UCRL- 83056
PREPRINT
CONF- 791135--7

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This paper was prepared for submission to the American Physical Society meeting to be held in Boston, Mass. on November 12-16, 1979.

November 6, 1979

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Abstract

We report recent results obtained by using a 10 channel, filtered XRD detector system to record sub-keV x-ray emission from laser-irradiated targets. Targets materials were Be, Al, Ti, Sn, Au and U, with Z ranging from 4 to 92. Targets were irradiated with 1ns FWHM, 1.06 μm wavelength pulses at an intensity of 5 X 10^{14} W/cm^2. *Time-resolved x-ray emission pulses show* systematic *and* striking variations with Z. These variations can most probably be attributed to the onset of inhibited electron conduction. Time-integrated x-ray yields are obtained as a function of target Z as well as calculated charge states $\bar{Z}$, indicating the type of physical processes that give rise to the x-ray emission. Typical sub-keV x-ray spectra are presented; in some cases such as Ti where prominent lines are present, the charge state of the plasma can be directly deduced from line ratios, agreement with numerical simulation is very good.

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48.

A preliminary study of the Z dependence of sub-keV x-ray production from laser-produced plasmas was performed on the Argus Laser Facility,[1] using one beam at a nominal laser pulse of 800 J and 1ns FWHM. The typical intensity on the target was usually 5 X 10^{14} W/cm^2. The targets consisted of disks, 600-700 μm in diameter and 12.7-25 μm thick. Target materials consisted of beryllium, aluminum, titanium, tin, gold and uranium, with atomic numbers (Z) ranging from 4 to 92. A 10 channel, filtered x-ray detector system, called DANTE-T,[2] was used to record the sub-keV emission from the laser-irradiated targets.

The targets were irradiated by f/2.2 focusing optics. The incidence angle was 30°, the incident beam was linearly polarized, 12° out of the plane of incidence. Dante-T viewed the x-ray emission at an angle of 60° from the target surface normal in the plane of incidence, away from the incidence beam. The solid angle subtended by each detector was 2.11 X 10^{-5} steradians for the lower four energy channels as well as a flat response channel and 4.36 X 10^{-5} steradians for the higher five energy channels.

One of the interesting features of this series is the systematic Z dependence of the time-resolved sub-keV x-ray emission, as shown in Figure 1. The data were obtained at a 300-520 ev channel, with a time resolution of better than 190ps. Note that as the target Z is decreased from high to low (i.e. from uranium to beryllium), the x-ray pulse shape deviates from a smooth "gaussian" to an irregular shape, the peak of the pulse becomes progressively flattened as Z decreases. The transition is shown most clearly by a titanium target, where the x-ray emission starts to increase rapidly, presumably following the rise of the incident laser intensity, then at a well defined point, the x-ray emission changes abruptly to a show "linear" rise (a better resolved channel indicates that there are oscillations in the "linear" rise region, see Figure 2) and then drops after ~1ns. For the same Z material, but at different laser intensities, the x-ray emission pulses can be quite different. This is shown in Figure 3 for gold disks. The data in this figure were obtained at a 650-940 eV channel, with a time resolution of better than 170ps. Note the x-ray emission pulse at the lower laser intensity (5×10^{14} W/cm^2) is fairly smooth (actually the top on the rising part of the pulse is very slightly flattened), but at a higher laser intensity (3.3×10^{15} W/cm^2), the x-ray emission pulse rises normally at first, then breaks away abruptly. It has been suggested that the flattening of x-ray emission pulses is due to inhibition of electron thermal conduction,[3] and that the laser intensity threshold for electron thermal conduction is dependent on the Z of the target material, the threshold increasing with Z. Following the argument of inhibited thermal conduction, one can notice the striking similarity between pulse shapes of gold at 3×10^{15} W/cm^2 and beryllium at 5×10^{14} W/cm^2. This is because conduction inhibition sets in almost immediately at the beginning of the x-ray emission for both cases.

A sample of some typical low-energy x-ray spectra are shown in Figure 4. The spectral shapes of different materials are quite distinct and can readily be reproduced by code calculations. For high Z materials such as uranium and gold, the spectral shapes are quite similar. Likewise for low Z materials such as aluminum and beryllium, which shows a much faster decay in the spectrum with increasing x-ray energy. The titanium spectrum is quite different from the rest in the sense that in the energy band between about 500-800 eV, there are strong L-line emissions. On the other hand, the small bump at ~700 eV on the aluminum spectrum is most probably due to an oxygen-line since an aluminum-oxide layer forms quite readily on an aluminum target. Figure 5 shows how well code calculations are able to reproduce the features of the measured spectrum for a titanium target. Because of the presence of the L-lines of a titanium target, it was possible to use the data of Kelly and Palumbo[4] on relative line intensities to obtain a dominant charge state from the measured spectrum, which was $\bar{Z}_{exp} = 16 \pm 1$ in this case. Also, numerical simulations can obtain the average ionic charge in a computational zone with maximum x-ray emission power. The computed charge state was $\bar{Z}_{code} = 16 \pm 2$; the $\pm$ 2 does not represent an error bar in the calculation, but indicates the variation in $\bar{Z}$ over the FWHM of the x-ray emission region.

The integrated x-ray energy from ~100 eV to 1.8 keV can be obtained from the Dante signals. The integrated x-ray energy normalized by the incident laser energy is plotted against target Z in Figure 6. Since sub-keV x-rays away from the energy regions dominated by line emission are presumably generated by bremsstrahlung of low energy electrons, these low energy electrons actually see a screened nucleus, therefore, it would be perhaps more meaningful to plot the normalized x-ray energy as a function of $\bar{Z}$, where $\bar{Z}$ are the code calculated charge states. It is interesting to note that the normalized x-ray energy is almost linear with respect to $\bar{Z}$. This result is quite similar to the bremsstrahlung data obtained with an ordinary thick target x-ray tube where the x-ray energy is proportional to target Z.[5] The difference being that the x-ray energy produced per unit incident laser energy is one to two orders of magnitude larger than the x-ray energy produced per unit cathode ray energy.[6]

Effects such as Z-dependent absorption of laser light and angular distribution of x-rays can also influence the interpretation of the experimental results. However, preliminary absorption measurements indicate that absorption has a weak Z dependence. Also, code calculations seem to indicate that the Z-dependent angular distribution does not effect the data interpretation too much because of the angle (60° with respect to target normal) at which the measurements were made. Further experiments are planned to investigate the issues of absorption and angular distribution.

References

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Z DEPENDENCE OF THE TIME-RESOLVED SUB-keV X-RAY EMISSION FROM LASER-PRODUCED PLASMAS

Laser

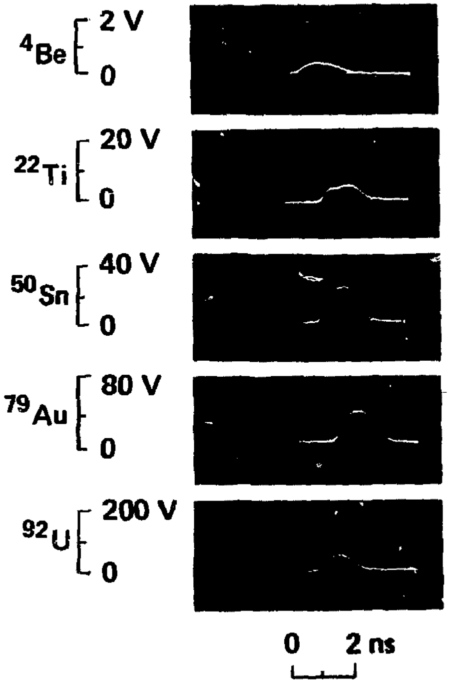
$I = 5 \times 10^{14}$ W/cm^2

1 ns FWHM

XRD

520 eV channel

190 ps resolution



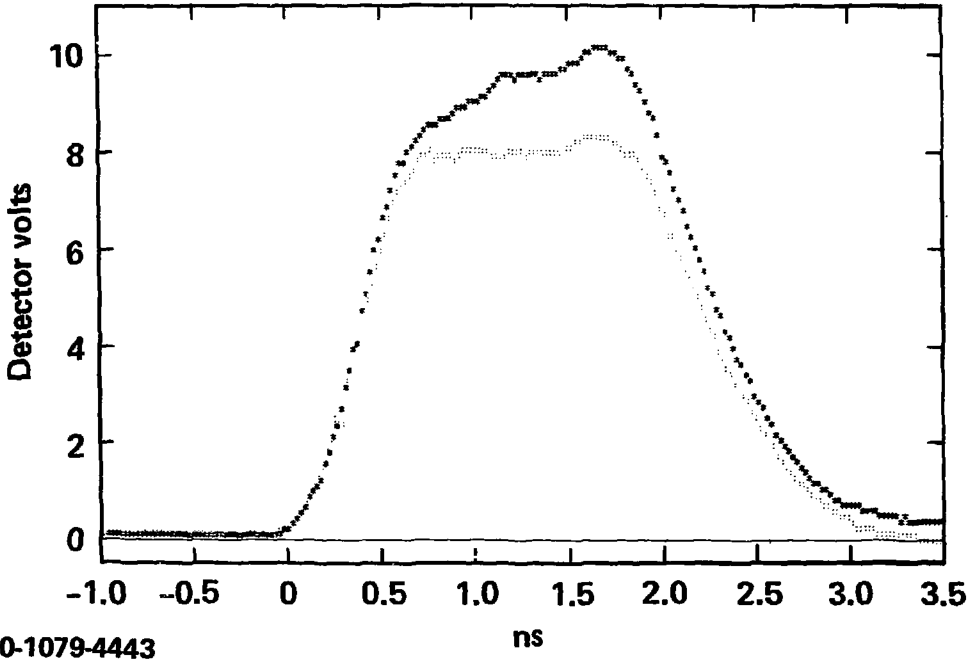
20-50-0679-1864

Figure 1

OSCILLATIONS CAN BE SEEN IN THE "FLATTENED" PORTION OF THE X-RAY EMISSION PULSE

Ti targets, $I = 5 \times 10^{14}$ W/cm^2, 1 ns FWHM

XRD: 940 eV channel, 170 ps resolution



20-90-1079-4443

Figure 2

TIME-RESOLVED SUB-keV X-RAY EMISSION FOR Au-DISKS AT DIFFERENT LASER INTENSITIES (XRD: 940 eV CHANNEL, 170 ps RESOLUTION)

$I = 5 \times 10^{14}$ W/cm^2

$I = 3.3 \times 10^{15}$ W/cm^2

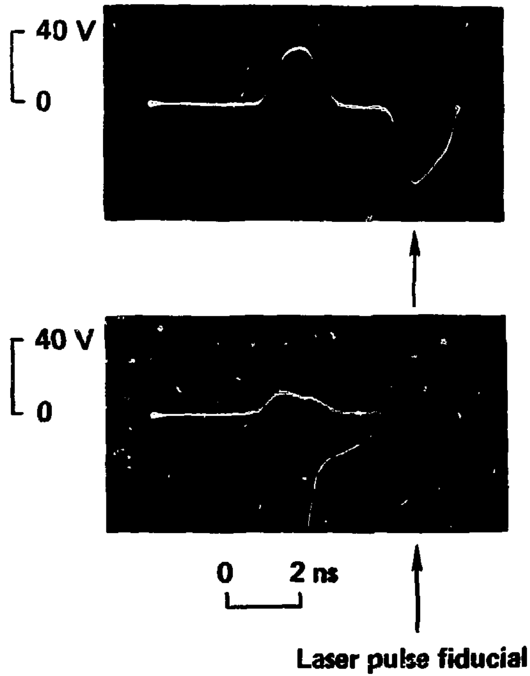


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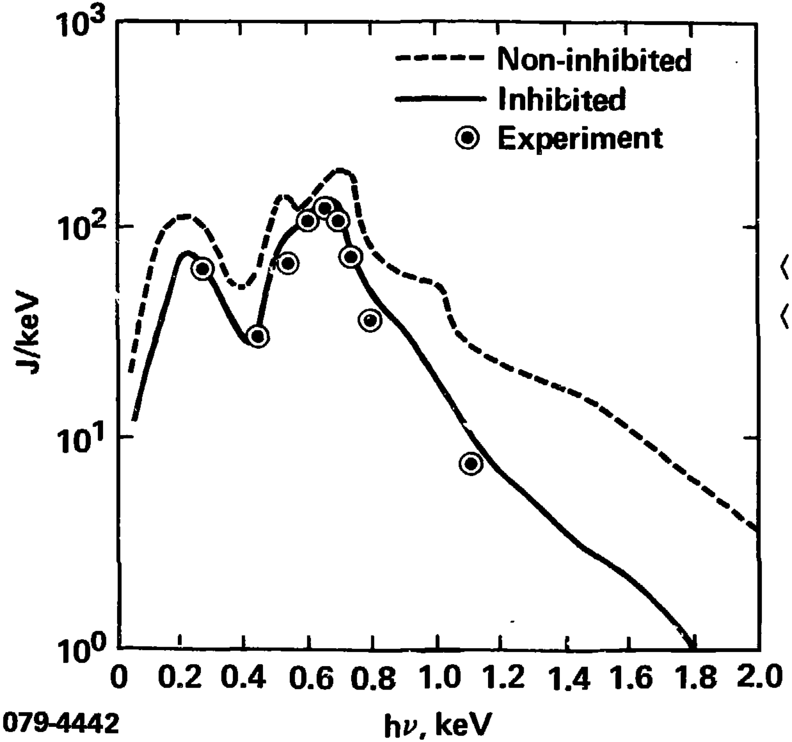
Figure 3

CODE CALCULATIONS REPRODUCE THE FEATURES OF THE MEASURED SPECTRUM

Ti taget, I = 5 X 10^{14} W/cm^2, 1 ns FWHM



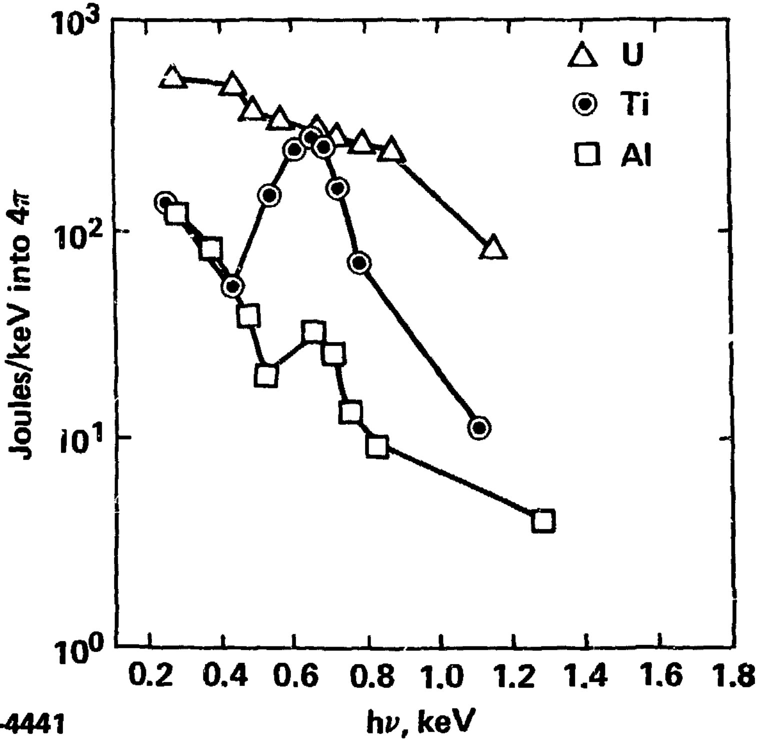
$\langle \bar{Z} \rangle_{exp} = 16 \pm 1$
$\langle \bar{Z} \rangle_{code} = 16 \pm 2$

20-90-1079-4442

Figure 4

LOW ENERGY X-RAY SPECTRA OF DISK TARGETS OF DIFFERENT MATERIALS

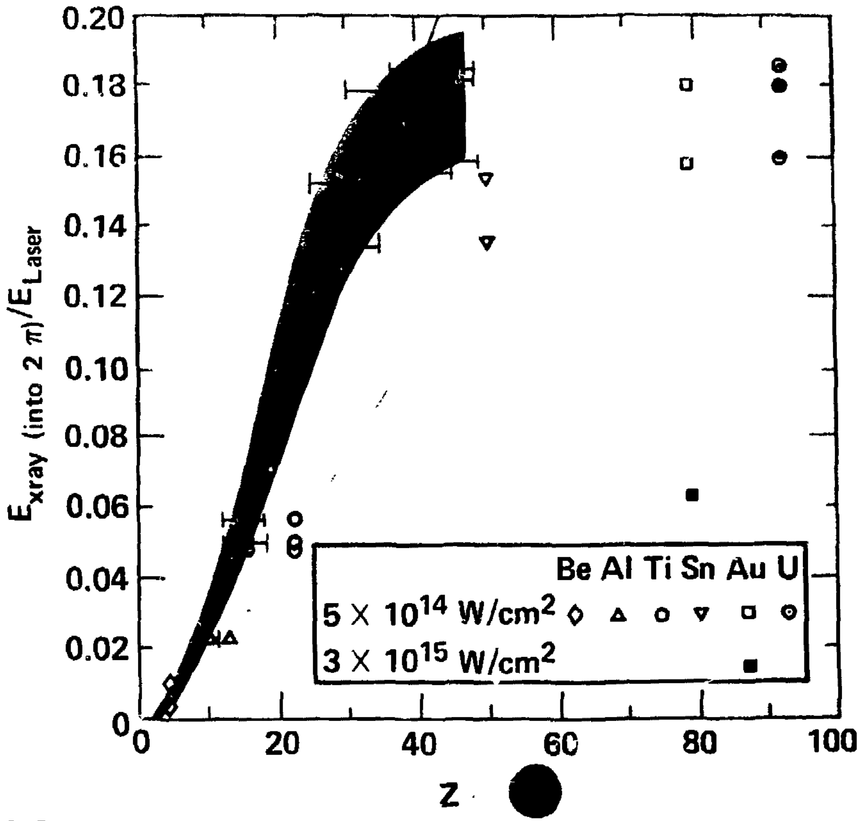
Laser: I = 5 × 10^{14} W/cm^2, 1 ns FWHM



20-90-1079-4441

Figure 5

X-RAY ENERGY AS A FUNCTION OF TARGET Z AND CHARGE STATE $\bar{Z}$



20-50-0679-1945

Figure 6