Nuclear Instruments and Methods in Physics Research B 267 (2009) 669–673

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Time evolution of ion guiding through nanocapillaries in a PET polymer

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ARTICLE INFO

Article history:
Received 2 October 2008
Received in revised form 15 October 2008
Available online 31 October 2008

PACS:
34.50.Fa
32.80.Fb

Keywords:
Nanocapillaries
PET polymer
Highly charged ions
Capillary guiding
Time evolution

ABSTRACT

We measured the time evolution of the guided transmission of 3 keV Ne^{7+} ions through nanocapillaries in insulating PET polymers. Capillaries with a diameter of 200 nm and a density of 4×10^6 cm^{-2} were used. The angular distribution of the transmitted ions was measured as a function of the charge deposited on the sample surface, which is a measure of time. The evolution of the angular transmission profiles was acquired for different tilt angles ranging from 0° to 5°. The transmission profiles appear as a superposition of essentially 3 localized peaks which exhibit significant changes in intensity as time varies. This observation provides evidence for the formation of temporary charge patches produced in the interior of the capillary besides the primary charge patch created in the entrance region.

1. Introduction

In recent years, the guided transmission of highly charged ions through nanocapillaries in insulating material has received considerable attention. The guiding phenomenon implies that a highly charged ion preserves its incident charge state during the transmission through the capillaries. Evidently, the ions do not suffer close collisions with the capillary wall even when they are tilted with respect to the incident beam direction. This behavior is in contrast with results of pioneering work at RIKEN at Wako-shi (Japan) using capillaries in metals [1,2]. Investigations with insulating materials have been started in the Ionenstrahllabor (ISL) Berlin (Germany) [3–8] using capillaries in polyethylene terephthalate (PET) polymers. Due to the increasing interest in this subject, several laboratories performed studies of capillary guiding using PET [9–11], SiO_2 [12] and Al_2O_3 [13–15]. Moreover, electrons were used as projectiles guided through capillaries in Al_2O_3 [16] and PET [17]. Various contributions from the different laboratories created a lively field with animated discussions.

To understand the guiding phenomena, it was proposed that the incident ions deposit positive charge at the inner wall of the capillaries in a self-organizing process [3] as depicted in Fig. 1. For a tilted foil the deposited charge in the entrance region increases until the electrostatic field is sufficiently high for a deflection of the ions towards the direction of the capillary exit. The capability of insulating capillaries to guide ions is referred to as the *guiding power* [18,19]. The fraction of transmitted ions at equilibrium generally decreases with tilt angle ψ. The guiding power can be quantified by the *guiding angle* ψ_c for which the normalized transmission fraction drops to $1/e$.

Monte-Carlo simulations [21,22] explicitly show that most of the deposited charge is located near the entrance region. Additional weaker patches may temporarily be produced after the formation of the first patch (Fig. 1). At equilibrium, i.e. at sufficiently long time at which the guiding power reaches a constant value, the temporary patches are found to loose significance [21,22]. Then, the electric field in the inner part of the capillary plays a minor role, since a homogeneously charged tube is field free (similarly as in a Faraday cage). However, a certain field is expected in the exit region, since there the longitudinal symmetry is broken.

The potentials expected in the entrance and exit region are schematically drawn in Fig. 1. For the entrance region, the potential drops quasi linearly in the transverse direction along the capillary diameter and in the longitudinal direction it has a maximum value near the center of the charge patch. Hence, the incident ion experiences different transverse fields as it travels along the entrance charge patch. Moreover, the transverse fields change with the trajectory of the ion, which enters the capillary in a statistical manner.

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doi:10.1016/j.nimb.2008.10.069

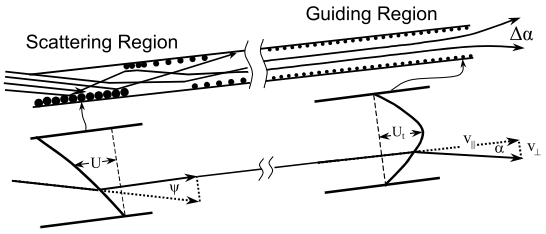

Fig. 1. Capillary guiding of ions in an insulating capillary. In the entrance region the main charge patch is created that deflects the ions to the capillary exit. The quantity U is a characteristic potential across the capillary diameter and ψ is the tilt angle. The exit region is affected by a symmetric potential of depth U_t in which the ions can gain transverse velocity $v_\perp$. For details see [20].

Similar effects influence the ions in the exit region. However, there, in good approximation the field is radially symmetric with respect to the capillary axis [22]. Therefore, the deflection of the ions is also radially symmetric giving rise to the Gaussian like angular distributions (transmission profiles) of the ions observed in this work. Thus, the ions in the exit region experience different transverse fields when leaving the capillary. Recently, similar scaling rules were found for the guiding angle and the width of the transmission profile [20], which are governed by the potentials in the entrance and exit regions, respectively.

It should be kept in mind that the formation of a radially symmetric field in the exit region is expected primarily for the time period after equilibrium is reached. The Monte-Carlo simulations [21,22] show that before equilibrium the temporary patches play a significant role in the guiding process. The temporary patches change their position and strength so that dynamic aspects become important during the pre-equilibrium period. Experimentally, the dynamic aspect of the capillary guiding can be observed by scanning transmission profiles as a function of time. Experimental work has shown that the formation of temporary patches is revealed by angular shifts of the transmission profiles [10,18,23].

In the present work, we study the dynamic aspects of 3 keV Ne^{7+} guiding through capillaries in insulating PET. We observed distinct peaks in the angular transmission profiles, which were analyzed by fitting them with a sum of 3 Gauss functions. The peak structures change in a characteristic manner resulting in a damped oscillation of the mean transmission angle. At equilibrium, the mean transmission angle reaches a value equal to the tilt angle of the capillary. The observations are interpreted assuming temporary charge patches formed inside the capillaries.

2. Experimental method

The experiments were conducted in an ultra-high vacuum chamber mounted at the 14 GHz electron cyclotron resonance (ECR) ion source of the ZERNIKE-LEIF facility at KVI Groningen (Netherlands) [24]. The base pressure in the chamber was some 10^{-8} mbar. The chamber was operated on high voltage to allow for the deceleration of the incident Ne^{7+} ions from 49 keV to 3 keV. The current was varied within the range of 10–1000 pA. The beam was collimated to a diameter of 1 mm with a divergence better than 0.2° full width at half maximum (FWHM).

The target foils were mounted on a goniometer, which allowed for tilting the capillaries with high precision relative to the incident beam in two directions specified by the angles ψ and ϕ. The tilt angle ψ was varied to change the angle between the incident beam and the capillary axis. The angle ϕ was kept constant after its zero value was determined. The ions transmitted through the capillaries were measured using an electrostatic analyzer, which was rotated by the angle θ in the same sense as the tilt angle ψ. The angular resolution of the spectrometer was 0.2° FWHM. The energy resolution was 0.5% which was sufficient to separate the charge states of the transmitted ions.

For the present experiments, PET samples with the capillary density of 4×10^6 cm^{-2} were used as prepared at ISL in Berlin [20]. The capillaries have a diameter of about 200 nm and a length of 12 μm. The angular spread of the capillary inclination was estimated to be ~0.2° FWHM which is significantly smaller than the aspect angle of ~1°. The density of 4×10^6 cm^{-2} implies a geometric opening of 0.12% and a mean distance of about 5 μm between neighboring capillaries. It is evident that an overlap of adjacent capillaries is unlikely to happen. Gold was evaporated under 45° on the front and the back of the PET foil forming a film of ~20 nm thickness.

The PET target foil was mounted on a circular frame with an inner diameter of 7 mm. The goniometer can move the target foil with respect to the ion beam in two dimensions (up–down and right–left). Thus, the ion beam could be located at different spots within the target area of 7 mm in diameter. With the beam diameter of 1 mm FWHM we were able to locate the ion beam on 5 well-separated spots (denoted center, up, down, right and left). The right or left beam spot was used for finding the zero position of the angles ψ and ϕ. The remaining 4 spots were used for the experiments. Hence, the results described below for each tilt angle were obtained with fresh capillaries, which have not been irradiated since more than 3 months.

3. Experimental results

In the following, we study uniquely transmitted Ne^{7+} ions, whose incident charge state was preserved during the passage through the capillary. The left column of Fig. 2 contains a series of transmission profiles that represent the angular distribution of the ions transmitted through the capillaries. The yield of transmitted Ne^{7+} ions is plotted as a function of the observation (or emission) angle θ defined relative to the incident beam direction. The emission angle relative to the capillary axis is obtained as $\alpha = \theta - \psi$ (Fig. 1). For the plot the tilt angle of $\psi = 5°$ was chosen. Each transmission profile is normalized to the integrated current of $Q_d = 1$ nC, i.e. the beam charge deposited on the front surface of the PET target foil. Knowing the incident beam current this deposited charge is a measure of time. Each graph indicates the total charge Q_d collected till the instant when the profile is measured. The charge deposited during the time needed to scan the profile is small in comparison with the total charge collected.

The transmission profiles exhibit peak structures, which strongly change with time or deposited charge. Hence, we fitted the experimental data by a superposition of 3 Gauss functions. Except for the beginning of the charge deposition, the locations of the individual peaks were found to be approximately constant. Hence, for charge depositions of more than 150 nC the widths and the locations of the Gauss function were kept constant, i.e. only their heights were treated as an adjustable parameter. The FWHM of all 3 peaks were set to be equal to 1.35°. The position of the 3 peaks were 3.4°, 5.0° and 6.5°. The central peak coincides with the tilt angle of 5°. The first and third peak are displaced with respect to the capillary axis by −1.6° and 1.5°, respectively, whose absolute values are larger than the aspect angle of 1°. For charge deposition of less than 150 nC the third peak appears at the observation angle of 6° (see Fig. 2(a) and (b)) and it readily moves to its final position of 6.5° as the charge deposition exceeds 150 nC. Hence, the individual peaks may move in the beginning, but their position is stable after some charge deposition.

From the transmission profiles it is seen that the individual peaks vary significantly in intensity with progressing charge