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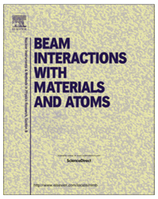

Ion guiding in curved glass capillaries

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ABSTRACT

Straight and curved glass capillaries were tested for the guiding of 8 keV Ar^{8+} ion beams. The straight capillary was about 50 mm long and 0.87 mm/1.1 mm in inner/outer diameter. One of the two curved capillaries was similar, but was curved with a 270 mm radius. The other was 53 mm long, had diameters of 2.34 mm/2.99 mm, and was curved with a 150 mm radius. The corresponding bending angles of the two curved capillaries were 9.6° and 17.5°, respectively. Transmission through the straight capillary disappeared when the tilt angle was larger than 5°. The curved capillaries guided the ion beams into their corresponding bending angles, which were much larger than 5°, with transmission efficiencies of a few tens percent. This demonstrates the possibility of developing a new scheme of simple small beam deflectors and related beam optics.

1. Introduction

In recent years, ion beam guiding in insulator capillaries has been of great interest in the fields of atomic and molecular physics, surface science, material science, etc. Such guiding was first observed by Stolterfoht et al. in micro-capillaries made on thin (~10 μm) polyethylene terephthalate (PET) foil [1]. Upon irradiating the foil with 3 keV Ne^{7+} ions, they found that a certain fraction of the incident beam was transmitted and deflected in the direction of the foil's tilt. They attributed the phenomenon to the formation of a self-organized charge patch on the inner wall surface of the capillaries. The mechanism was explained as follows: the first impacts of ions on the inner wall surface of the capillaries produced a self-organized charge distribution there, and the potential of those charges then deflected and guided subsequently arriving ions to the outlet. Guiding with micro-capillaries in insulator materials such as PET and ceramics has subsequently been intensively studied both experimentally [2–9] and theoretically [10–12].

In previous studies we found that this guiding also occurs in macro-size single tapered glass capillaries that are a few centimeters long and some tens to hundreds of micrometers in diameter [13,14]. In those works, we concluded that the observed focusing and guiding of 8 keV Ar^{8+} ions arose in a way similar to that observed in micro-capillaries, with self-organized charge patch on the inner wall surface. In this case, transmission was observed for tilt angles up to ± 5°. Such guiding in a macro-size single glass capillary was also reported by Bereczky et al., who observed the transmission of 4.5 keV Ar^{9+} beams through a single straight capillary for tilt angles up to 2.5° [15]. Gruber et al. reported the temperature dependence of the guiding phenomenon in macro-size glass capillaries, finding that the tilt angle range that allowed guiding decreased upon heating [16,17]. They attributed this to the temperature dependence of the charge–discharge equilibrium (i.e., the formation of self-organized charge distribution), because the electrical conductivity of the glass strongly depends on temperature. Note that in most of the works with micro and macro capillaries, the injected current was very small and the corresponding transmission was at most a few thousand particles per second. However, a macro-size capillary should have enough durability for higher beam intensities owing to its large dimensions; therefore, the guiding of higher-current beams could be expected. If a macro-size capillary could guide ion beams with intensities of a few hundred picoamperes or more, it might be used as a simple, easy beam bender instead of using a heavy sector dipole magnet or an electric deflector with a high-voltage power supply. Ion guiding in macro-size capillaries might represent a new scheme of developing simple small beam optics.

Recently, we tested such expectations using straight and curved macro-size Teflon capillaries that were about 50 mm in length and 1.0 and 2.0 mm in inner and outer diameter, respectively [18]. That work employed one straight capillary and three curved ones with bending angles $\phi = 9.6°$, 17.5°, and 26.7°. We observed guiding phenomena with both straight and curved Teflon capillaries with Ar^{8+} beams of a few hundred picoamperes, and found that a curved capillary could guide ion beams into a bending angle much larger

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than the maximum tilt angle (≈7°) at which a straight capillary barely guided a sufficient fraction of ions. The estimated transmission efficiency of the curved capillaries was 40–60% for injected beams of several tens of picoamperes. However, we also found that transmission through both the straight and curved Teflon capillaries was rather unstable, in particular with higher-current (~1 nA) injection.

As an extension of that work, we studied the guiding capability of straight and curved macro-size capillaries of glass instead of Teflon using Ar^{8+} ion beams of a few hundreds of picoamperes. In this paper, we present recent results on ion guiding in straight and curved glass capillaries.

2. Experimental

The experiments were performed at the Slow Highly-Charged Ion Experimental Facility at RIKEN, Wako, Japan. The experimental setup and procedure were similar to those of our previous experiments using Teflon capillaries [18]. Briefly, Ar^{8+} ions produced in the 14.5 GHz electron cyclotron resonance (ECR) ion source were extracted with 1 kV acceleration. After mass and charge selection with a sector dipole magnet, the ions were transported through the beam line to the experimental chamber. Passing through a 2 mm diameter aperture at the entrance of the chamber, the ion beam was injected into the capillary sample. The size of the beam at the sample position was typically about 2 mm (i.e., the full width at half maximum, FWHM), and its typical angular dispersion was about 2.5° (FWHM). The vacuum in the chamber was kept better than 5×10^{-5} Pa.

Fig. 1a represents the setup in the chamber, and Fig. 1b shows a photograph of the sample holder assembly. To avoid stray ions flying into the transmitted current monitor without passing through the capillary, a shield plate with a 2 mm-diameter aperture was placed in front of the holder. The holder had several sample ports, and all three capillaries were installed in it (see Fig. 1b). The shield and holder were assembled on a rotating linear feed-through system, which had capabilities of azimuthal rotation, vertical shift (within a range of 25 cm), polar angle adjustment (within ±6°), and horizontal position (X–Y) adjustment (within ±5 mm in each direction). The holder assembly was aligned to the beam by optimizing the beam current through a blank (empty) port of the holder, which was regarded as a short straight metal capillary. As the inlets of the capillaries were parallel to the aligned port, each capillary could be set on the beam axis by changing the holder's vertical position appropriately with the alignment maintained. The entrance of the capillary was on the axis of azimuthal rotation. Therefore, the tilt angle dependence of the transmission through the straight capillary could be measured.

The glass capillaries used in this work are shown in Fig. 2, and their properties are summarized in Table 1. One was straight, and the other two were each curved with a well-defined radius of curvature: $R = 270$ and 150 mm. The definition of the bending angle ϕ is given in Fig. 1. To align the capillary inlet to the beam axis, each curved capillary had a 5 mm straight section before the curvature, and the section was covered with a few layers of aluminum foil and guarded with a stainless steel ring. All the capillaries were made of soda-lime glass and were provided by Hamamatsu Photonics Co. Ltd. Their inlet faces were coated by electrically conductive paste. Note that the first 5 mm (with the guard ring) and the next 5 mm (in the holder) of each capillary were covered by metal materials and electrically connected to the holder, while the rest of each capillary was not.

The transmitted ion current I_t through each capillary was measured with an aluminum plate set just after the outlet of the capillary, and its time dependence was recorded every second by

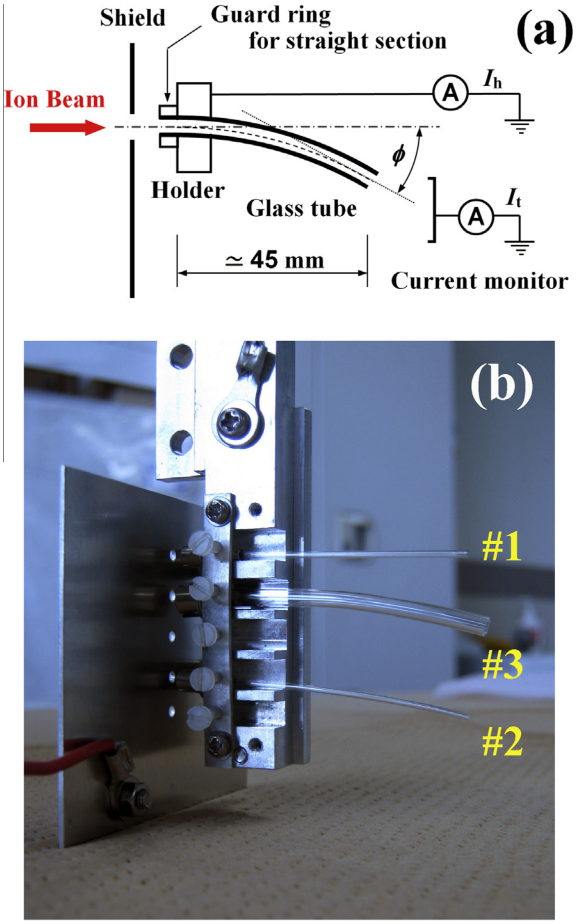

Fig. 1. Experimental setup. (a) Schematic of the setup. The diameter of the aperture on the shield plate is 2 mm; the bending angle is labeled as ϕ. (b) Photograph showing all three capillaries (#1–3) installed.

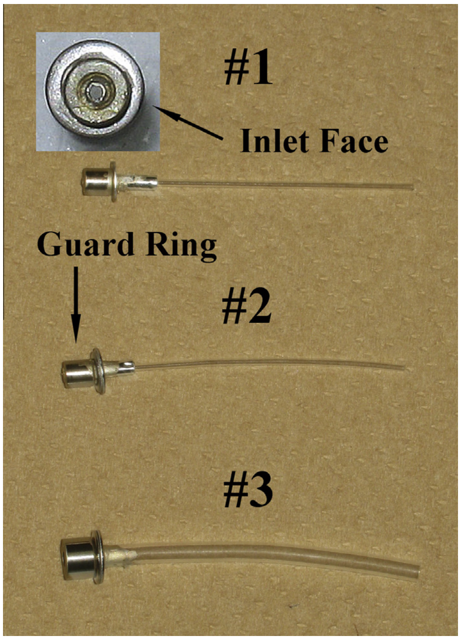

Fig. 2. Photograph of three capillaries with guard rings for their straight sections. The inlet face was coated with electrically conductive paste. Except for the straight section and subsequent 5 mm of the capillary, the capillary was neither coated nor covered with metal or conductive material.