Bifurcation of radial electric field in tokamak edge plasmas due to ion orbit loss

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Abstract: The ion orbit loss and the formation of radial electric field *Er* in tokamak edge region are calculated. The ion orbit loss generates a negative *Er*, which in turn affects the ion loss. As a result, *Er* can saturates at either a low or a high value, depending on the plasma parameters. When the ion temperature in the plasma edge is higher than a threshold a self-sustaining growth in both the ion loss and *Er* is found, leading to a high saturation value of Er in the milliseconds time. This mechanism provides a possible explanation for the formation of the edge radial electric field during the L to H-mode transition observed in tokamak experiments.

1. Introduction

The formation of the radial electric field and related spontaneous plasma rotation in fusion devices are of great interest in plasma physics. The underlying mechanism is not well understood despite extensive experimental and theoretical efforts devoting to it. It is well known that intrinsic plasma rotation exists even in Ohmic tokamak discharges without momentum input. Experimental measurements have revealed that the L to H-mode transitionis triggered by a sudden increase of a negative radial electric field *Er* in the edge region, and the resulting *Er* shear suppresses the local plasma turbulence and anomalous transport, leading to the so-called pedestal region inside the last closed flux surface (LCFS) of H-mode plasmas [1-4]. In L-mode plasmas, a weaker radial electric field has also been observed in the edge region. It has been a long standing challenge to find out a proper nonambipolar transport mechanism which can lead to such a strong *Er* inside the LCFS during L-H transition. Experimental evidences show that a heating power threshold exists for this transition. Usually a low ion collisionality in the edge correlates with the occurrence of an H mode, while at high collisionality the plasma remained in the L mode for the same amount of heating power [5]. Lower ion collisionality can lead more collisionless ions to loss through the X point region to the divertor target plates in a divertor configuration. Hamiltonian guiding center simulations show that a strong *Er* can be generated in a thin layer just inside the separatrix because of ion orbit loss [6,7]. By considering the orbit loss, *Er* in the tokamak plasma edge has been simulated by using neoclassical Monte Carlo particle following code, and the *Er* shear is found to reach a high value. However, a spontaneous bifurcation in *Er* has not be revealed yet [8,9].

In the tokamak edge region, the radial electron transport is affected by the microscopic instabilities. Studies indicate that these instabilities can cause enhanced radial electron transport [10,11]. According to the non-ambipolarity ion loss and electron loss, Itoh and Itoh have proposed a L-H transition model, in which the bifurcation phenomena and critical condition are deduced [10]. However, a more positive value of *Er* was found to correlates to improved plasma confinement.

As the bifurcation in the edge radial electric field is one of the most important characteristics in L-H transition, in this paper a new model based on the ion orbit loss together with electron turbulence transport is considered. The calculation results show that, if the ion temperature in plasma edge region is higher than a threshold, a self-sustaining growth in the ion loss and *Er* will be triggered, and *Er* saturates at a high value in milliseconds. In the opposite case, *Er* only reaches a lower saturation value. Such a bifurcation in *Er* provides a possible explanation for the L-H mode transition.

2. Model and Results

An equilibrium magnetic field for a single null divertor configuration, obtained from EFIT code, is utilized with the following parameters: plasma major radius R_0=1.75m, minor radius a=0.46m, elongation k=1.7, tri-angularity δ=0.56, plasma current I_p=1MA, and toroidal field B_0=2T. Using guiding center approximation and assuming the conservation of ion energy, magnetic moment, and toroidal angular momentum [12], the ion motion orbit is calculated.

Fig. 1 shows the change of ion loss region in velocity space for different values of negative Er, where δ is the angle between the direction of ion motion and that of the magnetic field line, and E is the ion energy. Initially ions are assumed to have a Maxwellian distribution and be located at a launch point L, which is 1 cm inside the LCFS in the horizontal midplane on the low field side. The lost ion are found from calculations if they drift outside the LCFS and hit the divertor plate. For a given magnetic configuration and launch point, a minimum ion energy E_{min} is required for the ion orbit loss. With the increase of negative Er, the nose region [12] (the long and narrow part on the left part of the loss region) is prolonged to smaller δ values and narrowed, since the ion drift orbit is affected by the electric drift in addition to the magnetic field gradient/curvature drift. When $Er=Er_0$, the nose region becomes longest. When $Er=Er_m$, it disappears. The fraction of ions in the nose region is affected by the ion temperature. For deuterium plasmas with an ion temperature T_i=200eV at the L point, almost all the loss ions come from the nose region where the ion energy is not too high.

Corresponding to Fig. 1, E_{min} is shown in Fig. 2 as a function of the radial location of the launch point in the horizontal midplane on the low field side. E_{min} increases exponentially with increasing the distance from the LCFS. The choice of the launch point to be 1cm away from the LCFS for Fig. 1 is based on the existing results that the plasma turbulence is important just inside the LCFS, which could lead to locally enhanced radial electron (and ion) flux being comparable to that due to ion orbit loss. The radial correlation length of plasma edge turbulence, Lr, is measured to be about 1cm on ASDEX [13]. Therefore, we assume that the radial electron and ion flux are comparable inside the Lr region as marked in Fig. 2, but it is much smaller in the inner part extending from the left edge of the Lr region towards the magnetic axis. The regions labeled as "ion loss region" and "ion loss region and electron loss region" in Figure 2 shows the assumption mentioned above.

The fraction of deuterium ions in the loss region, $\eta=d\Gamma_{iloss}/\Gamma_i$, is shown in Fig. 3 as a function of the negative Er, where $d\Gamma_{iloss}$ and Γ_i are the number of ions in the loss region and in the whole velocity space respectively. It is clearly that the ions in the loss region gradually become more and more with the increase of the negative Er till to a critical value Er_c that is just a little bit bigger than the Er_0 shown in figure 1. For $Er> Er_c$, the lost ion fraction decreases sharply.

In Figs. 1-3 the ion loss is only considered at the L-point as mentioned above. With the magnetic configuration utilized here, the loss fraction changes with the polodal location of the launch point along the magnetic surface. However, because of the fast ion motion along the magnetic field line, the ion loss averaged on the magnetic surface is close to that at the L-point. The averaged ion orbit loss over polodal angles on the same magnetic surface is found to be about 1/8 of at the L-point.

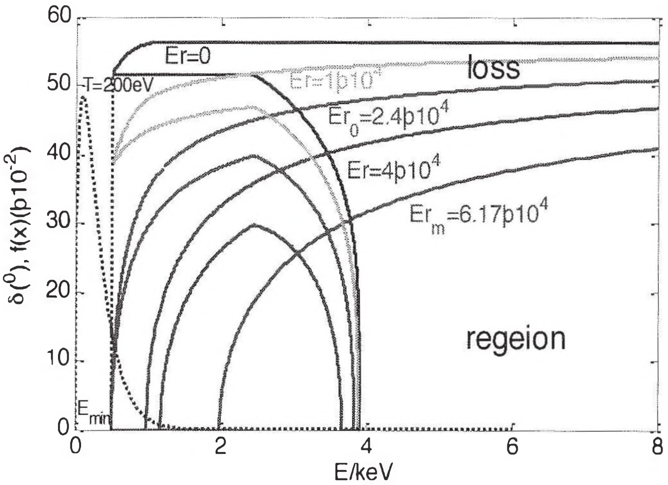

Fig. 1 The changes of deuterium ion loss region in velocity space for different negative *Er* (Unit of *Er*: -V/m) and the Maxwellian distribution of deuterium ion with T_i=200eV (dotted line).

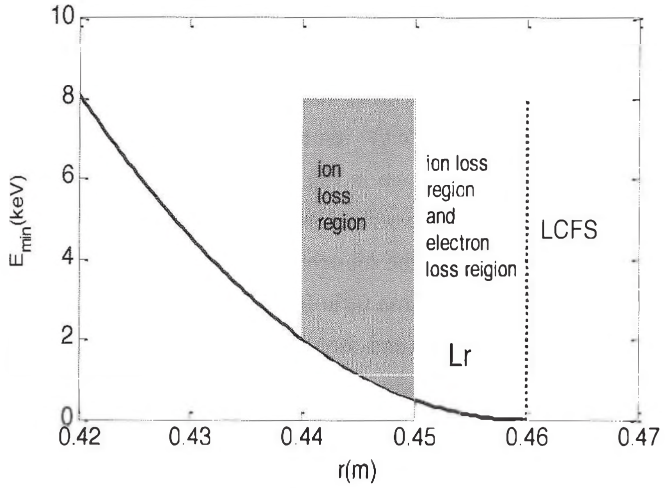

Fig. 2 Minimum ion energy E_{min} required for ion loss versus the location of the ion launch point on the low field side in the horizontal midplane (solid curve).

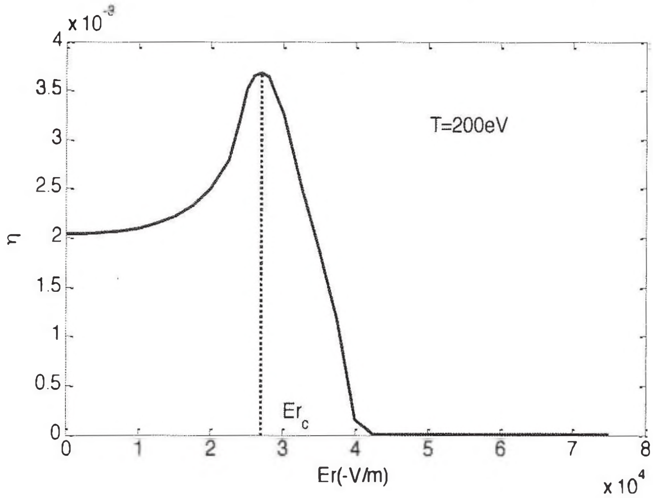

Fig. 3 The fraction of deuterium ions in the loss region *versus* negative *Er*.

The ion orbit loss will lead to the formation of a negative *Er*. Because *Er* and the ion loss region affect each other as seen from Figs 1 and 3, the generated radial electric field by ion orbit loss are quite different for different plasma parameters. Fig. 3 indicates that the increase of the ion loss fraction for Er<Er_c can lead to a self-sustaining growth of Er for a sufficiently high ion temperature. To simplify the calculation of self-sustaining growth process, the following assumptions are made which don't affect the general characteristics of our results: (1) plasma is electrically neutral in the initial time; (2) the electron losses is only important within the *Lr* region as shown in Fig.2, and the radial electrical field is assumed to be zero at the LCFS and to linearly increase towards the launch point due to the combined role of ion and electron radial flux , (3) The ion temperature and density linearly decreases from inner region towards the LCFS, and (4) the negative *Er* at the *L* point due to ion orbit loss is a linearly proportional to the ion loss fraction in the *L* point neighborhood (the actual *Er* is of course a nonlinear increasing function of the ion orbit loss fraction in the *L* point neighborhood, but our calculations have shown that the above assumption has no significant effect on the self-sustaining growth process of *Er*).

Under above assumptions, the obtained ion orbit loss fraction η is shown as a function of time in Fig. 4 for the ion density $n_i=1\times10^{19}$. When the ion temperature is lower than the threshold, the loss fraction decreases in time as shown by Curve 1. Only when the ion temperature is higher than a threshold, the self-sustaining growth process in ion loss fraction is seen (curve 2). After a peak loss fraction with η=0.018%, the ion loss fraction decreases due to the formation of a strong radial electric field.

The change of radial electric field as a function of time, corresponding to the self-sustaining growth of η shown by curve 2 in Fig. 4 , is shown in Fig. 7. *Er* saturates at a high value in the milliseconds. While for a lower ion temperature, Ti=50ev, only a low value of Er is formed. The time period of the self-sustaining growth in *Er* is usually found to be in the order of milliseconds, and the time scale decreases with increasing ion temperature and density.

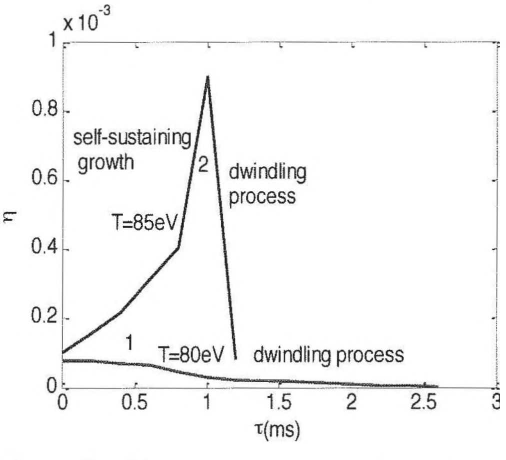

Fig. 4 The bifurcation in ion orbit loss fraction.

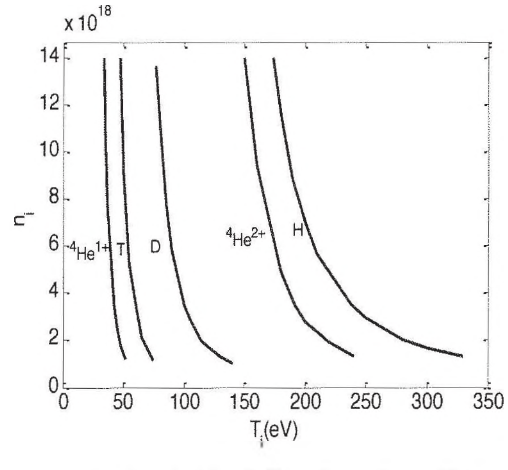

Fig 5 Threshold of T_i and n_e for self-sustaining growth of Er in the *L* point neighborhood

The threshold for the self-sustaining growth of *Er* is shown as a function of T_i and n_e for different type of ions in Fig 5. Only when the edge plasma parameters T_i and n_e exceed the threshold, a self-sustaining growth in *Er* is found. The threshold is lower for the ions with the higher mass number or smaller electric charge number.

The effect the toroidal field B_t on the threshold is shown in Fig. 6, where threshold for the self-sustaining growth of *Er* is shown as a function of T_i and n_e for B_t = 1 and 2T, respectively. The threshold is higher with increasing B_t.

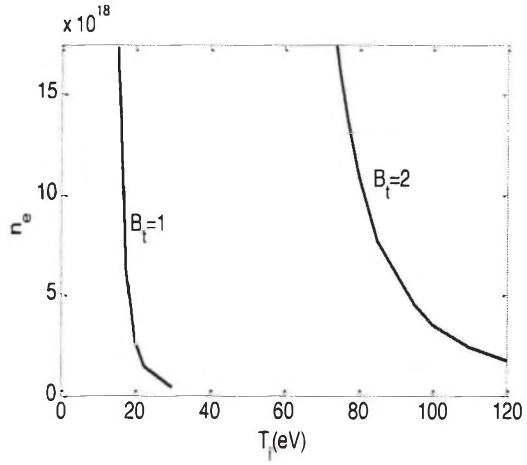

Fig. 6 The effect of B_t on the threshold.

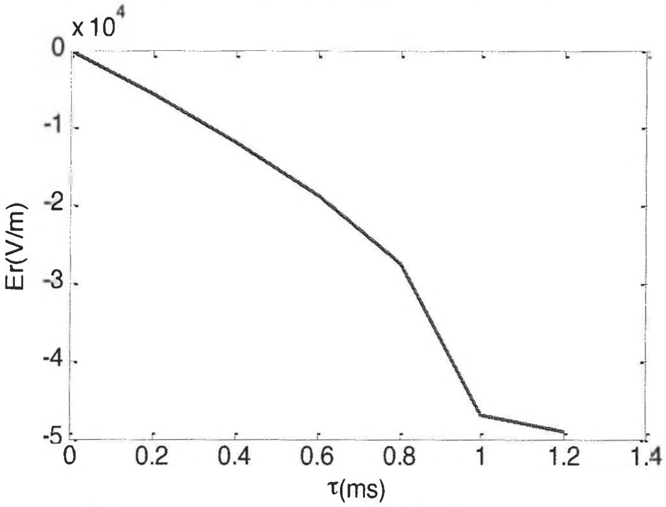

Fig. 7 Corresponding to figure 3, *Er* versus time

Assuming that the ion temperature and density at 1 cm inside the *L* point are 1.2 times of those at *L* point, the calculated *Er* profiles for different ion temperature are shown in Fig. 8. Here the *Er* profiles within the *Lr* region are simply assumed to be a linear function of the minor radius, and the value of *Er* at the LCFS is assumed to be zero, as mentioned above. It is seen that only a low value of Er is obtained for low ion temperature at L point, T_L=70eV and 80eV. However, a much larger Er is found for a slightly higher ion temperature, T_L=85eV, indicating a bifurcation in *Er* with increasing ion temperature. The values of *Er* decrease sharply with decreasing the minor radius, indicating that a strong *Er* can be formed only in a few cm inside the LCFS due to ion orbit loss, in agreement with H-mode experimental results [16].

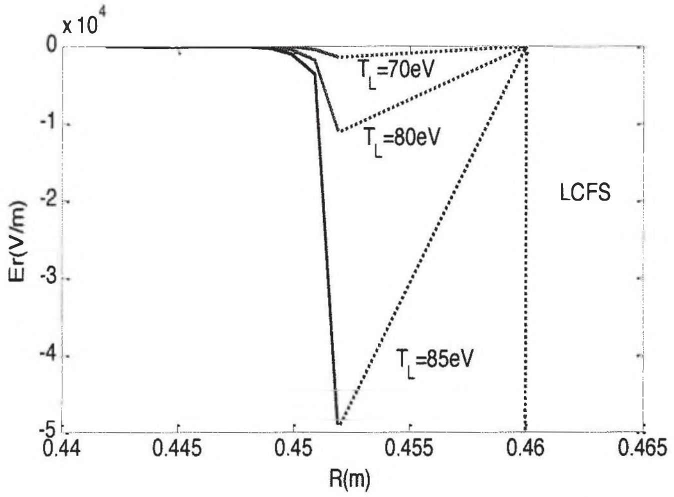

Fig. 8 The *Er* profiles for the different ion temperature and density inside the LCFS.

L-H mode transition as a bifurcation phenomenon has been manifested in all experiments if a heating power threshold is exceeded, and a strong negative *Er*, in the order 10^4-10^5V/m, is observed inside the LCFS in milliseconds after L-H transition, indicating a self-sustaining growth of the *Er* during the transition. The heating power threshold for L-H transition corresponds to a threshold in the edge ion temperature for the same ion density or a threshold in the ion density for the same temperature. Our results show that, if the edge ion temperature and density are sufficiently high, there is a self-sustaining growth in the radial electric field due to the interaction between the ion orbit loss and the radial electric field, and the ion loss fraction can reach the order 1/1000 in edge region, leading to a strong negative *Er* in milliseconds, as seen in the experiments. The results shown in Fig.5 and Fig.6 are consistent with ASDEX Upgrade experimental results[15], which demonstrate a similar dependence of the L-H transition threshold on the ion temperature and density. Regarding the isotope effect for L-H transition, a larger ion mass is found to correspond to a lower threshold for the self-sustaining growth in Er as seen from Fig. 5, being in agreement with experiment observation [17,18]. In ^{4}He discharges, usually there is also a considerable fraction of $^4\mathrm{He}^{1+}$ ions in the plasma edge [19], so the power threshold changes from a lower value to a higher one with increasing $^4\mathrm{He}^{1+}$ fraction. Our results predict that, if the ions are all $^4\mathrm{He}^{1+}$ in the edge, the threshold is less than that of D plasmas; while for pure $^4\mathrm{He}^{2+}$ ions, the threshold will be higher, being in agreement with JET experimental results [18]. These can give a reasonable explanation about the variability of the L-H transition power threshold in a helium-4 discharge in Ref. [20]. If the plasma temperature *T* is proportional to the heating power and the toroidal field B_t, the effect of the toroidal field on the threshold as shown in Fig. 6 is in line with experimental results. Our results extend the early understanding about the bifurcation of *Er* [9,14].

By scanning over the plasma density in experiments, it is found that there is a minimum in the power threshold for L-H transition in the low plasma density regime. Our results is more relevant for the low plasma density regime, since ion collisions have not been taken into account in our model, and which could be important for plasmas with high edge density. The collisional effect will be further considered in our future work.

In summary, a self-sustaining growth in radial electric field due to its interaction with the ion orbit loss is found for a sufficiently high edge ion temperature and density. The ion loss fraction reaches the order 0.1% in edge region, leading to a strong local negative *Er* as seen in H-mode experiments. The obtained results can explain some important features of experimental findings, such as the threshold power for L-H transition, the L-H transition time, isotope effect, and the radial width of *Er*.

This work is supportsed by the Natural Science Foundation of China (No. 11175210).

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