Characterization of x-ray lens for use in probing high energy density states of matter

Contact *paul.mabey@physics.ox.ac.uk*

P. Mabey, N. J. Hartley, J. E. Cross, L. Ceurvorst, A. Rigby, M. Oliver, P. A. Norreys, G. Gregori

Department of Physics, University of Oxford, Parks Road, Oxford, OX13PU, U.K.

H. W. Doyle

First Light Fusion, Begbroke Science Park, Woodstock Rd, OX51PF, U.K.

D. C. Carroll and C. Spindloe

Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot, OX11OQX, U.K.

M. Calvert and D. Riley

School of Mathematics and Physics, Queen's University Belfast, Belfast, BT71NN, U.K.

I. J. Kim and C. H. Nam

Centre for Relativistic Laser Science, Institute for Basic Science Gwangju, 500-712, Korea

Introduction

The study of dense plasmas is relevant to many fields including laboratory astrophysics [1], inertial confinement fusion research [2], and more broadly in the high energy density physics community [3]. In order to understand and model experiments in this regime, accurate measurements of plasma conditions such as temperature, density and ionization state are required. X-ray Thomson scattering techniques have subsequently been developed in the field of dense plasmas [4].

In order to make use of these techniques, high power optical lasers are routinely used to produce intense x-ray pulses by driving metal foils [5]. This provides the ability to pump and probe samples at solid densities and above, with time resolution of picoseconds or femtoseconds [6].

The x-ray source used to obtain these results must fulfil stringent requirements on photon number, bandwidth and divergence in single shot experiments [7]. These requirements often necessitate a very small separation (a few mm) between the backlighter target used to produce x-rays and the main sample to be driven. This inevitably leads to signal-to-noise problems with detectors such as CCDs or image plates and therefore numbers of x-ray photons are often insufficient to make meaningful conclusions. Note that here we define the signal as the x-ray photons emitted due to line radiation (e.g. He-α or T-α), whereas noise refers to x-ray photons emitted due to continuous emission as well as any other species created by the laser-target interaction that might interact with detectors, such as high energy electrons. Novel techniques for extracting meaningful data from background noise have been proposed but are not always applicable [8]. In addition to this, the geometry of many pump-probe experiments is restricted due to the need to shield detectors sufficiently from background noise.

Here, we demonstrate the use of an x-ray polycapillary lens to focus divergent laser-produced x-ray sources to sufficient intensities such that they can probe dense plasma physics phenomena that would otherwise have been inaccessible. For the first time, we outline the possibility of their use at larger national-scale facilities which often require minutes to hours between shots. The use of x-ray lenses with high power lasers opens up the possibility of using them in the high energy density physics community particularly for the study of warm dense matter (WDM) or other strongly coupled plasma states. One key advantage of this type of optic is that the backlighter and sample targets may be placed at a separation of 10's of cm, thus drastically increasing the signal-to-noise ratio.

Polycapillary Lens

The lens works similarly to an optical fibre, acting as a waveguide in reflecting x-rays along its length. The capillaries are aligned such that they are able to focus a source of several hundreds of microns 51.0 mm away from one end of the lens to a spot of diameter several hundreds of microns 50.0 mm away from the other side of the lens. The lens itself measures 141.3 mm in length and so in effect (minus throughput losses) the lens acts to move the x-ray source 242.3 mm away from the laser-target interaction. The lens has an output aperture of 10.3 mm and so has a theoretical angular divergence of 6°.

Experiment

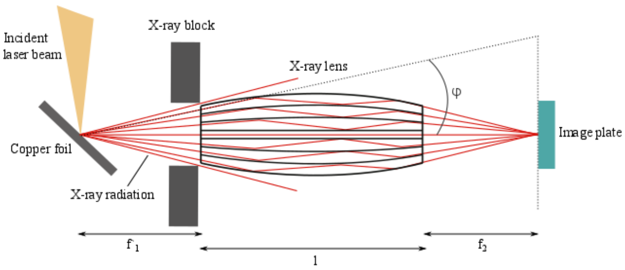

Figure 1. Top-down view of experimental setup. The laser beam incident from the top drives the K-α transition in the copper foil. The resulting line radiation is focused by the x-ray lens onto an image plate 242.3 mm away. A lead block shields the image plate from direct line of site to the copper foil such that all x-rays incident on the image plate have travelled through the lens.

The results shown here are from an experiment carried out at VULCAN, Target Area West. The experiment was carried out in two parts. The first part consisted of the production and subsequent focusing of 8 keV Cu K-α radiation using the polycapillary lens. The K-α radiation was produced in the usual manner with the interaction of a short pulse laser beam and a metal foil. The hot electrons generated at the front plasma surface interact with the solid target itself, producing bremsstrahlung radiation and line emission. In the case of mid-Z materials, K-α emission is found to dominate the spectrum [9]. Here we illuminated a 2 μm thick copper foil with a 10 ps short pulse laser beam operating at the fundamental wavelength (λ_0= 1054 nm). The laser pulse energy was ~175 J and the beam was focused by an f-15 parabola to a focal spot of 300 μm. These parameters were chosen in order to maximize the K-α production of the copper sample. The x-rays are emitted roughly isotropically with those directed towards the lens focused down to a spot on the image plate detector as shown in fig. 1. A lead shield was placed to prevent any x-rays travelling directly from the copper foil to the image plate. The lens was optimized and the x-ray spot was characterized for future use. The complete experimental setup including target, lens, shielding and detectors was placed inside a single vacuum chamber. The image plates used require scanning after each shot taken, thus the chamber could not remain at vacuum but instead had to be let-up and pumped down between shots.

In order to characterise the x-ray spot output from the polycapillary it is first necessary to align the lens to a high degree of precision (to within 10s of µm's). Initially two counter-propagating He-Ne lasers were used to define an axis running from the focal spot of the laser on the metal foil to a point in the plane of the image plate. The lens was then placed on this axis between the metal foil target and the image plate (see fig. 1). The short pulse beam was then fired to generate short pulse Cu K-α line radiation at 8.05 keV which was focused by the lens onto a spot on the image plate. The lens was then translated in both the x and y directions so as to optimize the intensity of the x-ray spot on the image plate. During this process the lens was not moved in the focal direction nor was it rotated around its axis. Ten shots were required on average to align the lens. A full characterization of the x-ray spot was carried out once the lens was fully aligned.

In the second part of the experiment four 1.5 ns long pulse beams frequency doubled to λ_0 = 527 nm were used to drive the He-α transition in titanium. A total of ~400 J was incident on the titanium target within a focal spot of 50 µm. The x-rays were again focused by the lens onto an image plate and the lens was aligned in the same manner. Once this was completed, a polycrystalline sample was placed at the focus of the x-rays as shown in fig. 2. The x-rays diffract from the sample by Bragg's law and are incident on the image plate detector situated behind the sample.

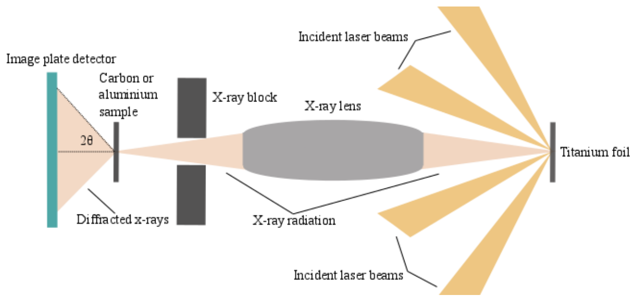

Figure 2. Top-down view of experimental setup. The incident laser beams drive the He-α transition in the titanium foil on the right hand side of the diagram. The resulting line radiation is focused by the x-ray lens onto the target. The x-rays are diffracted according to Bragg's law and are detected by the image plate. 2θ represents the angle through which the x-rays are diffracted from the sample.

X-Ray Spot Characterization

A flat HOPG (highly ordered pyrolytic graphite) spectrometer in Von Hamos geometry is placed 20 cm away from the backlighter target in order to capture the x-ray spectrum generated. Initially the HOPG crystal is aligned such that the Cu K-α peak is diffracted from the (004) plane of the crystal onto an image plate detector. Also seen is the characteristic He-α peak at a slightly higher energy. For the titanium targets, the setup is changed such that the Ti He-α radiation is diffracted from the (002) plane of the HOPG crystal onto the image plate. The He-α line is separated into three distinct peaks as is expected [10]. Also present are several satellite peaks whose intensity is several orders of magnitude weaker than the He-α line [11]. Results are shown in fig. 3 for the two cases.

We find that the Cu He-α x-ray spot has a FWHM in the x-direction of 392 ± 10 µm and in the y-direction of 403 ± 16 µm. In the case of the Ti K-α x-ray spot, the FWHM values were 385 ± 19 µm and 400 ± 20 µm respectively. These values are taken from the scans of an image plate placed at the focus of the lens as shown in fig. 2 and averaged over three shots.

The number of x-ray photons in each spot is also easily calculable from the PSL (photo-stimulated luminescence) value of the exposed image plate (see fig. 4). For the case of the copper targets,

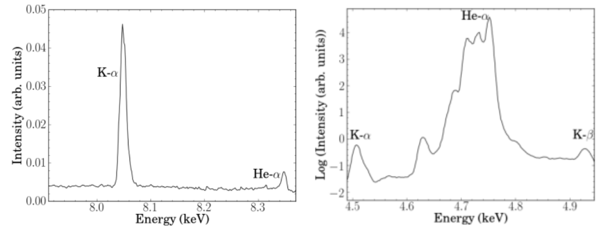

Figure 3. (Left) X-ray spectra produced by interaction of 175 J, 10 ps laser beam with 2 µm thick copper foil. The peaks correspond to K-α and He-α transitions respectively. (Right) X-ray spectra produced by interaction of four 100 J, 1.5 ns laser beams with 10 µm thick titanium foil. The three central peaks correspond to the three characteristic He-α transitions. Also seen are several satellite peaks including K-α and K-β. Note these spectra are taken directly from the emission of the backlighter target and are not focused through the polycapillary lens.

we find a peak intensity in PSL of 2 ± 0.2 × 10^3 which corresponds to ~2 × 10^6 photons. The total PSL contained in the spot is therefore 3.5 ± 0.3 × 10^4 corresponding to 3.5 × 10^7 x-ray photons. For titanium, the peak intensity in PSL is 4.5 ± 0.5 × 10^4 or 4.5 × 10^7 photons. In this case the total PSL in the spot is 8.8 ± 0.8 × 10^4 corresponding to 8.8 ± 10^8 x-ray photons. All calculations above followed the method described in [12] taking the spatial resolution of the image plate to be 100 µm.

The divergence of the x-rays output from the lens is also calculated by moving the image plate detector behind the focus of the lens and measuring the subsequent increase in size of the x-ray spot. The half angle of the x-ray cone is measured to be 6 ± 1°. This result agrees with the expected value of angular divergence given the geometry of the polycapillary lens as mentioned above.

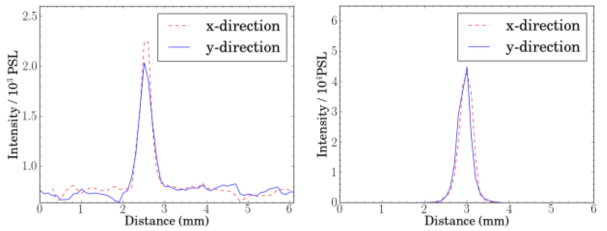

Figure 4. Lineouts in x and y directions of x-ray spot output from polycapillary lens. (Left) X-ray source produced by interaction of 175 J, 10 ps laser beam with 2 µm thick copper foil. (Right) X-ray source produced by interaction of four 100 J, 1.5 ns laser beams with 10 µm thick titanium foil.

The polycapillary lens focuses x-rays of all energies above ~1 keV. Therefore one question regarding the x-ray spot output from the polycapillary lens concerns its energy content. That is what percentage of the spot is line radiation (K-α or He-α) and what percentage comes from the continuous emission across a range of energies. It should be noted that this question is not unique to the experiment described here: the ratio of line radiation to continuous emission is always important in x-ray diffraction or scattering experiments. In all cases, it is preferable to maximise the conversion efficiency of laser energy into line emission.

X-Ray Diffraction

The lens-focused Ti He-α x-ray source is then used to study the structure of two materials: pyrolytic graphite and polycrystalline aluminium. The setup used is depicted in fig. 2 with a distance of 40 mm from the graphite or aluminium sample to the image plate. Pyrolytic graphite is characterised by its ordered nature; it comprises many graphite layers in a hexagonal close packed structure which have a relatively small angular spread. For this reason it is essential that the x-rays are incident onto the sample at an angle which satisfies the Bragg condition. In this case the incident angle of x-rays onto the sample is 23° which represents the Bragg angle for the diffraction of 4.75 keV x-rays from the (002) plane in graphite. The diffraction angle is calculated simply from the ratio of horizontal and vertical distances travelled by the x-rays between the sample and the image plate.

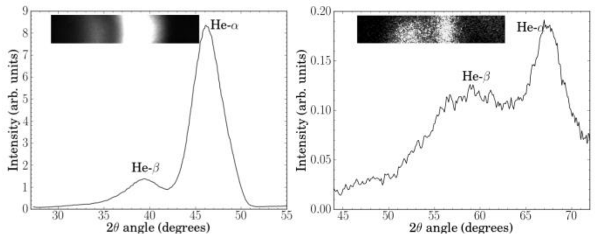

Figure 5. Plots of the diffraction from (left) the (002) plane in pyrolytic graphite and (right) the (111) plane in polycrystalline aluminium. The x-ray source used is titanium He-α focused by the polycapillary lens. Also visible is the satellite peak: the He-β line at 5.57 keV. Insets show part of diffraction line taken from image plate scan of single shot.

Finally, the pyrolytic graphite was replaced by a polycrystalline aluminium sample and the process was repeated. In this scenario the incident angle of the x-rays is unimportant due to the polycrystalline structure of the sample: there will always be some crystal structures orientated such that the Bragg condition is met regardless of incident angle. A diffraction ring (or strictly speaking part of a diffraction ring) is seen on the image plate and a lineout is taken in order to determine the angle in the same way as before. The results of both aluminium and graphite are displayed in fig. 5. These results demonstrate that the relayed x-ray source from the polycapillary lens can be used for diffraction experiments.

Conclusions

This work has shown the ability of x-ray polycapillary lenses to focus laser-produced x-ray sources to high intensities. Using a titanium backlighter target, the peak x-ray intensity output from the lens is 4.5×10^7 photons, with a total photon count of 8.8×10^8 in 0.13 ± 0.01 mm^2. Assuming a He-α conversion efficiency of 10^{-4} [13], this setup is equivalent to placing the backlighter target 3 mm from the sample with a 600 μm diameter pinhole. The polycapillary lens therefore enables the placement of the backlighter target 242.3mm from the sample to be studied rather than 3 mm, as would normally be done, without loss of signal. Assuming noise goes as $\sim 1/R^2$, the reduction in noise gained by using the lens is then a factor of $242.3^2/3^2 = 6500$, while the signal remains the same. Moreover, the large distances involved here enable the experimenter to place additional shielding between detector and backlighter target that would otherwise have been impossible if the two were closer together, thus potentially further reducing noise. The function of the lens is demonstrated by two simple diffraction experiments using pyrolytic graphite and polycrystalline aluminium. The diffracted He-α and He-β lines were seen with a good signal-to-noise ratio in both cases. Future experiments to study high energy density states of matter could achieve better x-ray scattering or diffraction results using the setup described in this paper.

Acknowledgements

The authors gratefully acknowledge the help received from the CLF staff in obtaining the results presented. This work was supported in part by EPSRC and by the Science and Technology Facilities Council of the United Kingdom. Additional support from AWE Plc. is also acknowledged.

References

[1] B.A. Remington, R.P. Drake and D.D. Ryutov, Rev. Mod. Phys. **78**, 755 (2006).

[2] R. Kodama et al., Nature **412**, 798 (2001).

[3] S.H. Glenzer and R. Redmer, Rev. Mod. Phys. **81**, 1625 (2009).

[4] G. Gregori et al., Phys. Rev. E **67**, 026412 (2003).

[5] D. Riley et al., Phys. Rev. E **71**, 016406 (2005).

[6] T.G. White et al., Phys. Rev. B **90**, 014305 (2014).

[7] M.K. Urry et al., J. Quant. Spectrosc. Radiat. Transf. **99**, 636 (2006).

[8] A. Higginbotham et al., Rev. Sci. Instrum. **85**, 033906 (2014).

[9] D.C. Eder et al., Appl. Phys. B **70**, 211 (2000).

[10] A. Ravasio et al., Phys. Rev. Lett. **99**, 135006 (2007).

[11] S.N. Chen et al., Phys. Plasmas **14**, 102701 (2007).

[12] S.G. Gales and C.D. Bentley, Rev. Sci. Instrum. **75**, 4001 (2004).

[13] D. Riley et al., J. Quant. Spectrosc. Radiat. Transf. **99**, 537 (2006).