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T. Takayanagi, T. Ikehata, Y. Okumura, et al.

Optimization of negative ion extractor in a JAERI 400 keV H^- ion source

T. Takayanagi,[a] and T. Ikehata
Department of Electric and Electronic Engineering, Ibaraki University, Hitachi-shi, Ibaraki-ken 316-8511, Japan

Y. Okumura, K. Watanabe, M. Hanada, T. Amemiya, and M. Kashiwagi
Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken 311- 0193, Japan

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The influence of a dipole magnetic field in the extractor on the beamlet deflection has been investigated using a JAERI 400 keV H^- ion source. The beam deflection angle decreased from 10.2 to 7.0 mrad when the integrated value of the magnetic field was changed from 2530 to 910 G cm. The measured deflection angle was larger than the estimated value from the ion trajectory considering the magnetic field. To understand the dominant factor that enhances the beam deflection angle, three-dimensional trajectory simulation was performed. It was confirmed that the axis of the beamlet deflected by the magnetic field in the extractor is displaced from the center of the aperture at the grounded grid (GRG). This displacement enhances the beam deflection angle due to the effect of the electrostatic lens at the GRG. This phenomenon is similar to the beam deflection by aperture displacement of the GRG. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1430526]

I. INTRODUCTION

In the negative ion sources, permanent magnets are inserted in the extraction grid to prevent the extracted electrons from flowing out to the accelerator. These permanent magnets are arranged to produce a dipole magnetic field for the electron suppression.

The plasma grid is placed typically at 6 mm from the extraction grid in the JAERI 400 keV H^- ion source.[1–3] The integrated value of the magnetic field along the beam axis from the extraction surface is not zero. Therefore the negative ions are slightly deflected. Such a deflection produces high heat load in the accelerator[1] and increases overall beam divergence.

It was reported that the beam deflection due to the magnetic field is compensated with beamlet steering by aperture displacement of the electron suppression grid.[3–5] However, it is difficult to determine the reasonable displacement distance for the compensation of the deflection at variable beam energy, since the compensation depends on the beam energy. Quantitative analysis of the influence of the dipole magnetic field on the beam trajectory is required to compensate the deflection precisely.

The beam deflection due to the magnetic field seems to be determined by the integrated magnetic field. However, measured deflection angle of the beamlets was larger than the simple estimation. To clarify the reason for the large deflection angle, the beam deflection was studied both experimentally and theoretically. A three dimensional trajectory simulation using OPERA-3D code[6] has been also carried out.

In the present article, measurement of the beam deflection angle for various integrated magnetic fields is reported. Detailed investigation of the beam trajectory in the accelerator by the 3D trajectory simulationl code is also presented.

[a]Electronic mail: yhk02610@nifty.ne.jp

II. EXPERIMENTAL APPARATUS

Multiple H^- ion beamlets of 25 (5×5) were produced in the JAERI 400 keV negative ion source[1–3] The extractor consists of three grids, called a plasma grid (PG), an extraction grid (EXG), and an electron suppression grid (ESG). The accelerator consists of three grids, called A1G, A2G, and the grounded grid (GRG). Acceleration gap length is designed to be shorter downstream of the accelerator while the same voltage is applied for each acceleration gap. Therefore the electric field strength increases stage by stage, and the electrostatic convex lens is formed in each grid aperture. The beam is converged by the electrostatic lens.

Figure 1 shows the distribution of the extraction holes and the permanent magnets in the EXG. There are 25 apertures for beam extraction. The polarity of the magnets is alternated between aperture rows. This arrangement of the magnets produces the dipole magnetic field in the extraction region. The electrons extracted from the source plasma are deflected and collide with the EXG.

A distribution of the dipole magnetic field along the beam axis is shown in Fig. 2. The open circle and the solid line indicate the measured profile and the calculated profile, respectively. The strength and the polarity of the dipole magnetic field vary along the beam axis due to the configuration of the magnetic field.

To vary the integrated value of the magnetic field along the beam axis from the extraction surface, the distance between the PG and EXG (gap length) was changed. By changing the gap length from 3 to 9 mm, the integrated magnetic field decreases from 2530 to 910 G cm. This nonzero magnetic field gives the deflection of the beamlet.

The beamlets footprint was monitored with an infrared camera by observing the temperature rise of the beam target plate[1,2] The target was placed 1.6 m downstream from the GRG.

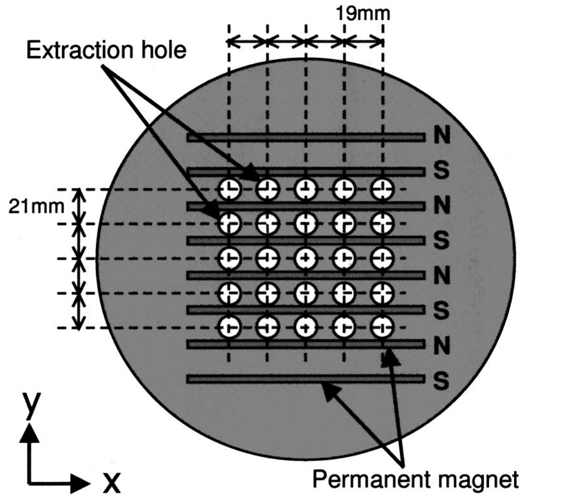

FIG. 1. Distribution of the extraction holes and the permanent magnets in the EXG. There are 25 apertures for beam extraction. The polarity of the magnets is arranged alternately between aperture rows to produce the dipole magnetic field.

III. EXPERIMENTAL RESULTS

The H^- ion beam was produced at an optimum perveance that gives the minimum beam divergence. At the acceleration energy of 140 keV, the optimum current density and divergence of the beamlet were 4.6 mA/cm^2 and 5.5 mrad, respectively. The footprint of 5×5 beamlets is shown in Fig. 3. Each beamlet was clearly distinguished. Adjacent beamlets rows were deflected alternately in the horizontal direction. This deflection is attributed to the dipole magnetic field in the extractor. The beam deflection angle due to the magnetic field θ_x was defined as follows:

$$\theta_x=\frac{\Delta x}{L}, \tag{1}$$

where Δx is the displaced distance of the beamlets row in the horizontal direction on the footprint (see Fig. 3) and L is the distance from the GRG to the target of 1.6 m. The outermost beamlets were deflected more than others due to the beamlet–beamlet interaction.[2]

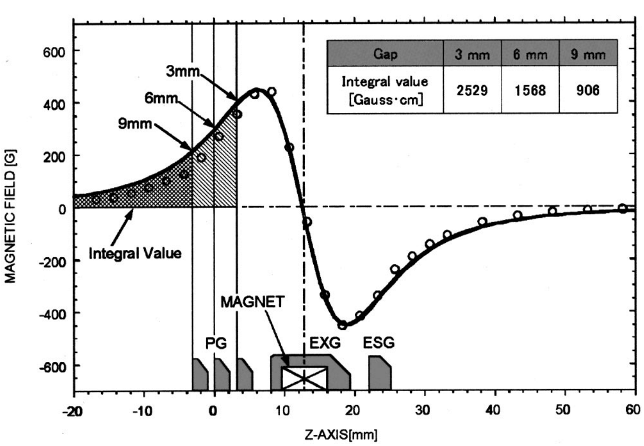

FIG. 2. Distribution of the dipole magnetic field in the extraction region. The open circle and solid line indicate the measured profile and calculated profile, respectively. To vary the integrated value of the magnetic field the distance between the PG and EXG was changed.

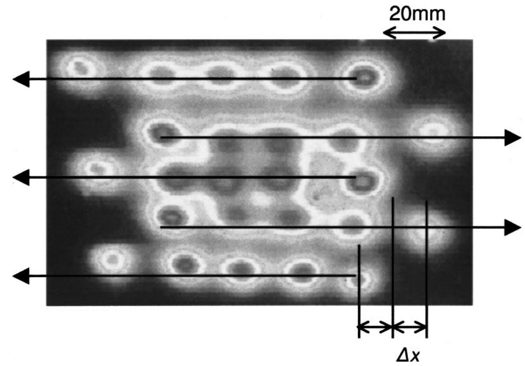

FIG. 3. An infrared image of the H^- ion beamlets, footprint by optimizing at 140 keV. The beam current and the divergence were 4.6*m* A/cm^2 and about 5.5 mrad, respectively. Adjacent beamlets rows were deflected alternately in the horizontal direction due to the dipole magnetic field.

The deflection angle of the beamlets row was measured for each gap length, 3, 6, and 9 mm. The beam deflection angle as a function of the acceleration energy is shown in Fig. 4. The beam deflection angle decreased from 10.2 to 7.0 mrad by changing the gap length from 3 to 9 mm. The beam deflection angle θ is simply expressed as follows:

$$\theta\propto\frac{1}{r_i}\approx\frac{B}{\sqrt{V_E}}, \tag{2}$$

where r_i is ion Larmor radius, and B and V_E are the magnetic field and the beam acceleration energy, respectively. The beam deflection angle estimated from Eq. (2) is also indicated by solid lines in Fig. 4. It was confirmed that the beamlet deflection angle decreased with $V_E^{-1/2}$.

IV. COMPARISON BETWEEN EXPERIMENT AND SIMULATION

The beamlet deflection angle was estimated by 2D and 3D numerical analysis. In the 2D analysis the motion of the single H^- ion was analyzed by the finite difference method. The profile of the dipole magnetic field (see Fig. 2) was

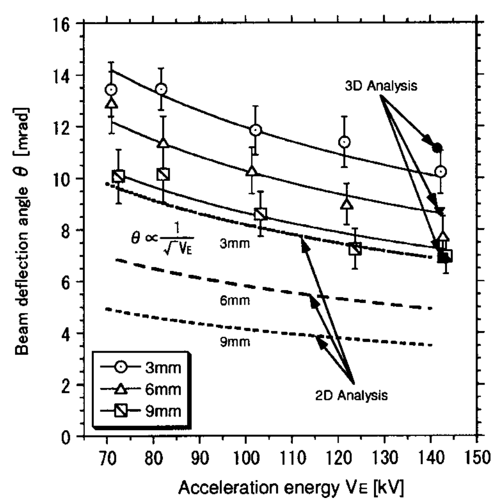

FIG. 4. The beam deflection angle of the experiment and the numerical analysis. Open markers are the experimental results. The calculation results of the 2D and the 3D analysis are indicated by lines and plots, respectively.

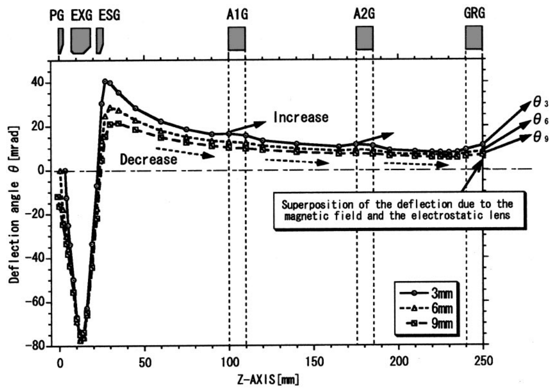

FIG. 5. The beamlet deflection angle in the accelerator. The markers are calculated points. The deflection angle decreased gradually in each acceleration gap and also increased at the entrance of each aperture.

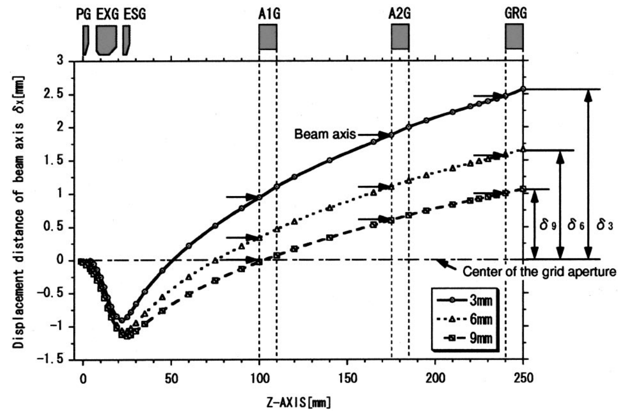

FIG. 6. The beamlet trajectory in the accelerator. The axis of the beamlet deflected by the magnetic field in the extractor was displaced from the center of the aperture.

simulated by the magnetic Coulomb method. The motion of the H^- ion in the magnetic field $\mathbf{B}$ and the electric field $\mathbf{E}$ is expressed as follows:

$$m\frac{dv}{dt}=q(v\times\mathbf{B}+\mathbf{E}), \tag{3}$$

where m is the mass of the H^- ion, v is the drift velocity, and q is the electric charge. The equipotential surface in the accelerator is assumed to be flat, $\mathbf{E}=E(z)$. The calculation results are indicated by broken lines in Fig. 4. The results were smaller than the experimental results.

To clarify the reason for the difference, the beamlets' trajectory of 5×5 was simulated in more detail using the 3D trajectory simulation code. The estimated angles are also plotted in Fig. 4. The results agreed well with the experimental results.

V. DISCUSSION

The deflection angle and the trajectory of 5×5 beamlets in the accelerator were simulated using the 3D trajectory simulation code. The typical characteristics of the beamlet are shown in Figs. 5 and 6. The deflection angle decreased gradually in each acceleration gap and also increased at the entrance of each grid aperture (see Fig. 5). The beamlet was deflected by the magnetic field in the extractor so that the axis of the beamlet was displaced from the center of the aperture (see Fig. 6). This offset axis of the beamlet produces an additional deflection due to the electrostatic concave lens at the GRG. This is similar to the effect of aperture displacement of the GRG.[1–3]. It was confirmed that the beamlet was deflected to the opposite direction after the extraction grid due to the dipole magnetic field.

It has been clarified that the beam deflection due to the magnetic field in the extractor is enhanced by the effect of the electrostatic lens. These results are useful for designing the compensation of the deflection precisely.

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