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Incident beam intensity dependence of the charge-up process of the guiding of 1 MeV proton microbeam through a Teflon microcapillary[⋆]

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Abstract. The ion guiding phenomenon was studied in the case of a single, straight, micrometer sized insulator capillary using a micro focused 1 MeV proton beam. The axis of the incident ion beam was tilted to 1° relative to the axis of the capillary. The aspect ratio of the target and the small beam divergence ensured the geometrical non-transparency of the capillary for the incoming beam. The intensity of the beam transmitted through the capillary was measured as the function of time and as a function of the incident beam intensity. At each constant incident beam intensities the time required for the charge-up process of the stable transmission was determined. We found that the time required to establish a stable guided transmission decreases reciprocally with the increasing incident beam current.

1 Introduction

Ion guiding phenomenon might appear when a charged particle beam enters to an insulating capillary whose axis is tilted with respect to the direction of the beam and the tilting disables the geometrical transmission of the projectiles through the capillary [1]. First the arriving ions collide to the inner wall of the capillary and start to deposit their charge in a self-organized process (charge-up phase). When the formed electric field becomes strong enough to deflect the beam towards the capillary exit the subsequent ions can leave the capillary without touching its inner wall. The fact that the beam deflected inside the capillary escapes from the exit preserving the initial energy and charge state suggests that the accumulated charge on the capillary inner wall can prevent the close collision with the inner surface of the capillary wall. Previous experiments and theoretical works revealed that a stable transmission can evolve when the deposited charge inside the capillary reaches a dynamical equilibrium: a fraction of the arriving ions maintains charge deposition to compensate the loss due to leakage currents caused by the small but finite electrical conductivity of the insulator material [2].

Since the discovery of the guiding effect numerous researcher groups have studied the phenomenon from many points of view. Initially arrays of nanocapillaries in insulating foils were used as targets and slow heavy highly charged ions (HCIs) as projectiles. Later the type of the bombarding beams was extended, thus electrons [3], light ions [4] or even exotic particles [5,6] were proposed to prove the possibility of the guiding effect. Similarly, more and more types of targets were used both in the aspects of size (micrometer-scale) [7] and shape (e.g. tapered, funnel-shaped, flat, curved) [8–11]. The rapid development of this research area leads to the appearance of real practical applications [12–14].

In our present work we studied the guided transmission of an MeV/amu ion beam through an insulating capillary. During the experiments we used a single, straight, micrometer-sized capillary made of Polytetrafluoroethylene (PTFE) and a micro focused beam of 1 MeV protons. The use of the microbeam resulted that only a small area of the inner wall was charged depending on the beam divergence. The position of the created charge patch is around at the centre of the capillary determined by the tilting angle and the dimensions of the target. Therefore the charge patches could not discharge easily and fast because the resistance increases with the distance which contributed to an efficient transmission of the proton microbeam. The motivation of the present work was to investigate the length of the charge-up phase, i.e. the time required to reach the maximum transmission through the capillary, as a function of the incident beam intensity. A reciprocal connection is expected between the incident beam current and the time since we assume that a constant amount of charge is required to deflect the incident beams with the same charge-state and energy.

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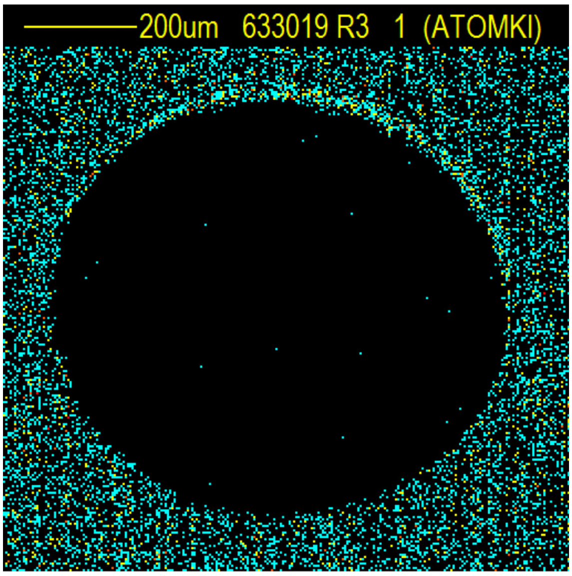

Fig. 1. Rutherford Backscattering (RBS) map of the entrance of the capillary. The sample was moved until it was in the centre of the scanable area. After the positioning, the beam scan was turned off and the beam was steered to the centre of the sample.

2 Experimental

After the successful construction of our new experimental setup for studying the ion guiding phenomenon [15], we became able to carry out ion guiding experiments on the scanning nuclear microprobe facility of MTA Atomki. During the measurements we used H^+ ions. The proton beam was focused down to 2×2 μm^2.

The sample positioning was carried out by a 5-axis sample stage (3 moving and 2 rotation axes) with the help of an optical microscope and elastic backscattering mapping (Rutherford Backscattering Spectroscopy or RBS) technique. The optical microscope was used to roughly position the sample, and after that, an RBS map was recorded by scanning the microbeam on the entrance of the capillary and collecting the backscattered particles with a particle detector. The sample was then gently moved until the hole was in the centre of the scanned area as it can be seen in Figure 1. Finally the beam scanning was stopped, thus the centre of the target was aligned to the optical axis of the proton microbeam. This method resulted a very precise and easily reproducible sample positioning.

In our recent experiments the time evolution of the transmission (i.e. the ratio of the guided beam intensity to the incident beam intensity) of the proton beam was investigated. Figure 2 shows the schematic view of the experimental arrangement. We used a beam chopper to continuously monitor the intensity of the incident beam. The chopper consists of a rotating vane that periodically chops the beam and a particle detector in front of the vane which collects backscattered particles from the vane. The frequency of the rotation is constant, therefore the signal of the backscattered particle on the detector is nearly linearly proportional to the intensity of the incident beam. After a proper calibration of the chopper the beam current can be easily tuned with the signal of the particle detector. The intensity of the transmitted beam was measured by a Faraday-cup (F-cup) behind the capillary exit. The F-cup is grounded through a picoamper ranged current meter, and since it prevents escaping secondary electrons it contributes to precise measurement of the beam current. The F-cup took place on a rotatable disk, along with a Surface Barrier (SB) type particle detector. By replacing the F-cup with the detector during the measurements, we could collect the energy spectra of the transmitted beam at arbitrary stages of the transmission.

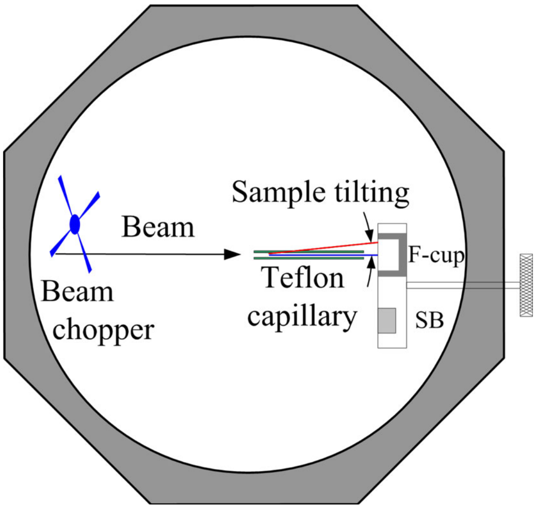

Fig. 2. Schematic view of the experimental setup. The beam chopper is used for the incoming current control. The Faraday-cup behind the target is used to measure the intensity of the transmitted beam. The SB type particle detector measures the energy distribution of the transmitted beam.

The sample used during this experiment was a single, straight, micrometer-sized insulator capillary made of PTFE or as it is often called, Teflon. The length of the capillary was $L = 44.5$ mm and its diameter was $d = 800$ μm. The tilt angle of the capillary during the experiments was 1° relative to the beam axis. Since the aspect ratio (L/d) of our capillary sample is $\sim$56 and the divergence of the proton microbeam is less than 0.3° [16] therefore these conditions ensure the geometrical non-transparency of the arrangement.

The energy of the proton microbeam was 1 MeV, the beam focus was on the entrance of the capillary. The intensity of the incident and the transmitted beam was recorded simultaneously.

3 Results and discussion

During the measurements seven different incident beam intensities were used. These intensities were as follows: 8 pA, 19 pA, 22 pA, 24 pA, 44 pA, 68 pA and 150 pA. The transmission is expressed in percentage as the function of the incident beam intensity. Figure 3 shows the time

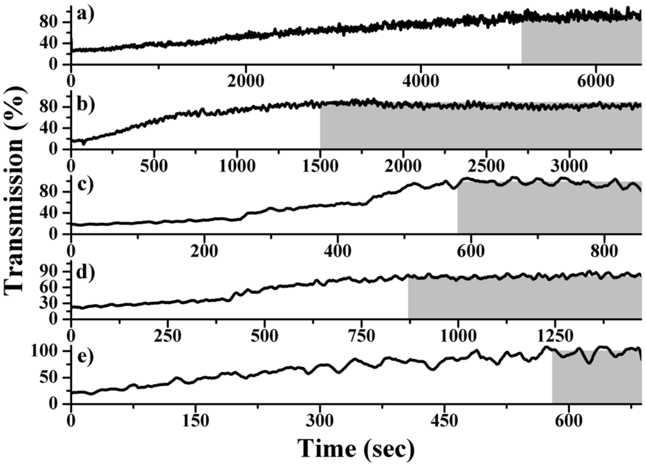

Fig. 3. Time trend of the transmission at different incident beam intensities: (a) 8 pA, (b) 24 pA, (c) 44 pA, (d) 68 pA and (e) 150 pA. The grey boxes are to guide the eye from where we found the transmissions to be saturated.

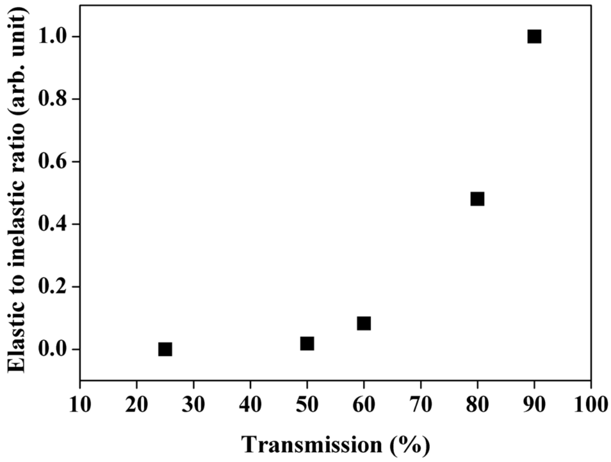

Fig. 4. Ratio of the elastic to inelastic region of the spectra in the function of the transmission.

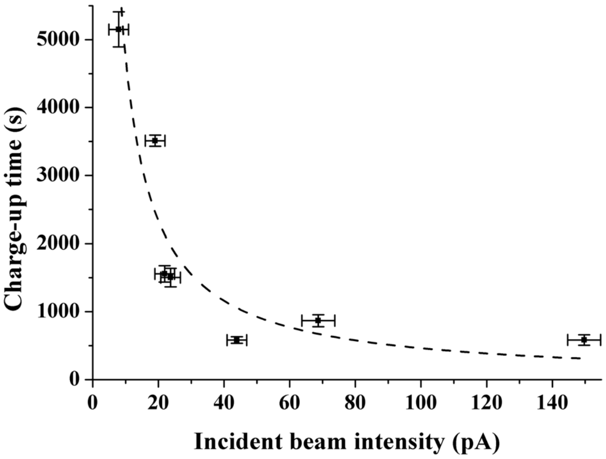

Fig. 5. Required time of the charge-up process at different incident beam intensities. The dashed line is a reciprocal fit of the measured data.

evolutions of the charge-up process at five incident beam intensities.

The transmission started from around 25% in each case. This is the result of forward scattering, because at this stage the majority of the transmitted particles suffered energy loss (inelastic region). The transmission started immediately and increased gradually until it reached its maximum value at around 90%. At the maximum intensities the transmitted beam did not suffer energy loss which is a consequence of the ion guiding (elastic region). Figure 4. shows the ratio between the elastic and inelastic region of the spectra at 25%, 50%, 60%, 80% and 90% of the transmission.

The time required to reach the maximum transmission at different incident beam intensities is plotted in Figure 5. An obvious trend is that the required time of charge-up process of the guiding phenomenon is decreasing with the increasing incident beam current. This is because the guiding phenomenon is due to the self-organized charge-up of the inner wall of the capillary. Higher incident beam intensity leads to a faster formation of the charge-patches on the target wall, which contributes to a more steep increase of the transmission. If we assume that the same amount of charge q, is required to be accumulated on the inner wall of the capillary to deflect a beam with the same energy and charge, independently of its intensity, a reciprocal dependence is expected between the elapsed time t, of the charge-up process and the incident beam current I, ($t = q/I$). The $t = (a + bI)^{-1}$ reciprocal function fits our measured data, which proves our assumption that independently of the incident beam intensity the same amount of charge is accumulated on the target.

4 Conclusions

The required time of the charge-up process of the ion guiding phenomenon was investigated with a single, straight, insulator microcapillary using 1 MeV proton microbeam. The tilt angle of the sample relative to the axis of the proton beam was 1° which resulted a geometrically non-transparent system due to the aspect ratio of the capillary and the small divergence of the focused proton beam. The transmitted current, normalized to the incident beam intensity between 8 pA and 150 pA, was measured as a function of time. In all cases the transmission started from around 25%. The time until the maximum transmission evolved (∼90% relative to the incident current) was measured. We found that the time required to reach the maximum transmission at around 90% decreases reciprocally with the increasing incident beam current.

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