Capsule implosions for continuum x-ray backlighting of opacity samples at the National Ignition Facility

Y. P. Opachich,¹ R. F. Heeter,² M. A. Barrios,² E. M. Garcia,³ R. S. Craxton,³ J. A. King,¹ D. A. Liedahl,² P. W. McKenty,³ M. B. Schneider,² M. J. May,² R. Zhang,³ P. W. Ross,¹ J. L. Kline,⁴ A. S. Moore,² J. L. Weaver,⁵ K. A. Flippo,⁴ and T. S. Perry⁴

¹National Security Technologies, LLC, Livermore, California 94550, USA

²Lawrence Livermore National Laboratory, Livermore, California 94550, USA

³Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

⁴Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

⁵Naval Research Laboratory, Washington, D.C. 20375, USA

(Received 16 March 2017; accepted 9 May 2017; published online 8 June 2017)

Direct drive implosions of plastic capsules have been performed at the National Ignition Facility to provide a broad-spectrum (500–2000 eV) X-ray continuum source for X-ray transmission spectroscopy. The source was developed for the high-temperature plasma opacity experimental platform. Initial experiments using 2.0 mm diameter polyalpha-methyl styrene capsules with $\sim 20 \mu\text{m}$ thickness have been performed. X-ray yields of up to $\sim 1 \text{ kJ/sr}$ have been measured using the Dante multichannel diode array. The backlighter source size was measured to be $\sim 100 \mu\text{m}$ FWHM, with $\sim 350 \text{ ps}$ pulse duration during the peak emission stage. Results are used to simulate transmission spectra for a hypothetical iron opacity sample at 150 eV, enabling the derivation of photometrics requirements for future opacity experiments. *Published by AIP Publishing.*

<http://dx.doi.org/10.1063/1.4985076>

I. INTRODUCTION

X-ray backlighting is useful for many different types of experiments at the National Ignition Facility (NIF),¹ and much effort has gone into the development of a variety of backlighting techniques.^{2–6} Most of the effort has been focused on the development of monochromatic or nearly monochromatic X-ray sources. These monochromatic backlighters have been used to provide information on the hydrodynamic evolution of both inertial confinement fusion (ICF) targets and High Energy Density (HED) targets. By taking appropriate radiographs, the hydrodynamic behavior of the target can be analyzed. Material motion, areal densities, and locations of shock fronts are just some of the physical quantities that can be investigated.

X-ray opacity experiments require a broadband X-ray source for use with absorption spectroscopy to measure the electronic states of a material at a given density and temperature. The proposed NIF opacity experiments⁷ will use a hohlraum to heat an iron sample to temperatures of $\sim 150 \text{ eV}$ and a laser driven backlighter to produce a pulsed X-ray source, as depicted in Fig. 1(a). NIF experiments aim to measure the opacity to 10% precision at each point in the spectrum. In order to accurately measure the opacity via the X-ray transmission of a sample over a large spectral range, a well characterized broadband, continuum backlighter is required. In early laser driven X-ray opacity experiments, this was accomplished by directly illuminating a high-Z foil.^{8,9} This method produced a quasi-continuum backlighting source, because the numerous X-ray lines produced tended to merge together. There was still residual line structure that had to be removed in the data analysis. A more uniform, continuum backlighter can be obtained by using an imploding capsule.

Capsule implosions have been used for both Extended X-ray Absorption Fine Structure (EXAFS) and Opacity measurements on the OMEGA laser.^{10,11} In these experiments, a subset of the laser beams directly heat a spherical plastic or glass shell, using the ablation rocket effect to accelerate the interior of the shell to high velocity, resulting in bright X-ray output from the stagnated core. NIF has demonstrated the ability to implode similar capsules,^{10–12} but previous works were focused on fusion yields rather than X-ray yields. In this work, we report on the development and the emission characteristics of a bright, continuum point projection X-ray backlighter on NIF produced by an imploding plastic capsule. The resulting backlighter emission is then used to simulate hypothetical Fe opacity spectra and provide an estimate of the experimental X-ray transmission for the upcoming Fe opacity experiments.

II. EXPERIMENTAL CONFIGURATION

The performance of the broadband, short pulse capsule backlighter source was characterized at NIF. NIF is a 1.8 MJ, 500 TW ultraviolet laser system. Individual laser beams are focused toward the center of the experiment chamber and can be independently aimed and timed to provide any spatial and temporal overlap needed for experiments. The uniformity of the focal spot size and shape is conditioned with the use of continuous-contour phase plates; in our experiments, the beams were $\sim 1 \text{ mm}$ in diameter.¹² To generate the backlighter, we used 64 beams to deliver $\sim 80 \text{ TW}$ of power to the capsule, with the expectation that the majority of laser beams will deliver energy to heat the opacity sample in the final experimental arrangement. An asymmetric laser drive pattern, shown in Fig. 1(b), was applied to the top and

FIG. 1. (a) A schematic showing the experimental setup of a proposed opacity experiment. The plastic (CH) capsule is driven by a subset of NIF lasers, shown in (b), and used as a broadband backlighter. Photons are collimated before passing through the sample and toward the spectrometer. The sample is heated by a laser driven hohlraum. X-ray transmission data are recorded with a spectrometer that is located above the hohlraum along the axial line of sight. (b) Experimental setup of the backlighter development experiments. The NIF laser setup used 23.5° and 30.4° beams. The approximate viewing locations for all diagnostics are shown along with the NIF coordinates (θ, ϕ).

bottom (polar) regions of the target. The pattern is natural for the portion of the laser used to drive the backlighter in the opacity platform, and has two benefits. First, the polar drive creates a pancake-shaped core flash, which is optically thick. The greater surface area facing the poles results in enhanced emission toward the poles, along the line of sight to be used by future transmission opacity measurements. Second, compared to a symmetric implosion, the asymmetric core appears to generate a higher proportion of soft (sub keV) X-rays, which are desirable for opacity measurements, and relatively fewer multi-keV X-rays which might create background in the opacity spectrometer. This directional emission was verified experimentally and is discussed in the results section of this manuscript. Inner cone beams, shown in Fig. 1(b), were focused and arranged in a pattern that enhanced coupling to the target and improved backlighter performance. Figure 2 shows the calculated laser intensity distribution over the capsule. The pattern, although slightly non-uniform, provided the best beam overlap and improved backlighter performance. In the final experimental arrangement, a 2.5 ns square laser pulse was used to deliver an on-target energy of ~ 200 J. The target emission spectrum, time history, emission yield, and source size were characterized

with a variety of diagnostics. The diagnostic setup is shown in Fig. 1(b) and described in Secs. II A–II D.

A. Dante

The full spectral and temporal content of the backlighter emission was fully characterized using the Dante 1 and Dante 2 detectors, these have the 37° and 64° view of the target, respectively. The Dante^{13,14} diagnostic is a set of filtered X-ray diodes designed to collect spectrally and temporally resolved flux measurements. The diagnostic utilizes up to 18 channels that are individually set up for a specific set of spectral bands between 50 eV to 10 keV. Each channel has a set of calibrated filters, mirrors, and an X-ray diode providing absolute flux measurements. Scope trace voltages are recorded for each channel and are used to reconstruct the spectrum and temporally resolve the emission flux. Several analysis algorithms can be used to determine the spectrum from the data,¹⁵ the algorithm chosen for this work relied on matching the signal recorded in each band to a blackbody curve.

The Dante diagnostics provide the top and bottom view of the backlighter emission area. In this set of experiments, the Dante detectors were setup to accurately measure flux and spectra of imploding shells in the 200 eV–5 keV range, with a few channels that were used to characterize emission above 5 keV. Emission data collected in the various channels were used to infer the duration of the flash emission in the 500–2000 eV band, by deconvolving the diode temporal response (150 ps) from the collected signal traces.

B. Gated X-ray detector with soft X-ray imager

The shape and size of the emission source were characterized using a gated imager. The Gated X-ray Detector (GXD)^{16,17} is a microchannel plate (MCP) based diagnostic that uses several independently timed strips to provide two dimensional, spatially resolved, time snapshots of laser driven targets. At NIF, this diagnostic is primarily used to study implosion shape. In a typical setup, a set of pinholes is used to project images of the target onto the gated MCP strips. The MCP generates an electron cascade that is

FIG. 2. A plot of the laser power distribution over the capsule backlighter. 64 inner-cone beams (incident angles from 23.5 to 30.4 degrees off axis) were distributed to generate a reasonably uniform power profile without sacrificing energy on target.

projected onto a phosphor screen. The resulting set of images is recorded with a CCD camera or film. When used with the soft X-ray imager, the resulting diagnostic provides snapshots of spatially resolved images within a given X-ray energy band. Band selection is obtained with a set of mirrors and filters that are placed along the line of sight of the diagnostic. The soft X-ray imager mirrors are coated with Au and Cr and paired with V, Cr, and Al filters to provide three spectral bands in the 500, 700, and 1200 eV range, respectively. This diagnostic was placed both in the NIF polar and equatorial lines of sight to provide information on the source shape and core emission size during the backlighter emission.

C. NIF X-ray spectrometer with DISC

The NIF X-ray Spectrometer (NXS) coupled with the Diagnostic Insertion Manipulator (DIM) Imaging Streak Camera (DISC)¹⁸ were used to gather time resolved spectra of the backlighter emission. Essentially, the combination of the two instruments provides a streaked X-ray spectrometer. The NIF X-ray spectrometer (NXS) utilizes an elliptically curved crystal. Time resolved data are recorded with DISC, by spatially spreading the spectrum across the streak camera slit. The experiments described here used the KAP crystal NXS configuration, with an X-ray bandwidth of 1.7–3.7 keV. The spectrum was filtered with 75 μm of polyimide, 2.5 μm of aluminized polyethylene, and 25 μm of Polyphenylene Sulfide, $\text{C}_8\text{H}_7\text{S}$ (PPS). PPS was used to provide a Sulphur K-edge (2472 eV) as a wavelength calibration.

Streak cameras convert time varying intensity profiles, i.e., of X-ray sources, to spatial (position) information on an imaging detector. Within the DISC detector, a slit and photocathode are used to image and convert X-ray photons to electrons. The electrons are then extracted from the photocathode with a strong electric field, spread in time with the use of a set of voltage ramps and focused onto an imager with electrostatic lenses. The resulting image provides a temporal profile of the emission vs. position, or wavelength when used with the NXS. DISC has a low magnification lens (1.2 times) and provides varying spatial resolution between 80 and 100 μm . In the setup, the streak camera photocathode is located 1117 mm from Target Chamber Center (TCC). The camera was configured to collect data over a 10 ns time window, set to record the entire emission profile, with temporal resolution of ~ 160 ps. We used the temporal information collected with DISC to verify the duration of the flash emission. The measured flash duration is discussed and compared to the Dante results in Sec. IV.

D. Virgil spectrometer

The Virgil spectrometer used during this experiment was recently installed in a previously vacant line-of-sight within the lower Dante X-ray diagnostic routinely operated at NIF. Virgil shares the Dante 1 view in the NIF chamber. This new spectrometer uses a dual channel arrangement with a single (unique) convex-curved crystal in each channel to record temporally and spatially integrated spectra for photon energies from 1.5 to 6 keV on Fujifilm TR imaging plate.

It achieves moderate spectral resolution (i.e., $E/dE \sim 100\text{'s} - 1000\text{'s}$) with an initial design objective to assess M-band emission from Au hohlraums. A KAP (001) crystal is used to record the 1.5–3 keV range, and a quartz (10–10) crystal covers the 3–6 keV range. There is an additional overlap in photon energy between the channels to allow comparison of the two spectra. The primary light blocking filter for both channels is Be. This material completely covers the entrance apertures of each channel and has been overlaid with narrow strips of additional single-element foils along each outer edge to provide *in-situ* wavelength fiducials. Al and Mo foil strips are currently used in the lower energy channel and Ag and V foils are used for the higher energy channel. Preliminary throughput calibrations are known for each of the components such that absolute emission can be estimated, although further refinements are ongoing. The mechanical design facilitates straightforward alteration of the selected energy range (filters and crystals) and can accommodate future upgrades to time-resolving detectors or to alternate vacuum ports. The Virgil spectrometer was used to collect time integrated spectra in our experiment in order to provide an independent measurement of the backlighter emission, and to verify the measured Dante results.

III. BACKLIGHTER DESIGN

The backlighter design for opacity measurements had several requirements. Because the final result of the experiments is a set of transmission data, the backlighter needs to be devoid of X-ray line structure in the band from 500 to 2000 eV. A reproducible, slowly varying spectral shape is needed over the spectral range. A small source size of $\sim 150 \mu\text{m}$ FWHM is required to approximate a point projection backlighter. The X-ray flash duration needs to be less than 300 ± 100 ps FWHM with reproducible timing with respect to the laser drive in order to successfully probe the heated opacity sample over a stable temperature range. Subject to these constraints the design objective is to maximize X-ray output between 500 and 2000 eV to obtain transmission spectra with minimal noise from photon statistics.

In addition to the physics requirements, the design has to meet NIF operation requirements. Capsule sizes must be large enough to absorb sufficient laser light so as not to pose risks to opposed-beam optics including refraction around the capsule and the pulse shape energy low enough to avoid laser optics damage. Facility requirements limited choices for capsules to plastics which are pure CH, carbon or diamond, boron carbide or beryllium. CH was readily available as these capsules are used for the production of precision ICF targets and was thus selected for initial development. The capsules discussed in this work are made by General Atomics. These targets consisted only of the Poly alpha-methylstyrene (PAMS) sphere, which is the substrate for ICF implosion capsules and are made of pure CH.^{19–22} PAMS capsules are well characterized and are available in varied diameters and thicknesses. During the backlighter development work, we tested capsules that ranged from 16 to 32 μm in thickness. Results reported in this manuscript were

collected with best performing capsules that were $2\text{ mm} \pm 5\text{ }\mu\text{m}$ in diameter and $20\text{ }\mu\text{m} \pm 0.3\text{ }\mu\text{m}$ thick.

The flash emission yield, spectrum and duration, is dependent on the shell diameter, thickness, and choice of the material, laser beam selection (overlap and number of beams), focal spot size, pulse shape, and energy. That there exists an optimal value (or range) of shell parameters can be seen by considering the limiting cases. Shells that are very large, or very thick, will implode very slowly, delivering a low X-ray yield. Alternatively, shells which are too small cannot absorb much laser light, and shells which are too thin will burn through before imploding, also resulting in low X-ray yields.²³ It follows that for intermediate values of diameter and thickness, there should be a region of optimal performance. In our case, this is seen for the $20\text{ }\mu\text{m}$ thick shells.

1-D HYDRA simulations were performed to estimate the X-ray flash time and output for varied shell thicknesses and pulse durations. These simulations were very useful in identifying key characteristics of the X-ray emission expected from the implosions: a small but significant level of X-ray generation during the plasma run-in, a sizable X-ray flash with a soft (nonthermal) spectrum, reduced yield when the shell is too thick or too thin, and differences depending on pulse shape. These simulations provided a starting point for the initial capsule thickness and laser drive shapes and parameters in early experiments.

IV. CAPSULE PERFORMANCE RESULTS

The performance of the capsule backlighter is characterized by measuring the X-ray spectrum, the emission time history, the X-ray yield in the 500–2000 eV band, and the source size during the flash stage. The emission spectra of the broadband shell backlighter are collected with the Dante and Virgil diagnostics. Two similar shots are discussed in this section, and the details of these two shots are listed in Table I. The first shot (N150824-002-999) provided the best performance and will be presented as a demonstration of the total emitted X-ray yield and to provide the measured flash spectra. The second shot (N151014-001-999) produced invaluable spectral data due to the availability of Virgil, along with the emission time history available from the streaked X-ray spectrometer. This data provide verification of the measured Dante emission spectrum and the duration of the flash emission. Although four beams did not participate on the second shot, these measurements are needed for complete spectral characterization of the capsule backlighter. The varied locations of the detectors used in this study also provided information about the directionality of the emission. Dante 1 and Virgil had a 37° viewing angle of the implosion, Dante 2 was located closer to the equatorial

emission direction (64° viewing angle), the gated imager had the polar view, while the streaked X-ray spectrometer captured the emission time history along the equator. We expect the X-ray yield and source shape to vary directionally, and the time history to be independent of the viewing angle during the flash stage of the emission where the source size is smallest and emission time differences are much smaller than the temporal resolution of our instruments.

The differences in the position of the Dante detectors, i.e., the 37° and 64° viewing angles of the target, were used to study the directionality of the backlighter emission. On average, the Dante 2 recorded flux was measured to be $\sim 12.6\%$ lower, indicating that emission toward the poles was brighter. Both Dante detectors covered the 200 eV–5 keV range. The recorded flash and time integrated spectra are presented in Fig. 3. The flash spectrum was integrated over 350 ps, while the time integrated data covered the entire emission time of $\sim 4\text{ ns}$. A peak is seen at 700 eV, with a clean roll-off in intensity near 400 eV and 2000 eV. Carbon line features may be present below 500 eV with the Dante spectral fit showing structure at 277 eV; this is not an issue as it appears well outside of our required spectral region.

Virgil was setup to collect complementary spectral emission information. Dante 1 and Virgil shared the same view of the implosion and overlapped the measurement in the 1.5–4.5 keV range. Figure 4 shows both spectra. The time integrated Dante 1 spectrum is shown in black. Here, both the run in and flash emission contribute to the spectral shape. Virgil data collected with the KAP and quartz crystals are overlaid in the 1.5–4.5 keV energy range. Good agreement in the slope and shape of the spectra and the measured yield is seen between the two instruments. Both show exponential decay above 1500 eV. The matched slope implies that the spectral peak occurs below 1.5 keV, likely near 700 eV as seen in the Dante data. The Virgil spectra also show Si lines; we believe these to be a contribution from the glue that is used to attach the shell to the manipulator. We do not expect these lines to contaminate our spectrum as the emission is blocked geometrically by the collimator.

As predicted by HYDRA simulations, the observed CH backlighter X-ray emission time history generally consisted of two stages. During the first stage, X-ray emission is

TABLE I. Details of shots used for backlighter performance characterization.

Shot number	Beams used	Energy used (kJ)	Shell thickness (μm)	Laser pulse shape
N150824-002-999	64	196	20	2.5 ns square
N151014-001-999	60	180	20	2.3 ns square

FIG. 3. Time integrated Dante 1 spectrum, and peak emission spectrum collected on shot 150824-002-999.

FIG. 4. The time integrated Dante 1 emission spectrum is shown in black. This data include both run in and flash stage spectra. Virgil data cover emission in the 1.5–4.5 keV range.

generated by depositing laser energy, through inverse Bremsstrahlung, onto the shell poles. The capsule implosion is initiated through ablation of these outer shell walls. This run-in stage produces emission that scales with the laser energy. As the capsule implodes further, the emission transitions to the second stage where the shell is quickly driven toward the center. A rapid increase in temperature is seen as the remaining material stagnates against itself, generating bright bremsstrahlung emission in an X-ray flash.

The emission time history is recorded both with Dante and with the streaked X-ray spectrometer described in Sec. II. A maximum yield of ~ 1000 J/sr was achieved with our best performing target. The duration of the peak emission is determined by deconvolving the response function of both instruments from the recorded peak widths. In both cases, the width of the flash emission is measured to be ~ 350 ps. The flash occurred 500 ps after the main drive in both shots, at ~ 3 ns. Figure 5 presents the emission time history recorded by Dante 1, along with the simulated result. The uncorrected

FIG. 5. Emission time history. Shot data (N150824-002-999) is shown in black, and the HYDRA post shot simulation in red.

streaked X-ray spectrometer data are shown in Fig. 6. The flash time recorded with the streaked spectrometer occurs ~ 100 ps earlier, as would be expected for a 2.3 ns drive with reduced laser power. The measured duration of the flash in the second experiment was expected to be similar to what is generated with a 2.5 ns laser pulse due to the temporal resolution limitations of both measurements.

The source size during peak emission is measured with a Soft X-ray Imager snout and a Gated X-ray Detector. The measurements are done normal to the capsules emitting surface, i.e., at the future location of the opacity spectrometer, and provide an estimate of the needed collimation for the upcoming opacity campaign. Source sizes varied depending on the capsule thickness and laser pulse parameters. The $20\text{ }\mu\text{m}$ thick shells driven by a 2.5 ns square pulse showed the smallest size of $\sim 100\text{ }\mu\text{m}$ in diameter. An example of the 2-D gated image recorded at peak emission of the flash stage is shown in Fig. 7. Here, we see the central emission from the core, along with a low emission region extending out to several hundred microns. The core flash is saturating the detector and may be smaller than the measured $100\text{ }\mu\text{m}$. In future experiments, a collimator will be used to eliminate this low emission region and reduce the backlighter source size to $150\text{ }\mu\text{m}$.

V. SYNTHETIC TRANSMISSION ESTIMATE

The measured X-ray yield and spectrum can now be used, in conjunction with calculated opacities and expected measurement geometry, to estimate the transmission spectrum expected on an opacity measurement using this source as a backlighter. Previous work⁷ used the X-ray spectrum from a pre-shot one-dimensional HYDRA radiation-hydrodynamics

FIG. 6. Uncorrected streaked X-ray spectrometer image (top), along with a spectrally averaged time history for the 1.8–2.7 keV range for shot N151014-001-999 (bottom).

FIG. 7. GXD image recorded during peak emission of a $20\ \mu\text{m}$ capsule driven by the 2.5 ns flat top pulse shape. The hot spot in the image is $\sim 100\ \mu\text{m}$ in diameter, with additional emission extending out to $\sim 325\ \mu\text{m}$.

simulation, but it is now possible to use the measured backlighter spectrum from Fig. 3 as an input.

This calculation assumes a sample plasma with a mass density of $0.04\ \text{g/cm}^3$, corresponding to an electron density of about $7 \times 10^{21}/\text{cm}^3$ and similar to that obtained in the iron opacity experiments on Z at 156 eV.²⁴ Pure iron plasma in local thermodynamic equilibrium at 150 eV, with a thickness (X-ray path length) of $50\ \mu\text{m}$ is considered. Following the prior work,⁷ the calculations assume a $1\ \text{mm}^2$ emitting area for the iron plasma, and a 2 ns effective duration; also, the same VISTA opacity model (provided by B. G. Wilson) is used to calculate both the absorption and self-emission of the sample. However, the present work extends the prior work by using recently published data for the NIF Opacity Spectrometer,²⁵ particularly the photometric efficiency (source/detected ratio of $\sim 10^{-12}$) and expected resolving power ($E/\Delta E \sim 1000$). This makes it possible to compute the expected backlighter, absorption, and self-emission spectra in terms of photons per detector pixel.

Computing the expected photons per pixel at the detector plane enables both photon statistical noise and digitizer noise to be simulated as well, with the latter expected to be about 3%–5% of the signal. These are incorporated into the expected spectra. Finally, and again following the design of the proposed experiment,⁷ this new calculation assumes that each portion of the spectrum is imaged spatially across at least 2 mm of detector (orthogonal to the spectrally-resolved direction), with a $25\ \mu\text{m}$ scan resolution, so that the pixel to pixel noise is attenuated by averaging over at least 80 pixels. Digitizer noise is expected to dominate, but it should be noted that instrumental backgrounds (including possible emission from the hohlraum) have not been included and are likely to degrade the results.

To properly simulate the actual instrument, the spectra incident onto the detector are calculated using the full resolution of the opacity model (including experimental noise), and then also smoothed to approximate the effects of source broadening and the rocking curve of the diffracting crystal. These spectra are then used to estimate the expected experimental

FIG. 8. Synthetic estimate of experimental X-ray spectral lineouts for the NIF Opacity Spectrometer from an iron plasma at 150 eV and $0.04\ \text{g/cm}^3$. Statistical noise sources are included, using an approximate model for the instrument photometric efficiency. Spectra are blurred to an effective resolving power $E/\Delta E \sim 1000$. However, effects of filter transmission and potential systematic effects (e.g., background subtraction errors) are not included.

transmission measurement, which can then be compared with the theoretical transmission (calculated directly from the opacity model) to infer the expected level of accuracy of the experiment. To ensure a proper comparison, the theoretical transmission calculation must be smoothed in the same manner as the estimated experimental spectra.

Following the prior work,⁷ Fig. 8 shows the anticipated signal levels on three regions of the detector, from which an opacity measurement can be made. Figure 9 shows the X-ray transmission inferred from this approximation to the experiment, the theoretical transmission, and the expected difference. Based on the current assumptions, the capsule backlighter output, instrument throughput, and digitization noise levels appear to be adequate (in the absence of systematic errors) to deliver X-ray transmission measurements with root-mean-square statistical errors substantially less than ± 0.02 absolute. As

FIG. 9. Synthetic estimate of experimental X-ray transmission calculated from the data in Fig. 6, and compared with expected transmission calculated directly from the underlying opacity model (VISTA). Transmission error plotted using the absolute difference between the synthetic experiment and the theoretical expected transmission.

discussed previously,⁷ this would be sufficient to measure spectroscopic opacities with statistical errors less than $\pm 10\%$. However, systematic errors (e.g., incorrect background subtraction) must also be minimized, and with finite instrumental resolution, it is difficult to accurately measure the peak opacities of very narrow (unresolved) spectral features.

VI. SUMMARY

Direct drive implosions of plastic capsules have been performed at NIF to provide a broad-spectrum (500–2000 eV) X-ray continuum source for X-ray transmission spectroscopy. The source has been developed for the high-temperature plasma opacity experimental platform. Initial experiments using 2.0 mm diameter poly alpha-methyl styrene (PAMS) shells with $\sim 20\ \mu\text{m}$ thickness have been performed. X-ray yields of up to $\sim 1\ \text{kJ/sr}$ have been measured using the Dante multichannel diode array. The measured flash emission spectrum peaks at $\sim 700\ \text{eV}$, with a brightness of $\sim 0.67\ \text{kJ/sr/eV}$. The backlighter source size is measured to be $100\ \mu\text{m}$ FWHM, with $\sim 350\ \text{ps}$ pulse duration during the flash stage, providing a point-like short-pulse source for point-projection spectroscopy measurements. Backlighter performance results used to simulate transmission spectra for a hypothetical iron opacity sample at $150\ \text{eV}$ demonstrate ample photon statistics for future opacity experiments.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, National Nuclear Security Administration [Subprogram Office, (e.g., Office of Emergency Operations)]. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The U.S. Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>). DOE/NV/25946—3139. This work was performed under the auspices of the U.S. Department of Energy, by the LLNL authors under Contract No. DE-AC52-07NA27344, by the LANL authors under Contract No. DE-AC52-06NA25396, and by the University of Rochester authors under a Cooperative Agreement.

- ¹G. H. Miller, E. I. Moses, and C. R. Wuest, *Nucl. Fusion* **44**(12), S228 (2004).
- ²S. G. Glendinning, P. A. Amendt, K. S. Budil, B. A. Hammel, D. H. Kalantar, M. H. Key, O. L. Landen, B. A. Remington, and D. E. Desenne, *Proc. SPIE* **2523**, 29 (1995).
- ³M. A. Barrios, K. B. Fournier, S. P. Regan, O. Landen, M. May, Y. P. Opachich, K. Widmann, D. K. Bradley, and G. W. Collins, *High Energy Density Phys.* **9**(3), 626–634 (2013).
- ⁴O. L. Landen, D. R. Farley, S. G. Glendinning, L. M. Logory, P. M. Bell, J. A. Koch, F. D. Lee, D. K. Bradley, D. H. Kalantar, C. A. Back, and R. E. Turner, *Rev. Sci. Instrum.* **72**, 627 (2001).
- ⁵B. E. Blue, H. F. Robey, S. G. Glendinning, M. J. Bono, S. C. Burkhart, J. R. Celeste, R. F. Coker, R. L. Costa, S. N. Dixit, J. M. Foster, J. F. Hansen, C. A. Haynam, M. R. Hermann, J. P. Holder, W. W. Hsing, D. H. Kalantar, N. E. Lanier, D. A. Latray, H. Louis, B. J. MacGowan, G. R.

- Maggelssen, C. D. Marshall, E. I. Moses, A. J. Nikitin Apos, D. W. Brien, T. S. Perry, M. W. Poole, V. V. Rekow, P. A. Rosen, M. B. Schneider, P. E. Stry, B. M. Van Wouterghem, R. Wallace, S. V. Weber, B. H. Wilde, D. T. Woods, and B. K. Young, *Phys. Plasmas* **12**(5), 056313 (2005).
- ⁶K. A. Flippo, J. L. Kline, F. W. Doss, E. N. Loomis, M. Emerich, B. Devolder, T. J. Murphy, K. B. Fournier, D. H. Kalantar, S. P. Regan, M. A. Barrios, E. C. Merritt, T. S. Perry, I. L. Tregillis, L. Welsler-Sherrill, and J. R. Fincke, *Rev. Sci. Instrum.* **85**(9), 093501 (2014).
- ⁷R. F. Heeter, J. E. Bailey, R. S. Craxton, B. G. DeVolder, E. S. Dodd, E. M. Garcia, E. J. Huffman, C. A. Iglesias, J. A. King, J. L. Kline, D. A. Liedahl, P. W. McKenty, Y. P. Opachich, G. A. Rochau, P. W. Ross, M. B. Schneider, M. E. Sherrill, B. G. Wilson, R. Zhang, and T. S. Perry, *J. Plasma Phys.* **83**(1) (2017).
- ⁸T. S. Perry, K. S. Budil, R. Cauble, R. A. Ward, D. R. Bach, C. A. Iglesias, B. G. Wilson, J. K. Nash, C. C. Smith, J. M. Foster, S. J. Davidson, F. J. D. Serduke, J. D. Kilkenny, and R. W. Lee, *J. Quant. Spectrosc. Radiat. Transfer* **54**(1–2), 317–324 (1995).
- ⁹T. S. Perry, S. J. Davidson, F. J. D. Serduke, D. R. Bach, C. C. Smith, J. M. Foster, R. J. Doyas, R. A. Ward, C. A. Iglesias, F. J. Rogers, J. Abdallah, R. E. Stewart, J. D. Kilkenny, and R. W. Lee, *Phys. Rev. Lett.* **67**(27), 3784–3787 (1991).
- ¹⁰C. Sorce, J. Schein, F. Weber, K. Widmann, K. Campbell, E. Dewald, R. Turner, O. Landen, K. Jacoby, P. Torres, and D. Pellinen, *Rev. Sci. Instrum.* **77**(10), 10E518 (2006).
- ¹¹B. R. Maddox, H. S. Park, B. A. Remington, C. Chen, S. Chen, S. T. Prisbrey, A. Comley, C. A. Back, C. Szabo, J. F. Seely, U. Feldman, L. T. Hudson, S. Seltzer, M. J. Haugh, and Z. Ali, *Phys. Plasmas* **18**(5), 056709 (2011).
- ¹²P. A. Baisden, L. J. Atherton, R. A. Hawley, T. A. Land, J. A. Menapace, P. E. Miller, M. J. Runkel, M. L. Spaeth, C. J. Stolz, T. I. Suratwala, P. J. Wegner, and L. L. Wong, *Fusion Sci. Technol.* **69**, 295–351 (2015).
- ¹³E. L. Dewald, K. M. Campbell, R. E. Turner, J. P. Holder, O. L. Landen, S. H. Glenzer, R. L. Kauffman, L. J. Suter, M. Landon, M. Rhodes, and D. Lee, *Rev. Sci. Instrum.* **75**(10), 3759–3761 (2004).
- ¹⁴J. L. Kline, K. Widmann, A. Warrick, R. E. Olson, C. A. Thomas, A. S. Moore, L. J. Suter, O. Landen, D. Callahan, S. Azevedo, J. Liebman, S. H. Glenzer, A. Conder, S. N. Dixit, P. Torres III, V. Tran, E. L. Dewald, J. Kamperschroer, L. J. Atherton, R. Beeler, Jr., L. Berzins, J. Celeste, C. Haynam, W. Hsing, D. Larson, B. J. MacGowan, D. Hinkel, D. Kalantar, R. Kauffman, J. Kilkenny, N. Meezan, M. D. Rosen, M. Schneider, E. A. Williams, S. Vernon, R. J. Wallace, B. V. Wouterghem, and B. K. Young, *Rev. Sci. Instrum.* **81**(10), 10E321 (2010).
- ¹⁵A. Seifter and G. A. Kyrila, *Rev. Sci. Instrum.* **79**(10), 10F323 (2008).
- ¹⁶J. A. Oertel, R. Aragonez, T. Archuleta, C. Barnes, L. Casper, V. Fatherley, T. Heinrichs, R. King, D. Landers, F. Lopez, P. Sanchez, G. Sandoval, L. Schrank, P. Walsh, P. Bell, M. Brown, R. Costa, J. Holder, S. Montelongo, and N. Pederson, *Rev. Sci. Instrum.* **77**(10), 10E308 (2006).
- ¹⁷L. R. Benedetti, P. M. Bell, D. K. Bradley, C. G. Brown, S. M. Glenn, R. Heeter, J. P. Holder, N. Izumi, S. F. Khan, G. Lacaille, N. Simanovskaia, V. A. Smalyuk, and R. Thomas, *Rev. Sci. Instrum.* **83**(10), 10E135 (2012).
- ¹⁸Y. P. Opachich, D. H. Kalantar, A. G. MacPhee, J. P. Holder, J. R. Kimbrough, P. M. Bell, D. K. Bradley, B. Hatch, G. Brienza-Larsen, C. Brown, C. G. Brown, D. Browning, M. Charest, E. L. Dewald, M. Griffin, B. Guidry, M. J. Haugh, D. G. Hicks, D. Homoele, J. J. Lee, A. J. Mackinnon, A. Mead, N. Palmer, B. H. Perfect, J. S. Ross, C. Silbernagel, and O. Landen, *Rev. Sci. Instrum.* **83**(12), 125105 (2012).
- ¹⁹S. A. Letts, E. M. Fearon, S. R. Buckley, M. D. Saculla, L. M. Allison, and R. Cook, *Fusion Sci. Technol.* **28**(5), 1797 (1995).
- ²⁰B. W. McQuillan, A. Nikroo, D. A. Steinman, F. H. Elsner, D. G. Czechowicz, M. L. Hoppe, M. Sixtus, and W. J. Miller, *Fusion Sci. Technol.* **31**(4), 381 (1997).
- ²¹B. W. McQuillan, R. Paguio, P. Subramanian, M. Takagi, and A. Zebib, *Inertial fusion Scie. Appl.* edited by B. A. Hammel, D. D. Meyerhoret, J. Meyer-ter-Vehn, and H. Azechi (American Nuclear Society, 2003) pp. 766–769.
- ²²A. Nikroo, J. Bousquet, R. Cook, B. W. McQuillan, R. Paguio, and M. Takagi, *Fusion Sci. Technol.* **45**(2), 165 (2004).
- ²³Y. Ping, D. G. Hicks, B. Yaakobi, F. Coppari, J. H. Eggert, and D. G. W. Collins, *Rev. Sci. Instrum.* **84**(12), 123105 (2013).
- ²⁴J. E. Bailey, G. A. Rochau, C. A. Iglesias, J. Abdallah, J. J. MacFarlane, I. Golovkin, P. Wang, R. C. Mancini, P. W. Lake, T. C. Moore, M. Bump, O. Garcia, and S. Mazevet, *Phys. Rev. Lett.* **99**(26), 265002 (2007).
- ²⁵P. W. Ross, R. F. Heeter, M. F. Ahmed, E. Dodd, E. J. Huffman, D. A. Liedahl, J. A. King, Y. P. Opachich, M. B. Schneider, and T. S. Perry, *Rev. Sci. Instrum.* **87**(11), 11D623 (2016).