Space charge effects in the Axis-Photonique PX-1 X-ray streak camera

M. H. Edwards, N. Booth, Z. Zhai and G. J. Tallents

Department of Physics, University of York, Heslington, York YO10 5DD, UK

Contact | mhe101@york.ac.uk

T. Dzelzainis, R. Ferrari and C. L. S. Lewis

School of Mathematics and Physics, Queen's University Belfast, University Road, Belfast BT7 1NN, UK

P. S. Foster, M. J. V. Streeter and D. Neely

Central Laser Facility, STFC, Rutherford Appleton Laboratory, HSIC, Didcot, Oxon OX11 0QX, UK

Introduction

Streak cameras have been used for over a century to observe and measure fast events. Early devices used to observe the temporal profile of emission from a ruby laser for example were mechanical in nature, comprising a rapidly rotating mirror to direct and streak the incident light pulse to the image plane several metres away. Such devices were large and could achieve streak rates of about 10 mm per micro-second with a resolution on the nano-second scale [1].

X-ray streak cameras were developed in the 1970s [2] with temporal resolutions of the order of 50 ps. These instrument resolutions have been steadily reduced over the last three decades using a variety of techniques to overcome the limiting factors of temporal dispersion in the photocathode emission. [3,4] Pulse charging the photocathode reduces temporal dispersion still further by enabling very high extraction fields (> 270 KeVcm^{-1}) to be applied for short periods of time. [5]

One contributor to the temporal resolution of an X-ray streak camera, which also limits the dynamic range, is the effect of space charge. High electron densities in the streak tube will result in large Coulombic repulsion and cause significant dispersion in both the temporal and non-temporal directions. Space charge effects can be reduced by filtering the incident light pulse to reduce the number of photoelectrons produced at the photocathode. However, a significant reduction in the signal brightness will result in images becoming unusable as they are barely distinguishable from background noise in the detector. Increasing the energy of electrons in the tube will also result in a reduction of space charge effects due to the lower electron densities and faster transit times.

Experiment

The experiment was carried out using the Astra laser facility at the Rutherford Appleton Laboratory and employed grazing incidence pumping [6] of a molybdenum slab target to produce a short pulse X-ray laser at 18.9 nm.

A 1 mm thick slab of molybdenum placed 424 mm from the grating was irradiated by two 800 nm laser pulses in a line focus geometry. The two beam lines were derived from a single 500 ps beam using a 70:30 beam splitter. The 70% beam was directed along a timing slide, and using a spherical and cylindrical lens was focussed to a line of nominal length 5 mm and width 50 μm to give an intensity on target of ~4×10^{11} Wcm^{-2}. The length of the line focus could be adjusted by changing the position of the cylindrical lens. The second beam was compressed to 200 fs and focussed to a line of nominal length 4 mm and width 50 μm using an on axis parabola of focal length 762 mm set to irradiate the target at a nominal grazing incidence angle of 20° with an intensity of ~4×10^{14} Wcm^{-2}. Overlapping the two line foci caused an X-ray laser at 18.9 nm to be emitted which was observed in both first and second orders using the flat field spectrometer. The delay between the pumping pulses was varied to optimise the X-ray laser brightness. The target length was varied to drive the X-ray laser emission into saturation to provide a more stable output beam. In some cases two lasing lines were detected, the stronger at 18.9 nm from the 4d-4p transition and the weaker at 22.6 nm from the 4f-4d transition, the population inversion in the upper level resulting from self photo-pumping [7]. A typical spectrum is shown in figure 1.

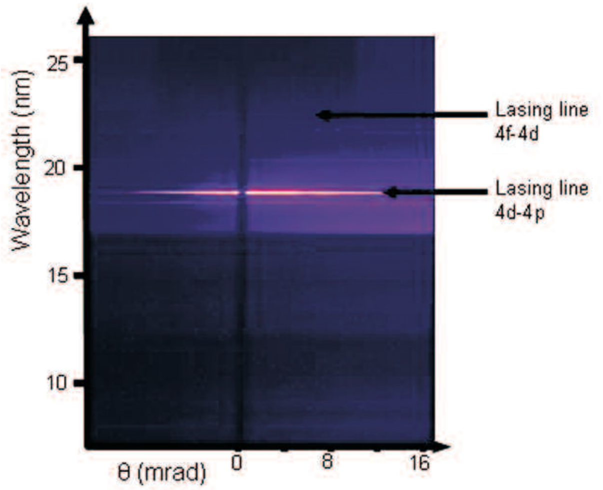

Figure 1. A first order time integrated flat field spectrometer image. The 4d-4p nickel-like molybdenum lasing line at 18.9 nm is clearly seen along with the weaker 4f-4d line at 22.6 nm. The image has been over-contrasted to show the aluminium L edge and fiducial wire. The target length was 4.5 mm and the line foci were each at their nominal settings of 5 mm length and 0.05 mm width.

The Axis-Photonique PX1 streak camera is based on the Philips Teltron tube. With a potassium iodide photocathode and a fixed extraction voltage of 15 KV the instrument

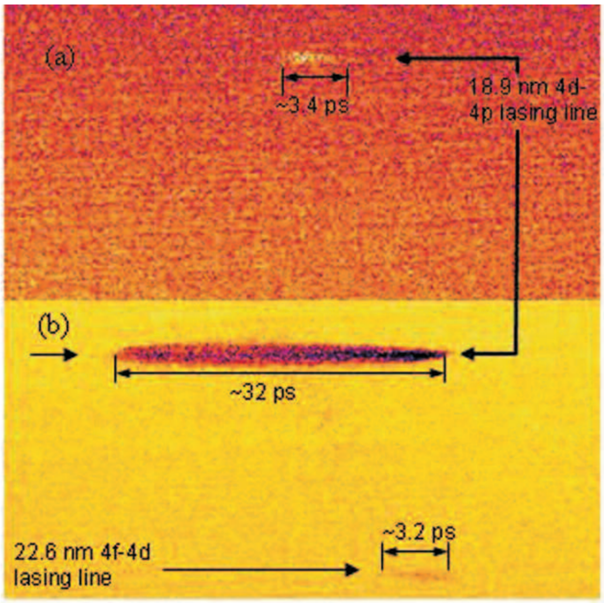

Figure 2. Streaked images from two different shots are shown. The X-ray laser pumping conditions were the same in both cases, but case (a) was filtered more strongly than case (b). In (a) just the stronger lasing line is visible and measured to have a duration of 3.4 ps. In case (b) both lasing lines are visible, though the stronger 4d-4p line has saturated the streak tube, measuring 32 ps.

resolution is better than 1 ps [8]. A flat field spectrometer containing an aperiodically ruled (~1200 lines per mm) grating of radius of curvature 5641 mm was designed to observe both first and second order X-ray emission simultaneously. With the grating angle set to 3.5° to give a vertical image plane in the first order. The second order was reflected by a gold mirror to an Andor DX420-BN CCD detector positioned perpendicularly to the streak camera. The X-ray source was filtered using aluminium foils of thickness 0.3 to 2.6 µm to vary the transmission in the range 0.66 and 0.026. Initially the first order signal was detected by an Andor DX436-BV CCD detector to optimise the X-ray laser emission and take measurements of its refraction and divergence angles. Subsequently the Axis streak camera replaced the time integrating CCD camera at the first order position with the photocathode located at the flat focal plane. To ensure the X-ray laser was detected the entrance slit to the photocathode was orientated vertically and at 90 degrees to the grating rulings.

Results

Several series of shots were taken, varying target length, grazing angle, delay between pumping pulses and the energy in the pumping pulses. In each case the filtering was initially set to a low value giving massively saturated images, but ensuring the detection of the X-ray laser. The filtering was gradually increased until the streaked image of the first order emission was no longer detectable. On some occasions the streaked signal was observable, but too weak to be useful in making a temporal measurement. Examples of typical saturated and non-saturated images from the streak camera are shown in figure 2.

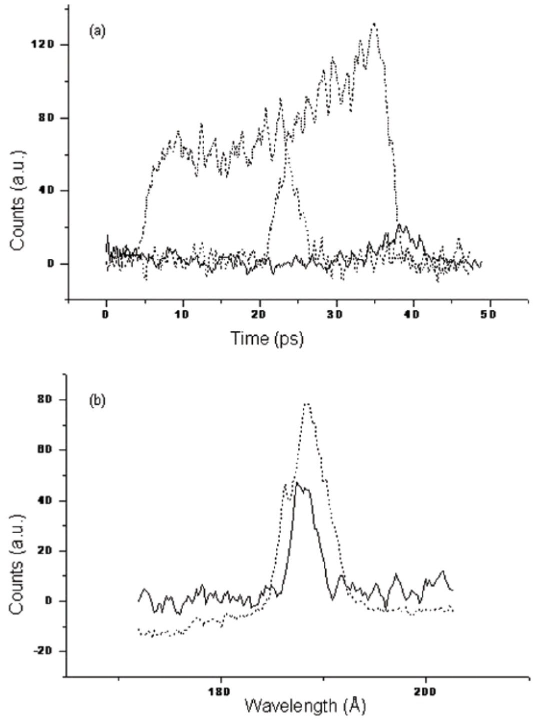

Figure 3. Line outs, (a) in the temporal direction and (b) in the spectral direction, taken through the streaked images in figure 2 are shown. In (a) the dashed plot resulting from figure 2(a) measures a FWHM pulse duration of 3.4 ps for the 4d-4p lasing transition in Ni-like Mo. The dot-dash plot resulting from figure 2(b) measures a duration of 32 ps for the same lasing line. Also shown is the line out through the second line visible in figure 2(b), measuring the duration as 3.2 ps for the 4f-4d lasing transition. In (b) the same 4d-4p lasing line is considered in both plots with a 2 Å dispersion measured for the image shown in figure 2(a) and a 5 Å dispersion for the image in figure 2(b).

A line-out in the temporal direction through each of the streaked images, integrated over a few pixels in the spectral direction was taken from which the full width at half maximum of the pulse duration was measured. The results are shown in figure 3. The X-ray laser brightness at the photocathode position was measured using the second order flat field diagnostic to compare the signal strength with the pulse duration measured. The results are shown in figure 4 and considered in more detail in the discussion section. Integrating the image over its full width in the temporal direction and taking a line-out in the spectral direction allows for the full width at half maximum of the non temporal dispersion to be measured (see figure 3(b)). The spectral dispersions of the images shown in figure 2 were measured as 2 Å and 5 Å for the non-saturated and saturated data respectively.

Discussion

Whilst there is no question in the suitability of the Axis streak camera for measuring pico-second pulse durations of X-ray lasers, care has to be taken to optimise the signal. If the signal strength is too high too many photoelectrons are produced resulting in tube saturation where Coulombic

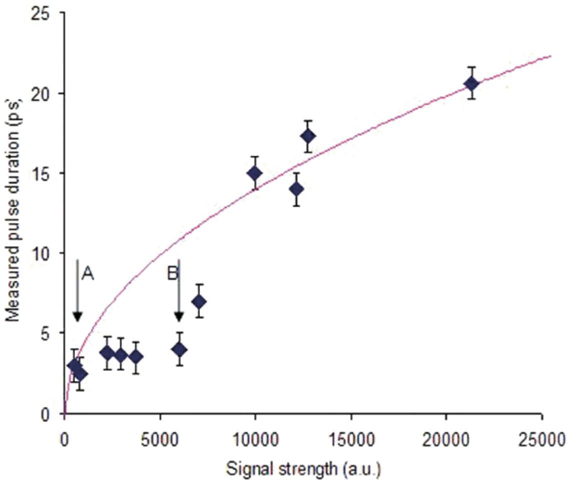

Figure 4. The plot shows the pulse duration (*ΔT*) measured using the Axis streak camera against a measure of the X-ray laser brightness (*I*) at the photocathode. The smooth curve through the data follows an $I^{1/2}$.

repulsion yields an image which is distorted in both the temporal and non-temporal directions. If the signal strength is too weak it may be undetectable or too close to the noise levels to be of any significant use. The dynamic range of the instrument is calculated by taking the ratio of the signal intensities at these extremes and the region within this range is where the streak camera gives accurate measurements of the pulse duration.

Using the information in figure 4 from the experiment at Astra with molybdenum targets, points A and B concur with previous results obtained by using the streak camera in a similar fashion at LULI, giving a dynamic range of ~6. In this analysis the upper signal strength location, B, is around the mark where the measured pulse duration has shown a 20 % increase due to space charge effects in the streak tube, whilst the point A is the lower limit of signal for which a reliable measure of pulse duration can be made.

Using an equation given by Fleischmann [9] and assuming that the number of photoelectrons emitted by the KI photocathode is proportional to the intensity of the incident radiation (I), it is simple to show that a cylindrical photoelectron beam in the absence of external fields will expand with distance travelled such that its radius is proportional to $I^{1/2}$. In the case of a large signal irradiating the photocathode of the streak camera space charge effects could be expected to dominate completely over the focussing electronics. In this limit the measured pulse duration as a function of signal strength (I) tends towards $I^{1/2}$ as shown in figure 4.

Conclusion

A short pulse Ni-like X-ray laser at 18.9 nm has been used to observe saturation effects in an Axis-Photonique PX-1 X-ray streak camera. The data have been used to measure the dynamic range of the streak camera to be ~6. Such a small dynamic range means that care must be taken to filter the input signal strength that accurate measurements of short X-ray pulse durations may be made.

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