HIGH DENSITY EXPERIMENT IN THE GAMMA 10 TANDEM MIRROR


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Abstract

After attainment of doubling of the density due to potential confinement, GAMMA 10 experiments have directed to higher density experiments in order to study relations between plasma confinement, density and ECRH power. The higher density experiments have advanced up to $4 \times 10^{12}$ cm$^{-3}$ with substantial density increase due to potential confinement. The higher density plasma was obtained with a higher frequency ICRF system and neutral beam injection in the central cell.

Introduction

GAMMA 10 experiments attained doubling of density due to potential confinement with a 50 ms duration [1]. A larger density increase and longer operation of potential confinement were reported at the last IAEA Conference [2]. Plasma densities on GAMMA 10 experiments were so far limited at about $2.5 \times 10^{12}$ cm$^{-3}$ by some density limiting mechanisms. Recently higher density plasmas were attained by use of a newly installed ion cyclotron range of frequency (ICRF) system and neutral beam injection in the central cell and studies of potential confinement have been extended into higher density region to obtain a density dependence of potential confinement.

Attainment of High Density in GAMMA 10

The GAMMA 10 tandem mirror consists of an axisymmetric central cell, two anchor cells with minimum-B configuration located at both ends of the central cell, and axisymmetric two plug/barrier cells located outside the anchor cells. Plasma guns located at both ends initiate plasma production and a plasma is sustained by ion cyclotron range of frequency (ICRF) heating in the central cell (RF2: 6.36MHz) and anchor cells (RF1: 10MHz) with hydrogen gas puffing in the central cell. A plasma confining potential is produced by fundamental electron cyclotron resonance heating (ECRH) at the plug region and second harmonic ECRH at the barrier region.

The central cell density and diamagnetism were increased 100% due to potential confinement.
which indicate the confinement improvement by three times over a single mirror confinement [1]. Figure 1 shows the particle confinement time and plasma confining potential as a function of ECRH power. The plasma density in the central cell was $1.3 \times 10^{12}$ cm$^{-3}$ for the case without ECRH and about $2.5 \times 10^{12}$ cm$^{-3}$ for the case with ECRH. The ion temperature in the central cell was about 4.5 keV with a temperature anisotropy defined as a ratio between perpendicular and parallel ion temperature of about 10. The ion temperature of end-loss ion was about 0.4 keV. The particle confinement time was obtained from $\frac{dN}{dt} = I_{\text{ion}} - I_{\text{loss}}$, where $I_{\text{ion}}$ is the equivalent ionization current and $I_{\text{loss}}$ is the loss current. The ionization current was determined by using DEGAS code [3] together with H$_\alpha$ measurements. The confinement time without ECRH corresponds to a single mirror confinement. There are anchor mirrors at both sides of the central cell. But the multiple mirror effects are estimated to be small.

Our next issue is to study a relation between confinement time and plasma density. However, it was difficult to increase the central cell density higher than about $2.5 \times 10^{12}$ cm$^{-3}$ with and/or without potential confinement due to some density limiting mechanisms and the changeable density region was narrow. The problem of density limit 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: 36-76MHz, $\omega/\omega_i \sim 6$ to 12) was installed. 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. In the present experimental conditions of GAMMA 10, with a plasma diameter of 36 cm and the RF1 frequency near the fundamental ion cyclotron frequency, a radial eigenmode of fast Alfvén waves with an azimuthal mode number $m = +1$ is excited as only one mode in the central cell. While in the case of 60 MHz, several radial eigenmodes are excited. The number of the modes increases as the density increases. The excited waves are affected by the non-uniformity of the magnetic field strength and plasma parameters in the axial direction, and eigenmodes are also formed in the axial direction. The modes depend strongly on the density. The existence of the axial eigenmodes means that the wave-field becomes weak as the density increases or decreases.
If there are large gaps between densities on which axial eigenmodes are excited strongly, the production of the plasma cannot be kept continuous and there is a possibility of the density clamping on a certain value. In the case of 60 MHz, the density gap between eigenmodes is much smaller than the case of 9.9 MHz, and more smooth density increase can be expected with RF3 power [4]. In experiments at a frequency of 63 MHz, a higher density plasma was produced as shown in Fig.2. In addition to RF3, a neutral beam injector (max 25 keV-30A) has been installed at the central cell and has became operational in April 2001. Under the present experimental condition, the absorption of the beam was 10 to 20% corresponding to the central cell line density. The density increase due to the beam injection was 10 to 20%, which is not large but is enough to fill the density gap of the eigenmodes to be excited with the RF3 power. Thus a smooth increase in density is expected with RF3 and central NBI under different experimental conditions and the density clamping can be avoided.

**Potential Confinement of High Density Plasma**

Potential confinement experiments in GAMMA 10 were carried out in higher density region with RF3 and NBI. Figure 3 shows a central cell line density (NLCC) and diamagnetism for the potential confinement of a high density plasma. The density increase due to the potential confinement was 10% because the plug ECRH power was 100 kW. More wall conditioning is required in order to apply a higher ECRH power. Wall conditioning is also required in order to avoid the decrease of the diamagnetism during ECRH. For obtaining a good wall condition, thousands of plasma shots will be

![Figure 2](image1.png)  
*Figure 2 (a) Central cell line density (NLCC) and (b) Diamagnetism when RF3 power was applied.*

![Figure 3](image2.png)  
*Figure 3 (a) NLCC and (b) Diamagnetism for potential confinement of a high density plasma produced by application of RF3 power and neutral beam injection. ECRH: 100kW.*
required. A larger density increment at a higher density is expected with progress of wall conditioning and by optimization of heating scenario with respect to ECRH, ICRF heating and neutral beam injection.

Summary

The potential confinement experiments in GAMMA 10 advanced in high density operation. The high density plasma was attained with a high frequency ICRF system and neutral beam injection in the central cell. A potential confinement experiment was carried out with central cell density of about $4 \times 10^{12}$ cm$^{-3}$. Though the density increment due to the potential confinement was 10%, we expect a larger density increase due to potential confinement with progress of experiments and will obtain a scaling relation between the plasma confinement and plasma density. 