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Development of a Slit Neutron Imager for Inertial Confinement Fusion Experiments at the Sandia Z machine.

D. N. Fittinghoff, M. J. May, C. L. Ruiz, P. J. Alberto, D. Ampleford, C. R. Ball, G. A. Chandler, J. Fisher, K. Hahn, C. Jennings, B. Jones, J. Torres, J. Vaugh, M. Gatu-Johnson, B. Lahmann

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D. N. Fittinghoff and M. J. May,
Lawrence Livermore National Laboratory,
P.O. Box 808, Livermore, CA 94551-0808

C. L. Ruiz, P. J. Alberto, D. Ampleford, C. R. Ball, G. A. Chandler, J. Fisher, K. Hahn, C. Jennings, B. Jones, J. Torres, and J. Vaughan
Sandia National Laboratories, Albuquerque, New Mexico, 87123, USA

M. Gatu-Johnson and B. Lahmann
Massachusetts Institute of Technology, Cambridge, Massachusetts 0213, USA

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Abstract
Understanding the neutron source shape is a critical for improving Magnetized Liner Inertial Fusion (MagLIF) implosions at the Sandia Z machine. Measuring the shape is challenging due to the yields, the extended axial source region, x-ray background and physical shock waves produced by MagLIF sources. In this work, we present the design and initial tests of a slit neutron imager for 1-dimensional neutron imaging along the axial dimension of MagLIF implosions.

Introduction

Magnetized Liner Inertial Fusion (MagLIF)[1-4] at the Sandia Z-Facility uses a magnetic field and laser heating to relax the pressure requirements of traditional inertial confinement fusion (ICF) schemes that use x-ray or direct laser radiation to drive surface ablation and compress fuel-filled capsules[5], and MagLIF experiments have already produced deuterium-deuterium (DD) fusion yields of greater than 10^{12} neutrons[4]. To understand the confinement and improve the yields, it is useful to measure the spatial distribution of the fusion along the axis of the experiment. While x-ray emission can provide significant information on plasma conditions, x-ray images are not an indicator of the actual fusion burn, and direct measurements of the neutrons produced along the axis are needed. Those measurements are, however, challenging. As shown in Figure 1, the source region can be elongated with a high aspect ratio. Moreover, full 2-dimensional imaging to include the radial variation would require ~10-µm resolution in the radial dimension combined with a ~1-cm field of view in the axial dimension. While the neutron imaging system (NIS) at the National Ignition Facility has shown 10-µm resolution in laser-driven ICF[6] with 10^{14} neutron, ~30-µm radius deuterium-tritium sources, the current MagLIF sources are much less bright with both lower yields and a larger emission regions, and the NIS system design is not sensitive enough for MagLIF. The NIS-type pinhole arrays required are also complex, fragile and too expensive for use in the environment at Z where large currents can produce 30-G ground shocks and significant shrapnel. Moreover, the lines of sight required to obtain the required magnification are typically 8 to 30 meters, which makes detector placement and pinhole alignment challenging in a machine that has limited long lines of sight available and that must be rebuilt between shots.

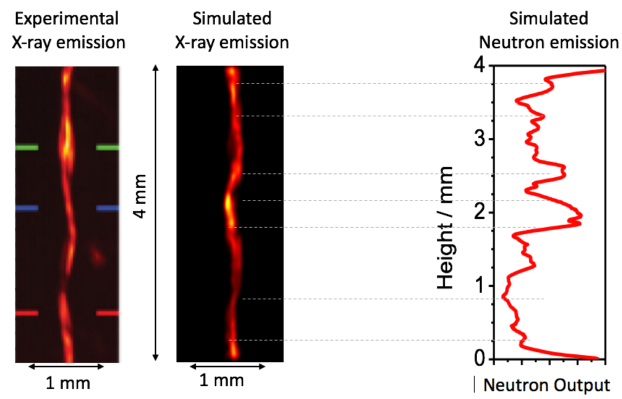

Figure 1 Experimental and simulated 6.28 x-ray images and DD neutron emission for a MagLIF shot, see [1]. The simulations are from the Gorgon code.

One solution to the problem of measuring the axial distribution of such high-aspect ratio sources is to abandon the high-resolution required for imaging in the radial dimension and to use a slit imager with lower resolution in the axial dimension. This allows significant improvements in the statistics of the measurement since the horizontal dimension of the image may be integrated and the vertical dimension requires fewer sampling points. A scintillator-based slit-imaging system was attempted previously[7], but fielding, environmental and alignment issues limited its success. In this work, we describe the development of the One-Dimensional Imager of Neutrons (ODIN), which uses a slit aperture, short line of sight and passive detectors such as CR-39

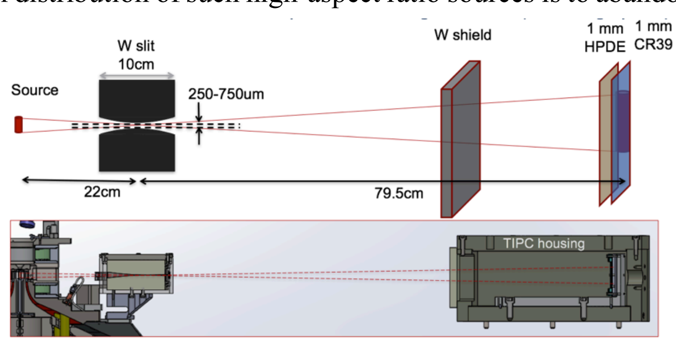

Figure 2 Schematic drawing of the ODIN slit imager. The slit assembly mounts directly to the source assembly inside the cylindrical blast shield (not shown). The detector assembly is a stack of passive detectors inside a tungsten shielding box.

[8] and image plates[9] and which can be simply installed inside the Z target chamber.

The main goal for ODIN is to create a 1-D image for a 2×10^{12} DD yield with 500-µm resolution over a 1-cm field of axial view. To make the alignment simple and compatible with the MagLIF shots in the Z chamber also requires that the slit aperture be attached directly to the source assembly inside the main blast shield with passive detectors such as CR-39 and image plates located in a separate tungsten-shielded housing (see Figure 2).

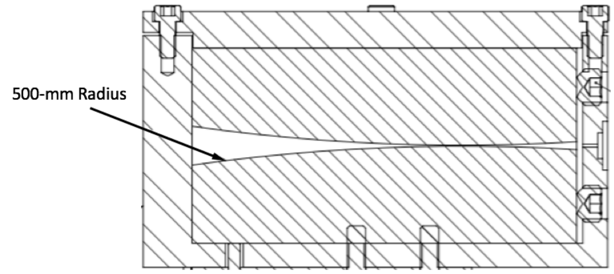

Figure 3 Cross-section of tungsten rolled-edge slit assembly used for ODIN. The slit is 10-cm thick in tungsten. The narrowest separation is variable but is typically set at 250 µm to allow a 500-µm overall system resolution.

To allow a large axial field of view, the slit is made of two tungsten rolled edges with radii of 500 mm as shown in Figure 3. The length of the slit is 100 mm with the apex 70-mm from the front face rather than centered in the length of the slit. This offset allows the slit to fit inside the blast shield and places the front of the slit at only 150 mm from source, which places the apex of the slit (narrowest separation of 250 µm) 220 mm from the source. A replaceable steel housing holds the slit and protects them from shock and debris. Allowing a 50% roll off in intensity across the image and considering neutron penetration of the tungsten, the slit has an effective separation of 365 µm for DD neutrons and provides a 9.8-mm field of view along the axis of the source.

Developing passive neutron detectors to work with this slit is an ongoing part of the experiments. We are testing CR-39 plastic [8] and image plate based detectors [9], which have been used as neutron detectors, with a variety of converter materials such as high-density polyethylene and beryllium. For plastic detectors and converters, the main contribution to the point spread function is the range of recoil protons in the plastic. This has been shown to allow imaging with 650-µm resolution for DT neutrons [9]. Using this resolution, achieving the desired 500-µm system resolution using the slit as described above requires a magnification of 3.61, which has required placing the detector pack at 1.015 m from the source, which is a short enough line of sight to keep entirely within the Z chamber.

For this application, it is important to optimize the ratio of sensitivity to neutrons to sensitivity to noise. The measured DD neutron sensitivity [8] of CR-39 is $(1.1 \pm 0.20) \times 10^{-4}$ tracks per neutron, modulo changes in the etching and counting. For image plates, we estimate that the sensitivity is $\sim 10^{-4}$ PSL/incident neutron with an approximate gain of 4 when an HDPE converter is used. Based on these numbers alone, the image plate with the HDPE converter should be more sensitive than the CR-39, but early tests indicate that the image plate sensitivity to the hard x-rays produced by the plasma produces a background significantly higher than the expected neutron signal. Unless the shielding for x-rays or neutron converter materials can be improved, the image-plate-based detectors appear less suitable as DD neutron detectors for Z than the CR-39. In

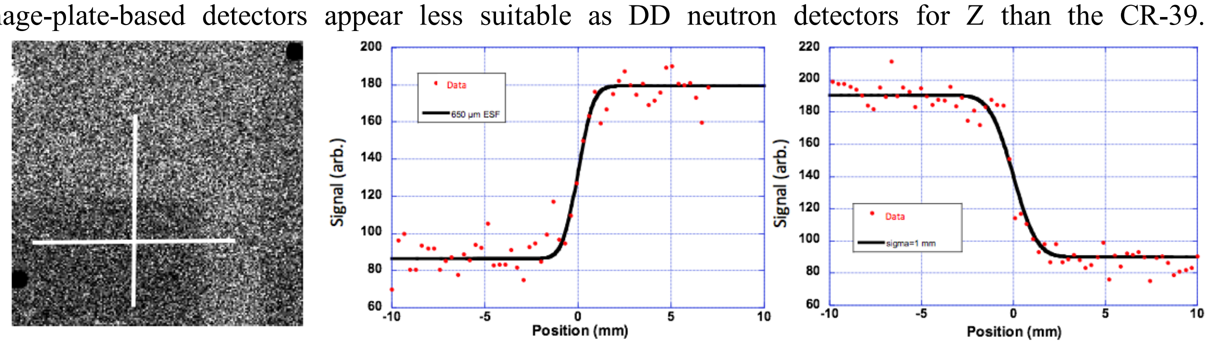

Figure 4 CR-39 image of a rolled edge for Z shot Z3018 horizontal and vertical lineouts across the rolled edges. The horizontal lineout is consistent with 650 µm edge-spread function. The vertical lineout is a long the axial dimension of the source and indicates that the source is extended in the vertical dimension.

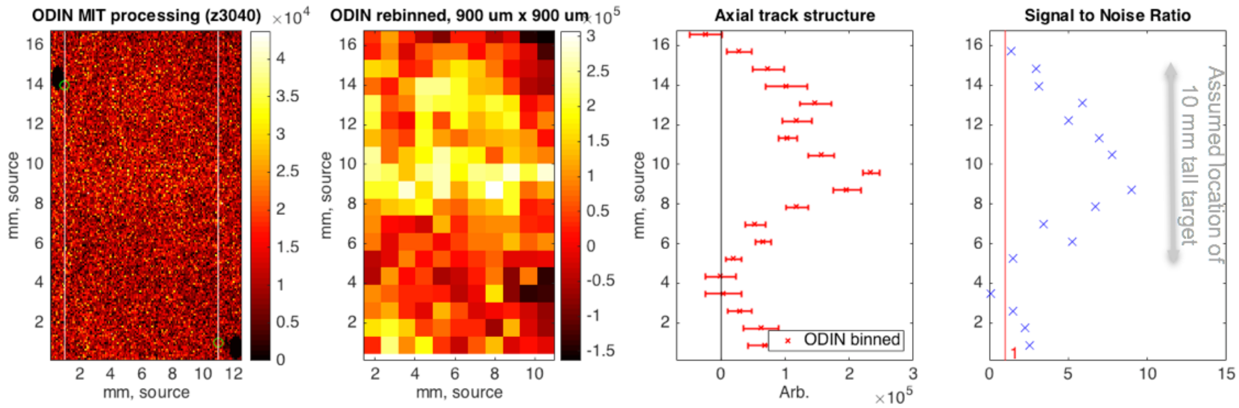

Figure 5 CR39 Images for Z3040. The left image is scanned at 100-µm per pixel. The next image is the 2D images rebinned at 900-µm per pixel along both axes. The next image is the axial lineouts (the mean and standard error) of binned data, and the right-hand plot is the signal to noise. The SNR >> 1 for ~8 mm height, which is most of the target height.

measurements of a tungsten rolled edge for CR-39, as shown in Figure 4, the lineout in the horizontal (radial) dimension is consistent with a 650 µm edge spread function as expected, and the signal levels are consistent with the expected neutron signals. The vertical (axial) line out, however, is consistent with an ~1-mm sigma edge spread function, which indicates that the source is extended in the axial dimension.

Imaging Tests

Imaging tests were performed for a number of Z shots with slit separations of 250 µm and 750 µm, respectively. Data from Z shot Z3040, which produced ~4 × 10^{12} DD neutrons, is shown in Figure 5 as an example. The initial scan of the image plate produced a track count per pixel for 100-µm square pixels at the source. The scan is displayed at the left of Figure 5 with the spatial dimension scaled to the source by a 3.61 magnification in both dimensions (although the magnification is strictly only applicable in the vertical dimension). At this resolution, the slit image is not visible, so the data was binned to 900-µm square pixels in the second image from the left. In this image, the slit image begins to become apparent. The plots to the right then then shows the mean and standard error of the binned dated (second from right) and the signal to noise ratio of the data (right).

Reality Checks

While the data shown above indicates that the system is imaging using CR-39, two reality checks were also available. First, since the slit does not image in the horizontal dimension, the image should be uniform when integrated across the imaging dimension. This has been observed in multiple cases, but we note that, as shown in Figure 6, clipping at the detector housing entrance can cause some loss of signal near the edges since the size of the entrance underfills the detector. Second, on a shot that does not produce neutrons, the noise background should be low and uniform. A failure of the ABZ magnetic field coils on Z3121 provided a test of this. As shown in Figure 7, the scanned data, rebinned data and axial lineout all show a low uniform background as expected.

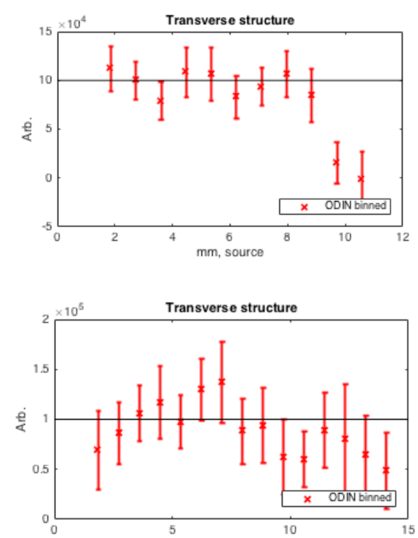

Figure 6 Transverse lineouts along the width of the slit for Z3040 (top) and Z3120 (bottom). These lineouts confirm are generally uniform to within the noise as expected. The drop off on right for 3040 may be a symptom of clipping on the entrance to the detector housing.

Comparison to X-ray Images

Another important test is a direct comparison to x-ray images. As shown in Figure 8, a direct comparison can be made between Axial DD neutron images and 6-keV x-ray images from the spherical crystal imager, which have been smoothed to the ODIN resolution. For shots Z3040 and Z3120, the figure shows the x-ray images on the left. Blurring the x-ray image by the resolution of the neutron imager and integrating across the axial dimension gives then gives the blue curves plotted on the right. The binned neutron data from ODIN is then plotted over the one-dimension x-ray images as the red points. The heights have been registered based on the data and cropped to regions with data, and the relative intensity scaling is arbitrary. While the comparison is not exact, as might be expected since the image information content is quite different for neutrons and x-rays, there is a strong correlation between the one-dimension neutron and x-ray images that suggests that the neutron imager is working as expected.

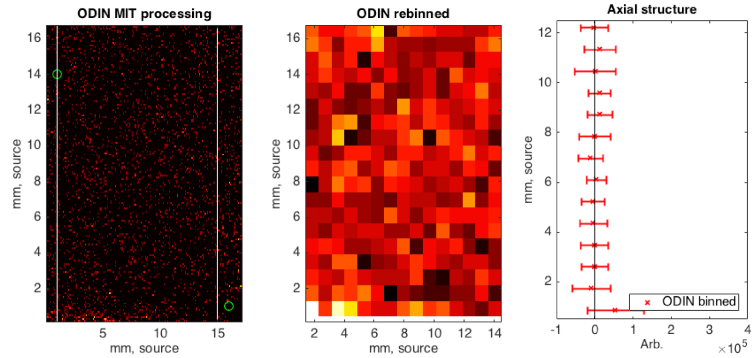

Figure 7 Imaging data for Z3121. The low shot yield of ~4e10 DD neutrons was dues to the failure of the ABZ magnetic field coils.

Future Work

While ODIN is producing neutron slit images at the Sandia Z machine using an HDPE converter and a CR-39 detector, improvements are needed to make the imager more useful. Improving the detective quantum efficiency by adding additional layers of CR-39 and by increasing the number of slits is possible and increase the SNR. Registering the neutrons to x-ray images taken on the same line of sigh would also help show the correlation (or potentially the lack of correlation) between the neutron and x-ray producing regions of the source.

Acknowledgment

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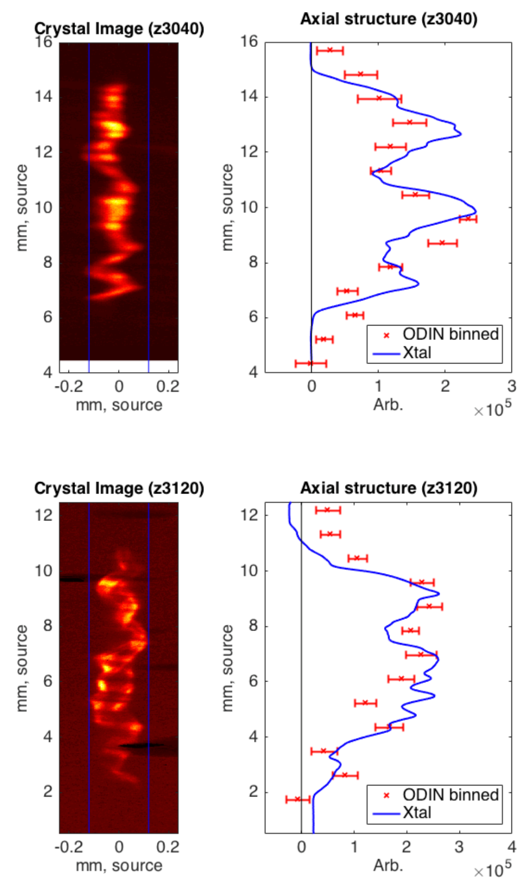

Figure 8 Axial DD neutron images for Z3040 and Z3120 (left column in red) compared to 6-keV x-ray images from the spherical crystal imager (right column), which have been smoothed to the ODIN resolution. The heights have been registered based on the data and cropped to regions with data, and the relative

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