Designing a Fast-Gated Scintillator-Based Neutron and Gamma Imaging System

Advanced Imaging Team
P-23 Neutron Science & Technology

11th World Conference
on Neutron Radiography
Sydney, Australia

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September 5th, 2018

Summary

1. The Advanced Imaging team has been providing neutron images of inertial confinement fusion processes at the National Ignition Facility since 2011

2. Two additional neutron & gamma lines-of-sight plus advanced reconstruction techniques will deliver 3D shape information

3. Building two new imaging systems drives necessity for careful design study at LANSCE & OMEGA

4. Focus on monolithic scintillator design over a fiber array for better resolution, light output & noise properties

Outline

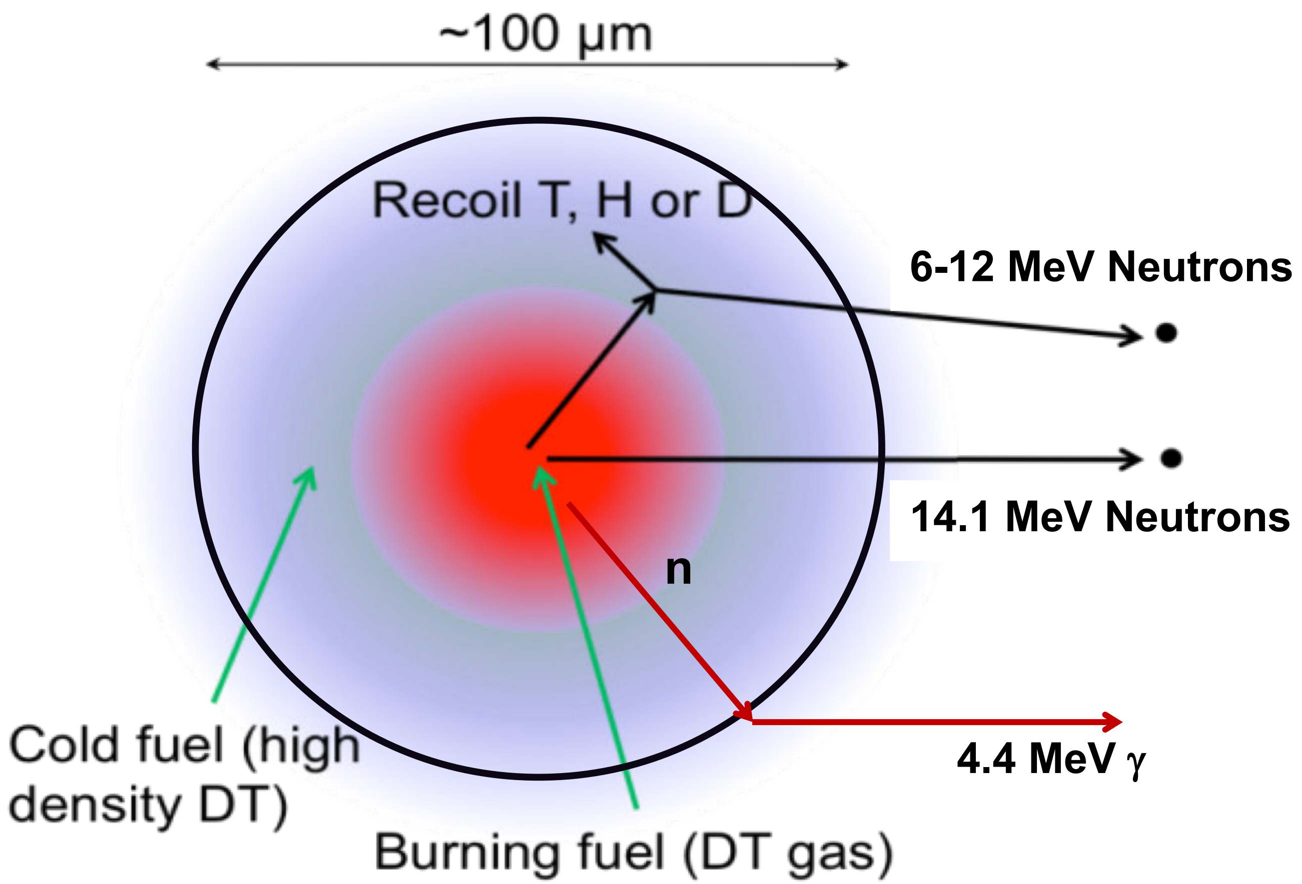
- The neutron imaging system at NIF
- Designing new systems for 3D reconstruction
- Scintillator characterization campaigns at LANSCE & Omega
- Light output, resolution, and noise results
- An ultra-fast imaging cell for a short line-of-sight

Neutron production is a direct indicator for fusion – making neutron imaging a powerful diagnostic

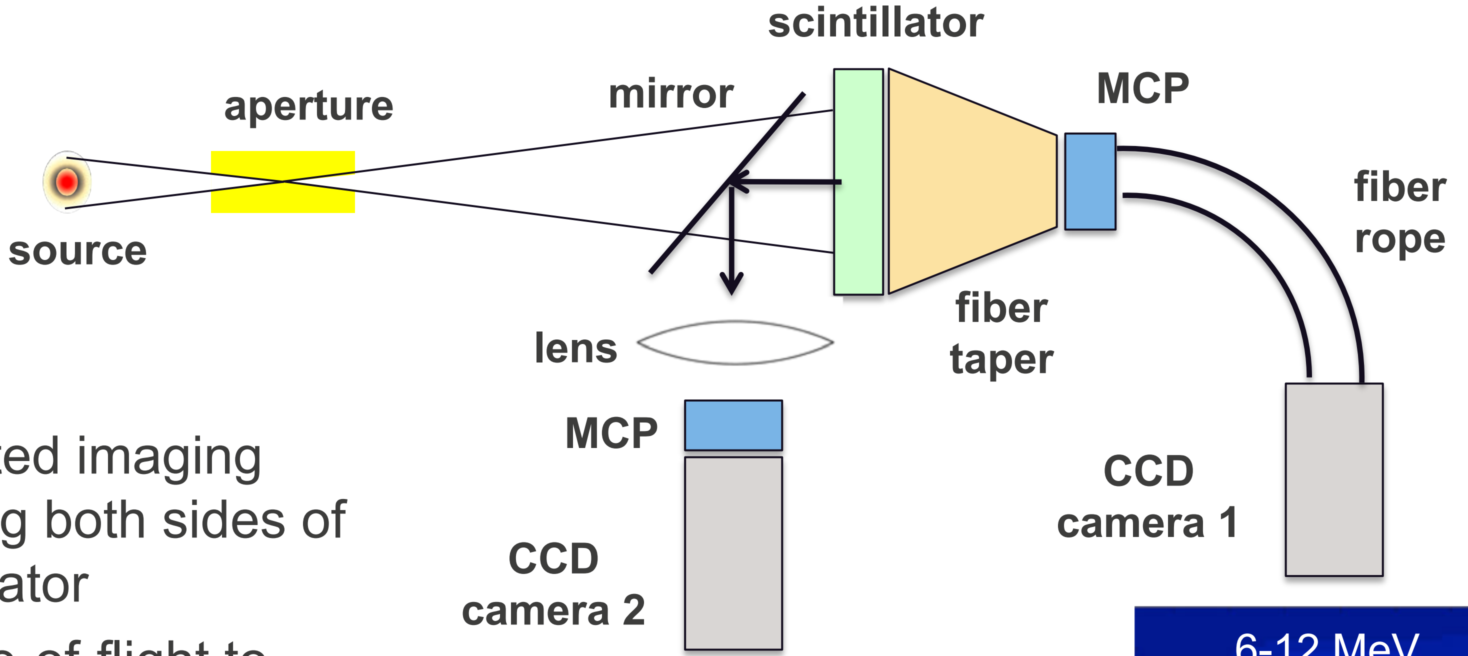
$${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

Deuterium-tritium capsules are compressed and heated using laser drive resulting in fusion

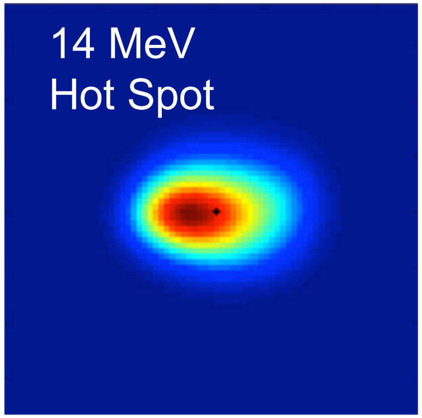
inertial confinement fusion ICF

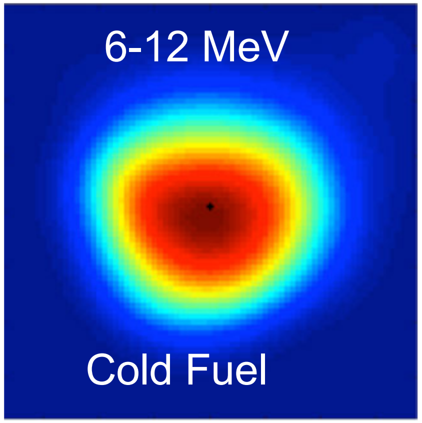


The current Neutron Imaging System at NIF – NIS1 has been providing images since 2011



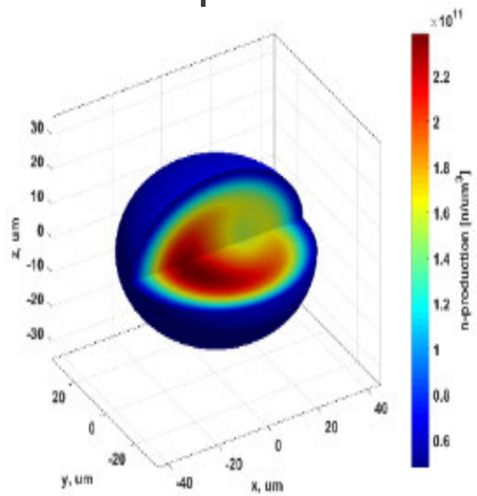
- Fast-gated imaging recording both sides of a scintillator
- Use time-of-flight to gate on fusion or down-scattered neutrons
- We image a 100 micron source from 28 m distance!



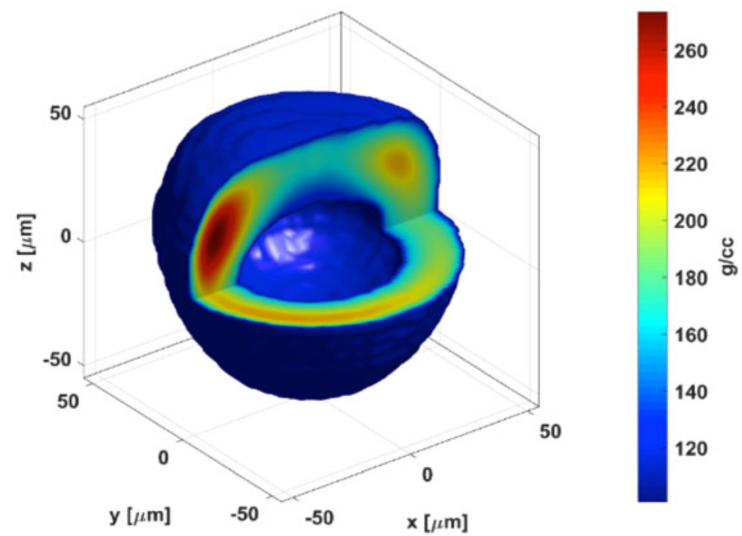


Planning two additional lines-of-sight:
3D neutron imaging provides hot spot and fuel density

3D Hot Spot



Cold Fuel Density Distribution

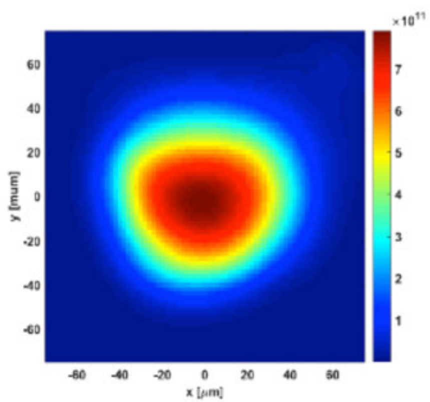


Proof of concept with image plate on second line-of-sight

record yield shot N170827-002

Petr Volegov

& Down-Scattered Image

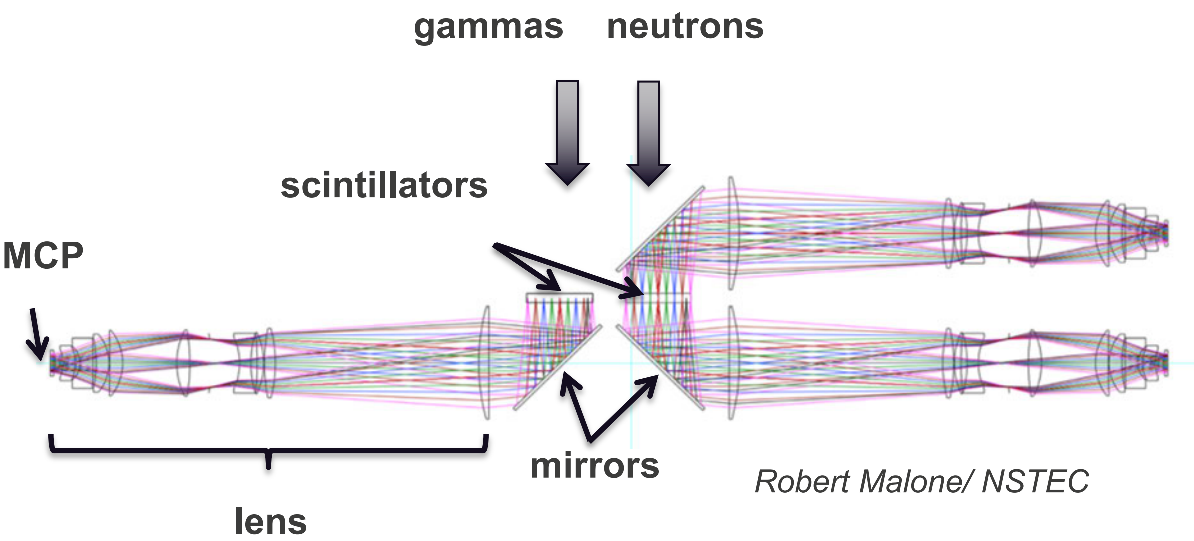


Structure of the compressed shell becoming clearer
=> Transformative result for NIF!

3D reconstruction algorithms in place

[1] Volegov et. al, Journal of Applied Physics, 122:17 (2017).
[2] Volegov et. al, Journal of Applied Physics, 118:20 (2015).

The baseline design for a dual line-of-sight: Two lens-coupled scintillators and three cameras

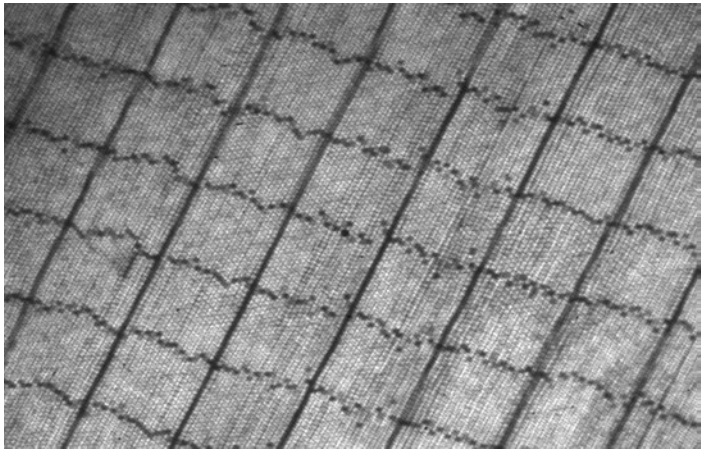


Scintillator is key design part for active system!

- high spatial resolution
- enough neutron interactions & light
- fast decay – little afterglow

Fiber scintillator drawbacks:

- Costly, difficult to procure
- Fixed pattern noise
- Dead space (packing fraction 60-70%)
- Light loss in extramural absorber
- Co-registration issue



LANSCE beam time allowed extensive design study in house to test various scintillator materials

OMEGA 60 at LLE

14 MeV fusion neutrons

High yield glass capsules

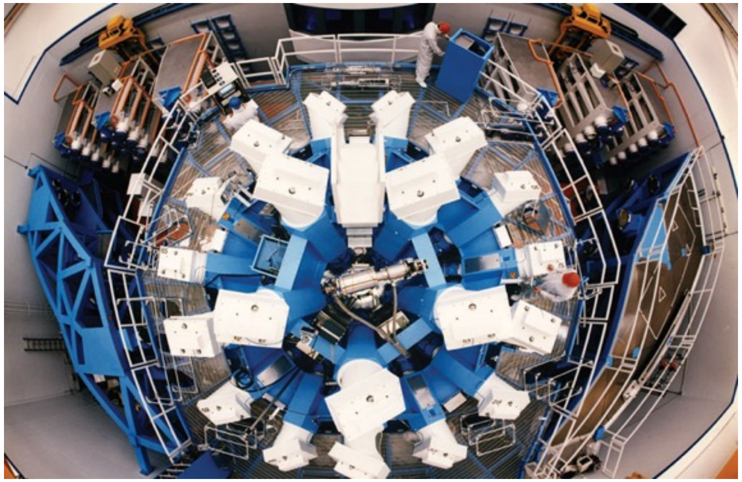


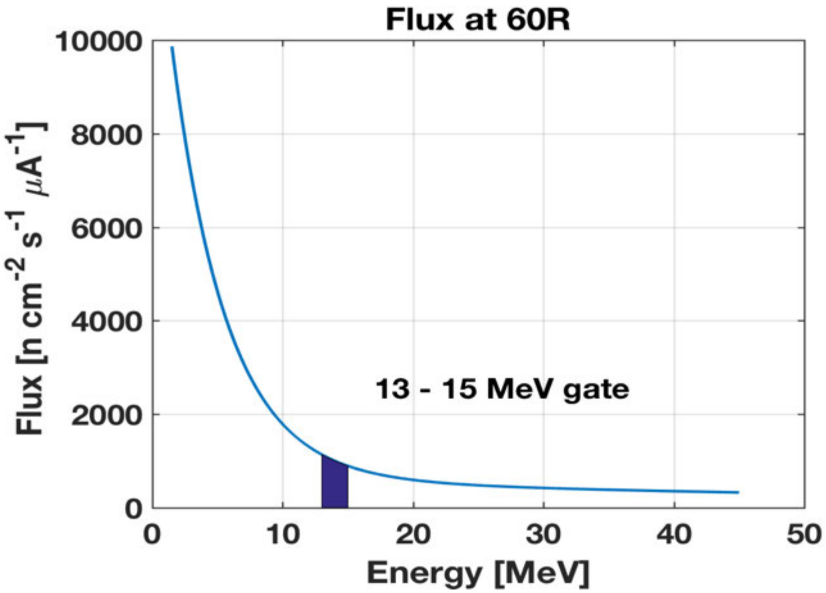
Image: LLE

WNR/LANSCE at LANL

800 MeV proton accelerator

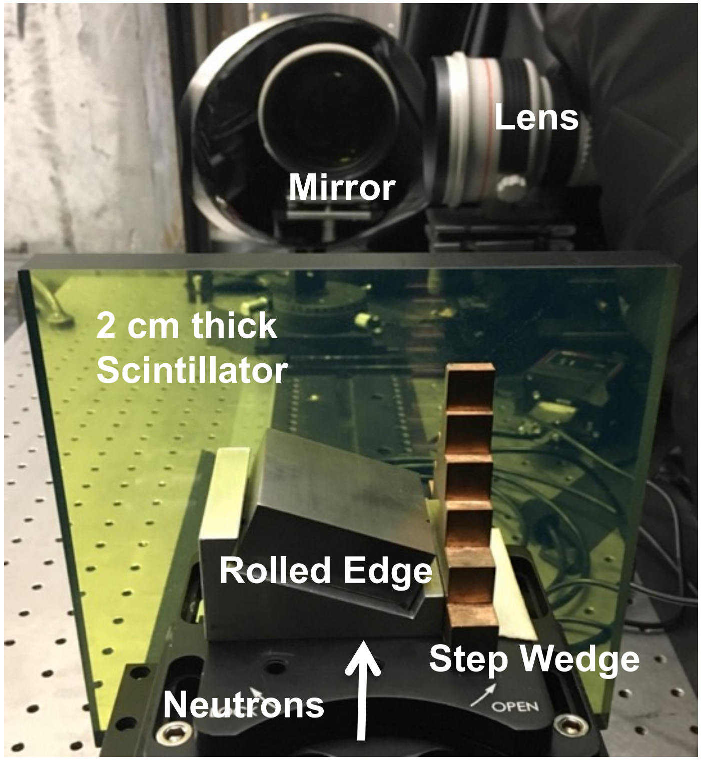
tungsten spallation target

Pulse structure (1.8 micros) -> TOF



$1.5*10^{14}$ yield shot at OMEGA = ~20 min at LANSCE WNR

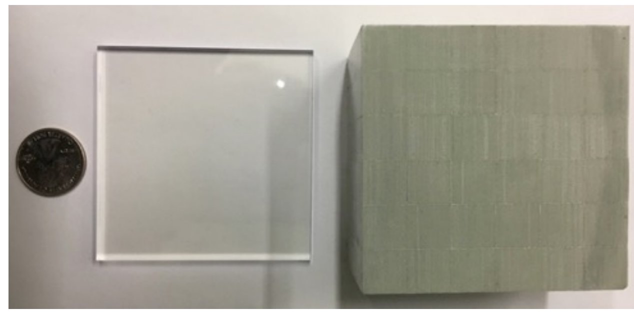
Prototype tests with commercial lens to fully characterize over 20 different scintillators

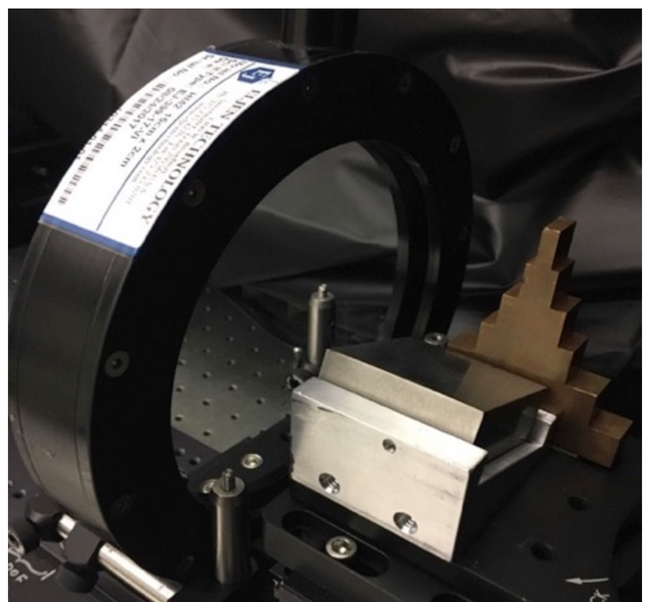


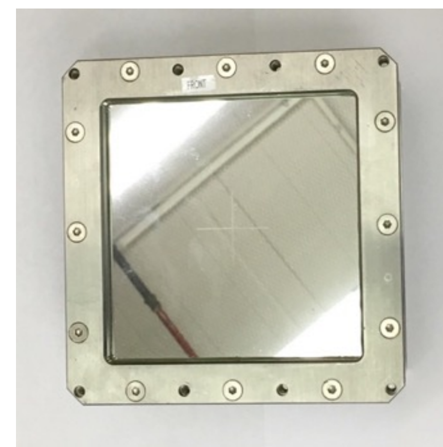
Lens (Canon f#1.8) coupled with 25mm Photek MCPII and SI800 CCD

Liquid VI imaging cell developed with *Eljen Technology*

22 scintillators studied - fiber vs monolithic
(Plastic, liquid, deuterated, 0.2 to 5 cm thickness)

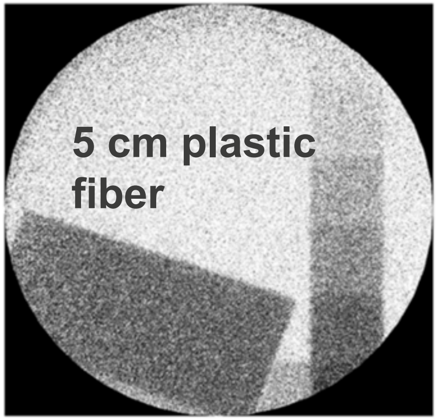


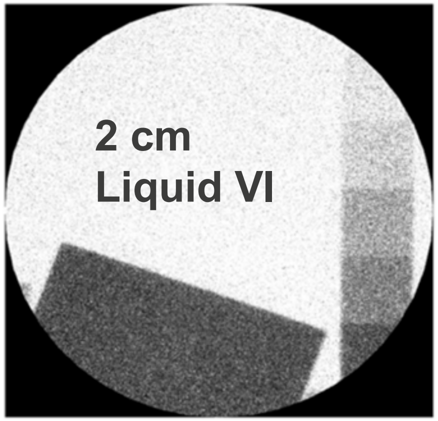


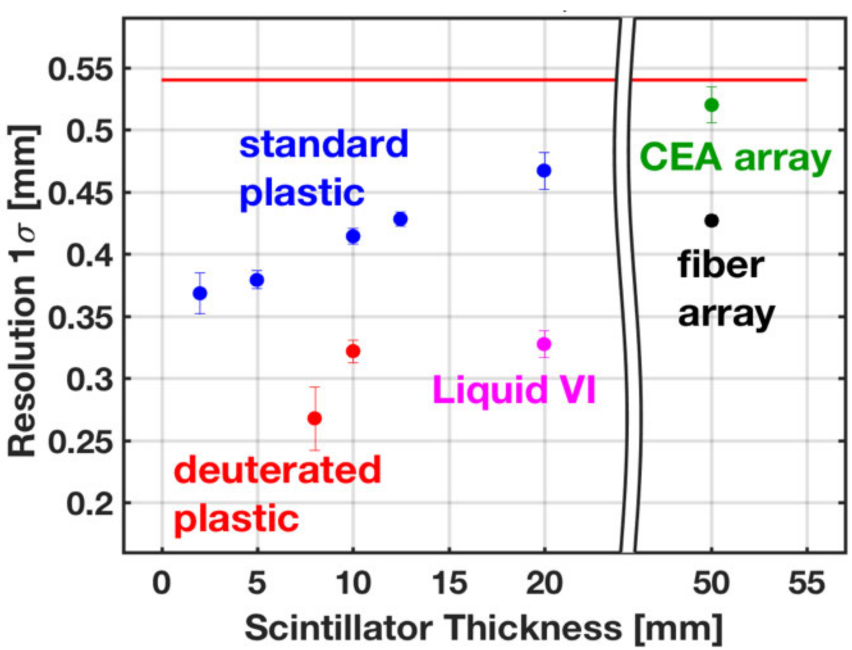


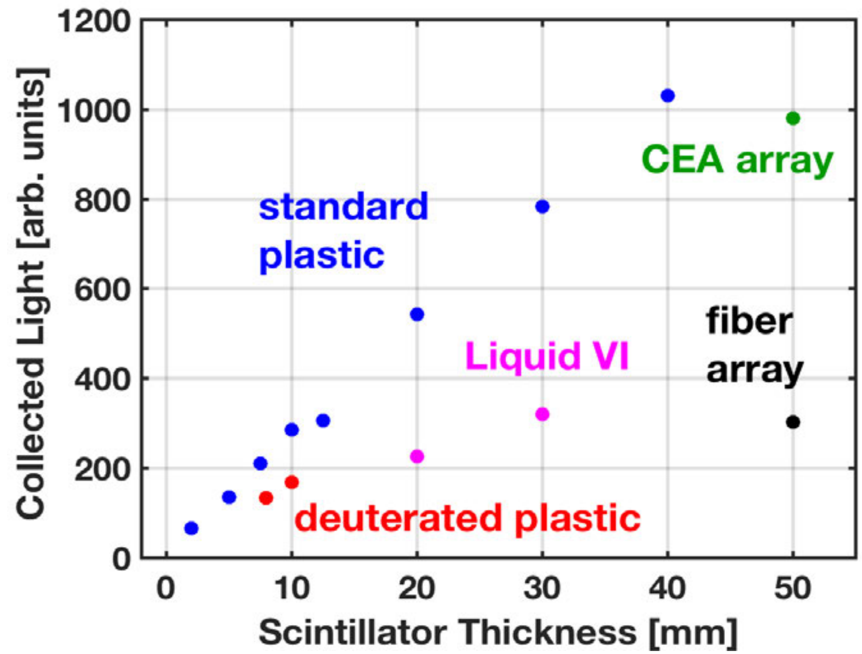
CEA deuterated liquid glass capillary array

A monolithic scintillator outperforms pixelated arrays when light is collected with a lens

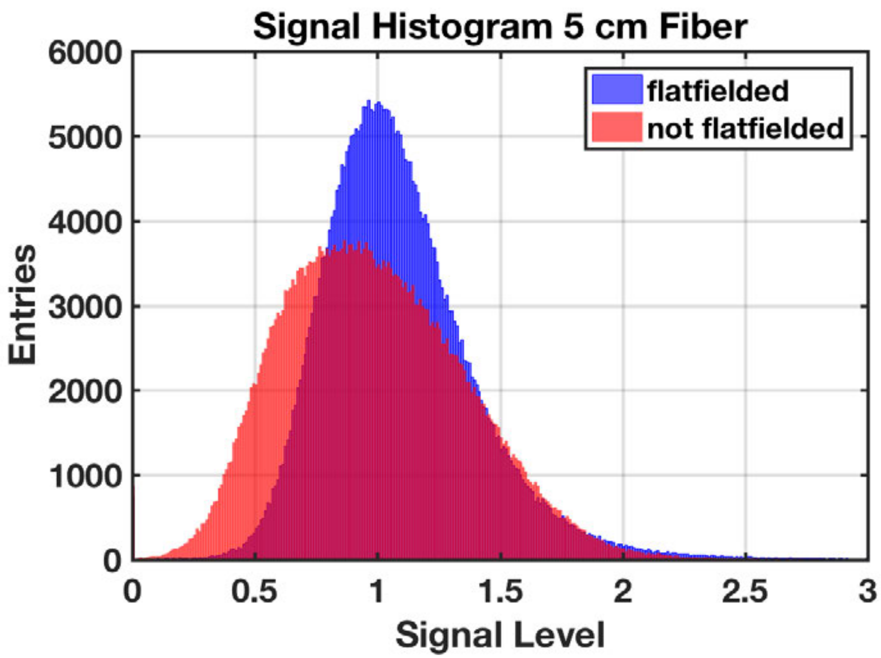


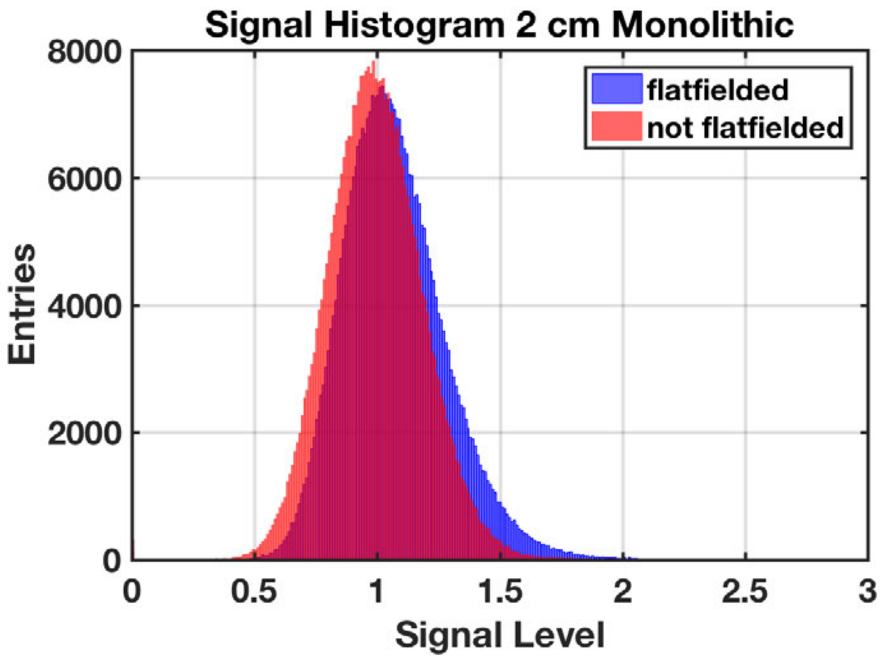


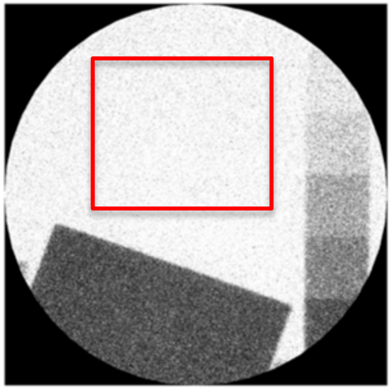


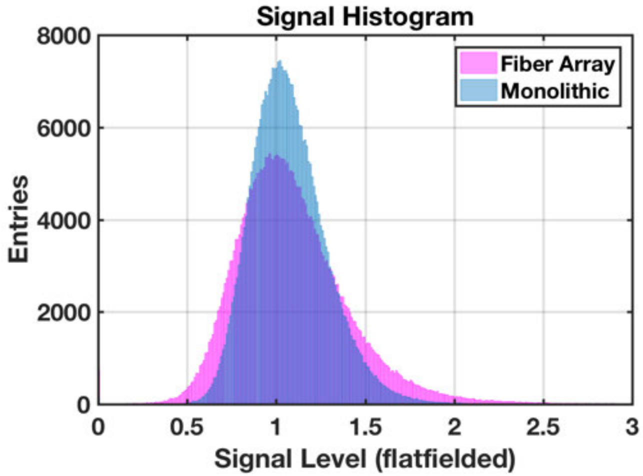


Fiber array introduces fixed pattern noise and requires a flatfield correction









Fiber array needs to be flatfielded (1/yr at NIF)

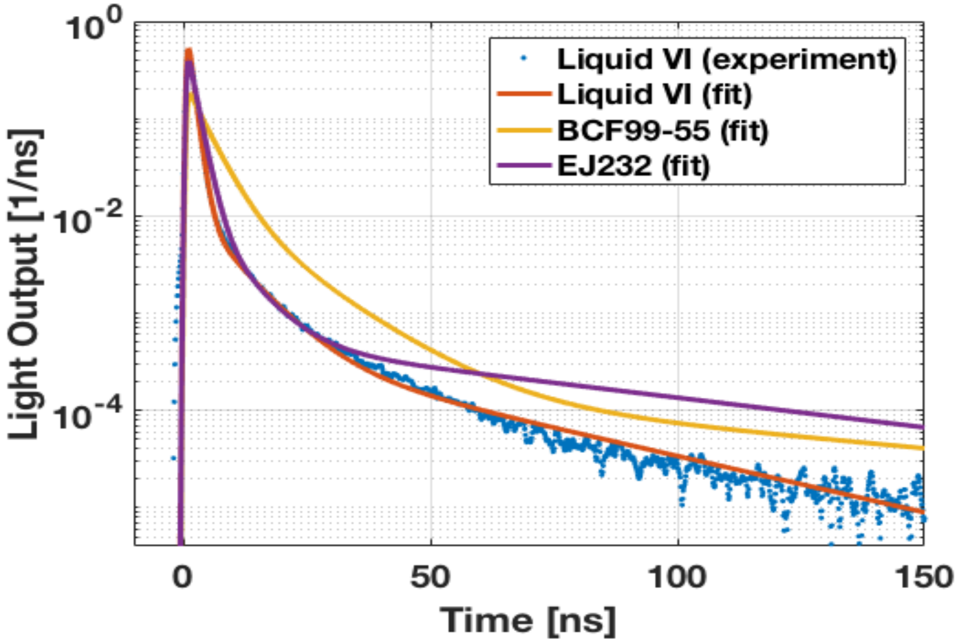
Uncertainty still larger than monolithic

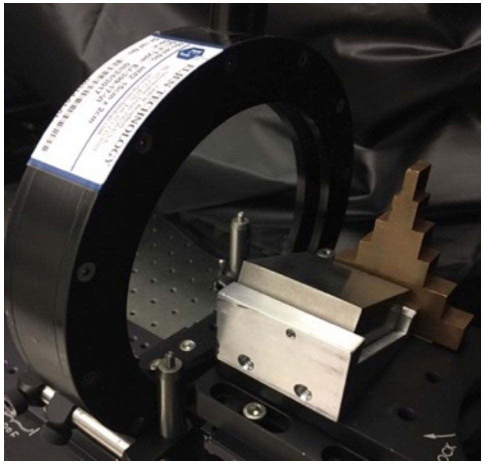
Considerations for shorter polar line-of-sight: Liquid VI is fast enough to move to 12 m

Magnification is similar = **resolution ok**

Liquid VI 30% of light output

~ half distance = 4x neutrons/ pixel -> **light ok**





[1] Geppert-Kleinrath et. al,, RSI (2018).

Ratio of light in down-scattered (6-12 Mev) vs primary window (13-17 MeV)

Distance	Liq-VI	EJ232	BCF99-55
28 m	0.6%	2.1%	**1.8%**
12 m	**1.8%**	2.9%	8.0%

Summary

1. Advantages of monolithic scintillators for flash neutron imaging

- 2x light of 5 cm fiber, equal resolution, equal DQE at 2 cm thickness
- Better SNR, no co-registration issue
- cost (<1k vs 500k), simple design -> allowing multiple LOS

2. Flexible options thanks to monolithic design (Liquid VI cell)

3. Using LANSCE allowed extensive design study for novel NIS

4. Upcoming work:

- NIF prototype, lens design, gamma scintillator study

Thank you for your attention!

Advanced Imaging Team

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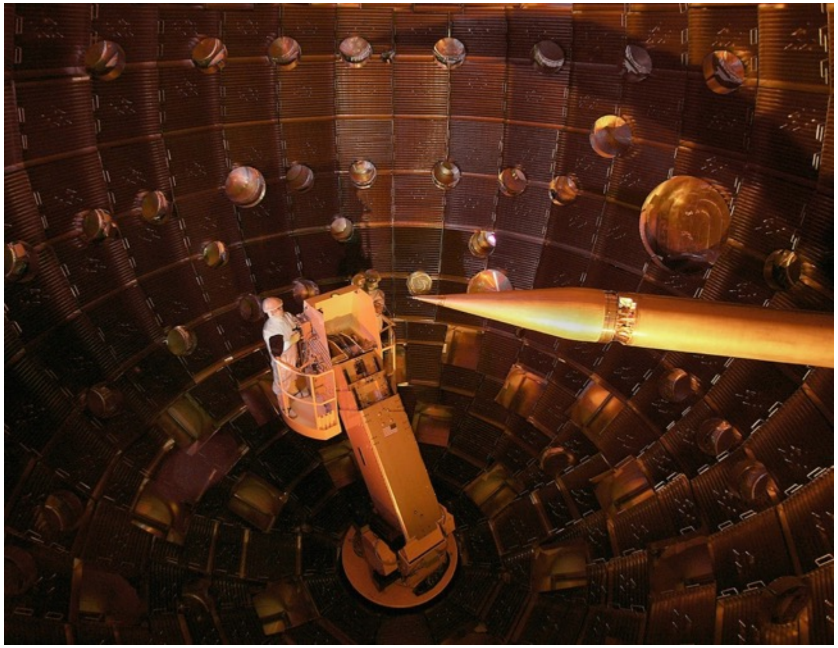
The National Ignition Facility (NIF)

NIF is the largest laser source in the world (& a Star Trek movie set)



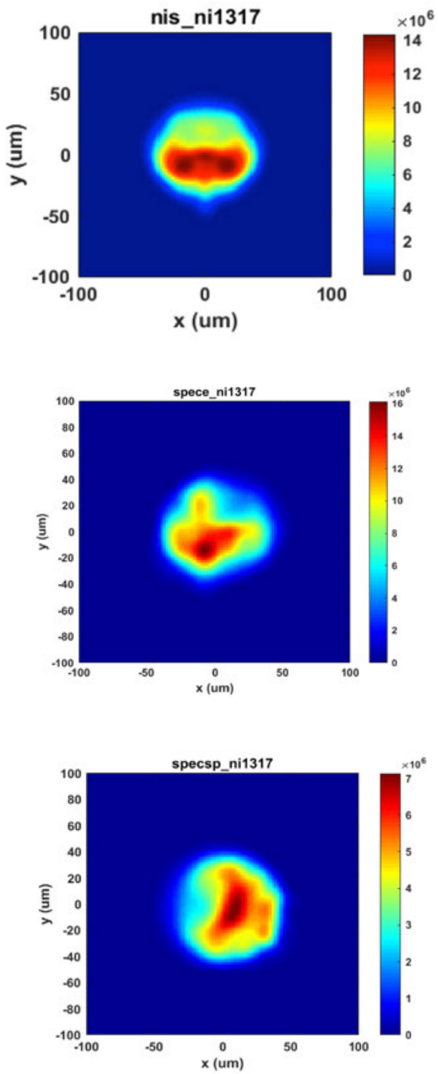
Lawrence Livermore National Laboratory

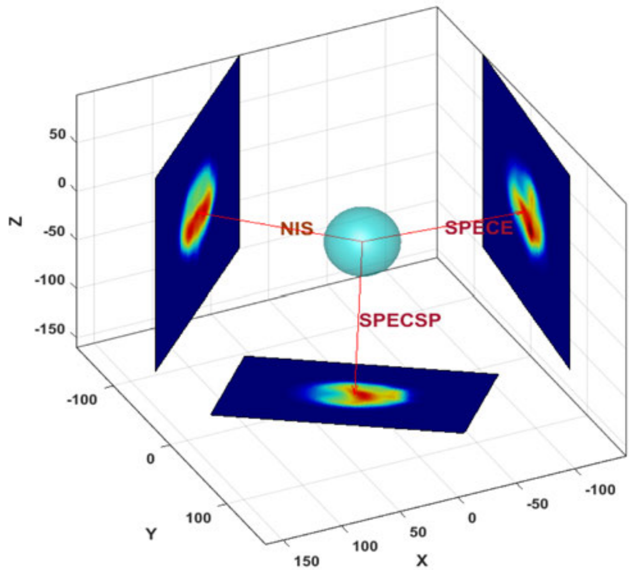
192 lasers deliver ~1.5MJ to the x-ray producing hohlraum

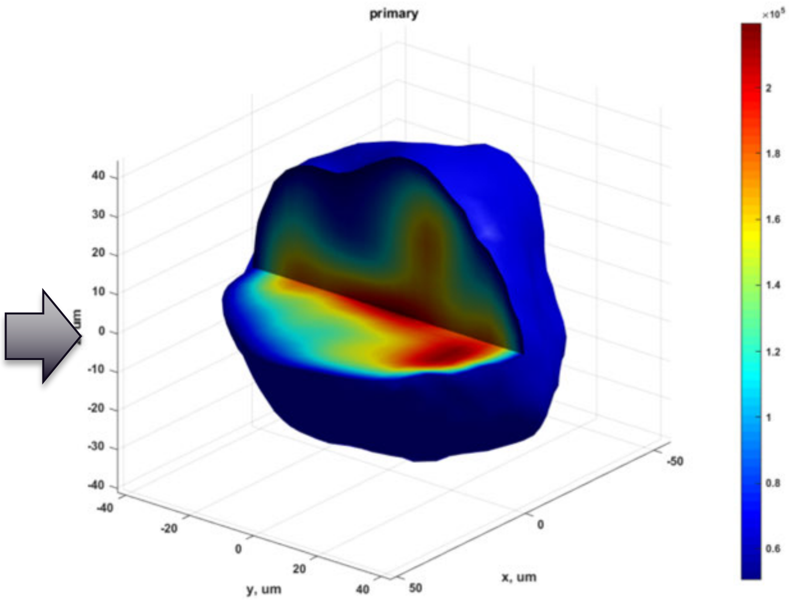
~150kJ absorbed by 1 mm target capsule

Paramount Pictures

Planning two additional lines-of-sight: Asymmetric drive simulation shows benefits of 3D neutron imaging







Brian Spears/ LLNL

2 additional lines-of-sight (LOS) with active scintillator detectors planned at NIF

Gamma ray imaging (GRI) will be added to new LOS

Fiber is less bright than originally assumed

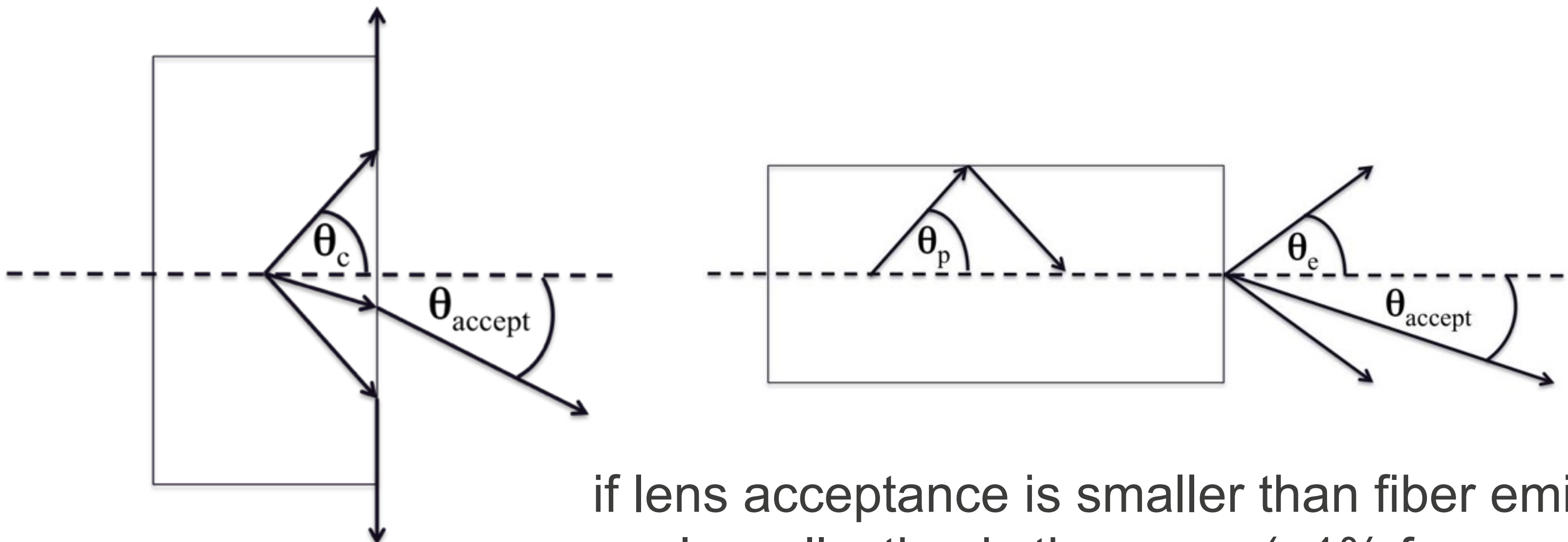
2 cm monolithic plastic is 2 times brighter than 5 cm thick fiber

DQE is ~equal if considering packing fraction

Light per MeV deposited is 70% for fiber versus monolithic

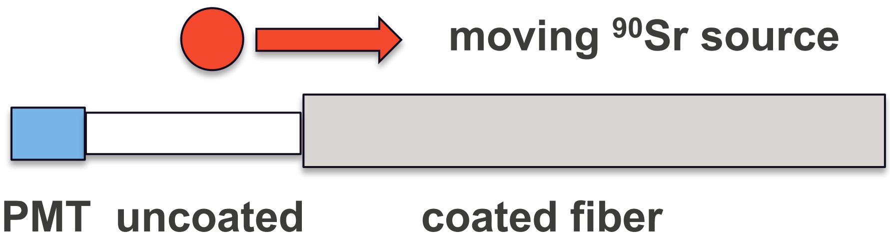
Fraction of light collected by lens is equal

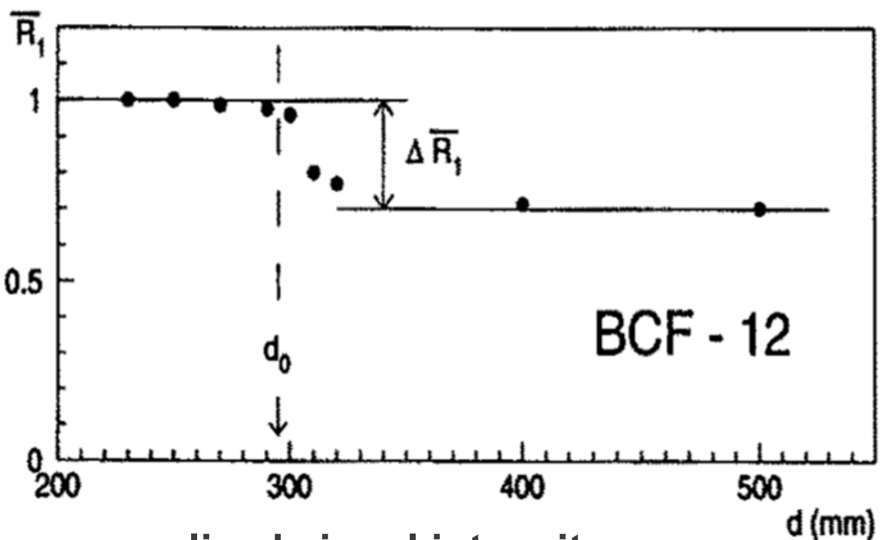
Fiber is only 65% as bright as expected



if lens acceptance is smaller than fiber emission angle, collection is the same (~1% for our main testing lens) for fiber and monolithic

Extra mural absorber dims fiber light emission



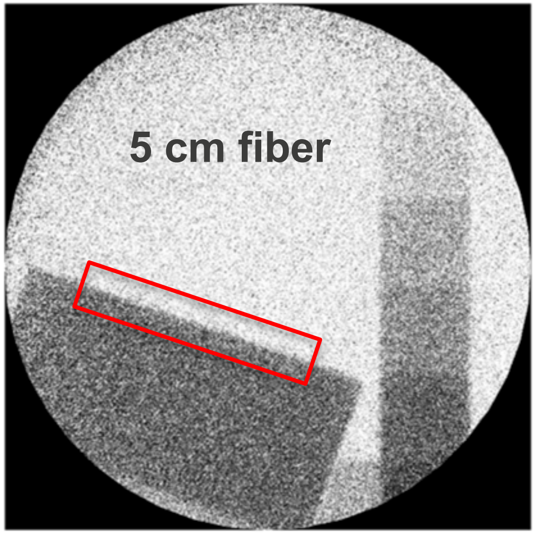


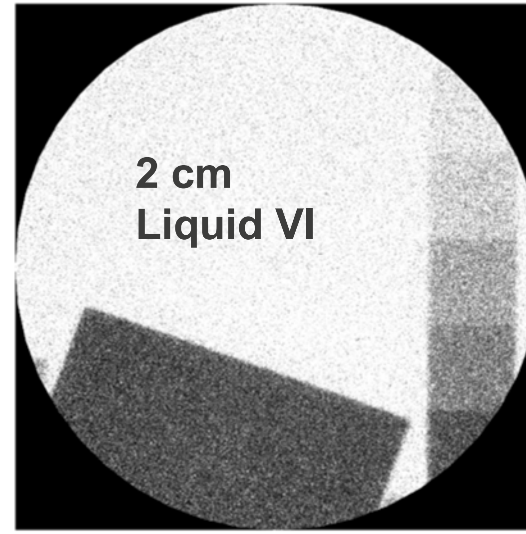
normalized signal intensity versus source position along fiber d

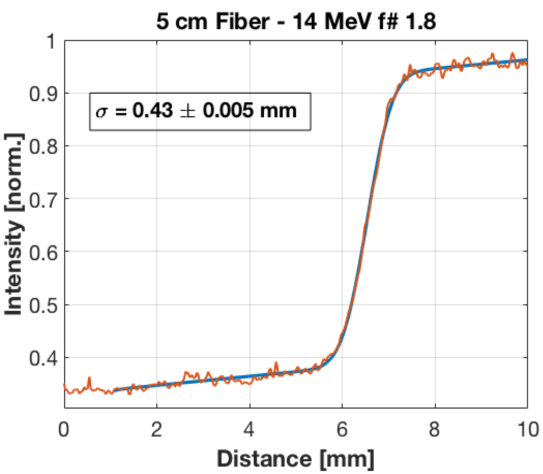
- single fiber experiment
- moving radioactive source (up to 2.25 MeV beta)
- shows effect of extra mural absorber
- 30% intensity reduction
- additional surface roughness effects possible (up to 20%)

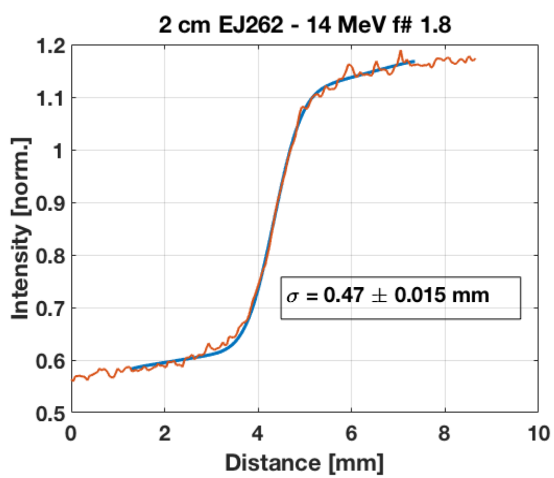
[1] D. Albers NIM A, 371 (1996).

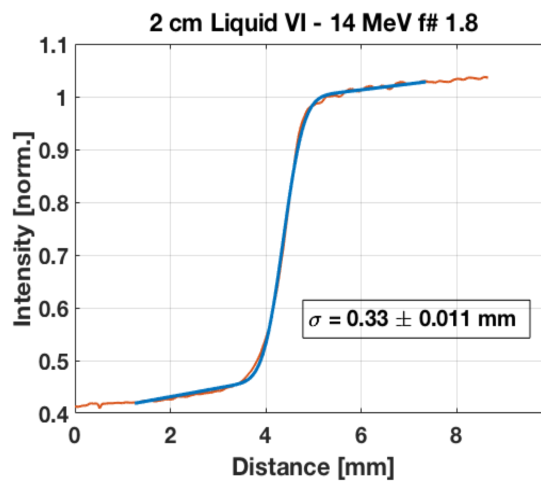
Edge spread function determines spatial resolution



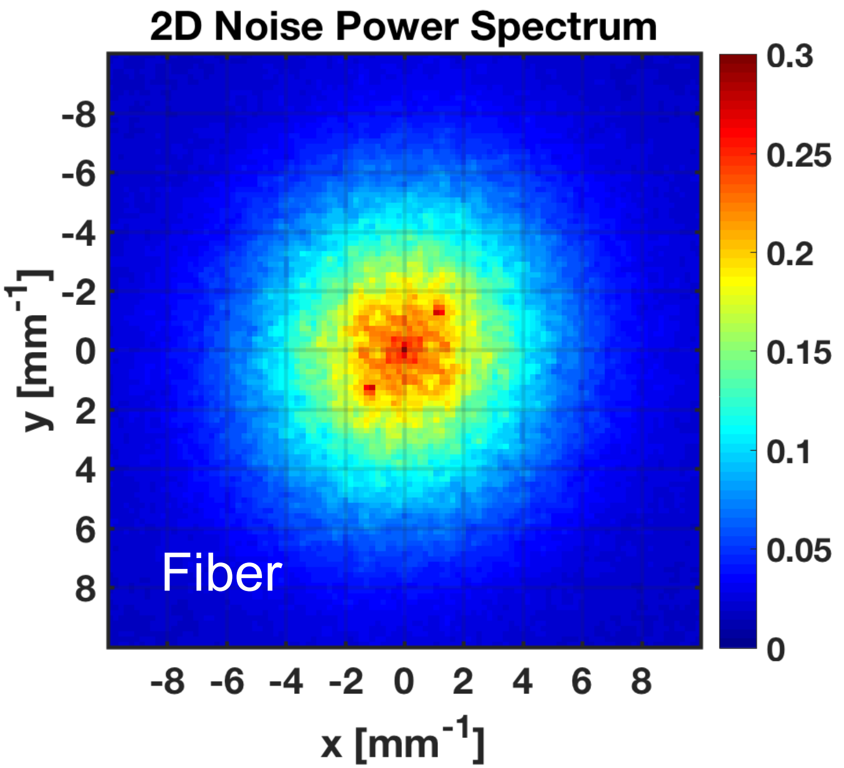


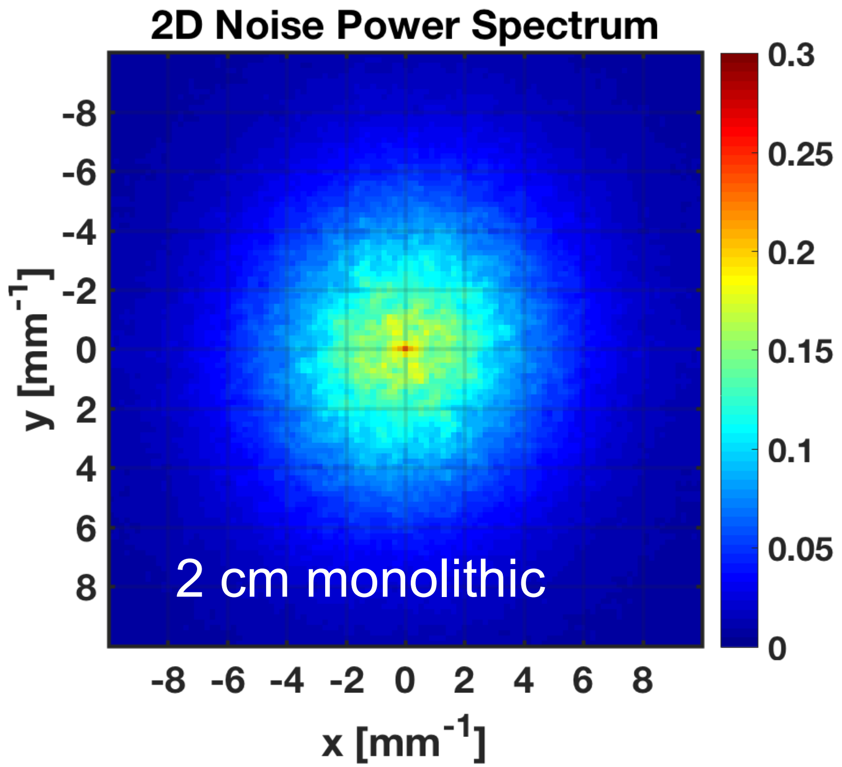






Fixed pattern noise even in flatfielded power spectrum

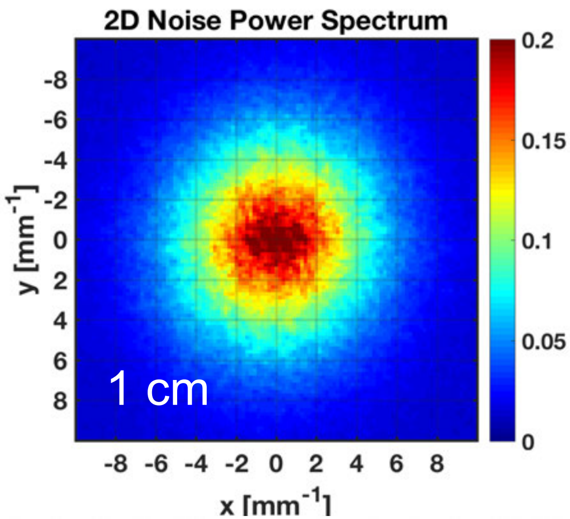


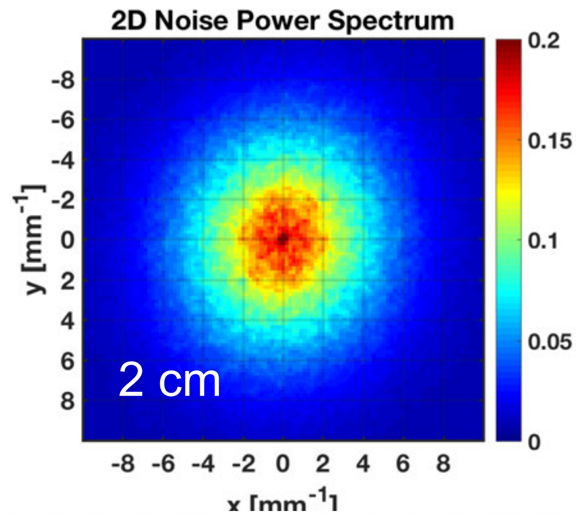


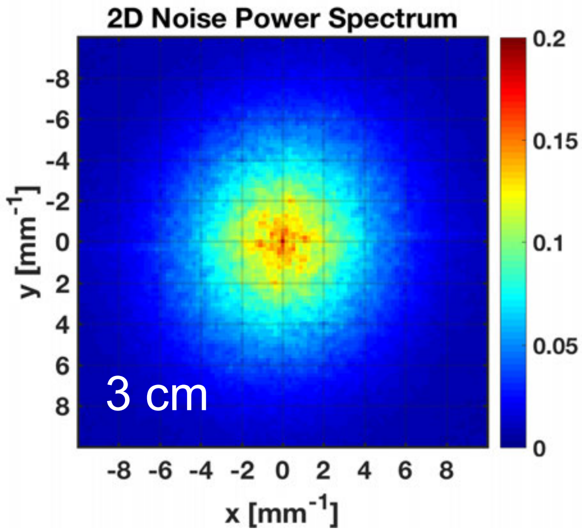
Higher absolute noise in fiber

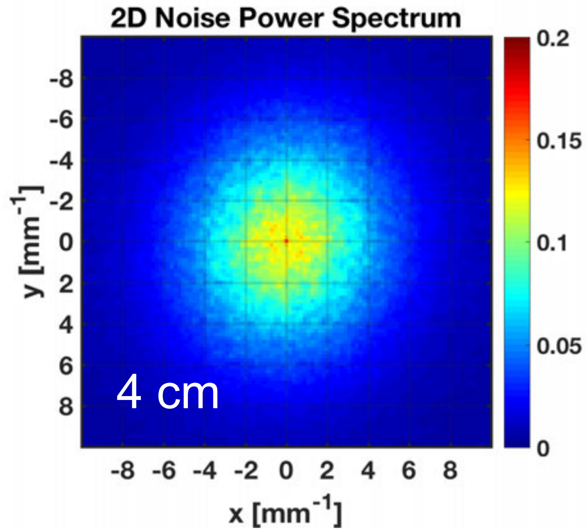
Noise power spectrum shows artifacts related to fixed pattern noise even after flatfield correction

Noise study: Power spectrum density vs thickness





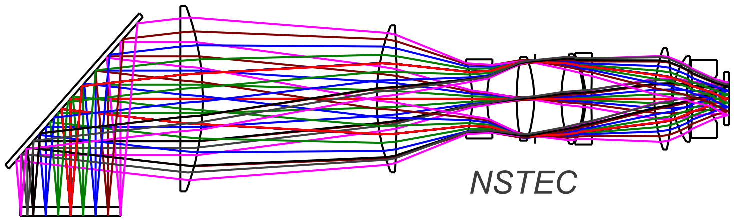




EJ204 plastic

1, 2, 3 and 4 cm NPS evolution

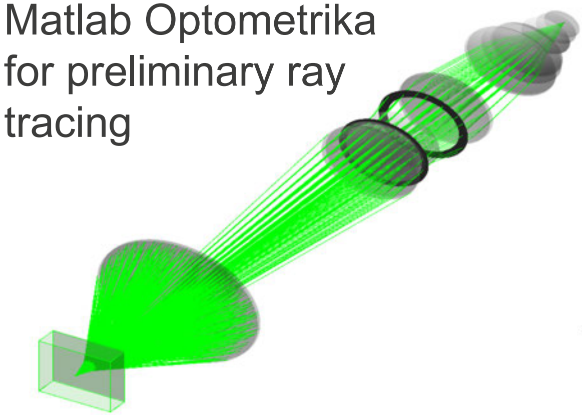
Lens design for monolithic scintillator requires large depth-of-field across field of view & telecentricity

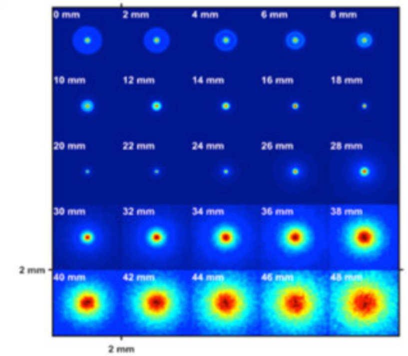


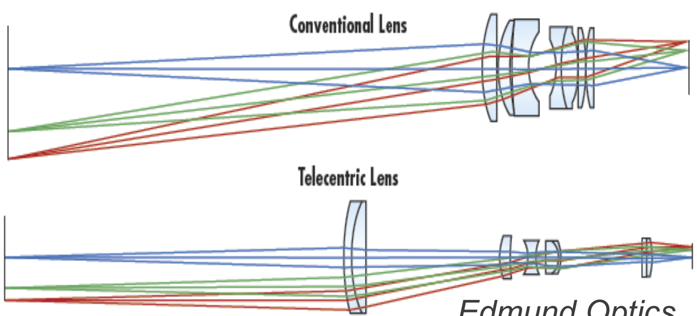
NSTEC

Numerical aperture f# < 2.5
to collect > 100 photons/neutron
optical blur < 200 micron

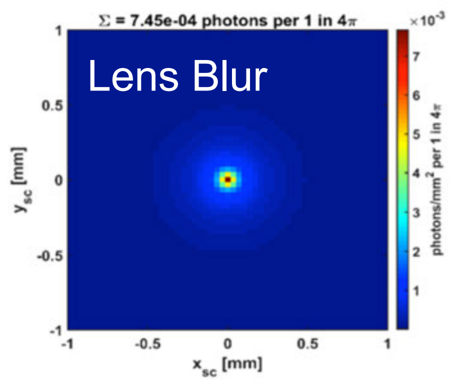
Matlab Optometrika for preliminary ray tracing

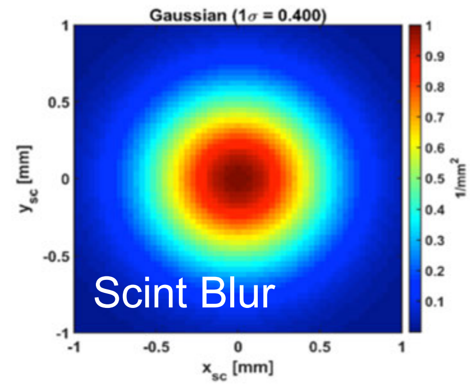






Edmund Optics





Lens design for thick scintillator: telecentric

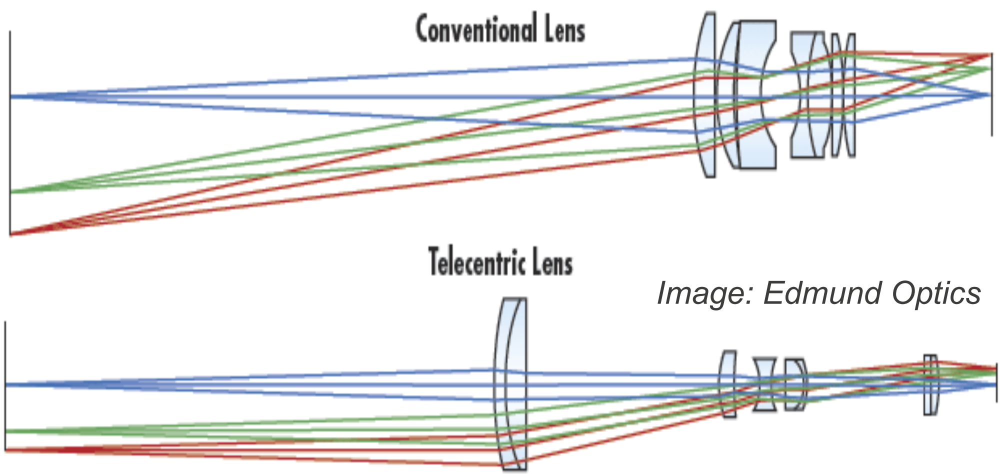
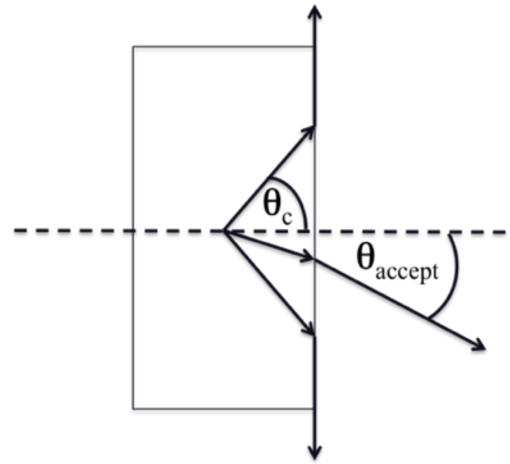


Image: Edmund Optics

Telecentric lenses remedy off-axis effects for thick scintillator

Magnification independent of object distance

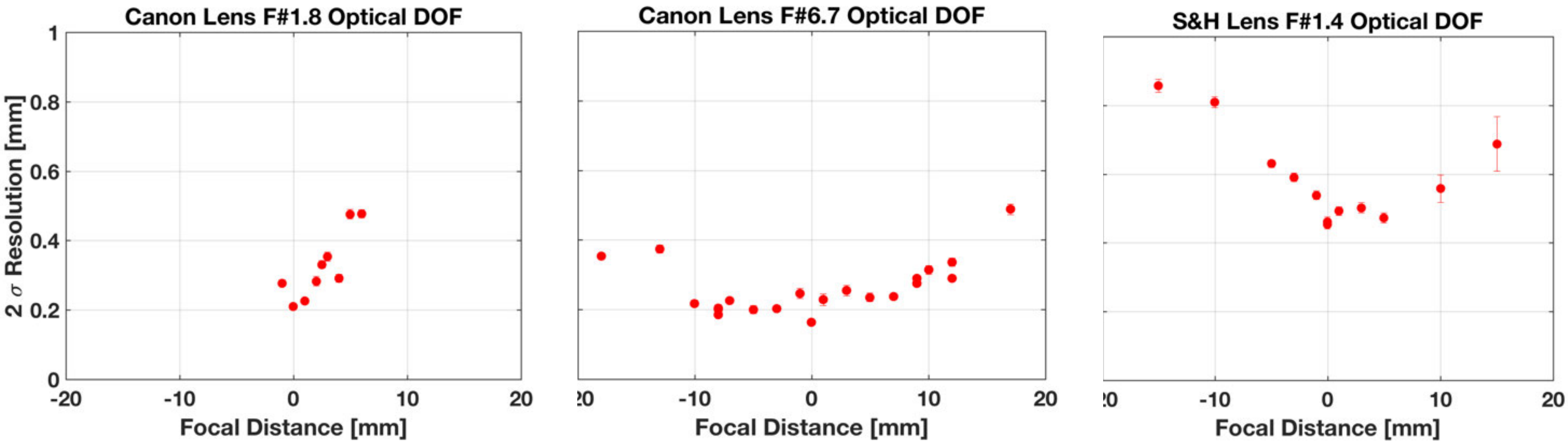


$$n_i \sin\theta_i = n_j \sin\theta_j$$

$$\theta_{acceptIn} = \sin^{-1}\left(\frac{NA_{lens}}{n_i}\right)$$

Circle of confusion optical blur depends on scintillator thickness and refractive index, and lens NA

Optical depth of field (circle of confusion) varies with f#



f#1.8 lens has highest optical resolution

steep DOF

f#6.7 lens has same highest resolution

very wide DOF

f#1.4 lens has lower optical resolution

ok DOF

NIS1 lens: ~ 200 micron resolution at +- 100 micron DOF

NA 0.15 f# ~3.3