

# Development of backlighting sources for a Compton radiography diagnostic of inertial confinement fusion targets (invited)<sup>a)</sup>

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(Presented 13 May 2008; received 14 May 2008; accepted 9 June 2008; published online 31 October 2008)

We present scaled demonstrations of backlighter sources, emitting bremsstrahlung x rays with photon energies above 75 keV, that we will use to record x-ray Compton radiographic snapshots of cold dense DT fuel in inertial confinement fusion implosions at the National Ignition Facility (NIF). In experiments performed at the Titan laser facility at Lawrence Livermore National Laboratory, we measured the source size and the bremsstrahlung spectrum as a function of laser intensity and pulse length from solid targets irradiated at  $2 \times 10^{17}$ – $5 \times 10^{18}$  W/cm<sup>2</sup> using 2–40 ps pulses. Using Au planar foils we achieved source sizes down to 5.5  $\mu$ m and conversion efficiencies of about  $1 \times 10^{-13}$  J/J into x-ray photons with energies in the 75–100 keV spectral range. We can now use these results to design NIF backlighter targets and shielding and to predict Compton radiography performance as a function of the NIF implosion yield and associated background. © 2008 American Institute of Physics. [DOI: 10.1063/1.2953593]

## I. INTRODUCTION

With the National Ignition Facility<sup>1</sup> (NIF) nearing completion, large-scale laser fusion experiments are approaching. In the indirect drive configuration,<sup>2</sup> about 1 MJ of laser energy will be delivered onto a high-Z hohlraum containing a capsule filled with deuterium and tritium, driving an implosion of the capsule with subsequent generation of a dense shell of relatively cold plasma surrounding a central hot spot of hot, low-density plasma. Successful ignition (neutron yield >1 MJ) will require precise control over a number of processes that could degrade implosion performance, including hydroinstabilities, entropy increases, and residual asymmetries in the laser drives.

Obtaining images at stagnation time of the dense and cold deuterium-tritium fuel will therefore be fundamental to distinguishing between the degradation mechanisms so they may be mitigated on later shots. These images can be obtained using transmission Compton radiography<sup>3</sup> with x rays having photon energies above 70 keV in order to allow spectral discrimination against the strong self-emission from the core and having fluxes larger than those associated with the extremely high backgrounds anticipated for the implosions at the NIF. The Compton scattering cross section can be approximated as  $\sigma \sim \sigma_T [1 - 2(h\nu/mc^2) + (26/5)(h\nu/mc^2)^2 + \dots]$ , where  $h\nu$  is the x-ray photon energy,  $\sigma_T$  is the Thomson scattering cross section, and  $m$  is the electron mass.

Therefore in the energy range between 70 and 200 keV, the process is largely independent of probing photon energy so that we can choose the wavelengths of the x ray photons merely according to signal-to-background considerations. Notice also that for the x-ray photon energies of interest here and for the expected typical parameters of the imploding plasma, the free-free absorption of the backlighter x rays is negligible, being always lower than 1% of the Compton scattering contribution to absorption and usually much less.

Analysis of simulated failure modes shows that a spatial resolution of 10  $\mu$ m is needed in order to resolve small features in the cold dense fuel at peak compression. In addition, to avoid motion blurring and freeze the picture of the fuel through its high-speed burn, a temporal resolution of 10 ps will be necessary. The latter requirement can be obtained using the picosecond lasers from the Advanced Radiography Capability<sup>4,5</sup> (ARC) that is being integrated on NIF to irradiate solid metal targets and create backlighting x-ray sources having about the same duration as the laser pulses. The first requirement can be fulfilled using wires as backlighters in an end-on, point-projection radiography geometry, which guarantees the minimum source size and the maximum laser-energy coupling into the backlighter.<sup>6</sup> Moreover ARC will have eight beams with energies between 0.5 and 1.6 kJ depending on the pulse duration, which varies between 0.7 and 50 ps. Therefore we can produce a series of radiographs of the dense fuel as the capsule evolves through compression and bracket the moment of peak burn during a single ignition attempt with picosecond temporal resolution.

In the case of the application of Compton radiography to ignition implosions, the main concerns are related to the ex-

<sup>a)</sup>Invited paper, published as part of the Proceedings of the 17th Topical Conference on High-Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 2008

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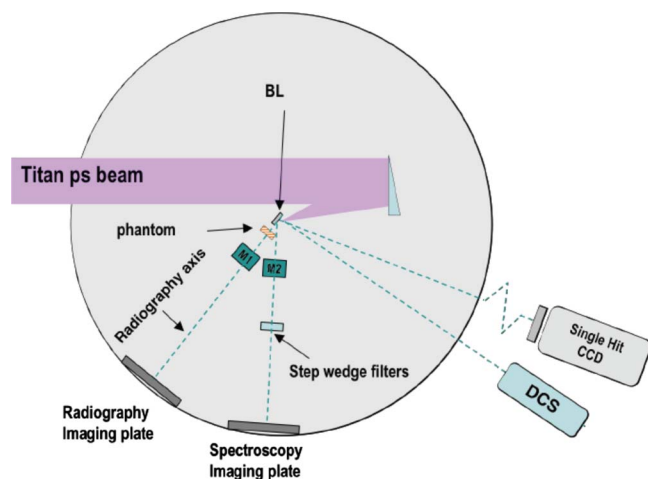


FIG. 1. (Color online) Experimental setup used on Titan for the characterization of high-energy backlighters. Magnets (M1 and M2) were used to prevent charged particles from reaching the imaging plates.

treme background levels expected during the implosion and mainly due to hard x rays emitted by the hot core, to hard x rays generated by hot electrons traversing the hohlraum walls, and to gamma rays from the  $n$ -gamma induced reactions in the various components inside the NIF target chamber. The spectra associated with these backgrounds extend from a few keV to a few hundred keV, therefore overlapping with the photon energy of any x-ray backlighting source. Assessing backlighter performance and their conversion efficiency (CE), in particular, is therefore crucial to estimating the signal that can be produced by the radiographic source, and this is the motivation for the work presented here.

## II. EXPERIMENTAL SETUP

In order to characterize the emission and source size of high-energy x-ray sources, we performed a series of experiments at the Titan laser facility at Lawrence Livermore National Laboratory. The experimental setup is shown in Fig. 1. The short pulse beam of Titan, with 1054 nm wavelength, was used to irradiate the targets placed at the target chamber center.

Line and continuum emission were recorded using a single photon counting (SPC) charged coupled device camera (for  $K\alpha$  lines with energy between 16 and 26 keV) and with the high-energy channel of the dual crystal spectrometer (DCS).<sup>7</sup> The DCS uses a (10-11) quartz crystal in transmission (Laue) geometry, bent to a radius of 254 mm, and covers the spectral range from 18 to 120 keV. The DCS was positioned outside the Titan target chamber and viewed the front side of the targets through a port with a Lexan vacuum window, with a source-to-crystal distance of 1.2 m. The spectral images were recorded using Fuji BaFBr:Eu<sub>2</sub> imaging plates<sup>8</sup> near the Rowland circle.

An imaging axis was set up in the direction parallel to the target surface in order to perform radiography of test objects to measure the source size of the backlighters. The radiographs were recorded on Fuji BAS-SR and BAS-MS imaging plates, sitting at about 80 cm from the target chamber center. At an angle of 20° from the radiography line of

sight, we fielded a second Fuji BAS-SR imaging plate. Half-way between this and the backlighter, we placed a step-wedge filter consisting of slabs of Pb of thicknesses between 0.2 and 8.0 mm. The combination of the step-wedge filter transmission and the imaging plate sensitivity was used as a low-resolution spectrometer to measure the high-energy band of the continuum emission from the backlighters. Indeed, under the assumption that the functional shape of the x-ray emission is known, the x-ray spectrum can be retrieved by a best fit of the exposure values relative to the different filter thicknesses, measured in the radiograph of the backilluminated step-wedge filter. In the present work we assume the emission to be dominated by bremsstrahlung, and we calculate the CE of laser energy into the energy of continuum emission in specific energy bands by integrating the derived spectra over the region of interest. The sensitivity of the imaging plate recording the step-wedge filter radiograph was simulated using the EGSnrc Monte Carlo code.<sup>9</sup> However, since the imaging plate exposure values are read by a fluorescent image analyzer, in our case the Fuji FLA-7000 scanner, the effective detection sensitivity is actually the combination of the imaging plate and the scanner used to analyze it. Therefore the calculated sensitivity has been absolutely rescaled using a few calibration points obtained by scanning the imaging plates after exposure to radioactive sources.

## III. EXPERIMENTAL RESULTS

A first experiment was devoted to the comparison of the CE into continuum and into  $K\alpha$  emission for different materials. 25  $\mu\text{m}$  thick foils, about  $0.5 \times 4 \text{ mm}^2$  in size were irradiated by the Titan short pulse laser beam. The laser parameters were maintained constant during the experiment, with a spot size of  $\sim 50 \mu\text{m}$ , a pulse duration of 40 ps, and an intensity on target of  $\sim 2 \times 10^{17} \text{ W/cm}^2$ . The raw spectra recorded by the DCS, for the sequence of elements Ag, Sn, Sm, Ta, Au, and Pb, are shown in Fig. 2. The spectral dispersion of the DCS was calibrated according to the procedure outlined in Ref. 7. The  $K\alpha$  and  $K\alpha_2$  lines, with photon energies from 22 to 75 keV, are bright and distinct for all elements, while the  $K\beta$  lines are clearly visible at least up to Au. To get the absolute flux of photons for the spectra shown in Fig. 2, the DCS was cross calibrated against the SPC using the Ag and Sn  $K\alpha$  lines. The procedure and the results for the absolute CE into  $K\alpha$  emission up to 75 keV (Pb  $K\alpha$ ) have been reported in Ref. 3. In the spectral region of interest for the application of Compton radiography as a laser fusion diagnostic, the CE reaches the values of a few  $1 \times 10^{-5}$  for the  $K\alpha$  emission lines from Ta, Au, and Pb at 58, 69, and 75 keV, respectively.

Using the above procedure over the same data set, we calculated the CEs into broadband continuum, between 75 and 100 keV, from the DCS spectra. The result of this analysis is shown in Fig. 3 and shows CEs increasing with the material density and reaching values of about  $2 \times 10^{-4}$  for Ta and Au. Figure 3 also shows, for comparison, the CEs into  $K\alpha$  emission lines immediately below 75 keV, i.e., from Ta, Au, and Pb, which are a factor of 4–5 lower than the values obtained in the continuum band. Due to the constancy of the

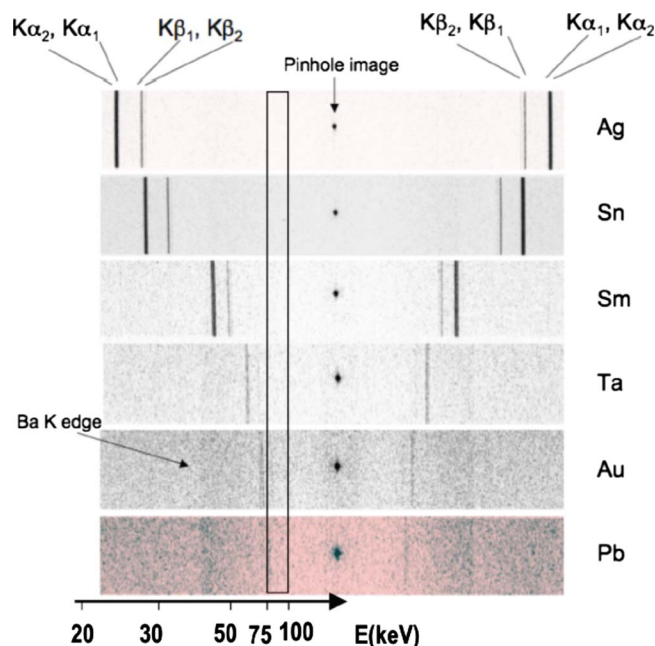


FIG. 2. (Color online) Raw spectra recorded with the DCS for the sequence of elements Ag, Sn, Sm, Ta, Au, and Pb.  $K\alpha$  and  $K\beta$  are clearly visible, as is also visible the  $K$  absorption edge of the barium, an element present in the imaging plate sensitive layer. The region above Pb  $K\alpha$ , spanning from 75 up to 100 keV, has been used for measuring the CE of laser energy into bremsstrahlung.

Compton cross section with probe energy and to the higher CEs for bremsstrahlung, a continuum emitting backlighter is the better option. Moreover, a broadband backlighter, in contrast to a line-emission one, has the advantage of requiring only a moderate bandpass for the radiography detector.

In a second experiment 10  $\mu\text{m}$  thick Au planar microfoils, having dimensions of  $300 \times 300 \mu\text{m}^2$ , were used to measure the CE in the continuum region above 75 keV as a function of laser intensity. The Titan short pulse laser beam was used to irradiate the targets with an incidence angle of  $35^\circ$  with respect to the surface and with a spot size of about 50  $\mu\text{m}$ . The intensity on target was varied between  $5 \times 10^{17}$  and  $5 \times 10^{18} \text{ W/cm}^2$  by changing the pulse duration in the 2–40 ps range, while the laser energy was kept at about 150 J. The bremsstrahlung spectra were calculated using the step-wedge filter diagnostic described above. A simplified sketch of the setup is shown in Fig. 4, together with a real

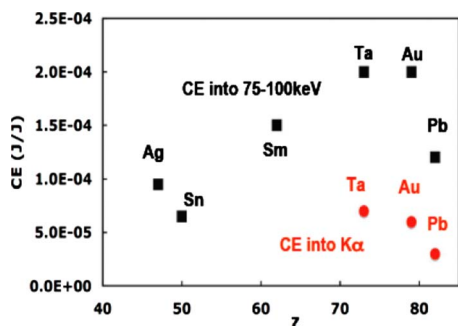


FIG. 3. (Color online) CEs into 75–100 keV continuum emission for the series of elements from Ag to Pb (squares), compared to the CEs into  $K\alpha$  emission lines from Ta, Au, and Pb, i.e., at about 58, 69, and 75 keV, respectively (dots). The CEs increase with material density.

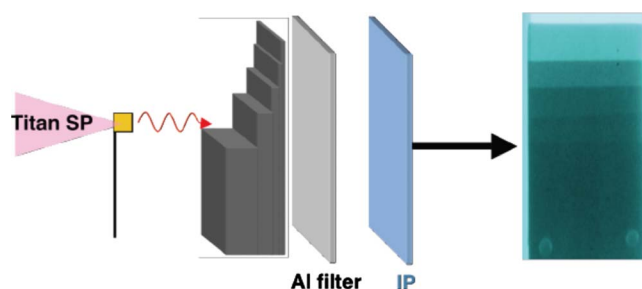


FIG. 4. (Color online) Setup to measure the bremsstrahlung spectra using step-wedge filters coupled to imaging plates (Fuji BAS-MS), IP. The radiograph shown on the right side, recorded by the IP, provides the exposure values from x rays traversing the different filter thicknesses. A best fit to these values is used to determine the bremsstrahlung spectrum.

radiograph of the step-wedge filter. In this particular case the filter pack consists of Pb slabs, with thicknesses of 0.5, 1.0, 2.0, 4.0, and 8.0 mm.

The scan versus laser intensity of the CE into 75–100 keV continuum is shown in Fig. 5. As shown by the linear fit in the logarithmic plot, the CE scales as  $\text{CE} \sim 4 \times 10^{-4} [I/(10^{18} \text{ W/cm}^2)]^{1/2}$  in the range of intensities used. We also performed experiments to test the source size of the backlights emitting at  $>75 \text{ keV}$ . One-dimensional radiographs of 300  $\mu\text{m}$  thick W cylindrical rods inside a 500  $\mu\text{m}$  thick Ta collimator were produced using microfoil backlighters in an edge-on geometry at a magnification of  $25\times$ . A 3 mm thick Cu filter was used to suppress the continuum emission below 70 keV. Figure 6 shows a radiograph obtained from a 10  $\mu\text{m}$  thick Au microfoil. The well-defined cylindrical profile of the rod and the spectral information obtained from the step-wedge filter allows the reconstruction of the source size from the rod radiographs. A detailed analysis results in a full width at half maximum source point spread function of  $10.0 \pm 2.0$  and  $5.5 \pm 1.0 \mu\text{m}$ , when using 10.0 and 5.0  $\mu\text{m}$  thick microfoils, respectively.

#### IV. CONCLUSIONS

We have presented scaled demonstrations of backlighter sources emitting bremsstrahlung x rays with photon energies above 75 keV. We compared the CE into broadband con-

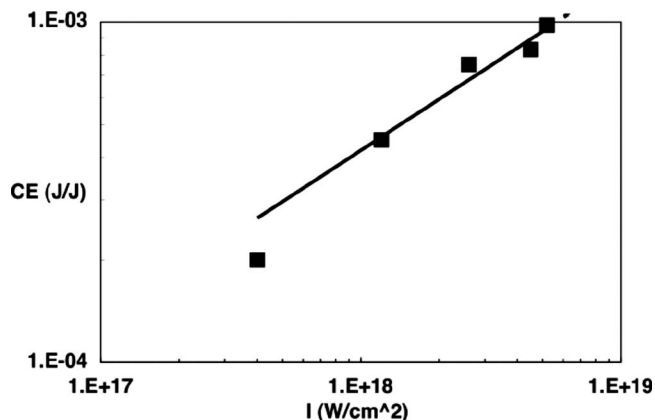


FIG. 5. CEs into 75–100 keV continuum emission from Au microfoils. The CE scales as  $\text{CE} \sim 4 \times 10^{-4} [I/(10^{18} \text{ W/cm}^2)]^{1/2}$ , in the range of intensities used.

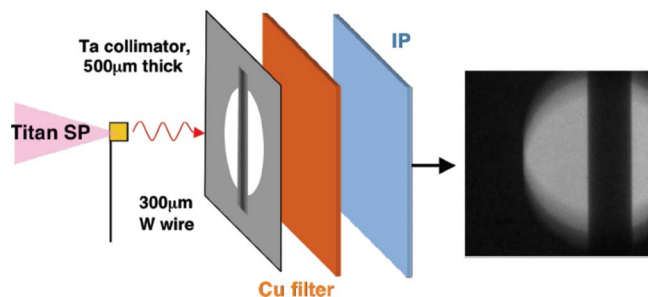


FIG. 6. (Color online) Edge-on geometry setup to produce radiographs with x rays of photon energy larger than 75 keV. The 3 mm thick Cu filter was used to suppress the continuum emission below 70 keV. The radiograph shown on the right was obtained using a 10  $\mu\text{m}$  thick Au microfoil backlighter.

tinuum and into  $K\alpha$  line emission with a variety of materials from Ag to Pb. Using the continuum region allows us to use higher photon energies, which are ultimately limited only by the quantum efficiency of available detectors. Therefore these sources are useful when the objects to be radiographed require relatively high fluxes of hard x rays and when monochromatic illumination is not a requirement. We measured the source size and the bremsstrahlung spectrum as a function of laser intensity and pulse length, from Au targets irradiated by Titan laser pulses having intensities in the range from  $5 \times 10^{17}$  to  $5 \times 10^{18} \text{ W/cm}^2$ . The CE into 75–100 keV continuum emission scales as  $\text{CE} \sim 4 \times 10^{-4} [I / (10^{18} \text{ W/cm}^2)]^{1/2}$ . Moreover, using Au planar foils we measured source sizes down to 5.5  $\mu\text{m}$  for x-ray photon energies exceeding 75 keV. We plan to use these hard x-ray backlighters to record x-ray Compton radiographic

snapshots of cold dense DT fuel in inertial confinement fusion implosions at the NIF. Therefore these results are particularly important and will be used to design NIF backlighter targets and shielding and to predict Compton radiography performance as a function of the NIF implosion yield and associated background.

## ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. The mention of commercial products does not represent an endorsement by the authors or their institutions.

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