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Guiding as a General Consequence of the Charged Particle Interaction with the Inner Surface of an Insulator Capillary—Guiding of 1 MeV Proton Microbeam through Polytetrafluoroethylene Macrocapillary

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Abstract: The transmission of energetic, 1 MeV proton microbeam through a single, cylindrical shaped, macrometer-sized polytetrafluoroethylene capillary was studied experimentally. The capillary axis was tilted with respect to the axis of the incident ion beam. The tilting, the aspect ratio of the capillary and the small beam divergence disabled the geometrical transmission of the beam through the target. The intensity, energy, deflection and charge state of the transmitted beam were investigated. We found that the pure guided transmission of a MeV/amu energy ion beam is observable. We clearly identified three completely different stages during the guiding process according to the measured energy distribution of transmitted particles. At the beginning the transmission intensity was low and only inelastic contributions with energy lower than 1 MeV were found in the spectrum. Later, in the second stage, the elastic peak appeared and became more and more significant. Finally, when the stable transmission evolved, only the elastic peak was present and the inelastic area was totally absent as a direct consequence of the ion guiding and as a result of the charged particle interaction with a charged inner surface of the insulator capillary.

Keywords: macro-capillary; transmission; charge-up process; insulator surface; energy distribution

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1. Introduction

One of the *unexpected* discoveries in 2002 was that highly charged ions (HCIs) are able to pass through insulator capillaries keeping their initial energy and charge state even if the capillary axis is tilted with respect to the incident beam axis larger than the geometrical limit [1]. In the first experiment it was found that around 10% of the incident 3 keV Ne^{7+} ions were transmitted through the nanocapillaries with large aspect ratio etched in a polyethylene terephthalate (PET) target foil even if it was tilted with 10 degrees relative to the direction of the incident beam. The fact that most of the guided ions keep their initial charge state suggests that the ions do not touch the inner wall of the capillary during the transport process, i.e., a surprisingly well-tuned electric field is formed in each nanocapillary. The phenomenon is called recently charged particle guiding and caused by the Coulomb-field of charge patches created on the surface of the insulator capillary inner wall due to the ion irradiation. Guiding sets in when the charge patches reach a dynamical equilibrium, i.e., the arriving and leaving ions result in a constant amount of charge on the wall. Arriving ions come from the incident beam, while the charge decreases by the transport into the bulk of the wall material, or along the surface towards the capillary entrance and/or exit.

Following the pioneering work of Stolterfoht et al. [1] several groups studied the ion guiding through insulating nanocapillaries like PET [2–4], silicon dioxide (SiO_2) [5] or aluminium oxide (Al_2O_3) [6–8] with aspect ratios around 100. A detailed theoretical description of the HCI interaction with nanocapillaries is given in [9].

Since in the first investigations, thin insulating foils with randomly distributed capillaries (produced by swift heavy ion bombardment) or with ordered arrays of regular nanocapillaries were used in the experiments, therefore collective effects due to the presence of neighboring capillaries must be taken into account for an accurate simulation of the ion trajectories [9]. These collective effects make the full description of the interaction between charged particles and insulator capillary walls rather difficult. Moreover, at this moment technically it is impossible to ensure perfect parallelism for each capillary in the sample. Last but not least more technical applications can be found for a single capillary than for multi-capillary arrays. Avoiding these difficulties, we recommended first to use a single capillary with cylindrical symmetry in the investigations [10].

Systematic measurements of collisions between slow HCIs and a macroscopic sized glass capillary with large aspect ratio and cylindrical shape have also been performed. The experimental results proved that the guiding effect known from nanocapillaries is also valid up to a few hundreds of µm capillary diameter [10].

During the past years many research groups joined to this field of research and carried out various experiments with insulator capillaries, partly keeping the original multicapillary samples [11–14], but more and more works tried to explore the fundamental interactions between HCIs and a single macrocapillary. These studies have been summarized so far in three reviews during the last years [15–17]. For the study of the special HCI transport, single tapered and conical shaped glass capillaries were also introduced [18–22]. Along this line, later, the new research interest focused on the light particle transport through capillaries and as projectile electrons [23–25], and other exotic particles, like positrons were used [26].

Steering or focusing MeV energy ion beams with tapered capillaries is also of great interest. Different applications are found, in which the required small beam size is achieved by using tapered glass capillary optics. Successful elemental mapping using micro-PIXE (Particle Induced X-ray Emission) analysis is reported in [27], as well as single cell irradiation ("cell surgery") [28]. However, the obvious energy loss of the incident beams in all of these works suggests that the transport mechanism for MeV ions is governed by multiple small angle scatterings with the inner capillary wall [27–29]. Here we note, however, that this kind of particle transmission is also denoted "guiding" in the literature.

In case of fast ion irradiation of crystal surfaces under grazing angles, a special case of specular reflection may occur. This results only a small (few keV) energy loss of the projectile beam [30], but it is caused by the surface channeling phenomenon, which requires a well-oriented crystallic target instead of amorphous materials or polymers that are used in the capillary guiding works as well as in the present experiment.

But, according to the particularity of "guiding", it must be able to be observed with any projectiles and energy if suitable conditions are ensured [31], i.e., if the ions are able to build up and maintain strong electric field on the inner surface of the insulator capillary. We note, however, it is not always possible due to the fact that we have finite values of conductivity and we cannot accumulate arbitrary amount of charge on the surface for higher particle energies. Also important to note that we need a well-defined position of the accumulated charges to ensure the strong electric field. But in principle we do not have any theoretical limitation, and in an ideal case the optimum conditions can always be found. At the same time nature destroys the optimal conditions, because the guiding phenomena shows strong material dependence.

To resolve the above mentioned problems and give clear evidence of the so called guiding with high energy particles, we do further simplification in our experiments and we use single straight capillary with singly charged ions. In our experiments the unique feature is the combination of 1 MeV proton microbeam and a single polytetrafluoroethylene (PTFE) macrocapillary. With the use of a focused microbeam we irradiate only a certain small area instead of the whole inner surface of the capillary, as it is the case using the divergent beam, and the low conductivity of PTFE ensures that we have a chance to keep high amount of charge on its surface for a long time.

So, the role of the used microbeam is somewhat trivial; the beam hits the target on a relative small surface. We note, however, the beam spot at the focus point is 1 μm but the beam diverges from here and upon reaching the wall has become ≈10 × 0.5 mm. This expansion is ascribed to dynamics, i.e., the time evolution of the charge patch, the charge spreads away to the entrance and exit of the capillary. A continuous transition of the charge patch forms between the highest potential (center region) and the edges (which are at ground potential). During the charging phase, the charged patch expands but the beam still can arrive near the center region and the accumulated charges will influence the next particles along a long path, and finally can deflect the particle trajectory toward the exit. Our simulation shows that the charged patch must not be highly localized. The charges move partly into the bulk and partly along the surface, thus the electric field does not reach a very high value. The average electric field along the long path will finally deflect the ions entering later into the capillary.

In this work we present experimental results of the transmission of energetic, 1 MeV proton microbeam through a single, cylindrical shaped, macrometer-sized polytetrafluoroethylene capillary. The intensity, energy, deflection and charge state of the transmitted beam were investigated.

2. Experiment

In our measurements the length of the single PTFE capillary was L = 44.5 mm, the inner diameter was d = 800 μm. The tilt angle of the sample was 1° relative to the beam axis. The neutrality of the inner wall was ensured by switching a thermal electron source on before each measurement. The beam spot size was 1 × 1 μm^2 with divergence less than 0.3°. This beam spot size can be considered point-like with respect to the capillary inner diameter. Although the capillary tilt angle in our investigations is only 1° relative to the incident beam axis, it is already geometrically non-transparent for the incoming ions because of the large capillary aspect ratio (≈56) and the small beam divergence (see Figure 1).

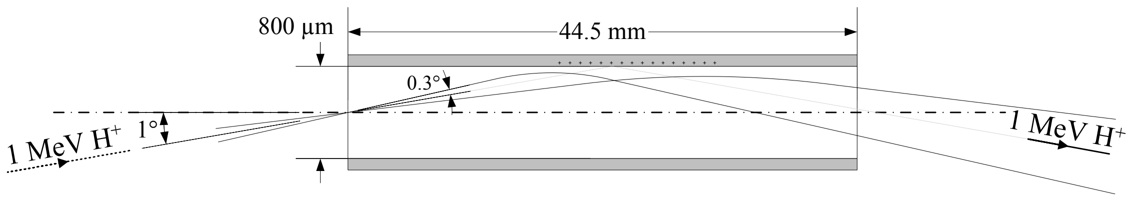

Figure 1. Schematic picture of our cylindrical shaped PTFE capillary sample. Note: the X and Y scales are different from the drawing, but the incident angle is shown as per calculations from the distances.

In order to perform the capillary experiments with proton microbeam, a new experimental setup had to be constructed. The Oxford-type scanning nuclear microprobe chamber installed on the 0° beamline of the 5 MV Van de Graaff accelerator of Atomki, Hungary, was modified. With the new setup we were able to measure the intensity, the energy distribution, the deflection and the charge state of the transmitted ions.

The crucial point of the precise measurement is the accurate alignment of the capillary with the beam axis. We aligned the sample with a 5-axis goniometer, which allowed the sample to be moved by 2 μm steps in 3 directions and to be rotated by 0.01° steps around 2 axes. Three different methods were combined for the alignment procedure, involving optical microscopy and Rutherford Backscattering Spectrometry (RBS) for the position alignment and observation of the transmitted beam for the angular alignment.

In order to measure the incident beam current, we placed a beam chopper [32] at the entrance of the target chamber, which allowed us to measure the incident beam current indirectly during the experiments, independently of what was being done behind the chopper in the vacuum chamber. At the exit of the capillary we placed a Faraday-cup in order to measure the intensity of the transmitted beam (see Figure 2a). The data acquisition software (OMDAQ2007, [33]) allowed us to log the signal of the current meter and the particle detector with 1 s time resolution. The transmitted current was compared to the incident current calculated from the signal of the beam chopper. The energy distribution of the transmitted particles was measured by a silicon surface barrier (SB) type particle detector that was mounted on a rotatable disk along with the Faraday-cup. In order to perform spectra collections, the Faraday-cup was replaced by the particle detector and the beam intensity was reduced down to about 1000 protons/sec by closing the object and collimator slits.

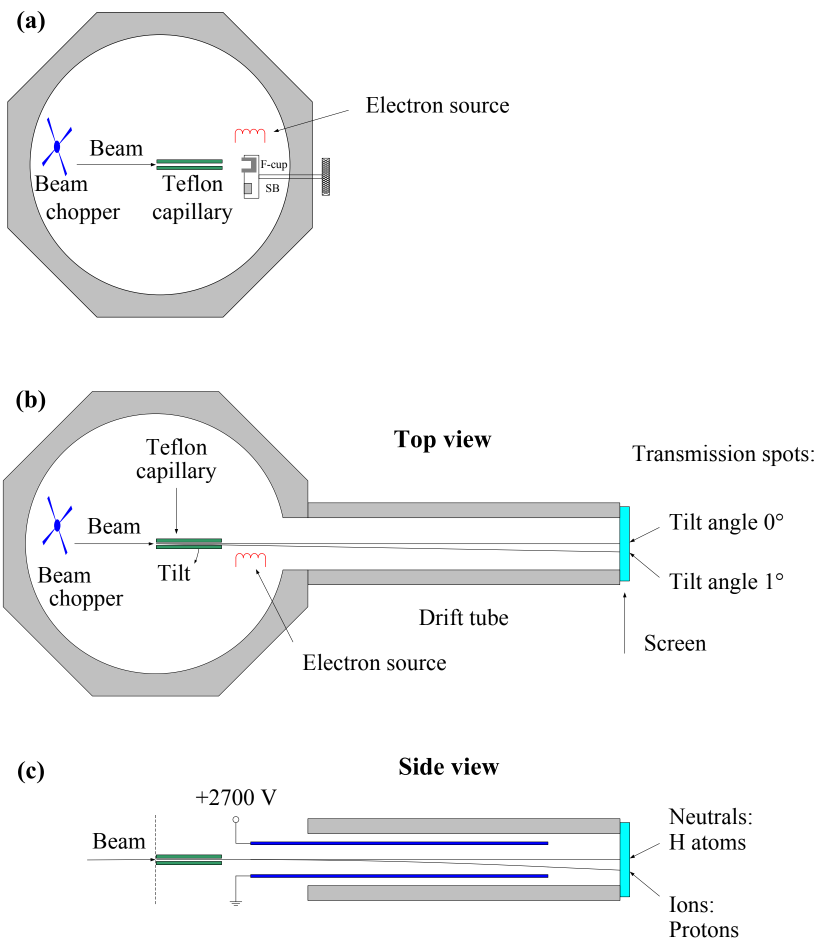

Figure 2. (Color online). Schematic view of the experimental setup: (**a**) was used for transmission measurements (Faraday-cup) and for energy determination (SB-detector); (**b**) is the top view of the fluorescent screen setup. It shows the observation of the beam spot shift due to the rotation; (**c**) is the side view. It shows the separation of charged and neutral particles.

The deflection and the charge state of the transmitted beam were also characterized. For this purpose the rotating disk containing the Faraday-cup and the detector was changed to a fluorescent screen which emits orange light where the beam hits it. 2.7 kV high voltage applied between two parallel copper electrodes was used to separate the protons and the neutral hydrogen atoms in order to determine the charge state of the transmitted particles (see Figure 2b,c).

3. Results and Discussion

First we studied the time dependence of the proton microbeam transmission. 25% of the incident beam was transmitted through promptly, which started to gradually increase immediately up to over 90%. This behaviour shows incident beam intensity dependence. Figure 3 shows the typical time dependence of the transmission rates. In the recent case the incident intensity is around 8 pA. When the transmission rate reached the plateau, a stable transmission was established, which is explained by the formed guiding electric field thanks to the accumulated charge on the inner wall of the capillary. The transmitted intensity ratio reached about 90% and then remained stable for over 2000 s, until the beam was turned off.

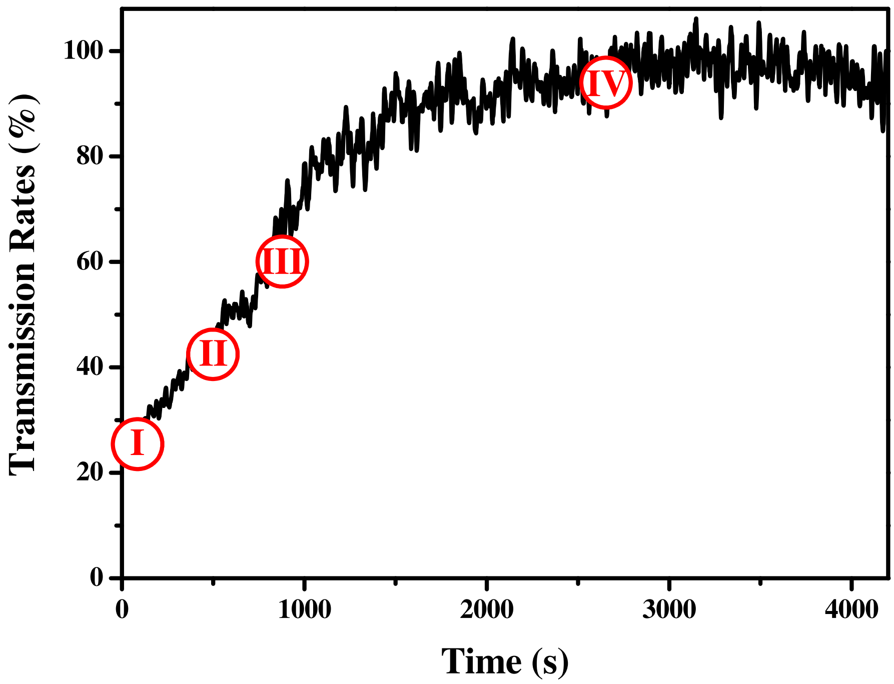

Figure 3. (Color online). Time dependence of the transmission rates. After the charge-up process the guiding remained stable until the measurement was stopped. The charge accumulated on the capillary wall was less than 14 nC, the surface charge density was 12 nC/mm^2. Circles with Roman numbers inside show the spectrum analysis moments.

During the charge-up process, we analyzed the energy spectra of the transmitted beam several times. We marked 4 time moments in Figure 3 where we present the corresponding energy spectra. First (I, in Figure 4) when the beam just entered to the capillary: here the transmission rate was about 25%. Next stages (II–III, in Figure 4) were near to the middle of the range of the transmission rate, and finally (IV, in Figure 4), when stable transmission is achieved. When the spectra were recorded, the particle detector was rotated into the beam axis instead of the Faraday-cup, and the beam intensity was reduced down to about 1000 protons/s, in order to save the detector from damage, by closing the object and collimator slits. After that, the detector was changed back to the Faraday-cup and the slits were opened out to their original state, thus the beam intensity was the same again. The transmission continued from where it stopped, so this behavior confirms that there was no significant loss of the charge on the wall during the measurement of the energy spectra.

Considering the collected spectra, we identified three completely different stages during the charge-up process in function of the transmission. At the beginning, when the transmission was low (25%), only inelastic contributions with energy lower than 1 MeV were found in the spectrum. This can be explained by the inelastic processes on the inner wall atoms. Later, when the transmission started to increase, the elastic (1 MeV) peak appeared besides the inelastically forward scattered region, and became more and more significant. Finally, when the stable transmission evolved, only the elastic peak was present and the inelastic area was totally absent due to the ion guiding (Figure 4). The width of this elastic peak is the same as the energy resolution of the particle detector.

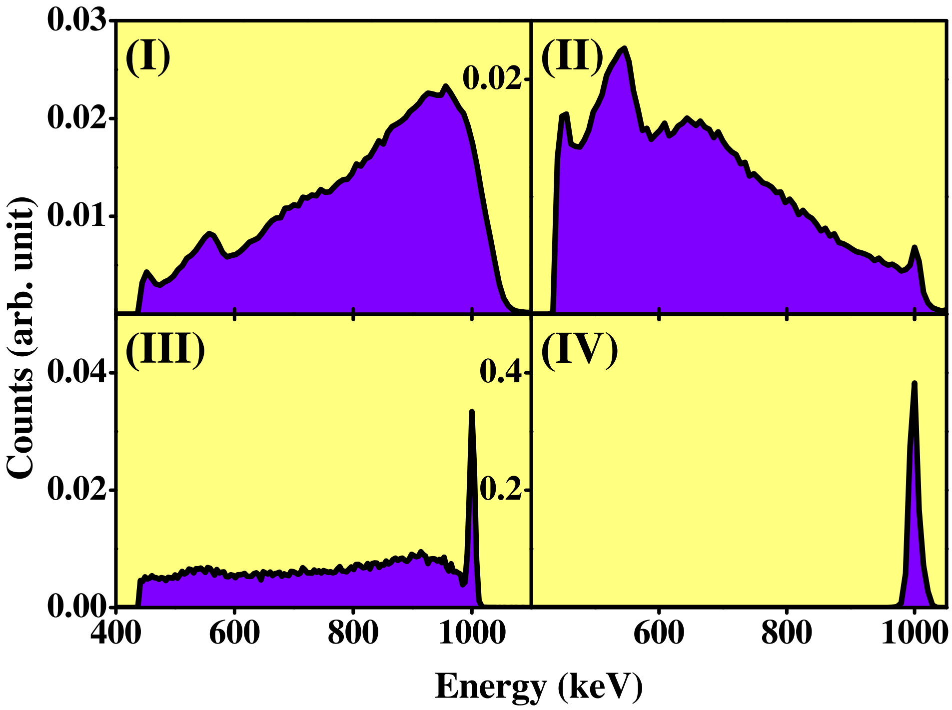

Figure 4. (Color online). Evolution of the energy distribution of the transmitted beam according to the time indicating by Roman numbers in figure 3. (I) At the time when the beam just entered to the capillary (the transmission rate was 25 %), (II) at the time when the transmission rate was 40 % (III) at the time when the transmission rate was 60 %, and (IV) at the time when stable transmission was achieved.

The results of our experiments, measuring the deflection of the incident beam showed, that the beam coming out from the capillary is parallel with the axis of that, i.e., the deflection of the beam is equal to the tilting angle (1°). In addition, the whole beam could be deflected vertically with the electrostatic deflectors, which proves, that the beam avoided the charge-exchange with the target and kept its initial 1+ charge state. Our experimental finding was certificated by our recent theoretical works [34].

4. Conclusions

Experimental results of 1 MeV proton microbeam transmission through PTFE capillary were presented. The single, straight PTFE macrocapillary was tilted to 1° with respect to the beam axis in the experiments. Evolution of the transmitted beam intensity was observed by a Faraday-cup and energy spectra of the transmitted particles were measured by a particle detector behind the capillary sample. The deflection was measured on a fluorescent screen and the charge state was determined with the help of an electrostatic parallel plate deflector. Our results proved that the guiding effect is observable for MeV energy ions, thus significant transmission can take place even through a tilted macrocapillary sample when the sample is geometrically not transparent. This can count on a wide and broad interest in the scientific community, since e.g., it can make a way to focus high energy ion beams using passive elements without any external power supplies. We have also analyzed the energy distribution of the transmitted protons at different stages of the charge-up process. We identified three completely different regions in the transmission as a function of time. First, at the beginning of the creation of the charge patch on the inner wall of the capillary, the energy spectrum of the transmitted protons contained only inelastic contributions. This is due to inelastic scattering on the inner wall atoms. Later, as time goes by, the elastic peak also appears and becomes more and more significant. Finally, in the third region, when the amount of deposited charge on the wall reached a dynamical equilibrium, a stable guided transmission was obtained. The dominant contribution in the energy distribution of the transmitted protons did not suffer energy loss. The whole beam kept its initial 1+ charge state, i.e., the transmitted particles remained protons instead of becoming neutral H atoms. The high efficiency transmission of the beam in initial kinetic energy and charge state proves that pure guided transmission of the energetic 1 MeV ion beam is possible by properly choosing the optimal conditions.

Author Contributions: K.T.: Design the measurements, participate in the measurements and evaluation of the data, writing—review and editing, supervision; I.R.: Design the measurements, participate in the measurements and evaluation of the data; G.N.: Perform the measurements, evaluation of the data, writing; R.J.B.: Participate in the measurements and evaluation of the data, writing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data in numerical form are available upon request.

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