

1 INTRODUCTION

Capillary/polycapillary optics is a promising x-ray and neutron optical system that allows experiments to be performed on large samples or with small-size beams (millimeter order) on a much smaller scale than usual. These optical elements consist of hollow tapered tubes that condense neutral particles by multiple reflections from the inner surface of a tube channel. The x rays and neutrons can be deflected efficiently through angles that are tens and hundreds of times larger than the Fresnel critical angle in a much smaller space than needed for conventional grazing-incidence optical systems. As a wave propagates down the tapered channel, the incident angle increases with each reflection until it exceeds the critical angle of total external reflection. Hence, it is possible to estimate the optimum profile of the capillary system to obtain the best transmission. In principle, capillary/polycapillary optics should come close to preserving the brilliance of the source if the optics is designed to transmit waves such that the critical angle is not exceeded.

X-ray tubes are currently the main sources of x rays. However, a lot of experiments are carried out only with synchrotron radiation due to the comparatively small intensity of conventional x-ray tubes and the requirements of beam divergence. The use of various kinds of polycapillary optics will allow a significant improvement in the x-ray beam parameters, e.g., intensity and divergence.

The present experiment had two objectives: first, to establish a procedure for choosing the best alignment of a polycapillary lens vs an x-ray source such as a *Cu* anti cathode tube; second, to evaluate the increase in the x-ray beam density at its focal point, i.e., to evaluate the so-called “intensity gain”.

2 THEORETICAL PRINCIPLES

X-ray optical systems of grazing incidence are based on the phenomenon of total external reflection, which arises because the permeability of practically all materials is less than a unit in the x-ray region. The vacuum in this range of the spectrum is an optically denser environment than matter. Therefore, the coefficient of reflection is close to a unit, provided that the grazing angle θ (the angle between an incident beam and a surface) does not exceed the critical angle of total external reflection $\theta_c = \varepsilon_p/\varepsilon$, where ε_p is the material plasmon energy ($\varepsilon_p \simeq 30$ eV for the glass substance), ε is the x-ray photon energy. When the reflecting surface represents a certain channel limited in space, such as a glass hollow tube (capillary), x-ray beams travel inside the capillary because of consecutive reflections from the capillary walls. Therefore we can estimate that if the reflection angle for each collision of a photon with the channel wall is less than the critical angle, the radiation

power inside the capillary decreases more slowly ($\propto L^{-1}$, where L is the distance from the x-ray source) than in free space ($\propto L^{-2}$).

The possibility of controlling x-ray beams by means of monocabillaries has already been discussed in papers by Hirsch, Pound, and collaborators [1,2]. Obviously, since the critical angle for total external reflection of x rays is small, the angular acceptance of a single monocabillary will also be small (Fig.1, a)

$$\Delta\varphi_m \propto \theta_c \ll 1 \quad (1)$$

Hence, we can conclude that the power of radiation transmitted by the monocabillary

$$W_m \propto \theta_c^2 T_m \quad , \quad (2)$$

is small, where T_m is the coefficient of transmission, which depends on the monocabillary diameter and length, on the channel shape in the transverse and longitudinal cross-sections, and also on the quality of the inner reflecting walls of the channel. If we consider a tapered monocabillary, i.e., with reducing channel diameter from entrance to exit, the radiation power at the exit can be increased by three or more orders [3,4]. However, such systems are very long and effective only for quasi-parallel radiation sources with small transverse sizes (in particular, third-generation synchrotron radiation sources).

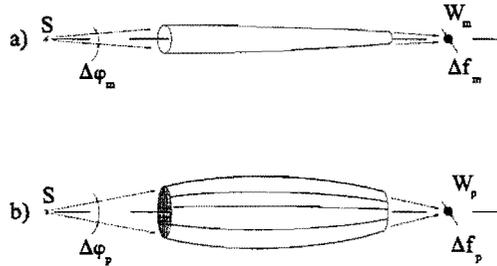


Figure 1: *Focusing schemes of monocabillary (a) and polycapillary (b) systems. S, the x-ray source; $\Delta\varphi$, the acceptance of the capillary system; W, the radiation power transmitted by the capillary system; Δf , the focal-spot diameter.*

The efficiency of these optical elements may be increased by using a system of monocabillaries tightly assembled in the transverse plane, i.e., a polycapillary system [5,6] (Fig.1, b). Since the angular acceptance of polycapillary systems may significantly exceed the critical angle for total external reflection

$$\Delta\varphi_p \gg \theta_c \quad , \quad (3)$$

the transmitted power increases,

$$W_p \propto (\Delta\varphi_p)^2 T_p \gg W_m \quad , \quad (4)$$

where T_p is the transmission coefficient of the polycapillary system, if the system transmittance is not small ($T_p \geq \%$). The system in its final design not only allows the radiation to be transported but also permits its density $\omega \simeq W / (\Delta f)^2$ to be increased by condensing the radiation in a micron-size spot Δf . Thus, the tapered capillary system works as a focusing lens. Let us consider a capillary lens with an angular acceptance $\Delta\varphi_p$. If such a lens has transmittance T_p , then the radiation power focused by the lens in a spot of diameter Δf will be proportional to

$$\omega_p \propto \pi \left(\frac{\Delta\varphi_p}{2} \right)^2 \frac{T_p}{(\Delta f)^2} \quad (5)$$

For comparison, the density of x rays at distance L from the source is estimated by the following

$$\omega_0(L) \propto \frac{1}{4\pi L^2} \quad (6)$$

This means that the use of a capillary lens will give us a gain in the radiation power

$$G \equiv \left(\frac{\omega_p}{\omega_0} \right)_L = \left(\frac{L\Delta\varphi_p}{\Delta f} \right)^2 T_p \quad (7)$$

The gain factor G determines the distance from the radiation source for which the radiation density without any optical element equals the radiation density at the focal spot of the capillary lens, i.e., $\omega_0(L_{eff}) = \omega_p(L)$. From this we can evaluate the effective distance from the source, due to using a capillary lens,

$$L_{eff} = \frac{L}{\sqrt{G}} = \frac{\Delta f}{\Delta\varphi_p \sqrt{T_p}} \quad (8)$$

For example, if the gain in the radiation power in the focus of the lens is 100, the effective distance from the x-ray source is one order less than the distance between the source and the focal plane of the capillary lens. Furthermore, if the effective distance is made three times smaller by varying the parameters $\Delta\varphi_p$, Δf and T_p , a three-order increase is obtained in the radiation flux density in the focal plane of the capillary lens.

3 EXPERIMENTAL SETUP

Optimum operation requires that the glancing angle of the x-ray beam striking the polycapillary lens entrance be fixed in the range of a few milliradians. Hence, for the lens

alignment, we decided to utilize a Huber four-circle diffractometer, which is normally used for single-crystal diffraction measurements.

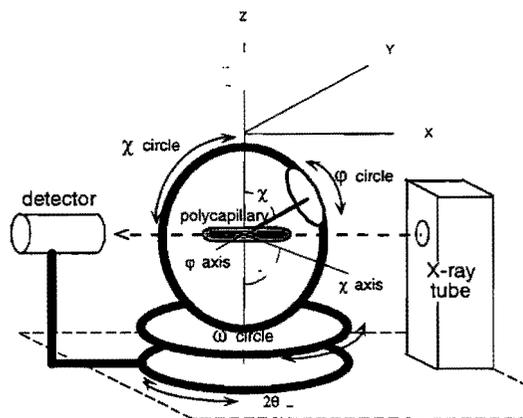


Figure 2: *Four-circle diffractometer configuration according to Hamilton [7]. The 2ϑ and ω circles can rotate around their common vertical axis. The detector is fixed on the 2ϑ circle. The χ -circle is fixed vertically onto the ω -circle and, hence, rotates together with it. The φ -circle can rotate by 360° around its axis and around the χ horizontal axis. The polycapillary lens is attached to the χ -circle at the geometric center of the goniometer by a goniometric head.*

In the four-circle diffractometer a heavy platform supports both the “2-theta” (2ϑ) and the “omega” (ω) coaxial circles, which have a common vertical axis. A scintillation detector is attached to the 2ϑ circle by means of a holder, while the ω -circle defines the vertical Eulerian cradle, i.e., the “chi” circle (χ) with the horizontal axis. A “phi” circle (φ) rotates inside the Eulerian cradle and always remains normal to the χ -circle axis. Both φ and χ circles can freely turn over the full 360° . A goniometric head, which usually holds up the single crystal, is fixed to the φ -circle. The goniometer is supplied with opto-electronic zero-point controls and stepping motors. The circle position is reproducible in ≤ 2 arcsec.

Our polycapillary lens (160 mm in length, 7.8 mm central diameter) was located inside a brass cylindric holder. The holder was fixed on a goniometric head that allows short x, y, z movements (± 20 mm) plus two orthogonal arc rotations ($\pm 10^\circ$). A Cu tube with a Ni filter attenuator but no monochromator was used as an x-ray source. The geometric center of the Cu tube was located at 221 mm from the center of the goniometer. The operating voltage was fixed at 20 kV, 20 mA. The entrance of the scintillation detector was placed about 78 mm from the polycapillary lens.

4 THE ALIGNMENT PROCEDURE

The first step in the alignment procedure was to place the polycapillary axis along the geometric line connecting the source to the detector. This was done by sight, utilizing two mechanical pointers, one in front of the source and the other in front of the detector. The manual controls of the goniometric head position made the operation easier. After this crude alignment, we used a fluorescent yellow target to observe the x-ray beam at the exit of the polycapillary, and we were unable to visualize the x-ray beam at the exit of the lens.

Following this preliminary step, the optimum polycapillary position vs the x-ray source was chosen by scanning its vertical and horizontal planes using the four-circle diffractometer.

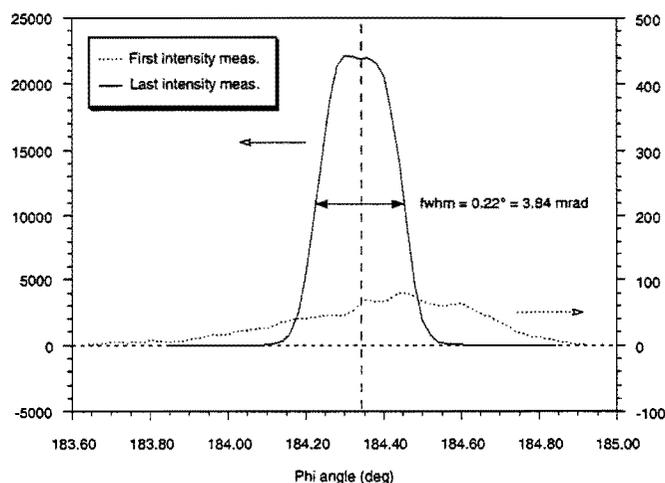


Figure 3: Vertical intensity profiles from the polycapillary collected by means of φ -scans around its horizontal axis. Intensity units: counts per second (cps). First scan (dotted line), last scan (solid line). The center of the last scan is at 184.345° , the FWHM is equal to 3.84 mrad.

The scan on the horizontal plane was obtained by rotating the ω -circle a few degrees around its vertical axis; while to rotate the polycapillary lens on the vertical plane, the φ -plane inside the Eulerian cradle χ was put at 90° with its rotation axis in the horizontal plane. The vertical scan was obtained through a few degrees rotation around the φ -axis. The first horizontal φ -scan around its zero position gave a poorly shaped broad peak with extremely low intensity (Cf. Fig. 3). Hence, as a better vertical position for the capillary system we chose the angle corresponding to the center of the φ -peak profile taken at full width half maximum (FWHM).

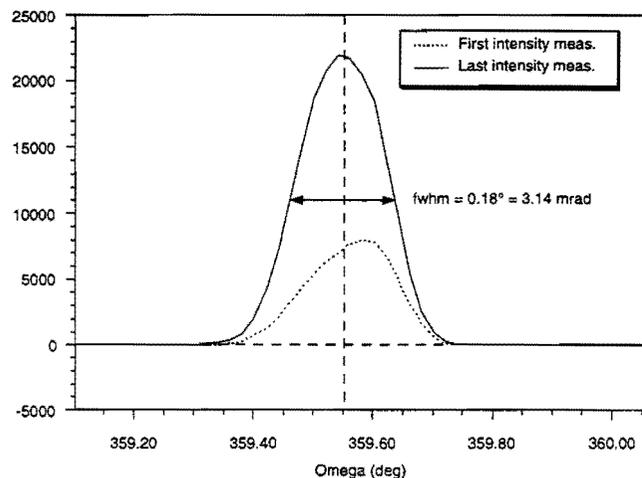


Figure 4: *Horizontal intensity profiles from the polycapillary collected by means of ω -scans around its vertical axis. First scan (dotted line), last scan (solid line). Intensity units: counts per second (cps). The center of the last scan is at 359.55° , the FWHM is 3.14 mrad.*

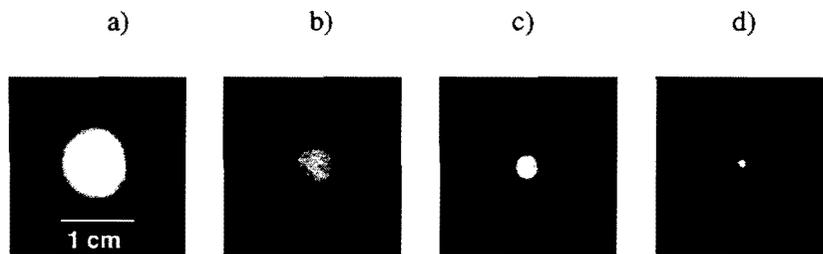


Figure 5: *Process of focusing by the polycapillary lens. (a) and (b), the x-ray distributions at the entrance and the exit of the lens; (c) and (d), images of the radiation spot behind the lens at 35 mm from the lens exit and at the lens focus (78 mm), respectively.*

For the horizontal adjustment, the ω -circle was scanned around its zero position. The collected ω -profile showed an increase in the profile intensity and symmetry (Fig. 4). Again, as a better horizontal position for the polycapillary lens, we chose the angular value corresponding to the center of the ω -peak at FWHM. The whole procedure, i.e., the φ -scan followed by the ω -scan, was recursively repeated two or three times until we reached the best profile shape with the highest intensity and the best symmetry. When we reached the best alignment, we were able to observe the focusing effect of the polycapillary by using the fluorescent target screen. We also took a set of four photos (Cf.

Fig. 5 a, b, c, d). Figures 5 a, b, show the direct source images at the entrance and at the exit of the lens; Figures 5 c, d, the beam-size at 35 mm behind the lens and at the focal point. Taking into account the blooming effect of the film we can conclude that the beam size diameter at the focal point is less than 2 mm. Finally, to quantitatively evaluate the beam density increase at the focal point, in front of the scintillation detector we placed a lead diaphragm covered by a fluorescent screen with a hole of the same size, i.e., 2 mm, at the center. With this configuration we measured an average intensity value of 21500 cps at the focal point, while, after removing the polycapillary lens, with the same experimental configuration, we obtained a counting value of 800 cps, which corresponds to an increase of about 27 in the local density of the x-ray beam.

The spot width is typically defined at half maximum. Therefore, if the diameter of the hole in the diaphragm is fixed at about 1 mm, the gain will reach about two orders of magnitude, which corresponds to the theoretical specification for the tested capillary lens.

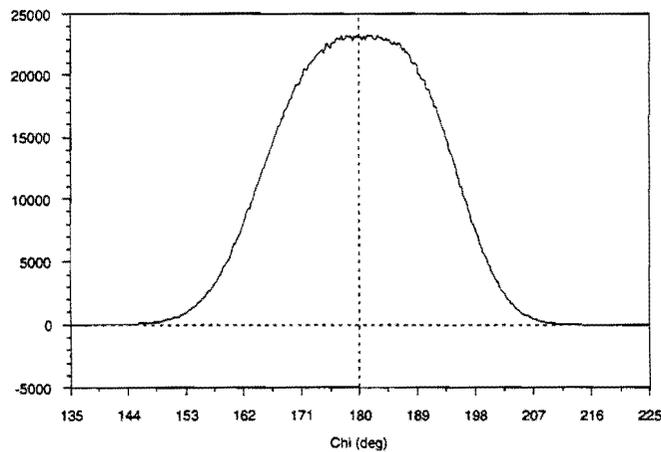


Figure 6: The χ -scan profile, i.e., a rotation of the polycapillary around its longitudinal axis, should give a constant intensity level; on the contrary, the collected intensity shows a quasi-Gaussian shape. Intensity units: counts per second (cps). See text for comments.

Another important point is that a rotation of the capillary around its horizontal axis does not affect the final intensity, which should always remain constant. To verify this observation, we also collected the intensity during a 180° rotation of the polycapillary lens around its horizontal axis by rotating the χ -circle.

The intensity distribution, shown in Fig. 6, can be explained by saying that even if in an ideal, perfect capillary system both the geometric and optical centers coincide, it is extremely difficult for this to happen in a real polycapillary sample, even of the best

quality. Furthermore, that although we chose the best positioning for our case, it did not satisfy the above condition. In other words, we reached, probably, a relative optimum but not the best.

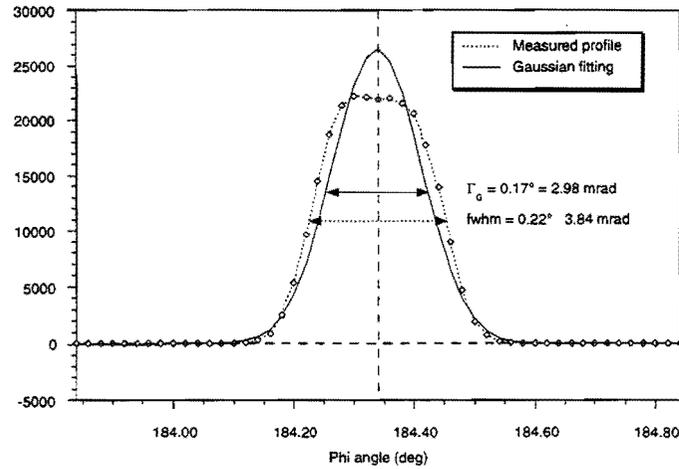


Figure 7: Comparison between the profiles of φ -scanning and its Gaussian best-fitting. Intensity units: counts per second (cps). The difference in the FWHM values can be explained by using the wave theory of x-ray propagation inside a capillary channel. See text for comments.

Using the "MacDUST" program [8] we fitted the φ -profile by a Gaussian function and found some disagreement between its FWHM value $\Gamma = 2.98 \text{ mrad}$ and that of the Gaussian function $\Gamma = 3.84 \text{ mrad}$ (Cf. Fig. 7). Theoretically we expected a FWHM value of about $2\theta_c \simeq 7 - 8 \text{ mrad}$, which exceeds both the experimental and the fitting values.

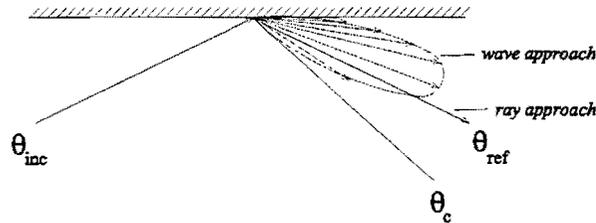


Figure 8: X-ray scattering in the ray and wave approximations. θ_{inc} , an incident ray with a glancing angle of θ_{inc} ; θ_{ref} , a reflected ray with a glancing angle of θ_{ref} ; θ_c , the Fresnel critical angle. The distribution of scattered waves has a maximum at angles less than the glancing angle of mirror-reflected ray.

This behavior can be illustrated by the wave theory of x-ray propagation into a capillary channel. We found that in a scattered wave distribution there is a strong angular dependence even for angles less than the critical angle. The distribution of scattered waves has a maximum at angles less than those of mirror-reflected rays [9], as is schematically shown in Fig. 8. Since the waves are mainly scattered into angles that are less than incident angles, the FWHMs of the φ and ω -profiles are significantly less than the values expected from the ray approximation. Moreover, the difference in the values of Γ_φ and Γ_ω could be due to the asymmetry of the capillary lens.

5 CONCLUSION

X-ray and neutron research activities over the last ten years have demonstrated that capillary optics is becoming a powerful instrument for guiding neutral particle beams. Capillary/polycapillary optics can be applied in numerous branches of x-ray radiation research, e.g., x-ray spectroscopy, x-ray fluorescence, x-ray crystallography, x-ray imaging, x-ray tomography, x-ray lithography, etc. Also capillary elements allow new optics to be used for a number of neutron research applications, such as instrumentation, neutron spectroscopy, medicine, biology, etc.

However, the alignment procedure is still one of the technical problems that prevents capillary optics applications from being used in industrial research laboratories. The main result of our work is that the technique of positioning the capillary optical system for a special experimental geometry has to be solved using precision optical and mechanical instruments. Unfortunately this process could take a long time. However, our analysis shows that conventional experimental setup for diffraction investigations (i.e., a Huber four-circle diffractometer) can be used for precisely adjusting the capillary lens in a short time.

It is also important to note that during our experiments we observed that the x-ray beam behind the capillary lens diverges less than expected. This observation is confirmed by the wave character of the x ray scattering inside the capillary channels: under the extremely small glancing angles, most of the waves are scattered into smaller angles than the incident ones, i.e., the beam "clings" to the channel walls. This feature of x-ray transmission by a grazing-incidence optical system could have a number of interesting applications, so it is necessary to continue studying the scattering processes of x rays from surfaces under the regime of total external reflection.

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References

- [1] P.B. Hirsch, and J. Kellar, "An X ray micro-beam technique: I - Collimation", *Proc. Phys. Soc. London Ser. B* **64**. pp.369-374. 1951..
- [2] E. Pound, and C. Rebka, "Gravitational red-shift in nuclear resonance", *Phys. Rev. Lett.* **3**. pp.439-441. 1959.
- [3] P. Engström, S. Larsson, and A. Rindby, "A submicron synchrotron X-ray beam generated by capillary optics", *Nucl. Instr. Meth.* **A302**. pp.547-552. 1991.
- [4] D.J. Thiel, D.H. Bilderback, A. Lewis, and E.A. Stern, "Submicron concentration and confinement of hard X-rays", *Nucl. Instr. Meth.* **A317**. pp.597-600. 1992.
- [5] V.A. Arkadiev, A.I. Kolomitsev, M.A. Kumakhov, et al. "Wide-band x-ray optics with large angular aperture", *Usp. Fiz. Nauk* **157**. pp.493-499. 1987.
- [6] M.A. Kumakhov, and F.F. Komarov, "Multiple reflection from surface X-ray optics", *Phys.Rep.* **191**. pp.289-350. 1990.
- [7] W.C. Hamilton, "Angle settings for four-circle diffractometers", in *International Tables for X-ray Crystallography IV*. pp.273-284. 1974.
- [8] E. Burattini, G. Cappuccio, P. Maistrelli, and S. Simeoni, "MacDUST - a powder diffraction package developed for the "Adone" high-resolution diffraction station", *Materials Science Forum* **133-136**. pp.309-316. 1993.
- [9] S.B. Dabagov, and A. Marcelli, "Single-reflection regime of x rays that travel into a monocapillary", *Appl. Opt.* **38**. pp.7494-7497. 1999.