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Development of backlighting sources for a Compton Radiography diagnostic of Inertial Confinement Fusion targets

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Development of backlighting sources for a Compton Radiography diagnostic of Inertial Confinement Fusion targets

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Abstract. An important diagnostic tool for inertial confinement fusion is time-resolved imaging of the dense cold fuel surrounding the hot spot. Here we report on the source and diagnostic development of hard x-ray radiography and on the first radiographs of direct drive implosions obtained at photon energies up to about 100keV, where the Compton effect is the dominant contributor to the shell opacity. The radiographs of direct drive, plastic shell implosions obtained at the OMEGA laser facility have a spatial resolution of ~ 10um and a temporal resolution of ~10ps. This novel Compton Radiography is an invaluable diagnostic tool for Inertial Confinement Fusion targets, and will be integrated at the National Ignition Facility (NIF).

INTRODUCTION

In both direct and indirect drive scheme [1], the implosion aimed at achieving ignition can be spoiled by a number of reasons, for instance asymmetries in the laser drives or

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hydrodynamic instabilities. An important tool to understand the reasons for possible failure or success will be time-resolved imaging of the dense cold fuel surrounding the hot spot, by recording radiographs from x-ray backlighters. Indeed, images at stagnation time of the dense and cold deuterium-tritium fuel are fundamental to distinguishing between the various degradation mechanisms so they may be mitigated on the following attempts.

These images can be obtained using transmission Compton radiography [2], where we use high energy Compton scattering rather than traditional photo-absorption to cast a shadow of the imploding capsule. The Compton scattering cross section below and around 200 keV is largely independent of the probing photon energy. As a consequence, the optical depth of the fuel of a simulated ignition attempt at the National Ignition Facility (NIF) [3], as seen in Figure 1, shows a plateau above ~50keV, where the Compton scattering dominates allowing one to use a broadband detector and, at the same time, to accurately infer the ρR of the implosion even using a polychromatic backlighter.

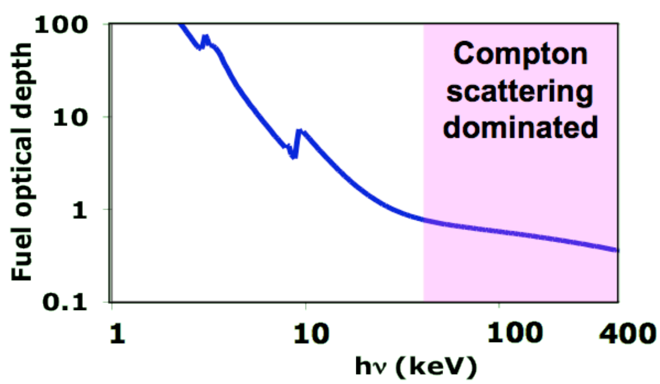

FIGURE 1. Above ~50keV, the optical depth of the fuel of a simulated NIF implosion is dominated by Compton scattering.

The advantages of operating in the Compton-scattering regime are multiple. A broadband Bremsstrahlung emitting source is perfectly suited and one can choose the wavelengths of the x-ray photons, by coupling high-pass filter to the detector response, merely according to signal-to-background needs. For instance, the use of high-energy photons allows for dramatic filtering of the core self-emission, that, in the case of NIF implosions is spectrally concentrated at photon energies below 20keV, and which has been troublesome for radiographs of implosions with lower photon energies. Short-wavelength photons will also minimize the refraction of the probing x-ray beam as it traverses the shell and thus will keep the spatial resolution close to the backlighter source size. Finally, from a practical point of view, our technique does not require narrowband detection devices and therefore greatly simplifies the experimental setup and apparatus. The energy band of interest for the detected x-ray signal will be the convolution of a high pass filter and the detector spectral response, and will be typically limited within 70keV-200keV region.

TITAN EXPERIMENTS: COMPARISON OF Kα AND BREMSSTRAHLUNG BACKLIGHTING SOURCES

In the case of the application of radiography to ignition implosions, the main concerns are related to the extreme background levels expected during the implosion. While the background associated with neutrons interacting with the detector can be eliminated using gating techniques, prompt background signals represent a formidable obstacle. These are mainly due to the x-rays emitted by the hot core, the hard x rays generated by hot electrons traversing the hohlraum walls, and the 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 performance, and their conversion efficiency in particular, is therefore crucial to estimating the signal that can be produced by the radiographic source.

In a first series of experiments at the TITAN laser facility at the Lawrence Livermore National Laboratory we compared the performances of Kα and Bremsstrahlung sources. The experimental set-up is shown in Figure 2.

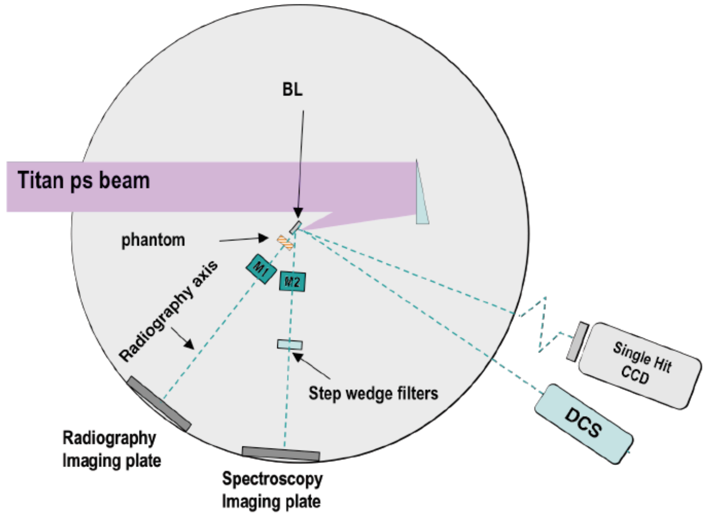

Figure 2. Experimental setup used on TITAN for the characterization of high-energy backlighters. Magnets (M1 and M2) were used to prevent charged particles from reaching the imaging plates.

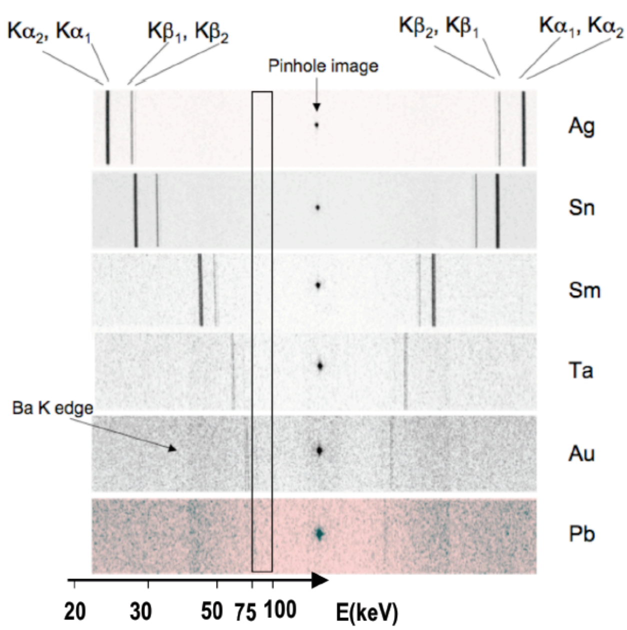

FIGURE 3. Raw spectra recorded with the DCS for the sequence of elements Ag, Sn, Sm, Ta, Au and Pb. Kα and Kβ are clearly visible, as is also visible the K absorption edge of the barium, an element present in the imaging plate sensitive layer. The region above Pb Kα, spanning from 75 keV up to 100 keV, has been used for measuring the conversion efficiency of laser energy into Bremsstrahlung.

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 covers 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.

The comparison of the CE into continuum and into Kα emission was done using different materials: 25 μm thick foils, about 0.5 mm by 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 intensity on target of ~ 1e17 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 3. The spectral dispersion of the DCS was calibrated according to the procedure outlined in Ref. [7].

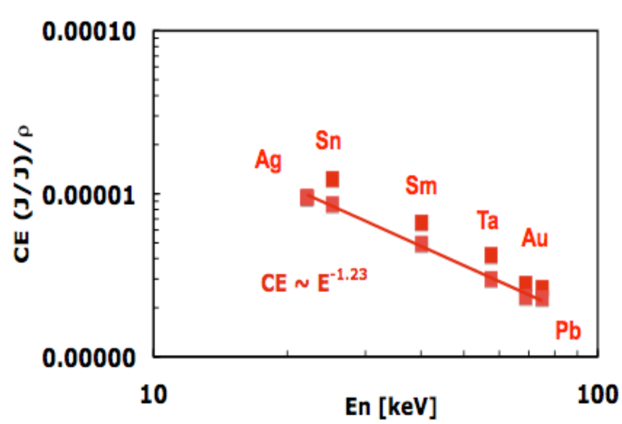

FIGURE 4. Conversion efficiencies (normalized by density) into Kα emission lines for foils of different elements

The $K\alpha_1$ and $K\alpha_2$ lines, with photon energies from 22 keV 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 Figure 3, 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. [2].

Figure 4 shows the results obtained with foils of different materials ranging from Ag to Pb. 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 $K\alpha$ emission lines from Ta, Au and Pb at 58 keV, 69 keV and 75 keV, respectively.

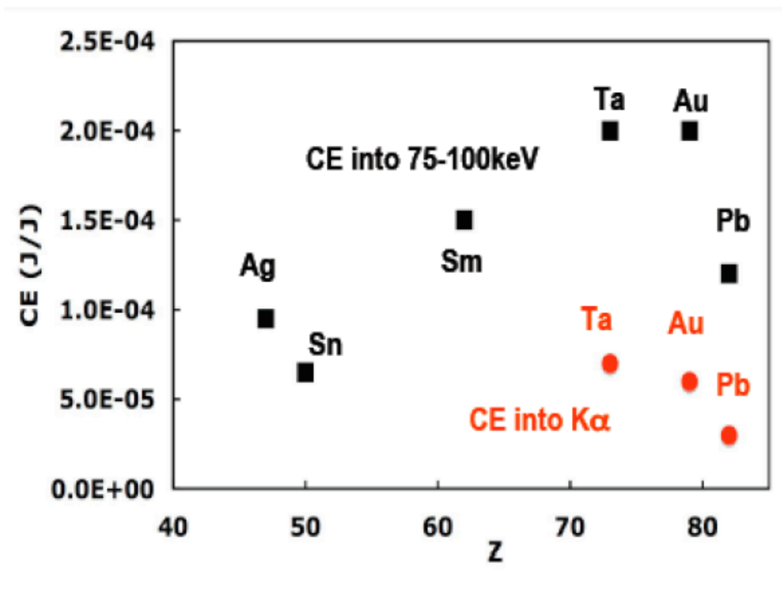

Figure 5: Conversion efficiencies into 75 keV to 100 keV continuum emission for the series of elements from Ag to Pb (squares), compared to the conversion efficiencies into $K\alpha$ emission lines from Ta, Au and Pb, i.e. at about 58 keV, 69 keV and 75 keV, respectively (dots). The conversion efficiencies increase with material density.

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 5 and shows conversion efficiencies increasing with the material density and reaching values of about 2e-4 for Ta and Au. Figure 5 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 to 5 lower than the values obtained in the continuum band.

TITAN EXPERIMENTS: BRIGHT, 10-MICRONS SOURCE-SIZE BREMSSTRAHLUNG BACKLIGHTERS

The analysis of ICF 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 a second series of experiments we measured the CE in the continuum region above 75 keV, as a function of laser intensity, and the source size of micro-wire Au backlighters. These backlighters consist of a 10 μm-diameter, 300 μm-long Au, wires on a 5μm-thick, 300μm x 300μm, Al substrates. For comparison we also used 10 μm-thick Au planar micro-foils, having dimensions of 300 μm by 300 μm. Again, 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 incidence angle was chosen to match the future implementation on NIF-ARC. The intensity on target was varied between 5e17 and 5e18 W/cm^2 by changing the pulse duration in the 2 ps to 40 ps range, while the laser energy was kept at about 150 J.

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 edge-on foil and end-on wire backlighters. The radiographs were recorded on FUJI BAS-SR and BAS-MS imaging plates, sitting at about 80 cm from the target chamber center. To measure the continuum spectrum above 100keV, the upper operational limit of the DCS, we deployed high-Z step filters. At an angle of 20 degrees from the target surface, we fielded a second FUJI BAS-MS imaging plate. Halfway between this and the backlighter we placed a step-wedge filter consisting of slabs of Pb and Ta of thicknesses between 0.1 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 and calculate the conversion efficiency (CE) of laser energy into energy of continuum emission in specific energy bands. 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 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.

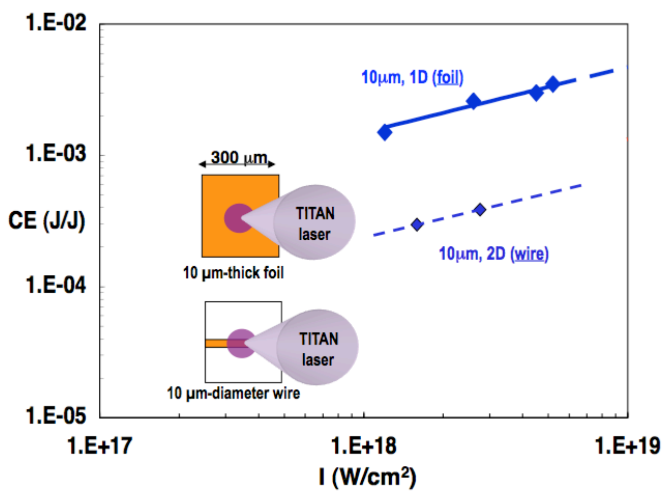

Figure 6: Scan vs. laser intensity of the CE into 100 keV to 200 keV continuum for Au foils and Au micro wires.

The scan vs. laser intensity of the CE into 100 keV to 200 keV continuum is shown in Figure 6. We note that the ratio of wire/foil CE into Bremsstrahlung is consistent with a relative area exposed to ≈70 μm beam of hot electrons.

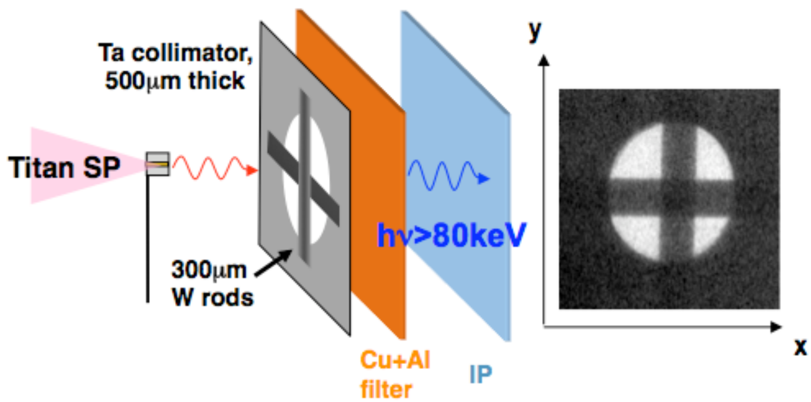

Figure 7: End-on point-projection setup, using Au micro-wires, to produce 2D radiographs with x-rays of photon energy higher than 80 keV. A combination of Cu and Al filters was used to suppress the continuum emission below ~80 keV. The radiograph shown on the right was obtained using a 10 μm-diameter Au micro-wire backlighter on a Al substrate.

Figure 7 shows the sketch of the end-on point-projection setup used to measure the 2D source size of the Bremsstrahlung backlighters, by recording radiographs of crossed, 300-μm thick W cylindrical rods inside a 500 μm thick Ta collimator. The radiograph shown in figure was recorded on a imaging plate at a magnification of 25X. A combination of Cu and Al filters was used to suppress the continuum emission below ~80 keV. The well-defined cylindrical profile of the rods and the spectral information obtained from the step-wedge filter allows the reconstruction of the source size from the rod radiographs. A detailed analysis of the imaged rods lineout results in a FWHM source size of (10.0+/-2.0)μm in both x and y directions, when using 10μm diameter Au micro-wires.

OMEGA-EP EXPERIMENTS: BREMSSTRAHLUNG BACKLIGHTERS

In preparation to test Compton Radiography on implosions at the OMEGA laser facility at LLE, we conducted preliminary experiments on the EP laser system in order to confirm the performance and the source size of the backlighters, when irradiated at intensities and pulse durations relevant to NIF-ARC.

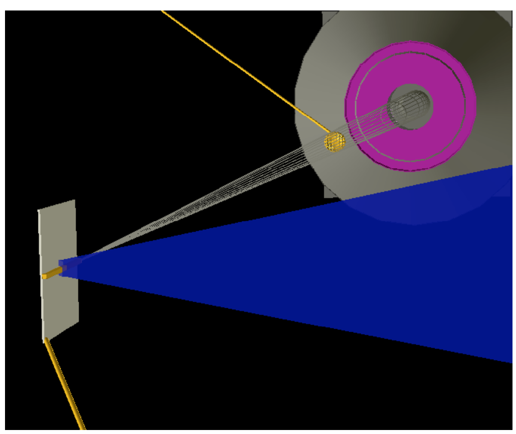

Figure 8: Geometry used in the OMEGA EP target chamber to obtain 2D radiographs of W spheres at photon energies above 75keV. The short pulse beam drives an Au micro-wire on a low-Z substrate. The CRS front collimator is shown in magenta.

We used, as backlighters, 10μm thick, 300μm x 300μm, Au foils and 10μm diameter, 300 μm long, Au wires on a low-Z substrate, in a point-projection, end-on, geometry. Bremsstrahlung radiation was generated by irradiating the Au with the OMEGA EP short pulse beam, delivering ~800J in 10ps. As radiography samples we used 200μm-diameter solid W spheres, located at a distance of 10mm from the backlighters.

In order to record the radiographs we designed and built a dedicated Compton Radiography Snout (CRS) consisting of a three-stage collimator, a layered structure of Al-Pb to shield against neutrons and high energy x and gamma rays, and a permanent magnetic field to deflect electrons away from the radiography lone of sight. CRS allows the insertion of filters at different locations and hosts a Fuji BAS imaging plate detector at about 400mm from target chamber center and features a built-in step-wedge filter/collimator that allows the reconstruction of the Bremsstrahlung spectrum along the line of sight. A combination of high- and low-Z filters was used inside the snout to restrict the backlit photon energies to above 75 keV. Figure 8 shows the experimental geometry in the OMEGA EP target chamber: the short pulse beam of OMEGA-EP drives an Au micro-wire on Al substrate. Solid W spheres, 200 um in diameter, where used to measure the source size of the backlighter along all transverse directions. As in the case of the cylinder rods, using spheres as radiography samples relaxes the alignment requirements for the radiography sample, and offers even simpler implementation, while requiring smaller field of view.

We obtained several good quality 1D and 2D radiographs of the solid W spheres and good data from the step wedge filters. Figure 2 shows a transparency of the step wedge built in the CRS collimator, and the 2D radiograph of the solid W sphere, both

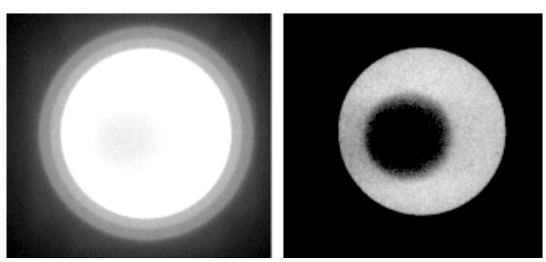

Figure 9: Left: transparency of the step wedge built in the CRS collimator, as recorded by the Fuji BAS imaging plate. Right: the 2D radiograph of the solid W sphere obtained using an Au micro wire shows source size of about 10um. Note that the two pictures are the rendering of the same imaging plate recorded image, using two different contrast settings.

recorded by the same imaging plate and obtained using an Au micro wire. The 2D radiograph of the W spheres shows a source size of about 10mm for the backlighter.

TITAN EXPERIMENTS: ROLE OF THE SUBSTRATE AND FREE STANDING MICRO-WIRES

As shown in Figure 9, the 2D radiographs of the solid W sphere recorded at OMEGA-EP show a secondary radiograph, appearing as a smearing along the horizontal axis of the figure, and due to the Al substrate acting as a backlighting source, elongated in the direction parallel to the target surface. To confirm this and better understand the role of the substrate, we performed additional experiments on TITAN, employing Au micro-wires on Al and CH substrates, as well as freestanding Au micro-wires. As a radiography detector we used the CRS, in the same configuration as in the OMEGA-EP experiments.

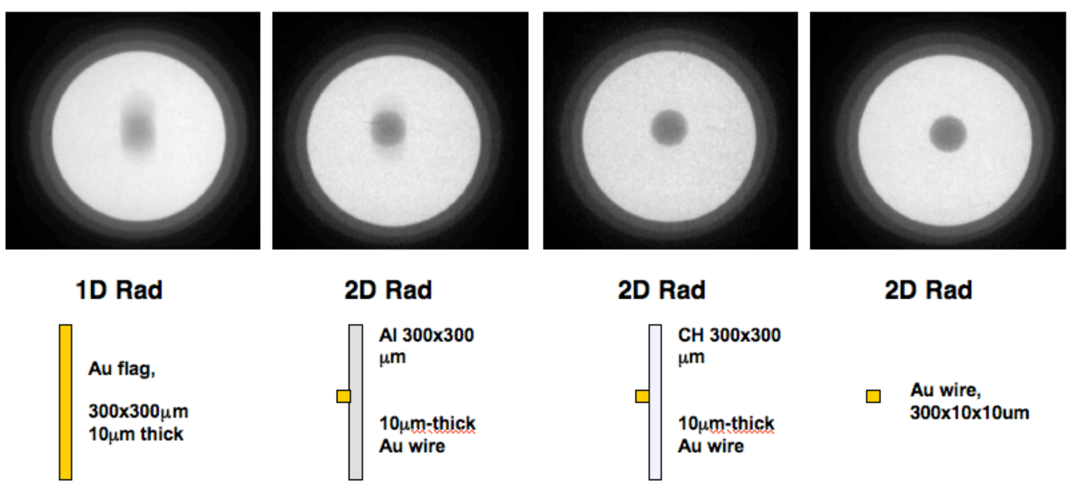

Figure 10: radiographs of solid W spheres obtained using different types of backlighters. The Al-substrate is causing ~10% 1D background radiograph, similar to the one obtained using a Au foil, superimposed onto the 2D radiograph from the Au wire. The CH substrates give very week 1D background. Freestanding wires give the cleanest 2D radiographs.

The TITAN short pulse laser beam was used to irradiate the targets with an angle of ~70 degrees with respect to the surface and with a spot size of about 50 μm, a pulse duration of 10ps and energy on target of about 200 J. Figure 10 shows the radiographs of the solid W spheres, 200um diameter, obtained using the different types of backlighters. The Al-substrate is causing a secondary radiograph, similar to the 1D radiograph obtained using a Au foil, and superimposed onto the 2D radiograph from the Au wire. As expected, given the lower Z and density of the substrate with respect to Al, the CH substrates give very week, almost absent, secondary radiograph. Freestanding wires give the cleanest 2D radiographs. The analysis of the sphere profiles shows a source size of (10.0+/-1.5) um along all radial directions, for freestanding and on-CH 10um-diameter Au micro-wire. Our measurements of x-ray yield also show that the freestanding wires perform as good as the wires on substrates.

OMEGA/OMEGA-EP INTEGRATED EXPERIMENTS: DEMONSTRATION OF COMPTON RADIOGRAPHY OF IMPLOSIONS

As the final step of this LDRD, we successfully obtained the first ever Compton-based radiographs of implosions [10]. For these experiments we used 60 beams of the OMEGA laser facility for direct-drive implosions of 40µm thick, 870µm diameter CH capsules filled with 3atm and 8atm DD gas, located at the target chamber center of OMEGA. As a backlighter we used a 10µm diameter Au wire, 300 µm long, in a point-projection, end-on, geometry at 10mm distance from the CH shell. The

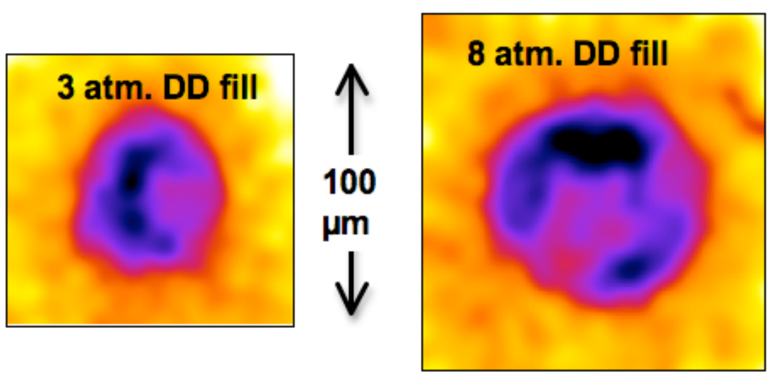

Figure 11: Compton Radiographs of CH imploding shells obtained at OMEGA/OMEGA-EP. Compression. Left: radiograph of the 3atm-DD-fileld CH shell, at about 150ps from peak compression, obtained at a photon energy of ~60keV. Right: radiograph of the 8atm-DD-fileld CH shell, within 100ps from peak compression, obtained at a photon energy of ~100keV.

backlighter was driven by the OMEGA EP short pulse beam, delivering ~1kJ at 10ps in a 100um square spot size. The time delay between the OMEGA EP short pulse and the OMEGA laser pulses was chosen to match the time of peak compression predicted by LILAC 1D simulations, however a perfect timing was not possible during to the temporal jitter between the EP short pulse beam and the OMEGA driver beams. The radiographs were recorded using the CRS. By progressively increasing filtration in the CRS, we obtained good quality radiographs at (average) photon energies of approximately 60keV, 80keV and 100keV and with 10ps, 10um, temporal and spatial resolution, respectively. As an example, Fig.11 (left) shows a radiograph of the 3atm-DD-fileld CH shell, at about 150ps from peak compression, obtained at a photon energy of ~60keV. The average diameter measured from the radiograph is 70um.

Fig.11 (right) shows a radiograph of the 8atm-DD-fileld CH shell, within 100ps from peak compression, obtained at a photon energy of ~100keV. The average diameter measured from the radiograph is 90um. Figure 12 shows the azimuthally averaged radial lineout along the darkest half of the Compton radiographs from Fig. 11, resulting in average ρR values of 90mg/cm^2 and 170 mg/cm^2, for the 3atm DD fill and the 8 atm DD fill, respectively.

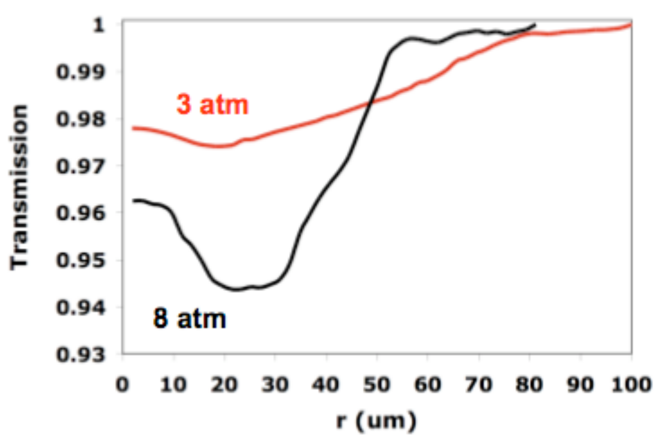

Figure 12: Azimuthally averaged radial lineout along the darkest half of the Compton radiographs from Fig. 11.

SUMMARY

We have developed the sources and the diagnostics for the hard x-ray radiography of ICF implosion based on Compton scattering. We have demonstrated Bremsstrahlung backlighting sources with 10um/10ps spatial/temporal resolution [11]. We have validated this novel Compton Radiography technique by obtaining the first radiographs of direct drive implosions the OMEGA/OMEGA-EP laser facility [10]. Our novel technique is now being adapted to programmatic measurements on the NIF.

Due to the progress we made through this LDRD, we plan to use Compton Radiography to record snapshots of the cold dense DT fuel in inertial confinement fusion implosions at the NIF.

ACCOMPLISHMENTS IN FY09

More in detail, in FY09 we (1) measured the CE into 100-200keV broadband Bremsstrahlung exceeding 1e-4 and approaching 1e-3 from Au microwires, (2) demonstrated source sizes of about 6um micrometers for x-ray photon energies greater than 100 keV using 5um thick Au foils and wires, (3) demonstrated radiographs based on Compton scattering using thick CH samples, (4) performed experiments on the Omega EP laser where we extended the results obtained on TITAN to higher energies and obtained 2D radiographs of W spheres at photon energies exceeding 100keV using Au micro-wire backlighters, (5) demonstrated 2D Compton radiography on imploding DD-filled plastic shells at Omega/Omega EP, (6) finalized the design of backlighter targets and shielding for NIF, and (7) predicted Compton radiography performance as a function of implosion yield and associated background.

The successful completion of this project allowed us to develop efficient Bremsstrahlung backlighters and to record for the first time 2D radiographs of imploding shells near peak compression. These radiographs have spatial and temporal resolution of 10um and 10 ps, respectively, and demonstrate a novel technique of x-ray backlighting and areal density measurements for inertial confinement fusion experiments and more in general for plasma physics.

INVITED TALKS AND PUBLICATIONS

- ‘’Development of Compton radiography using high-Z backlighters produced by ultra-intense lasers, ‘’ Riccardo Tommasini, Hye-Sook Park, Prav Patel, Brian Maddox, Sebastien Le Pape, Stephen P. Hatchett, Bruce A. Remington, Michael H. Key, Nobuhiko Izumi, Max Tabak, Jeffrey A. Koch, Otto L. Landen, Dan Hey, Andy MacKinnon, John Seely, Glenn Holland, Larry Hudson, Csilla Szabo, **Invited Talk**, The 15th International Conference on Atomic Processes in Plasmas, Gaithersburg, March 19-22, 2007

- R. Tommasini, et al. , “Development of backlighting sources for a Compton radiography diagnostic of Inertial Confinement Fusion targets,” **Invited Talk**, 17^{th} topical conference HighTemperature Plasma Diagnostics, Albuquerque, New Mexico, May 11-15, 2008

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4. R. Tommasini, et al., "*Compton radiography of direct-drive Implosions,"* to be submitted to Physical Review Letters, 2010

5. R. Tommasini, et al., “Development of high-Z backlighters produced by ultra-intense lasers”, to be submitted to Physics of Plasmas, 2010

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11. R. Tommasini, et al., “Development of high-Z backlighters produced by ultra-intense lasers”, to be submitted to Physics of Plasmas, 2010