Measurement of the x-ray emission source size from solid targets irradiated with intense laser pulses

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Abstract

We present the design and first results from a novel penumbral measurement diagnostic, and detector stack capable of measuring the source size of high energy ($> 100keV$) x-ray beams. The diagnostic was fielded in Vulcan Target Area West measuring a source size of $130 + / - 15\mu m$ in agreement with previous work, and shown to be valid from high magnification radiograph images of a precision made tungsten spatial resolution test grid.

1 Introduction

As a high intensity laser interacts with a solid target, electrons are accelerated into the target at relativistic energies, these electrons interact with the target material causing heating in the target and emitting a bright bremsstrahlung pulse as the electrons pass through [1][3]. These x-rays, particularly those of high energy ($> 100keV$), provide an unparalleled view of the internal electron transport. As such, the more we can understand about the x-ray source from laser plasma interaction the more we can understand what is happening internally. Unlike escaping electron and proton measurements, x-rays that escape the target do so unabated by the fields on the target surfaces, or transition from solid to vacuum. Measuring the source size of these x-rays provides us with information about the electron divergence through the target and a lower limit on the achievable radiography resolution for the system. Laser-solid sources of x-ray radiography are beneficial for imaging large dense objects [2] compared to traditional x-ray tube or linear RF accelerator methods due to the inverse relationship between x-ray energy and the emission zone of x-rays. This arises from the gaussian intensity distribution of the laser pulse giving rise to highest intensities on axis, and therefore highest electron energies and x-ray emission energy from the central focal spot region and lower energies from a wider region. . This annual report covers the design and deployment of a new diagnostic capable of measuring the emission area of high energy x-rays produced during laser-plasma interactions with thick high atomic number, Z, targets, like Tantalum. Addressed throughout are the challenges with measuring high energy ($> 100keV$) x-rays.

2 Methods of measuring x-ray emission size

Beside penumbral measurements there are two keys ways to measure an x-ray source used in laser-plasma physics. The first is pinhole cameras; these work in the same fashion as those used to look at solar eclipses. In the case of x-rays a pinhole (smaller than the source) is made in a dense high Z material, this then casts an image onto the detector plane of the source. The magnification of the system and the resolution of the detector then provide a measurement of the source size. Another method used is Bragg diffraction, x-rays of a specific energy/wavelength will reflect off atoms in a crystal structure and constructively interfere with one another producing a bright mono-energetic image. With knowledge of the crystal, and by using Bragg's law, a measurement of the source can be reconstructed from the image detected. Penumbral measurements are already deployed within the field in the form of a 'knife edge' technique, which relies on the same principles of the diagnostic presented here. Drawbacks of these three techniques are discussed in the next section, along with how the penumbral aperture draws on the pinhole camera and traditional knife edge techniques. [5][6][4]

2.1 Evolution from previous designs

In each case there are issues that prevent these from being extended up to high energies. For Bragg-diffraction crystals, the viable inter-atomic spacing prevents energies $> 15keV$ being reliably imaged ($40keV$ corresponds to the atomic radii of a hydrogen atom).

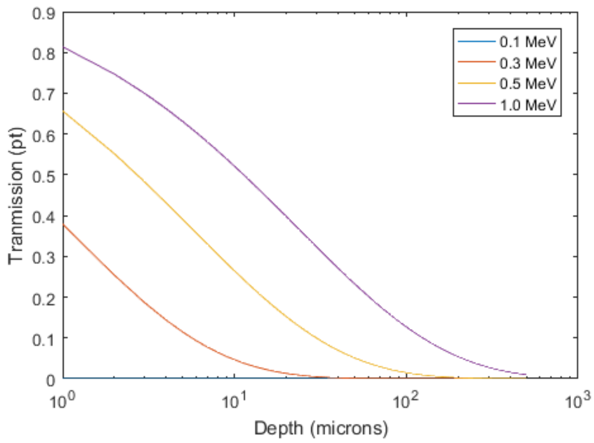
The smallest resolvable source of a x-ray pinhole camera is dictated by the size of the aperture. However, for pinholes smaller than $10\mu m$ vignetting and diffraction begin to degrade the image quality and interfere with the measurement. Vignetting happens as the aspect ratio between the pinhole diameter and thickness increases. Decreasing the thickness of the pinhole material would resolve the issue but increase the overall transmission potentially creating an untenable signal to noise. If the emission from the target was limited to soft x-rays ($< 15keV$) diffraction would still present issues when attempting to resolve below μm level features. Pinhole diffraction is dependent on both the diameter of the hole and the wavelength of the light, for a $5keV$ x-ray and a $1\mu m$ pinhole diffraction would contribute 10% of the image seen at the detector plane.

Knife edge measurements are much closer in design to the penumbral aperture proposed here. The single edge reduces the contribution from diffraction by several orders, and increasing the energy resolution is relatively simple - increasing the thickness or z of the material allows the energy resolution to increase. The issue with this becomes the overall alignment. Unless the object is directly perpendicular to the source the transmission length experienced will be non-uniform leading to a blurring of the penumbra on the detection plane. Another minor issue with the knife edge technique is the loss of the ability to measure the source in multiple axis, a pinhole provides a full 360 degree measurement of the source, from which internal source details can be reconstructed during post analysis.

2.2 Design Features

In order to rectify both of these issues a penumbral aperture was designed. The aperture is significantly larger than the source measuring 10mm in diameter with a curved internal bore, and machined in Tungsten Carbide. This design removes the contribution from pinhole diffraction. The curved inner bore means that a uniform length is always perpendicular to the emission (within 2mm field of view), and the large radius of curvature on the inner bore allows this design to be effective up to $100keV$ with $< \mu m$ accuracy and up-to $500keV$ with $< 10\mu m$ accuracy.

The following graphs demonstrate the energy and spatial resolution expected from a tungsten carbide aperture and a 0.5m radius of curvature for the inner bore. This design was used for the final diagnostic. As x-ray transmission increases with energy the cut-off was set at 10% transmission, this value sets the dark value between which the penumbral is measured.



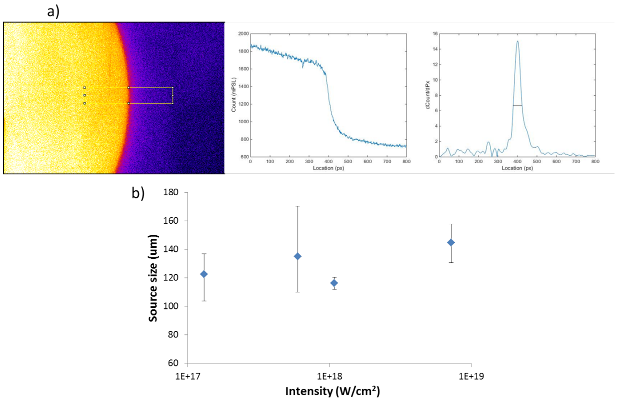
Figure(1) shows the transmission through a tungsten sphere at a specified depth - this provides the blurring depth for different energy x-rays. This corresponds to the 1D attenuation for path lengths through a tungsten carbide "sphere" with a radius of curvature of 0.5m. [7]

3 Experimental Results

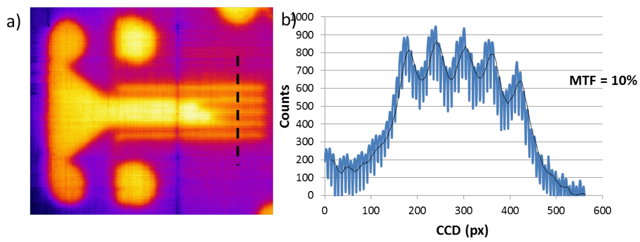
This penumbral aperture was deployed during an experimental campaign on the Vulcan laser system in Target Area West. In order to take advantage of the diagnostics energy range a layered detector stack was used with two sheets of image plate and a CsI pixelated scintillator. Each layer of the detector stack was filtered with different materials in order to increase the peak absorbed energy. We measured the source size for a range of laser focal spot sizes on 100um Ta, the results showed that, across the defocus range tested, the effective source size at $40keV$ (the first layer of the detector) was $130+/-15\mu m$. This measurement was corroborated by subsequent radiographs of a precision made Tungsten Test Grid (figure 3b) which demonstrated that 200 micron size features were resolved with this imaging system.

4 Discussion

The goal of this diagnostic was to allow for high energy high resolution measurements of x-ray emission size. For the curved edge design, the 1D attenuation results can be assumed correct for x-rays $< 500keV$. Beyond this scattering processes begins to dominate the attenuation of the x-ray through the diagnostic - which contributes to the source measurement. It also becomes more difficult to detect these x-rays at high resolution. Measurements recorded on the CsI array consistently produced higher source measurements than those in the lower energy bands contradicting the fact that for laser driven sources the opposite is true, higher energy electrons are less divergent through the source resulting in a smaller source size for their x-rays. This was due to the blur-

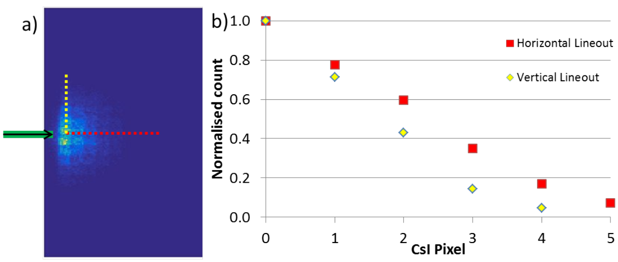


Figure(2) *a)* an example image cast by the penumbral aperture, with the two subsequent inlet graphs being a lineout and the gradient showing the source size *b)* shows the results from the defocus scan on 100um tantalum, error bars shown account for the asymmetry of the source and variance in the source further corrections can be made by accounting for the point spread function (PSF) of the filter layers.



Figure(3) *a)* shows a high magnification radiograph from the high energy phantom, *b)* is the corresponding line out across the 200um slits shown and an MTF when of the background subtracted image. Features are clearly visible with an modulation transfer function (MTF) of 10% indicating that the source must have been smaller than $200\mu m$.

ring introduced by the detector itself dominated over the source size measurement. In a separate offline test we illuminated the array with a green HeNe laser and measured the resultant spread of light from pixel to pixel. The results suggest that the pixel walls transmit 75% of the light incident on them to the next pixel.



Figure(4) *a)* Image of the CsI scintillator leaking light across numerous pixels, *b)* Horizontal and vertical normalised line out showing a 75% transmission from one to the next

Due to the extent of the blurring the original source cannot be deconvolved. If the system was run under higher magnification, to ensure that the region of interest is greater than that of the intrinsic blur, the source size could be retrieved.

5 Conclusions

Presented in this report is the design and initial testing of a high energy, high resolution, penumbral aperture capable of measuring sources upto $300keV$ with $< 10\mu m$ resolution. In combination with high resolution image plate measurements of the x-ray source were measured at $130 + / - 15\mu m$, and confirmed by the radiography of a x-ray phantom. The resolution of the detector stack prevented the full range of the aperture being utilised and for subsequent runs improvements need to be made to high energy x-ray detection in order to get the most out of the diagnostic.

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