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Production of a microbeam of slow highly charged ions with a tapered glass capillary

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The authors have developed a method to produce a microbeam of slow highly charged ions based on a self-organized charge-up inside a tapered glass capillary. A transmission of 8 keV Ar^{8+} beam through the capillary 5 cm long with 800/24 μm inlet/outlet inner diameters was observed stably for more than 1200 s. The transmitted beam had the same size as the outlet with a beam density enhancement of approximately 10 and a divergence of ±5 mrad. The initial beam was guided through a capillary tilted by as large as ±100 mrad, and it still kept the incident charge. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2362642]

A thin foil with a multitude of straight holes of ~100 nm in diameter had been used to study above-surface interactions of slow highly charged ions (HCIs) with insulators[1,2] and metals.[3–7] Particularly in the case of metal-plated insulator foils,[2,8] a so-called guiding effect was observed, where slow HCIs were deflected along the capillary axis keeping their initial charge states even when the capillary is tilted against the incident HCI beam.

In the present letter, we demonstrate that a single tapered glass capillary can collimate a slow HCI beam with relatively poor emittance down to micrometer range, keeping the initial charge state and kinetic energy. Considering the high reactivity of slow highly charged ions with surface, one can conclude that the ions never touched the inner wall of the capillary during transmission. A self-organized charge-up of the capillary inner wall is expected to play a vital role in these peculiar phenomena. A similar glass capillary was used to transport proton or He ion beam in a MeV region.[9] In this case, however, the beam touches the inner wall and suffers small angle scattering with the wall surface during the transport.

Slow HCIs have a high ability to modify surfaces and cause efficient sputtering without damaging the substrate very much. For example, a single HCI induces a nanometer dot on graphite[10–12] and Al_2O_3 surfaces.[10] It was also found that the F–Si bond direction of a Si(001)–F surface can be reconstructed from the three-dimensional momentum distribution of F^+ ions desorbed by slow HCIs; i.e., a stereochemical analysis can be done with slow HCIs.[13] Once a microbeam is available, these functions specific to slow HCIs can be used to realize, e.g., micropatterning of nanodots and element-sensitive microimaging. It is noted, however, that a microbeam of slow HCIs was not practically available because the HCI beam is relatively weak and the emittance is also not good.

An ion beam of 8 keV Ar^{8+} was extracted from a 14.5 GHz Caprice electron cyclotron resonance ion source at RIKEN, and then transported to an experimental chamber via an analyzing magnet. The ion beam was then collimated by a 2 mmϕ aperture [see Fig. 1(a)], injected in a tapered glass capillary, and finally detected by a position sensitive detector (PSD) via a deflector. The divergence of the incoming beam after the aperture was at most ±3.3 mrad. The deflector was used for the charge-state analysis of the transmitted ions. The outer and inner diameters of the capillary at the inlet were 2 and 0.8 mm, respectively, and 55 and 24 μm, respectively at the outlet. A typical length of the capillary was 50 mm [Fig. 1(b)]. To avoid macroscopic charge-up of the entrance surface of the capillary, it was covered by an Al foil with a

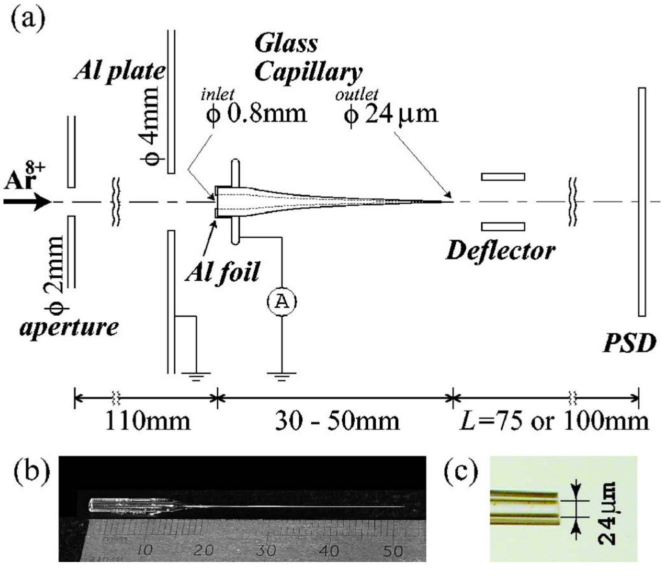

FIG. 1. (Color online) Schematic view of the experimental setup, (b) photo of the tapered glass capillary, and (c) microscope image of the capillary outlet.

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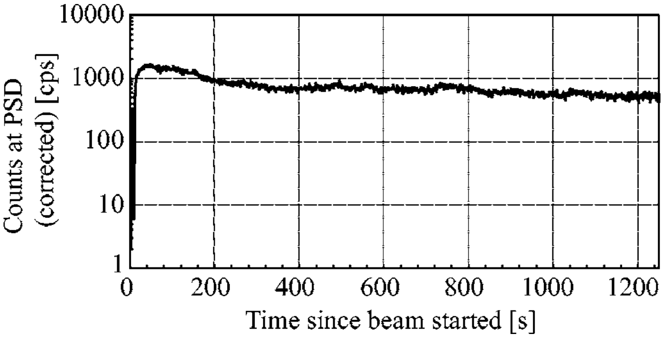

FIG. 2. Time dependence of the number of transmitted ions. The counts at the PSD were corrected to be divided by the detection efficiency of 50%. It took several tens of seconds to saturate the transmission rate.

0.8 mm hole. The foil was used to monitor the incoming ion current of 0.1–5 pA. The secondary electron yield for several keV Ar^{8+} ion from the Al foil is expected to be ~7;[14] the real current should be reduced by 0.47 times. The ion current injected in the 0.8 mm hole of the capillary was evaluated from the beam diameter on the Al foil and the hole diameter. The incident currents hereafter correspond to the corrected current above. The PSD consisting of a stack of multichannel plates and a wedge-and-strip-type anode and its detection efficiency was ~50%.

The glass capillary was made of borosilicate, which has a volume resistivity of 10^{15} Ω cm at 25 °C and a softening temperature of 821 °C. The tapered capillary was prepared by heating a straight glass tube, and then stretched by pulling both ends with a constant force. The taper angle can be controlled by tuning the temperature and the force. Figure 1(c) shows a microscope image of such a capillary used for the present experiment.

Figure 2 shows the transmitted ion intensity as a function of time for the tapered capillary injected with an 8 keV Ar^{8+} ion beam of 0.2 pA ($\sim 1.5\times10^5$ Ar^{8+} ions/s) with a stability of ~10%. It is seen that the transmission current grew slowly with a time constant of several tens of seconds, and then got more or less stable for more than 1200 s. The peak counts in Fig. 2 was about 1600 cps. A focusing factor defined by the ratio of N_t/S_o to N_i/S_i is estimated to be ~10, where N_t is the number of transmitted ions, N_i the number of injected ions into the capillary, and S_o and S_i the geometrical outlet and inlet cross sections of the capillary, respectively. This factor depends on the taper angle, the outlet size, and also the input current.

The upper left inset of Fig. 3 shows the position of the transmitted beam on the PSD ($L=100$ mm) when the capillary was tilted relative to the axis of the incident current of ~0.01 pA. The relation between the tilting angle of the capillary and the deflected angle of the beam is shown in Fig. 3, which proves that the beam was well guided to the direction of the capillary tilted by as large as 100 mrad. It is noted that the deflection angle is an order of magnitude larger than the half opening angle (~8 mrad) of the tapered capillary when the cross section of the capillary along its axis is assumed to be trapezoid.

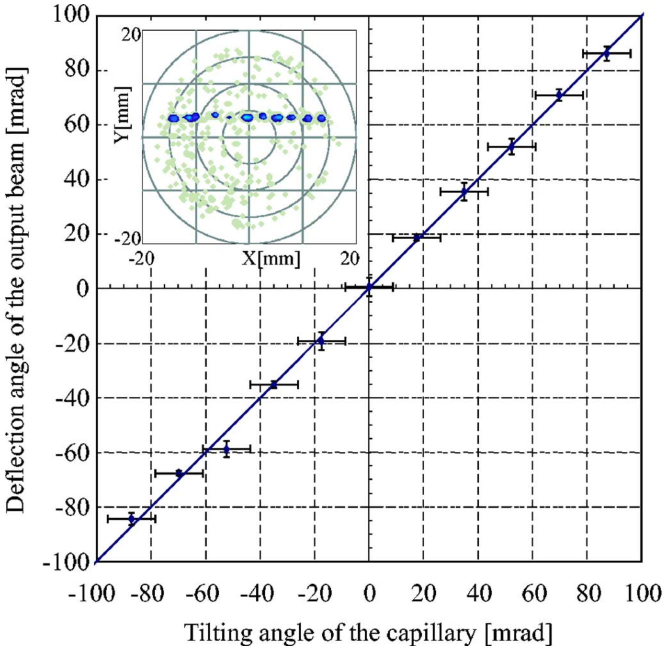

FIG. 3. (Color online) Tilting angle dependence of the peak position for the incident current of ~0.01 pA. The horizontal axis is the tilting angle. The vertical axis corresponds to the reconstructed deflection angle of the beam from the peak positions at the PSD. The horizontal and vertical error bars show the accuracy of the tilting dial reading and the spot size (FWHM), respectively.

The charge-state distribution of the transmitted HCIs for the incident current of 0.3 pA was measured by biasing the deflector downstream of the capillary without tilting. Figure 4(a) shows the circular spot at the PSD ($L=75$ mm) without the deflector bias, while Fig. 4(b) shows the spot with the bias of 280 V, which was still circular and shifted to the position corresponding to the initial charge. The peaks in Fig. 4(c) show the projected beam profiles corresponding to Figs. 4(a) and 4(b). In the region corresponding to charge-changed components, there were no peaks but some background events, i.e., the transmitted ions were really guided along the capillary without changing the incident charge state. The angular divergence of the transmitted beam was evaluated from the spot sizes seen in Fig. 4(c), and was found to be ~±5 mrad.

The results here could be explained as follows [see Figs. 5(a) and 5(b)]: The saturation time shown in Fig. 2 suggests

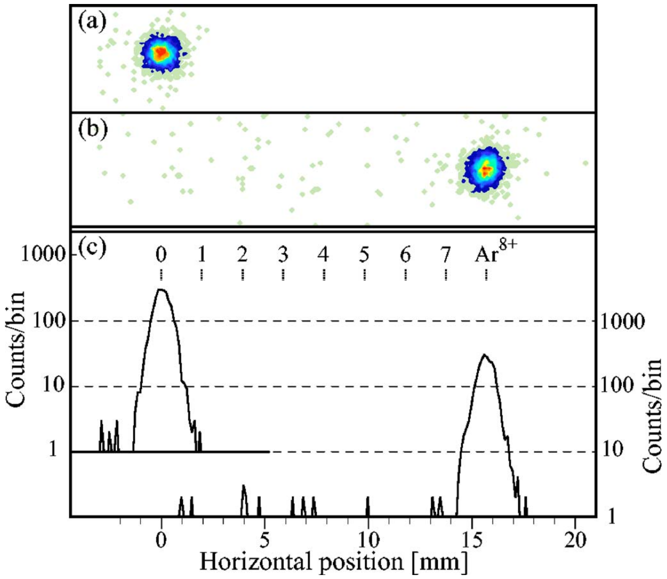

FIG. 4. (Color online) (a) and (b) show the spots at the PSD without and with the deflection bias, respectively. (c) The projected beam profiles corresponding to (a) and (b).

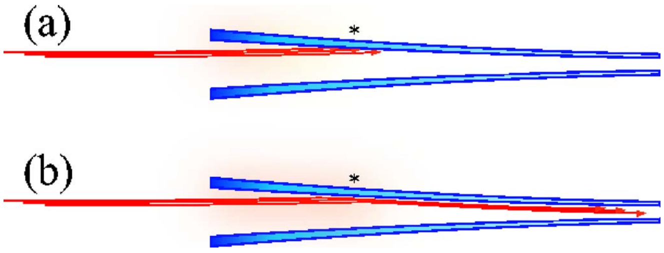

FIG. 5. (Color online) Model of the guiding effect.

that the incident ions entering the capillary hit and charge up the inner wall [Fig. 5(a)]. When the accumulated charge gets big enough to prevent the following incident ions from touching the inner wall, the ions travel more or less parallel to the wall [Fig. 5(b)], and the guiding is realized. The charge-state distribution (Fig. 4) indicates that the transmitted ions never touched the inner wall of the capillary.

Conventionally, magnetic and/or electrostatic lenses have been employed to produce microbeams. Using such lenses, submicron ion beam of a few tens of keV region was reported,[15] where lenses with small aberration and an ion source with good emittance were employed. Our method presented here is not so sensitive to the initial beam with broad energy spread and divergence, and was realized just by a tiny tapered glass tube of ~50 mm in length. In irradiation experiments, the beam position can be determined easily.

Summarizing, we have observed the stable transmission of slow HCIs through a single tapered glass capillary with a focusing factor of approximately 10 for the outlet diameter of 24 μm. The transmitted beam obtained by such a simple setup was guided, as large as ±100 mrad, and had a circular spot and a divergence of ±5 mrad without the charge transfer inside the capillary.

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