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R. Tommasini, A. MacPhee, D. Hey, T. Ma, C. Chen, N. Izumi, W. Unites, A. MacKinnon, S. P. Hatchett, B. A. Remington, H. S. Park, P. Springer, J. A. Koch, O. L. Landen, J. Seely, G. Holland, L. Hudson

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Lawrence Livermore National Laboratory, Livermore CA

John Seely and Glenn Holland
Naval Research Laboratory, Washington DC

Larry Hudson
National Institute of Standards and Technology, Gaithersburg MD

Abstract. 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 2e17-5e18 W/cm^2 using 2-40 ps pulses. Using Au planar foils we achieved source sizes down to 5.5 µm, and conversion efficiencies of about 1e-3 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.

Keywords: laser-plasma interaction, hard x-rays, x-ray spectroscopy, radiography.
PACS: 52.50.Jm; 87.59.Bh; 52.70.La

1. INTRODUCTION

With the National Ignition Facility (NIF) [1] nearing completion, large-scale laser fusion experiments are approaching. In the indirect drive configuration [2], 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 hydro-instabilities, 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 [3] 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) $(h\nu/mc^2)^2$ + ...], where hν is the x-ray photon energy, σ_T is the Thomson scattering cross section and m is the electron mass. Therefore in the energy range between 70 keV and 200 keV, the process is largely independent of probing photon energy so that we can choose

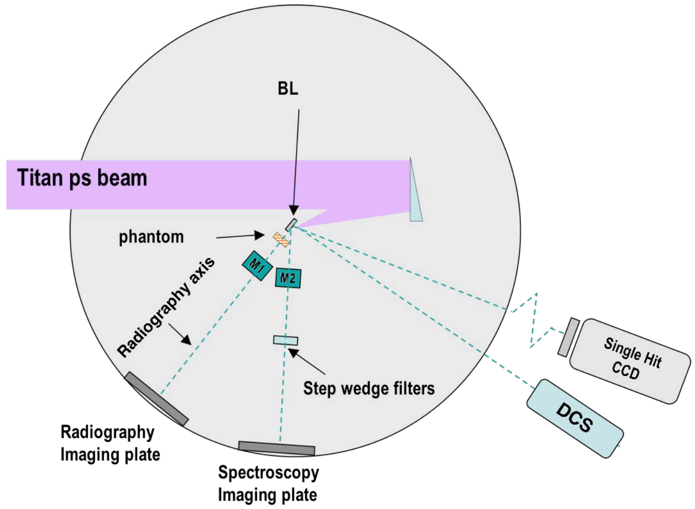

Figure 1: Experimental setup used on TITAN for the characterization of high energy backlighters. Magnets (M1 and M2) were used to prevent charged particles from reaching the imaging plates.

the wavelengths of the x-ray photons merely according to signal-to-background considerations.

Analysis of simulated failure modes shows that a spatial resolution of 10 μm 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 (ARC) [4,5] 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 [6]. Moreover ARC will have 8 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 time-wise 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 extreme 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 the backlighter performances, and the conversion efficiency 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.

2. 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 set-up is shown in Figure 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 (CCD) camera (for K-α lines with energy between 16 keV and 26 keV) and with the high-energy channel of the Dual Crystal Spectrometer (DCS) [7]. The DCS uses a (10-11) quartz crystal in transmission (Laue) geometry, bent to a radius of 254 mm, and covering the spectral range from 18 keV 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_2 imaging plates [8] 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

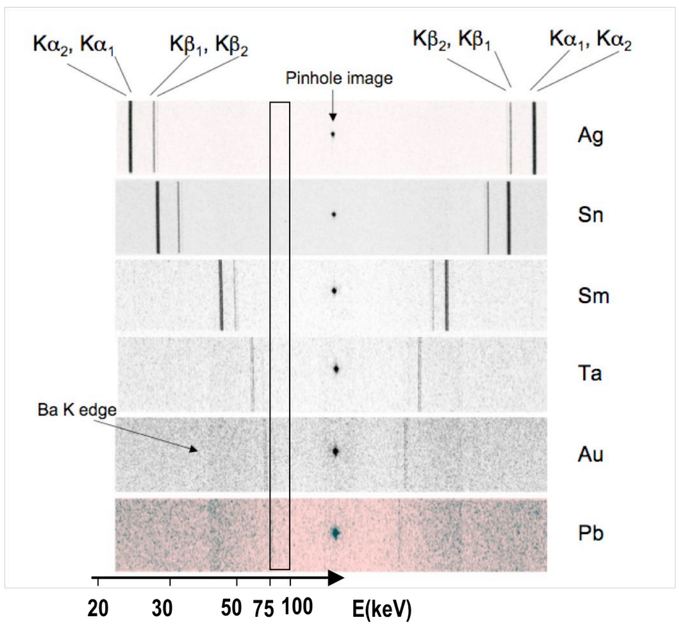

Figure 2: Raw spectra recorded with the DCS for the sequence of elements Ag, Sn, Sm, Ta, Au and Pb. Kα and Kβ are clearly visible, as is also visible the K absorption edge of the barium, an element present in the imaging plate sensitive layer. The region above Pb Kα, spanning from 75keV up to 100 keV, has been used for measuring the conversion efficiency of laser energy into Bremsstrahlung.

cm from the target chamber center. At an angle of 20 degrees from the radiography line of sight, we fielded a second FUJI BAS-SR imaging plate. Halfway between this and the backlighter we placed a step-wedge filter consisting of slabs of Pb of thicknesses between 0.2 mm 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 back-illuminated step-wedge filter. In the present work we assume the emission to be dominated by Bremsstrahlung, and we calculate the conversion efficiency of laser energy into energy of continuum emission, CE, 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 [9]. However, since the imaging plate exposure values are read by a fluorescent image analyzer, in our case the FUJI FLA-7000 scanner, the effective detector 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.

3. EXPERIMENTAL RESULTS

A first experiment was devoted to the comparison of the CE into continuum and into Kα emission for different materials. 25 μm-thick foils, about 0.5 mm × 4 mm 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 ~ 50 μm, a pulse duration of 40 ps and an

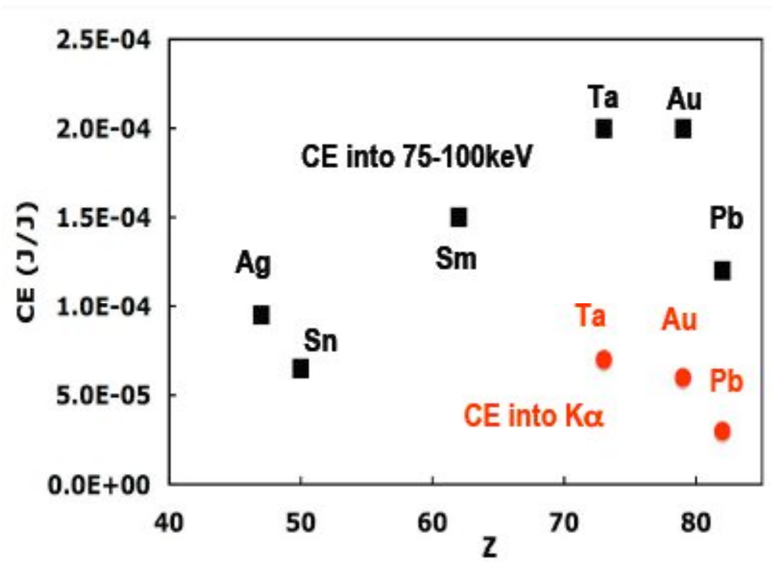

Figure 3: Conversion efficiencies into 75keV-100keV continuum emission for the series of elements from Ag to Pb (squares), compared to the conversion efficiencies into Kα emission lines from Ta, Au and Pb, i.e. at about 58 keV, 69 keV and 75 keV, respectively (dots). The conversion efficiencies increase with material density.

intensity on target of ~ 2e17 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 Figure 2. The spectral dispersion of the DCS was calibrated according to the procedure outlined in Ref. [7]. The Kα_1 and Kα_2 lines, with photon energies from 22 keV to 75 keV, are bright and distinct for all elements, while the Kβ lines are clearly visible at least up to Au. To get the absolute flux of photons for the spectra shown in Figure 2, the DCS was cross-calibrated against the SPC using the Ag and Sn Kα lines. The procedure and the results for the absolute CE into Kα emission up to 75 keV (Pb Kα) 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 1e-5 for the Kα emission lines from Ta, Au and Pb at 58 keV, 69 keV and 75 keV, respectively.

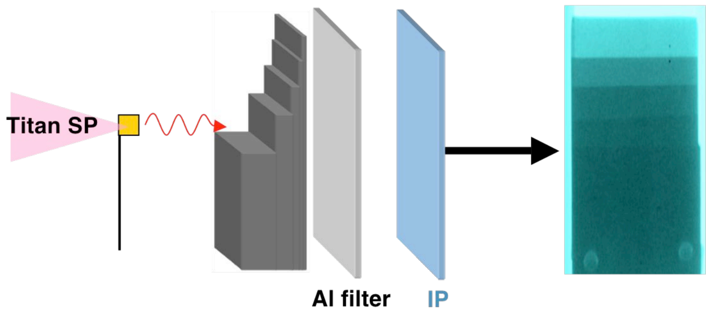

Figure 4: Set up to measure the Bremsstrahlung spectra using step-wedge filters coupled to Imaging Plates (Fuji BAS-MS), IP. The radiograph shown on the right side, recorded by the IP, provides the exposure values from x-rays traversing the different filter thicknesses. A best fit to these values is used to determine the Bremsstrahlung spectrum.

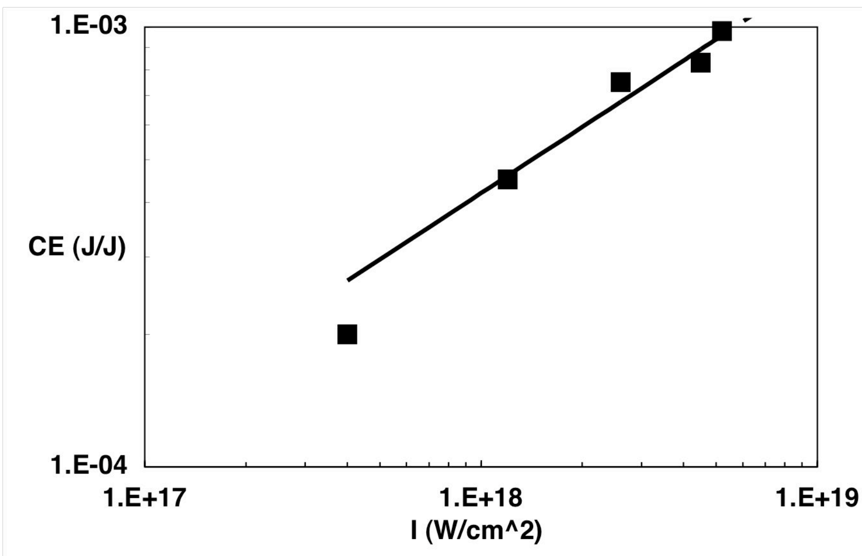

Figure 5: Conversion efficiencies into 75keV-100keV continuum emission from Au micro foils. The conversion efficiency scales as C.E.~ 4e-4 $[I / (10^{18} W/cm^2)]^{1/2}$, in the range of intensities used.

Using the above procedure over the same data set, we calculated the conversion efficiencies into broadband continuum, between 75 keV and 100 keV, from the DCS spectra. The result of this analysis is shown in Figure 3 and shows conversion efficiencies increasing with the material density and reaching values of about 2e-4 for Ta and Au. Figure 3 also shows, for comparison, the conversion efficiencies into Kα 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 Compton cross-section with probe energy and to the higher conversion efficiencies 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 band-pass for the radiography detector.

In a second experiment 10 μm-thick Au planar micro-foils, having dimensions of 300 x 300μm, 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 degrees with respect to the surface and with a spot size of about 50 μm. The intensity on target was varied between 5e17 and 5e18 W/cm^2 by changing the pulse duration in the 2 ps- 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 Figure 4, together with a real 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, 8.0) mm.

The scan vs. laser intensity of the CE into 75 keV-100 keV continuum is shown in Figure 5. As shown by the linear fit in the logarithmic plot, the conversion efficiency scales as CE ~ $4x10^{-4}$ $[I / (10^{18} W/cm^2)]^{1/2}$, in the range of intensities used. We also performed experiments to test the source size of the backlights emitting at > 75 keV. 1D radiographs of 300 μm-thick W cylindrical rods inside a 500 μm-thick Ta collimator were produced using micro-foil backlighters in an edge-on geometry at a magnification of 25X. 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 μm thick Au micro-foil. 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 FWHM source point spread function of (10.0+/-2.0) μm and (5.5+/-1.0) μm, when using 10.0 μm- and 5.0 μm-thick micro-foils, respectively.

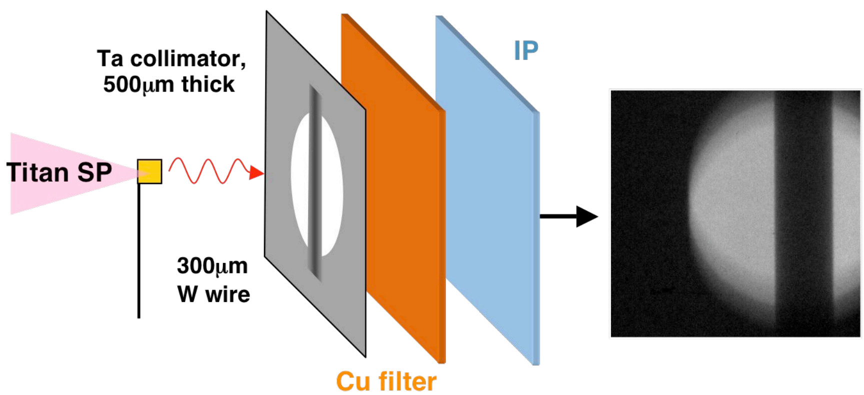

Figure 6: Edge-on geometry set up to produce radiographs with x-rays of photon energy larger than 75keV. The 3 mm-thick Cu filter was used to suppress the continuum emission below 70 keV. The radiograph shown on the right was obtained using a 10 μm-thick Au micro-foil backlighter.

4. 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 continuum and into Kα 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 5e17 to 5e18 W/cm^2. The conversion efficiency into 75 keV - 100 keV continuum emission scales as CE ~ $4x10^{-4}[I/(10^{18}W/cm^2)]^{1/2}$. Moreover, using Au planar foils we measured source sizes down to 5.5 µm 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.

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