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X-ray microbeams based on Kumakhov polycapillary optics and its applications: Analytical consideration

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Abstract. Kumakhov polycapillary optics is based on the effective passage of X-ray radiation through bundles of monocapillaries of various configurations. The passage of radiation takes place because of the total external reflection of X-rays from the inner capillary walls. In this work, the basic characteristics of intense quasi-parallel X-ray polycapillary microbeams from a laboratory source with microfocus X-ray tube/polycapillary cylindrical structure are investigated theoretically (analytical consideration). The data generated from theoretical estimations are compared with the experimental results. Several new generations of X-ray analytical devices like, laboratory synchrotron, fluorescent spectrometers, reflectometers/refractometers, diffractometers, X-ray microscopes and combinations of several such devices, are developed based on polycapillary optics. Besides, a number of devices can be developed for the most modern research problems such as nanomateriology, namely, X-ray nanoscanner, portable X-ray nanothickness indicator etc. X-ray tubes and the radiators, specially developed for polycapillary optics as efficiently as possible, are used in all the devices mentioned above.

Keywords. X-ray microbeams; Kumakhov polycapillary optics; X-ray analytical instruments.

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1. Introduction

It is well known that Kumakhov polycapillary optics (PO) is based on the effective passage of X-ray radiation through bundles of monocapillaries of various configurations. The passage takes place because of the total external reflection (TER) of X-rays from the inner capillary walls [1].

Nowadays, based on polycapillary optics, new-generation devices are developed [2] because of the distinctive features of polycapillary optics such as large angular aperture (∼0.1 rad) and broad-band energy spectrum (0.1–60 keV [3]).

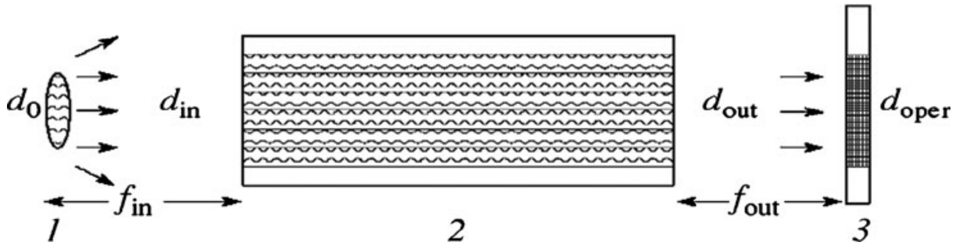

Figure 1. Schematic diagram illustrating the formation of an X-ray microbeam using a cylindrical polycapillary structure: (1) focal spot, (2) cylindrical polycapillary structure, (3) detector.

Application of polycapillary optics to conventional low-power X-ray tubes allows receiving X-ray microbeams with high density of a flux. So, a microfocus semilens with focal length of millimetre order allows to receive X-ray microbeam with the divergence of about critical angle for TER and the density of the order of 10^{10} photon/s (mm^2) for monochromatic characteristic radiation [4,5]. The area of cross-section of the resulting beams is defined by the exit diameter of a semilens that finally provides focal spot size of the order of millimetre.

In [6,7] at the output of a system of microfocus X-ray generator/cylindrical polycapillary system (figure 1), the authors received intense quasi-parallel X-ray microbeams with the density of radiation flux close to that provided by synchrotron. In [8,9] the application of this method of getting the microbeams in scanning X-ray microscopy on the basis of a raster X-ray system was considered. In another work based on this method, X-ray tube with polycapillary lens has been used [10]. Due to the absence of a microfocus source to approach a focal spot, the source along with Kumakhov lens focussing on the input of a cylindrical polycapillary structure was applied.

In this work the results of the theoretical (analytical) as well as experimental investigation of X-ray microbeams obtained in the scheme of microfocus X-ray source/cylindrical polycapillary structure are compared.

2. Polycapillary X-ray microbeams

2.1 *Theoretical estimation*

Entrance intensity W_{in} for polycapillary cylindrical structure can be obtained by the following equation:

$$W_{\text{in}} = W_n + W_F, \tag{1}$$

where W_n is the direct radiation intensity passing through polycapillary without reflection from the walls, and W_F is the radiation intensity directed by the polycapillary due to consecutive reflections from its walls. W_n is given by the expression

$$W_n = W_0(\pi r^2)/(4\pi(f_{\text{in}} + L)^2) = W_0(r/(2(f_{\text{in}} + L)))^2, \tag{2}$$

where $f_{\rm in}$ is the distance from a source to the entrance the capillary, L is the length of the polycapillary, r is the radius of the monocapillary, W_0 is the source intensity. $W_{\rm F}$, on the otherhand, is expressed as

$$\begin{aligned} W_F &= W_0\left(\pi\theta^2/4\right)/4\pi - W_n \\ &= W_0\theta^2/16 - W_n \\ &= W_0\left(\theta/4\right)^2 - W_n \\ &= W_0\left(2\theta_{\kappa\rm p}/4\right)^2 - W_n \\ &= W_0\theta_{\rm cr}^2/4 - W_n, \end{aligned} \tag{3}$$

where $\theta = 2\theta_{\rm cr}$ is the capture angle. In the expression for W_n we take radius of the monocapillary instead of polycapillary entrance flare. Even when the area of flare is greater than the area of monocapillary entrance, X-rays pass only in the diameter of a monocapillary and radiation with greater angles will be reflected from wall. Therefore,

$$W_{\rm in} = W_n + W_F = W_0\theta_{\rm cr}^2/4. \tag{4}$$

This expression suits originally for the case of a point source. In our case the focus spot cannot be considered as a point, but can be considered as a set of point sources with smaller intensity

$$W_0 = W_1 + W_2 + \cdots + W_n. \tag{5}$$

Expression for the intensity captured by a capillary is characteristic for each point source. Therefore

$$\begin{aligned} W_{\rm in} &= W_1\theta_{\kappa\rm p}^2/4 + W_2\theta_{\kappa\rm p}^2/4 + \cdots + W_n\theta_{\kappa\rm p}^2/4 \\ &= \left(W_1 + W_2 + \cdots + W_n\right)\theta_{\kappa\rm p}^2/4 = W_0\theta_{\kappa\rm p}^2/4. \end{aligned} \tag{6}$$

As we can see, expression (4) can also be applied for a source with extended spot.

Exit intensity can be determined also by an entrance transparency, which is the ratio of the area of apertures and walls, and losses on internal reflections. All these factors as a whole are considered in experimentally received transmission factor $T_{\rm r}$. Thus, exit intensity of radiation will be equal to

$$W_{\rm out} = W_{\rm in}T_{\rm r.} \tag{7}$$

2.2 *Calculations and experimental results*

Let us estimate the entrance intensity. Following [5], with intensity of the X-ray tube $W_0 = 4.5 \times 10^{12}$ photons/s, and critical angle of the total external reflection for 8 keV $\theta_{\rm cr} = 4$ mrad

$$W_{\rm in} = W_0\theta_{\rm cr}^2/4 = 4.5 \times 10^{12} \times \left(4 \times 10^{-3}\right)^2/4 = 1.8 \times 10^7\ \text{photons/s}. \tag{8}$$

In the work described in [7], a beam of 25 μm diameter at a distance of 1 mm from the output of a polycapillary column is obtained. Diameter of the beam on a column output is 25 μm − 2 (1 mm × 4 mrad) = 17 μm. The radius of capture area of a polycapillary is, therefore, equal to 17 μm/2 = 8.5 μm. Intensity of radiation, which would pass in a diaphragm ($W_{\rm diaf}$) of the same size makes

$$\begin{aligned} W_{\rm diaf} &= W_0\big(\pi r_{\rm diaf}^2\big)/(4\pi\,(f_{\rm in}+L)^2) = W_0\,\big(r_{\rm diaf}\big/(2\,(f_{\rm in}+L))\big)^2 \\ &= 4.5\times 10^{12}\times\big(8.5\times 10^{-6}\big/\big(2\times\big(0.5\times 10^{-3}+10.0\times 10^{-3}\big)\big)\big)^2 \\ &\approx 7.372\times 10^5\ \text{photons/s}. \end{aligned} \tag{9}$$

As we see, a component of the radiation, which is passing through a diaphragm, is much less than that transferred by means of total external reflection from the walls.

Transmission factor $T_{\rm r}$ for 10 mm length, from our experimental data, can be taken as $T_{\rm r} = 0.7$. Therefore $W_{\rm out} = W_{\rm in} T_{\rm r} = 1.8\times 10^7 \times 0.7 = 1.26\times 10^7$ photons/s, and the density of radiation flux, for example, at a distance of 1 mm from the end face of polycapillary structure (diameter of a beam – 25 microns) will be $\big(1.26\times 10^7\ \text{photons/s}\big)/(\pi\ (12.5\ \mu\text{m})^2) \approx 2.57\times 10^4\ \text{photons/s}/\mu\text{m}^2 = 2.57\times 10^{10}\ \text{photon/s/mm}^2$.

The measured intensity of a beam on an output of polycapillary structure has made 3×10^5 photons/s with a power on a tube of 0.25 W, photon energy 8 keV and polycapillary length 10 mm [7]. For 10 W, the intensity will be, accordingly, 1.2×10^7 photons/s. We have obtained flux density $W_{\rm out}/S = \big(1.2\times 10^7\ \text{photons/s}\big)/(\pi(12.5\ \mu\text{m})^2) \approx 2.44\times 10^4\ \text{photons/s}/\mu\text{m}^2 = 2.44\times 10^{10}\ \text{photons/s/mm}^2$.

We can see the calculation and experimental values practically agree within the accuracy limits of measurements and calculations.

2.3 *Gain of flux density*

It is possible to estimate the gain of flux density radiation at the exit of the polycapillary structure using the following expression:

$$\begin{aligned} G &= W_{\rm out}\big/W_{\rm diaf} = W_{\rm in}T_{\rm r}\big/W_{\rm diaf} \\ &= W_0\left(\theta_{\kappa p}^2/4\right)T_{\rm r}\big/(W_0\left(r_{\rm diaf}\big/(2\,(f_{\rm in}+L))\right)^2) \\ &= \left(\theta_{\rm cr}^2/4\right)\mathrm{Tr}\big/\left(r_{\rm diaf}\big/(2\,(f_{\rm in}+L))\right)^2 \\ &= \left(\frac{\theta_{\rm cr}}{r_{\rm diaf}\big/(f_{\rm in}+L)}\right)^2\times T_{\rm r}\left(\frac{\theta_{\rm cr}\,(f_{\rm in}+L)}{r_{\rm diaf}}\right)^2\times T_{\rm r}\,, \end{aligned} \tag{10}$$

where $W_{\rm diaf}$ is the intensity of radiation which would pass through a diaphragm of the same size as the beam and given in eq. (9). Estimation of radiation flux density gain on the output from a polycapillary column (diameter of the beam is 17 μm) is $G = W_{\rm out}/W_{\rm diaf} \approx 1.26\times 10^7/7.37\times 10^5 \approx 17.1$ at a distance from exit $L_{\rm out} = 1$ mm (beam diameter is 25 μm):

$$\begin{aligned} G &= \left(\frac{\theta_{\rm cr}(f_{\rm in}+L+f_{\rm out})}{r_{\rm beam}}\right)^2\times T_{\rm r} \\ &= (4\times 10^{-3}\times(0.5+10+1)\times 10^{-3}/(12.5\times 10^{-6}))^2\times 0.7 \\ &\approx 9.48. \end{aligned} \tag{11}$$

At a distance of 10 mm from the exit face of a polycapillary, the diameter of the beam $d_{\rm out} = d_0 + 2f_{\rm in}\theta_{\rm cr} = 17 + 2 \times 10$ mm $\times$ 4 mrad $= 97$ μm, and the factor of increase in flux density is $\big(4 \times 10^{-3}/\big((48.5 \times 10^{-6}\big)/(0.5 + 10 + 10) \times 10^{-3}\big)^2 \times 0.7 \approx 2$. At a distance of 20 mm from the exit of a polycapillary, the diameter of a beam will be 17 μm $+ 2 \times 20$ mm $\times$ 4 mrad $= 177$ μm, and factor of increase in flux density is $\big(4 \times 10^{-3}/\big((88.5 \times 10^{-6}\big)/(0.5 + 10 + 20) \times 10^{-3}\big)^2 \times 0.7 \approx 1.33$, and for a distance of 40 mm the factor is 1.006. With a distance of 41 mm, the factor of increase will be below 1.

The complete expression for an estimation of change of gain of radiation flux density in the exit beam on distance from an exit will be

$$G = \left(\frac{\theta_{\rm cr}\,(f_{\rm in} + L + f_{\rm out})}{r_{\rm beam}}\right)^2 \times T_{\rm r} = \left(\frac{\theta_{\rm cr}\,(f_{\rm in} + L + f_{\rm out})}{r_{\rm out} + f_{\rm out}\theta_{\rm cr}}\right)^2 \times T_{\rm r}, \qquad (12)$$

where $r_{\rm out} = \big(r_0 + d_{\rm cap} + f_{\rm in}\theta_{\rm cr}\big)$ is the radius of the exit beam and r_0 denotes the radius of focal spot of the X-ray tube.

3. Devices with polycapillary X-ray microbeams

Nowadays, based on the polycapillary optics, new-generation devices are developed, and made commercially accessible [2,11], e.g. laboratory synchrotron [4–7], fluorescent spectrometers, reflectometers/refractometers, diffractometers, X-ray microscopes [12,13] and combinations of several devices.

Besides, many devices can be developed for the most modern research problems such as nanomateriology that includes X-ray nanoscanner and X-ray nanothickness indicator based on X-ray small-angle scattering and X-ray interferometry. Determination of the size, form and concentration of nanoparticles, interstices and technologically created details of the structure, and also the measurement of characteristic distances between them are carried out by X-ray small-angle scattering. X-ray interferometry method is the most exact and unequivocal for the measurements of layer thickness for any material in nanometer ranges.

The miniature X-ray tube enables unique capabilities when combined with polycapillary optics because of the possibility of putting optics very close to anode. Such supercompact geometry makes it possible to obtain superbright X-ray fluxes from microfocus low-power X-ray tubes after polycapillary optics [4–7]. Miniature X-ray tubes and radiators [14], specially developed for use in combination with polycapillary optics and allowing as much efficiency as possible to use it, can be used in all devices described here.

4. Conclusions

As we see the resulting calculated and experimental values practically agree within the limits of accuracy of the measurements and the calculations. The applications of the above-stated researches of polycapillary microbeams provide the opportunity of additional optimization of the devices on the basis of polycapillary optics.

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