J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 58–62

Long-Pulse Operation of the GAMMA 10 Tandem Mirror

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(Received: 19 January 2000 / Accepted: 29 April 2000)

Abstract

The improvement of potential confinement was attained in the GAMMA 10 tandem mirror by employing axisymmetrization of heating systems for the plasma production, heating and potential formation. Significant increase in the density and diamagnetism by potential confinement was observed. The long pulse operation during almost 0.5 sec is performed and quasi steady-state plasma is produced during discharge. The duration of the potential formation is attained during 0.15 sec by operating two ECRH systems in series. The continuous increase of the density near 50% is observed during ECRH pulse.

Keywords:

tandem mirror, long pulse operation, axisymmetrization, potential formation

1. Introduction

The steady state operation and the high beta (ratio of the plasma pressure to the magnetic field pressure) plasma production are the most important goals on the tandem mirror experiments. On the tandem mirror, plasmas are produced typically by applying rf pulses and/or injecting neutral beams. The maximum discharge duration is restricted by these power supplies. The realization of the high beta plasma in a quasi-steady state is an important mile stone of the tandem mirror research.

GAMMA 10 is designed to be an effectively axisymmetrized tandem mirror. Recently, the improvement of potential confinement has been attained and the significant increase of the density and diamagnetism was observed [1]. With a strong ion cyclotron range of frequency (ICRF) heating, an ion temperature above 10 keV has been attained in the density of 2×10^{18} m^{-3} [2]. The MHD stabilty of the GAMMA 10 is maintained by ICRF heated plasmas in the minimum-B anchor cells. With keeping MHD stability, the emission of D-D fusion neutrons has been observed on the experiments with the mixture of hydrogen and deuterium [3]. The strong ICRF heating with the resonance layer near the midplane of the mirror field produces plasmas with a strong pressure anisotropy. The macro- and micro-stabilities in the tandem mirror plasma are affected by the pressure anisotropy [4].

In this manuscript, the experimental setup is described in Section II, the improvement of the uniformity of the plasma and heating systems in Section III, a long pulse operation of the plasma and long pulse potential formation in Section IV and V, respectively. Summary is described in Section VI.

2. The GAMMA 10 Tandem Mirror

The magnetic field line of GAMMA 10 is shown in Fig. 1 and profiles of the magnetic field strength and

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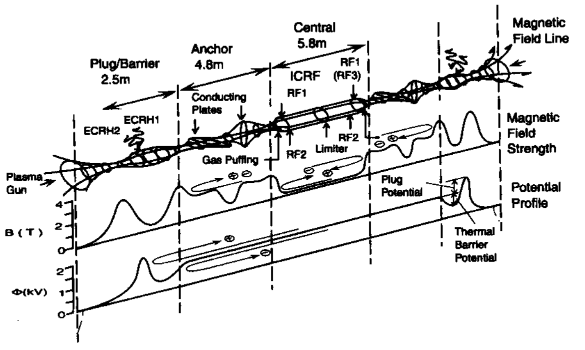

Fig. 1 Schematic drawing of magnetic field line, axial profiles of magnetic field strength and potential

potential distribution of the GAMMA 10 plasma are also illustrated. The central cell has an axisymmetric mirror configuration and the anchor cells located on both sides of the central cell have a minimum-B mirror configuration with non-axisymmetric magnetic fields. The strength of the magnetic field at the midplane of the central cell and the anchor cell is typically 0.4 T and 0.6 T, respectively. The stainless steel limiter with a diameter of 0.36 m is located near the midplane. ICRF antennas for the ion heating of the anchor cell (RF1) and of the central cell (RF2) are installed on both ends of the central cell. The frequencies of RF1 (9.9, 10.3 MHz) and RF2 (6.36 MHz) are adjusted to the fundamental cyclotron resonance frequencies near the midplane of the anchor cell and the central cell, respectively. The frequencies of RF1 on both sides are slightly different from each other in order to avoid the strong interference. When RF1 is driven by the same frequency, the amplitude of the wave field has strong density dependences due to the interaction between waves launched from both antennas. The phase control between both antennas is needed to keep the wave amplitude high. The short pulse (1 msec) gun produced plasmas are injected initially from both ends and the main discharge is sustained with ICRF power of RF1 in combination with the hydrogen gas puffing in the central cell. The maximum discharge duration of 0.5 sec is limited by the ICRF power supply. The radiated power of RF1 and RF2 is typically 100 kW.

Recently, conducting plates to fix the potential at the plasma boundary were installed near the surface of the plasma in the fanning magnetic flux tube of the transition regions on both sides of non-axisymmetric minimum-B anchor cells as indicated in Fig. 1. By using 4 discrete pairs of plates, the spacing is set so as to follow the shape of the magnetic flux tube which maps to a circular magnetic flux tube of 0.4 m diameter at the central cell midplane [1].

Positive potentials for the ion confinement are formed in the axisymmetric end mirror cells by injecting fundamental electron cyclotron resonance heating (ECRH) with a frequency of 28 GHz. The duration of the potential formation is also limited by the gyrotron power supply. Recently, two-beam microwave heating scheme was performed at each plug region, that is, the second ECRH pulse (ECRH2) with a frequency of 28 GHz is applied on superposition or in series to the first ECRH pulse (ECRH1). The maximum duration is reached to 0.15 sec in series operation. The locations of the heating systems are also indicated in Fig. 1.

3. Improvement of The Uniformity of the Plasma and Heating Systems

3.1 ICRF heating system

So-called Nagoya Type III antennas with four plate elements surrounding the plasma column are used for RF1. The rf currents on each plate are supplied with phase difference of 90 degrees and generates a rotating electromagnetic field (m = + 1) in the direction of the electron cyclotron motion. These plates consist of two pairs, one with vertical plates and the other with horizontal plates. When the power of RF1 into the four plates is equally increased, the profile of the floating potential of the limiter which is segmented into 8 sections shows a non-uniformity of the plasma in the azimuthal direction [5]. It is considered the axisymmetry of the central cell plasma is affected from the non-axisymmetry of the minimum-B configuration in the anchor cells which are located on both sides of the central cell. The reduction of the diamagnetic signal related to the non-uniformity of the floating potential is also observed. The standard deviation of the potential profile from the uniform profile of the averaged value is evaluated. Figure 2 shows the reduction of diamagnetic signals with increase of the standard deviation. As indicated in the inlets of Fig. 2, the azimuthal distribution of the floating potential and the degree of the non-uniformity is strongly related to the reduction of the diamagnetism under the conditions of fixed RF2 power. The uniformity of the plasma is improved by changing the RF1 anntenna configuration. When the power of RF1 is supplied only into the antenna pair of the thin side in the projection of the elongated cross section at the transition region between the anchor cell and the central cell, the uniformity of the plasma is improved. Figure 3 shows the RF1 power dependence of the diamagnetism of the central cell on both uniform and non-uniform cases. The diamagnetic signal is kept high in the uniform case and decreases strongly in the non-uniform case under the fixed RF2 power.

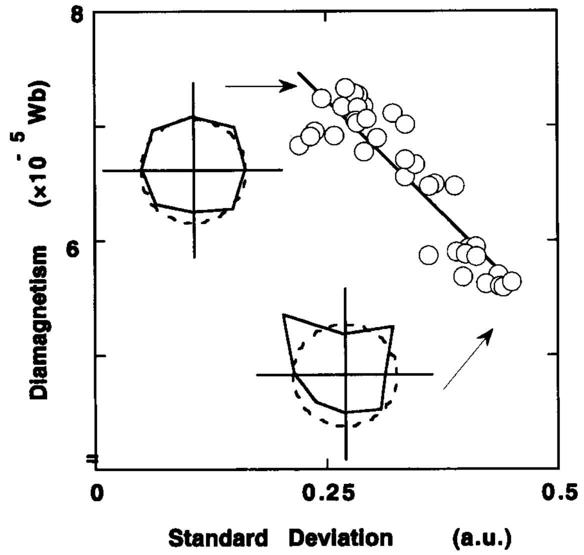

Fig. 2 Relation between diamagntisms of the cenral cell and the standard deviation of the floating potential profile from the averaged value

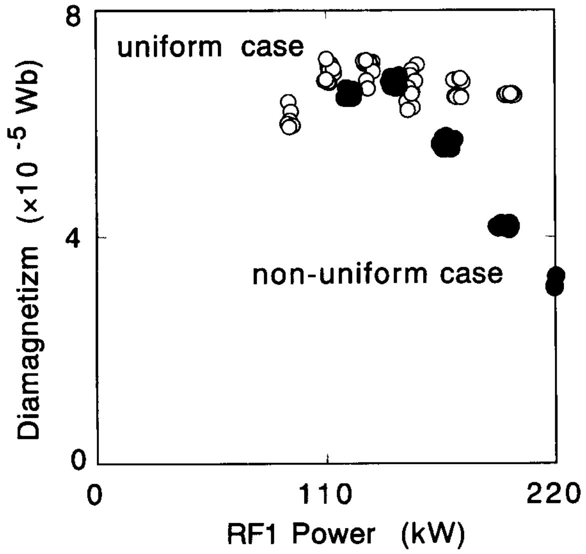

Fig. 3 RF1 power dependence of the diamagnetism in the cenral cell on both cases of uniform and non-uniform floating potentials

3.2 ECRH system

Gyrotrons with a frequency of 28 GHz are used for the potential formation at the plug region with the fundamental resonance layer in the axisymmetric mirror cell. The radiation pattern of the microwave beam from ECRH antenna on the resonance layer becomes non-axisymmetric because the microwave beam is injected at an angle of about 50 degrees respect to the machine axis. A two dimensional potential profile measured with a gold neutral beam probe is vertically elongated. The non-axisymmetric radiation pattern may lead to radial losses of a plasma [6]. For axisymmetrization of the radiation pattern on the resonance layer, it is necessary to focus the microwave beam in the vertical direction. The antenna system for the fundamental ECRH has been modified [7]. Between the conventional Vlasov antenna and the resonance layer, a cylindrical reflector is inserted and adjusted its position and focal length. With the modification, the radiation pattern becomes axisymmetric and the potential profile also becomes axisymmetric [8].

3.3 Conducting plate

In the anchor transition regions between the axisymmetric mirror field of the central cell and plug/barrier mirror cell have a strongly elliptical magntic flux tube. Because the distance across the plasma in the thin side of the elliptical shape is short, the radial loss will occur easily in the case of the existence of the irregular electric field in the azimuthal direction. When the ECRH power for potential formation is applied, the endloss current decreases significantly and the radial loss of passing particles is suggested [9]. If the ionization source is unchanged and the radial loss is not enhanced, the same endloss current as before the potential formation should come out on the steady state condition. Then, the radial loss can be estimated from the measurements of the ionization source and the endloss current. The mechanism of the loss and the region where the loss takes place have not been identified up to now. In order to reduce the irregular electric field near the plasma surface, the conducting plates are installed in the fanning magnetic flux tube of the transition region. Reproducibility and controllability of experiments are improved and a large density increase with potential confinement is observed. All plates are electrically independent. The potential of each plate can be changed by changing a resistance connected to the plate. In the floating potential case, the increment of the density is larger than that in the grounded case

[1].

4. Long Pulse Operation of the High Temperature Plasma

As mentioned previously, the maximum discharge duration of the GAMMA 10 plasma is 0.5 sec which is determined by the power supply of ICRF systems. Figure 4 shows the temporal evolution of the plasma parameters on a typical long pulse operation. The line density (Fig. 4a) and the diamagnetisms (Fig. 4b) are kept almost constant during 0.5 sec. During the discharge, a small power ECRH is applied and the density increases slightly with the potential confinement. Quasi-steady state plasma of the peak density 2×10^{18} m^{-3} and the peak ion temperature about 4 keV is sustained by keeping constant ICRF power and gas fueling rate. In Fig. 4b, the diamagnetic signal at the off-midplane of the central cell is also indicated. The difference of the diamagnetism between at the midplane and off-midplane indicates the pressure anisotropy. In the GAMMA 10 plasma, the anisotropy becomes stronger with increase of the diamagnetism. Above a threshold value of $\beta_\perp A^2 \approx 0.3$, where A is the temperature anisotropy (the ion temperature ratio of the perpendicular to the paralell to the magnetic field line) and $\beta_\perp$ is defined at the center of the plasma, Alfvén ion cyclotron (AIC) modes are spontaneously excited [10]. Due to the appearance of AIC modes, the temperature anisotropy saturates. In the open ended device, it is impotant to sustain the MHD stability by using an averaged minimum-B configuration and so on. The pressure anisotropy of the central cell affects to the MHD stability because of the reduction of the pressure weighting on the bad curvature region near the mirror throat of the central cell [11]. The GAMMA 10 plasma has a stability boundary for a flute interchange mode, that is, a critical ratio between the central cell to the anchor cell beta values. The beta values are defined at the midplane of both cells. This critical value increases with an increase of the anisotropy by more than one order of magnitude compared with a theoretical predictions in the isotropic pressure distribution [12].

The estimation of the recycling of the hydrogen gas has been performed in the long pulse operation. By changing the RF2 power for the ion heating, the neutral gas pressures in the central cell and end cell are measured. Figure 5 shows the temporal evolution of the plasma parameters on three RF2 input power cases (32, 68 and 96 kW). The neutral gas pressure becomes almost stationary around 0.3 sec from beginning of the discharge.

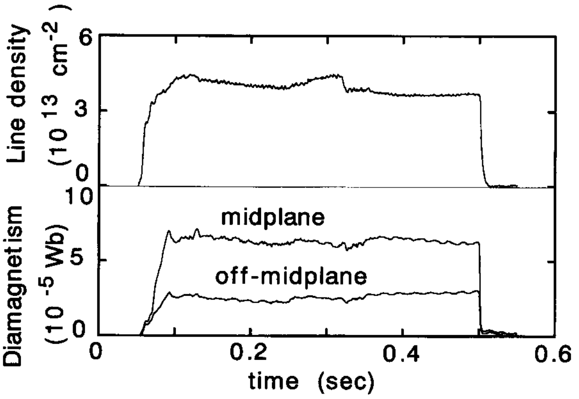

Fig. 4 Temporal evolution of line density (a) and diamagnetisms (b) on a typical long pulse operation.

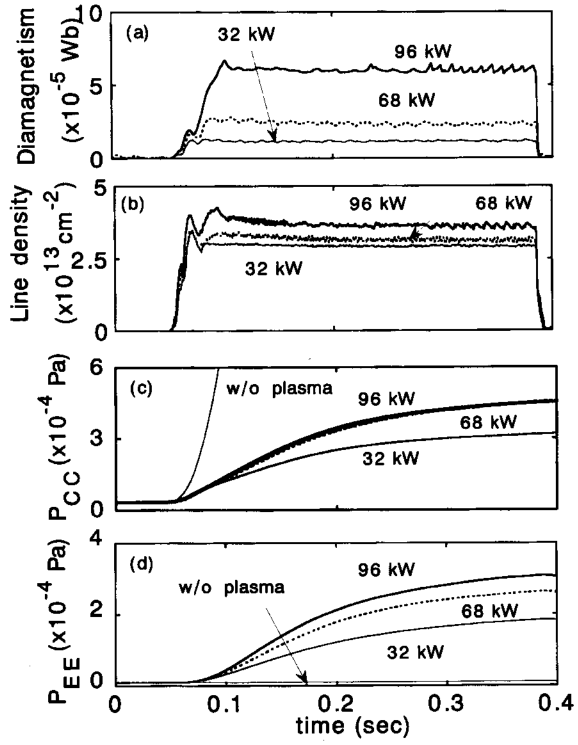

Fig. 5 Temporal evolution of the plasma parameters (a) (b) and neutral gas pressures in the central cell (c) and end cell (d) on three RF2 power cases.

In the case of Fig. 5, the gas fueling rate is kept to be constant. In the case without plasma, the pressure in the central cell increases rapidly and reaches to a value which is almost one order of magnitude higher than the values with plasmas. The pressure in the end does not increase without plasma. Such a strong decrease of the pressure in the central cell comes from pumping to the end cell region by plasmas. The plasmas are recombined at the end cell region and the gas pressure increases. The diamagnetisms depend on the RF2 power, however, the line density is almost kept constant. The difference of the absolute values of the pressure on each case comes from the difference of RF2 power, that is, a recycpling particle flux from the wall which is enhanced by the RF2 power. The recycling coefficient is estimated by solving pressure balance equations in the GAMMA 10 vacuum vessel [13,14]. The results of the numerical calculation show the recycling coefficient in both cases of 68 kW and 96 kW exceeds unity. In the open ended system, the neutral gas pressure is determined by the gas fueling, wall recycling and plasma pumping to the end.

5. Long Pulse Potential Formation

The duration of the potential formation by applying ECRH pulse is restricted also by the power supply of gyrotrons. In order to perform the long pulse potential formation, new ECRH antennas have been installed on the outer side of both plug/barrier cells. With the new antennas, the confining potential on the fundamental resonance layers is produced by superposing and applying in series after the first ECRH pulse. Because the injection angles of the microwave beam are different on both ECRH systems, some differences are observed between effects of both systems. When the second ECRH pulse is applied in series after the first pulse, the maximum duration of the potential formation becomes 0.15 sec. Figure 6 shows the typical long pulse potential formation in the GAMMA 10 plasma.

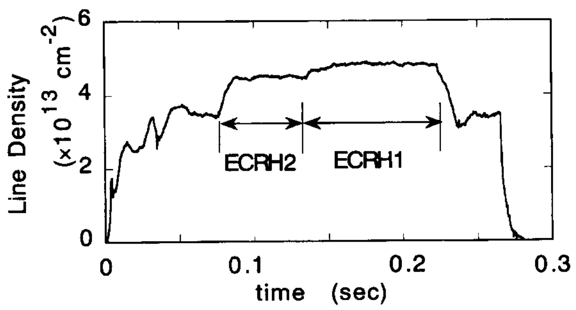

Fig. 6 Temporal evolusion of the line density in the case of two ECRH systems operating in series.

6. Summary

The long pulse operation is performed in the GAMMA 10 tandem mirror. The maximum duration of the discharge is 0.5 sec which is restricted by the power supply of the ICRF systems. The maximum duration of the potential confinement is 0.15 sec which is also restricted by the power supply of gyrotrons. Quasi steady-state plasma is produced during the discharge. The improvement of the uniformity of the plasma and heating systems are performed and significant increase of the density due to the potential confinement is observed.

Acknowledgements

The authors are deeply grateful to the members of GAMMA 10 for their collaboration in the experiments and discussions.

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