Imaging X-Ray Fluorescence Using Microchannel Plate (MCP) Optics

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Abstract

X-ray fluorescence imaging is a widely used, nondestructive method for determining the distribution and relative concentration of metals within a sample. To create a two-dimensional map of an image, x-rays are usually sent through a 25-250 μm wide aperture, then point by point an image is scanned. Microchannel plates contain an array of tiny holes that can be used to collimate x-rays fluorescing off a sample. When a microchannel plate is used as a collimator between a sample and detector, the sample can be uniformly illuminated and imaged onto a detector. This method allows many different metals to be detected within a sample and it reduces scan time from hours to minutes. The transmissions through a circular channel plate and square channel plate have been found to be 48% and 64% respectively. The transmission percentages are nearly equal to the open-air percentages. The square channel microchannel plate was able to resolve two copper wires fluorescing at 8.046 keV. In this image, the three component cruxiform predicted for an ideal square channel plate is seen. An image created from a 0.66 mm copper wire had a FWHM that was 20% larger than the theoretical value. The extra width is believed to be due to smearing through the channel walls. This experiment demonstrates that microchannel plates are capable of resolving images for x-ray fluorescence at energies as high as 8 keV.

Keywords: x-ray fluorescence, microchannel plates

Introduction

Imaging x-ray fluorescence applies to diverse fields such as biology, material analysis and medical research. Imaging XRF produces a two dimensional map of the distribution and relative concentration of metals in a sample by scanning a narrow x-ray source across a sample using motorized x and y stages. Data is collected point by point and an image is reconstructed.

A microchannel plate is an array of holes that can collimate x-rays. When placed between a source and detector, a microchannel plate allows the entire sample to be uniformly illuminated and imaged by a detector. Using a microchannel plate as an x-ray collimator should allow a sample to be imaged in less time than conventional scanning methods. When a microchannel plate collimator is used with a crystal analyzer, images containing the distribution of many different metals can be created by varying the bragg angle of the crystal.

The use of microchannel plates as x-ray collimators has been demonstrated for x-rays in the 1 keV range (Martin 1999) as well as x-rays in the 1-8 keV range (Yamaguchi

1987). The focusing ability of both square channel (Chapman 1991) and circular channel (Chapman 1993) microchannel plates has been theorized. Experiments have also been done investigating the focusing ability of square channel (Fraser 1992) and circular channel (Chapman 1993) microchannel plates.

When focusing through an ideal square channel plate, a three component cruxiform image is expected (Chapman 1991). This image includes a component consisting of rays that go straight through a channel without being reflected, ending up either above or below the focus. This is seen as a diffuse halo around the focus. Rays can also be reflected only once in either the x or y directions. These rays will be focused in one dimension but not the other, creating a line through the focus in either the x or y directions. This creates a cross image centered on the focus. The third component is the true point focus. The true focus is created by rays that are focused in both the x and y directions. In most applications, about one quarter of the rays go into the true focus, one quarter into each line focus and one quarter into the diffuse halo. Because the area of the true focus is much smaller than the areas of the other components, the intensity of the focus is much greater than the other components.

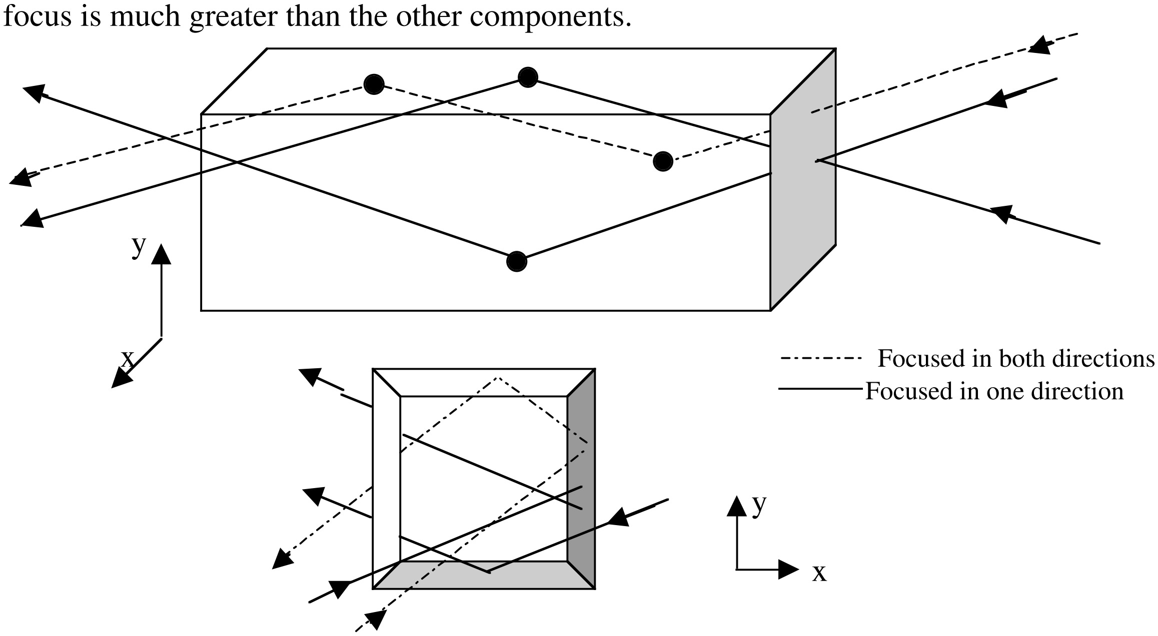

Figure 1. Focusing rays through a square channel microchannel plate. Rays that only reflect from one of the orthogonal sets of channel walls are only focused in one direction. Rays reflecting off both sets of orthogonal walls are focused in both directions.

According to the theory of the three-component cruxiform structure, an image taken through a square channel microchannel plate depends rays that a) reflect off the channel walls and b) transmit through the channels without reflecting. Rays incident on the walls of a channel with an angle less than or equal to the critical angle of reflection will reflect. The critical angle of reflection is given by the equation,

$$\theta_c=1.65\ \lambda \sqrt{\rho}\ [\mathrm{mrad}] \qquad (1)$$

where ρ is the density of the material in g/cm^3 and λ is the x-ray wavelength in angstroms.

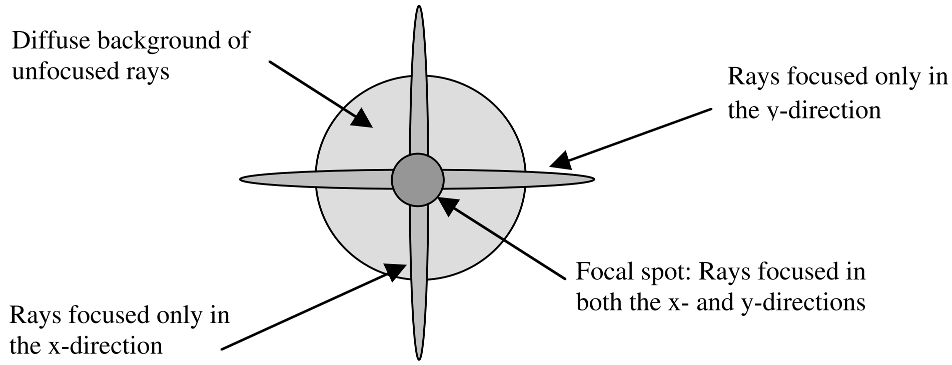

Figure 2. Cruxiform image expected to be seen through a square channel microchannel plate.

The rays that transmit through the channels without reflecting have some divergence that is limited geometrically to the ratio of the channel diameter, *d* and its length, *l*. The ray path is limited to an angle 2α, where

$$\alpha=\tan^{-1}(d/l) \tag{2}$$

(Yamaguchi 1987). The half-maximum intensity point in the profile is used as the divergence of the beam, so the geometrical beam divergence angle is approximately equal to α.

The spatial resolution of the microchannel plate is determined by

$$\Delta r \approx x\Delta\theta \tag{3}$$

where x is the source-to-output distance and θ is the divergence angle (Yamaguchi 1987). Either the angle of reflection or the geometrical divergence angle is used for the divergence angle, depending on which is greater. In the case of both microchannel plates tested, the geometrical divergence angle is greater than the critical angle. Therefore the geometry of the plate is the limiting factor in the resolution for this experiment.

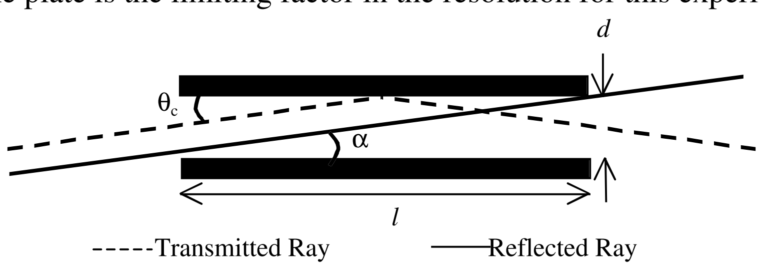

Figure 3. Diagram of rays transmitting through and reflecting off the walls of a microchannel plate. The channel diameter, *d* and channel length, *l* are also defined.

Materials and Methods

Microchannel Plates

Transmission percentage was determined for a circular channel plate provided by Burle Industries, Lancaster Pennsylvania and a square channel plate provided by Nova Scientific, Sturbridge Massachusetts.

Table I. Specifications of the microchannel plates. The plate designers provided information on the material used to make the plates. All other specifications were obtained from scanning electron microscope images.

	Square Channel Plate	Circular Channel Plate
Plate thickness (*l*)	1.5 mm	1.0 mm
Pore diameter (*d*)	27.58 µm	23.6 µm
Center-center spacing	34.58 µm	33.2 µm
Open area percentage	64%	46%
Material	50% Lead Glass	PbSiO3
Density	5.22 g/cm^3	11.35 g/cm^3
Critical angle at 8.046 keV	8.57 mrad	5.81 mrad
Geometrical divergence angle	18.4 mrad	23.6 mrad

a) b)

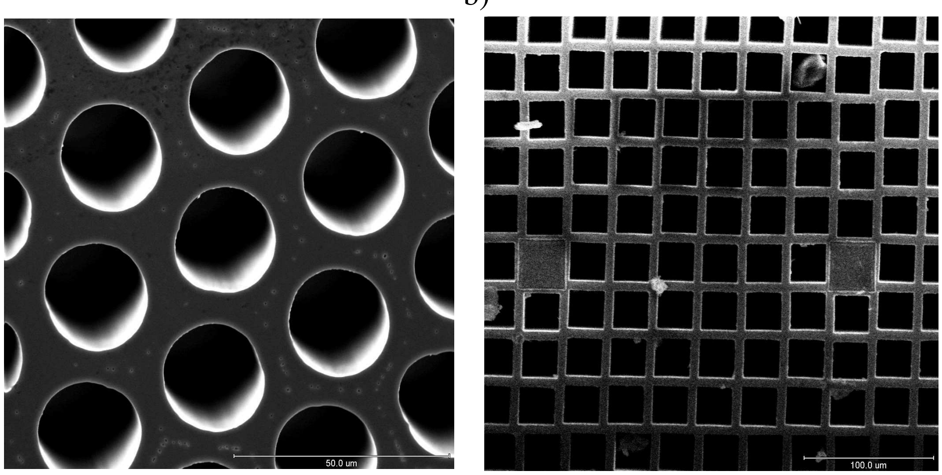

Figure 4. Scanning electron microscope images of the a) circle channel and b) square channel MCPs. Some squares are left closed so as to absorb x-rays that transmit through the channel walls.

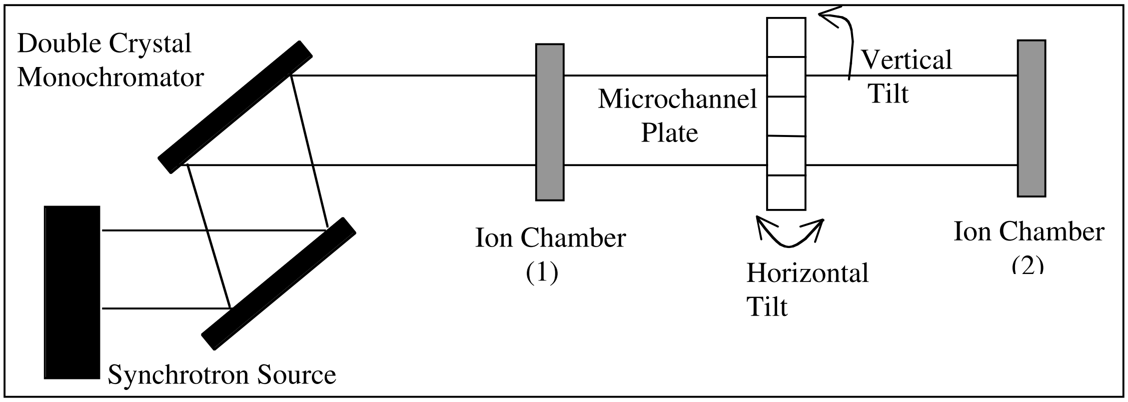

Figure 5. Schematic diagram of the experimental setup in the F3 Hutch at CHESS. The transmission of both MCPs was tested using this setup.

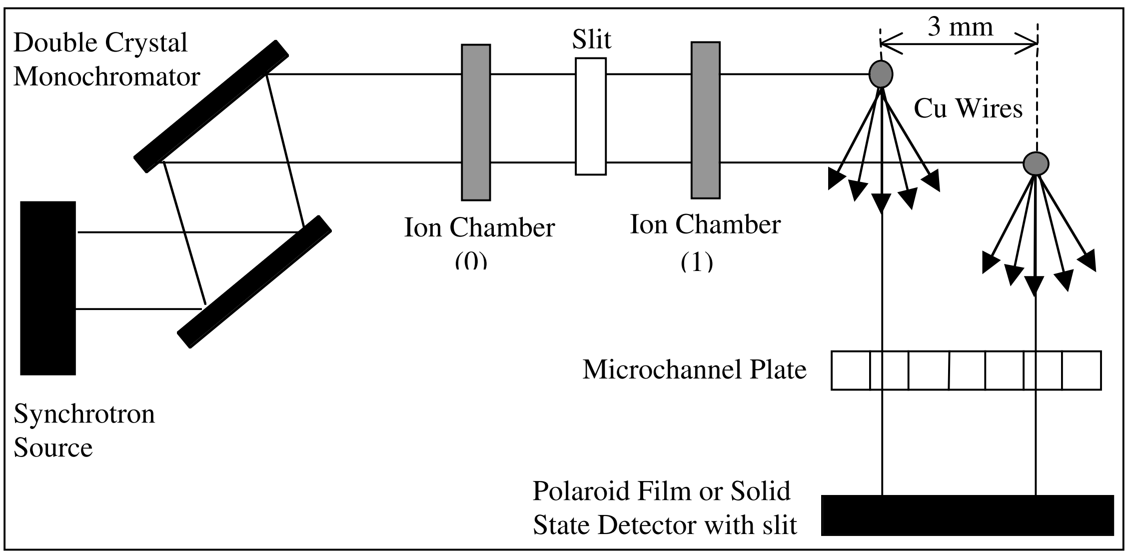

Figure 6. Schematic diagram of the experimental setup in the D1 Hutch at CHESS. The spatial resolution of the square channel plate was tested using this setup.

X-Ray Setup

Experiments were conducted at the Cornell High Energy Synchrotron Source (CHESS). The transmission of the plates was measured using the setup shown in figure 5. Aligning the channels with the beam maximized the transmission of x-rays through the plates. This alignment was done using a tilt stage with two directions of tilt: one in the horizontal direction and one in the vertical direction. The ion chambers were 101 mm apart and the MCPs were 47 mm from ion chamber 1. The beam energy was 12 keV and the beam size was 7 mm in the horizontal direction and 2 mm in the vertical direction.

The resolution of the square channel MCP was tested using the setup in figure 6. A 12 keV energy was chosen because it is higher than the absorption edge of copper (8.979 keV) and it is far enough from the Kα emission of copper (8.046 keV) so as to be easily separated from copper by an energy resolving detector. The MCP was adjusted for maximum transmission using two directions of tilt and a Ge Solid State Detector coupled with an adjustable slit and movable y- and z-stages. Polaroid type 57 film was exposed using a fluorescent screen.

Results

To obtain the transmission through the circular channel and square channel microchannel plates, the MCPs were positioned for maximum transmission and a one second photon count was taken in Ion Chamber 1 (Figure 5). Next the MCPs were taken out and another photon count was taken for one second in Ion Chamber 1. A transmission percentage was found by dividing the number of photons counted through the MCP by the number of photons counted without the MCP. The circular channel plate had 48% transmission and the square channel plate had 64% transmission. These results agree with the open air percentage of the plates: 64% for the square channel plate and 46% for the circular channel plate (calculated from the dimensions seen in the SEM images).

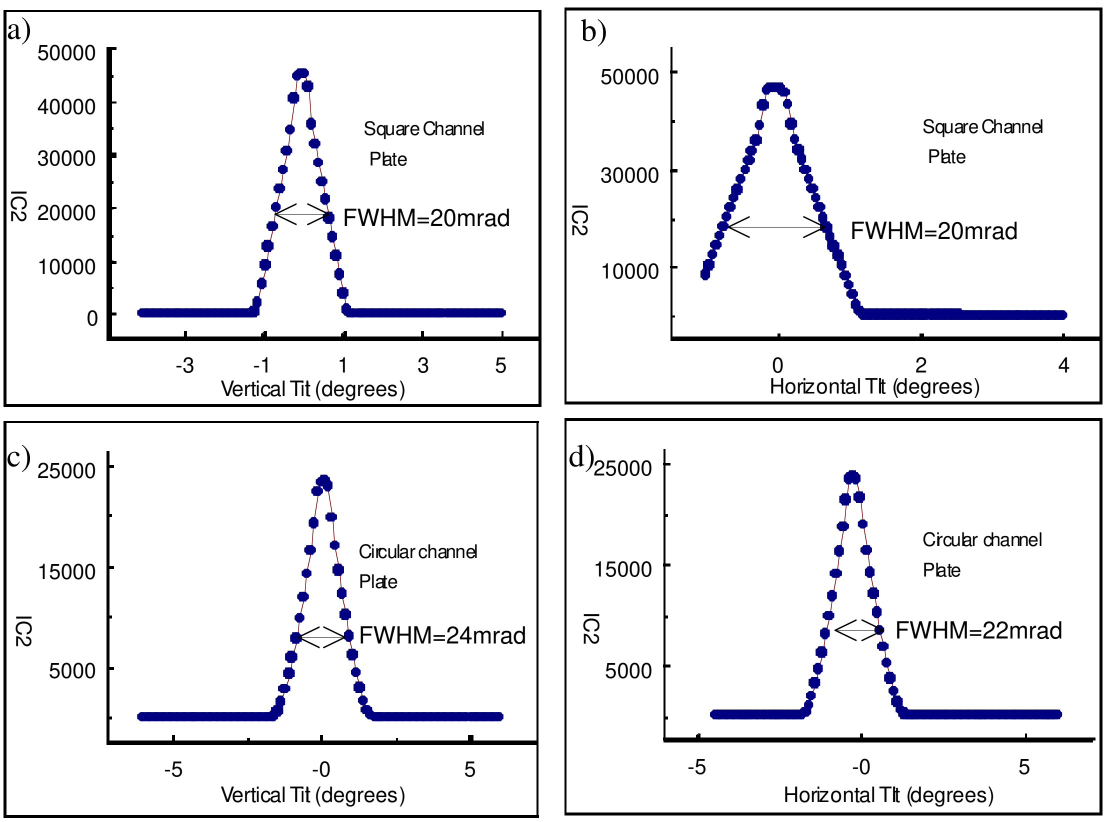

Figure 7. Tilt scans used to find the divergence angles of the plates. Experimental setup shown in figure 5. Energy = 12 keV. a) Vertical tilt of square channel MCP. FWHM = 20mrad. b) Horizontal tilt of square channel MCP. FWHM = 20mrad. c) Vertical tilt of circular channel MCP. FWHM = 24mrad. d) Horizontal tilt of circular channel MCP. FWHM = 22mrad.

Figure 7 shows tilt scans in the vertical and horizontal directions for both the square and circular channel MCPs. The Full Width Half Maximum of the peak is used to define the divergence angle of the plate. The FWHM values are very close to the calculated geometrical divergence angles of the plates: $\alpha = \tan^{-1}(27.58\ \mu m/1.5\ mm) = 18.4 mrad$ for the square channel plate and $\alpha = \tan^{-1}(23.6\ \mu m/1.0\ mm) = 23.6\ mrad$ for the circular channel plate.

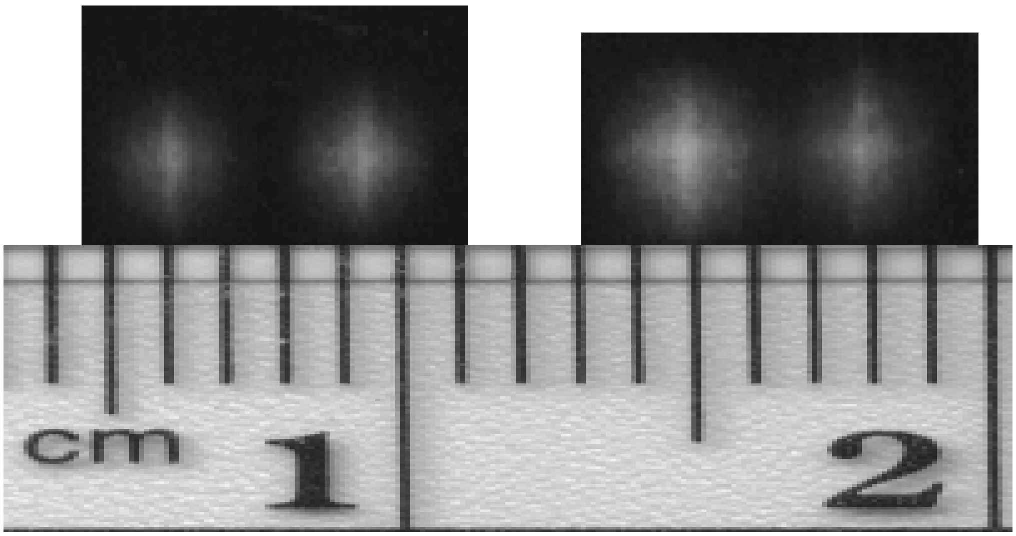

Figure 8. 33 mm MCP-film distance, two 0.10 mm Cu wires. 10 second exposure.

Figure 9. 43 mm MCP-film distance, two 0.10 mm Cu wires. 10 second exposure.

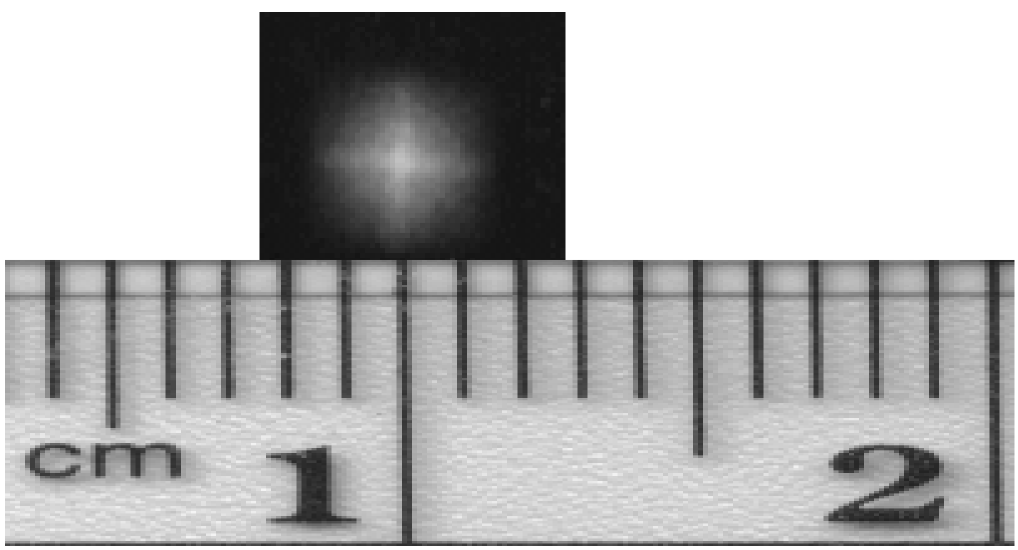

Figure 10. 33 mm MCP-film distance, one 0.66 mm Cu wire.

Figures 8-10 are fluorescent images of copper wires obtained using the setup shown in figure 6. In figures 8 and 9, fluorescent images of two copper wires can be distinguished. All pictures have 33 mm source-MCP distance. In figures 8 and 9, the 0.10 mm diameter wires were placed 3 mm apart on the sample stage. In figure 8, at 33 mm MCP to film distance, the centers of the spots are 3 mm apart and the arms of the cross are 2 mm in both directions. In figure 9, at 43 mm MCP to film distance, the centers of the spots are 3 mm apart and the arms of the cross are 2 mm in both directions. All of these images show the cruxiform structure predicted by Chapman and Nugent in 1991. Figure 10 shows the most clearly defined three component cruxiform image that we photographed.

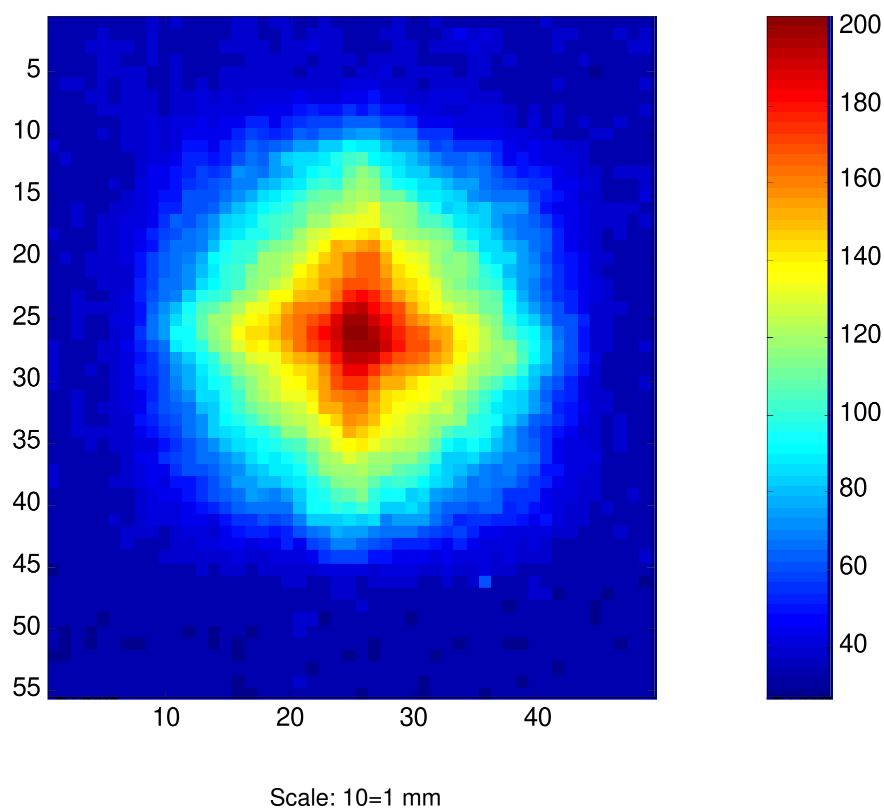

Figure 11. Color enhanced image of figure 10. Image of a 0.66 mm Cu wire through a square channel microchannel plate, 66 mm source to output distance, 3 minute exposure. In this image the source-MCP distance = MCP-film distance.

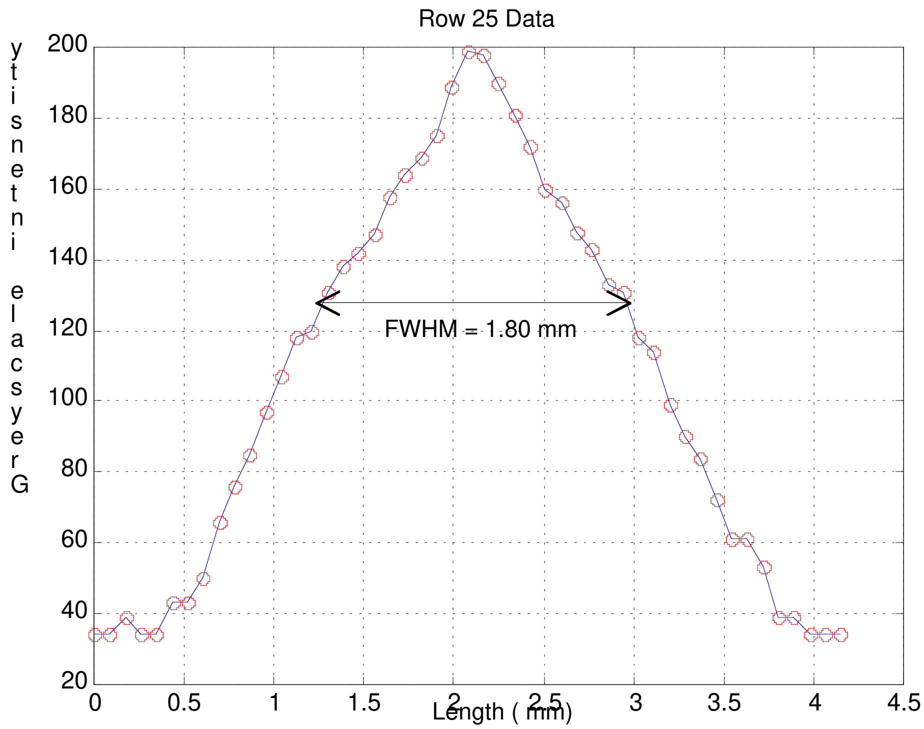

Figure 12. Plot of intensity vs. length across row 25 in figure 11.

According to Eq. 3, the resolution of the image in figures 10 and 11 should be $\Delta r = 1.32$ mm. This was calculated using the 20mrad divergence angle experimentally found for the square channel plate and 66 mm source-output distance. The wire diameter is 0.66 mm so the theoretical value for the FWHM is $\sqrt{(0.66^2+1.32^2)} = 1.48$ mm.

Conclusions

The square channel microchannel plate was able to resolve two copper wires fluorescing at 8.046 keV. In this image, the three component cruxiform predicted for an ideal square channel plate is seen. This experiment demonstrates that microchannel plates are capable of resolving images for x-ray fluorescence at energies as high as 8 keV.

The FWHM of the fluorescent image created by the 0.66 mm copper wire is 20% larger than the theoretical value. This could be due to smearing through the channel walls of the microchannel plate. The attenuation length of the lead glass used to make the square channel plate is 44 µm at 8 keV.

A microchannel plate with a much smaller *d/l* ratio is needed for the resolution to be sufficient for analysis of biological systems. Minimizing this ratio reduces the diffuse halo that can be seen in our pictures. Capillary plates with channels on the nanometer scale are currently available. Adding a reflective coating such as gold to the walls of the channels would allow the reflective properties of microchannel plate collimators to be used at energies around 8 keV. This would also reduce smearing through the walls of the channel. Using microchannel plates in parallel would also be an effective way to improve resolution. Experiments testing the transmission and resolution of improved microchannel plates should be done to determine their potential application to biological element analysis.

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