Numerical Simulation of a High-Brightness Lithium Ion Gun for a Zeeman Polarimetry on JT-60U

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A lithium ion gun is under construction for a lithium beam Zeeman polarimetry on JT-60U. The performance of the prototype ion gun has been estimated by the numerical simulation taking the space charge effects into account. The target values of the ion gun are the beam energy of 30 keV, the beam current of 10 mA and the beam divergence angle within 0.13 degrees. The low divergence of 0.13 degrees is required for the geometry of the Zeeman polarimetry on JT-60U where the observation area is 6.5 m away from the neutralizer. The numerical simulation needs to be carried out for the design study because the requirement of the divergence angle is severe for the development of the high-brightness ion gun. The simulation results show the beam loss of 50 % caused by the clash to the electrode such as the cathode and the neutralizer. Moreover, the beam transport efficiency from the neutralizer to the observation area is low due to the broadening of the divergence angle. The total beam efficiency is about 5 %. Extracted beam profile affects the beam focusing and the efficiency. The peaked profile achieves better efficiency than the hollow one. As a result, beam current of 1 mA is obtained at the observation area by the simulation for the prototype ion gun.

Keywords: plasma and fusion, lithium beam, beam probe, ion gun, JT-60U

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1. Introduction

Understanding of the structure of the edge pedestal region is one of the important issues for tokamaks because the performance of the fusion plasma depends on the pedestal parameter. Particularly, the edge current caused by a strong pressure gradient accompanied by H-mode affects magneto-hydrodynamic (MHD) instability including edge localized modes (ELM) [1]. The detailed measurement of the edge current profile is expected in order to understand the MHD activity at the pedestal region, and also to obtain the accurate magnetic equilibrium.

Polarization spectroscopy has been used to measure the magnetic field and the causative plasma current. The motional Stark effects (MSE) diagnostic has worked successfully on various fusion devices [2, 3]. However, the MSE diagnostic is affected by the strong radial electric field which is about 5 % of the motional Stark electric field in the edge pedestal region. In such region, a Zeeman polarimetry is one of the candidates for the measurement of the edge current profile. The Zeeman polarimetry using a lithium beam probe (LiBP) has been developed on ASDEX, TEXT and DIII-D [4–6]. The pitch angle of the magnetic field is measured from the polarization characteristics of the Zeeman component of the lithium 2^2S–2^2P line (670.8 nm), which is utilized for the strong constraints for the equilibrium calculation. Recently, the direct calculation of the edge current density without the equilibrium calculation has been successfully carried out on DIII-D [7] demonstrating the powerfulness of this method. The lithium beam Zeeman polarimetry is under construction for the edge current profile measurements on JT-60U.

Diagnostics using the lithium neutral beam have been utilized for the edge plasma measurement in various fusion devices [8–11]. A thermionic ion source using β-eucryptite soaked to a porus tungsten disc and a neutralizer using the alkali metal vapor are normally used. Typically, beam current density of 5 A/m^2 is obtained on DIII-D, ASDEX-U, and CHS. Below the current density of 5 A/m^2, the space charge does not affect the beam focusing property. However, in order to obtain a high signal to noise ratio and the high time resolution, a high-brightness ion gun over 10 A/m^2 need to be developed. In addition, the low beam divergence is essential for the efficient beam transport, the clear separation of the polarization components and the high spatial resolution. However, the transport length of the neutral Li beam on JT-60U is longer than the other devices. Therefore to develop the high-brightness and low divergence ion gun, the numerical simulation taking the space charge effect into account needs to be carried out. Then the performance of the prototype ion gun is estimated by the numerical simulation for the design study of the high-brightness ion gun. Particularly, we focus on the impacts of the initial beam profiles from the ion source

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because the beam focusing and the transport efficiency strongly depend on the initial beam profile. Then the strategy for the optimization of the high-performance ion gun is discussed.

2. Configuration of the Ion Gun on JT-60U

The configuration of the Li ion gun and the calculated electrostatic potential are shown in Figs. 1 and 2. The ion gun consists of the ion source, the acceleration electrodes, the electron suppresser, the Einzel lens, the XY deflectors, and the neutralizer. The thermionic ion source with a diameter of 50 mm and the flat surface is biased to 30 kV, and the cathode electrode is grounded. They give the beam extraction field of about 500 kV/m. The Li ion beam is extracted and focused by the extraction electrodes which have larger angle than the standard Pierce electrode because of the focusing of the large current beam. The electron suppresser is biased to $-500\ V$ in order to prevent the back-flow of secondary electrons. The ion beam is focused by the Einzel lens, and then neutralized in the sodium vapor neutralizer. The divergence angle of the neutral beam depends on the focusing property and the location of the neutralizer.

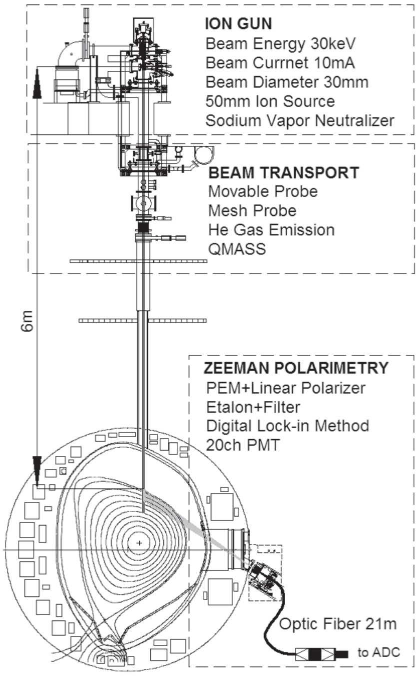

Fig. 1 Schematic view of the lithium beam Zeeman polarimetry on JT-60U.

The well collimated beam is required for the diagnostic of the Zeeman polarimetry because the divergence of the beam causes the loss of the beam current at the observation area and the broadening of the Doppler shift of the emission line. As the distance from the neutralizer to the observation area is about 6.5 m in JT-60U case, the divergence angle within 0.13 degrees is required to attain the beam diameter of 30 mm which is the spot size in the observation area. The prototype ion gun on JT-60U aims at the extraction of the collimated beam with the target values of the beam energy of 30 keV, the beam divergence angle of 0.13 degrees, and the beam current of 10 mA in the observation area.

3. Numerical Simulation

The performance of the prototype ion gun is investigated by the numerical simulation taking into account the space charge effects. The TriComp beam simulation code (Field Precision) is used for the simulation. The mesh size of 1mm is taken for the calculation of the electric field and the beam trajectory. The extracted beam current is limited by the space charge effect.

Three different initial beam profiles at the ion source are assumed in the simulation, which are peaked, flat and hollow profiles as shown in Fig. 3(a). Each profile is feasible due to the non-uniform beam emission at the ion source, which is caused by the ion source heating characteristics, the extraction field profile, and the coating quality of the β-eucryptite.

The beam trajectories are calculated for each profile in order to confirm the difference of the beam focusing and the efficiency. In the simulation, the efficiency is estimated by the beam loss caused by the beam clash to the electrodes and the neutral beam spreading according to the divergence angle. Then, the resultant beam current is calculated at the observation area.

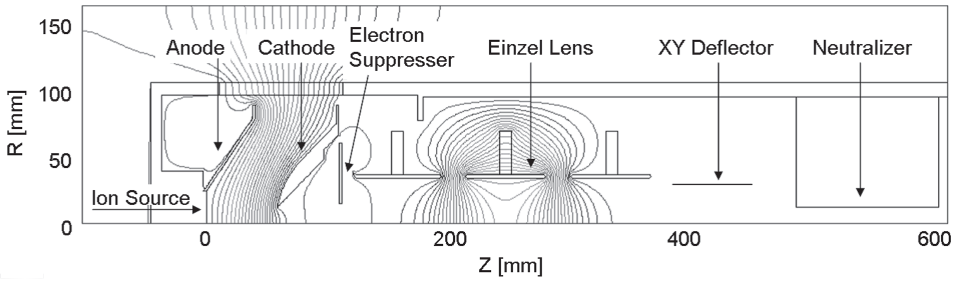

Fig. 2 Geometry of the ion gun on JT-60U. Contour lines show an example of electrostatic potential used in numerical simulation.

3.1 Beam transport efficiency

Space charge limited current of the ion gun is calculated for the investigation of the performance of the ion gun as shown in Fig. 3(b). Theoretical Child-Langmuir current density j is described as follows;

$$j = 5.5 \times 10^{-8} \left(\frac{Z}{M} \right)^{1/2} \frac{V^{3/2}}{d^2}, \qquad (1)$$

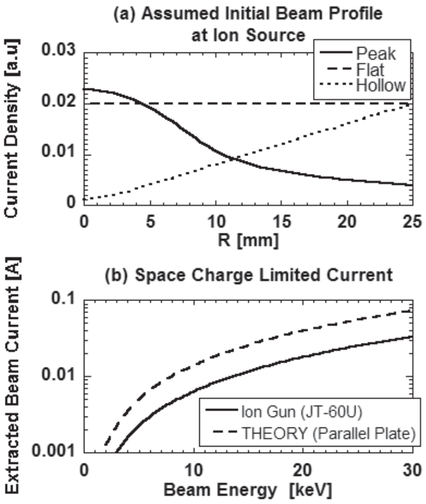

Fig. 3 (a) Assumed extracted beam profiles at the ion source with the radius of 25 mm. (b) Calculated space charge limited extracted current. Dashed line shows the theoretical value of the parallel beam extraction.

where Z is charge number, M is mass number, V is accelerating voltage, and d is distance between electrodes. Space charge limited current of the ion gun is lower than the theoretical one due to the fringing field of the cathode aperture and non-parallel extraction. The maximum extracted current is limited to 33 mA in the case of the beam energy of 30 keV.

Figure 4 shows the beam trajectories for three different initial beam profiles with the fixed beam current and the applied voltages. The beam divergence angles at the neutralizer are also shown in the figure. It is shown that the peaked profile has better focusing property than the other profiles. However, the divergence angle varies from −0.8 to 1.4 degrees, and the target value of 0.13 degrees is attained in only narrow range of radius. Then the total beam transport efficiency is low due to the broadening of the divergence angle. The efficiency varies depending on the extracted current and has an optimum value for a given potential distribution.

Figure 5(a) and (b) show the beam loss fraction at the cathode and the neutralizer as a function of the extracted current. The applied voltages of the Einzel lens are optimized for the highest efficiency. The ion beam loss at the cathode electrodes rapidly increases when the extracted current exceeds 10 mA, which is caused by the spreading due to the space charge effect. The peaked and hollow profiles have smaller loss fraction than the flat one. The beam loss in the neutralizer indicates the focusing property by the Einzel lens. Figure 5(c) shows the total loss fraction

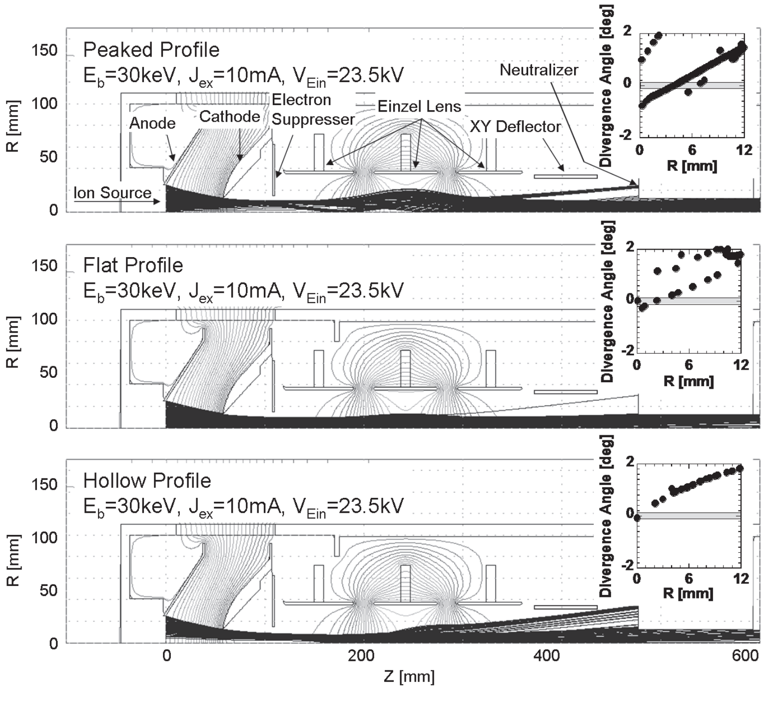

Fig. 4 Beam trajectories in cases of peaked, flat and hollow profiles with the same applied voltages. Acceleration voltage is 30 kV, extracted current is 10 mA, and focusing voltage is 23.5 kV. The divergence angle at the neutralizer is also shown. The requirement of the divergence angle is shown as belts from −0.13 to 0.13 which is the range corresponding to the diagnostic spot size.

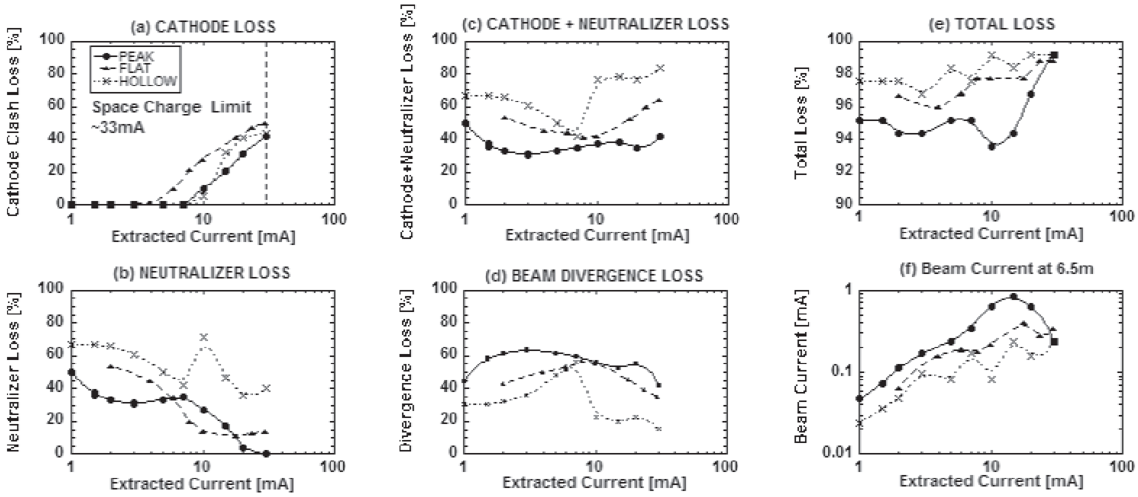

Fig. 5 Beam loss fraction and obtained beam current for peaked, flat and hollow profiles with optimized Einzel lens voltages. Acceleration voltage is 30 kV. (a) Loss due to clash the cathode electrodes. (b) Loss due to clash at the neutralizer (c) Total loss in the ion gun. (d) Beam divergence loss which means the transport efficiency from the neutralizer to the observation spot. (e) Total loss. (f). Resultant current at the observation area which is 6 m away from the neutralizer.

in the ion gun. The peaked profile achieves the better efficiency of 60 %, while 80 % of the beam is lost in the case of the hollow profile.

The beam divergence loss arising from the divergence angle of the neutral beam is shown in Fig. 5(d), which means the loss fraction from the neutralizer to the observation area. The observation area is a diameter of 30 mm at a distance of 6.5 m from the neutralizer. The divergence loss fraction of each profile is about 90 % and it becomes larger as the extracted current increases. The peaked profile has the optimized divergence angle near the extracted current of 10 mA. However, 90 % of the neutral beam can not contribute to the diagnostics. Figure 5(e) and (f) show the total loss and the obtained current in the observation area. The obtained beam current increases linearly as the extracted current is increased. However, it saturates and even reduces in larger current than 15 mA due to the increase of the beam divergence loss. The low efficiency of the prototype ion gun mainly arises from the divergence loss of the neutral beam. Therefore, the divergence angle is the most important parameter for the development of the ion gun on JT-60U because of the long transport of the neutral beam. Geometries of the Einzel lens and the neutralizer need to be improved for the enhancement of the efficiency.

As a whole, the peaked profile has better performance in terms of the beam focusing and efficiency. The prototype ion gun has the maximum efficiency of 6 % near the extracted current of 10 mA. The beam current about 0.9 mA is obtained at the observation area when the extracted current is 15 mA. It is found that the profile of the extracted current is also important for the realization of the high-brightness ion gun. Then the extracted current of 10 to 15 mA is the extraction for the prototype ion gun.

4. Summary

The performance of the ion gun for the lithium Zeeman polarimetry on JT-60U is investigated by the numerical simulation. The results indicate the importance of the extracted current profile because the beam focusing and transport efficiency depend on the initial beam profiles. It is found that the ion beam with peaked profile has better performance. In order to develop the high-brightness ion gun for JT-60U, the divergence angle is the most important because the diagnostic geometry requires the long beam transport. The beam divergence loss strongly depends on the property of the Einzel lens and the position and the length of the neutralizer. The optimized configuration and geometry need to be considered.

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