Sensitivity Check of Background Plasma Parameter during SMBI in the GAMMA 10 Central-Cell by 3-D Monte-Carlo Simulations*)

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(Received 3 October 2018 / Accepted 8 December 2018)

The gas fueling by supersonic molecular beam injection (SMBI) has been carried out in the world largest tandem mirror device GAMMA 10 and higher plasma density has been achieved compared with conventional gas-puffing. Three-dimensional Monte-Carlo code DEGAS is applied to GAMMA 10 and the spatial distribution of neutral particle density during SMBI is investigated. $\sigma_{\rm div}$ is introduced as divergence angle index of the initial particle to simulate the molecular beam injected by SMBI. It is defined to be unity in the case of cosine distribution of the angular profile of launched particles. It is found that the particles are suppressed and localized in the injection point according to the reduction of divergence angle index, $\sigma_{\rm div}$ and well explained the GAMMA 10 SMBI experimental results at divergence angle index, $\sigma_{\rm div} = 0.33$. In this paper the simulation is carried out in the different profiles of electron temperature in order to check the sensitivity of the background plasma parameter. The simulation results indicate that the penetration depth depended on the background plasma parameter, electron temperature.

Keywords: GAMMA 10, neutral transport simulation, DEGAS, supersonic molecular beam injection, Laval nozzle, high-speed camera

DOI: 10.1585/pfr.14.2403017

1. Introduction

In magnetically confined plasmas, the proper control of gas fueling is very important issue. The supersonic molecular beam injection (SMBI) is an effective fueling method developed by L. Yao, *et al.* [1] which can inject neutral particle deeper into the core plasma compared to conventional gas puffing [2, 3]. SMBI system is very simple and economically feasible to develop. Many experiments have been performed in many devices, such as HL-2A tokamak [4], Heliotron J [5], NSTX [6], JT-60U [7], EAST tokamak [8] and Large Helical Device (LHD) [9] in order to understand the mechanism of the high fueling efficiency of SMBI. However, the tokamak devices are very complicated and difficult to investigate the physical mechanism in high performance plasmas. On the other hand, GAMMA 10 is an open system tandem mirror device which has very simple configuration and have many observation ports to observe the plasma behavior. Therefore, SMBI experiments has been performed to the GAMMA 10 tandem mirror device as a new particle fueling method to produce high density plasmas [2, 3]. Investigation of neutral particle behavior during SMBI is an important task for understanding the plasma-neutral interaction. Three-dimensional Monte-Carlo DEGAS code is applied to GAMMA 10 in order to investigate the neutral transport during SMBI. A parameter $\sigma_{\rm div}$ is introduced which defines the divergence angle index of the initial particle. If $\sigma_{\rm div} = 1.0$, the angular profile of launched particles follows a cosine distribution. In the previous study, it is found that the simulation results well agreed with experimental results in the case of $\sigma_{\rm div} = 0.33$ and the particles are suppressed and localized in the injection point according to the reduction of divergence angle index [10]. However, the penetration depth is independent of divergence angle index. The purpose of this study is to investigate the sensitivity of the background plasma parameter with fixed divergence angle index in which the experimental results well agreed. In this paper, the neutral transport during SMBI is investigated with varying the electron temperature.

GAMMA 10 is the world largest tandem mirror and an open magnetic plasma confining device with thermal barrier [11]. The length of the device is 27 m and consists

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*) This article is based on the presentation at the 12th International Conference on Open Magnetic Systems for Plasma Confinement (OS2018).

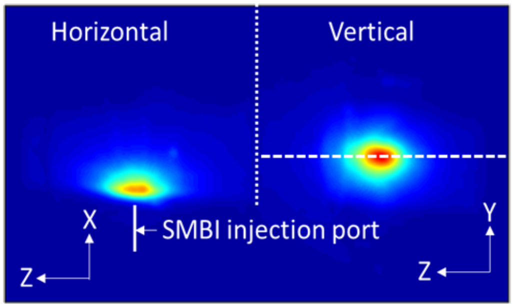

Fig. 1 2-D image captured by high-speed camera during SMBI.

of seven cells; the central-cell, anchor-cells, plug/barrier-cells and end-cells. The main plasma confinement region of GAMMA 10 is the central-cell whose length is 6 m. The position of the mid-plane of the central-cell is $z = 0$ cm. SMBI system has been installed at $z = -14.5$ cm near the mid plane in the central-cell [3]. A high-speed camera is installed at central-cell to observe the plasma behavior during SMBI. The camera system has dual branch optical fiber bundles. Therefore, the high-speed camera observes the two-dimensional (2-D; i.e., x-z, or y-z) response of the plasma to SMBI and is sufficiently capable of measuring visible-light emission as shown in Fig. 1. The left and right side of Fig. 1 shows the intensity emitted in the horizontal and vertical direction, respectively. SMBI experiments in GAMMA 10 has been performed only ICRF heated plasma by using straight nozzle, Laval nozzle and only valve case. The first SMBI experimental results with only valve case showed that SMBI achieved higher density plasmas at the core region than the conventional gas puffing [2]. It is also reported that the degree of diffusion of the injected neutral particles decreases with the increase of SMBI plenum pressure. In order to improve the directivity of the molecular beam, SMBI experiment have been performed by using straight and Laval nozzle. It is reported that the directivity of the molecular beam was improved [3].

2. Mesh Model for the DEGAS Code and Particle Source

The three-dimensional neutral transport simulation has been carried out by using the DEGAS of version 63 (DEGAS ver.63) Monte-Carlo code [12–14]. Figure 2 (a) shows the fully three-dimensional mesh model applied to the central-cell. In this model, the simulation space is divided into 32 segments circularly and 11 segments radially. In the axial direction, 83 segments are defined in the central-cell of length 6 m ($z = +3$ m and $z = -3$ m). In simulation model, the limiter and ICRF antennas are precisely implemented in a realistic configuration. This mesh model is improved for modeling SMBI experiments with Laval nozzle which is expanded around the SMBI port. This new mesh is added in a realistic configuration about the SMBI

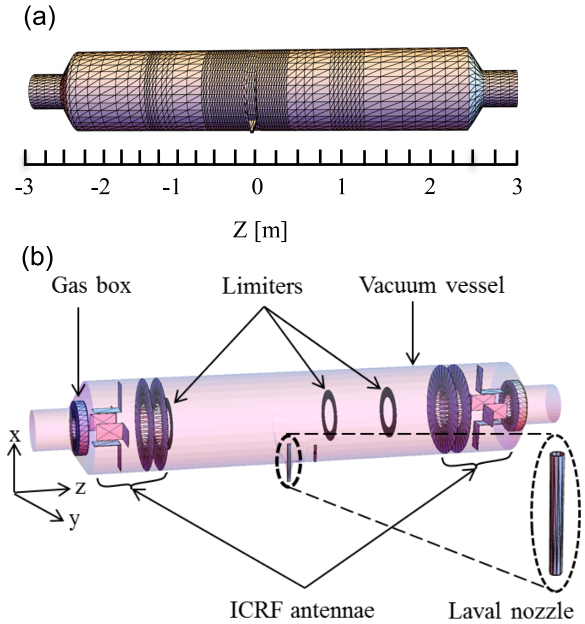

Fig. 2 Mesh model used for the 3D-DEGAS simulation, (a) surface structure of the vessel, (b) structure of second wall and vicinity of Laval nozzle.

valve with Laval nozzle. The schematic view of the vicinity of the Laval nozzle is shown in Fig. 2 (b).

In the simulation, divergence angle index of initial particle σ_{div}, is introduced to simulate the molecular beam injected by SMBI. The angular profile of launched particles has a cosine distribution in the case of $\sigma_{\mathrm{div}} = 1.0$.

When $\sigma_{\mathrm{div}} = 0.5$, the horizontal component (y or z) of the velocity vector in the cosine distribution is reduced to half. The jet becomes less divergent by reducing the value of divergence angle index along y and z-direction. The background plasma parameters on each mesh is given based on the experimental data. The background plasma parameters are $T_{\mathrm{e}} = 10 \sim 80$ eV, $T_{\mathrm{i}} = 5$ keV and $n_{\mathrm{e}} = n_{\mathrm{i}} = 2 \times 10^{18}\,\mathrm{m}^{-3}$.

3. Simulation Results and Discussion

In the previous simulation study, it was observed that the experimental results well agreed with simulation results at divergence angle index, $\sigma_{\mathrm{div}} = 0.33$ [10]. It was also observed that the penetration depth is not depend of divergence angle index. In this simulation study, the divergence angle index is fixed at 0.33 and varied the electron temperature in order to check the sensitivity of the background plasma parameter. The radial profile of electron temperature is shown in Fig. 3.

The 2-D image captured by high-speed camera as shown in Fig. 1 is reproduced by the Monte-Carlo simulation code DEGAS. The two-dimensional images (x-z or y-z) calculated by DEGAS by changing the background electron temperature is shown in Fig. 4 for $T_{\mathrm{e}} = 80$ eV, $T_{\mathrm{e}} = 40$ eV and $T_{\mathrm{e}} = 15$ eV. The Hα emission in smaller

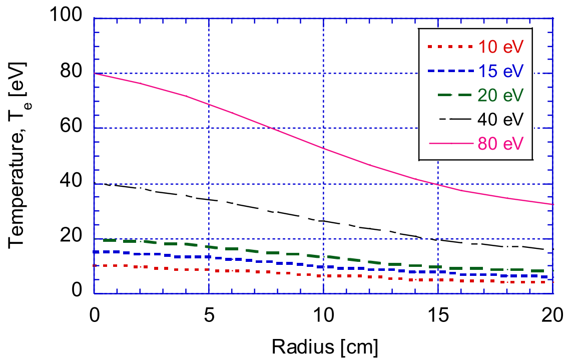

Fig. 3 Radial profile of electron temperature, T_e.

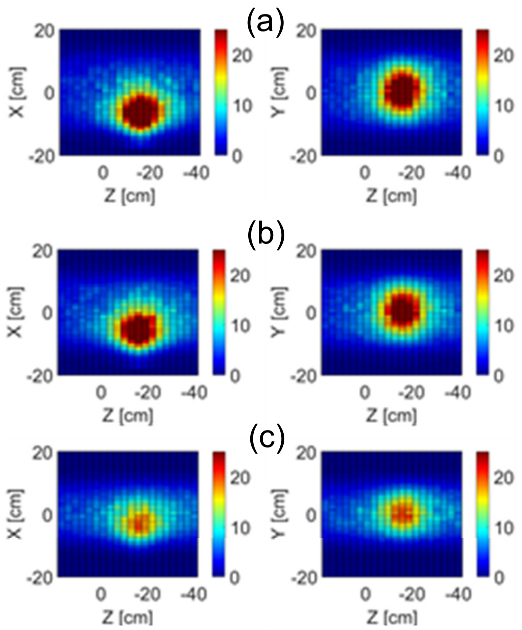

Fig. 4 2-D image calculated by DEGAS code for (a) T_e = 80 eV, (b) T_e = 40 eV and (c) T_e = 15 eV.

area is observed in the case with low electron temperature. From this figure it is observed that the emission intensity reduces when electron temperature is decreased. However, the emission area shifts towards the core region. The axial distribution of Hα emission near the SMBI injection port is shown in Fig. 5 (a). The Hα intensity peak value reduces with decrease of background electron temperature. The FWHM value is evaluated from the axial distribution of Hα emission for each background electron temperature. The variation of FWHM value with electron temperature is shown in Fig. 5 (b). From this figure it is observed that the FWHM value decreases with increase of electron temperature.

The distribution of the Hα emissivity on the plasma cross-section with different background electron temperature are shown in Fig. 6 at different distances from the injection point z = −14.5 cm, −17.5 cm and −20.5 cm for T_e = 80 eV, 40 eV and 15 eV. As shown in the Fig. 6, neu-

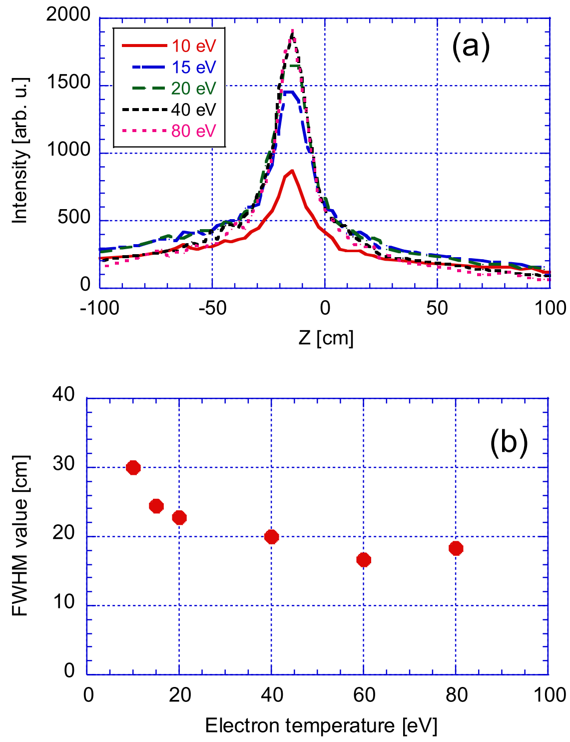

Fig. 5 (a) Distribution of emission intensity, (b) variation of FWHM value for different T_e.

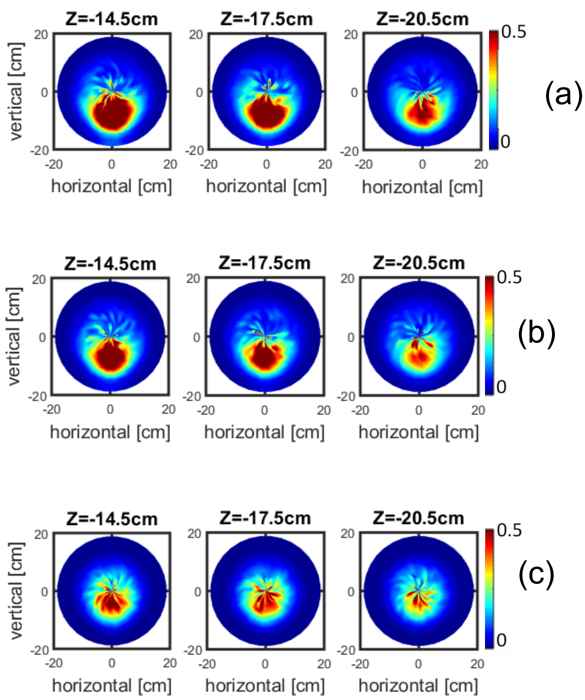

Fig. 6 Cross-sectional view of Hα line emission at different distances from the SMBI injection position for different T_e (a) 80 eV, (b) 40 eV and (c) 15 eV.

tral particle ionized in peripheral region was decreased in the case of low electron temperature. On the basis of this result, we evaluate the penetration depth at injection point

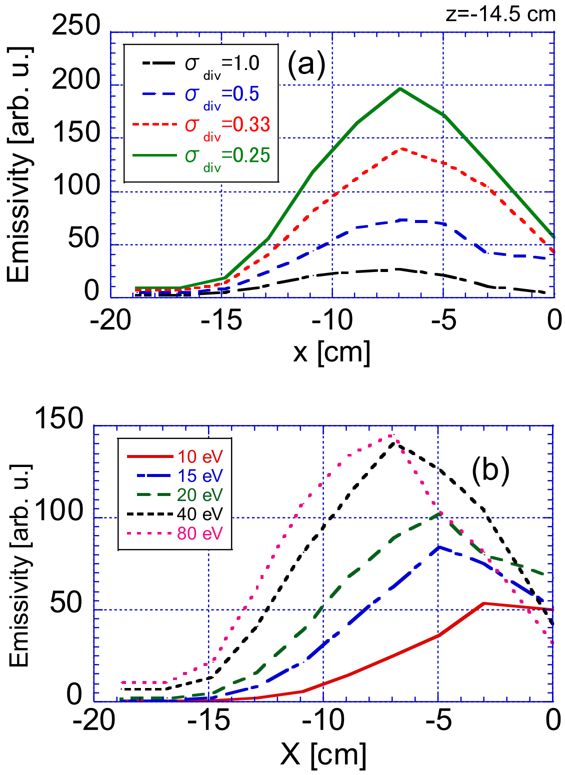

Fig. 7 Evaluation of penetration depth with (a) $\sigma_{\rm div}$ and (b) $T_{\rm e}$.

$z = -14.5$ cm. From Fig. 7 (a) it is observed that the penetration depth does not depend on $\sigma_{\rm div}$. On the other hand, the penetration depth depends on background electron temperature as shown in Fig. 7 (b). This result indicates that radial electron profile significantly influences the penetration depth. Besides, plasma edge cooling of another effect of SMBI is a key point of clarifying the mechanism of penetration depth.

4. Summary

It is important to study the neutral transport during SMBI for optimizing fueling characteristics to the plasma. In GAMMA 10 central-cell, the neutral transport during SMBI is investigated with varying divergence angle index and background plasma parameter based on the Monte-Carlo simulations. The radial and axial distribution of Hα emission area shifts towards the core region in the case of low electron temperature. It is also observed that the penetration depth depends on the background plasma parameter. This result implies that radial electron temperature profile significantly influences the penetration depth. The beneficial knowledge obtained from this study may contribute for the optimization of fueling in future plasma confinement devices such as ITER and DEMO.

The present DEGAS code could be coupled with the fluid code "LINDA" [15–18] to study the neutral transport in the D-module of GAMMA 10/PDX [19, 20].

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