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Fast generation of an inward electric field due to ion orbit losses in the tokamak edge plasma during transition from low-to-high confinement

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Abstract
The formation of radial electric field E_r in the tokamak edge region is calculated based on the collisionless ion orbit loss. The ion orbit loss generates a negative E_r, which in turn affects the ion loss. As a result, E_r can saturate 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 ion loss and E_r is found, leading to a high saturation value of E_r in milliseconds. This mechanism provides a possible explanation for the formation of a strong radial electric field during the transition from the low (L) to the high (H) confinement regime observed in tokamak edge plasmas.

Keywords: ion orbit loss, negative radial electric field, self-sustaining growth, L–H transition

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

1. Introduction

The formation of a radial electric field and related spontaneous plasma rotation in fusion devices are of considerable interest in plasma physics. The underlying mechanism is not well understood despite extensive experimental and theoretical efforts devoted to it. It is well known that intrinsic plasma rotation exists even in ohmic tokamak discharges without momentum input. In L-mode plasmas only a weaker radial electric field has been observed. During the L- to H-mode transition, however, a strong negative radial electric field E_r is formed in milliseconds, and the resulting E_r 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]. It has been a long standing challenge to find a proper non-ambipolar transport mechanism which can lead to such a bifurcation in E_r inside the LCFS during an L–H transition. Numerous theoretical explanations have been proposed for the change in edge E_r structure observed in H-mode formation [5]. Ion loss theory suggested that the production of the negative well structure in the radial electric field is caused by a non-ambipolar transport mechanism in the tokamak edge. Hamiltonian guiding centre simulations show that a local E_r can be generated in a thin layer just inside the separatrix because of ion orbit loss [6, 7], and the E_r shear is found to reach a high value [8, 9]. However, a spontaneous bifurcation in E_r has not yet been revealed.

In the tokamak edge region, the non-ambipolar radial particle transport is also affected by the microscopic instabilities in addition to the ion orbit loss. Studies indicate that these instabilities can cause enhanced radial electron transport [10, 11]. According to the non-ambipolar ion and electron losses, Itoh and Itoh have proposed an L–H transition model, in which the bifurcation phenomena and critical condition are deduced [10]. However, they concluded that depending on the assumption a more positive value of E_r also was found to correlate with the improved plasma confinement.

As the bifurcation in the edge radial electric field is one of the most important characteristics in the L–H transition, in this paper a new model based on the ion orbit loss together with plasma turbulence transport just inside the LCFS is considered. The interaction between the radial electric field and ion orbit loss is taken into account in our calculations. It is found that if the ion temperature in the plasma edge region is higher than a threshold, a self-sustaining growth in the ion loss and E_r is triggered, and E_r saturates at a high value in milliseconds. In the opposite case, E_r attains only a lower saturation value. Such a bifurcation in E_r provides a possible explanation for the L–H mode transition.

2. The ion loss model

An equilibrium magnetic field for a single null divertor configuration, obtained from EFIT code, is used with the following parameters: plasma major radius $R_0 = 1.75\,\text{m}$, minor radius $a = 0.46\,\text{m}$, elongation $\kappa = 1.7$, tri-angularity $\delta = 0.56$, plasma current $I_p = 1\,\text{MA}$ and toroidal field $B_0 = 2\,\text{T}$. Ions are launched at the L point 1 cm inside the LCFS in the horizontal midplane to analyse the loss region of escaped ones in the initial velocity space. The choice of the launch point is based on the existing results that the plasma turbulence transport is important, when it intersects the LCFS, and could lead to locally enhance radial electron and ion flux [12]. Experiment shows that the ion transport coefficient χ_i and the electron transport coefficient χ_e satisfy $\chi_i \sim (1-10)\,\chi_i^{NC}$, $\chi_e \sim 100\chi_e^{NC}$, $\chi_i \sim \chi_e$, where χ_i^{NC} and χ_e^{NC} are the neoclassical ion transport coefficient and the electron transport coefficient, respectively. In the edge plasma turbulence region, the ion orbit loss cannot form a strong negative E_r because of the electron turbulence transport, which can prompt the anomalous electron flow to go into the scrape-off layer (SOL) or arrive at the divertor plate, and there is only a weak E_r oscillation. So only when there are sufficient ion losses inside, exceeding the edge turbulence region, can a strong E_r be formed. The edge plasma turbulence region is determined by the radial correlation length of plasma edge turbulence, L_r, which is measured to be about 1 cm on ASDEX Upgrade [13]. Therefore, the launch point is chosen at the L point 1 cm inside the LCFS in the horizontal midplane, and in the simulations it is assumed that the electron loss is equal to or even greater than the ion loss due to the plasma turbulence within the L_r region during the formation of the negative E_r.

First the collisionless ion orbit loss is considered. Using the guiding centre approximation and assuming the conservation of ion energy, the magnetic moment μ and the toroidal angular momentum P_Φ [14]

$$E = \frac{1}{2}mv^2 + Ze\Phi \tag{1}$$

$$\mu = \frac{mv_\perp^2}{2B} \tag{2}$$

$$p = \psi(R, Z) - \frac{Rv_\parallel m}{Ze}, \tag{3}$$

where Φ is the electrostatic potential, $P = mP_\Phi/(Ze)$, $\psi(R, Z)$ is the poloidal magnetic flux, $\psi = \Psi/(2\pi)$ is the poloidal magnetic flux function, $B \approx B_t = B_0R_0/R$. Merging the above polynomials, there is

$$\left(1 + \frac{Ze\Delta\Phi}{1/2mv^2}\right)R^2 - RR_b - \kappa^2(\psi - p)^2 = 0, \tag{4}$$

where $R_b = 2\mu B_0R_0/(1/2mv^2)$, $\kappa = Ze/(mv)$, $\Delta\Phi$ is the electric potential difference between the initial place and the ultimate place. The guiding centre orbit in (R, Ψ) phase space can be confirmed from equation (4). In the edge region of a tokamak, if an ion at the L point can escape from the X point to the moment, then it will satisfy

$$v_{\parallel L} = v\sqrt{1 - \frac{R_b}{R_L}} \tag{5}$$

$$v_{\parallel X} = \pm v\sqrt{1 - \frac{R_b}{R_X} + \frac{Ze\Delta\Phi}{1/2mv^2}} \tag{6}$$

$$\Delta\psi_L = \frac{m}{Ze}(v_{\parallel L}R_L - v_{\parallel X}R_X), \tag{7}$$

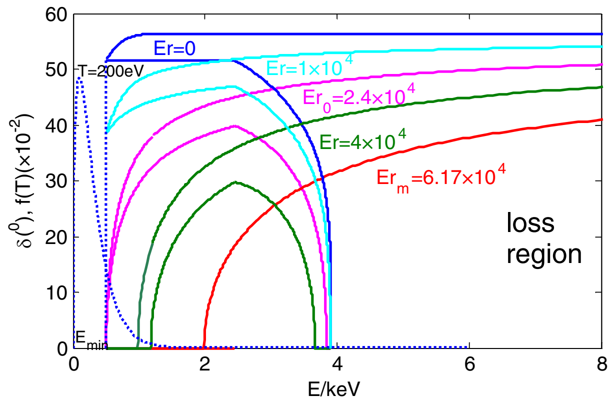

Figure 1. Change in the deuterium ion loss region in the velocity space for different negative E_r (unit of E_r is V m^{-1}) and the Maxwellian energy distribution of deuterium ion with $T_i = 200\,\text{eV}$ (dotted line), where E_{r_0} represents the E_r in which the nose region is prolonged longest and E_{r_m} represents the E_r in which the nose region disappears exactly.

where $v_{\parallel L}$ is the parallel velocity of a critical ion at the initial place. It will be $v_{\parallel X}$ when it arrives at the X point. $\Delta\psi_L$ is the difference in the value of the poloidal magnetic flux function between the L point and the X point. According to equations (5)–(7) the ion orbit loss region in the initial velocity space can be obtained. Figure 1 shows the change in the ion loss region in the velocity space for different values of negative E_r, where δ is the angle between the direction of ion motion and that of the magnetic field line, E is the ion energy, and the plasma current direction is opposite to that of the toroidal magnetic field. Initially, ions are assumed to have a Maxwellian distribution and be located at a launch point L. The lost ions 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. Only when the ion energy in the Maxwellian distribution is more than the minimum energy E_{min} and the ion pinch angle satisfies a certain condition can the ion be lost. When there exists a negative E_r, the loss region will change significantly since the ion drift orbit is affected by the electric drift in addition to the magnetic field gradient/curvature drift. In the calculations, a potential Φinside the LCFS is introduced as $\Phi = A\psi^2 + B\psi + C$, where A, B and C are constants. If the negative $E_r < E_{r_0}$, with the increase in negative E_r the nose region [14] (the long and narrow part on the left part of the loss region) is prolonged to smaller δ values and becomes narrow. When $E_r = E_{r_0}$, the nose region becomes the longest, and then it will be squashed. When $E_r = E_{r_m}$, it disappears exactly. The ions in the nose region are all big banana particles. The ion orbit loss in the nose region has a very high ratio, which is affected by the ion temperature. For deuterium plasmas with an ion temperature $T_i = 200\,\text{eV}$ at the L point, almost all the loss ions come from the nose region.

Corresponding to figure 1, E_{min} is shown in figure 2 as a function of the radial location of the launch point in the horizontal midplane on the low-field side. E_{min} increases with increasing distance from the LCFS. The edge plasma turbulence region is marked the 'ion loss region and electron loss region' in figure 2. In the inner part extending from the left edge of the L_r region towards the magnetic axis, marked

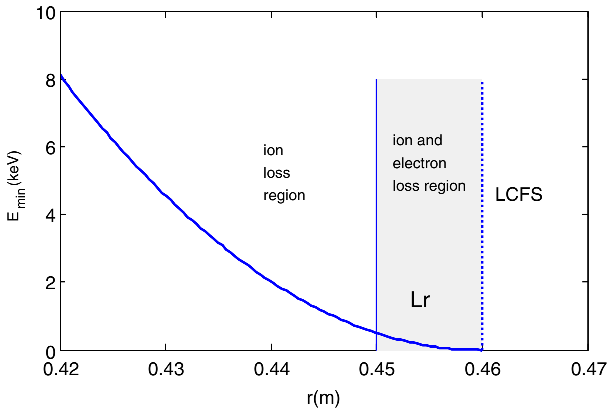

Figure 2. Minimum ion energy E_{min} required for ion loss versus the location of the ion launch point on the low-field side in the horizontal midplane (solid curve). The radial particle flux is assumed to be also affected by plasma turbulence inside the 'ion loss region and electron loss region' with a radial width L_r, and the ion orbit loss in the 'ion loss region' leads to an additional radial ion flux.

the 'ion loss region' in figure 2, the ion orbit loss leads to an additional radial ion flux, which is not compensated for by the local radial electron transport caused by plasma turbulence.

In the launch point neighbourhood region, the number of ions in the loss region Γ_{orbit} is given by

$$\Gamma_{orbit} = n_i \int_{\text{loss region}}\int f(T)\, d\delta\, dT, \qquad (8)$$

which can be obtained by a Monte Carlo simulation, where n_i is the ion density, $f(T)$ is the Maxwellian energy distribution. The fraction of deuterium ions in the loss region, $\eta = \Gamma_{orbit}/n_i$, is shown in figure 3 as a function of the negative E_r. It is seen that the number of ions in the loss region increases steadily with the increase in the negative E_r until a critical value E_{r_c}, which is only slightly larger than the E_{r_0} shown in figure 1. The fact that the existing negative E_r might enhance the ion losses and might increase the amplitude of the potential step has also been found in [15]. For $E_r > E_{r_c}$, the lost ion fraction decreases sharply. The loss ion fraction is smaller for a lower ion temperature, but its changes in the negative E_r are the same as those at a higher ion temperature.

In figures 1–3 the ion loss is only calculated at the L point as mentioned above. With the magnetic configuration used here, the loss fraction changes with the poloidal location of the launch point along the magnetic surface. The averaged ion orbit loss on the same magnetic surface is found to be about 1/8 of that on the low-field side by measuring the loss fraction at a different poloidal location of the launch point on the same magnetic surface.

The ion orbit loss can lead to the formation of a negative E_r. During the formation of the negative E_r, ion loss is a continuous process. The negative E_r makes the loss region continuously change before saturation appears. The negative E_r and ion loss are interrelated and depended on each other. A very small increment of dE_r comes from the ion loss $d\Gamma_{loss}$ at a certain hour, and the dE_r will change the ion loss region and lead some new ions $d\Gamma_{in}$ to go into the loss region. Simulations show that if the plasma edge parameter T_i profile and the n_i

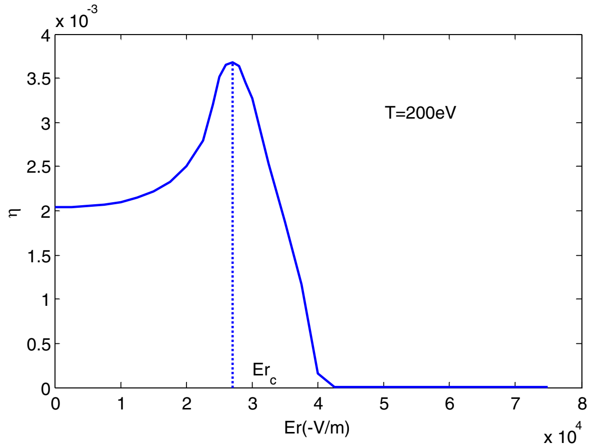

Figure 3. Fraction of deuterium ions in the loss region versus negative E_r for $T_i = 200$ eV.

profile satisfy certain threshold conditions, the new loss ions $d\Gamma_{in}$ are always more than the foregoing loss ions $d\Gamma_{loss}$, i.e. the equation

$$d\Gamma_{in} \geqslant d\Gamma_{loss} \qquad (9)$$

can be achieved before the saturation appears; a self-sustaining growth mechanism of the ion orbit loss and the negative E_r will be triggered, as a result E_r will reach a very high saturation value in a very short time. The increase in the ion loss fraction with the increase in the negative E_r before E_{r_c} shown in figure 3 also indicates the possibility of the self-sustaining growth. If equation (9) cannot be satisfied, $d\Gamma_{in}$ will decrease continuously. A dwindling process of the ion orbit loss and the negative E_r will occur, and the E_r will only reach a very low saturation value. If equation (9) is satisfied just when $E_r = E_{r_c}$, then the corresponding temperature and density are called threshold conditions for the self-sustaining growth mechanism.

To simplify the calculation of the self-sustaining growth process, the following assumptions are made which do not affect the general characteristics of our results: (1) plasma is electrically neutral at the initial time, (2) the radial electrical field is zero at the LCFS and linearly increases towards the launch point within the L_r region because the radial particle flux is also affected by plasma turbulence, as shown in figure 2, (3) the ion temperature and density linearly decrease from the inner region towards the LCFS.

Under the above assumptions, at given temperature and density profiles the radial E_r profile can be obtained by iteratively solving the Poisson equation. In figure 4, the ion orbit loss fraction η is shown as a function of time for the ion density $n_i = 0.85 \times 10^{19}$. When the ion temperature is lower than the threshold, the loss fraction decreases with time, as shown by curve 1. Only when the ion temperature is higher than a threshold can the self-sustaining growth process in the ion loss fraction be triggered (curve 2). After a peak loss fraction with $\eta = 0.011\%$, the ion loss fraction decreases due to the formation of a strong radial electric field.

The ion loss time varies widely depending on its location in the velocity space. Also during the formation of E_r the ion loss time can decrease with the increase in E_r. So we consider a statistical orbit loss time τ_l to be the time for half of

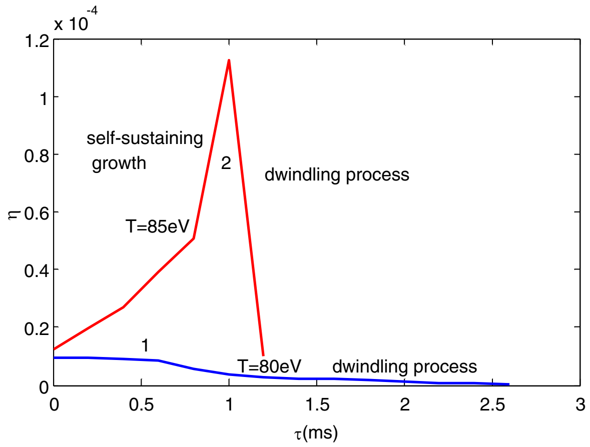

Figure 4. Time evolution of the ion orbit loss fraction η. There is a bifurcation in the η value. Only a sufficiently high ion temperature (curve 2) leads to a high value of η.

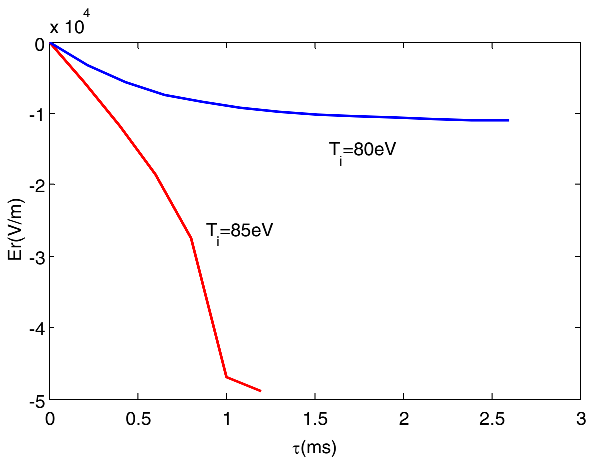

Figure 5. Corresponding to figure 3, E_r versus time for $T_\mathrm{i} = 85$ and 80 eV.

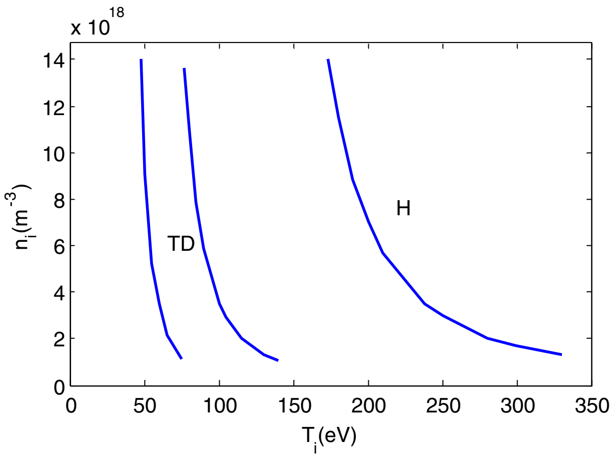

Figure 6. Threshold of T_i and n_i for self-sustaining growth of E_r in the L point neighbourhood.

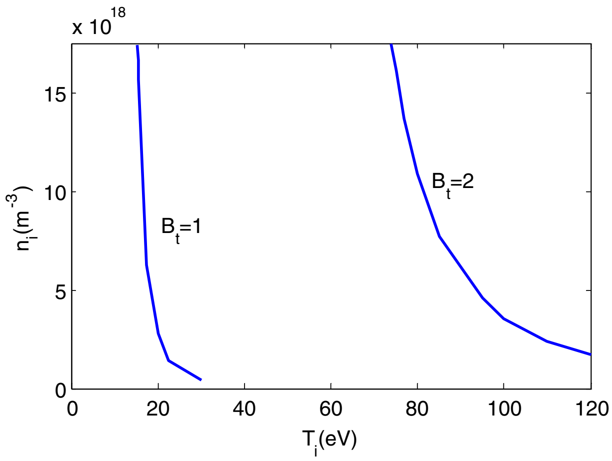

Figure 7. Effect of B_t on the threshold (D is considered).

the ions in the loss region to escape beyond the horizontal X plane. The change in the radial electric field as a function of time, corresponding to the self-sustaining growth of η shown by curve 2 in figure 4, is shown in figure 5. E_r saturates at a high value in milliseconds. While for a lower ion temperature, $T_\mathrm{i} = 80$ eV, only a low value of E_r is formed. The time period of the self-sustaining growth in E_r is usually found to be in the order of milliseconds.

In addition to the effect of edge ion temperature on the E_r bifurcation, as shown in figure 6, the ion density also affects the results. In the simulations, it is assumed that the negative E_r at the L point due to ion orbit loss is linearly proportional to the ion loss fraction in the L point neighbourhood during the calculation of the threshold conditions of the self-sustaining growth. The actual E_r is of course a nonlinearly increasing function of the ion orbit loss fraction in the L point neighbourhood, but our calculations have shown that the above assumption has no effect on revealing the self-sustaining growth process of E_r because the ion loss in the self-sustaining growth is greater above an order of magnitude than the ion loss in the more inner layer magnetic surface. The threshold for the self-sustaining growth of E_r is shown as a function of T_i and n_i for different types of ions in figure 6. Only when the edge plasma parameters T_i and n_i exceed the threshold is a self-sustaining growth in E_r found. The threshold is lower for the ions with a higher mass number.

The effect of the toroidal field B_t on the threshold is shown in figure 7, where the threshold for the self-sustaining growth of E_r is shown as a function of T_i and n_i for $B_\mathrm{t} = 1$ T and 2 T, respectively. The threshold is higher with increasing B_t.

Assuming that the ion temperature and density at 1 cm inside the L point are 1.2 times those at the L point, the calculated E_r profiles for different ion temperatures are shown in figure 8. Here the E_r profiles within the L_r region of plasma turbulence are simply assumed to be a linear function of the minor radius, and the value of E_r at the LCFS is assumed to be zero as mentioned above. When $n_\mathrm{L} = 0.85 \times 10^{19}$ it is seen that only a low value of E_r is obtained for a lower ion temperature at the L point, $T_\mathrm{L} = 70$ and 80 eV. However, a much larger E_r is found for a slightly higher ion temperature, $T_\mathrm{L} = 85$ eV, indicating a bifurcation in E_r with increasing ion temperature. The values of E_r decrease sharply with decreasing minor radius, indicating that a strong E_r can be formed only in a few cm inside the LCFS due to ion orbit loss and radial correlation length L_r of plasma turbulence, in agreement with H-mode experimental results [16].

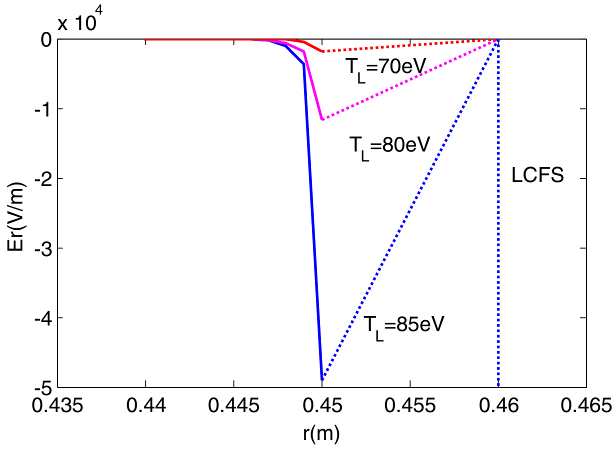

Figure 8. E_r profiles for different ion temperatures inside the LCFS (D is considered).

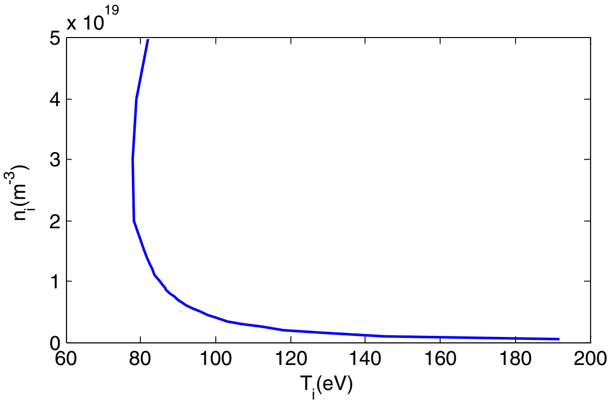

Figure 9. Deuterium threshold of T_i and n_i for the self-sustaining growth of E_r in the L point neighbourhood considering collisionality.

3. Collision effect

In section 2, we have given the basic physical image of the formation mechanism of the negative E_r owing to the collisionless ion orbit loss. However, an actual ion loss process is both collisional and collisionless [6]. Thermal ions in the loss region experience frequent pitch angle scattering into and out of the loss region before they reach the separatrix surface. In a thermal equilibrium the number of ions scattered into the loss region from outside are the same as those scattered out of the loss region in a large time interval. If the loss region has no change or only has a slight change, the collision refilling effect will appear—some ions refill into the empty loss region by collision. In low collisionality, the ion loss time is lower than the collision time. Moreover, during the self-sustaining growth of the negative E_r the loss region changes rapidly under the effect of the changed E_r. When ions refill into the original loss region, they cannot become lost ions because of the change in the loss region. So in the calculations the collision refilling effect can be neglected. Another collision effect is to reduce the ion loss. If a loss ion collides in a loss period in the rapid change process of the loss region, then it can be considered to be no longer lost.

In the self-sustaining growth, as shown in figure 4, the ion loss time τ_l is about 0.4 ms, and the ion collisionality time in the loss region is greater than 1.3 ms, so the ion loss is collisionless. However, many ions in the loss region cannot be lost because of collision, especially for high collisionality, and the self-sustaining growth cannot be triggered with the earlier given plasma parameters. But if the temperature T_i increases and there is enough collisionless ion orbit loss the self-sustaining growth can still be triggered. Considering collisionality, the ion loss is given as

$$\Gamma_{\mathrm{loss}} = \Gamma_{\mathrm{orbit}} - \Gamma_{\mathrm{col}}, \qquad (10)$$

where Γ_{col} is the number of collisional ions, which can be obtained by Monte Carlo simulation. The effect of collision on the deuterium threshold of T_i and n_i for self-sustaining growth of E_r in the L point neighbourhood is shown in figure 9. At a low ion density, the ion loss time is much less than the ion collision time in the loss region, and almost all the loss ions are collisionless. The threshold T_i can decrease with an increase in n_i and the threshold curve of T_i and n_i is the same as that in figure 6. At a high density, many ions cannot be lost because of collision in the loss region. In particular, when the collision time in the loss region is close to the ion loss time, the increase in n_i can reduce the ion loss, so T_i has to increase to ensure sufficient ion loss. At a very high ion density, the physics is more complex, which will be further considered in our future work.

4. Discussion and summary

The 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 E_r, in the order 10^4–$10^5\,\mathrm{V\,m^{-1}}$, is observed inside the LCFS in milliseconds, indicating a self-sustaining growth of E_r during the transition. The heating power threshold for the 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 and there are enough ion losses inside the width L_r of the LCFS, a self-sustaining growth in the radial electric field can be triggered due to the interaction between the ion orbit loss and the radial electric field, leading to a strong negative E_r in milliseconds, as seen in the experiments. The results shown in figures 6 and 7 are consistent with ASDEX Upgrade experimental results [17], which demonstrate a similar dependence of the L–H transition threshold on the ion temperature and density. Our results also reveal the critical role of L_r; only when the region width of the numerous ion losses exceeds L_r can a strong negative E_r be formed, and this also implies that the width of the H-mode is associated with L_r, about 1–2 cm. Regarding the isotope effect for the L–H transition, a larger ion mass is found to correspond to a lower threshold for the self-sustaining growth in E_r, as seen in figure 6, being in agreement with experimental observation [18, 19]. If the plasma temperature is proportional to the heating power and the toroidal field B_t, the effect of the toroidal field on the threshold, as shown in figure 7, is in line with experimental results. Concerning the effect of collisionality, the threshold conditions of the self-sustaining growth mechanism are the same as the results found in [20, 21]. Our results extend the early understanding about the bifurcation in E_r [9, 22].

In summary, a self-sustaining growth in the 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 region inside exceeds the edge turbulence region and the ion loss fraction reaches the order 0.1% in the edge region, leading to a strong local negative E_r as seen in H-mode experiments. The obtained results can explain some important features of experimental findings, such as the threshold power for the L–H transition, the L–H transition time, the isotope effect, the effect of the toroidal field, the radial width of E_r, and the temperature and density threshold relation.

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