ICRF Heating in the Plug/Barrier Region to Control End-Loss Ions on GAMMA 10/PDX

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Abstract. On the GAMMA 10/PDX tandem mirror machine, divertor simulation experiments are carried out in the west end region by utilizing the particle flux from the confinement region. In order to control the particle flux and the ion temperature on the west end region, we have tried ICRF heating experiments with two types of antennas, double half turn (DHT) and Nagoya Type-III antennas, located in the west barrier cell. The ICRF heating in the barrier cell is effective for increasing the ion temperature at the end region. On the other hand, the particle flux is decreased due to the trapping of the ions from the central cell. This effect is more explicit by use of the Type-III antenna than the DHT antenna. The direct heating of the end-loss ions in the end region has been demonstrated to be effective for the increase of both ion temperature and particle flux.

I. INTRODUCTION

On the GAMMA 10/PDX tandem mirror machine, divertor simulation experiments are carried out in the west end region by utilizing the particle flux from the confinement region [1]. The particle flux of a few 10^{22} m^{-2}s^{-1} and the parallel ion temperature of 100 - 400 eV are observed at the end region in a standard operation. The ion temperature of more than 100 eV is comparable to SOL plasma in large tokamaks. However, over tenfold increase of the particle flux is required for simulating the SOL plasma. Ion cyclotron range of frequency (ICRF) heating is one of appropriate ways for controlling end-loss ions in GAMMA 10/PDX. In previous experiments, the particle flux was increased to 1.7×10^{23} m^{-2}s^{-1} with the parallel ion temperature remained over 100 eV at the end region during ICRF heating in the central cell and both anchor cells [2,3]. In order to increase the particle flux and the ion temperature more, we tried ICRF heating with antennas installed in the west barrier cell.

II. EXPERIMENTAL SETUP

GAMMA 10/PDX is 27 m in axial length and consists of five mirror cells; a central cell for production and heating of the main plasma, minimum-B anchor cells located both sides of the central cell for magnetohydrodynamic (MHD) stabilization, and plug/barrier cells at both ends for potential formation with electron cyclotron heating (ECH) [4]. There are three ICRF systems in GAMMA 10/PDX called RF1, RF2 and RF3. RF1 and RF2 have two final amplifiers, and RF3 has one amplifier. Eight sets of antennas for ICRF heating are installed in GAMMA 10/PDX as shown in Fig. 1; two Nagoya Type-III (Type-III) antennas and two double half turn (DHT) antennas in both sides of the central cell, three double arc type (DAT) antennas in the anchor cells, and one DHT antenna in the west barrier cell (WB-DHT).

In normal discharges on GAMMA 10/PDX, the seed plasma is injected with the plasma gun located at both ends of machine. Fast waves excited from Type-III antennas with RF1 produce plasma and heat ion in the midplane of the both anchor cells [5,6]. On the other hand, slow waves excited from DHT antennas with RF2 heat ions near the
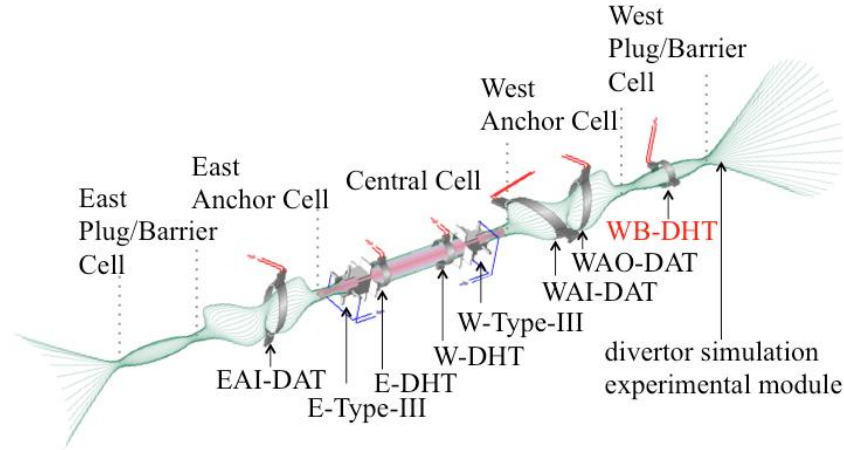
FIGURE 1. Schematic drawing of the magnetic field configuration and ICRF antennas of GAMMA 10/PDX.

midplane of the central cell. After the plasma built up with RF1 and RF2, an additional heating with RF3 have been applied.

III. EXPERIMENTAL RESULTS

III.A ICRF Heating in Barrier Cell

By using WB-DHT antenna with RF3 of 7.7 MHz, we have tried ICRF heating in the west barrier cell. The resonance layer of 7.7 MHz is located near the midplane of the barrier cell. Figure 2 shows the influence of the additional heating on the west end-loss ions and the west barrier cell. Figure 2(a) shows the decrease of the particle flux on the west side and the increase on the east side during the additional heating. The parallel ion temperature of the west end-loss ions increases (Fig. 2(b)) and the line density of the west barrier cell increases remarkably (Fig. 2(c)). It is suggested the particles from the central cell are trapped in the barrier cell. Furthermore, ions are reflected to the east side due to the potential formation with the density increase.

In order to increase the particle flux on the end region, we have injected hydrogen gas with the additional heating. Figure 3 shows the ratio of the particle flux and the parallel ion temperature at the west end region during to before the barrier heating with WB-DHT antenna as a function of the plenum gas pressure. The increase of the particle flux is observed with the additional gas injection in the barrier cell. The particle flux increases over 20% with the plenum pressure of 500 torr. In that case, the parallel ion temperature does not increase. The line density of

(a)

(b)

(c)
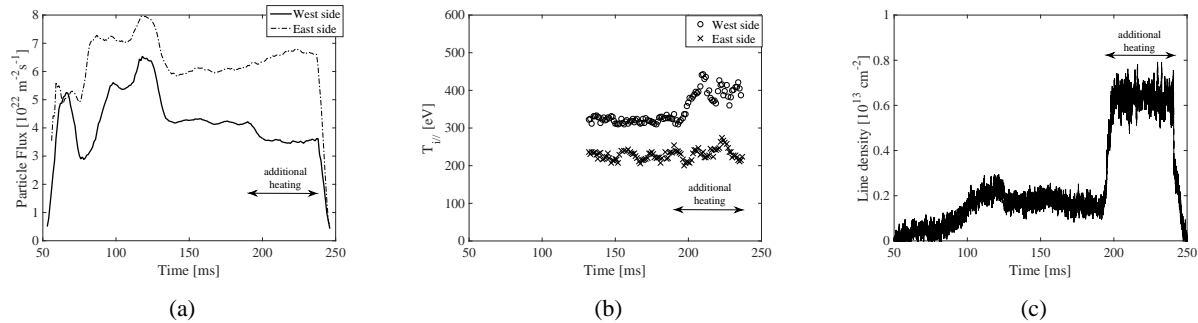
FIGURE 2. The influence of the additional heating on the west end-loss ions and the west barrier cell. RF3 is used from 190 ms to 240 ms to drive WB-DHT with 7.7 MHz. RF3 input power is 85 kW. Time evolution of (a) particle flux and (b) parallel ion temperature on the end region and (c) line density of the west barrier cell.
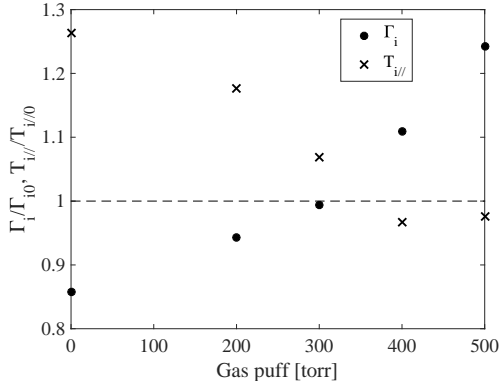
FIGURE 3. The ratio of the particle flux (Γ_i) and the parallel ion temperature ($T_{i//}$) during to before the barrier heating (Γ_{i0}, $T_{i//0}$) as a function of the plenum gas pressure. RF3 powers are about 85 kW.
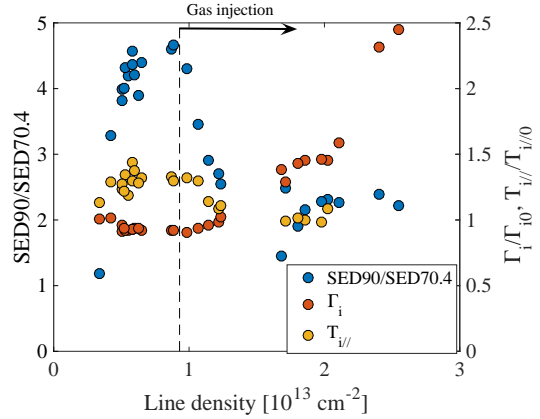
Figure 4. The heating effect in the barrier cell, and the ratio of the particle flux (Γ_i) and the parallel ion temperature ($T_{i//}$) during to before the barrier heating (Γ_{i0}, $T_{i//0}$) with WB-Type-III as a function of the line density of the west barrier cell.

the west barrier cell increases as the plenum pressure rises. The line density has reached 1.8×10^{13} cm^{-2}.

To evaluate the heating effect at the resonance layer, two secondary electron detectors (SED), which detect the charge-exchange neutral particles with pitch angles of 90 degrees (SED90) and 70.4 degrees (SED70.4), are installed in the west barrier cell. The ratio of both SED signals indicates the heating effect at the resonance layer. Figure 4 shows the heating effect, and the ratio of the particle flux and the parallel ion temperature during to before the additional heating with Type-III antenna installed in the west barrier cell (WB-Type-III), as a function of the line density of the west barrier cell. The WB-Type-III antenna is described in Sec. III.B. The decrease of the particle flux and the increase of the parallel ion temperature are observed with the additional heating. On the other hand, the parallel ion temperature and the heating effect decrease, and the particle flux increases as the gas injection. It is suggested the ion heating in the barrier cell is effective for increase of the parallel ion temperature, and the plasma production in the barrier cell is effective for increase of the particle flux.

III.B Comparison Between ICRF Heating with DHT Antenna and Type-III Antenna

DHT antenna has been replaced to Type-III antenna to compare the effect for the end-loss ion control. Figure 5 shows the influence of the additional heating on the west barrier cell with both antennas. As shown in Fig. 5(a), the

(a)   (b)   (c)
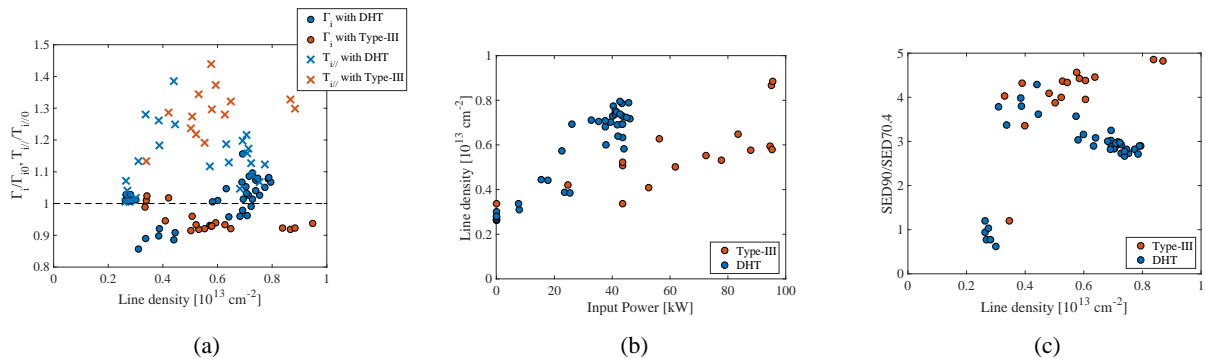
FIGURE 5. Influence of the additional heating on the west barrier cell with DHT antenna and Type-III antenna. (a) End-loss ions parameters on the west side against the line density of the west barrier cell, (b) the line density against the input power of ICRF waves, and (c) heating effect of both antenna against the line density.

(a)

(b)
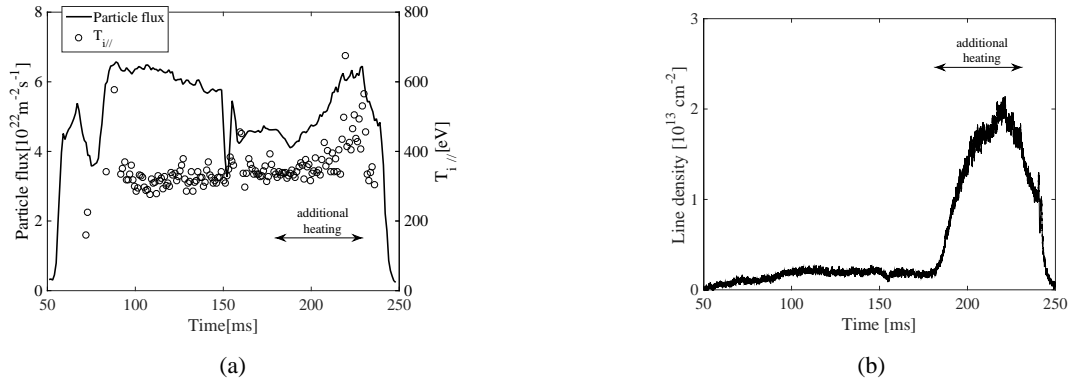
FIGURE 6. The influence of the ICRF heating with WB-DHT driven by 7.2 MHz ICRF waves. RF3 is used from 180 ms to 230 ms with 52 kW input power. Time evolution of (a) the particle flux and the parallel ion temperature on the west end region and (b) the line density of the west barrier cell.

particle flux on the west end region is increased with DHT antenna, and decreased with Type-III antenna. Type-III antenna is more effective for increase ion temperature on the west end region. The ICRF heating with DHT antenna is more effective for increase of the line density of the barrier cell as shown in Fig. 5(b). The heating effect of Type-III antenna is stronger than that of DHT antenna as shown in Fig. 5(c). It is suggested the DHT antenna is effective for plasma production, and the Type-III antenna is effective for ion heating.

## III.C End-Loss Ion Heating with WB-DHT Antenna

In order to increase both of the particle flux and the ion temperature on the west end region, a heating experiment of end-loss ions at the resonance layer in the end region has been performed with WB-DHT antenna. A frequency of 7.2 MHz is used for the experiment. Because there are no resonance layers in the barrier cell, waves with a frequency of 7.2 MHz can propagate to the end region and heat the end-loss ions directly. Figure 6 shows the result of the experiment. The increase of the particle flux and the line density of the west barrier cell is observed. The parallel ion temperature on the west end region is also increased, even though the additional gas is injected in the west barrier cell. However, the parallel ion temperature on the east end region does not increase.

IV. SUMMARY

As shown in Fig. 7, we have controlled both the ion temperature and the particle flux on the west end region with ICRF antennas in the west barrier cell. In the case that the resonance layer exists in the west barrier cell, the increase of the line density and the parallel ion temperature, and the decrease of the particle flux due to the trapping ions from the central cell is observed. With the additional gas injection, the particle flux increases, however, the parallel ion temperature does not increase.

Two types of antennas have been used for the barrier heating. It is confirmed that the DHT antenna is effective for the plasma production and the Type-III antenna is effective for the ion heating.

Finally, ICRF waves with the frequency of 7.2 MHz have been used for the end-loss ions heating. In that case, there is no resonance layer in the barrier cell and waves can propagate to the end region. The increase of both the particle flux and the parallel ion temperature is confirmed as shown in Fig. 7.
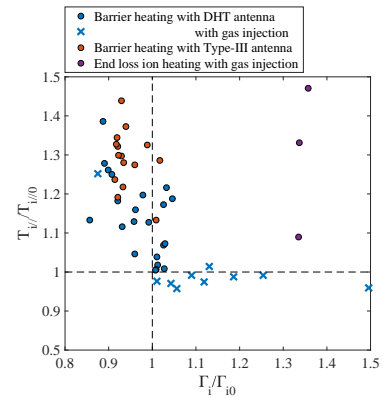
FIGURE 7. The ratio of the west end-loss ions parameters during to before the barrier heating.

ACKNOWLEDGMENTS

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