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Experimental multi-keV x-ray conversion efficiencies from laser exploded germanium foil.

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Target design for multi-keV x-ray laser-produced experiments is necessary in Inertial Confinement Fusion and hence for future LMJ experiments. On the way to ignition, a series of experiments is scheduled to reach hot and dense plasma regimes. The need in backlighters for target radiography goes toward brighter x-ray sources linked with higher photon energies [1]. Solid targets enable the creation of multi-keV sources at various photon energies but exhibit low efficiencies. X-rays mainly originate from hot underdense region of the ablated material of the solid target [2]. Underdense radiators such as gas, doped foam or doped aerogel are more efficient but have a limited spectral domain limited to photon energies accessible with materials for which such targets can be made [3]. Experiments with a thin foil irradiated with 2 laser pulses (one delayed in time) lead to hot and underdense plasmas ($n_e / n_c < 0.2$ and electron temperature of few keV), which are efficient to produce multi-keV K-shell emission since ablation and hydrodynamics energy losses are low and the major part of the laser energy is efficiently absorbed by inverse Bremsstrahlung. A large plasma volume is heated by a bleaching wave leading to high electron excitation and multi-keV x-ray emission [4,5].

The concept of exploding metallic thin foils by two laser pulses delayed in time has been tested at the OMEGA laser facility (University of Rochester). The first laser pulse creates an underdense plasma, and the second laser pulse heats the plasma plume, which produces strong K-shell line emission. Previous works [5-7] with prepulsed foils of titanium (He_α at 4.7 keV) and copper (He_α at 8.3 keV) showed high multi-keV x-ray conversion efficiencies (CEs). CEs are increased by a factor of more than 2 in comparison with thick disks and are close to efficiencies obtained with gas targets. Experiments to measure CEs obtained with thin foils of germanium (He_α at 10.3 keV) are shown here

OMEGA laser is a 60-beams facility delivering a maximum of 30 kJ at 3ω (λ=351 nm), designed for direct drive implosions. Our experiment uses a subset of the laser beams grouped in three cones focused on a planar foil: one cone for the prepulse (incident on the foil at 21° from target normal axis) and two cones for the heating pulse (with angles 42° and 58.8° to the target axis). The beams were equipped with polarization smoothing plates (DPR) but no other smoothing technique was used on these experiments. All the beams pointed the center of the target located at the chamber center. In the experiments we show here, the germanium thin foil has been irradiated on both sides by 19 OMEGA beams per side. All the beams had the same pulse shape (flat square 1ns, ~500 J@3ω). Per side, 5 beams were used for the prepulse and 14 beams for the heating pulse. The influences of the prepulse on CEs have been evaluated for two delays of the heating pulse relatively to the prepulse: 2 and 4 ns. The laser energy and the fluence for each pulse and for the three shots are compiled in *Table 1*. The average energy per beam was 490 J and the beams were defocused to have different fluences for the 2 pulses. The laser intensities obtained were ~6.6×10^{14} W.cm^{-2} per side for the prepulse and ~6.5×10^{15} W.cm^{-2} per side for the heating pulse taking into account the angles of incidence of the beams on the target under the assumption of uniform irradiation over a focal spot, crudely evaluated from the beam aperture (f/6.2). Targets were composed of a thin germanium foil (6 µm thick) held by a mylar washer of 2 mm inner diameter, 4 mm outer diameter and 100 µm thick. The direction perpendicular to the foil is the axis of symmetry of laser cones. Germanium x-ray emission has been consistently observed with an x-ray diodes based absolutely calibrated diagnostic DMX and time integrating or time resolved x-ray imaging diagnostics.

Delay (ns)	Pre-pulse energy (kJ)	Heating pulse energy (kJ)	Pre-pulse fluence (x10^{15} W.cm^{-2})	Heating pulse fluence (x10^{15} W.cm^{-2})
/	/	6.8	/	6.5
2	2.45	6.8	0.66	6.5
4	2.5	6.85	0.67	6.5

Table 1 Prepulse and heating laser pulse parameters for the three shots on germanium foils. Energies and fluences are given per side of the foil.

DMX is a broadband spectrometer (time resolved x-ray diodes array [8]) measuring the x-ray power emitted by the target. It is configured to look after the high-energy part of the spectrum (2-20 keV), with eight channels covering the helium-like and hydrogen-like germanium lines spectral region within the range 10-12 keV. The spectral range of each channel was adjusted by choosing appropriate filter materials. DMX had a view at a 37.6° angle with respect to the foil normal. Hard x-ray CEs are assessed from DMX data time integrating from the beginning of the heating pulse for two spectral and integrating over a spectral bandwidth. CE is the ratio of measured x-ray energy (energy per steradian multiplied by 4π) produced by the heating pulse to its laser energy. The overall relative uncertainty is 20% on the CE numbers from DMX data considering the filter transmission and detector sensitivity calibrations and the data reduction treatment necessary to take into account the broadband response of the DMX channels.

For photon energies between 10 and 13 keV, the CEs are 1.2 % without prepulse and 1.3 % and 2.6 % when the heating pulse arrives 2 ns and 4 ns after the prepulse respectively. For the same laser conditions, CEs are 1.3 % without prepulse, 1.3 % and 2.7 % respectively, for photon energies above 10 keV.

These results (cf. *figure 1*) show a significant effect of the plasma preforming by a first laser pulse on the x-ray conversion efficiency: the CE is increased by a factor of 2.2, considering the narrow spectral bandwidth of germanium K-shell emission (from 10 to 13 keV), showing the emission mainly comes from the K-shell emission. Another important feature is that there is no increase in CE with a delay of 2 ns, for which the plasma had not enough time to expand and the plasma parameters are not optimum: large low density volume for laser absorption and high Te for K-shell excitation. This behaviour is also shown in figure 2 with time resolved signals of the platinum DMX channel, which integrates photon energies from 10 to 11.6 keV.

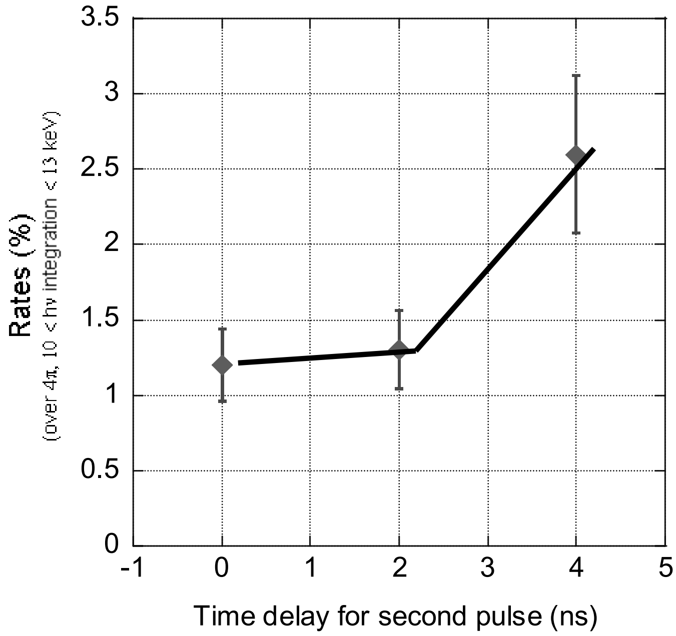

figure 1 Absolute germanium multi-keV X-ray conversion rates obtained with DMX for spatial integration over 4p and photon energies between 10 and 13 keV.

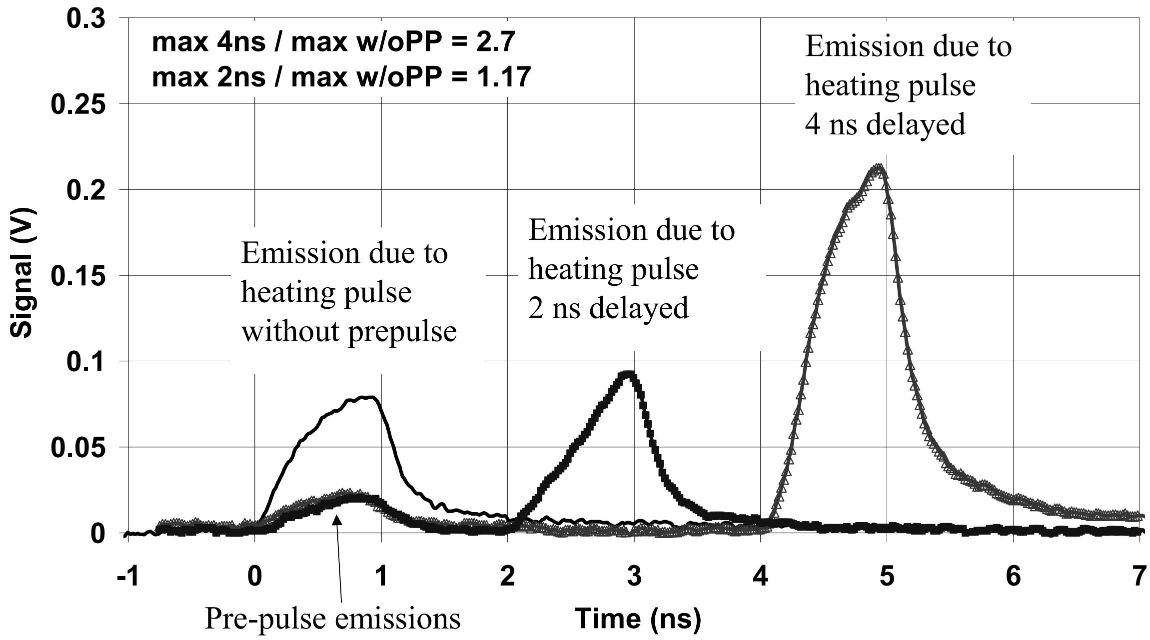

figure 2 Time resolved signals of the DMX Pt channel representative to the mutil-keV x-ray emission of germanium produced by the heating laser pulse, delayed in time or not.

X-ray emission is observed by two time-integrating pinhole cameras. PHC 9 has a side view at 149° angle with respect to the target axis and PHC 12 has an opposite side view at a 44.5° angle. The magnification is 4 and a 150 µm beryllium filtering plus a 25 µm aluminium filter restrict the energy above 4 keV. PHC images in *figure 3* show the increase of the hard x-rays emission size when the foil is exploded by the prepulse (for two heating pulse delays) compared to the case without prepulse. This emission size enlargement is true for both sides as well. The diameter of the x-ray emission spot is doubled when the heating pulse is delayed by 4 ns compared to the case without prepulse.

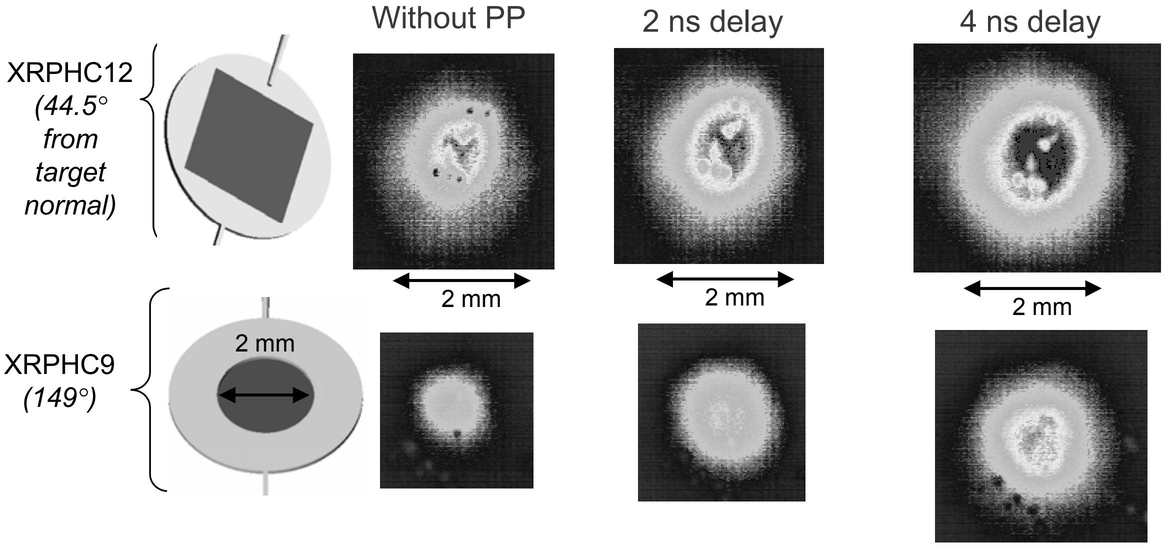

figure 3 X-ray pinhole images taken from both sides of the target for the case without prepulse and for 2 delays for the heating pulse.

In summary, a new method for improving multi-keV x-ray sources has been tested with germanium foils. This method is based on the creation of an underdense plasma by exploding a thin foil with a first laser pulse and then heating the plasma by another laser pulse delayed in time. These experiments showed high conversion efficiencies for germanium, which produces up to 2.8 % of multi-keV x-rays around 11 keV relatively to the laser energy. Thin prepulsed foils reveal a gas-like behaviour associated with a potentially wider spectral range for future x-ray sources development since the extrapolations to high Z materials show as well high multi-keV x-ray production in the range 6-12 keV.

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