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Scaling of x-ray K-shell sources from laser-solid interactions

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Abstract

The application of x-ray sources to imaging of dense objects is a standard technique. The quality of the x-ray image depends both on the x-ray source wavelength and on the flux. To improve the flux of the x-ray source it is important to understand how the conversion efficiency scales with laser irradiance and target material. We present measurements of x-ray conversion efficiency in solid Cr, Fe, Ni, Zn and Ge targets as a function of the laser irradiance using the OMEGA laser facility. The results show a steep decrease in the conversion efficiency with increasing Z while the scaling of conversion efficiency with laser irradiance can show a peak. Values for x-ray yield are determined using time-integrated crystal spectrometer data.

Keywords: x-ray, conversion efficiency, x-ray yield, x-ray imaging, laser plasma, x-ray spectra

1. INTRODUCTION

The study of ICF related phenomena including shocks, density gradients and perturbations, opacity, size and interface position is most often studied using the technique of x-ray imaging.¹ X-rays can come from either self-emission or an independent backlighter. In either case, the quality of the x-ray image depends on the brightness of the x-rays at the desired wavelength. For high-density objects, such as those found in ICF related experiments, x-rays of up to 10 keV are needed for the desired penetration and contrast. In addition, laser based experiments use extremely small targets, often requiring spatial resolutions of only a few microns. This constraint on resolution leads to high magnification that further reduces x-ray flux density at the detector.

For x-ray backlighting the production of x-rays from laser solid interactions involves the absorption of laser light, the ionization of the target, hydrodynamic motion, propagation of heat and radiation into the target and finally transport of the radiation out of the plasma. Quantitative information about x-ray brightness is difficult to model accurately. With this in mind it is important to rely on experimental data to determine scaling laws for x-ray production. However, the number of x-rays produced depends on laser parameters including color, spot size, pulse-length, energy, irradiance, beam smoothing, polarization and angle of incidence.^{2 3 4 5 6 7} A collection of studies had shown that target material, composition and density also strongly affect the x-ray output.^{8 9 10 11} In order to generate sufficient x-ray flux for recording an image on the detector with sufficient signal-to-noise, resolution, dynamic range and at the needed x-ray energy requires detailed knowledge of how the x-ray yield scales with the parameters listed above. Some of this experimental work has previously been done.²⁻¹¹ The problem encountered by the experimentalist is that the number of data points is limited and those that do exist often disagree. In some cases discrepancies can be explained by the differences between lasers (in particular the far field distribution). This is often seen most clearly in the x-ray spectra.³ In this paper we investigate the scaling of x-ray yield and conversion efficiency over a large range of energies using the OMEGA laser facility at the University of Rochester.¹² In particular we concentrate on the scaling of x-ray yield and conversion efficiency with laser irradiance and target material. Specifically, irradiances from

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10^{14} to 6×10^{16} W/cm² using up to 6 kJ of laser energy were used while targets with emission at energies ranging from 5 to 11 keV were studied.

2. EXPERIMENTAL ARRANGEMENT

Experiments were performed on the OMEGA laser facility at LLE using flat solid disk targets. Targets were of diameter 1 and 3 mm with a nominal thickness of 12 μ m. Rotation and translation alignment fiducials were used on the targets in order to position targets such that multiple beams would overlap when tightly focused. The primary diagnostic was a time-integrated multi-channel crystal spectrometer (Henway¹³) recording on Direct Exposure Film (DEF¹⁴). This spectrometer observed the irradiated side of the target at an angle of 34 degrees with respect to the target normal. It should be kept in mind that typical applications of x-ray backlighters use the transmission through the foil to image the object reducing the number of photons by approximately one-quarter to one-half. As shown in Fig. 1, targets were oriented normal to the H7-H14 axis in the OMEGA chamber where opposing ten-inch manipulators (TIMs) had views normal to the target surface from front and rear. Additional diagnostics included an aluminum step-filtered DEF film pack to look at integrated x-ray yields, a lower energy-resolution streaked spectrometer, static pinhole cameras at magnification 4X (one of which observed the rear side of the target at an angle of 34 degrees), and two framing cameras at magnification 6X.

Figure 1: Experimental setup on the OMEGA chamber. Target is positioned at target chamber center. X-ray framing cameras (XRFC) are positioned normal to the rear surface and at 37 degrees from the irradiated surface at a magnification of 6X. The streaked spectrometer (SSCA) is positioned at 79 degrees from the target normal and the time-integrated x-ray spectrometer is positioned at 34 degrees. In addition 5 static pinhole cameras at 4X observe the target from various angles.

Targets were irradiated with anywhere from 3 to 12 laser beams using a 1 ns square temporal shape and an average energy of 500 J per beam. The beams are frequency tripled to 351 nm wavelength. Irradiance on target was varied both by changing the number of laser beams and by changing the focal spot size with some overlap in irradiance between the two methods. No beam smoothing was used in these experiments (including RPPs, DPPs and SSD). As shown in the face on view of Fig. 1, laser beams were incident on the target in two cone angles with six beams in each cone, the first of which was at 23 degrees from the target normal and the second at 48 degrees. Unless all 12 beams were used, only the inner cone was used to minimize the angle and alignment tolerances.

The primary diagnostic, the Henway spectrometer, consists of 4 convex crystals in separate channels with some overlap between energy ranges in the channels. The overlap allows for relative reflectivity calibration between the different channels. The crystals used included ammonium dihydrogen phosphate (ADP), pentaerythritol (PET) and silicon, covering an energy range from about 4-13 keV. Si<111> was used for the highest energy recording and found to have the lower reflectivity due to higher energy resolution. The time-integrated x-ray spectra were recorded on DEF x-ray film and processed using the method prescribed by Henke *et al.*¹⁵ The film was then digitized using a microdensitometer with a step size of 20 μ m along the spectral direction for a length of about 15 cm, averaging over a width of

700- μm perpendicular to the scan direction. The actual exposure on the film was then determined using calculated and measured values.¹⁵ The spectrometer does not use a slit such that the spectral resolution of the instrument is a function of the source size. This does not affect the yield measurements as they are integrated over an energy range much larger than the instrument resolution, however, details of the spectra are obscured at large focal spot sizes.

3. EXPERIMENTAL RESULTS

Most of the results reported below were taken with the time-integrated Henway spectrometer. Spectrometer data used a fit to identifiable emission lines to determine the energy scale. The optical density on the film was then converted into photons per square micron using data from Henke. Total emission from the target was then determined using the distance of the target to the spectrometer as well as the attenuating filters. Reflectivities of the crystals have been estimated from published results.¹⁶

3.1 X-ray Yield and Conversion Efficiency Scaling

Scaling of the x-ray yield and conversion efficiency with laser irradiance was performed with Cr, Fe, Zn and Ge. Data is presented in terms of total x-ray energy out in Joules from the source into 4π steradians. Conversion efficiency is in terms of total x-ray energy out in Joules divided by the incident laser energy in Joules (denoted X-ray/Laser in some instances). Corrections for distance and filters have been made with only estimates of crystal reflectivities. Yield and conversion efficiency was determined by integration over a bandwidth of 550 eV spanning the He-like $n=2-1$ transition ($1s^2-1s2p$) and in some cases containing part of the H-like $n=2-1$ transition ($1s-2p$). The details of the spectra used are shown in a later section. Defocusing of the laser spot was accomplished by translating the lens toward the target i.e. converging beams on target.

Measurements of Cr emission at 5.68 keV were performed, motivated by a slightly higher energy alternative to Ti (4.75 keV). Six beams (3 kJ) were used on each shot while the irradiance was changed using the focal spot diameter varying from 200 to 650 μm . Based on data from other sources the irradiance scan started at $1 \times 10^{15} \text{ W/cm}^2$.¹² It was anticipated that we would see a rise and fall in the yield near this value. Figure 2 shows that the irradiance was not low enough to see the turn around in the conversion efficiency. Conversion efficiency was very high, greater than 3%, at an irradiance near $1 \times 10^{15} \text{ W/cm}^2$. This appeared to be a trend in all the data points, mainly that the peak in the conversion efficiency is at lower irradiance than measured on other laser systems.

Figure 2: Scaling of Cr emission and conversion efficiency with laser irradiance. 3 kJ of laser energy were used for each data point while the spot size was changed.

Figure 3 shows the x-ray yield and conversion efficiency for emission from solid flat Fe targets. The emission is measured about the He-like transition at 6.7 keV. Three different spot sizes were used in order to vary the laser irradiance significantly, including 600 μm , 300 μm and a best focus of approximately 80-100 μm . In addition, the laser energy was varied by reducing the number of laser beams used, including 2, 4 and 6 with energy of about 500 J per beam. The three lowest irradiance data points were taken with a 600 μm laser spot diameter and 2, 4 and 6 beams respectively. The x-ray yield and conversion efficiency peaked at an irradiance of about $3 \times 10^{15} \text{ W/cm}^2$ corresponding to a spot size of roughly 300 μm and an incident energy of 3 kJ (6 beams) using a 1 ns square pulse. The final data point was obtained with 6 beams overlapped and tightly focused. Error bars in irradiance are large at the higher irradiance due to a lack of framing camera data. Measurements of the spot size were determined from saturated static pinhole images. The lower bound on irradiance, which is likely an overestimate of the spot size, was determined from the saturated images. The upper bound on irradiance assumes perfect overlap of the focused beams. Errors in the yield are relative error, determined by the relative reflectivities of the crystals used and the transmissions of the filters as well as the ability to determine noise and energy dispersion. These values are estimated to be $\pm 10\%$. Absolute values may have errors due to absolute crystal reflectivity. Crystals used for the Fe data points were PET with different radii of curvature. Conversion efficiency is similar to the yield with a peak in conversion of roughly 3%. This conversion efficiency appears to be quite high in these experiments compared to those of some previous work. However, these values are consistent with data taken on the NOVA laser.¹⁷ Some discussion of this is included in another section. Details of the spectra used to determine the data in Fig. 3 will also be discussed in a later section. An often-used scaling law is also included in Fig. 3 where conversion efficiency scales with laser irradiance to the negative one-third power. This scaling law was determined from experimental data taken on other laser systems.

Figure 3: X-ray yield scaling and conversion efficiency from Fe targets as a function of laser irradiance. The left vertical axis is the energy generated at the source into 4π steradians without correction for crystal reflectivity. The right vertical axis is the conversion of laser energy into x-ray energy. The additional curve is a power law for the irradiance, $I^{-1/3}$, which is typically used for conversion efficiency.

Data taken with solid flat Zn targets looked at x-ray emission from the He-like $n=2-1$ transition ($1s^2-1s2p$) at 9 keV. Energy and focal spot sizes were varied from 1.5-6.0 kJ and 100-300 μm . An attempt was made to look at the effect of varying energy versus spot size by repeating laser irradiance using both methods. Figure 4 shows the data taken with the Zn targets. Data taken with three beams at tight focus had similar irradiance to that taken with 12 beams at a 200 μm focal spot. Data taken with 6 beams at a 200 μm focal spot was similar in irradiance to that taken with 12 beams at a 300 μm focal spot. The

conversion efficiency was higher for the larger focal spot size in one case and lower in the other leading to inconclusive evidence whether the spot size mattered. Unfortunately, resources were not available to make drastic changes in spot size and retain the same laser irradiance. Two of the data points were repeated under the same conditions, namely irradiance of 1×10^{16} and 4×10^{16} W/cm², and showed consistent results. Throughout the data taken, results have been reproducible to the level of 20% or better. Again the peak in the conversion efficiency has not necessarily been measured. At an irradiance of 4.5×10^{15} W/cm² the conversion efficiency has not begun to fall. The maximum conversion efficiency was about 0.8% while the lowest measured was about 0.25%, not inconsistent with measurements on NOVA.¹⁸

Figure 4: Scaling of Zn yield and conversion efficiency with laser irradiance. Various combinations of energy and spot sizes were used.

Interest in producing very high-energy backlighters is motivated by current experiments at OMEGA as well as by future NIF¹⁹ experiments at LLNL and ‘Z’²⁰ experiments at SNL. The larger targets will require higher-energies to match the increased path lengths. Unfortunately one typically sees a rapid decrease in conversion efficiency and yield as higher Z targets are used to produce the higher energies. Alternative approaches to flat disks, using gas filled Be cans are being pursued elsewhere.²¹

We have made an attempt to determine what x-ray energies the OMEGA laser is capable of producing using up to 12 beams (6 kJ) on solid disk targets. Measurements of Ge emission at 10.28 keV were made at high laser irradiance from $\sim 7 \times 10^{15}$ to 7×10^{16} W/cm². Figure 5 shows the results of the x-ray yield and conversion efficiency. At this energy a Si<111> crystal was used with no duplicate recording on other spectrometer channels. All measurements were made with tightly focused overlapped beams using no beam smoothing. The number of beams was varied using 1, 2, 6 and 12 beams. Accuracy of the overlap of 12 beams is undetermined as the outer 6 beams were incident at angles of 48 degrees from the target normal. Framing camera measurements were again unavailable due to large amounts of background noise. Small deviations in positioning the target would lead to large difficulties in overlapping the beams. Some information on overlap was determined from static pinhole images. Unfortunately, most diagnostics had large amounts of background noise produced by high-energy (>15 keV) interactions of hot electrons. Duplicate sets of data were taken at the two highest irradiances showing similar results. This indicates that target positioning and beam pointing were consistent if not accurate. Conversion efficiency appears to peak near 4×10^{16} W/cm², however, the error in the irradiance for the following point may be quite large. Data taken at the two lowest intensities had very low yield with 50% error bars due to noise. The data point using one beam did show an 80-100 μ m diameter x-ray emission spot on the static camera. The two beam shot showed an offset between focused spots of ~ 50 μ m center to center.

Figure 5: Scaling of Ge emission and conversion efficiency at 10.3 keV as a function of laser irradiance. All shots were taken at best focus ($\sim 100\mu\text{m}$) using one, two, six and 12 beams respectively. At 6 and 12 beams there are duplicate data sets.

Figure 6: X-ray yield scaling as a function of x-ray energy (target Z) using Fe, Ni, Zn and Ge targets. Laser irradiance was $\sim 2\text{-}4 \times 10^{16} \text{ W/cm}^2$ using 6 tightly focused overlapped beams. Total laser energy was $\sim 3 \text{ kJ}$.

In order to see the difficulties of generating higher energy backlighters one can look at the conversion efficiency as a function of the target Z, or emitted K-shell energy. Figure 6 shows data obtained with Fe, Ni, Zn and Ge under the same irradiance conditions. Conversion efficiency is plotted versus the x-ray energy produced for an irradiance of $2\text{-}4 \times 10^{16} \text{ W/cm}^2$ corresponding to 6 beams overlapped and tightly focused. It should be noted that the scaling of conversion efficiency will depend on

the laser irradiance due to the strong dependence on irradiance for a given target type. Ideally one would like to plot the peak conversion efficiency versus emission energy. The total number of photons is also plotted, which do not change the scaling significantly over this small energy range. Error bars in energy denote the bandwidth over which the emission was integrated. There is also some variation in the laser irradiance. The Zn and Ni laser irradiance were much better characterized than the Fe and Ge data. There is also some error in the relative crystal reflectivities.

3.2 Detailed Spectra

Details of the spectra used to obtain the yield and conversion efficiency are presented below. This data was taken using the four channels of the time-integrated Henway spectrometer. Because the spectrometer does not have a slit, source size broadening affects the details of some of the spectra. The results are consistent with measurements made from the opposite side of the target using a separate time-integrated spectrometer with a slit.²²

Figure 7: Fe spectra obtained at different laser irradiances. The spectra have been post-processed to correct for filter responses (Al attenuators). The vertical axis is in terms of keV/keV-sphere. This is the emission into a sphere of 4π steradians.

Figure 7 shows the detailed time-integrated spectra from Fe targets. These spectra were taken on two different PET crystals with three different attenuation channels. Aluminum was used for attenuation, as it has a relatively flat transmission over a large energy range and minimizes fluorescence.²³ The spectra have been corrected for the aluminum attenuation and relative crystal reflectivities. Noise in the spectra below 6.5 keV is severely amplified by the thick (240 μm) aluminum filter correction. Integration over the 550-eV bandwidth was done before corrections to the spectra for filters (and thus before the amplification

of the noise). The change in ionization balance is not dramatic but can be seen to shift to higher ionization states. As the laser irradiance is increased we see evidence of H-like emission and a decrease in the ratio of the He- α to He- β emission intensity indicating an increase in the plasma temperature.²⁴ There is only a small trace of K- α (6.4 keV) emission at the highest irradiance. The small amount of K- α emission does not correlate with other measurements that indicate a high-energy x-ray component, presumably from hot-electrons. It is apparent that the drop in conversion efficiency is not due to burning through the He-like ionization stage.

Figure 8: Zn spectra corrected for filters and relative crystal reflectivity. Spectra at 2 & $4 \times 10^{16} \text{ W/cm}^2$ were taken using a PET crystal while the rest used a Si<111> crystal.

In Fig. 8 spectra are shown for the Zn emission. Spectra were taken using PET and Si crystals and are corrected for aluminum filter transmission. Relative reflectivity of the two crystals was determined by integrating duplicate spectra on the two crystals. The spectra at 2 and $4 \times 10^{16} \text{ W/cm}^2$ were taken using the lower resolution PET crystal while the rest used the Si<111> crystal. Relative reflectivity between the PET and Si crystals near 9 keV was about a factor of 5 . Hydrogen-like emission is not prominent even at the highest intensities indicating that the drop in yield is not due to burning through the ionization stage. Some small amount of cold K- α emission is evident in all the spectra. At the highest irradiance there is some evidence of H-like emission. It is interesting to note that the He-like 2-1 transition resonance line appears to be smaller than the intercombination line, however, this may be a satellite on the blue side of the 2-1 transition. This is also true for the Ge spectra and may be investigated further in a future paper.

Figure 9 shows the Cr spectrum taken using 6 beams (3 kJ) defocused to a $650 \mu\text{m}$ diameter spot size. He-like series emission can be seen up to the $n=5-1$ transition (He- δ). Sufficient resolution allows distinction of the He-like resonance, intercombination and some of the Li-like satellite transitions. The

total energy in the He- α emission was greater than 90 J. Additional lines associated with the higher n transitions have not been identified but have been seen in other spectra using different crystals. These are most likely satellite transitions.

Figure 9: Cr spectrum taken with 6 beams (3 kJ) defocused to a 650 μm diameter spot size. He-like emission is seen up to the $n=5-1$ transition.

3.3 Time-Resolved Spectra

Figures 10 and 11 show the time resolved emission from Fe, Cr and Zn targets. Figure 10 shows the He-like Fe emission when 6 beams are defocused to 300 μm on the target. The x-ray duration is significantly longer than the 1 ns laser pulse duration shown in the figure and shows the long decay of the emission on the log scale. The laser pulse is plotted on a linear scale. It appears that the H- α emission turns on after the He- α emission and is of shorter duration as would be expected for the higher ion state.

Figure 10: Time resolved spectrum of He-like Fe emission near 6.7 keV. The time scale is approximate but indicates a longer x-ray pulse duration than the laser pulse. The laser pulse is shown as the dotted line and is plotted on a linear scale. On the log scale of exposure the tail of the emission after the laser turns off is evident.

The time-resolved emission from the Cr targets is shown in Fig. 11 at the top using 6 beams defocused to a 200 μm diameter spot size. Although the He- α emission is saturated (top), it shows a shorter pulse duration than the Fe emission. One can also see the long decay of the emission on the log scale. The bottom of Fig. 11 shows the He-like emission from Zn using 12 beams defocused to 300 μm . Streak records with tightly focused beams showed large amounts of background noise indicating the presence of high-energy x-ray and/or hot-electrons. The duration of the Zn emission is longer than the laser pulse but appears to be shorter than the Fe or Cr emission with much less of a decay. The slope of the Zn He- α also shows the longer time that it takes to generate the higher Z K-shell emission. The slight dip in the laser pulse, seen in Fig. 10, shows up in the Zn emission showing the closer correlation for Zn to the laser pulse.

Figure 11: Time resolved spectrum of He-like emission from Cr (top) and Zn (bottom). The time scale is approximate but indicates a longer x-ray pulse duration than the laser pulse. The energy scale has not been accurately determined. Emission from the Cr He- α at 5.68 keV is saturated in the streaked image. Exposure levels are not absolute.

4. DISCUSSION

The data taken with Cr, Fe, Zn and Ge on the OMEGA laser show quite different results from some of the previous work. In particular the conversion efficiencies seem to be significantly higher than those reported in the 1980's. (The data does seem to agree with more recent work done on the NOVA laser.) The peak in the conversion efficiency also appears to be at lower laser irradiance. Many of these differences can be attributed to the far field distribution of the laser. Smooth profiles will give very different results than beams with hot spots and large modulation. Scaling of the conversion efficiency with laser irradiance does seem to follow some previously derived laws in some cases. The Fe conversion efficiency does not fall too far from the $I^{-1/3}$ scaling. The decrease in the Cr conversion efficiency scales with laser irradiance as $I^{-0.3}$ power. However, the decrease in the Zn conversion efficiency scales more closely to $I^{-0.5}$ power. As seen in the Zn spectra, there is little change in the spectral features, particularly ionization balance. This is a good indication that the drop in conversion efficiency results from poor coupling of laser energy into thermal energy due to backscatter or hot-electron production. No attempt was made to fit the Ge data. The scaling of conversion efficiency with emission energy (target Z) seems to follow a scaling of $(h\nu)^{(2.5-4.0)}$ where $h\nu$ is the emission energy and power is between 2.5 and 4.0. The plasma temperature determines the rise in conversion efficiency with laser irradiance. There is a minimum temperature that must be reached in order to excite a given ionization state. At higher laser irradiance

there are more mechanisms that come into play. One can reach a temperature where the ion is fully stripped. This is apparently not the case here as evidence suggests that the Hydrogen like states of the ions are barely reached. At high enough irradiance a significant amount of laser light can be scattered due to ion and electron plasma waves. In addition, at high laser irradiance a significant amount of laser energy can be converted into hot-electrons. These electrons typically collide with material in the experiment to create large amounts of high-energy x-rays either through bremsstrahlung or fluorescence. Although emission of cold material x-rays is usually a sign of hot electrons we have seen very little indication in the field of view of the spectrometer. However, measurements with step filtered film (large field of view) show indications of significant amounts of >15 keV x-ray emission. In addition, large backgrounds on the framing cameras, streak cameras and static pinhole cameras indicate a high-energy background.

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