Active diagnostic of the eigenmode formation in the ion-cyclotron frequency range in the GAMMA10 central cell

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(Received 4 May 2006; presented on 9 May 2006; accepted 23 May 2006; published online 26 September 2006)

A wide-band radio-frequency (rf) probe system was constructed for the active diagnostic of the eigenmode formations in the ion-cyclotron range of frequency (ICRF) in GAMMA10. An antenna was installed in the peripheral region in the central cell. The low power rf pulse with the frequency sweep is applied to the antenna. The waves excited in the plasma are detected with a magnetic probe. The excitation of eigenmodes is described by using the antenna-plasma-probe transfer function. The transfer function can be obtained from the antenna current signal and the magnetic probe signal. When the real and imaginary parts of the transfer function are plotted on the complex plane, the resultant curves are approximately circular, indicating an eigenmode formation. The results of the measurement show that several eigenmodes can be excited in the present experimental condition. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2219377]

I. INTRODUCTION

The radio-frequency (rf) waves in the ion-cyclotron range of frequencies (ICRFs) are widely used for plasma production, heating, and stabilization against the magnetohydrodynamic (MHD) instability. In the GAMMA10 tandem mirror experiments, the production of high density and high temperature plasmas is required.[1] Although the high ion temperature above 10 keV has been realized in GAMMA10, the density is relatively low on such a high performance discharge.[2] The plasma production with fast Alfvén waves depends on the wave excitation in the plasma. In the present experimental conditions, the inhomogeneity scale length of the plasma and the magnetic field configuration are in the same order of the wavelength. Wave excitation is strongly affected by the boundary conditions. The formation of the eigenmodes in the GAMMA10 central cell has been studied computationally by using a full-wave code.[3] It is found that the excitation of waves is strongly affected by the plasma density. For higher density plasma production, the eigenmodes must be formed continuously in the plasma as the density increase.[4]

In order to investigate the eigenmode formation experimentally, a wide-band rf probe system[5] was constructed. An antenna for the excitation of the probe wave was installed in the peripheral region. The low power rf pulse is applied to the antenna via a wide-band impedance matching network. The applied frequency is swept in the ICRF. The current on the antenna and the electromagnetic oscillation in the plasma are measured. The formation of eigenmodes is represented by using the antenna-plasma-magnetic probe complex transfer function. The transfer function can be directly obtained from the complex amplitude of the excited oscillations by dividing that of the current on the antenna.

The analysis, in which the transfer function is used, has been performed for studying the fusion oriented Alfvén eigenmodes in the Joint European Torus.[6] The propagation of ICRF waves was investigated in the tokamak fusion test reactor from the spectroscopic point of view.[7] In this article, the experimental results are presented for the active diagnostic of the eigenmode formation in the central cell of GAMMA10.

II. EXPERIMENTAL SETUP

GAMMA10 consists of five mirror cells, which are a central cell, two minimum-*B* anchor cells located at both sides of the central cell, and two plug/barrier cells at both ends. The central cell has an axisymmetric mirror configuration and is 5.6 m in length with the field strength of 0.405 T at the midplane. The mirror ratio of the central cell is 5. The diameters of the central cell vacuum vessel and the stainless steel limiter installed near the midplane are 1 and 0.36 m, respectively. Two ICRF sources (RF1, RF2) are currently used for plasma production and heating. Figure 1 shows the profile of the magnetic field strength in the axial direction and the locations of the antennas installed in the central cell. Nagoya type-III antennas that are installed near both ends of the central cell are driven by the RF1 system. The frequencies of RF1 (about 10 MHz) are selected as the fundamental ion-cyclotron frequency near the midplane of the anchor cells. RF1 is used for the plasma production in the central cell and for ion heating in the anchor cells for MHD stabilization.[8] The double half-turn (DHT) antennas that are installed just inside of Nagoya type-III antennas are driven

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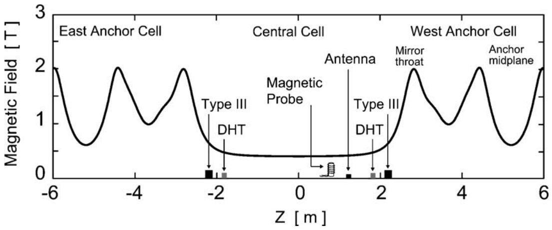

FIG. 1. The axial profile of the magnetic field strength and the locations of the ICRF antennas and the location of the newly installed wide-band rf probe system, which consists of a three-turn loop antenna and a magnetic probe in the central cell.

by RF2 and are used for the main ion heating. The frequency of 6.36 MHz is adjusted to the ion-cyclotron resonance frequency near the midplane of the central cell. The ICRF power coupled to the plasma is about 100 kW for each rf system. A discharge is started by injecting a short pulse (1 ms) gun-produced hydrogen plasma from each end, and is sustained by applying ICRF power in combination with hydrogen gas puffing in the central cell.

III. WIDE-BAND rf PROBE SYSTEM

A. Experimental apparatus

Figure 2 shows the schematic diagram of the experimental arrangement of the rf probe system. The rf signals from a function generator in the power level of milliwatts are mixed with the output of a pulse generator, which determines the pulse width and the timing of the injection. The resultant rf pulse is amplified to several hundred watts and is applied to the antenna installed on the plasma surface ($z=120$ cm) via a wide-band impedance matching network. The transmitting antenna is a three-turn loop, which has a diameter of 4 cm and a pitch of 1 cm. To adjust the matching condition, the forward power from the amplifier and the reflected power are monitored by using a bidirectional coupler set near the output of the amplifier. The current driven in the antenna is measured by a small pickup coil. The radial component of the excited magnetic field in the plasma is detected by a magnetic probe located close to the plasma surface at $z=98$ cm. The frequency range of the injected rf signals is from 4 to 9 MHz. In this frequency range, no change of the impedance matching is necessary because the matching network is arranged for a relatively wide range. Consequently, the reflected power is kept low, and sufficient current for the wave excitation flows in the antenna. The value of the current flowing on the antenna and signals from the magnetic probe are digitized in 8 bits by a fast analog/digital converter with 100 MHz sampling. By using a conventional fast Fourier transform (FFT) method, signals are converted into the frequency spectra of complex amplitude.

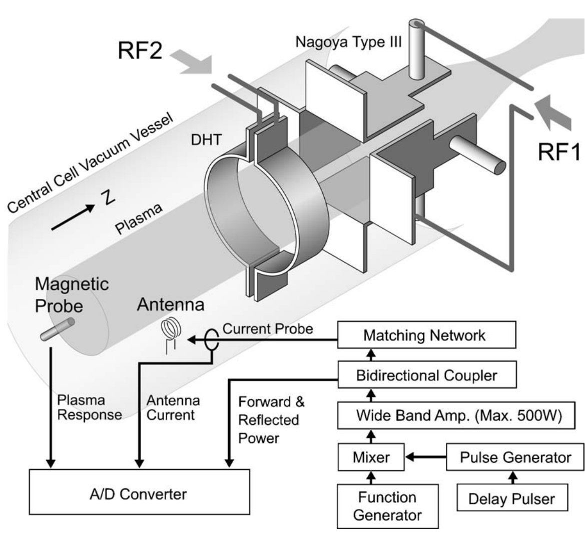

FIG. 2. The schematic diagram of the rf probe system.

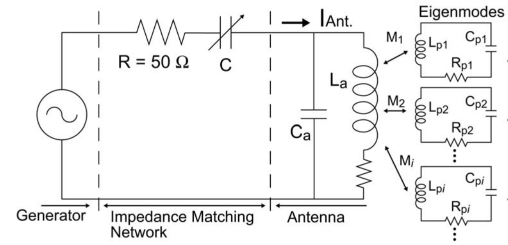

FIG. 3. A simple circuit model of the antenna-eigenmodes coupling. Each eigenmode can be represented by a RLC resonance circuit. R_{pi}, L_{pi}, and C_{pi} are the resistance, inductance, and capacitance of the *i*th eigenmode in the plasma. M_i is the mutual inductance between the antenna and the eigenmodes.

B. Diagnostic method using complex transfer function

The magnetic probe measurements are limited in the peripheral regions in order to avoid disturbances due to the probe insertion. In order to see the eigenmode formations in the plasma, an antenna-plasma-magnetic probe complex transfer function is used.[6] The relationship between an input and an output for a linear, time-invariant system is called a transfer function,

$$G(j\omega)=\frac{Y(j\omega)}{U(j\omega)}. \tag{1}$$

Here, ω is the angular frequency of the exciter signal. $U(j\omega)$ and $Y(j\omega)$ are the Laplace transform of the input and output signals for the system. In this case, the transfer function can be directly obtained by dividing the complex amplitude of the magnetic probe signal by that of the current on the antenna.

The coupling between the antenna and the plasma can be described by electric circuit models with discrete components.[9] Each eigenmode can be modeled by a *RLC* resonance circuit. A simple equivalent circuit of the antenna-eigenmodes system is shown in Fig. 3. Using this model, $G(j\omega)$ can be written as

$$G(j\omega)=\sum_i \frac{j\omega Mi(1-\omega^2 L_a C_a + j\omega C_a R_a)^{-1}}{R_{pi}+j[\omega L_{pi}-(1/\omega C_{pi})]}, \tag{2}$$

where R_a, L_a, and C_a are the resistance, inductance, and capacitance of the antenna. If the real and imaginary parts of the transfer function are plotted against each other as they pass through an eigenmode resonance, the resultant curve becomes a circle. By using this characteristic of the transfer

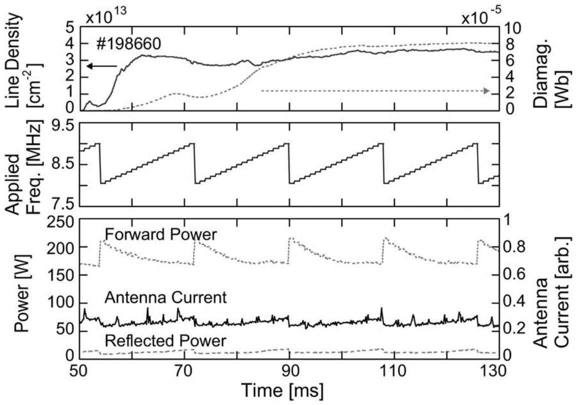

FIG. 4. The variation of the plasma and the transmitter parameters in a typical discharge. The frequency is swept in a staircase pattern since a certain length of the step width is required for the FFT analysis.

function, the eigenmode formation is evaluated in the central cell plasma.

IV. PRELIMINARY RESULTS

In a series of experiments, parameters were fixed except for the rf frequencies. To sweep the frequency from 4 to 9 MHz, several discharges with almost the same plasma parameters were used. The temporal variations of the plasma density, diamagnetism, applied frequency, rf power, and current on the antenna in a typical discharge are indicated in Fig. 4. The frequency is swept in a staircase pattern since a certain width is required for the FFT analysis. To measure the frequency dependence, the steady state of the plasma was used. In order to eliminate the spurious frequency spectra due to the cavity resonance of the vacuum vessel and the circuit resonance of the transmitter and the magnetic probe, the calibration of the signals is performed. The resonances which occur regardless of plasmas are measured by injecting the frequency swept pulse to the system with no plasmas. The frequency spectra obtained during the discharge are normalized by those measured with no plasmas.

Figure 5(a) shows the frequency-gain diagram. In this frequency range, several discrete peaks are clearly observed, which indicate the large enhancement of the excited wave fields. To confirm the resonant excitation of the eigenmodes, the real and imaginary parts of the complex transfer function are estimated. The frequency dependence of the real and imaginary parts of the complex transfer function are shown in Fig. 5(b). As shown in the figure, large changes are seen near the frequencies of each peak. An example of the complex plane representation for the second peak near 6.4 MHz in the frequency-gain diagram is shown in Fig. 5(c). Since the traced curve is approximately circular, this peak is found to be an eigenmode. Also the same curves are obtained for the other peaks.

V. DISCUSSION

A rf probe system was constructed for studying the eigenmode formation of ICRF waves in the central cell of the GAMMA10 tandem mirror. The experimental apparatus has been installed and the diagnostic method has been successfully demonstrated. To confirm the eigenmode formation in the plasma, the antenna-plasma-probe complex transfer function is adopted. When the frequency is swept across the frequency on which the eigenmode is formed, the trajectory of the complex transfer function becomes a circle in the complex plane. It is found that several ICRF eigenmodes can be formed in the present experimental condition in the central cell. This experimental investigation is expected to provide an important contribution to the optimization of the ICRF wave excitation for the higher density plasma production in GAMMA10.

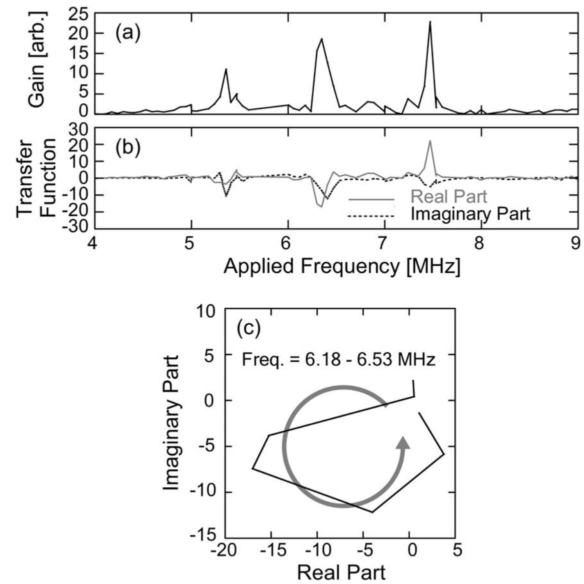

FIG. 5. (a) The gain-frequency diagram. The eigenmodelike discrete peaks are clearly observed at 5.35, 6.40, and 7.45 MHz. (b) The frequency dependence of the real and imaginary parts of the complex transfer function. (c) An example of the complex plane representation for the fourth peak near 6.4 MHz. The trajectory is approximately a circle, which indicates the resonant excitation of an eigenmode.

ACKNOWLEDGMENTS

The authors would like to thank to the GAMMA10 team of the University of Tsukuba. This work is partly supported by the bidirectional collaborative research program of the National Institute for Fusion Science, Japan (NIFS04KUGM003), Grant-in-Aid for Scientific Research (No. 18035002), and by the 21st Century COE (Center of Excellence) Program under MEXT (the Ministry of Education, Culture, Sports, Science and Technology), Japan.

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