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Significant differences in ion and electron guiding through highly insulating capillaries

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ABSTRACT

Outstanding phenomena of capillary guiding are discussed in accordance with a recent review in the field. Experiments concerning highly charged ions of a few keV energy guided through insulating nanocapillaries are shown. Studies of the temporal evolution of ion transmission are presented. Attention is focused on oscillatory structures in the ion emission and the independence of the ion guiding on the beam intensity. A few experiments of electron guiding are presented showing a significantly different temporal evolution of the transmitted intensity. The onset of the electron transmission is very sudden accompanied by a considerable energy loss within the capillary. To achieve more insight into the different guiding mechanisms, theoretical aspects of the capillary guiding are analyzed. A scenario is offered to explain the abrupt rise of transmitted electrons. Altogether, these studies show that ion and electron guiding are accomplished through different manifestations of the charge build up that underlies both.

1. Introduction

After the observation of ion guiding through insulating nanocapillaries [1] the topic has received considerable attention during the past decade. The essential property of the capillary guiding is a self-organizing process, which forms a suitable charge patch in the capillary entrance region together with a repulsive electric field that is capable to deflect the following ions at large distances. Thus, the ions are guided along the capillary axis maintaining their incident charge state. Finally, at equilibrium, the charge deposition and the discharge via surface and bulk conduction is balanced.

The first investigations with capillaries in insulating polyethylene terephthalate (PET) [1,2] were followed by experimental studies at several laboratories using different insulating materials [3–8]. The guiding of ions has also been explored with single microcapillaries of tapered geometry [9–11] and of straight geometry [12–14]. Monte-Carlo simulations [15,16] were performed in good agreement with the guiding experiments providing detailed information about the guiding mechanisms for slow incident ions.

Apart from ion impact, experiments with electrons as projectiles were carried out using multiple nanocapillaries in Al_2O_3 [17,18] and PET [19–21]. Furthermore, electron experiments were performed with single capillaries in glass with straight and tapered geometry [22–25]. More information about the experiments in various laboratories may be obtained from recent review articles summarizing the field [26,27].

Electron guiding is essentially different from the guiding of slow positive ions. Instead of being deflected at relatively large distances, electrons suffer inelastic collisions within the surface or bulk of the capillary wall. Evidence for the passage of the electrons through solid material is provided by energy losses observed for the transmitted electrons [19]. In a theoretical study [28] it was concluded that the transmission of electrons occurs primarily via small-angle scattering at atoms located within the surface layer. This mechanism involves the immediate start of the electron transmission after beam insertion.

Subsequent measurements [20,21] indicated that electron transmission occurred with a time delay, which provided evidence that a negative charge patch plays a definite role in electron guiding. The start of the electron transmission occurred after a considerable charge insertion into the capillary and it rose much faster than observed for ions. Up to now a detailed interpretation of these surprising differences between electrons and ions is missing, suggesting that certain questions regarding electron transmission processes are unsolved.

In this work, the guiding of charged particles through capillaries are presented in view of previous experiments and simulations [27]. The first part is devoted to the transmission of highly charged ions through nanocapillaries. Experimental results concerning the independence of the ion guiding on the beam intensity are described. Simulations are presented showing details of the temporal evolution of charge patches

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within the capillaries. Detailed instrumental information is not given as it can be obtained from the original work.

The ion work is complemented by results obtained from experimental work with electrons. A detailed discussion about patch assisted electron guiding through different types of capillaries is given elsewhere at this conference [29]. Here, emphasis is given to a comparison of the differences observed for ions and electrons to analyze the corresponding mechanisms for the capillary guiding. A scenario is provided in an attempt to explain the abrupt onset of the electron transmission accompanied by a significant energy loss within the capillary. The latter interpretation is preliminary as it is not based on realistic simulations.

2. Guiding of slow ions

The following discussion is devoted to results of capillary guiding obtained with 3-keV Ne^{7+} ions transmitted through nanocapillaries with a diameter of 200 nm and a length of 12 μm. The experiments were performed at the ECR (electron cyclotron resonance) source of KVI at the University of Groningen [6]. The capillaries were prepared in polyethylene terephthalate (PET) at the Hahn-Meitner-Institut Berlin (today denoted Helmholtz-Zentrum) by etching tracks produced by high-energy ions. The PET material is highly insulating so that charges deposited at the capillary surface remain for relatively long times. The transmitted ions were measured using an electrostatic energy analyzer.

The ions are emitted with an angular distribution represented by the doubly differential yield $dY(\theta,\phi)/d\Omega$ measured at $\phi = 0$ as a function of the observation angle θ. The measured distribution of ions emitted from the capillary exit is denoted as the transmission profile. First, let us focus on the time evolution of the transmission profiles [6], which are shown in the left-hand column of Fig. 1. The tilt angle of the capillaries is $\psi = 5°$. Each graph displays the total charge Q collected within each capillary until the instant when the profile is measured. For a constant incident beam current the deposited charge is a measure of time.

The transmission profiles exhibit peak structures, which strongly change with time or deposited charge. The experimental data were fitted by a superposition of 3 Gaussian functions, whose positions are seen to be rather stable whereas their intensities change significantly with increasing charge deposition. The centroid values of the first and third peaks were found to be at 3.7°±0.2° and 6.4° ± 0.3°, respectively. Thus, these peaks are displaced with respect to the tilt angle of 5° by ~ 1.4°, which is larger than the aspect angle of 1°.

In accordance with the changing peak intensities, the mean value of the emission angle varies as shown in the right-hand column of Fig. 1. The labels (a) to (e) in the left-hand column correspond to the same labels in the right-hand column. At the extremes (reversal points) either the first or third peak dominates in intensity. As the charge insertion progresses, the oscillations are damped. Finally, the central peak becomes dominant and the mean angles coincides with the tilt angle of 5°.

Next, we consider the evolution of the total ion yield $Y(Q)$ with the charge inserted into a capillary. It is obtained by integration of $dY(\theta,\phi)/d\Omega$ over the angles θ and ϕ. The integration was performed analytically assuming that the dependence on ϕ to be determined by Gaussian functions. The total yield $Y(Q)$ is converted to the transmitted ion fraction $f(Q) = Y(Q)/Y_{in}$, i.e., the ratio of transmitted to incident ions in a given capillary.

In Fig. 2 the results are shown for the total currents of I_p= 0.1, 0.2, and 1 nA incident onto the capillary front surface [5]. The experimental data are fitted by the well-known expression

$$f(t) = f_\infty\,[1-\exp(-(Q-Q_s)^2/Q_c^2)] \quad (1)$$

where $f_\infty = f(Q \to \infty)$[1]. The charge Q_c is characteristic for the capillary charging and Q_s denotes the delay for the ion transmission. The fit parameters Q_c and Q_s are given in the graphs. It is seen that the quantity Q_c increases only by ~25 % when the current increases by one order of magnitude from 0.1 to 1 nA. Moreover, the threshold value Q_s and the equilibrium ion fraction f_∞ do not change within the experimental uncertainties.

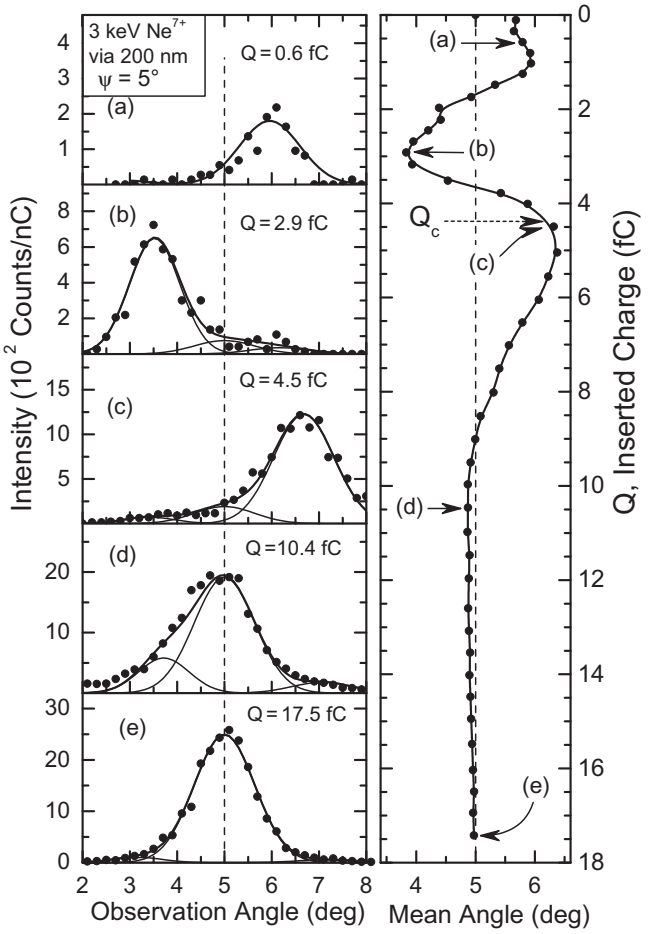

Fig. 1. Transmission profiles and mean angle for 3 keV Ne^{7+} ions transmitted through capillaries of 200 nm diameter [6]. In the left column the profiles are shown for increasing charge Q inserted into each capillary. The profiles are fitted by a sum of Gaussian functions given as solid lines. The right column shows the related mean emission angle. The arrow labeled Q_c indicates the charge for which ~ 63 % of the equilibrium intensity of the transmitted ions is reached.

The fact that the equilibrium fraction f_∞ is rather constant implies that the charge in the entrance patch, responsible for the field deflecting the ions, does not change much with varying ion beam. The equilibrium charge deposited in the entrance patch can be estimated approximately by

$$Q_\infty \approx (Q_s + Q_c) \quad (2)$$

Indeed, the charge Q_∞ changes only weakly. The weak current dependence has important consequences for the description of guiding phenomena. From the constancy of the accumulated charges it is evident that a possible overcharging by the incident current can only be avoided by a rapid depletion of the deposited charges. Thus, with rising incident current the depletion current must increase stronger than linearly. The non-linear dependence of the depletion current is taken into account by Frenkel's approach [30], which is an important property of the simulations presented further below.

3. Guiding of electrons

The electron measurements were performed at Western Michigan University using an electron gun which provided a beam with an energy of between 500 and 1000 eV [20,21]. Nanocapillaries in a PET foil,