Momentum-space analysis of suprathermal electrons generation under conditions of gas puffing during runaway tokamak discharges

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1. Introduction

The energy of disruption generated runaway electrons can reach as high as tens of mega-electron-volt energy and they can cause a serious damage of plasma-facing-component surfaces in large tokamaks like ITER [1]. The precise measurement of runaway electron parameters during disruptions is not so easy to carry out. At the same time, the quiescent runaway electron generation during the flat-top of DIII-D low density Ohmic discharges allows accurate measurement of all key important parameters to runaway electron excitation [2, 3]. Precise measurements of RE distribution functions and dissipation rates in the spatial, temporal and energy domains were carried out, a new effective diagnostic called the "Gamma Ray Imager" was applied. Quantitative discrepancies between experimental measurements and modeling were found for all RE energies, but the most qualitative discrepancy was found at low energy.

Our analysis of electron trajectories in the 2-D runaway region ($p_{\parallel}, p_{\perp}$) shows that the suprathermal electron population with $p_{\parallel} < p_{\perp}$ occurs ($p_{\parallel}$ and $p_{\perp}$ are longitudinal and transversal components of momentum with respect to the confining magnetic field, respectively). In this case, the suprathermal electrons, which are trapped in a non-uniform magnetic field, may appear in tokamak [4]. A possibility of formation of such suprathermal electrons during recent DIII-D experiments [2, 3] is investigated in the report.

2. Momentum-space analysis of suprathermal electrons generation

In DIII-D, the parameters of REs were investigated during flat-top stage of low density Ohmic discharges with the next parameters: toroidal magnetic field was B_t = 1.4T, plasma current was I_p = 0.8 MA and loop voltage was V_{loop} = 0.6 V [2, 3]. In these experiments near the end of the discharge, strong gas puff was used, which cause variations in the REs. During this puffing the value of plasma density increased approximately from the value of $n_e \approx 0.5\ 10^{-13} \cdot \mathrm{cm}^{-3}$ to the value of $n_e \approx 1.5\ 10^{-13} \cdot \mathrm{cm}^{-3}$ and the ion effective charge $Z_{eff}(t)$ dropped from the value of 2 to 1.25.

In the report, we model this situation. To qualitatively study, the behavior of electron trajectories in runaway region during the gas puff duration ($\tau \approx 0.5$ s), the plasma parameter evolution in time is given by the next equations:

$$n_e(t/\tau) = n_e(0) + \left(n_e(1) - n_e(0)\right) t/\tau, \qquad (1)$$

$$Z_{eff}(t/\tau) = Z_{eff}(0) + \left(Z_{eff}(1) - Z_{eff}(0)\right) t/\tau, \qquad (2)$$

where $n_e(0)$ = 0.5 $10^{-13}\cdot$cm^{-3}, $n_e(1)$ = 1.25 $10^{-13}\cdot$cm^{-3}, $Z_{eff}(0)$ = 2, $Z_{eff}(1)$ = 1.25.

We use 2-D equations (like [5]) of test electrons in normalized form:

$$\frac{dp_{\|}}{dt} = \tau \frac{eE_{\|}}{p_{cr0}}\left(1 - n_e(t)\left(Z_{eff}(t)+2\right)\frac{p_{\|}}{\left(p_{\|}^2+p_{\perp}^2\right)^{3/2}}\right), \tag{3}$$

$$\frac{dp_{\perp}^2}{dt} = 2\tau \frac{eE_{\|}}{p_{cr0}}\frac{n_e(t)}{\sqrt{p_{\|}^2+p_{\perp}^2}}\left(\left(Z_{eff}(t)+2\right)\frac{p_{\|}^2}{p_{\|}^2+p_{\perp}^2} - 1\right), \tag{4}$$

where $p_{\|,\perp} \rightarrow p_{\|,\perp}/p_{cr0}$, the electron density $n_e(t) \rightarrow n_e(t)/n_e(0)$, $t \rightarrow t/\tau$, $E_{\|}$ is the toroidal electric field, e, m_e are the charge and rest mass of electron, respectively, L is the Coulomb logarithm ($E_{\|}$ = 50 mV/m, L = 15) and

$$p_{cr0}^2 = 4\pi e^3 m_e n_e(0) L / E_{\|}. \tag{5}$$

Here we analyze the suprathermal region that is why the acceleration due to the toroidal electric field and the effect of the collisions with the plasma particles are taken into account in Eqs. (3) and (4) only.

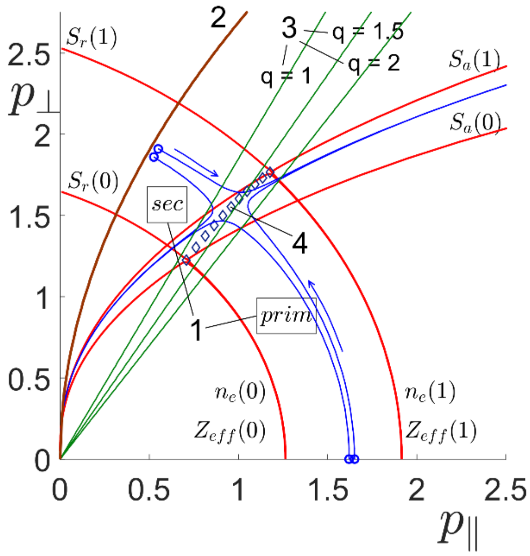

Fig. 1. The primary and secondary runaway regions (1) are presented (normalized variables are used); $S_r(0,1)$ and $S_a(0,1)$ (red) are separatrixes [5, 6] for plasma parameters at t = 0 or t = 1. The curve $p_{\perp} = \sqrt{(2m_e c/p_{cr0})p_{\|}}$ is shown by brown (2), the locus of the knocked-on electrons lies below this curve. Straight lines $p_{\perp}/p_{\|} = 1/\sqrt{2\varepsilon}$ (q = 1, 3/2, 2) are marked by green (3). Typical test electron trajectories (flowing around "virtual" saddle point ($p_{\|,S}, p_{\perp,S}$)) are shown by blue dots correspond to starting points at t = 0.5, directions of electron motion are shown by arrows. The evolution of the "virtual" saddle point location in time is shown by dark blue (4).

3. Discussions

For constant values of parameters n_e and Z_{eff} at t = 0 and 1 the separatrixes $S_r(0,1)$ and $S_a(0,1)$ separate trajectories of test electron by usual way [5, 6]. For 0 < t < 1 these parameters n_e and Z_{eff} are not constants, the dynamic situation takes place. Coordinates of the saddle point ("virtual" saddle point) change in time:

$$p_{\perp,S}^2(t) = n_e(t)\left(Z_{eff}(t)+1\right)/\sqrt{Z_{eff}(t)+2}, \tag{6}$$

$$p_{\|,S}^2(t) = n_e(t)/\sqrt{Z_{eff}(t)+2}. \tag{7}$$

For trajectories near "virtual" saddle point the inequality $p_{||} < p_{\perp}$ holds and the motion of electrons here is not so fast in 2-D plane (~ (0.06-0.1)τ).

Recall, in accordance with the conservation laws of energy and momentum, the knocked-on electrons of secondary generation are arranged on elongated ellipses, the major axes of which are equal to the momentum of the incident mega-electron-volt electrons. Secondary runaway region in the phase space ($p_{||}, p_{\perp}$) is filled by these ellipses. This region is bounded from the top by the curve (see, e.g. [4])

$$p_{\perp} = \sqrt{(2m_e c / p_{cr0}) p_{||}} \, . \tag{8}$$

Straight lines

$$p_{\perp} / p_{||} = 1 / \sqrt{2\varepsilon} \tag{9}$$

for the values of safety factor q=1, 3/2 and 2 are shown in Fig. 1 ($\varepsilon = r/R$, the data from Fig. 2h of Ref. 2 are used). The practically the entire range of locus of the knocked-on electrons in ($p_{||}$, $p_{\perp}$) lies above straight lines of Eq. (9), it is possible to expect that they will be trapped in a non-uniform tokamak magnetic field. At $t > 0.5$ the crossing of saddle point curve with the q = 3/2 straight line is visible, hence, here the decreasing probability of such trapping is possible.

As it is clear from analysis for primary test electron trajectories in Fig. 1, the probability of such trapping in a non-uniform magnetic field is not so high for these electrons.

Note, the strong inequality $\omega_{bs} >> \nu_{effcoll}$ holds, where ω_{bs} is the oscillation frequency of the bounce motion of trapped suprathermal electrons in a non-uniform magnetic field and $\nu_{effcoll}$ is the effective collision frequency (regime of banana trajectories). Ratio $\omega_{bs} / \nu_{effcoll}$ can reach about five orders of magnitude. The pitch angle was taken into account in estimation of the value of $\nu_{effcoll}$.

It is necessary to distinguish situation on the outer and inner sides of the tokamak discharge. The suprathermal electrons are trapped in the low field region, more strong losses of these trapped electrons occur from the plasma region where these electrons are located (outer part of discharge). It is possible even formation of supertrapped electrons (on the ripples of a longitudinal magnetic field) which escape from the plasma owing to toroidal drift.

The runaway energy $E \geq 25$ MeV was deduced in Ref. [2] from the DIII-D experimental data analysis. It means that in the DIII-D experiment [2, 3] the secondary runaway generation process should take place with avalanching time t_{av} [6]

$$t_{av} \approx \sqrt{12} m_e c L (2 + Z_{eff}) / 9 e E_{||} \, . \tag{10}$$

For the DIII-D experiments [2] $t_{av} \approx 1$s. The value of $t_{av} \approx 1$s is the same order of the value of duration of gas puff ($\tau \approx 0.5$ s). However, because of the trapping of the knock-on electrons, the avalanching process may be suppressed in part.

Recall, due to the radial viewing geometry of the ECE radiometers on DIII-D, these diagnostics probe the high pitch-angle RE population [2, 3]. This non-thermal electron cyclotron emission (ECE) must be strongly enhancement due to existence of the suprathermal electron population with high values of the $p_{\perp}$ momentum, $p_{\perp} > p_{||}$.

Our comment to Fig. 14 in [2] and Fig. 3 in [3], where ECE emission signal drop was observed after exceeding of a pre-set trip level. In our opinion, the more detail study of the influence of the trapped suprathermal electrons on the plasma stability is needed (see, e.g. Chapter 16 in Ref. 7). Detail investigations of such instabilities for suprathermal electrons are planned in the future.

In the DIII-D case [2], the inequality $3E_{CH} < E_{\|} < 5E_{CH}$ holds, where $E_{CH} = 4\pi e^3 n_e L / m_e c^2$ [8]. That it is why the nonrelativistic Eqs. (3, 4) are used. It was verified that presented results obtained from relativistic equations practically coincided with nonrelativistic one.

4. Summary

The analysis of electron trajectories in the 2-D runaway region ($p_{\|}$, $p_{\perp}$) are carried out for parameters close to the DIII-D experiments [2, 3]. The formation population of suprathermal electron with $p_{\|} < p_{\perp}$ is investigated (phenomenon is strong for knocked-on electrons) during gas puffing, when plasma density n_e and Z_{eff} are changed in time. Such population exists also before gas puff, but during gas puff, the test electron trajectories are modified in comparison with case of constant plasma parameters.

Main conclusions:

- The trapping of suprathermal electrons in non-uniform magnetic field must be taken into account.
- Additional losses of such electrons must take place from outer part of discharge.
- The ECE signal must be strongly enhancement due to existence of the suprathermal electron population with a high value of transversal momenta, when $p_{\perp} > p_{\|}$.
- The plasma instability on trapped suprathermal electrons may occur and take effect on such electrons loss, on the ECE signal behavior and the RE distribution function changes in the region of low energies.

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