ION-CYCLOTRON RESONANCE HEATING EXPERIMENT IN THE QUADRUPLE MINIMUM-B FIELD ON GAMMA 10

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In the GAMMA 10 tandem mirror, Magneto Hydro Dynamic (MHD) stabilization is kept with quadruple minimum-B anchor configuration. In the previous heating experiments, Ion-Cyclotron Range of Frequency (ICRF) antenna installed in the central cell was used for the anchor heating. Fast Alfvén wave excited in the central cell is partly converted to the slow wave in the non-axisymmetric transition region between the central and the anchor cells, and heats ions in the minimum-B well. In order to produce higher performance plasmas in the central cell, the ion heating should be enhanced in the anchor cell. In this study, an experiment is carried out in the anchor cell to heat ions by ICRF waves without mode conversion. A bar-type antenna is installed in the anchor cell. Applied frequency is adjusted to ion-cyclotron resonance frequency in the minimum-B well. By the additional ion heating with the bar-type antenna, remarkable increase in the diamagnetic signal has been observed in the anchor cell. It is confirmed that the additional heating by the bar-type antenna can also keep MHD stabilization.

I. INTRODUCTION

Magneto Hydro Dynamic (MHD) stabilization of confined plasmas is sustained on tandem mirror devices with minimum-B field. A concept of magnetic well stabilization was first proposed and demonstrated by Ioffe's group [1]. Following mirror machines have achieved high performance plasmas with minimum-B stabilization [2]. The GAMMA10 tandem mirror also has two quadruple minimum-B anchor cells at both sides of the central cell to keep the MHD stability. So far, high pressure plasmas with the electron density of ~10^{18} m^{-3} and the ion-temperature above 10 keV have stationary sustained with the help of the anchor stabilization [3]. Anchor stabilization is given by producing the high pressure plasma in the minimum-B well. In GAMMA10, The radio-frequency (RF) waves in the Ion-Cyclotron Range of Frequency (ICRF) are used for ion heating of the minimum-B plasmas. In the standard discharge, the RF power is coupled to the fast Alfvén wave by Nagoya Type-III antenna in the central cell. The fast wave excited in the central cell propagates to the anchor cell. In the flux tube with an elliptical cross section which is located between the central and the anchor cells, a part of the fast wave is converted to the slow wave and heats ions in the anchor cell [4]. In order to produce higher performance plasmas in the central cell, it is essential to sustain high-β plasma in the minimum-B well. To avoid the power loss associated with the mode-conversion on the present heating regime, direct excitation of the slow wave is expected under the "magnetic-beach" configuration in the anchor cell [5]. In this study, direct heating of the minimum-B plasma without mode-conversion is investigated in the anchor cell. A bar-type antenna is installed near the minimum-B well, where the flux tube has a vertically long elliptical cross section. The excited wave with the frequency of 9.7MHz has the resonance layer with the ellipsoidal closed surface in the magnetic well. In the experiments, normally a power of 130kW was coupled, and a significant increase in the diamagnetism was obtained. According to a full wave analysis under the three-dimensional inhomogeneities, it is suggested that more effective ion-heating can be expected by the modification of the present antenna configuration.

This manuscript is organized as follows. Experimental setup is shown in the next section. The experimental results discussed in section III are followed by a summary in section IV.

II. EXPERIMENTAL SETUP

GAMMA 10 consists of five mirror cells, which are a central cell, two quadruple minimum-B anchor cells placed immediately outside the central cell, and the plug/barrier cells at both ends (Fig. 1). The central cell has an axisymmetric mirror configuration and is 5.6 m in length with the field strength of 0.4 T at the midplane. The mirror ratio of the central cell is 5. The anchor cell has a non-axisymmetric minimum-B field configuration and is 1.6 m in length with the field strength of 0.6 T at the midplane.

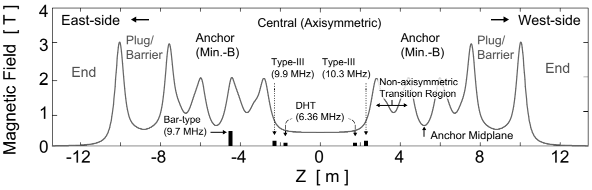

Fig. 1(a). Axial profile of the magnetic field strength, locations of the ICRF antennas in the central and anchor cells

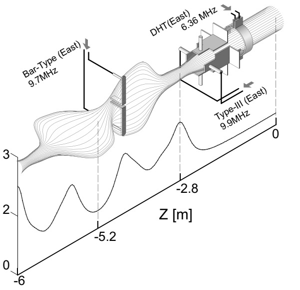

Fig. 1(b). Schematic drawing of the ICRF antennas

A discharge is started by injecting a short pulse (1 ms) gun-produced hydrogen arc-jet from each end, and is sustained by applying RF power in combination with hydrogen gas puffing in the central cell. Configuration of three ICRF antennas is also shown in Fig. 1. Nagoya Type-III (Type-III) antennas are coupled to fast Alfvén waves, which are used for plasma production in the central cell and ion-heating in the anchor cell [3]. The frequency of west Type III antenna (~ 10 MHz) is slightly higher than the frequency of the east one in order to avoid the strong interference between two antennas. Double half-turn (DHT) antennas are driven with the frequency of 6.36 MHz, which is the ion-cyclotron resonance frequency near the midplane of the central cell. Production of the high pressure plasma with DHT antenna is allowed by the help of the anchor stabilization with Type-III antennas.

A bar-type antenna is newly introduced for additional heating of the anchor cell plasmas. The antenna consists of a straight strap, which is set on the vertical half-section of the plasma surface. The wave with 9.7 MHz has the resonance layer with the ellipsoidal closed surface in the magnetic well. The equipments are set for the measurements of RF current flowing on the antenna, forward and reflected power. Then, antenna loading efficiency is estimated from those parameters.

III. EXPERIMENTAL RESULTS

In the experiment, RF power is superposed by the bar-type antenna to the target plasmas, which is produced by the Type-III and DHT antennas. Normally a power of 130kW was applied to the bar-type antenna, and a significant increase in the diamagnetism has been observed (Fig. 2). The applied RF power to the bar-type antenna is quite higher than that to the Type-III antenna. However the amount of increase in the diamagnetism with the bar-type antenna is lower than that with the Type-III antenna. The antenna loading was measured as shown in Fig. 2, and it is found that the radiation efficiency of the bar-type antenna is relatively low as compared with the other antennas. In this experiment, the loading of Type-III antenna did not measured. In the standard discharge, Type-III antenna has the loading efficiency of ~0.4 on average. According to a theory with a cylindrically uniform plasma model which is evaluated by Hosea, et al. [6], it is required that ω/ω_{ci} is close to 1.0 at the antenna for the effective antenna-plasma coupling on the beach heating. Where, ω and ω_{ci} indicate the angular frequencies of applied RF and the ion-cyclotron resonance just in front of the antenna, respectively. In the case of the bar-type antenna, ω/ω_{ci} becomes 0.75, which is less than that of DHT antenna (ω/ω_{ci} = 0.92). To confirm the dependence of the loading resistance on ω/ω_{ci}, a full wave analysis was performed on the minimum-B configuration. We used a computer code, which is developed by one of the authors (A. Fukuyama) [7]. This code solves the Maxwell's equation for the wave electric-field as a boundary-value problem using the finite element method. In the model, it is assumed that the cold and inhomogeneous plasma surrounded by the conducting walls. The power absorption with the collisional damping is described by introducing effective collisions in the dielectric tensor. The antenna loading resistance versus applied frequency was calculated for the anchor cell plasma (Fig. 3). In the present magnetic field

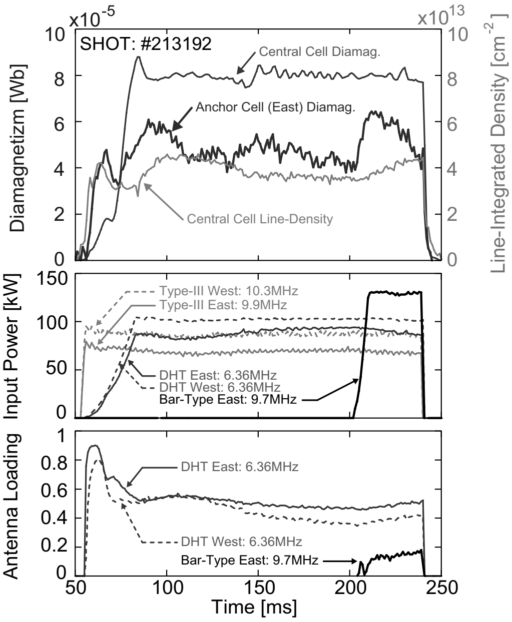

Fig. 2. The temporal evolution of a typical discharge is shown, where the diamagnetism remarkably increases with the ion-cyclotron resonance heating in the minimum-B anchor cell.

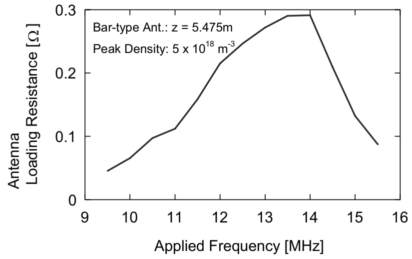

Fig. 3. The calculation result of the antenna loading resistance versus applied frequency for the anchor-cell plasma. As increase in the applied frequency, a resonance layer appear in the center of the minimum-B well at 9.5 MHz, then the antenna loading increases till the ω/ω_{ci} exceeds 1 at 14 MHz.

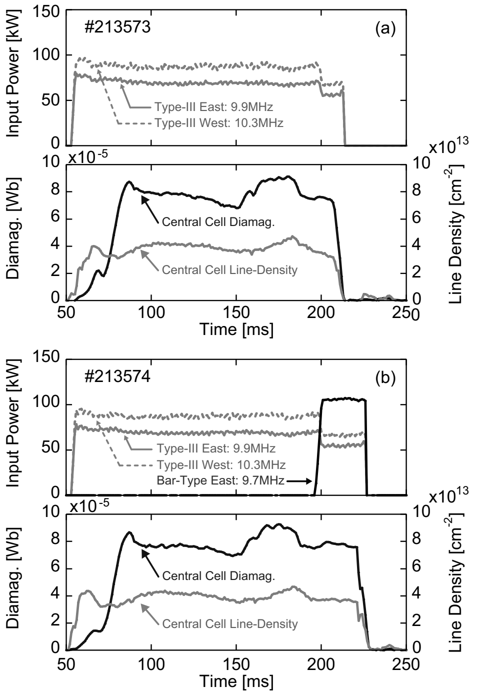

Fig. 4. (a) By the power down of the Type-III antenna, the discharge is disrupted with the interchange instability. (b) By the superposition of the heating power with the bar-type antenna, MHD stabilization is kept, and the discharge is sustained.

configuration, as increase in the applied frequency, the resonance point appears at the anchor midplane from 9.5 MHz. If the frequency becomes greater than 14 MHz (ω/ω_{ci} = 1.0), the coupling resistance falls sharply. This characteristic is similar to the case of axisymmetric uniform plasma in Ref. [6]. The amount of the power absorption depends on the antenna-plasma coupling. In the "magnetic-beach" configuration, almost all power is found to be absorbed near the resonance layer. In order to enhance the coupling efficiency of the bar-type antenna, the applied frequency should be increased. However, as increase in the frequency, the resonance surface gets away from the core plasma region. In order to produce the high pressure plasmas, it is necessary to heat ions in the core plasma region. It is suggested that the present antenna configuration should be modified for more effective ion-heating in the minimum-B region.

We also performed the experiments to confirm whether the additional heating by the bar-type antenna can stabilize the MHD instability. During a plasma discharge, the applied power to the Type-III antenna is decreased with keeping the plasma pressure in the central cell (Fig. 4a). If the heating power of the anchor cell plasma is reduced, then interchange flute instability grows up and eventually disrupts the discharge. The density fluctuation, which is observed just before the disruption, is identified to be the flute ihterchange mode by use of electro-static probe arrays. On the other hand, the superposition of heating power with the bar-type antenna compensates the power down of the Type-III antenna, which provides the sufficient minimum-B stabilization (Fig. 4b).

IV. SUMMARY

In this study, direct heating of the minimum-B plasma without mode-conversion is investigated with a bar-type antenna in the anchor cell. By use of the bar-type antenna, remarkable increase in the plasma pressure is obtained in the anchor cell. The wave excitation and the absorption are calculated with a three-dimensional full-wave code, and compared with the experimental results.

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