CLRC

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RAL-TR-96-081

HCM Large Facilities Access Programme Table-Top Ultrasoft X-ray Continuum Light Source

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Table-Top Ultrasoft X-ray Continuum Light Source

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SUMMARY

This report describes the experiment entitled "Table-Top Ultrasoft X-ray Continuum Light Source", carried out in the Central laser Facility (CLF) at the Rutherford Appleton laboratory over a five week period in July/August 1995. The experiment, funded through the large Facilities Access Programme involved established and young researchers from Dublin City University, The Queen's University of Belfast and the Rutherford Appleton Laboratory.

Experimental Results

- A compact table-top ultrasoft X-ray light source of high average power and short pulse duration has been developed.
- Emission spectra of a range of source plasmas (Mylar, Al, Fe, Cu, Sm, Au and Pb) have been measured in the 60 - 220 eV (50 - 200 Å) photon energy range.
- 'Line free' continuum emission is observed right across this spectral range for all high-Z target plasmas studied [Sm (62), Au(78) and Pb(82)].
- The most intense emission is obtained from lead (Pb) plasmas
- In slitless (imaging mode) bright *single shot* spectra are readily recorded with the multichannel Flat Field Spectrometer. (Note: The addition of a toroidal coupling mirror should make single shot high resolution spectra possible).
- An *upper limit* of 750 psec on the duration of the continuum emission has been established. The effect of ASE generated preplasma is thought to be a significant factor in the observed pulsewidth

Publications

The results of this experiment have been submitted for publication in Applied Physics Letters (September 1996), and presented at International Conferences including the 28th EGAS Conference (Graz, 16th-19th July 1996), and the 17th International Conference on X-ray and Inner Shell Processes (Hamburg, Germany, 8th-13th September 1996). Additionally, two laboratory reports have been published.

The CLF makes beam time at it's facilities available to European Researchers with funding from DG-XII, CEC under the Large Facilities Access Scheme. For further information contact Dr. Chris Edwards at the CLF. Tel: (0) 1235 445582, e-mail: c.b.edwards@rl.ac.uk

Publications List

Journals

O. Meighan, A. Gray, J.P. Mosnier, W. Whitty, J.T. Costello, C.L.S. Lewis, A. MacPhee, R. Allott, A. Lumb, I.C.E. Turcu, "Short-Pulse Extreme-UV Continuum Emission from a Table-Top Laser-Plasma Light Source", Submitted to **Appl. Phys Lett.** (September 1996).

Conferences

28th EGAS Conference, Graz, 16th-19th July 1996

O. Meighan, A. Gray, J.P. Mosnier, W. Whitty, J.T. Costello, C.L.S. Lewis, A. MacPhee, R. Allott, A. Lumb, I.C.E. Turcu, "Table Top Picosecond Laser Plasma Based XUV Continuum Light Source".

17th International Conference on X-ray and Inner Shell Processes, Hamburg, Germany, 8th-13th September 1996.

O. Meighan, A. Gray, J.P. Mosnier, W. Whitty, J.T. Costello, C.L.S. Lewis, A. MacPhee, R. Allott, A. Lumb, I.C.E. Turcu, "Short Pulse Line-Free XUV Continuum Emission from a Table-Top Laser Plasma Light Source".

Reports

O. Meighan, A. Gray, J.P. Mosnier, W. Whitty, J.T. Costello, C.L.S. Lewis, A. MacPhee, R. Allott, A. Lumb, I.C.E. Turcu, "Table Top Ultrasoft X-ray Continuum Light Source", Central laser Facility Annual Report 1995-96, RAL Report TR-96-006.

O. Meighan, A. Gray, J.P. Mosnier, W. Whitty, J.T. Costello, C.L.S. Lewis, A. MacPhee, R. Allott, A. Lumb, I.C.E. Turcu, "Table Top Ultrasoft X-ray Continuum Light Source", RAL Technical Report, RAL-TR-96-081, 1996.

Abstract

An experimental feasibility study of the generation and measurement of extensive 'line-free' UltraSoft X-Ray - USXR{or Extreme-UV - XUV} continuum emission from the RAL picosecond KrF table-top laser plasma light source has been undertaken - the first such experiments with this system. Using dispersive spectroscopy the evolution and spectral purity of continuum emission as a function of target atomic number has been measured. Importantly, with a laser pulse energy of < 20 mJ per pulse, single shot spectra can be recorded which has implications for applications involving the study of kinetics. The high repetition rate of the RAL laser system (100 Hz and 1600 pps in multiplexed beam mode) ensures high average power is possible for those applications where this attribute may be required. Many potential applications in plasma/atomic physics, materials science, etc. (until now the preserve of synchrotron light sources) can be envisaged.

The experiment described here took place over a five week period in July/August of 1995. The time allocated split into a two week setup period followed by three weeks of experimentation and data recording. The bulk of this time was allocated to recording spectra of a variety of low, medium and high-Z targets on a multichannel USXR spectrometer. Efforts were also made to record the time history of USXR emission from lead plasmas with the aid of a streak camera.

The key idea of the experiment was to utilise the short pulse (7 ps.) and high rep-rate (up to 100Hz) of the RAL X-ray light source [1] for the generation of bright pure 'line free' soft X-ray continuum emission from high atomic number targets - the first such experiments with the RAL source. Preliminary findings from an ongoing analysis of experimental data are reported.

Introduction

Although continuum emission from laser-produced plasmas (LPP) has been noted many times in the open literature and indeed can be used as a plasma diagnostic, it is most often accompanied by discrete line structure thereby reducing its attractiveness for applications requiring tunability over a wide spectral band (e.g, absorption spectroscopy, photoelectron spectroscopy etc.). A comprehensive study of the spectra emitted from laser-plasmas of the rare-earth and neighbouring elements by Carroll and co-workers [2,3] demonstrated strong, line free and extensive continuum emission for an irradiance on target of $\sim 10^{11}$ $\mathrm{Wcm^{-2}}$ with a 30 ns Q-switched ruby laser. The continuum emission (strectching from 4 - 200 nm) is predominantly recombination radiation modulated by complex unresolved transition arrays (UTA) resulting from 4d-4f transitions for a range of ion stages with open 4d subshells. Confining the ion stage distribution to a narrow range about $4d^5$ ensures 'continuum' purity., Such table top laser plasma continuum light sources with a pulse duration of ca. 10’s - 100’s of nanoseconds are now in routine use [e.g., 4,5 and refs within].

Using a 80 psec laser driver, delivering 10's of joules per pulse, rare earth continuum emission at photon energies of kilovolts has been observed and used in point projection absorption spectroscopy [6,7]. The sub-nanosecond quasi-continuum M-band emission from high-Z (e.g. Yb and W) target plasmas is however overlaid with some emission lines. In contrast USXR spectra from plasmas of e.g., samarium and thulium demonstrate the pure continuum seen previously with nanosecond driver lasers but with a pulse duration of ca. 100 picoseconds [8,9,10].

The main aim of the present experiment was to combine both the convenience of a table top laser system with the attributes of picosecond pulse width and high repetition rate to produce a compact, subnanosecond and potentially high average power laser plasma continuum light source.

Key objectives of the experiment were;

- To extend the compact RAL X-ray source to the generation of continuum as well as line emission
- To study the interaction of picosecond UV laser pulses with high-Z targets at moderate irradiances
- To establish conditions under which extensive 'line free' USXR continuum emission can be obtained
- To record the evolution of USXR continuum emission as function of target-Z using dispersive spectroscopy (Flat Field Spectrometer coupled to an USXR sensitive CCD).
- To establish the 'spectral purity' of the continuum
- To determine values for USXR flux emitted and assess the potential of the source for applications requiring single shot sensitivity.
- To determine an upper limit on the duration of USXR continuum emission

Experimental Procedure

A schematic diagram of the experimental setup for recording time integrated spectra is shown in figure 1. All plasmas were created by focussing 10 - 20 mJ/7ps pulses of 248 nm laser light onto solid targets (usually cylindrical) *in vacuo* to an irradiance of ca. 10^{13} W/cm^2 at a spot size of ca. 100 μm dia.

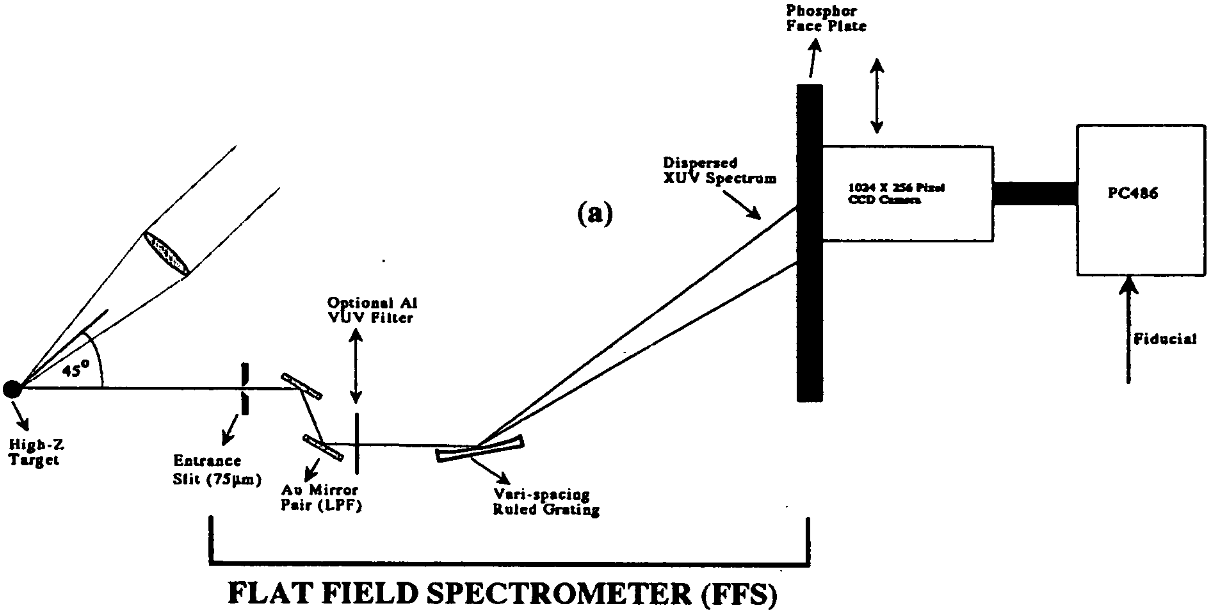

Figure 1. Experimental setup for:
Multichannel dispersive spectroscopy for recording laser plasma spectra
Gold mirror pair functions as optical low pass filter by rejecting all radiation above 300 eV photon energy.

The laser typically operated in 2 pulse mode in which a single excimer laser shot yielded two pulses separated by 12 ns. with a total energy of 20 - 30 mJ. The laser system has been described in detail elswhere [1]. The flat field spectrometer [9] was operated in both slitless (imaging) and high resolution modes. The former mode provided the advantage of high throughput but with a significant loss in resolution while the latter ensures a resolution of better than 1 Angstrom (typ.) at a slit width of 75 μm. One further advantage of the slitless mode of operation is that an estimate of the emitting size of the source can be made as the resolution of line spectra recorded is determined by emitting source size. A phosphor coated faceplate coincident with the focal plane of the spectrometer converts the

USXR spectrum to a visible light image which is then recorded with a butt coupled CCD array (1024 X 256) pixels. Each CCD pixel is 27 X 27 μm^2 while the 1024 pixel length of the CCD covers a range of ca. 200 Angstroms at USXR wavelengths corresponding to a sampling interval of 0.2 Angstroms per pixel (approx). A pair of gold coated mirrors oriented at a grazing angle of 8^{o} (and hence acting as optical low pass filters) suppressed X-ray emission below 40 Angstroms from the plasma source. Hence the 40 - 80 Angstrom range in the spectra recorded is free from order sorting problems.

In figure 1 (b) we show the experimental configuration chosen for recording time resolved USXR emission.

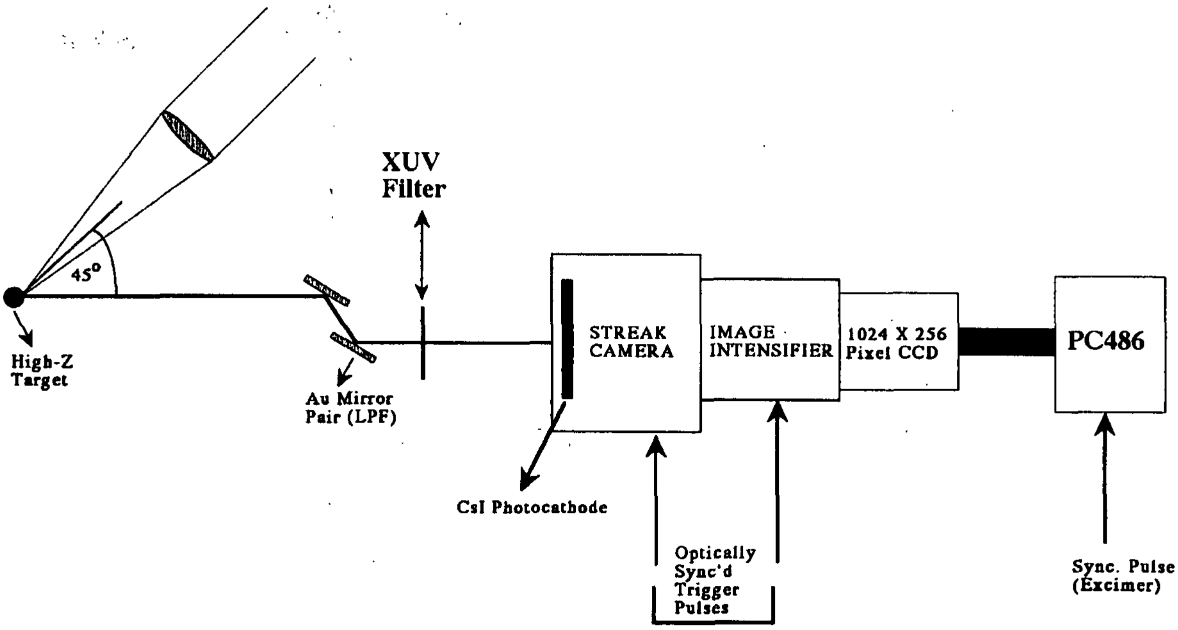

Figure 1b. Experimental setup for:
Time resolved broadband (50eV@140eV) XUV emission measurements.

Due to the small energy per laser pulse on target, the continuous nature of the spectra recorded (leading to a dilution of the USXR flux available per CCD pixel) and the lack of toroidal coupling optics between plasma source and spectrometer it was decided not to attempt to streak disperse spectra in this initial feasibility experiment. Instead, thin film filters were used to define spectral bands of interest while admitting reasonable USXR fluxes to impinge on the CsI photocathode of the streak camera. The USXR windows defined by the Au mirror pair and either (i) a 0.4 μm thick CHO film or (ii) a 0.4 μm CHO with 0.3 μm Ag thin film filters are shown in figure 2.

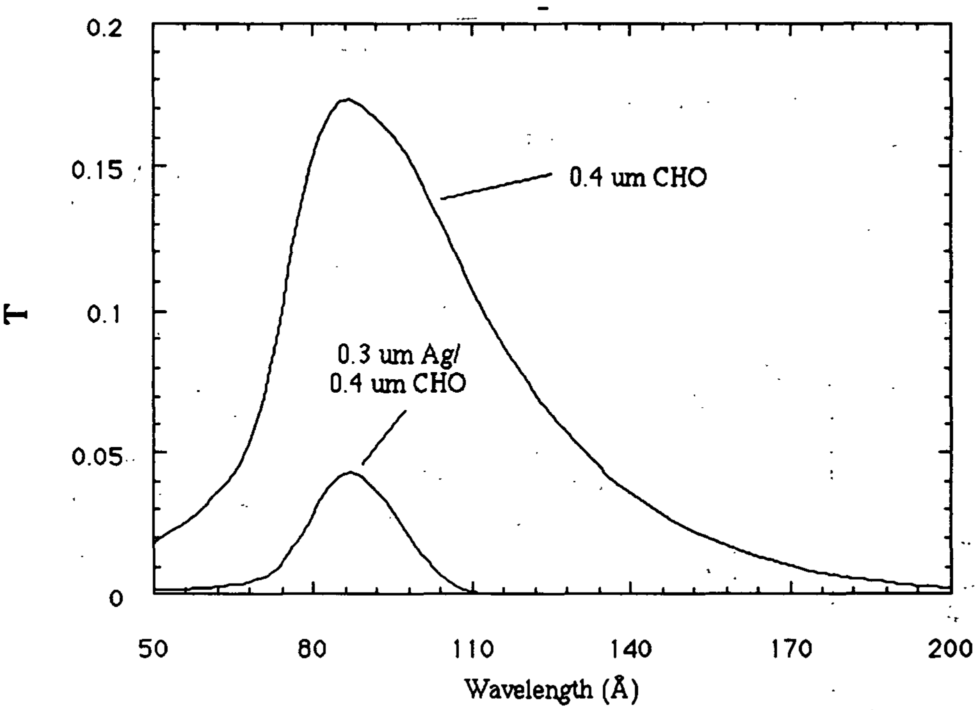

Figure 2. Ultra soft X-ray windows defined by the Au mirror pair with different filters.

While both filters peak at approximately 85 Angstroms the CHO provides a FWHM bandpass of 50 Angstroms with a maximum transmission of 18 % compared to figures of 20 Angstroms and 4% for CHO/Ag. However, whereas the CHO provides excellent VUV blocking it has a small transmission in the UV and visible region of the spectrum. On the other hand the CHO/Ag filters blocks VUV, UV and visible radiation which may provide a long 'tail' superimposed on the USXR emission pulse.

Results

In figure 3. we show three spectra (Mylar-CHO, Cu and Sm) recorded in the higher resolution mode operating the flat field spectrometer (FFS) with an entrance slit of width 75 μm. The evolution from predominantly line to predominantly continuum emission with increasing Z is clearly demonstrated. It should be noted that the Mylar spectrum has an offset added and the y axis graduation refers only to the Cu and Sm spectra. The continua represent the average of up to 500 laser shots on target at an average energy of 20 mJ per shot.

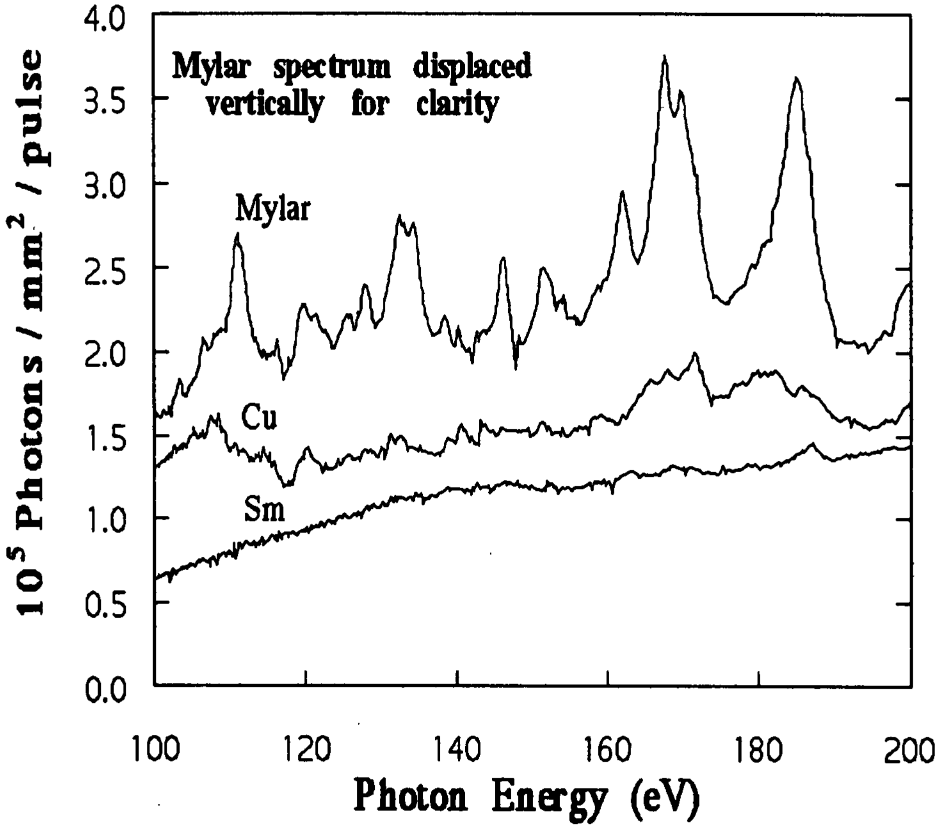

Figure 3. Comparison of low, medium and high Z plasma specta showing transition from predominantly line to continuum emission.
Spectometer operated with a 75 μm slit.

Figure 4. shows the scaling of the continuum emission from three high atomic number target plasmas investigated, Sm, Au, Pb. The spectra have superimposed contributions from higher orders of the flat field grating and as part of the ongoing analysis we are estimating the value of these additional multiple order contributions. However they do not affect the observation that the USXR continuum intensity increases from Sm to Pb. The spectra were recorded in the slitless mode of FFS operation and represent the average of 50 laser shots at ca. 10 - 15 mJ/shot. Pb makes an excellent candidate as a USXR source -

low cost material, easily machined/shaped and emits a bright, smooth continuum. However, it is soft and the extent of material ablation may be a problem in some applications.

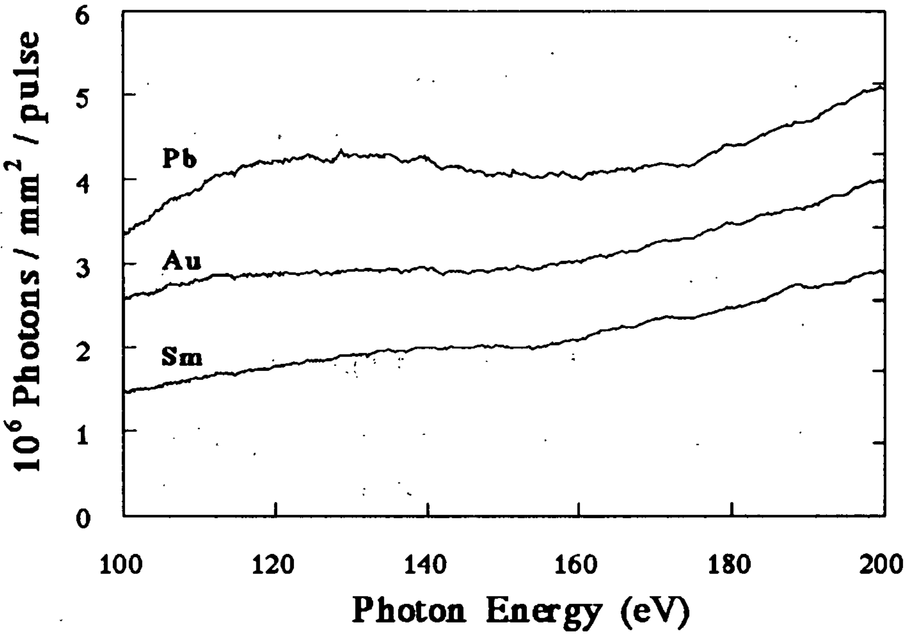

Figure 4. Comparison of Sm (Z=62), Au (Z=79) and Pb (Z=82) continuum spectra. Each spectra represents the accumulation of 50 shots with the spectrometer in slitless mode.

In many applications of laser plasma continua single shot sensitivity can be desirable, especially in the study of transient species (e.g, reaction kinetics, laser ablation/deposition etc.). In figure 5. we show a single shot Pb spectrum recorded with the FFS in slitless mode in the 100 - 200 eV (50 - 180 Angstrom) spectral range. For comparison we show the result of numerical averaging of 5 single shots in order to obtain a better mean yield (in CCD counts). By comparing spectra taken with and without an entrance slit on the FFS we know that the intensity gain in imaging mode is ca. 20 - 25. Hence in high resolution mode (~ 0.5 Angstroms) we would expect an average single shot count of only ca. 10 counts. However the addition of toroidal coupling optics between source and FFS could give rise to a throughtput gain of 50 or more bringing the average single shot count to 1000 which provides a sufficient dynamic range for most applications. If required a further gain could be obtained by the use of an image intensified CCD (but with a possible loss in spatial resolution especially in gated mode).

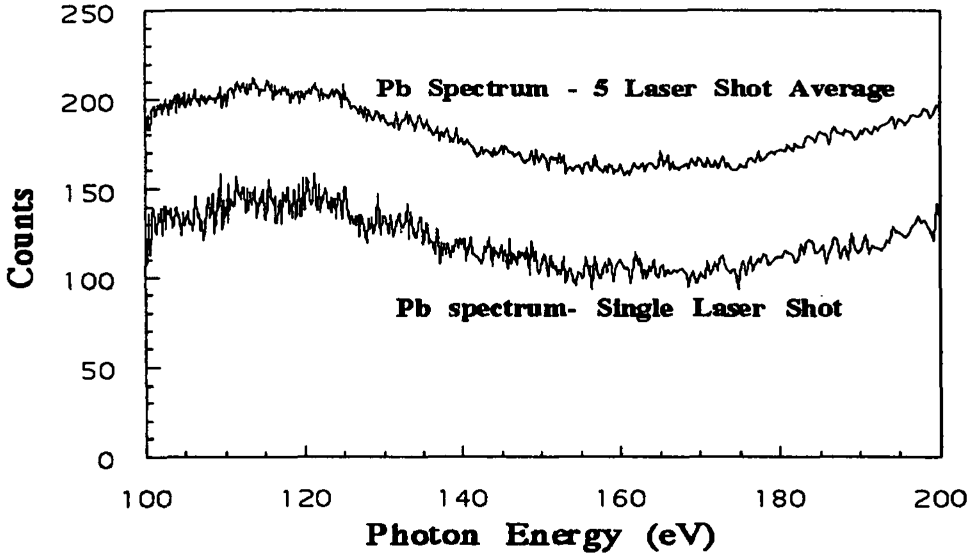

Figure 5. Comparison of single shot with five shot averaged Pb plasma continuum emission - Spectrometer in slitless (imaging) mode.

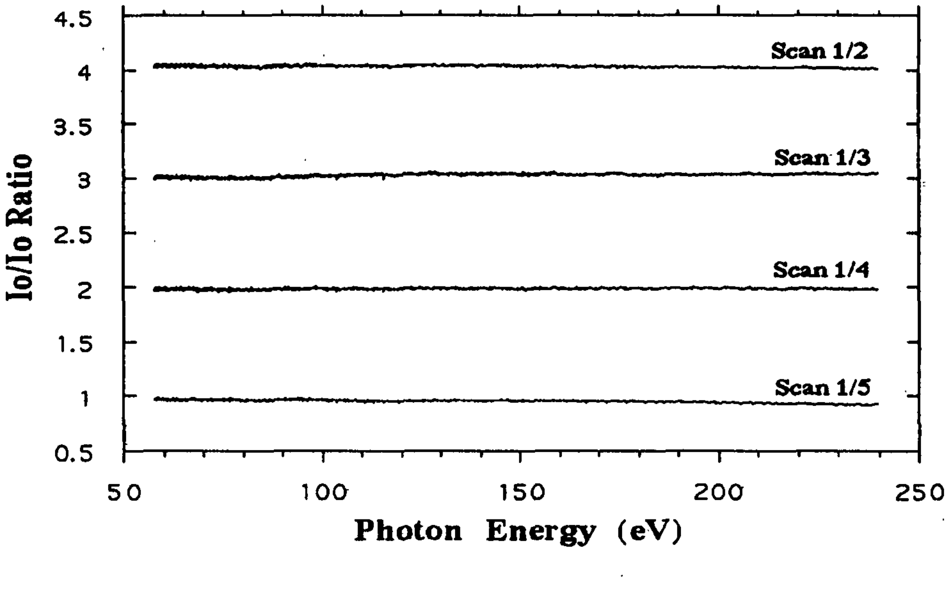

Figure 6. Ratio of successive Pb continuum spectra (each displayed by unity for clarity)

An important aspect of any light source is its 'spectral' reproducibility. Any change in the oscillator strength distribution from shot to shot can give rise to source features in e.g., photoabsorption spectra. In figure 6. we show the result of an experiment in which five successive Pb plasma spectra are recorded in slitless mode of the FFS and ratio's (Io/Io) plotted.

Ideally each such ratio should equal unity at all pixel values. In fact the ratios computed lay within a band of 10% or so of unity. In figure 6. we show the ratios with added offsets just for clarity. The results show that the Pb continuum is very reproducible and displays strong spectral integrity from scan to scan.

Figure 7. shows a scan of the plasma emission as viewed through the transmission window determined by the combination of a 8° gold mirror pair reflection plus 0.4 μm CHO transmission filter (Figure 2.).

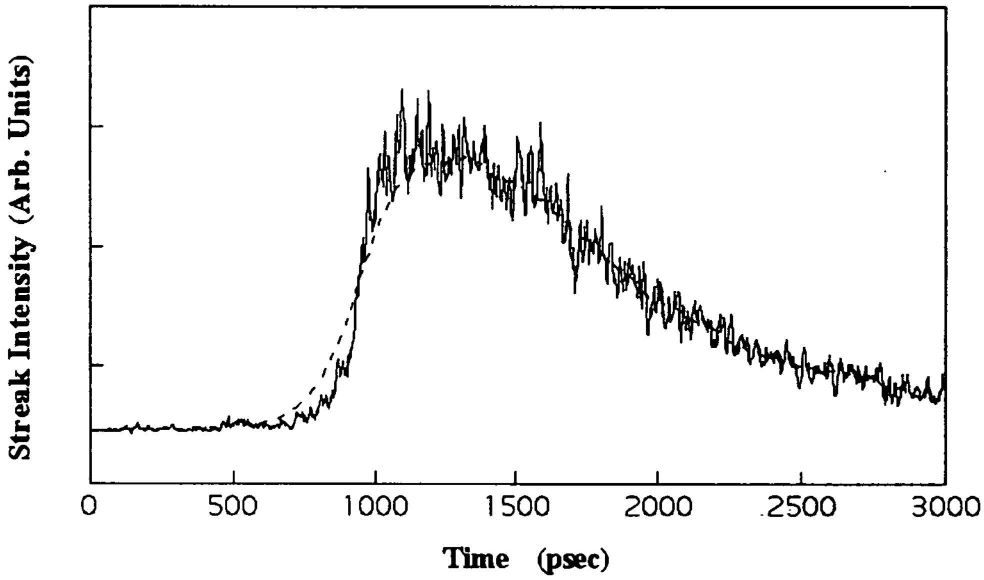

Figure 7. Al L-edge measured with Pb continuum
Note offset from zero due to significantly Higher spectral order radiation appearing at photon energies <100 eV.

The pulse shows a rapid rise (< 100 psec as set by the time resolution of the streak camera) followed by a long tail and a FWHM is ca. 750 psec. This pulse width appears at first sight to be longer than expected particularly when compared with the result of Davidson [8] who obtained ca. 100 psec at a wavelength of 30 Angstroms for a thulium target with a 80 psec. incident laser pulse. However, figure 7. refers to broadband emission at longer wavelengths (50 - 200 Angstroms) where, due to recombination time considerations, longer pulse widths should not be too surprising. Two other points should be noted and warrant further investigation. Although the plasmas generated are quite hot (estimated $T_e \sim 150$ eV) and hence one should expect the bulk of radiated energy to appear at USXR wavelengths one cannot rule out the effect of UV leakage by the CHO filter which could give rise to a long emission tail similar to that observed in figure 7.

Although we tried to tackle the problem of UV leakage through the CHO filter by making a composite 0.4mm CHO/0.3mm Ag thin film filter yielding the narrow USXR transmission window shown in figure 2. and providing strong UV attenuation due to technical problems with the streak camera we do not have confidence in the results obtained which displayed substantial variations in the pulse widths (from the resolution limit of ca. 100 psec. to 1 nsec.). Secondly, the 7 ps. pulses used to generate plasmas were accompanied by a significant level of ASE from the excimer amplifiers (ca. 25 mJ in a 20 ns. pulse) capable of generating a dilute preplasma offering the potential to alter the dynamics of the expanding plasma (cooling rate, expansion velocity, radiative loss mechanisms etc.). Hence we can only at this stage of analysis offer an upper limit on the duration of USXR continuum emission of < 800 psec. However the initial goal of obtaining subnanosecond, bright, ‘line free’ USXR continuum emission has been achieved and the source should be ideal for probing sample dynamics on this timescale.

Conclusions to date:

- A compact table-top ultrasoft X-ray light source of high average power and sub-nanosecond pulse duration has been demonstrated
- Emission spectra of a range of source plasmas have been measured in the 50 - 200 Å range
- 'Line free' continuum emission is observed right across this spectral range for all high-Z target plasmas studied [Sm (62), W(74), Au(78) and Pb(82)]
- The most intense emission is obtained from Pb plasmas
- In slitless (imaging mode) bright *single shot* spectra are readily recorded with the multichannel Flat Field Spectrometer. (Note: The addition of a toroidal coupling mirror should make single shot high resolution spectra possible.)
- As yet only an upper limit of 750 psec on the duration of the continuum emission has been established. The effect of ASE generated preplasma is thought to be a significant factor in the observed pulsewidth

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