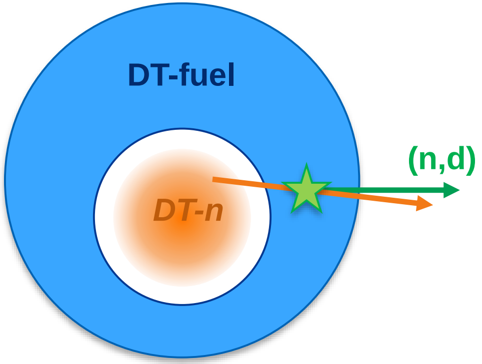
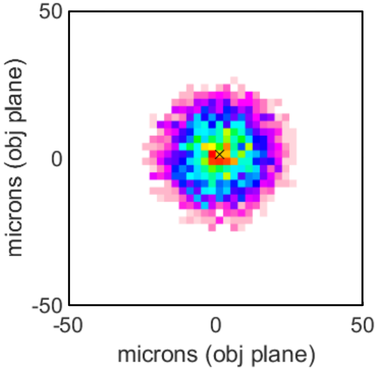
Hot spot and fuel imaging using nuclear diagnostics on direct-drive cryogenic implosions at OMEGA

Synthetic (n,d) images:



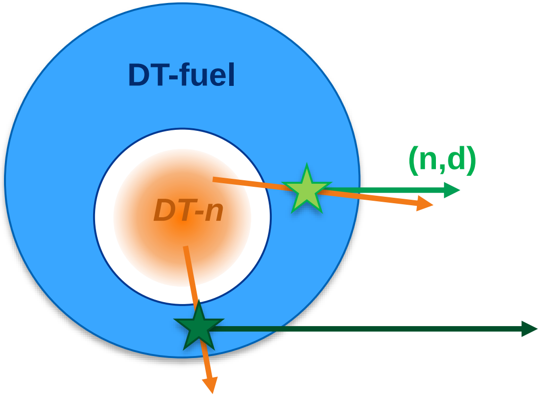
High-energy deuterons (> 12 MeV) record hotspot shape



Hans Rinderknecht
University of Rochester
Laboratory for Laser Energetics

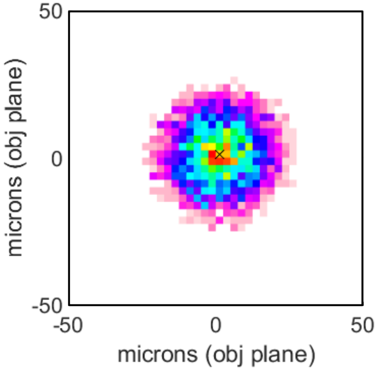
61st Meeting of the APS Division of Plasma Physics
Fort Lauderdale, FL
October 21—25, 2019

Hot spot and fuel imaging using nuclear diagnostics on direct-drive cryogenic implosions at OMEGA

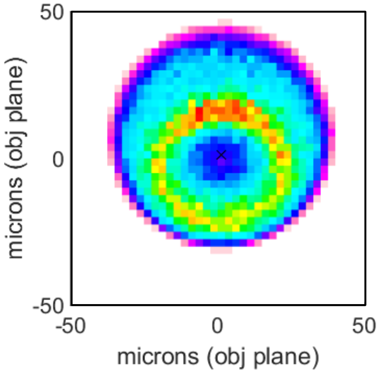


Synthetic (n,d) images:

High-energy deuterons (> 12 MeV) record hotspot shape



Low-energy deuterons (2—3 MeV) record cold fuel morphology



Hans Rinderknecht
University of Rochester
Laboratory for Laser Energetics

61st Meeting of the APS Division of Plasma Physics
Fort Lauderdale, FL
October 21—25, 2019

Summary

Deuteron imaging offers a uniquely powerful diagnostic of hotspot and fuel ρR symmetry for directly-driven inertial confinement fusion implosions

- **Deuterons scattered from the dense DT-fuel layer by 14-MeV neutrons have an energy that depends on the scattering angle and ranging as they leave the fuel:**
  - High energy deuterons (E > 12 MeV) encode an image of the neutron producing region
  - Lower energy deuterons (E < 8 MeV) encode information about ρR symmetry

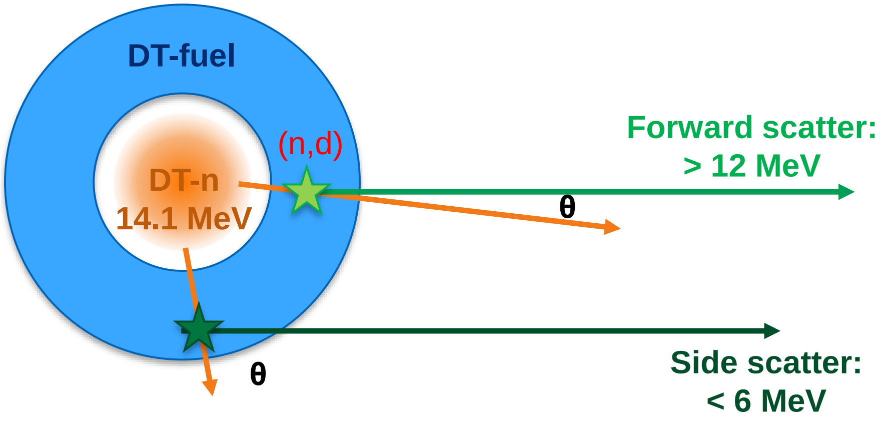
- **A Knock-on Deuteron Imager (KoDI) is under development for cryogenic implosions on OMEGA**
  - A Monte Carlo code has been developed to predict diagnostic signatures and develop analysis methods
  - Experimental tests with warm and cryogenic implosions are ongoing

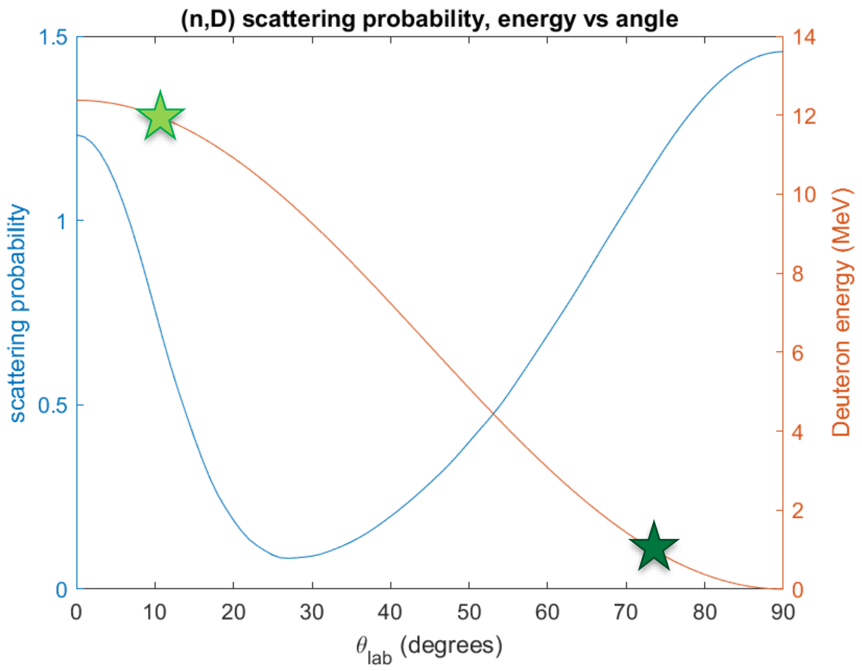
Collaborators

C. J. Forrest, J. P. Knauer, W. Theobald, and S. P. Regan
Laboratory for Laser Energetics, University of Rochester, USA

R. Simpson, M. Gatu Johnson and J. A. Frenje
Massachusetts Institute of Technology, USA

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

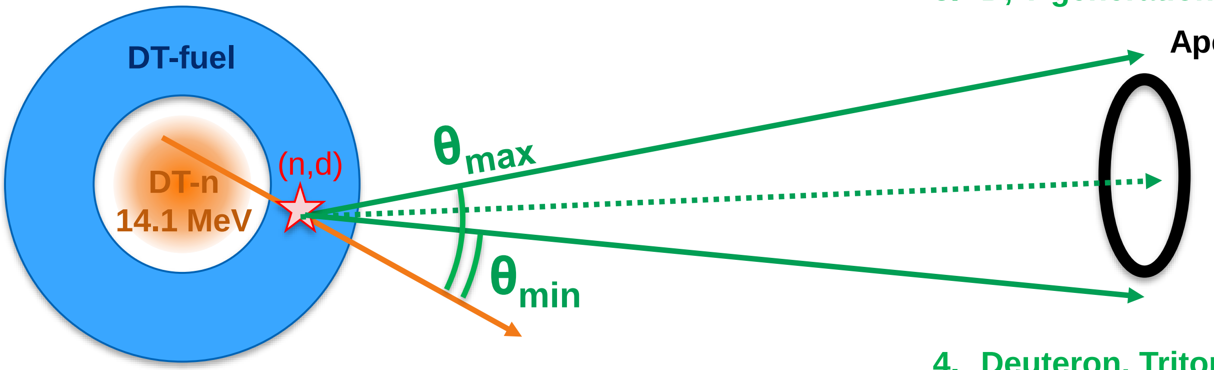




- *Deuteron yield scales with ρR:* $Y_D \approx 7.7\times10^{11}\left(\dfrac{\rho R}{100\mathrm{mg/cm^2}}\right)\left(\dfrac{Y_N}{10^{14}}\right)$

A Monte Carlo algorithm was developed to calculate scattered deuteron images

1. **Neutron generation in hotspot:** *position & velocity*



2. **Probability of (n,D), (n,T) reaction in fuel:**

$$W_n = 1 - \exp\left[-\sigma_{(n,d)} n_d L_{max}\right]$$

3. **D, T generation in fuel (x N per neutron):**

Aperture geometry limits allowed angles:

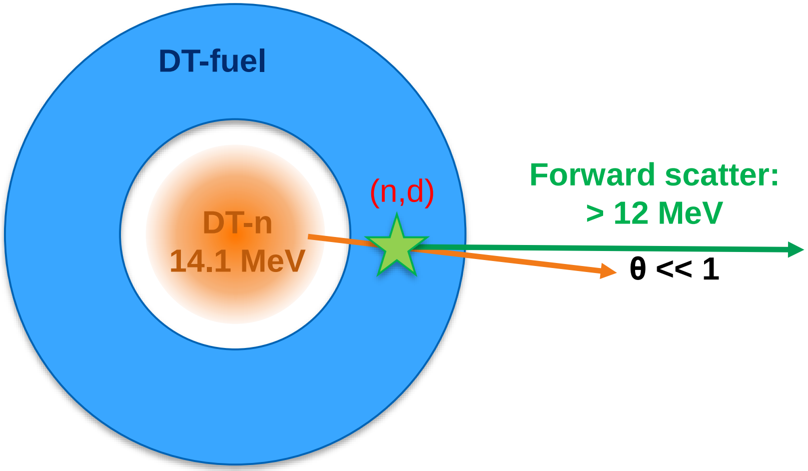
$$W_\theta = \int_{\theta_{min}}^{\theta_{max}} \frac{\partial P}{\partial \theta} d\theta \qquad W_\phi = \frac{\phi_{max} - \phi_{min}}{2\pi}$$

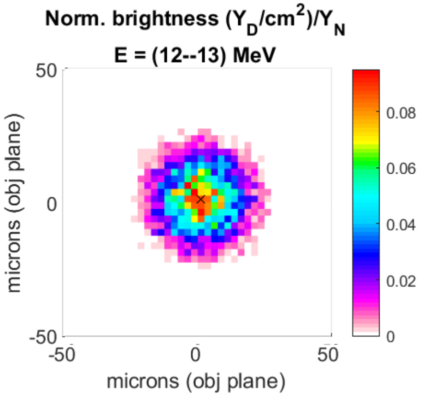
4. **Deuteron, Triton ranging in fuel**

Maynard-Deutch stopping power

Total probability for each particle:	$P_d = W_n W_\theta W_\phi \frac{N_{detected}}{N_{neutrons}}$	…for $N_{neutrons}$ launched with a given (x_{n0}, v_{n0}) producing $N_{detected}$ deuterons through the aperture.

Knock-on Deuteron Imaging (KoDI) is complementary to neutron imaging and provides information on both hotspot size and converged fuel shape

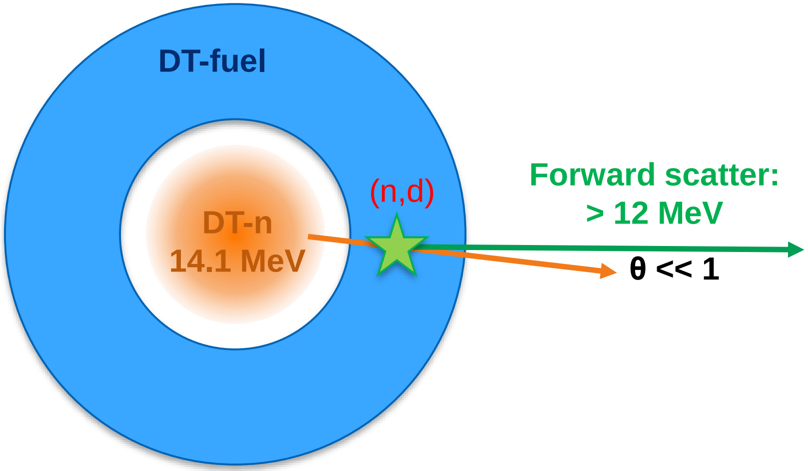


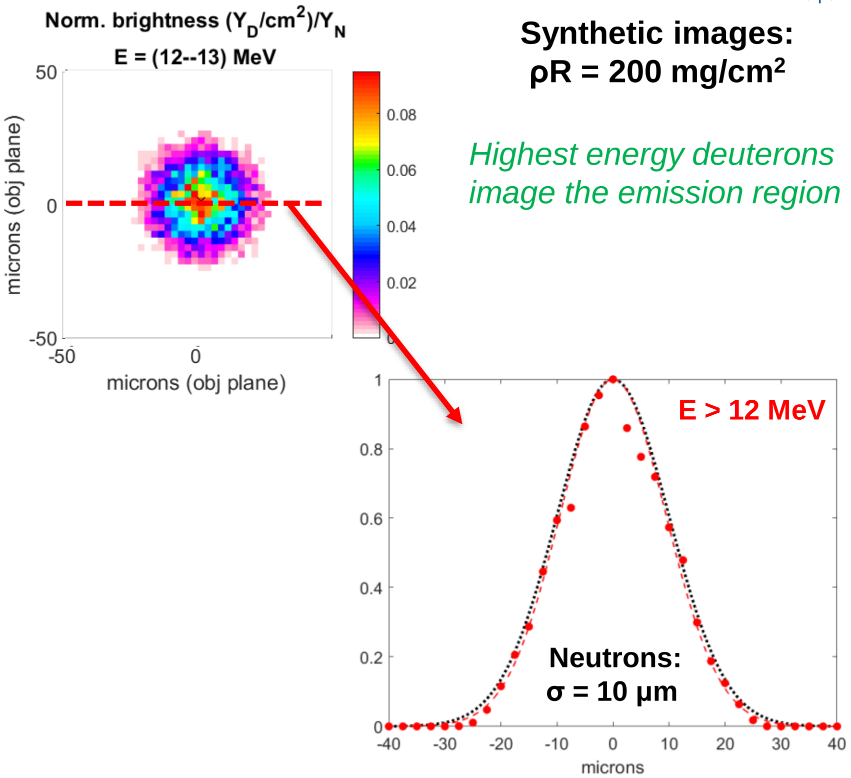


Synthetic images:
ρR = 200 mg/cm^2

Highest energy deuterons image the emission region

Knock-on Deuteron Imaging (KoDI) is complementary to neutron imaging and provides information on both hotspot size and converged fuel shape

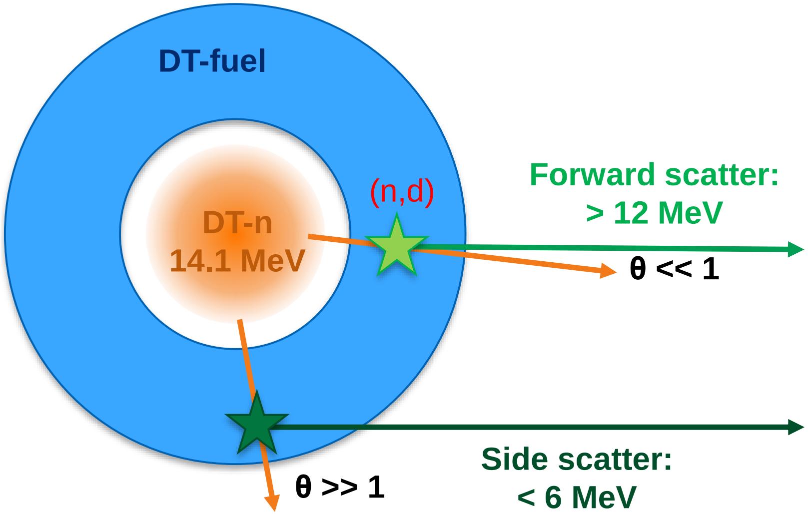


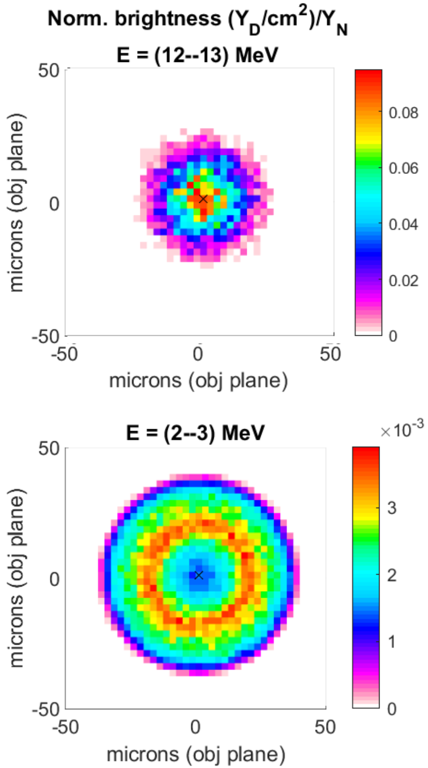


Synthetic images:
ρR = 200 mg/cm^2

Highest energy deuterons image the emission region

Knock-on Deuteron Imaging (KoDI) is complementary to neutron imaging and provides information on both hotspot size and converged fuel shape





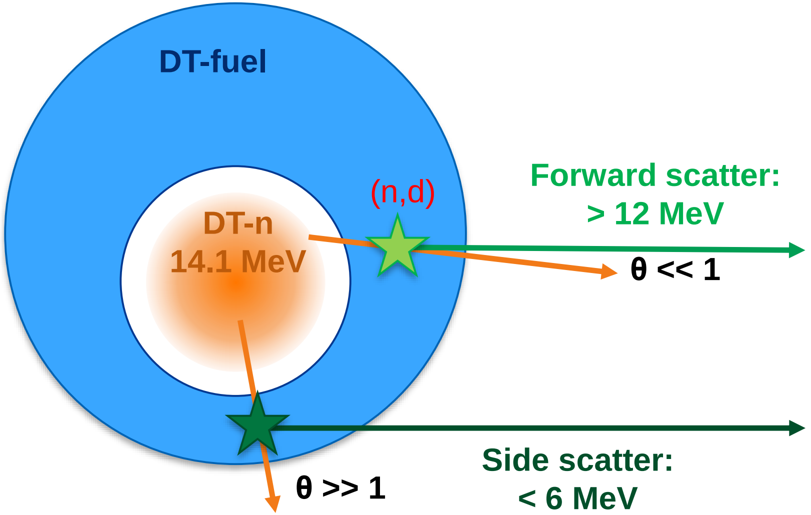
Synthetic images:
ρR = 200 mg/cm^2

Highest energy deuterons image the emission region

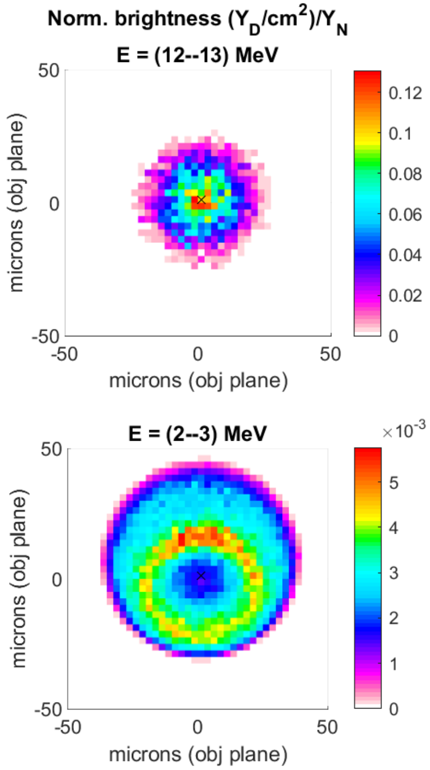
Lower energy deuterons image ρR vs. shell position.

With OMEGA yields, a resolution of < 10 μm is expected.

Knock-on Deuteron Imaging (KoDI) is complementary to neutron imaging and provides information on both hotspot size and converged fuel shape



With OMEGA yields, a resolution of < 10 μm is expected.



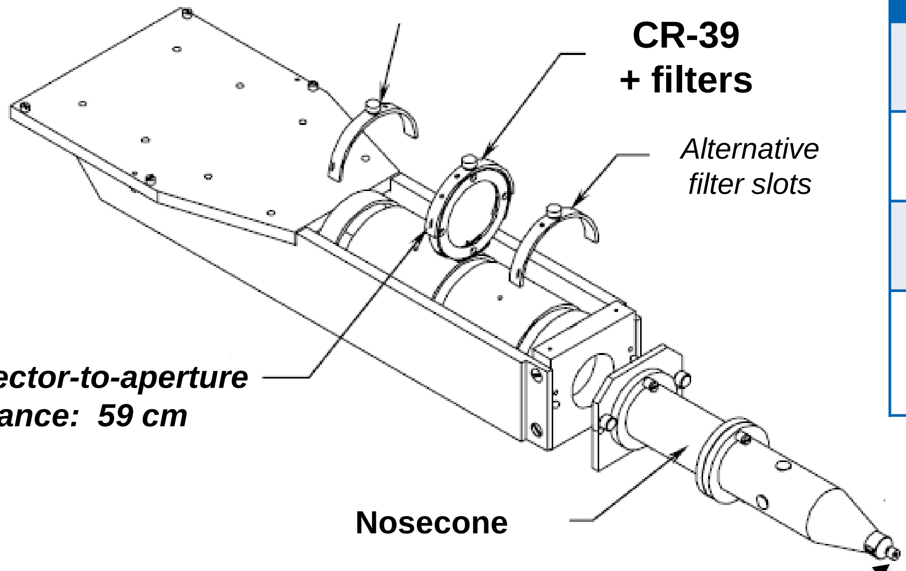
Synthetic images with 50% mode-1 perturbation

Highest energy deuterons image the emission region

Lower energy deuterons image ρR vs. shell position.

We are developing an (n,d) measurement capability based on the existing Penumbral Core Imaging System (PCIS) diagnotic

Existing PCIS hardware

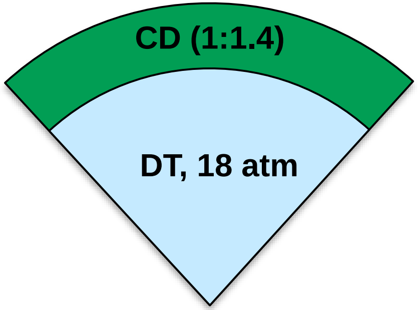


	Goal	Experiment
Stage 0	Demonstrate proof-of-concept using PCIS	✓ 12/4 Expl. Pushers • ***CD(DT) implosion***
Stage 1	Image high-energy D: PCIS with optimized aperture	Cryogenic implosions ***First test: Oct 2019***
Stage 2	Spectral resolution: PCIS with optimized hardware	Cryogenic implosions FY20 Q2
Stage 3	High-resolution spectral imaging & background reduction: optimized KoDI	…

As a TIM-based instrument, this capability can readily be used on up to 6 lines of sight to image the fuel layer in three dimensions.

Implosions of deuterated plastic shell (CD) filled with DT will provide a demonstration of the imaging technique for areal density

UR LLE

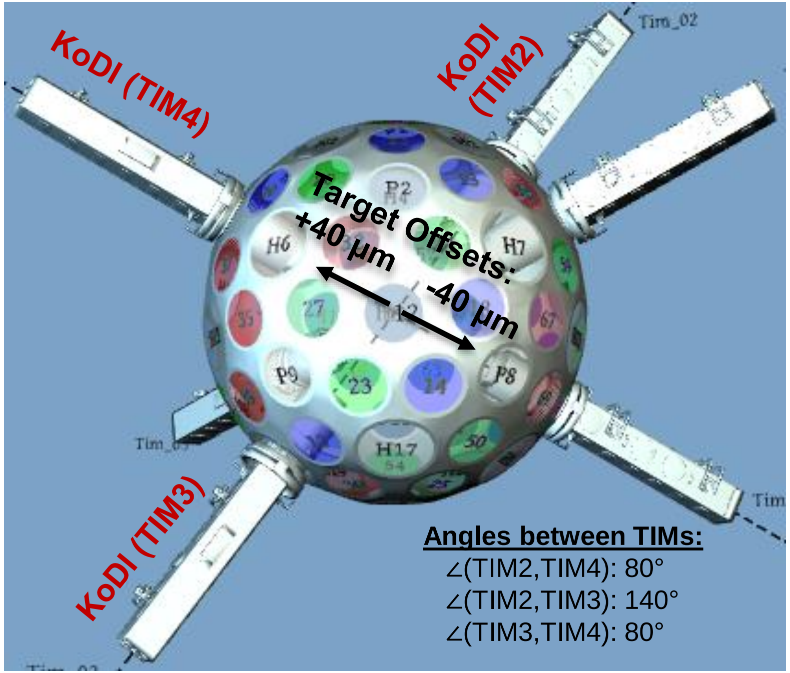


- **Expected performance:**
  - ρR ~ 50 mg/cm^2, DT yield ~ 3e12

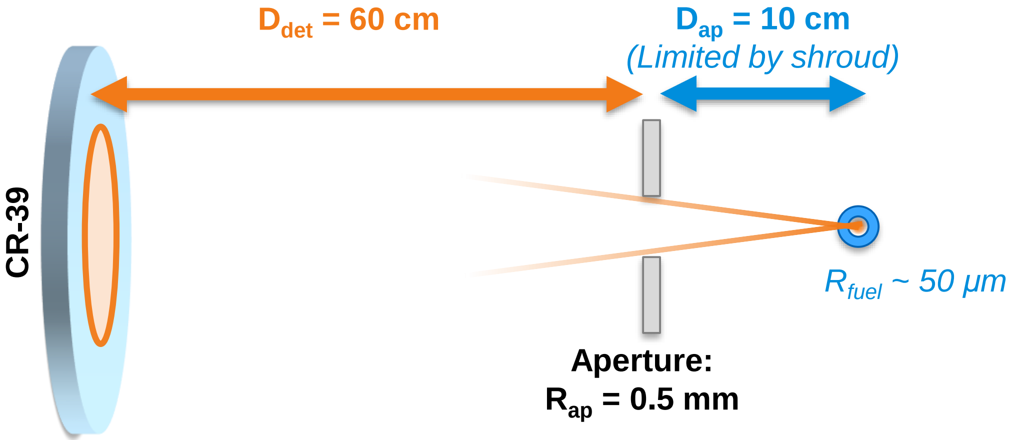
  → *~5e9 scattered deuterons*

- **'Single-channel' test of spectral imaging measurement:**
  - knock-on deuterons only, tritons suppressed

- **Six shots will vary ρR and test induced asymmetry**



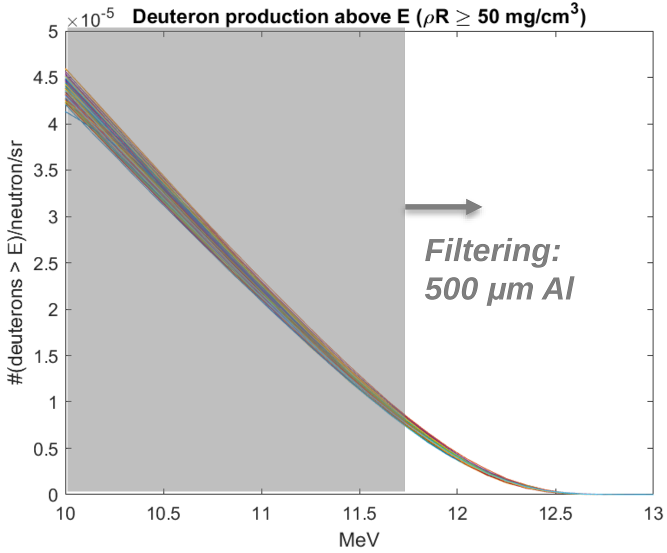
Initial cryogenic tests will record only the high-energy deuterons (E > 12 MeV) to demonstrate hotspot imaging



- Magnification M_{rad} = 7
- Aperture solid angle = 7.9e-5 sr

Assuming a DT-n yield = 1e14 → Y_D(>12 MeV) < 1e9/sr

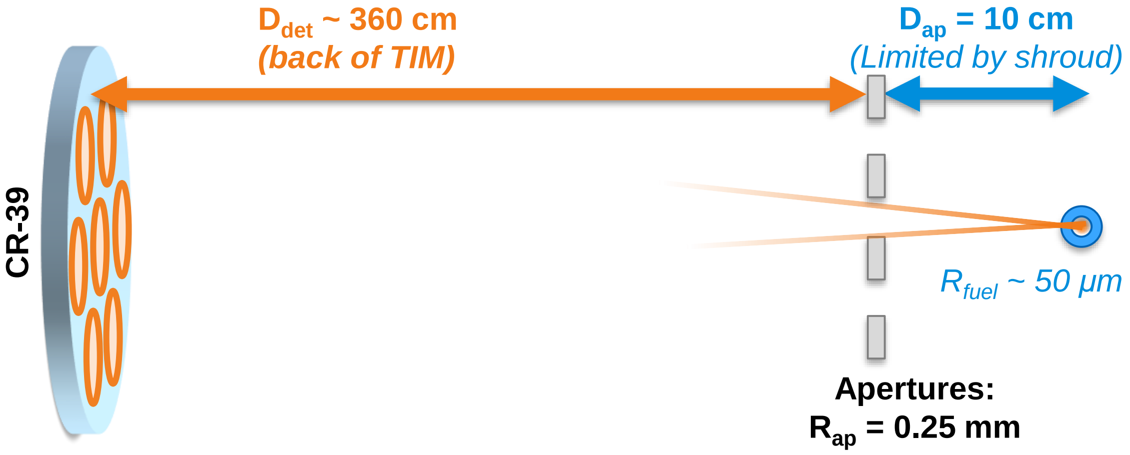
- N in aperture = 8e4 deuterons
- Fluence @ 70 cm = 1.5e5 tracks/cm^2
- N in penumbra = (2π M_{rad} R_{ap})(M_{pin} R_{fuel})F/2 = 5e3



Scattered tritons are blocked by the filtering: a robust (n,d) hotspot image is expected

Stage 2

Modified PCIS hardware will increase magnification and reduce fluence on the detector, allowing spectral information to be resolved

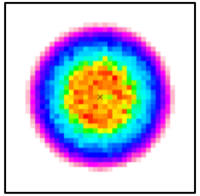


- Magnification M_{rad} = 34
- Aperture solid angle = 2e-5 sr

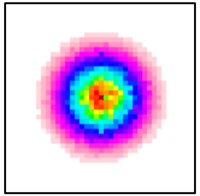
Assuming a DT-n yield = 1e14 → Y_D = 1.2e11/sr

- N in aperture = 2.4e6 deuterons
- Fluence @ 340 cm = 9.3e5 tracks/cm^2 *(full spectrum)*
- N in penumbra = $(2\pi\, M_{rad}\, R_{ap})(M_{pin}\, R_{fuel})F/2$ = 5e5

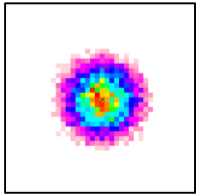
Deuteron + Triton images ρR = 200 mg/cm^2



50 µm Al filtering:
E_D = [2.9, 4.9] MeV
E_T = [3.3, 5.3] MeV



150 µm Al:
E_D = [5.7, 7.7] MeV
E_T = [6.7, 8.7] MeV



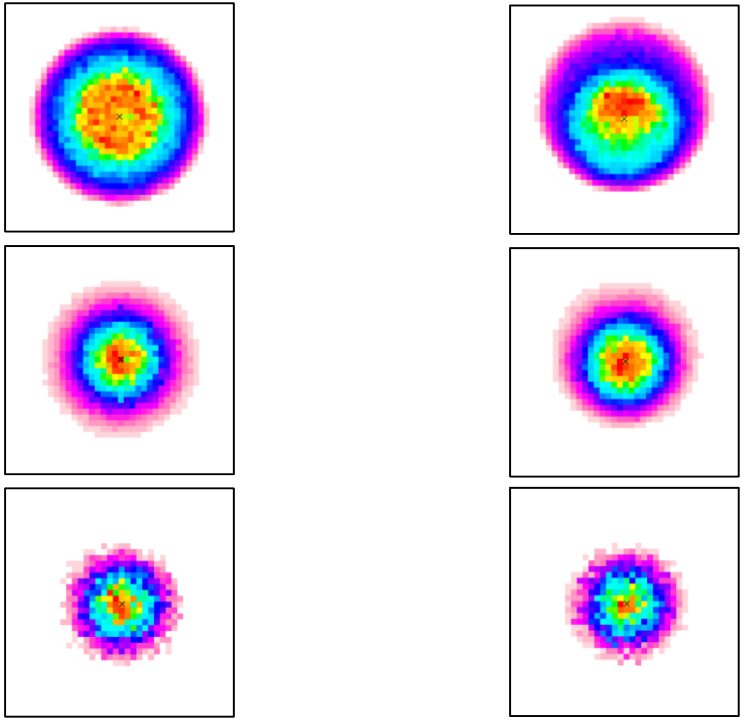
500 µm Al:
E_D = [11.8, 13.8] MeV
no tritons

Filtering may be used to select different parts of the (n,d),(n,t) spectra in different penumbra

With reduced fluence and higher magnification, KoDI is predicted to be sensitive to variations in the shape of the cold fuel

Deuteron + Triton images:
ρR = 200 mg/cm^2

Symmetric | **50% offset**



50 μm Al filtering:
E_D = [2.9, 4.9] MeV
E_T = [3.3, 5.3] MeV

150 μm Al:
E_D = [5.7, 7.7] MeV
E_T = [6.7, 8.7] MeV

500 μm Al:
E_D = [11.8, 13.8] MeV
no tritons

Deuteron imaging offers a uniquely powerful diagnostic of hotspot and fuel ρR symmetry for directly-driven inertial confinement fusion implosions

- **Deuterons scattered from the dense DT-fuel layer by 14-MeV neutrons have an energy that depends on the scattering angle and ranging as they leave the fuel:**
  - High energy deuterons (E > 12 MeV) encode an image of the neutron producing region
  - Lower energy deuterons (E < 8 MeV) encode information about ρR symmetry

- **A Knock-on Deuteron Imager (KoDI) is under development for cryogenic implosions on OMEGA**
  - A Monte Carlo code has been developed to predict diagnostic signatures and develop analysis methods
  - Experimental tests with warm and cryogenic implosions are ongoing

See also: R. Simpson, Friday 10:30 (YO5.6)!

Appendix

Stage 1

Cryogenic implosions on OMEGA are expected to produce deuteron fluxes that are too large for the current diagnostic system

Deuteron fluence on detector:

$$F_D \approx \frac{Y_n \sigma_{n,D} \rho R}{4\pi \mathrm{D}_{tot}^2 \langle A \rangle} = 1.22 \times 10^7\ \mathrm{cm}^{-2} \left(\frac{\rho R}{100\ \mathrm{mg/cm}^2} \right) \left(\frac{Y_n}{10^{14}} \right) \left(\frac{D_{tot}}{100\ \mathrm{cm}} \right)^{-2}$$

>> 10^6 cm^{-2},
Upper limit for CR-39

Neutron fluence on detector:

$$F_n = \frac{Y_n}{4\pi D_{tot}^2}$$

Signal to background ratio:

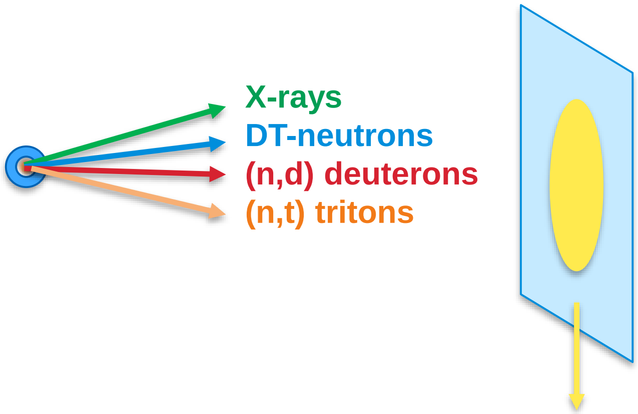
$$\frac{S}{B} = \frac{F_D \epsilon_D}{F_n \epsilon_n} = 380 \left(\frac{\rho R}{100 \mathrm{mg/cm}^2} \right)$$

- *deuteron detection efficiency:* $\varepsilon_D \sim 1$
- *neutron detection efficiency*:* $\varepsilon_n \sim 4e\text{-}5$

*J. A. Frenje et al., "Absolute measurements of neutron yields in DD and DT implosions at the OMEGA laser facility using CR-39 track detectors", Rev. Sci. Instrum. 73 (2002) 2597.

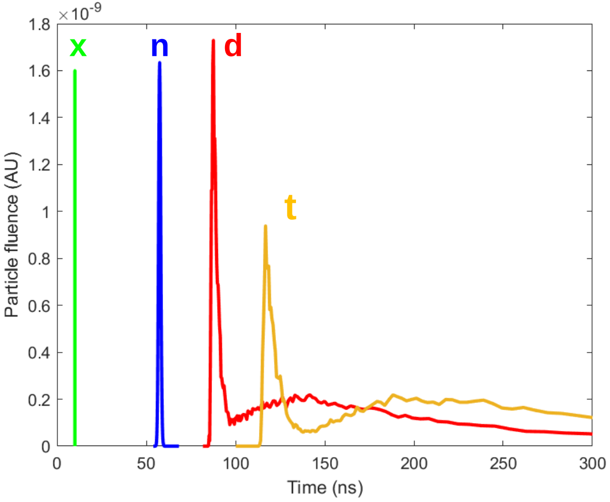
Ultimately, a time-of-flight/scintillator imaging design may allow detailed resolution of deuteron energy bins with significant background reduction.

Scintillator: ns decay time,
Thickness matched to deuteron range

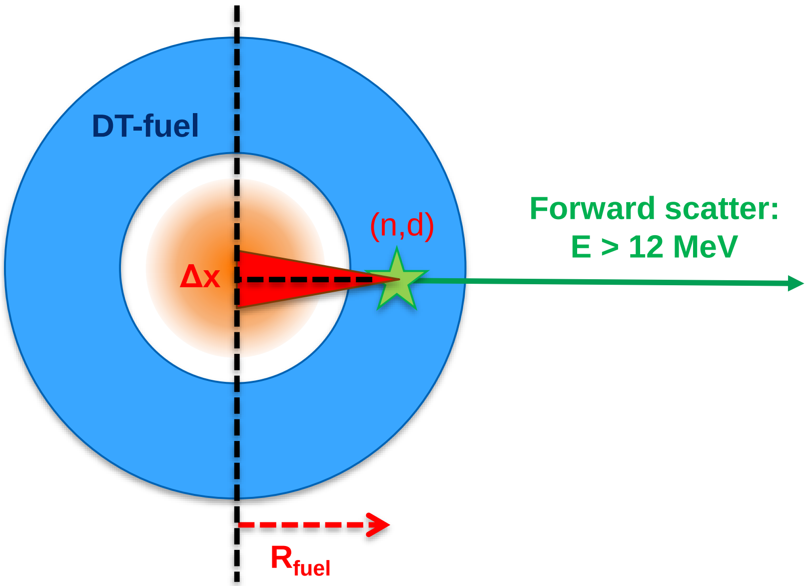


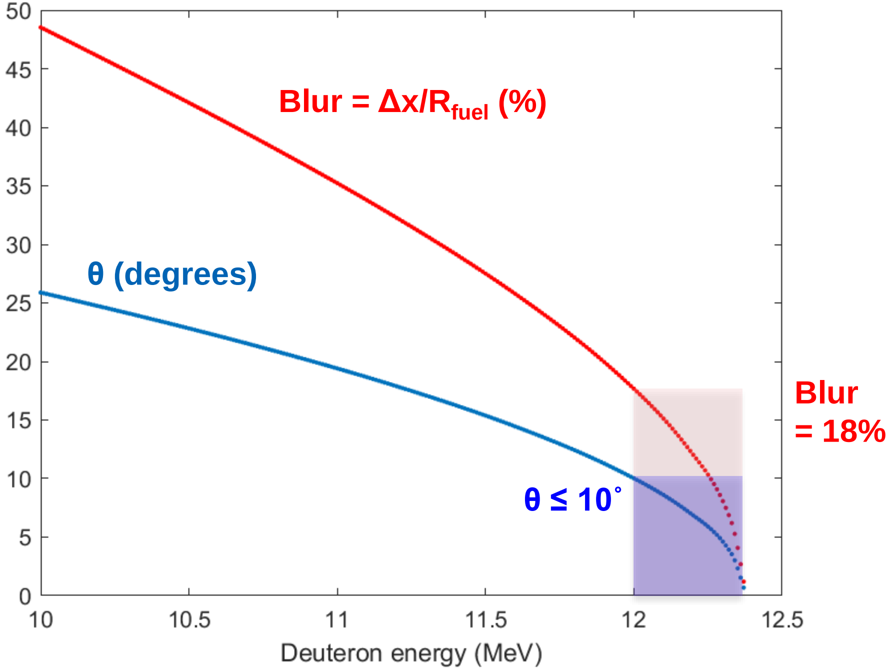
Light is imaged/fiber-coupled to 2+ gated cameras

Particle intensity vs time (3 meters, low ρR)



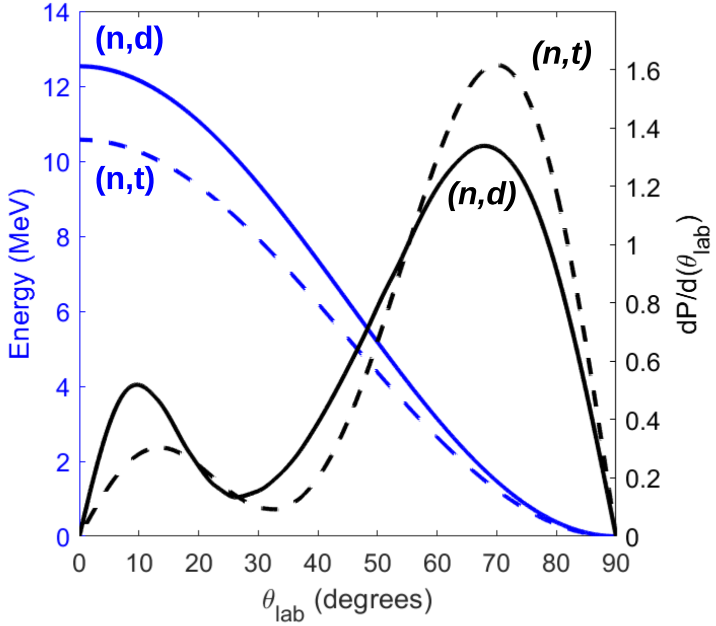
In the limit of recording only the highest-energy deuterons (E > 12 MeV), the deuteron image is equivalent to a neutron image with blur ≤ 20% of fuel radius





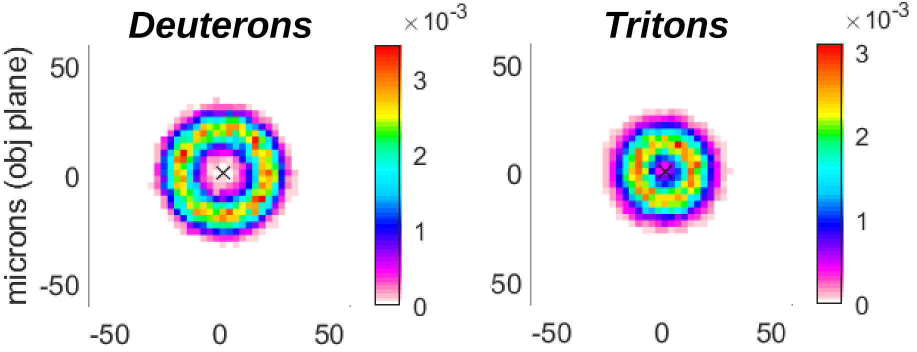
Amplitude of deuteron signal will not depend on ρR:
all deuterons with E>12 are born near the outer edge of fuel.

A fundamental challenge (or opportunity): if scattered deuterons are observed, there are also scattered tritons – and detectors cannot generally discriminate between them



6—7 MeV particle images:

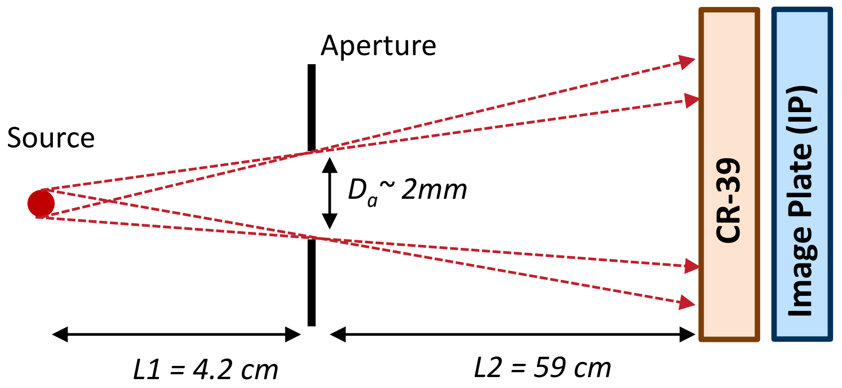
ρR = 100 mg/cm²



Analysis procedures will be developed to interpret both particle channels simultaneously.

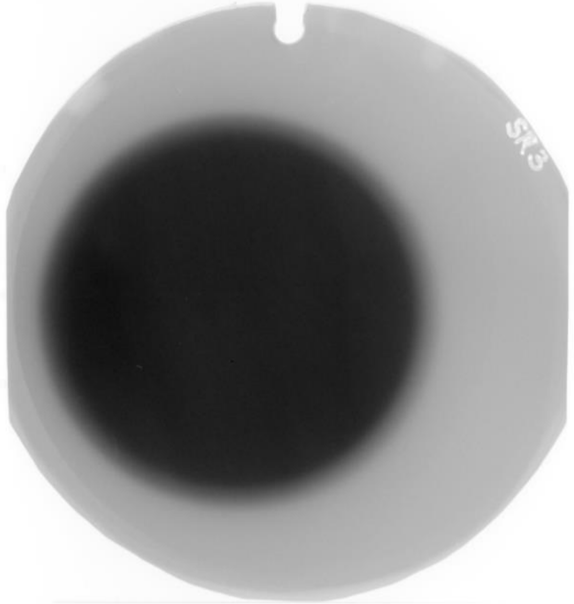
OMEGA PCIS was tested as a ride-along to do simultaneous knock-on deuteron imaging (with CR-39) and x-ray imaging (with Image Plates)

PCIS-IP Geometry



Magnification (M) = L2/L1 = 14

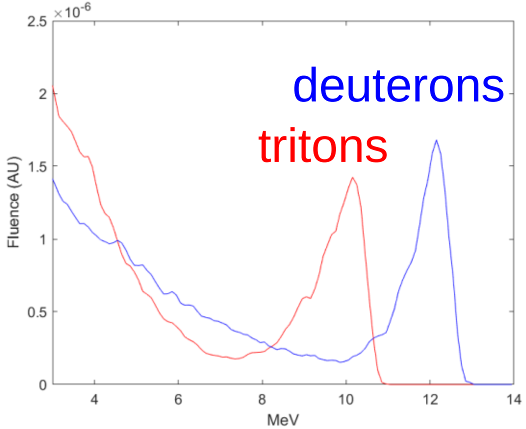
X-ray penumbral image from Shot 91966



- The x-ray imaging tests were very successful – implications for measuring spatially resolved Te
- CR-39 analysis for knock-on deuteron imaging is underway at MIT.
- Thanks to Sandia for letting us ride along!

Four filter configurations were fielded: goal was to isolate high-energy deuterons on some shots, obtain spectral slices of D, T signal on others

Shot #	DT-n Yield	Filtering type (µm Al)	Minimum D energy (MeV)	Minimum T energy (MeV)
91962	1.42E+14	350	9.5	n.a.
91963	1.43E+14	350/250	9.5/7.8	n.a./9.2
91964	1.48E+14	75/125/ 425/475	3.7/5.1/ 10.7/11.4	4.3/6.0/ n.a./n.a.
91965	1.51E+14	250/300/ 350/400	7.8/8.7/ 9.5/10.3	9.2/10.2/ n.a./n.a.
91966	1.33E+14	350	9.5	n.a.
91968	8.75E+13	350/250	9.5/7.8	n.a./9.2
91969	1.55E+14	75/125/ 425/475	3.7/5.1/ 10.7/11.4	4.3/6.0/ n.a./n.a.
[illegible]	[illegible]	250/300/	7.8/8.7/	9.2/10.2/



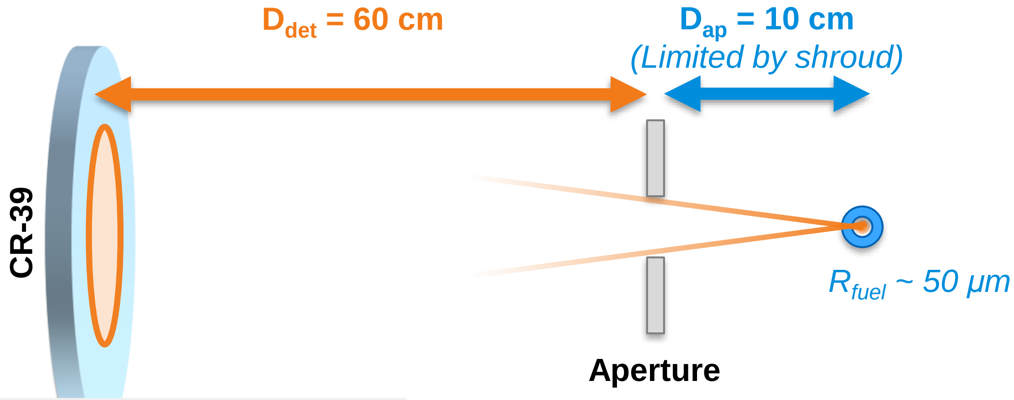
Due to low ρR ~ 1 mg/cm², these experiments are close to a worst-case scenario for signal-to-background.

A plan for KoDI-PCIS implementation and testing aims to demonstrate the technique on cryogenic implosions in FY19

Tasks	FY19Q1	Q2	Q3	Q4	FY20
Experiments: Stage 0	12/4 Expl. Pushers: *collect proof-of-concept data.*	CD(DT) experiment: *Demonstrate "layer" image, multiple TIMs*			
Stage 1		Finalize & order Stage 1 apertures	Field KoD-PCIS on cryo: High-energy D only	Multiple TIMs	
Stage 2				Finalize design, order hardware	Field Stage II: spectral resolution
Stage 3			Conceptual design/whitepaper		CDR
Analysis development	Develop processing methods Analyze Stage 0 data		Develop analysis algorithms Analyze Stage 1 data		Analyze Stage 2
Modeling development		LLE: simulate (n,d) images with profiles (DEC2D) MIT: model realistic spectra w/ profiles			

Stage 1

Due to high deuteron fluences, initial cryogenic tests will record only the high-energy deuterons > 11 MeV (for hotspot imaging): only ~5% of deuterons are detected



1. Penumbral imaging:

1 mm diameter aperture

N ~ 5.5e4 deuterons in the penumbra

Fluence = $Y_D/4\pi(70\ \text{cm})^2$ ~ 6.5e5 tracks/cm^2

2. "Ring" penumbral imaging:

1 mm diameter, ~ 10 μm wide circular slit:

N = $Y_D\ 2\pi(R_{ap})(W_{slit})/4\pi(D_{ap})^2$ ~ 1e4 deuterons

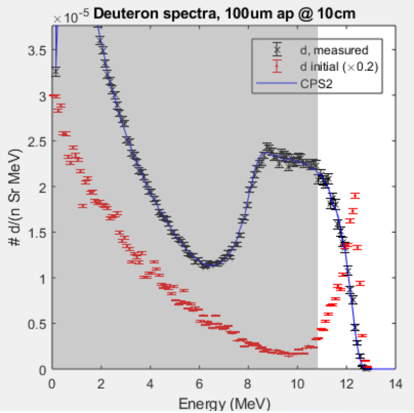
Fluence = $N/[2\pi(R_{ap}{*}M_{rad})]/[R_{fuel}{*}M_{pin}]$

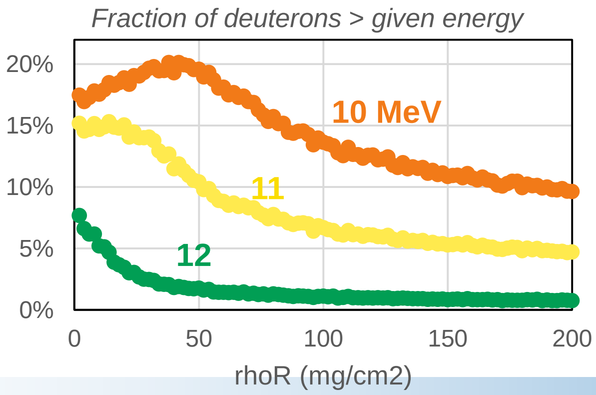
~ 1.5e5/cm^2

3. Multi-pinhole imaging: *for 10 μm OD pinhole, 30 images across the detector → ~700 images total:*

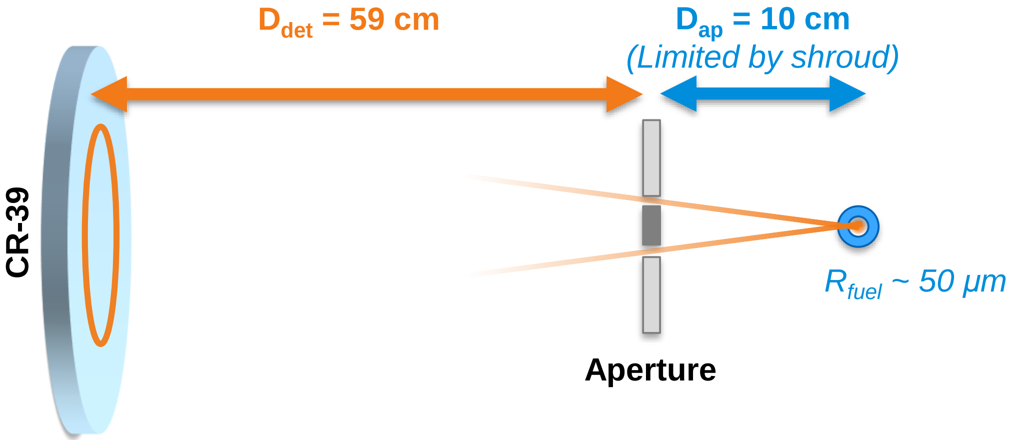
N = 24 d/pinhole → 1.7e4 d total

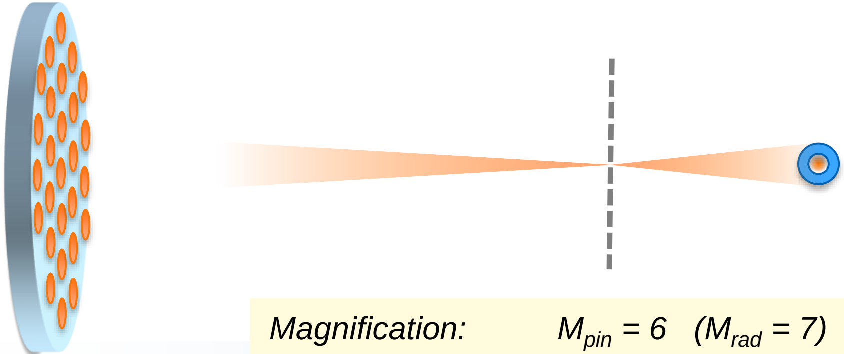
Fluence = 7e3 /cm^2





Due to high deuteron fluence on Yn = 10^{14} shots, alternative aperture ideas are needed. Initial cryogenic experiments will focus on high-energy (> 10 MeV) deuterons for simplicity.





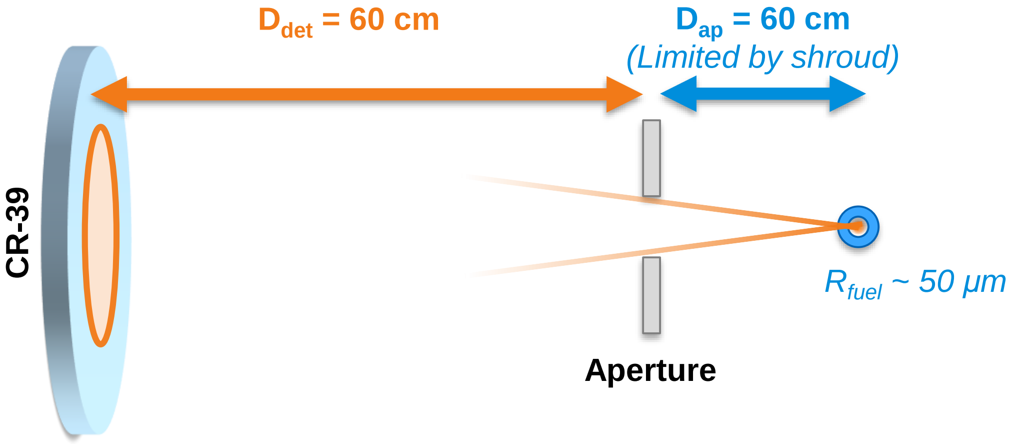
1. Penumbral imaging:
1 mm diameter aperture
N ~ 1.1e6 deuterons in the penumbra
Fluence = $Y_D/4\pi(70\text{ cm})^2$ ~ 1.3e7 tracks/cm^2

2. "Ring" penumbral imaging:
1 mm diameter, ~ 10 μm wide circular slit:
$N = Y_D\, 2\pi(R_{ap})(W_{slit})/4\pi(D_{ap})^2$ ~ 2e5 deuterons
Fluence = $N/[2\pi(R_{ap}*M_{rad})]/[R_{fuel}*M_{pin}]$
~ 3e6/cm^2

3. Multi-pinhole imaging: *for 10 μm OD pinhole, 30 images across the detector → ~700 images total:*
N = 480 d/pinhole → 3.4e5 d total
Fluence = 1.3e5 /cm^2

Magnification:	*M_{pin} = 6 (M_{rad} = 7)*
CR-39 size:	*5 cm diameter*

What if we did multi-penumbral, low-magnification imaging?



1. Multi-penumbral imaging:

200 μm diameter aperture

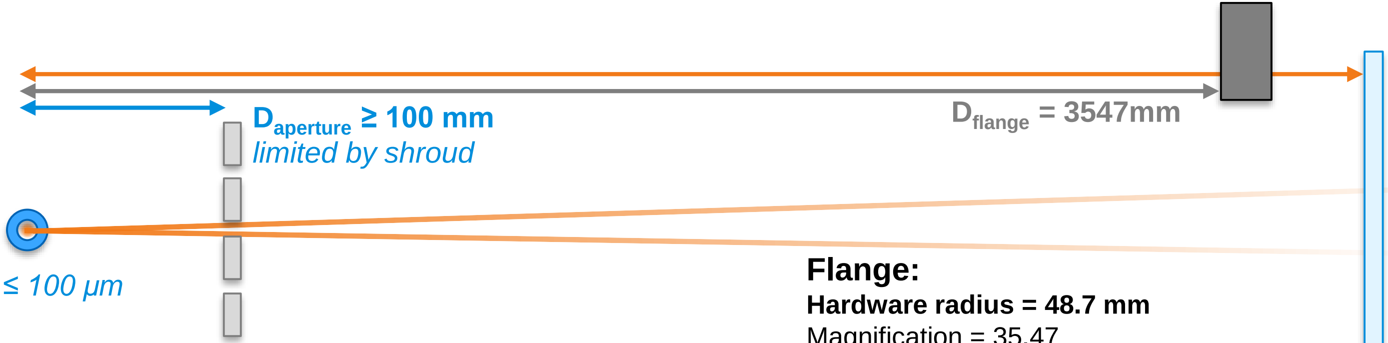
N ~ 5300 deuterons in each image
R_image = 200 microns;
image spacing ~ 1 mm → 45 img across detector
→ 1500 images total
N ~ 8e6 deuterons total

Fluence = $Y_D/4\pi(120\text{ cm})^2$ ~ 4.3e6 tracks/cm^2
~ 8e5 > 10 MeV
Neutron background = $1e14*4e\text{-}5/4\pi(120\text{ cm})^2$
~ 2.2e4 tracks/cm^2

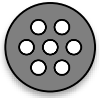
Magnification:	*M_{pin} = 1 (M_{rad} = 2)*
CR-39 size:	*5 cm diameter*

Stage 2

Modified PCIS hardware holding the CR-39 attached to the rear of the TIM will increase magnification and reduce fluence on the detector, enabling seven penumbral images to be recorded near the same line of sight.

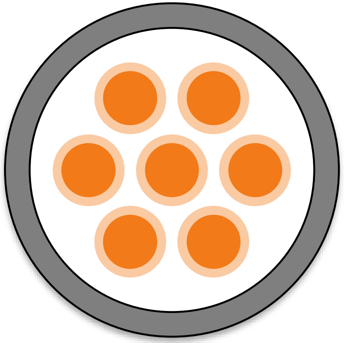


Aperture Array:
Ta, 200 μm substrate
Aperture radius = 0.25 mm
Aperture spacing = 0.8 mm
Hexagonal pattern:



Scale x10

Flange:
Hardware radius = 48.7 mm
Magnification = 35.47
Projected aperture R = 8.87 mm
Penumbra half width ≤ 3.45 mm
Total data radius ~ 44.3 mm



CR-39: 10x10cm
Detector radius ~ 48 mm
Magnification = 36.47
Projected aperture R = 9.12 mm
Penumbra half width ≤ 3.55 mm
Total data radius ~ 45.5 mm