Plasma Expansion in H_2, He, Ar, and H_2-He Plasma*)

Toshikio TAKIMOTO, Ryuta ENDO, Akira TONEGAWA,
Kohnosuke SATO[1)] and Kazutaka KAWAMURA

Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
[1)]*Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan*

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We had performed the fundamental experiments to investigate the characteristic of the plasma expansion due to ion species configuring the plasma by using a linear device. Our results confirmed that the plasma expands due to magnetic field divergence and the peak value of the ion flux contributing to the plasma heat load decreases with magnetic field divergence even if the ion configuring the plasma changes to different species or mixes.

Keywords: divergent magnetic field, divertor, heat load, linear plasma device, mixed plasma, plasma-wetted area

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1. Introduction

In the divertor of magnetic confinement fusion reactor, unless the exhaust heat from the core plasma is diffused, the resulting steady-state heat fluxes will exceed the material limits of ~10 MW/m^2 in devices such as ITER [1], and they will be higher in DEMO [2,3]. Therefore, for developing advanced reactors, it is necessary to achieve additional heat removal. The use of advanced divertors with innovative magnetic configurations to reduce heat load, such as the X-divertor (XD) [4], Super-X divertor (SXD) [5, 6], and Snowflake divertor (SFD) [7, 8], is one possible solution to the heat load issue. Several studies have simulated advanced divertors [6, 9, 10], and experiments have been conducted on several large devices [8, 11, 12]. However, the number of such experiments remains inadequate, and the solutions are not yet practical.

The divertor plasma has several species of particle such as fuel particles (deuterium and tritium), helium, wall materials and additional cooling gases. The ion species show different characteristics each other. Also, the mixture plasma characteristics are different from those of pure plasma. The characteristics appear as plasma-material interactions, plasma parameters, particle behaviors, and so on. The plasma expanding due to the magnetic field divergence is also affected by species of particles configuring the plasma. In the divertor with the innovative magnetic field configurations, it is important to understand the plasma behavior due to the magnetic field. Therefore, we had performed the fundamental experiments to investigate the characteristic of the plasma expansion due to ion species configuring the plasma by using our linear divertor simulator in Tokai University, which is called Test plasma Produced by Directed current for Sheet plasma IV (TPD-Sheet IV) [13–15].

2. Experimental Setup

The experiment was performed using the TPD-Sheet IV apparatus, which is schematically illustrated in Fig. 1. Hydrogen plasma was produced by DC discharge between an LaB_6 hot cathode and an anode with a slit [4 cm (width) × 0.2 cm (height)]. Thirteen floating electrodes were placed between the cathode and the anode. These electrodes, including the anode, served as orifices that maintained high pressure in the discharge chamber. The ion species configuring the plasma were changed by the incident gas species in the discharge chamber. In our experiment, the discharge current was maintained at 50 A. The generated plasma was compressed into a sheet by passing it through the slits of the floating electrodes and the anode. It was then led to the experimental region under the stationary magnetic field generated by 11 rectangular coils. The plasma was terminated at the electrically floating target located at the end of the experimental region (downstream). The neutral pressures in the midstream P_M and the downstream P_D were measured using a Baratron vacuum gauge. In the downstream region, a three-dimensional (3D)-driving probe measurement system was installed to measure plasma parameters and plasma thickness H_D which is reflect value of plasma expansion.

In our experiment, the magnetic field in the downstream region was reduced to simulate innovative magnetic configurations in simply. This was done by controlling the current passing through the third coil from the downstream-side I_C separately from the other coils. In addition, an iron-block was installed at the bottom of the downstream chamber to maintain the magnetic field strength at the target value. Moreover, this block served the purpose of curving field lines to simulate the magnetic configurations found in advanced divertors. Actual mag-

author's e-mail: 2bsp1208@hope.tokai-u.jp
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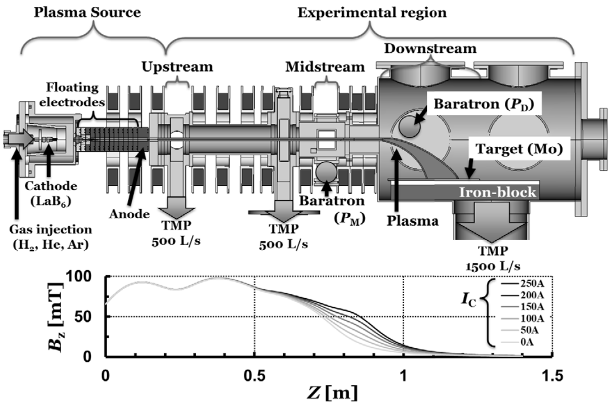

Fig. 1 Cross-sectional diagram of TPD-Sheet IV. The lower figure shows the distributions of center magnetic field strength along Z-axis in the case without an iron-block when the current of the third coil from the right I_C was varied.

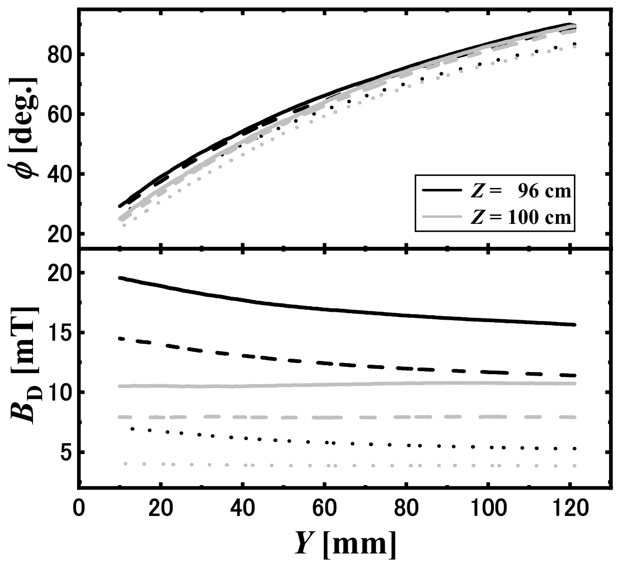

Fig. 2 Y-axis profiles of B_D and ϕ were obtained from the magnetic field strength measurements by teslameter. The colors denote Z-positions, where black and gray represent Z = 96 cm and 100 cm, respectively. The line type denotes differences of I_C, where solid, dashed, and dotted represent 250 A, 150 A and 0 A, respectively.

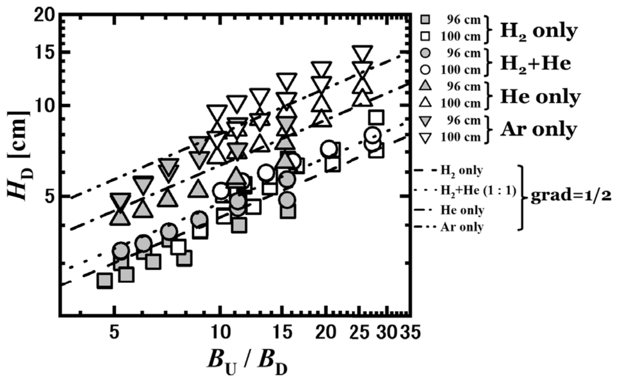

Fig. 3 H_D obtained from half-widths of Y-axis profiles of ion saturation current is plotted against magnetic field divergence in various plasma. The colors denote differences in Z, where gray and white represent Z = 96 cm and 100 cm, respectively. The shapes denote kinds of discharge gas, where square, circle, triangle, and inversed triangle represent H_2 only, H_2+He (1:1), He only and Ar only, respectively. This graph is a log-log plot.

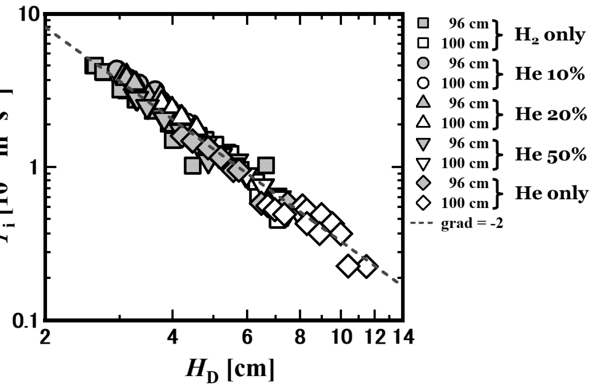

Fig. 4 Dependence of Γ_i on H_D in H_2-He mixed plasma. The colors denote differences in Z, where gray and white represent Z = 96 cm and 100 cm, respectively. The shapes denote mixture ratio of discharge gas flow rate, where square, circle, triangle, inverted triangle, and rhombus represent 0%, 10%, 20%, 50%, and 100%, respectively. This graph is a log-log plot.

netic field strength in the upstream B_U and the downstream B_D was measured by a teslameter. In this experiment, B_U at center of the chamber remains constant at ~87.5 mT under all conditions. Figure 2 shows the typical Y-axis profiles of B_D and ϕ (the angle between X-Y section and B_D) at Z = 96 cm and 100 cm when I_C was varied.

3. Results

Figure 3 shows a plot of actual plasma thickness values H_D obtained from the half-widths of the profiles against magnetic field divergence (B_U/B_D) in H_2-, He-, Ar-pure and H_2-He mixed plasma. H_D increases with proportional to square root of magnetic field strength ratio between the upstream and the downstream. This tendency corresponds to the theoretical value of the plasma thickness H_W which is obtained by plasma-wetted area [5] as follows:

$$H_W = \sqrt{\frac{B_U}{B_D}} \frac{H_U}{\sin(\phi)}. \quad (1)$$

Here, H_U is the plasma thickness of upstream and ϕ is the angle between X-Y section and B_D. We assumed that the plasma thickness does not vary under identical magnetic conditions. Accordingly, we considered that each plasma had its own H_U independent of B_U/B_D. From Fig. 3, it

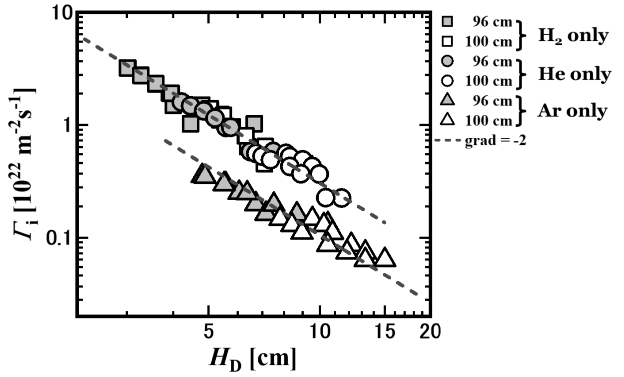

Fig. 5 Dependence of Γ_i on H_D in various pure plasmas. The colors denote differences in Z, where gray and white represent Z = 96 cm and 100 cm, respectively. The shapes denote kind of discharge gas, where square, circle, and triangle represent H_2, He, and Ar, respectively. This graph is a log-log plot.

is suggested that the plasma expansion is according to magnetic field divergence even if the ion configuring the plasma changes and mixes.

Figure 4 shows the dependence of the ion flux, Γ_i, at the plasma center in downstream on H_D when the proportion of He for H_2 in the discharge gas flow rate of H_2-He mixed plasma was varied (100%, 50%, 20%, 10%, and 0%). They were measured by Langmuir probe. In Fig. 4, Γ_i decreases with inversely proportional to the square of H_D, irrespective of the ion species. This tendency was also same at Ar-pure plasma as shown in Fig. 5. Therefore, it is expected that the ion flux decreases by magnetic field divergence even if the ion configuring the plasma changes and mixes.

4. Summary

We experimentally examined the effect of magnetic field on plasma heat load in various plasmas by using the linear device TPD-Sheet IV. Our results confirmed that the plasma expands due to magnetic field divergence and the peak value of the ion flux contributing to the plasma heat load decreases with magnetic field divergence even if the ion configuring the plasma changes to different species or mixes. These results suggest that magnetic field divergence can effectively reduce the heat load in actual divertor condition. In the future, we will examine details of these experimental results and the characteristics of plasma expansion with cooling gas (H_2, Ar and N_2) in high pressure conditions including the detached condition.

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