J. Plasma Fusion Res. SERIES, Vol.1 (1998) 84–87

Electric Field Bifurcation and Transition in CHS Heliotron/Torsatron

FUJISAWA Akihide*, IGUCHI Harukazu, IDEI Hiroshi, KUBO Shin, LEE Seishu, MATSUOKA Keisuke, OKAMURA Shoichi, TANAKA Kenji, MINAMI Takashi, MORITA Shigeru, OHDACHI Satoshi, OSAKABE Masaki, AKIYAMA Ryuichi, YOSHIMURA Yasuo, TOI Kazuo, SANUKI Heiji, ITOH Kimitaka, TAKAHASHI Chihiro, KOJIMA Mamoru, HIDEKUMA Shigeru, IDA Katsumi, NISHIMURA Shin, EJIRI Akira, HAMADA Yasushi, ITOH Sanae-I.[1], INOUE Noriyuki, SAKAMOTO Ryuichi and FUJIWARA Masami

National Institute for Fusion Science, Toki 509-5292, Japan

[1]RIAM, Kyushu University, Kasuga 816-8580, Japan

(Received: 30 September 1997/Accepted: 20 January 1998)

Abstract

Transition in radial electric field has been observed in CHS plasmas during a combined heating phase of ECH+NBI, using a heavy ion beam probe. The transition occurs in a timescale of a few dozen or a hundred microseconds. Radial current to induce the transition is evaluated by high temporal resolution of the heavy ion beam probe. Neoclassical dependence of radial electric field on a plasma parameter will be discussed to clarify the nonlinearity to allow the transition.

Keywords:

transition, bifurcation, radial electric field, potential, nonlinear relation, multiple steady state, heavy ion beam probe, toroidal helical plasma

1. Introduction

In toroidal helical plasmas, the helical ripple transport is strongly dependent on the radial electric field, particularly in collisionless regime[1-3]. The neoclassical theory predicts that the toroidal helical plasmas can take multiple steady states in the radial electric field when a certain condition for plasma parameter is satisfied. In the neoclassical framework, the plasma with the positive electric field should have better confinement property than that with the negative one. This nonlinear dependence of the property in toroidal helical plasmas on radial electric field can give birth to dynamic structural reformation between these steady states.

In fact, a transition in the radial electric field has been observed in the CHS plasma, using a heavy ion beam probe. The nonlinear relationship between radial electric field and radial current has been already experimentally confirmed and reported[4]. In this paper, we will present two examples of the transition phenomena. Neoclassical dependence of radial electric field on electron temperature will be presented to discuss the nonlinearity to allow the transitions.

2. Experimental Setup and Background

The CHS is a medium size heliotron/torsatron device; the major and minor radii are 1.0 m and 0.2 m, respectively[5]. In order to measure the potential profiles, the CHS has an HIBP which adopts a unique method to control the beam trajectory. In this method, which is denoted as 'active trajectory control'[6,7], the observation location can be changed by sweeping both primary and secondary beams. The advantages of this method are (1) the accessible region of plasmas is

*Corresponding author's e-mail:fujisawa@nifs.ac.jp

extended widely for several different configurations, (2) potential measurement errors can be reduced by keeping the beam injection angle into the energy analyzer constant. High temporal and spatial resolution of the HIBP allows us to investigate the transition nature of the electric field.

The experiments we will present here were performed on the magnetic field configuration whose axis is located on $R_{ax}=0.921$ m with field strength of 0.88 T. In this configuration, the necessary beam energy is 72 keV when cesium is used. Initial results of potential profile measurements have been already reported for this configuration[8]. The plasma with ECH heating feature shows a positive electric field (electron root), while the plasma of NBI feature does a negative electric field (ion root). The plasma is found to show various characteristics in potential according to different heating scheme, or different plasma parameter regimes.

In low density plasma $n_e=3\sim5\times10^{18}$ m^{-3}, where higher ECH heating (200 ~ 300 kW) is applied with the resonance on the magnetic axis, the potential profile has exhibited a remarkable feature. The potential profile has a sharp peak around the core, and the steep change in radial electric field exists at $\rho=0.3\sim0.4$. Figure 1 shows a potential profile of an ECH heated plasma with 300 kW input power, together with a potential profile of 100 kW case. These profiles show clear difference around the core region of $\rho<0.3$.

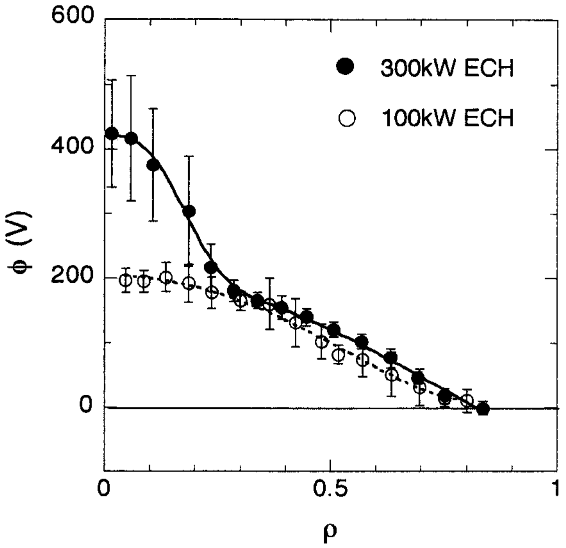

Fig. 1 Potential profiles of ECH plasmas. The open and close circles show the plasmas with ECH input powers of 100 kW and 300 kW, respectively.

In a combined ECH+NBI heated plasmas, the transition has been observed to occur around the core when the potential profile has such a prominent peak. The plasma parameters are as follows. The central electron temperature is approximately 1 keV from a Thomson scattering system. The ion temperature is expected to be 300 eV. The electron density has a flatter profile, and the line averaged electron density ranges from $n_e=3\sim5\times10^{18}$ m^{-3}. The heating powers of ECH and NBI are usually 300 kW and 800 kW, respectively.

3. Observation of Bifurcation Phenomenon

Here we will present two examples of transition phenomenon. The first one is shown in Fig. 2(a). In this case, the electron density is $n_e\simeq5\times10^{18}$ m^{-3}. A pair of transitions occurs around $t=88$ ms. The potential at the plasma center exhibits abrupt drop by ~ 400 V, being followed by the second transition to the initial state in a few microseconds. The detail of this change can be also analytically obtained by fitting a function of tanh $((t-t_0)/\tau)$ to the slopes. The analysis shows that the timescale parameters are $\tau=16$ μs and $\tau=59$ μs for the drop and rise, respectively.

The second one is shown in Fig. 2(b). The electron density of this case is $n_e\simeq3\sim4\times10^{18}$ m^{-3} A pair of transitions is also observed around $t=55$ ms. In this case, the plasma stays shortly in a steady state for ~ 1 ms after the first transition. The central potential changes by ~ 200 V and by ~ 400 V in the first and second transition, respectively. The fitting procedure of tanh $((t-t_0)/\tau)$ gives the timescale parameters of $\tau=60$ μs and $\tau=220$ μs to the first and second transition, respectively. Note that the scales of the horizontal axes in Figs. 2(a) and 2(b) are different. For both cases, no significant change can be seen outside of the radius of $\rho>0.4$.

Figure 2(c) shows the radial electric field and radial current to induce the transition for the case of Fig. 2(b). Here, the measured potential is transformed into the average radial electric field, which is defined as $\bar{E}_r=-(\phi(0.3a)-\phi(0))/0.3a$. The thin line indicates the time averaged electric field using a wavelet analysis with an assumption of $\phi(0.3a)=$const. The bold line represents radial current deduced by use of the following formula, $\epsilon_\perp\epsilon_0\,\partial E_r/\partial t=-j_r$, where ϵ_0 represents the vacuum dielectric constant. The perpendicular dielectric constant $\epsilon_\perp$ is given by $\epsilon_\perp=M_{tor}(1+c^2/v_A^2)$ with the toroidal enhancement factor being $M_{tor}\simeq1+2q^2$, where q is the safety factor, and c and v_A the light and Alfvén velocities, respectively. Here, $\epsilon_\perp\simeq2.7\times10^4$ with $q=3$ and $v_A=8\times10^6$ m/s, which corresponds to $n_e = 3\times10^{18}$ m^{-3}.

4. Nonlinear Dependence of Radial Electric Field on Plasma Parameter in Neoclassical Theory

Transition phenomenon is generally caused by nonlinearity of the system. For our case of the CHS plasmas, nonlinear dependence of radial electric field on a parameter or parameters (*e.g.*, control parameter), should be responsible for the observed transitions. In neoclassical theory, the radial electric field is determined by equating nonambipolar fluxes of ions and electrons as $\Gamma_i(E_r) = \Gamma_e(E_r)$. This equation can yield multiple roots to the radial electric field when plasma satisfies a certain condition.

Figure 3(a) shows a neoclassical nonlinear dependence of radial electric field on a control parameter, which is chosen to be the electron temperature. The dependence is obtained using a formula derived by Hastings[2]. The calculation is performed with plausible plasma parameters for the present experiments; $T_i = 350$ eV, $n_e = 5\times10^{18}$ m^{-3}, and $dn_e/d\rho = 0$. The helical ripple and toroidal coefficients are $\varepsilon_h = 0.023$ and $\varepsilon_t = 0.16$, respectively. This corresponds to the radial position of $\rho = 0.3$. If another plasma parameter, such as density, ion temperature, *etc.*, is chosen as the control parameter, a similar diagram can be obtained.

The state represented by the point A (or C) is unstable, therefore, the transition should occur from A to B (or C to D). The transition from A to B (C to D) in Figs. 3 corresponds to the observed first and second transitions in Figs. 2(a) and 2(b). The electric field can take multiple steady states when the electron temperature ranges from 650 eV to 690 eV. The temperature range to allow the multiple roots tends to become larger as the density gradient becomes larger in the calculation. The calculation also shows the neoclassical radial current to induce the transition is a few A/m^2. The order of neoclassical current is within the experimental value. This fact suggests that nonambipolar parts of anomalous fluxes may be less dominant than those of neoclassical fluxes. For the precise comparison between experiments and theories, more accurate measurements of plasma parameters are essential.

5. Summary

We have presented two examples of transition phenomena which were observed in the CHS heliotron/torsatron plasmas. The transition occurs in a few dozen microseconds order. According to a neoclassical calculation, the radial electric field can have multiple steady

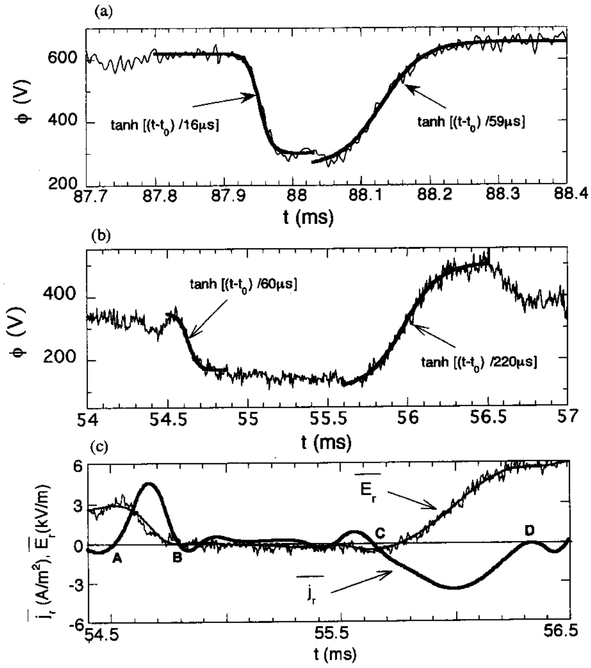

Fig. 2 Examples of transition phenomenon observed in a combined heating phase of ECH+NBI in CHS heliotron/torsatron. (a) An example of transitions in a plasma with its electron density of 5×10^{18} m^{-3}. (b) The other example of transition in a plasma with its density of $3\sim4\times10^{18}$ m^{-3}. (c) Time evolution of radial current and electric field during the transition for the case of (b).

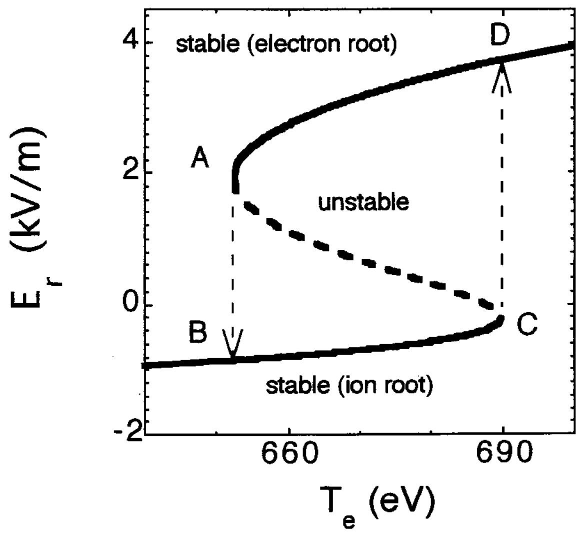

Fig. 3 A neoclassical calculation. Dependence of radial electric field on a control parameter. Here, the control parameter is chosen to be the electron temperature.

states and satisfy bifurcation conditions for the plasmas where we have observed transition phenomena.

References

[1] K. Itoh and S.-I. Itoh, Phys. Control. Fusion **38**, 1 (1996).

[2] D.E. Hastings, W.A. Houlberg and K.C. Shaing, Nucl. Fusion **25**, 445 (1985).

[3] L.M. Kovrizhnykh, Nucl. Fusion **24**, 435 (1984).

[4] A. Fujisawa, H. Iguchi *et al.*, Phys. Rev. Lett. **79**, 1054 (1997).

[5] K. Matsuoka, S. Kubo, M. Hosokawa *et al.*, *Plasma Physics and Controlled Nuclear Fusion Research, 1988* (*Proc. 12th Int. Conf.*, Nice, 1988), International Atomic Energy Agency, Vienna, 1989, Vol. 2, p.411.

[6] A. Fujisawa, H. Iguchi *et al.*, Rev. Sci. Instrum. **67**, 3099 (1996).

[7] A. Fujisawa, H. Iguchi *et al.*, Rev. Sci. Instrum. **63**, 3694 (1992).

[8] A. Fujisawa, H. Iguchi, S. Lee, T. P. Crowley, Y. Hamada *et al.*, Phys. Plasmas **4**, 1357 (1997).