Guiding of Highly Charged Ions through Insulating Nano-Capillaries

- Properties of different insulating capillary membranes
- Experimental schemes
- Transmission of highly charged ions guided through insulating nano-capillaries in
  - PET
  - SiO_2
  - Al_2O_3
- Conclusions

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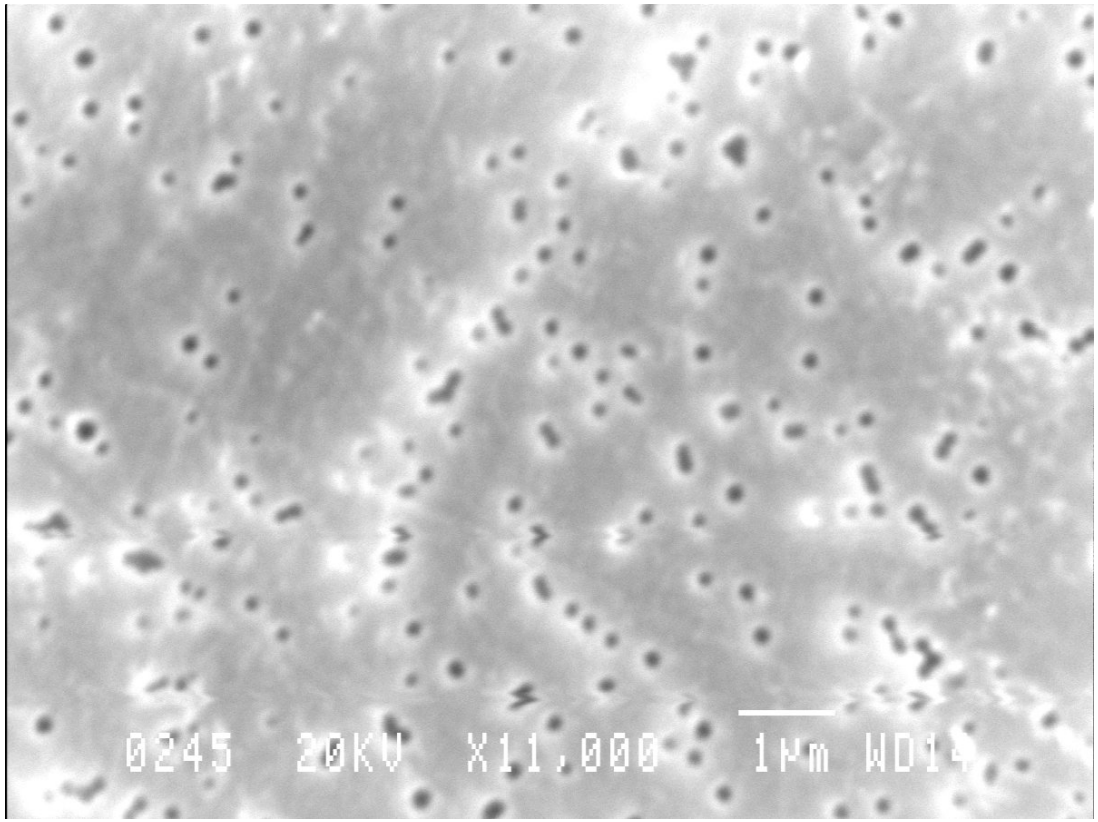
PET nano-capillaries



Nano-capillaries made by etching of random ion tracks from heavy ion bombardment

Randomly distributed, non-parallel nano-capillaries

Ø 100 nm, Length 10 μm

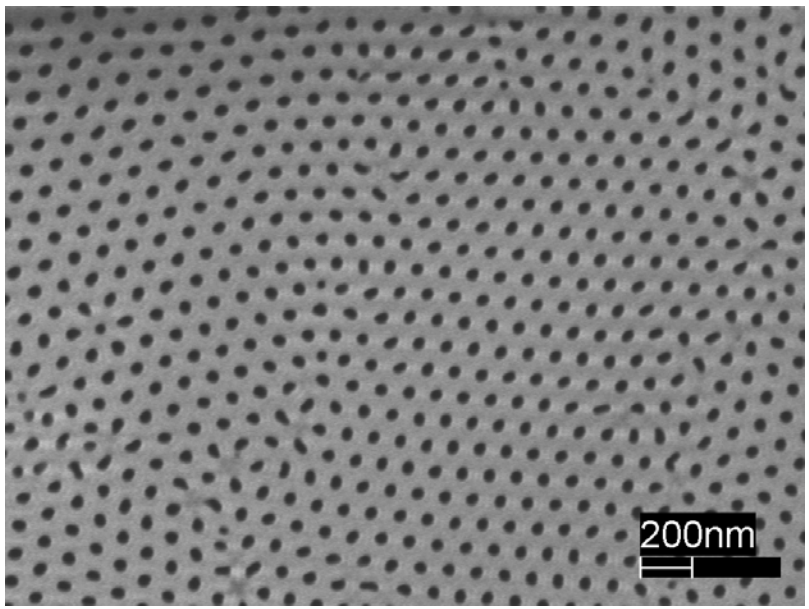
Geometric transparency ≈3.5 %

Al_2O_3 nano-capillary fabrication

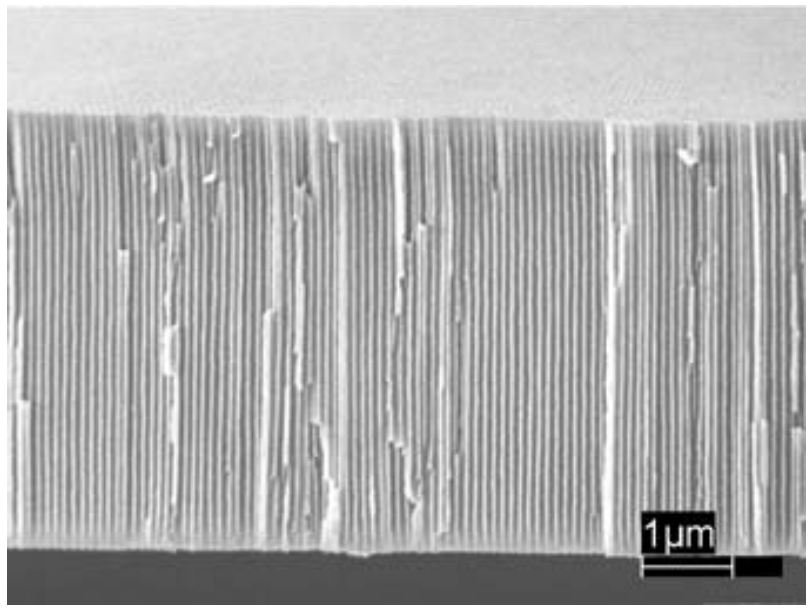
Wet etching and anodizing of Aluminium

Resulting in formation of capillaries ordered in a honeycomb pattern

Top view



Cross-sectional view

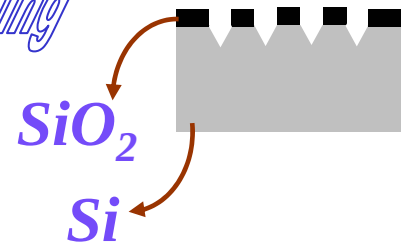


Highly ordered within regions, parallel nano-capillaries
Ø 60 nm, Length 10 µm
Geometric transparency ≈20 %

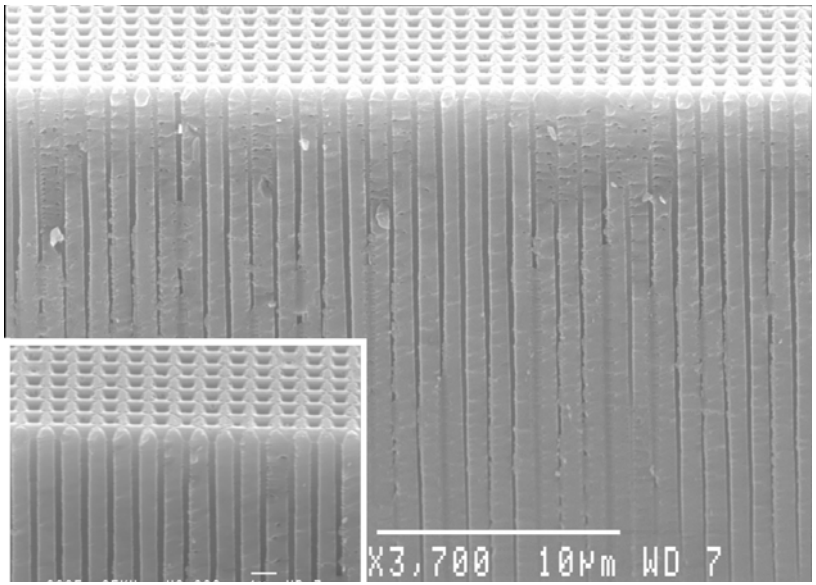
SiO_2 capillaries

Lithographic patterning Si(100) → *Photo-assisted electrochemical etching*

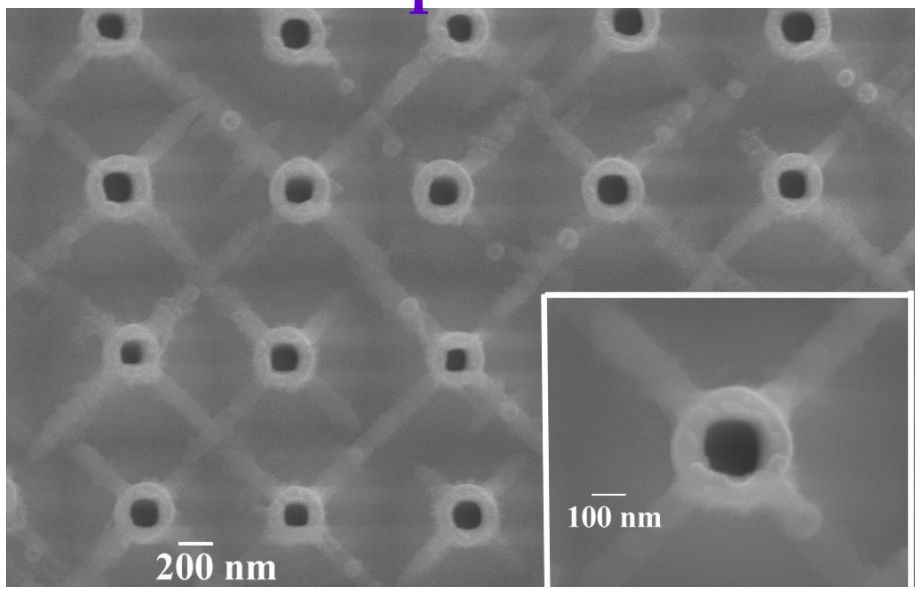
... → *Bulk-Si back-etching* ... → *Au sandwitching*



Cross-sectional view



Top view



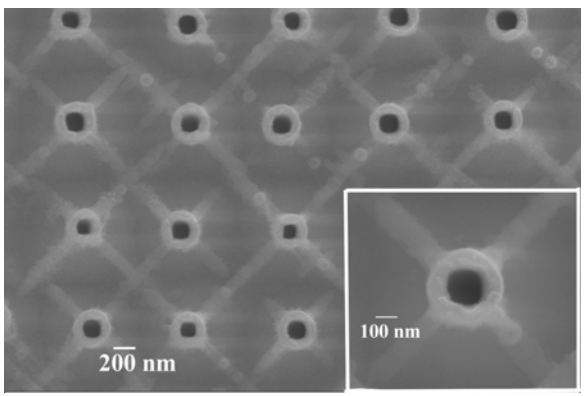
Highly ordered, highly parallel nano-capillaries

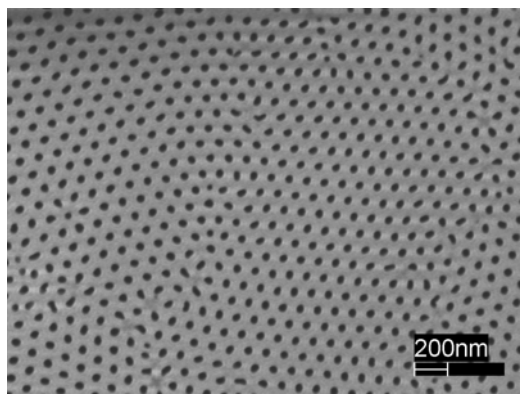
Ø 100 nm, Length 25 µm

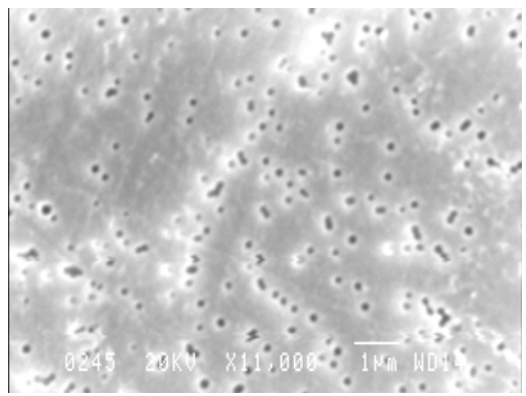
Geometric transparency ≈0.4 %

Properties of the nano-capillaries

SiO_2 on Si	Al_2O_3	PET
Highly ordered Highly parallel	Ordered within regions, parallel	Random capillaries clustered, < 2º spread
100 nm diam. 25 μm length	60 nm diam. 10 μm length	100 nm diam. 10 μm length
0.3% 10^{-6} mm^{-2}	20 % 10^{-6} mm^{-2}	0.4 % 10^{-6} mm^{-2}
100 nm SiO_2 on n-doped Si	Only dielectric material	Only dielectric material



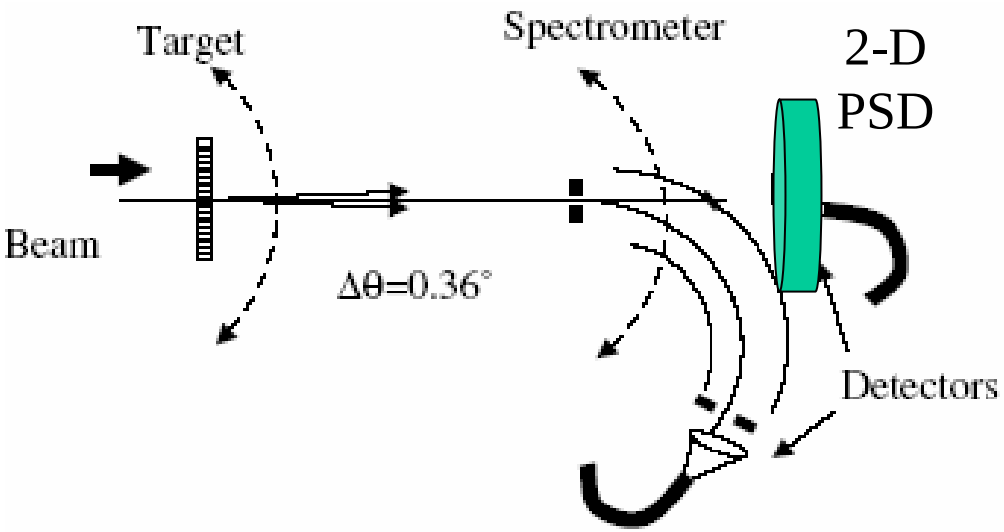


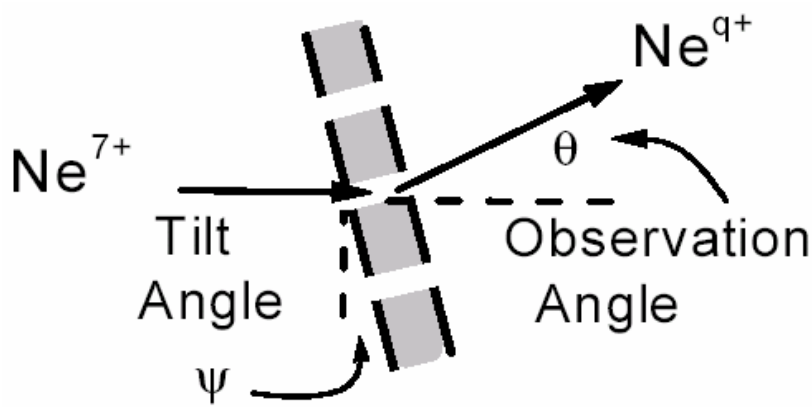


Experimental details

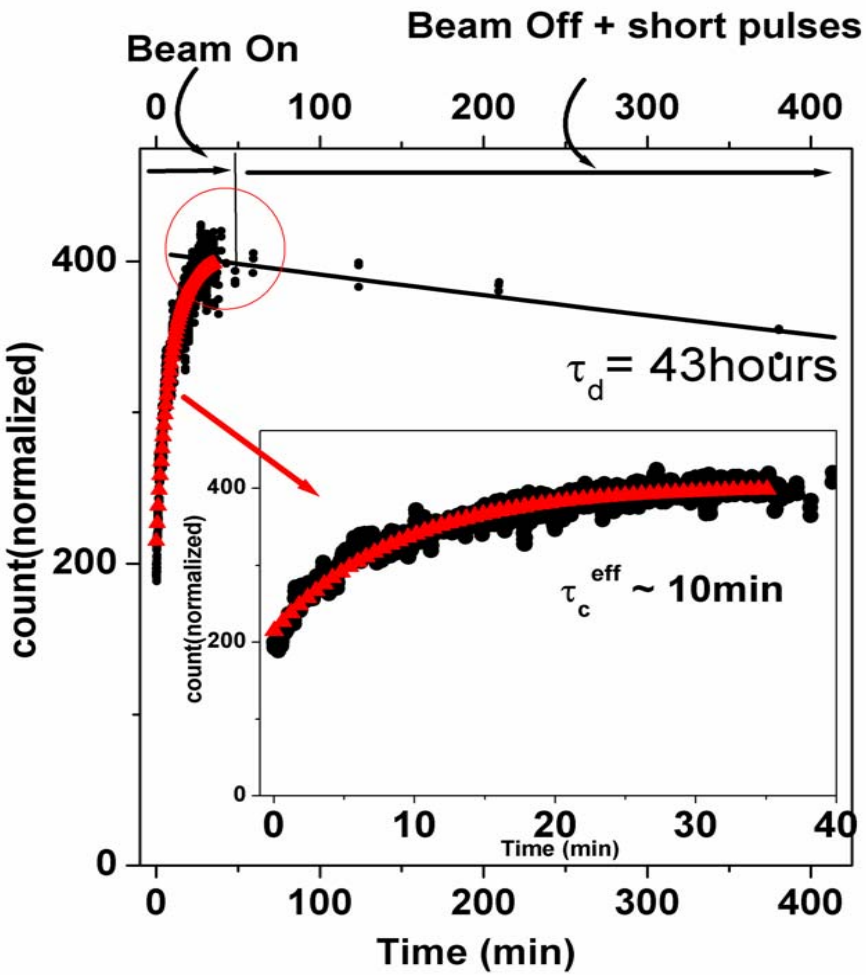
- Ion beam = 7 keV Ne^{7+} 🕔 0.1 nA mm^{-2},
- Ion sources = 14 GHz ECR source at MSL,

  \+ 40keV EBIT, AlbaNova, Stockholm
- UHV chamber pressure 10^{-9}- 10^{-8} mbar



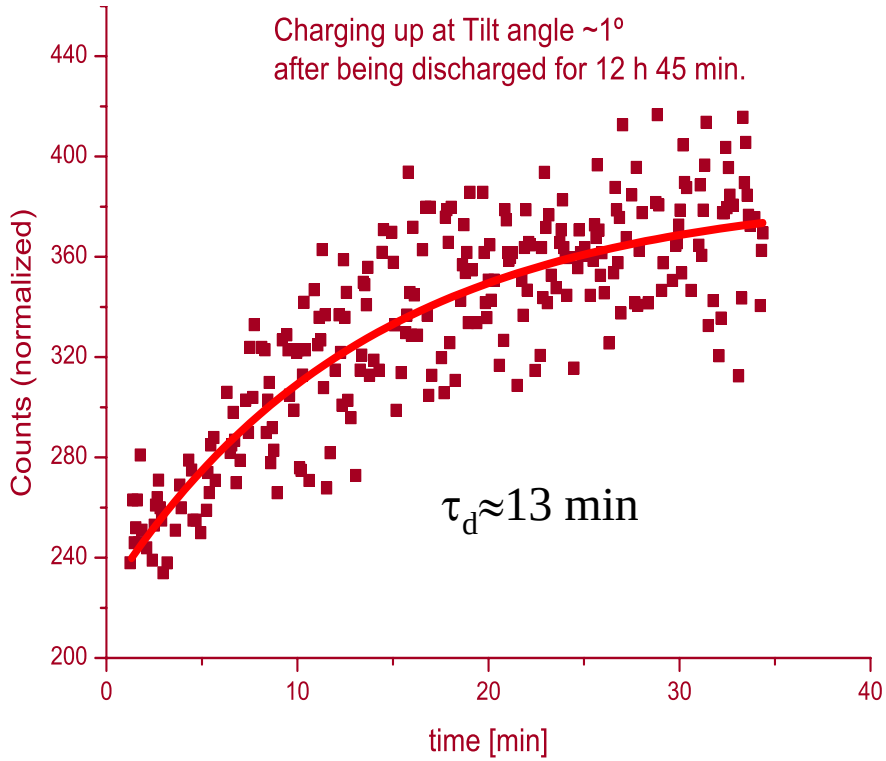


Time dependence of transmission



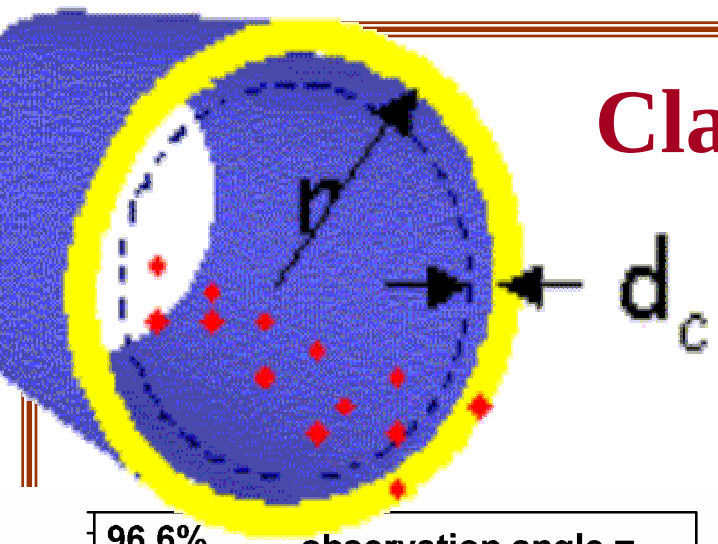
SiO_2

- Large discharge time
- Charging-up measured after discharging for 12 hours

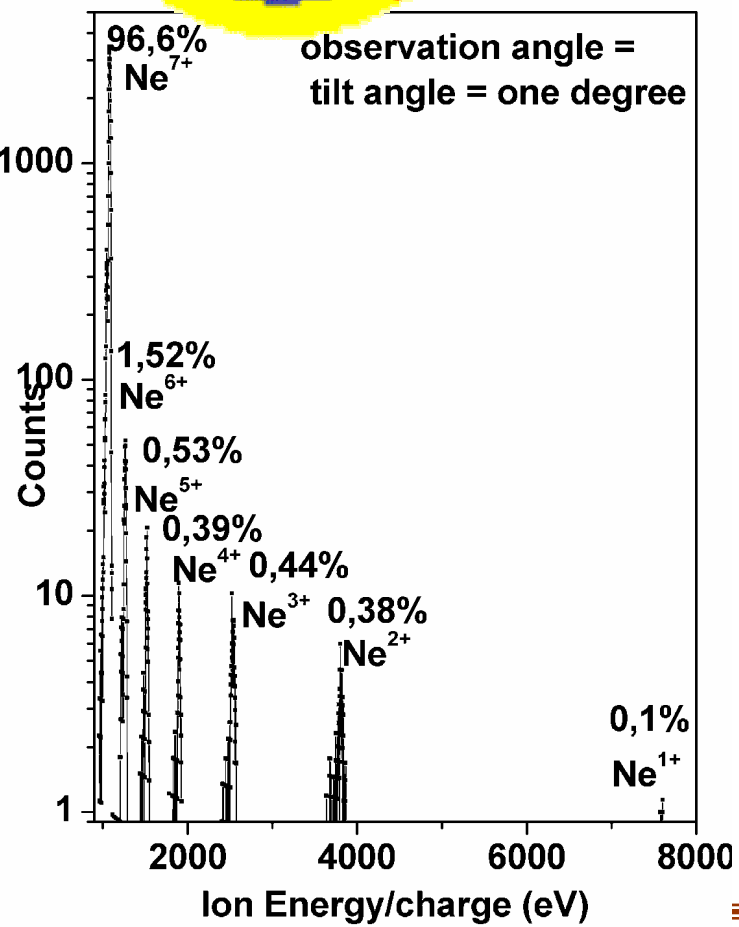


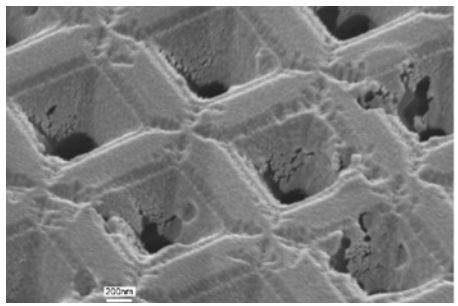
Al_2O_3

Classical over-barrier model



critical distance $d_c \approx \frac{\sqrt{2q}}{W}$





q = charge of the ion

W = work function

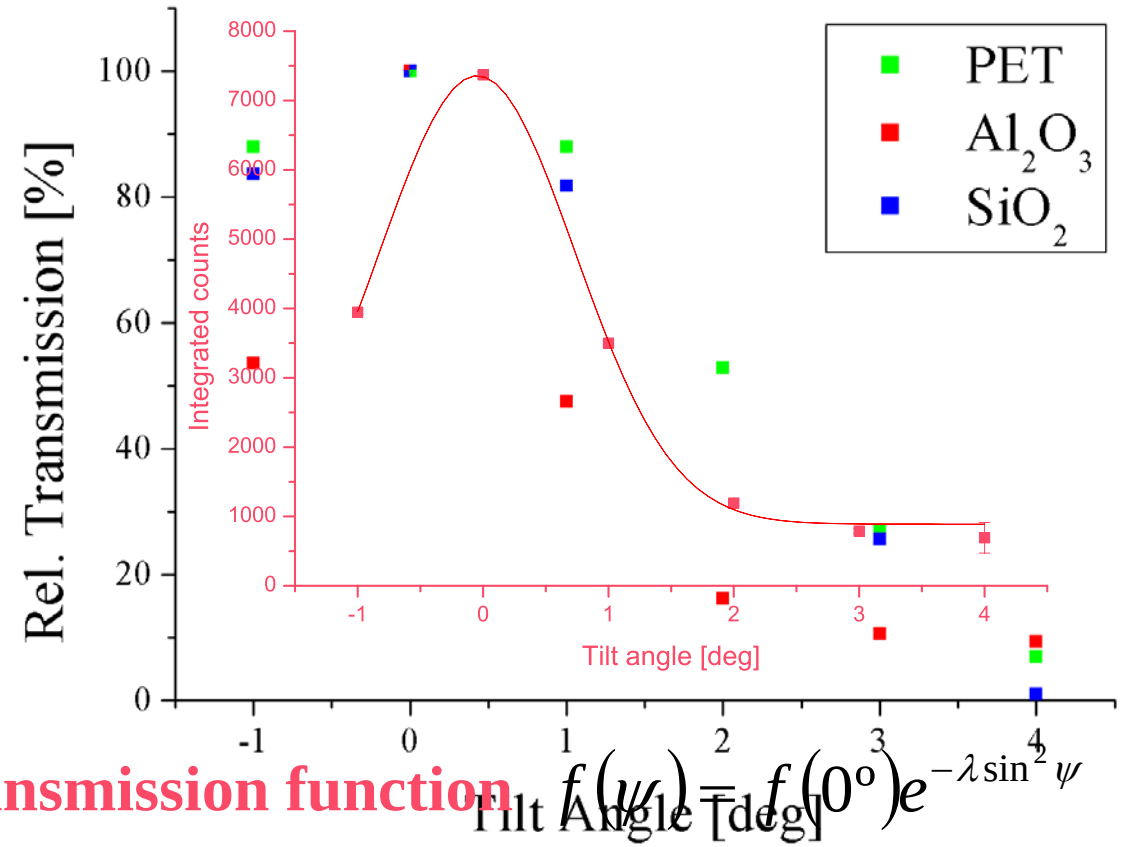
0º tilt angle

100 nm capillary

COB $\rightarrow \frac{2d_c}{r} \approx 4\%$

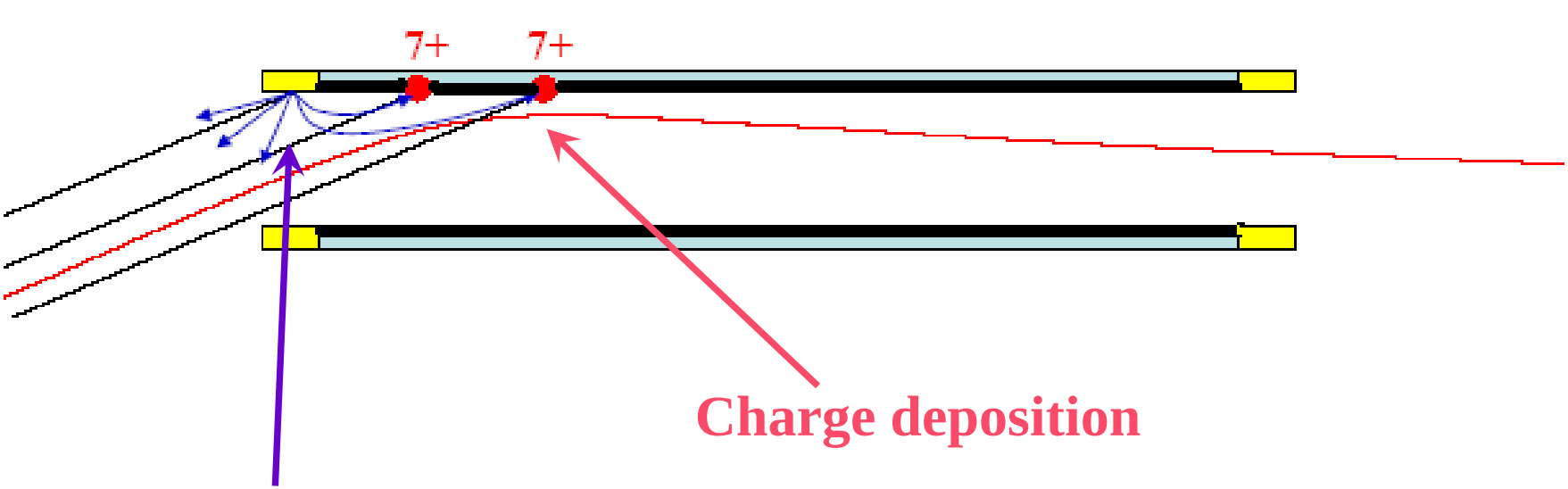
$dc_{Ne7+,\,Au} \approx 1\ nm << r$

Transmission of 7 keV Ne^{7+}



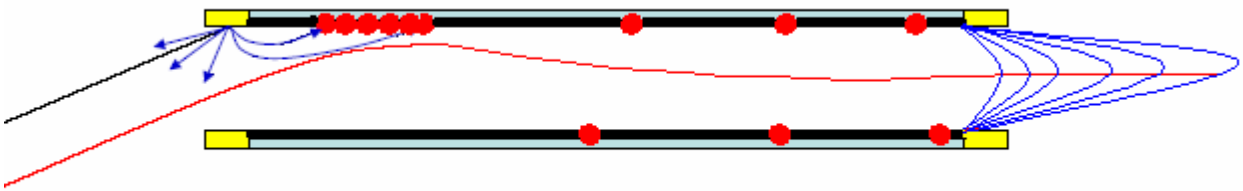
- Transmission function $f(\psi) = f(0^o)e^{-\lambda \sin^2 \psi}$
- $1/\lambda$ corresponds to the Guiding ability
  - Guiding ability similar for SiO_2 and PET
- Best fit with $\lambda \approx 2800$
  - Smaller for Al_2O_3

Self arranged ion guiding



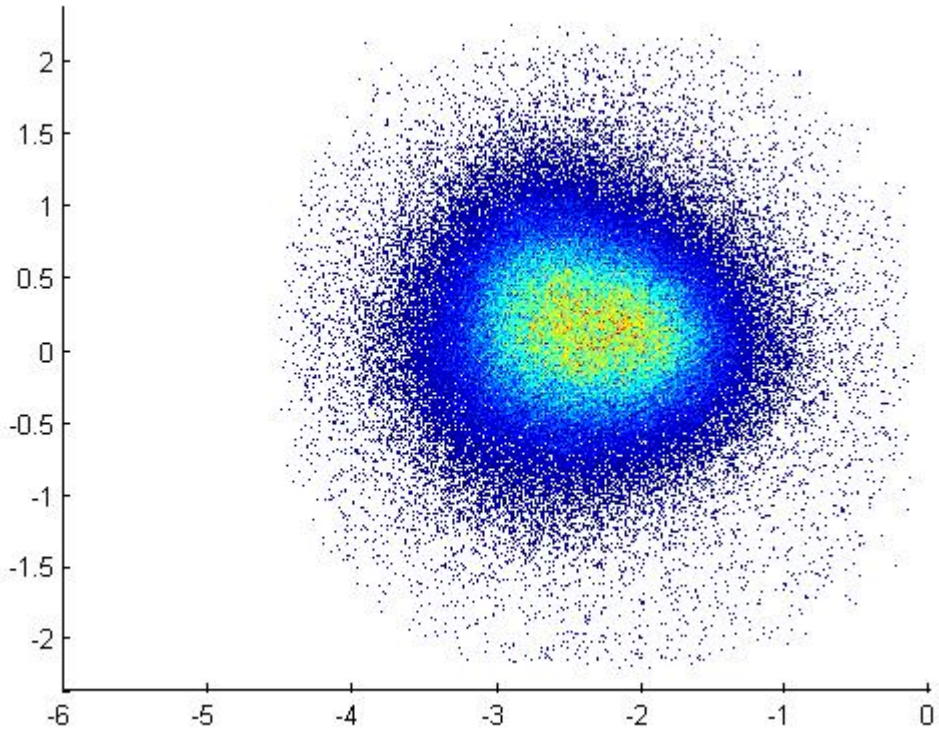
80 pA/mm$_2$

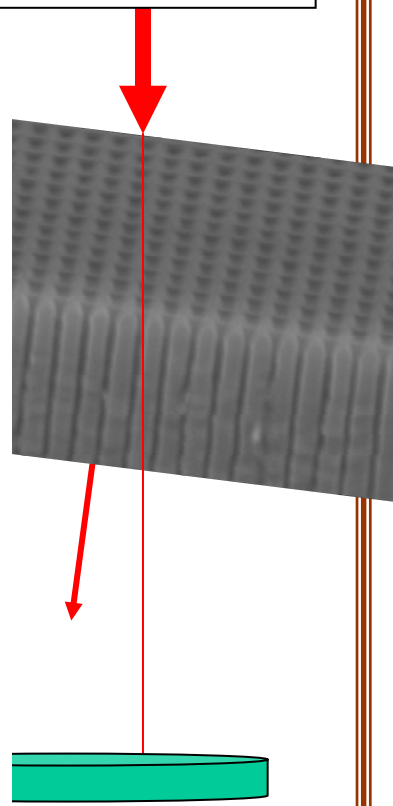
100 ions/cap./s.



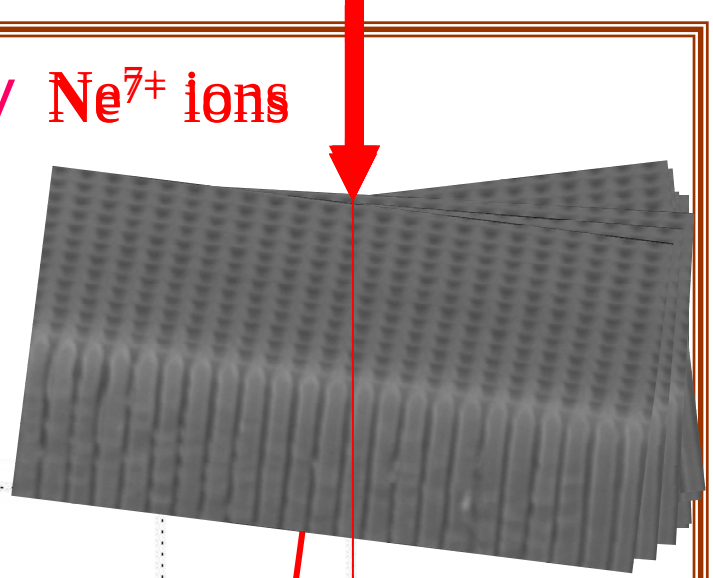
exit field broadening

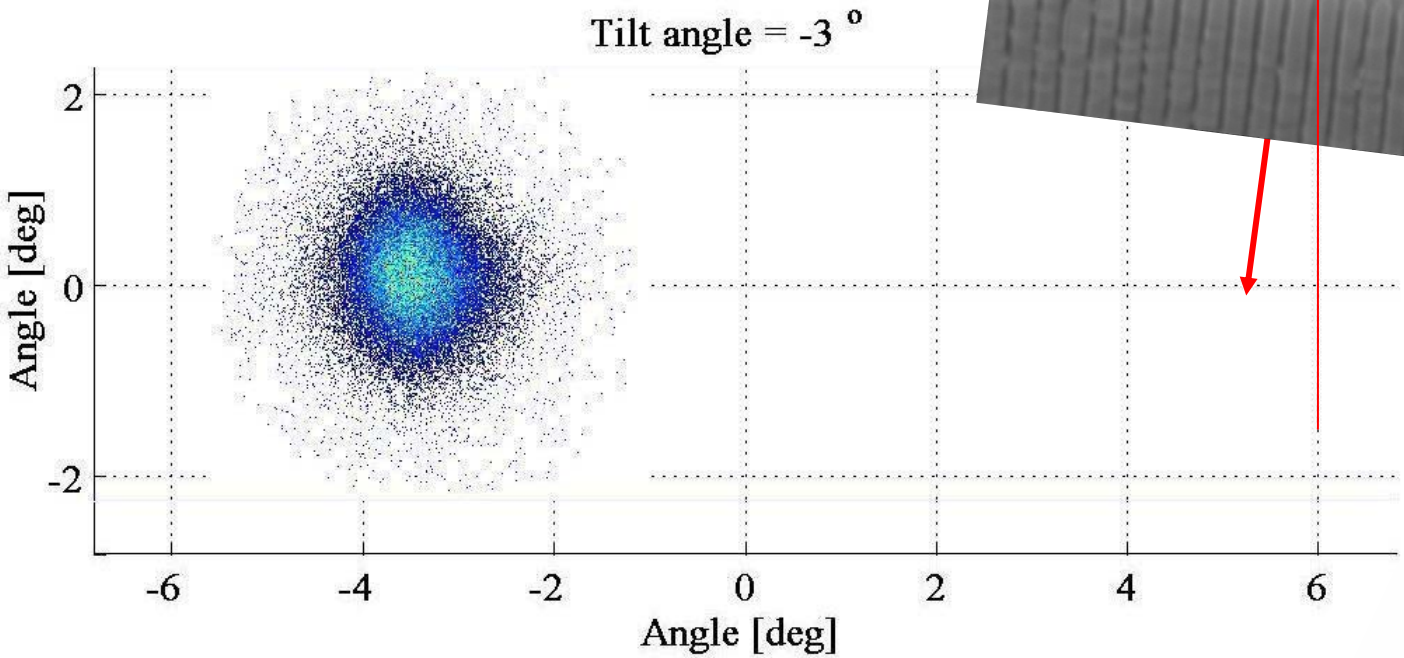
80nC, 2deg, Saturated

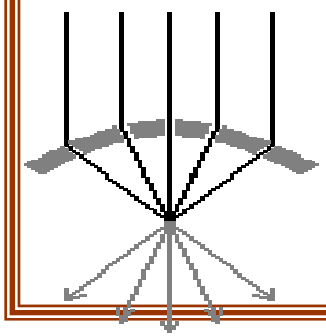


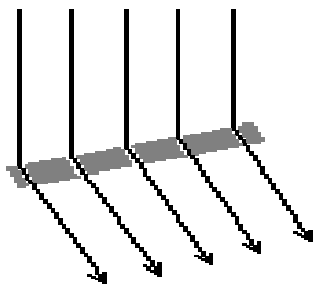


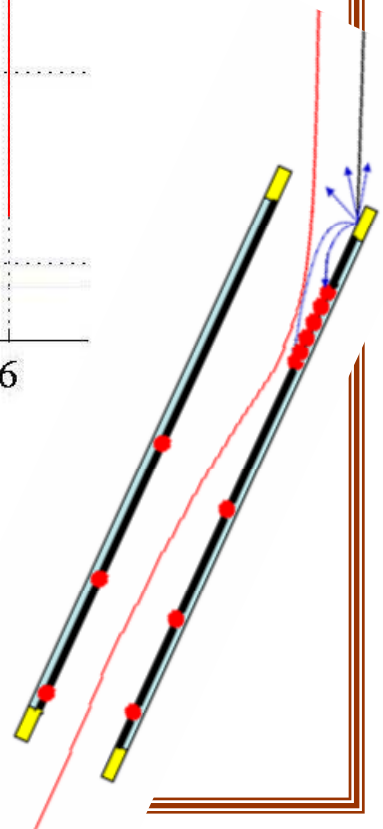
Guiding of HCI in Al_2O_3 (60nm$^{\varnothing}$, 10μm) nano-capillaries



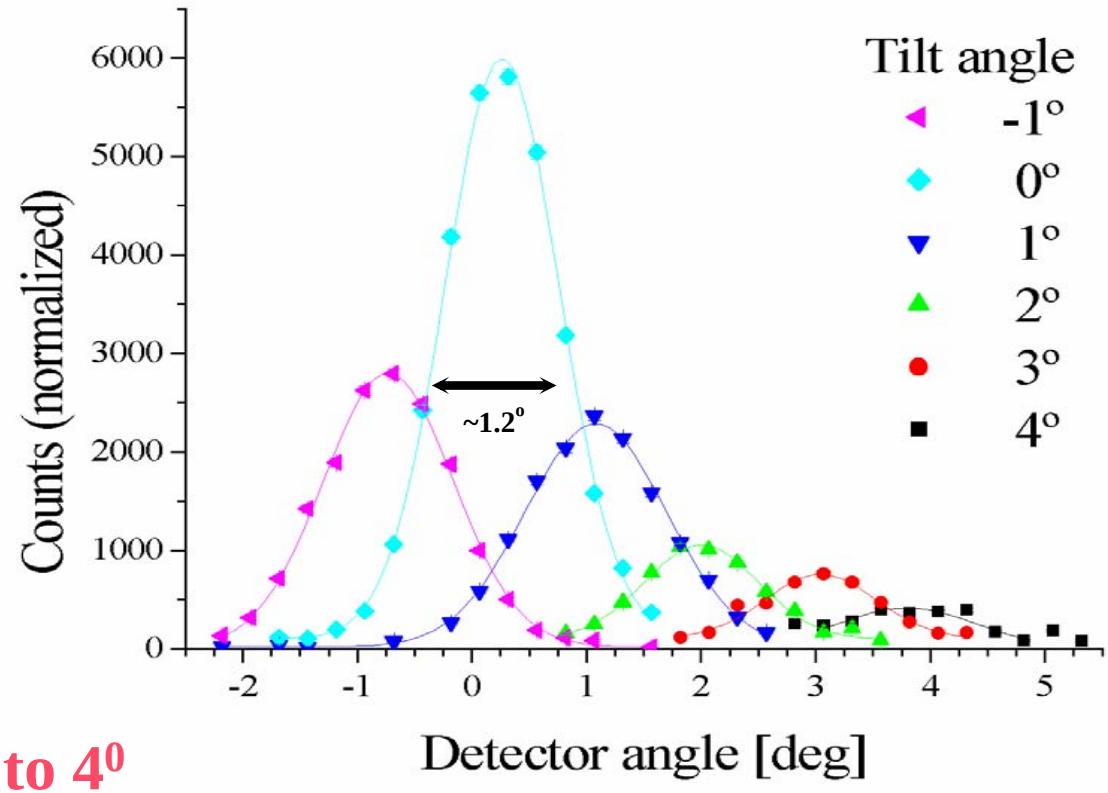








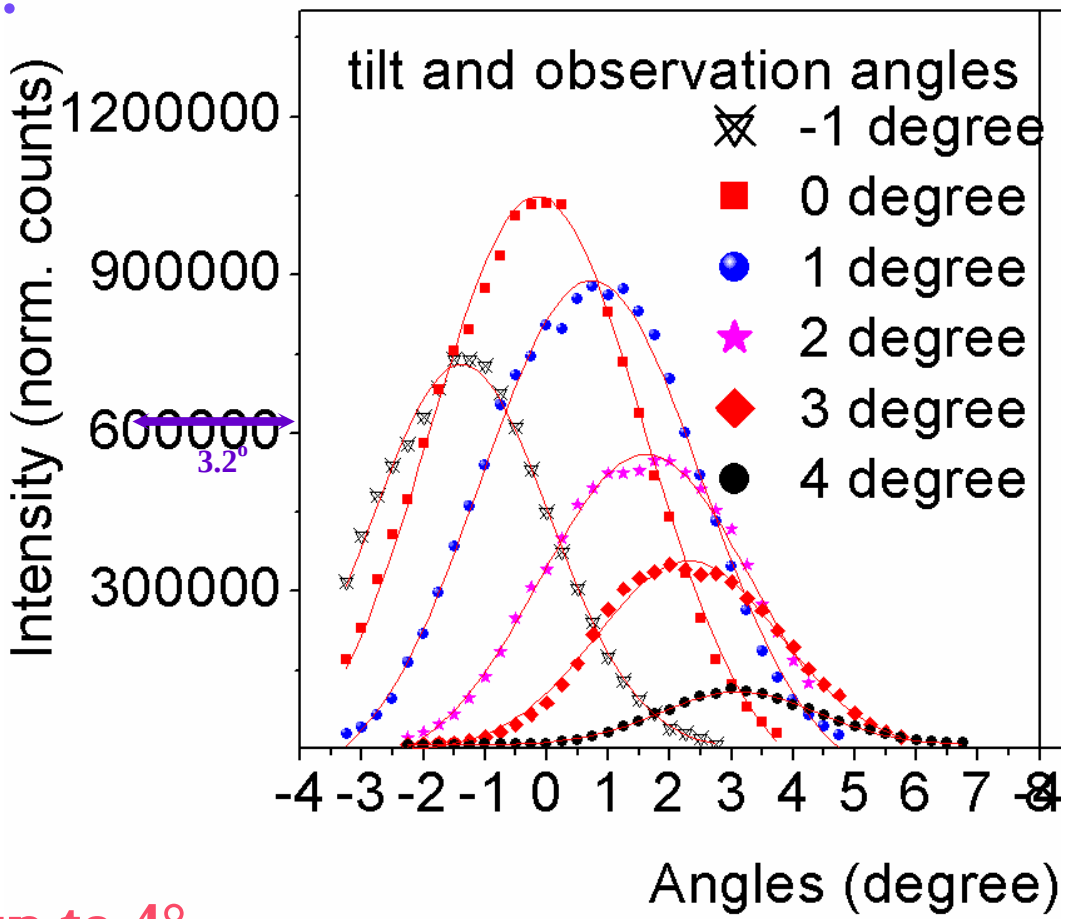
Angular distributions of 7 keV Ne^{7+} ions through Al_2O_3



- Guiding up to 4^0
- Transmission at 0^o < 1% relative to primary beam (geometrical transparency of 20 % accounted for)

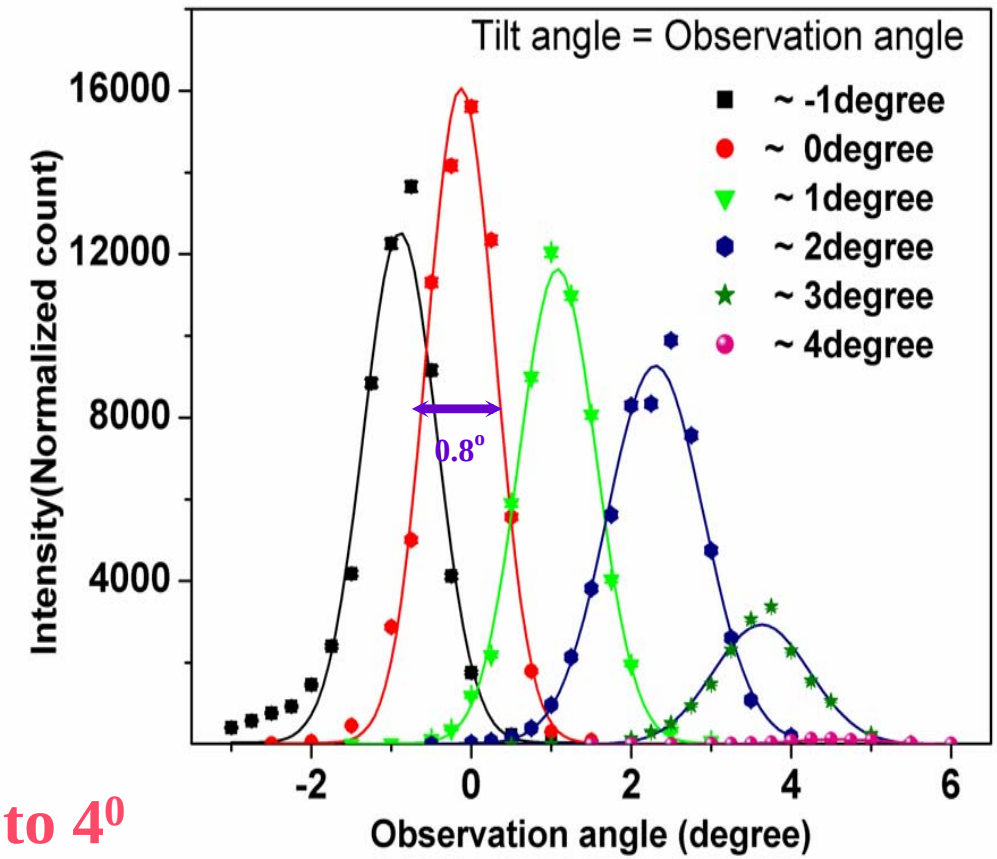
7 keV Ne^{7+} through PET nanocapillaries

Angular distribution:



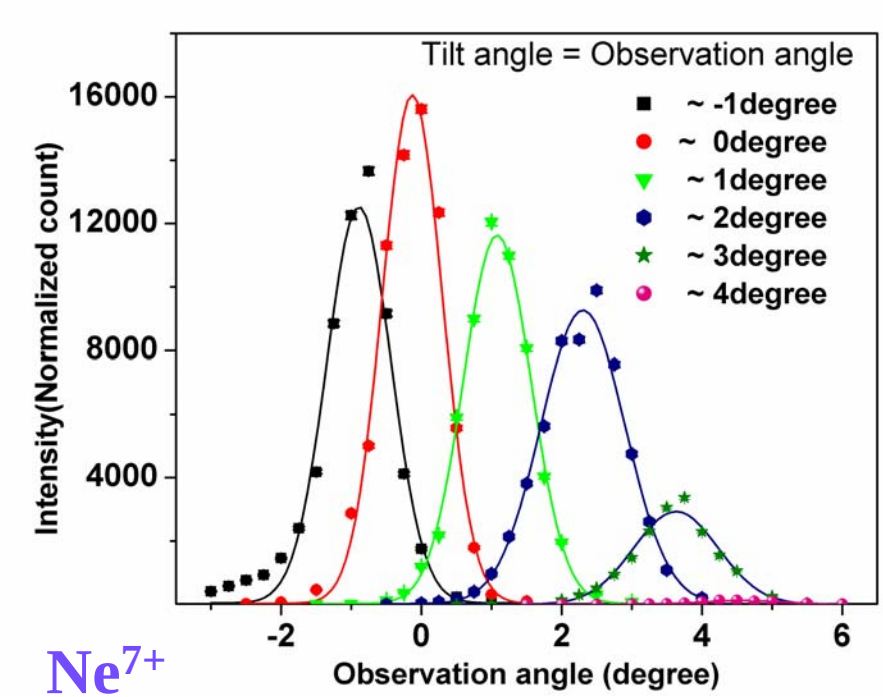
- Guiding up to 4°
- FWHM 3.2°

Angular distributions of 7 keV Ne^{7+} ions through SiO_2

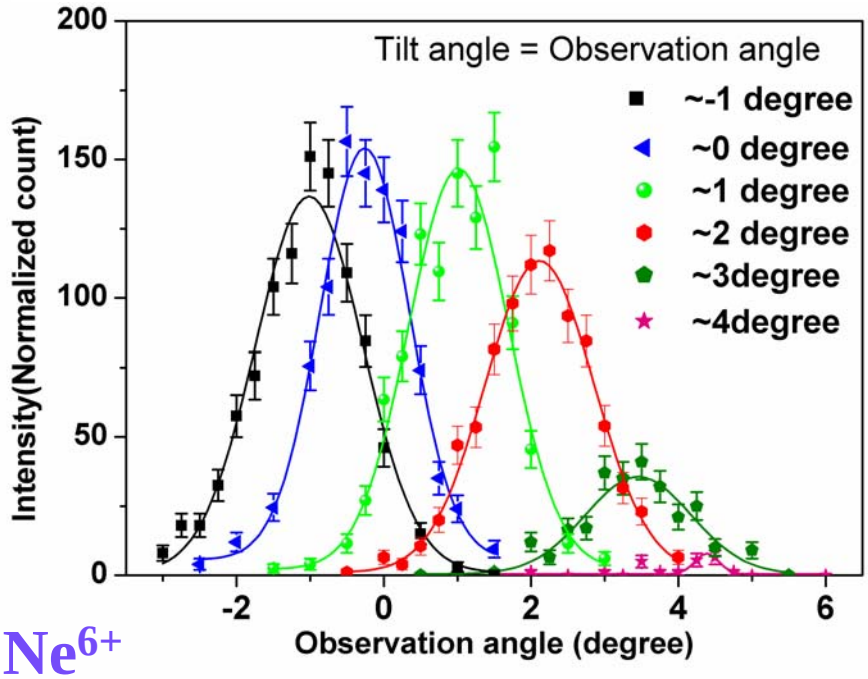


- Guiding up to 4^0
- Transmission at $0^o \approx 20\%$ relative to primary beam (geometrical transparency of 0.4 % accounted for)

Angular distributions of 7 keV Ne^{7+} ions through SiO_2



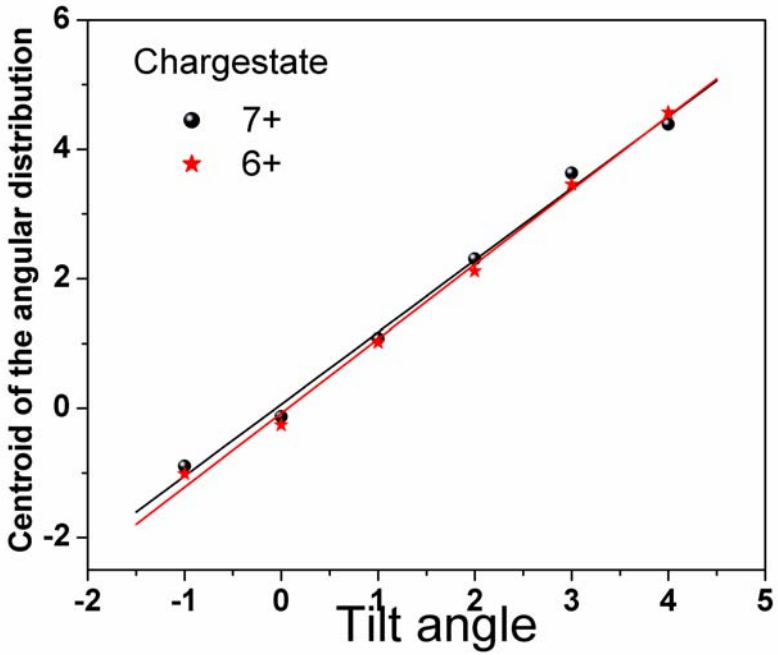
Ne^{7+}

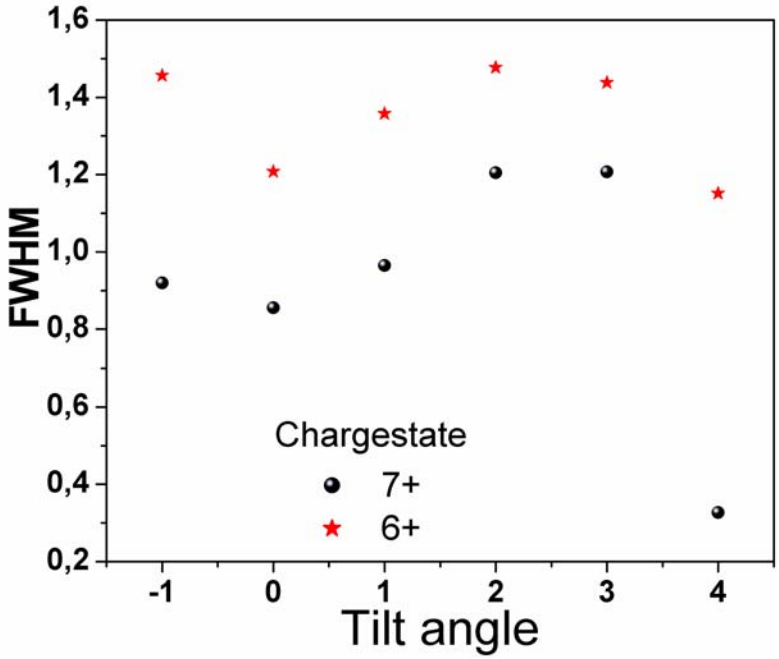


Ne^{6+}

- Peaks of the angular distribution shift with tilt angle
- Guiding up to 4^0 measured
- Transmission at $0^o \approx 20\%$ relative to primary beam (geometrical transparency of 0.4 % accounted for)

Variation in FWHM and peak position with tilt angle for SiO_2





- Linear dependence of peak position on tilt angle
- Smallest width at 0° tilt angle

FWHM of transmitted Ne^{7+} ions

	FWHM [deg]		
Tilt angle [deg]	PET	Al_2O_3	SiO_2
-1	3.3	1.3	0.9
0	3.2	1.2	0.8
1	3.3	1.5	0.9
2	3.1	1.2	1.1
3	2.7	1.1	0.9
4	2.1	1.6	1.1
geom. value	0.9	0.6	0.8
(aspect ratio+beam spread)			

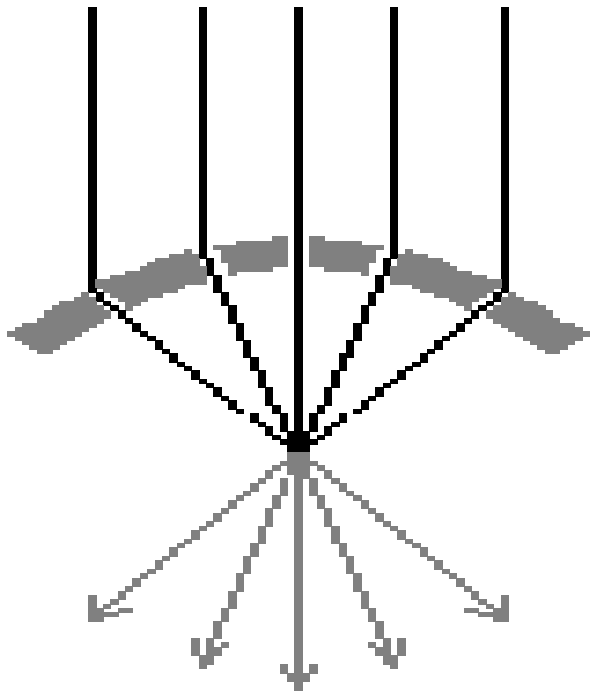
- FWHM larger at ±1-2º than at 0º
- Tilt angle span: 5º - Centre pos. span: 5.46º

Conclusions& Outlook

- Insulating capillaries charge up and form self-arranged ion guiding.
- Bends keV ion beams a few degrees.
- The angular distribution of the guided beam is narrow for ordered, parallel capillaries.
- Ions are deflected by the charge patch close to entrance of the capillary, patch at exit widens distribution
- HCI focusing-, bending- elements based on guiding?
- High ion charges? higher energies? non-linearities? singular shaped capillaries? ……

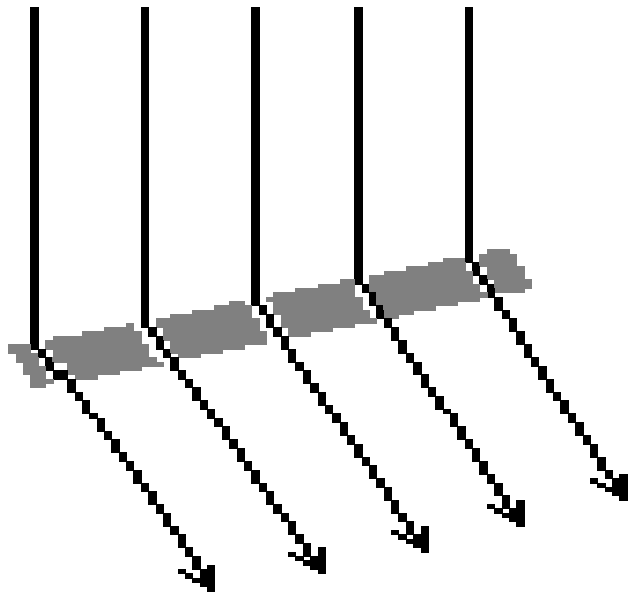
Possible uses of ion guiding phenomena in insulating nano-capillaries

Curved nano-capillary membrane



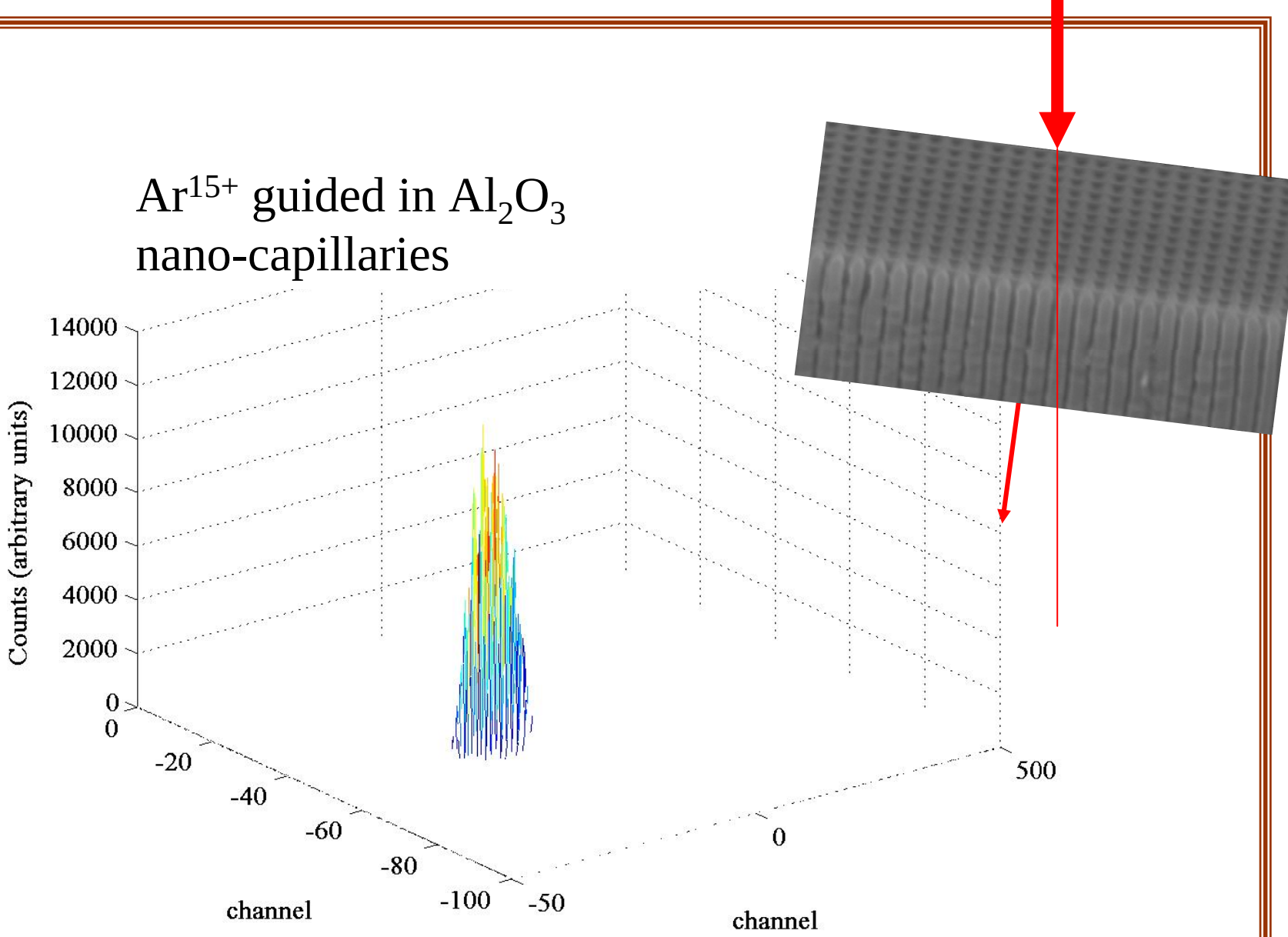
Focusing element

Tilted nano-capillary membrane

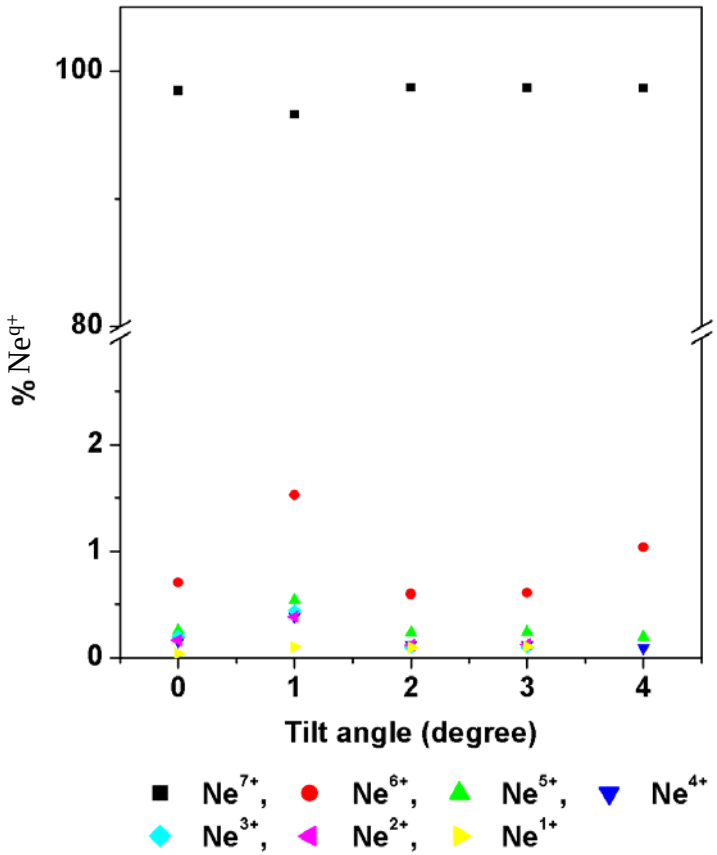


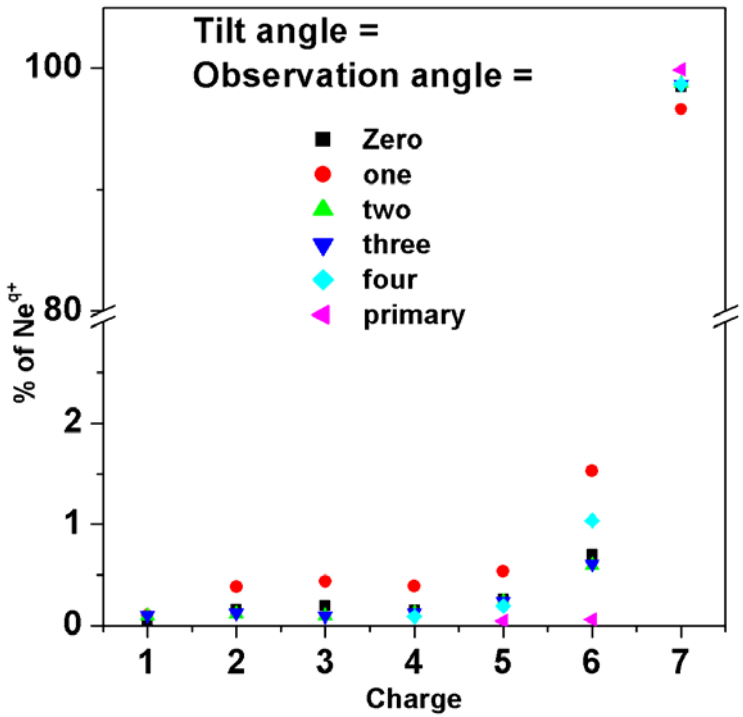
Bending element

Ar^{15+} guided in Al_2O_3 nano-capillaries



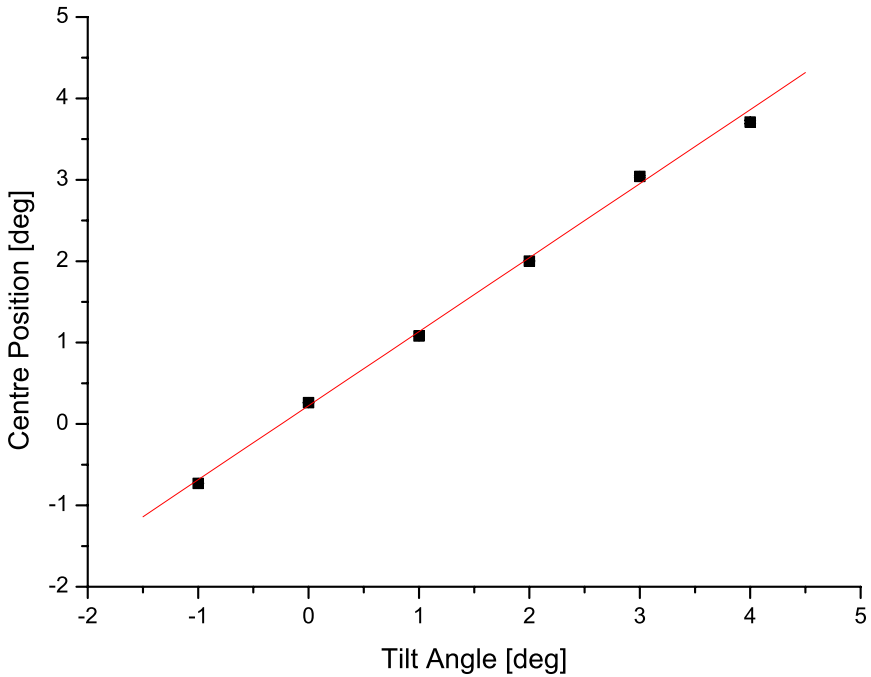
Variation in the charge state distribution with tilt angle for SiO_2

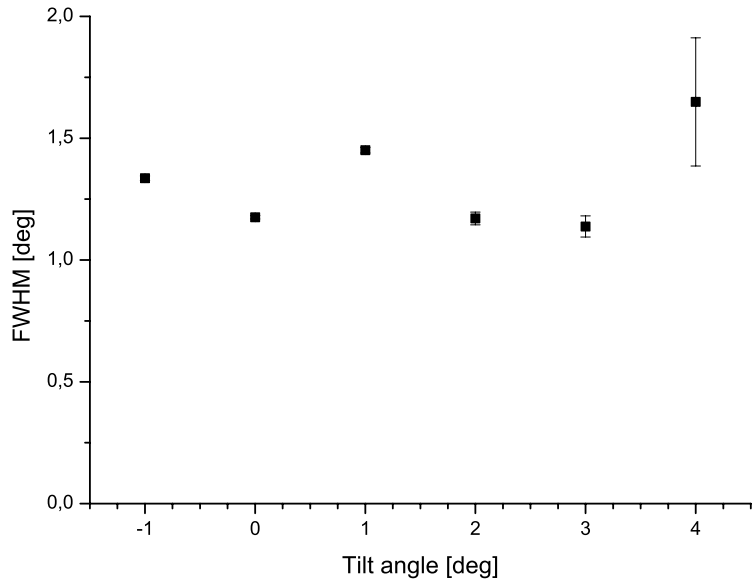




Largest fraction of ions that have undergone charge exchange with the walls for 0° tilt angle

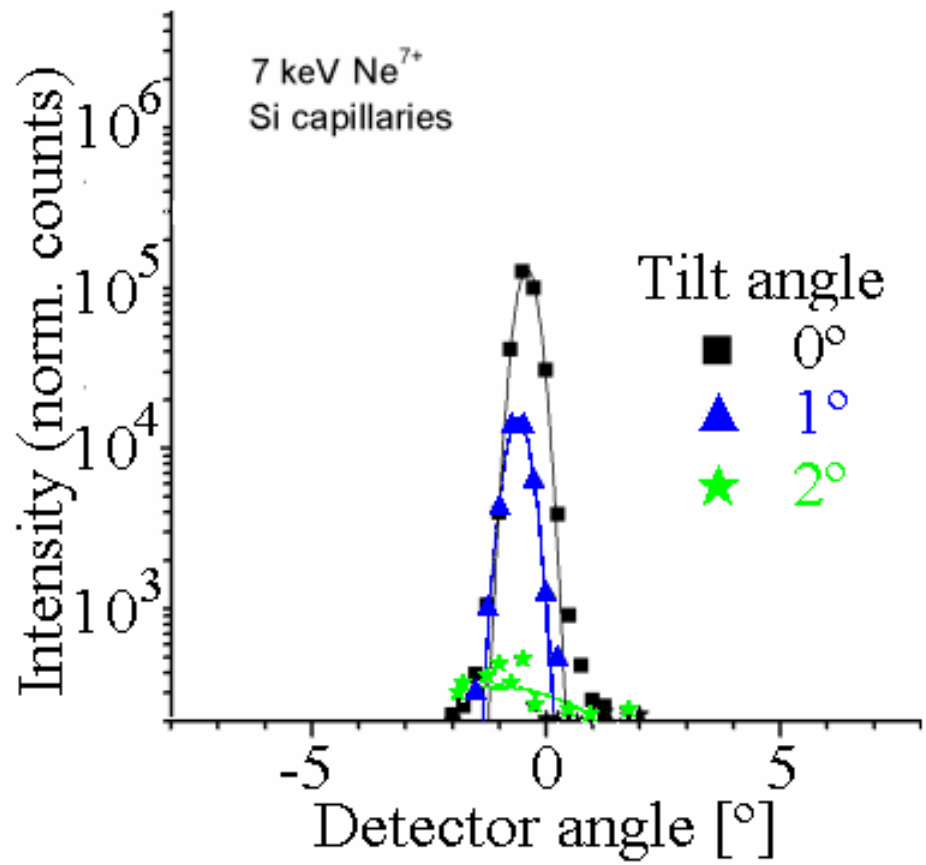
Variation in FWHM and peak position with tilt angle for Al_2O_3





HCI through Si nanocapillaries

Angular distribution



Silicon capillaries
Diameter ~300nm
Length ~10 μm

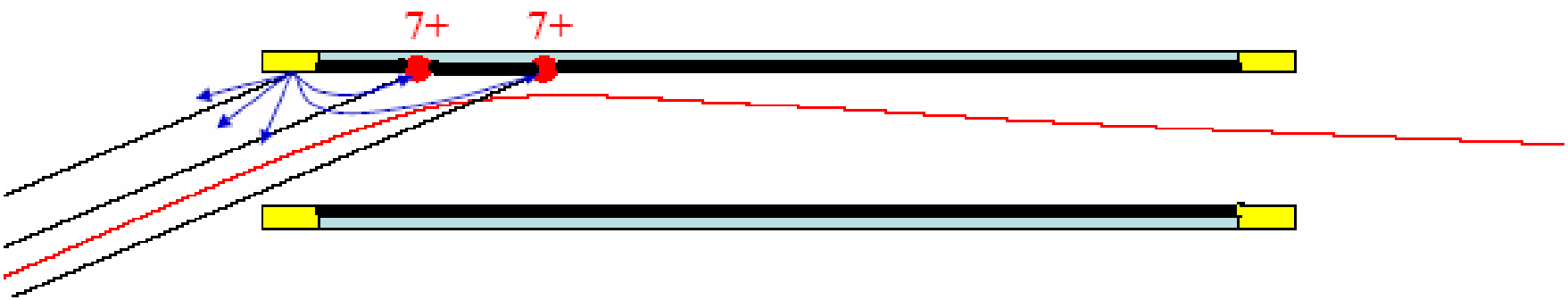
- **FWHM of the transmitted ions = 0.4^0**
- **Peaks of the angular distribution do not shift with capillary tilt angle**

Angular distributions of 7 keV Ne^{7+} ions through Al_2O_3

Tilt angle [deg]	Rel. Counts	FWHM [deg]
-1	0,54	1.34
0	1,00	1.18
1	0,47	1.45
2	0,16	1.17
3	0,11	1.14
4	0,09	1.60

- At 4º transmission only 9% compared to transmission at 0º
- FWHM larger at ±1º than at 0, 2, 3º
- Tilt angle span: 5º - Centre pos. span:4.44º

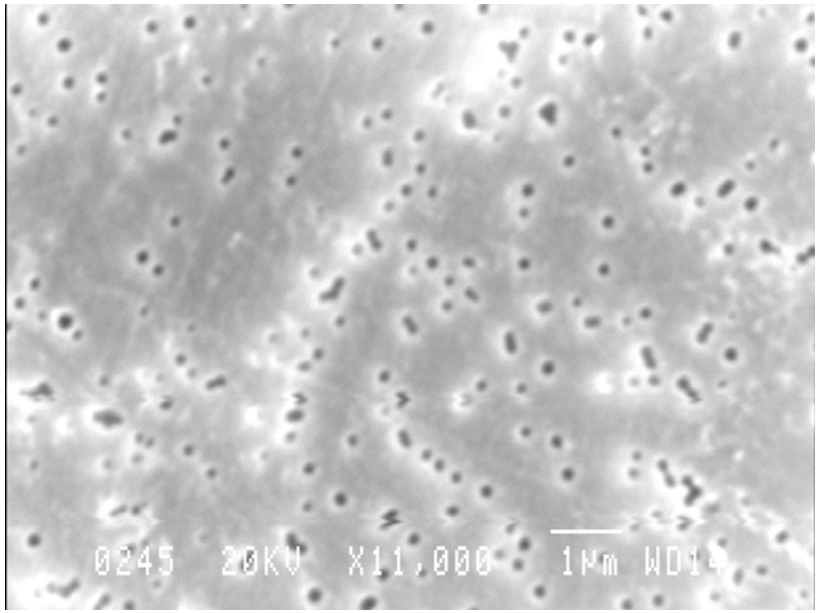
Self arranged ion guiding

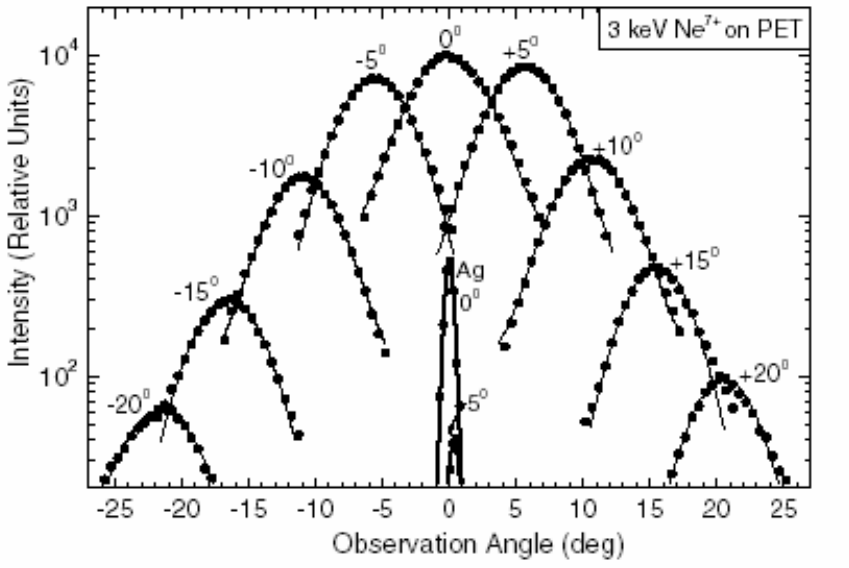


- Coulomb field of captured ions
- Charge transport within insulator (hopping conduction)
- Electron emission from metal covered entrance
- Dynamical equilibrium between charging of the surface and hopping of surface charges from the insulating part to the conducting part

HCI through PET nanocapillaries

(Stolterfoht et al. PRL, 88, 133201-1, 2002)





Angular distribution of 3 keV Ne^{7+} ions

- Guiding up to 20°
- FWHM ≈5°
- Peaks of the angular distribution shift with capillary tilt angle

Pre-EBIT facilities in Stockholm:

EBIS (CRYSIS⊠), ECR Ion Source, Ion Storage Ring CRYRING, SMILETRAP at MSL

University Physics Center:

New HCI Lab. :

arrived May 05 from Physics& Technology, Livermore