

Demonstration of ignition-driven radiation transport through a THOR hohlraum

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The achievement of fusion ignition at the National Ignition Facility opens new opportunities for foundational studies in opacity, radiation transport, and high-flux astrophysics in regimes previously unattainable. We have succeeded in the critical enabling step of demonstrating ignition in a hohlraum modified with diagnostic windows that burn through prior to ignition, granting experimental access to the brightest radiation source in the laboratory. This Letter reports the results of a deuterium-tritium-layered capsule implosion that achieved 2.4 ± 0.09 MJ neutron yield in a hohlraum with windows designed to allow the escape of radiation energy from the capsule without significant loss of implosion symmetry, thus establishing a validated platform for next-generation radiation-driven experiments.

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In the indirect drive approach to inertial confinement fusion [1,2] on the National Ignition Facility (NIF), up to 2.2 MJ of laser energy is used to illuminate the inside of a high-Z cylindrical hohlraum to generate a uniform x-ray bath that drives the implosion of high-density carbon capsules filled with deuterium and tritium (DT). At high temperatures and densities, DT fusion produces alpha particles that are redeposited into the plasma, driving a thermal instability called ignition [3] that has demonstrated energy gain [4,5]. This process has also produced a method for generating extreme x-ray fluxes, exceeding $\gtrsim 30$ TW/sr, in the laboratory [6]. Nevertheless, despite the unprecedented radiation environment produced by burning fusion capsules, current hohlraum designs are inherently closed systems, optimized to confine energy, not release it. This constraint has both limited the ability to directly study

internal hohlraum conditions during ignition experiments and prevented any applications of these extreme x-ray fluxes. To address this, the THOR (Thinned-Hohlraum Optimization for Radflow) platform introduces engineered “windowed” hohlraums designed to burn through and allow access to post-bang-time x-ray emission while preserving sufficient implosion integrity. While diagnostic apertures have been utilized in previous hohlraum experiments, integrating windows that burn through into an ignition-scale hohlraum while preserving implosion performance has not previously been demonstrated. Since capsule performance is highly sensitive to implosion symmetry [7–13] and absorbed energy [1,14], such a modification risks fatally compromising implosion symmetry or energy coupling to the capsule, thereby precluding ignition. We report here a successful demonstration of a DT-layered implosion with THOR windows that achieved a target gain greater than unity while maintaining symmetry, thereby validating this concept and ushering in opportunities for probing astrophysical radiation transport, validating opacity models [15,16], and benchmarking high-energy-density (HED) simulations. Beyond demonstrating ignition compatibility, the THOR platform provides a controlled means of studying radiation transport from burning fusion

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TABLE I. Summary of experiments.

Shot ID	Laser energy (MJ)	THOR windows	THOR shields	Yield (MJ)
N240304	1.8	No	No	—
N230729	2.05	No	No	3.88
N250316	1.8	Yes	Yes	—
N250622	2.05	Yes	Yes	2.4 ± 0.09
N250713	1.8	No	Yes	—

plasmas, enabling quantitative measurements of emergent flux during and after ignition.

The experiments discussed in this work are summarized in Table I. Our layered DT implosion our layered DT implosion N250622 was a repeat of the HybridE implosion N230729 [17], modified to include THOR diagnostic windows on the hohlraum. N250622 achieved a 2.4 ± 0.09 MJ yield, compared to 3.88 MJ produced in N230729. In addition to achieving ignition, N250622 successfully demonstrated burn-through of the THOR windows prior to bang time, allowing radiation to escape with minimal attenuation. Because capsule performance is highly sensitive to factors such as capsule quality [18] and the geometry of the DT fill tube [19], accounting for these degradation sources is essential to understanding the full effects of THOR windows on capsule performance. Detailed postshot modeling of N250622 and N230729 using the XRAGE radiation-hydrodynamics code [20–23] with strategies described in Ref. [24] suggests that the presence of the THOR windows reduced the yield on N250622 by approximately 5% and by no more than 20%.

The THOR hohlraum assembly, shown in Fig. 1, incorporates two precision-engineered diagnostic windows positioned at polar and azimuthal angles (90° , 150°) and (90° , 330°) in NIF target chamber coordinates. Two opposing windows were used to minimize mode-1 asymmetries, which are particularly

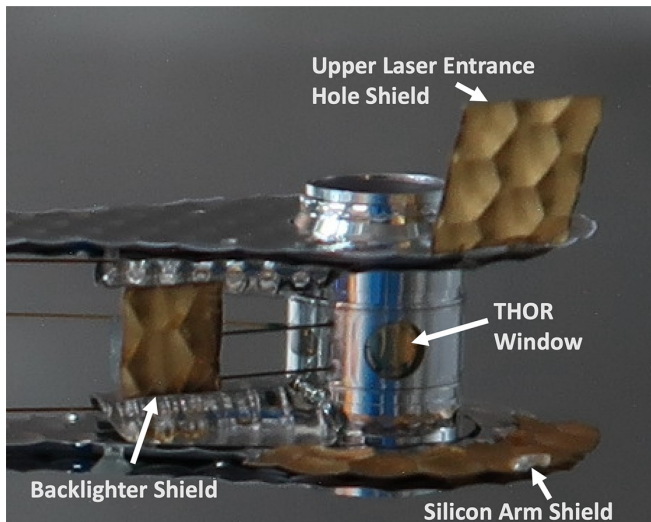


FIG. 1. 2DConA target assembly, showing the THOR window modification at the equator and the additional shielding used to block x-ray emission from the upper laser entrance hole, silicon arm shield, and backlighter.

detrimental to capsule performance [25]. Importantly, opposing windows will enable A/B radflow experiments, allowing the experimental designs to control for variations in capsule yield. Each window consists of a thin circular aperture—2 mm in diameter composed of 2.5–3.6 μm of pure gold, on the interior face, tamped by 35 μm of EPON resin $\text{C}_{21}\text{H}_{28}\text{NO}_4$, with a density of 1.185 g/cm^3 . These windows were designed to sit flush with the inner hohlraum wall, matching its curvature.

The choice of pure gold for the window surface was intentional: pure gold closely mimics the radiative behavior of the standard gold-depleted uranium (DU)-gold hohlraum wall [26], allowing the capsule to be driven by a similar x-ray bath. While DU is standard in high-performance ignition hohlraums [27], it was excluded here due to fabrication complexity and oxidation concerns. Preshot simulations indicated that at window thicknesses below 3 μm , the presence of DU offered negligible benefit relative to pure gold. Gold's high opacity and x-ray reemission capability made it sufficient to generate the necessary radiation field, maintaining symmetry in the drive. With the window material configuration finalized, we estimated the radiation transmission through the THOR window to determine the optimal gold thickness. These calculations were critical for evaluating how much of the internal hohlraum radiation would escape through the window and whether this energy loss would perturb the symmetry or drive conditions of the capsule. By modeling the window's optical properties, we could assess whether the chosen geometry would maintain drive uniformity within acceptable tolerances for ignition performance. Using a simplified gray-opacity model [28,29], where material opacity is assumed to be frequency independent, the optical depth τ through a window of thickness L is

$$\tau(L) = \frac{L}{\lambda_{\text{Au}}(T_h)}, \quad (1)$$

where λ_{Au} is the Rosseland mean free path of gold at radiation temperature T_h (typically 300–350 eV) [1,30]. At $L = 2.5 \mu\text{m}$, and assuming the Au density is $\approx 1 \text{ g}/\text{cm}^3$, the resulting $\tau \sim 5$ allows measurable x-ray transmission. The transmitted radiation flux F_{trans} , attenuated by this optical depth, follows the planar Eddington approximation [31] with a Marshak boundary condition [32–34] as

$$F_{\text{trans}} = \frac{\frac{4}{3}F_{\text{inc}}}{\tau + \frac{2}{3}}. \quad (2)$$

This analytical result was used to benchmark the one-dimensional (1D) XRAGE simulations, providing quantitative estimates for the radiative flux that would escape through the windows after burnthrough. These benchmarks helped predict the expected diagnostic signal and informed the minimum gold thickness required to ensure sufficient x-ray transmission.

Having established the material configuration and thickness, we evaluated the effect of flux asymmetries introduced by the windows on the imploding capsule. Specifically, we performed a Legendre mode decomposition of the radiation drive to assess how localized changes in x-ray illumination could translate into low-mode shape distortions during the implosion. The dominant contribution was captured by the P_2 mode, which characterizes the oblate-prolate asymmetry. Its

relative amplitude is given by

$$\frac{\Delta P_2}{P_0} \approx \frac{2.5nAS_2}{4\pi r^2} \left(\frac{\Delta\alpha}{\alpha} \right) \left(\frac{F}{F+1} \right), \quad (3)$$

where $\Delta\alpha/\alpha$ represents the fractional change in albedo of the thinner gold window; F is the recirculation factor, which accounts for the x-ray coupling between the hohlraum walls and the window; and nAS_2 encapsulates factors related to the number of windows n , their area A , and a geometric smoothing factor S_2 , which describes the redistribution of flux across the hohlraum wall [35,36]. For two windows with $2.5 \mu\text{m}$ of gold, these calculations yielded a drive ΔP_2 of approximately -0.9% and a corresponding $\Delta M_2/M_0$ of less than 1.5% . While the drive ΔP_2 suggests a modest asymmetry in the x-ray drive, the corresponding core asymmetry is amplified by the implosion convergence ratio (≈ 33) and would, in isolation, be consistent with a modestly nonround implosion. However, because the reference target configuration was designed to reproduce a prolate implosion, this drive asymmetry was expected to partially offset the intrinsic core shape, resulting in a more spherical implosion. These analytical estimates were used to define the parameter space for XRAGE simulations, which confirmed that the resulting flux (ΔP_2) and mass ($\Delta M_2/M_0$) asymmetries had a negligible impact on capsule performance and would not inhibit ignition.

Backing the gold, the EPON layer serves as an outer tamper, suppressing the hydrodynamic motion that otherwise occurs when laser energy directly ablates a thin membrane. This effect has been observed in previous diagnostic windows where the window material rapidly detached from the hohlraum wall under laser illumination. The EPON layer—at $35 \mu\text{m}$ —was optimized to prevent such motion, while still allowing transmission of emergent radiation for external detection. Modeling showed that the total transmission through the window was minimally affected by this thickness and that the signal could still be used to resolve time-resolved x-ray flux from the burning capsule.

A key challenge in the window design was the presence of small gaps at the interface between the gold window and the hohlraum wall, which could not be precisely measured prior to the experiment. While these gaps were expected to be minimal, if they were too large, the plasma ablation front could fail to fill them during the duration of the pulse, allowing radiation to escape, significantly degrading energy confinement. The precise radius of curvature, as well as positional accuracy during assembly, were therefore critical to minimizing unintended asymmetries or energy losses. The 2-mm window diameter was chosen to strike a balance between preventing energy loss and allowing sufficient diagnostic access with margin for future expansion. The fact that ignition was achieved with this initial, aggressive design represents a major technical validation of the THOR concept.

A crucial precursor to this experiment was a lower-power walk-up shot, N250316, a convergent ablator experiment (i.e., 2DConA) [37] designed to probe the symmetry implications of the window geometry using backlit x-ray images of the implosion [38,39]. Neutron and x-ray images from that shot showed the expected small perturbation to implosion roundness and small reduction in implosion velocity relative to an identical reference shot without windows, N240304, as seen in Fig. 2. In fact, N250316 was slightly less prolate

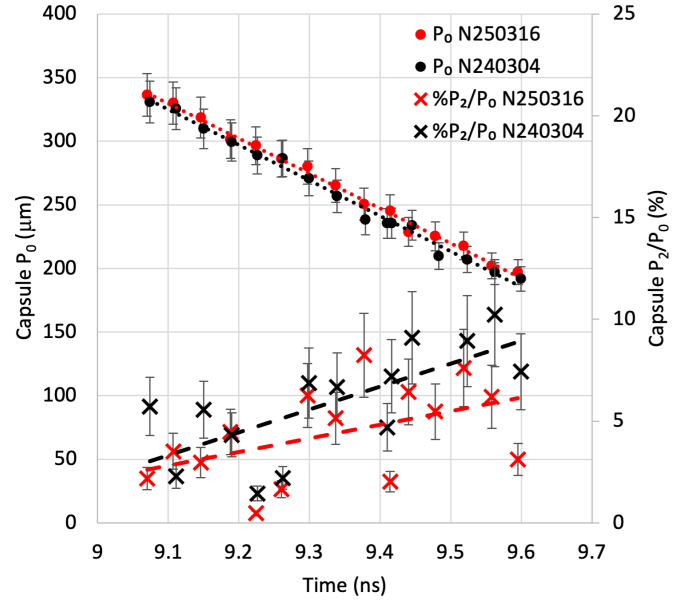


FIG. 2. Comparison of shell trajectories from 2DConA indicating no measurable deviation between the reference implosion N240304 and the THOR experiment N250316.

due to the presence of the THOR windows. The result gave confidence to proceed to a full DT-layered capsule.

The DANTE 2 [40] diagnostic, located near the $(64^\circ, 350^\circ)$ axis, is an absolutely calibrated time-resolved spectrometer used to measure the x-ray flux through the THOR window on the $(90^\circ, 330^\circ)$ line of sight. In order to avoid contamination of the signal from other sources around the hohlraum, physical shields were installed directly on the silicon arm, the backlighter structure, and the upper laser entrance hole (LEH), extending above the hohlraum axis to occlude background emission from LEH radiation and improve the signal-to-noise ratio. These are observable in the photograph in Fig. 1.

Implementing these shields required a significant hardware innovation. A new variant of the cryogenic shroud system, known internally as the Asgard shroud, was developed to accommodate the taller shielding geometry. The Asgard shroud modifies the traditional NIF cryogenic setup by expanding the clear volume between the upper LEH and the inner shroud vessel, allowing the placement of extended shields without interfering with alignment or thermal conditioning. This adaptation was imperative: without increased shield height and coverage, it was predicted that there would be excessive late-time signal contamination that would prevent accurate deconvolution of the window-emergent flux.

We assessed the DANTE 2 background signal (i.e., the x-ray flux from the LEH that can still be seen despite shielding) by comparing the signal from N250316 to an experiment with a shield but no THOR window, N250713. This comparison is shown in Fig. 3.

The temporal structure of the excess signal—appearing only after the predicted burnthrough time (≈ 8 ns) and absent in the shielded reference shot—supports the interpretation that the observed flux originates from radiation escaping through the THOR window, rather than residual LEH background or diagnostic line-of-sight contamination.

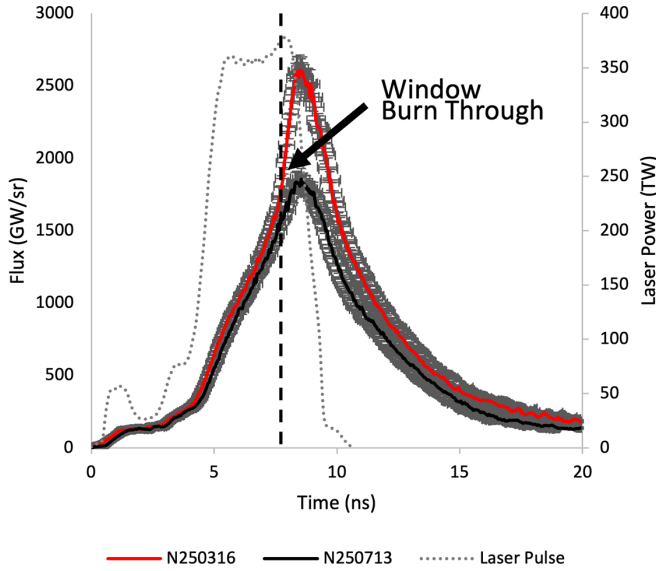


FIG. 3. DANTE 2 flux comparison for experiments with (red) and without (black) THOR windows. Both shots used identical additional shielding configurations. The increase in signal near ≈ 8 ns indicates the burnthrough of the THOR windows, allowing additional radiation to escape from the hohlraum.

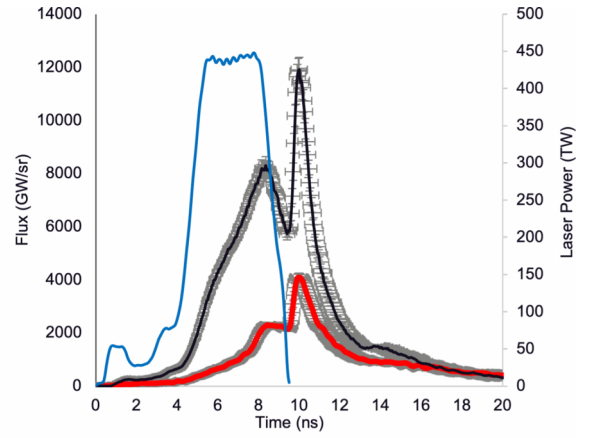
Figure 4 illustrates the procedure used to extract the radiation emerging through the THOR window. With the improved shielding in place, the temporal profile exhibits distinct features corresponding to burnthrough ($t \approx 7.5$ ns), peak drive ($t \approx 8$ ns), and post-bang-time emission ($t \approx 10$ ns).

Because the DANTE 1 signals through the lower LEH are nearly identical between the reference shot N230729 (no top LEH shielding) and N250622 (with shielding and THOR windows), the two shots are inferred to have comparable drive conditions. This enables a direct comparison of their DANTE 2 signals, shown in Fig. 4(a).

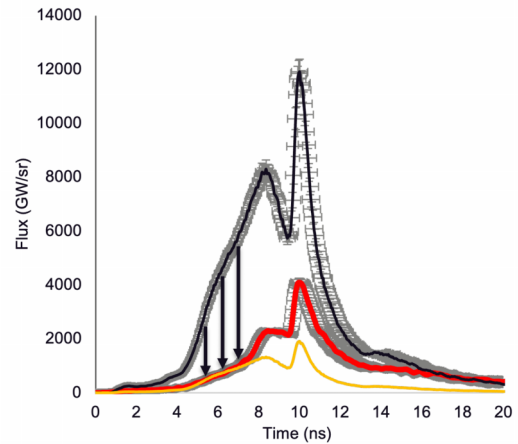
To isolate the window-emergent component, the N230729 DANTE 2 signal is scaled to match N250622 during the foot of the laser pulse [Fig. 4(b), gold curve], where no transmission through the THOR window is expected. This scaled signal provides an estimate of the residual background arising from incomplete shielding of the upper LEH.

Subtracting this background (gold curve) from the measured N250622 DANTE 2 signal (red curve) yields the true radiation emerging through the THOR window, shown as the green curve in Fig. 4(c).

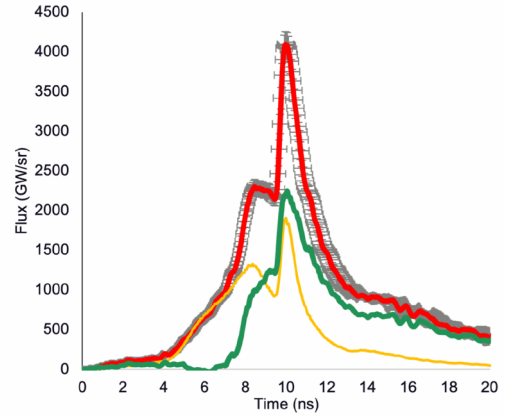
Two key features emerge in the signal. First, the leading edge at 7.5 ns marks the initial x-ray emergence from the hohlraum emission, coincident with the prediction that the window would burnthrough prior to bang time. Second, the peak at 10 ns captures the reemission [6] burst from the hohlraum wall illuminated by the burning capsule, a phenomenon that is at the very heart of the motivation for this work. The successful observation of both features—free from major LEH or background contamination—demonstrates that the shielding strategy and window design collectively enabled high-fidelity measurements of radiation transport from within the hohlraum. Importantly, the shielding introduced no



(a) Raw DANTE 2 signals



(b) Scaled reference



(c) Background-subtracted signal



FIG. 4. Extraction of THOR window-emergent radiation from DANTE 2 measurements. (a) Raw signals for N250622 and N230729. (b) Scaled reference constructed from matched rise behavior. (c) Background-subtracted DANTE 2 flux measurement to isolate THOR signal. The red curve is the measured N250622 flux, the yellow curve is the scaled N230729 reference, and the green curve is their difference.

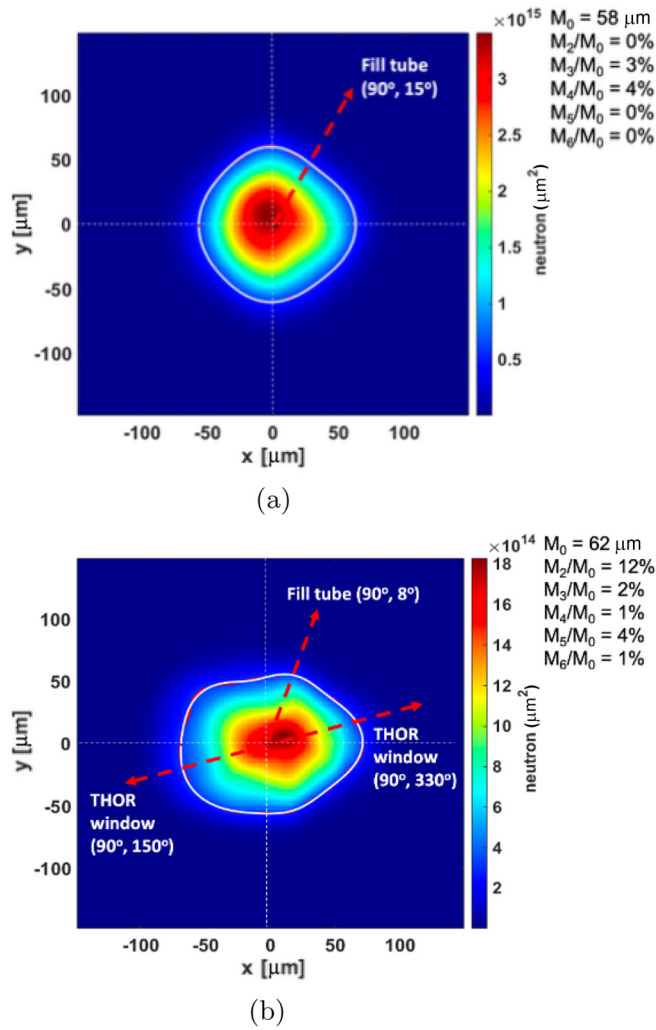


FIG. 5. Comparison of time-integrated neutron images from (a) polar neutron image for reference experiment N230729 and (b) polar neutron image from THOR experiment N250622. Dashed lines indicate the fill tube and THOR window orientations. The THOR shot exhibits a modest elongation aligned with the orientation of the windows while maintaining overall hot-spot symmetry comparable to the reference implosion.

measurable perturbation to implosion symmetry, nor did it interfere with cryogenic layering or drive balance. The success of this integrated design demonstrates that even under the constraints of ignition-scale NIF operations, target fielded diagnostics can be selectively shielded with high precision, provided sufficient platform flexibility—in this case, enabled by the Asgard shroud. The fidelity of these data enables detailed comparisons with radiation-hydrodynamic simulations and, more critically, establishes the viability of using ignition as a controlled source for radiation-driven experiments, such as opacity measurements, radiation transport studies, and high-flux astrophysical platform development.

To independently verify that these modifications did not compromise implosion performance, we turn to neutron imaging diagnostics. While DANTE provides a direct view of the emergent x-ray flux, neutron imaging provides a direct measure of implosion symmetry and hotspot geometry. Fig-

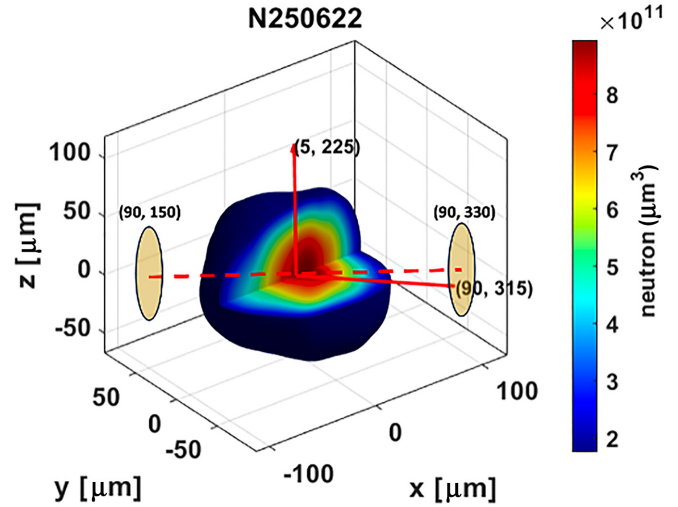


FIG. 6. 3D reconstruction of the neutron image for the THOR experiment N250622, with THOR window orientations overlaid for reference.

ure 5 shows polar neutron images from the reference shot N230729 [Fig. 5(a)] and the ignition-scale THOR shot N250622 [Fig. 5(b)]. Arrows in the THOR image indicate the orientations of the fill tube and THOR windows, depicting a slight elongation along the window axis, consistent with the predicted level of asymmetry.

Quantitative shape analysis reveals modest changes in low-order Legendre modes between the two implosions. The reference shot had a primary hot-spot radius of $M_0 = 58 \mu\text{m}$, with shape deviations of $M_2/M_0 = 0\%$, $M_3/M_0 = 3\%$, and $M_4/M_0 = 4\%$. In contrast, the THOR shot exhibited a slightly larger hot spot ($M_0 = 62 \mu\text{m}$), an M_2/M_0 distortion of 12%, and reduced higher-order modes of $M_3/M_0 = 2\%$, and $M_4/M_0 = 1\%$. Importantly, the M_2 deviation reflects mild elongation consistent with asymmetric x-ray drive, likely linked to partial radiation leakage through small gaps at the window-hohlraum interface.

Despite this, the overall symmetry held remarkably well. The 3D reconstruction in Fig. 6 provides a visualization of the neutron-emitting region. No major distortions or hot-spot breakup are observed. When compared with the reference implosion, which had a P_2 asymmetry of 9% prolate, the THOR shot achieved a P_2 of -1% , indicating a more spherical core. This suggests that while the windows may introduce M_2 asymmetry, they did not degrade the implosion enough to prevent ignition—and may have even contributed to correction of a preexisting prolate bias.

Taken together, these imaging results confirm that the THOR platform preserved implosion integrity. The windows, even at a relatively large 2 mm diameter, did not introduce shape distortions beyond the tolerances required for ignition-scale performance. The agreement in neutron shape analysis and 3D reconstruction to a well-characterized reference implosion provides compelling evidence that THOR windows can be integrated into hohlraum walls without fatally compromising capsule performance.

To quantify the radiative output through the THOR window, we time integrate the total x-ray flux $\phi(t)$ recorded by

DANTE 2 to obtain the energy per unit solid angle

$$\frac{E}{\Omega} = \int_0^t \phi(t) dt. \quad (4)$$

Assuming an accurate calibration of the diagnostic solid angle Ω , this yields a first-order estimate of the emergent radiation energy. Applying this methodology, we estimate that 60 kJ of x-rays escaped through the window, compared with a total of 400 kJ emitted by the igniting capsule. While DANTE 2 was originally configured for LEH-based measurements, this experiment confirmed its viability for THOR-based lines of sight, pending accurate geometric corrections.

The success of this experiment represents a turning point for postignition application science. THOR demonstrated a modified hohlraum design that delivered fusion ignition while offering clear radiation egress for experimental study. The shot successfully captured the temporal evolution of emergent flux, confirmed burnthrough timing, and isolated postignition radiation reemission—all without perturbing implosion symmetry or degrading yield substantially. Future experiments will focus on optimizing the window configuration to identify

the minimum thickness that maintains both ignition symmetry and yield while maximizing emergent radiation flux. These experiments will enable a range of radiation-driven studies, including precision opacity measurements under ignition-relevant conditions, validation of radiation transport models in high-energy-density plasmas, and laboratory studies of astrophysical radiation environments. These results demonstrate THOR's readiness as a next-generation ignition-applications platform for studying previously inaccessible regimes of high-energy-density physics.

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Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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