Analysis of the Variability of the L-H Transition Power Threshold in a Helium-4 Discharge*

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Abstract In this paper, a mechanism about the variability of the L-H transition power threshold $P_{\rm L-H}$ is proposed which is based on the ion orbit losses. Only in the edge where there are enough ion orbit losses and the negative radial electric field $E_{\rm r}$ is high enough can the H-mode be triggered. The ion orbit losses are determined by the ion in the loss region under certain edge conditions. For different mass A and different charge Z, the critical loss energy $E \propto Z^2/A$ in the loss region. In H and D charges, because the D^+ loss region is larger than H^+, it can be deduced that the $P_{\rm L-H}$ of H is larger than that of D. In a ^{4}He discharge, experiment finds there exist a considerable number of $^4He^{1+}$ in the plasma edge. The actual ion orbit losses are determined by the mixing ratio of $^4He^{1+}$ and $^4He^{2+}$. The $^4He^{1+}$ loss region is larger than that of $^4He^{2+}$, and the loss region of D^+ interposes between $^4He^{1+}$ and $^4He^{2+}$. Different $^4He^{1+}$ content can cause the edge ion losses in a ^{4}He discharge to be greater than, less than or equal to that in a D discharge. So a ^{4}He discharge can exhibit multiple experimental phenomena in the $P_{\rm L-H}$.

Keywords: ^{4}He discharge, the L-H transition, the ion orbit loss region, the variability of $P_{\rm L-H}$

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(Some figures may appear in colour only in the online journal)

1 Introduction

Because the $P_{\rm L-H}$ for ^{4}He plasmas is lower than that for H plasmas, ITER will operate with ^{4}He to explore the physics and technology during its low activation phase. In view of the importance of ^{4}He, many H mode experiments have been operated in several tokamaks [1−3]. A direct fitting of the ^{4}He power threshold data gives [1]

$$P_{\rm L-H} = (1.23 \pm 0.13)\overline{n}_{\rm e}^{(0.77\pm0.17)} B_0^{(0.92\pm0.12)}, \qquad (1)$$

where $\overline{n}_{\rm e}$ is the line-averaged electron density in 10^{19} m^{-3}, B_0 is the vacuum magnetic field at the plasma centre in tesla. Comparison with H-mode power threshold database [1,4] for D plasmas

$$P_{\rm L-H} = 0.87\overline{n}_{\rm e}^{0.77} B_0^{0.92}, \qquad (2)$$

shows that ^{4}He plasmas similarly had $P_{\rm L-H} \approx$ 1.3-1.5 times that of D plasmas. However, the 2009 JET experiment showed that the threshold power of $P_{\rm L-H}$ has a marked difference in the ^{4}He and D data for different electron densities $n_{\rm e}$[5]. The ^{4}He and D plasmas had similar $P_{\rm L-H}$ at some higher $n_{\rm e}$, while $P_{\rm L-H}$was significantly higher for ^{4}He plasmas than that for D plasmas at other lower $n_{\rm e}$. Physics understanding about the $n_{\rm e}$ dependence of $P_{\rm L-H}$ in a ^{4}He discharge remains to be improved.

In this paper, a theory based on the ion orbit loss model for this phenomenon is proposed. Due to a divertor X point in a tokamak geometry, there exists an ion orbit loss region in the initial velocity space near the plasma edge. As a consequence, a strong negative radial electric field has been theoretically observed in a thin layer just inside the separatrix by a Hamiltonian guiding center simulation, which then generates a strong density pedestal [6]. It is envisaged that the ion losses can have a very important influence on the $P_{\rm L-H}$. In the edge plasma, the ion orbit losses are determined by the quantity of the ions in the loss region. The loss region is directly related to not only the plasma configuration but the kind of ions. In a discharge involving ^{4}He, there will be a considerable number of $^4He^{1+}$ components in the edge region, which is confirmed by FT-2 experiment [7]. The actual ion orbit losses are determined by the mixing ratio of $^4He^{1+}$ and $^4He^{2+}$ in a ^{4}He discharge. However, the important effect of $^4He^{1+}$ on the L-H transition is rarely recognized. The present work studies the difference of the ion orbit loss region for $^4He^{1+}$, D^+, $^4He^{2+}$ and H^+, calculates the effect of $\alpha(={}^4He^{1+}/({}^4He^{2+}+{}^4He^{1+}))$ on edge ion orbit losses, and then analyzes the variability of $P_{\rm L-H}$ in a ^{4}He discharge.

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2 The edge ion orbit losses

The following data are afforded by plasma equilibrium code EFIT (Equilibrium Fitting) calculated for EAST, and the parameters of EAST with an single null (SN) divertor configuration are as follows: major radius R_0=1.86 m, minor radius r_0=0.47 m, R_{in}=1.39 m, R_{out}=2.33 m, R_X=1.61 m, I_p=1 MA, B_0=2 T (see Fig. 1). The edge radial correlation length of turbulence L_r is experimentally measured as about 1 cm in the L-mode [8], so ions are launched at L point 1 cm inside the LCFS in the horizontal midplane of the low field side to analyze the ion losses in the initial velocity space.

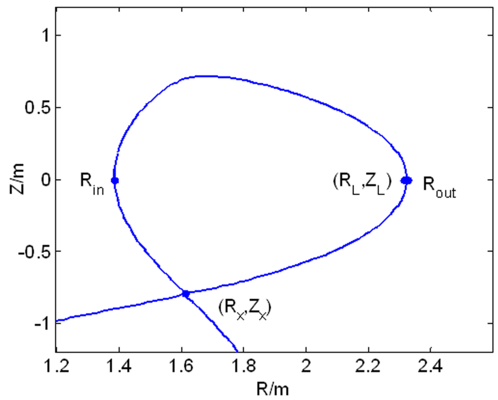

Fig.1 EAST SN diveertor geometry

The ion orbit loss is caused by lack of poloidal magnetic field near the X point. Ions with low parallel flow speed will have little poloidal flow out of the X region. The vertical $\boldsymbol{v}_{\nabla B+CB}$, drift velocity of gradient magnetic field and curvature magnetic field, drift motion then moves these ions across the LCFS into the divertor chamber. In the plasma edge, only those ions that satisfy certain critical conditions can be lost. If an ion at L point can escape from X point exactly, when it arrives near the X point, the different value of poloidal magnetic flux function between L point and this point has $\triangle\Psi \geq \triangle_L$. Because the $\boldsymbol{v}_{\nabla B+CB}$ of an ion is determined by the velocity and the incidence angle, the loss region can be formed in the velocity space. For the given tokamak parameters, the $^4He^{1+}$ orbit loss region can be obtained according to the method presented in Ref. [9] (see Fig. 2), where E is the energy, δ is the incidence angle (δ=$\cos^{-1}(v_{||L}/v)$, $v_{||L}$ and v respectively are the parallel velocity and total velocity of an incident ion at L point). E_0 is the loss threshold energy, which means that the ion with this minimum energy can escape across LCFS and reach the target.

The ion orbit losses in Fig. 2 only present the status of L point, which is 1 cm inside the LCFS in the horizontal midplane of the low field side. As a matter of fact, the ion orbit losses can also be affected by the position of the launching point in the plasma to a large extent. On the same magnetic surface, the ion orbit loss region will change dramatically with the increase of major radius R of the launching point. The $^4He^{1+}$ ion orbit loss ratio η, where η=Γ_{iloss}/Γ_i, Γ_{iloss} and Γ_i are the ions in the loss region and the total ions respectively, in the different positions on the same magnetic surface is calculated, as shown in Fig. 3. During plasma heating, the ion orbit losses are actually the mean value of the magnetic surface due to the faster response time of the electron. So it is meaningless to calculate the ion orbit losses in a specific region. But the mean ion orbit losses on the same magnetic surface can be estimated by the losses in a certain region in a specific configuration. In the present configuration, assuming that the ion temperature is of the Maxwell distribution, the mean ion orbit loss is calculated by averaging the loss rate on the same magnetic surface which is about 1/6 of the loss in the horizontal midplane of the low field side on the same magnetic surface, which has nothing to do with the nuclear charge number and the mass number.

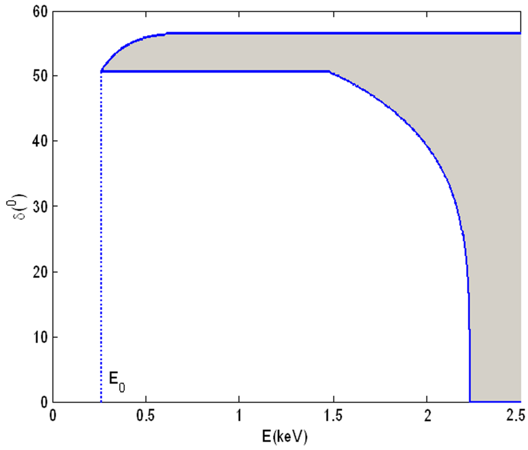

Fig.2 Ion loss region in the point neighborhood

3 The L-H transition threshold condition

Although how to impact the L-H transition of the ion orbit losses is still unintelligible so far, it is widely accepted that the negative radial field E_r is derived from the ion orbit losses and a sudden increase of E_r triggers the L-H transition. Since E_r plays a key role in the L-H transition, the edge ion orbit losses must have an important effect on P_{L-H}.

During plasma heating, because the edge ion temperature T_i is usually very low, only a small part of the ions which exceed certain threshold in energy and satisfy loss conditions can be lost. The high energy part of the Maxwell distribution can increase as the temperature increases and, as a result, the ion orbit losses increase with increasing temperature (see Fig. 3). The increase of n_e can also enhance the quantity of the ion in the loss region. So the ion orbit losses are determined by T_i and n_e in a specific configuration. In this paper, it may be assumed that different plasmas have the same ion losses at the L-H transition, and T_i=100 eV and n_e=1×10^{19} m^{-3} in the L point neighborhood can trigger the L-H transition of D plasma exactly. Because the ion orbit losses can be calculated as ηn_e, by calculating η for different temperatures and keeping ηn_e unchanged, the threshold condition of T_i and n_e for the L-H transition is shown in Fig. 4 in the L point neighborhood, and this is consistent with previous investigations in ASDEX Upgrade, which demonstrates a similar relationship between critical temperature and electron density [10]. It is obvious that the threshold condition represents the P_{L-H}.

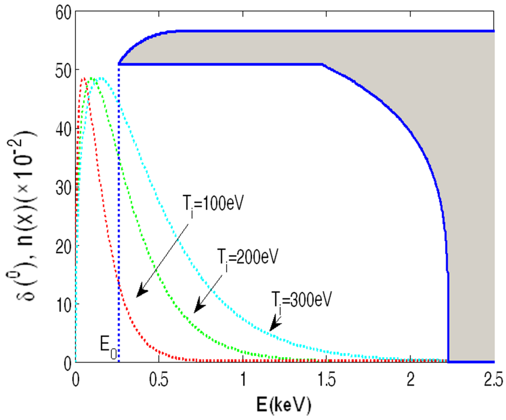

Fig.3 The enhancement of ion orbit losses with increasing ion temperature T_i

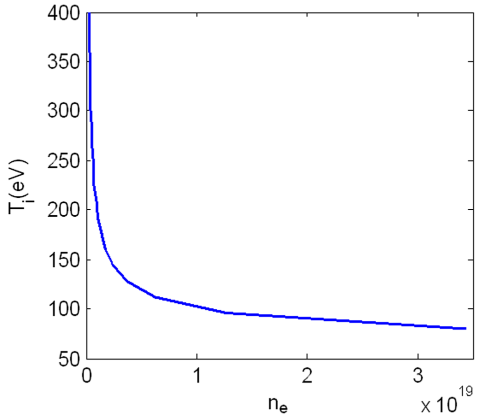

Fig.4 Threshold condition of T_i and n_e for the L-H transition in the L point neighborhood

In plasmas involving different charges, the critical loss energy can change with the mass number A and the charge number Z. For H^+, D^+ which have the same charge and different mass, the critical loss energy $E \propto 1/A$ (see Fig. 5(a)). For $^4He^{1+}$ and $^4He^{2+}$ which have the same mass and different charge, the critical loss energy $E \propto Z^2$ (see Fig. 5(b)). For ions with different mass and different charge, the critical loss energy $E \propto Z^2/A$ (see Fig. 5(c)). The loss region of H^+ is identical to that of $^4He^{2+}$ because of the same Z^2/A. The Z^2/A dependence of the loss region must lead to the Z^2/A dependence of the threshold condition of T_i and n_e. Fig. 6 shows that the ions with higher mass number have a lower threshold condition, while the ions with higher nuclear charge number have a higher threshold condition. It is clear that the threshold condition of D is higher than that of $^4He^{1+}$ while it is lower than that of H and $^4He^{2+}$.

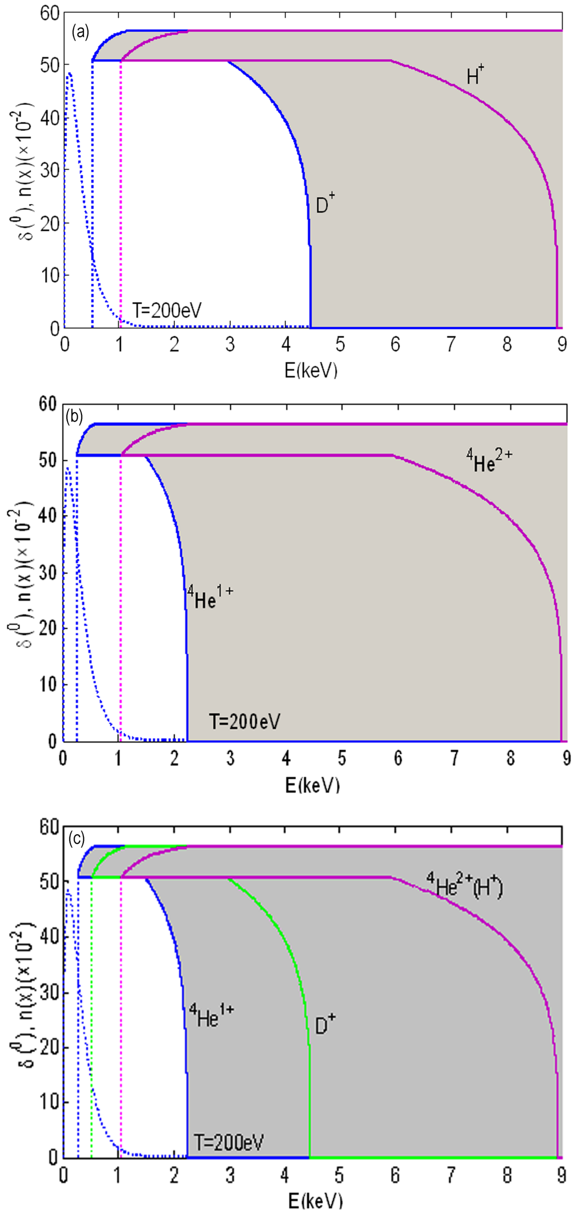

Fig.5 The loss regions of different ions in the L point neighborhood. (a) The loss regions of ions with the same charge and different mass, (b) The loss regions of ions with different charge and the same mass, (c) The loss regions of ions with different mass and different charge

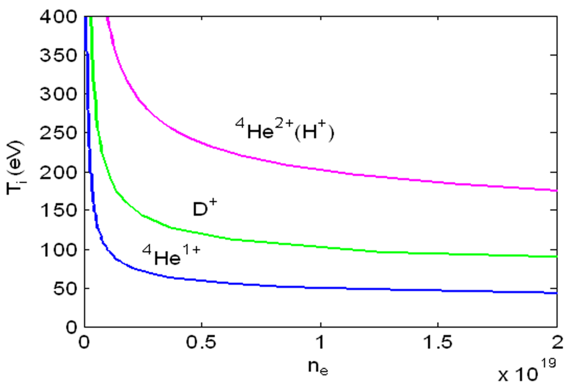

Fig.6 Threshold condition of different ions for the L-H transition in the L point neighborhood

4 The analysis of the variability of $P_{\mathrm{L-H}}$ in ^{4}He discharge

JET isotope scaling of the H mode experiment indicated that the power threshold of mixture HD is less than that of pure H and greater than that of pure D [11]. The result gives a useful reference for the H mode of multi-charge state ions. In a ^{4}He charge, the ion orbit losses are actually determined by α when the electron density remains unchanged, because there are a considerable number of $^4\mathrm{He}^{1+}$. Different α cause the ion orbit losses to change between the losses of pure $^4\mathrm{He}^{1+}$ and the losses of pure $^4\mathrm{He}^{2+}$. Then the threshold condition must change with the change of α as well. Fig. 7 illustrates that the H mode threshold conditions of T_{i} and n_{e} change with α. It is clear that the threshold condition in a ^{4}He discharge changes between that in pure $^4\mathrm{He}^{1+}$ and that in pure $^4\mathrm{He}^{2+}$, which confirms the conclusion of the mixture plasma H mode obtained in Ref. [11]. It can also be seen from Fig. 7 that the threshold condition in a ^{4}He discharge can be identical to that in a D discharge in a certain condition. In the present configuration, if n_{e} or T_{i} remains unchanged, when α >0.1 the threshold condition of ^{4}He is less than that of D. When α=0.1 ^{4}He and D have the same threshold condition and when α <0.1 the threshold condition of ^{4}He is more than that of D. However, if both n_{e} and T_{i} are changed, there will be a lot of changes in the threshold condition of ^{4}He.

In a D discharge, the losses of D^+ interpose between $^4\mathrm{He}^{1+}$ and $^4\mathrm{He}^{2+}$, there are sure to be the same ion losses between a ^{4}He discharge and a D discharge, or even the losses in a D discharge are less than that in a ^{4}He charge under certain conditions. Fig. 8 illustrates the difference of the threshold condition between the mixture ^{4}He and pure D. In high edge ion temperature cases, the ion orbit losses are affected by $^4\mathrm{He}^{2+}$ more greatly, so the ion losses in a ^{4}He discharge can be less than that in a D discharge and the threshold condition of ^{4}He can be greater than that of D. When the edge ion temperature decreases, the effect of $^4\mathrm{He}^{1+}$ on the ion orbit losses will gradually become larger, the ion orbit losses in a ^{4}He discharge with the same α will gradually approach and exceed that in a D discharge, which make it possible that the threshold condition of ^{4}He approaches and falls off that of D in low edge ion temperature H mode. Simultaneously during the ^{4}He ionization, the $^4\mathrm{He}^{1+}$ content is directly proportional to n_{e} and inversely proportional to T_{i} according to Saha equation [12], and this can further weaken the threshold condition of ^{4}He. So, in a high ion temperature and low electron density H mode, the $P_{\mathrm{L-H}}$ of D can be greater than that of ^{4}He. But with the increase of the electron density, the$P_{\mathrm{L-H}}$ of ^{4}He will gradually approach that of D. In a very low ion temperature and very high electron density H mode, the $P_{\mathrm{L-H}}$ of ^{4}He is even less than that of D. These results are consistent with the electron density dependence of the $P_{\mathrm{L-H}}$ of ^{4}He in Ref. [5].

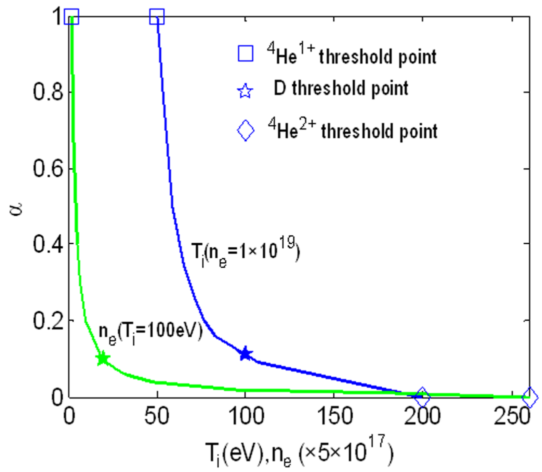

Fig.7 Threshold condition of T_{i} and n_{e} with α

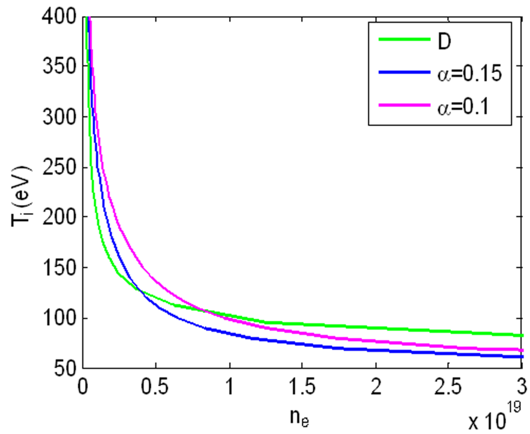

Fig.8 Contradistinction of threshold condition between the mixture ^{4}He and pure D

5 Conclusions

The edge ion orbit losses are analyzed systematically in a ^{4}He charge. Also a comparison of ion orbit losses is made among $^4\mathrm{He}^{1+}$, D^+, $^4\mathrm{He}^{2+}$ and H^+. The losses of H^+ are identical to that of $^4\mathrm{He}^{2+}$, so the ion losses in a H discharge are less than those in a ^{4}He discharge under the same conditions. In the plasma edge, there exist a considerable number of $^4\mathrm{He}^{1+}$ in a ^{4}He discharge, which can have a great influence on the ion orbit losses and the formation of E_{r}. Because the losses of D^+ interpose between $^4\mathrm{He}^{1+}$, $^4\mathrm{He}^{2+}$ under the same conditions, different α can cause the edge ion losses in a ^{4}He discharge to be greater than, less than or equal to that in a D discharge. At the L-H transition, the increase of the electron density can cause the critical temperature to decrease. So, in the high edge ion temperature and low electron density H mode the $P_{\mathrm{L-H}}$ of ^{4}He can be greater than that of D, while in the low edge ion temperature and high electron density cases the P_{L-H} of ^{4}He can be equal to or less than that of D. This theory is employed to explain the complicated experiment phenomena about $P_{\mathrm{L-H}}$ in a ^{4}He discharge. In the future ITER ^{4}He discharge, the edge ion temperature should be controlled to a relatively lower level so as to ensure a lower $P_{\mathrm{L-H}}$.

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