XA0053983

CHARACTERISTICS OF HOT IONS WITH A STRONG RF HEATING IN THE GAMMA 10 TANDEM MIRROR

M.ICHIMURA, H.HOJO, K.ISHII, A.MASE, Y.NAKASHIMA,
T.SAITO, T.TAMANO, K.YATSU
Plasma Research Center, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan

Abstract

Radio frequency waves in the ion cyclotron range of frequency (ICRF) are mainly used for the plasma production and heating in the central cell of the GAMMA 10 tandem mirror. The GAMMA 10 has minimum-B anchor cells with a non-axisymmetric magnetic field configuration. The ICRF heating system in the central cell has been improved to create a more axisymmetric plasma. A high ion temperature is attained with the system and high energy ions more than 50 keV are detected in both parallel and perpendicular directions to the magnetic field line. Strong temperature anisotropy is observed and strong Alfvén ion cyclotron (AIC) modes are excited due to the anisotropy. With the AIC modes, high energy ions detected at the end increase and high energy ions with nearly 90 degrees pitch angle in the central cell decrease.

1. INTRODUCTION

The GAMMA 10 tandem mirror is designed to be an effectively axisymmetrized tandem mirror. The central cell has an axisymmetric mirror configuration and the anchor cells have a minimum-B mirror configuration with non-axisymmetric magnetic fields. Recently, the density increase due to the potential confinement has been attained by improving the non-axisymmetry of the heating systems[1]. Two ion cyclotron range of frequency (ICRF) sources are used in the central cell for an initial plasma production and a main plasma heating, which are called as RF1 and RF2, respectively. A fast Alfvén wave excited with the RF1 is also used for sustaining MHD stability[2]. The wave is converted into a slow Alfvén wave which propagates towards the minimum-B anchor cell and heats ions on the cyclotron resonance layer[3,4]. Another ICRF source RF2 is applied in the central cell for main ion heating with cyclotron resonance layers near the midplane. By changing the ICRF antenna configuration, non-axisymmetry of the plasma and the heating efficiency are improved. An ion temperature of 10 keV has been attained with the high power ICRF heating[5].

With a strong ICRF heating, the temperature anisotropy defined as a ratio between perpendicular and parallel ion temperatures becomes greater than 10 since the cyclotron resonance layer is located near the central cell midplane. Unstable Alfvén ion cyclotron (AIC) modes are driven because of the strong anisotropy. The AIC modes have a frequency range just below a local ion cyclotron frequency. This mode is excited as an eigenmode in the axial direction and has a standing wave region near the midplane of the central cell[6]. High energy ions are detected in both directions of a parallel and a perpendicular to the magnetic field line. The interactions between the high energy ions and spontaneously excited Alfvén waves may become a constraint in future fusion devices. A clear correlation between the AIC modes and behaviors of the high energy ions has been observed.

In this manuscript, the improvement of the axisymmetry of the plasma by changing the ICRF antenna configuration and its effects on the plasma heating are described. The AIC mode excitation due to the strong temperature anisotropy and the correlation with the characteristics of high energy ions are also presented.

2. EXPERIMENTAL SETUP

The magnetic field profile in the central and anchor cells of the GAMMA 10 is shown in Fig.1. The strength of the magnetic field at the midplane of the central cell is typically 0.4 T and the mirror ratio is 5. The stainless limiter with a diameter of 0.36 m located near the midplane is segmented to eight elements in the azimuthal direction. The locations of the limiter and ICRF antennas of RF1 and RF2 are shown in Fig.1. For the initial plasma production, so-called Nagoya

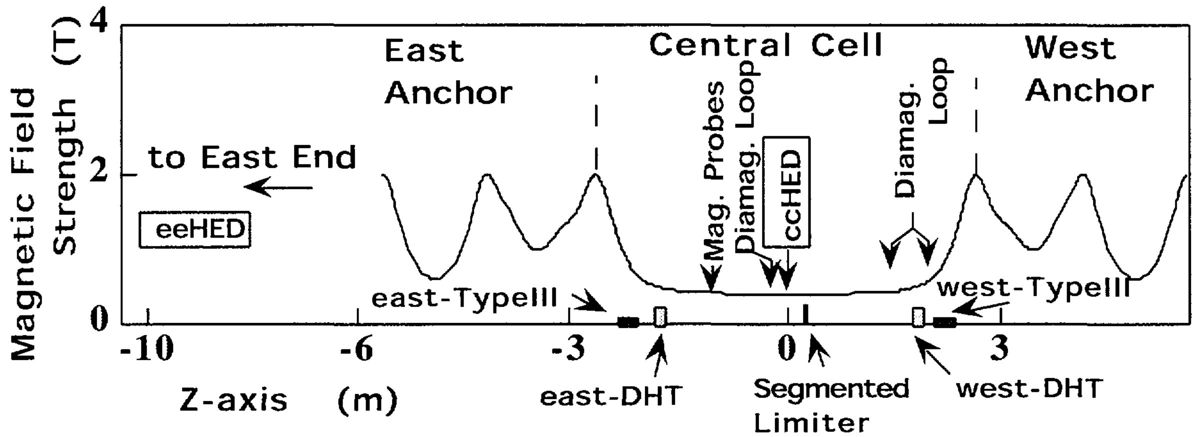

FIG.1 Magnetic Field Strength Profile and locations of a segmented limiter, ICRF antennas and diagnostics in the GAMMA 10 tandem mirror.

Type-III antennas (RF1) are used in combination with the hydrogen gas puffing in the central cell. The four plate elements of the Nagoya Type-III antenna consist of two pairs, one with vertical plates and the other with horizontal plates, in order to generate a rotating electromagnetic field. They are located near both east and west ends of the central cell. To avoid a strong interference between the waves excited with both antennas, the frequency of the west antenna is slightly higher than that of the east antenna. For the plasma heating, the conventional double half-turn (DHT) antennas (RF2) are placed on the location inside of the RF1 antenna.

The central cell has an axisymmetric mirror configuration and the transition regions to the anchor cells have non-axisymmetric configuration with an elliptic cross section. A degree of plasma non-axisymmetry in the central cell is evaluated from the azimuthal distribution of the floating potential on the eight elements of the segmented limiter. The temperature anisotropy is evaluated from three diamagnetic loops arrayed in the direction of the magnetic field line. AIC modes excited spontaneously in such a hot plasma with strong anisotropy are detected by magnetic probes set in the peripheral region of the plasma. To measure the behavior of high energy ions, two semiconductor detectors are installed on the east end (eeHED) for the end-loss ions and in the central cell (ccHED) for the magnetically trapped ions. Silicon surface barrier (SSB) detectors (nominal depletion depth 300 μm) are used in this experiment. The nominal value of the depletion depth of 300 μm is enough to measure high energy protons. The structure of eeHED and the sensitivity of the SSB detector for protons are described in Ref. 7. The ccHED is inserted perpendicularly to the magnetic field line and is positioned just outside of the limiter radius in the midplane of the central cell. By rotating the ccHED against the normal axis to the magnetic field line, a pitch angle distribution of hot ions in the central cell can be measured[8]. The locations of diagnostics are also indicated in Fig.1.

3. IMPROVEMENT OF THE PLASMA NON-AXISYMMETRY

When the RF1 power into the four antenna elements is increased equally, a reduction of the central plasma pressure is observed for the same RF2 power. In this case, the floating potentials of the limiter segments show a nonuniformity of the plasma in the azimuthal direction. To evaluate the effect of non-axisymmetry of the RF1 antenna elements, the injection power to each antenna pair is changed separately under the fixed total RF1 power condition. The non-axisymmetry is affected by the balance of the RF power applied to each antenna pair. When the portion of the power applied to the vertical pair of the east RF1 antenna increases, the non-axisymmetry of the plasma is improved and the diamagnetic signal increases as shown in Fig.2. The inlets of Fig.2 indicate the azimuthal distribution of the floating potential and the degree of the non-axisymmetry. The dotted circle means the positive floating potential averaged over eight elements and potentials of each element are connected by solid lines. When the west RF1 antenna is used, the result is vice versa, that is, the non-axisymmetry of the plasma is improved and the diamagnetic signal increases when the portion of the power applied to the horizontal antenna pair increases under the fixed total RF1 power condition. By using the standard deviation

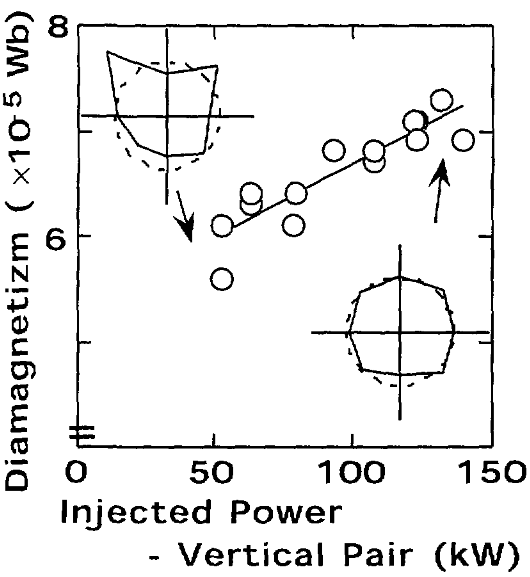

FIG.2 Power dependence of a diamagnetizm of the plasma (Power injected to the vertical pair of east RF1 antenna)

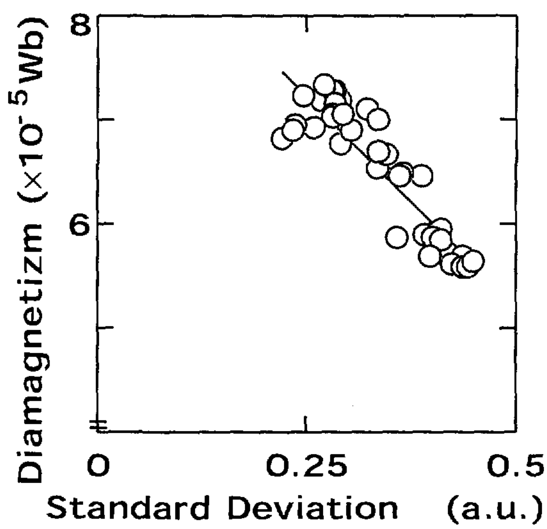

FIG.3 Reduction of diamagnetizm associated with non-axisymmetry of the floating potential of the segmented limiter.

of the potentials from the averaged value, the reduction of the diamagnetic signal associated with non-axisymmetry is presented as shown in Fig.3. The reduction is strongly related to non-axisymmetry of the floating potential distribution. A shape of the magnetic flux tube at the transition region, which corresponds to a circular flux tube in the central cell, is an elongated shape in a radial direction. When the antenna pair of the thin side in the projection of the elongated region is used, the non-axisymmetry of the plasma is improved in both east and west RF1 antenna cases. When the vertical pair of the east antenna and the horizontal pair of the west antenna are used, no reduction of the diamagnetizm is observed with an increase of the RF1 power. In the opposite case, a significant reduction of the diamagnetic signal is observed. It is suggested that the non-axisymmetry due to the minimum-B configuration is improved by the ICRF antenna configuration. When the heating by the RF2 is higher, higher power of RF1 is needed for sustaining MHD stability with keeping on the axisymmetry of the plasma.

4. BEHAVIOR OF HIGH ENERGY IONS

With a strong ICRF heating, a temperature anisotropy becomes greater than 10 and AIC modes are spontaneously excited in the central cell. Semiconductor detectors are used for the measurement of high energy protons in both parallel and perpendicular directions to the magnetic field line. The minimum energy of the detection is roughly estimated to be around 10 keV. The pitch angle distribution of high energy ions at the central cell midplane can be obtained by rotating the ccHED as mentioned previously. When mirror confined ions have their turning point at $B = B_\theta$, their pitch angle θ at the midplane is given by $\sin^2\theta = B_0/B_\theta$, where B_0 is the magnetic field strength at the midplane. The cyclotron resonance layer in this experiment is located at about 1 m from the central cell midplane which corresponds to the pitch angle of 80 degrees. The obtained peak of the pitch angle distribution is just below the angle of cyclotron resonance layer. Figure 4 shows the temporal evolution of (a) the diamagnetic signal near the midplane, (b) the temperature anisotropy, (c) the AIC amplitude, (d) the signal of ccHED and (e) the signal of eeHED. The diamagnetic signal is increasing with time till 100 ms. In this experiment the ion temperature is several keV and the density is around 2×10^{12} cm^{-3}. Because the electron temperature is relatively low (less than 100 eV), the variation of the diamagnetic signal corresponds to the variation of the ion temperature. When the diamagnetic signal reaches a threshold value, the signal of the ccHED appears and abruptly increases with the diamagnetic signal since the SSB detector can detect only high energy ions of which pitch angle is nearly 90 degrees. The ccHED signal and the anisotropy increase with the diamagnetic signal on the initial

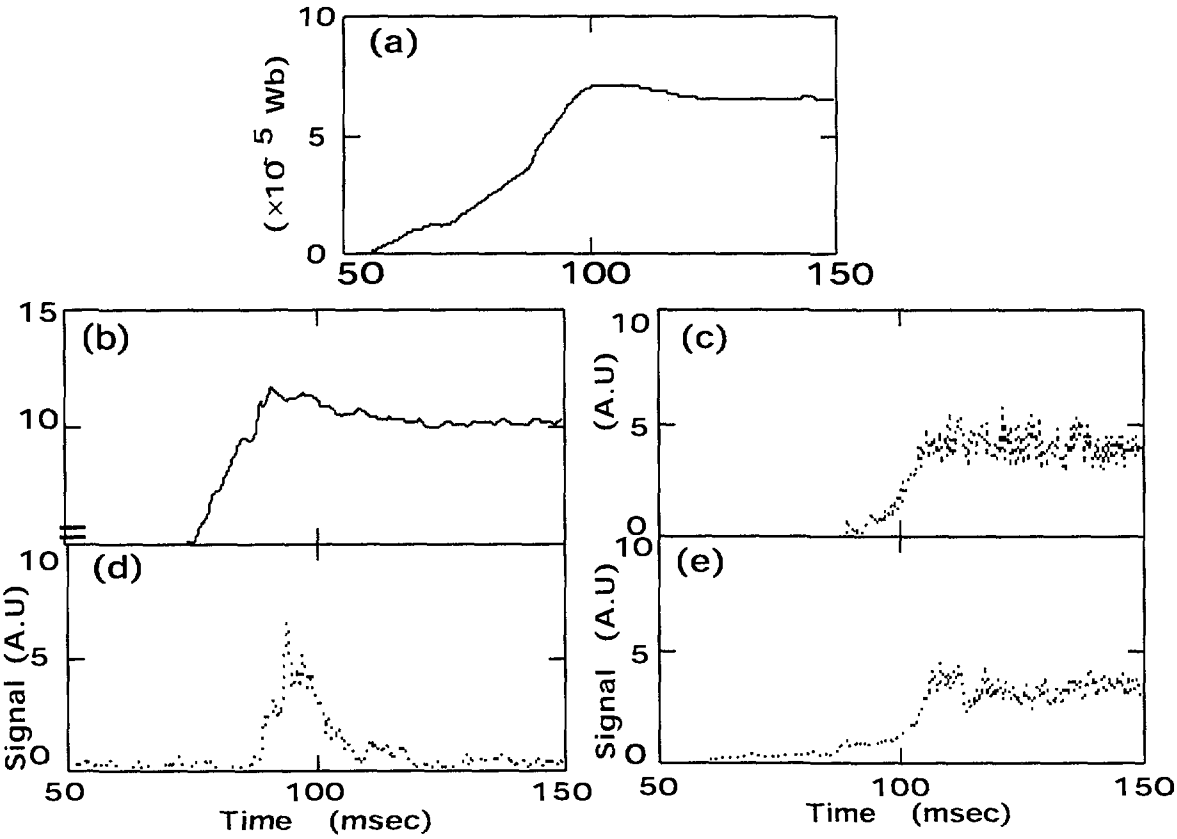

FIG.4 Temporal evolution of (a) diamagnetizm, (b) temperature anisotropy, (c) AIC amplitude, (d) signal of ccHED and (e) signal of eeHED.

phase and begin to decrease though the diamagnetic signal is still increasing. The AIC modes appear under the certain conditions of the anisotropy and plasma beta. The eeHED signal increases as the AIC modes are excited. The temporal evolution of the end-loss high energy ions is almost the same as that of the AIC amplitude. When the amplitude of the AIC modes becomes strong, high energy ions with a pitch angle near 90 degrees in the central cell midplane begin to decrease and the anisotropy becomes weak as shown in Fig.4. These data suggest the pitch angle scattering of hot ions due to excited waves in the plasma.

5. SUMMARY

In summary, non-axisymmetry of the plasma in the central cell of the GAMMA 10 tandem mirror is improved by rearranging the ICRF antenna configuration and higher ion temperature is effectively attained. Strong AIC modes are excited in such a high beta plasma with strong temperature anisotropy. The pitch angle scattering of hot ions in the central cell and the enhancement of the end-loss high energy ions due to the spontaneously excited Alfvén waves are observed.

REFERENCES

[1] K.YATSU, et al., in this conference EX4/6.
[2] M.ICHIMURA, et al., Nuclear Fusion, **28** (1988) 799.
[3] M.INUTAKE, et al., Phys. Rev. Lett., **65** (1990) 3397.
[4] H.HOJO, et al., Phys. Rev. Lett., **66** (1991) 1866.
[5] T.TAMANO, et al., Phys. Plasmas, **2** (1995) 2321.
[6] R.KATSUMATA, et al., Jpn. J. Appl. Phys. **31** No.7 (1992) 2249.
[7] T.SAITO, et al., Rev. Sci. Instrum., **68** (1997) 1433.
[8] M.ICHIMURA, et al., Rev. Sci. Instrum., **70** (1999) in press.