Development of Internal ICRF Wave Detection Using Microwave Reflectometry on GAMMA 10

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Abstract. The microwave reflectometer system in the GAMMA 10 central cell has been recently upgraded using PIN diode switches and an axial array of transmitting and receiving horn antennas to investigate internal structures of ICRF waves. The system successfully worked to measure high-frequency density fluctuations accompanied by ICRF waves at multi axial locations in a single discharge. By using several discharges for radial scan with the axial antenna switching, radial and axial measurement of the density fluctuations was achieved. Obtained profiles of 6.36 MHz ICRF wave for ion heating show axial variation in those intensity, suggesting the effect of cyclotron damping. Furthermore, in accordance with the unexplained variation of diamagnetism before the main ramp-up, the intensity near the ICRF antenna is found to also vary in time. The developed system is useful to study the behavior of ICRF waves inside a hot plasma.

INTRODUCTION

There is a long history for ion-cyclotron range of frequencies (ICRF) heating in tandem mirror devices. Plasma production and sustainment solely by ICRF heating was firstly attained in Phaedrus device, and then also achieved in GAMMA 10, where yet-to-be-defined interesting phenomena in association with ICRF waves have been observed in the past. Boundary condition leading to excitation of Alfvén-ion-cyclotron (AIC) waves [1-3] with discrete frequencies in an unstable frequency range is one of these unexplained phenomena. Other examples are saturation of confined energy against the heating power, transition-like variation of heating efficiency, significant sensitivity of heating efficiency to the magnetic field strength, and so on. For the studies on above issues, information of ICRF waves inside the hot plasma has been desired.

In order to access internal plasma with high ion temperature in the GAMMA 10 central cell, we have recently used a microwave reflectometer, which is suited for a local measurement with relatively compact system. The reflectometer has already shown its usefulness especially on nonlinear phenomena occurring inside the hot plasma; a magnetic probe installed at periphery has less sensitivity for such phenomena compared with the reflectometer. Enhanced wave-wave couplings between ICRF waves including the AIC waves have been observed along with the saturation of confined energy [4]. Bispectral analysis applied to fluctuation data obtained by the reflectometer showed that the difference frequencies between the discrete AIC frequencies were produced by wave-wave coupling between the AIC waves with radial dependence; stronger coupling occurred near the core region [5]. Such fluctuations with the difference frequencies may be important for the saturation mechanism of confined energy since there was a clear measurement showing burst-like axial loss of high-energy (over 6 keV) ions with the difference frequencies [4]. There are also some demonstrative measurements of ICRF waves done by reflectometers; such as [6,7].

Followed by wealth results made by reflectometers, we have recently upgraded our system for more powerful one; the main point of the upgrade comes from an importance of axial information for wave-related physics in an axially inhomogeneous plasma confined in a mirror field.

MEASUREMENT SETTING

Here, we briefly describe the constitution of the reflectometer system; the details of the system are described in elsewhere. Main features of our new reflectometer are (i) an axial array of transmitting and receiving horn antennas, (ii) fast switching of horn antennas in a single discharge using PIN diode switches, (iii) simultaneous two-point measurement in either radial and axial direction and switching of these two functions, (iv) flexible radial scan by two independent frequency-tunable microwave oscillators, (v) both O- and X-mode measurement in one cross section. Heterodyne circuit is used for decomposing phase and amplitude components included in a microwave reflected from a cutoff layer. The constitution of the system aims at measurement of high-frequency density fluctuations accompanied by ICRF waves and is not for density profile measurement. With these features, the system enables flexible measurements in a radial and axial space, and two-point correlation analysis in a wide radial and axial region is possible to see such as the phase profiles of ICRF waves, which are another key to investigate wave structures in addition to those intensity profiles.

We used an antenna arrangement shown in Fig. 1 in this preliminary study aiming at demonstrating the capability of radial and axial scans and its usefulness for wave-related physics research. Two antennas at each axial position constitute one set for transmitting and receiving microwave. At present, five antenna sets are installed in total (antennas will be added in the near future); four sets of them are X-band with O-mode orientation and the remaining one set is Ku-band with X-mode orientation. Observable radial region is shown later using actual experiment data. In this study, two microwaves with different frequencies, generated by two independent microwave oscillators, were launched and received using the same O-mode antenna set. Its antenna set was routinely switched at 5 kHz in order of z = 0.52, 1.42, 1.93 m by two synchronized PIN diode switches. Note that the antennas at z = 1.12 m are not used when this radial two-point measurement with antenna switching is operated; for the present system connection, antennas at z = 1.12 m are used for the reference when axial two-point measurement is performed or when both O- and X-modes are used.

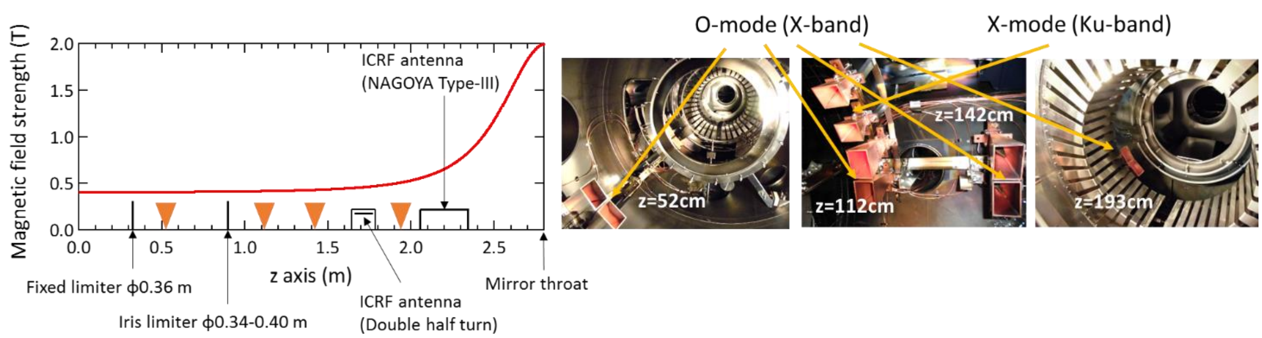

FIGURE 1. Microwave horn antenna arrangement inside the vacuum vessel of the GAMMA 10 central cell.

DETECTION OF DENSITY FLUCTUATIONS OF ICRF WAVES

We have successfully separated phase and amplitude fluctuation components included in a reflected microwave in the frequency range up to 25 MHz; here phase fluctuation is a variation of the phase difference between a fixed phase of the reference microwave and a variable phase of the plasma path, which is mainly caused by a variation of the cutoff layer position as long as some ideal conditions for reflectometry such as low fluctuation amplitude, long wavelength of the target fluctuation, etc. are satisfied (ICRF waves in GAMMA 10 are suitable). Therefore, from separated phase component, radial variation of a fixed density point can be measured when the probe microwave is launched normal to a cutoff layer. However, to relate the data to ICRF waves, transformation of phase fluctuation to density fluctuation is firstly needed. The density fluctuation level is described using density gradient scale L_n as $\tilde{n}_e/n_e = (\lambda/4\pi L_n)\tilde{\phi}$, where λ is effective wavelength of microwave inside the plasma and $\tilde{\phi}$ is phase fluctuation.

Figure 2(a) shows diamagnetism and line integrated electron density for a discharge we measured. A movable interferometer operates near the midplane of the central cell and electron density profile can be reconstructed from a set of data obtained for identical discharges where the chord of the interferometer is moved shot to shot. The reconstructed density profile for the discharge shown in Fig. 2(a) is shown in Fig. 2(b). The density profile of ICRF-produced GAMMA 10 plasma is normally a monotonically decreasing function of radius, which is a necessary condition for reflectometry, over all radius as can be seen in Fig. 2(b). In the ramp-up phase of diamagnetism, the density gradually varies in time mainly due to uncontrollable recycling gas from surrounding materials enhanced by the increasing diamagnetism with the progress of discharge.

Figure 3 shows temporal evolution of the calculated cutoff radius and density gradient scale for 8 – 13 GHz O-mode microwaves. For the discharge shown, microwave in X-band accesses a wide radial region excepting periphery. Access to the core is largely affected by a variation of the core density. A cutoff radius fluctuates in some degree according to fluctuating density profile, which leads to large temporal variation of L_n near the core region as seen in Fig. 3(b). Therefore, we need careful treatment to see temporal behavior near the core region.

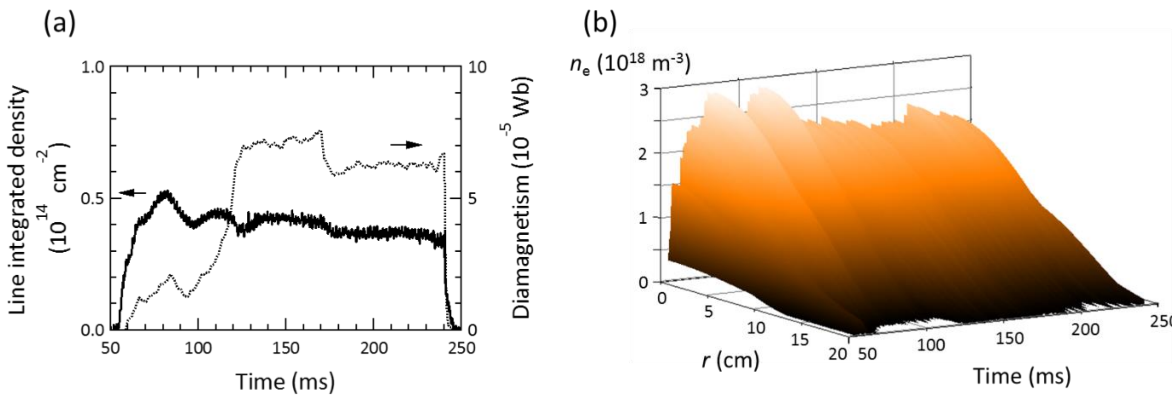

FIGURE 2. Temporal evolution of (a) diamagnetism and line integrated electron density, and (b) reconstructed electron density profile for a GAMMA 10 discharge.

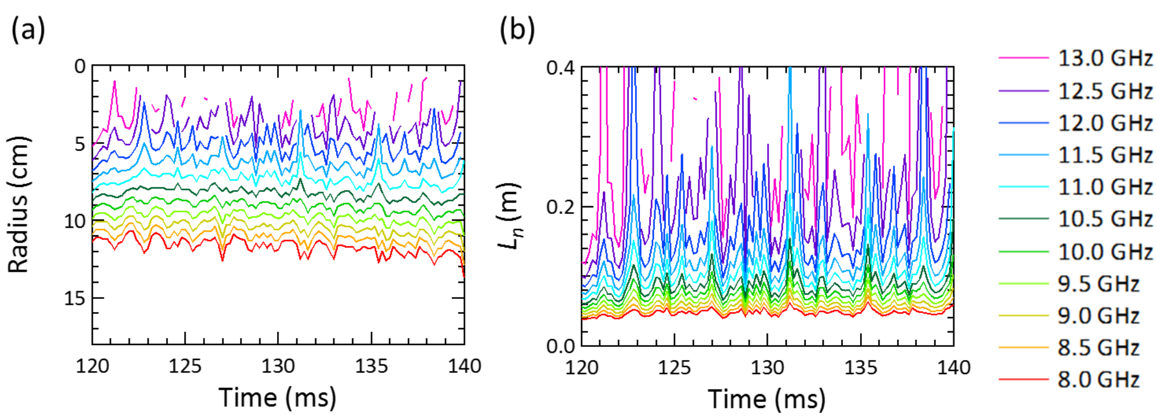

FIGURE 3. Temporal evolution of (a) radial positions of 8 – 13 GHz O-mode microwave cutoffs and (b) density gradient scales at the cutoff positions in the discharge shown in Fig. 2.

Radial two-point measurements with antenna switching were performed with changing the microwave frequencies shot to shot for a series of identical discharges, of which waveforms were those of Fig. 2 and, then, we calculated density fluctuation profiles at three axial positions. As an example, the density fluctuation of 6.36 MHz is shown in Fig. 4 as a function of radius and time. ICRF wave of 6.36 MHz was excited by double half turn (DHT) antennas located near z = -1.7 and 1.7 m with the pulse form denoted on the top of Fig. 4. This wave plays a prominent role in ion heating in the central cell by fundamental beach heating. The diamagnetism shown in Fig. 2 roughly varies in accordance with the pulse form. Comparing the profiles at three locations, it is found that the intensity at z = 0.52 m is weak with the similar profile with that at z = 1.93 m. The reduced intensity at z = 0.52 m should be a result of cyclotron damping while careful consideration is still needed especially near the core region.

The fundamental resonance of 6.36 MHz ICRF wave in the vacuum field exists before z = 0.52 m when seen from the DHT antenna.

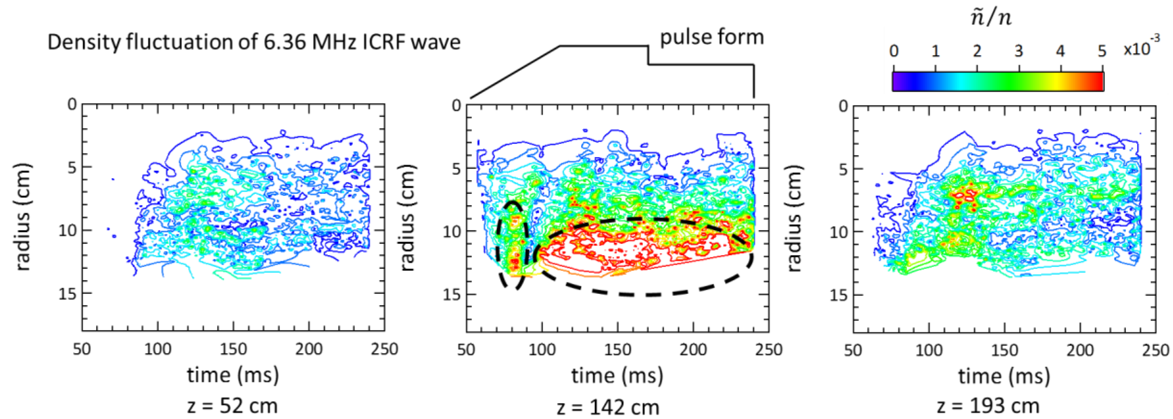

FIGURE 4. Time evolving radial profiles of the density fluctuation of 6.36 MHz ICRF wave at three axial locations. Each color scale is comparable each other for three locations. It should be noted that there is no data near the core and the periphery.

The profile at z = 1.42 m near the DHT antenna shows a distinctive distribution; much higher intensity in the outer region and transient variation of intensity at t ~ 80 ms are observed. There is a notable relation between the transient rise of intensity and the rise of the diamagnetism before the main ramp-up as can be seen in Fig. 2(a). Although this transient evolution of diamagnetism during initial ramp-up phase always occurs for normal discharges, the reason has not been clarified. Variation of boundary condition for eigenmode formation in relation to changes in the plasma parameters and background magnetic field profile by beta effect may be important for this phenomena. The observation made by this system may become an important key to resolve it.

SUMMARY

Radial profiles of density fluctuations arising from ICRF waves were successfully measured at three axial locations in the GAMMA 10 central cell by introducing an axial array of horn antennas and PIN diode switches to a reflectometer. Axial dependence indicating cyclotron damping and temporal variation related to the variation of diamagnetism were firstly obtained. From these measurements both in radial and axial directions, made possible by this upgraded reflectometer system, wave-related physics in a hot plasma is expected to largely progress. We are going to perform some elaborate experiments with this measurement to assess beta effect on resonance modification and Doppler effect on ion cyclotron resonance in the future.

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