EXPERIMENTAL RESULTS OF THE BEAM DYNAMICS BY USING GLASS CAPILLARIES FOR THE ESA-2

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Abstract

In comparison with the existing tools for formation of micrometer-sized beams, capillary method is undoubtedly simpler and less expensive. At the same time, is satisfies all the requirements of submicron Rutherford backscattering spectrometry (RBS) or analysis with application of induced characteristic X-rays. The processes of interaction of accelerated protons with the surface of insulating capillaries have been investigated to determine the character of motion of particles during such interaction. The angular distributions of 240 keV protons transmitted through glass capillaries have been measured, and splitting of the distribution into a series of lines equally spaced from each other is revealed. Protons passed through the glasses (boron-silicon) capillaries with a diameter of 0.1, 0.5 and length of 30, 65, 178 mm at the axial entry angles of particles ± 0.2º and in the range of proton beam currents from $8{,}5\cdot10^{-13}$ to 10^{-11} A. Ion-optical characteristics of an tapered glass capillary were studied. We present evidence of the focusing effects of fine glass capillary optics for proton ion beams. The glass capillary optics is formed by a puller as to have inlet diameters of about 3 mm and outlet diameters of submicrons. The total length of the optics is about 80 mm. Impingent 240 keV protons to such optics are reflected by the inner wall several times, in a very similar process to the so-called surface channeling.

INTRODUCTION

Aberrations of electron and ion optical systems are the fundamental restriction for designing of any optical systems [1]. Applying additional charges, non-uniform static and alternating fields or different kind of field symmetry approach the compensation of aberrations to a great extent can be reached. However, such compensations are technically complicated and essentially increase cost of the setups as whole. The more efficient way is to apply inside of the setups such elements and systems which could ensure the necessary minimum aberrations itself. This work is aimed to give an analysis of the operation of such systems.

Recently the guiding of highly charged ions through insulating cylindrical capillary has been studied in several laboratories [2-4]. A phenomenon of slipping of charged particles beams along the charged dielectric surface can be used for some practical applications. In general, this is based on interaction of slipped ion beams with a smooth internal surface of a glass capillary wall. The new systems of transformation, controlling and transporting of charged particle beams could be developed based on this principle. Also, micro- and nanometer size ion beams can be reached that especially have importance for applications in the local elemental and structures analysis, nanolithography, biology, radio-ecology and medicine. Comparing with already existing micrometer size ion techniques the offered method is simpler and cheaper. This can simply ensure the method of less than one micrometer size RBS spectroscopy and X-ray analysis [5].

Studies devoted to interaction of ion beams with insulators take a particular place in the investigations of the effect of charged particles on materials. Analysis of the effect of surface charges on the character of motion of the ion beam forming this charge on an insulator is of interest both for new ionic optics and for analysis of the interaction of radiation with insulators at small angles of beam incidence with respect to the surface.

In order to analyze the microsized area of materials surface by utilizing ion scattering or ion-beam induced radiation, we often need micro-ion beams. Today several kinds of optics are commercially available for that purpose; however, we would like to introduce completely new optics based on the focusing effect of fine glass capillaries. The principle is quite simply based on the interaction of glancing ion beams and a smooth inner wall surface of glass capillary [6]. The tapered angle is designed to be less than the critical angle of channeling so that the ion beam can penetrate the inner space just like channeled ions in single crystals.

The interaction of energetic ion beams with the surface of solids is defined by a number of parameters. For light ion beams (H^+ or He^+) at glancing angles of incidence the interaction might be roughly divided into three types depending on the impact parameter value. Those ions approaching close enough to the target atoms nuclei undergo Rutherford scattering loosing sufficient part of energy and changing the direction of moving. On the other hand, ions reflected by the surface potential barrier loose much less part of their energy. Ions of intermediate type loose energy and change their trajectory due to the interaction with inner shells electrons of the target atoms. The question which type of interaction is dominant is defined by the ion–surface combination, ion energy and angle of incidence, surface topography and a number of other circumstances. That is why ion–surface interaction is one of the main subjects in the research on ion–solid interactions. The purpose of this study is to analyze the processes of interaction of accelerated protons with the inner surface of glass capillaries.

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EXPERIMENTAL SETUP

To study the efficiency of propagation of ions through the capillaries and capillary systems the special experimental setup has been developed and manufactured. The schema of the experimental setup designed for studying the transmission of accelerated ions through capillaries and capillary systems is shown in Fig. 1. This setup, which enters the implantation complex formed on the basis of a Van de Graaf accelerator (ESA-2), consists of four units: 1) a system of ion beam formation, 2) a scattering chamber, 3) a measuring chamber, and 4) a system for detecting scattered ions. Monoenergetic proton beam, generated by the ESA-2, is collimated by 1 mm circular diaphragm.

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. and the error in the capillary orientation with respect to the beam axis is not larger than 2.5×10^{-2} deg. Measurement of the angular divergence of the initial beam gave $\pm3.0\times10^{-2}$ deg. The energy of the proton beam was set by the calibrated magnetic analyzer with the accuracy of ±0.1%. The overall measured energy resolution of the recording system, taking into account the energy spread in the initial beam, does not exceed 19 keV [7]. The pressure in the vacuum chamber during measurements was 3×10^{-5} Pa.

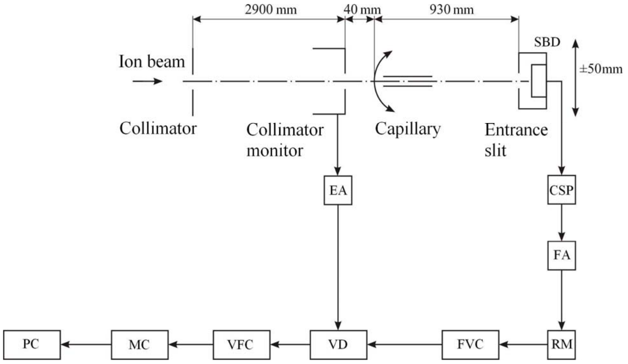

Figure 1: The schema of the experimental setup. (MC) matching circuit, (VFC) voltage-frequency converter, (VD) voltage divider, (EA) electrometric amplifier, (FVC) frequency-voltage converter, (RM) programmable rate meter, (FA) forming amplifier, (CSP) charge-sensitive preamplifier, (SBD) silicon surface barrier detector, and (PC) personal computer.

ANGULAR AND TIME DISTRIBUTION OF PROTONS WITH ENERGY 240 KEV TRANSMITTED BY INSULATING CAPILLARIES

The angular and time distributions of 240 keV protons transmitted through glass (borosilicate) capillaries with a diameter of 0.5 mm and lengths of 65 and 178 mm in the range of beam currents from 10^{-12} to 5×10^{-11} A at the proton entrance angles with respect to the capillary axis from –0.20° to +0.20°, as well as the protons transmitted through a capillary with a diameter of 0.1 mm and length of 30 mm, oriented along the beam axis (at input currents from 8.5×10^{-13} to 10^{-11} A) were measured.

The angular distributions of the protons transmitted through capillaries at opposite (with respect to their axes) entrance angles, have mirror-reflected shapes and the same widths. The shape of the angular distributions of the protons transmitted through a 65-mm-long glass capillary is determined to a large extent single by scattering of charged particles from the inner surface of the capillary. At zero entrance angle (Fig. 2), three peaks are observed in the central part of the distribution, and the distribution width is 17% larger than for entrance angles of 0.1° and 0.15°; with an increase in the entrance angle to 0.1°–0.15°, only a trace of the central peak can be seen. A change in the entrance angle of protons with respect to the capillary axis to 0.20° facilitates suppression of one of the lateral peaks and decreases the width of the other one. An increase in the capillary length to 178 mm leads to a change in the shape and width of the angular distributions of the protons transmitted through the capillary. At zero entrance angle, the angular distribution, instead of the central peak (caused in the previous case by the particles transmitted through the capillary without scattering), contains two peaks with a dip at the center (Fig. 2). Such transformation of the central part of the angular distribution is due to the effect of the charge accumulated on the inner surface of the capillary, which leads to the redistribution of the central part of the beam over the angles of exit from the capillary.

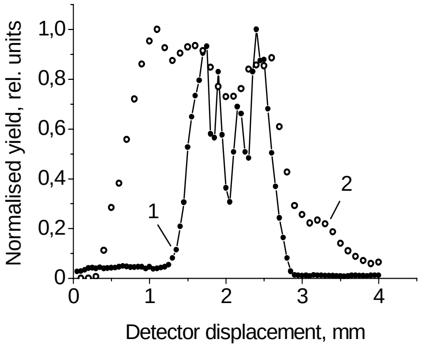

Figure 2: Angular distribution of 240 keV protons transmitted through capillaries with a diameter of 0.5 and length (1) 178 and (2) 65 mm. The angle between the proton beam and the capillaries is 0.0°.

The effect of the accumulated charge is even more pronounced in Fig. 3, which shows the time dependences for 240 keV protons transmitted through a capillary with a diameter of 0.1 mm and a length of 30 mm at different currents at the input of the capillary (a, b). It can be seen in Fig. 3 that an increase in the ion current at the input of the capillary leads to a significant increasing of the average number of protons transmitted through it. It should be noted that there is a reverse proportionality between the increasing in the current and the time interval between similar peaks; this relationship is indicative of gradual compensation for the capillary leakage currents.

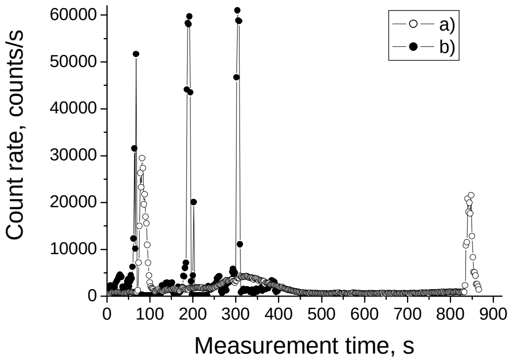

Figure 3: Time distributions of 240 keV protons transmitted through a capillary with a diameter of 0.1 mm and a length of 30 mm at the axial entry angle of particles ± 0.0°. The proton current at the input of the capillary is (a) 0.85, and (b) 10 pA.

Fig. 4 shows the angular distribution of quantity protons transmitted through the capillary with a diameter of 0.1 and a length of 30 mm. Angle between beam and capillaries 0.15° and a current 0.8 pA at the input. The distribution has the form of a series of equally spaced peaks of almost identical width and amplitude gradually decreasing to the distribution edges. The comparison of the output angular distribution of protons with angular distribution the input beams allows revealing some particularities: the proton beam becomes much wider than the initial one after transmission through the capillary, which is most likely due to the large entrance angle; 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 splited in the field of the charged capillary into a series of lines with transverse energies differing by $\Delta E_\perp = E\ (\Delta\varphi)^2 \approx 0.24$ eV.

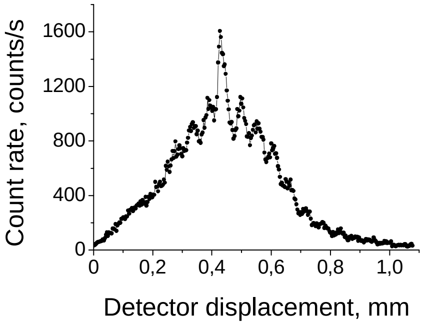

Figure 4: Angular distribution of quantity of protons transmitted through a capillary with a diameter of 0.1 mm and a length of 30 mm at a disorientations angle of 0.15°.

FOCUSING OF ION BEAMS BY MEANS OF TAPERED GLASS CAPILLARY OPTICS

We present evidence of the focusing effects of fine glass capillary optics for H^+ ion beams. In this article we describe the fabrication method and the results of performance test of such tapered glass capillaries, and indicate that a very strong focusing effect does exist. The glass capillary optics is formed by a puller as to have inlet diameters of about 3 mm and outlet diameters of submicrons. The total length of the optics is about 80 mm. Impingent 240 keV protons to such optics are reflected by the inner wall several times, in a very similar process to the so-called surface channeling. The tapered angle is designed to be less than the critical angle of channeling so that the ion beam can penetrate the inner space just like channeled ions in single crystals. Compared with the conventional micro-ion beam facilities, the present method is certainly simple and low cost, thus providing an easy method of submicron Rutherford backscattering spectrometry or particle induced X-ray emission analyses. In addition, if the ion species are extended to heavier elements, the present method provides versatile maskless ion implantation techniques.

CONCLUSIONS

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° from each other, in the charged capillary field.

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