Model of H/L Transition in Tokamak

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Abstract

New model of L/H transition in tokamak plasmas is presented. Nonambipolar particle losses determine the consistent radial electric field near plasma periphery. "Cusp type catastrophe" among the radial electric field, particle flux and edge gradients is found. At the transition , plasma loss can take multiple values for one profile of density/temperature near the edge. Critical edge condition for transition is obtained.

After the discovery of the H-mode in ASDEX[1], the transition between the L-mode and H-mode has been observed in many other machines[2-7]. The H-mode, on one hand, gave a break-through to improve the plasma parameters in an additional heating experiment, and on the other hand, cast a new problem of the anomalous transport across the magnetic surface.

The experimental observations on the natures as well as the conditions of L/H transition (or H/L transition) have become recently increased. There has been several theoretical work on modeling the H-mode[8-17], however, the transition characteristics have not been fully explained.

The characteristics of the transition are [18-20] that the heat flux carried by charged particles out of the outermost magnetic surface reduces very rapidly at the onset of the transition, that the transition is initiated at the plasma boundary, and that the steep gradients of the density and the temperature establish. The transition occurs in both the separatrix and the limiter configurations[5]. Experimental observations suggest that the transition is originated by (or at least accompanied by) the change of the transport inside the outermost magnetic surface.

The transition is often initiated by the sawtooth and the large sawtooth can reduce (or can even annihilate) the threshold power of the L/H transition. However, there are also many cases where the transition occurs independently of the sawtooth. It seems that there must be a critical condition for the electron temperature, and/or its gradient, near the edge rather than for the threshold power. In the case where there is no sawtooth at transition , if one compares the heat flux which is going out of the separatrix magnetic surface, one sees that the flux before and after the transition differ much while the temperature and density do not change much. This is because a finite interval of the time is necessary for the change of the background plasma parameters.

In order to explain these experimental observations, the transition should have a nature that the heat and particle fluxes take the two (or more than two) values at the same condition of temperature and the density. The radial electric field is a candidate to play the role to cause such a transition as a hidden variable.

In this article, we propose a possible mechanism of the L/H (H/L) transition associated with the changes in the particle flux (and the convective energy loss) near the plasma edge. Nonambipoar ion loss near the plasma periphery has been discussed by Hinton and Ohkawa[11,14]. Extending their theory, we include the nonambipolar electron loss in order to obtain the consistent radial electric field. Bifurcation in the particle fluxes associated with the change of the radial electric field is found. This transition is generated by the change of the radial electric field near the edge and occurs for both limiter/separatrix configurations. By this mechanism, the fluxes can take multiple values at the same density/temperature condition near the periphery. The critical edge condition for the transition is obtained. The nature of the edge localized modes (ELMs) is also discussed.

We study the ambipolar condition of the electron and ion fluxes near the plasma boundary (inside of the outermost magnetic surface, which is determined either by the limiter or by the separatrix). The direct loss of ions is important if we consider the region of $|a-r| < \rho_p$ (r: minor radius, a: plasma minor radius, ρ_p: poloidal gyroradius, $\rho_p = v_T mqR/aeB_t$, q: safety factor, R: major radius, v_T: thermal velocity of ions, B_t: toroidal magnetic field). In this region, the ion loss is given by[11)]

$$\Gamma_i = \frac{n_i}{\sqrt{\epsilon \tau_{ii}}} \rho_p F \tag{1}$$

where the coefficient F is proportional to the relative number in the losscone in the velocity space ($\varepsilon = r/R$, τ_{ii}^{-1}: ion-ion collision frequency, n_i: ion density). In the presence of the radial electric field, the losscone shifts in the velocity space. The poloidal rotation is canceled for the particles which satisfy the relation $v_{\parallel}/qR \simeq E_r/rB$; these ions are lost as the direct orbit loss. This relation gives an approximate location of the losscone. If we assume that the ion distribution function f_i is close to the maxwellian, $f_i \propto \exp(-v_{\parallel}{}^2/v_T{}^2)$, the ion loss has the form as

$$\Gamma_i = \frac{1}{\sqrt{\epsilon}} \frac{n_i}{\tau_{ii}} \rho_p \hat{F} \exp\left\{-\left(\frac{\rho_p e E_r}{T_i}\right)^2\right\}, \tag{2}$$

where the coefficient $\hat{F}$ is the contribution from the bounce average and can weakly depend on E_r.

Electrons are affected by the microturbulence. This turbulence-driven loss can also be nonambipolar (NA). Firstly, it is nonambipolar if the local momentum balance between electrons and ions via wave does not hold[21,22]. Near the edge, the wave (which is excited by electrons) can propagate across the plasma boundary to the scrape-off plasma so as to take the electron momentum. Under such condition, the turbulence-driven flux of electrons is not ambipolar. Secondly, it is also nonambipolar if it is driven by the magnetic braiding[23]. We therefore take the NA part of electron loss and write as[23]

$$\Gamma_e^{(NA)} = -D_e n\left(\frac{n'}{n} + \frac{eE_r}{T_e} + \frac{\alpha T'_e}{T_e}\right) \tag{3}$$

where α is a numerical constant of the order of unity. D_e can be represented in a form of the local turbulence spectra[21-23].

Equating the nonambipolar fluxes, $\Gamma_i = \Gamma_e (\equiv \Gamma)$, we have the equation to determine E_r as

$$\exp\left\{-\left(\frac{\rho_p eE_r}{T_i}\right)^2\right\} = d\left\{\lambda - \left(\frac{\rho_p eE_r}{T_i}\right)\right\} \tag{4}$$

where $d = D_e \tau_{ii}\sqrt{\varepsilon}/\hat{F}\rho_p^2$ and $\lambda = T_e\rho_p(n'_e/n_e + \alpha T'_e/T_e)/T_i$. The convective energy loss is given by $Q_c = (T_e + T_i)\Gamma_i$.

Figure 1 illustrates $\hat{\Gamma}_{e,i}$ ($\hat{\Gamma}_{e,i} = \Gamma_{e,i}\tau_{ii}\sqrt{\varepsilon}/\hat{F}\rho_p^2$), as a function of $\rho_p eE_r/T_i$. (The coefficient d may have a weak E_r dependence, which is neglected in this article). As is seen from Fig. 1, Eq. (4) gives the transition of E_r, Γ and Q_c. When λ is small, Eq. (4) has one real solution with a large value of flux; E_r is negative (i. e., the electric field directs inward). With the increase of λ or d, the bifurcation of the solution appears (dotted lines in Fig. 1).

The figure 2 illustrates a λ dependence of $\hat{\Gamma}$, $\hat{Q}$ ($= Q_c\tau_{ii}\sqrt{\varepsilon}/\hat{F}\rho_p^2(T_e + T_i)$). There appears a cusy-type catastrophe[24,25] (Riemann-Hugoniot catastrophe). The solution of Eq. (4) forms the cusp-type surface in the space (λ, d, E_r (or $\hat{\Gamma}$, $\hat{Q}$))[24]. The upper branch I corresponds to L-mode and lower branch II is H mode. The transition from L to H occurs as A→B'→C→C'→D and that from H to L occurs as D→C'→B→B'→A. The transitions occur at particular values of λ_c (which is a function of d). Because λ_c for L→H is larger than that for H→L, there is a hysteresis as is shown in Fig. 2. The value λ_c is of the order of unity (about 1.5 in this case). This value is in the range of the experimental observation[18]. As a result of the transition C→C', the particle flux Γ and the convective energy flux Q_c become about 1/10 times smaller. The sudden reduction of the losses allows that T' and n' become large. Because this reduction occurs in a thin layer near the boundary, $|a-r| < \rho_p$, the transition C→C' gives rise to a formation of the temperature/density pedestral. In the branch of the lower fluxes, the electric field takes the value $eE_r\rho_p/T_i \simeq \lambda$ ($\lambda > \lambda_c$).

The loss flux of the lower branch (H), which is obtained here, is a decreasing function of the gradient. A thermally stationary state may not be realized after transition C→C', if there is no other loss and if the source is not affected by the transition. Therefore, after the transition C→C', the gradient near the boundary continues to increase until the other losses (such as the conductive energy loss, the charge exchange loss, the radiation loss, the loss by the edge localized modes (ELMs), ect.) increase and balance with the heat and particle input to the layer.

From Fig. 2a, we see that the sawtooth and ELMs play the comprementary roles in L→H and H→L transitions, respectively. The sawtooth can increase edge electron temperature and cause transition L→H. The ELMs reduce the gradient at the edge. If the ELMs are so large as the gradient becomes smaller than the critical value after the ELMs onset, then the plasma jumps from the branch H to branch L.

In this model, the threshold value λ_c is predicted. The threshold power should be interpreted as the necessary power to reach the critical value λ_c. Because there is the conductive energy loss, the peak value of Q_c does not directly coincide with the threshold power. If the confinement is good enough (or the sawtooth is large enough) to make $\lambda > \lambda_c$, the transition can occur even in the zero additional-heating power. Our model predicts that the gradient of the order of ρ_p^{-1} (i.e. the high edge density/temperature) is necessary for the L/H transition. For instance, to this end the reduction of the neutral gas density, which requires the lower limit of electron density, is also necessary as is discussed in Refs. [11, 16]. The role of the X-point location may be explained in the relation to increase λ. If the location of the X-point is to the direction of the ion ∇B-drift, then the conductive ion loss is predicted to be reduced and hence the edge temperature is enhanced[11]. In the same configuration, also the electron edge temperature can become high because the distance between the heat flux source and heat flux sink along the field line is longer compared to the case of the opposite ∇B-drift direction[26]. These mechanisms help to increase λ for the same heating power.

According to this model, the transition occurs at the plasma boundary (inside the boundary, and the width is of the order of the poloidal ion gyroradius) and may propagate inside. The transition here is essentially dictated by the particle flux (convective loss). Just after the transition, the improvement of the particle flux is expected and the convective loss to the the SOL should be reduced. Improvement of the particle confinement may further raise the edge temperature, hence the conduction to the SOL may be also reduced due to the collisionless neoclassical effect.[11] The transition is usually monitored by the reduction of the H_α/D_α radiation in experiments. The reduction of H_α/D_α radiation is considered to be the result of the reduced convection/conduction losses. Our model predicts the change of the radial electric field associated with the transition. An indication of the potential change has been observed[27]. The experimental data in Fig. 4 of Ref. [18] seems to support the model that the loss takes two values for one temperature near the edge at the transition condition. The quantitative comparison with experiments on the changes of the convective/conductive energy loss after the transition is the subject of future work.

The improvement in the confinement of the core plasma may be the consequence of the improvement of the edge-confinement. The mechanism for the core plasma is beyond the scope of this article. Several mechanisms to reduce the turbulence-driven anomalous loss in the case of the high edge temperature have been discussed[15,17]. It is speculated that the reduction of the convective loss can enhance the edge temperature so that the modes are stabilized and further reduction of the conductive loss occurs after the transition.

We finally note a possible origin of the ELMs. After the onset of the transition the radial electric field at the edge becomes positive. In the core plasma E_r is usually negative. The transition causes the shear flow of E x B motion. The Kelvin-Helmholtz (KH) instability can occur if $\partial E_r/\partial r$ becomes large enough[28]. The region of the positive E_r has the thickness of $O(\rho_p)$ and E_r nearly equals $\lambda T_i/e\rho_p$. The KH instability can be unstable if the value $\lambda T_i/e\rho_p{}^2$ is high. The precise comparison requires future work.

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References

1] F. Wagner et al.: Phys. Rev. Letters **49** (1982) 1408.

2] M. Nagami et al.: Nucl. Fusion **24** (1984) 183.

3] R. J. Fonck et al.: in Proc. 4th Symposium on Heating in Toroidal Plasmas, Rome, March 21-28, 1984, Vol. 1, p. 37.

4] K. McGuire et al.: in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 10th Int. Conf., London, 1984), IAEA, Vienna, Vol. 1 (1987) p. 117.

5] K. Odajima et al.: in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 11th Int. Conf., Kyoto, 1986), IAEA, Vienna, Vol. 1 (1987) p.151.

6] J. Luxon et al.: in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 11th Int. Conf., Kyoto, 1986), IAEA, Vienna, Vol. 1 (1987) p. 159.

7] A. Tanga et al.: 11th IAEA Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, Japan, 13-20 Nov. 1986, IAEA-CN-47/K-I-1.

8] T. Ohkawa et al.: Phys. Rev. Letters **51** (1983) 2101.

9] F. L. Hinton et al.: in Plasma Physics and Controlled Nuclear

Fusion Research (Proc. 10th Int. Conf., London, 1984), IAEA, Vienna, Vol. 2 (1985) p. 3.

10] S. K. Wong: Research report of Max-Planck-Inst. Plasma Phys., IPP III/106, August 1985.

11] F. L. Hinton: Nucl. Fusion **25** (1985) 1457.

12] H. P. Furth: Plasma Phys. Contr. Fusion **28**, No. 9A (1986) 1305.

13] N. Ohyabu et al.: Nucl. Fusion **26** (1986) 593.

14] T. Ohkawa: KAKUYUGO KENKYU **56**, No. 4 (1986) 274.

15] C. M. Bishop: Nucl. Fusion **26** (1986) 1063.

16] T. Ohkawa: KAKUYUGO KENKYU **56**, (1986) 427.

17] T. S. Hahm and P. H. Diamond: Phys. Fluids **30** (1987) 133.

18] M. Keilhacker et al.: Plasma Phys. Contr. Fusion **30**, (1984) 49.

19] F. Wagner et al.: J. Nucl. Mater. **121** (1984) 103.

20] F. Wagner et al., "The H-Regime of ASDEX" in Basic Physic Processes of Toroidal Fusion Plasma (Varenna, 1985).

21] S. Inoue, et al., Nucl. Fusion **19** (1979) 1253.

22] C. W. Horton, Plasma Phys. **22** (1980) 345.

23] J. D. Callen, Phys. Rev. Letters **39** (1977) 1540.

24] R. Thom, "Stabilite Structurelle et Morphogenese" (1972). ("Structural Stability and Morphogeneses" transl. D. H. Fowler, Benjamin 1975, Sec. 5).

25] T. E. Stringer, Phys. Fluids **13** (1970) 810.

26] S. I. Itoh and K. Itoh, paper in prepargation.

27] M. Shimada et al.: in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 10th Int. Conf., London, 1984), IAEA, Vienna, Vol. 1 (1985) p. 281.

28] F. F. Cap, "Handbook on Plasma Instabilities" (Academic press, 1976) Vol. 1 p. 298.

Figure Captions

Fig. 1 Fluxes $\hat{\Gamma}_i$, $\hat{\Gamma}_e$ vs the radial electric field. Four cases of λ (with constant d) are shown. Dotted lines indicate the bifurcation condition.

Fig. 2 Solution of the flux (a) and radial electric field (b) as a function of λ (for the case of d = 1.3). Points A to D correspond to those in Fig. 1. Transition from the branch of large flux to that of small flux occurs at $\lambda=\lambda_c$.

Fig. 1

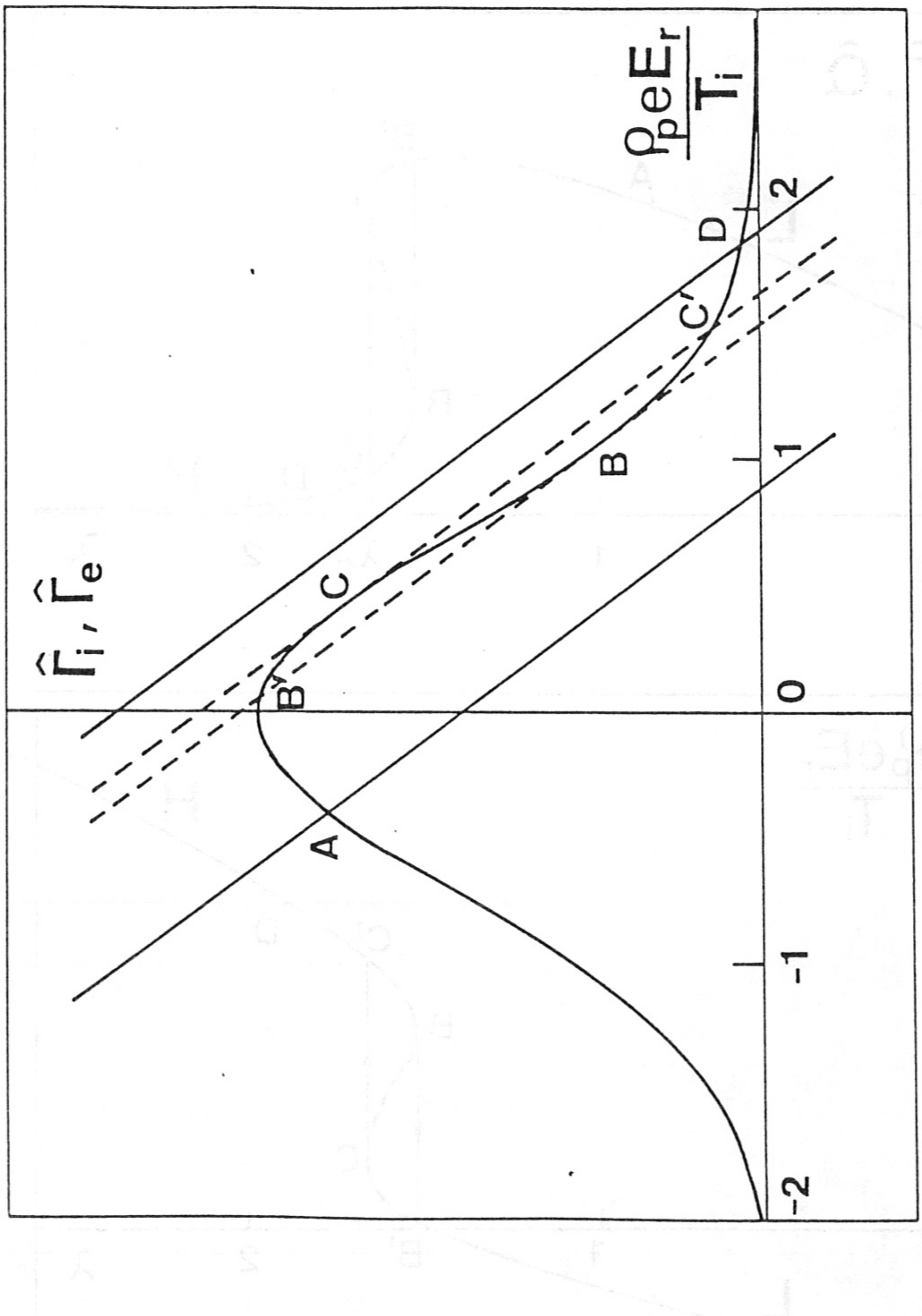
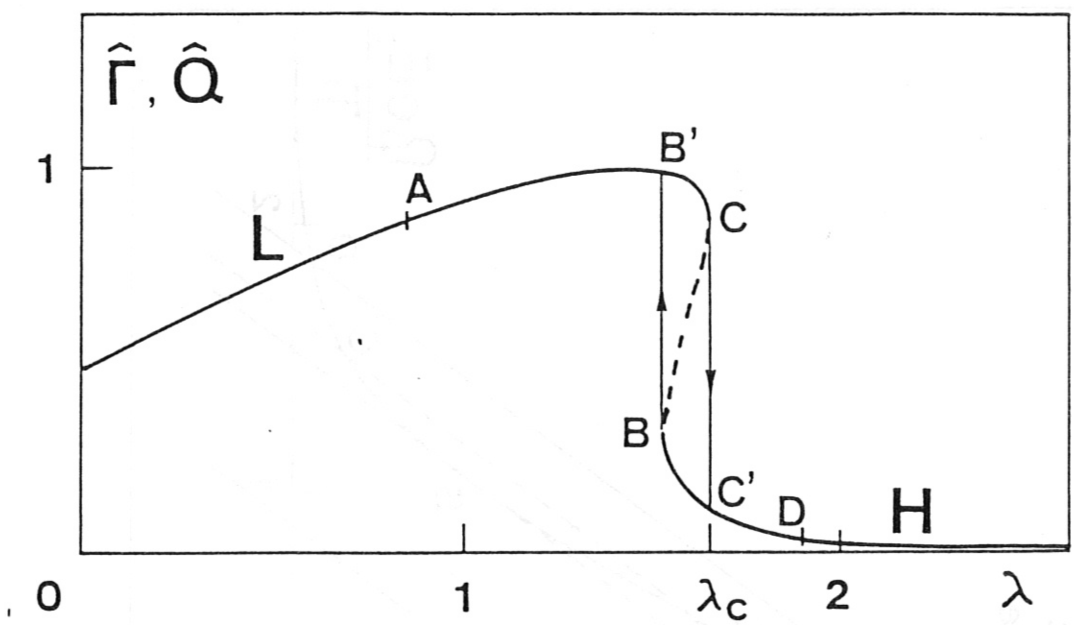
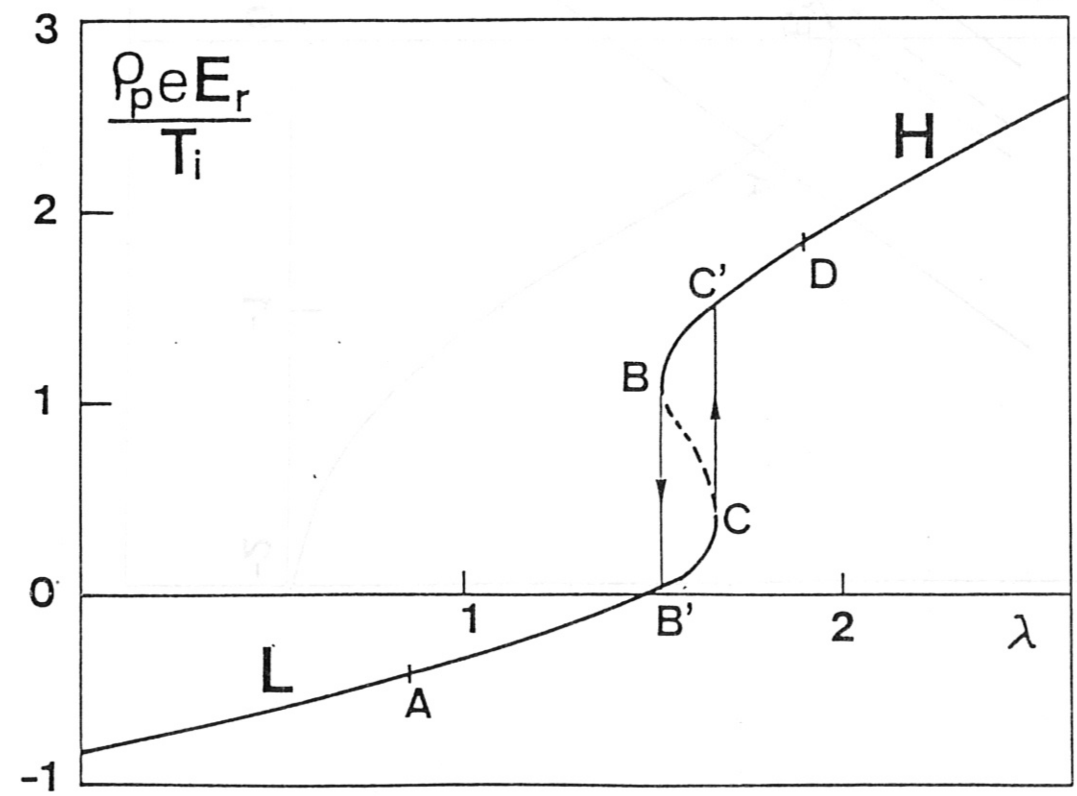


Fig. 2



$\hat{\Gamma}, \hat{Q}$
1
0
1
λ_c
2
λ
L
A
B'
C
B
C'
D
H

(a)



$\frac{\rho_p e E_r}{T_i}$
3
2
1
0
-1
1
2
λ
H
D
C'
B
C
B'
L
A

(b)