ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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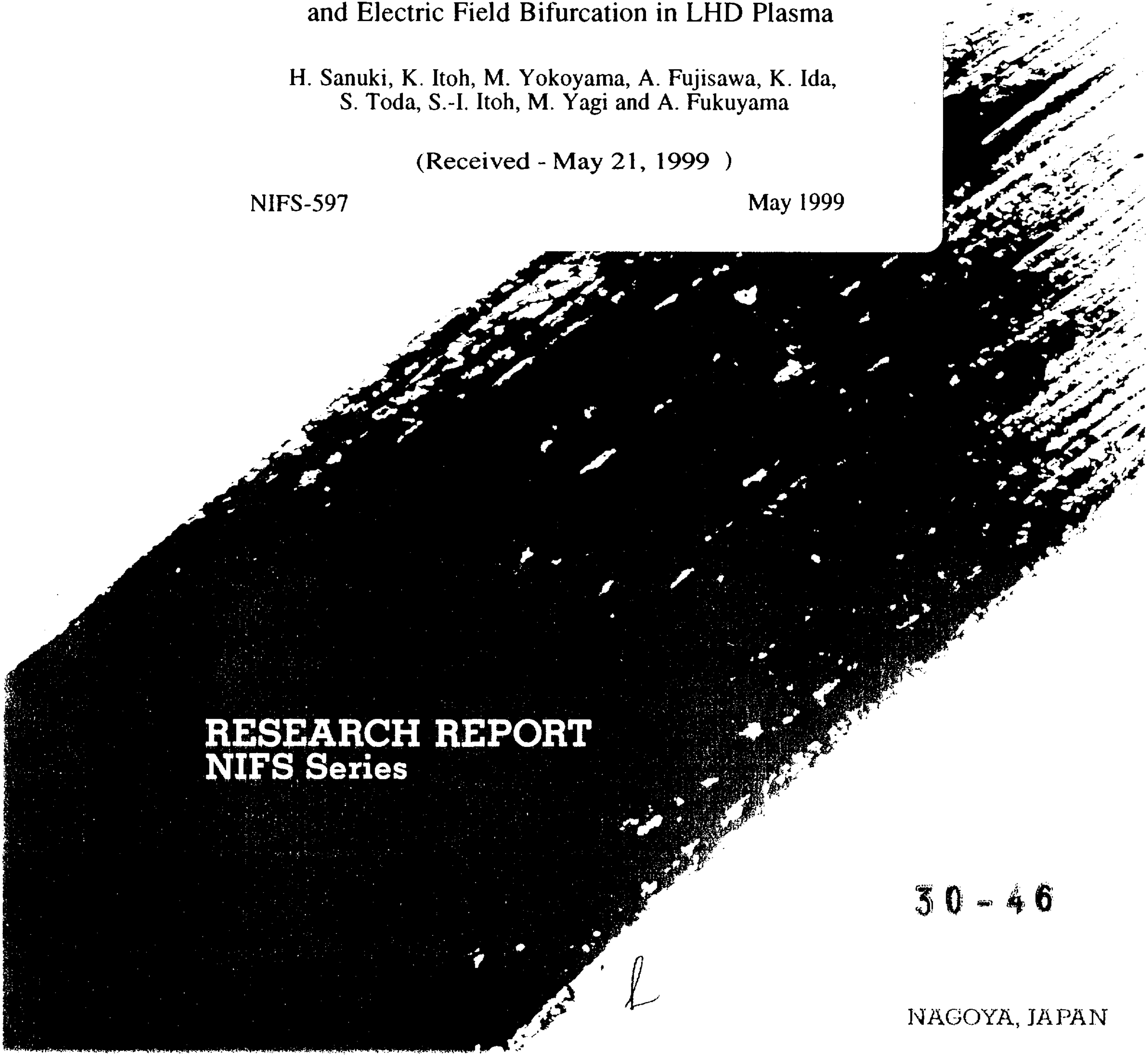
(Received - May 21, 1999)

NIFS-597 May 1999



RESEARCH REPORT
NIFS Series

30 - 46

NAGOYA, JAPAN

Possibility of Internal Transport Barrier Formation and Electric Field Bifurcation in LHD Plasma

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Abstract

Theoretical analysis of the electric field bifurcation is made for the LHD plasma. For given shapes of plasma profiles, a region of bifurcation is obtained in a space of the plasma parameters. In this region of plasma parameters, the electric field domain interface is predicted to appear in the plasma column. The reduction of turbulent transport is expected to occur in the vicinity of the interface, inducing a internal transport barrier. Within this simple model, the plasma with internal barriers is predicted to be realized for the parameters of $T_e(0) \sim 2\mathrm{keV}$ and $n(0) \simeq 10^{18}\mathrm{m}^{-3}$.

Keywords: Internal Transport Barrier, Electric FIeld Bifurcation, LHD plasma

1. Introduction

In the last two decades, various types of improved confinement states have been identified in tokamaks [1]. Among the variety of improved confinement modes, the H-mode [2] has been studied most thoroughly. The electric field bifurcation model [3] has been proposed to explain the physics of the H-mode, and the role of radial electric field structure on various improved confinement modes has been widely recognized [4, 5].

In high temperature plasmas which are confined in CHS and LHD, anomalous energy transport dominates over neoclassical energy transport. The improved energy confinement, if it exists, could be realized when the anomalous transport is suppressed. Based on the turbulent transport model, the improved confinement has been analyzed in a geometry of Heliotron configuration [6]. A possibility of existence of internal transport barrier has been theoretically predicted; the electric field domain interface could be established, and transport reduction at the interface takes place [7]. The electric field domain interface has been identified in CHS plasma [8], and the internal transport barrier has been found in the CHS plasma [9]. These developments of confinement theory and experiment strongly suggest the possibility of existence of internal transport barrier in the LHD plasma.

In this article, we first study a condition for the electric field domain interface to appear in the LHD plasma. On the parameter space of temperatures and density, the region is identified for the presence of electric field domain interface. The electric field gradient is estimated; it is strong enough to cause the reduced turbulent transport.

2. Model

2.1 Electric domain interface and internal transport barrier

For the transparency of an argument, we take the following simplification: The radial current is dominated by the neoclassical transport, while the energy transport is governed by the anomalous transport. Although progress has been made in the theory of turbulence in helical systems [10], the deductive theory has not been completed to predict the profiles of plasma density and temperature. Therefore the radial electric field is solved for a given profiles of the density and temperature. This simplification has been tested on CHS plasma, and was shown to be sufficient as a zeroth-order estimate of the radial electric field [11].

The radial electric field in the stationary state is governed by the charge neutrality equation

$$\sum_{e,i} e_j \Gamma_j = 0 \qquad (1)$$

where e_j is the charge and Γ_j is the radial flux of the j-th particle. In this equation, Γ_j consists of two parts $\Gamma_j^{\mathrm{local}}$ and $\Gamma_j^{\mathrm{diffusive}}$. The former, $\Gamma_j^{\mathrm{local}}$, is expressed by the local plasma parameters alone, while the latter, $\Gamma_j^{\mathrm{diffusive}}$, depends on the curvature of the radial electric field [4, 5]. As a result, Eq.(1) is a nonlinear diffusion equation. Analyses of equation (1) have been performed. The equation of the balance of local current

$$\sum_{e,i} \Gamma_j^{\mathrm{local}} = 0 \qquad (2)$$

can have three solutions for one set of plasma parameters, two of which are stable solutions [12, 13]. More positive electric field solution is usually called 'electron root', and the other, less positive solution, is called 'ion root'. It was shown that the electric field interface appears in the plasma when Eq.(2) has multiple solutions in some region, say $r_1 < r < r_2$ [4, 5]. There could exist a surface $r = r_*$ ($r_1 < r_* < r_2$) across which the domain of electron root and that of ion root touches each other.

When the electric field interface exist in the plasma, the transport barrier could be realized. The turbulent transport coefficient χ for the Heliotron plasma has been derived as [6]

$$\chi = \left(1 + \frac{\omega_E^2}{2G_0}\right)^{-1} \chi_L \qquad (3)$$

where $\omega_E = E_r' \tau_{Ap}/B$ is the normalized gradient of electric field, τ_{Ap} is the poloidal-Alfven-transit time, and G_0 is the normalized pressure gradient multiplied by the magnetic field gradient. χ_L is the transport coefficient in the absence of the electric field gradient, and the explicit formula is given in [10]. One sees that the electric field gradient $E_r' \simeq 10^6 \mathrm{Vm}^{-2}$ is the level of gradient which causes the reduction of transport for the parameters of interest. The difference of radial electric field across the domain interface is a few times of $|\nabla T_e/e|$. The layer thickness of the interface is dictated by the anomalous viscosity and collisional viscosity, and can be of the order of cm or less. The gradient at the interface can exceed the critical level of gradient to drive the turbulence suppression [7].

Based on these theoretical analyses, it has been predicted that the internal transport barrier can exist at the electric domain interface, i.e., under the circumstance that Eq.(2) has multiple solutions. This theoretical prediction has been tested on CHS plasmas [9]. It has been confirmed by experiments that the internal transport barrier is established at the electric domain interface. Figure 1 illustrates the parameter space in which the multiple solutions of Eq.(2) exist in the plasma [7]. The region depends on the ratio of the electron and ion temperatures. The experimental region of electric domain interface is also shown by the hatched region. Plasma discharge with internal transport barrier exists in this hatched region [9]. One can conclude that the theoretical prediction for the existence of the internal transport barrier has been semi-quantitatively confirmed.

2.2 Analytic Model

The analysis of [7, 11] is extended to the LHD plasma. The objective of the present study is to provide an analytic insight, i.e., the level of comparison with CHS plasmas, so that a simplified theoretical model is used. The model Heliotron/torsatron configuration is employed, in which the magnetic field is characterized by the helical ripple and toroidal ripple as

$$B = B_0\left(1 - \varepsilon_t \cos\theta - \varepsilon_h \cos\left(m\theta - \ell\varphi\right)\right). \qquad (4)$$

In this expression, quasi-toroidal coordinates $\left(r, \theta, \varphi\right)$ are used (r is the minor radius, θ is the poloidal angle, φ is the toroidal angle), $\varepsilon_t = r/R$ is the toroidal ripple, ε_h is the helical ripple, ℓ is the polarity of the field, and m is the toroidal pitch number. Limit of high aspect ratio, $R/a \gg 1$, is employed (R and a being the major and minor radius, respectively). The radial profile of the ripple is approximated as $\varepsilon_h(r) = 2\varepsilon_0 I_2(mr/R)$ with $\varepsilon_0 = \sqrt{1 - \left(2\iota(0)/m - 1\right)^2}$, where I_2 is the second order modified Bessel function and $\iota(0)$ is the central rotational transform divided by 2π.

The local radial current due to the neoclassical diffusion is calculated by use of the formula

$$\Gamma_j^{\mathrm{local}} = \Gamma_j^{\mathrm{s}} + \Gamma_j^{\mathrm{as}} \qquad (5)$$

where Γ_j^{s} is the particle flux associated with transit or toroidally trapped particles, corresponding to the one in axisymmetric systems, and Γ_j^{as} indicates the flux due to helically trapped particles. The explicit expressions for Γ_j^{s} and Γ_j^{as} are Eqs.(6)-(13) of Ref.[12]. This formula is simple, but was useful in understanding the Heliotron experiments.

3. Parameter Region of Domain Interface

Equation (2) with Eq.(5) is solved for a given plasma profiles. We choose the profiles as parabolic,

$$n/n(0) = T_e/T_e(0) = T_i/T_i(0) = 1 - r^2/a^2 \qquad (6)$$

Within this choice, the plasma profiles are characterized by a set of parameters $n(0), T_e(0), T_i(0)$. Other parameters are chosen as $R = 3.75$ m, $a = 0.576$ m, and $B_0 = 3.0$ T.

The region of multiple solutions for Eq.(2) is searched for in the parameter space of $(n(0), T_e(0), T_i(0))$. Figure 2 illustrates regions of radial electric field structures. There are three characteristic regions in this diagram; the regions of electron root, multiple solutions, and ion root.

The electron root dominates over the whole plasma column, if the temperature is high enough. In the high density region, the ion root dominates. In between these two regions, the region of multiple solutions exists. The region of multiple solution is shown on the $\left(n(0), T_e(0)\right)$ plane for various values of the ratio of electron temperature to ion temperature. For the ratio of $T_e(0)/T_i(0) = 1$, the multiple solutions are possible in the temperature region

$$1\mathrm{keV} < T_e(0) < 2\mathrm{keV} \qquad (7)$$

at the low plasma density $n_e(0) \simeq 10^{18}\mathrm{m}^{-3}$. The condition for the interface to exist in the LHD plasma is that the plasma parameter lies in the hatched region, which is bounded like Eq.(7). When the temperature is in this region and high (for fixed density), the interface exists near the plasma boundary. When the temperature is lower, the interface appears near the center. For the fixed temperature, the interface approaches to the edge when the density is lower.

As the density increases, the region of interests moves to the higher temperature region. In this region, the electric domain interface is predicted to appear. On the boundary between these regions, the bifurcation occurs from one radial structure to the other.

The appearance of the multiple solution, i.e., the electric domain interface, is influenced by the ion temperature. Figure 3 shows the electric field structure on the $\left(T_e(0), T_i(0)\right)$ plane for the fixed density, $n(0) = 5 \times 10^{18}\mathrm{m}^{-3}$. The lower boundary of the region of our interests weakly depends on the ion temperature. An empirical fit of the lower boundary of the electron temperature for transition, $T_{e,c}(0)$, is observed as

$$T_{e,c\,[\mathrm{keV}]}(0) \sim 2\, T_{i\,[\mathrm{keV}]}(0)^{1/4} \qquad (8)$$

for this density. On the other hand, the upper boundary is modified by ion temperature more strongly. In the low ion temperature limit, $T_i(0)/T_e(0) < 1/5$, or in the high ion temperature limit, $T_i(0)/T_e(0) > 7/3$, the upper boundary merges to the lower boundary: When two boundaries merge, the whole plasma column is dominated by either the electron root or ion root solutions, so that the electric domain interface is difficult to appear.

From these analyses, one can conclude that, when the electron temperature reaches as $T_e(0) \simeq 2\mathrm{keV}$, the electric domain interface is sustained in the plasma column. If the domain interface appears in the plasma column, the gradient of the electric field at the domain is possible to reach the level of $E_r' \sim 10^6\mathrm{Vm}^{-2}$. Therefore, the internal transport barrier is predicted to appear under such circumstance, based on the study of the turbulent transport and comparison with CHS experiments.

4. Summary and discussion

In this article, we studied the region of plasma parameters for which the electric field domain interface appears in the LHD plasma. If the domain interface exists, the gradient of the field at this interface is so strong as to cause the reduction of turbulent transport. Based on this theoretical hypothesis, which has been successfully tested on CHS plasma, the possibility to sustain the internal transport barrier is examined. By employing a model of profiles, the parameter survey is performed. The condition for the possible existence of internal transport barrier is identified.

Within this simple model, the plasma with electric domain interface could be realized for the parameters of $T_e(0) \sim 2\text{keV}$ and $n(0) \simeq 10^{18}\text{m}^{-3}$. This parameter range is not far from the experimentally-accessible parameters. More quantitative analysis must be performed by employing profiles which are observed in experiments. The objective of this article is to point out the possible existence of the internal transport barrier; more quantitative estimate shall be reported in future.

Before closing this article, a role of energetic electron is discussed. In the presence of intense electron heating by ECH, considerable amount of energetic electrons is confined in plasmas. The radial flux of such energetic electrons, which is not included in Eq.(2), could influence the radial electric field [14, 15]. There are two ways in influencing the electric field. One is the quantitative modification of the transition condition. An additional loss of energetic electrons modifies the boundaries in Fig.2 to a higher-density region. This is the quantitative shift, and it does not change the conclusion of this article. The second way of the influence of the energetic electrons is a possibility to induce a strong positive electric field in the edge region. The analysis has been developed in [15, 16], and recent qualitative computation is seen in [17]. This induced electron root was observed in the higher density region [18] in the CHS plasma. The improved confinement associated with the electric field interface has been observed experimentally under the circumstance that the stronger radial electric field is observed in the central region of the plasma. The electric interface, which is sustained without the contribution of energetic electrons, has been verified to provide an improved confinement.

Acknowledgements

This work is partly supported by the Grant-in-Aid for Scientific Research and the Grant-in-Aid for International Scientific Research of Ministry of Education, Science, Sports and Culture of Japan. Authors wish to thank the collaboration programme of National Institute for Fusion Science and the collaboration programme of Advanced Fusion Research Center, RIAM of Kyushu University.

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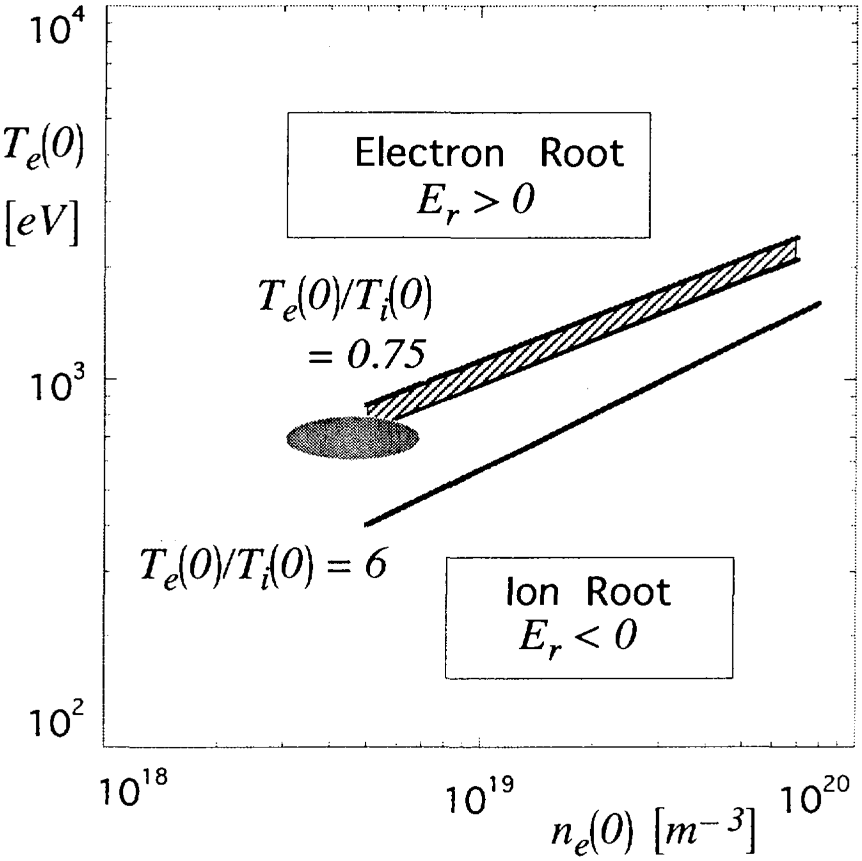
Figure Captions

Fig.1 Boundary in the plasma parameter space for the positive radial electric field and negative one. Hatched region indicates the possibility of multiple solutions. Computations are made for the case of CHS plasma with B = 1T. Bifurcation is experimentally observed in the area which is denoted by a shaded ellipse. This comparison suggests that the present theoretical method provides a rough and qualitative explanation of radial electric field.

Fig.2 Regions of the multiple electric solutions, electron root, and ion root are shown on the $\left(n(0), T_e(0)\right)$ plane. In the shaded area, the multiple solution is possible and the electric domain interface could be sustained in the plasma column. The cases of $T_e(0)/T_i(0) = 1$ (a) and $T_e(0)/T_i(0) = 3$ (b) are shown.

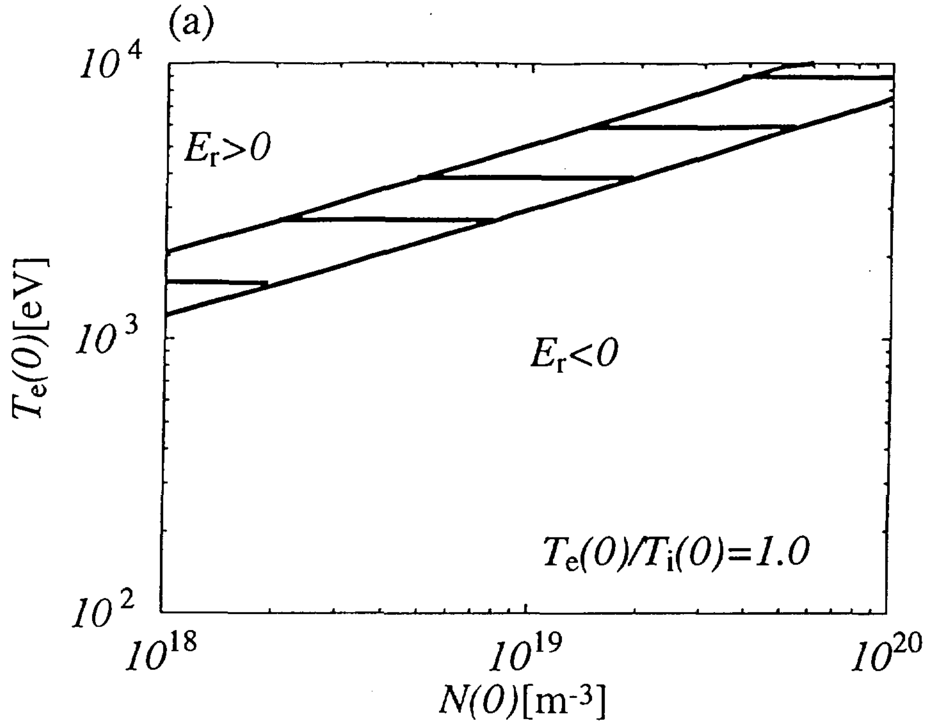
Fig.3 Regions of the multiple electric solutions, electron root, and ion root are shown on the $\left(T_e(0), T_i(0)\right)$ plane for the parameter of $n(0) = 5 \times 10^{18} \mathrm{m}^{-3}$. In the shaded area, the multiple solution is possible and the electric domain interface could be sustained in the plasma column.

Fig.1



10^4
$T_e(0)$
$[eV]$
10^3
10^2
Electron Root
$E_r > 0$
$T_e(0)/T_i(0)$
$= 0.75$
$T_e(0)/T_i(0) = 6$
Ion Root
$E_r < 0$
10^{18}
10^{19}
10^{20}
$n_e(0)\ [m^{-3}]$

Fig.2


(a)
10^4
10^3
10^2
$T_e(0)$[eV]
$E_r>0$
$E_r<0$
$T_e(0)/T_i(0)=1.0$
10^{18}
10^{19}
10^{20}
$N(0)$[m^{-3}]

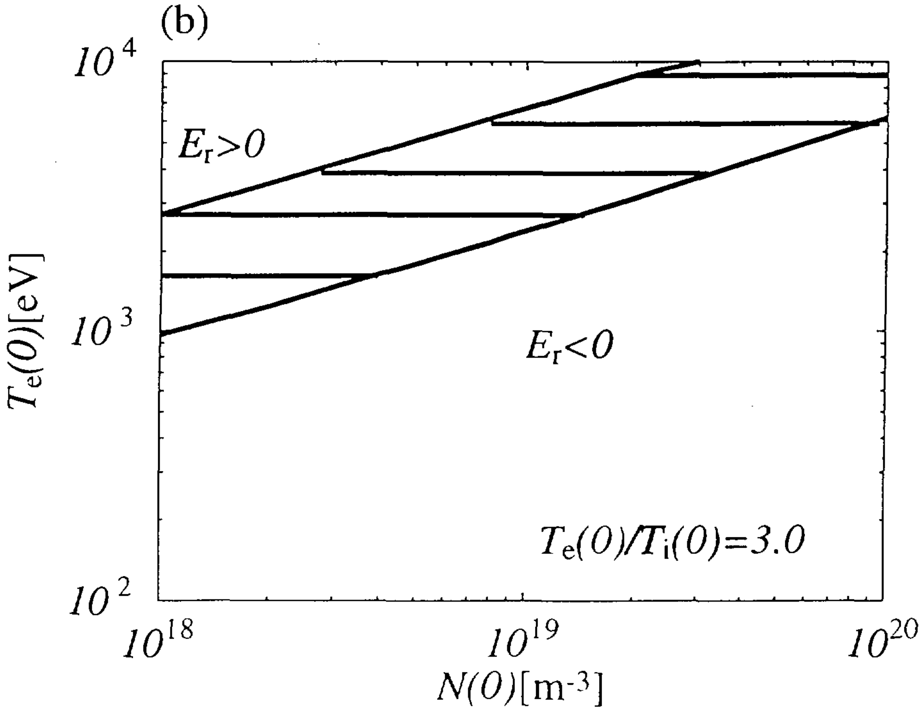
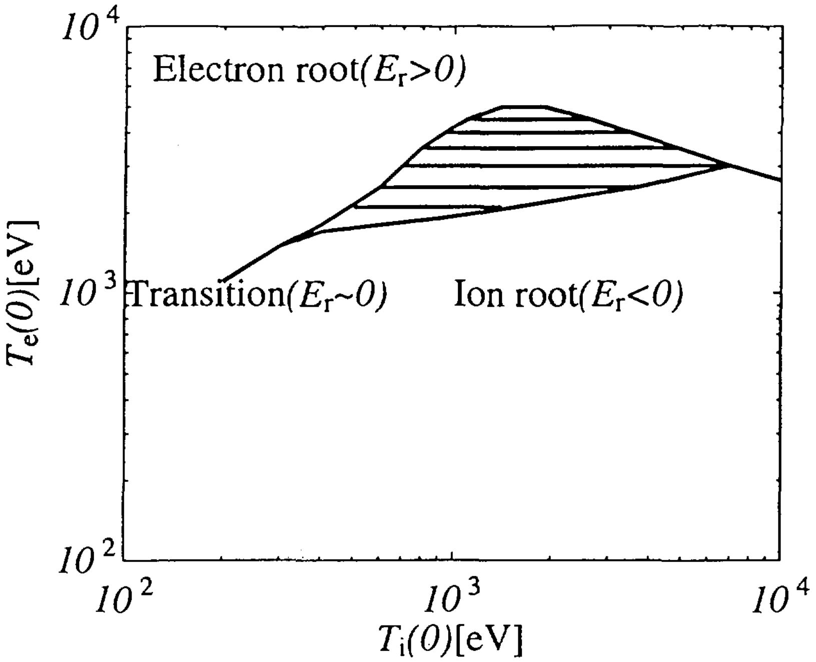

(b)
10^4
10^3
10^2
$T_e(0)$[eV]
$E_r>0$
$E_r<0$
$T_e(0)/T_i(0)=3.0$
10^{18}
10^{19}
10^{20}
$N(0)$[m^{-3}]

Fig.3



Electron root(E_r>0)
Transition(E_r~0)
Ion root(E_r<0)
$T_e(0)$[eV]
$T_i(0)$[eV]
10^2
10^3
10^4

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