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Improved modeling of microchannel plate response to hard X-rays

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ABSTRACT

An improved model for microchannel platequantum efficiency and response at higher X-ray energies (up to 100's keV) is described, which builds on previous models by incorporating a more detailed consideration of photoelectron energies released in the MCP bulk. The contribution of multiple channel walls is included in the total response calculation. This model shows that MCP quantum efficiency and response decay as power law functions with energy, for photon energies > 140 keV.

1. Introduction

A microchannal plate (MCP) is often used for both amplification and high-speed temporal gating of incoming photons during scientific experiments, prior to recording media such as film or a charge-couple device (CCD). At the National Ignition Facility (NIF), either film or CCDs are used in conjunction with a MCP for various experimental measurements, including backlit radiography and core self-emission of imploding Inertial Confinement Fusion (ICF) capsules. To design experiments, determine proper timing and gain bias settings for existing experimental campaigns, and to accurately analyze measured results, quantification of MCP response is needed. While MCP response quantification has been published for low- to medium-energy incident photons (<10 keV) [1,2], there is still uncertainty as to the response at high photon energies (up to 100's keV) [3], although some experimental data shows a rather constant response of $\sim$2% in this photon energy range [4,5].

For clarity, MCP plate response will be defined here as the total number of secondary electrons that enter the MCP channels, and cause detectable electron avalanches, per incident photon; whereas MCP quantum efficiency is the probability that at least one secondary electron enters a MCP channel and causes a detectable avalanche per incident photon. With this set of definitions, the response will always be greater or equal to the quantum efficiency and, in the limit of low energies, should be equal.

The present model follows the probability methodology of Shikhaliev [3], but goes further by incorporating the different probabilities of photoelectron generation from multiple atomic shells of the leaded-glass MCP matrix material. Also, the electron range equation used by Shikhaliev appears to be inaccurate, as will be shown subsequently. As such, the present effort can be considered an improvement to the modeling method published by Shikhaliev [3].

A general assumption will be that only the low-energy (<50 eV) secondary electrons created by primary photoelectrons at the wall-channel boundary contribute to the MCP electron avalanche. Secondary electrons created within the MCP matrix bulk contribute insignificantly to the response in comparison with those created at the channel surface, because the range of these secondary electrons is $\sim$50–100 Å. This is justified since the probability of secondary electron production from lead atoms is very high at the lead densities of typical MCPs, such that one can think of the primary photoelectron as leaving a trail of secondary electrons in its wake. The cross-section calculated for lead at 1 keV is $\sim 1.5 \times 10^{-16}$ cm^2 [6] (note that Hou et al. mistakenly labeled their cross-sections in m^2 whereas they should be labeled in cm^2) such that the mean free path between ionization events is of the order of 100 Å for 1 keV photoelectrons($n_{\mathrm{Pb}} = 6 \times 10^{21}$ cm^{-3} in the MCP matrix) and decreases to $\sim$1 Å for $\sim$100 keV electrons (electron-impact cross-section scales as $\ln E/E$). This is less than the secondary electron range, so every primary electron that reaches the channel wall surface is expected to create a secondary electron that can escape into the pore.

The model developed below will be an analytic formulation, although numerical methods are needed to calculate the resulting equations. Monte Carlo modeling is not done here, but such

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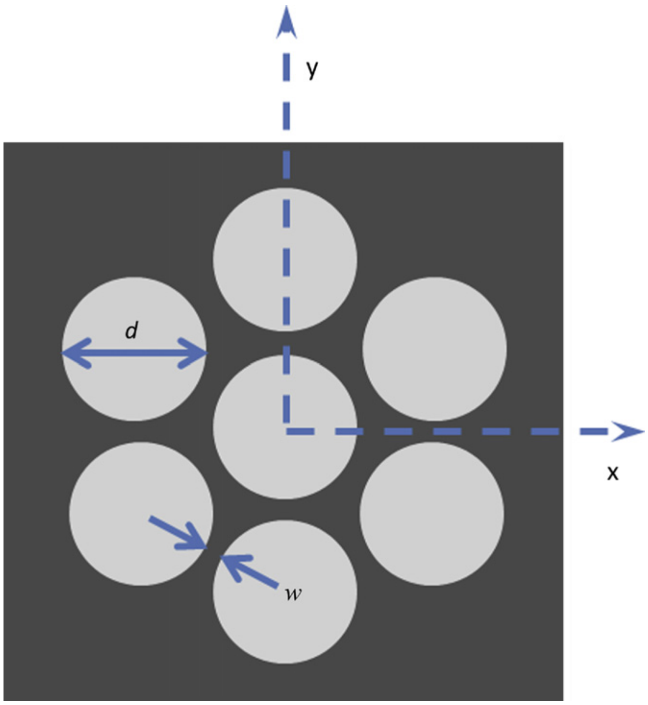

Fig. 1. Schematic of MCP face-on view of hexagonal array of circular channel pores in leaded-glass matrix.

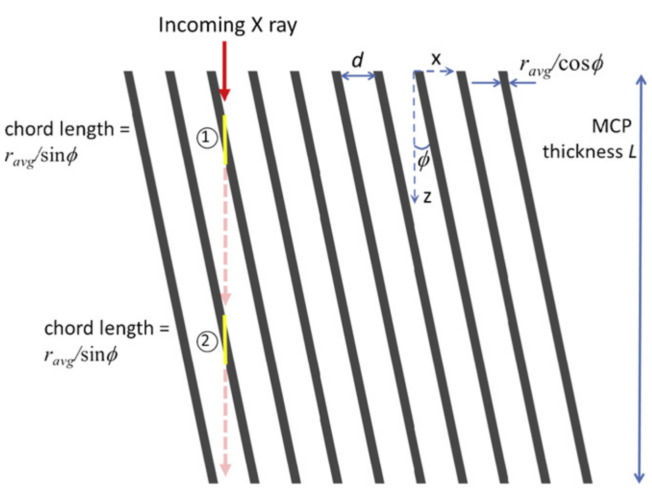

Fig. 2. Schematic of MCP side-on view with channels slanted at bias angle ϕ degrees relative to normal.

results from other researchers would be a welcome complement to our predictions.

2. MCP model

Fig. 1 shows a typical hexagonal array of circular channels in a leaded-glass matrix material. For MCPs used at NIF, the channel diameter is $d=10$ μm and the minimum wall thickness $w=2$ μm. The glass density is about $\rho=4$ g/cm^3 and is composed mainly of lead atoms (∼50% by weight), oxygen atoms (∼26% by weight), and silicon atoms (∼18% by weight) [7]. The lead atoms dominate the photoelectric absorption of X-rays by an order of magnitude over that of silicon and oxygen.

The average path length of matrix material between channel pores is given by [3]

$$r_{avg}=\frac{\sqrt{3}}{4}w\left(2+\frac{w}{d}\right)+\left(\frac{\sqrt{3}}{4}-\frac{\pi}{8}\right)d \quad (1)$$

which is ∼2.3 μm for NIF MCPs. Modern MCPs generally are manufactured with the channels slanted from normal at a bias angle ϕ ($\phi=8^\circ$ for NIF MCPs). As depicted in Fig. 2, the bias angle changes the chord length of the channel wall seen by an incoming photon by $1/\sin\phi$. Here, the three-dimensional MCP structure has been idealized as a 2-D array of channel walls of thickness $r_{avg}/\cos\phi$, separated by the pore diameter d, as has been done previously [8]. With this idealization, the total chord length of the bulk material that can potentially be traversed by an incoming photon is less than the MCP manufactured thickness L ($L=460$ μm for NIF MCPs). The total chord length across the MCP of thickness L is given by

$$z_{max}=L\left(\frac{r_{avg}}{r_{avg}+d}\right) \quad (2)$$

Note that the photon could potentially stop in any of the walls in its path, as shown in Fig. 2. For example, depending on its energy, the photon may most probably stop in chord 1 as labeled in Fig. 2, or it may stop in chord 2, or subsequent chords.

The MCP configuration of Fig. 2 can be reduced to the idealized model schematic shown in Fig. 3. As shown in Fig. 3, the photon is absorbed at a depth z, which could correspond to any chord segment, as was illustrated in Fig. 2. The probability of a photon stopping at depth z is $P(z)=\mu\exp(-\mu z)$, where μ is the photoelectric absorption coefficient (to be discussed in more detail later). The fraction of penetration within a given chord will be denoted f, as shown in Fig. 3. The fraction f can be calculated for arbitrary penetration depth z through

$$f=\frac{z}{r_{avg}/\sin\phi}-INT\left[\frac{z}{r_{avg}/\sin\phi}\right] \quad (3)$$

where the operator INT means to take the integer part of the expression. Upon the photon being absorbed at depth z, the emitted photoelectron can be ejected at an angle θ relative to the incoming photon direction, with a normalized probability

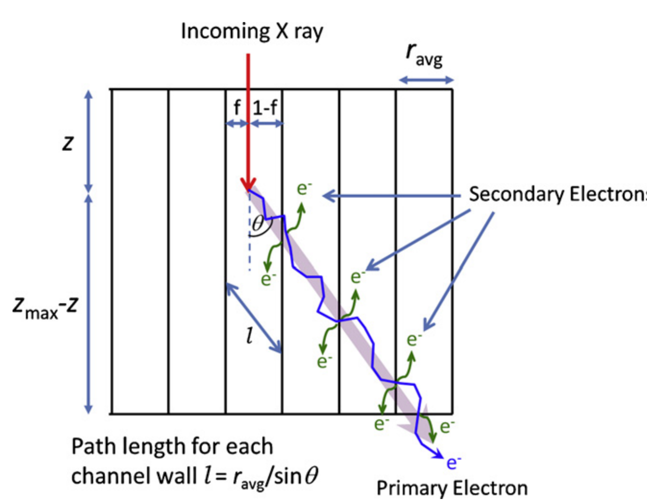

Fig. 3. Idealization of the MCP as an axisymmetric series of channel walls of thickness r_{avg} and total effective MCP thickness z_{max}. The path length for the primary electron in a wall is $l=r_{avg}/\sin\theta$. Upon photoelectric absorption at depth z, the ejected primary photoelectron departs at an angle θ relative to the incoming photon direction with probability $P_{eject}(\theta)$.