Time and Angular Distributions of Ions Transmitted through Insulating Capillaries

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Tasks and Objects

- ✓ Introduction and motivation
- ✓ Experimental setup designed for studying the transmission of swift ions through capillary systems
- ✓ Micro- and nanocapillary systems
- ✓ Transmission of 240 – keV protons through capillaries

Transport of charge particle beams through dielectric capillaries

The principle of new optics discussed in this report is based on interaction of slipping beams of charged particles with a charged insulating surface of capillary walls. To a certain degree, it resembles us the motion of charged particles in **channeling** regimes along the low-index directions of crystal lattices, or quanta motion in the **wavequide** regime.

Wave mechanical behaviour in angular distributions of transmitted heavy particles may be revealed for such capillary systems.

Potential implementations of the phenomenon

Analysis of the effect of surface charge on the character of motion of the ion beam forming this charge on an insulator is of interest both for new ion optics and for analysis of the interaction of particles with insulators at small angles of beam incidence with respect to the surface.

The phenomenon of slip of ion beams along a charged dielectric surface can be used to develop systems of transformation, control, and transport of charged particle beams; in particular, to obtain micro- and nanosized beams, which are interesting in local elemental and structural analysis, nanolithography, and applications in biology and medicine.

Potential implementations of the phenomenon

In comparison with the existing tools for formation of micrometer- and nanometer-sized beams, this method is undoubtedly simpler and less expensive. At the same time, is satisfies all the requirements of submicron Rutherford backscattering spectrometry or analysis with application of induced characteristic X rays (PIXE).

Previous publications on these topics:

- N. Stolterfoht *et al*. Phys. Rev. Lett., 88 (2002) 133201.
- T. Nebiki *et al*. J. Vac. Sci. Technol., A21 (2003) 1671.
- A. Razpet *et al*., NIM B222 (2004) 593.
- T. Nebiki *et al*., NIM B249 (2006) 226.
- F.F. Komarov *et al*., Bulletin of the Russian Acad. Sci: Phys. 72 (2008) 644.

Porous systems based on ion tracks

A suitable tool for producing straight nanocapillaries with a large aspect ratio (of 100 and more) is that of ion tracks created by energetic heavy ions in the solid. Using well-known etching techniques, the ion tracks can be transformed to mesoscopic capillaries whose dimensions range from a few nm to a few µm.

There is a wide range of applications linked either to direct pattering of materials or to depositing materials into the pores of etched ion track membranes.

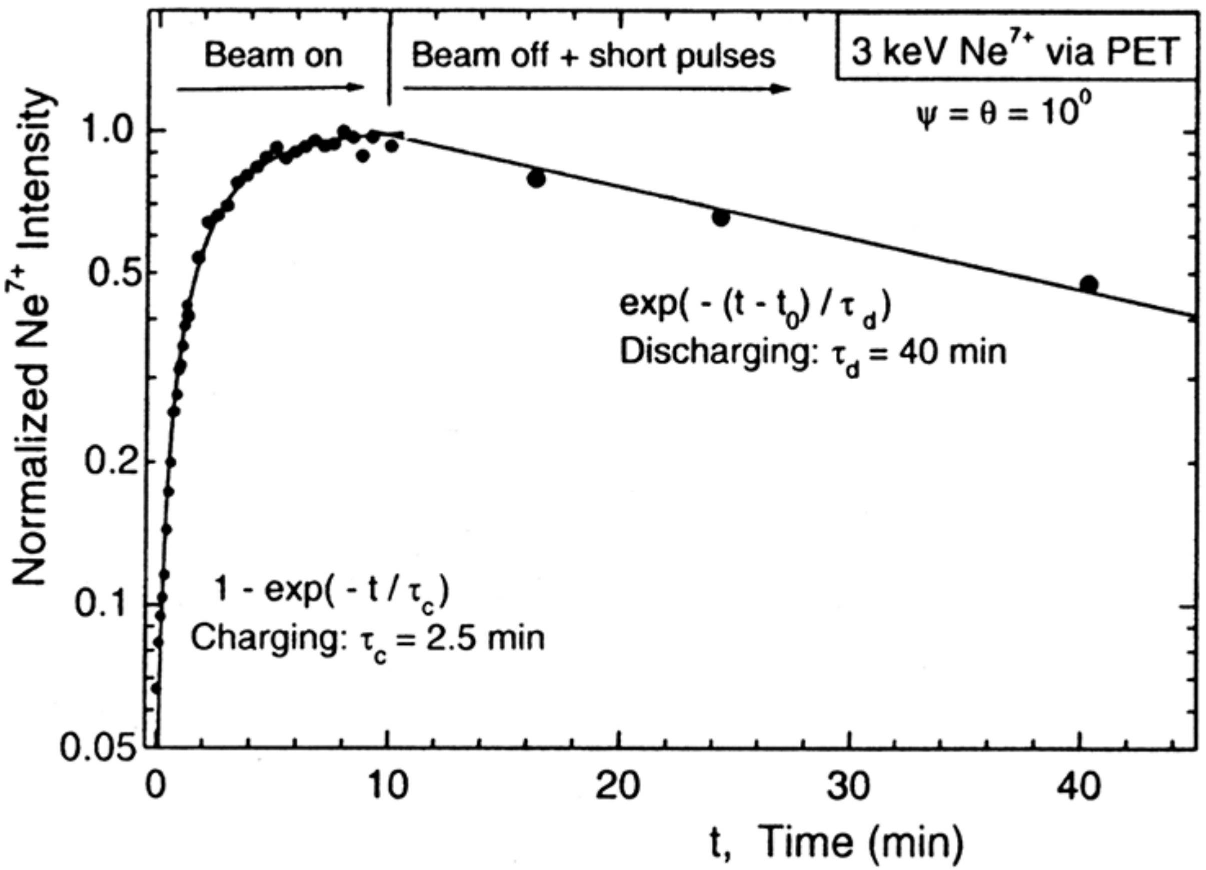
Fabrication of nanocapillaries in polymers

As a unprecedented result on the low energy ion transmission through such capillaries I illustrate an experiment of N. Stoltefoht *et el*. (NIM B203 (2003) 246).

They measured the transmission of 3 keV Ne^{7+} ions through capillaries of 100 nm diameter and 10 μm length produced by etching ion tracks in a polyethylene terephthalate polymer foil. The foils were tilted up to ±25°. The majority of Ne^{7+} ions were found to survive the transmission in their initial charge. This capillary guiding of the Ne^{7+} ion provides evidence that the inner walls of the capillaries become charged and electron capture from the surface is suppressed in a self-organizing process.

Capillary systems based on ion tracks

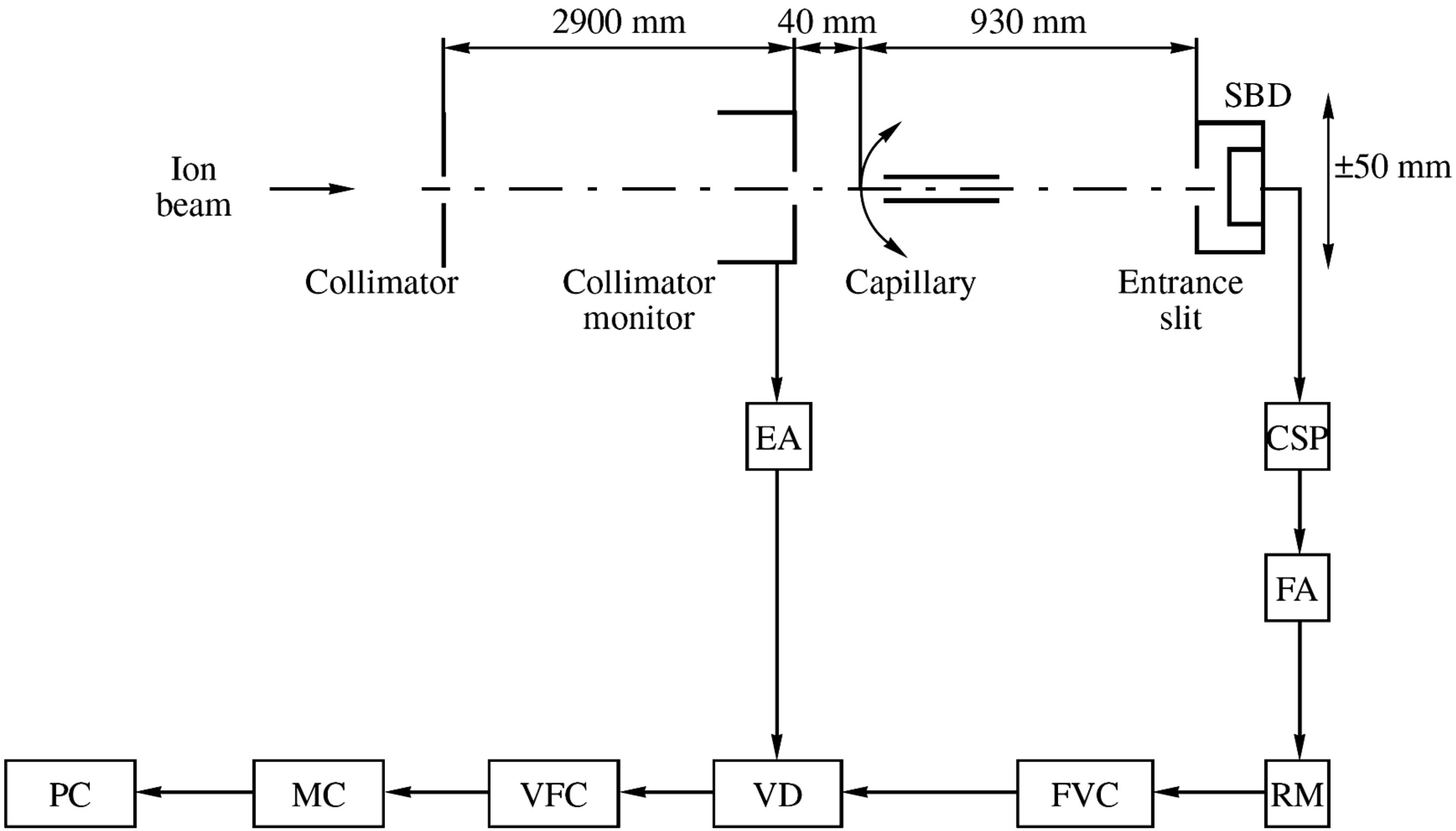
Time dependence of the transmitted Ne^{7+} intensity showing the charging and discharging phenomena of capillaries in PET



A beam of 1.3 nA Ne^{7+} ions is directed onto the PET foil tilted at 10°.

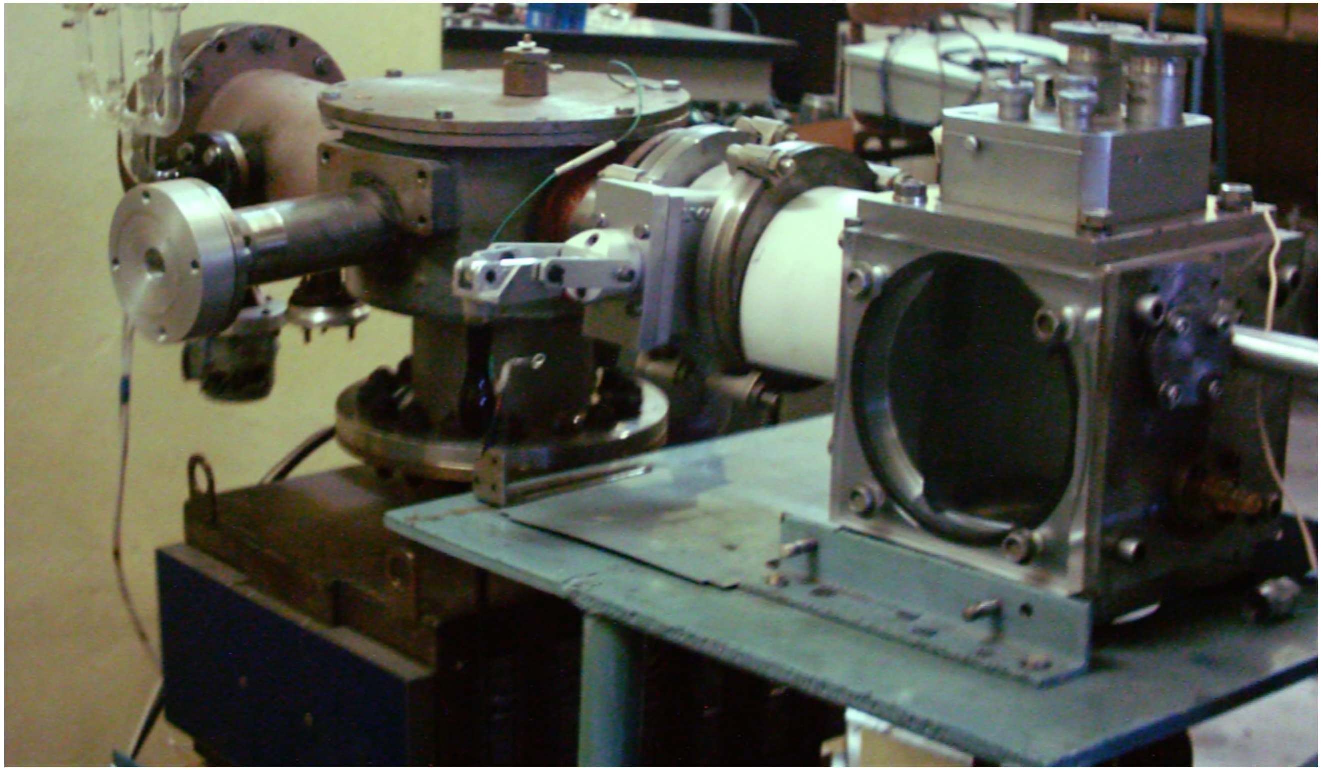
The transmitted Ne^{7+} intensity measured at 10° increases exponentially with a time constant of 2.5 min. After 10 min the beam is turned off. Short beam pulses probe the decrease of the transmission with a time constant of 40 min.

Experimental Setup



Schematic of the experimental setup: (MC) matching circuit, (VFC) voltage-frequency converter, (VD) voltage divider, (EA) electrometric amplifier, (FVC) frequency-voltage converter, (RM) programmable rate meter, (FA) forming amplifier, (CSP) chargesensitive preamplifier, (SBD) silicon surface barrier detector, and (PC) personal computer.

Experimental Setup



Analytical equipment to study processes of charged particle interaction with capillary systems

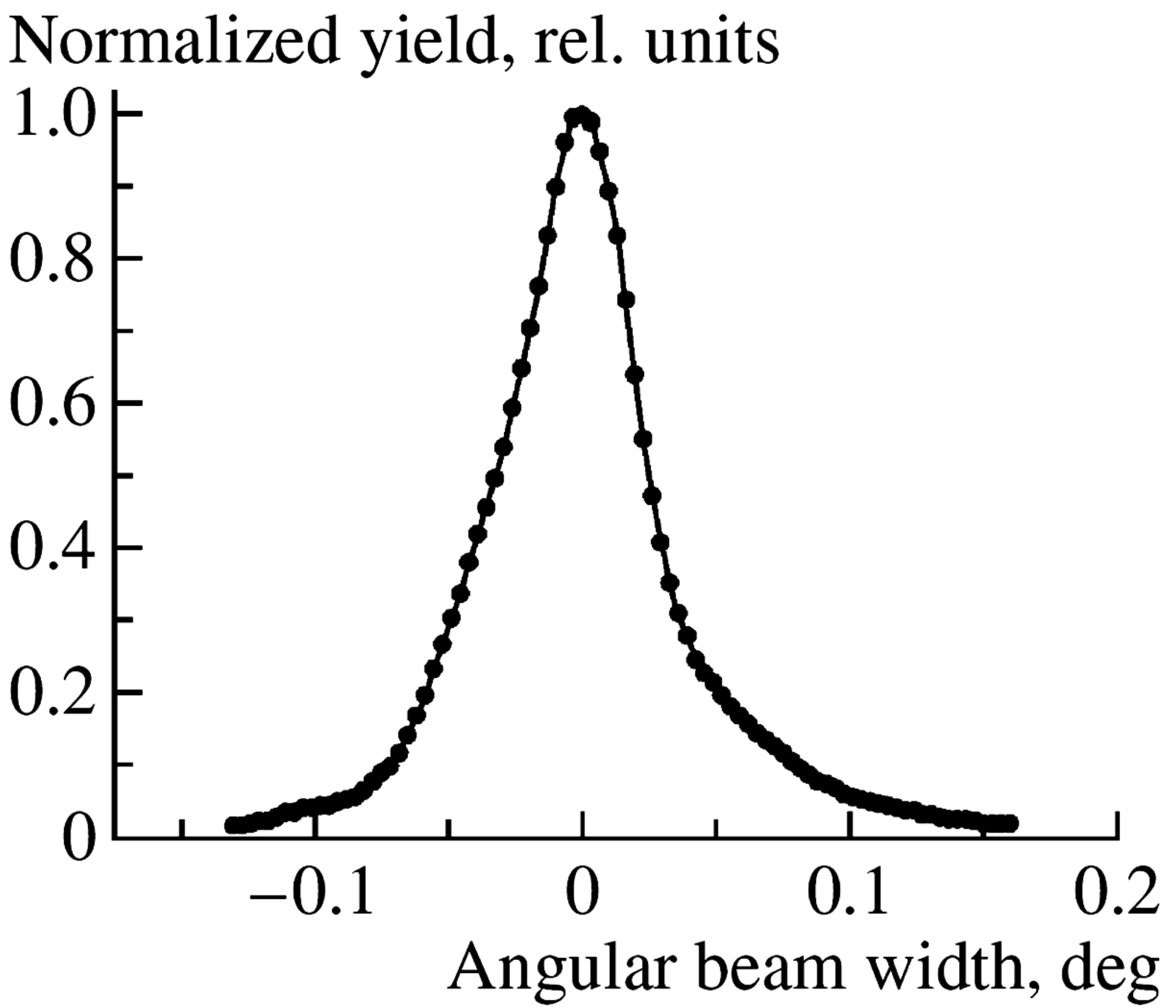
Experimental Setup

This setup, which enters the implantation complex, formed on the basis of an ESU-2 electrostatic ion accelerator, consists of four units: **(1)** a system of ion beams formation, **(2)** a scattering chamber, **(3)** a measuring chamber, and **(4)** a system for detecting scattered ions.

The parameters of the setup are as follows:

- ✓ the error in determining angles in measurement of angular distributions is not larger than 3.3×10^{-3} deg.
- ✓ the error in the capillary orientation with respect to the beam axis is not larger than 2.5×10^{-2} deg.
- ✓ the angular divergence of the initial beam $\pm$ 3.0×10^{-2} deg.
- ✓ the total measured energy resolution of the recording system does not exceed 20 keV

Measurement of the angular divergence of the initial beam



Shape and angular width of a 240-keV proton beam

Micro – and nanocapillary systems

- glass
  (borosilicate)
  capillaries
  wi
  th a diameter of 0.5 mm and lengths of 65 and 178 mm;
- glass
  (borosilicate)
  ca
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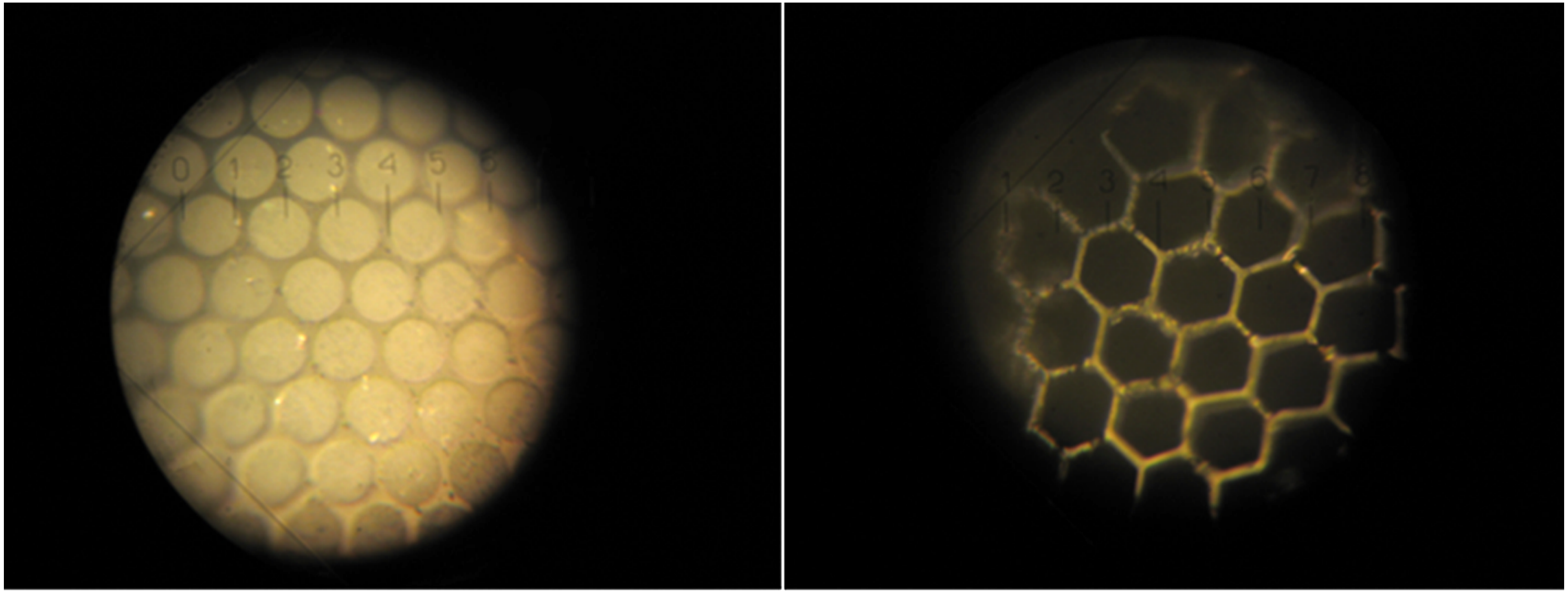
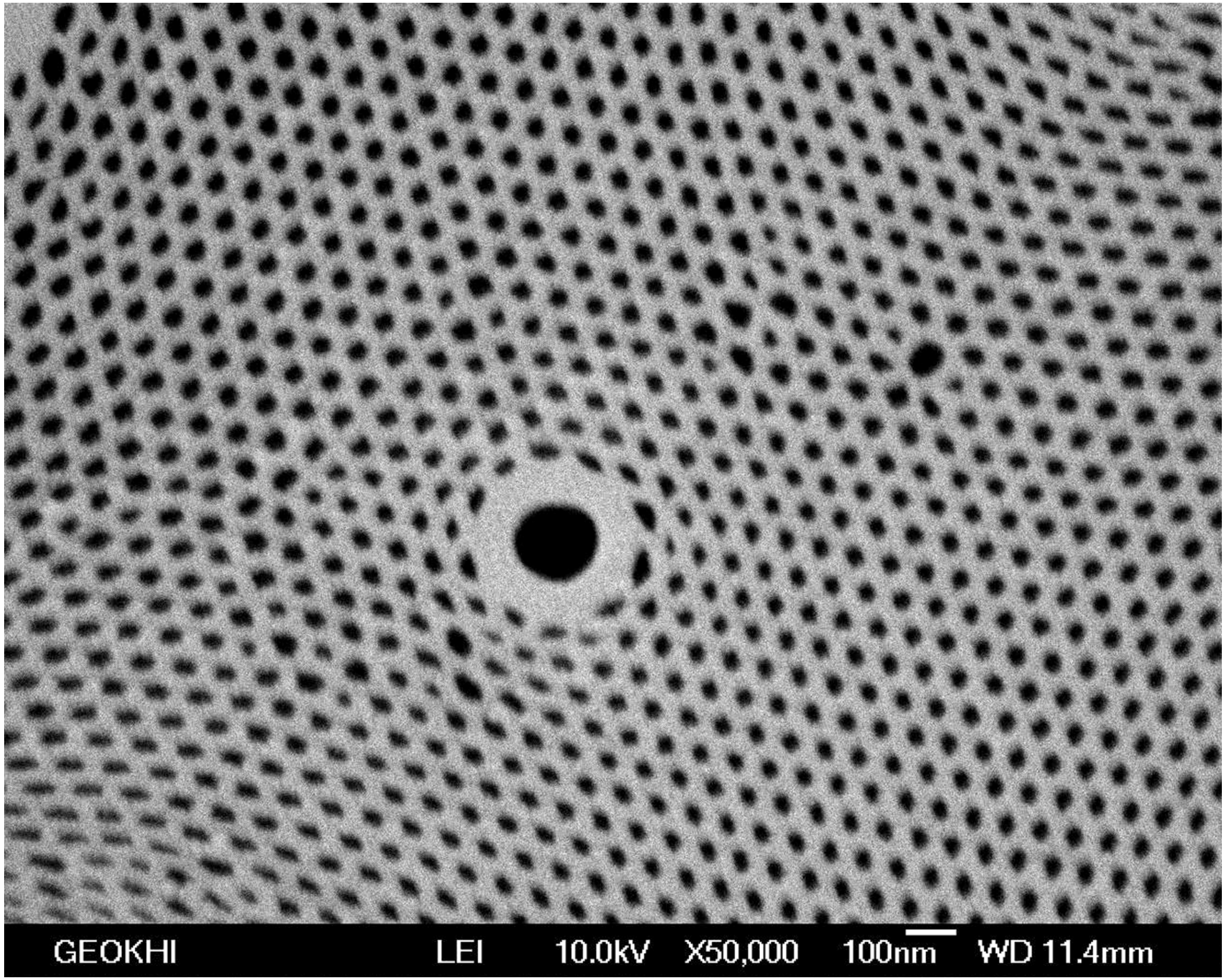
  illaries with a diameter of 0.1 mm and length of 30 mm;
- the Kumakhov's
  micr
  ocapillaries systems, with a diameter of 10 μm to 30 nm;
- arrays of uniform-sized
  n

Micro – and nanocapillary systems



The Kumakhov′s
microcapilla
ry system with a diameter of 5 µm of individual glass capillaries

Micro – and nanocapillary systems



The Kumakhov's
microcapillary system with a diameter of 30 nm of individual glass capillaries

Top view SEM pictures of ordered alumina pore arrays

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An alumina membrane produced under certain electrochemical conditions posses a porous structure with uniform and parallel nanopores. Pore densities as high as 10^{11} pores/cm^2 are obtained and typical membrane thickness can range from 10 to 200 μm

Micro – and nanocapillary systems

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Highly-ordered carbon nanotube arrays

(a) SEM image showing oblique view of periodic carbon nanotube array. The inset at the lower left is an enlarged view of the tubes. The inset at the lower right is a histogram of the nanotube diameter showing a narrow size distribution around 47 nm.

(b) Top-view SEM image of the carbon nanotubes showing hexagonal closepacked geometry.

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The shape of angular distribution of the protons transmitted through such a short capillary is determined to a large extent by single scattering of particles from the inner surface of the capillary.

Angular distribution of 240-keV protons transmitted through capillaries with a diameter of 0.5 mm and length of 65 mm.

Displacement angle of:

a) 0.0°; **b)** 0.15°; **c)** 0.20°

Transmission of 240-keV protons through capillaries

The registered transformation of the central peak of the angular distribution in the previous case to the dip at the center here is due to the effect of the charge accumulated on the inner surface of the capillary.

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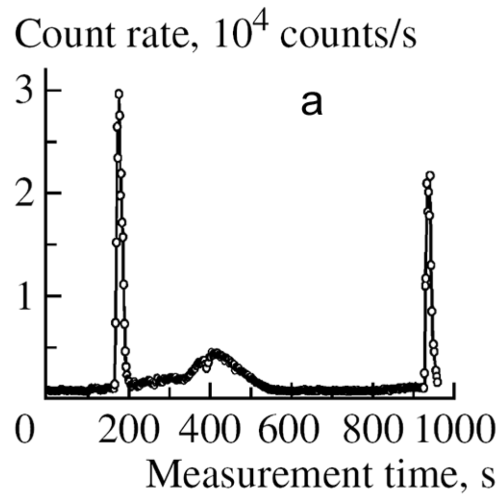
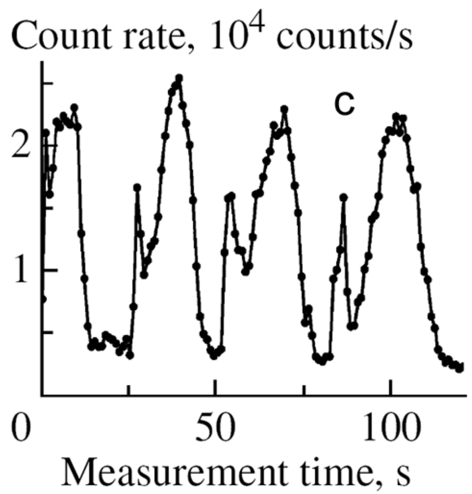
Angular distributions of 240-keV protons transmitted through capillaries with a diameter of 0.5 mm and length of 178 mm.

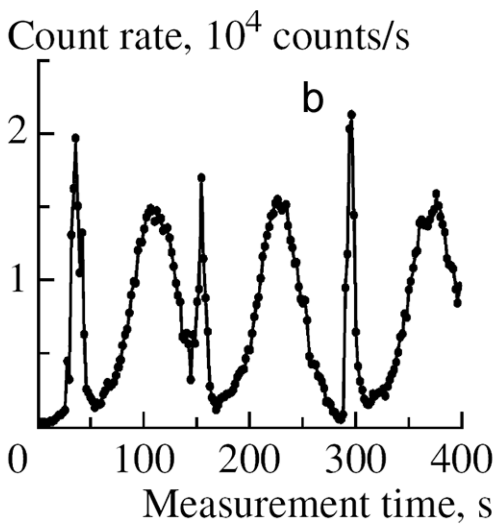
Displacement angle of:

a) 0.0°; **b)** 0.05°; **c)** 0.1°

Transmission of 240-keV protons through capillaries





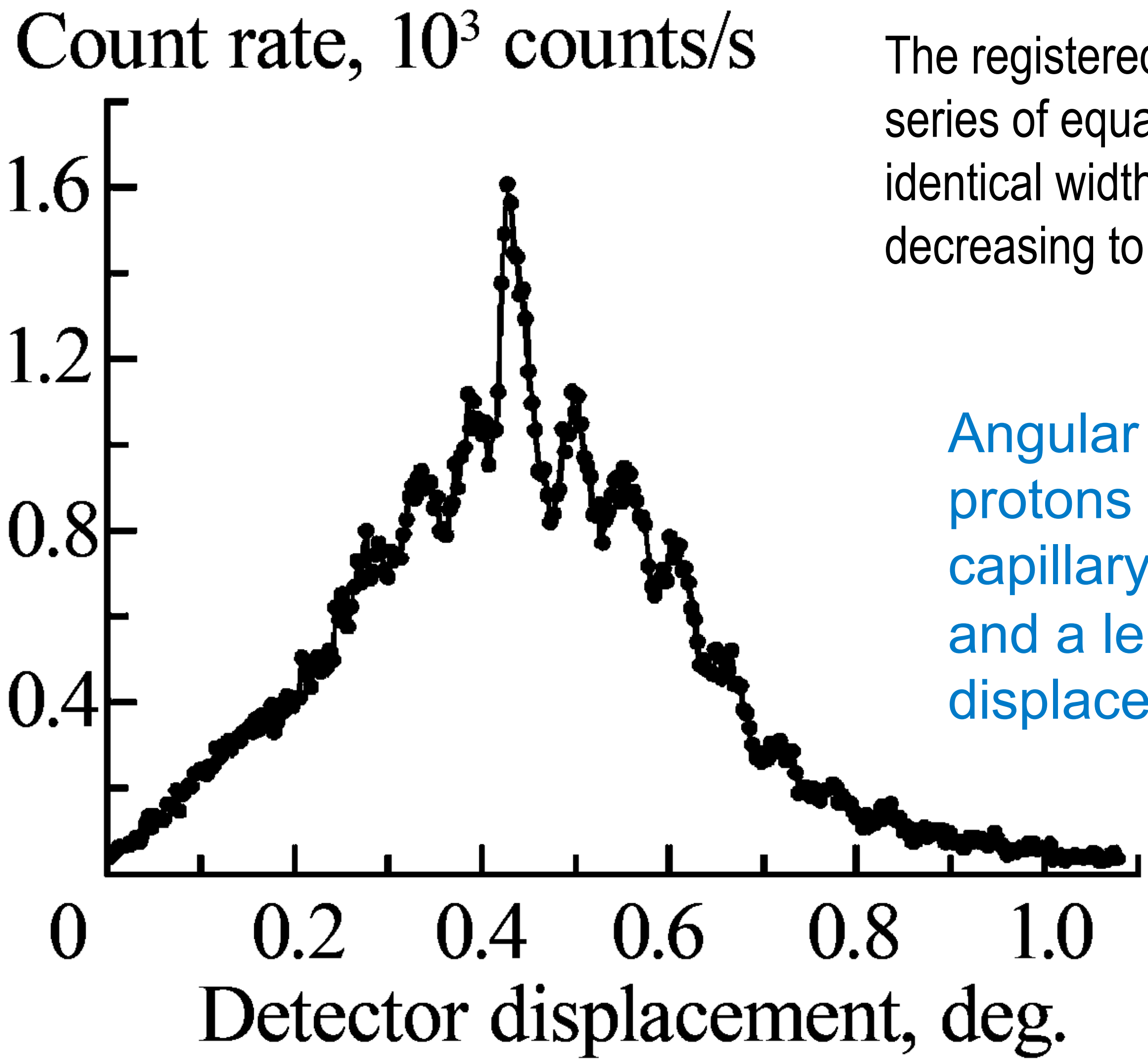


The effect of the accumulated charge is even more pronounced in this Fig. It can be seen that increase of the ion current at the input of the capillary leads to a significant increase in the average number of protons transmitted through it. A reverse proportionality between the increase in the current and the time interval between the similar peaks is indicative of gradual compensation for the capillary leakage currents.

Time distributions of 240-keV protons transmitted through a capillary with a diameter of 0.1 mm and a length of 30 mm at a constant displacement angle.

The proton current at the input of the capillary is **a)** 0.85, **b)** 3.7, and **c)** 15 pA.

Transmission of 240-keV protons through capillaries



The registered distribution has the form of a series of equally spaced peaks of almost identical width and an amplitude gradually decreasing to the distribution edges.

Angular distribution of 240-keV protons transmitted through a capillary with a diameter of 0.1 mm and a length of 30 mm at a displacement angle of 0.15°

Transmission of 240-keV protons through capillaries

The continuous angular distribution of the initial beam is transformed into a line one, with a spacing of 0.06° between lines. One might suggest that under the above experimental conditions the initial beam is split in the field of the charged capillary (capillary potential) into a series of lines with transverse energies differing by $\Delta E_{\perp} = E(\Delta\varphi)^2 = 0.24$ eV.

Prof. M.W. Thompson in his review paper "The channeling of particle in crystals" (Contemp. Phys. 9 (1968) 375) postulated that for heavy particles classical theory can explain any experiments performed so far, but it is just possible that the interpretation of more precise proton experiments may require wave mechanics.

Our estimation of a field formed by proton beam in the capillary and corresponding potential well show extremely low distances between levels of the transverse energy (about 10^{-7} eV).

Summarizing

- ✓ The shape of the angular distributions of protons transmitted through a glass capillary with a diameter of 0.5 mm and a length of 65 mm is determined to a large extent by single scattering of charged particles from the inner surface of the capillary.
- ✓ With an increase in the capillary length by a factor of 3, the angular distribution shape begins to be affected by charging of the inner surface of the capillary.
- ✓ A decrease in the diameter of the capillary to 0.1 mm revealed that transmission of protons through it is determined mainly by the degree of charging of its inner surface. Competition of the processes of charging of the inner surface and charge leakage in narrow capillaries results in an oscillating time dependence of the transmitted ion current.
- ✓ An effect of redistribution of an ion beam over exit angles is revealed; i.e., the initial beam is split into a series of lines, spaced by 0.06° ($\Delta E_{\perp}$ = 0.24 eV) from each other, in the charged capillary field.

THANKS FOR ATTENTION