Ion-insulator interactions inside ion-guiding nanocapillaries

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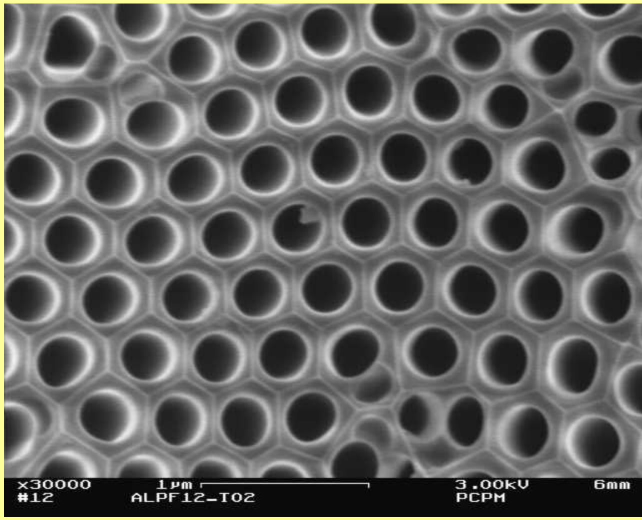
Experiments at ATOMKI

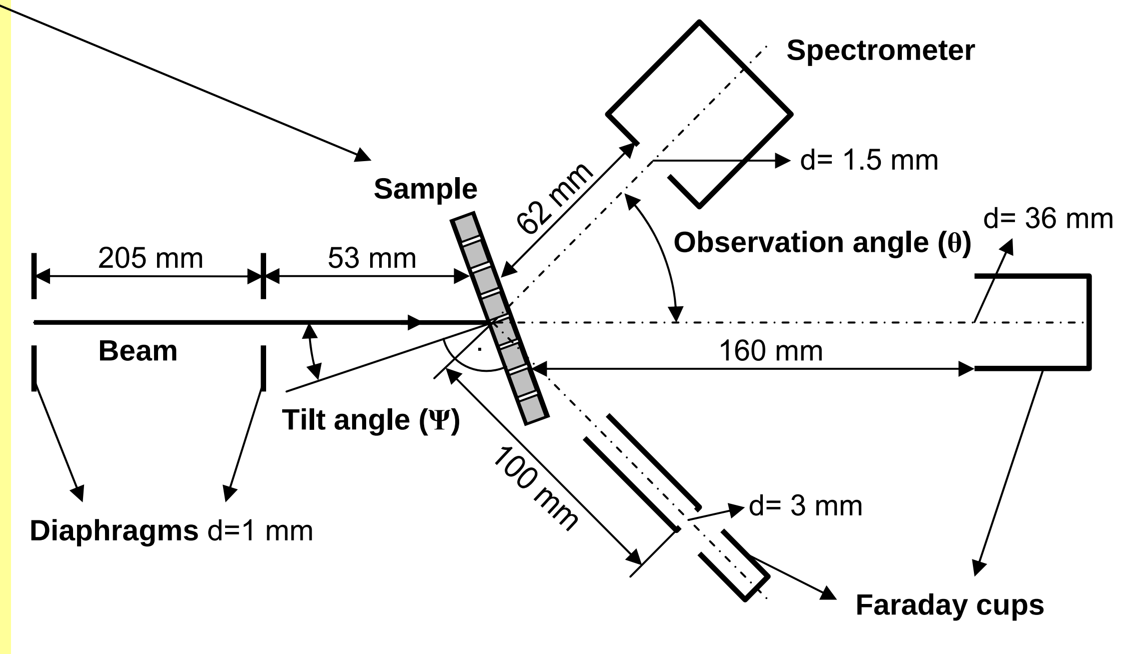


Insulating nanocapillaries (arrays of tiny tubes) can guide slow ions
Discovered by Stolterfoht et al.
for polyethylene terephthalate (PET)

We investigate transmission of Ne^{6+} ions through Al_2O_3 capillaries

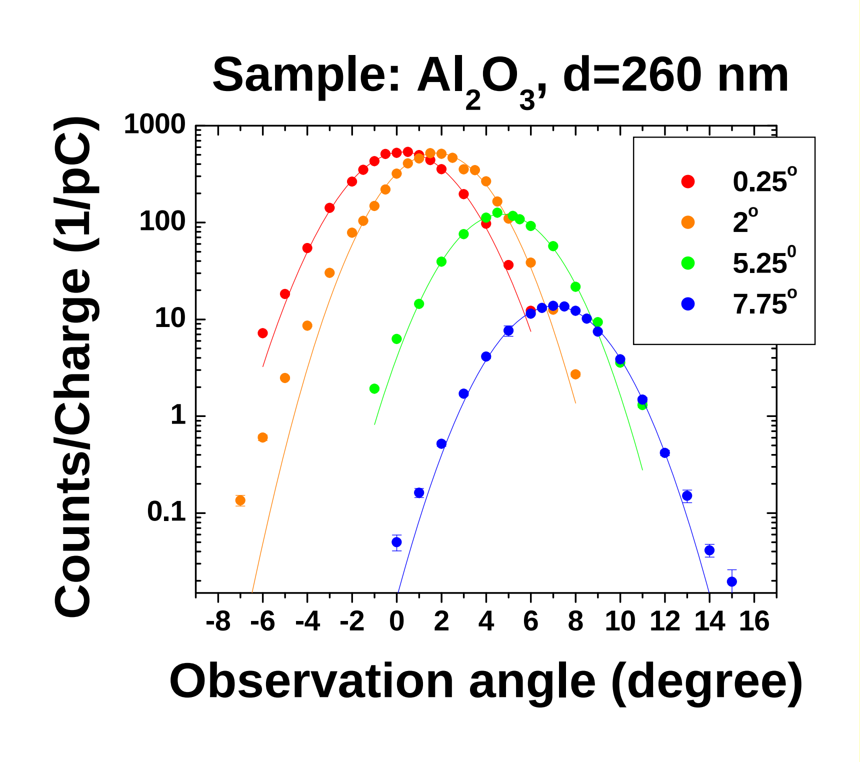
Al_2O_3 capillaries prepared at UCL, Louvain

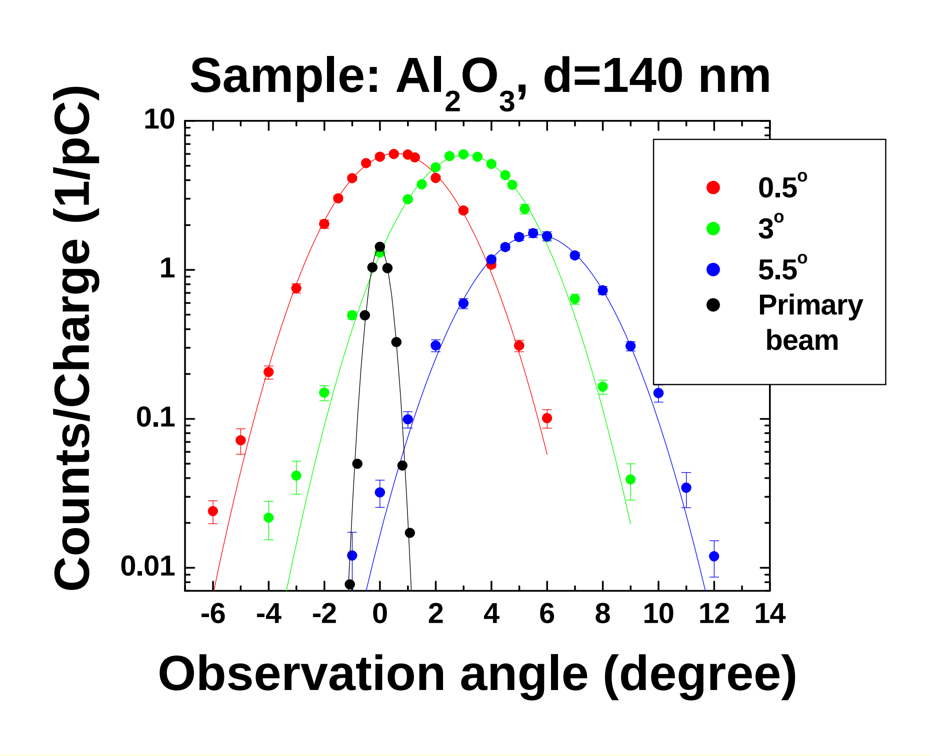
d=140 nm, 260nm
L=15 µm
aspect ratio: ~100
Membranes covered by Nb



Angular distributions of the transmitted ions

ion counting at the spectrometer





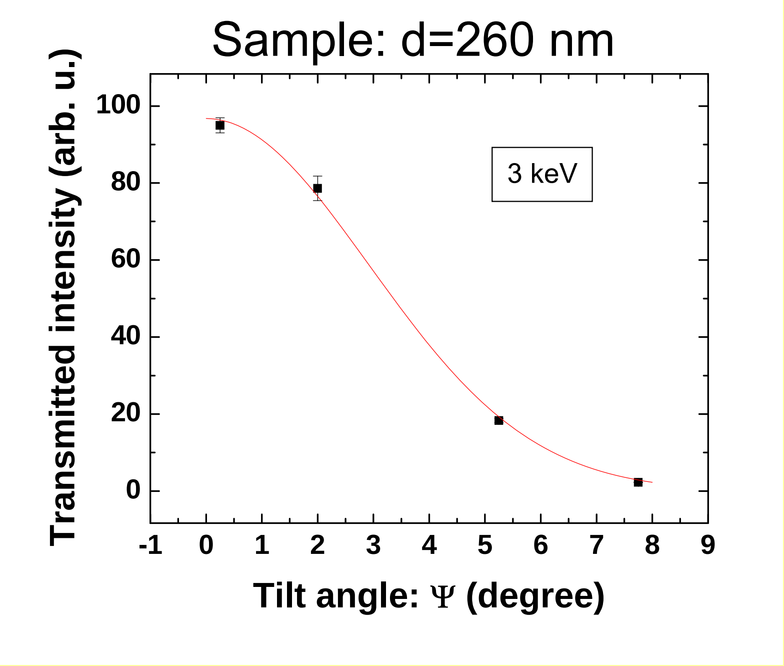
FWHM: ~4.25° for both alumina samples, nearly independent of tilt angle

Previous measurements: -PET: ~5° (bulk insulator)

-SiO_2: 1-1.2° (insulator surfaces on semiconductor)

Tilt angle dependence of the transmitted intensity

Relative transmission
ion counting data



Fitting by semi-empirical formula [Stolterfoht et al] :

$$f(\Psi) = f(0^\circ)\, e^{-\lambda \sin^2 \Psi} = f(0^\circ)\, e^{-\frac{\sin^2 \Psi}{\sin^2 \Psi_c}}$$

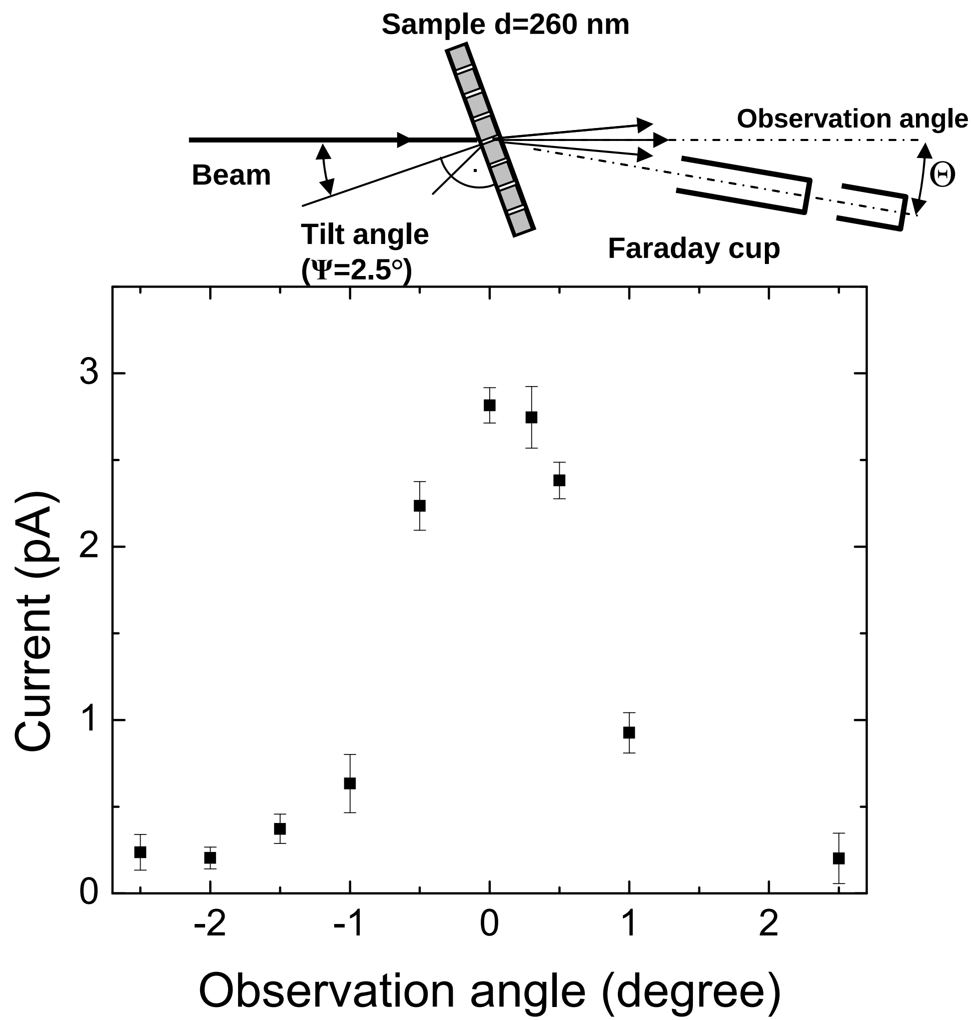
$$\Psi_c = 4.13^\circ$$

Absolute transmission at Ψ=0°
(current measurements in Faraday cup): 2.5%

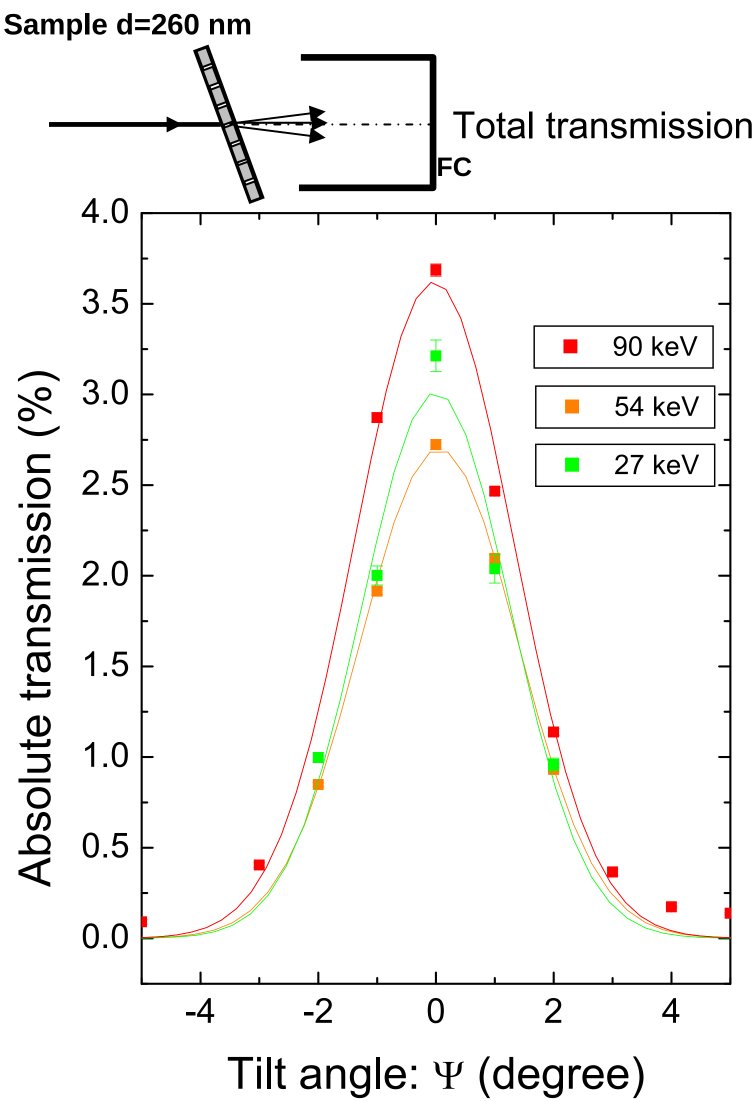
Much lower than the geometric opening: 28.2%

Measurements with high energy beams

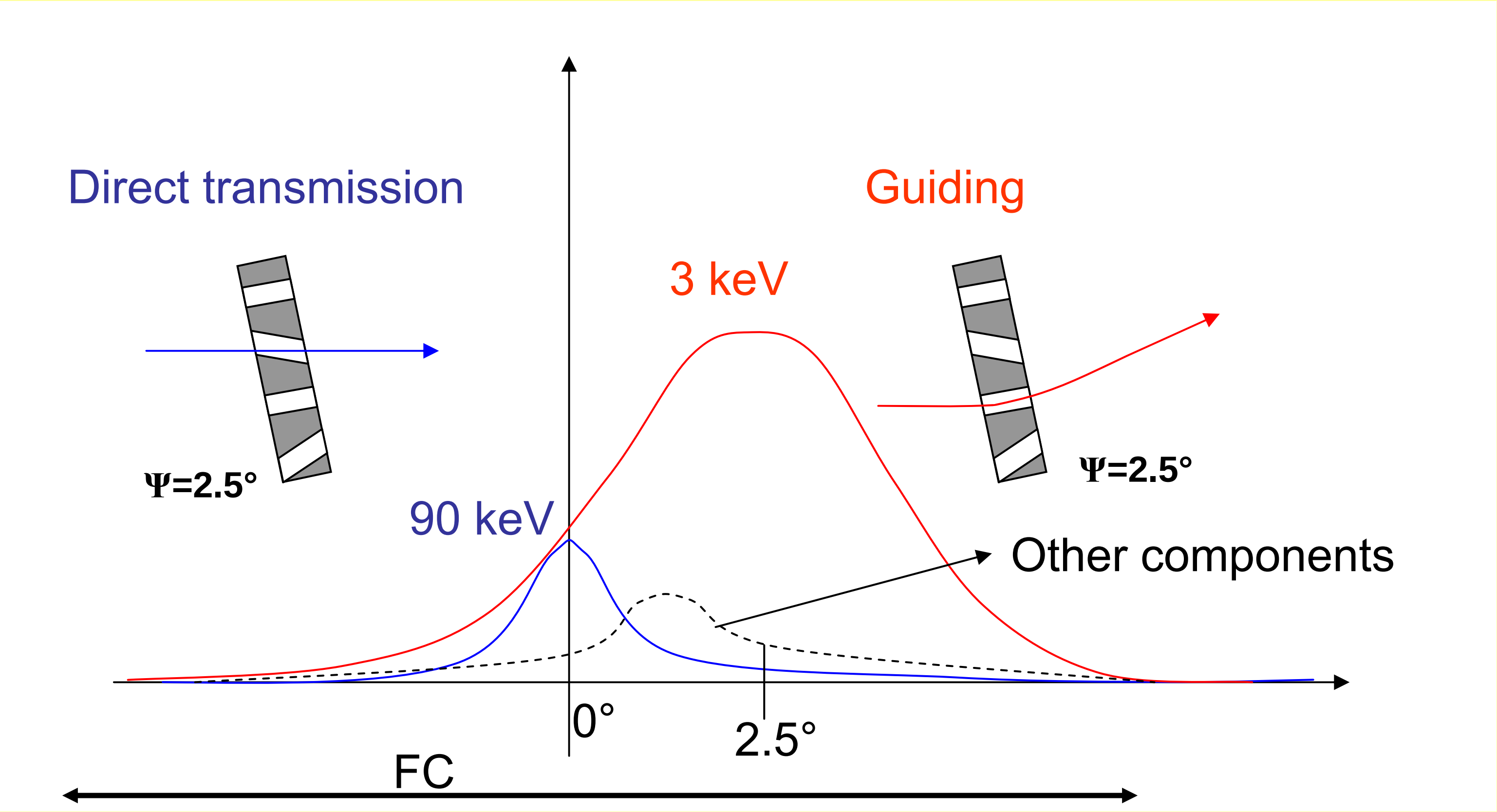
No beam deflection is observable at 90 keV



Ions can penetrate trough tilted samples



Transmission mechanisms



Determining the guiding (transmission) power

The semi-empirical formula [Stolterfoht et al] for the transmission for a tilted capillary sample:

$$f(\Psi) = f(0^\circ)\, e^{-\lambda \sin^2 \Psi} = f(0^\circ)\, e^{-\frac{\sin^2 \Psi}{\sin^2 \Psi_c}}$$

Nearly Gaussian with FWHM: $$\tilde{\Psi}_c = 2\sqrt{\ln(2)}\,\Psi_c$$

For a realistic sample it is convolved with the *angular distribution of the capillary axes* (previously unknown in our case)

Assuming Gaussian capillary angular distribution with w FWHM the tilt angle dependence of the transmission is Gaussian with

FWHM: $$\tilde{\Psi}_{meas} = \sqrt{\tilde{\Psi}_c^{\,2} + w^2}$$

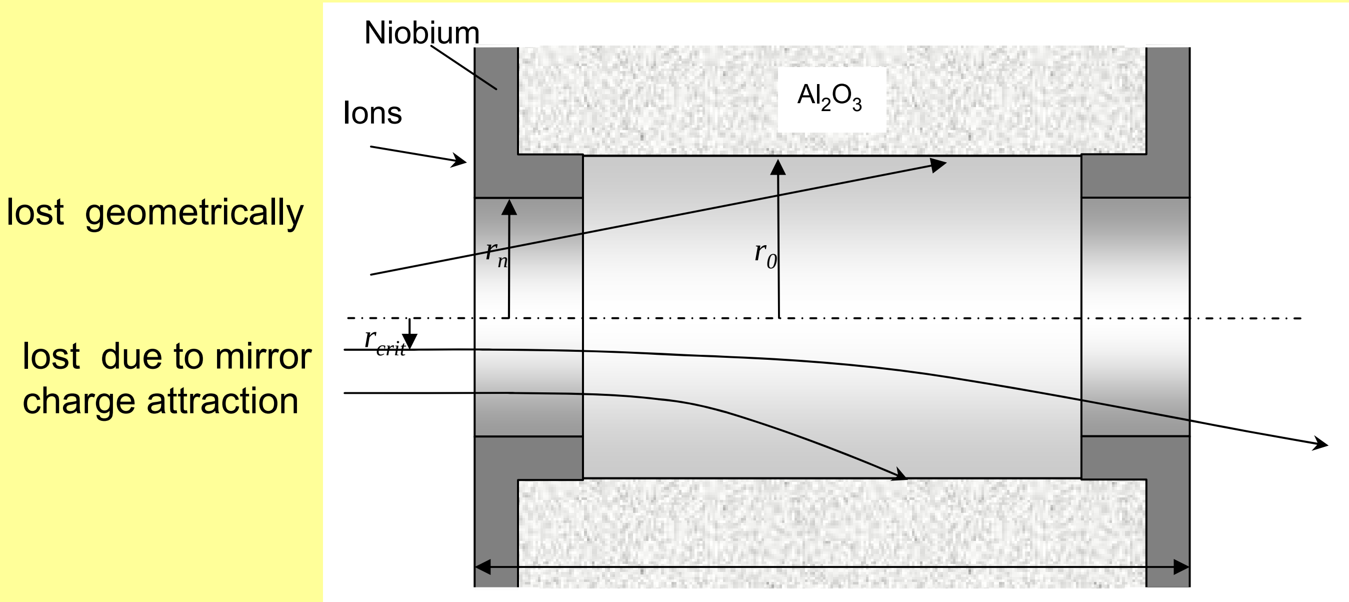
Maximum transmission (at 0°): $$A = f(0^\circ)\,\frac{\tilde{\Psi}_c^{\,2}}{\tilde{\Psi}_c^{\,2} + w^2}$$

Indirect method for determining w and $\tilde{\Psi}_c$

Measured quantities

Determined by model calculation

Calculation for the transmission of non-tilted capillaries: $f(0°)$



Geometric transmission:

-opening area

-beam divergence

Mirror charge effect depends on the beam energy!

$$T_{geom} = 11.5\% \qquad (260\ nm)$$
$$= 0.69\% \qquad (140\ nm)$$

$$T_{mch} = 84.8\%\ (90keV),\ 31.1\%\ (3keV)$$
$$= 69{,}6\%\ (90keV),\ 4\%\ (3keV)$$

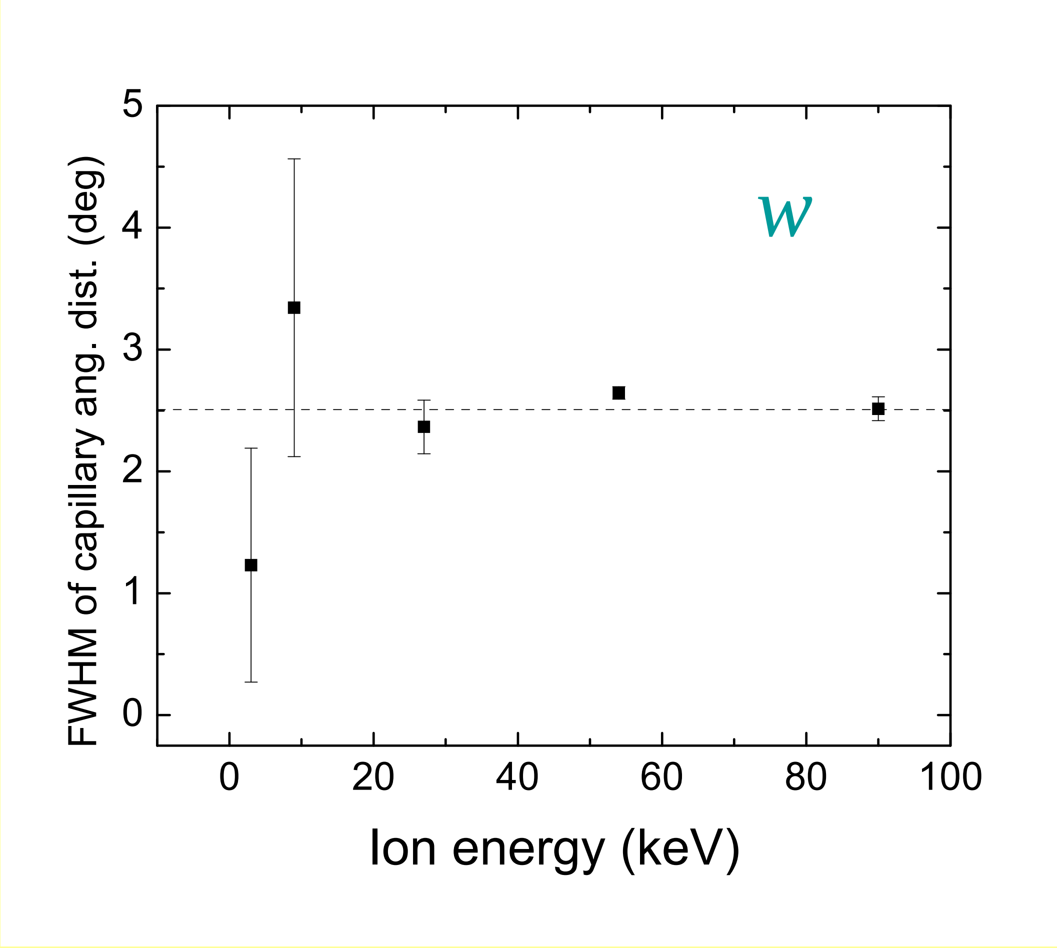
$$f(0°) = T_{geom} \cdot T_{mch}$$

FWHM of the capillary angular distribution

Results obtained at different energies can be compared

At high energies we got nearly the same results with small error bars (the guiding power is small – w dominates)

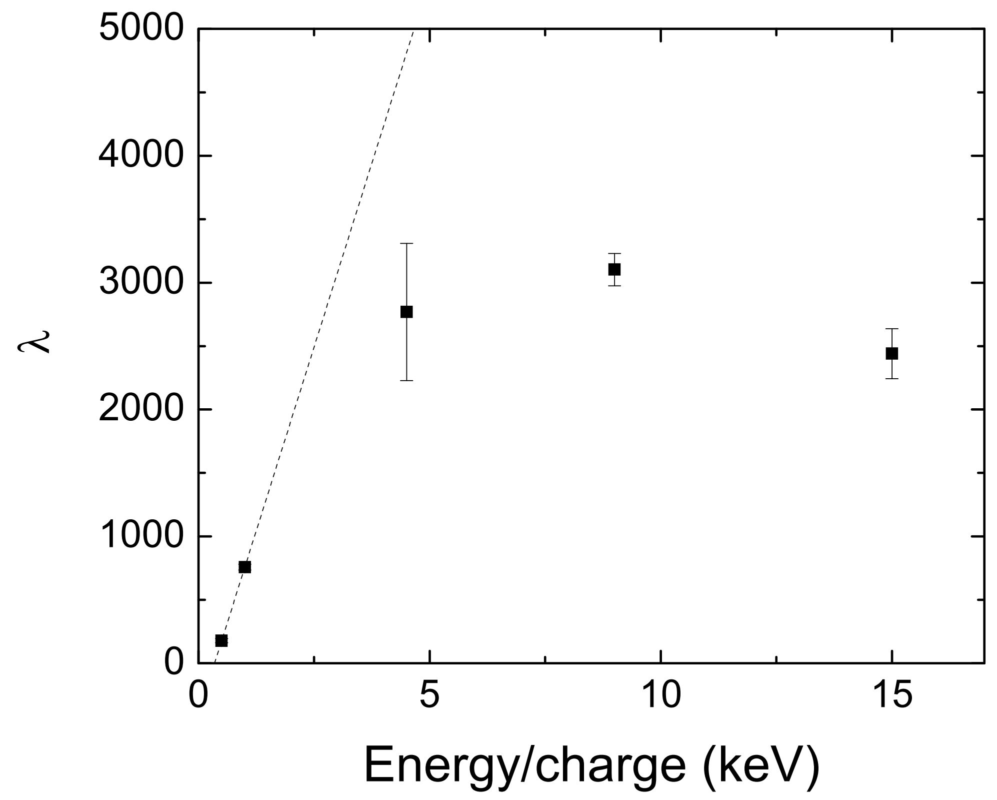
At low energies the uncertainties are large



Energy dependence of $\lambda = \dfrac{1}{\Psi_c^{\,2}}$

Within the semi-empirical model [Stolterfoht et al] :

$$\lambda = \frac{E}{qU} + c_s$$



At high energies the measured values deviate from the semi-empirical model!

Conclusions

-alumina capillaries have similar guiding power as PET capillaries

-the transmission is poor in which fact the relatively wide capillary angular distributions play a role

-the effects of the beam divergences and the mirror charge attraction also cannot be neglected and can lead to significant ion losses

-the guiding parameter λ follows the predictions in the low energy range, at high energies deviations are found

-deviations may be due to:

-reflections at walls

(different charge states are not separated by current measurements)

-other guiding mechanism at high energies?

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