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Transmission of highly charged ions through mica nanocapillaries of rectangular cross-section

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ABSTRACT

We investigated the transmission of 7-keV Ne^{7+} ions through nanocapillaries of rectangular cross-section in phlogopite mica both by experiments and computer simulations. In the experiment, the role of the deposited charge in the transmitted ion intensity and angular distribution was studied. It is found that the rhombic angular profile is degraded during the process of rearrangement of the deposited charge on the capillary walls. Trajectory simulations are performed to understand the shaping of ion beam by the image force at tilt angles within the geometrical opening angle, as well as the degrading of the shaping due to the deposited charge when the tilt angle is larger than the geometrical opening angle. This reveals the interplay of the deposited charge and the image charge on the shaping of the ion beams when transmitting them through nanocapillaries of various geometrical cross sections.

1. Introduction

The transmission of ions through insulating nanocapillaries at tilt angles larger than the geometrical opening angle given by the aspect ratio of the capillaries is termed as "guiding". This so-called guiding effect has inspired many studies, in particular with highly charged ions (HCI) during the last decade [1–34]. A characteristic result is that the majority of the transmitted ions maintain their initial charge state and kinetic energy. Their angular distribution is centred around the direction of capillary axis with a width larger than the aspect ratio.

The guiding effect is due to charges deposited on the capillary walls by primary ion impacts, which prevents the followed ions from close wall collisions. Observations support the guiding mechanism by charge patch formation in an increase of the transmission rate of the ions up to saturation due to a balance between the deposited charge and the relaxation of the deposited charge through various discharge channels. Additionally, one finds an oscillatory angular distribution of transmitted projectiles that shows the sequential building-up of the charge patches [25–28]. Theoretical work comprising Monte Carlo simulations has explained the main characteristic features and given some insight into the guiding phenomenon [21–24].

The guiding effect was studied in various structures of capillaries from macro-scale down to nano-scale in insulating materials. The following insulating materials have been used: nanocapillaries in *polyethylene terephthalate* (PET) [1], different types of mica, SiO_2, Al_2O_3, and polycarbonate (PC) [4–9]. Also, other macro to micro structures in glass were widely investigated, i.e., single tapered capillaries of borosilicate glass were used to make microbeams [15–18].

Modern techniques in the field of nanotechnology facilitated the formation of nanocapillaries of various cross-sections in different materials. Recently, we fabricated nanocapillaries of rectangular cross-section and those of rhombic cross-section in mica [29,33]. A new phenomenon was found that ion beams can be tailored into rectangular or rhombic shape by using capillaries of rhombic or rectangular cross-section, respectively [29]. Various aspects of this phenomenon have been studied in our previous work [29,33,34]. The ion beam shaping was shown to result from image charges induced inside the capillary walls [29,33]. The influence of the image charge has not been clearly identified in experiments and in Monte Carlo simulations of ion-guiding through insulating nanocapillaries of circular cross-section [21,22]. The image charge force is an instantaneous process, contrary to guiding by the deposited charges which is time dependent due to the gradual charging-up of the capillary inner surfaces.

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In this study we focus mainly on the role of the deposited charge in the beam shaping effect. This was investigated for rhombic capillaries in two cases: (i) by varying the tilt angle of the capillaries with respect to the beam direction; (ii) by the time evolution of the transmitted angular distribution for the discharged capillaries at the tilt angle within the geometrical opening angle [33]. In the case (i), the tailored beam profile is distorted by deposited charge when the capillaries are tilted at angles larger than the geometrical opening angle. In the case (ii), the deposited charge shifts the angular distribution while the tailored beam profile remains intact during charging-up. Here we show for the rectangular capillaries that the already deposited charge from the previous tilt angles, larger than the geometrical opening angle, distorts the tailored angular distribution at the tilt angle within the geometrical opening angle. This is different from the previous work where the transmission angular profile is rhombic in the initial stage of charging-up of the initially discharged capillaries [29]. The rearrangement of the deposited charge reduces the distortion but does not recover fully the tailored angular profile. In the second half of the paper we report about detailed trajectory simulations. These are performed to see how the image force evolves the tailored shape in the traversing ions on their way out of the capillaries in the case where the tilt angle is within the geometrical opening angle. Clearly, the tailoring effect with the rectangular capillaries is weaker than that of the rhombic capillaries of smaller cross section due to the then stronger image force. Degrading the transmitted angular distributions by the deposited charge is studied by simulations for the case of the tilt angles larger than the geometrical opening angle, by taking into account the image force as well as the Coulomb repulsive force from the deposited charge.

2. Experimental setup

The nanocapillaries of rectangular cross section were produced by chemical etching of latent tracks formed by bombarding 10-μm thick phlogopite sheets with 1.4-GeV Xe ions provided at the linear accelerator UNILAC of the GSI Helmholtz Centre [29]. The fluence was limited to 5×10^7 ions/cm^2 to ensure non-overlapping of the ion tracks. The specific etching rate of a given crystal orientation results in the channels of rectangular cross-section, in contrast to earlier findings of triangular cross-sections [31]. Etching in a 20% hydrofluoric acid solution for 3 min produces capillary with a rectangular cross-section of 215 nm in width and 450 nm in length. The capillaries have the geometrical opening angle of $\beta_{\text{short}} = 1.23°$ along the short side and 2.58° along the long side of the capillary. For the transmission experiment both, the entrance and the exit surfaces of membrane were sputter-coated by a 10-nm thick Au layer to avoid macroscopic charging-up by the incident ions. Taking into account the number and the cross-section of the channels the geometrical transparency is 4.8%.

The ion transmission experiments were carried out using a beam of 7-keV Ne^{7+} ions from the 14.5 GHz ECR ion source of MSL in Stockholm. The ion beam was collimated to a size of 3×3 mm^2 and divergence of <0.2° with an intensity ranging from 10 to 100 pA at the target. The capillary membrane was mounted on a goniometer with five degrees of freedom, allowing independent adjustment of the membrane in three spatial directions and around two rotational axes with respect to the beam direction. The ions transmitted through the capillaries in the mica membrane were detected using a two dimensional (2D) micro-channel plate (MCP) with a resistive anode, placed at a distance of 59 cm from the target. The data acquisition system works in the event mode [28]. The experimental chamber was pumped down to 10^{-9} mbar.

The capillary membrane was oriented in such a way that the long side of the rectangular capillaries was aligned along the vertical axis (along a plane perpendicular to the incident beam direction). The geometrical angles through the paper were defined as described in our previous work [28,29,33,34]. The azimuthal angle between the capillary axes and the incident beam direction is referred to as the tilt angle α. The observation angles ϕ and θ are given with respect to the direction of the incident beam. The observation angle ϕ is in the same plane as the tilt angle α and θ is an elevation angle in a plane perpendicular to this. The capillaries are aligned to the incident beam by scanning tilt angles and elevation angles for maximum transmission.

The beam size (FWHM) at the detector was measured to be 5 mm in the Φ-plane and 3 mm in the θ-plane with reduced beam current by defocusing the beam far from the collimating slits to avoid saturation at higher count rates (see Fig. 1), which corresponds to a beam divergence of less than 0.2°.

3. Experimental results

We show here the effect of previously formed charge patches on the transmission profiles. After charging up at large tilt angle we measured the transmission angular profile at smaller tilt angle and rearrangement of the deposited charge to newly placed charge patches that optimize transmission. This is different from charging-up the capillaries from the initially uncharged state. The capillaries were charged at a tilt angle, $\alpha = -3.0°$, and then oriented to a tilt angle, $\alpha = -0.5°$ to see the effect of already deposited charge. The two-dimensional transmission profiles as a function of incident charge per capillary (e/capillary) are shown in Fig. 2.

As can be seen, at the start of transmission, the two-dimensional transmission profile has a non-rhombic shape, while a rhombic angular profile was observed at the same tilt angle, $\alpha = -0.5°$, for the discharged capillaries in the initial stage of charging-up [29]. Instead the transmission profile has two components; a small component is centred around $-1.1°$ and a large component around $-2.0°$. With increasing incident charge, both components merge and turn the shape into the rhombic-like pattern but it is not fully recovered, and the transmission profile moves towards to $-1.0°$ as the steady state of transmission is reached.The splitting of angular distributions of transmitted ions into two components is getting clearer by looking at the projections of transmitted ions in the observation plane, φ-plane, especially in the beginning of the transmission (see Fig. 3). Clearly a

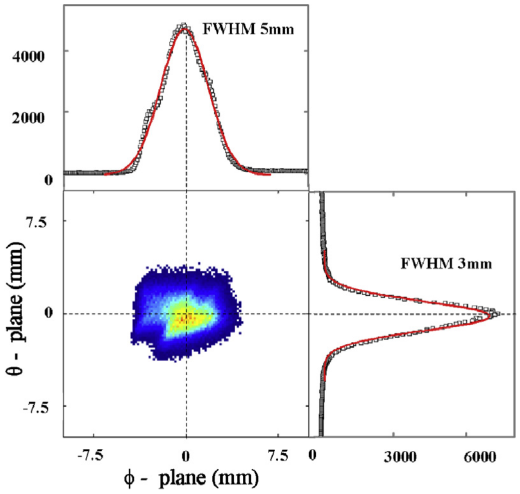

Fig. 1. Image of incident 7-keV Ne^{7+} ion beam with corresponding projections on ϕ-plane (top) and θ-plane (right). Red solid lines in the projections are Gaussian fit curves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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