

Observation of Ion Heating Using the Difference Frequency of Two ICRF Waves in GAMMA 10/PDX^{*)}

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GAMMA 10/PDX is a linear plasma confinement device that mainly uses slow waves in ion cyclotron range of frequencies (ICRF) for heating, and it can achieve a high ion temperature that is in the range of several keV. Although slow waves are effective for ion heating, it is difficult to excite them with antennas at high densities, such as those over 10^{19} m^{-3} . In this study, we considered a way to excite a slow wave using the frequency difference of input waves. Two fast waves having different frequencies, which are both adequate for high-density plasma, were applied with antennas to excite a slow wave as a difference-frequency wave between the fast waves. As a result, the excitation of difference-frequency waves inside the plasma was confirmed from magnetic probe and reflectometry measurements, and an increase in diamagnetism was also observed. These results firstly demonstrate the possibility of slow-wave heating using a DF wave in a high-density linear plasma, where direct slow-wave heating is not feasible.

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1. Introduction

It is crucially important to deal with the numerous particles and huge heat flux incident upon the plasma-facing components of future fusion reactors. Thus, to understand the physics in the divertor of a DEMO reactor, investigation of the plasma-wall interaction (PWI) that occur under high temperature and flux plasma conditions over a long timescale is needed. Linear plasma devices have some advantages, such as good operability and access for plasma measurements, because of their simple magnetic configurations. While many linear plasma devices have been used to simulate divertor conditions previously, none of the devices had attained the required conditions to simulate DEMO perfectly [1]. An important component for DEMO simulation is the achievement of a high ion temperature of $\sim 100 \text{ eV}$ in high-density plasma (over 10^{19} m^{-3}). Therefore, it is very important to develop an efficient method for heating ions in high-density linear plasma.

Slow-wave heating in the ion cyclotron range of frequencies (ICRF) has been used in mirror confinement devices to heat ions in a direction that is perpendicular to a magnetic field. This is called beach heating, wherein slow waves are excited from the high magnetic field side

and they heat ions using resonance at the location where the magnetic gradient is small. Beach heating is so efficient that an ion temperature in the range of several keV in the direction perpendicular to the magnetic field line has been routinely observed in GAMMA 10/PDX. GAMMA 10/PDX is the largest tandem mirror device that uses ICRF heating system for plasma production and ion heating [2]. The ion temperature in the direction parallel to the magnetic field line is $100\text{--}400 \text{ eV}$, with an electron density of $2 \times 10^{18} \text{ m}^{-3}$ in the main confinement region. Divertor simulation equipment was installed to the end cell, and plasma-wall and plasma-gas interactions have been studied by taking advantage of fluxes with high ion temperature [3, 4]. However, some parameters, such as plasma duration ($< 0.5 \text{ s}$) and electron density, are not sufficient for simulating DEMO divertor plasma. We plan to construct a new linear device that can be operated in the steady state using superconductive coils. One of the target plasma parameters of the device is $T_i \sim 100 \text{ eV}$ with an electron density of a few 10^{19} m^{-3} . Therefore, the development of an efficient method for heating ions in high-density plasma is an important and urgent issue.

An ICRF heating system is suitable for steady-state operations; thus, ICRF slow-wave heating is a possible method for ion heating in our new high-density linear device. However, there is a major problem for applying ICRF

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slow-wave heating. In high-density plasma, ICRF waves in relatively low frequencies are shielded by the plasma, and are hard to be excited in high-density core plasma in the limit of cold plasma approximation [5]. In recent years, experiments adopting a normal beach heating scheme have been conducted in a high-density linear plasma in the order of 10^{19} m^{-3} in Proto-MPEX [6, 7]. The increase of ion temperature was observed primarily at the peripheral region.

It has been reported that when two waves with frequencies f_1 and f_2 are excited, a wave with difference frequency ($|f_1 - f_2|$) is observed in the plasma center [8–11]. We call these waves as DF waves. We propose a method for the excitation of a slow wave as the DF wave between two high-frequency fast waves, which can be excited from antennas also in high-density plasmas. This paper reports the initial results of a trial with DF-wave heating in the GAMMA 10/PDX central cell, performed taking advantage of its multi ICRF heating systems.

2. Experimental Device

2.1 GAMMA 10/PDX

GAMMA 10/PDX is a minimum-B anchored tandem mirror with outboard plug/barrier cells, as shown in Fig. 1. It has an axial length of 27.1 m, and the total volume of the vacuum vessel is 180 m^3 . GAMMA 10/PDX lies in the east-west direction, and this orientation is used to reference its components. The central cell, where plasmas are primarily confined, has an axisymmetric mirror configuration with an axial length of 5.6 m. The magnetic flux density at the midplane of the central cell is set to 0.42 T in this experiment, and the mirror ratio is 4.9. The diameter of the plasma in the central cell is approximately 0.36 m.

2.2 ICRF systems and antennas

There are five ICRF systems on the GAMMA 10/PDX. Three types of ICRF antennas were used in our experiments. These are the Nagoya Type-III (Type-III) antennas, Double Half Turn (DHT) antennas, and Double Arc Type (DAT) antennas, which are similar to DHT antennas and shaped to fit the plasma cross-section in the anchor cell. Two Type-III antennas are installed near the throats of the central cell, and DAT antennas are located in both anchor cells. Plasmas having a higher density than that for standard operation can be produced by controlling the phase difference between the east-side Type-III and DAT antennas and between the west-side Type-III and DAT antennas [12, 13].

As shown in Fig. 2, the ion cyclotron frequency is approximately 6.36 MHz at the midplane of the central cell, and the magnetic field is almost uniform in the radial direction. The z -axis is set in the direction of the magnetic field line at the plasma center, and the origin ($z = 0$) is set at the midplane of the central cell. A fixed limiter is installed at $z = 0.3 \text{ m}$. The frequencies of the East and West Type-III antennas are set to 9.9 and 10.3 MHz, respectively. The

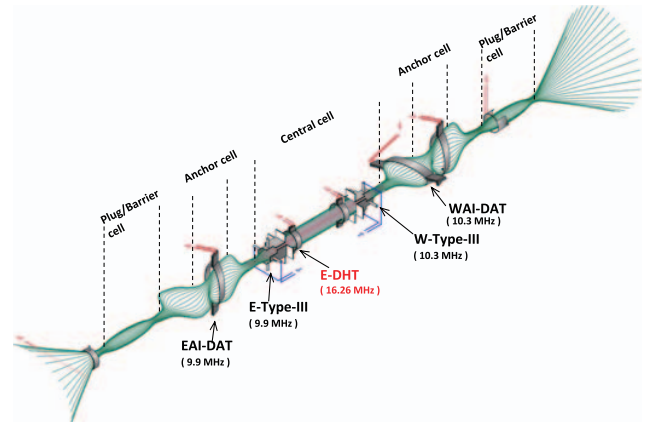


Fig. 1 Schematic drawing of the magnetic field configuration of the GAMMA 10/PDX with ICRF antennas and frequencies used in this experiment.

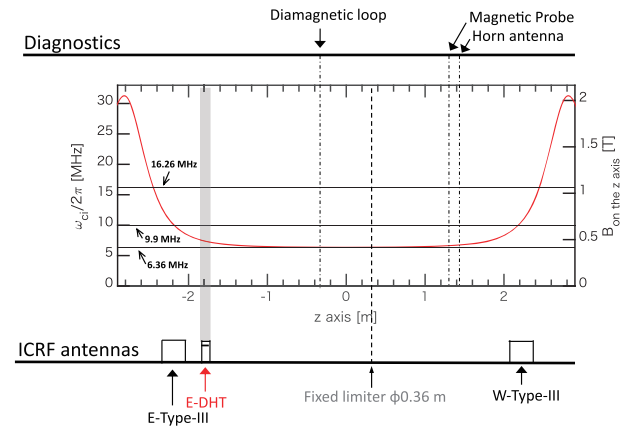


Fig. 2 Profile of the magnetic field strength and ion cyclotron frequency (hydrogens) in the central cell. Frequencies of 6.36, 9.9 and 16.26 MHz are indicated, and locations of the ICRF antennas and diagnostics are indicated.

Type-III antennas are used for the excitation of $m = +1$ mode fast waves, where m is the azimuthal mode number, to produce plasmas in the central cell and to heat ions in the anchor cells [14]. In standard operation, the frequency of both DHT antennas is set to 6.36 MHz (f_{ci}) for slow-wave beach heating around the midplane.

In this report, the frequency of E-DHT antennas is set to 16.26 MHz for the excitation of a 6.36 MHz DF wave between waves with frequencies of 16.26 and 9.9 MHz. At the location of the DHT antenna, the frequency of 16.26 MHz is much higher than the cyclotron frequency; thus, a wave of 16.26 MHz will be excited as the fast wave. The 16.26 MHz fast wave will not heat ions in the central cell. For the excitation of the $m = -1$ slow wave as the DF wave, it is important to excite the $m = 0$ fast wave of 16.26 MHz in this experiment. Fast waves with $m = 0$ cannot propagate in cylindrical plasmas under the condition of $\omega < \omega_{\text{cut}}$, where ω is the wave frequency and ω_{cut} is the cut-off frequency, which is higher than the ion cyclotron

frequency [15].

2.3 Diagnostics

The radial profile of the electron density can be obtained from the movable microwave interferometer installed at $z = -0.6$ m. A Thomson scattering system is installed at $z = 0.6$ m, and a diamagnetic loop, located at $z = -0.35$ m, estimates the plasma stored energy. From diamagnetism and the density in the central cell, the averaged plasma temperature $\bar{T} (= \bar{T}_i + \bar{T}_e)$ can be calculated. In this experiment, a magnetic probe that can measure the radial profile of the RF waves is installed at $z = 1.28$ m. By a reflectometer system, the density fluctuation in the plasma can be measured. A horn antenna pair (O-mode), used to launch and receive microwaves, is installed at $z = 1.42$ m. We evaluate the excitation of RF waves from the density fluctuation level [16].

3. DF-Wave Heating Experiment and Discussion

3.1 Experimental set up

The excitation of waves in the plasma largely depends on the density. In this experiment, the frequency of the EAI-DAT and E-Type-III antennas are set to 9.9 MHz, and the frequency of the WAI-DAT and W-Type-III antennas are set to 10.3 MHz. Figure 3 shows the time evolution of the (a) RF pulse, (b) diamagnetism, and (c) line density. Plasmas are produced from 50 to 240 ms. DAT antennas are powered from about 110 ms, and their powers are increased at 150 ms. When RF pulses are applied to the DAT antennas, the line density increases, as shown in Fig. 3 (c). Because additional gas is injected at 180 ms, the diamagnetism decreases and line density increases.

3.2 Heating effect of additional 16.26 MHz

Figure 4 shows the diamagnetism and line density when an additional RF of 16.26 MHz is applied on the E-DHT antenna. As shown in Fig. 4 (b), the diamagnetism clearly increases when the line density is over $4.5 \times 10^{17} \text{ m}^{-2}$, while the line density does not change much. This means that the averaged temperature, \bar{T} , is increased by adding the 16.26 MHz fast wave. After 180 ms, gas is injected; thus, charge exchange loss must increase.

The estimated increase of averaged temperature, $\bar{T} (= \bar{T}_i + \bar{T}_e)$, is approximately 50 eV. T_e around the plasma center, measured with a Thomson scattering system, is about 30 eV and unchanged when the additional RF of 16.26 MHz is applied. This result is thought to be highly relevant for the achievement of DF-wave ion heating.

3.3 Results of the wave measurements

Figures 5 (a) and (b) show the strength of the magnetic fluctuation (radial component) obtained from the magnetic probe inside the plasma. Peaks of the input waves (16.26, 10.3, and 9.9 MHz) and DF waves (6.36 and 5.96 MHz)

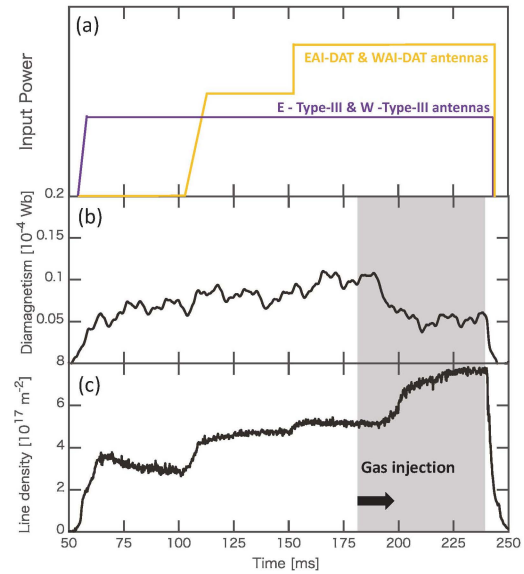


Fig. 3 The time evolution of the (a) RF input power (schematic drawing), (b) diamagnetism and (c) electron line density. Additional gases are injected at $t = 180$ ms.

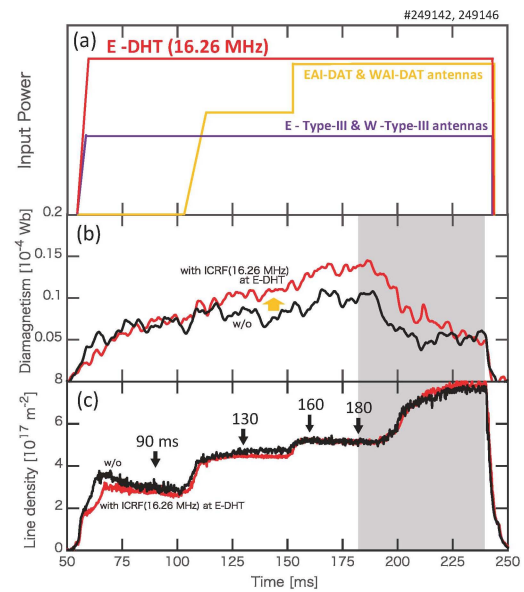


Fig. 4 The time evolution of the (a) RF input power (schematic drawing), (b) diamagnetism and (c) electron line density. In (b) and (c), black lines indicate the signals w/o the E-DHT antenna (16.26 MHz) shown in Fig. 3.

are clearly detected. Figure 5 (c) shows the radial profiles of electron densities and the radial component of the magnetic fluctuation of the 16.26 MHz signals at $t = 90$ and 130 ms. At 130 ms, \tilde{B}_r of the 16.26 MHz signal increased significantly. This result suggests that the diamagnetism increases when the fast wave of 16.26 MHz is strongly excited. Figure 6 shows the input power dependences of time-averaged ($160 < t < 180$ ms) diamagnetism and density fluctuation level. The density fluctuation level of

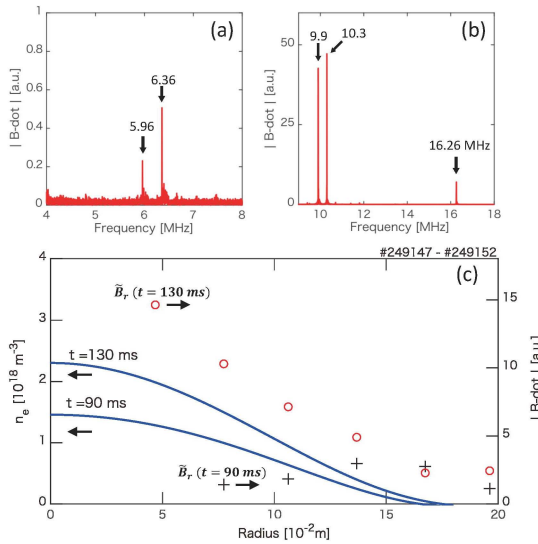


Fig. 5 (a), (b) Frequency spectrum of \tilde{B}_r at $r \sim 5 \times 10^{-2}$ m, $t = 130$ ms. (c) Radial profile of the electron density and \tilde{B}_r of the 16.26 MHz at $t = 90$ and 130 ms, obtained from the magnetic probe located at $z = 1.28$ m.

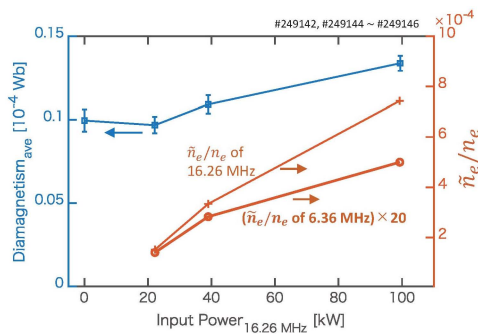


Fig. 6 Input power dependence of the diamagnetism and density fluctuation level of 16.26 and 6.36 MHz at $z = 1.42$ m. Density fluctuations are measured at the radius of approximately 9×10^{-2} m.

6.36 MHz is multiplied by 20. The amplitude of the excited DF wave and diamagnetism increase with the additional RF power.

4. Summary

Plasmas with high density ($> 10^{19} \text{ m}^{-3}$) and high ion temperature (~ 100 eV) are required in liner devices to contribute to the physical understanding of boundary plasmas. We propose to excite a slow wave using the frequency difference between two fast waves because the excitation of low frequency slow wave with an ICRF antenna should be difficult in high-density plasmas. In this experiment, two fast waves of 9.9 MHz and 16.26 MHz were excited. As a results, difference-frequency (DF) wave with 6.36 MHz, which has the ion cyclotron resonance near the midplane of the central cell, was excited, and an increase in diamagnetism was clearly observed. While the density in this experiment is still low and not all of the measurement is positive such as the relatively low DF-wave amplitude, the results show the possibility of slow-wave heating with DF waves between two fast waves in high-density plasma.

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