IOP Publishing Journal of Physics: Conference Series **58** (2007) 319–322
doi:10.1088/1742-6596/58/1/071 13th International Conference on the Physics of Highly Charged Ions

Charging and discharging of nano-capillaries during ion-guiding of multiply charged projectiles

M Fürsatz[1], W Meissl[1], S Pleschko[1], I C Gebeshuber[1], N Stolterfoht[2], HP Winter[1] and F Aumayr[1]

[1]Institut für Allgemeine Physik, Technische Universität Wien, Austria
[2]Hahn Meitner Institut Berlin, D-14109 Berlin, Germany

E-mail: aumayr@iap.tuwien.ac.at

Abstract. Slow multiply charged ions are efficiently guided through nano-capillaries with large aspect ratio in polyethylene terephthalate (PET), due to self-organized charging of the inner capillary walls which prevents close collisions with the surface. In order to gain more insight into this interesting phenomenon we have measured the 2-D scattering distribution of transmitted ions during the charge-up process.

1. Introduction

Efficient guiding of slow (typ. keV) highly charged ions (Ne^{7+}) through insulating nano-capillaries has been observed even if the capillaries were tilted by up to 20° with respect to the incoming ion beam direction [1]. Surprisingly, the majority of the projectile ions were found to survive the transmission through the insulating capillary in their initial charge state. Measured 1-dim. scattering distributions of the transmitted particles indicated propagation of the projectile ions along the capillary axis. As reason for this “guiding effect" a charging-up of the inner walls of the capillaries in a self-organized way due to impact of preceding projectile ions has been proposed [1-4].

Theoretical modelling of the experimental observations has so far proven to be a challenging task [1-4]. Difficulties arise especially due to the different characteristic times observed in the experiment for capillary-wall charging and discharging [3, 4].

2. Experiment

To gain more insight into this interesting phenomenon we have measured the 2-dim. scattering distribution of transmitted projectiles during the charging-up process. The capillary target for these experiments consisted of a 10 μm thick PET (polyethylene terephthalate) foil and has been obtained from HMI-Berlin. It was characterized with atomic force microscopy-AFM at TU Wien (mean capillary diameter: 200 nm ± 25%, capillaries per unit area: $4x10^6$ cm^{-2}). The PET foil has been coated on both sides (front and exit) by a thin (20-40 nm) conducting gold layer which was kept at ground potential during experiments. As projectiles we used 12 keV Ar^{8+} ions (300 eV/amu) extracted from our 14.5 GHz ECR ion source [5]. The ion beam was collimated to a beam divergence of about 0.5° FWHM before hitting the capillary target, which was mounted on a standard x,y,z,ϕ target manipulator in an UHV chamber. The transmitted ions were registered by a 2-D position sensitive channel-plate detector about 15 cm behind the capillary target.

3. Results and discussion

In figure 1 we show the intensity of the transmitted projectiles (left) and the observed angle of the peak intensity (right) of "guided" projectiles after transmission through the PET capillary target as a function of capillary tilt angle. These measurements have been performed in the following way. After setting the tilt angle of the PET foil (starting at 0°), a very small current of 1 pA Ar^{8+} ions (kinetic energy of 12 keV) was used to measure the peak position of the transmitted ions through the "uncharged" foil. During this procedure a total charge of less than 1 nC was deposited. Then the capillaries were charged with a mean current of 100 pA for typically 2000s. After a charge of 200 nC was deposited on the target (and the intensity of the transmitted ions had saturated), the peak position and intensity of the transmitted ions (full data points in figure 1) were recorded. Then the capillary tilt angle was increased by 1° and measurements were repeated, starting with a small probing current (open symbols in figure 1) followed by full charging-up to 200 nC, and so on, in steps of 1°. We observe "guiding" up to a capillary tilt angle of about 4°. Taking into account our experimental conditions (capillary diameter and density, ion impact energy) our results for the case of fully charged capillaries (full data points connected by a solid line) are in accordance with previous findings for PET [1, 2, 6 - 9], and also for SiO_2 capillaries [10]. The dash-dotted curve in the left part of figure 1 shows the results of modeling calculations [11] using the theoretical framework described in [3, 4]. Interestingly our data for the "uncharged" capillaries (open symbols in figure1) indicate a certain time/charge dependence of the guiding effect, which we wanted to investigate in more detail.

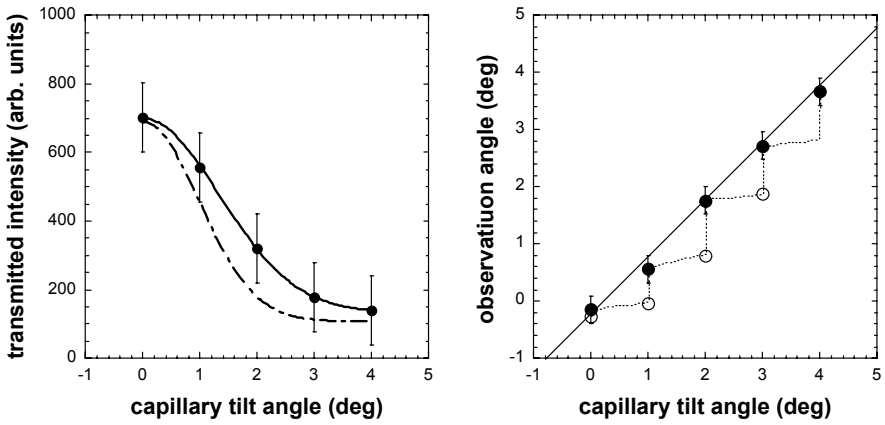

Figure 1. Intensity of the transmitted projectiles (left) and observed peak angle of "guided" projectiles (right) after transmission through the PET capillary target as a function of capillary tilt angle for 12 keV Ar^{8+} projectiles (c.f. text).

To this purpose we fixed the capillary tilt angle at 4° with respect to the incident beam direction and monitored the 2-dim. scattering distribution of transmitted projectiles during the charging process as a function of time and total charge starting with a fully discharged capillary (2 days discharge time). As shown in figures 2 and 3, for a capillary tilt angle of 4° the peak position of the transmitted ions shortly after beginning of the irradiation starts at a deflection angle of 2° only and moves with increasing total charge until it saturates at a deflection angle nearly equal to the capillary tilt angle. During the charging the 2-dim scattering distribution develops a slightly oval shape (figure 2) and also deviates from the horizontal direction. This deviation is probably due to a small miss-alignment of the PET foil (0.8° tilt out of plane direction) and can be corrected by proper alignment of the capillary target with respect to the incident beam as shown in [9].

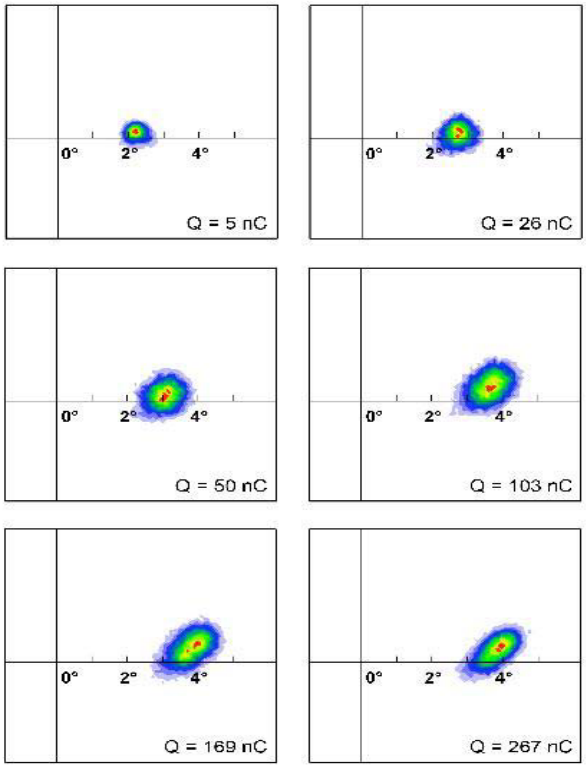

Figure 2. Evolution of the measured 2-dim. scattering distribution for 12 keV Ar^{8+} ions transmitted through PET capillaries (tilt angle 4° with respect to the incident ion beam direction) during the charging-up phase. 0° indicates the position of the incident ion beam (i.e. when removing the nano-capillary target). For our experimental situation the average number of ions in a single capillary can be estimate to 50 Ar^{8+} ions per each nC of incident charge. Partial guiding therefore starts already after a few hundred projectiles have entered a single capillary and less than 10^4 Ar^{8+} ions are needed to obtain full guiding.

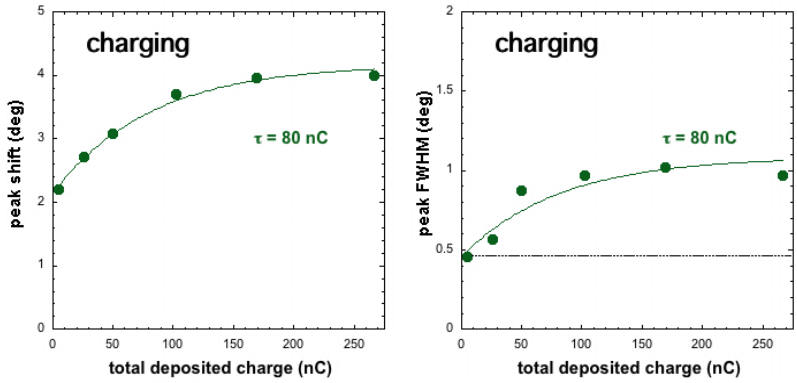

Figure 3. Peak position and width of the guided projectiles as a function of total deposited charge during the charging-up phase. Data for 12 keV Ar^{8+} projectiles and 4° tilt angle.

The width of the scattering distribution increases during the charging process from a value close to the primary beam (FWHM of 0.5° in our case) to a FWHM of about 1° (figure 3). This is in good agreement with theoretical simulations [3, 4, 11] but differs from previous measurements [1, 2], where a PET target with a higher capillary density (>10^8 holes/cm^2) was used and an angular width of > 5° for 3 keV Ne^{7+} has been reported. There are however indications that the angular divergence of the

guided projectiles strongly decreases with increasing beam velocity (12 keV Ar^{8+} ions are faster than 3 keV Ne^{7+}) [7], increasing capillary diameter [6] and probably also with decreasing capillary density.

.

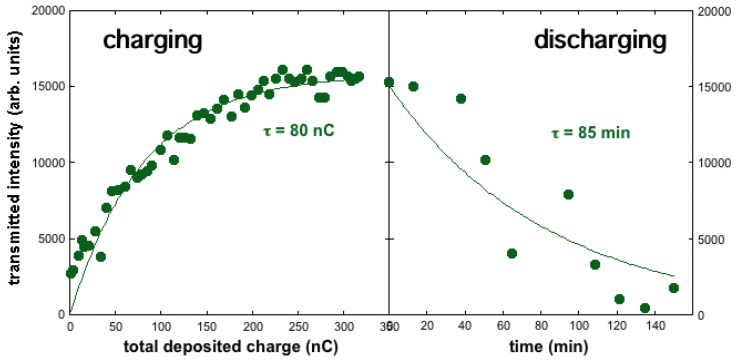

Figure 4. Evolution of the transmitted intensity as a function of total deposited charge during the charging-up phase (left) and as a function of time during the discharging phase (right). Data for 12 keV Ar^{8+} projectiles and 4° tilt angle.

Peak position, peak width and transmitted intensity as a function of deposited charge Q can be nicely fitted by a functional form of (1-exp(-Q/τ)) with a resulting charging constant of typically τ = 80 nC (see figures 3 and 4). We have also monitored the discharging of the capillaries. Although the scattering in the data is unexpectedly large, a typical discharge time constant of 85 minutes can be evaluated (figure 4). Both charging and discharging constants are in good agreement with results for PET foils by other groups [6-9] and consistent with the time constant for discharging via bulk transport of charges (long time behavior) used in the simulation calculations [3, 4].

In summary, we have observed the time dependence of guiding through insulating nano-capillaries during the charge-up phase using a 2-dim. position sensitive detector. Already a few hundred ions hitting the capillary wall are able to significantly deflect ions entering the capillary thereafter. With increasing total charge the deflection angle slowly moves until it reaches an angle nearly equal to the capillary tilt angle. There the charge deposition and diffusion have come into in equilibrium [3, 4]. We demonstrate that less than 10^4 Ar^{8+} ions per individual capillary are necessary to achieve saturated transmission.

Acknowledgements
This work has been supported by Austrian Science Foundation FWF and was carried out within Association EURATOM-ÖAW.

References

[1] Stolterfoht N *et al* 2002 *Phys. Rev.Lett.* **88** 133201
[2] Stolterfoht N *et al* 2004 *Vacuum* **73** 31
[3] Schiessl K, Palfinger W, Lemell C, Burgdörfer J 2005 *Nucl. Instrum. Meth.* B **232** 228
[4] Schiessl K *et al* 2005 *Phys. Rev.* A **72** 062902
[5] Galutschek E *et al* 2006 these proceedings
[6] Stolterfoht N *et al* 2005 *Surface & Coatings Technology* **196** 389
[7] Hellhammer R *et al* 2005 *Nucl. Instrum. Meth.* B **232** 235-243
[8] Stolterfoht N *et al* 2005 *Nucl. Instrum. Meth.* B **235** 460-467
[9] Kanai Y *et al* 2005 *Proc. XXIV ICPEAC*, Rosario, Argentina p. Fr131
[10] Sahana M B *et al* 2006 *Phys. Rev.* A **73** 040901(R)
[11] Schiessl K and Lemell C private communication