CONTROL OF PARALLEL AND PERPENDICULAR POTENTIAL PROFILES IN OPEN-ENDED PLASMA CONFINEMENT SYSTEMS

N. SATO, R. HATAKEYAMA, T. KANEKO,
M. INUTAKE, M. YOSHINUMA, K. HATTORI, A. ANDO
Graduate School of Engineering, Tohoku University
Aza-Aoba 05, Aramaki, Sendai 980-8579
Japan

Abstract

A plug potential with thermal barrier is clearly observed to be formed along a field-aligned plasma flow in the presence of a single electron-cyclotron-resonance point under a simple magnetic-mirror configuration. Drift-mode fluctuations are controlled by varying a radial electric field and a related azimuthal drift shear.

1. INTRODUCTION

Concepts of a plug potential with thermal barrier (plug/barrier potential) and a thermal dike have been proposed in order to realize the effective plasma confinement necessary for tandem-mirror devices and to reduce the heat transport in tokamak divertors, respectively. According to the original tandem-mirror scenario for the plug/barrier potential formation, a neutral beam injection (NBI) producing sloshing ions is required in addition to the electron cyclotron resonances (ECR) at two positions with different magnetic fields in each mirror cell. Recent experiments on the GAMMA 10 [1], however, have shown that this potential structure is formed without NBI in the presence of the two ECR points. Since the overall field-aligned potential profiles have never been measured and the physical mechanism of the potential formation has been unsolved, it remains unsettled whether an expected scenario of the potential formation is really valid or not.

The L-H transitions observed in tokamak, stellarator, and mirror devices indicate that potential profiles perpendicular to magnetic field lines, which are closely related to edge-plasma fluctuations, play a crucial role in the plasma transport [2]. Thus, it is one of the most urgent needs to carry out experiments on effects of radial electric field and its shear on fluctuations by using compact devices where it is much easier to measure and control spatial profiles of plasma parameters.

Here we demonstrate a simple experiment on a clear-cut formation mechanism of the plug potential with thermal barrier in the presence of a single ECR [3] and present stabilizing and destabilizing effects of radial electric field and its shear on low-frequency fluctuations [4].

2. FORMATION OF PLUG POTENTIAL WITH THERMAL BARRIER

An experiment on the plug potential with thermal barrier has been carried out in the Q_{T}-Upgrade machine under a simple magnetic-mirror configuration (the top figure in Fig. 1(a)) where a fully-ionized collisionless plasma of density $n_{e0} \simeq 1 \times 10^9$ cm^{-3} and ion flow energy $E_{i0} \simeq 10T_{e0}/e$ ($T_{e0} \simeq 0.2$ eV: electron temperature) is injected at $t = 0$ and $z = 160$ cm from the right-hand side. A microwave with frequency $\omega/2\pi = 6$ GHz and power $P_\mu = 0 \sim 1$ W is launched into the plasma through a circular waveguide at $z = -150$ cm, propagating axially in the region of $\omega/\omega_{ce} < 1$ toward the plasma source, and the ECR takes place around $\omega/\omega_{ce} = 1$ ($\omega_{ce}/2\pi$: electron cyclotron frequency) at $z = 0$ cm.

A typical example of the results is presented for $P_\mu = 0$ W (dotted lines) and 0.5 W (solid lines) in Fig. 1(a). J_{es} is the electron saturation current of a Langmuir probe, which is proportional to the electron density, and ϕ is the plasma potential. The axial J_{es} and ϕ profiles on the axis clearly demonstrate that the plasma flow is almost plugged under the field-aligned potential configuration modified by the ECR, which consists of a potential dip $\Delta\phi_d$ (< 0) formed at $z \simeq 0$ cm and a subsequent potential hump $\Delta\phi_p$ (> 0) along the plasma flow. Figure 1(b) shows spatial profiles of ϕ at $t = 0.6$ ms with P_μ as a parameter. With an increase in P_μ, both $\Delta\phi_p$ and $-\Delta\phi_d$ increase, being gradually saturated for $P_\mu > 0.5$ W. For $P_\mu \simeq 0.8$ W, we have $e\Delta\phi_d \simeq -7T_{e0}$ which is large enough to prevent cold electrons supplied by the plasma source from merging with hot electrons in the ECR region and $e\Delta\phi_p \simeq 12T_{e0}$ which is of the order of the ion flow energy E_{i0} and large enough to plug ions. Thus, $\Delta\phi_d$ and $\Delta\phi_p$ are called "thermal-barrier" and "plug" potentials, respectively.

The mechanism of the potential formation is based on the selective electron trapping in the magnetic well, which is due to perpendicular electron heating provided by the ECR, and electrostatic ion trapping resulted self-consistently to satisfy the charge-neutrality condition. It is not necessary in our potential formation to take account of the conventional scenario for the tandem-mirror devices, which needs two ECR points: the one for barrier formation and the other for plug formation. A single ECR is sufficient to provide the plug/barrier potential structure. This physics of the plug/barrier potential formation might be applied also to such a large tandem-mirror device as the GAMMA 10. In this case, however, the ion flow energy E_{i0} has to be replaced by the ion temperature $T_{i\parallel}$ parallel to the magnetic field in evaluating the height of the plug potential, because the ion temperature in the GAMMA 10 is much larger than the ion flow energy.

In Fig. 2(a), $\Delta\phi_p$ in the $Q_{\rm T}$-Upgrade and GAMMA 10 are compared as a function of P_μ. Here, $\Delta\phi_p$ and P_μ are normalized by the parallel ion energy, i.e., E_{i0} in the $Q_{\rm T}$-Upgrade and $T_{i\parallel}$ in the GAMMA 10, and the number $n_e \cdot S$ of electrons in the ECR region, respectively (S:

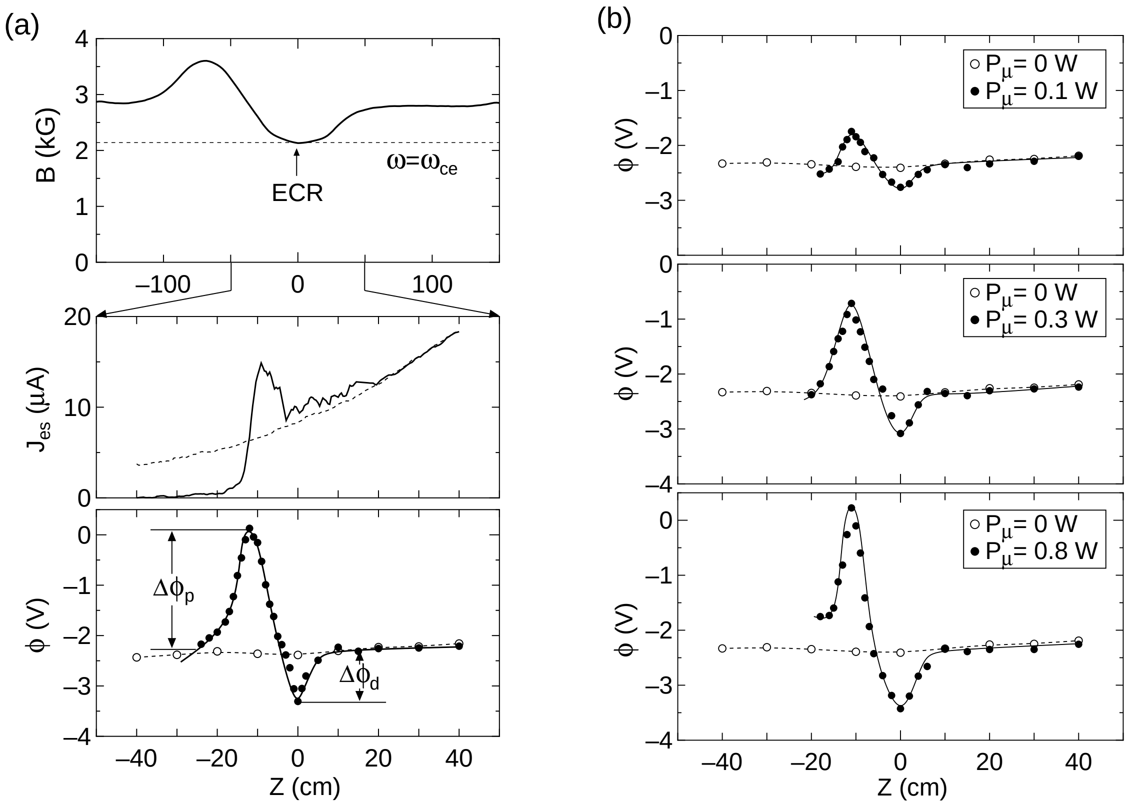

FIG. 1. (a) A typical example of plasma-flow plugging due to the ECR, together with magnetic field configuration. This shows profiles of electron saturation current J_{es} of the probe and plasma potential ϕ at $t = 0.6$ ms in the plasma flow injected at $t = 0$ ms along the magnetic field for $P_\mu = 0$ W (dotted lines) and 0.5 W (solid lines). (b) Spatial profiles of ϕ at $t = 0.6$ ms with P_μ as a parameter.

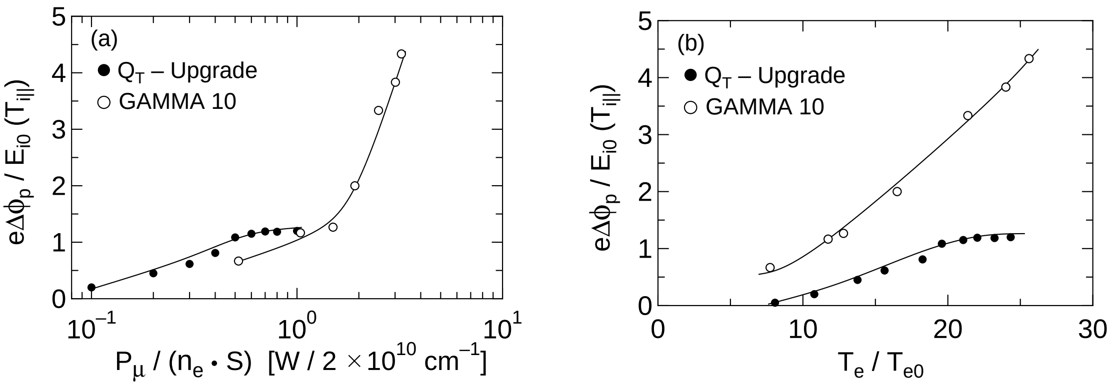

FIG. 2. Comparison of potential humps $\Delta\phi_p$ between the Q_T-Upgrade and GAMMA 10 (a) as a function of microwave power P_μ and (b) as a function of electron temperature T_e in the ECR region. $\Delta\phi_p$, P_μ, and T_e are normalized by the parallel ion energy (temperature) $E_{i0}(T_{i\|})$, the number $n_e{\cdot}S$ of electrons in the ECR region (S: plasma cross section), and the cold electron temperature T_{e0} without the ECR heating, respectively .

plasma cross section). Although the normalized plug potentials increase with an increase in the normalized microwave power in a similar way in both devices, the normalized plug potential in the GAMMA 10 attains to a value about four times as much as that in the Q_{T}-Upgrade. This is due to the difference between the ion velocity distributions. The large $\Delta\phi_p$ is necessary to plug the tail-component ions in the GAMMA 10. On the other hand, the normalized microwave power in the Q_{T}-Upgrade, which is required to make $\Delta\phi_p$ large enough to plug most of the ions, is smaller than that in the GAMMA 10. This is caused by the higher heating efficiency of the ECR in the Q_{T}-Upgrade, where the microwave is not used for additional ionization. T_e/T_{e0} in both devices are almost the same when $\Delta\phi_p$ becomes large enough, as shown in Fig. 2(b) where T_e and T_{e0} are the electron temperature in the ECR region and the cold electron temperature without the ECR heating, respectively. It is to be remarked that $\Delta\phi_p$ in our work plays the same role on plasma confinement as in the GAMMA 10, although $\Delta\phi_p$ and E_{i0} in the Q_{T}-Upgrade are much smaller than $\Delta\phi_p$ and $T_{i\|}$ in such a big fusion-oriented device as the GAMMA 10.

3. CONTROL OF RADIAL POTENTIAL PROFILE AND LOW-FREQUENCY FLUCTUATIONS

Concerning transport phenomena across the magnetic field lines, another experiment of radial potential-profile effects on low-frequency fluctuations is carried out in an ECR-discharge argon plasma of $n_{e0} \simeq 1 \times 10^{10}$ cm^{-3} and $T_{e0} \simeq 7$ eV in a uniform magnetic field ($B \simeq 2.3$ kG). The plasma is produced by a 6 GHz microwave with a power of 200 W in a narrow mirror region at the one end of the machine. The plasma diameter ($D \simeq 9$ cm) is determined by a limiter located between the source and experimental regions. The radial profile of plasma potential is controlled by biasing the segmented endplate located at the other end [5], which consists of five circular concentric electrodes. The potential profile is changed from hill-typed to well-typed and therefore the radial electric field is controlled by varying the bias voltage applied to the center electrode of the segmented endplate (case 1). In addition, the potential profile is changed more precisely by varying the bias voltage applied to the second electrode of the segmented endplate in order to control the electric-field shear strength (case 2).

In both cases 1 and 2, low-frequency fluctuations below a few tens kHz are observed in a radial region where the density gradient is steep. According to measurements of azimuthal mode number and propagating direction of the fluctuations, some of the fluctuations are identified to be a flute-mode instability around the ion diamagnetic drift frequency. Other fluctuations are identified to be a drift-mode instability around the electron diamagnetic drift frequency.

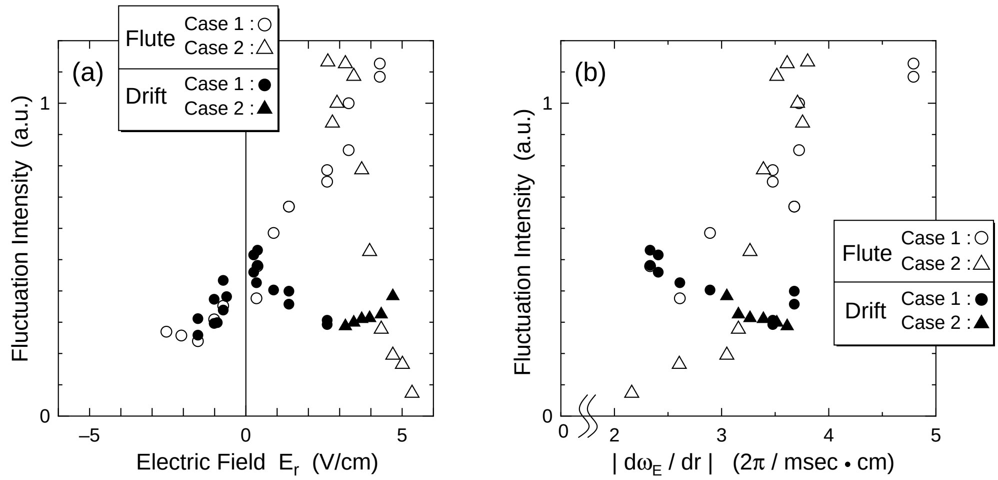

FIG. 3. Dependences of fluctuation intensities on (a) radial overall-electric field and (b) shear of $\boldsymbol{E}\times\boldsymbol{B}$ *drift frequency* ω_E.

In Fig.3(a), the fluctuation intensities are plotted as a function of the radial overall-electric field obtained by fitting a parabolic potential profile to the measured potential profile, which coincides with the rigid plasma rotation frequency observed. When the radial electric field is increased, the flute-mode intensity increases in the case 1 while decreases in the case 2. Here we take account of not only the radial overall-electric field but also fine potential structure, i.e., its shear for understanding the phenomenon. Figure 3(b) shows dependences of the fluctuation intensities on the shear of $\mathbf{E}\times\mathbf{B}$ drift frequency, which is estimated around the radial position of the maximum intensities by the 6th order polynomial fitting to the measured potential profiles. Since the flute mode is definitely enhanced by an increase in the shear of $\mathbf{E}\times\mathbf{B}$ drift frequency in both cases, the mode is considered to be the Kelvin-Helmholtz instability. In the case 1 the drift-mode intensity, on the other hand, is observed to be maximum at a small overall-electric field, decreasing when the radial electric-field strength is increased regardless of its sign [6], as shown by closed circles in Fig.3(a). In both cases 1 and 2, the drift mode is stabilized by the shear of $\mathbf{E}\times\mathbf{B}$ drift frequency, as shown by closed symbols in Fig.3(b).

4. CONCLUSIONS

Our experiment under a simple mirror configuration clearly demonstrates that a single ECR point is sufficient to provide the plug potential with thermal barrier. It is not necessary in our potential formation to take into account the conventional scenario for the tandem mirror devices, which needs two ECR points: the one for barrier formation and the other for plug formation. In the experiment of radial potential-profile control, the drift-mode instability is observed to be stabilized with an increase in the radial electric field regardless of its sign, which is also stabilized by the $\mathbf{E}\times\mathbf{B}$ drift shear.

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