Potential Formation and Confinement in High Density Plasma on the GAMMA 10 Tandem Mirror

K.Yatsu, T.Cho, H.Higaki, M.Hirata, H.Hojo, M.Ichimura, K.Ishii, Y.Ishimoto, A.Itakura, I.Katanuma, J.Kohagura, R.Minami, Y.Nakashima, T.Numakura, T.Saito, S.Saosaki, Y.Takemura, Y.Tatematsu, M.Yoshida, M.Yoshikawa

Plasma Research Center, University of Tsukuba, Tsukuba, Japan

E-mail: yatsu@prc.tsukuba.ac.jp

Abstract. GAMMA 10 experiments have advanced in high density experiments after the last IAEA Fusion Energy Conference in 2000 where we reported the production of the high density plasma through use of ICRF heating at a high harmonic frequency and neutral beam injection in the anchor cells. However, the diamagnetic signal of the plasma decreased when ECRH was applied for the potential formation. Recently a high density plasma has been obtained without degradation of the diamagnetic signal and with much improved reproducibility than before. The high density plasma was attained through adjustment of the spacing of the conducting plates installed in the anchor transition regions. The potential confinement of the plasma has been extensively studied. Dependencies of the ion confinement time, ion-energy confinement time and plasma confining potential on plasma density were obtained for the first time in the high density region up to a density of 4×10^{12} cm^{-3}.

1. Introduction

After the attainment of doubling of the density owing to the potential confinement [1], GAMMA 10 experiments have been directed to realization of a high density plasma with potential confinement and also to study dependencies of the confining potential and confinement time on plasma density. These problems are important for understanding the physics of potential formation in tandem mirrors and also for development of tandem mirror reactors. However, it had previously been difficult to obtain a high density plasma owing to some density clamping mechanisms. GAMMA 10 experiments have advanced in high density experiments after the last IAEA Fusion Energy Conference in 2000 [2] where we reported the production of the high density plasma through use of the ion cyclotron range of frequency (ICRF) heating at the high harmonic frequency. However, the diamagnetic signal of the high density plasma decreased when electron cyclotron resonance heating (ECRH) was applied owing to some instabilities. Recently, a high density plasma has been obtained without degradation of the diamagnetic signal and with improved reproducibility through adjustment of the spacing of the conducting plates installed in the anchor transition regions [1]. In this paper we report production of a high density plasma with potential confinement and dependencies of the ion confinement time, ion-energy confinement time and confining potential on the density up to a density of 4×10^{18} m^{-3}.

2. GAMMA 10 tandem mirror

The GAMMA 10 tandem mirror consists of a central cell, two anchor cells and two end mirror cells. Ions in the central cell are heated by ICRF (RF2: 6.3 MHz) power applied to a double-half-turn (DHT) antenna at the east end of the central cell. ICRF (RF1: 10 MHz) power is also applied to the Nagoya Type III antennas at both ends of the central cell and the excited wave also propagates to the anchor cells. The ions in the anchor cells are heated by the propagated wave and ensure the MHD stability of the GAMMA 10 plasma. The high harmonic ICRF (RF3: 41.5 MHz) power is applied to the DHT at the west end of the central cell for increasing the density in the central cell. Neutral beam injectors (max. 25 kV, 50 A) are installed both anchor. A neutral beam injector (max. 25 kV, 30 A) is also installed at the central cell. Positive plasma-confining potentials are formed in the axisymmetric plug/barrier cells by fundamental ECRH. The plasma is initiated by plasmas injected from magneto-plasma-dynamic plasma guns located at both ends. The plasma is sustained by the ICRF heating with hydrogen gas puffing in the central cell. The end loss current and the ion energy spectrum at the end are measured by using an end-loss ion energy analyzer (ELA) [3]. Plasma potentials in the central cell and in the barrier region of the plug/barrier cell are measured by beam probes [4]. The plasma potential in the plug region is determined from the energy spectrum of the end loss ions. The plasma confinement potential is determined as the potential difference between potentials in the central cell and plug region.

3. High Density plasma production and confinement

3.1. Production of high density plasma

In the last IAEA Fusion Energy Conference in 2000, we reported the production of the high density plasma through use of the high harmonic ICRF heating (RF3) and neutral beam injection (NBI) in anchor cells. However the diamagnetic signal of the high density plasma decreased with application of ECRH for the potential formation. One cause of the decrease is the instabilities originating from plasma wall interactions since the decrement of the diamagnetism decreases with progress of wall conditioning. Anther causes are some MHD instabilities originating from non-axisymmetric density and potential profiles. In order to suppress the instabilities, the conducting plates were reinstalled. Figure 1 shows waveforms of line densities (a) and diamagnetic signals (b) for the present experiment and last two Conferences. The time sequence indicated above of the figure corresponds to the present experiment. The line density of the present experiment increased 30% by application of RF3 power at 100 kW. In experiments without RF3, line densities saturated at around 5×10^{17} m^{-2} even if the RF1 power for plasma production was increased more than 100 kW. So the high harmonic ICRF heating is effective for high density plasma production. The line density further increased owing to the potential confinement by application of ECRH and neutral beam injection in the central cell. In Fig.1(b), the diamagnetic signal shown at the last IAEA Fusion Energy Conference decreased with application of ECRH (waveform (2) in Fig.1(b)), while the diamagnetic signal slightly increased in the present experiment.

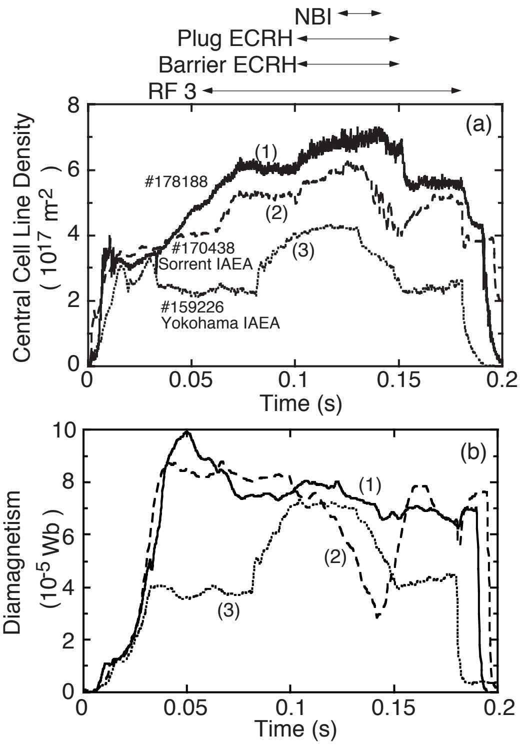

Fig. 1 (a) Waveforms of line densities for the present one (1), Sorrent (2), and Yokohama (3). (b)Waveforms of diamagnetic signals corresponding to the line densities.

The high density plasma of the present experiment has been obtained through adjustment of the spacing of the conducting plates. Figure 2 shows a cross sectional view of the conducting plates, which extend 140 cm along the surface of the flat shaped plasma at the anchor transition region. Three cases of the conducting plates are shown in Fig.2. The case AP1 used from 1997 to 1998 is the one which was used for the first time and we obtained the data of density doubling owing to the potential confinement [1]. However, the beta value in the anchor cell decreased with the installation of AP1 owing to decrease of the propagation power of RF1 from the central cell to the anchor cell. The decrease of the anchor beta is considered to be one cause of the density clamping mechanism. Then the spacing of the plates was expanded as AP2 for increasing the propagation power of RF1. The data taken with AP2 are shown in Fig.1. We obtained the higher density plasma with AP2, however, the degradation of the diamagnetism persisted with AP2. The persistent degradation of the diamagnetic signal is considered to be owing to less effectiveness of the conducting plates. So we reinstalled the conducting plates close to the plasma as AP3 by sacrificing the decrease of the anchor beta value. The high density plasma was obtained with AP3 as shown in Fig.1. Figure 3 shows relations between the beta value at the anchor cell and that at the central cell for the three cases of the conducting plates. For the cases of AP1 and AP3 the anchor beta values are lower than the case AP2 for the attained beta values at the central cell. This indicates that the lower beta value in the anchor cell can sustain a higher beta plasma in the central cell with AP3 and that the conducting plates contribute to stabilization of MHD instabilities.

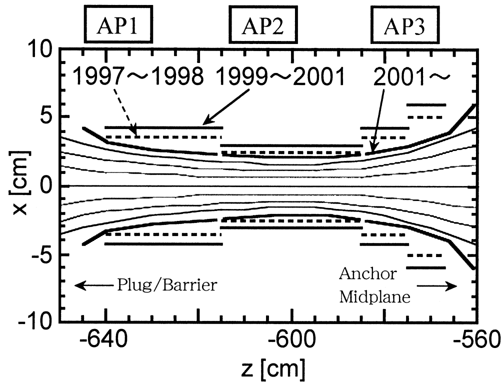

Fig. 2 Cross sectional view of conducting plates.

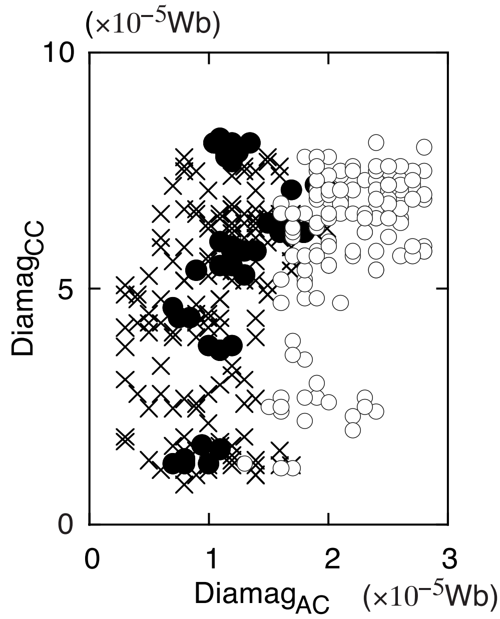

Fig. 3 Central cell diamagnetism (Diamag$_{CC}$) as a function of anchor cell diamagnetism (Diamag$_{AC}$) for three cases of the conducting plates corresponding to AP1 (×), AP2 (○), and AP3 (●).

3.2. Plasma confinement studies

The ion temperature in the central cell was anisotropic with different perpendicular temperature of about 3 keV and 0.3 keV to the magnetic field. The electron temperature increased from 0.06 keV to 0.08 keV during ECRH. The axial ion confinement time $\tau_{//}$ is determined as $\tau_{//} = eN/I_{loss}$, where e is the unit charge, N is the total number of ions in a flux tube and I_{loss} is the end loss current from the flux. At a time just before ECRH turned on, that is without confining potential, the axial ion confinement time was 0.005 sec and the radial confinement time was estimated to be longer than 0.03 sec. With application of ECRH for the potential formation the axial ion confinement time increases, while the radial confinement time decreases owing to increased fluctuations in the high density region. In Fig.4 the axial ion confinement time $\tau_{//}$ and plasma confining potential ϕ_c are plotted with respect to the plug ECRH power for plasmas with relatively low densities around 1.5×10^{18} m^{-3}. With the plug ECRH power of 140 kW, the confining potential was 550 V and the plasma density increased from 1.3 $\times 10^{18}$ m^{-3} to 2.5×10^{18} m^{-3} owing to the potential confinement. The confinement time without ECRH corresponds to mirror confinement time in the GAMMA 10 magnetic field. The energy confinement time $\tau_{//E}$ is determined as $\tau_{//E} = W/P$, where W is the stored ion-energy in the central cell, P is the absorbed power of the ICRH (RF2) and ECRH is not acounted because its contribution for the ion heating is slight.

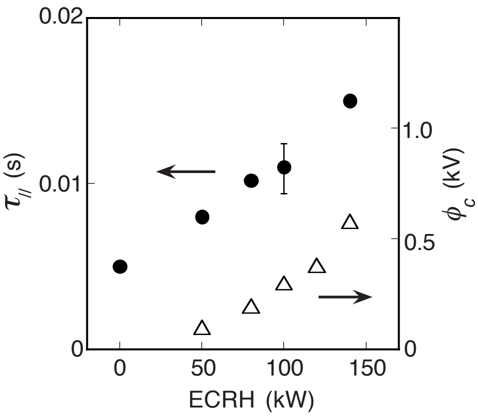

Fig.4 Axial ion confinement time $\tau_{//}$ (●) and plasma confining potential ϕ_c (△) as a function of Plug ECRH power for relatively low density plasmas.

In Fig.5, the axial ion confinement time, ion energy confinement time and confining potential are plotted with respect to the plasma density. These dependencies are obtained for the first time in the high density region. Recently, a theoretical model was developed for the potential formation mechanism [5]. In this model, however, the potential depends only on the axial density profile but not on the absolute value. Therefore, we are to study experimentally the dependence of the potential on density. The magnitude of the confining potential depends strongly on the anisotropy of the plug electron distribution function. The electron velocity anisotropy is considered to be relaxed when the plasma density increases. Then the decrease of the confining potential with the plasma density in Fig.5 is expected. The theoretical study and high density experiments are to be continued to study the potential formation mechanism and confinement scaling relations of tandem mirrors.

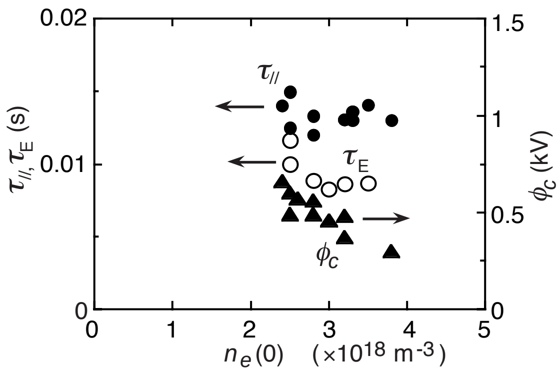

Fig.5 Axial ion confinement time $\tau_{//}$ (●), energy confinement time τ_E (○), and plasma confining potential ϕ_c (▲) as a function of plasma density. Plug ECRH power: 140-150 kW

4.Summary

A high density plasma has been obtained without degradation of the diamagnetic signal with application of ECRH. It has been attained through adjustment of the spacing of the conducting plates and use of the RF3. Dependencies of the particle and energy confinement times and confining potential on the plasma density were obtained for the first time in the high density region. These data will contribute to the study of the potential formation mechanism in tandem mirrors. A more detailed experiments in wider density region will be necessary for determining a scaling relation for the dependencies.

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