Examination of High-Density Plasma Heating on the GAMMA 10/PDX Central Cell with 3D Wave Analysis Code*)

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In GAMMA 10/PDX, ion heating is achieved using slow wave in the ion cyclotron frequency absorbed near the resonance layer. However, in high-density plasma, the slow wave is less likely to be excited due to the shielding effect. To overcome this challenge, researchers have investigated difference frequency (DF) waves excited by the nonlinear interaction of fast waves have been investigated. The fast waves can propagate to the core plasma even in high-density plasma making DF-waves an efficient option for ion heating. This study has suggested that a DF-wave with left-handed polarization, which is excited as a slow wave, is effective for ion heating in high-density plasma. The characteristics of the DF-wave were analyzed using a three-dimensional (3D) wave analysis code, TASK/WF3D, to investigate the ion resonance absorption of DF-wave heating. The results showed that when the antenna is positioned inside the core plasma to simulate DF-wave heating, ion resonance absorption is higher in high-density plasma than in low-density plasma. These results indicate that DF-wave heating is effective in high-density plasmas.

Keywords: GAMMA 10/PDX, difference frequency wave, slow wave, ion resonance absorption, TASK/WF3D

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1. Introduction

GAMMA 10/PDX is a large mirror plasma confinement device that generates cylindrical plasma in its central cell. The device consists of anchor cells, plug/barrier cells, and end regions located on the east and west sides of the central cell. Type-III antennas and Double Half Turn (DHT) antennas are installed at both ends of the central cell and are used to excite fast Alfvén waves and slow Alfvén waves, respectively.

Antennas apply Alfvén waves with azimuthal mode number (m) of ± 1 from outside the plasma for ion heating. In cylindrical plasmas, the Alfvén wave with $m = -1$ is predominantly excited as a slow wave [1]. GAMMA 10/PDX employs slow waves in the ion cyclotron frequency range (ICRF) for ion heating. These waves propagate from the strong magnetic field side to the resonance layer, transferring energy to the ions through attenuation in the resonance layers. This method is known as "beach heating." GAMMA 10/PDX has achieved ion temperatures of up to several keV in low-density plasma (on the order of 10^{18} m^{-3}) through beach heating using slow waves generated by antennas located outside the plasma [2].

However, in high-density plasma (above 10^{-19} m^{-3}), external antenna heating has become a critical issue [3]. As the plasma density increases, the slow wave in ICRF is less likely to be excited and cannot effectively reach the core plasma, leading to difficulties in heating.

Researchers have focused on difference frequency (DF) wave heating to address the challenge of external antenna heating in high-density. The DF-wave is generated spontaneously in plasma through the interaction of two waves with different frequencies. For instance, when two waves with f_1 and f_2 frequencies are excited, a DF-wave with the $|f_1 - f_2|$ frequency is produced [4–7]. To heat ions in the high-density plasma, researchers have investigated DF-wave between two fast waves, as fast Alfvén waves can still propagate to the core plasma in high-density conditions.

The study of DF-wave heating requires investigation from multiple angles, including wave measurement, particle measurement, and simulation. In this study, we focus on an analysis of DF-wave's wave structure and ion resonance absorption on the central cell of GAMMA 10/PDX using the three-dimensional (3D) wave analysis code TASK/WF3D [8]. The simulation is grounded in the measurement of DF-wave excitation obtained through experiments using a magnetic probe and microwave reflectometry.

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2. The Setup of Difference Waves Excitation Experiments

The experimental conditions, such as magnetic field distribution, the location of the resonance layer, and the antenna placement, are the same as in the initial trial of DF-wave heating in the GAMMA 10/PDX central cell [4]. In this experiment, the frequency of the east DHT antenna is 16.26 MHz for the excitation of fast waves ($m = 0$) and the east Type-III and DAT antennas are 9.9 MHz for the excitation of fast waves ($m = +1$) to generate a slow wave of 6.36 MHz ($m = -1$).

In the GAMMA 10/PDX central cell, wave measurement is performed using a microwave reflectometer, which measures the density fluctuation at the cutoff layer as a phase fluctuation of the reflected wave, and a magnetic probe, which measures the induced electromotive force from the magnetic field fluctuation. In this study, the mode number and phase difference between the radial component (B_r) and azimuthal component (B_θ) of the magnetic field fluctuation of the DF-wave are measured using the microwave reflectometer and magnetic probe, respectively, which are located outside the resonance region.

3. Wave Measurement

Figure 1 presents the mode number of the DF-wave in the core plasma, measured using two horn antennas of the microwave reflectometer, separated azimuthally by 91°. During the period between 130 and 180 ms, the DF-wave is excited with $m = -1$ when the fast waves from the antennas and the DF-wave display relatively high coherence, which implies that the mode number of the DF-wave ($m = -1$) aligns with the intended fast waves of 16.26 MHz ($m = 0$) and 9.9 MHz ($m = +1$). This result suggests that the DF-wave is being excited as a slow wave in the core plasma, as the Alfvén wave with $m = -1$ is primarily excited as a slow wave in cylindrical plasmas like the GAMMA 10/PDX [1].

Figure 2 displays the phase difference between and B_θ of the DF-wave in the plasma periphery, as measured by a magnetic probe. The phase difference has a positive value between 130 and 180 ms, which indicates that the DF-wave is right-handed polarized in the plasma periphery, while a negative value implies a left-handed polarized wave. This suggests that the DF-wave is excited as a left-handed polarized in the core plasma, as the rotation direction of plasma of Alfvén waves with $m = \pm 1$ in cylindrical plasma, like that in the GAMMA 10/PDX, is reversed between the radial inside and outside [9].

The results from the wave measurement indicate that DF-wave between the fast waves from the antennas can be excited as a left-handed polarized slow wave in the core plasma, which is effective for ion heating.

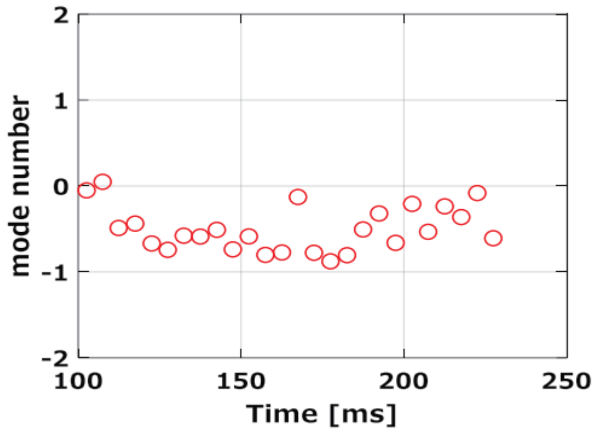

Fig. 1 Mode number of DF-wave in the core plasma measured by a microwave reflectometer.

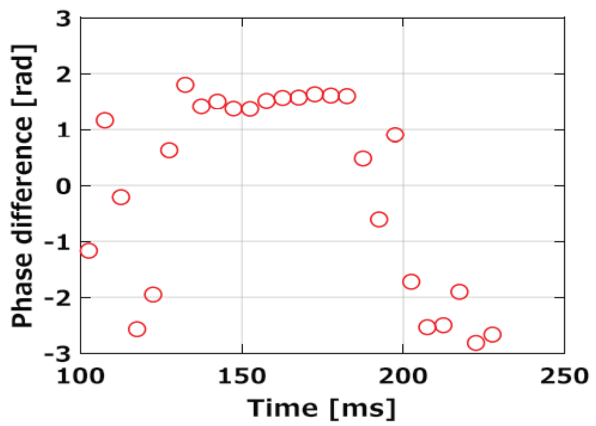

Fig. 2 Phase difference between B_r and B_θ of the DF-wave in the plasma periphery measured by a magnetic probe.

4. Simulation Settings on TASK/WF3D

TASK/WF3D is a 3D wave analysis code that models a cold plasma with collision frequency and solves Maxwell's equations using the 3D finite element method [10, 11]. With the inclusion of collision frequency, cyclotron absorption is represented as collisional absorption, also allowing for evaluating the absorbed power of ions and electrons along electrons and magnetic field strengths.

The collisional absorption in TASK/WF3D is divided into resistive and resonance absorptions. Resistive absorption occurs near the antenna with a strong electric field due to electrical resistance. Resonance absorption occurs near the resonance layer where the wave number is high in the wave dispersion relation. High collision frequencies lead to the reproduction of resistive absorption, while low collision frequencies result in the replication of resonance absorption. However, if the collision frequency is too low, the resonance layer becomes too narrow compared to the grid spacing, causing numerical errors that reduce the total absorption power. Therefore, it is crucial to set an appro-

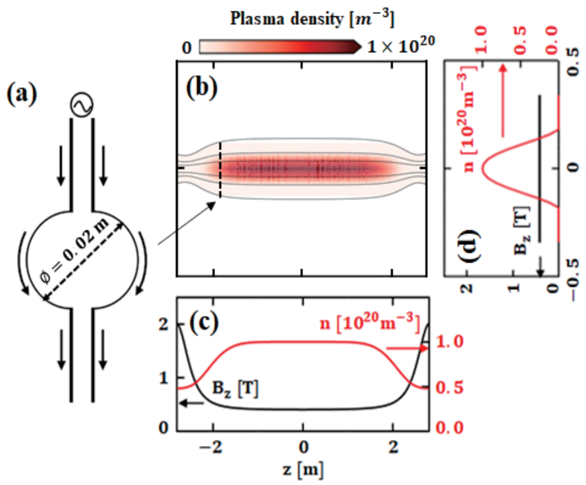

Fig. 3 (a) Schematic drawing of the current line simulating DHT e-mail: antenna, (b) electron density profile with a peak of 1×10^{20} m^{-3} in x-z plane, and its cross sections at (c) x = 0, (d) z = 0 along with the magnetic field profile.

priate collision frequency. TASK/WF3D sets the collision frequency as the ratio of the collision frequency to the wave frequency. In this study, we set the ratio at 4×10^{-3} to reproduce resonance absorption while minimizing error.

The results from the DF-wave excitation experiment indicated that the DF-wave was excited as a left-handed polarized slow wave, which is effective for ion heating in the core plasma. To reproduce these results on the GAMMA 10/PDX central cell, TASK/WF3D was used with the following conditions: the plasma radius was set at 0.18 m, and the central cell axial length at 5.60 m. Absorption media was added at both ends to simulate wave propagation toward the ends of the central cell without reflection. The grids in the axial and radial directions were set finely relative to the wavelength and were made finer near the resonance layer where the wavelength was shorter. In this study, the peak of electron density was varied from 3×10^{18} m^{-3} to 1×10^{20} m^{-3}. Figure 3 (a) shows the current lines of the DHT antenna for an exciting wave with a mode number of −1, which was set at z = −1.85 m and had a radius of r = 0.01 m for exciting a slow wave inside the core plasma. The frequency of the current through the antenna was set at 6.36 MHz and the current was 620 A. Figure 3 (b–d) show examples of the electron density for profiles and magnetic fields determined based on the GAMMA 10/PDX central cell for a peak electron density of 1×10^{20} m^{-3}.

5. Simulation Results

The results of the calculation, shown in Figs. 4 (a–d), demonstrate that the left-handed electric field is excited in the core plasma before the resonance layer, which suggests that even in high-density plasma, a left-handed polarized wave can be excited in the core plasma, which is different from external antenna heating where left-handed polarized

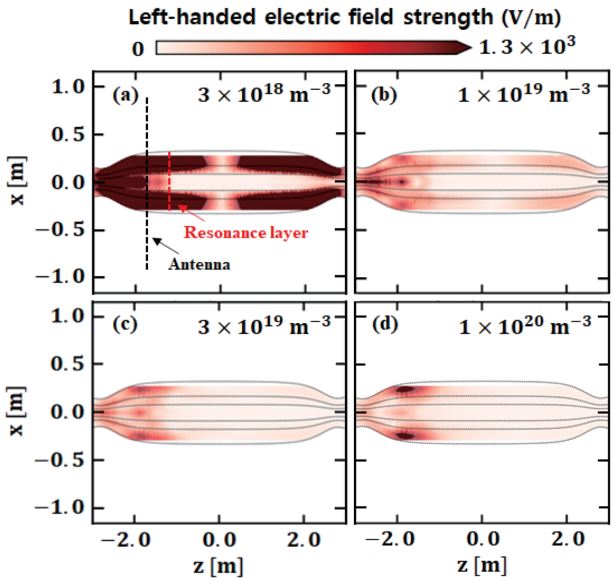

Fig. 4 Profile of left-handed electric field strength at electron density of (a) 3×10^{18} m^{-3}, (b) 1×10^{19} m^{-3}, (c) 3×10^{19} m^{-3}, (d) 1×10^{20} m^{-3}.

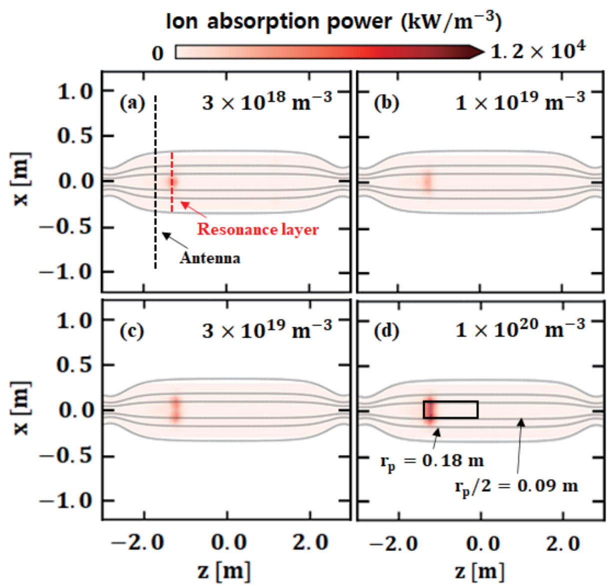

Fig. 5 Profile of ion absorption power at electron density of (a) 3×10^{18} m^{-3}, (b) 1×10^{19} m^{-3}, (c) 3×10^{19} m^{-3}, (d) 1×10^{20} m^{-3}.

waves in the core plasma are rarely excited in high-density plasma ($\geq 3 \times 10^{19}$ m^{-3}) [3].

Figures 5 (a–d) indicate strong ion absorption in the core plasma near the resonance layer. This suggests that even in the high-density plasma, which supports the idea that the slow wave can still be excited in high-density plasma and absorbed near the resonance layer. However, if the antenna is located axially within the resonance layer, strong absorption is observed near the antenna instead of the resonance layer. Hence, it is imperative to position the antenna axially outside the resonance layer to reproduce

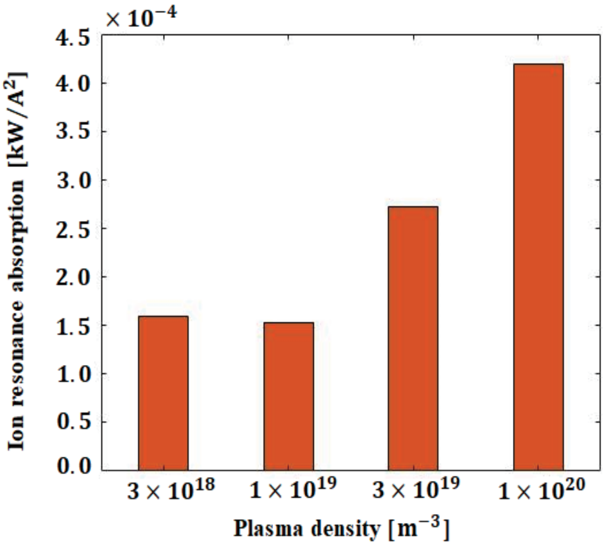

Fig. 6 Ion resonance absorption normalized by the square of the current.

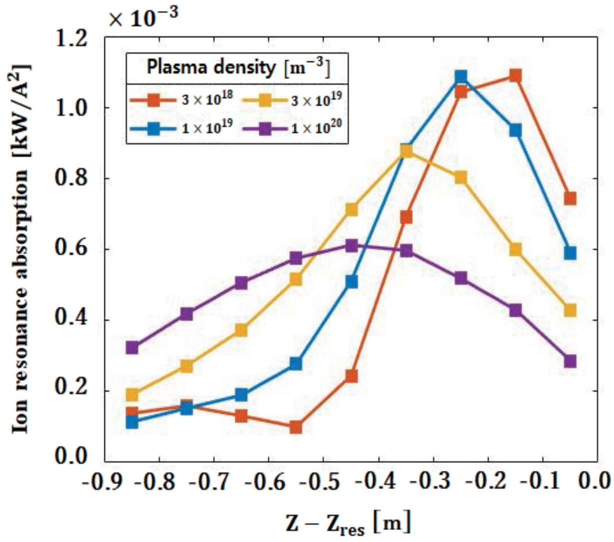

Fig. 7 Ion resonance absorption calculated by changing the z-axial position of the antenna.

resonance absorption accurately. These conditions are considered sufficient to recreate the characteristics of DF-wave as established in the DF-wave excitation experiment.

The ion absorption power inside the black rectangular frame of Fig. 5 (d) was integrated to estimate ion resonance absorption in the core plasma. The area within the frame satisfied two conditions: $r < r_p/2$ and $0.97 \leq B/B_{ci} \leq 1.03$. Here, r_p represents the radius of the plasma, and B_{ci} represents the magnetic field strength of the ion cyclotron resonance.

Figure 6 demonstrates that ion resonance absorption is normalized by the square of the current when simulating inner antenna heating. When the antenna is positioned inside the core plasma, ion resonance absorption in high-density plasma (3×10^{19} and $1 \times 10^{20}\,m^{-3}$) is found to be higher than that in low-density plasma (3×10^{18} and $1 \times 10^{19}\,m^{-3}$). This result indicates the efficacy of inner antenna heating in high-density plasma.

The dependence of wave excitation position on inner antenna heating was confirmed by changing the z-axial position of the antenna (Z) in the calculation. Z_{res} is the z-axial position of the resonance layer (at $z = -1.12\,m$). The difference $Z-Z_{res}$ implies the distance between the antenna and the resonance layer, where a negative value indicates that the antenna is positioned outside the resonance layer.

Figure 7 reveals that the high-density plasma exhibits less variation in ion resonance absorption as the z-axial position of the antenna is altered compared to the low-density plasma, which suggests that the dependence of ion resonance absorption on the wave excitation position is weaker in the high-density plasma and that the absorption remains somewhat stable regardless of the location of the wave's excitation. However, it indicates that the ion resonance absorption in low-density plasma varies significantly based on the wave excitation positioned, with the maximum absorption being observed when the antenna is positioned near the resonance layer. This shift toward the resonance layer is evident with the decrease in plasma density.

6. Summary

On the GAMMA 10/PDX, beach heating from an antenna installed outside the plasma is ineffective for high-density plasma. A solution to this is investigating the difference in frequency between fast waves. The results of the DF-wave excitation experiment confirmed that a left-handed polarized slow wave, effective for ion heating in the core plasma, can be excited. These characteristics were reproduced using the TASK/WF3D wave analysis code to investigate ion resonance absorption by positioning the DHT antenna inside the core plasma. The results indicate that inner antenna heating is effective in high-density plasmas and that dependence on wave excitation is weak in high-density plasmas but strong in low-density plasmas. Future research should use the Pilot GAMMA PDX-SC, a new mirror plasma confinement device capable of creating high-density plasmas ($\geq 1 \times 10^{19}\,m^{-3}$).

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