11-05251

LA-UR-

Approved for public release; distribution is unlimited.

Title: Downscattered neutron images from ICF Experiments at the National Ignition Facility

Author(s): Nevzat Guler + OTHERS (ATTACHED LIST)

Intended for: Inertial Fusion Sciences and Applications (IFSA) 2011

Los Alamos
NATIONAL LABORATORY
EST. 1943

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Form 836 (7/06)

LLNL-ABS-475242

ANALYSIS OF DOWNSCATTERED NEUTRON IMAGES FROM THE NATIONAL IGNITION FACILITY

Nevzat Guler[1], Gary P Grim[1], Frank E Merrill[1], George L Morgan[1], Douglas C. Wilson[1], Steven H Batha, Chris R Danly[1], Eric N Loomis[1], Petr L Volegov[1], Carl H Wilde[1], Mark D Wilke[1], David N Fittinghoff[2]

[1]*Los Alamos National Laboratory, Los Alamos, NM, USA*

[2]*Lawrence Livermore National Laboratory, Livermore, CA, USA*

Controlling fuel compression is one of the key elements for accomplishing ignition in inertial confinement fusion (ICF) experiments. Thus, cold fuel areal density measurements are one of the primary analysis topics in these experiments. By using two camera systems, gated with adjustable timings, the neutron imaging system at the National Ignition Facility (NIF), Lawrence Livermore National Laboratory, Livermore, CA, can image the primary neutrons and pre-selected fraction of the down-scattered neutrons from ICF implosions. We will present reconstructed intensity profiles of the hot fusion core and the cold fuel region surrounding it, as well as the inferred downscattered ratio of the neutron yields from these regions, and the status of studies to relate these ratios to the cold fuel areal density.

This work was performed for the U.S. Department of Energy, National Nuclear Security Administration and by the National Ignition Campaign partners; Lawrence Livermore National Laboratory (LLNL), University of Rochester -Laboratory for Laser Energetics (LLE), General Atomics (GA), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL). Other contributors include Lawrence Berkeley National Laboratory (LBNL), Massachusetts Institute of Technology (MIT), Atomic Weapons Establishment (AWE), England, and Commissariat à l'Énergie Atomique (CEA), France. Prepared by LANL under Contract DE-AC-52-06-NA25396. Prepared by LLNL under Contract DE-AC52-07NA27344

Down-scattered neutrons imaged for the first time in ICF experiments at the National Ignition Facility

Gary P Grim[1], Robert J Aragonez, Thomas N Archuleta[1], Steven H Batha[1], David D Clark[1], Deborah J Clark[1], Chris R Danly, Robert D Day, Valerie E Fatherley, Joshua P Finch[1], Robert A Gallegos, Felix P Garcia, Nevzat Guler[1], Albert H. Hsu, Steven A Jaramillo, Eric N Loomis, Danielle Mares[1], Drew D Martinson, Frank E Merrill, George L Morgan, Carter Munson, Thomas J Murphy, John A Oertel, Paul J Polk, Derek W Schmidt, Ian L Tregillis, Adelaida C Valdez, Petr L Volegov, Tai-Sen F Wang, Carl H Wilde, Mark D Wilke, Douglas C Wilson[1], Dennis P Atkinson, Dan E Bower[2], Owen B Drury, John M Dzenitis, Brian Felker, David N Fittinghoff, Matthias Frank, Sean N Liddick, Michael J Moran, George P Roberson, Paul Weiss, Robert A Buckles, Jerry R Cradick, Morris I Kaufman, Steve S Lutz, Robert M Malone, Albert Traille

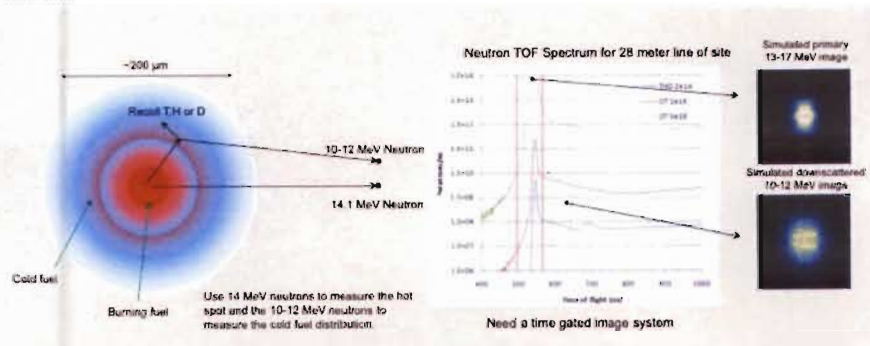
Los Alamos National Laboratory, Los Alamos, NM USA
Lawrence Livermore National Laboratory, Livermore, CA USA
National Security Technologies, Las Vegas, NV USA

Nevzat Guler[1] for Neutron Imaging Collaboration

Neutron images are collected at NIF to measure the hot spot size and the cold fuel distribution

Controlling the fuel compression is crucial for accomplishing ignition in inertial confinement fusion (ICF) experiments. The neutron imaging diagnostics provide the size and shape of the hot spot from primary neutrons and that of the cold fuel distribution from down scattered neutrons by using two fast gated camera systems. The gates on the camera systems can be adjusted to observe any fraction of the down scattered neutrons. The energy of the primary neutrons is 14.1 MeV while the selected down scattered neutrons come in 10-12 MeV range. This range was selected to minimize the background from interactions other than scattering and at the same time to maintain good statistics.

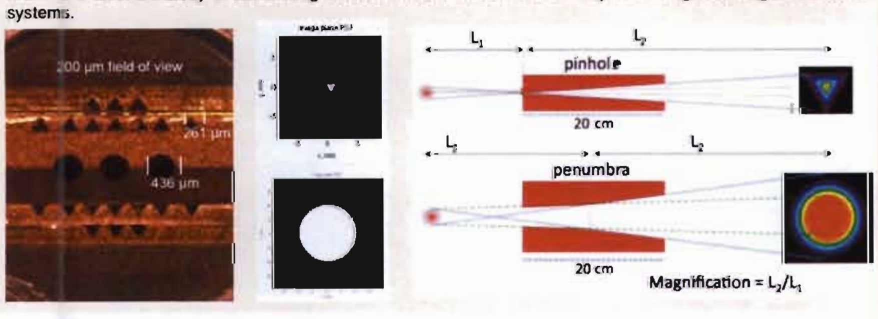
An array of 23 pinhole and mini-penumbral apertures were used to take a snapshot of the implosion and the images were inverted using iterative maximum likelihood techniques to reconstruct the source distribution. Then, the estimated distributions were fitted to Legendre modes to calculate the size and shape of the hot spot as well as the cold fuel. The reconstructed intensity profiles will be used to calculate time integrated density distribution of the cold fuel. In addition, the inferred down scattered ratio of the neutron yields from primary and scattered neutrons is related to the spatially averaged and time integrated cold fuel areal density. This poster is mainly focused on the down scattered neutrons. For more information on the neutron imaging system at NIF and its diagnostic capabilities, please see the talk by Gary Grim and poster by David Fittinghoff.



Neutron images are used to diagnose NIF implosions. Temporal separation of neutrons after 28 m drift results in ability to collect two neutron images: Primary (13-17 MeV) & Down Scattered (10-12 MeV)

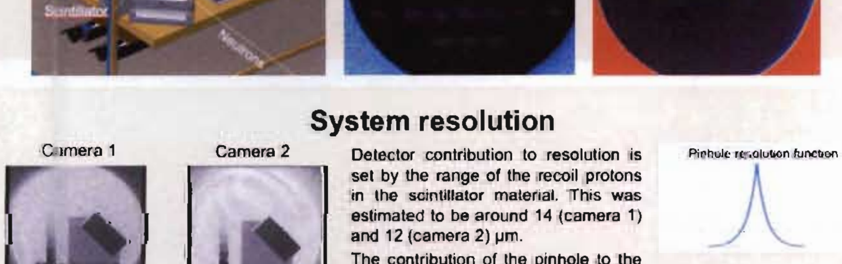
Imaging

The imager is composed of 20 pinholes and 3 mini-penumbra, machined in 20 cm of layered gold and tungsten, with an apex at 32.5 cm from the source, to produce images in a scintillator array at 2800 cm. This geometry provides a magnification factor of ~85 for the pinholes and ~65 for the penumbra at the scintillator location, which is a coherent array of scintillating fibers, viewed from the two ends by two fast-gated image collection systems.

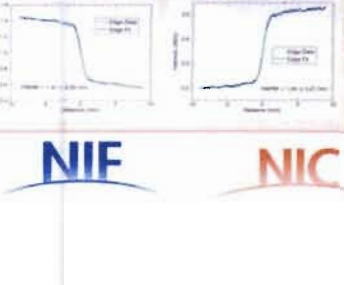


Gated camera system

Flat field data were collected in calibration shots to study different pixels in the scintillator array. Before and after each shot, dark field data were collected to measure the background in the CCD camera outputs. The image is corrected for these backgrounds. Occasionally, nuclear interactions with some pixels show themselves as saturated signals. Those pixels are corrected by taking average of neighboring pixels. Downscattered image must be aligned to the primary image and intensity measurements for each pixel must be corrected for the residual light in the scintillator from primaries. Direct drive (~ 0 cold fuel ρR) implosion data provides this correction. Residual light background was found to be ~1%.



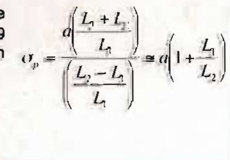
System resolution



Detector contribution to resolution is set by the range of the recoil protons in the scintillator material. This was estimated to be around 14 (camera 1) and 12 (camera 2) µm.

The contribution of the pinhole to the resolution was determined by the effective pinhole size, which is ~19 µm. The total system resolution can be approximated by:

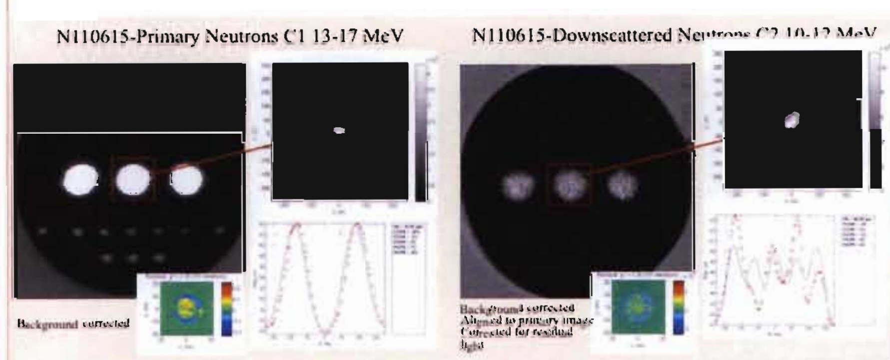
$$\sigma_t = \sqrt{\left(\frac{r}{m}\right)^2 + \sigma^2} \approx 23\mu m$$

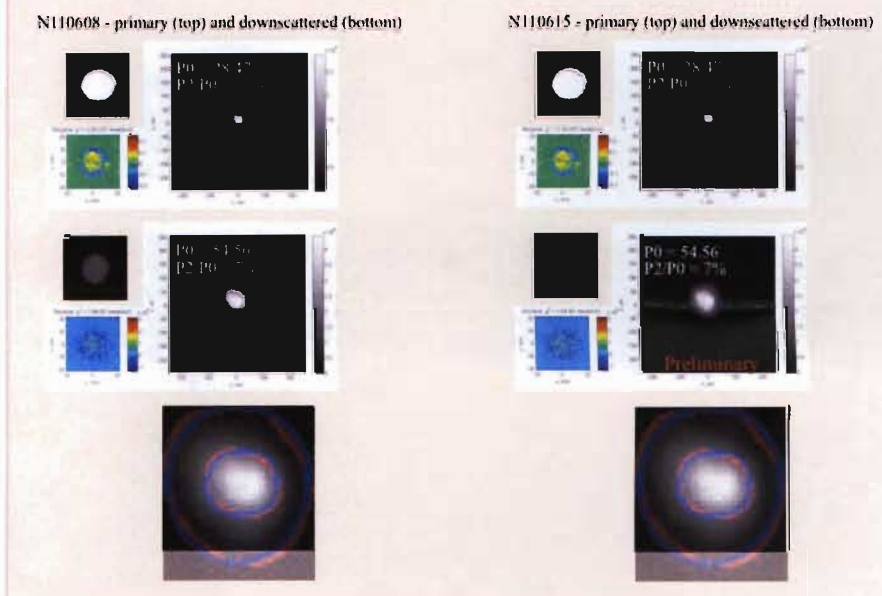


$$\sigma_p = \frac{a\left(\frac{L_1+L_2}{L_1}\right)}{\left(\frac{L_2-L_1}{L_1}\right)} \cong a\left(1+\frac{L_1}{L_2}\right)$$

Data reconstruction and results

The current yields from ICF implosions enabled us to observe the down scattered neutrons with the penumbral apertures. The pictures below show the steps in the reconstruction of the source intensity profiles from the raw images. The first step is to determine the pointing offset of the selected aperture with respect to the source position and produce appropriate point spread function. The pointing information was obtained by comparing the intensity variation in the pinhole array with the roll-off function of intensity through the pinhole for different source positions. The PSF function was also obtained by calculation of neutron transmission through the aperture by using MCNP simulations. Then the image is inverted with iterative maximum likelihood technique to obtain source intensity distribution.





We are in preparation to extract the number density distribution of scattering centers in the cold fuel, from which spatial distribution of the areal density of the cold fuel can be calculated. Understanding the areal density distribution of the cold fuel for each implosion experiment is important because the energy deposition of α particles that drive the ignition depends on it. High areal density will result with high energy deposition, which means a better chance of success to start ignition and burn the cold fuel with high efficiency. Currently, we are using a spatially averaged areal density to tune the ignition efforts. One of the important parameters for ignition is the ratio of the cold fuel shell radius to its thickness, which is referred as 'in-flight aspect ratio' (IFAR). With spatially averaged areal density, IFAR calculation will not account for the asymmetry of the cold fuel distribution. An asymmetry can cause non-uniform energy deposition from α particles and stop the propagation of burn throughout the cold fuel.

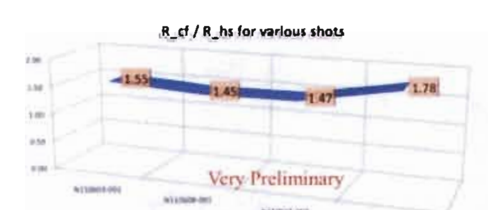
To calculate downscattered density distribution we define a new transport matrix, $\mathbf{M_{jk}}$ that directly relates the number density distribution of the cold fuel $\mathbf{n_j}$ to flux of downscattered image $\mathbf{\Psi_k}$ such that

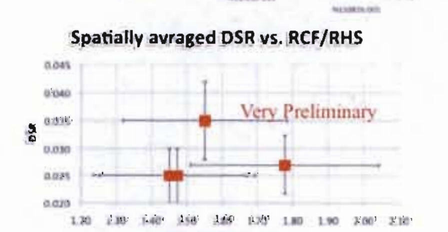
$$\Psi_k = \sum_j M_{jk} n_j$$

The new transport matrix is defined by

$$M_{jk} = A_{jk} \sum_i \frac{Q_i}{l_{ij}^2} S_{ijk}$$

where $\mathbf{A_{jk}}$ is the aperture PSF, $\mathbf{Q_i}$ is the hot spot source distribution (reconstructed from primary neutron image), l_{ij} is the distance between primary neutron sources in the hot spot and the scattering centers in the cold fuel and $\mathbf{S_{ijk}}$ is the angular scattering distribution of the scattering centers in the cold fuel. At the moment, this calculation assumes a cylindrical symmetry in the hot spot and cold fuel distributions since we can only get two dimensional flux distribution of three dimensional source.





Calculated from penumbra signals by taking the ratio of average intensities. Currently our spatially calculated DSR values are ~20% different than other diagnostics calculate.

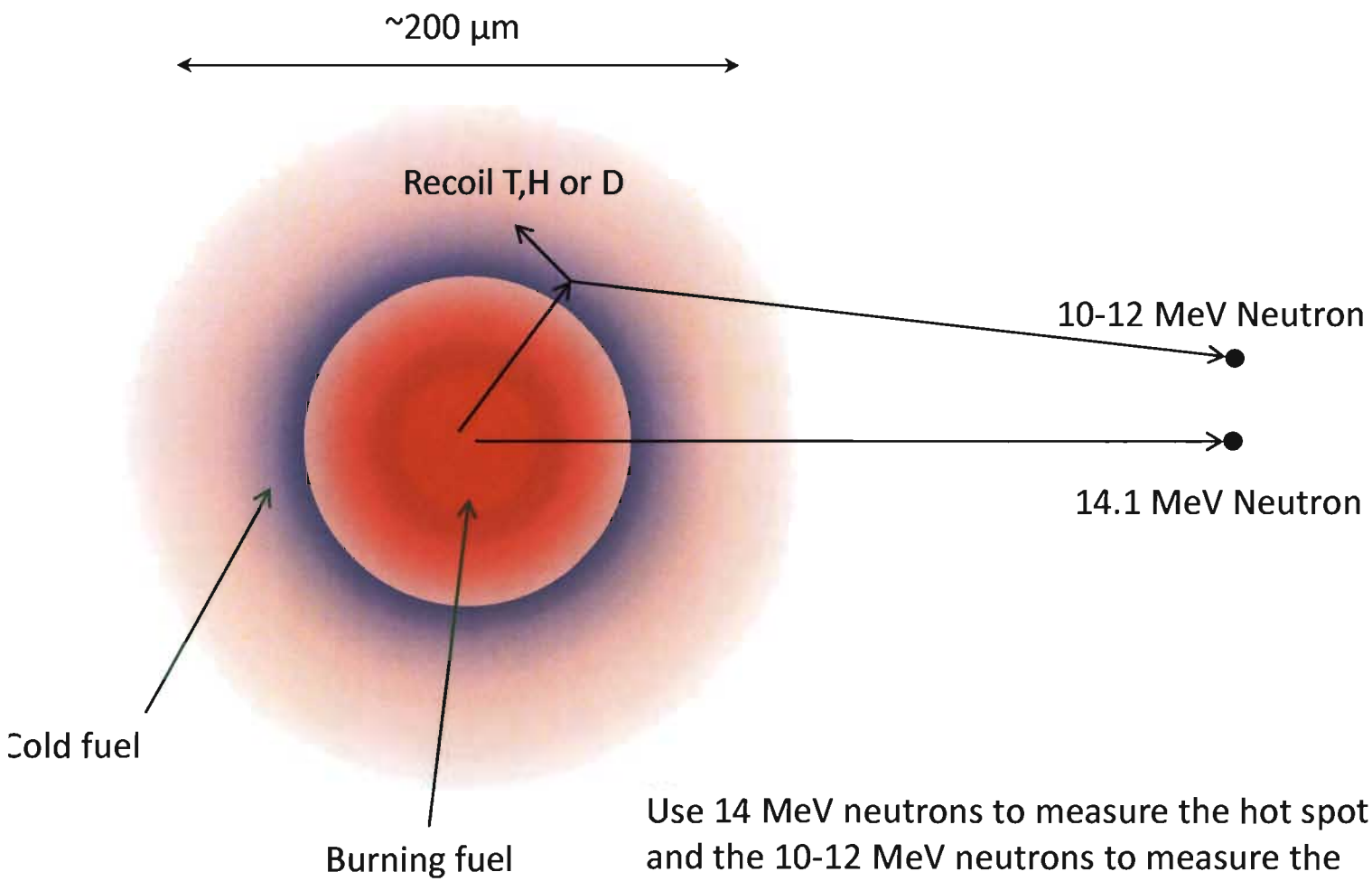
Acknowledgements

This work was performed for the U.S. Department of Energy, National Nuclear Security Administration and by the National Ignition Campaign partners; Lawrence Livermore National Laboratory (LLNL), University of Rochester - Laboratory for Laser Energetics (LLE), General Atomics (GA), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL). Other contributors include Lawrence Berkeley National Laboratory (LBNL), Massachusetts Institute of Technology (MIT), Atomic Weapons Establishment (AWE), England, and Commissariat à l'Énergie Atomique (CEA), France. Prepared by LLNL under Contract DE-AC52-07NA27344

Neutron images are collected at NIF to measure the hot spot size and the cold fuel distribution

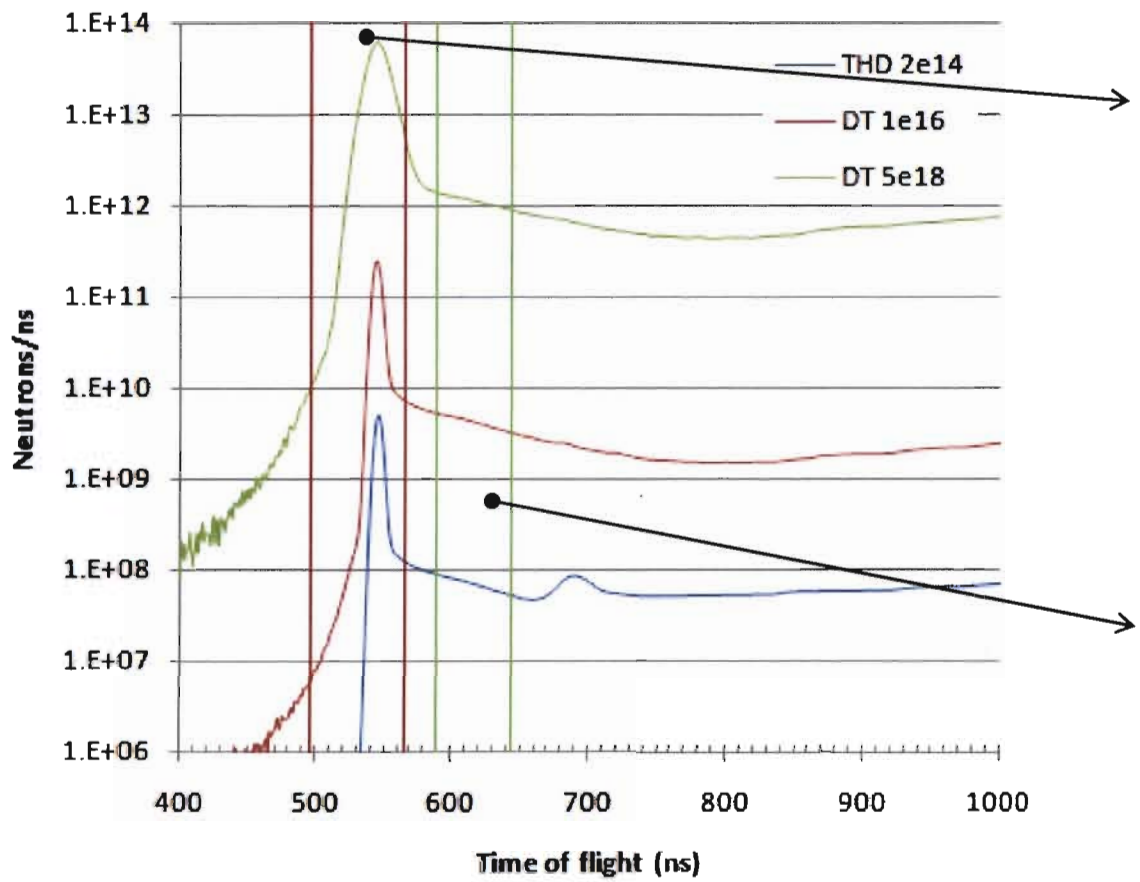
Controlling the fuel compression is crucial for accomplishing ignition in inertial confinement fusion (ICF) experiments. The neutron imaging diagnostics provide the size and shape of the hot spot from primary neutrons and that of the cold fuel distribution from down scattered neutrons by using two fast gated camera systems. The gates on the camera systems can be adjusted to observe any fraction of the down scattered neutrons. The energy of the primary neutrons is 14.1 MeV while the selected down scattered neutrons come in 10-12 MeV range. This range was selected to minimize the background from interactions other than scattering and at the same time to maintain good statistics.

An array of 23 pinhole and mini-penumbral apertures were used to take a snapshot of the implosion and the images were inverted using iterative maximum likelihood techniques to reconstruct the source distribution. Then, the estimated distributions were fitted to Legendre modes to calculate the size and shape of the hot spot as well as the cold fuel. The reconstructed intensity profiles will be used to calculate time integrated density distribution of the cold fuel. In addition, the inferred down scattered ratio of the neutron yields from primary and scattered neutrons is related to the spatially averaged and time integrated cold fuel areal density. This poster is mainly focused on the down scattered neutrons. For more information on the neutron imaging system at NIF and its diagnostic capabilities, please see the talk by Gary Grim and poster by David Fittinghoff.

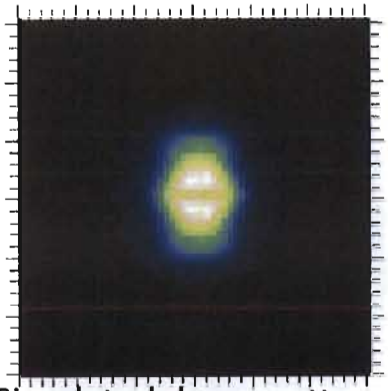


Use 14 MeV neutrons to measure the hot spot and the 10-12 MeV neutrons to measure the cold fuel distribution.

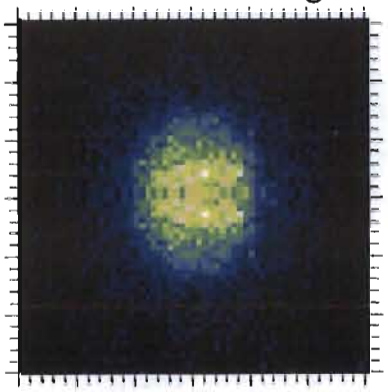
Neutron TOF Spectrum for 28 meter line of site



Simulated primary 13-17 MeV image

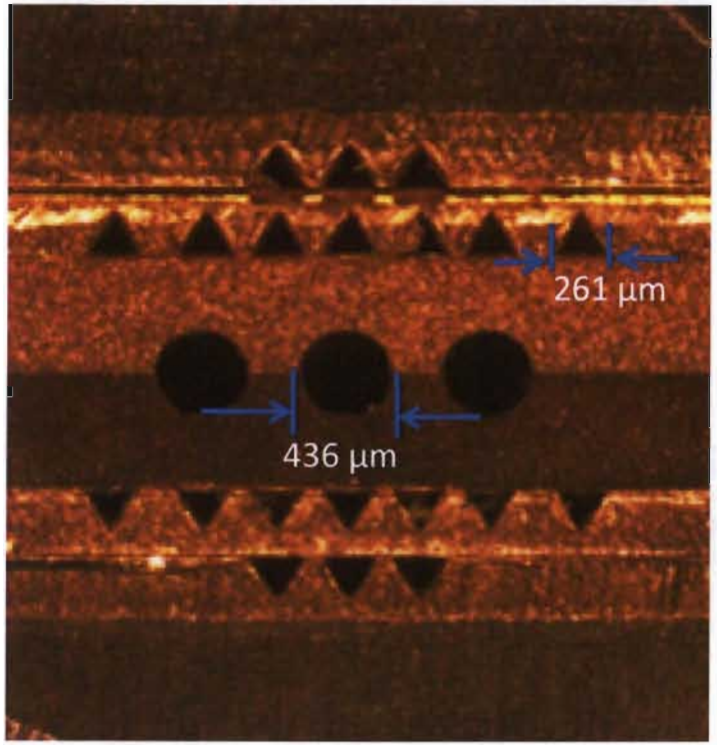


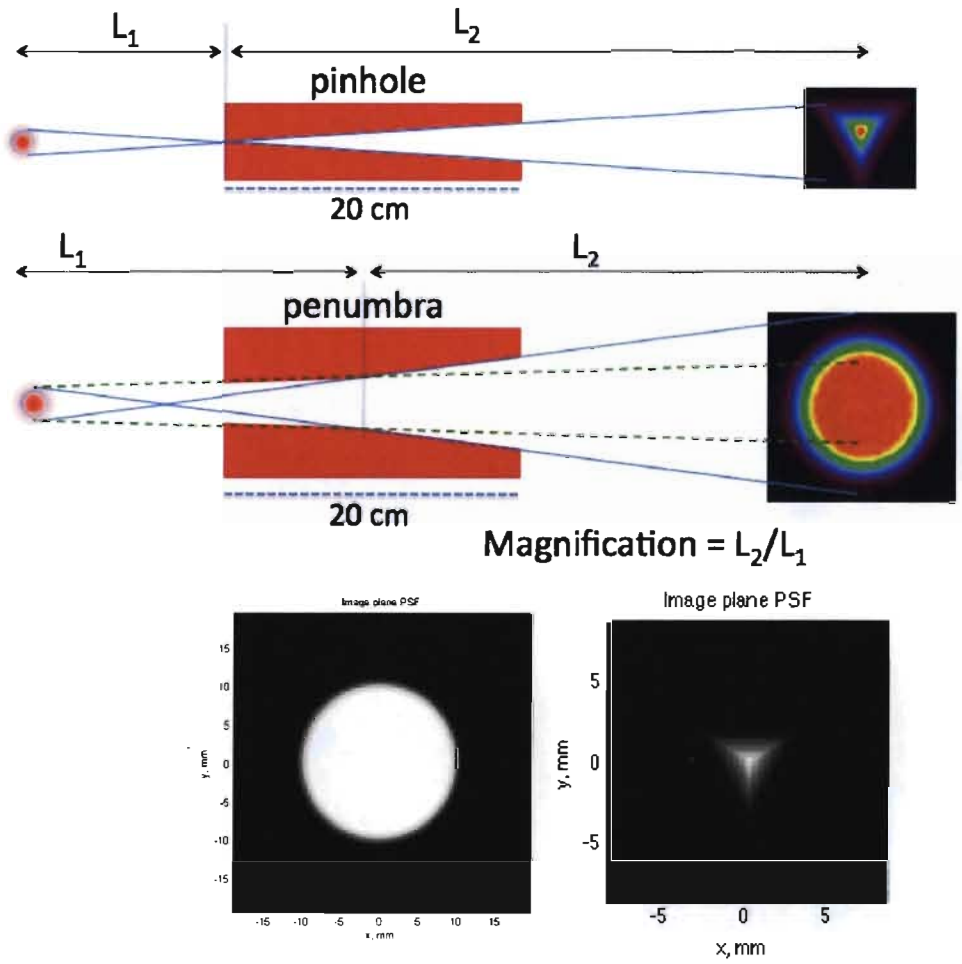
Simulated downscattered 10-12 MeV image



Need a time gated image system

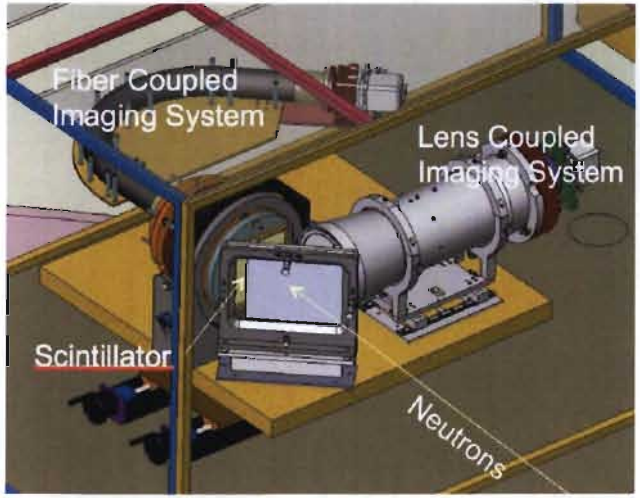
Neutron images are used to diagnose NIF implosions. Temporal separation of neutrons after 28 m drift results in ability to collect two neutron images: Primary (13-17 MeV) & Down Scattered (10-12 MeV)

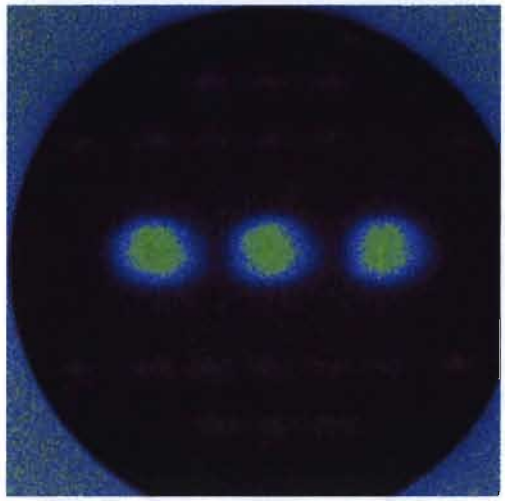




Imaging

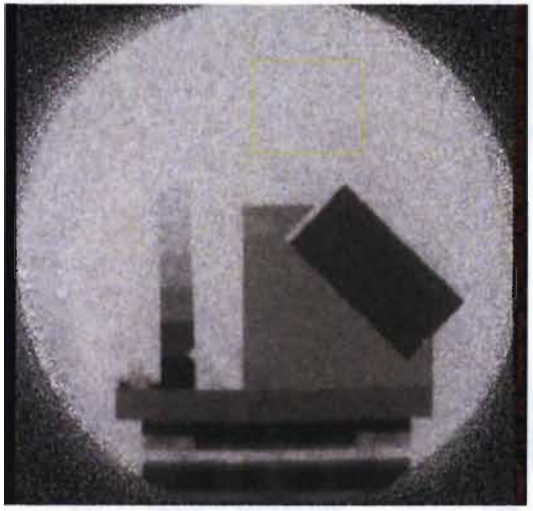
The imager is composed of 20 pinholes and 3 mini-penumbra, machined in 20 cm of layered gold and tungsten, with an apex at 32.5 cm from the source, to produce images in a scintillator array at 2800 cm. This geometry provides a magnification factor of ~85 for the pinholes and ~65 for the penumbra at the scintillator location, which is a coherent array of scintillating fibers, viewed from the two ends by two fast-gated image collection systems.

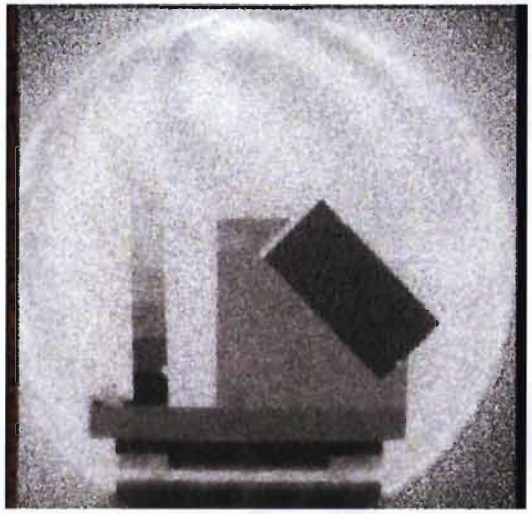


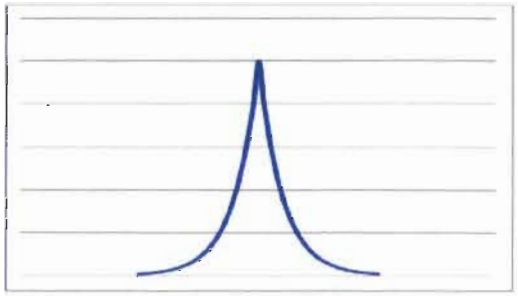


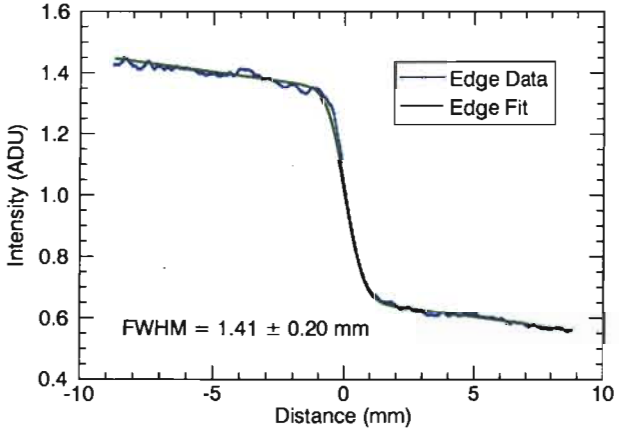
Gated Camera system

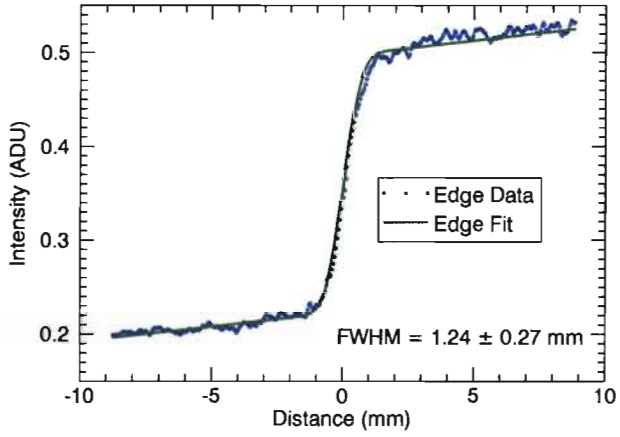
Flat field data were collected in calibration shots to study different pixels in the scintillator array. Before and after each shot, dark field data were collected to measure the background in the CCD camera outputs. The image is corrected for these backgrounds. Occasionally, nuclear interactions with some pixels show themselves as saturated signals. Those pixels are corrected by taking average of neighboring pixels. Downscattered image must be aligned to the primary image and intensity measurements for each pixel must be corrected for the residual light in the scintillator from primaries. Direct drive (~ 0 cold fuel ρR) implosion data provides this correction. Residual light background was found to be ~1%.











$$\sigma_T = \sqrt{\left(\frac{r}{m}\right)^2 + a^2} \approx 23\mu m$$

$$\sigma_p = \frac{a\left(\frac{L_1 + L_2}{L_1}\right)}{\left(\frac{L_2 - L_1}{L_1}\right)} \cong a\left(1 + \frac{L_1}{L_2}\right)$$

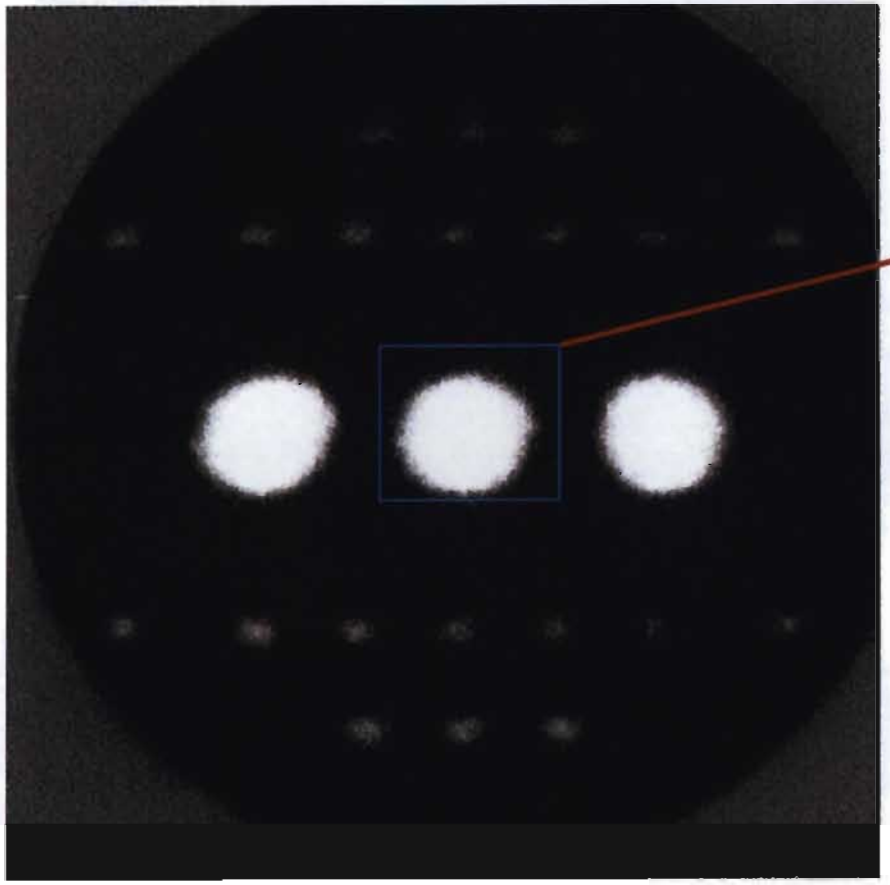
Detector contribution to resolution is set by the range of the recoil protons in the scintillator material. This was estimated to be around 14 (camera 1) and 12 (camera 2) µm.

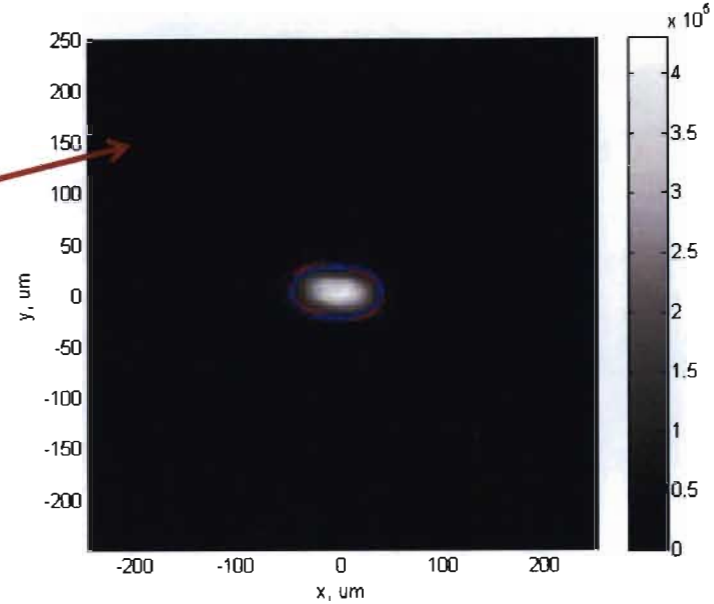
The contribution of the pinhole to the resolution was determined by the effective pinhole size, which is ~19 µm. The total system resolution can be approximated by:

Data reconstruction and results

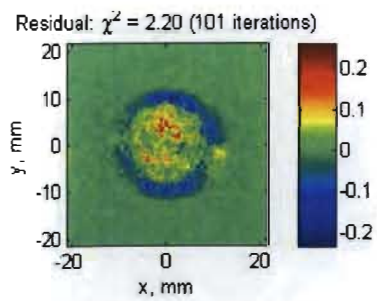
The current yields from ICF implosions enabled us to observe the down scattered neutrons with the penumbral apertures. The pictures below show the steps in the reconstruction of the source intensity profiles from the raw images. The first step is to determine the pointing offset of the selected aperture with respect to the source position and produce appropriate point spread function. The pointing information was obtained by comparing the intensity variation in the pinhole array with the roll-off function of intensity through the pinhole for different source positions. The PSF function was also obtained by calculation of neutron transmission through the aperture by using MCNP simulations. Then the image is inverted with iterative maximum likelihood technique to obtain source intensity distribution.

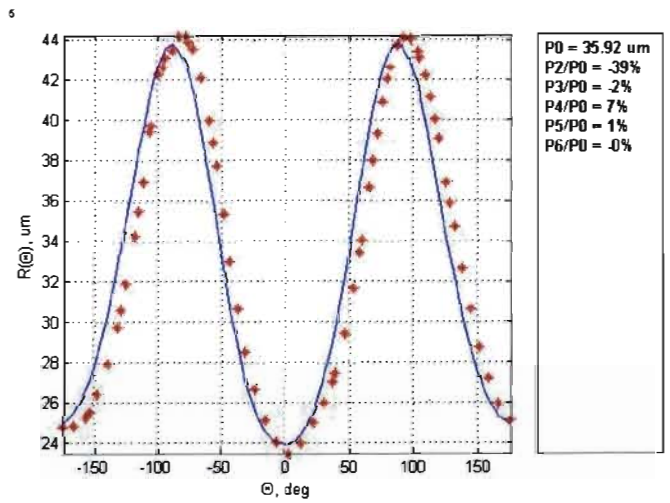
N110615-Primary Neutrons C1 13-17 MeV



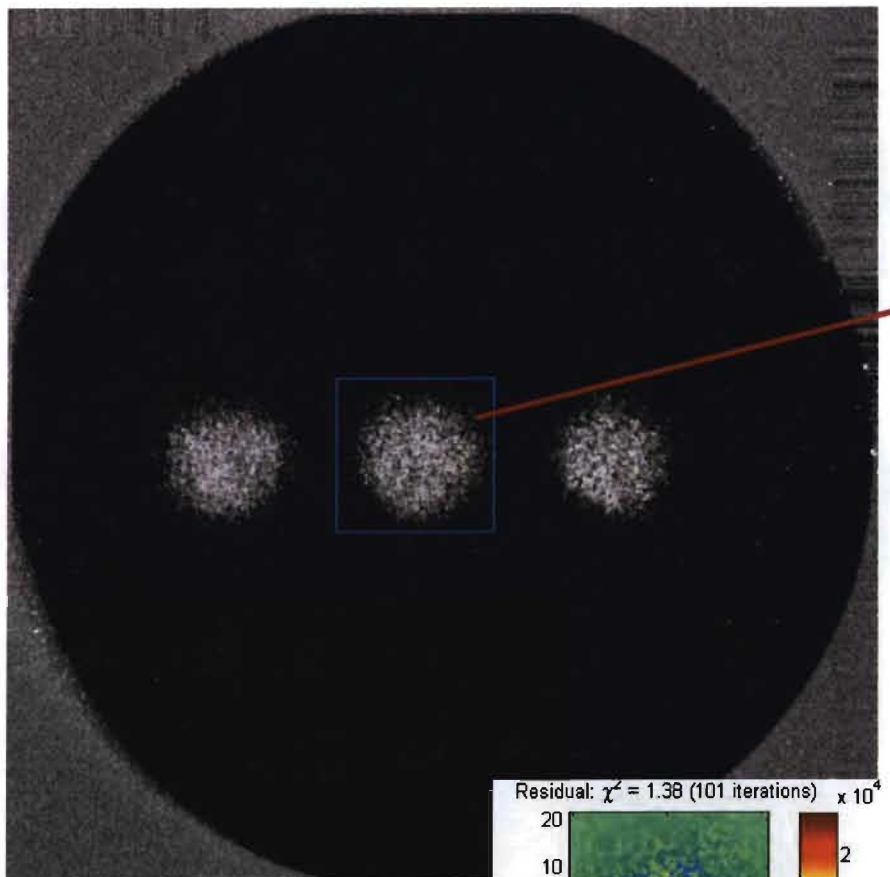


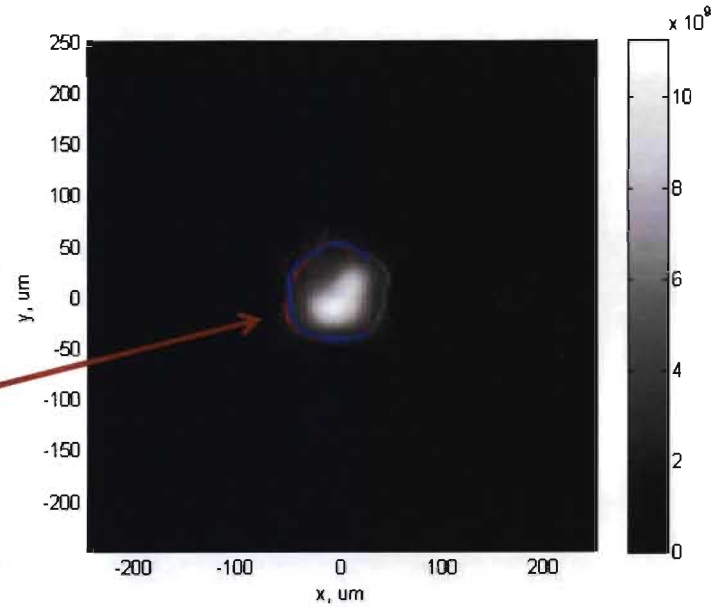
Background corrected

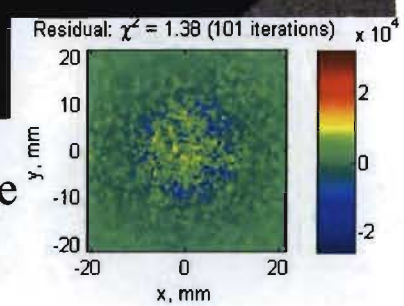


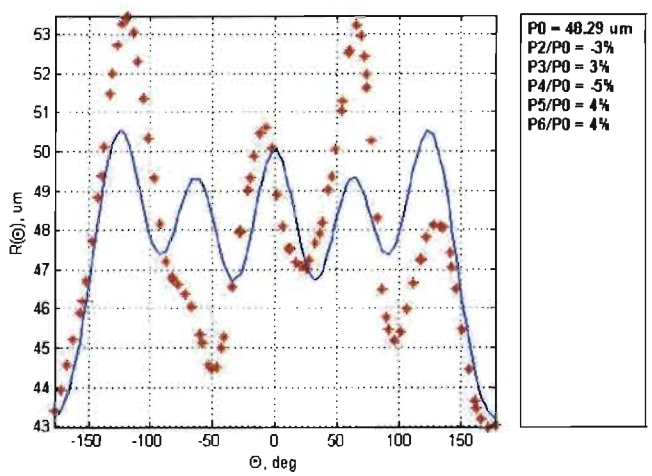


N110615-Downscattered Neutrons C2 10-12 MeV



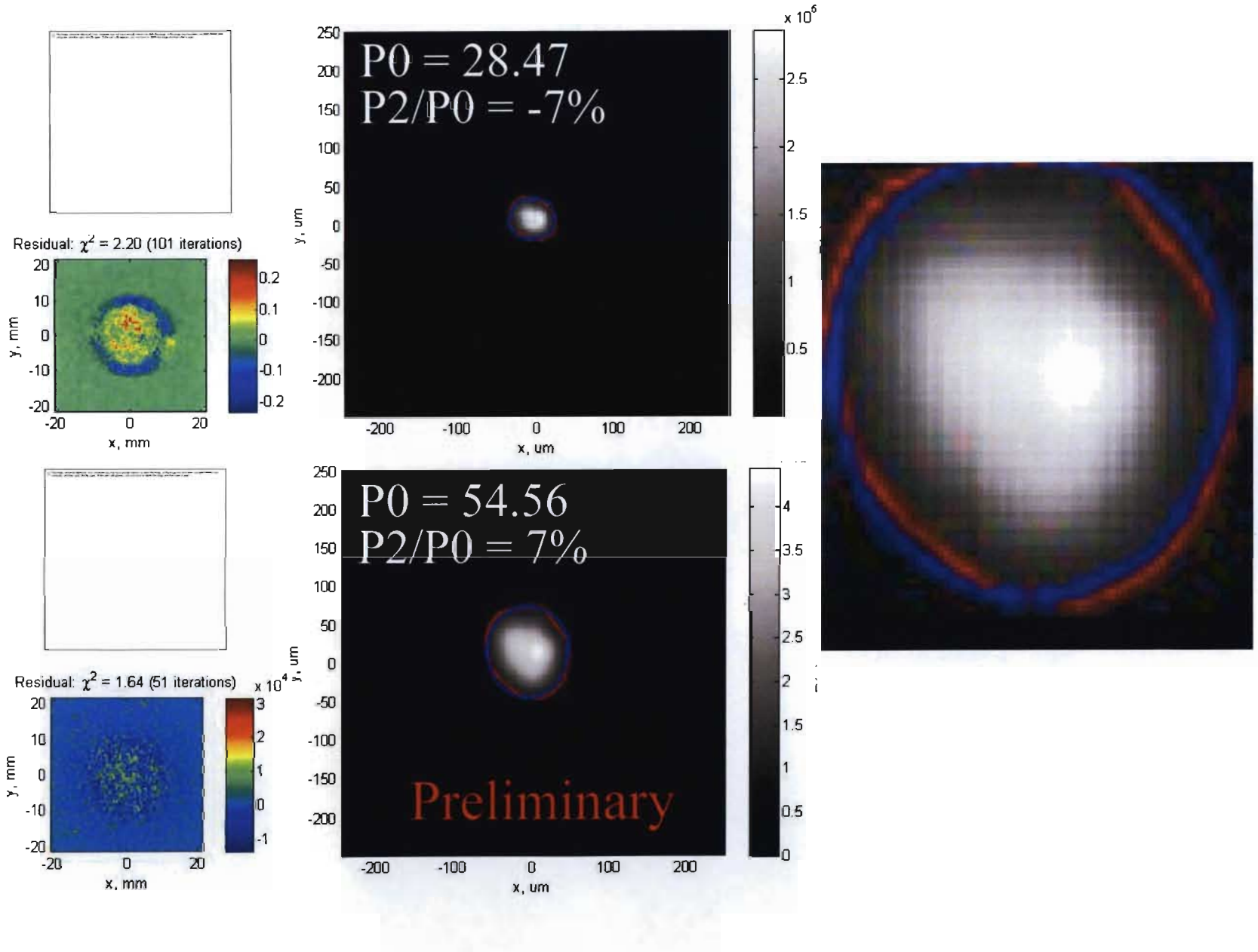




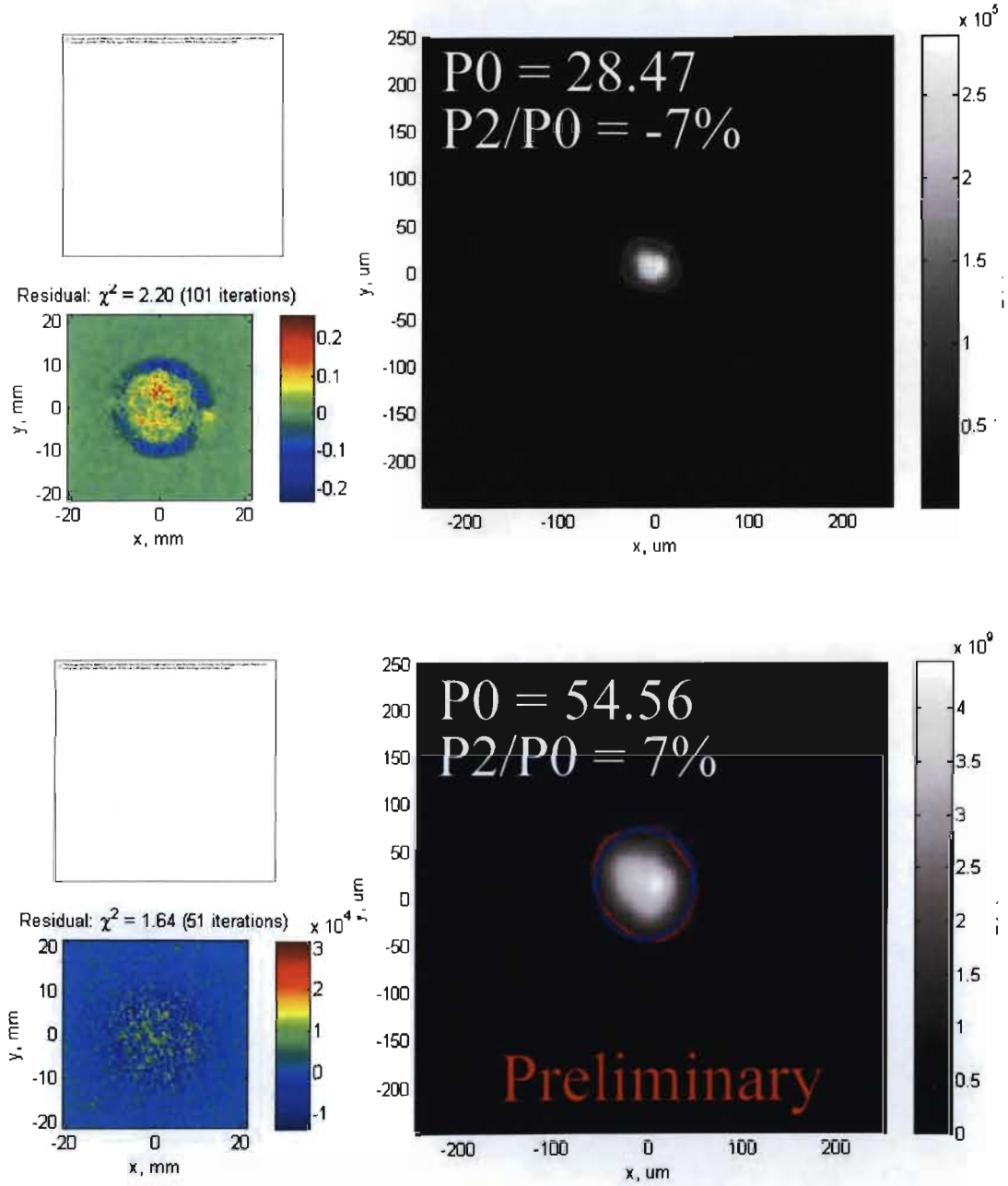


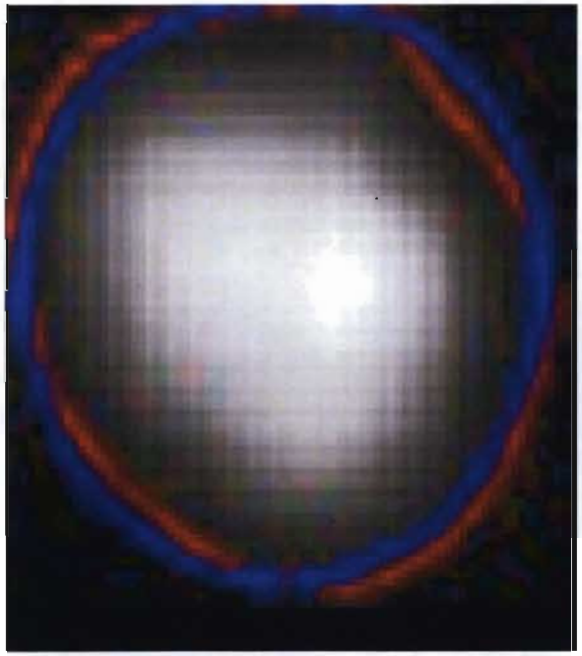
Background corrected
Aligned to primary image
Corrected for residual light

N110608 - primary (top) and downscattered (bottom)



N110615 - primary (top) and downscattered (bottom)





We are in preparation to extract the number density distribution of scattering centers in the cold fuel, from which spatial distribution of the areal density of the cold fuel can be calculated. Understanding the areal density distribution of the cold fuel for each implosion experiment is important because the energy deposition of α particles that drive the ignition depends on it. High areal density will result with high energy deposition, which means a better chance of success to start ignition and burn the cold fuel with high efficiency. Currently, we are using a spatially averaged areal density to tune the ignition efforts. One of the important parameters for ignition is the ratio of the cold fuel shell radius to its thickness, which is referred as 'in-flight aspect ratio' (IFAR). With spatially averaged areal density, IFAR calculation will not account for the asymmetry of the cold fuel distribution. An asymmetry can cause non-uniform energy deposition from α particles and stop the propagation of burn throughout the cold fuel.

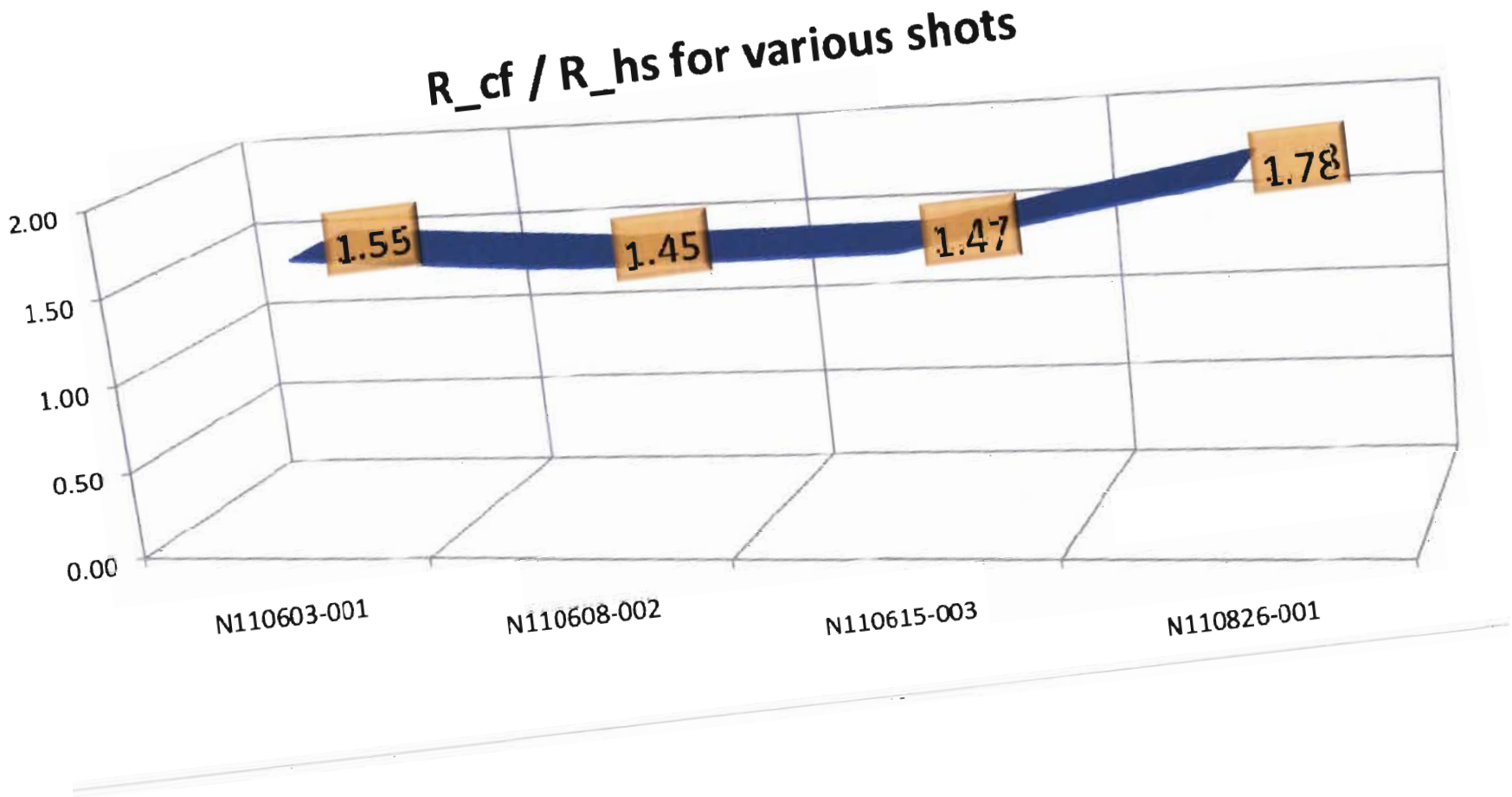
To calculate downscattered density distribution we define a new transport matrix, $\mathbf{M_{jk}}$ that directly relates the number density distribution of the cold fuel $\mathbf{n_j}$ to flux of downscattered image $\mathbf{\Psi_k}$ such that

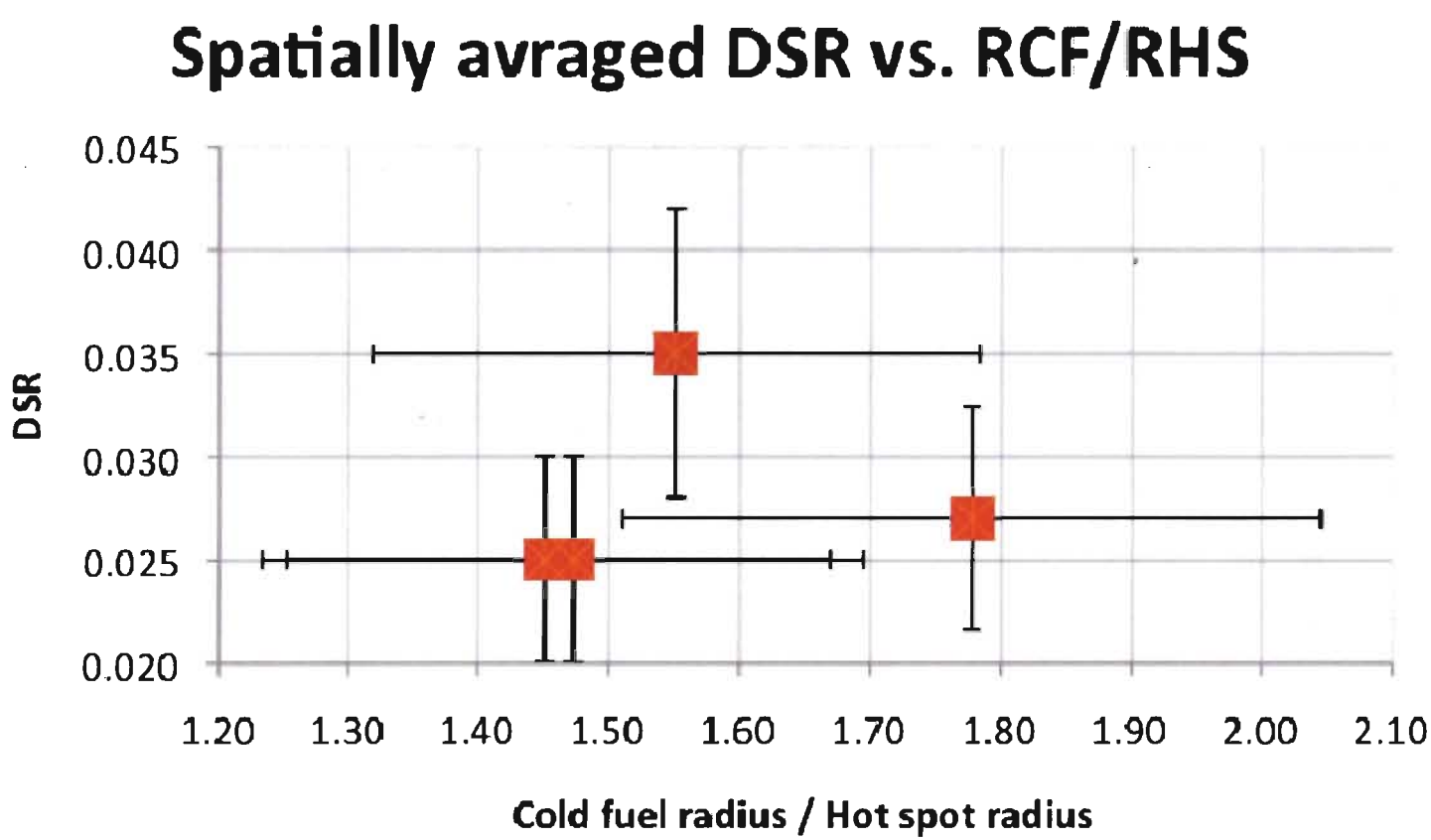
$$\Psi_k = \sum_j M_{jk} n_j$$

The new tra

$$M_{jk} = A_{jk} \sum_i \frac{Q_i}{l_{ij}^2} S_{ijk}$$

where $\mathbf{A_{jk}}$ is the aperture PSF, $\mathbf{Q_i}$ is the hot spot source distribution (reconstructed from primary neutron image), $\mathbf{l_{ij}}$ is the distance between primary neutron sources in the hot spot and the scattering centers in the cold fuel and $\mathbf{S_{ijk}}$ is the angular scattering distribution of the scattering centers in the cold fuel. At the moment, this calculation assumes a cylindrical symmetry in the hot spot and cold fuel distributions since we can only get two dimensional flux distribution of three dimensional source.


R_cf / R_hs for various shots
2.00
1.50
1.00
0.50
0.00
1.55
1.45
1.47
1.78
N110603-001
N110608-002
N110615-003
N110826-001



Calculated from penumbra signals by taking the ratio of average intensities. Currently our spatially calculated DSR values are ~20% different than other diagnostics calculate.

Acknowledgements

This work was performed for the U.S. Department of Energy, National Nuclear Security Administration and by the National Ignition Campaign partners; Lawrence Livermore National Laboratory (LLNL), University of Rochester -Laboratory for Laser Energetics (LLE), General Atomics (GA), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL). Other contributors include Lawrence Berkeley National Laboratory (LBNL), Massachusetts Institute of Technology (MIT), Atomic Weapons Establishment (AWE), England, and Commissariat à l'Énergie Atomique (CEA), France. Prepared by LLNL under Contract DE-AC52-07NA27344