MeV ion beam extraction into air with a glass capillary filled with He

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Abstract. In order to obtain an intense ion beam, we have newly developed He-capillary optics, which is a tapered glass capillary filled with low pressure He gas to extract ion beam into atmospheric air. We have measured the energy spectra of an ion beam extracted from the He-capillary as a function of He gas pressure. We have observed that the intensity of the extracted ion beam is enhanced by using the He-capillary with He gas, although peak energy is shifted to a lower energy. Furthermore, in order to evaluate the performance of the He-capillary in detail, we have measured the intensity distribution of the ion beam via the He-capillary by using a 25 µm pinhole slit and have found that the He-capillary optics provides an intense ion beam without further spread of the extracted ion beam. Here, we discuss transmission properties of the ion beam via the He-capillary.

1. Introduction
Development of an in-air-analysis technique with a MeV ion beam has been desired in various fields such as biology, archaeology, etc., because wet samples without drying have to be analyzed, or valuable samples of artistic, historic, and archaeological importance must be analyzed without destroying. Although ion beam extraction under atmospheric conditions has been performed by means of a thin film window as a boundary between vacuum and air, in general, a technique to extract an ion beam into air using capillary optics instead of a thin film has attracted considerable attention within the last decade. The transmissions and guiding of an ion beam via a capillary has been well reviewed in detail in reference [1]. The technique of MeV ion beam extraction into air by means of a capillary has been developed by Nebiki et al. , and they have performed in-air particle induced X-ray emission for sea sludge [2]. In our laboratory, we have also developed several in-air-analysis techniques using not only glass but also metal capillaries [3, 4]. We have also reported transmission properties of an ion beam through several kinds of capillaries [5].

In the case of using a narrow capillary as a vacuum window, the incident ion beam is spread not only in the atmospheric air around the outside of the capillary, but also inside of the capillary because atmospheric gas penetrates inside through the capillary outlet. To extract an ion beam from the capillary into the atmospheric air efficiently, it is important to decrease the ion beam lateral struggling inside. As is well known that the Rutherford differential scattering cross section is proportional to $Z_T^2/E^2$, where $Z_T$ is an atomic number of the target atom and $E$ is incident energy[6], the ion scattering is suppressed under atmospheric gas with small atomic number.
Namely, the lateral struggling would be suppressed. In this work, we have newly developed a 'He-capillary', which is a tapered glass capillary filled with low pressure He gas. Here, we report the transmission properties of the ion beam in the 'He-capillary'.

2. Experiment

This experiment was carried out using a 1.7 MV tandem van de Graaff accelerator at Nara Women’s University[7]. We installed a beam line equipped with a differential pumping system, which is described in detail in a previous work [8], and set the He-capillary at the end of the beam line. Figure 1 (a) shows a schematic diagram of pump system for the capillary. To connect a capillary to the beam line of the accelerator, we use four rotary pumps and a turbo molecular pump as a differential pumping system. Figure 1 (b) shows the details of the end part of the beam line and detection systems. A capillary with 100 $\mu$m outlet inner diameter and 800 $\mu$m inlet inner diameter is put in the capillary holder, which is made of a Teflon tube with a He gas inlet pipe, on a goniometer. The pressure in the He-capillary can be estimated by a vacuum gauge upstream from the differential pumping system. When the He-capillary is not filled with He gas, the background pressure is $1.3 \times 10^{-4}$ Pa.

In the case of using a narrow capillary as a vacuum window, the incident ion beam is spread not only in the atmospheric air around the outside of the capillary but also inside of the capillary, because atmospheric gas penetrates inside this region through the outlet of the capillary. Here, we report the transmission properties of the ion beam in the He-capillary.

3. Result and discussion

At first, the energy of the ion beam through the He-capillary with varying He gas pressure inside are directly measured by the Photodiode(PD) without the slit condition. Figure 2 (a) shows the energy spectra of a 2.0 MeV proton beam via the He-capillary with several He pressures inside. As is seen in Figure 2 (a), a peak and low energy tail is observed in each energy spectrum. It should be noted that the intensity of the peaks in the energy spectra increases with increasing He pressure, while the energy of the peaks shifts to a lower energy. Figure 2 (b) shows the integral counts of peak components and low energy components in the energy spectra as a function of He pressure in the capillary. As is seen in Figure 2 (b), it is clear that both peak and tail components increase with increasing He pressure in the He-capillary, and the degree of increase of peak components is larger than that of low energy components. This indicates that the quality of ion beam is improved with increasing He pressure in the He-capillary.
Figure 2. (a): Energy spectra of ion beam extracted from the He-capillary. (b): The integral counts of peak components and low energy components as a function of He pressure in the He-capillary.

In order to verify the performance of the He-capillary in detail, we measured the intensity distributions of the ion beam via 100 µm He-capillary by means of a 25 µm pinhole slit. Figure 3 shows the intensity distribution of the ion beam via He-capillary, where $x$ is the horizontal position and $y$ is the vertical position. As is shown in Figure 3, the intensity of each distribution consistently increases with increasing gas pressure for the measurement with the non-slit condition as is seen in Figure 2 (a).

To elucidate the spread of the ion beam via the He-capillary, we fit the measured intensity distributions with a Gaussian distribution,

$$F(x) = I_x \exp \left[ -\frac{(x - x_0)^2}{2\sigma_x^2} \right], F(y) = I_y \exp \left[ -\frac{(y - y_0)^2}{2\sigma_y^2} \right],$$

where $I_{x,y}$ are peak intensities for $x$ and $y$, $x_0$ and $y_0$ are center positions of the distributions, and $\sigma_{x,y}$ are standard deviations of the distributions plotted by solid lines in Figure 3. Table 1 tabulates the parameters of the Gaussian distributions. It is found that values of $\sigma_{x,y}$ only vary slightly with increasing He pressure in the He-capillary although the intensities, $I_{x,y}$, on the distributions with He increase by an amount that is approximately two times larger than that without He. Hence, the technique using the He-capillary is quite useful to obtain an intense ion beam in air.
Figure 3. Intensity distributions of ion beam via He-capillary.

Table 1. The intensities, \( I_{x,y} \), center positions of distributions \( x_0 \) and \( y_0 \), and the standard deviations, \( \sigma_{x,y} \), of the Gaussian distributions.

| He pressure[Pa] | \( I_x \)  | \( I_y \)  | \( x_0 \) | \( y_0 \) | \( \sigma_x \) | \( \sigma_y \) |
|----------------|-----------|-----------|---------|---------|-------------|-------------|
| 1.3 \( \times 10^{-4} \) | 13056     | 12108     | 2.2     | -1.8    | 38.7        | 43.2        |
| 7.7 \( \times 10^{-4} \) | 15704     | 15438     | -0.9    | -2.9    | 41.3        | 43.2        |
| 1.9 \( \times 10^{-3} \) | 27199     | 28637     | 1.7     | -3.0    | 41.0        | 43.7        |

4. Conclusion
We have developed the He-capillary to obtain intense an ion beam in atmospheric air and have measured the energy spectra and intensity distributions of this ion beam via the 100 \( \mu m \) He-capillary. We found that the intensity of the ion beam extracted from the He-capillary was enhanced with increasing He pressure in the capillary, although the energy of the ion beam decreased. By using a 25 \( \mu m \) pinhole slit, we have verified the performance of the He-capillary optics. The present results suggest that the quality of the ion beam via the He-capillary is better than a normal capillary.

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