ISSN 1063-7850, Technical Physics Letters, 2008, Vol. 34, No. 9, pp. 782–784. © Pleiades Publishing, Ltd., 2008.
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Decreasing the Total Divergence of Polycapillary X-ray Microbeams

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Received December 4, 2007

Abstract—The divergence characteristics of intense quasi-parallel X-ray microbeams have been studied at the output of the "microfocus X-ray generator–cylindrical polycapillary structure" system by scanning the beam with a knife edge. It us established that the total microbeam divergence decreases in the region near the output edge of the polycapillary structure (divergence quasi-decrease effect).

PACS numbers: 41.50.+h

DOI: 10.1134/S1063785008090204

Previously, high-intensity quasi-parallel X-ray microbeams were obtained [1, 2] at the output of the "microfocus X-ray generator–cylindrical polycapillary structure" system with an output radiation flux density comparable with the values typical of synchrotron radiation sources. The possible applications of this method to scanning X-ray microscopy were considered in [3, 4]. For such applications, it is important to know how the microbeam size varies with the distance from the polycapillary structure output, which is characterized by the divergence. The divergence of polycapillary beams is conventionally assumed to be constant and (within the framework of the geometric optics approach with neglect of losses) equal to the double critical angle of the total external reflection (TER) of the X-ray radiation from the inner walls of the polycapillary structure.

The beam divergence past polycapillary structure is conventionally subdivided into local and global types [5–8]. The local divergence is determined by the deviation due to TER from the capillary walls, while the global divergence characterized the spread of the angle between capillaries.

It is also expedient to introduce the concept of a total or effective divergence, which characterizes the combined effect of both factors and determines a change in the effective beam size. By the effective beam size is implied the value determining the main region of its action in the given cross section. It is the effective divergence value, which is provided by the methods of beam scanning with a knife edge in various cross sections. According to this method, the effective beam size is determined as the full width at half maximum (FWHM) of a Gaussian approximating the experimental data (differential intensity curve in the case of a beam scanned with the knife).

To the best of the author's knowledge, no detailed consideration of the total divergence characteristics for polycapillary beams probed by means of scanning knife [9, 10] has been published until now. The aim of this study was to fill this gap [11].

For this purpose, the dependence of the cross-sectional diameter of a polycapillary microbeam was experimentally studied as a function of the distance from the knife section to the output edge of the polycapillary structure. The polycapillary structure had a channel diameter of 2.5 μm, a total polycapillary diameter of 2.5 mm, ad a length of 30 mm. The experiments were performed with a microfocus X-ray generator based on a BS-11 tube with a copper anode, generating CuK_α radiation. The X-ray beam was scanned with a tantalum knife.

In order to determine the beam size in a given cross section with a certain coordinate along the axis, a dependence of the detector signal intensity on the knife position was measured with the knife scanned across the beam. Then, the obtained profile was differentiated and approximated by a Gaussian, the FWHM value of which was assumed to be the beam size in the given cross section.

Figure 1 shows the results of measurements plotted as the beam size d versus distance f from the polycapillary structure output. As can be seen, the character of the beam divergence varies as is characterized by the slope of the tangent drawn to the curve at the given point. In the region close to the polycapillary structure output, the total divergence exhibits a decrease, which is caused by a characteristic redistribution of the radiation source field by the polycapillary structure.

According to the obtained experimental data and to the general considerations, the beam diameter in the region close to the polycapillary structure output corre-

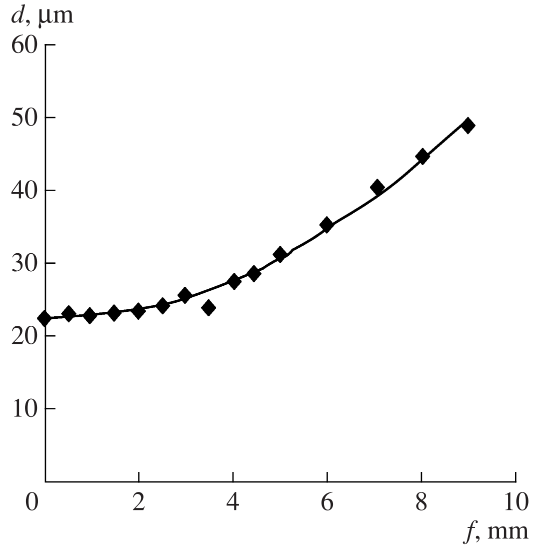

Fig. 1. Plot of the beam diameter d versus distance f from the polycapillary structure output. Points present the experimental data; solid curve shows the best quadratic approximation using the relation $y = 0.351x^2 - 0.147x + 22.787$ ($R^2 = 0.9791$).

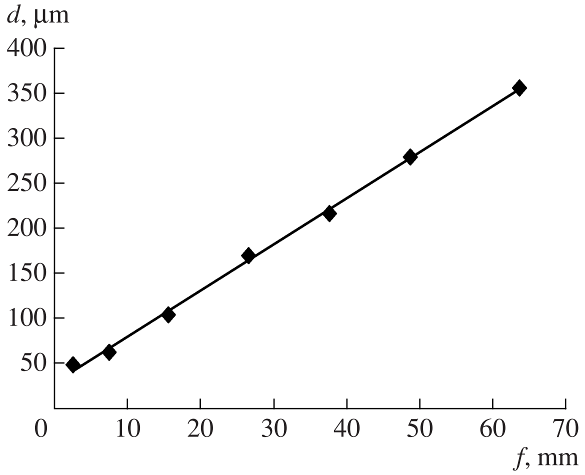

Fig. 2. A plot of the polycapillary microbeam diameter d versus distance f in the region of maximum divergence. Points present the experimental data; solid curve shows the best linear approximation using the relation $y = 5.0871x + 30.479$ ($R^2 = 0.9982$).

sponds to the source diameter [12], which amounted to ~23 µm. The maximum divergence, which is determined by the local component dependent on the multiple TER angle, is apparently attained at a distance of $F_{\text{m.d.}}$ determined by the diameter $d_{\text{f.s.}}$ of the focal spot of the tube and by the maximum partial divergence $Q_{\max} \sim \vartheta$ determined by the beam divergence in a separate monocapillary. The $F_{\text{m.d.}}$ value is proportional to the critical TER angle ϑ, which can be written as

$$F_{\text{m.d.}} \approx d_{\text{f.s.}}/Q_{\max}. \tag{1}$$

The total divergence of a polycapillary beam takes place when all monocapillary components emerge from the polycapillary structure (i.e., when all hidden microbeams begin to participate in the formation of the overall pattern). Therefore, the polycapillary beam diameter d at a given distance f from the polycapillary output edge is given by the following expression:

$$d \approx d_{\text{f.s.}} + Q_{\max}(f - F_{\text{m.d.}}). \tag{2}$$

The focal spot size of the source can be evaluated from the beam cross section at the polycapillary structure output as follows:

$$d_{\text{f.s.}} \approx d - Q_{\max}(f - F_{\text{m.d.}}). \tag{3}$$

It is also interesting to follow the experimental curve of the total divergence in the region where the individual monocapillary beams no longer contribute to the combined beam, that is, at distances exceeding $2d_{\text{f.s.}}/Q_{\max}$ (Fig. 2). In this case, the beam intensity profile in the cross section was obtained using a CCD-matrix-based photodetector. The experimental data were processed as described above for the knife scan technique. As can be seen, the effective divergence at distances greater than $2d_{\text{f.s.}}/Q_{\max}$ is constant and is determined approximately by a double critical TER angle.

The effect analogous to the divergence quasi-decrease probably also takes place in the case of a polycapillary structure of finite dimensions combined with a focal spot of greater size, which should be taken into account in optimization of the spot size. This phenomenon should be taken into account in investigations of the divergence of polycapillary microbeams and calculations of the beam diameter in the application to microanalysis [1–4] and X-ray spot diagnostics [12].

Apparently, this phenomenon accounts for considerable difficulties in determining the divergence of semilenses using methods based on the beam cross section imaging at various distances [13]. For a semilens employed in the magnification scheme, the effect of quasi-decrease in the total divergence in the region near the output edge will be even more pronounced than for a polycapillary column. This is caused both by an additional decrease in the divergence due to a curvature of the semilens and by an increase in the source size in the semilens. Accordingly, for a semilens employed in the contraction scheme, the effect of divergence quasi-decrease is less pronounced. Thus, for polycapillary systems changing the source size, formula (1) should be modified as follows:

$$F_{\text{m.d.}} = (kd_{\text{f.s.}})/Q_{\max}, \tag{4}$$

where k is the transformation (magnification/contraction) coefficient.

The effect under consideration was not observed previously, probably, because the beam cross sections were studied predominantly at large distances. This was related to the fact that polycapillary microbeams were not considered as a special type of quasi-parallel microbeams. Using the Kumakhov polycapillary optics, quasi-parallel microbeams were obtained using semilenses, where this effect is difficult to reveal.

Both the absolute values of beam divergence and the shape of the beam size versus distance from the output edge depend on the method used for determining the effective beam size. This was demonstrated in [8], where the beam size behind a diaphragm was measured as a function of the distance from it. The beam size was alternatively determined as FWHM of the beam profile, FWHM of the approximating Gaussian, or width of the area corresponding to 90% intensity. The curves were different both in absolute values of the divergence and in the rate of its growth with the distance.

It would be expedient (i) to study this phenomenon as dependent on the focal spot size, polycapillary length, and monocapillary dimensions, (ii) to analyze the behavior of divergence for different variants of the beam size evaluation (which can lead to different characteristics of divergence [8]), and to attempt at analytical description of the effective beam size as a function of the distance from the polycapillary structure edge.

REFERENCES

1. A. Yu. Romanov and I. V. Dmitriev, Pis'ma Zh. Tekh. Fiz. **30** (18), 65 (2004) [Tech. Phys. Lett. **30**, 784 (2004)].
2. A. Yu. Romanov and I. V. Dmitriev, Poverkhnost, No. 8, 32 (2005).
3. V. D. Gelever and A. Yu. Romanov, Pis'ma Zh. Tekh. Fiz. **31** (5), 52 (2005) [Tech. Phys. Lett. **31**, 202 (2005)].
4. V. D. Gelever and A. Yu. Romanov, Proc. SPIE **5943**, 313 (2005).
5. C. A. McDonald, J. X-Ray Sci. Technol. **6**, 32 (1996).
6. Z. W. Chen, R. Youngman, T. Bievenue, et al., Proc. SPIE **3767**, 52 (1999).
7. W. M. Gibson, C. A. MacDonald, and J. B. Ulrich, Proc. SPIE **3767**, 199 (1999).
8. H. Huang, W. Gibson, I. Ponomarev, and R. Youngman, Proc. SPIE **4781**, 112 (2002).
9. A. Yu. Romanov and I. V. Dmitriev, Poverkhnost, No. 2, 17 (2005).
10. A. Yu. Romanov, Izv. Vyssh. Uchebn. Zaved., Priborostr., No. 1, 324 (2005).
11. A. Yu. Romanov, *Proceedings of Symp. "Nanophysics and Nanoelectronics* (IFM RAN, Nizhni Novgorod, 2006), pp. 40–43.
12. A. Yu. Romanov, Izmerit. Tekhn., No. 7, 20 (2004) [Measurement techn. **47**, 670 (2004)].
13. S. V. Nikitina, A.S. Scherbakov, and A. N. Nikitin, Proc. SPIE **2519**, 179 (1995).

Translated by P. Pozdeev