An efficient polycapillary beam collimator for laboratory-based soft X-ray metrology

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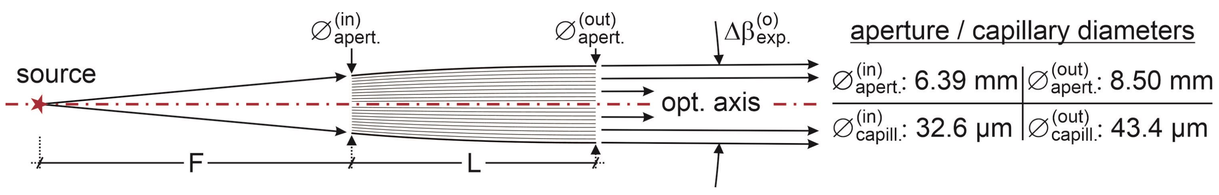
Schematic of the polycapillary half lens (to scale) with parameters

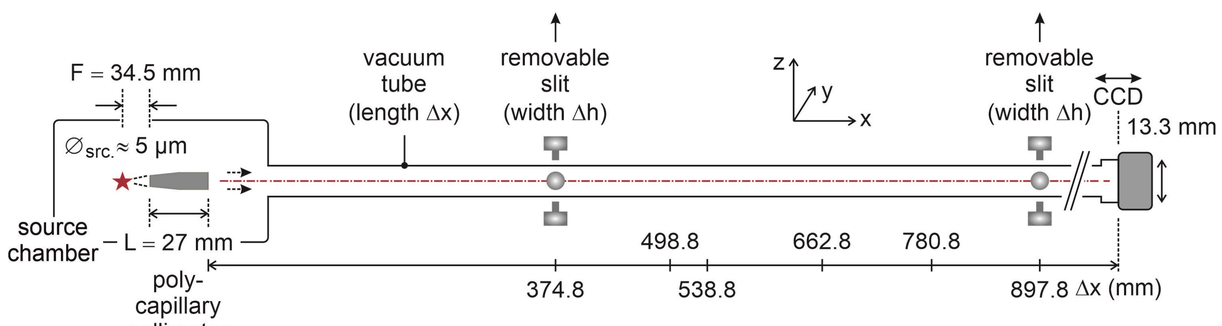


aperture / capillary diameters

$\varnothing^{(in)}_{apert.}$: 6.39 mm	$\varnothing^{(out)}_{apert.}$: 8.50 mm
$\varnothing^{(in)}_{capill.}$: 32.6 µm	$\varnothing^{(out)}_{capill.}$: 43.4 µm

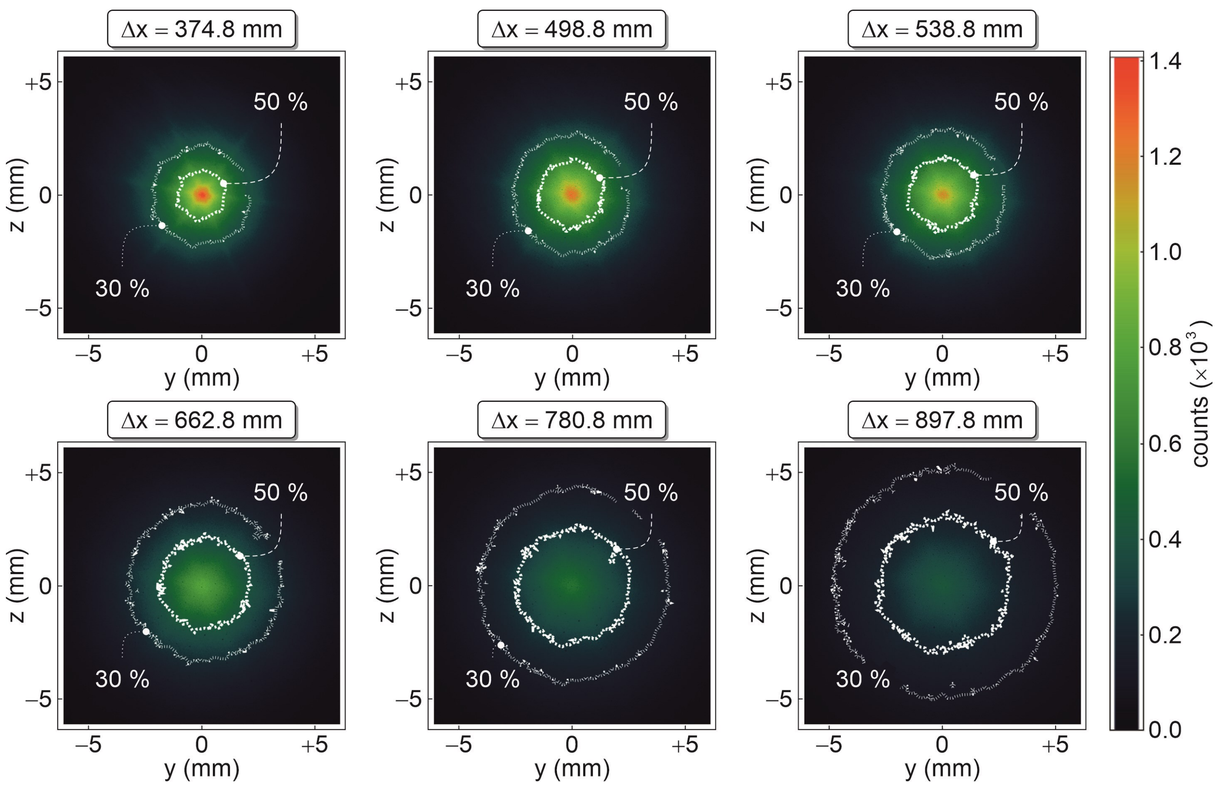
- borosilicate glass ($Si_{81}O_{215}B_{26}Na_8K_8Al_4$) with a density of 2.23 g cm^{-3},
- critical angle of total external reflection @ 277 eV: $\theta_c = 5.55°$ (CXRO),
- acceptance solid angle 26.7 × 10^{-3} sr with a transmisssion of ≈ 50 %,
- wall thickness ≈ 4 µm & slope error / roughness ≈ ± 1.8 arcsec (rms).

Experimental setup for Carbon K_α (277 eV), evacuated to 10^{-5} mbar

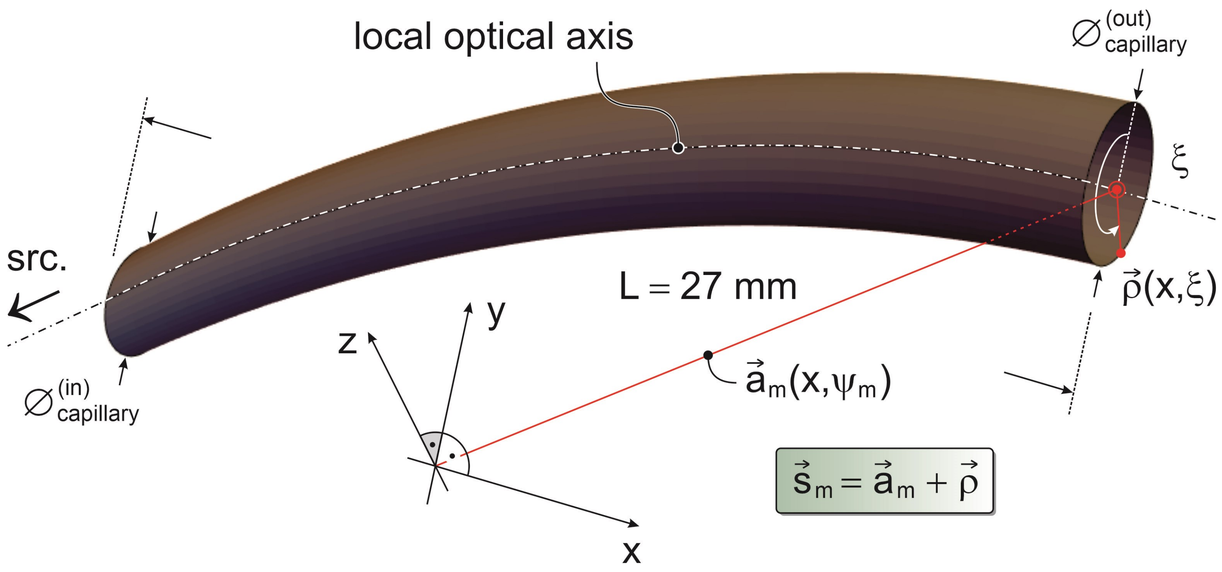


CCD at free-space distance Δx from exit aperture, or slit of width Δh

Experimental 2-D beam profiles, by CCD (940 × 940 pixels à 13 µm)



Geometry of a single capillary tube, used for simulations (Optica™)



ellipsoidal curvature of local optical axis & tapered capillary diameter:

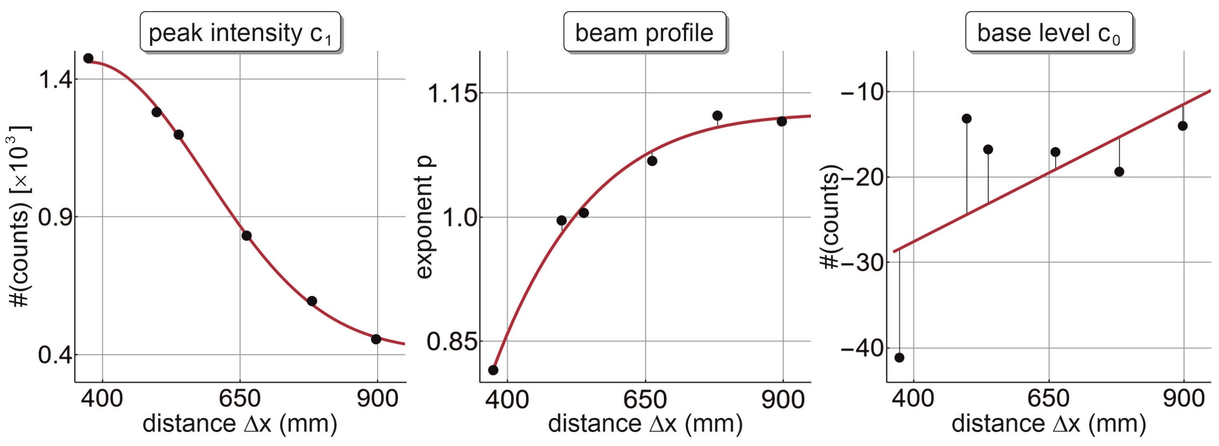
$$\vec{s}_m(x,\psi_m,\xi) = x\vec{e}_x + \left[r^{(m)}_{aper.}\cos\psi_m + \rho^{(o)}_{cap.}\cos\xi\right]\mathcal{F}(x)\vec{e}_y + \left[r^{(m)}_{aper.}\sin\psi_m + \rho^{(o)}_{cap.}\sin\xi\right]\mathcal{F}(x)\vec{e}_z$$

$$\mathcal{F}(x) \equiv [1 - a_S^{-2}(L/2 - x)^2]^{1/2}$$

#(rays) = 6.6 × 10^4, traced through 1 ≤ m ≤ 9.5 × 10^3 tubes (2 runs)

Nonlinear fit model to measured 2-D beam profiles $I_\perp(r)$ and values

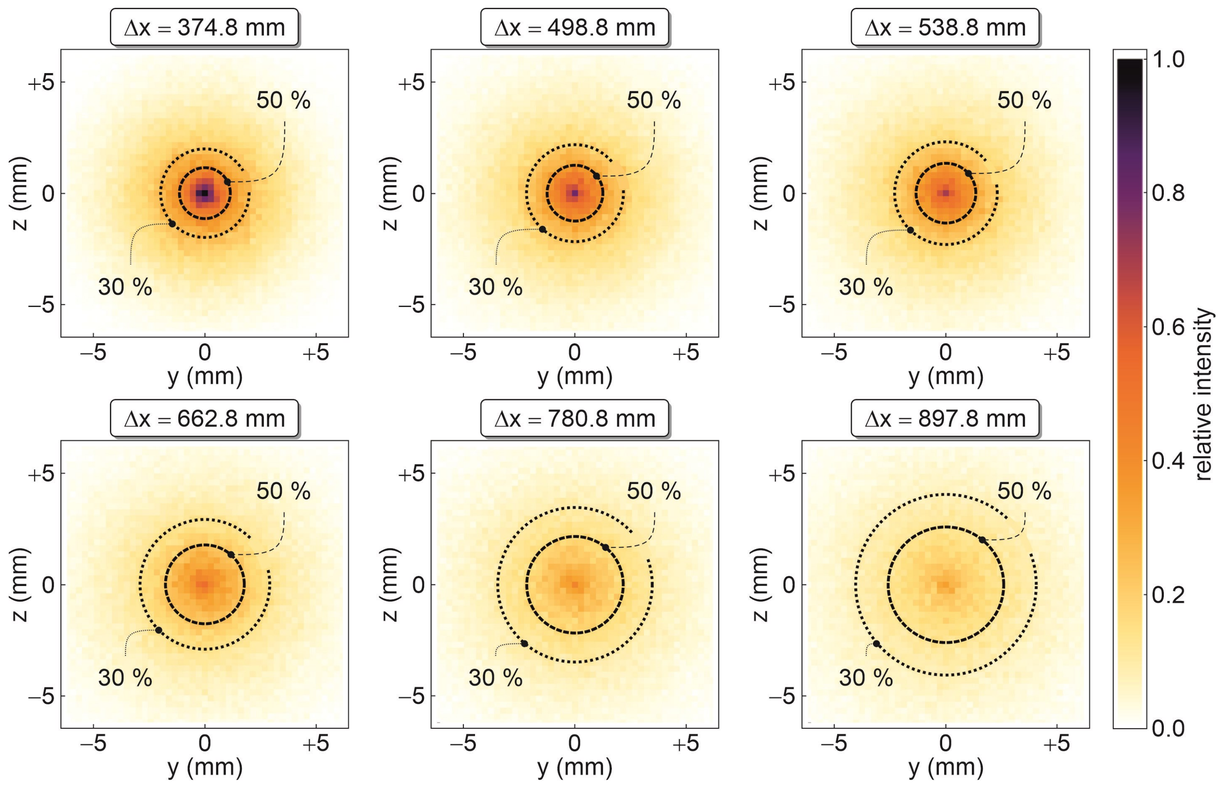
$$I_\perp(r) = c_0 + c_1 \exp[-4\ln 2\ (r/w_0)^p] \quad \text{with} \quad r^2 \equiv y^2 + z^2 \quad \text{and} \quad p \in \mathbb{R}_+$$



beam diameter: $\varnothing^{(p)}_{FWHM}(w_0) = 2w_0/\sqrt[p]{4}$ (evaluated at Δx)

goodness of fit: $\langle R^2 \rangle$ = (99.73 ± 0.11) % "coefficient of determination"

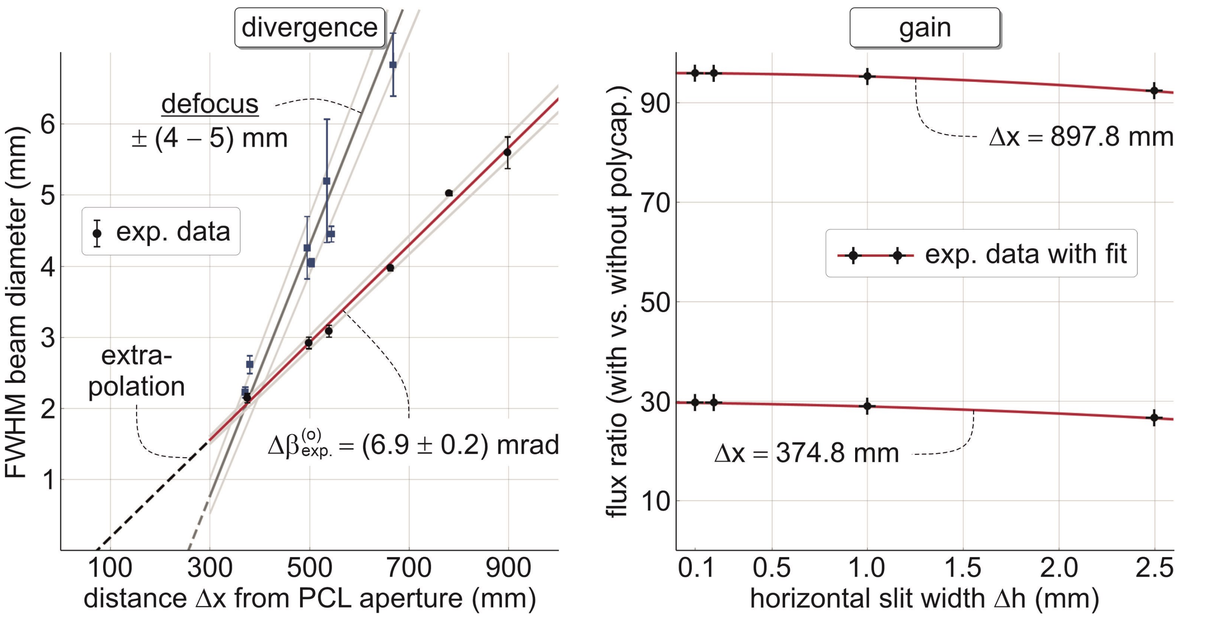
Simulated intensity patterns for a source size distribution of (5 ± 3) µm



far field (Δx ≥ 0.53 m) angular divergence: $\Delta\beta^{(o)}_{sim.}$ = (7.0 ± 0.1) mrad

goodness of fit: $\langle R^2 \rangle$ = (99.5 ± 0.2) % → ≈ applies to simulation, too;

Measured angular divergence and gain in photon flux on a sample



flux density on a mirror, grating, … under test (27 — 96) × enhanced

Reference

J. Probst, H. Löchel, M. Thiel, S. Bjeoumikhova, C. Braig, and C. Seifert, "Collimation by a polycapillary half lens at 277 eV," Opt. Express **31**, 30379—30389 (2023).

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