Plasma Confinement and Behavior of Plasmas in the Minimum-B Region of the GAMMA 10 Tandem Mirror

NAKASHIMA Yousuke, YATSU Kiyoshi, ISLAM Khairul, SATO Daisuke, WADA Atsushi, ISHII Kameo, ITAKURA Akiyosi, ICHIMURA Makoto, KATANUMA Isao, KAJIWARA Ken, KUBOTA Shigeyuki, KOHAGURA Junko, KOBAYASHI Shinji, SAITO Teruo, SASUGA Takeshi, TATEMATSU Yoshinori, TAMANO Teruo, CHO Teruji, TOBUWAKAWA Tokihiko, NISHIZAWA Yuki, HAMADA Minoru, BABA Ryuta, HIRATA Mafumi, BRUSKIN Leonid, HOJO Hitoshi, MASE Atsushi, MINAMI Ryutaro and YOSHIKAWA Masayuki

Plasma Research Center, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan

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Abstract

Recent results of the plasma confinement and the behavior of the edge plasma in the minimum-B regions of the GAMMA 10 tandem mirror are described. In this experiment conducting plates are newly installed in the anchor-cells in order to improve the performance of plasma confinement. The conducting plates are fixed closely to the plasma surface where the cross-section of the plasma is flatly elongated in the anchor transition region. After conditioning the conducting plates, basic characteristics on the conducting plates are investigated. A fairly good symmetry between the two plates facing each other is found in the drain current and in the floating potential. The axial profiles of these measured data also show a symmetry with respect to the central-cell mid plane. The dependence of the resistance connecting the plates to the machine ground shows that the floating condition of the plates provides the better property of particle confinement. As the result of optimization of the heating and gas puffing systems a significant improvement of the plasma parameters is observed during potential formation. According to the increase of plug ECRH power, the central-cell line density and the diamagnetism increase and both parameters are nearly doubled at the ECRH power of 140 kW under the floating condition of the conducting plates.

Keywords:
tandem mirror, GAMMA 10, potential confinement, conducting plate, minimum-B field, edge plasma, Langmuir probe

1. Introduction

Improvement of axial plasma confinement by potential formation (end plugging) is an essential mechanism in tandem mirror concept. In the GAMMA 10 tandem mirror, research aiming higher confining potential and improvement of plasma confinement time has been performed since the early period of the GAMMA 10 project [1-3]. Several years ago a new research started using a plasma production mode (hot ion mode) in which hot ions are produced in the central-
cell with Ion Cyclotron Range of Frequency (ICRF) waves [4]. In hot ion mode plasmas, relatively high ion-temperature (~10 keV) was attained, however the confining potential which interrupts passing ions through the mirror loss cone was small and the resultant density increment due to potential formation was observed to be small (~10%).

Recently an operating condition with a remarkable density increase due to the end plugging was found in hot ion mode plasmas and the experimental results clearly giving the proof of principle on the axial plasma confinement by potential formation were reported [5, 6]. In this operation condition the confinement property was investigated based on measurements of density and end-loss flux with newly developed End-Loss Ion energy Analyzer (ELA) [7]. The confining potential is determined from the potential difference between that measured in the central-cell by using a heavy-ion beam probe system [8] and that obtained as a plug potential from the energy distribution of end-loss ions. In these circumstances it is clarified that a rapid reduction in the end-loss current associated with application of Electron Cyclotron Resonance Heating (ECRH) for potential formation was observed and the resultant central-cell density was significantly increased. Thus the improvement of plasma confinement due to potential formation is experimentally confirmed and the density increase with more than 50% has been achieved by optimizing the heating pattern of ICRF and ECRH waves. However, it was also found that there should be some amount of radial loss of passing ions in hot ion mode plasmas.

In the beginning of 1998 four sets of conducting plates were newly installed in the vacuum chamber of the GAMMA 10 anchor-cells in order to improve the performance of plasma confinement furthermore. The objective of the conducting plates is to fix the potential of the plasma boundary in the anchor transition region where the plasma cross-section is elongated flatly and to suppress irregular electric fields which is suspected of radial loss in this region, since such electric fields can be easily caused by strong wave heating. The conducting plates are installed close to the plasma surface in both inner and outer transition regions in each anchor-cell. After conditioning the conducting plates, basic characteristics on the conducting plates in plasma discharges and their effect on the plasma parameters during potential formation are investigated by using Langmuir probes and calorimeters installed in the outer transition region of the east anchor-cell. In this paper details of the anchor conducting plates and their characteristics in plasma discharges are presented. The behavior of the edge plasma in the minimum-B region and the improvement of plasma performance after installing the anchor conducting plates are also discussed from the view point of the plasma confinement.

2. Experimental Apparatus

2.1 The GAMMA10 device

Figure 1 shows a schematic view of the GAMMA 10 tandem mirror device. GAMMA10 consists of an axisymmetric central-mirror cell, anchor-cells with minimum-B magnetic fields, and plug/barrier cells with axisymmetric mirrors. The configuration of the coil system and the shape of the magnetic flux tube are shown in Fig. 1(a) and (b), respectively. The length of the central-cell is 6 m and the magnetic strength is normally 0.43 T and varied from 0.3 T to 0.57 T. Both ends of the central-cell are connected to the anchor-cells through the mirror throat regions. Initial plasma is injected from both ends by plasma guns, then a plasma is built and heated up with two types of ICRF waves together with gas puffing. One of the ICRF waves (RF1) is mainly used for MHD stabilization and excited by a pair of so-called NAGOYA type III antennas. Central-cell ions are heated by another ICRF wave (RF2) excited by a pair of the double half-turn antennas. Both types of antennas are located near the ends of the central-cell as shown in Fig.1(b). Seven gas puffers are installed in the central-cell and most of them are located away from the resonance layer of RF2 (near the central-cell mid plane) in order to avoid the charge-exchange loss of hot ions. The length of the plug/barrier cell is 2.5 m and the intensity of the magnetic field is 0.5 T at the mid plane. The mirror ratio is 6.2 in this region. Hot ions in the anchor-cell produced by the RF1 wave propagating from the central-cell provide MHD stability of the whole GAMMA 10 plasma. Figures 1(c) and (d) show axial profiles of the magnetic field intensity and the potential along the machine axis. Leaking particles along the magnetic field lines are confined by the plug potential produced with ECRH by using gyrotrons installed in both plug/barrier cells. The plasma with the ion temperature of ~10 keV is confined in the central-cell at the electron density of 2~3 x 10^{12} cm^{-3} under the above conditions [9].

2.2 Anchor conducting plates

The schematic of a quarter part of the cross-section
of the magnetic flux tube in the west anchor-cell is illustrated in Fig. 2 together with the anchor conducting plates. The flux tube is represented as that mapped to the central-cell mid plane at the radial position of $r_{cc} = 0.2$ m. As shown in the figure, the circular cross-section of the magnetic flux tube in the central-cell is elongated elliptically in the transition regions of the anchor-cell. The conducting plates are made of stainless steel with 2...
mm thickness and installed facing each other closely to the plasma surface along such a flat magnetic flux tube in the both inner and outer transition regions of the anchor-cells as shown in Fig. 2. The conducting plates are separated to four pieces in an axial direction (z-direction). The length of all the plates are 1.24 m in the transverse direction to z-axis. The space between the plates facing each other is changed from 0.05 m to 0.1 m so as to keep the distance from the plasma edge nearly constant (less than few cm). The width (z-direction) of each plate is also changed from 0.08 to 0.25 m for the same reason.

Figure 3 shows the schematic view of the conducting plates and diagnostics for the investigation of edge plasmas near the anchor transition region. The conducting plates are placed parallel to the longer axis of the elliptic plasma cross-section. At both ends along the longer axis, side plates are installed facing each other. These plates surrounds the plasma surface and are named Top, Bottom, North and South according to their locations. Table 1 shows the relationship between the plate name and its location.

On the side plates of the east outer-transition region, arrays of calorimeters and Langmuir probes are installed in order to investigate the behavior of the edge plasmas. The potential of each plate is changed in floating and grounded conditions individually, moreover can be biased by using external power supplies. A set of movable Langmuir probes is installed at the south side of the east outer transition region. The movable probe is capable of scanning edge plasmas of this area in the vertical (upward and downward) and horizontal (north and south) directions by rotating and inserting the probe shaft, respectively.

3. Experimental Results

3.1 Basic characteristics of the anchor conducting plates

After conditioning plasma discharges to reduce the outgassing from the plates, experiments to examine the basic characteristics of the conducting plates have been started. Figure 4 shows the axial profile of the drain currents into the conducting plates under the condition that each plate is connected to the machine ground with 1 Ω resister (grounded mode). The errors in the measured values, which are though to be governed by shot-reproducibility and noise signals due to the plasma heating devices, are roughly estimated to be within 20%.

The results shown in Fig. 4(a) are obtained in the case without ECRH and those in Fig. 4(b) correspond to the
case with ECRH. In both cases the axial profiles of the currents is almost symmetry with respect to the central mid plane (the machine mid plane). In each side (east and west) positive currents are observed on all the conducting plates and decrease outwardly from the central-cell side to the anchor mid plane (from the plate number #1 to #4 at inner transition regions). There are very low current observed near the anchor mid plane (#4 plates). On the other hand, negative currents are observed on all the side plates. A fairly good symmetry between the two plates facing each other is found in the drain currents and there are no remarkable difference generally observed between cases with ECRH and without ECRH.

In Fig. 5 the potential of each plate is represented in the case that all the plates are connected to the machine ground through high resistivity (1 MΩ) resisters (floating mode). Higher positive potentials are observed in both inner transition regions and the potentials are found to decrease toward the anchor mid plane (from the plate number #1 to #4). Although the measured data are slightly scattered more than those of the drain current, the symmetry between the plates facing each other is observed. The axial profile of the plate potential is also observed to be almost symmetrical with respect to the central-cell. These symmetrical characteristics indicate that there are no remarkable imbalance of plasma parameters generally in the anchor transition regions and that the installation of the anchor conducting plates has no bad influences which cause such imbalances in the non-axisymmetric minimum-B configuration.

From the above mentioned results it is found that ion currents are mainly coming from the central-cell and flowing into the anchor conducting plates. The electron current, on the other hand, are flowing into the side plates. This is the first observation in GAMMA 10 plasmas and there are very few reports about the polarity difference of plasma flow in non-axisymmetric magnetic field configurations. The mechanism that causes this phenomenon is not well understood at present. However, it is important to investigate the...
above characteristics in detail for understanding the radial transport of the plasma in this region.

3.2 Behavior of edge plasmas in the anchor transition region

Measurements of the edge plasmas and the heat flow in the anchor transition region are carried out by using the movable Langmuir probe, arrays of calorimeters and fixed Langmuir probes installed on the side plates of the outer transition region. Figure 6(a) shows the shape of the magnetic field line in the east outer transition region and the arrangement of the probes and calorimeters. The axial profiles of the heat flow measured in cases of grounded and floating modes are shown in Fig. 6(b). The sensitivity of each calorimeter is calibrated and the accuracy of the measured heat flow is estimated to be less than 15%. The peak positions of the heat flow in z-direction are found to be the same between the facing two plates. Each peak position, however, is observed to be shifted by about 200 mm to the central-cell side from the position where the magnetic field line makes the closest approach to the side plate. Although the direction of this shift corresponds to that of the plasma production region (i.e. central-cell), the cause of this difference between the two positions is not clarified yet. Note that the larger heat flow is observed on the north side plates than the south ones in the case of grounded mode. However, the imbalance of the heat flow between north and south is improved in the floating mode within the experimental error.

Figure 7 shows the profile of the ion and electron saturation currents measured with the movable Langmuir probe. This profile is measured by rotating the probe shaft with a small angle from the horizontal plane at the location where the probe tip is set at y = -28.7 cm, z = -660 cm. A noticeable shift to the negative direction in x-axis (downward) is observed in both saturation currents. This location on the horizontal plane (y-z plane) is equivalent to the radial position of r_{cc} = 13 cm at the central-cell mid plane. In this plasma edge region a strong gradient of the magnetic field strength toward the central axis exists and the direction of the shift corresponds to the gradient B drift for ions. If this observed fact is dominated by the gradient B drift, the direction of the shift on the opposite side (north side) must be inverse (upward). Hence the symmetry between facing plates is thought to be kept by canceling the charge separation. Though the reason for such a shift is not clarified yet, both saturation currents are reduced in the floating mode as shown in the figure. Furthermore, axially-aligned probe array installed on the side plates shows a reduction of ion saturation current in the floating mode. These data implies that the floating condition of the conducting plates improves the potential imbalance between the plates and suppresses the radial loss to some extent.
4. Effect of the Anchor Conducting Plates

Figure 8 shows an example which indicates an improvement of plasma confinement by controlling the potential of the conducting plates. The vertical axis of the figure represents the increment ratio in the line density of the central-cell due to the potential confinement \( \frac{n_{lc}}{n_{lc}} \) (with ECRH) / \( n_{lc} \) (w/o ECRH) and the data are plotted as a function of the resistance between the conducting plates and the machine ground \( R_{anchor} \). It is found that the density increment ratio changes between the resistances of 100 Ω and 10 kΩ and that the ratio increases by 10% with \( R_{anchor} \leq 10 \text{kΩ} \) in spite of keeping the other experimental conditions fixed (i.e. plasma heating power, amount of gas puffing, etc.). This phenomenon shows qualitatively that the improvement of particle confinement due to potential formation is enhanced by using the conducting plates in the floating condition.

Under the optimized condition of plasma heating and gas puffing systems the ECRH power dependence on the confinement performance is investigated. In Fig. 9 the confining potential \( \phi_c \) and the density increment ratio \( n_{lc} \) (with ECRH) / \( n_{lc} \) (w/o ECRH) are plotted as a function of the plug ECRH power. The confining potential increases with the ECRH power and the increment of the line density increases up to twice without a tendency of saturation at the ECRH power of 140 kW. At this time the confining potential is observed to increase up to 0.6 kV. Figure 10 shows the time evolution of the plasma parameters obtained in the floating condition of the conducting plates. Both the central-cell line density and the diamagnetism are observed to be doubled in the period of potential formation during the plug ECRH pulse as shown in Figs. 10(a) and (b). The confining potential shown in Fig. 10(c) is also measured to be 0.5 kV at the same period. The ion and electron temperature at the central-cell are determined by investigating the highly similar discharges to that shown in Fig. 10. The ion temperature of 4.5 keV and electron temperature of 80 eV are attained on the plasma axis during the potential confinement.

From the estimation of ionization rate based on Hα and end-loss ion flux measurements, the particle confinement time is examined using particle-balance calculations. Considering the temporal change of plasma density, the particle confinement time at the plasma center is determined to be 40 ms just after the onset of the plug ECRH (\( t = 85 \text{ ms} \)). Then the particle confinement gradually decreases to 15 ms in the steady state phase (\( t = 120 \text{ ms} \)). As shown in Fig. 10(c) the confining potential also decreases with time. From the Pastukhov scaling [9], the particle confinement time can be calculated using the observed parameters, such as central plasma density, ion parallel temperature and confining potential, and machine parameters (configuration of the magnetic field, etc.) [10]. The values at \( t = 85 \text{ ms} \) and \( t = 120 \text{ ms} \) are estimated to be 38 ms and 12 ms, respectively. The values from the two different methods are in good agreement within the experimental errors.
5. Summary

In GAMMA 10, conducting plates were installed close to the plasma surface in the anchor transition regions in order to improve the confinement property. The effect of the plates on plasma parameters was investigated and the increase of the plasma density and the diamagnetism due to the potential confinement was found to be doubled under the floating condition of the plates. Obtained major results are summarized as follows:

1. Polarity difference of plasma flow in the anchor transition region is observed for the first time: Ion currents are mainly flowing into the conducting plates and the electron current are flowing into the side plates. The drain current into the conducting plates (under grounded condition) and their floating potentials (under floating condition) are on the whole symmetric with respect to the machine mid plane (east and west) and between facing plates. This result indicates that there are no remarkable imbalance of plasma parameters generally in the anchor transition regions and that the installation of the anchor conducting plates has no bad influences which cause such imbalances in the non-axisymmetric minimum-B region.

2. A noticeable asymmetry of the probe current in the vertical direction are observed at the plasma edge in the outer transition region. This observation indicates that the gradient B drift affects the edge plasmas to some extent in the outer transition region.

3. The dependence of the resistance connecting the plates to the machine ground shows that the floating condition of the plates improves the property of particle confinement.

4. In the case of the floating mode, the particle confinement time during potential confinement is examined from the particle-balance calculations and the obtained value is found to be in good agreement with the Pastukhov scaling.

As described above, the improvement of plasma confinement using newly installed conducting plates in the anchor transition region is successfully achieved. However, the detailed mechanism of the conducting plates for improving the plasma property is not clarified yet. Therefore it is necessary to carry on detailed investigation near the conducting plates and related researches such as plate biasing experiments.

References