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Optic Parameters of a Middle-Focus Kumakhov Lens for Hard X-rays

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Abstract—Middle-focus Kumakhov polycapillary lenses for hard X-ray optic systems are created for the first time. The performance of such a lens has been studied for X-rays in the 20–65 keV range. The radiation energy density amplification coefficient of the lens in this energy range falls within four to two orders of magnitude. Thus, the upper boundary of the energy range for effective use of the Kumakhov polycapillary X-ray optics has been increased to over 60 keV. © *2005 Pleiades Publishing, Inc.*

The main working energy range of the existing devices of the Kumakhov polycapillary X-ray optics extends approximately from 0.5 to 30 keV, and most of the previous investigations of the performance of Kumakhov lenses were performed in this very range [1–3]. This situation is explained by the fact that (i) the effective transmission of polycapillary lenses sharply decreases with increasing X-ray photon energy and (ii) a part of the radiation penetrates through the capillary walls and contributes to parasitic transmission [4–8]. The development of polycapillary X-ray lenses capable of effectively operating in the range of energies up to 60 keV would open new possibilities for use of the Kumakhov optics in medicine, microelectronics, and other fields. Recently, the first systems of this kind have been created at the Institute for Roentgen Optics (Moscow). The new systems are employed in combination with X-ray sources having a power above 1 kW and a focal spot size within 0.1–0.3 mm. A divergent radiation beam from the X-ray source is transferred via a Kumakhov lens and focused into the spot with a diameter of about 50 μm, which is sufficiently small for many applications. This Letter presents the results of investigation of the performance of a middle-focus Kumakhov polycapillary X-ray lens.

Some parameters of the Kumakhov polycapillary X-ray lens studied are presented in the table, where D_1 is the input diameter of the lens; L is the length; F_1 and F_2 are the front and back focal distances of the lens, respectively; and Q_1 is the acceptance angle. The X-ray transmission measurements were performed using the radiation of an X-ray tube monochromated by filters so as to retain the hard X-ray component.

Figure 1 shows the dependence of the focal spot size d on the radiation energy at the output of the Kumakhov lens. At each energy, the spot size was determined by scanning the beam cross section with a knife edge at a focal distance F_2 from the lens output. The d value was defined as a full width at half-maximum of the differential intensity distribution. On the whole, the result corresponds to the theoretical estimate $d = 2F_2\vartheta_{cr}$, where ϑ_{cr} is the critical total reflection angle. However, there is some tendency to underestimate the spot size at lower energies, which agrees with the results reported in [1]. An increase in the spot size for higher energies is probably related to the penetration of radiation through the glass capillary walls.

Figure 2 shows a plot of the Kumakhov lens transmission (defined as the ratio of the input and output radiation intensities) for several X-ray photon energies in the range studied.

Using the obtained experimental data, it is possible to calculate the coefficient of amplification, $G(E)$, of the radiation energy density at the focal spot of the lens in the energy range studied. The results of these calculations are presented in the table. The amplification coefficient $G(E)$ is defined as the ratio of the radiation energy density at the focal spot of the lens to the energy

Some parameters and performance characteristics of a middle-focus Kumakhov polycapillary lens for hard X-rays

D_1, mm	L, mm	F_1, mm	F_2, mm	Q_1, rad	E, keV	25	30	35	40	45	50	55	60	65
3	265	180	95	0.017	G	2130	1205	976	656	425	318	236	171	130
					R_{eff}, mm	11.6	15.5	17.2	20.9	26	30	34	41	47

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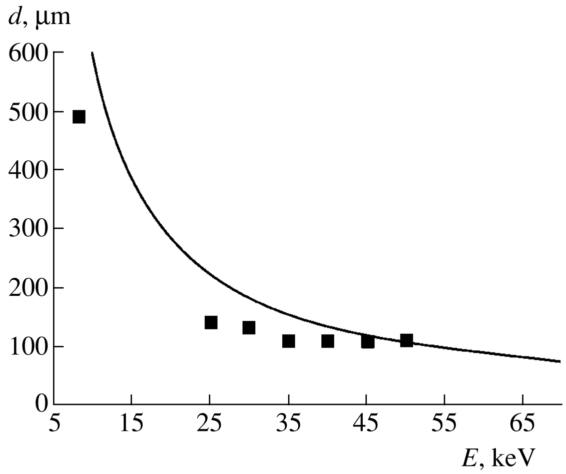

Fig. 1. A plot of the focal spot size *d* versus the X-ray photon energy *E* for the Kumakhov lens studied. The curve shows the theoretical dependence $y = a/x$; black squares represent the results of experimental measurements.

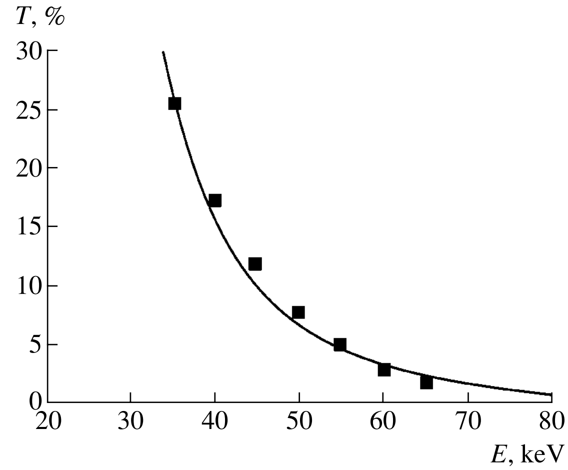

Fig. 2. A plot of the Kumakhov lens transmission *T* versus the X-ray photon energy *E*. Black squares represent the experimental data; the curve is drawn so as to provide the best fit to experiment.

density created by the same radiation source in the same plane in the absence of the lens:

$$G = \left(\frac{D_1}{d}\right)^2 \left(\frac{F_1 + L + F_2}{F_1}\right)^2 T. \quad (1)$$

The *G* values calculated using this formula fall within four to two orders of magnitude, which implies that the upper boundary of the energy range for effective use of the Kumakhov polycapillary X-ray optics has been increased to over 60 keV.

A more illustrative characteristic is the effective distance R_{eff}, defined as

$$R_{\text{eff}} = \frac{F_1 + L + F_2}{\sqrt{G}}, \quad (2)$$

which describes an equivalent approach of the irradiated object to the source provided by the lens at various radiation energies (see table).

As can be seen, the amplification characteristics, despite a decrease at high energies, are nevertheless significant in the entire energy range studied. At a distance of ~50 cm, a radiation energy density at the object obtained with the aid of the lens is equivalent to approaching the source to a distance several times shorter. In real systems, this approach is frequently either impossible because of peculiarities in the X-ray tube design or undesirable for certain experimental conditions. Thus, the use of a Kumakhov lens simplifies the problem of arrangement of the equipment. The achieved parameters of X-ray focusing make the Kumakhov lenses useful in physical experiments, microelectronic technologies, medicine, and some other applications. In view of the fact that such lenses significantly attenuate hard X-rays with energies above 80 keV, there is no need to use additional filters.

Thus, significant technological difficulties have been surmounted, and the range of high X-ray photon energies (40–60 keV) is now accessible for the Kumakhov polycapillary X-ray optics.

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