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Studies of edge plasmas in an anchor minimum-B region of the GAMMA 10 tandem mirror

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Abstract

Results of edge plasma investigation in a minimum-B region of the GAMMA 10 tandem mirror are described. In this experiment, the spatial profile of the ion saturation current and the floating potential in the edge plasmas are measured by using arrays of Langmuir probes installed on conducting plates in anchor cells together with a movable probe near the plate in the east anchor cell. From these measurements, a significant asymmetry to the axis of the plasma was observed in both probe currents and floating potentials. It is also found that there are some impurity-deposited layers partially observed on all the conducting plates and that their locations show a rotational symmetry to the magnetic axis at 180°. In this region, a strong gradient of the magnetic field strength toward the axis exists. The direction of the expected plasma shift corresponds to the $\nabla \vec{B}$ and curvature drift for ions. The results of ion orbit calculation taking account of the above effect show a good agreement with the measured results. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Gamma 10; Tandem mirror; Edge plasma

1. Introduction

A minimum-B configuration is an important component of tandem mirror devices for sustaining MHD stability in the plasmas. The GAMMA 10 tandem mirror [1] contains two minimum-B anchor cells at both ends of the central cell. In the anchor cell there are two transition regions: an inner-transition region, which connects the magnetic field line from the central cell to the anchor cell, and an outer-transition region, which is located between the anchor cell and the plug/barrier cell, as shown in Fig. 1. A number of experiments have been carried out on the anchor-cell plasmas from the viewpoint of MHD stability [2,3]. However, the behavior of edge plasmas in the anchor transition regions has not been investigated well.

Recently an operating condition with a remarkable density increase due to the end plugging was found in the hot-ion mode of the GAMMA 10 plasmas [4,5]. In these experiments, it is clarified that a rapid reduction in the end-loss current associated with application of electron cyclotron heating (ECH) for potential formation was observed and the resultant central-cell density was significantly increased. However, it was also found that there should be some amount of radial loss of passing ions between axially confining potentials in both plug/barrier cells. In the beginning of 1998, four sets of conducting plates were installed in the vacuum chamber of the anchor cells in order to improve the performance of plasma confinement furthermore [6].

The behavior of edge plasmas in this region have been investigated by using arrays of fixed Langmuir probes and a movable probe. This paper describes the characteristics of edge plasmas measured with these

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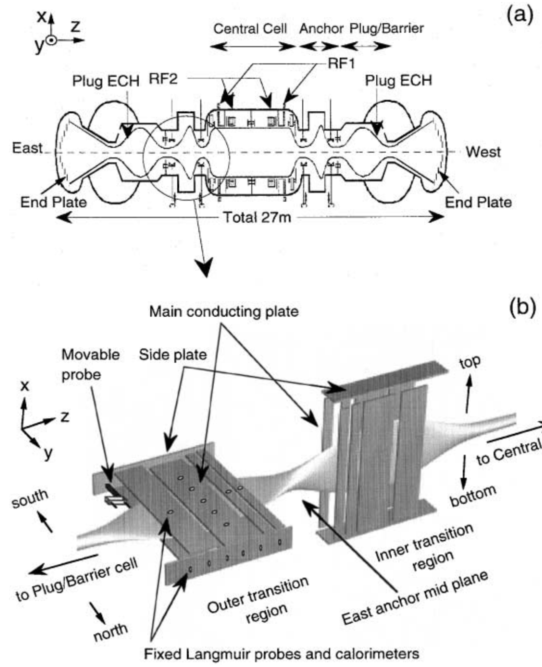

Fig. 1. The schematic view of the GAMMA 10 tandem mirror (a), and the anchor conducting plates and the shape of the magnetic-flux tube in the anchor cell, together with the location of the diagnostic system (b).

diagnostics and discussion of the radial particle transport in this area is made on the basis of particle orbit calculations.

2. Experimental apparatus

2.1. The GAMMA 10 device

Fig. 1 shows the schematic view of the GAMMA 10 tandem mirror and the detail of an anchor cell together with the diagnostics used for this study. GAMMA 10 has a total length of 27 m and consists of an axisymmetric central-mirror cell, anchor cells with minimum-B field, and plug/barrier cells with axisymmetric mirrors. The length of the central cell is 6 m and the diameter of the vacuum chamber is 1 m. Initial plasma is injected with plasma guns from both ends, then a plasma is built up with ion cyclotron range of frequency (ICRF) waves together with gas puffing. One of the ICRF waves (RF1) is mainly used in the anchor cell for MHD stabilization. Another wave (RF2) is used for heating the central-cell ions by ion cyclotron damping near the midplane of the central cell. Escaping plasma particles along the magnetic field lines from the central-cell plasma are confined by the plug potential produced with the plug ECH in both plug/barrier cells.

2.2. Anchor conducting plates and diagnostic system

The schematic illustrations of the magnetic flux tube in the anchor cell and the conducting plates are shown in Fig. 1(b). Conducting plates are made of stainless steel with 2 mm thickness and installed closely to the plasma surface along a flat magnetic flux tube in the inner- and outer-transition regions of both anchor cells. The main conducting plates, which are installed in parallel with the longer axis of the elliptic plasma cross-section, are separated into four pieces in an axial direction. At both ends along the longer axis, side plates are installed facing each other. On the 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, and also can be biased by using external power supplies. A movable Langmuir probe is installed at the south side of the east outer-transition region as shown in Fig. 1(b). The movable probe is capable of scanning edge plasmas of this area in the vertical (upward and downward) and horizontal (north and south) directions.

3. Experimental results

Fig. 2 shows a typical time evolution of the plasma parameters measured at the central cell and the east end cell in a standard hot-ion mode plasma used in the

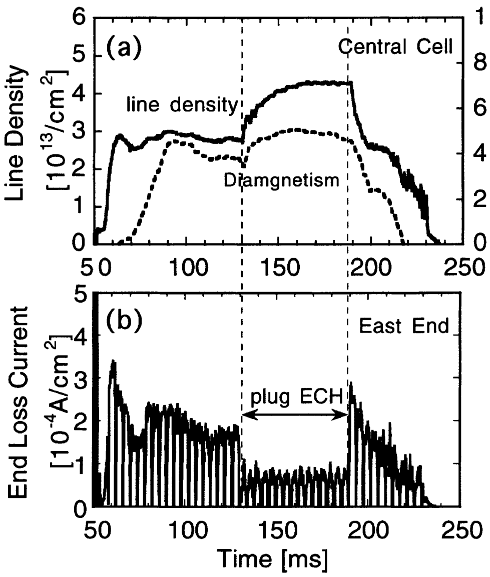

Fig. 2. A typical time evolution of the plasma parameters measured in the present experiment: (a) line density of electrons at the central cell; (b) diamagnetism at the central cell; and (c) end-loss current at the east end.

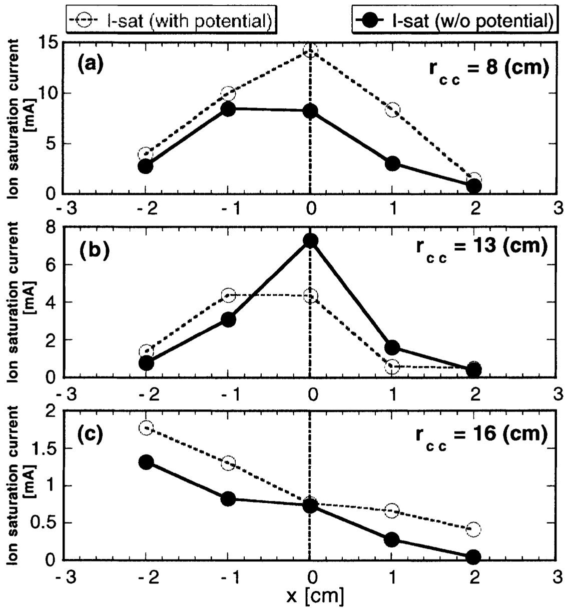

Fig. 3. Spatial profile of the ion saturation current in the vertical direction at the outer-transition region of the east anchor cell. Open circles are data measured in the case with potential formation and closed ones correspond to the case without potential formation. (a) $r_{cc} = 8$ cm, (b) 13 cm and (c) 16 cm.

present experiment. In this experiment, the anchor conducting plates are in the floating mode and the injected powers of RF1 and RF2 are 70 and 100 kW, respectively. The plug ECH power is in a range of 100–150 kW. Rapid decrease of the end-loss ion flux (Fig. 2(b)) is observed corresponding to the plug ECH and the resultant increase of electron line density and the diamagnetism (Fig. 2(a)) are recognized in the central cell.

Fig. 3 shows the spatial profile of ion saturation current measured with the movable probe. A considerable asymmetry in x (vertical) direction is observed in the periphery region $r_{cc} \geqslant 13$ cm). In this figure r_{cc} represents the effective radius of the probe position which is mapped on the central-cell midplane along the magnetic field line. The asymmetry has a tendency to be enhanced with the distance from the plasma axis. This feature is found to be independent of the potential formation produced by the plug ECH.

Spatial profile of floating potentials in y (horizontal) direction measured with arrays of fixed probes installed on the conducting plates facing each other at the same region are shown in Fig. 4. The signals on the top plate array show that the floating potential increases with the positive y-direction and those on the bottom plate array present an opposite dependence to the top plate case. Note that in both cases, these characteristics are also independent of the potential formation. Since the position of the main plates is enough away from the plasma boundary $r_{plate} \geqslant 1.5 r_{plasma}$, it is rather difficult for electrons to reach the plates across the magnetic field lines. Furthermore, the fact that positive potentials are measured in almost all the main plates indicates that the dominant particles flowing into the plates are ions. From these results, the asymmetry of the edge plasma parameters measured in the outer-transition region is ascribed to the effect of ion drift motion in this region.

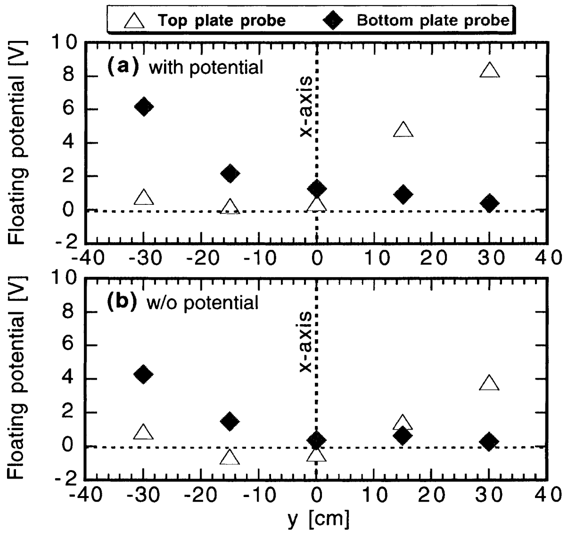

Fig. 4. Spatial profile of the floating potential in the horizontal direction at the outer-transition region of the east anchor cell. Open triangles represent data measured with the probe array at the top plate and closed diamonds correspond to the bottom plate. (a) With potential formation; (b) without potential formation.

Fig. 5 shows photographs of the plasma facing side of the main plates which were taken after being used in the experimental period of a year (~7000 plasma shots). There are some deposited layers of impurities observed partially on the main plate at locations opposite to the ion drift side. This phenomenon shows a structure containing a rotational symmetry in 180°. This observation is explained by such mechanism that plasma ions hitting on the plate sputter impurities from the plate (and/or impurity ions making self-sputtering on the plates) due to the drift effect and that the sputtered impurities are redeposited on the opposite plate.

4. Discussion

To understand the asymmetry in the measured data, the effect of $\vec{\nabla} B$ and curvature drift for ions is investigated. In the anchor transition region, a strong gradient of the magnetic field exists. According to a rough estimation of $\vec{\nabla} B$ drift for passing ions, the extent of the

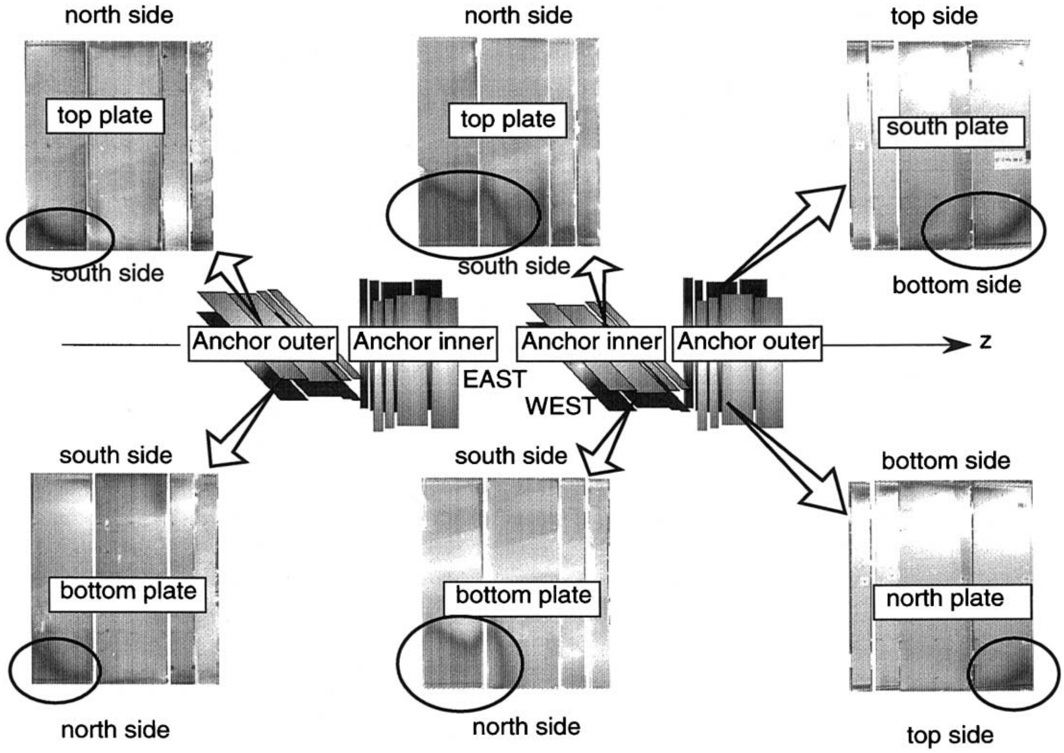

Fig. 5. Photographs of the anchor conducting plates used in a year. The circles show the area of typical deposition layer by carbon material. All the plates are shown in inner surface (plasma facing side).

shift is calculated to be 0.5 cm in vertical direction [7]. In order to investigate the detailed behavior of passing ions in this region, a numerical calculation for tracking the ion orbit has been carried out. In this calculation, the ion orbit is determined from an equation of motion in which the above effect is taken into account by using the Runge–Kutta–Gill method. In the present plasma parameter region, mean free path of passing ions are much longer than the machine length (few hundred meters). Therefore we consider the orbit calculation valid for investigating this mechanism. As the launching position of test particles, two positions (the central-cell midplane and the anchor-cell midplane) are selected and both calculation results are compared. Initial parameters of test particles (ions) are determined from perpendicular ion temperature measured with a neutral particle analyzer [8] installed at the central cell and from parallel ion temperature measured at the end cell by using end-loss analyzer [9]. At the anchor-cell midplane, the initial value is given by assuming the conservation of magnetic moment and energy of ions coming from the central cell.

The obtained results are shown in Fig. 6. In the left-hand side of the figure, ions launched from circumference of a circular flux tube ($r_{cc} = 13$ cm) at the central-cell midplane (a) are traced through the east anchor midplane (b) to the location of the movable probe in the east outer-transition region (c). This result shows that in the case of passing ions starting from the central-cell midplane, the $\vec{\nabla}B$ drift caused in the inner-transition regions is canceled out in the outer-transition region and the resultant shift of the ion orbit becomes very small. On the other hand, in the right-hand side of the figure, a significant shift of 0.5 cm in the $-x$-direction is recognized at the transition region for passing ions launched from the anchor-cell midplane. As shown in Fig. 3(b), the peak position of the measured ion saturation current locates between $x = 0$ and $x = -1.0$ cm. This result agrees well with the calculation results. From the above calculation, the observed asymmetry in the probe measurements and in the localization of impurity-deposited areas on the plates is mainly ascribed to the $\vec{\nabla}B$ drift of ions originating from the anchor-cell midplane.

It is difficult to precisely estimate the extent of the influence of this drift mechanism on the amount of radial transport in the whole GAMMA 10 plasma. However, the radial loss due to this drift effect is thought to be not large, since the orbit calculation indicates that only particles launched from the anchor midplane are strongly affected in the outer-transition region by this effect. The number of plasma particles localized in

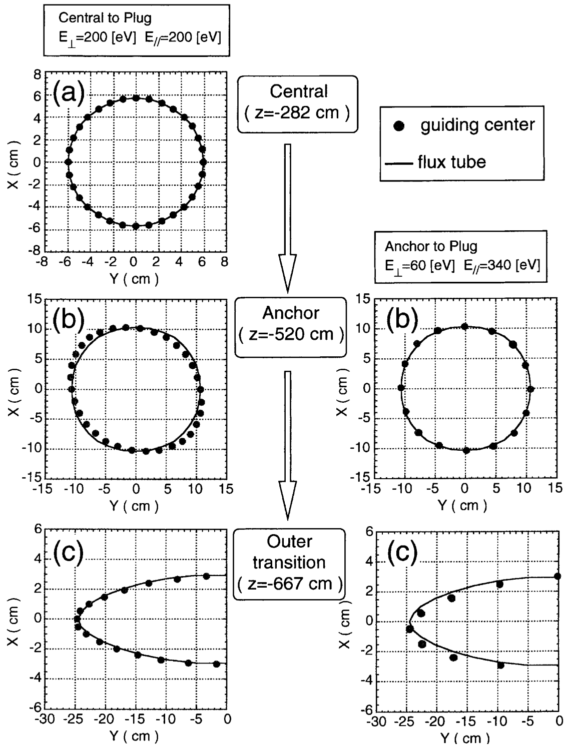

Fig. 6. Results of the orbit calculations. Filled circles represent the guiding-center trace of ions. In the left graphs, the results of test particles launched at the central cell are presented and the ones at the right correspond to those launched at the anchor-cell midplane.

the anchor cell is small compared to those in other axisymmetric cells such as the central cell and the plug/barrier cells. In addition, this drift takes place regardless of potential confinement. The experimental results that the balance between the fueling rate into the central cell plasma and the quantity of the end-loss flux is generally preserved under the condition without confining potentials also support the above speculation [10].

5. Conclusions

Edge plasmas in the anchor outer-transition region were investigated by using Langmuir probe arrays and a movable probe. A significant asymmetry in the ion saturation current and the floating potential is recognized, which corresponds to the direction of $\vec{\nabla}B$ and curvature drift for ions. Impurity-deposited areas observed on the conducting plates showed the same asymmetry and the structure of rotational symmetry in 180°. The results of orbit calculation taking account of the above effect indicated that the $\vec{\nabla}B$ and curvature drift are the dominant factors that cause the asymmetry of ions observed at the outer-transition region. However, it is also found that this drift effect exerts little influence on the radial loss for the passing ions from the central cell. Further investigation is therefore needed to clarify the radial loss mechanism of core plasma based on more detailed experimental results.

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