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The theory of compact and efficient circular-pore MCP neutron collimators

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Abstract

A novel type of thermal and cold neutron collimators based on microchannel plates (MCPs) doped with neutron absorbing atoms is discussed. Opposite to widely used Soller slit collimators, the microchannel plates collimate a beam of neutrons in 2 dimensions simultaneously and they are very compact. A detailed model of the circular-pore MCP collimator performance, described in this paper, can be used for optimization of MCP parameters in order to achieve the most efficient collimation for a given application. Among these parameters are the MCP geometrical dimensions, the type of absorbing atoms and their concentration in the MCP glass mixture, all constrained by the manufacturing limitations. The model predicts that the MCP collimators can be very efficient (rocking curve $<0.1^{o}$ wide with high background suppression in the wings) and very compact (only few mm thick). In addition to collimation, the same microchannel plates can also be used for neutron imaging with a high spatial (~20 μm) and temporal

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(~1 μs) resolution, opening up new possibilities for simultaneous beam collimation and monitoring.

Keywords: Collimators, Neutron optics, Neutron instrumentation

1. Introduction

Neutron beam collimators are frequently used in neutron scattering experiments and are usually of the Soller slit type, comprising an array of absorbing films separated by neutron-transparent spacers [1],[2] or honeycomb-like packed structures [3]. In order to achieve the optimal collimation and transparency, the thicknesses of the spacers and the absorbing coating are optimized. The ratio of the transmission channel length to its width is one of the key parameters determining the efficiency of collimation. The larger that ratio is the better collimation can be achieved with a given structure (providing the absorption of neutron-opaque section is sufficient). Thus the shorter the collimator, the narrower the transmitting channel must be in order to obtain the required performance. There are obvious challenges in manufacturing micro-scale periodic neutron absorbing structures with high degree of geometric accuracy, especially for large length-to-width ratios required for effective collimation. Thin silicon wafers, refined by the semiconductor industry during many years, coated with gadolinium metal, were used for the production of relatively short (only few cm) collimators [1],[2]. Stacked arrays of stretched polyethylene films with absorbing coatings also formed compact collimators. Even more compact collimators can be made by using the geometric structure of microchannel plates (MCPs), where the periodic structure is typically on the scale of ~10

μm. Microchannel plates are currently widely used in electron multiplying and photon counting imaging applications [4]-[7] as well as in X-ray focusing applications [8]. The existing microchannel plates typically consist of several million microchannels fused together into a monolithic disk-like structure (a section of which is shown in Fig. 1). The pores are usually of a circular or square geometry with 6-12.5 μm wide pores with 7.2-15 μm center-to-center spacing. The thickness L_{MCP} of the disk is typically 40-250 times larger than the pore diameter (equivalent to 0.24-3.125 mm), and MCPs can be fabricated with an area as large as 10 x 10 cm^2.

Modification of the MCP glass mixture by adding a neutron-absorbing material without changing the remainder of the manufacturing process has been suggested by Fraser and Pearson [9] and successfully implemented for thermal [9]-[12] and fast [13] neutron detection. The neutrons in doped microchannel plates are absorbed within the entire volume of the MCP glass, in contrast to Soller slit collimators, where the absorption only occurs in a thin film deposited on a non-absorbing substrate. Therefore the MCPs can collimate a neutron beam in two orthogonal planes simultaneously, rather than in only one plane as in case of Soller slits. Although the glass mixture can contain only a limited proportion of neutron-absorbing atoms, this deficiency is compensated in MCP collimators by the possibility to produce structures with very large aspect ratios. The ratio of pore length to its width L_{MCP}/d for current technology can be as high as 250:1 (Fig. 1). The few nuclides that are useful for thermal neutron detection and can be considered as candidates for the glass mixture include ^{6}Li, ^{10}B, ^{113}Cd, ^{155}Gd and ^{157}Gd and some others. Microchannel plates doped with ^{10}B atoms (with thermal neutron cross

section of 3835 barns) were already produced and tested for neutron detection applications [12]. First experimental evaluation of a Gd-doped microchannel plate neutron collimator was recently performed by Nova Scientific Inc. and National Institute of Standards and Technology [14]. The MCP was doped with 3 mole % of ^{nat}Gd (natural Gd contains 15.7 % and 14.8 % of ^{157}Gd and ^{155}Gd isotopes with thermal neutron capture cross sections of 259000 and 61100 barns, respectively) and was only 0.6 mm thick. Although that MCP was not optimized for collimation applications and was primarily built for neutron detection, it demonstrated a reasonably efficient collimation (~1 degree wide) for such a thin microchannel plate.

In this paper a detailed model of circular-pore MCP neutron collimators is presented together with the predicted performance of collimators which can be produced with the existing manufacturing technology.

2. Probability of single neutron absorption

The probability of neutron absorption inside glass walls of an MCP can be calculated from [11]

$$P_{absorb} = 1 - \exp\left(- L_{eff} \sum N_i \sigma_i \right) \tag{1}$$

where N_i is the number of neutron-absorbing atoms of a particular material i per unit volume of the MCP glass, σ_i is the cross section for the neutron capture reaction by those atoms [15],[16], and L_{eff} is the length of neutron trajectory contained within the MCP glass doped with absorbing atoms. In our first experimental measurements of MCP

collimators we used MCPs doped with $^{nat}Gd_2O_3$. Currently we are also investigating MCPs doped with $^{10}B_2O_3$ and also doped with both $^{nat}Gd_2O_3$ and $^{10}B_2O_3$. The number of neutron-absorbing atoms per unit volume in MCP glass can be found from

$$N_i = \frac{\rho_{glass} m_i \mu_i}{M_i \sum_n m_n \mu_n} \tag{2}$$

where ρ_{glass} is the MCP glass density, m_i, μ_i and M_i are respectively atomic mass, the mass percentage and the mass of neutron absorbing atom of material *i* in the glass and the sum $\sum_n m_n \mu_n$ in the denominator is the sum over all *n* constituents of MCP glass.

2.1. The length of neutron trajectory L_{eff} within the MCP glass

Let's place the center of system of coordinates at the middle of the triangle with its corners at three adjacent MCP pores (see Fig. 2). The center of $(i,j)^{th}$ MCP pore will have the following ($x_{i,,j}$, $y_{i,,j}$) coordinates:

$$x_{i,j} = (d+W)\left(i - \frac{1}{4}\left[1-(-1)^{j+1}\right]\right); \qquad y_{i,j} = (d+W)\left(\frac{\sqrt{3}}{2}\, j + \frac{1}{2\sqrt{3}}\right) \tag{3}$$

where *d* is the diameter of MCP pores and *W* is the thickness of MCP walls (Fig. 1, Fig. 2).

Now let's assume that neutron falls on the MCP at point (x_0,y_0) and the angles of incidence are θ and φ (Fig. 1). Then the intersection of neutron trajectory with plane of the MCP output surface (x_1,y_1) can be found from:

$$x_1 = x_0 + L_{MCP} Ctg\,\theta \cos\varphi \tag{4.a}$$

$$y_1 = y_0 + L_{MCP} Ctg\,\theta \sin\varphi \tag{4.b}$$

where L_{MCP} is the thickness of microchannel plate.

In the following discussion we will disregard the edge effects (when neutron falls close to the MCP edge and thus it leaves the MCP through its side, without reaching the back end) since the angles of neutron incidence are typically only few degrees off the maximum collimator transmission (corresponding to normal incidence in our case). In other words the MCP dimension in xy-plane is assumed to be much larger compared to the projection of neutron travel on this plane.

In case of hexagonally packed circular pores, considered in the present paper, the length of neutron travel through the MCP glass L_{eff} can be found from the following equation:

$$L_{eff}(\theta, \varphi, x_0, y_0) = \begin{cases} 0; & \theta = \pi/2; \quad (x_0 - x_{i,j})^2 + (y_0 - y_{i,j})^2 < \dfrac{d^2}{4}; \\ L_{MCP}; & \theta = \pi/2, \quad (x_0 - x_{i,j})^2 + (y_0 - y_{i,j})^2 \geq \dfrac{d^2}{4}; \\ L1_{eff}; & \theta \neq \pi/2 \end{cases} \tag{5}$$

The first two lines in the equation (5) correspond to normal incidence of neutron, with first condition for the neutron trajectory contained within a single pore (neutron passes straight trough the MCP without intersecting glass walls), and the second line

corresponding to the case when neutron trajectory is completely contained by the MCP glass all the way to the output surface.

The value $L1_{eff}$ for the case when $\theta \neq \pi/2$ can be found from equation:

$$L1_{eff} = \frac{L_{MCP}}{\sin \vartheta} \left(1 - \sqrt{\frac{\left(S_x^{(pore)}\right)^2 + \left(S_y^{(pore)}\right)^2}{(x_1 - x_0)^2 + (y_1 - y_0)^2}} \right) \tag{6}$$

where $S_x^{(pore)}$ and $S_y^{(pore)}$ are the x- and y-axis projections of neutron path within all MCP pores, which it traverses, Fig. 2, while $(x_1\text{-}x_0)$ and $(y_1\text{-}y_0)$ are the projections of the entire neutron path (including both travel within MCP pores and MCP glass). To find $S_x^{(pore)}$ and $S_y^{(pore)}$ we can sum up all the projections of neutron's travel within individual pores:

$$S_x^{(pore)} = \begin{cases} 0; & \varphi = \pi/2, 3\pi/2 \\ \sum_{i_{\min}}^{i_{\max}} \sum_{j_{\min}}^{j_{\max}} u_{i,j}^{(pore)}; & \varphi = 0, \pi \\ \sum_{i_{\min}}^{i_{\max}} \sum_{j_{\min}}^{j_{\max}} x_{i,j}^{(pore)}; & \varphi \neq 0, \pi/2, \pi, 3\pi/2 \end{cases} \tag{7.a}$$

$$S_y^{(pore)} = \begin{cases} 0; & \varphi = 0, \pi \\ \sum_{i_{\min}}^{i_{\max}} \sum_{j_{\min}}^{j_{\max}} v_{i,j}^{(pore)}; & \varphi = \pi/2, 3\pi/2 \\ \sum_{i_{\min}}^{i_{\max}} \sum_{j_{\min}}^{j_{\max}} y_{i,j}^{(pore)}; & \varphi \neq 0, \pi/2, \pi, 3\pi/2 \end{cases} \tag{7.b}$$

where $u_{i,j}^{(pore)}$ and $v_{j,j}^{(pore)}$ are projections of neutron path within individual MCP pores for the simple cases when either $S_y^{(pore)}$ or $S_x^{(pore)}$ are equal to zero, respectively.

Let's select new start (x_s,y_s) and end (x_e,y_e) points of neutron trajectory within MCP so that $x_s \leq x_e$ and $y_s \leq y_e$:

$$x_s = \min(x_0, x_1),\ x_e = \max(x_0, x_1) \tag{8.a}$$

$$y_s = \min(y_0, y_1),\ y_e = \max(y_0, y_1) \tag{8.b}$$

The indexes i_{min}, i_{max}, j_{min} and j_{max} used in equations (7) are the minimum and maximum indexes (for x- and y-axis, respectively) of the pores which neutron crosses during its travel within MCP:

$$i_{\max} = \text{int}\left(\frac{x_e}{W+d}\right)+1,\ i_{\min} = \text{int}\left(\frac{x_s}{W+d}\right)-1 \tag{9.a}$$

$$j_{\max} = \text{int}\left(\frac{2y_e}{\sqrt{3}(W+d)}\right)+1,\ j_{\min} = \text{int}\left(\frac{2y_s}{\sqrt{3}(W+d)}\right)-1 \tag{9.b}$$

Definition of function int(x) used in the equations (9): it is equal to the largest integer value, which is still less than x: (e.g. int(0.877)=0, int(21.32)=21, int(-2.14)=-3, int(-9.8)=-10).

The projections $u_{i,j}^{(pore)}$ and $v_{i,j}^{(pore)}$ can be found from the following equations:

$$u_{i,j}^{(pore)} = \begin{cases} 0; & x_e \le x_{i,j}^s \quad or \quad x_s \ge x_{i,j}^e \quad or \quad \left|y_s - y_{i,j}\right| \ge \dfrac{d}{2} \\ \min\left(x_e, x_{i,j}^e\right) - \max\left(x_s, x_{i,j}^s\right); & x_e > x_{i,j}^s \quad and \quad x_s < x_{i,j}^e \quad and \quad \left|y_s - y_{i,j}\right| < \dfrac{d}{2} \end{cases} \tag{10.a}$$

$$v_{i,j}^{(pore)} = \begin{cases} 0; & y_e \le y_{i,j}^s \quad or \quad y_s \ge y_{i,j}^e \quad or \quad \left|x_s - x_{i,j}\right| \ge \dfrac{d}{2} \\ \min\left(y_e, y_{i,j}^e\right) - \max\left(y_s, y_{i,j}^s\right); & y_e > y_{i,j}^s \quad and \quad y_s < y_{i,j}^e \quad and \quad \left|x_s - x_{i,j}\right| < \dfrac{d}{2} \end{cases} \tag{10.b}$$

where $x_{i,j}^s$ and $x_{i,j}^e$ are the left and right x-coordinates of the intersection of the horizontal line $y=y_s$ and the walls of $(i,j)^{th}$ MCP pore:

$$x_{i,j}^s = x_{i,j} - \sqrt{\frac{d^2}{4} - \left(y_s - y_{i,j}\right)^2}\ ; \qquad x_{i,j}^e = x_{i,j} + \sqrt{\frac{d^2}{4} - \left(y_s - y_{i,j}\right)^2} \tag{11.a}$$

and $y_{i,j}^{s}$ and $y_{i,j}^{e}$ are the bottom and top y-coordinates of the intersection of the vertical line $x=x_s$ and the walls of $(i,j)^{th}$ MCP pore:

$$y_{i,j}^{s} = y_{i,j} - \sqrt{\frac{d^2}{4} - \left(x_s - x_{i,j}\right)^2}\ ; \qquad y_{i,j}^{e} = y_{i,j} + \sqrt{\frac{d^2}{4} - \left(x_s - x_{i,j}\right)^2} \tag{11.b}$$

For the remaining case, when $\varphi \neq 0, \pi/2, \pi, 2\pi/3$, the projections of neutron travel within $(i,j)^{th}$ MCP pore $x_{i,j}^{(pore)}$ and $y_{i,j}^{(pore)}$ are found from equations:

$$x_{i,j}^{(pore)} = \begin{cases} 0; & x_e \le x_{i,j}^{s} \quad or \quad x_s \ge x_{i,j}^{e} \quad or \quad D \le 0 \\ \min\left(x_e, x_{i,j}^{e}\right) - \max\left(x_s, x_{i,j}^{s}\right); & x_e > x_{i,j}^{s} \quad and \quad x_s < x_{i,j}^{e} \quad and \quad D > 0 \end{cases} \tag{12.a}$$

$$y_{i,j}^{(pore)} = \begin{cases} 0; & y_e \le y_{i,j}^{s} \quad or \quad y_s \ge y_{i,j}^{e} \quad or \quad D \le 0 \\ \min\left(y_e, y_{i,j}^{e}\right) - \max\left(y_s, y_{i,j}^{s}\right); & y_e > y_{i,j}^{s} \quad and \quad y_s < y_{i,j}^{e} \quad and \quad D > 0 \end{cases} \tag{12.b}$$

where D is calculated from:

$$D = \frac{d^2}{4}\left(1 + k^2\right) - k^2 x_{i,j}^2 - \left(b - y_{i,j}\right)\left(b - y_{i,j} + 2x_{i,j}k\right) \tag{13}$$

with the line represented by the equation $y=kx+b$ corresponding to neutron travel path in xy-plane, with coefficients k and b found from:

$$k = \frac{y_e - y_s}{x_e - x_s},\ b = y_s - kx_s \tag{14}$$

and $x_{i,j}^{s}$ and $x_{i,j}^{e}$ are the left and right x-coordinates of the intersection of the neutron trajectory with the walls of $(i,j)^{th}$ MCP pore:

$$x_{i,j}^{s} = \frac{x_{i,j} - k\left(b - y_{i,j}\right) - \sqrt{D}}{k^2 + 1}; \qquad x_{i,j}^{e} = \frac{x_{i,j} - k\left(b - y_{i,j}\right) + \sqrt{D}}{k^2 + 1} \tag{15}$$

and $y_{i,j}^{s}$ and $y_{i,j}^{e}$ are the bottom and top y-coordinates of these intersections:

$$y^{s}_{i,j} = kx^{s}_{i,j} + b\,; \qquad y^{e}_{i,j} = kx^{e}_{i,j} + b \tag{16}$$

3. Results of calculations

The performance of MCP collimators with different parameters is predicted with the help of presented model. Obviously the manufacturing constraints determine the range of possible MCP parameters, such as the largest achievable ratio L_{MCP}/d limited by the core glass etching process (currently approximately 250:1 for etched microchannel plates). Results of calculations presented in this section are obtained with a realistic set of parameters achievable with the existing technology and thus only predict the performance of collimators, which can be manufactured at the existing MCP production facilities. This paper does not predict the ultimate best characteristics of microchannel plate collimators, which we believe can be produced in the nearest future with some modifications of the MCP manufacturing process optimized for neutron collimators. For example, we are trying to increase the aspect ratio L_{MCP}/d in order to achieve collimation with very sharp rocking curves (less than 0.05 degrees wide).

The validity of the presented model was already confirmed by our first experimental measurements with an MCP collimator doped with 3 mole % of $^{nat}Gd_2O_3$ (d=8 μm, W=3.5 μm, L_{MCP}/d=75:1). The predicted performance is in good agreement with the measured data [14].

3.1. MCP coefficient of transmission T_{MCP} for a single neutron

Having found N_i from equation (2) and L_{eff} from equations (5)-(16) we can calculate the probability of single neutron absorption $P_{absorb} \equiv P_{absorb}(\theta, \varphi, x_0, y_0)$ from equation (1), as well as the coefficient of transmission of the collimator:

$$T_{MCP}(\theta, \varphi, x_0, y_0) = 1 - P_{absorb}(\theta, \varphi, x_0, y_0)$$

The predicted thermal neutron transmission of a 2.5 mm thick MCP collimator with 10 μm hexagonally packed circular pores on 12 μm centers, doped with 3 mole % of $^{nat}Gd_2O_3$ is shown in Fig. 3. The transmission $T_{MCP}(\theta, \varphi, x_0, y_0)$ is plotted there as a function on neutron incidence position (x_0, y_0), with angles of incidence θ and φ fixed. The MCP neutron transmission obviously exhibits a periodic structure on the scale of MCP pore-to-pore distance (typically 7-15 μm), as seen in Fig. 3.a and Fig. 3.b, when angle of incidence θ is close to normal. The MCP transmission quickly falls to ~0.01 level for angles of incidence θ ≤89 degrees.

The MCP neutron transmission plotted as a function of incidence angles θ and φ with the position of neutron incidence (x_0, y_0) fixed is shown in Fig. 4 for neutrons entering the MCP in the center of a pore, Fig. 4.a and in between two pores, Fig. 4.b. These figures demonstrate that microchannel plates collimate neutrons in both x- and y-axes simultaneously with practically the same efficiency, as confirmed by our first experimental measurements [14].

3.2. The MCP transmission<T_{MCP}> for a neutron beam

Most present neutron sources have finite dimensions of the output neutron beam. These beams are almost never reduced to a point-source configuration due to a limited intensity of existing sources (with exception of only few experiments like neutron phase radiography [17],[18], requiring long acquisition times). Therefore the neutron beam to be collimated is typically much larger in dimension than the MCP pitch period of ~7-15 μm. Thus the performance of an MCP collimator in most cases can be represented by the transmission coefficient $\langle T_{MCP}(\theta,\varphi)\rangle$ averaged over positions of neutron incidence (x_0,y_0). As seen from Fig. 3 the microstructure of the MCP neutron transmission corresponds to the periodic MCP geometry. For a neutron beam with spatial dimensions larger than MCP period (typically 7-15 μm) the parameter of interest is the transmission of the collimator averaged over an elementary cell of that periodic transmission variation (shown by the shaded diamond-like area in Fig. 2). We will calculate the averaged transmission $\langle T_{MCP}(\theta,\varphi)\rangle$ by integrating function $P_{absorb}(\theta,\varphi,x_0,y_0)$ over that region according to the following equation:

$$\left\langle T_{MCP}(\theta,\varphi)\right\rangle = 1-\left\langle P_{absorb}(\theta,\varphi)\right\rangle = \int_{x_{\min}}^{x_{\max}}\int_{y_{\min}}^{y_{\max}} P_{absorb}(\theta,\varphi,x_0,y_0)dx_0dy_0 \Big/ \left(\sqrt{3}/2\,(d+W)^2\right) \tag{17}$$

where

$$x_{\min} = -\frac{d+W}{2};\quad x_{\max} = \frac{d+W}{2};\quad y_{\min} = \sqrt{3}|x| - \frac{d+W}{\sqrt{3}};\quad y_{\max} = -\sqrt{3}|x| + 2\frac{d+W}{\sqrt{3}}$$

The predicted averaged thermal neutron transmission $\langle T_{MCP}(\theta,\varphi)\rangle$ is shown in Fig. 5 for both $^{nat}Gd_2O_3$- and $^{10}B_2O_3$-doped microchannel plates. The MCP parameters

are the same as in Fig. 3 and Fig. 4. The maximum transmission obviously corresponds to the normal beam incidence and it is equal to the open area fraction of microchannel plates. Fig. 5 indicates that even for a 2.5 mm thin microchannel plate doped with 3 mole % of $^{nat}Gd_2O_3$ the transmission of thermal neutrons will be on the scale of only 1-2 percent for angles of incidence θ deviating by more than ~0.3 degrees from normal, with very small variation of transmission with azimuthal angle φ. Obviously thicker (or properly stacked) MCPs should provide much sharper collimation.

3.3. Rocking curves of an MCP collimator

Neutron collimators are usually characterized by a rocking curve, representing the transmission of the collimator as a function of neutron angle of incidence. Since most neutron collimators work only in one axis their respective rocking curves are sufficient to represent their efficiency and to determine their applicability for a particular application. Microchannel plates collimate neutron beam in both axis simultaneously with very weak dependence on angle φ, as described in the previous section, and therefore for a given MCP we will calculate a set of rocking curves with angle θ varying while angle $\varphi = \varphi_0$ is fixed. The transmission of MCP collimator $\langle T_{MCP}(\theta, \varphi_0) \rangle$ (usually represented on the rocking curve as the intensity in terms of the fraction of the main beam) thus can be calculated from $\langle P_{absorb} \rangle$ according to the following equation:

$$\left\langle T_{MCP}\left(\theta, \varphi_0\right)\right\rangle = 1 - \left\langle P_{absorb}\left(\theta, \varphi = \varphi_0\right)\right\rangle \tag{18}$$

Here we again use the averaged probability of absorption since most neutron beams are considerably larger in dimension than the MCP period ($d+W$). To represent the results of our calculations in conventional "rocking curve" form we still have to make some transformation: the "rocking angle" (referred later to as ξ) has the value of 0 at the maximum transmission and therefore is equal to $\xi=\pi/2-\theta$. The negative values of ξ can be calculated from equation (18) with angle φ shifted by π. Thus the rocking curve $T'_{MCP}(\xi,\varphi_0)$ can be found from the equation:

$$T'_{MCP}(\xi,\varphi_0)=\begin{cases}1-\left\langle P_{absorb}\left(\frac{\pi}{2}-\theta,\varphi=\varphi_0\right)\right\rangle, & \xi\geq 0\\ 1-\left\langle P_{absorb}\left(\frac{\pi}{2}-\theta,\varphi=-\varphi_0\right)\right\rangle, & \xi<0\end{cases} \tag{19}$$

The rocking curve calculated from equation (19) obviously represents an idealized collimator measured in an ideal experimental system, where neutron beam is perfectly parallel. The experimental rocking curves in fact represent the combination of the collimator performance and the neutron angular beam divergence, to be more precise the convolution of the angular profile of the beam itself with the angular profile of the collimator. The finite divergence of existing neutron beams results in all measured rocking curves to be Gaussian-like functions instead of a triangular-shaped transmission function of an ideal collimator. There are also some possible imperfections of the MCP geometry as well as possible reflection and scattering processes inside the MCP pores, which are not taken into account in the current model. All of the above may obviously alter the ideal triangular-like rocking curve. However, we believe that the geometry of existing MCPs, thoroughly studied and optimized for application of MCPs in X-ray [8]

and neutron [19] optics, where requirements on the geometric accuracy is much stronger, is accurate enough for efficient neutron collimation. The problem of small-angle scattering and reflection off the MCP walls can be overcome by increasing the surface roughness of glass walls with the means of some chemical etching. Therefore we expect that the MCP geometric imperfections, neutron scattering and small angle reflection inside the pores will not considerably affect the collimator performance beyond moderate smoothing of the triangular shape of the rocking curve. The results of our first measurements with an MCP collimator doped with ^{nat}Gd are in good agreement witht the predicted performance thus supporting the latter statement.

The predicted rocking curves for $^{nat}Gd_2O_3$- and $^{10}B_2O_3$-doped collimator of different thickness are shown in Fig. 6. In case of $^{nat}Gd_2O_3$ doping an MCP with L_{MCP}/d ratio of 250:1 should reject about 98 % of all neutrons incident at angles 0.5 degrees of larger relative to MCP normal. To achieve the rejection ratio of 10^{-3} the MCP thickness should be increased to correspond to L_{MCP}/d = 500:1 value. Such collimator should reject almost all thermal neutrons falling at angles larger than 0.1 degree off the MCP normal and when L_{MCP}/d = 1000:1 the collimator should reject almost all neutrons incident at angles $>0.06^{o}$ off MCP normal with the rejection ratio of 10^{-7}. An MCP doped with 10 mole % of $^{10}B_2O_3$ require much larger L_{MCP}/d ratio in order to be an efficient neutron collimator and only MCPs with the ratio value of 1000:1 (or four properly stacked MCPs of 250:1 aspect ratio) can be used as effective thermal neutron collimators, unless the glass mixture has much higher doping concentrations of absorbing ^{10}B atoms. Fig. 7 shows predicted rocking curves for different doping concentrations in MCP collimators

with the aspect ratio L_{MCP}/d = 250:1. The results of our calculations indicate that increasing doping level of $^{nat}Gd_2O_3$ above 3 mole % does not reduce the width of the rocking curve (although it improves the background suppression ratio), while even 15 mole % of $^{10}B_2O_3$ doping is still not enough for an efficient thermal neutron collimation with a microchannel plate with L_{MCP}/d=250:1. However, if cold neutrons are to be collimated, the same 250:1 MCP with 10 mole % of $^{10}B_2O_3$ doping performs almost as efficiently as 3 mole % $^{nat}Gd_2O_3$-doped MCP because of the larger absorption cross section of ^{10}B for cold neutrons of 5 meV [15],[16] (see Fig. 8).

4. Conclusions

The presented model of microchannel plate neutron collimators can be used for optimization of MCP collimators for particular applications. Both MCP geometric parameters and the concentration of neutron-absorbing atoms in the glass mixture can be varied within the manufacturing limits in order to achieve the optimal performance depending on a particular application. The most effective way to improve the collimation is to increase the thickness of microchannel plate with all other parameters fixed. Although current electron multiplying MCPs are manufactured with maximum aspect ratio of $L_{MCP}/d \approx 250:1$, we believe that ratio can be substantially increased by some modifications of the production process. These modifications are possible due to the fact that MCP collimators do not require all the stages of the standard MCP production process. In particular the surface of the pores does not have to provide the electron multiplication and there is no voltage applied across the MCP. The other alternative considered presently is to stack several “thin” microchannel plates. We believe the

demanding requirements on the accuracy of this stacking can be met by an introduction of some new steps in the MCP manufacturing.

Although the results of calculations presented in this paper do not determine the best possible performance of microchannel plate collimators, they indicate that MCP collimators based on the existing manufacturing technology can be very efficient ($<0.1^{o}$ wide) and very compact (only few mm thick) and perform in 2-dimensions simultaneously. Different MCP pore geometries (circular, square and rectangular pores) can be implemented in order to separately control collimation in two axes and to increase the collimator maximum transmission. In addition to collimation the same microchannel plates can be used for simultaneous high resolution imaging of thermal and cold neutrons (with spatial and temporal accuracy for each individual neutron as small as <20 μm and <1 μs, respectively) [20], allowing simultaneous real-time collimation and monitoring of neutron beams.

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6. Figure captions

Fig. 1 A section of a circular pore microchannel plate (not to scale).

Fig. 2. 2-D projection of neutron path in microchannel plate with wall thickness W and pore diameter d and system of coordinates used for calculation of absorption probability $P_{abs}(\theta,\varphi,x_0,y_0)$.

Fig. 3. Calculated transmission $T_{MCP}(\theta,\varphi,x_0,y_0)$ of an MCP collimator as a function of neutron incidence position (x_0,y_0). The MCP with 10 μm pores and 2 μm walls is 2.5 mm thick (L_{MCP}/d=250:1) and is doped with 3 mole % of $^{nat}Gd_2O_3$. Angle φ is fixed at 20 degrees, while angle θ is **(a) -** 90 degrees, **(b)** - 89.8 degrees, **(c)** - 89.5 degrees and **(d)** - 89 degrees. The transmission is calculated for thermal neutrons of 25 meV for which absorption cross section of ^{nat}Gd is 49700 brans. The microstructure of the transmitted beam intensity (on the scale of pore diameter d=10 μm) almost disappears for angles θ smaller than 89 degrees.

Fig. 4. Calculated transmission $T_{MCP}(\theta,\varphi,x_0,y_0)$ of the same MCP collimator as in Fig. 3 as a function of incidence angles θ and φ with position of thermal neutron incidence (x_0,y_0) fixed at **(a)** the center of a pore ($x_0=(d+W)/2, y_0=(d+W)/2\sqrt{3}$) and **(b)** between two pores ($x_0=0, y_0=(d+W)/2\sqrt{3}$).The six-fold symmetry of figure **(a)** over angles φ corresponds to 6 adjacent pores. Transmission sharply falls with the deviation of angle θ from the MCP normal.

Fig. 5. Calculated transmission $\langle T_{MCP}(\theta,\varphi)\rangle$ of an MCP collimator for a thermal neutron beam as a function of incidence angles θ and φ. The transmission $T_{MCP}(\theta,\varphi,x_0,y_0)$ is averaged over positions (x_0,y_0) of neutron incidence on the MCP surface. The same 2.5 mm thick MCP as in Fig. 3. The MCP glass is doped with **(a)** 3 mole % of $^{nat}Gd_2O_3$ and **(b)** 10 mole % of $^{10}B_2O_3$. The peak transmission (normal incidence, θ=90 degrees) equal to the MCP open area fraction of 63 %. The transmission of Gd-doped collimator drops to a ~0.01 level for angles θ deviating by 0.25 degree from the normal, indicating that L_{MCP}/d ratio of 250:1 can be sufficient for some applications. In case of boron doping the L_{MCP}/d ratio should be increased in order to achieve efficient collimation (see Fig. 6).

Fig. 6. Predicted rocking curves $T'_{MCP}(\xi,\varphi_0)$ of MCP collimators (d=10 μm, W=2 μm, same as in Fig. 3) for thermal neutrons of 1.8 Å (25 meV) calculated for MCPs of different thickness: L_{MCP} = 1.25, 2.5, 5 and 10 mm (L_{MCP}/d=125:1. 250:1, 500:1, 1000:1, respectively). The glass mixture is doped with **(a)** 3 mole % of $^{nat}Gd_2O_3$ and **(b)** 10 mole % of $^{10}B_2O_3$. The rocking curves are calculated along a line parallel to x-axis (φ_0=0).

Fig. 7. Predicted rocking curves $T'_{MCP}(\xi,\varphi_0)$ of MCP collimators (L_{MCP}/d=250:1, d=10 μm, W=2 μm, same as in Fig. 3) for thermal neutrons calculated for MCPs with different doping levels shown in the legend. The glass mixture is doped with **(a)** $^{nat}Gd_2O_3$ and **(b)** $^{10}B_2O_3$. The rocking curves are calculated along a line parallel to x-axis (φ_0=0).

Fig. 8. Predicted rocking curves $T'_{MCP}(\xi,\varphi_0)$ of MCP collimators (L_{MCP}/d=250:1, d=10 μm, W=2 μm, same as in Fig. 3) for cold neutrons of 4 Å (5 meV). Solid line – the glass mixture is doped with 3 mole % of $^{nat}Gd_2O_3$; dashed line – 10 mole % of $^{10}B_2O_3$ doping. The rocking curves are calculated along a line parallel to x-axis (φ_0=0).

Reference numbers for equations (do not delete them):

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Fig. parameters:

Figures with fixed Theta, Phi and over area of X0Y0 coordinates.

Fig. 3.a L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd2O3, thermal neutrons of 25meV; Xmin = -1.2*P Xmax = 1.9*P; Ymin = -1.3*P Ymax = 1.8*P, Steps 100, Phi=20; Theta=89.999

Fig. 3.b L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd2O3, thermal neutrons of 25meV; Xmin = -1.2*P Xmax = 1.9*P; Ymin = -1.3*P Ymax = 1.8*P, Steps 100, Phi=20; Theta=89.8

Fig. 3.c L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd, thermal neutrons of 25meV; Xmin = -1.2*P Xmax = 1.9*P; Ymin = -1.3*P Ymax = 1.8*P, Steps 100, Phi=20; Theta=89.5

Fig. 3.d L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd, thermal neutrons of 25meV; Xmin = -1.2*P Xmax = 1.9*P; Ymin = -1.3*P Ymax = 1.8*P, Steps 100, Phi=20; Theta=89.0

Fixed X0Y0 and varied Theta,Phi

Fig. 4.a L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd, thermal neutrons of 25meV; Theta varies 89-90 degr, Phi=0-360degr, Xo=P/2,Y0=P/2/SQRT3 (center of pore).

Fig. 4.b L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd, thermal neutrons of 25meV; Theta varies 89-90 degr, Phi=0-360degr, Xo=0, Y0=P/2/SQRT3 (between two pores).

Array of Theta, Phi averaged over X0Y0

Fig. 5.a L/D=250:1, 10um pores on 12 um centers, 3 mole % of ^{nat}Gd, thermal neutrons of 25meV; Theta varies 89-90 degr, Phi=0-360degr.

Fig. 5.b L/D=250:1, 10um pores on 12 um centers, 10 mole % of ^{10}B, thermal neutrons of 25meV; Theta varies 89-90 degr, Phi=0-360degr.

Rocking curves:

Rocking curves at diff. L/D

Fig. 6.a 10um pores on 12 um centers, 3 mole % of ^{nat}Gd2O3, thermal neutrons of 25meV; Phi=0, L/D-varying.

Fig. 6.b 10um pores on 12 um centers, 10 mole % of ^{10}B2O3, thermal neutrons of 25meV; Phi=0, L/D-varying.

Rocking curves at diff. doping levels

Fig. 7.a L/D=250:1, 10um pores on 12 um centers, thermal neutrons of 25meV; Phi=0, Doping-varying: 0,1,2,3 mole % of ^{nat}Gd2O3.

Fig. 7.b L/D=250:1, 10um pores on 12 um centers, thermal neutrons of 25meV; Phi=0, Doping-varying: 5,10,15 mole % of 10B2O3.

Rocking curves for cold neutrons

Fig. 8 L/D=250:1, 10um pores on 12 um centers, **thermal neutrons of 5meV**; Phi=0, 3 mole % of $^{nat}Gd_2O_3$ and 10 mole % $10B_2O_3$.