Dynamic Behavior Associated with Electric Field Transitions in CHS Heliotron/Torsatron

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Abstract

A new kind of oscillatory steady state is discovered in observation of potential with a heavy ion beam probe in Compact Helical System Heliotron/Torsatron. Bulk plasma parameters, such as electron temperature and density profile, change being synchronized with the pulsation of potential. The phenomenon can be regarded as successive transitions between two bifurcative states of the plasma. The pulsation can be self-sustained and create a dynamic steady state in low density plasma with electron cyclotron heating. The cause of phenomenon is associated with the bifurcation nature of radial electric field, that is inherent with toroidal helical plasmas. This paper presents two examples of the phenomenon in different density regimes. Dependence of pulsation characteristics on several parameters is described. The bifurcation property predicted by a neoclassical theory is presented for comparison with the experimental observations.

1. Introduction

Bifurcation-related phenomenon has been reported widely in many toroidal plasmas since the H-mode in ASDEX tokamak was discovered[1]. Many theories and experiments have been devoted to investigating roles of the radial electric field on confinement improvement[2], such as in H-modes[1,3-9] and reversed magnetic shear related modes[10-12]. Commonly for all toroidal plasmas, dynamics of the radial electric field has been an important issue associated with the formation of these improved confinement modes.

In toroidal helical plasmas, non-ambipolar fluxes induced by helical ripple diffusion play an important role on formation of the radial electric field. The neoclassical theory has predicted that toroidal helical plasmas can show bifurcation nature in the radial electric field[13,14]. And there transitions, accompanied by a change in the transport property, can occur between the multiple steady states under a certain condition for bulk plasma parameters.

This nature can give birth to dynamic behavior in toroidal helical plasmas that have been supposed to be static in a sufficiently low beta regime since the plasma is nearly free of current driven instabilities. Actually in the Compact Helical System (CHS) Heliotron/Torsatron[15], a self-sustained pulsation has been discovered in electrostatic potential observed with a heavy ion beam probe (HIBP). This oscillatory steady state consists of repetitive transitions between the bifurcative states.

In this paper we introduce the dynamic steady state, that is named *electric pulsation*, by presenting two patterns of pulsation in different density regimes. Several findings of pulsation characteristics are described, together with a phase diagram of radial electric field on a density-temperature plane to show the bifurcation characteristics predicted by a neoclassical theory.

2. Experimental Set-up

The CHS is a medium size Heliotron/Torsatron device; the major and minor radii are 1.0m and 0.2m, respectively[15]. The device has a pair of helical winding coils and four pairs of poloidal coils to control the position and shape of plasma. The magnetic field configuration has a periodicity of l=2 and m=8 in poloidal and toroidal directions, respectively. The CHS has co-and ctr-injection lines of neutral beam, and three gyrotrons; two of 53.2GHz and one of 106GHz.

The CHS has an HIBP[16,17] in order to measure structure of potential and its temporal behavior. The HIBP has a unique feature that the beam sweep system is installed on analyzer side as well as on injection side. Using this method, *active trajectory control* [18-20], the accessible region of plasma is extended widely for several different configurations. Generally, HIBP has excellent temporal and spatial resolutions that are powerful to investigate fine structure of potential profiles and fast time scale phenomena. The experiments we will present here are performed on the magnetic field configuration whose axis is located on R_{ax}=92.1cm and strength at the center is 0.88T. In this configuration, the necessary beam energy is 72keV when cesium is used. And almost full radial scan is possible. The temporal resolution is up to 450kHz.

3. Experimental Observations

3-1. Electric Pulsation in Lower Density Regime

The electric pulsation is observed in plasmas with rather low density $n_e=3\text{-}7\times10^{12}cm^{-3}$ for 0.88T operation. Here, we present an example of the electric pulsation in a low density of $n_e\sim4\times10^{12}cm^{-3}$[20]. Figure 1 shows the electric pulsation observed in the potential at the plasma center. Time evolution of line-averaged electron density is also shown by the dashed line. The plasma is initially sustained with neutral beam injection(NBI). Combined ECH+NBI heating continues from t=44ms to t=96ms in this case. After ECH is on, the electron density decreases and relaxes to a steady state of $n_e\sim4\times10^{12}cm^{-3}$ approximately in 5ms. In the steady state(55 <t < 95ms), the internal plasma energy measured by a diamagnetic loop is about 400J and the average β is about 0.2%. There, negative pulses of potential by –0.6kV occur quasi-periodically in every

2ms.

We interpret this pulsating behavior as that the plasma swings repeatedly between two quasi-steady states with higher and lower central potential of $\varphi(0)$=0.8kV and 0.2kV, respectively. Figure 2 shows two quasi-steady states of potential during this electric pulsation. The plasma stays longer in the higher potential state. The change of potential outside the *pivot* point (see Fig. 2) at ρ~0.53 is positive when the plasma goes from the higher to the lower state. The potential at these points shows quasi-periodic positive pulses whose intervals remain the same, contrarily to the waveform near the plasma center. It has been also reported about this case that profiles of electron temperature and density change are correlated with potential pulsation[21].

3-2. Electric Pulsation in Higher Density Regime

Another example of long-term pulsation in higher electron density of $n_e \sim 7\times10^{12}\,cm^{-3}$ is shown in Fig. 3a. Time evolution of central potential and line-averaged electron density is demonstrated. After ECH on, the electron density decreases and relaxes to an oscillatory steady state with $n_e \sim 7\times10^{12}\,cm^{-3}$. Simultaneously, the central potential increases up to its maximum of 0.3~0.4keV.

The line-averaged density slightly increases with a decrease in potential toward the end of the combined heating phase of ECH+NBI. The central potential at the higher state of the period from t=80ms to t=90ms is lower than that from t=50ms to t=60ms. In these two periods, the frequency of the later phase(~1.5kHz) is higher than that of the earlier phase(~1.0kHz). These changes are ascribed to a gradual change of bulk plasma parameters, which are represented simply by the electron density. The slight increase in density causes that the amplitude of pulsation becomes smaller and the frequency becomes higher.

Figure 3b shows another time evolution of potential. Being different from the example of Fig. 3a, the observation point of HIBP is altered step by step in every 10ms; ρ=0.21(50-60ms), ρ=0.37(60-70ms), ρ=0.53(70-80ms) and ρ=0.05(80-90ms). No pulsation can be seen in the period of ρ=0.53, while the pulsation is still observed in the following period of ρ=0.05. This fact clearly shows that the pulsation regime is confined within ρ~0.53.

Figure 4a shows the change of potential profiles before and after crashes for this case of electric pulsation. Each point data is taken in the period from t=50ms to t=70ms for avoiding the characteristic change due to the bulk parameter development. The plot also demonstrates that the pulsation occurs inside of ρ~0.53, and the change of central potential is about 0.3kV. The potential outside of ρ~0.53 (×-marks) shows no change during the pulsation. The potential profiles swing repeatedly between two `Mexican hat profiles' with higher and lower domes during the pulsation.

3.3. Comparison of Electric Pulsation in Different Density Regimes

In both examples, the typical time scales of transitions from high to low potential states, or lower to higher states, are of a few dozen or a hundred microseconds. These time scales are much faster than the diffusive one (~milliseconds). This fast time scale manifests the transitory nature of the phenomenon. Therefore, it is reasonable to consider that the plasma repeats transitions between two quasi-steady states that can be realized for a set of bulk plasma parameters; temperature, density and so on.

In these examples of different density regimes, a clear difference can be seen in the bifurcative potential profiles between that the plasma repeats transitions. As density decreases, the pulsation regime becomes wider, and is extended to the plasma periphery. In case of the pulsation with lower density, its effect reaches plasma periphery. This is because that H_α signal is well correlated with pulsating potential. In the higher density case, the effect is limited within narrower region around the plasma core. The correlation with H_α signal is ambiguous.

It has been known that features of the electric pulsation alter with respect to the electron density. The followings are the preliminary findings. (1) As the electron density increases under a constant power input of ECH(+NBI), the radial extent of electric pulsation becomes narrower and to be limited around the plasma core. (2) Density dependence of amplitude and frequency of pulsation has been examined. As the density increases, frequency increases with a decrease in pulse amplitude. (3) Threshold power of ECH to induce the electric pulsation appears to become higher as the density increases; at the ECH input power of 200kW, the electric pulsation cannot be seen when the density is above $5\times10^{12}cm^{-3}$. In case of the ECH input power of 300kW, the corresponding density is $5\times10^{12}cm^{-3}$.

4. Discussion

4-1. Multiple Steady States in Neoclassical Theory

The phenomenon of electric pulsation should be associated with the bifurcative nature of the radial electric field on plasma parameters. Here, bifurcation property in a neoclassical theory[13] is presented for a set of plasma parameters in a probable range of the CHS. The assumptions are as follows; B=0.9T, $T_i(r)$=350eV, Z_{eff}=2, dln[n_e(r)/dr]= –0.5 and dln[T_e(r)/dr]=dln [T_i(r)/dr]= –0.6. The ion species is assumed to be hydrogen. We choose ε_h=0.023 and ε_t=0.16, which correspond to ρ~0.3 of the CHS plasma.

Under these assumptions, the balance of non-ambipolar neoclassical fluxes yields the electric field as a function of plasma parameters. Figure 5a shows a calculation result in an n_e-T_e plane, and the painted crescent region indicates an area where multiple steady states exist. The contour of E_r=0 is indicated by the bold dashed line, while other contours of constant electric field are also shown by the thin dashed lines.

Radial electric field on a line crossing the crescent region shows bifurcation characteristics. The upper and lower boundaries correspond to bifurcation points from an unstable root to the other stable root. Inside of these boundaries, two stable and an unstable roots are found. The examples of curves exhibiting bifurcation characteristics are shown in Figs.5b and 5c, where the electric field is shown as a function of electron density and temperature, respectively.

4-2. Electric Pulsation as a Limit Cycle Oscillation

Here, we present qualitative expectation obtained from the neoclassical calculation in Fig. 5. The electric pulsation could be regarded as a limit cycle in a phase space of plasma parameters. In case of Fig 5b(or 5c), the control parameter is chosen to be density (or temperature). If the plasma stays in the points A(or B), the transition spontaneously occurs from the state A to A'(B to B') in a faster time scale than confinement time scale. Then the transport alters, and the plasma parameter should change gradually toward the next bifurcation points in a confinement time scale. During the pulsation, the plasma is recognized as going around the circuit surrounded by the points A-A'-B-B' in Fig. 5b(or 5c).

In this scenario, a period of pulsation consists of two phases, slow phases of A'-B or B'-A, and fast phases of A-A' or B-B'. The slow phase determines pulsation frequency. The time scale of the fast phase, A-A' and B-B' is expected by a neoclassical theory. In the previous works[22], the time scale of the transition is compared, and the transition time scale could be consistent with the neoclassical theory. However, the change in density profile accompanied with potential profiles is much faster than the expectation of the neoclassical theory. Therefore, the change of density profile during pulsation should contain more than the neoclassical theory.

4-3.Several Aspects in Neoclassical Phase Diagram

It is worth while discussing several aspects expected from Fig. 5. First, there is a critical density where the electric field has a unique solution. The electric field is uniquely defined above

n_e~1.3×10^{13}cm^{-3}. The existence of multiple steady states is essential to allow transitions in fast time scale. No pulsation is, therefore, expected above the critical density. In fact, it is confirmed experimentally that the pulsation disappears above a critical density.

Second, higher temperature is necessary in higher density range that the multiple steady states should exist. If the density increases with a fixed heating power, the condition should be satisfied at a smaller radius where the electron temperature is higher. This could be associated with the change in the pattern of potential profile for higher and lower density. As was already shown in the previous section, the radial extent of pulsation becomes narrower in higher density case.

Finally, in a higher density (or a higher temperature) of the crescent regime, the temperature (or density) range for multiple steady states (corresponding to length A-B' or A'-B in Fig. 5) becomes narrower. The width of the limit cycle loop is expected to be smaller. Therefore, it takes a shorter time that the plasma reaches the next bifurcation point. This feature could be connected with the experimental fact that the repetition frequency becomes higher as the density increases.

The following point should be mentioned. The neoclassical calculation is performed for a spatial point, while the actual pulsation occurs in the scale of the whole plasma volume. Accordingly, the comparison presented here is very rough. In the actual plasma, the number of parameters to indicate the plasma state is so large. There are many other parameters or their combinations that are possible to draw similar bifurcation curves; for example, electron density, ion and electron temperatures, their gradients and so on. It is a future work to extract a control parameter to define the electric pulsation among many elemental parameters.

4-4. Comparison with Other Oscillatory Steady States

The phenomenon, electric pulsation, shows unique features from other oscillatory states, such as sawtooth oscillations and ELMs (e.g.,type I, type III and dithering)[23]. The sawtooth oscillation is associated with current driven instabilities, while type I and type III ELMs are related with ballooning and resistive MHD instabilities, respectively. In electric pulsation, however, no special link with a magnetohydro dynamics(MHD) activity has not been detected so far.

The other oscillatory states can be related with a special plasma radius. The ELMs are linked with edge transport barrier whose location is fixed, independently of plasma parameters. The sawtooth oscillation is associated with q=1 surface.The radial extent of our pulsation, however, varies according to the plasma density. Consequently, the potential structural change is not related with special points like the sawtooth and the ELMs. If the dithering ELM can be also successive transitions between L- and H-modes[24], the dithering ELMs has some analogy to the presented phenomenon. The presented electric pulsation is, however, a new kind of oscillatory state that can occur in toroidal helical plasmas.

5. Summary

In summary, we have introduced a dynamic steady state that was discovered in the CHS Heliotron/Torsatron plasma; so-called *electric pulsation*. The pulsation characteristics alter according to plasma density. In this paper, we presented two different patterns of electric pulsation for different density regimes. The cause of the dynamic steady states can be ascribed to bifurcation property of radial electric field. Transition time scale between the states could be explained within neoclassical frame works, although change in transport, or effects on bulk parameter profiles cannot be described by the neoclassical theory. The clarification of the electric pulsation will contribute to understanding other bifurcation phenomena in toroidal plasmas.

REFERENCES

[1] WAGNER, F. et al., Phys. Rev. Lett. **49**, 1408(1982).
[2] ITOH, K., ITOH,S.-I., Phys, Contr. Fusion **38**, 1(1996).
[3] TOI, K. et al., 1993. *in Plasma Physics and Controlled Nuclear Fusion Research 1992* (IAEA, Vienna) **2**, p461.
[4] ERCKMANN, V. et al., Phys. Rev. Lett. **70** 2086(1993).
[5] BURREL, K.H., Phys. Plasma **4**, 1499(1997).
[6] ITOH, S. -I., and ITOH, K., Phys. Rev. Lett. **60**, 2276(1988).
[7] SHAING, K. C., CRUME,E. Jr., Phys. Rev. Lett. **63** 2369(1989).
[8] GROEBNER,J. K., BURREL, H. and SERAYDARIAN, R. P., Phys. Rev. Lett. **64** 3015(1990).
[9] IDA, K., HIDEKUMA, S., MIURA, Y., et al., Phys. Rev. Lett. **65** 1364(1990).
[10] LEVINTON,F. M., et al., Phys. Rev. Lett. **75** 4417(1995).
[11] STRAIT, E. J. et al., Phys. Rev. Lett. **75** 4421(1995).
[12] STABLER, G.M. et al., Phys. Plasmas **1** 909(1994).
[13] HASTINGS, D. E., HOULBERG,W. A., SHAING, K. C., Nucl. Fusion **25**, 445(1985).
[14] KOVRIZHNYKH, L.M., Nucl. Fusion **24,** 435(1984).
[15] MATSUOKA, K., KUBO, S., HOSOKAWA, M. et al., *in Plasma Physics and Controlled Nuclear Fusion Research 1988* (Proc. 12th Int. Conf. Nice, 1988), International Atomic Energy Agency, Vienna, 1989, Vol. 2, 411.
[16] JOBES, F. C., HICKOK, R. L., Nucl. Fusion **10** 195(1970).
[17] HALLOCK, G. A., MATHEW, J. W., JENNINGS, C.*et al.*, Phys. Rev. Lett. **56** 1248(1986).
[18] FUJISAWA, A.,IGUCHI H., LEE,S. et al., Phys. Plasmas **4** 1357(1997).
[19] FUJISAWA, A.,IGUCHI H. et al., Rev. Sci. Instrum. **67**, 3099(1996).
[20] FUJISAWA, A.,IGUCHI H. et al., Rev. Sci. Instrum. **63**, 3694(1992).
[21] FUJISAWA, A.,IGUCHI, H. et al., Phys. Rev. Lett. **81** 2256(1998).
[22] FUJISAWA, A., IGUCHI, H. et al., Phys. Rev. Lett. **79** 1054(1997).
[23] ZOHM,H., WAGNER, F. et al., Nucl. Fusion **32** 489(1992).
[24] ITOH, S.-I., ITOH, K., FUKUYAMA, A. et al. Phys. Rev. Lett. **28**, 2485(1991).

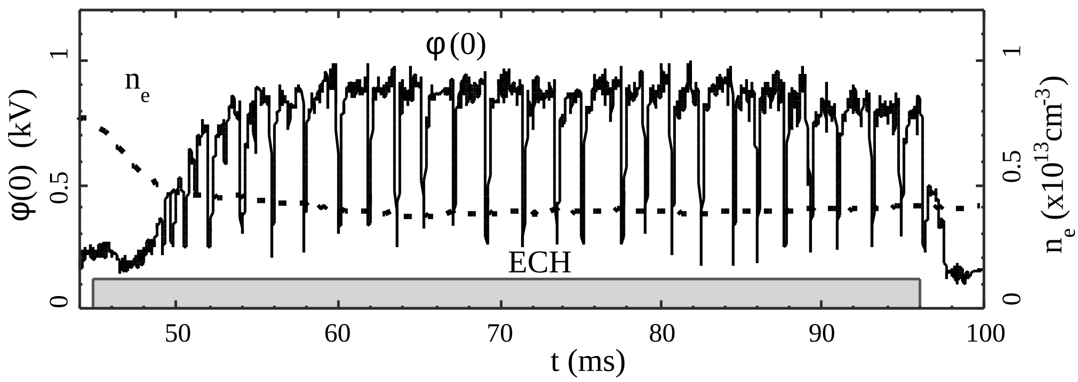

FIGURE 1: Pulsating behavior of the central potential of CHS plasmas(solid line). This phenomenon, being referred to as electric pulsation, is observed in a combined ECH+NBI heating phase. The dashed line represents the line averaged electron density measured with an HCN interferometer.

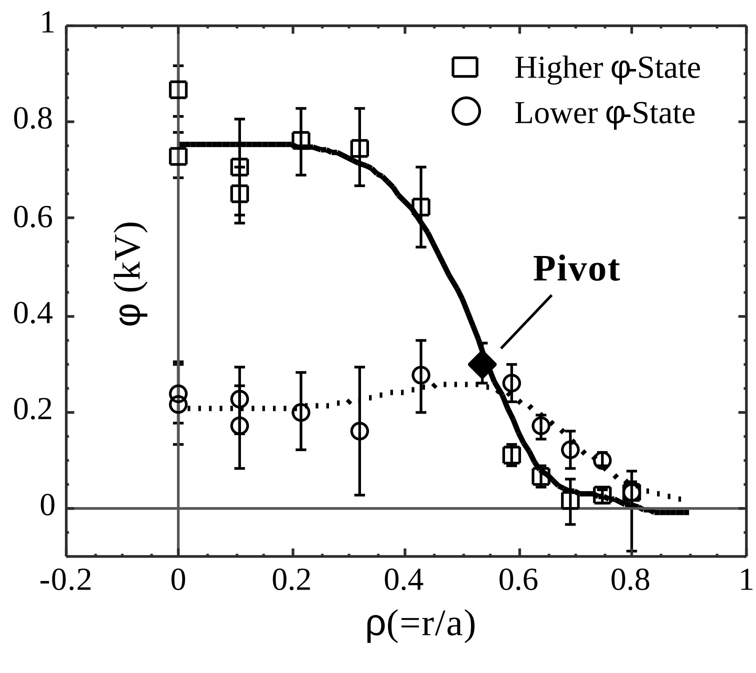

FIGURE 2: Potential profiles of higher and lower states. Here ρ is the normalized minor radius.The change of potential profile is seen even in the periphery.

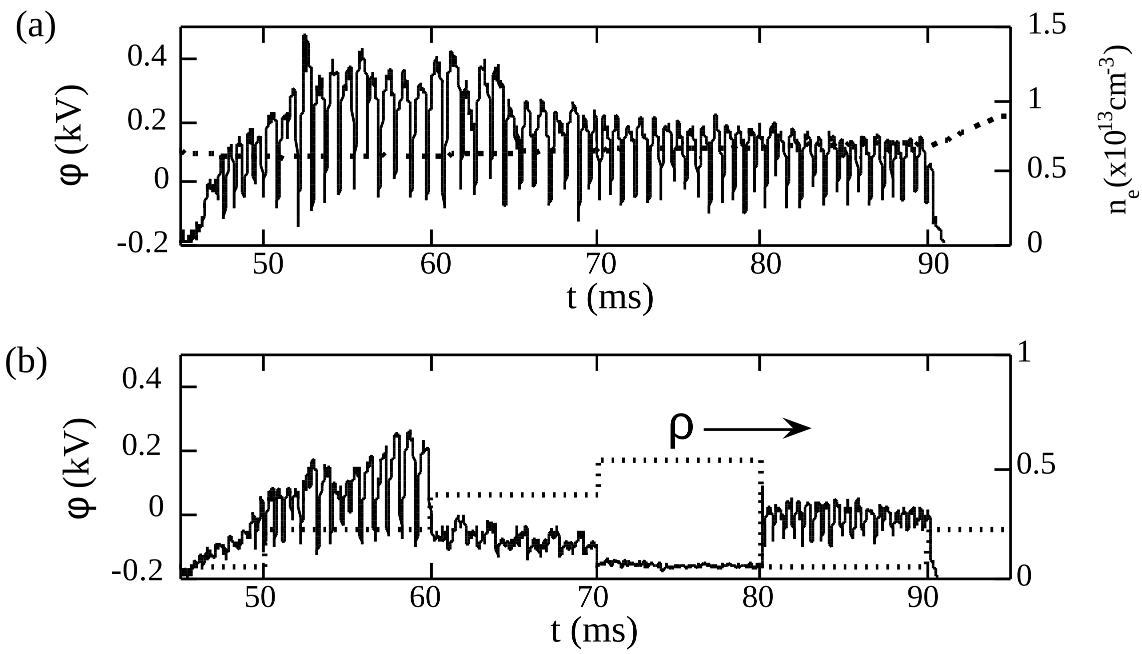

FIGURE 3: An example of long-term electric pulsation. In this case, the electron density is rather higher about n_e~7x10^{12}cm^{-3}, and the pulsation regime is confined to inside of ρ=0.5.(a) Time evolution of potential near the center and line averaged electron density. (b) Time evolution of potential. The observation point of potential alters in 10ms step; ρ=0.21(50-60ms), ρ=0.37(60-70ms), ρ=0.53(70-80ms) and ρ=0.05(80-90ms).

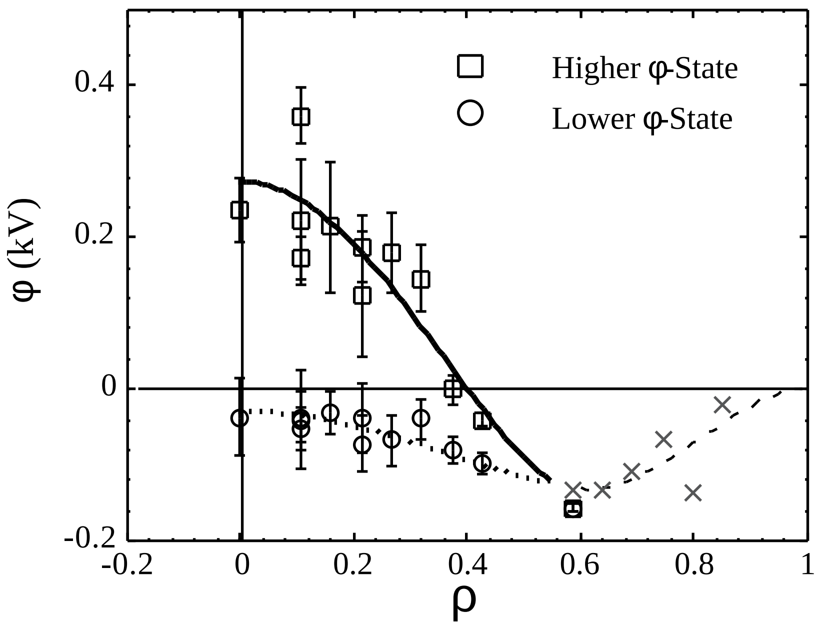

FIGURE 4: Potential profiles of higher and lower potential states are shown in case of electric pulsation with lower density. Outside of ρ=0.53, no change is seen during the pulsation. The data represented by the ×-marks is taken in radial scans.

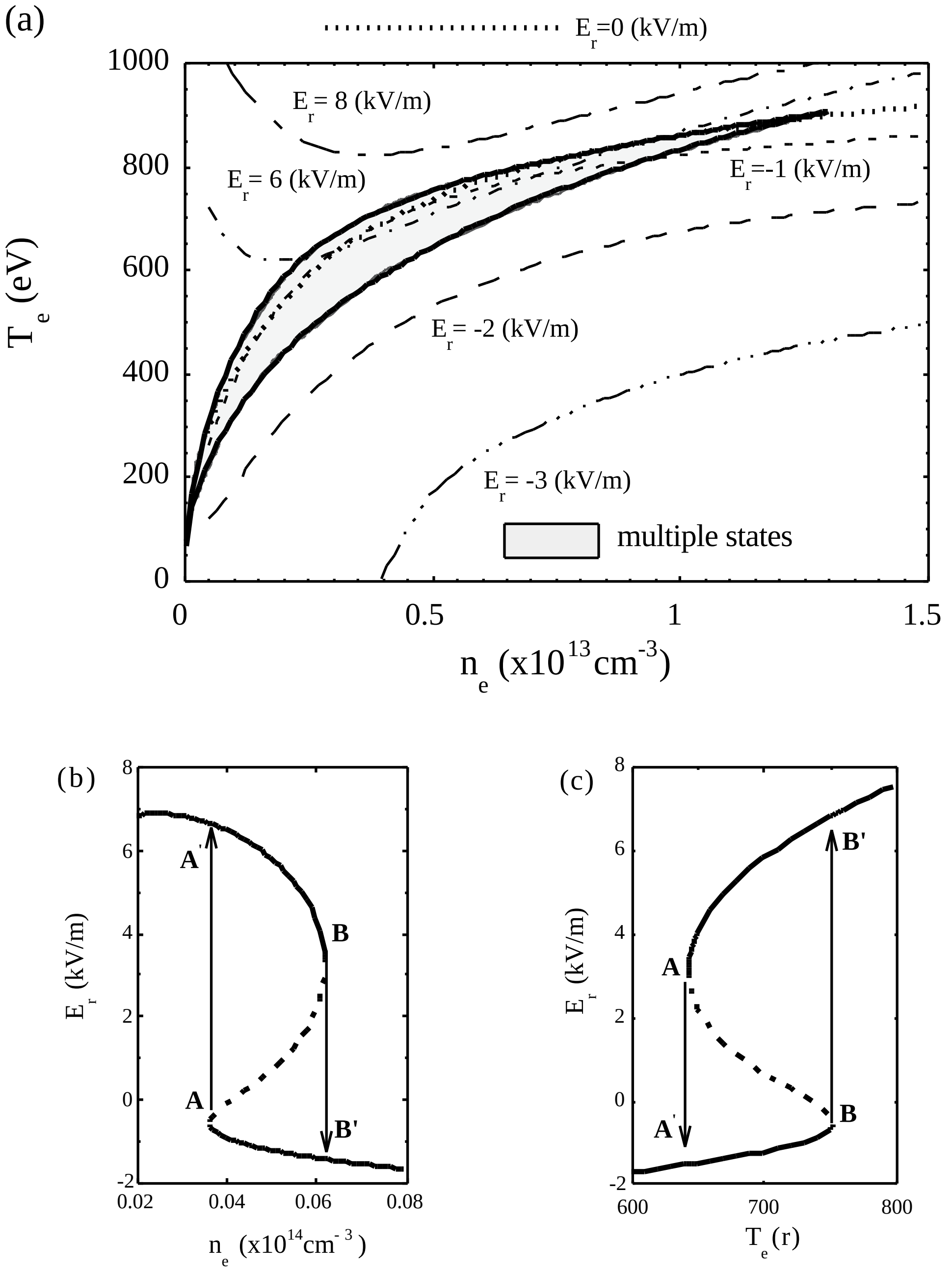

FIGURE 5: An example of neoclassical calculation. The assumptions used in the calculation are $T_i(\rho)$=350 eV, Z_{eff}=2, dln $n_e(\rho)/d\rho$=-0.5 and dln $T_e(\rho)/d\rho$=dln $T_i(\rho)/d\rho$=-0.6. We choose ε_h=0.023 and ε_t=0.16, which correspond to ρ ~ 0.3 of the CHS hydrogen plasma. (a) Region where multiple steady states exist in n_e-T_e plane (painted region). Contours of constant electric field are shown by dashed lines.(b) Bifurcation curve of radial electric field is shown as a function of density. $T_e(\rho)$=600eV is assumed.(c) Bifurcation curve of radial electric field is shown as a function of electron temperature. $n_e(\rho)=5\times 10^{12}$ cm^{-3} is assumed.