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Accessibility to a Double-Peaked E_r Shear Layer Structure by Double Electrode Biasing in Tokamak Plasmas

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Bifurcation of the radial electric field in the tokamak edge, which is induced by electrode biasing, is studied. A case of multiple electrodes is investigated in order to obtain a structure of multiple peaks in the radial electric field. It is found that a double-peaked structure is accessible with an applied voltage rampup, allowing the possibility of obtaining double transport barriers.

Keywords:

radial electric field, solitary structure, electrode biasing, bifurcation, improved confinement

It is well known that the radial electric field plays a crucial role in the L/H transition [1]. A large gradient of the radial electric field can reduce transport in plasmas [2]. Electrode biasing is one of the methods for controlling the radial electric field externally, and can induce a transition to an improved confinement state in tokamaks [3]. An electrode is inserted into a plasma and a voltage is applied between this electrode and a toroidal limiter (Fig. 1). A peaked structure (solitary structure) in the radial electric field is observed by electrode biasing [4], and was explained by the nonlinearity in the conductivity of the radial current [5]. A multiple-peaked structure, which has multiple shear layers, has been predicted theoretically [6], but accessibility was not demonstrated. In this letter, the double-peaked structure is found to be accessible with an applied voltage rampup. This allows the possibility of obtaining double transport barriers in experiments.

The radial electric field structure is determined by the following equation [6],

$$\frac{\partial}{\partial t} E_r = -\frac{1}{\varepsilon_0 \varepsilon_\perp}(J_r^{\mathrm{NET}} - J_{\mathrm{ext}}),\qquad(1)$$

where J_r^{NET} is the net radial current in the plasma, J_{ext} is the current driven into the electrode by the external
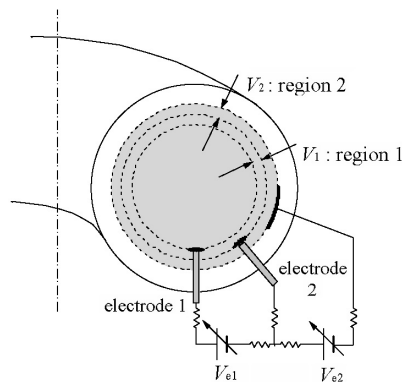

Fig. 1 Setup of a double biasing experiment. Two electrodes are inserted into the plasma. The usual electrode biasing uses only one electrode (without electrode 2).

circuit, ε_0 is the vacuum susceptibility, and $\varepsilon_\perp$ is the dielectric constant of a magnetized plasma. Only the structure in the radial direction is considered here. The neoclassical current J_r and the shear viscosity current J_{visc} (anomalous) are taken into account in J_r^{NET}. The nonlinear E_r dependency of J_r gives a structural bifurcation in E_r [7], and a spatially constant solution (A in Fig. 2) and a solitary solution (B in Fig. 2) are
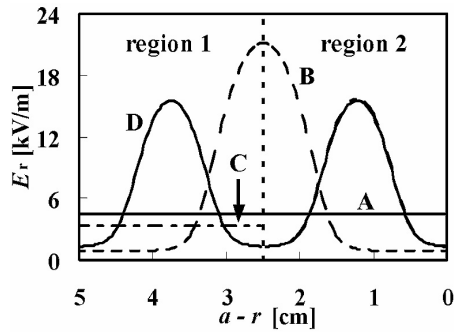
Fig. 2 Spatial profiles of E_r. The electrode and the limiter are located at $a - r = 5$ and 0 cm, respectively. A transition takes place from A to B, C and D with single biasing, double biasing w/o and with an applied voltage rampup, respectively. Structures C and D are almost the same in region 2, but are different in region 1. Structure C is an equilibrium that has a jump at $a - r = 2.5$ cm.
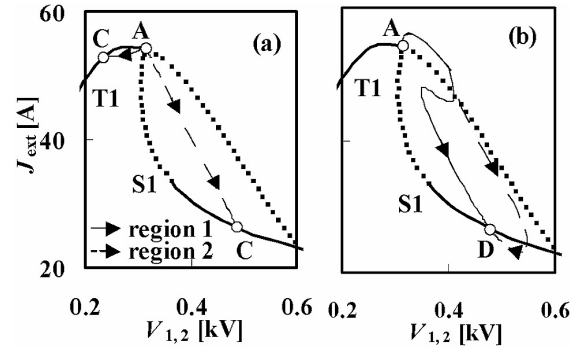

Fig. 3 Time evolution for a transition from a spatially constant solution with double biasing is plotted in the relationship between the voltage and the electrode current. The double-peaked structure is obtained by an applied voltage rampup. The labels A, C, and D correspond to those shown in Fig. 2.

obtained from Eq. (1) under the same condition. Multiple-peaked solutions such as D in Fig. 2 are also possible, but the selection rule given by a mode stability analysis shows that the single-peaked structure, which is observed experimentally, is realized after the transition [8]. Multiple-peaked structures are not accessible in the usual way with a single electrode.

To obtain a double-peaked structure, inserting another electrode at the middle point of the biasing region is effective (Fig. 1). The biased region is divided by the additional electrode into two regions: regions 1 and 2 where the potential differences are denoted by V_1 and V_2 in Fig. 1, respectively. A simple example in which regions 1 and 2 are equivalent to each other can be considered by setting $V_{e1} = V_{e2} = V_{ext}$ and the position of electrode 2 at $a - r = 2.5$ cm, indicated by the vertical dashed line in Fig. 2. In fact, inserting another electrode is not sufficient to obtain a double-peaked structure. A voltage rampup at the transition point is needed. The dynamics of the E_r structure are discussed next.

In order to obtain the transition rule, time evolutions of the E_r structure are calculated by solving Eq. (1). A spatially constant E_r structure is realized below a critical voltage as is shown by the solid line T1 in Fig. 3. As in the case of single electrode biasing [8], this structure becomes unstable beyond point A. With a fixed applied voltage, the E_r structure makes a transition to an asymmetric structure C in Fig. 2 [Fig. 3 (a)], i.e., solitary in one region and spatially constant in another (an additional electrode can make the radial current discontinuous between regions 1 and 2). We find that

ramping the applied voltage makes a transition to the double-peaked structure D possible [Fig. 3 (b)]. The external control is chosen as follows: V_{ext} is increased from 490 V (point A) linearly by the amount ΔV during the time $\Delta \tau$ and then V_{ext} is kept constant. The case of $\Delta V = 76$ V and $\Delta \tau = 1$ ms is shown in Fig. 3 (b), demonstrating that the double-peaked structure is accessible. It is found that ΔV must be larger than the critical value ΔV_c in order to realize the double-peaked structure ($\Delta V_c = 65$ V for $\Delta \tau = 1$ ms). If $\Delta V < \Delta V_c$, the solution in one region crosses the S1 branch (to the left in Fig. 3), and it evolves into the spatially constant solution branch T1; however, if $\Delta V > \Delta V_c$, it evolves into the stable region of the S1 branch. The solitary solution branch S1 in Fig. 3 acts as a separatrix for the settled state after the transition. ΔV_c is a weakly increasing function of $\Delta \tau$. The rampup must be sufficiently fast compared to the time scale of E_r variation by spontaneous instability. The transition from A to C under a fixed value of V_{ext} takes about 10 ms, giving a typical time scale of E_r variation by instability.

In summary, the double-peaked structure becomes accessible by the electrode at the middle point with the aid of the applied voltage rampup. Such structures can give double $E \times B$ flow shear layers. Therefore, electrode biasing can be used to make wider transport barriers. This analysis provides a new experimental test to provide new freedom in realizing further improvement of confinement.

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