Focusing of MeV Ion Beams by Means of Tapered Glass Capillary Optics

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要約：ゆるやかなテーパー付きのガラスキャピラリーがMeV領域のイオンビームを効果的に収束できることを示す。約1mmの口径を持つガラス管を加熱して引っ張ると、出口口径がサブーμmで全長が約50mmの中空キャピラリーができる。その軸方向にイオンビームを入射させると、個々のイオンはなめらかな内壁によって数回散乱した後、中央部に集まり出口から出て来る。もちろん入射したイオンの大部分は途中で大角散乱して失われるが、出て来るイオンの数は入射イオンの約1％に達し、かつエネルギー損失もほとんどない。1％という透過率は出口／入口の面積比の約10^5倍に相当し、キャピラリーによってイオンビームが効果的に収束されることを示している。こうして収束されたイオンビームは各種イオンビーム解析のプローブとして、またイオンビームによる微小領域の表面改質に応用が可能である。

Abstract : We present evidence of the focusing effects of fine glass capillary optics for MeV He ion beams. The glass capillary optics are formed by a puller as to have inlet diameters of about 1 mm and outlet diameters of sub-microns. The total length of the optics is about 50 mm. Impingent MeV ions to such optics are reflected by the inner wall several times, a well known process of the so-called surface channeling. The majority of incident ions are lost by the dechanneling process, however, a part of them, actually more or less about 1 %, is emitted through the outlet without significant energy loss. Compared with the conventional micro-ion beam facilities, the present method is certainly simple and low-cost, thus providing an easy way of sub-micron Rutherford Backscattering Spectrometry (RBS) or Particle Induced X-ray Emission (PIXE) analyses. Also if the ion species are extended to heavier elements, the present method provides versatile maskless ion implantation techniques.

1. INTRODUCTION

The interaction between energetic ion beams and the solid surface varies in the nature according to many parameters. For light ion beams like H^+ or He^+ which are obliquely incident on smooth solid surfaces with very small angles of about 10 mrad or less, the interaction may be roughly classified into three categories depending on the magnitude of the impact parameter. The ions that may approach close enough to the target nuclei suffer conventional Coulomb scattering or Rutherford scattering thus losing significant amount of their energy and their direction is largely changed. In contrast, the ions that may be reflected by the surface potential barrier without such hard collisions would not lose their energy significantly.[1-3] The intermediate ions exist of course and they experience an energy loss and directional change through the interaction with inner shell electrons. The problem of what kind of interaction dominates depends on the ion and surface species, the incidence ion energy and its angle with respect to the surface, the surface geometry, and many others.

J.A. van Kan[4] examined scattering characteristics of 2.5 MeV H^+ ion beams incident on a smooth Au thin film on SiO_2 substrate with very small incidence angles. He measured the angular distribution of reflected protons through detection of the Cu-K line from a fine Cu wire mounted on a movable stage. His results indicated that the proton beam is totally reflected for the incidence angles below 4 mrad, and when the incident angle is larger the reflected beam profile shows a rather broad profile peaking at

$$\theta = (1.8 \pm 0.2) \cdot \phi,$$

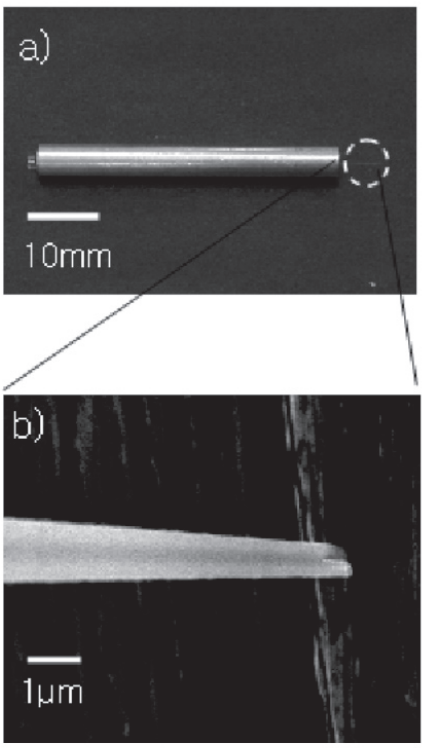
where ϕ is the incidence angle i.e. the angle between the beam direction and the surface plane and θ is the scattering angle. Furthermore, his measurements indicated that a 2.5 MeV proton beam is almost totally reflected by an evaporated Au layer at incidence angles around 10 mrad. The point in his experiments is that the reflected beam peaks at slightly smaller angles than the mirror reflection angle. For instance, when the incidence angle was 0.6° (10.5 mrad) the reflected beam peaked at the scattering angle of around 1.0° instead of 1.2°.

In order to analyze micro-sized 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. Similar optics have already been realized in focusing of x-rays.[5, 6] A bundle of fine glass capillaries are formed to have a slight curvature within the critical angle for x-ray total reflection. Such an optic works to focus or to parallel x-rays greatly improving the efficiency of x-ray fluorescence spectroscopy or x-ray diffraction, as an example. The ion beam optics introduced in this paper are slightly tapered to become narrower and narrower towards the outlet. The taper 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. However, since the incidence angle of ions to the inner wall surface increases gradually in fact after each reflection, the behavior of ions in the capillary is never ideal as described by Lindhard,[7] still we believe the situation is in a very good analogy to general channeling phenomena.

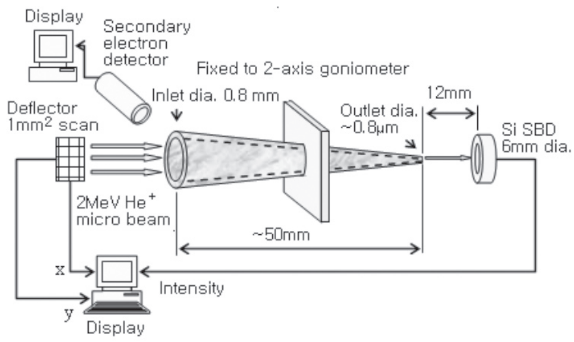
In this paper we describe the fabrication method and the results of performance test of such tapered glass capillaries, and indicate that a very strong focusing effect does exist.

2. FABRICATION OF CAPILLARY OPTICS

As a starting material we used conventional lead glass which is shaped into a pipe of 90 mm long with 2 mm outer diameter and 0.8 mm inner diameter. Both ends of the pipe were clamped tightly and pulled while the central region was heated. Typical heating temperature and the tensile stress was 400 ～ 550°C and 0.15 kg/mm^2, respectively. The lead glass has merits such that it has a relatively low softening temperature and a very smooth surface structure after shaping as verified in x-ray optics. By controlling the heating temperature and the tensile stress we can fabricate variously shaped capillary optics. Figure 1 shows a photograph of a whole optic (a) and a SEM image of the vicinity of the outlet (b). Thus fabricated tapered capillary was molded into an Al pipe for the convenience of handling.



pipe and (b) SEM image of the vicinity of the capillary outlet. The outlet dia. is about 0.3 μ m in this case.



The puller itself used in this study is only a slightly modified version of those widely used in the field of biology and medical science, and the materials are just commodities. Therefore nothing special exists in our fabrication technology but only a patient trial and error procedure.

3. TRANSMISSION CHARACTERISTICS

3.1 Experimentals

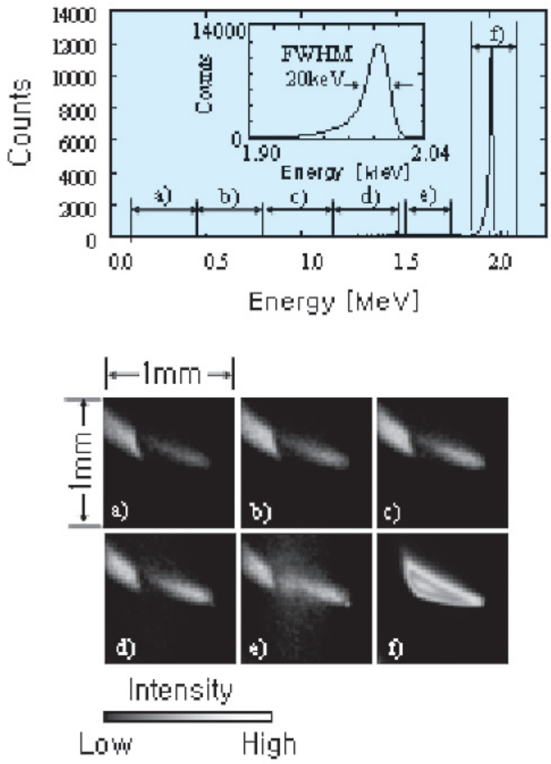
Figure 2 shows schematics of the experimental arrangement. Focused 2 MeV He$^+$ ion beam is forwarded to the capillary optic and the incidence position is scanned in the area of 1 mm^2 covering the total area of the optic inlet. The focal point is adjusted to be about the middle of the optic and the beam size there is estimated to be approximately 3 μm. A secondary electron detector located near the optic inlet helps to bring the optic within the scanned area. The optic is mounted on a 2-axis goniometer to ease alignment with respect to the beam direction. Outcoming ions are detected by a conventional Si surface barrier detector (SBD) located right behind the optic outlet 12 mm apart. The output of the SBD detector gives energy spectrum of transmitted ions. Also the x,y scanning signal and the SBD output signal are displayed on a monitor , giving the transmission distribution as a function of incidence position.

The incidence beam intensity is limited by forestage slits to be extremely weak, only 7×10^4 ions/s・mm^2, and each image is collected by integration of transmitted ions in certain energy region of interest (ROI) for 300 sec. The transmission probability is calculated dividing the SBD output counts for each ROI by the total incident ions, that is the number of ions incident within the inlet circle of 0.8 mm in diameter.

3.2 Experimental results

Typical energy spectrum and displayed images are shown in Fig.3. Each image corresponds to ROI indicated in the energy spectrum. The strong peak at 2 MeV in the energy spectrum mostly comprises the ions incident in the central area, which is somehow crescent shaped. This point will be discussed later. Lower energy ions are also included in the central region, but their intensity is negligibly small as clearly shown in the spectrum. An interesting feature in the images a) through e) is that considerable number of ions are detected after incidence at the upper left region in the images. These ions probably correspond to those penetrating the glass wall near the outlet. Since the stopping power of the glass against 2 MeV He^+ ions is calculated to be roughly 0.2 MeV/μm[8] and the wall thickness near the outlet ranges 0.5 through 1 μm, the result may be reasonable if we take into account that the ions hit the inner surface with various incidence angles and then penetrate through the wall. The intensity of these peripheral ions is again negligible in comparison with the main peak. The "elastic" transmission probability, which is defined as the transmission probability for ROI (f), is calculated to be 0.77 % in this case.

If the optic is inclined by 2° from the previous case, the energy spectrum shows a drastic change as shown in Fig.4. We note the vertical scale and recognize that practically no transmission occurs in this case. Low energy ions are assumed to correspond to those penetrating through the glass wall near the capillary outlet.



Energy spectrum is divided into six regions of interest (ROI). Displayed images correspond to ROI indicated in the energy spectrum.

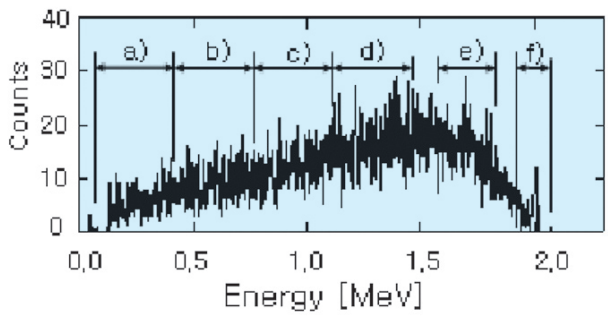
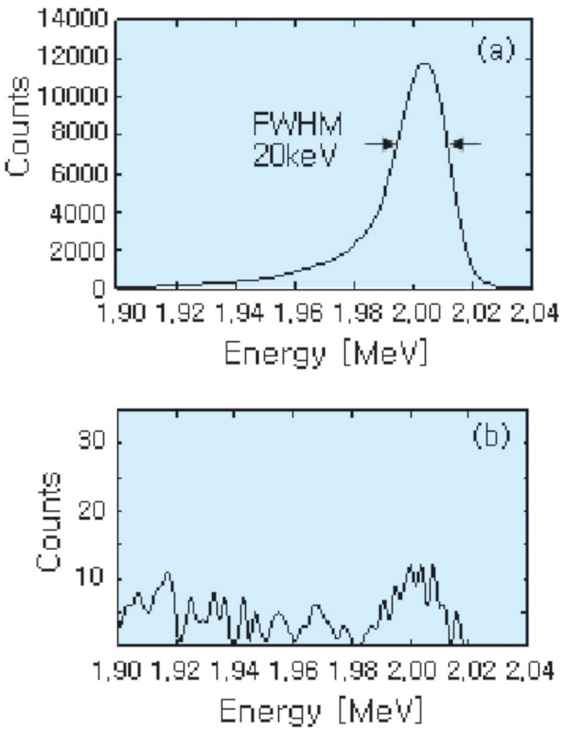


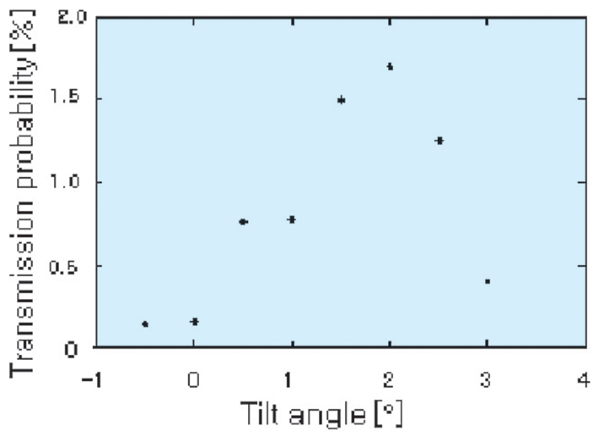
Fig.3.

The spectral profiles in the energy region of about 2 MeV are compared in Fig.5 between above two cases, (a) and (b). In Fig.5(a) we see the peak width of approximately 20 keV and a low energy tail down to 1.93 MeV. The peak width is mainly limited by the detector resolution, and the low energy tail corresponds to the energy loss of multiply reflected ions.[9] The interaction of transmitted ions and the glass wall seems quite gentle, or in other words, only such gently reflected ions can be transmitted. This is nothing but the channeling phenomenon of energetic ions through single crystal lattices. On the other hand, Fig.5(b) is a spectral profile in the energy region of about 2MeV of Fig.4. It shows almost randomly distributed energy spectrum for ions reflected by the glass wall or penetrated through the wall losing large energies.



2MeV of (a) Fig.3 and (b) Fig.4. In (a), there is a strong peak at 2MeV and FWMH is 22.3keV. In (b), there is no strong peak and the ions are distributed in a wide energy range.

The "elastic" transmission probability is summarized in Fig.6 as a function of tile angle of the optic. The origin of the horizontal scale of this figure is arbitrarily determined and less important. The most significant point is that the maximum of the transmission probability reaches up to 1.8 %, which is 1.8×10^4 times larger than the inlet-to-outlet area ratio. Another point is that the angular profile is rather broad. This would help practical usage of the optics by easing alignment to the beam axis.



tilt angle of the optic.

4. DISCUSSION AND CONCLUSION

In spite of our initial expectation that the ROI(f) image would be like a full moon, the fact is crescent as shown in Fig.3. We have seen more circle-like and smaller images, however as far as concerning the transmission probability, the good images are always crescent. We do not know the reason exactly yet but several origins can be contemplated. Most simple is a particle (dust), that exists in between the passage of ions and works obstructive. This is possible because we fabricate and carry the optics without so great care as in the case of LSI chips. Other defects are also conceivable. In fabrication we just pull and tear off fragile glass tubes, therefore a perfect shaping is never expected. As shown in the SEM photograph (Fig.1) the top structure is not a perfect circle. The premise of cylindrical symmetry of the whole optic is doubtful if we look into the details. All of these defects affect the ROI images, resulting in the data we have collected from one piece of optics. This is certainly one reason and perhaps most probable.

Another conceivable effect that may disturb successful function of our optics is the charging-up of the glass wall. Irradiation and embedding of the high energy ions into the glass causes of course the secondary electron emission,[10] and the wall would be either positively or negatively charged-up. The electric field originating from such charges inevitably affects more or less the ion trajectories. If the inner wall is partially charged-up, the asymmetric ROI images can result. This problem becomes more important when we put more incident ions for practical use of the optics. Coating of conductive thin films will remove the difficulty. Selection of conductive materials instead of the lead glass is another choice.

Geometrical profile of the transmitted ion beam is unknown in the present study because our detector is just an energy analyzer but not a position-sensitive detector. This is a practically important issue and left to future study. However, at this moment it is easy to suppose that the beam spreads out significantly after the outlet. We have not estimated so far the beam diameter at some distance from the outlet, but it must certainly increase with the distance. Therefore, in order to use the resultant ion beam as a microprobe we need to put the sample as close as possible to the optic outlet. Owing to the developments of scanning probe microscopy, such tools are easily available these days so we feel no serious difficulty in this point.

To summarize the present study, we have shown quite an effective focusing function of tapered glass capillary optics. The beam density can be enhanced more than 4 orders without significant energy loss. Several issues have been left to future studies, but the capability of our optics is clearly suggested in this study.

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