Imaging the photons during transmission of ions through glass capillaries

N Akram and R Schuch
Physics Department, Stockholm University, S-106 91 Stockholm, Sweden
E-mail: schuch@fysik.su.se

Abstract. Charged particles, in particular slow highly charged ions, can be guided through nanocapillaries in various insulating materials by self-organized charge patches. We present a technique for observing directly the formation of these patches in glass capillaries. It is based on imaging the emitted visible photons. We report here on tests with 4.5 keV Ar$^+$-ions transmitted through straight and tapered borosilicate capillaries, using a highly sensitive digital camera. Simultaneously, the ions transmitted through the capillaries were detected. The number of emitted photons decreases by increasing the tilt angle of the capillary. The time evolution of emitted photons revealed a change of location of the charge patches during charging-up the capillary walls.

1. Introduction
Highly charged ions (HCI) can be transmitted through nanocapillaries in insulating materials even when the injection angles are larger than the geometrical opening angle of the capillaries without changing charge and energy. A single glass capillary also exhibits a similar feature of transmitting incident HCI (for larger injection angles). Such a phenomenon has been termed as “guiding” and is credited to the self-organized formation of charge patches by the incident ions on the capillary inner walls which guide the subsequent ions along the capillary axis.

Since the first observation of guiding phenomenon in polyethylene teraphthalate (PET) nanocapillaries [1], several other groups have extensively studied the guiding of HCI in different insulating materials like Al$_2$O$_3$, SiO$_2$, polycarbonate and mica [2-7]. Also for a single glass capillary the guiding and transmission process was characterized[8, 9]. In particular, as single tapered glass capillary have a potential application to selectively damage a single biological cell [10] and for controlled surface modifications [11].

Guiding involves charging-up of the inner capillary walls which is a time dependent process and the steady state of transmission is achieved when equilibrium between deposition of charges and drainage of charges is attained. The time evolution of the transmitted ion intensity and direction gives an indirect insight to the charge patches formed on the capillary walls [5,6,12,13].

In this paper, we report first results from directly visualizing the formation of charge patches inside a glass capillary. This was done by imaging the emitted visible photons when 4.5 keV Ar$^+$-ions interact with the inner walls of a glass capillary, by means of a highly sensitive digital camera. When forming charge patches in the capillary to guide subsequent ions, the initially incident ions hit its wall and by that the incident ions and atoms in the wall are excited which results in emission of photons. By imaging these emitted photons we can infer information about the location of charge patches. In the first part, we present the images of emitted photons for different orientations of the capillary with respect to the incident beam direction. Later, the temporal evolution of the emitted visible photons is presented as images for 0º tilt angle with respect to the incident beam direction and capillary axis.

1 To whom any correspondence should be addressed.
2. Experimental setup

The experiments were performed at S-EBIT laboratory of Stockholm University, Stockholm. Intense beams of Ar\(^{\text{+}}\)-ions were extracted at the energy of 4.5 keV from a Penning Ion Gauge (PIG) source and collimated on the way to the experimental chamber. The overall pressure was maintained at \( \sim 10^{-7} \) mbar. The glass capillary samples were mounted on a goniometer with three spatial and two-angular adjustments, to align it with the incident beam. To avoid charging-up effects at the entrance of the capillary, a grounded Al aperture of 0.4 mm diameter was placed there. A schematic of the experimental setup is shown in Fig.1. The beam current incident on the entrance aperture was around 50 nA. The transmitted ions were detected using a Faraday cup or a channeltron detector which was placed at 50 cm from the capillary exit.

We used two borosilicate glass capillary samples of length 54 mm with an outer diameter of 1.0 mm and inner diameter of 0.5 mm. But one capillary was tapered to have an exit size of 50 \( \mu \)m. The straight one had a geometrical opening angle of 0.53° or an aspect ratio of 110. The tapered one had a geometrical opening angle of 0.06°. It was prepared by heating and pulling a straight glass tube using a Sutter laser puller. Both glass capillary samples have same composition of SiO\(_2\) 72 %, B\(_2\)O\(_3\) 12%, Al\(_2\)O\(_3\) 7%, Na\(_2\)O 6%, K\(_2\)O 3%, CaO 0.5% and MgO 0.2%.

A Nikon D3s camera at an ISO setting of 12.8k was used to image the photons. It should have a quantum efficiency of \( \sim 53 \% \) [14]. In order to avoid background photons, it was completely shielded from room light, as well as from photons from ions hitting apertures. In the selection of a lens, focal length and aperture, an optimum in transmitted light intensity and image size for the given geometry was found essentially from: relative transmitted light intensity \( I = (a-f)^2/(aF)^2 \). That optimum was for a =220 mm (distance to object) at a focal length of \( f=55\text{mm} \) and aperture number \( F=1.2 \). That gives an image ratio (magnification) of 0.4. The CCD chip has a size of 24 x 35 mm\(^2\) with 12 x 10\(^6\) pixels, thus, each pixel images an area of 21 x 21 \( \mu \text{m}^2 \) of the capillary. The total relative solid angle is (assuming the photon-emission is isotropic) \( 2 \times 10^{-3} \), and with the quantum efficiency of the D3s, the total detection efficiency per pixel is roughly \( 1 \times 10^{-10} \).

![Figure 1](image.png)

**Figure 1.** Schematic of the experimental setup. Tilt angle is the angle between capillary axis and the incident beam direction.

3. Results and discussions

3.1. Photon imaging at different tilt angles

First, we investigated the emitted visible photons with the tapered glass capillary for different tilt angles (see Fig. 1) in steps of 0.6°. Fig. 2 shows the images taken for an exposure time of 30 sec for each angle. As seen, with increasing tilt angle the radiant portion of the capillary is shortened towards
the entrance side of the capillary. Also the photons from ions hitting the tapered exit of the capillary
disappears already at 0.6°. This corresponds to the exposed length of the capillary to the incident beam
(the geometrical acceptance angle is 0.53°).

![Schematic view from camera](image)

**Figure 2.** Images for an exposure time of 30 sec for different tilt angles with a tapered borosilicate
glass capillary. First and second images show the mounted capillary (in colour on-line).

For quantitative analysis: we use that all ions, entering the capillary (3.2×10^9 ions/sec), interact with
the capillary wall, because transmission through the capillary is less than 2 % in steady state. If
we assume that every ion hitting the capillary wall contributes with the emission of a photon, then
a rate of 3×10^6 photons/sec should be detected. If we assume additionally that the ions are lost
uniformly along the inner surface of the capillary, in that case 5×10^4 photons/sec should be
projected on a single pixel on the CCD. Counting the illuminated pixels in the images, we find a
much lower rate. That could mean a much lower photon emission efficiency per ion and also that
much more then one or two photons hit a pixel.

We also find that the normalized number of illuminated pixels decreases with increasing tilt angle of
the capillary (nearly exactly inverse proportional). However, with increasing the tilt angle, the density
of ions increases that hits the inner wall of the capillary which should result in an increase of the
number of emitted photons from this area. Hence, the number of detected photons per pixel should
increase there which can not be registered with such a camera and thus for longer exposure times the
photon number hitting a pixel can be much larger then unity.

3.2. Time evolution of charge patches from imaged photons
The photon imaging method should allow “to see” the temporary behaviour of charging-up and
formation of charge patches on the capillary walls. For this purpose we started with an initially
uncharged glass capillary. The capillary was oriented at a tilt angle, 0°, and then left to discharge for
20h. The time evolution of emitted photon patterns for tapered glass capillary is shown in Fig. 4. It is
clearly seen that the emitted photons come from different locations on the capillary with time when the
wall is charged up.
Figure 3. Images for $0^\circ$ tilt angle, with initially uncharged tapered glass capillary as function of time (in colour on-line). The recording time intervals are stated to the right of each image.

We also performed measurements of the time evolution of emitted photons for straight borosilicate glass capillary. Fig. 4 shows the time evolution of emitted photons from the inner wall of the straight glass capillary when 4.5 keV Ar$^{1+}$-ions are transmitted through it for a tilt angle of $0^\circ$. As seen, the location of emitted photons varies slightly during the course of time.

Figure 4. Images for $0^\circ$ tilt angle and initially uncharged straight glass capillary as function of time.

It is seen in Fig. 4, the number of emitted photons increases with time, as also shown in Fig. 5a, whereas the transmitted current decreases with the deposition of charge inside the capillary as shown in Fig. 5b. We observe a short burst in transmitted current in the start and a decrease to a constant value relative to the incident current. A similar behaviour was also seen by other groups at $0^\circ$ tilt.
angle[15]. As the increase of emitted photons is in accord with the decrease of transmitted current, we conclude that the ions are blocked inside the capillary and interact with the wall leading to higher photon emission.

4. Summary

We report imaging of visible photons which are emitted during interaction of 4.5 keV Ar$^{1+}$-ions with inner walls of borosilicate glass capillary. This new method provides a direct visualization of charge patches formed inside the glass capillary during ion-transmission. The time evolution of the imaged visible photons reveals that the charge patches change their location in the process of reaching the steady state of transmission. It is also found that the intensity of emitted photons is reasonably consistent with that of the transmitted ions.

We acknowledge support by the K&A Wallenberg foundation and Swedish Research Council (VR).

References

[1] Stolterfoht N et al. 2002 Phys. Rev. Lett. 88, 133201
[2] Sahana M B, Skog P, Víkor G, Rajendra Kumar R and Schuch R 2006 Phys. Rev. A 73, 040901
[3] Mátéfi-Tempfli S et al. 2006 Nanotechnology 17, 3915
[4] Skog P, Zhang HQ, and Schuch R 2008 Phys. Rev. Lett. 101, 223202
[5] Kanai Y et al. 2009 Phys. Rev. A 79, 012711
[6] Zhang HQ, Akram N, Skog P, Soroka I L and Schuch R 2012 Phys. Rev. Lett. 108, 193202
[7] Lemell C, Burgsdörfer J, Aumayr F 2013 Progr. in Surface Sci. 88, 237
[8] Ikeda T et al. 2006 Appl. Phys. Lett. 89 (16) 163502
[9] Bereczky R J, Kowarik G, Aumayr F, Tőkési K 2009 Nuclear Instr. Meth. B 267 317
[10] Iwai Y et al. 2008 Appl. Phys. Lett., 92(2):023509
[11] Lemell C et al. 2007 Solid State Electr, 51, 1398
[12] Stolterfoht N et al. 2009 Phys. Rev. A 79, 022901
[13] Cassimi A et al. 2009 Nuclear Instr. Meth. B 267, 674
[14] http://forums.dpreview.com/forums/read.asp?forum=1019&message=34581894
[15] Kreller M, Zschornack G, Kentsch U 2011 Nuclear Instr. Meth. 269, 1032