X-ray measurements at high-power lasers

Relative conversion efficiencies of short pulse laser light into K X-ray radiation in medium to high Z elements

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Abstract. Conversion efficiencies of laser light into K x-ray radiation are used to characterize laser-solid interactions e.g. in measurements with back-lighter targets in Inertial Confinement Fusion research or in ultra short x-ray science where ultra short laser pulses are used to create x-rays for investigation of dynamic processes. In our measurements we observed high energy (few tens of keV) K x-ray radiation of element pairs created upon impact of a 1 ps, 100 J laser pulse on the target surface. The high-energy electrons created in this interaction ionise and excite the target material. We have used high purity alloy foils of Pd and Ag, as well as In and Sn and crystals of CsI and rare earth molybdates as target materials. Both constituents of these targets were simultaneously excited in one shot. The K x-ray radiation was dispersed and detected with the LCS (LULI Crystal Spectrometer), a Cauchois-type cylindrically bent transmission-crystal spectrometer. Measuring ratios in the x-ray spectra permits determination of relative conversion efficiencies for pairs of elements under identical laser-target interaction conditions.

1 Introduction

Advances in fast x-ray science and in high energy density physics (HEDP) including inertial confinement fusion (ICF) research show an increasing need for x-ray diagnostic tools. Imaging of ultra fast processes and x-ray radiography at ICF research facilities require detailed knowledge of laser produced x-ray sources. X-ray diagnostics need to be developed to anticipate the generation of high energy x-rays and hostile environments near the media to be detected. New instrument development \cite{1-3} by the Naval Research Laboratory (NRL) and the National Institute of Standards and Technology (NIST) provide solutions for detection of high energy x-rays in the time integrated mode at high-energy laser facilities like the OMEGA laser facility or the National Ignition Facility (NIF). With a cylindrically curved transmission crystal spectrometer the NRL-NIST team observed K radiation from gold targets \cite{3} at the TITAN laser facility at the Lawrence Livermore National Laboratory (LLNL).

The observation of high energy x-rays raises the question of efficiency of x-ray production by using high power lasers. X-Ray conversion efficiencies are of interest for inertial confinement fusion research in the case of indirect drive ICF targets where the fusion capsule is compressed and ignited by x-ray radiation produced by heating of the inside of a hohlraum with high-energy laser beams \cite{4}. Secondly, it is important for backlighter experiments in ICF and laser produced

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plasma research, where a backlighter laser-produced x-ray source can provide radiographic studies of the target [5]. Further study of the transformation of high intensity laser light into x-ray radiation is needed for fast ignition [6] research, where the laser created high energy electron beam properties can be studied through the x-ray light they produce when travelling through material [7]. The rapidly-developing field of ultra fast science increasingly needs relative and absolute conversion efficiencies at facilities that produce femtosecond x-ray sources with ultra short-pulse lasers [8].

There have been numerous theoretical approaches to provide optimization of the Kα radiation produced in the interaction between an ultra-short laser pulse and a solid target [9] and mechanisms of production of Kα generation in these systems [10]. Experiment has yet to support the theory where the typical absolute accuracy of conversion efficiency measurements is of the order of 200 percent.

When an ultra-short intense laser pulse (>10^{17} \text{ W/cm}^2) interacts with a solid target, electrons can be accelerated to relativistic energies inside the target [11]. These high energy electrons while circulating in the target material will be scattered and excite K x-ray radiation. In this paper we provide a method for relative conversion efficiency measurement of this x-ray radiation as a result of short pulse intense laser interactions with solid targets. The (small) difference in the cross sections of the high energy electrons to excite the K lines from different elements in the target can influence the inferred relative conversion efficiencies.

2 Experimental setup at the Pico 2000 facility

The measurements reported here have been carried out at the new Pico 2000 laser facility at “Laboratoire pour L’Utilisation des Lasers Intenses” (LULI) in Palaiseau, France. This facility can provide a high energy, ≈ 1 kJ, Nd:glass laser beam with a pulse duration of 1.5 ns and a short pulse beam at (currently) ≈ 100 J beam energy and with a pulse duration of 1 ps. With best focus the short pulse beam can reach 10^{20} \text{ W/cm}^2 power density on target. The primary diagnostic of the relative conversion efficiency measurements was the LCS cylindrically bent transmission crystal spectrometer [12], a Cauchois-type crystal spectrometer [13] made after the original design described in [14]. Figure 1 shows a schematic view of the spectrometer. It utilizes a cylindrically bent quartz transmission crystal (10-11 planes) in Chauchois geometry with thick lead shielding around the two spectrometer windows in the front side of the spectrometer (left on Fig. 1) and the crossover point. This shielding prevents direct x rays from the source to reach the detector, except for the image of a pinhole placed on the center axis of the spectrometer in the front lead plate. This pinhole image helps to align the instrument. LCS has two different detector positions, IP#1 on the Rowland focusing circle and a second one, IP#2, 200 mm behind the first one. This “off Rowland circle” geometry can increase resolution if the source can be considered point like. In this case, however, the resolution is source-size limited (for more details see [12]). The spectrometer utilizes Fuji MS1 type phosphor storage image plates (IP) as detecting media in the two detector positions. The crystal-to-source standoff was 600 mm. In the relative conversion efficiency measurements we have used alloy foil targets and rare earth molybdate and CsI crystals. Targets were prepared from the materials shown in Table 1. In the experiment the short pulse laser beam of the PICO 2000 facility was used with the maximum available laser energies (between 79 J and 101 J) at best focus and shortest possible pulse length, 1 ps. The short pulse beam was incident to the target plane at 56.25°, the axis of LCS was at 90° angle with the laser beam and was looking at the target at an angle of 33.75°. In most of the shots half an image plate was used in the first and second detector position (registering the left or right side of the mirror-symmetric spectra) but in some shots only one full IP was used in one of the positions.

\footnote{The identification of any commercial product or trade name does not imply endorsement or recommendation by the institutions performing this work.}
Table 1. Target materials and thicknesses.

<table>
<thead>
<tr>
<th>Type of target</th>
<th>Material</th>
<th>Composition ratio</th>
<th>Target thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>CsI</td>
<td>Cs 50%, I 50%</td>
<td>≈ 100 µm</td>
</tr>
<tr>
<td>Alloy foil</td>
<td>InSn</td>
<td>In 50%, Sn 50%</td>
<td>100 µm</td>
</tr>
<tr>
<td>Alloy foil</td>
<td>Pd-Ag alloy</td>
<td>Pd 70%, Ag 30%</td>
<td>150 µm</td>
</tr>
<tr>
<td>Alloy foil</td>
<td>Ag-Pd alloy</td>
<td>Ag 70%, Pd 30%</td>
<td>150 µm</td>
</tr>
<tr>
<td>Rare earth molybdate crystal</td>
<td>Gd₂(MoO₄)₃</td>
<td>2:3 Gd to Mo ratio</td>
<td>214 µm</td>
</tr>
<tr>
<td>Rare earth molybdate crystal</td>
<td>Tb₂(MoO₄)₃</td>
<td>2:3 Tb to Mo ratio</td>
<td>217 µm</td>
</tr>
</tbody>
</table>

3 Relative conversion efficiencies

LCS spectra are obtained upon digitization of the storage image plates. A small image rotation is performed if needed to align the spectral lines in a region of interest (ROI) before vertical summation of pixel values. The spectra presented are the pixel column averages of these corrected spectral images. The energy calibration of the spectra was performed based on the spectral lines appearing in the spectrum. We anticipate no line shifts due to highly charged ion formation within the range of accuracy needed here. Figures 2a) and b) show energy calibrated x-ray spectra from PdAg alloy targets obtained with the detector placed on the Rowland circle. One can observe that the peak ratios are different in the case of Ag70%(Pd30% on Figure 2a) and Pd70%(Ag30% on Figure 2b). At first sight the peak intensities of the Ag Kβ seem to be unexpectedly small but as shown on Figure 2c) the Ag Kβ lines are more susceptible to self absorption in the target material relative to the other peaks. From previous observations and from other experiments we know that the x-ray source size is not equal to the laser spot size but it is about 10 to 100 times larger. It is very likely that self absorption plays a big role in shaping the final detected spectrum. A correction for this self absorption might be a complicated problem if the x-ray source size and the emission depth are not precisely known. On the other hand there is no significant difference in the absorption for the Kα peaks of Ag and Pd, since of very similar energy, making them good candidates for the determination of relative conversion efficiency. Similar analysis has been done for the InSn and the CsI targets with the same overall conclusion to use of the Kα peaks for the analysis. Table 2 summarizes the result of the measurements. The two shots for each target mean a total of four independent measurements as the spectra of the left and right sides of the image plates are calibrated and analyzed separately. To get relative conversion efficiencies the area of the Kα peaks are calculated by fitting the Kα₁ and Kα₂ peaks with Voigt profiles and then the ratio of the sum of the two peaks in a form of (Peak areas of lower Z)/(Peak areas of higher Z) are shown. The final Kα peak ratios are the average of the measurements and are tabulated along with an estimated uncertainty. In the case of the AgPd alloy foils a normalization of the Kα peak areas is performed for the...
Fig. 2. Sample spectra and photoelectric absorption of the target materials. a) Energy calibrated spectra from Ag70%Pd30% alloy foil targets in shots #03 and #04. b) Energy calibrated spectra from Pd70%Ag30% alloy foil targets in shots #05 and #12. c) Photoelectric absorption cross sections [15] of the two PdAg alloy foils with different composition (Pd70%Ag30% and Ag70%Pd30%). The unexpected behavior of the Ag Kβ peak on a) and b) can be explained with self absorption based on c) (see text).

Table 2. Relative conversion efficiencies derived from Kα peak ratios for the measured targets. All ratios have also been normalized to account for target composition. Shots #10a and #03a are from an earlier set of shots during the testing of the LCS spectrometer in year 2007.

<table>
<thead>
<tr>
<th>Element pair</th>
<th>Composition ratio</th>
<th>Measurements</th>
<th>Ko peak ratios, rel. conv. eff. lower Z/higher Z</th>
<th>Estimated uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI</td>
<td>Cs 50%, I 50%</td>
<td>shot #10a, #03a</td>
<td>1.13</td>
<td>±0.15</td>
</tr>
<tr>
<td>InSn</td>
<td>In 50%, Sn 50%</td>
<td>shot #06, #16</td>
<td>1.21</td>
<td>±0.15</td>
</tr>
<tr>
<td>AgPd</td>
<td>Ag 70%, Pd 30%</td>
<td>shot #03, #04</td>
<td>1.64</td>
<td>±0.15</td>
</tr>
<tr>
<td>PdAg</td>
<td>Pd 70%, Ag 30%</td>
<td>shot #05, #12</td>
<td>0.75</td>
<td>±0.15</td>
</tr>
</tbody>
</table>

foil compositions (70% Ag and 30% Pd in one case, shots #03, #04 and 70% Pd and 30% Ag in the other case, shot #05, #12, as shown in Table 1). As seen in the last two lines of Table 2, the use of the factory given composition ratios for the AgPd alloy foils result in seemingly inconsistent Ko peak ratios. The conversion efficiency is expected to decrease with increasing periodic number as seen in [10] and for adjacent Z elements it is expected to be close to unity. The discrepancy may originate in the inaccurate knowledge of the composition of these alloy foils or in unexplained self-absorption processes in the high density plasma.

To investigate this further we have performed an x-ray fluorescence (XRF) measurement to deduce the foil composition. This XRF measurement performed on the whole surface of the foils gave the result that the foil composition are very close to the factory given compositions. The discrepancy in the laser produced data from the Ag/Pd alloys is unlikely to be caused by the inaccurate knowledge of the compositions. Further analysis of the spectra of the relative conversion efficiency measurement and comparison of these spectra with the XRF spectra showed that we can observe other unexpected peak ratios in the PdAg spectra. In addition to the anomalous Pd Ko and Ag Ko ratios in the two different-composition alloy cases we can also
observe that the K\(\beta\)/K\(\alpha\) peak ratios in all cases are (up to 2 times) larger than the natural line ratios \[16\]. This fact further suggests the presence of plasma-physical and absorption processes that require further investigations in the case of the alloy foil targets.

We also took conversion efficiency data with rare earth molybdate crystals. In this case the two peaks of interest (Mo and Gd or Mo and Tb) are far apart in energy (about 26 keV and 27 keV energy difference). This means that one would need to account for the changing efficiency of the spectrometer over this energy range. Both the crystal and the image plate detector have decreasing efficiencies toward higher x-ray energies. The fact that the resolving power of the spectrometer is going down with increasing x-ray energies will lead to lower accuracy in these measurements. To further analyze these data we have proposed an efficiency calibration of the LCS spectrometer at the SIMPA Electron Cyclotron Resonance Ion Source (ECRIS) facility of the “Laboratoire Kastler Brossel” (LKB) and the “Institut des Nanosciences de Paris” (INSP) in Paris. The x-ray bremsstrahlung spectrum of the high energy electrons (about 23 keV average electron temperature) in the plasma of SIMPA can be detected simultaneously with LCS and with a calibrated silicon solid state detector, providing a relative calibration in this measurement. With this technique a cross-calibration of the efficiency scale is in principle possible.

4 Summary

We have investigated a method for measurement of relative conversion efficiencies of laser light into x-rays by observing the x-ray radiation of metal alloy foils and other crystalline targets using a cylindrically bent transmission crystal spectrometer. We obtained preliminary results for relative conversion efficiencies in the case of targets with equal composition ratios (InSn, CsI), but found unexpected results in the case of variable-composition PdAg alloys that require further investigation. With well chosen targets this technique shows the potential to draw a relative conversion efficiency map for high-Z elements. With ongoing work and efficiency calibration of the curved transmission crystal spectrometer we are proceeding toward more accurate measurements over a larger energy range.

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References

