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High Harmonic Fast Wave Propagation in the GAMMA 10 Tandem Mirror

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Abstract

The formation of eigenmodes in high harmonic fast waves (HHFW) in the ion-cyclotron range of frequency (ICRF) was investigated in the GAMMA 10 central cell by using the two-dimensional wave code. The plasma production by ICRF waves depends on the wave excitation in the plasma. Eigenmodes are strongly excited when the boundary conditions in the axial and radial directions are satisfied. When HHFW is excited, eigenmodes with different radial structures are formed simultaneously in the wide density range. It was suggested that the excitation of several radial eigenmodes is effective for high density plasma production.

Keywords:

GAMMA 10, HHFW, ICRF, plasma production, mirror, eigenmode, mode transition, finite element method

1. Introduction

The production of high density plasmas (>10^{19} m^{-3}) is required in the present tandem mirror experiments. In the GAMMA 10 tandem mirror, the ion-cyclotron range of frequency (ICRF) waves are used for plasma production and heating. Although the high ion temperature above 10 keV has been realized, the density is relatively low on such a high performance discharge. When the ICRF source with a frequency near the fundamental ion-cyclotron frequency is used for the plasma production in the GAMMA 10 central cell, the saturation of the density has been observed. In the present experimental conditions, dimensions of the plasma and the characteristic length of magnetic field are the same order of the wave length. The wave excitation is strongly affected from the formation of eigenmodes due to boundary conditions. It is essential for the plasma production that eigenmodes are formed strongly in the plasma when the density is changed. In the case of the waves with near the fundamental ion-cyclotron frequency, an eigenmode exists in the present density range. The waves with higher frequency are more effective to form eigenmodes. High-harmonic fast waves (HHFW) in the ion-cyclotron range of frequency have been introduced for the high density plasma production, and the significant increase in density has been observed [1]. HHFW was used in the spherical tokamaks with the aim of providing electron heating and current drive. High-density plasma production by helicon waves with the frequency above 20 times cyclotron frequency near the midplane of the central cell was reported in the HIEI tandem mirror [2].

In order to investigate the formations of eigenmodes of HHFW in the central cell, the two-dimensional wave calculation code has been introduced. Since the wavelength is comparable to the characteristic length of the device, uniform plasma approximation is not appropriate and boundary conditions as well as inhomogeneity of the plasma parameters become important. This code is applicable to the systems which have two-dimensional inhomogeneity. In this manuscript, the distributions of electromagnetic wave fields are calculated in the GAMMA 10 central cell, and the formation of eigenmodes in HHFW is estimated.

2. GAMMA 10 device

GAMMA 10 has a central cell with an axisymmetric mirror configuration, and anchor cells with non-axisymmetric minimum-B field at both sides of the central cell. The plug/barrier cells with the axisymmetric mirror are located at both ends of GAMMA 10. Three ICRF sources (RF1, RF2, and RF3) are used for plasma production and heating. So-called Nagoya Type-III and double half-turn (DHT) antennas are installed near both mirror throats of the central cell. Figure 1 shows the profile of the magnetic field strength in the axial direction, and locations of antennas installed in the central cell. Type-III antennas are driven by RF1 system. The

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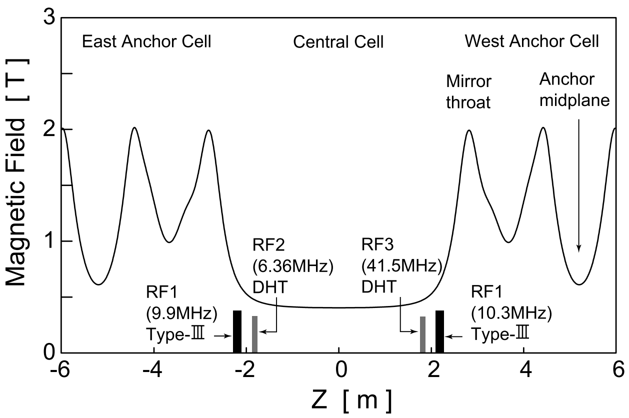

Fig. 1 Axial profile of the magnetic field strength and locations of ICRF antennas.

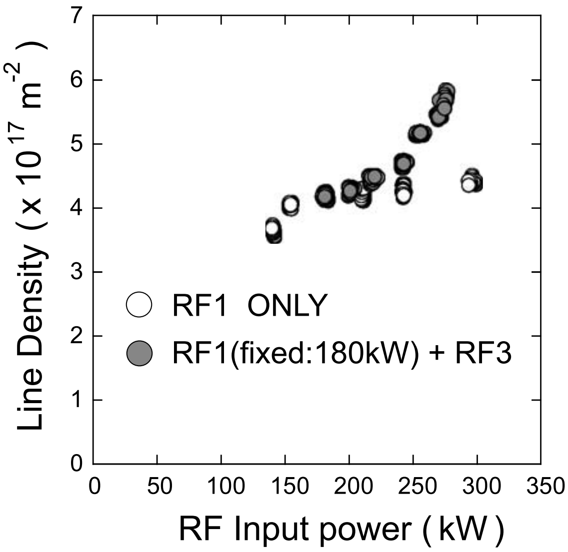

Fig. 2 RF1 power dependence of the line density (open circles) and (RF1 + RF3) power dependence of the line density with fixed RF1 power of 180 kW (closed circles).

frequencies of RF1 (9.9 & 10.3 MHz) are selected as the fundamental ion-cyclotron frequency near the midplane of the anchor cells. To avoid the strong interference between east and west antennas, the frequency of west RF1 is slightly higher than that of east RF1. RF1 plays two roles, that is, plasma production in the central cell, and ion heating in the anchor cells for the magnetohydrodynamic (MHD) stability. Fast Alfvén waves are excited in the central cell. A part of these fast waves is converted to slow waves and heats ions in the anchor cells. The east-side DHT antenna is driven by RF2 and is used for the main ion heating. The frequency of 6.36 MHz is adjusted to the ion-cyclotron frequency near the midplane of the central cell. RF3 system is introduced for the high density plasma production. RF3 is connected to the west-side DHT antenna. The frequency of RF3 is selected to be 41.5 MHz and excites the high harmonic fast waves (HHFW) in the central cell.

3. Experimental observations

In the previous experiments, the saturation of the density has been observed when RF1 with near the fundamental ion-cyclotron frequency was used for plasma production. The excitation of the fast waves depends strongly on the density under the fixed boundary conditions. In a relatively low density region, a radial eigenmode with a fundamental structure will be only formed. There are boundary conditions also in the axial direction and the excitation of the waves will be strongly affected from the density. As the optimum density for the formation of the axial eigenmode exists, the density will be clamped at the point on which the axial eigenmode is strongly formed. Figure 2 shows the dependence of the line-density increase for the input RF1 power. It is indicated that the line-density saturates near 4×10^{17} m^{-2} for the increase of RF1 power (plotted by open circles). In addition to the fast Alfvén wave with a frequency near the fundamental ion-cyclotron frequency (RF1), the high harmonic fast waves (HHFW: RF3) have been used for the plasma production. When RF3 is superposed to the plasma sustained by RF1, the line-density increases again with the RF input power as indicated by closed circles in Fig. 2. In this series of experiments, parameters were fixed except for the RF powers. In the case of HHFW, eigenmodes with different radial structures can be formed simultaneously in the wide density range. Because radial eigenmodes are always excited during the density change, the density clamping will be released.

4. Eigenmode formation

In order to investigate the propagation of the fast waves in the central cell, the two-dimensional wave calculation code has been introduced [3]. The formation of eigenmodes is compared between RF1 and RF3 under the present experimental conditions in the central cell. The excitation of waves strongly depends on not only the density profile, but also the configurations of antennas, the magnetic field profile, the shape of the vacuum vessel, and so on. In the calculation, the axisymmetric cold plasma surrounded by the conducting walls is assumed. Maxwell's equations are solved by using the finite element method (FEM) with boundary conditions. The parameters which are the shape of vacuum vessel, the locations of RF antennas, and the profiles of the magnetic field and the density are fixed to the present experimental conditions. Figure 3 shows typical parameters used in the calculation. The waves are excited by a loop antenna (DHT), or a parallel antenna (Nagoya Type-III). In the calculation, the boundary conditions at mirror throats are assumed to be the conducting walls which are not the real configuration. Fortunately, there are no big differences between results obtained in different boundary conditions. From the profiles of electric field, it is indicated that the number of radial eigenmodes increases with the applied frequency at a fixed plasma density.

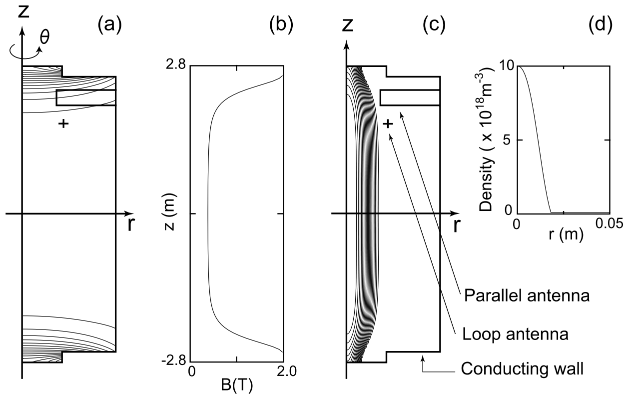

Fig. 3 Typical parameters used in the calculations. (a) Contour plot of external magnetic field profiles on r-z space. (b) Magnetic field profiles on z axis. (c) Contour plot of density profiles on r-z space. (d) Density profiles on r axis.

5. Density dependence of the wave excitation

The electric fields are calculated for RF1 and RF3 in the present density range. The density dependence of the axial wave number for m = + 1 fast Alfvén waves near the fundamental ion-cyclotron frequency (9.9 MHz) is shown in Fig. 4(a). Contour lines of the power of the electric field are plotted. The axial wave number is evaluated from the profile of electric fields on Z-axis by using fast-Fourier-transform (FFT) method. Figure 4(b) shows the electric field profiles on r-z space. In this case, an eigenmode with the fundamental radial structure is only formed in the present density range. When the eigenmode in the axial direction is formed, the wave amplitude becomes large. These eigenmodes are formed discretely when the density increases. In other words, there are gaps in the density where eigenmodes are weakly formed and plasma production becomes weak. If the ionization does not proceed beyond the density gaps, the density will be clamped at the point on which the eigenmode is strongly formed. In the experiments, the density clamping has been observed near the third peak of the power at the density of 2 $\times$ 10^{18} m^{-3}. The density 2 $\times$ 10^{18} m^{-3} corresponds to the line-density about 4 $\times$ 10^{17} m^{-2}, which is evaluated from the scaling of the density profile on r direction.

In the case of HHFW (41.5 MHz), several eigenmodes can be formed simultaneously in the present density range (Fig. 5). Each eigenmode has different radial structures in the electric fields. As the density increases, a new eigenmode with the higher radial structure appears and its amplitude becomes larger. As compared with the case of RF1, there are few gaps in the density where the formation of the eigenmodes becomes weak. Then, the plasma production can be kept continuously. As indicated in Fig. 5, the amplitude of the electric field of the eigenmode with a small axial wave number becomes larger than that with a large axial wave number. As the preliminary result, the transition from the mode with a lower radial structure to the mode with higher one has also been observed in the experiments [4].

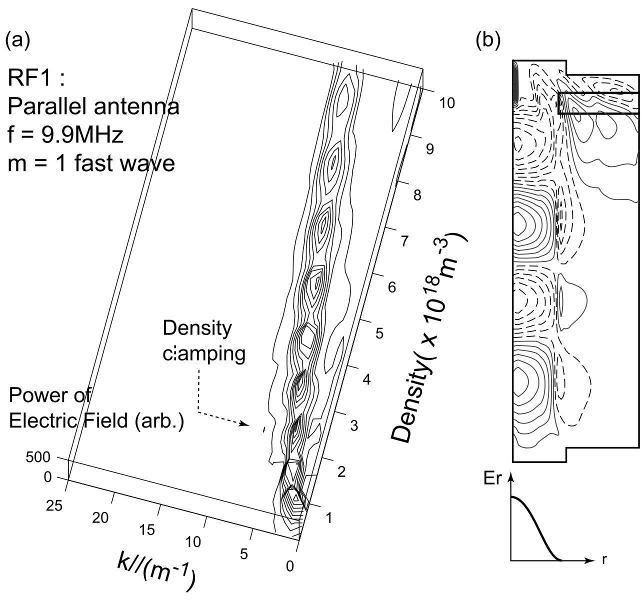

Fig. 4 (a) The dispersion relation of m = + 1 fast Alfvén waves in the case of RF1 (9.9 MHz), and (b) electric field profiles on r-z space.

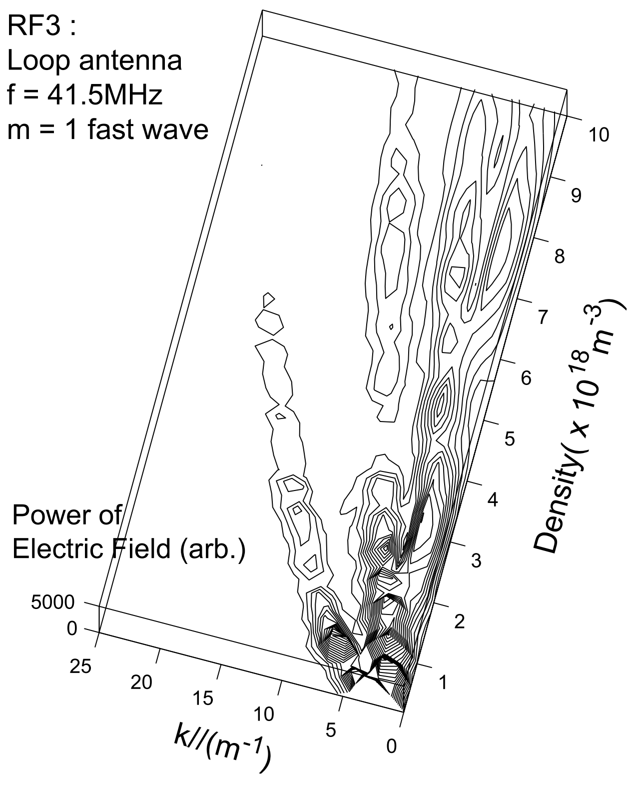

Fig. 5 The dispersion relation of m = + 1 fast Alfvén waves in the case of RF3 (41.5 MHz).

6. Summary

The propagation of HHFW in the central cell of the GAMMA 10 tandem mirror has been investigated with the two-dimensional wave code. It was found that several radial eigenmodes of HHFW can be formed simultaneously in the present experimental conditions. It is suggested that the excitation of multiple radial eigenmodes works effectively for the high density plasma production.

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