Progress in Long Sustainment and High Density Experiments with Potential Confinement on GAMMA 10

K. Yatsu, T. Cho, M. Hirata, H. Hojo, M. Ichimura, K. Ishii, A. Itakura, I. Katanuma, J. Kohagura, Y. Nakashima, T. Saito, T. Tamano, S. Tanaka, Y. Tatematsu, M. Yoshikawa

Plasma Research Center, University of Tsukuba, Tsukuba, Japan

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

Abstract. The improvement of potential confinement reported in the last IAEA meeting was attained by axisymmetrization of heating pattern of electron cyclotron resonance heating (ECRH). It was experimentally shown that the axisymmetrization of ECRH really produced axisymmetric potential profile. GAMMA 10 experiments have advanced in longer sustainment and high density operation of potential confinement. Experiments for long sustainment of potential confinement were carried out in order to study problems of steady state operation of a tandem mirror reactor. A confining potential was sustained for 150 ms by sequentially injecting two (ECRH) powers in the plug region. It was difficult before to increase the central cell density higher than about 2.5×10^{12} cm^{-3} with and/or without potential confinement due to some density limiting mechanism. In order to overcome this problem, a new higher frequency ion cyclotron range of frequency (ICRF) system (RF3: 36−76 MHz) has been installed. A higher density plasma has been produced with RF3. In addition to RF3, neutral beam injection (NBI) in the anchor cell became effective by reducing neutral gas from beam injectors. Potential confinement experiments have advanced to higher central cell densities up to 4×10^{12} cm^{-3} with RF3 and NBI. A 20% density increase due to the potential confinement was obtained in the high density experiments.

1. Introduction

In the tandem mirror GAMMA 10, a radial loss was observed in potential confinement experiments with strong ICRF heating. The radial loss has been greatly reduced by adjusting heating patterns of ECRH and ICRF heating as axisymmetric as possible. An almost axisymmetric potential profile was produced by the axisymmetrization of the ECRH heating pattern. In addition to the adjustment of the heating patterns of ECRH and ICRF, conducting plates have been installed in anchor transition regions to fix the potential at the plasma boundary thereby reducing possible irregular electric fields, which are considered to be a cause of the radial loss [1]. The radial loss has been much reduced with these procedures and a density increase of 125% was attained due to the potential confinement [2]. However, it was difficult to increase the central cell density higher than about 2.5×10^{12} cm^{-3} with and/or without potential confinement due to some density limiting mechanism. In order to overcome this problem, a new higher frequency ICRF system (RF3: 36−76 MHz, ω/ω_{ci} 6 to 12) was installed and a higher density plasma was obtained with RF3. In addition to RF3, neutral beam injection in the anchor cell became effective by reducing neutral gas from beam injectors. Experiments at higher central cell densities up to 4×10^{12} cm^{-3} were carried out with RF3 and NBI.

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) power applied to double-half-turn (DHT) antennas. Another ICRF (RF1) power is applied to the Nagoya-Type-III antennas at both end of the central cell and the excited wave also propagate to the anchor cell. The ions in the anchor cell are heated by the propagated wave. The hot ions in the anchor cells assure the MHD stability of the GAMMA 10 plasma. The RF3 power produces plasma in the central cell. The RF3 power is fed to a DHT antenna or a pare of the Nagoya-Type-III antenna. Neutral beam injectors (max. 25

kV, 50 A) are installed at both anchors and plug/barrier cells. The neutral beam injection in the anchor cell became effective recently by reducing gas from the beam injector with newly installed baffles in the injector tank. Positive plasma-confining potentials are formed in the axisymmetric plug/barrier cells by a fundamental ECRH. The plasma is initiated by plasmas injected from magneto-plasma-dynamic (MPD) plasma guns located at both ends. The plasma is sustained by the ICRF heating with hydrogen gas puffing in the central cell. Plasma diagnostics are explained in a previous paper [1].

3. GAMMA 10 Experiments

3.1 Axisymmetrization of ECRH

A large density increment during axial potential confinement was a result of suppression of radial losses. Among many efforts, the most significant factor of this improvement was axisymmetrization of ECRH. The ECRH antenna system was modified and the radiation pattern was axisymmetrized on the resonance surface at the plug [3]. In the former system, the microwave power was directly launched from a Vlasov antenna onto the resonance surface. This resulted in vertical elongation of the radiation pattern. In the new system, a cylindrical reflector was inserted and the microwave beam was focused in vertical direction. A low power test with infrared camera and in situ measurement with an antenna array showed an axisymmetric radiation pattern. Figure 1 depicts two-dimensional potential profiles measured at the barrier midplane with a beam probe before (a) and after (b) the axisymmetrization. The vertical elongation of the equi-potential contour in Fig. 1(a) corresponds to measured vertically elongated radiation pattern. Axisymmetrization of the radiation pattern produced an almost axisymmetric potential profile as shown in Fig. 1(b). The importance of axisymmetry of the potential profile was confirmed as follows. When the heating region was shifted vertically on the resonance surface, the potential profile became non axisymmetric and the density increment drastically decreased with a degree of non axisymmetry of the potential.

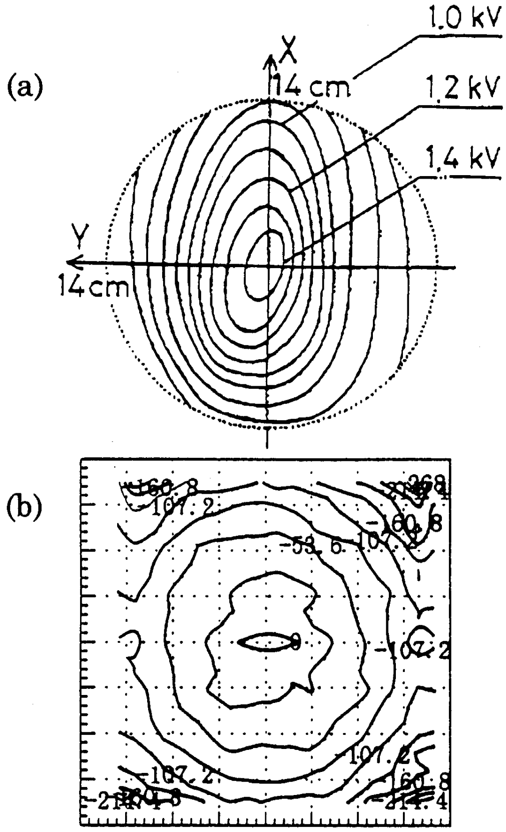

FIG. 1. Two-dimensional potential profiles before (a) and after (b) the axisymmetrization are depicted. These are measured at the barrier midplane with a beam probe.

3.2 Long sustainment of potential confinement

Experiments of two ECRH power application to the plug region were carried out. Two ECRH powers were applied at the same time in order to increase the plug potential or in series in time to obtain a long ECRH pulse duration. The two ECRH application increased the confining potential and density. In order to study an intrinsically steady state tandem mirror operation, experiments for longer sustainment of potential confinement were carried out by using two ECRH in series. Figure 2 shows time evolution of the central cell line density and potentials in the plug region (Φ_P) and in the central cell (Φ_C) when two ECRH powers were applied in series for 150 ms. Density increase of 40% and plug potential of 300 V were sustained during 150 ms. The mechanism of the potential sustainment is partially explained, but it is a remaining important problem [4]. The injection angle of ECRH power for ECRH1 is 50 degree to the axis while that for ECRH2 is 20 degree and some differences are observed on effects of each ECRH's power for producing the plug and/or thermal barrier potentials. These differences in effects of ECRH1 and ECRH2 were reported before [3].

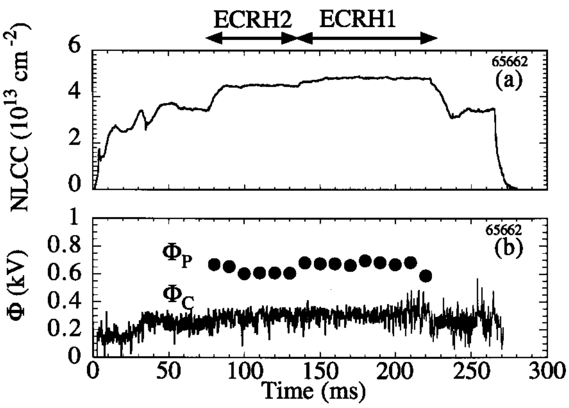

FIG. 2. (a) Waveform of the central cell line density, (b) time evolution of the plug potential (Φ_P) and central-cell potential (Φ_C). The plasma confining potential $\phi_C = \Phi_P - \Phi_C$.

3.3 High density experiments

It was difficult to increase the central cell density higher than about 2.5×10^{12} cm^{-3} with and/or without potential confinement due to some density limiting mechanisms. This problem is not yet well understood, but we considered that the ICRF frequency for plasma production in the central cell is not high enough due to the requirement for simultaneous ion heating in the anchor cell. In order to overcome this problem, a new higher frequency ICRF system RF3 was installed and became operational recently. In present low density experimental condition of GAMMA 10 with a plasma diameter of 36 cm and the RF1 frequency near the fundamental cyclotron frequency, a radial eigenmode of fast Alfvén waves with an azimuthal mode number of m=+1 is only excited in the central cell. The eigenmodes excited in the central cell have been calculated by using a simple model, where the plasma is assumed to be cold, cylindrical, uniform and surrounded by a conducting wall. Figure 3 shows the calculated dispersion relation under the fixed frequency of 9.9 MHz and 60 MHz in the central cell. In the case of 9.9 MHz, it is indicated that only one mode can be excited below the density of 10^{13} cm^{-3}. The second radial mode appears from the density above 10^{13} cm^{-3}. An arrow in the figure indicates the present experimental condition. In the case of 60 MHz, several radial eigenmodes are excited at the present density range. The number of the modes increases as the density increases. In the central cell, non-uniformity

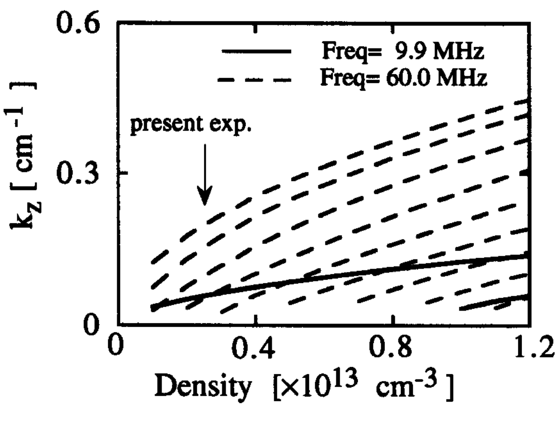

FIG. 3. Dispersion relation of fast Alfvén waves (m=+1) excited in the uniform cylindrical plasma column (radius of 18 cm) on the case of B=0.4 T. The solid lines and dashed lines indicate radial eigenmodes excited in the plasma when the applied frequecies are 9.9 MHz and 60 MHz, respectively.

of the magnetic field strength and the plasma parameters exists in the axial direction. The excited waves are affected from such a non-uniformity and will form eigenmodes also in the axial direction. Those eigenmodes depend strongly on the density. The existence of the axial eigenmodes means that the wave field becomes strong discreetly as the density changes. If there are large gaps between densities on which axial eigenmodes are excited strongly, the production of the plasma can not be kept continuously and there is a possibility of the density clamping on a certain value. In the case of 60 MHz, those eigenmodes are excited strongly at various densities, and the density can be increased more smoothly than in the case of 9.9 MHz. In a experiment at a frequency of 63 MHz, a higher density plasma was produced as expected [5].

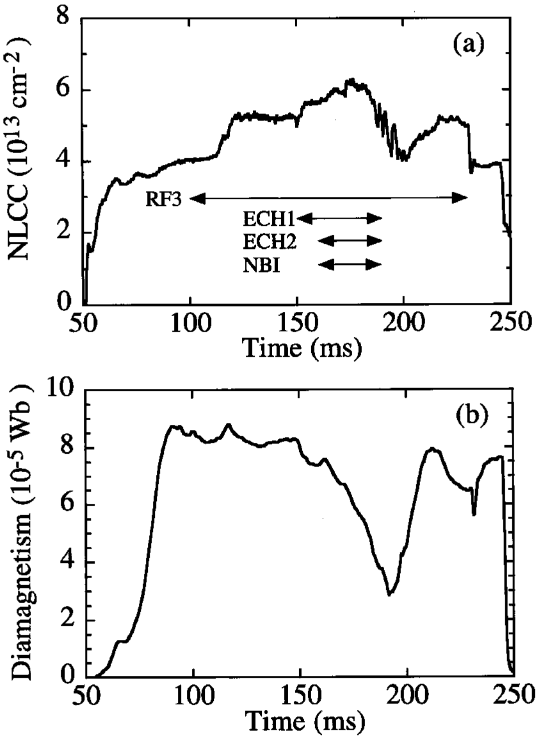

FIG. 4. Time evolution of the central cell line density (a) and diamagnetism (b) when RF3, NBI, and ECRH were applied, where powers of RF1, RF2, RF3 are 240 kW, 100 kW, and 80 kW, respectively.

In addition to RF3, neutral beam injection (NBI) in anchor cells has become effective by reducing gas from the neutral beam injectors to the anchor cells. The maximum beam energy and equivalent neutral beam current of the injector are 25 keV and 50 A, respectively. The beam is injected at an angle 80 degree to the axis. Neutral beam injection in the anchor cell was not effective before. The line density of a typical anchor cell plasma is 5×10^{13} cm^{-2}. So the shine through of the beam is more than 90% and the shine through beam caused a large amount of recycling gas. Then the plasma is disrupted by neutral beam injection due to the gas originated from the shine through beam. Recently new baffles were installed in the beam injector and dump tanks and the gas load to the anchor cell was much reduced. The neutral beam injection became effective with the reduction of gas load. The plasma density in the anchor cell was increased 70% for 20 ms with 25 kV-20 A NBI.

Potential confinement experiments at high density plasma were carried out with RF3 and NBI. Figure 4 shows a time evolution of the central cell density when RF3 and NBI were used. In this shot, the central cell peak line density was 6×10^{13} cm^{-2}, which corresponds to the density on the axis of 3.5×10^{12} cm^{-3}. The density increase due to the potential confinement was determined to be 20 % by comparing density increase with and without ECRH. In this shot the perpendicular ion temperature and electron temperature in the central cell are 3 keV and 0.08 keV, respectively, and the parallel ion temperature at the end and the confining potential are 0.4 keV and 0.3 kV, respectively. The diamagnetic signal decreased due to the recycling gas in the anchor cell and a further wall conditioning will be required to obtain a better shot.

Figure 5 shows the density increase due to potential confinement at different initial central-cell densities on the axis. As illustrated in the figure, filled circles indicate the central cell densities before potential confinement and filled triangles indicate those during potential confinement. The central cell density was limited at about 2.7×10^{12} cm^{-3} before RF3 and NBI were used. The plasma density of 4×10^{12} cm^{-3} was attained by using RF3 and NBI. The ion temperature on the axis and particle confinement time were 4.5 keV and 20 ms for the data with the initial density of 1.2×10^{12} cm^{-3} and those were 3 keV and 10 ms for the initial density of 3.5×10^{12} cm^{-3}. Though the density increment decreases with initial plasma density, we expect a larger density increment at a higher central cell density with progress of wall conditioning because these high density data were taken under the condition of insufficient wall conditioning.

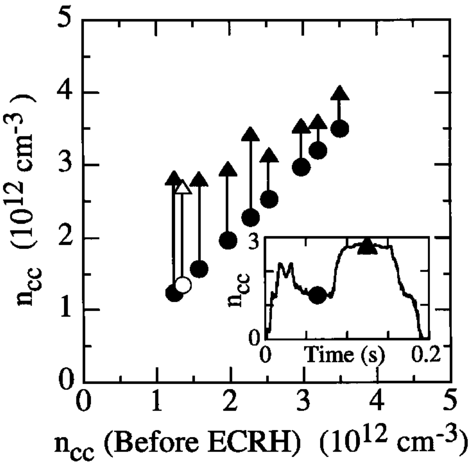

FIG. 5. Central cell density (n_{cc}) before ECRH (◉) and ECRH (▲) as a function of n_{cc} before ECRH. Open symbols indicate those reported at the last IAEA meeting. ECRH:140kW/plug.

4. Summary

The axisymmetrization of heating pattern of ECRH produced axisymmetric potential profile and much contributed to the reduction of the radial loss. Two ECRH powers were injected in the plug region at the same time or sequentially. By injecting two ECRH powers in series, the confining potential was sustained for 150 ms. For longer sustainment experiment, a gyrotron power supply with 500 ms pulse duration is under construction and the experiment will be started in January 2001. High density experiments advanced up to the density of 4×10^{12} cm^{-3} by using newly installed RF3 and effective use of NBI. A further improvement in high density confinement will be expected by optimization of heating scenario with respect to ECRH, ICRF heating and NBI.

References

[1] K. Yatsu, L. G. Bruskin, T. Cho, et al., Nucl. Fusion Vol. 39, No. 11Y, 1707 (1999).

[2] K. Yatsu, T. Cho, M. Hirata, et al., 26th EPS Conf. on Contr. Fusion and Plasma Physics, Marstricht, 14-18 June 1999, ECA Vol. 23J, 461 (1999).

[3] T. Saito, et al., to be published in Fusion Engineering and Design.

[4] T. Saito, I. Katanuma, T. Aota, et al., Fusion Energy 1996 (IAEA, Vienna, 1997) Vol. 2, 105.

[5] M. Ichimura, S. Tanaka, C. Nakagawa, et al., to be published in Transactions of Fusion Technology, January 2001.