X-Ray Focusing Using Capillary Arrays

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ABSTRACT

A new form of x-ray focusing device based on glass capillary arrays (GCAs) is presented and investigated both theoretically and experimentally.

1. INTRODUCTION

The principle underlying the focusing of x-rays using a GCA is illustrated in figure 1. The principle shown in this one-dimensional diagram is clear, however the two-dimensional properties will depend critically on the cross-sectional shape of the capillaries. In this paper we present theoretical and experimental results for arrays of circular capillaries in §2 and theoretical and computational results for square hole capillaries in §3. It is envisaged that devices such as these will find wide applications in x-ray optics as robust, achromatic condensers and collimators.

2. ARRAYS OF CIRCULAR CAPILLARIES

Theoretical results concerning these arrays have been presented elsewhere[1]. We characterise the gain, G, produced by these devices as the ratio of the number of photons directed by the array into a collector of diameter c located on the optic axis at a distance l_s from the array, to the number of photons that would strike that detector in the absence of the GCA. It can be shown that[1,2]

$$G = \frac{16\varepsilon\gamma_c^2 l_s m_T \mathcal{R}}{\pi c d}, \qquad (1)$$

where ε is the open area fraction of the GCA, γ_m is the critical angle of the radiation, $\mathcal{R}$ is the reflectivity of the surface, assumed constant for angles less than γ_c and $m_T = l_i/l_s$. Thus we see that $G \propto l_s$. Substitution of realistic numerical values suggest that G may exceed 100 quite easily.

A series of experiments was performed using flat Varian Micro Channel Plate (MCP) blanks. The plates had a channel diameter of 10 μm, a hole spacing of 12 μm and an open area fraction of 0.63. Cu $K\alpha$ x-rays were produced by a Hilger-Watts micro-focus x-ray source and detected using an energy dispersive Si(Li) detector. The gain of the plates into a 40 μm diameter collector was measured over a range of l_s and the results are shown in figure 2 along with the prediction of G assuming a channel surface reflectivity of 0.30. The roll-off in gain is thought to be due to channel misalignments. The distribution of radiation at various planes behind the MCP was measured and compared with Monte-Carlo computer simulations. In figure 3 is shown the experimentally measured distribution of radiation at a distance of 183 mm from the plate where the focus is 120 mm from the plate along with the prediction of a Monte-Carlo simulation of the data. The agreement is excellent in all measured planes.

Experiments were also performed on curved plates and it was found that a very high degree of collimation could be obtained.

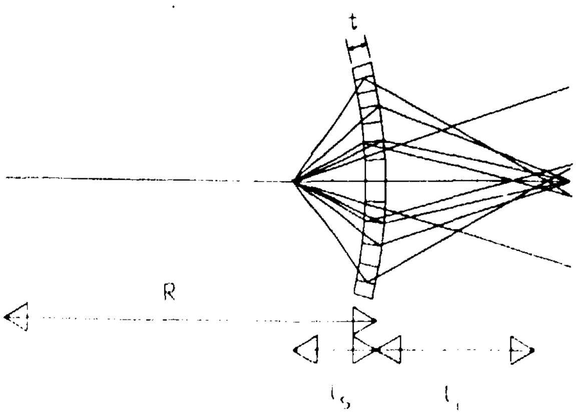

Fig 1: Principle of focusing by reflection by capillary arrays. R is the radius of curvature of the GCA.

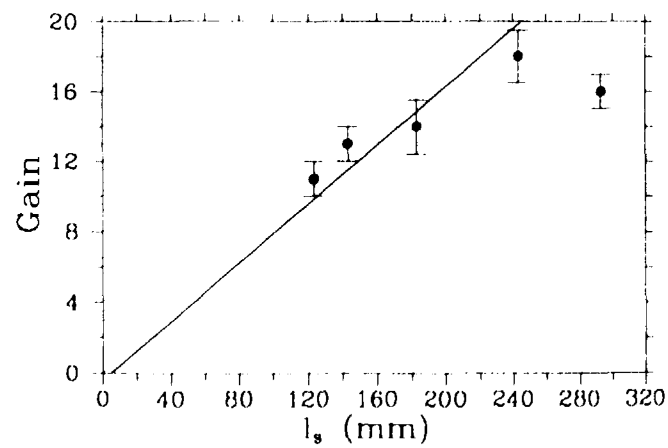

Fig 2: Measured MCP gain as a function of l_s. The line is the theoretical prediction assuming a channel surface reflectivity of 0.30.

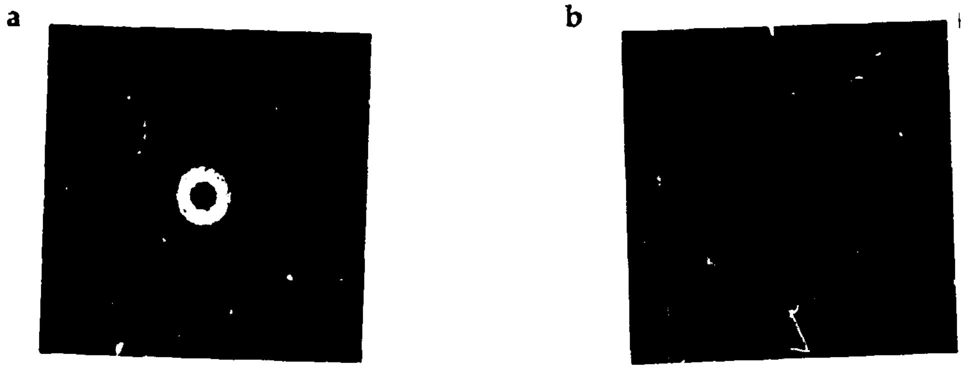

Fig 3: Experimental out-of-focus light distribution *(a)*, and the prediction from a Monte-Carlo simulation of the experiment *(b)*. The side-lengths of each photo are 5.1 mm.

3. ARRAYS OF SQUARE CAPILLARIES

We now consider the use of square cross-section channels. In this case the system is configured so that a ray is focused by being singly reflected from two orthogonal surfaces. Thus a form of the familiar corner-cube effect is used to redirect the ray towards the optic axis and thereby a relatively high quality focus is obtained. As a result, the family of arrays composed of rectangular channels appears to offer the best performance out of all possible channel cross-sections.

We have developed a rather detailed model to describe the performance of these arrays[3] and have used it to predict the properties of the arrays under two main assumptions about the reflectivity properties of the array material: what we term the "hard x-ray case" where the array material is assumed to have constant reflectivity out to a critical angle, and what we have termed the "soft x-ray case" where the reflectivity is assumed to decrease linearly out to some maximum grazing angle γ_m. It is predicted that, for the most straightforward configurations, a focussing efficiency (fraction of photons entering channels that ultimately arrive in the focal volume) is 0.34 in the hard x-ray case and 0.063 in the soft x-ray case. Although this efficiency can be quite small for the case of soft x-rays the collection aperture for the device is determined by γ_m and so can be quite large. In particular, if we characterise the device by an *f*-number then we find, for 3.0 nm x-rays, $f/\# \approx 1/(2\gamma_m) \approx 4$, which corresponds to a very fast condensor. In figure 4 is shown the curve produced by our analytical model for the efficiency of the plate versus $\alpha \equiv t\gamma_m/d$, where t is the plate thickness and d is the internal channel width, for a linear reflectivity curve and for the results of a Monte-Carlo simulation using measured reflectivity parameters for an x-ray wavelength of 3.0 nm. The agreement is very good.

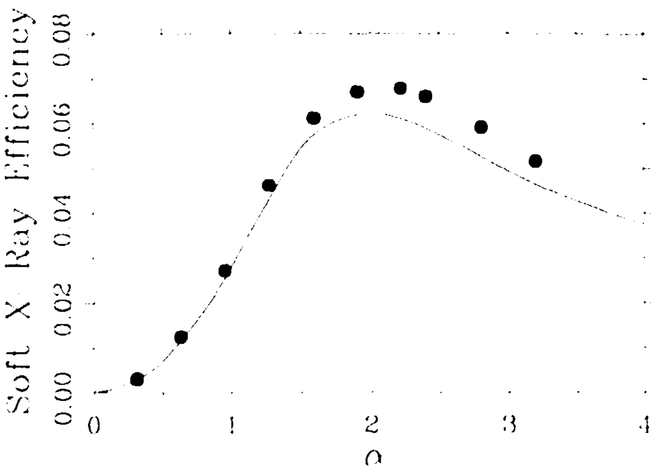

Fig 4: Plot of plate efficiency versus $\alpha = t\gamma_m/d$ for analytical model (line) and Monte-Carlo simulation (circles) using realistic reflectivity data for 3.0 nm radiation.

4. CONCLUSION

Capillary arrays represent a novel approach to the achromatic condensing and collimating of both hard and soft x-rays using devices which are compact and robust. We are currently exploring their applications in crystallographic and soft x-ray microscopy studies.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. S.W.Wilkins, A.W.Stevenson, K.A.Nugent, H.N.Chapman and S.Steenstrup, "On the concentration, focusing and collimation of x-rays and neutrons using microchannel plates and configurations of holes", Rev. Sci. Instrum., 60, 1026-1036 (1989)

2. H.N.Chapman, K.A.Nugent, S.W.Wilkins and T.J.Davis, "Focusing and collimation of x-rays using microchannel plates : an experimental investigation", J. X-Ray Sci. Tech., in press.

3. H.N.Chapman, K.A.Nugent and S.W.Wilkins, "X-ray focusing using square channel capillary arrays", in preparation.