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Temperature control of ion guiding through tapered capillaries

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ABSTRACT

We investigate the guiding of Ar^{7+} ions (kinetic energy of 4.5 keV) through a single macroscopic tapered glass capillary of conical shape as a function of capillary tilt angle with respect to the incident ion beam direction. At room temperature a minimum in the transmitted ion intensity appears around the forward direction, which was previously observed and interpreted by a blocking of the transmission by repulsive Coulomb forces due to a uniformly charged ring shaped region in the centre part of the capillary. By heating the tapered capillary to temperatures around 100 °C and thus drastically increasing the electrical conductivity of the capillary material we no longer observe a minimum in the transmission curve but the transmission curve now has its maximum in forward direction. Since the maximum transmission at high temperature in forward direction is still smaller than the minimum in transmitted intensity at room temperature, we conclude that even at room temperature and in forward direction the focusing effect due to guiding is dominant and only partially weakened by blocking. Our experimental results are well reproduced in simulations using a theoretical model originally developed for straight nano-capillaries.

1. Introduction

Guiding of highly charged ions (HCI) through tilted insulating capillaries [1–9] has developed from an area of basic research to a tool to efficiently collimate and focus ion beams (for a recent review see [10] and references therein). Possible applications range from production of nano-sized ion beams [11,12] for nanoscale modifications of surfaces, shaping of ion beams [13], ion beam compression during deceleration [14] and focusing of exotic charged particle beams [15] to irradiation of single living cells [16].

In a qualitative way the guiding effect can be described by a self-organized charge-up process by the incoming ion beam, which enables consecutive ions entering the capillary to be steered towards the exit of a tilted capillary [1,5,17,18]. Since the majority of the transmitted ions are observed in their initial charge state, it can be concluded that these ions never touch the inner walls, but are electrostatically deflected by the charged patches on the capillary wall. So far the guiding effect has been confirmed for capillaries of various sizes (from nanoscopic to macroscopic capillaries) and shapes (straight and tapered ones) [10]. For tapered capillaries, which are of particular interest for some of the above mentioned applications, several interesting features have been observed, when investigating the charging dynamics for a range of different capillary tilt angles around the forward direction [8,9]. Stable (i.e. equilibrium) transmission conditions could only be found for a small range of tilt angles [9] and a minimum in the transmitted ion fraction appears around the forward direction [8].

In this paper we investigate ion guiding through a macroscopic conically shaped tapered capillary. At room temperature we indeed confirm the existence of a transmission minimum in forward direction. Our setup allows us to vary the capillary temperature and thus its electrical conductivity. Similar to what we have demonstrated in [19] for straight capillaries, we also show that for tapered capillaries the electrical conductivity, whose dependence of temperature is nearly exponential, is a key parameter for transmission control and notably influences the transmission minimum in forward direction.

2. Experimental setup and measurement procedure

For our measurements we use a single tapered macroscopic glass capillary. The entrance diameter of the conical shaped

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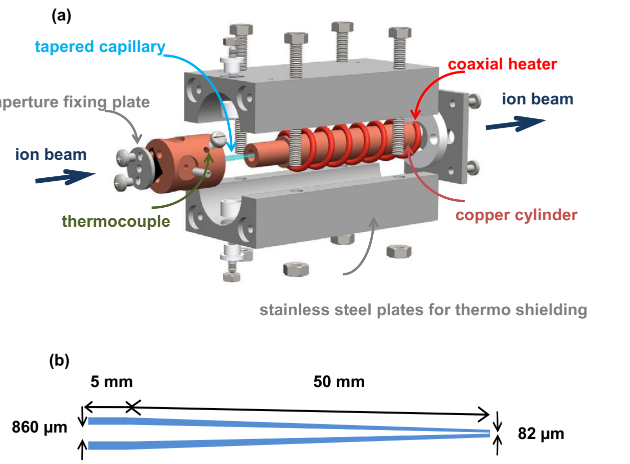

Fig. 1. (a) View of the heatable capillary holder; the capillary is placed in a copper cylinder surrounded by stainless steel coaxial heaters. The setup allows a uniform temperature variation between 22 °C and 110 °C. (b) Exact geometry of the conically shaped glass capillary used in the experiments.

capillary is 0.86 mm, while the exit diameter is 82 μm. After a 5 mm long straight section the conical part of the capillary is about 5 cm long. In order to achieve a uniform field distribution, the capillary's outside is graphited. The temperature dependent measurements are performed using a proper heatable capillary holder. The capillary is placed in a specially designed copper cylinder surrounded by stainless steel coaxial heaters and thermo shields (see Fig. 1). The temperature of the copper parts is monitored by a K-type thermocouple and the heating power regulated by the proportional-integral-derivative (PID) controlled heater. Using this setup a temperature range from 22 °C up to 110 °C ($295\ K \leqslant T \leqslant 383\ K$) can be probed. Within such a moderate variation the conductivity varies by almost four orders of magnitude [20,19]. All measurements are performed under UHV conditions at a base pressure below $5 * 10^{-9}$ mbar.

Ar^{7+} ions with a kinetic energy of 4.5 keV are provided by the ECR ion source in Vienna [21]. The extracted ion beam is focused, mass-to-charge separated and collimated to an angular divergence of less than 0.5°. The ion beam eventually hits a metallic entrance aperture directly in front of the capillary. This entrance aperture has a diameter of about 800 μm. The beam-spot diameter at this position is about 2.5 mm. For beam diagnostic and monitoring purposes, two reference apertures of different diameters (800 μm and 100 μm diameter) can be inserted into the beam instead of the capillary. Transmitted ions are measured by a position sensitive micro-channel-plate detector (PSD) of 50 mm diameter with a wedge-and-strip anode, located about 18 cm behind the capillary. Transmission rates are recorded after steady-state conditions (i.e. a constant count rate) are reached. The latter does not necessary imply stable guiding conditions.

Before starting any series of measurements the alignment of the capillary axis relative to the incident ion beam corresponding to a tilt angle of $\phi = 0°$ has to be determined. Due to the fact that the capillary can only be tilted in one plane, the straight direction can be found by increasing the temperature of the capillary. Increasing the temperature leads to a near exponential increase in electrical conductivity [20], which eventually results in the complete vanishing of the guiding effect as recently shown for straight capillaries [19]. At sufficiently high temperatures (typically 100 °C) the transmission curve is simply given by the geometric transmission through the capillary and the straight incident direction can be determined by optimizing the transmitted ion intensity while steering the incoming beam with several pairs of electrostatic deflection plates. Afterwards the capillary is cooled down and transmission curves are recorded at some fixed temperatures. For each transmission curve the tilt angle is stepwise increased until transmission becomes negligible. Subsequently, the capillary is tilted back stepwise and eventually into the opposite direction. For each tilt angle the total ion count rate onto the detector is summed up and dead-time corrected. During one measurement period the incident ion flux is kept constant and controlled by monitoring the beam intensity on the collimation diaphragms.

3. Experimental results

Measurements with the tapered capillary at room temperature indeed show a minimum of the transmission in forward direction close to $\phi = 0°$ (see Fig. 2). Such an intensity drop has already previously been reported by Nakayama et al. [9] and Kreller et al. [8] and qualitatively explained by repulsive Coulomb forces of a uniformly charged ring-shaped region in the tapered part of the capillary which supposedly is blocking the transmission. The measured transmission curve can be fitted by a Gaussian ansatz

$$f(x) = a \times e^{-\frac{x^2}{2\varphi_1^2}} - b \times e^{-\frac{x^2}{2\varphi_2^2}} \qquad (1)$$

with $b < a$ and $a, b > 0$. The parameter φ_1 is the guiding angle of the Gaussian ansatz. The second part of the fit function represents the 'suppression' of the transmission at small tilt angles. The magnitude and the width of the suppression are characterized by the parameter b and φ_2.

A systematic series of measurements at different temperatures (Fig. 2) show the well known effect that an increase of the capillary temperature leads to a decrease of the guiding power [19], because the charge patches necessary for guiding are no longer formed due to the increased electrical conductivity of the glass. In addition we find that by heating the tapered capillary to temperatures around 100 °C the minimum in the transmission curve vanishes and the transmission now has its maximum in forward direction (see Fig. 2). However, this maximum in (geometric) transmission at high temperature is still smaller by ∼25% than the reduced transmitted intensity in forward direction at room temperature. This leads us to the conclusion that even at room temperature and in forward direction the focusing effect due to the guiding is

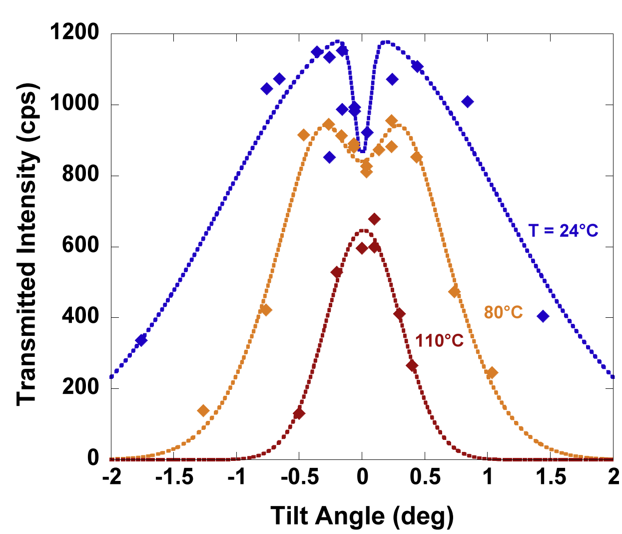

Fig. 2. Transmission curves for 4.5 keV Ar^{7+} ions guided through the tapered glass capillary for three different capillary temperatures. The flux of the incident ions was kept constant. The transmission curves (dotted lines) are fitted by a Gaussian ansatz Eq. (1) (for more details see text).