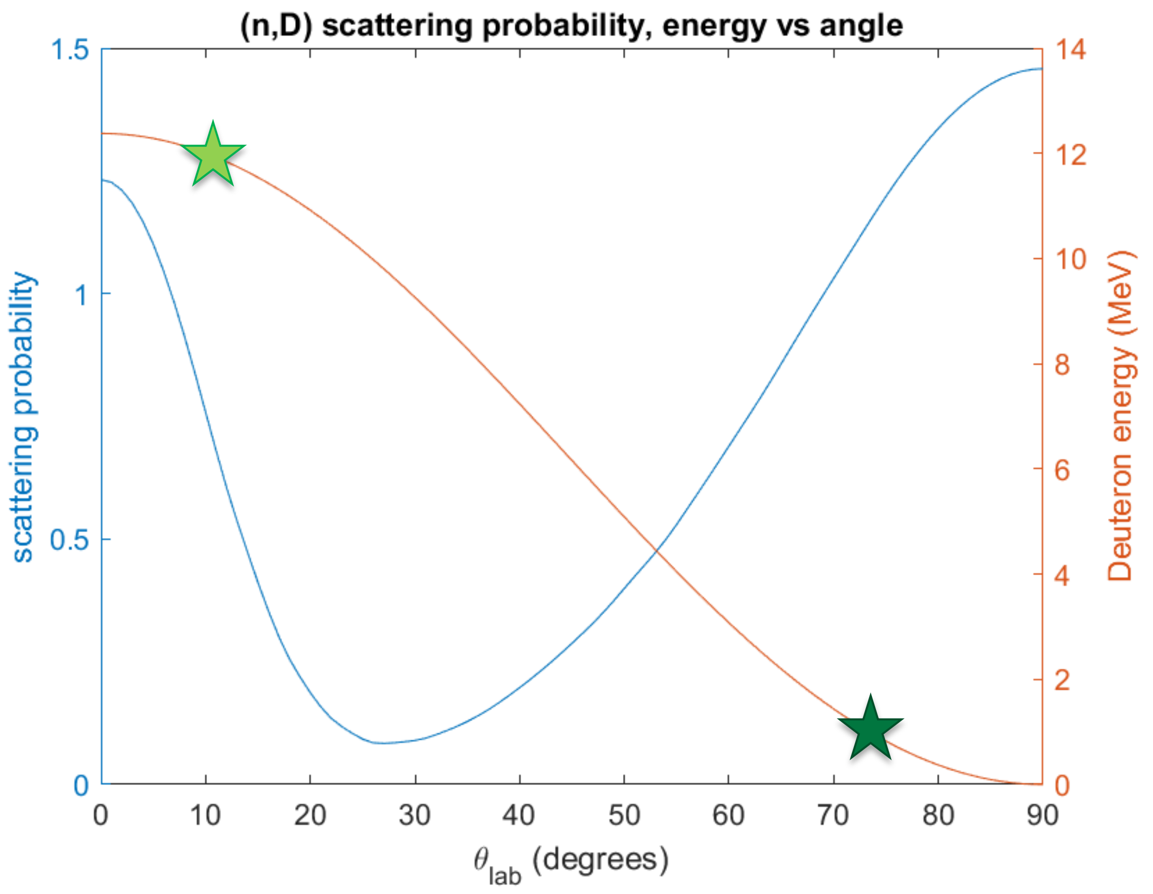


We need a diagnostic to measure detailed 3D fuel ρR distributions.

* O. M. Mannion *et al*., Nucl. Instrum. Methods Phys. Res. A 964, 163774 (2019).

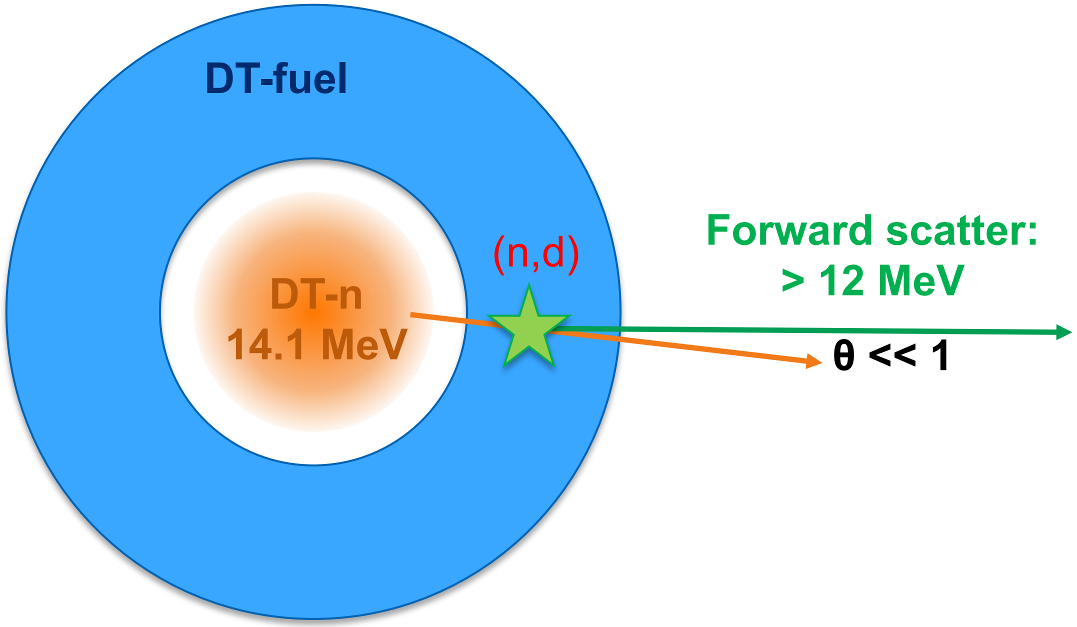
Elastic (n,d) scattering creates deuterons with energy in range 0—12.4 MeV, depending on the scattering angle θ

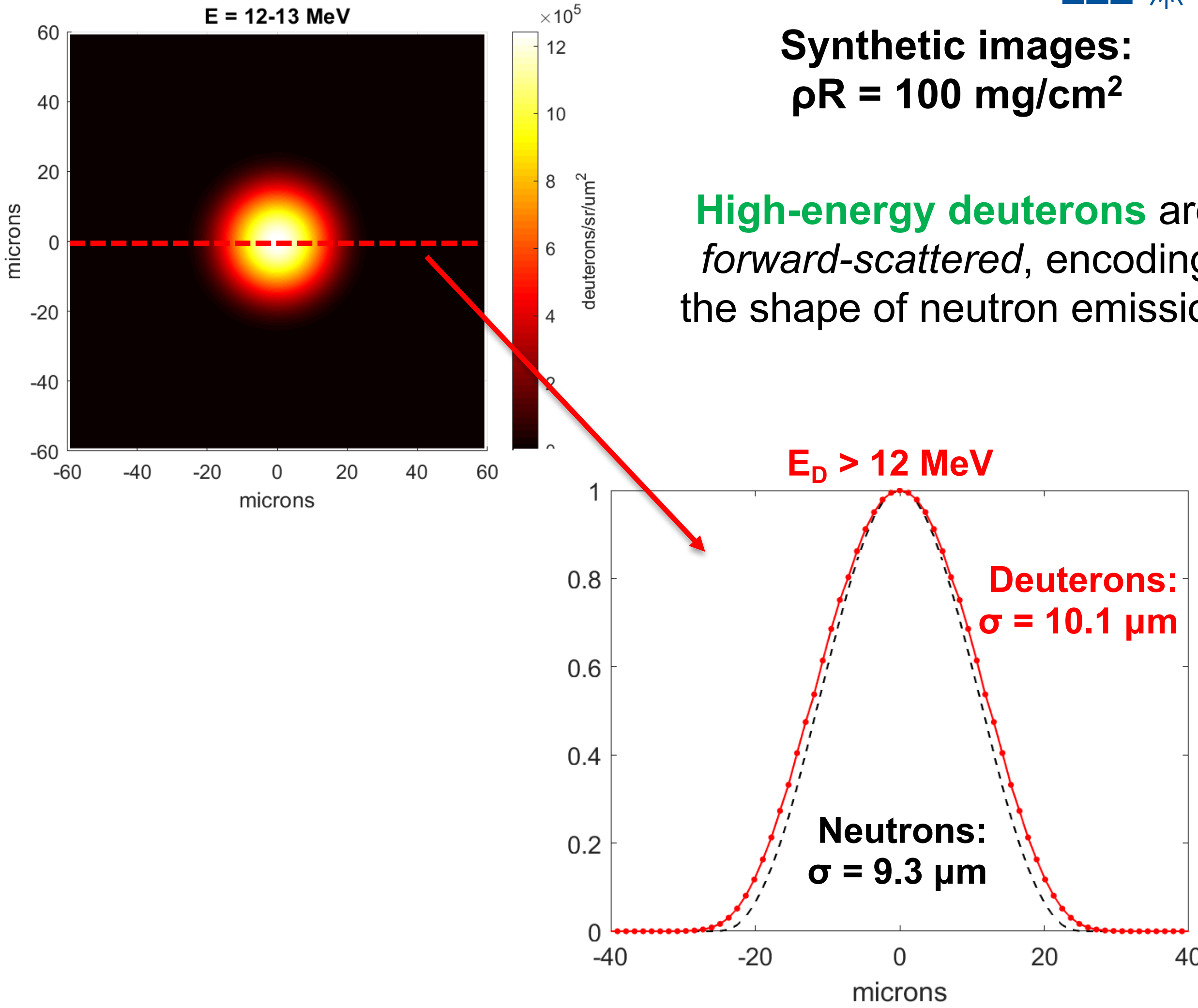




- *Deuteron yield scales with ρR:* $Y_D \approx 7.7\times10^{11}\left(\frac{\rho R}{100\mathrm{mg/cm}^2}\right)\left(\frac{Y_N}{10^{14}}\right)$

A Knock-on Deuteron Imager (KoDI) provides information on both hotspot size and converged fuel shape





Synthetic images:
ρR = 100 mg/cm^2

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

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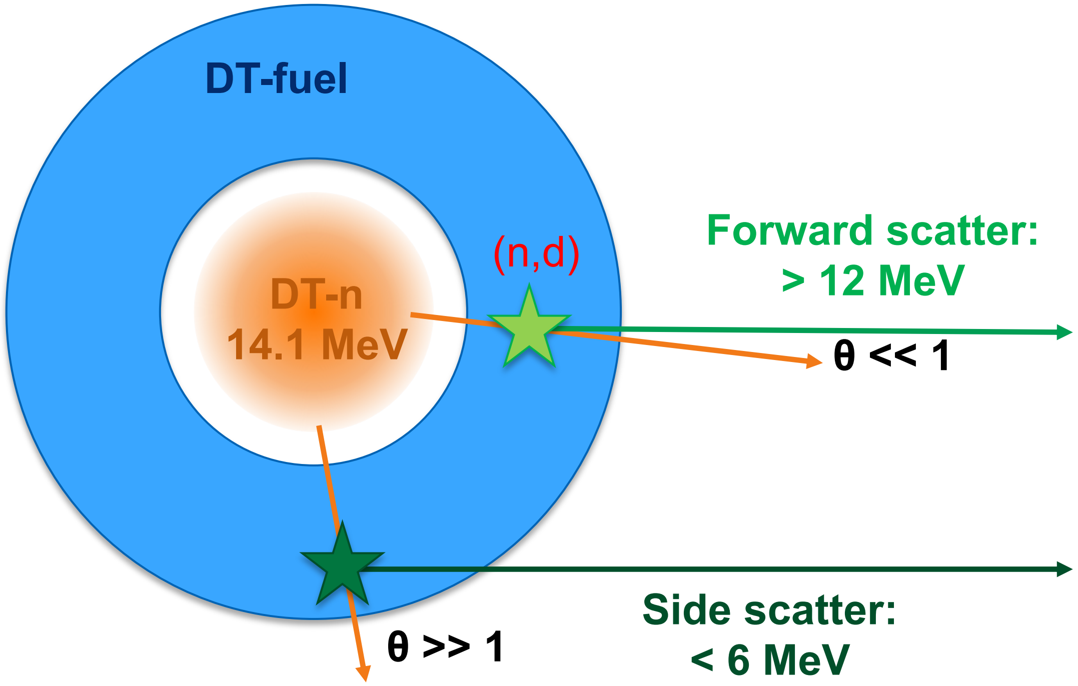
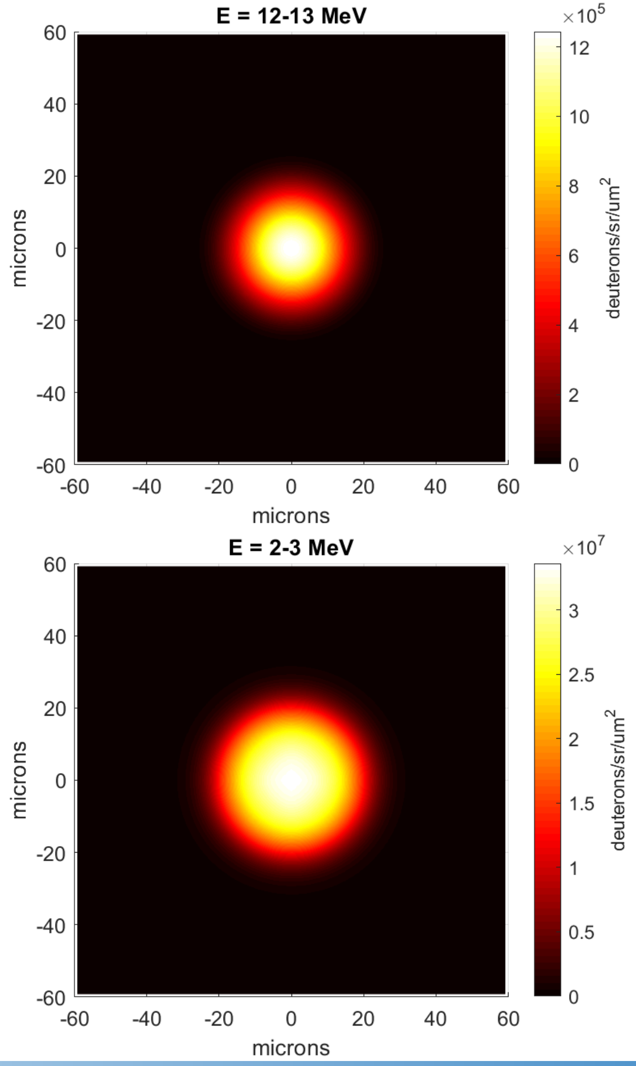




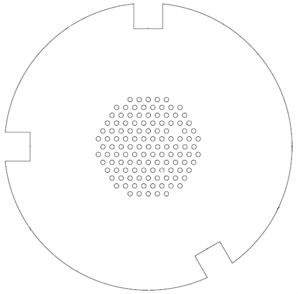
Synthetic images:
ρR = 100 mg/cm^2

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.

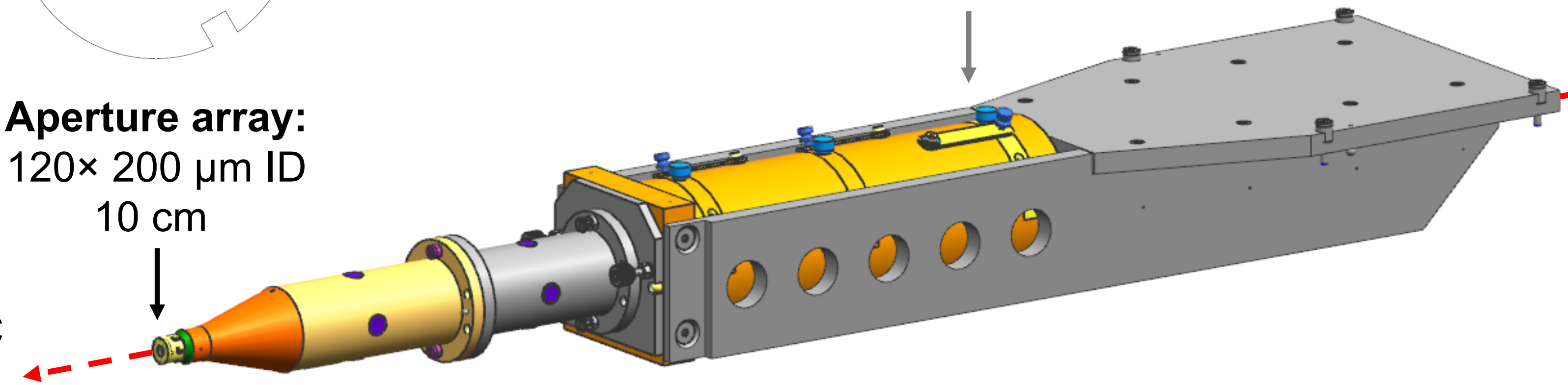
The Knock-on Deuteron Imager (KoDI) is a high magnification (~ 35×) penumbral imager for charged particles and x-rays on cryogenic ICF experiments



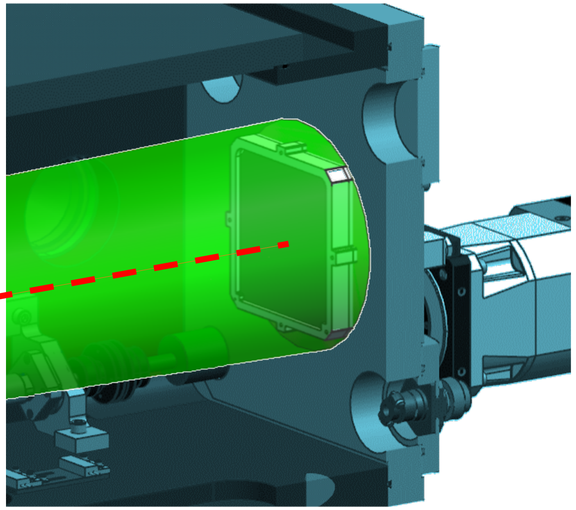
Aperture array:
120× 200 μm ID
10 cm

Previous detector assembly
70 cm

TCC



New detector assembly: 350 cm



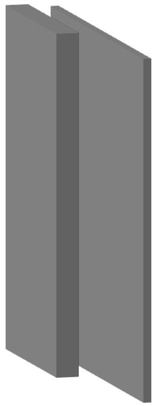
The diagnostic is based on the Particle Core Imaging System (PCIS), with a new detector location.

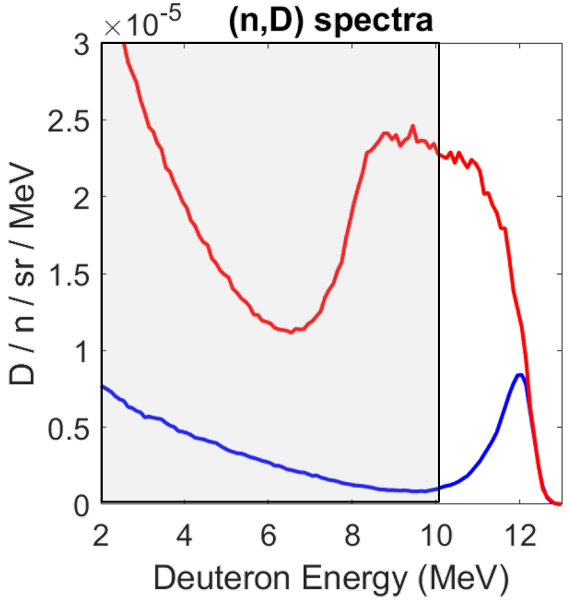
Deuteron energy is selected using differential filtering in the detector pack and track diameter in the CR-39

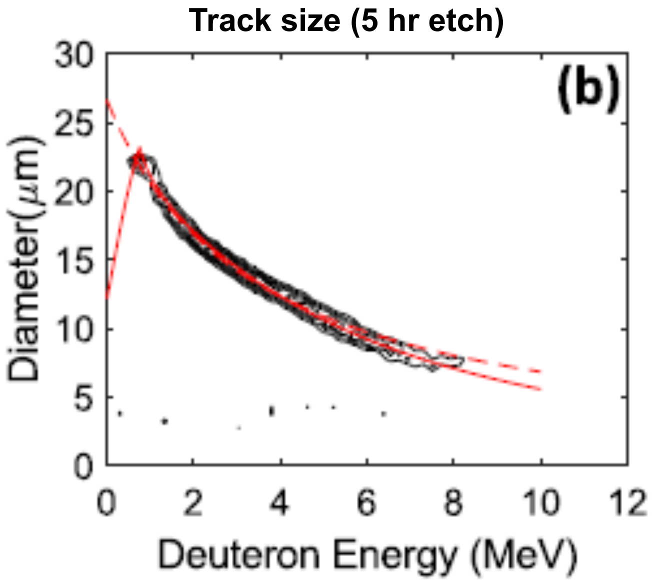
1. **Tantalum filters** stop deuterons below 2 MeV and 10 MeV, respectively.

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

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

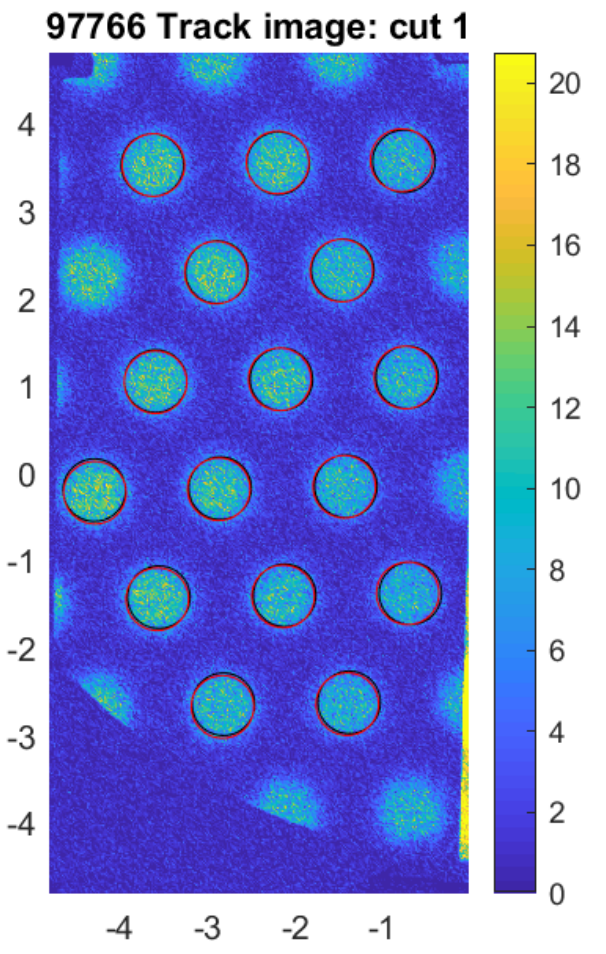




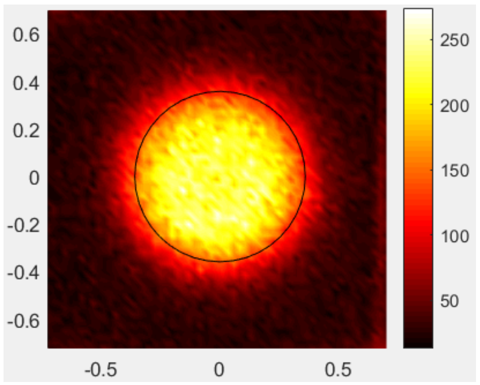


*B. Lahmann, RSI 91, 053502 (2020)

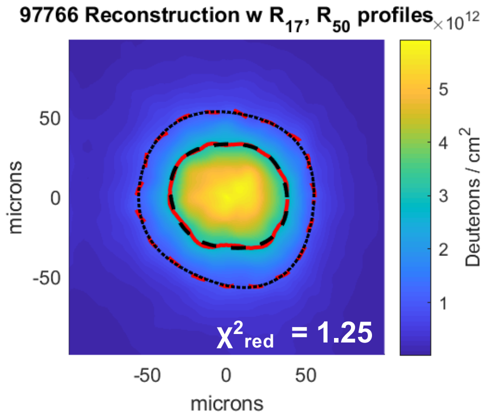
The penumbral projections are summed to increase statistics and the source is reconstructed using a maximum likelihood method



Composite penumbra



Reconstruction*



Energy > 10 MeV

Fit to 50% contour:

P0: 34.4 μm
P1/P0: 5.6%
P2/P0: 14.0%
P3/P0: 0.3%
P4/P0: 7.3%

Fit to 17% contour:

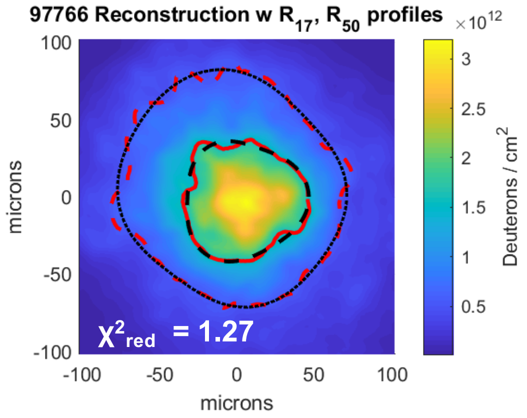
P0: 54.5 μm
P1/P0: 3.8%
P2/P0: 6.2%
P3/P0: 3.6%
P4/P0: 7.0%

*V. I. Gelfgat, et al., *Computer Physics Communications* 74, 335–348 (1993).

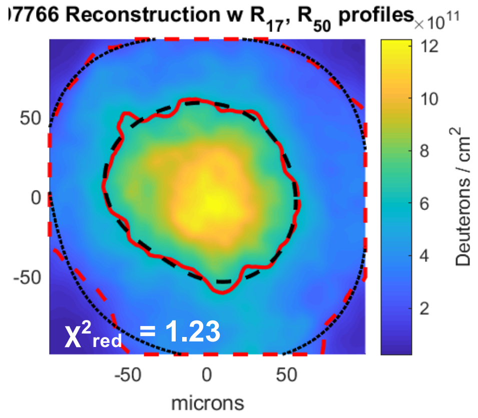
Different diameter cuts in the CR-39 data provide varying energy images

Reconstructions:

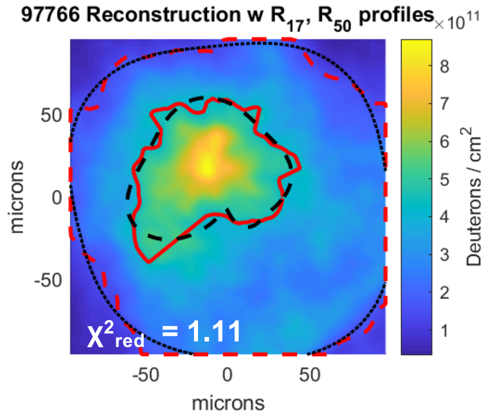
5.6 – 7.1 MeV*



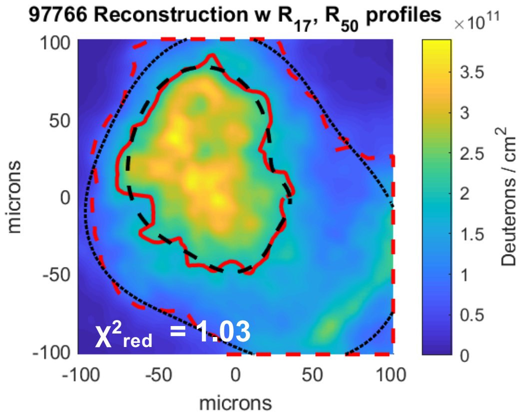
3.4 – 4.3 MeV*



2.7 – 3.4 MeV*



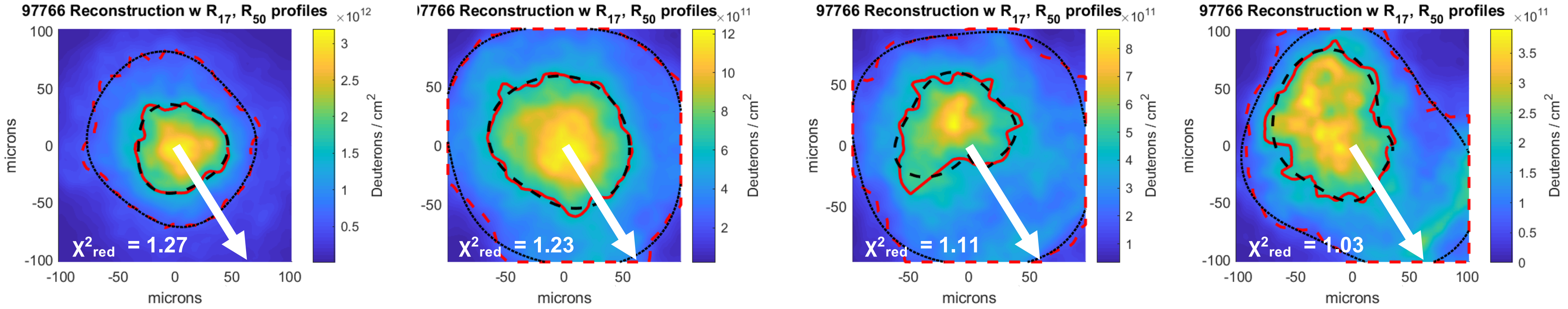
2 – 2.7 MeV*



*<u>approximate</u> 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*

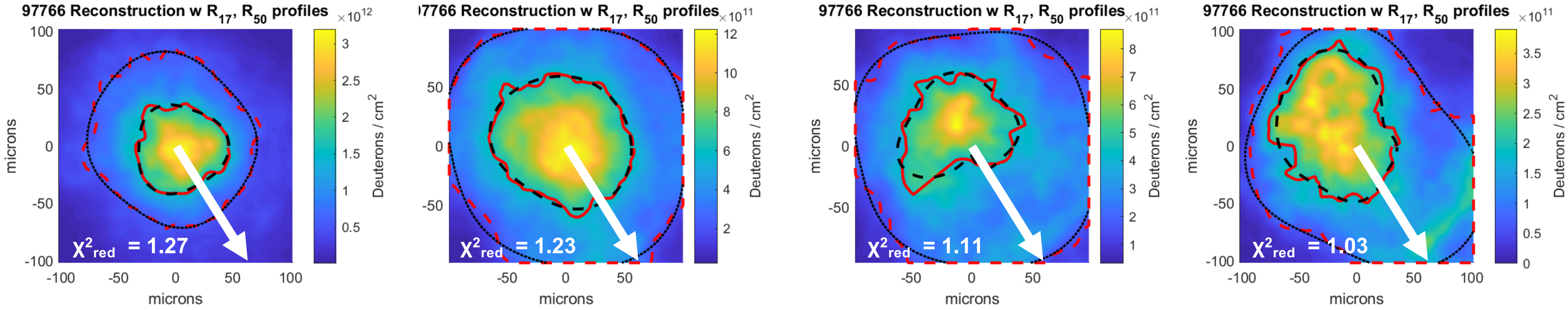


Arrow: direction of neutron-inferred hotspot velocity (O. Mannion)

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

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*

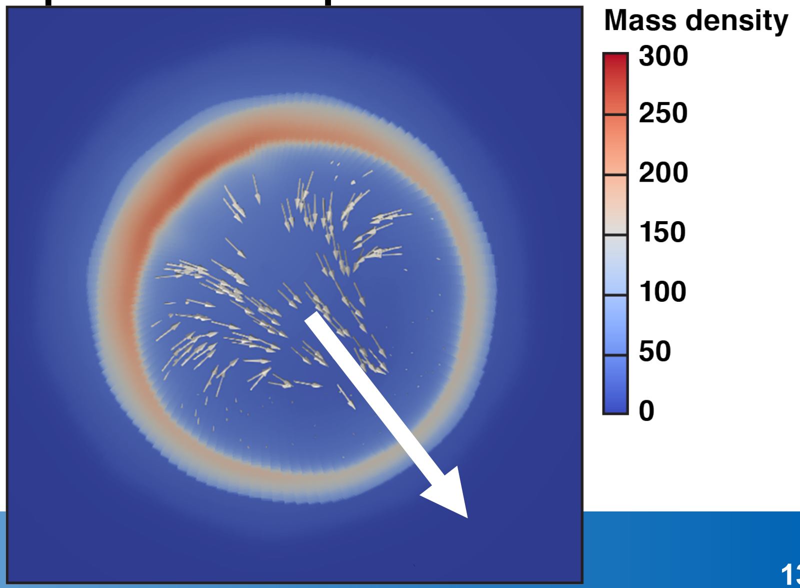


Arrow: direction of neutron-inferred hotspot velocity (O. Mannion)

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

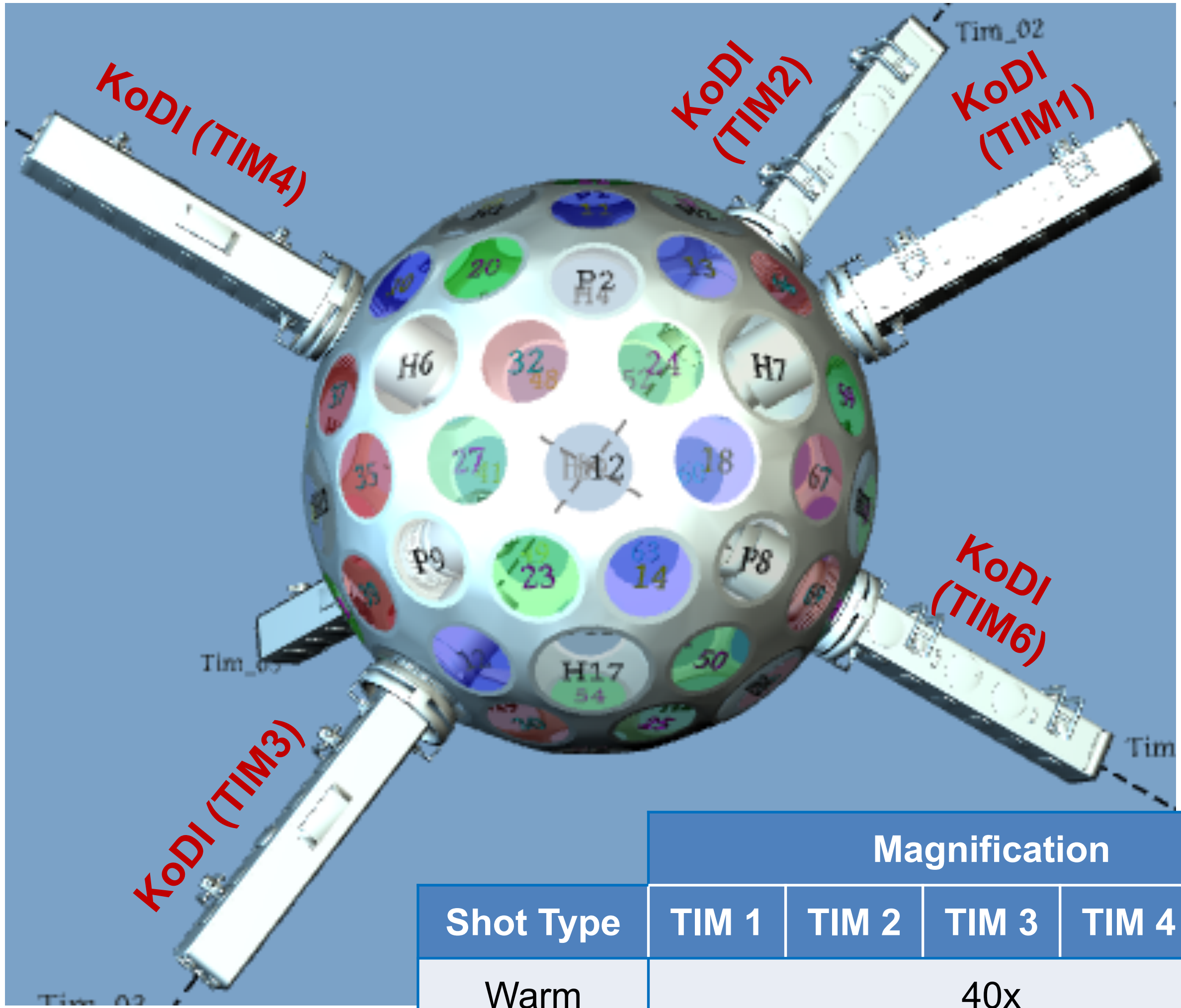
This is the expected direction, if it were caused by a large mode-1 in the fuel mass

***ASTER** simulation at peak neutron production*



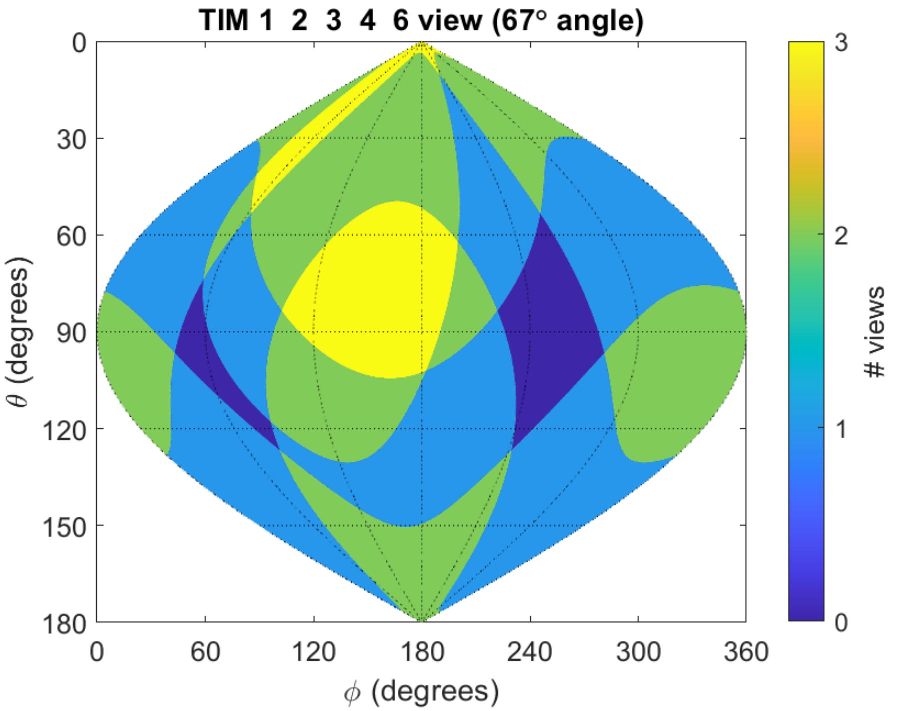
* I. V. Igumenshchev *et al*., Phys. Plasmas 23, 052702 (2016).

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



	Magnification				
Shot Type	TIM 1	TIM 2	TIM 3	TIM 4	TIM 6
Warm	40x				
Cryo	35x	18.75x	24.7x	35x	35x

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



**assuming 2 MeV deuterons → 67° scattering angle*

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