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Title: Neutron Image Analysis for the National Ignition Facility

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Form 836 (7/06)

Neutron Image Analysis for the National Ignition Facility

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To obtain ignition in inertial con¯nement fusion experiments (ICF) at the National Ignition Facility (NIF), sited at Lawrence Livermore National Laboratory, Livermore, CA, will require a careful balance of drive conditions created by the 192 beam, 1.8 MJ laser. Drive symmetry and strength in ICF experiments will be reflected in the shape and density of the deuterium and tritium fuel, and therefore collection and analysis of neutron images produced by thermonuclear reactions, or resultant scatters, will provide this diagnostic information. A description of the NIF neutron imaging system (NIS) analysis methods will be presented, including an overview of the imaging system, a theoretical description of the image formation process, current system models, resultant analysis methods, examples from recent sensitivity and validation studies, as well as imaging data obtained to date.

[1]Deceased

Neutron Image Analysis for the National Ignition Facility

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Division of Plasma Physics, 2010, Chicago, IL

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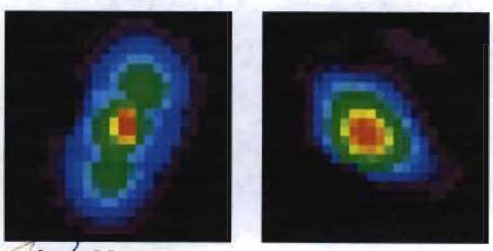
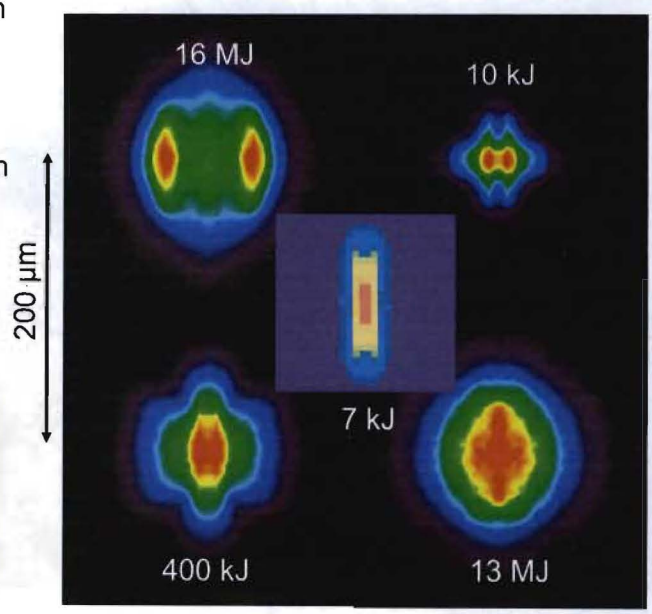
Neutron Imaging diagnoses low mode capsule asymmetry to guide laser beam pointing and power balance changes.

- A difficult task in calculating ignition in a 2D hohlraum is tuning beam pointing and power balance to achieve symmetry.
- Los Alamos will provide the neutron imaging system to diagnose symmetry as we make the final tune in FY10.
- Currently neutron images are used at Omega.





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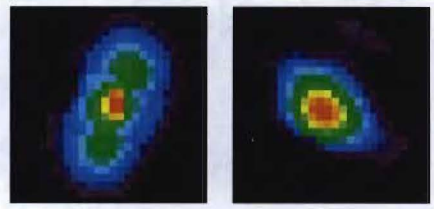
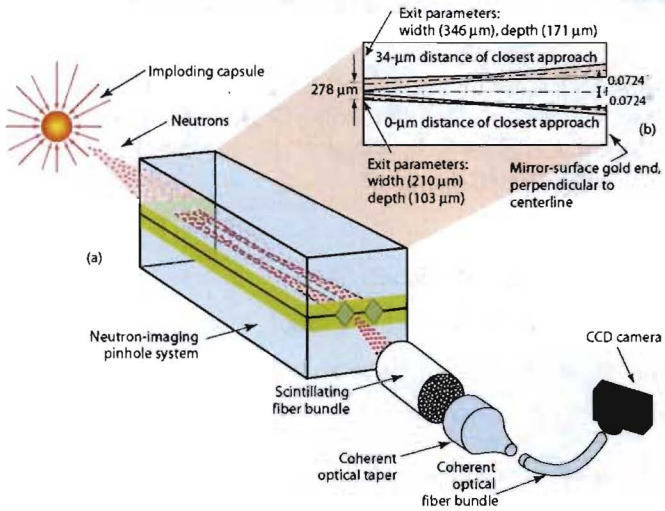
Neutron Source Imaging for ICF

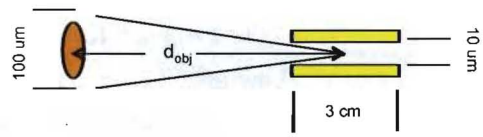
- An essential task in achieving ignition in a hohlraum is tuning beam pointing and power balance to achieve symmetry.
- Neutron source distributions provide this symmetry information.





$$\Delta_{src} \sim 50 - 100\ \mu m \Rightarrow \delta_{ph} \sim 10\ \mu m$$

$$\lambda_n^{mfp}(14\ \text{MeV}) \geq 3.0\ \text{cm}$$
$$\Rightarrow d_{obj} \sim 15\ \text{cm}$$



$$R_p(14\ \text{MeV},\ 1\ \text{g/cc}) \sim O(1)\ \text{mm}$$
$$\Rightarrow M \sim 100,\ \text{LOS} \geq 15\ \text{m}$$

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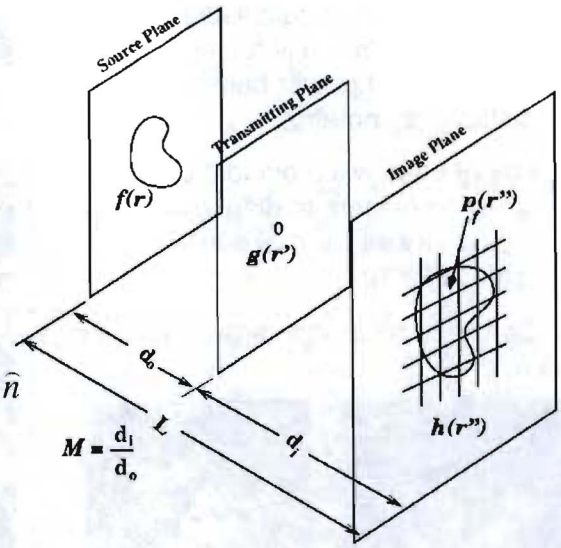
Assume a Filtered Linear Transport Model for Image Formation

- Source distribution: $f(\bar{r})$
- Transmitting aperture: $g(\bar{r}')$
- The resultant image is then assumed to be the transported and filtered source distribution with additive noise:

$$h(\bar{r}'') = \frac{1}{4\pi M^2 L^2} \tilde{f}(\bar{r}'') ** \tilde{g}(\bar{r}'') ** \tilde{p}(\bar{r}'') + \hat{n}$$

- Image analysis, to date, has focused on inversion of above equation.



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Two iterative inversion techniques have been implemented

Least Squares & Regularization

$$r = \|\mathbf{Mo} - \mathbf{i}\|_2^2 \qquad r = \|\mathbf{Mo} - \mathbf{i}\|_2^2 + \lambda^2\|\mathbf{Lo}\|_2^2$$

Minimizing with respect to solution leads to the normal equations

$$\mathbf{M}^T\mathbf{Mo} = \mathbf{M}^T\mathbf{i} \qquad \left(\mathbf{M}^T\mathbf{M} + \lambda^2\mathbf{L}^T\mathbf{L}\right)\mathbf{o} = \mathbf{M}^T\mathbf{i}$$

SVD

$$\mathbf{M} = \mathbf{U}\Sigma\mathbf{V}^T$$

$$\mathbf{o} = \sum_{j=1}^{rank}\left(1/\sigma_j\right)\mathbf{u}_j^T\mathbf{i}\mathbf{v}_j$$

Cut off expansion before reaching small singular values

Iterative (BCG)

$$\mathbf{d}_i = \mathbf{r}_{i-1} + \beta_i\mathbf{d}_{i-1}$$

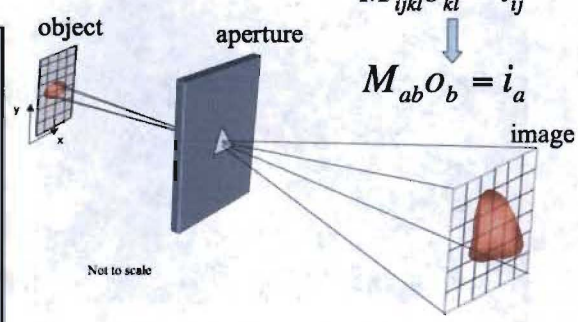
d is direction of steepest descent corrected for conjugacy to all other d

$$\mathbf{o} = \sum_i \alpha_i\mathbf{d}_i$$ Solution in this basis

$$\alpha_i = \frac{\mathbf{r}_{i-1}^T\mathbf{r}_{i-1}}{\mathbf{d}_i^T\mathbf{Md}_i} \qquad \beta_i = \frac{\mathbf{r}_{i-1}^T\mathbf{r}_{i-1}}{\mathbf{r}_{i-2}^T\mathbf{r}_{i-2}}$$

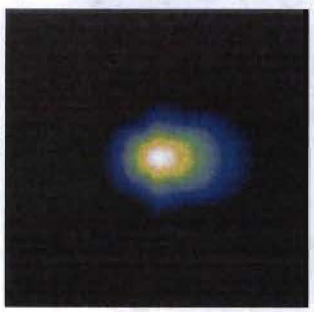
$$M_{ijkl}o_{kl} = i_{ij}$$

$$M_{ab}o_b = i_a$$

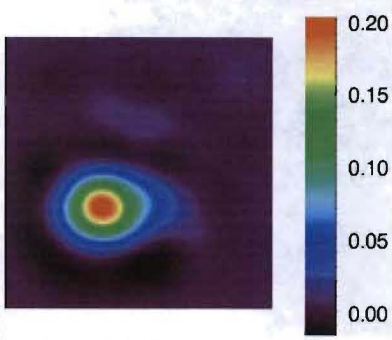


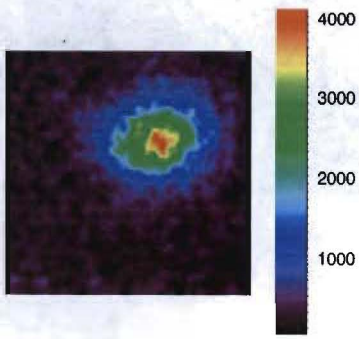
Monte Carlo simulations (MCNP) relied on for image reconstruction.
1. Used to construct transfer matrix
2. To transport source neutron fluence from radiation hydrodynamics simulations

Simulated Images…Primary (1-17 MeV) Image Workshop 01 – Yield 7.68e+13 (13-17MeV)

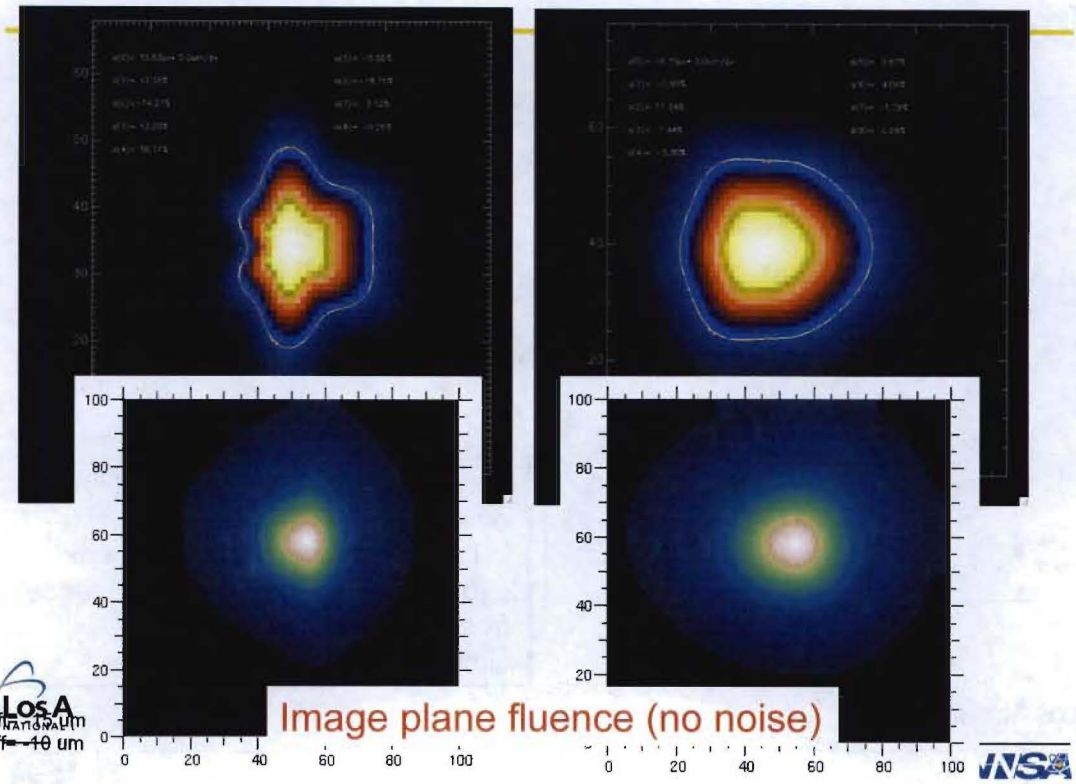


	P0 (μm)	P1/P0	P2/P0	P3/P0	P4/P0
Calc	26.5	0.252	0.219	0.070	0.108
Obs	39.9	0.045	0.286	0.024	0.113





Wkshp - 02 source distributions



Increasing S/N

1.19×10^{15} 1.19×10^{16}

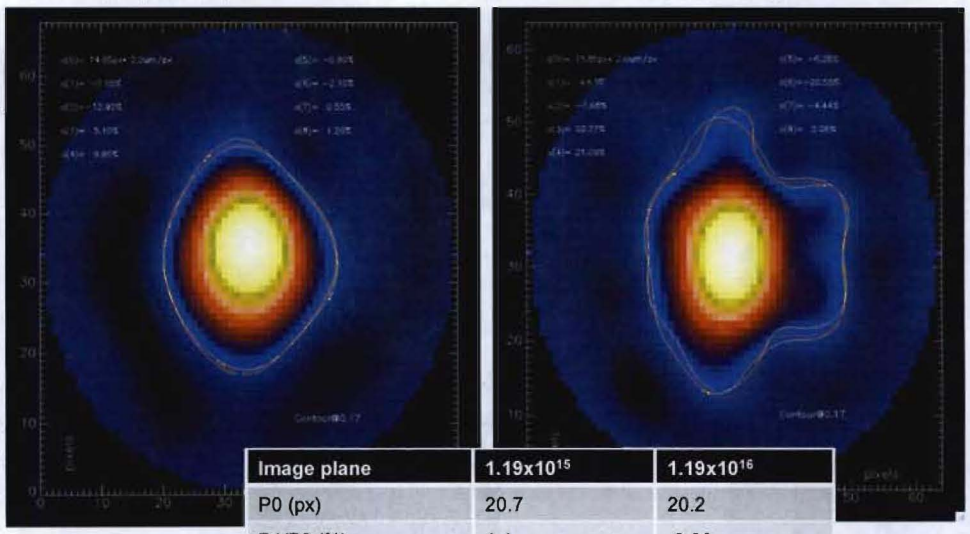


Image plane	1.19×10^{15}	1.19×10^{16}
P0 (px)	20.7	20.2
P1/P0 (%)	1.1	-0.26
P2/P0	-6.6	-6.4
P3/P0	2.8	3.9
P4/P0	1.5	1.5
P5/P0	-0.2	-1.0
P6/P0	-0.3	-0.4

Summary

- The NIF Neutron Imaging System has been designed to measure the shape of burning plasmas through source imaging of directed and scattered neutrons.
- Initial shape analyses use inversion of the transport and filtering operators through iterative techniques.
- Accuracy of the shape analysis depends on the underlying quantum statistics as well as the number of iterations and the amount of conditioning required.

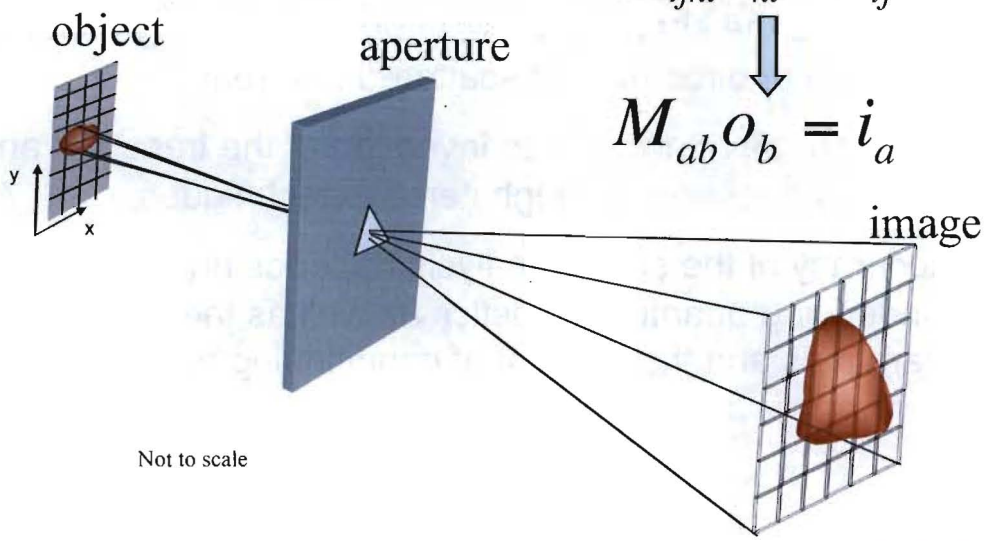
Backup/Alternative Slides

Problem description

$$M_{ijkl} o_{kl} = i_{ij}$$

$$\Downarrow$$

$$M_{ab} o_b = i_a$$



overview of BCG

$r = \|Ax - b\|^2 + \lambda \|\nabla^2 x\|$ something like a quadratic form with a minin

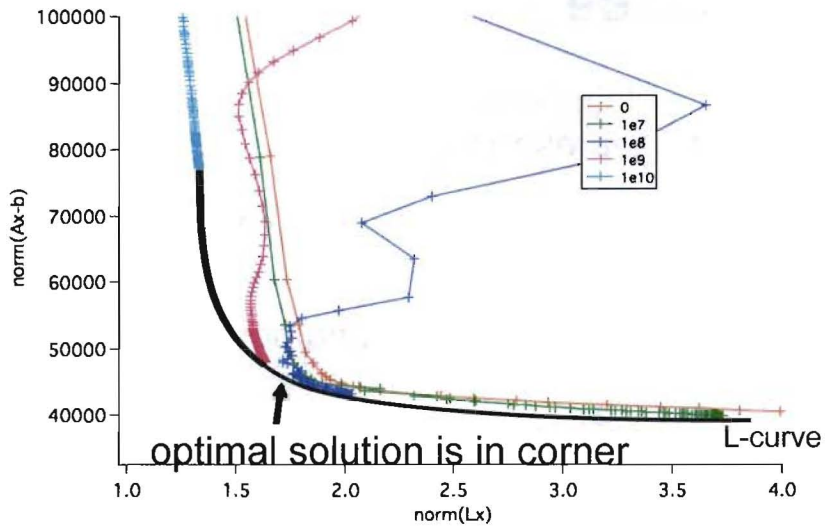
$\frac{\partial r}{\partial x} = 0 \rightarrow (A^T A - \lambda L^T L)x = A^T b$ this residual is in direction of steepest desce

$x = \sum \alpha \mathbf{d}$ choose **d** so that A-orthogonal to previous

(normally $d^T d = 0$ instead use… $d^T A d = 0$

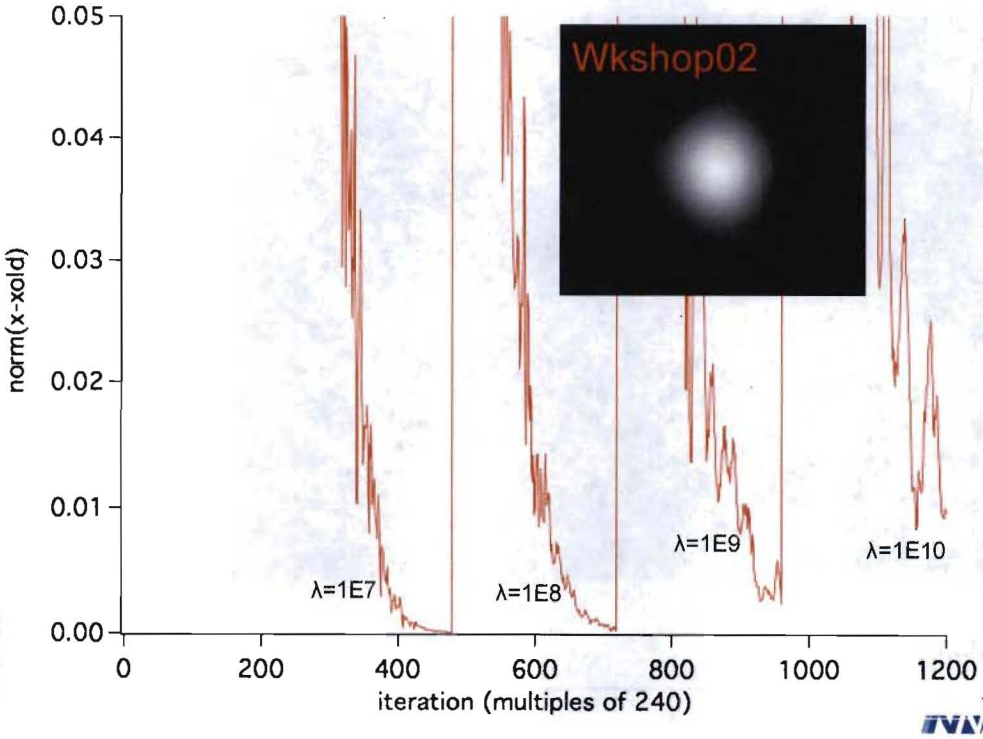
improves convergence time and a

stopping criteria and optimizing reconstruction



- wkshop2e, 240 iterations
- need run for more iterations to reach convergence
- ideal solution is around 1E9

convergence found when difference between consecutive solutions stops changing



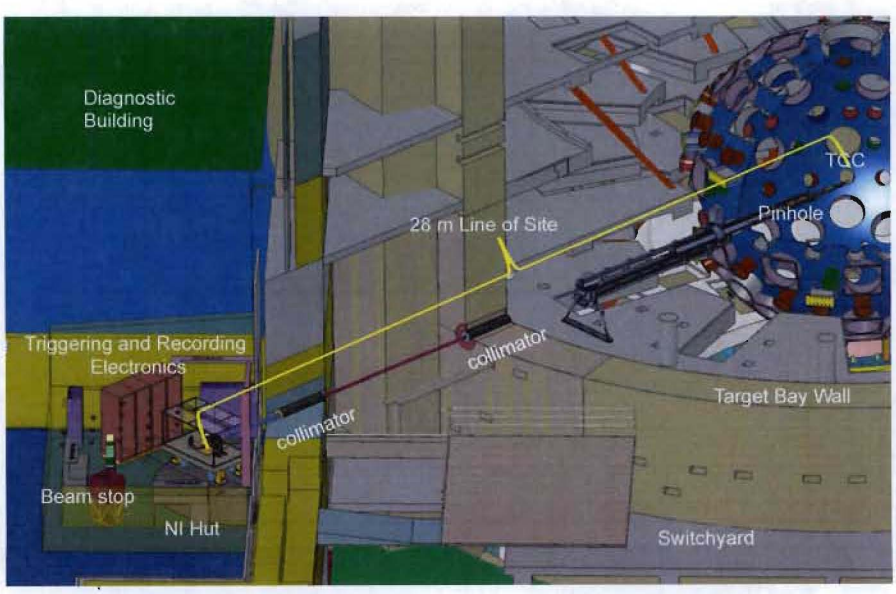
next version…total variation regularization accounting for non -gaussian noise

function to minimize

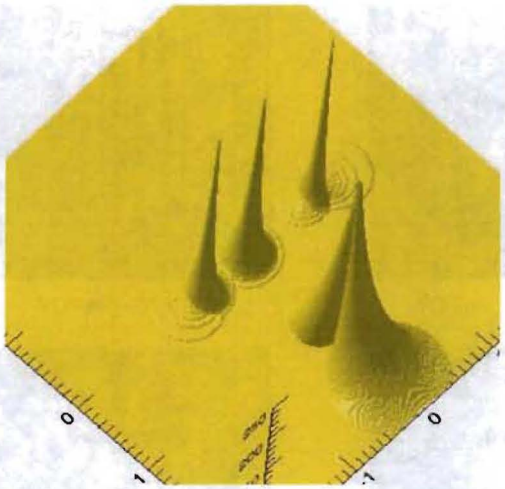
$$\min\left[|\nabla x| + \lambda\left(Ax - b * \log(x)\right)\right]$$

- grad(x) is better at preserving edges
- b*log(x) directly accounts for intensity variation dependence of Poisson noise
- nonlinear so have to use different numerical method

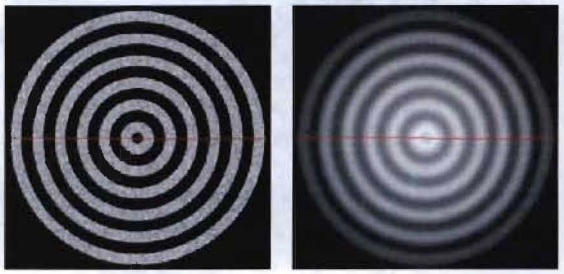
The NIF Neutron Imaging System

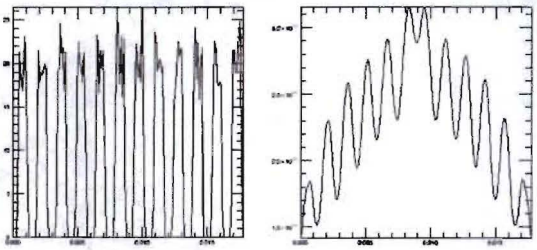


CLSI Not the best "assumption..."



Aperture PSF at varying radial positions within FOV.





Source Image

15 µm/cy

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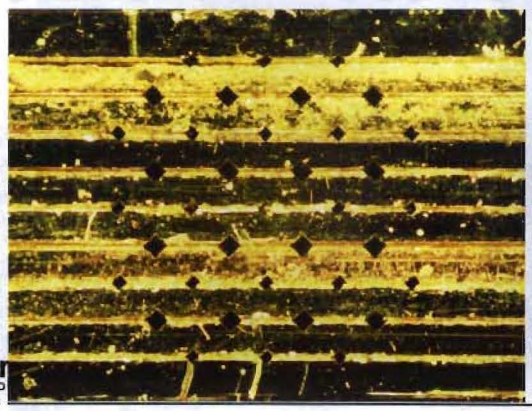
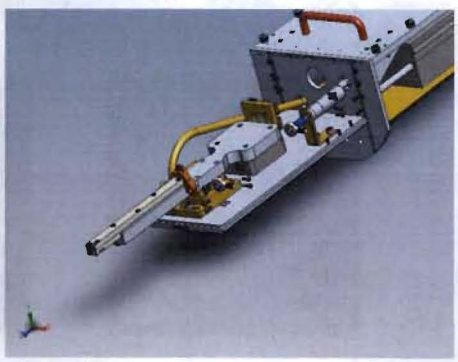
The aperture is an array of pinhole grooves scribed into gold layers and sandwiched together between tungsten plates

Trade off between resolution and distortion caused by aperture psf addressed by 2 sizes of pinholes





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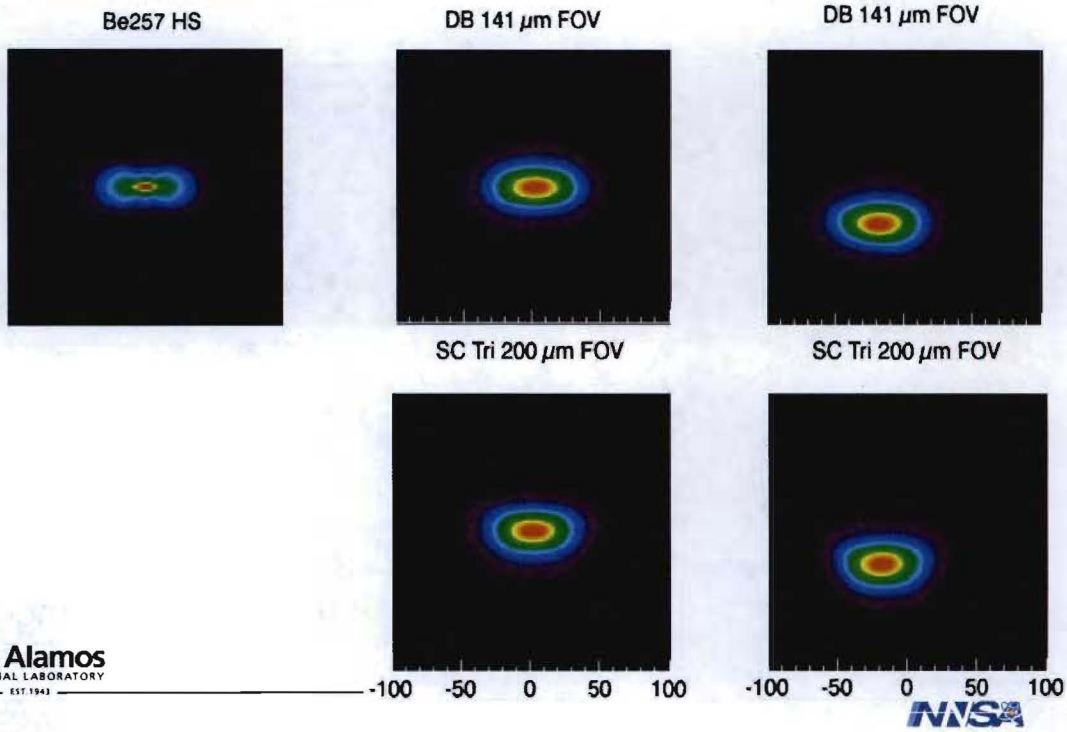
Drunk Bowtie & Triangle Pinholes



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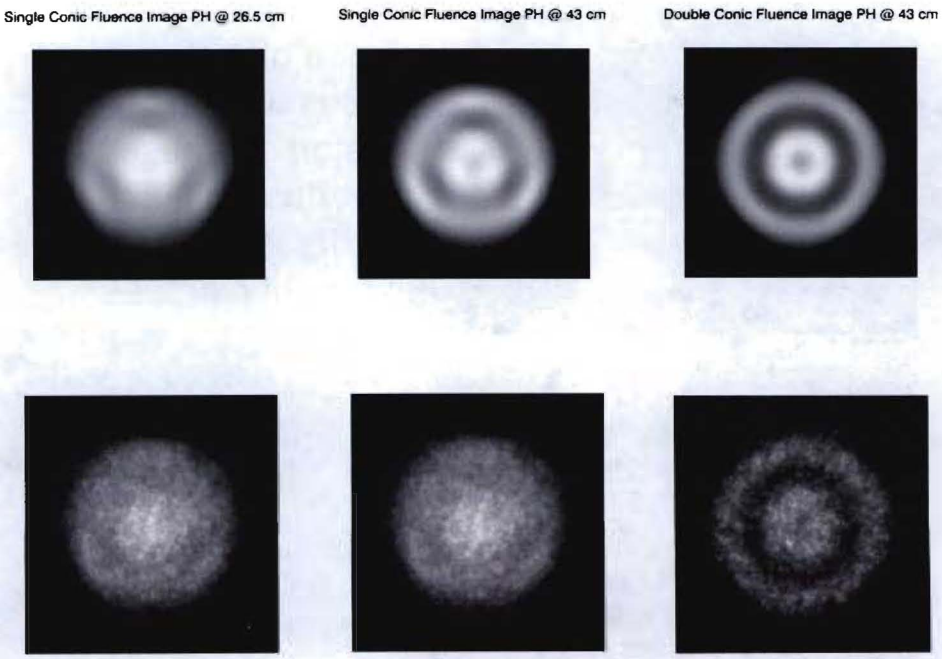
Forward model examples…



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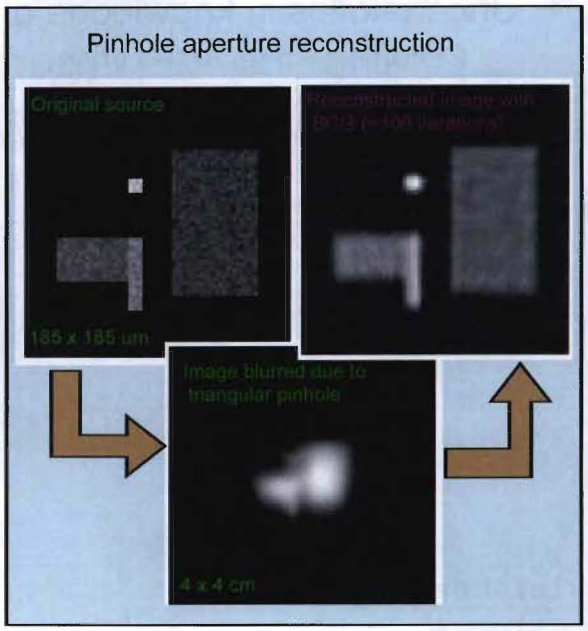
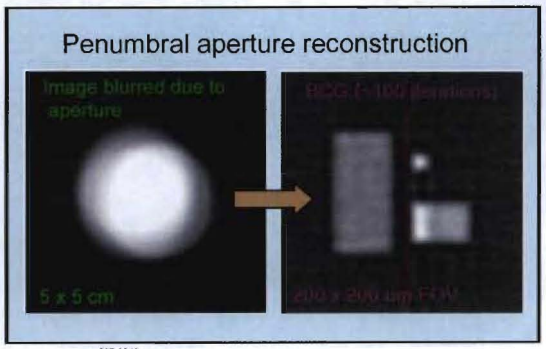
Development of reconstruction methods

- Technique is robust against source geometry, aperture type, and known misalignments
- **Effects of recording system resolution, noise, and unknown misalignments need to be determined**
- Large problem, slow for serial computation

Pinhole aperture reconstruction

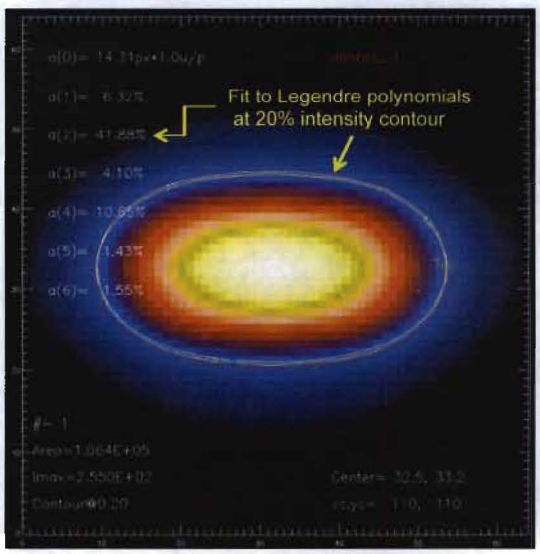


Penumbral aperture reconstruction

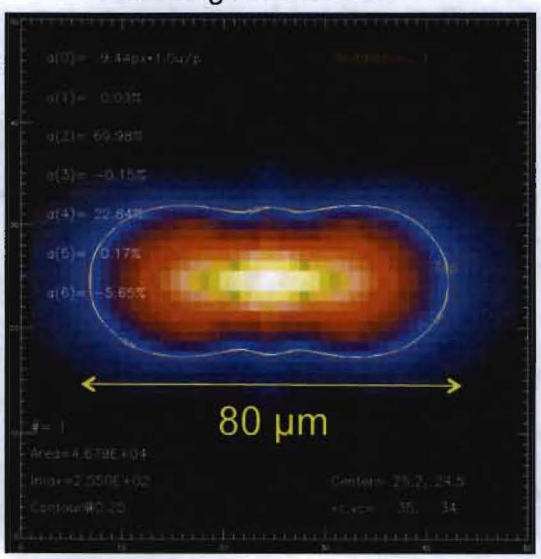


Smearing due to pinhole PSF almost completely removed following reconstruction

Neutron fluence at image plane



Following reconstruction



Raw source (be257) has 70%, 23%, -6% for p2/p0, p4/p0, and p6/p0

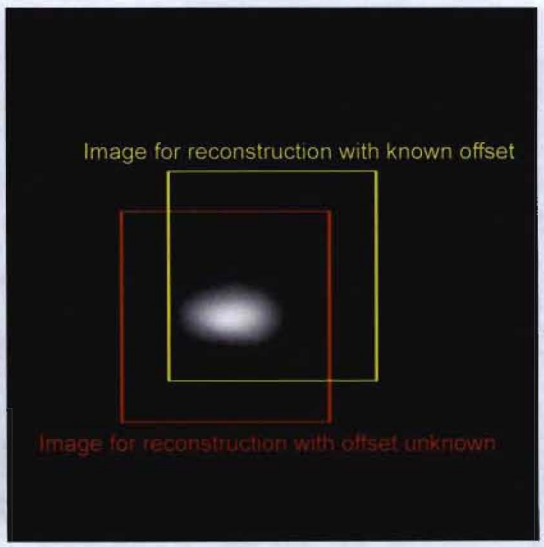
Testing whole system effects on reconstruction quality

- Uncertainties in knowledge of misaligned object
  - Distortions in recorded image could be from either asymmetric implosions of misalignment
  - Won't be able to distinguish one from the other
- Scintillator resolution
- Noise

Image of source translates and deforms as source is moved off axis

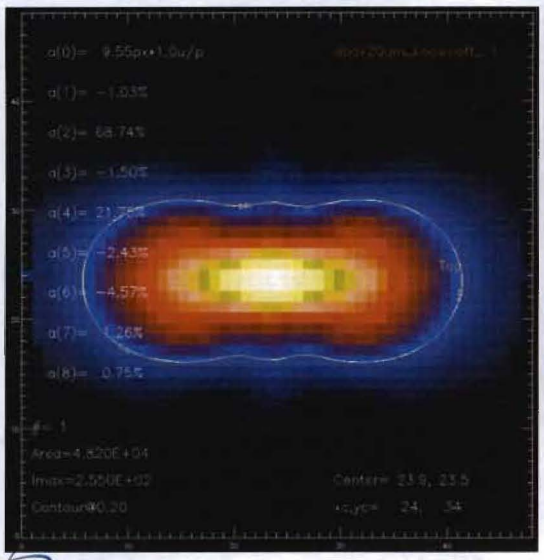
Source (be257) aligned in FOV

Source moved off-axis by 35, 35 μm in FOV



Known and unknown misalignments

Reconstruction with full knowledge of 20 μm source misalignment



Reconstruction without knowing source misalignment

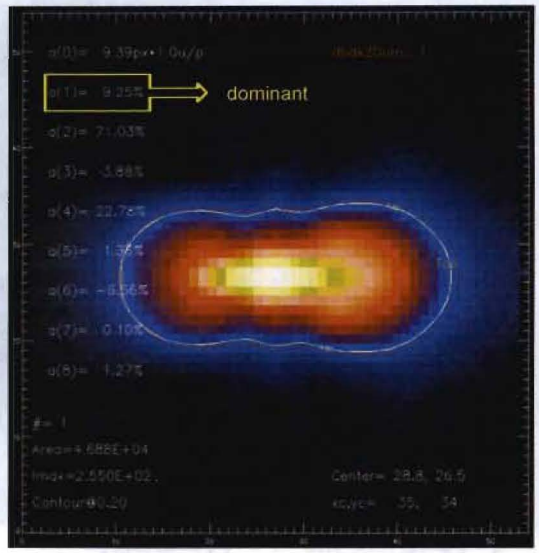
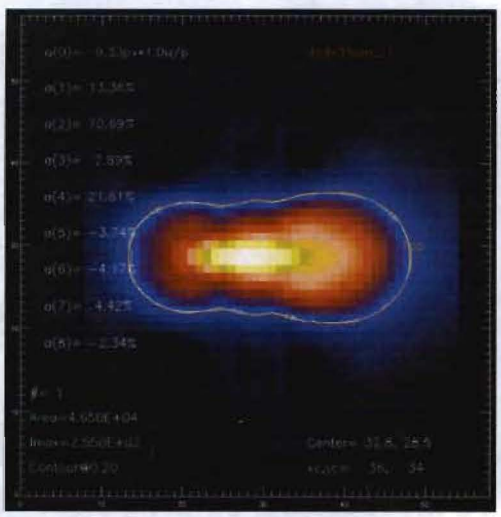
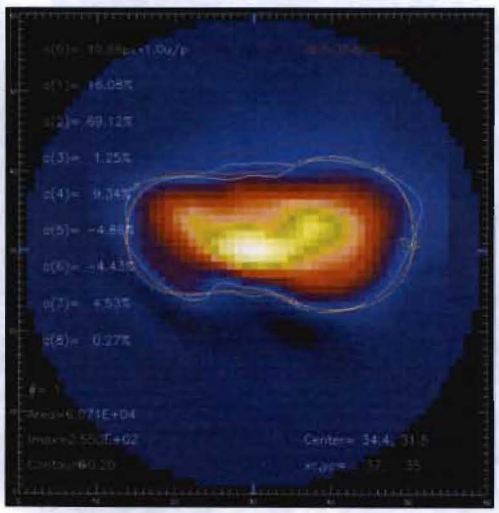


Image reconstructions with unknown offset

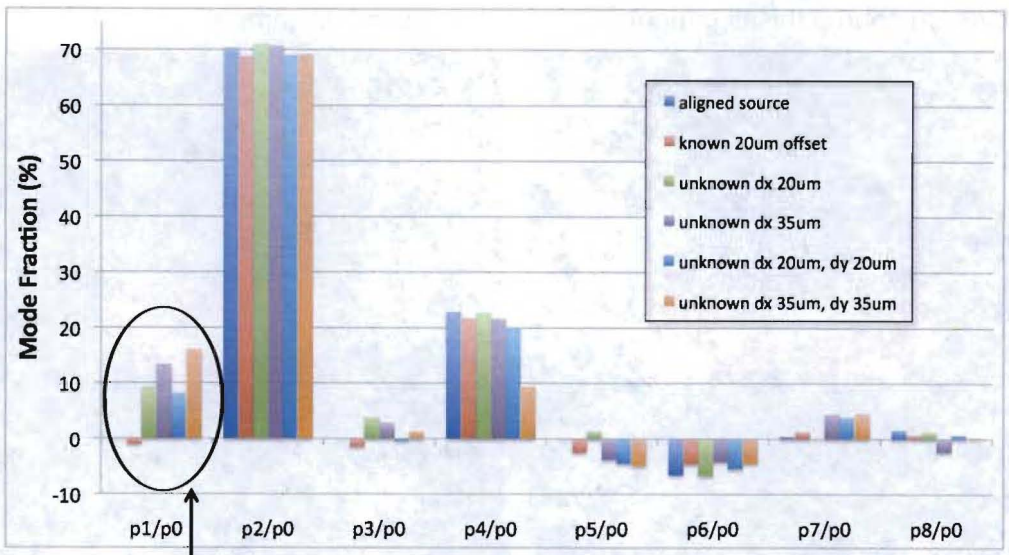
Source moved horizontally by 35 μm in FOV



Hard edge of pinhole shows up by 35, 35 μm in FOV (with this implosion)



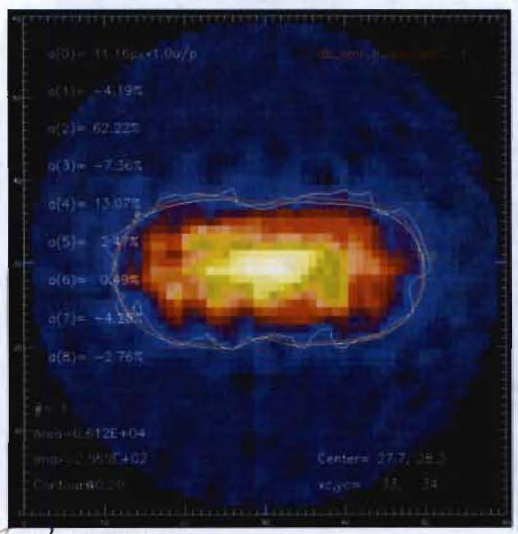
Summary of mode fractions for different (unknown) offsets



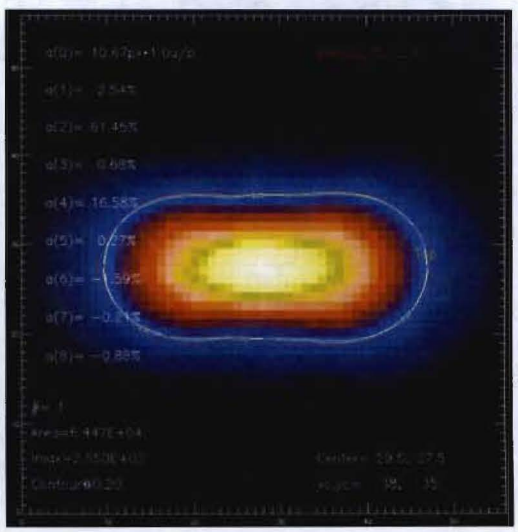
Biggest effect of misalignment uncertainty

Scintillator blurring "fattens" the reconstructions and reconstructions improve with greater SNR

Smeared with 1 mm Gaussian at image plane and Poisson noise at 10^{13} yield



Smeared with 1 mm Gaussian at image plane and Poisson noise at 10^{15} yield



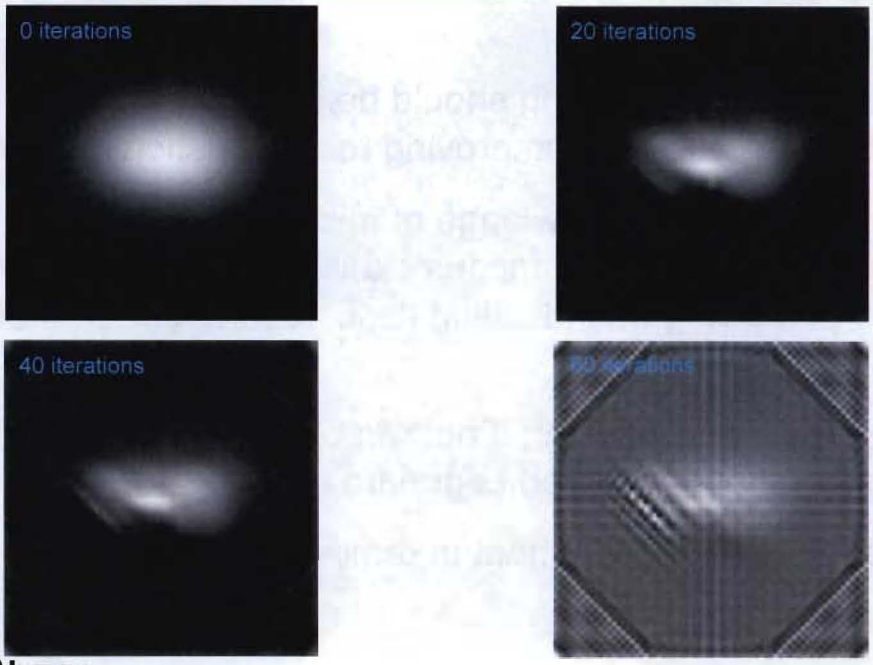
Conclusions and future work

- NIF pinhole array pointing should help to decrease alignment uncertainties improving reconstruction quality
- Without preexisting knowledge of misalignment, reconstructed Legendre modes exhibit an increased P_1/P_0 component giving an indication itself as to the degree of misalignment
- Blurring by the scintillator, if not removed, will diminish the accuracy of reconstructed Legendre modes
- Methods are in development to remove these effects

Acknowledgements

- Steve Batha, C10 program manager
- George Kyrala, Legendre fitting routine

Optimum number of iterations exists for BCG



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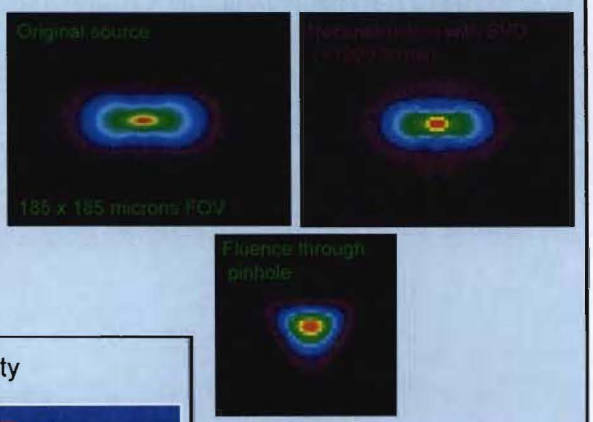
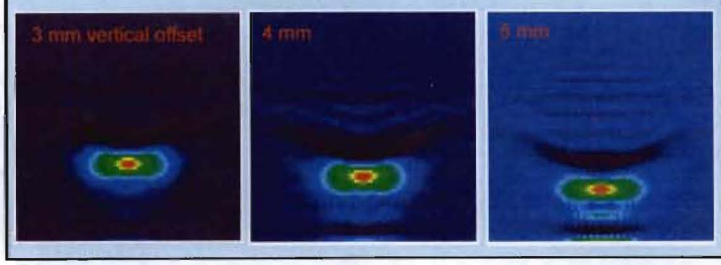
Effect of noise and uncertainty sources being investigated

- Performance checks
  - Resolution improvement tests
  - Intensity variations
  - Legendre mode analysis
- Noise
  - Scintillator fiber and PSF removal
  - Poisson
- Alignment uncertainty
  - Positional uncertainty at image plane
  - Uncertainty in alignment at source plane

Simulated low-mode asymmetric implosion



Effect of image position uncertainty



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