Performance Modeling of the NIF Neutron Imaging System

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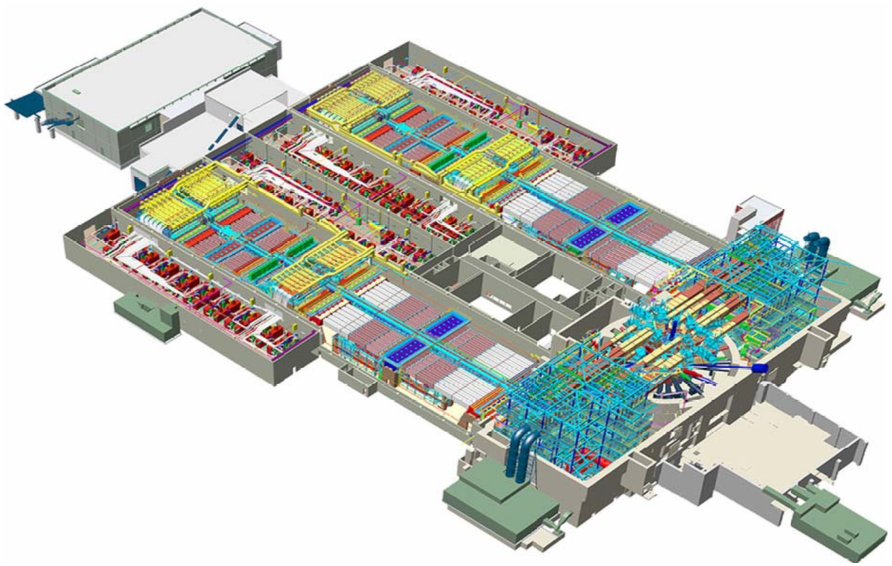
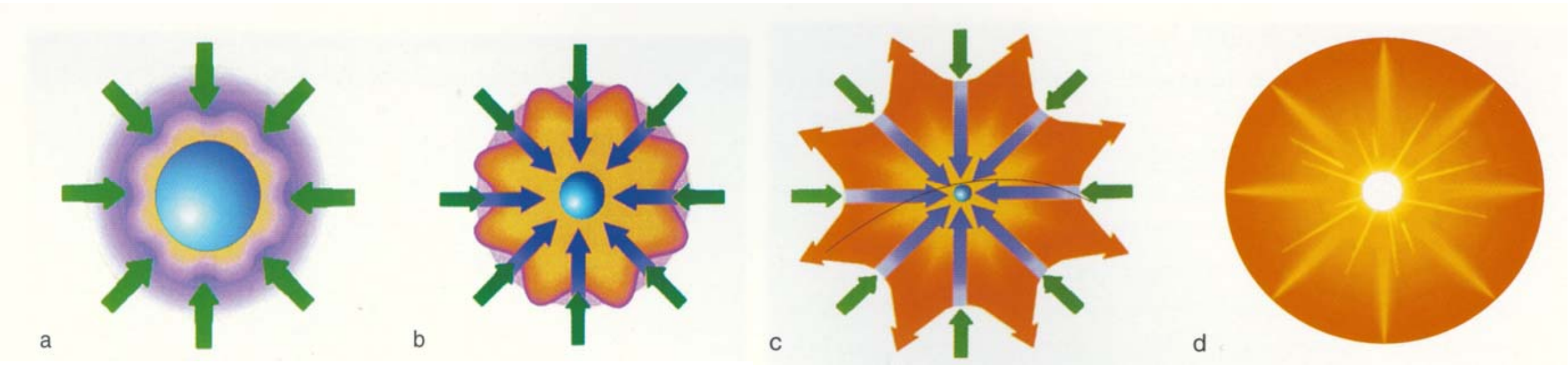
National Ignition Facility and ICF concept

- NIF is under construction
  - 85 % complete
  - Ignition Campaign in FY09

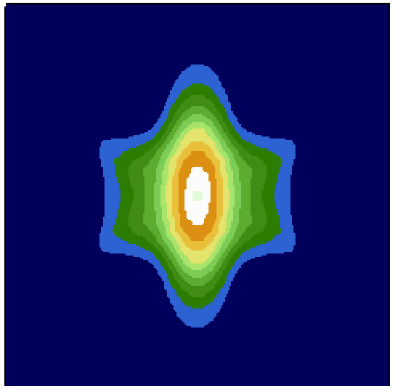


- Inertial Confinement Fusion
  a. Laser/X-ray illumination
  b. Capsule compression
  c. Fusion ignition
  d. Fusion burn

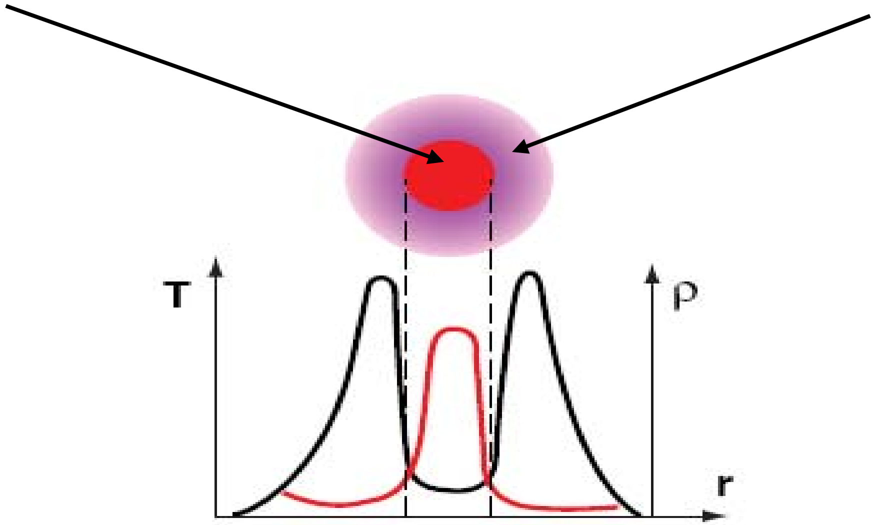


Neutron Imaging is useful as a failure diagnostic

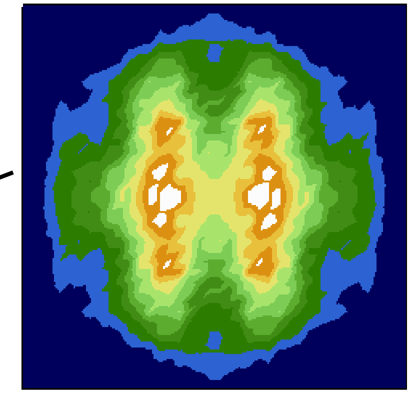
The National Ignition Campaign



Primary*



Low-density central spot ignites
a high-density cold shell

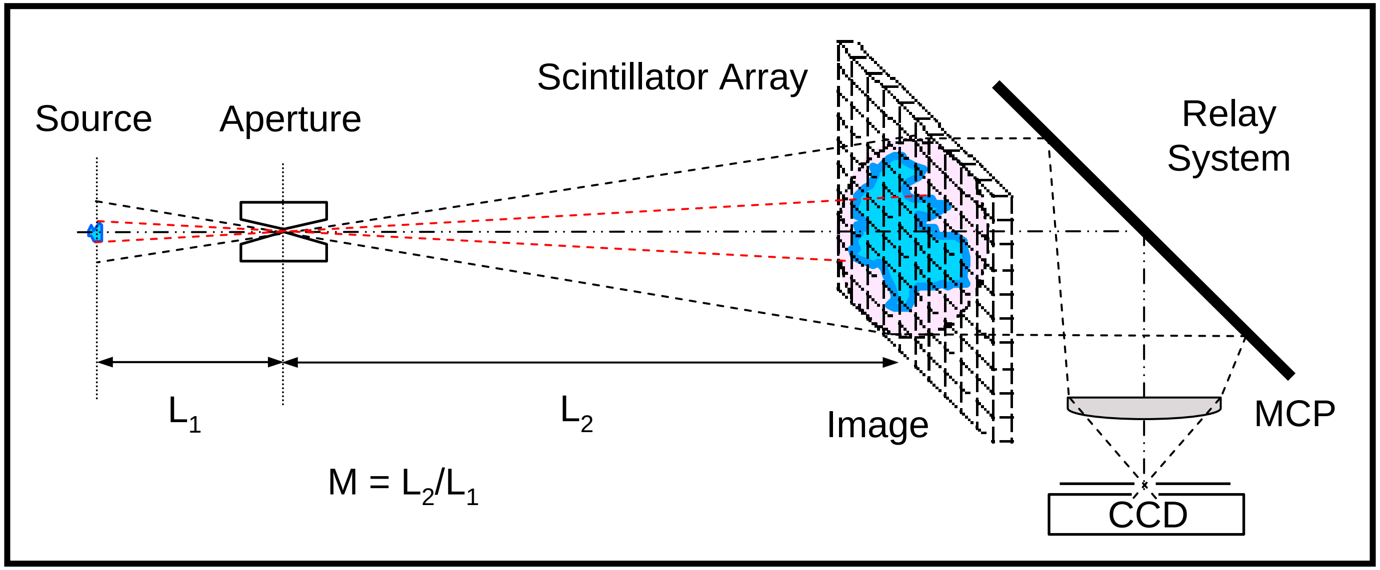


Downscattered*

- 14-MeV or primary neutrons are related to the central “Hot Spot”
- Downscattered neutrons (6 – 10 MeV) are related to the surrounding cold fuel
- Downscattered neutrons reveal the actual fuel distribution

* Simulated ICF images by S. Hatchett

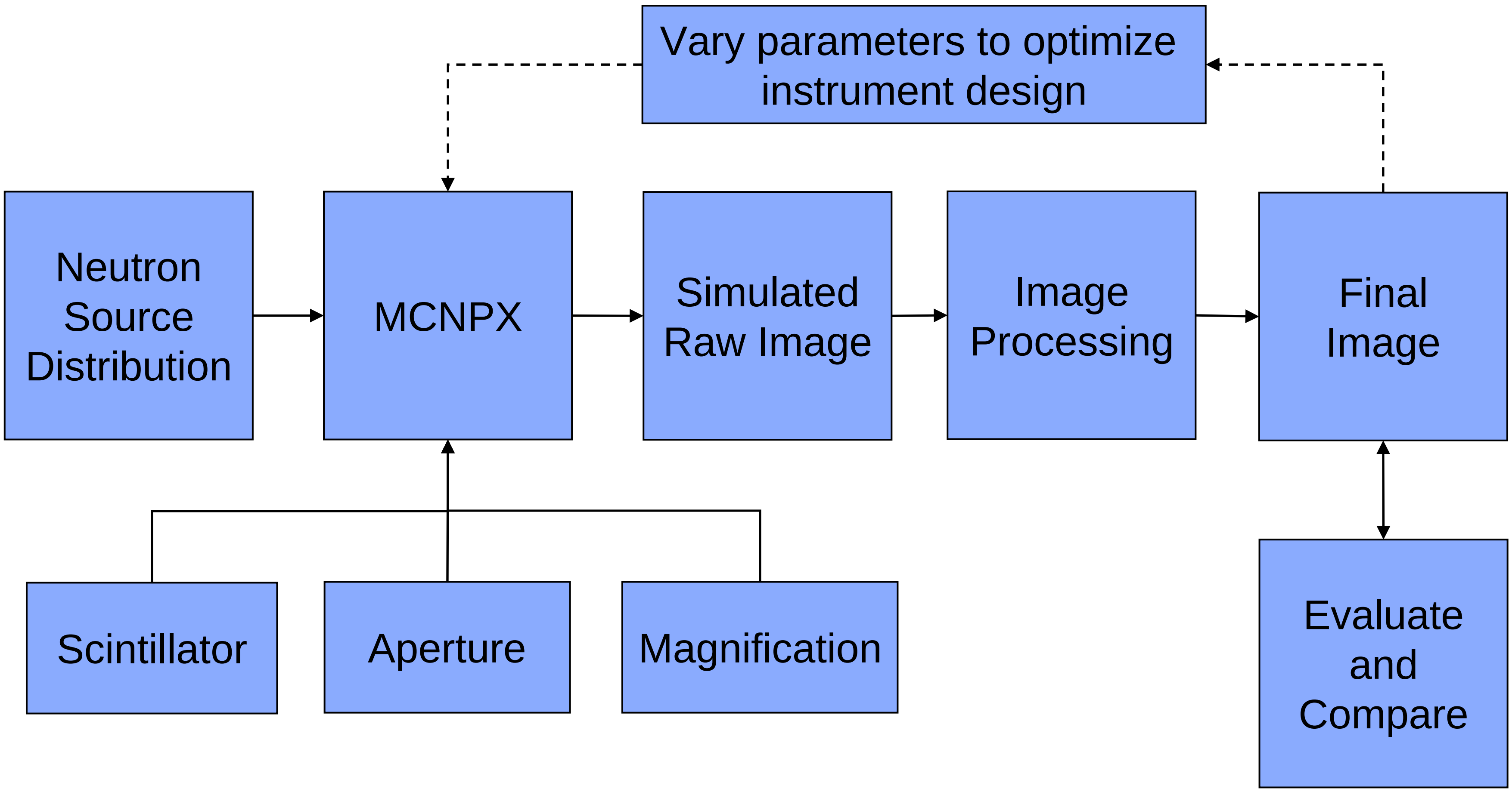
Neutron imaging concept: a typical line of sight



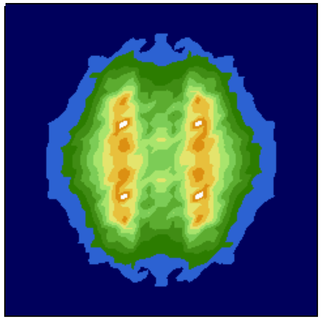
Typical NIF parameters:

- L1 = 40 cm
- L2 = 40 m
- M = 100
- Pinhole Material: Tungsten
- Pinhole Thickness = 13.7 cm
- Field of View (FoV) = 200 μm
- Resolution = 10 μm FWHM

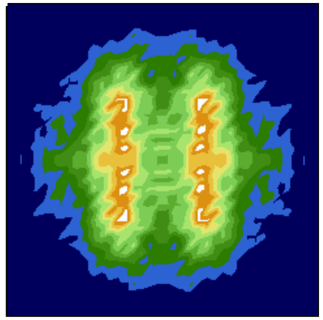
Overall system model being developed for neutron imaging design studies



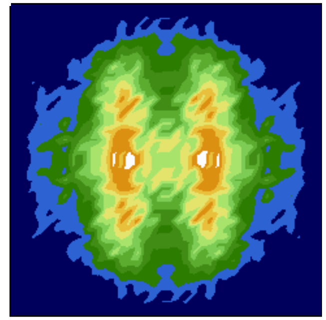
Starting point: Detailed source maps



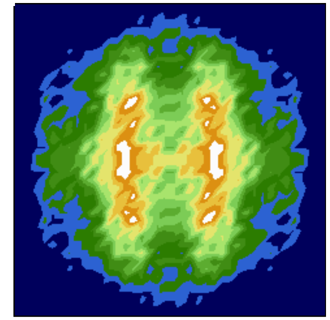
11 to 12 MeV



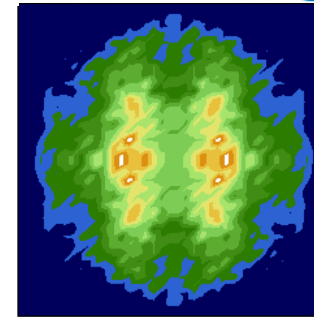
10 to 11 MeV



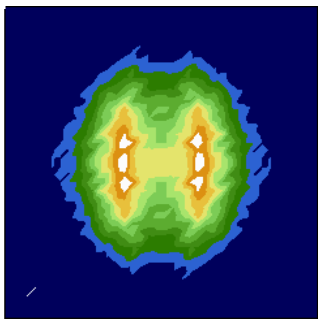
9 to 10 MeV



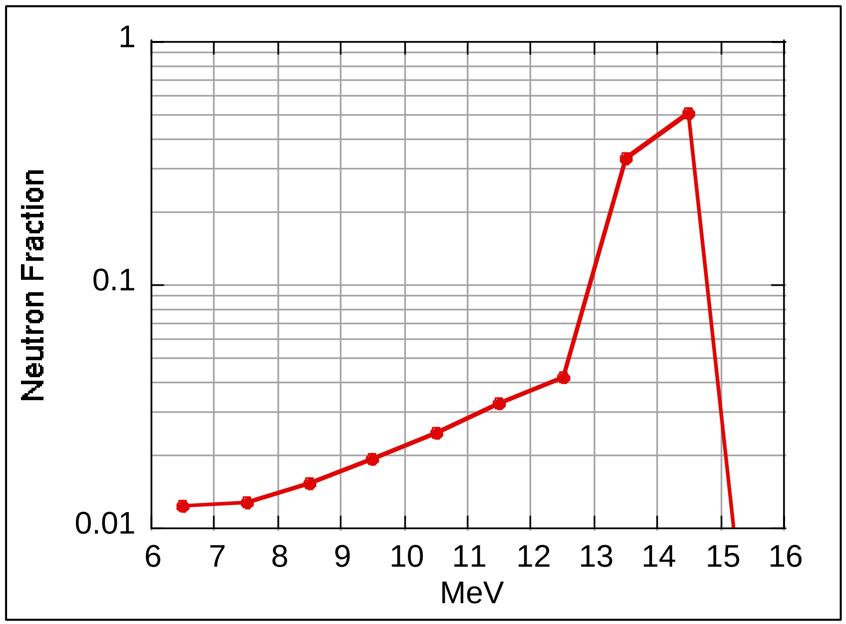
8 to 9 MeV

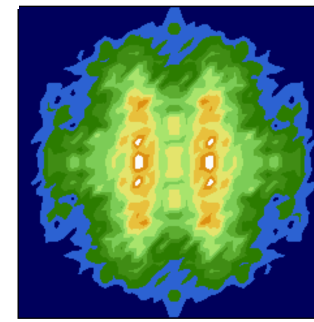


7 to 8 MeV

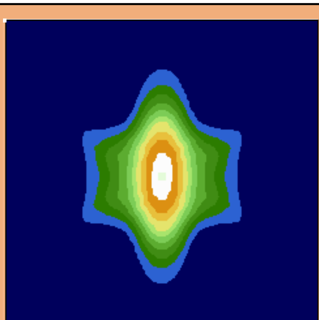


12 to 13 MeV



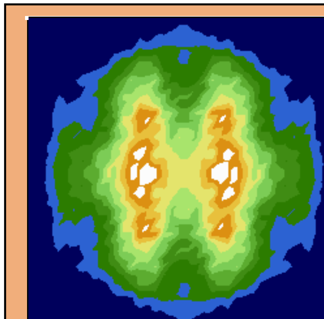


6 to 7 MeV



13 to 15 MeV
Prompt

- S. Hatchett ICF calculation of a failed implosion
- 100 micron FoV maps with 2.5 micron pixels
- P6 drive perturbation
- Yield 16 kJ (7E15 13-15MeV, 5E14 6-10 MeV)



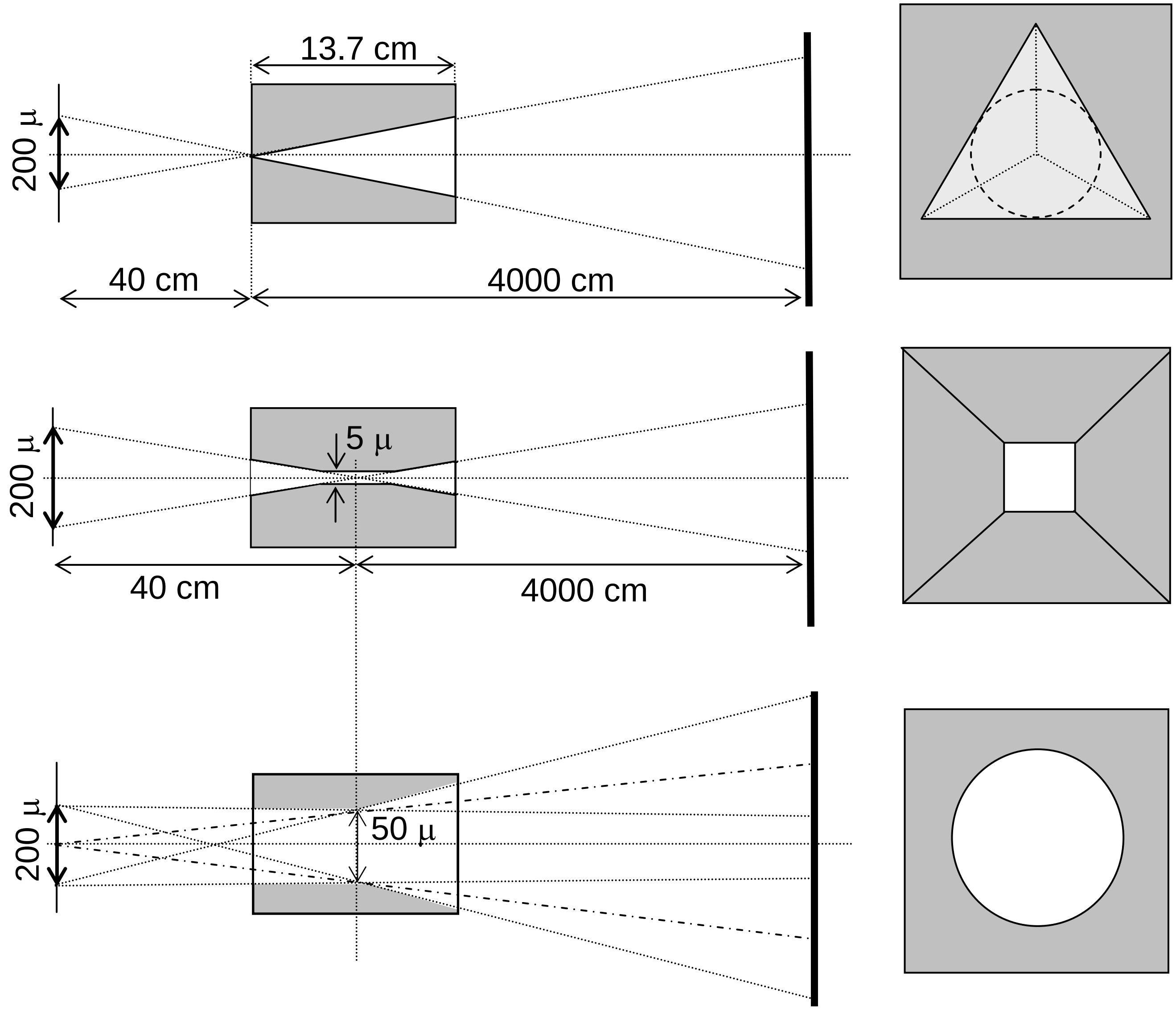
6 to 10 MeV
Downscattered

Aperture Geometry: 10 x 10 Arrays

Triangular Wedge

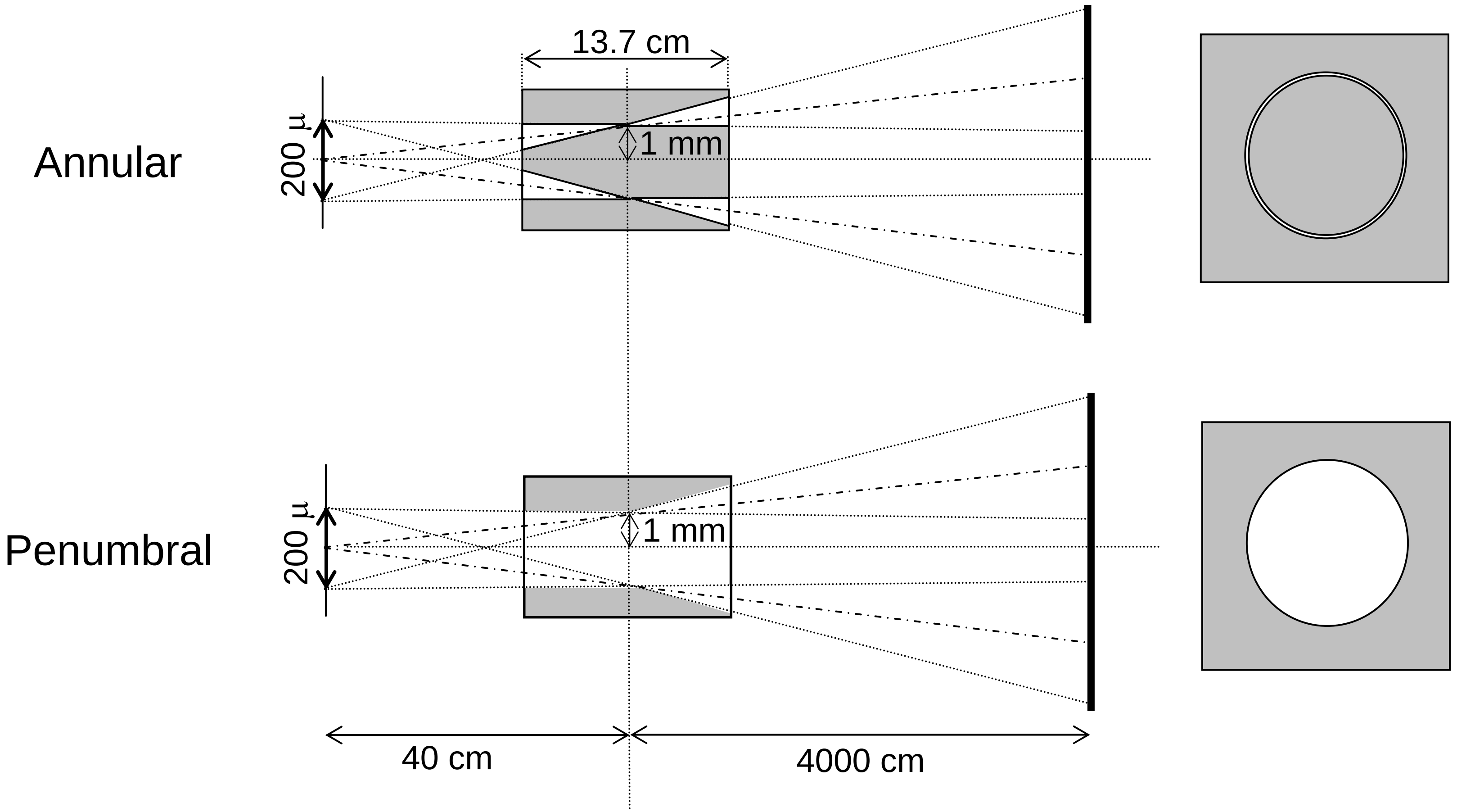
Square Pinhole

Mini Penumbral



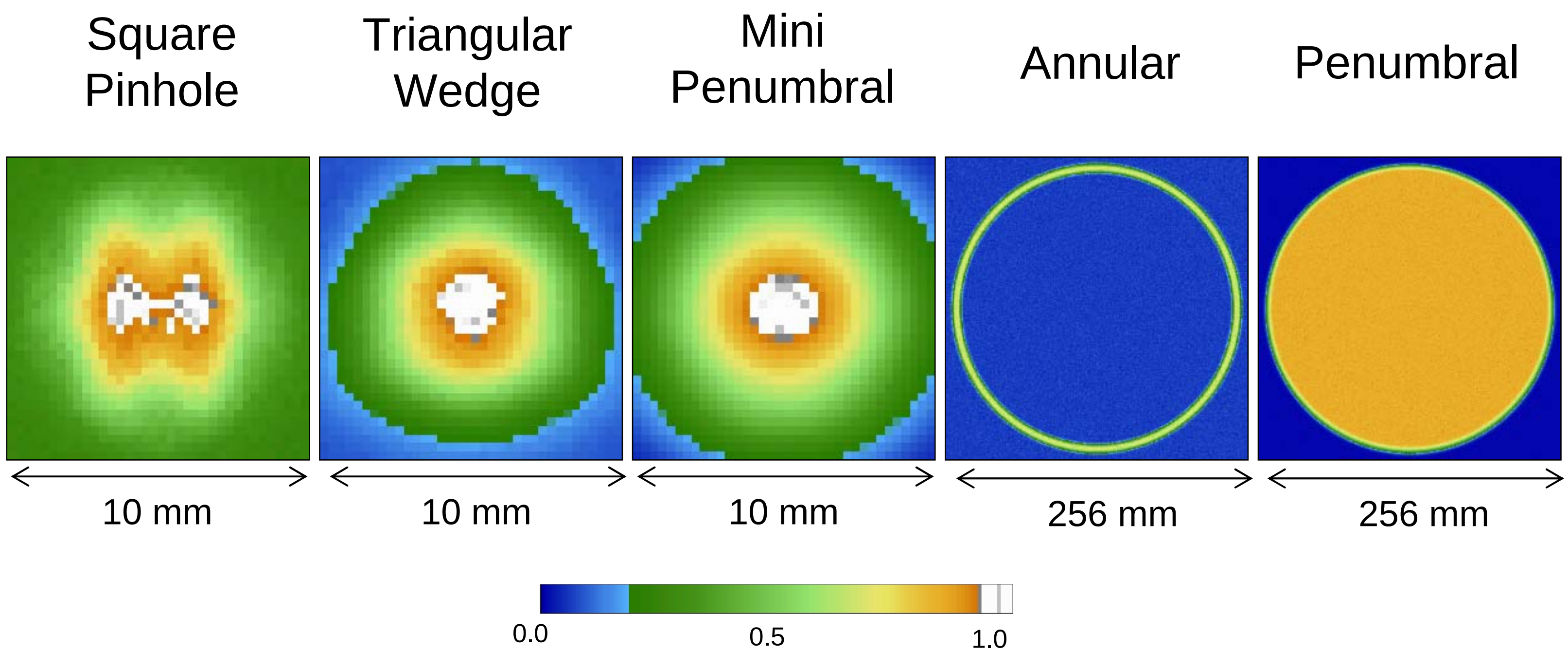
Drawings not to scale

Aperture Geometry: Single Aperture



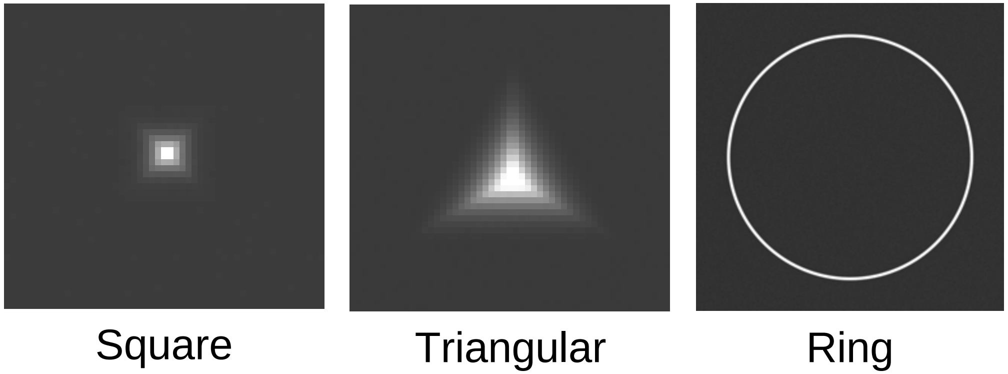
Drawings not to scale

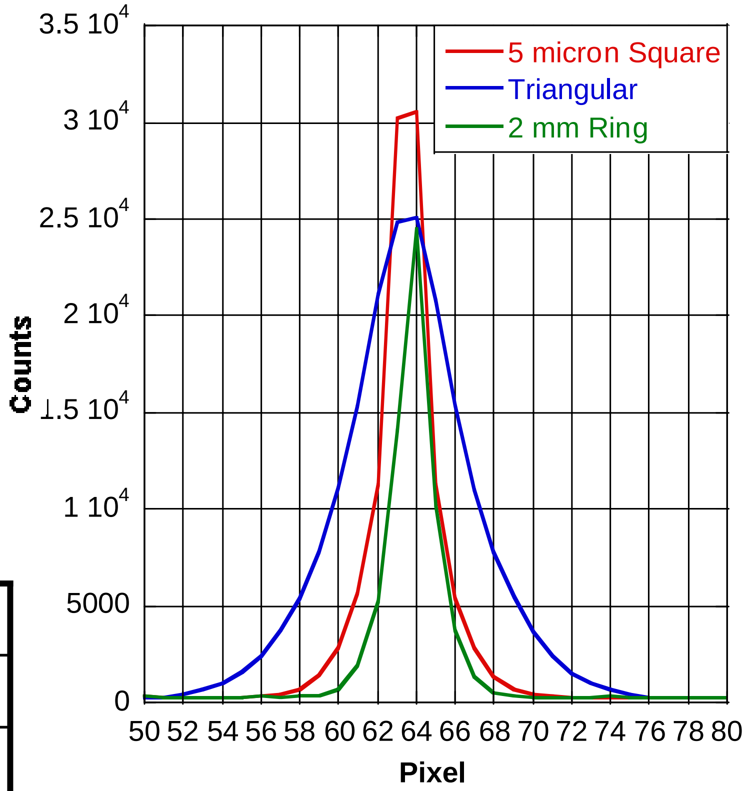
Simulated recorded downscattered raw images



- Detector Characteristics
  - BC422 Scintillator
  - Pixel geometry: 250 micron square, 4.6 cm long
- MCNPX calculation reflects aperture and scintillator Point Spread Functions (PSF)
  - No mathematical convolution
- Image arrays in proton energy deposited (MeV) per pixel
- Pinhole arrays are required due to single aperture small solid angle fraction

Accurate Aperture PSFs via MCNPX





- 10^{16} neutrons equivalent source
- Same size as expected image
- Not opaque (direct transmission)
- Single on-axis (Isoplanatic approximation)

	Square	Triangular	Ring
FWHM (μ)	7.5	15	5
$\Delta\Omega_{eff}$ *	2.517×10^{-11}	1.771×10^{-10}	4.424×10^{-8}
ϕ_{eff} (μ) **	8.02	24.91	336.55

* Effective solid angle fraction: based on actual neutron flux inside bright PSF region

** Effective aperture diameter: corresponds to the circle located at the leverage point (40 cm, 46.81 cm for triangular) that has a $\Delta\Omega = \Delta\Omega_{eff}$. For the ring the effective slit width ΔR_{eff} is 14.26 microns

Image deconvolution

Inverse filtering in frequency space

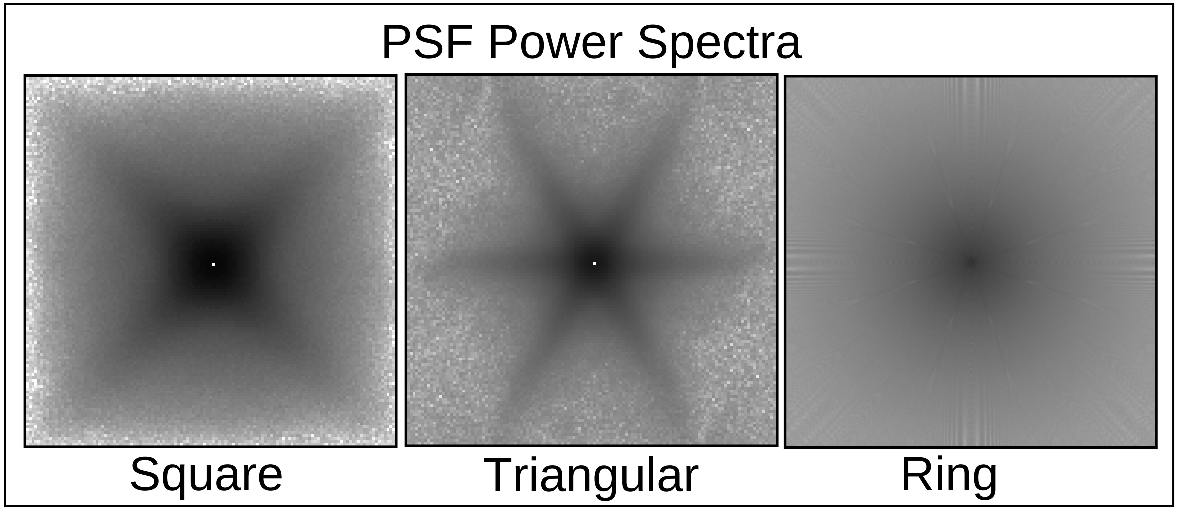
– Uses normalized on-axis PSF

– Usually shows singularities due to zeros in PSF

– MCNPX PSF does not have zeroes

– Noise amplification due to small values in PSF

$$I(k_x,k_y) = O(k_x,k_y) \cdot PSF(k_x,k_y) \qquad O(k_x,k_y) = \frac{I(k_x,k_y)}{PSF(k_x,k_y)}$$



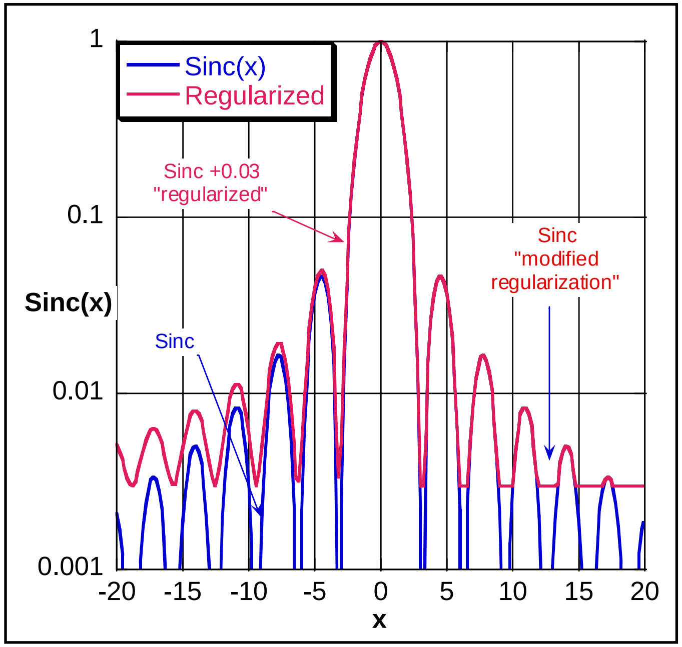
A conservative variation: Modified regularization

Regularization

- Shifts PSF by a constant

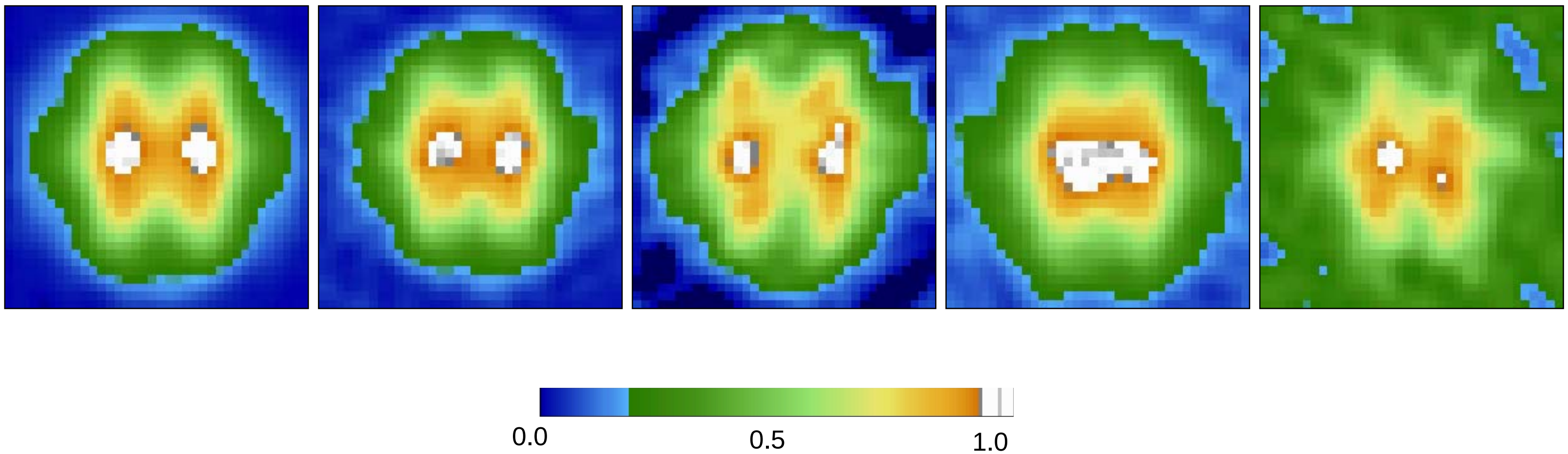
M-Regularization

- Replaces zeros and small values of PSF by a constant
- Regularization parameter is small
  - 0.001% - 0.1% of PSF maximum in frequency space
- Requires low-pass filtering
  - 7 - 15 micron FWHM Gaussian

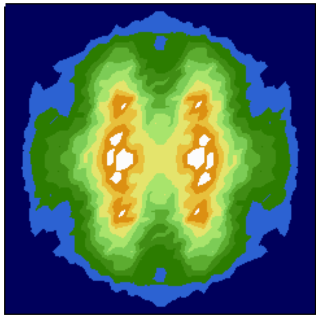


Deconvolved source comparison

Square Pinhole | Triangular Wedge | Mini Penumbral | Annular | Penumbral



- Images are equivalent to 100x100 microns at the source
- 10 microns FWHM low-pass Gaussian filter
- Same regularization parameter
  - Should be optimized for annular and penumbral apertures
- Impossible to accurately determine resolution and signal-to-noise ratio from images



Original Downscattered Source

A large uniform surrogate source is used to estimate SNR for the images at the 20% contour

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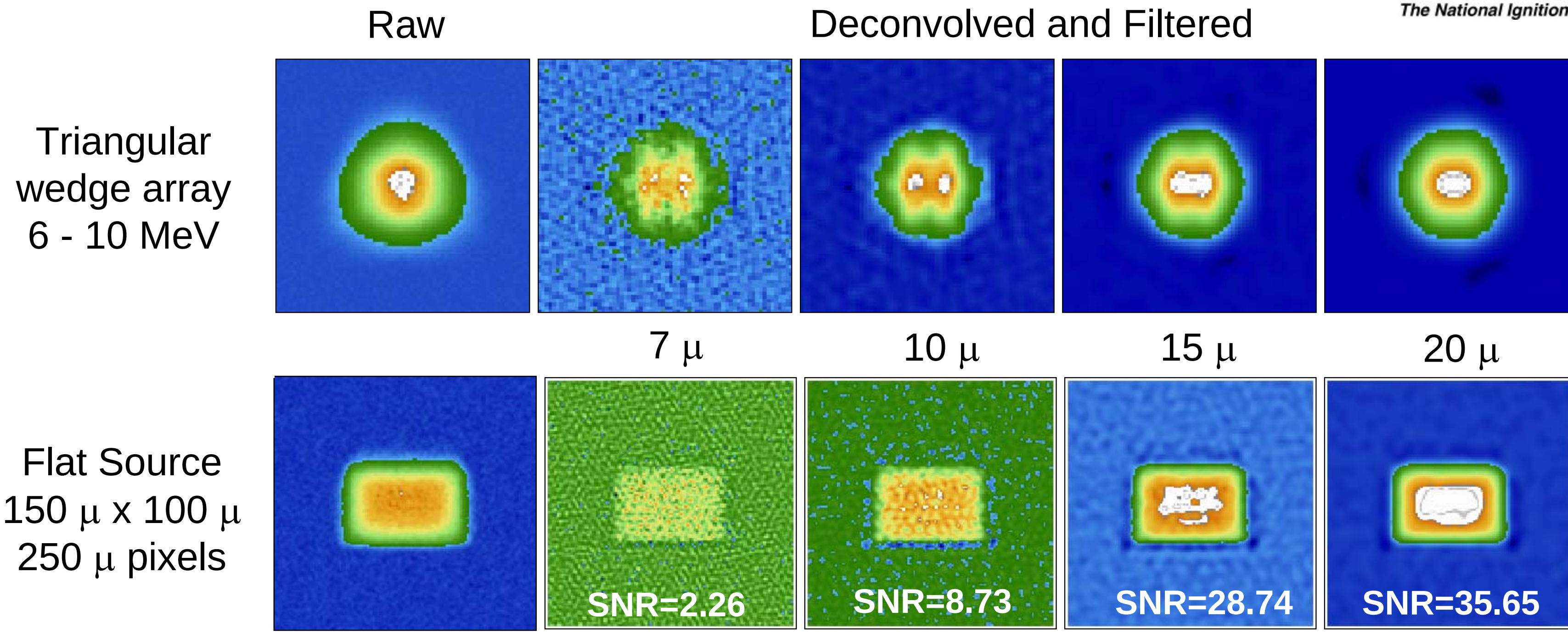

- Collisions per pixel follow Poisson statistics
- Energy deposited and photo-electrons per pixel are non-Poisson convolutions
  - Very close to Gaussian
- Artificial slab source can be used to “calibrate” 20% contour values after deconvolution
- NIS Requirements:
  Resolution = 10 microns SNR 20% contour = 10

A different surrogate source provides an estimate of resolution

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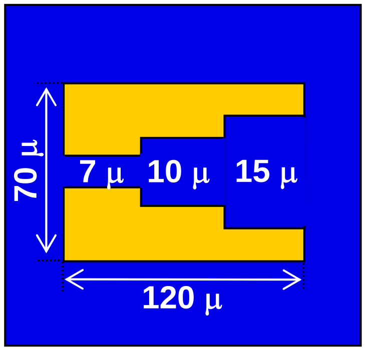
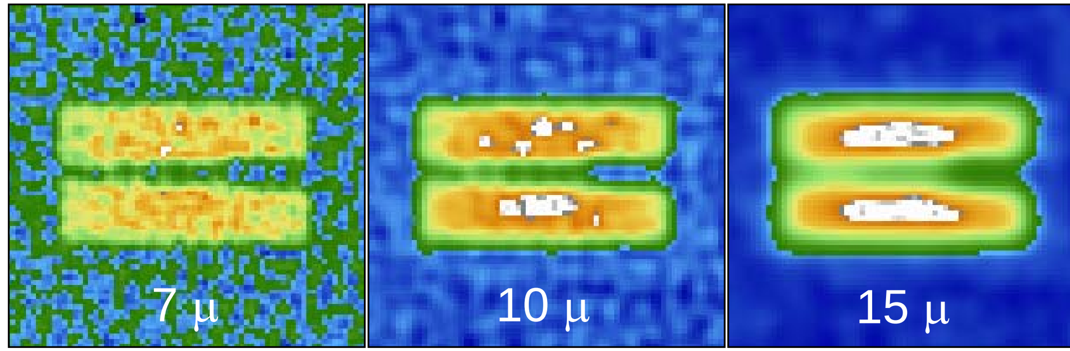
MCNPX Source Geometry

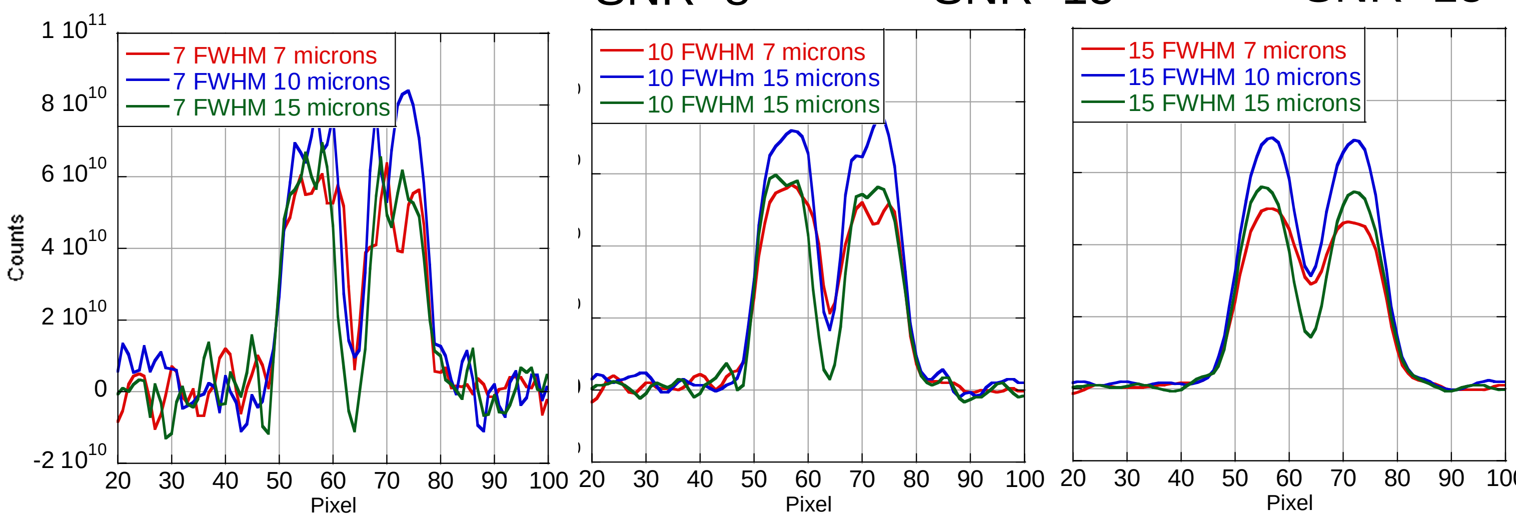


Not to scale

Square Pinhole Array
Deconvolved Sources



SNR=8 SNR=15 SNR>15



- Aperture satisfies the “Raleigh criterion” for resolution
- NIS Requirements:
  Resolution = 10 microns SNR 20% contour = 10

Conclusions and future work

- Developed imaging system end-to-end model
- MCNPX used to simulate various aperture geometries and neutron sources
- Surrogate sources show that some configurations satisfy the NIS resolution and signal-to-noise requirements
  – Final decision will be based on aperture fabrication
  – Optics / recording system must be included for final conclusions
- Simple image processing (modified regularization) is adequate for system studies

- Study sensitivities to system imperfections
- Aperture and detector options must be compared for optimization
- Refine calculations of aperture PSFs
- Refine calculations of resolution vs. SNR