MOMENTUM-SPACE ANALYSIS OF SUPRATHERMAL ELECTRONS GENERATION UNDER CONDITIONS OF GAS PUFFING DURING RUNAWAY TOKAMAK DISCHARGES

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Using the 2D test particle description, that includes acceleration in the toroidal electric field and collisions with the plasma particles, the generation of suprathermal electrons is analyzed under conditions of working gas puffing close to the Doublet III-D (DIII-D, General Atomics, USA) quiescent runaway shot #152895 parameters. As the result of close collisions, the formation of trapped suprathermal electron population in a nonuniform tokamak magnetic field has been shown.

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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 (RE) 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 2D 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 paper.

1. RUNAWAY DIII-D EXSPERIMENTS UNDER QUIESCENT CONDITIONS

In DIII-D, the behavior of REs were investigated during flat-top stage of Ohmic discharges with the parameters: toroidal magnetic field was B_t = 1.4 T, plasma current was I_p = 0.8 MA and loop voltage was V_{loop} = 0.6 V [2, 3]. Low density access led to the generation of a primary RE population which was built up over several seconds. Near the end of this discharge, strong puff of working gas was used, which cause RE parameter variations. During this puffing the value of plasma density increased approximately from the value of $n_e \approx 0.5\ 10^{19}$ m^{-3} to the value of $n_e \approx 1.5\ 10^{19}$ m^{-3} and the ion effective charge $Z_{eff}(t)$ dropped from the value of 2 to 1.25.

The primary generation mechanism was the dominated mechanism during these experiments. Specific behavior of the ECE signal was observed.

2. 2D-MOMENTUM-SPACE ANALYSIS OF SUPRATHERMAL ELECTRON GENERATION

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

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

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

where $n_e(0) = 0.5\ 10^{19}$ m^{-3}, $n_e(1) = 1.25\ 10^{19}$ m^{-3}, $Z_{eff}(0) = 2$, $Z_{eff}(1) = 1.25$. The zero of normalized time, 0, corresponds to gas puff start.

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

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

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

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

$$p_{cr0}^2 = e^3 m_e n_e(0) L / 4\pi\varepsilon_0^2 E_\parallel \,. \tag{5}$$

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.

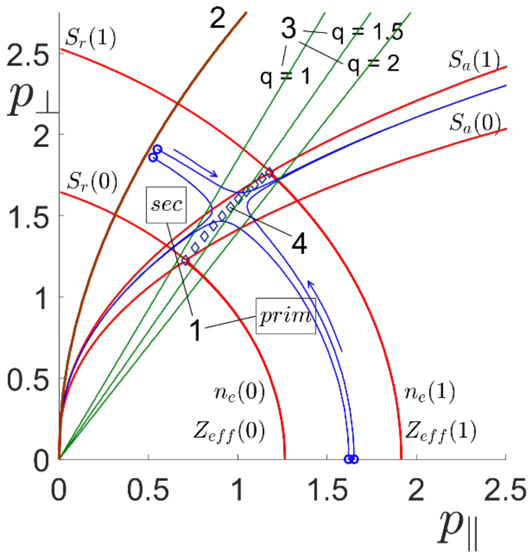

Fig. 1. The primary and secondary runaway regions (1) are presented (normalized variables are used); $S_r(0,1)$ and $S_a(0,1)$ (red) are separatrixes [5, 6] for plasma parameters at t=0 or t=1.
The curve $p_\perp = \sqrt{(2m_e c / p_{cr0}) p_\parallel}$ is shown by brown (2), the locus of the knocked-on electrons lies below this curve. Straight lines $p_\perp / p_\parallel = 1/\sqrt{2\varepsilon}$ (q = 1, 3/2, 2) are marked by green (3), q is the safety factor. Typical test electron trajectories (flowing around "virtual" saddle point ($p_{\parallel,S}$, $p_{\perp,S}$)) 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)

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]. Only electrons with coordinates initially situated above S_r may run away. 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:

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

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

For trajectories near "virtual" saddle point the inequality $p_\parallel < p_\perp$ holds and the motion of electrons here is not so fast in 2D plane, the time is the order of (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 ($p_\parallel$, $p_\perp$) is filled by these ellipses. This region is bounded from the top by the curve (see, e.g. [4])

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

3. BANANA ORBITS OF TRAPPED SUPRATHERMALS

Confining magnetic field in tokamak is non-uniform and is described by Eq. (9):

$$B(r,\theta) = \frac{B_0}{1 - \varepsilon \cos\theta} \,, \tag{9}$$

where $\varepsilon = r/R$, r is the radius of magnetic surface, R is the major radius, θ is the poloidal angle, the value $\theta = \pi$ corresponds to low field side (lfs).

Straight lines

$$p_\perp / p_\parallel = 1/\sqrt{2\varepsilon} \tag{10}$$

for the values of safety factor q=1, 3/2 and 2 are shown in Fig. 1 (the data from Fig. 2h of Ref. [2] are used). The entire range of locus of the knocked-on electrons in 2D plane ($p_\parallel$, $p_\perp$) lies above straight lines of Eq. (10). These electrons may be trapped in a non-uniform tokamak magnetic field. It is the necessary criterion, but not sufficient condition. At t > 0.5 the crossing of saddle point curve with the q = 3/2 straight line is visible.

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

It is necessary to distinguish situation on the outer (lfs) and inner sides of the tokamak discharge. The suprathermal electrons are trapped in the lfs region. Narrow banana orbits of these trapped suprathermal electrons are shown in Fig. 2. More strong losses of these trapped electrons may 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.

Bounce period of trapped suprathermal electrons is equal to T_b = 0.47μs (q = 1.5) and T_b = 0.59μs (q = 2) for Fig. 2,a. For Fig. 2,b T_b = 0.34 μs (q = 1.5) and T_b = 0.42 μs (q = 2). 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 $\nu_{effcoll}$.

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]

$$t_{av} \approx \sqrt{12} m_e cL(2+Z_{eff})/9eE_{\|} . \tag{11}$$

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.

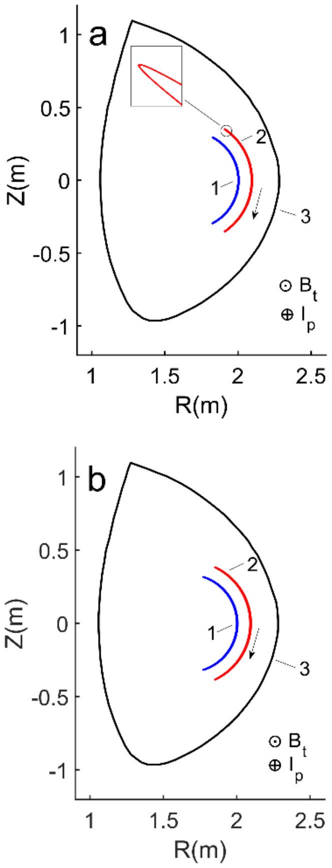

Fig. 2. Narrow banana orbits of suprathermal electrons (banana width is (0.3…0.6) cm).
The values of $p_\perp$ and $p_\|$ corresponds to point $\theta = \pi$, E_{st} is the energy of suprathermals: a) $p_\perp/p_\| = 1.6/0.5 = 3.2$, $E_{st} \approx 50$ keV,
b) $p_\perp/p_\| = 2.2/0.8 = 2.75$, $E_{st} \approx 100$ keV.
Numbers 1, 2 corresponds to orbits near $q = 1.5$ and $q = 2$, respectively. Plasma edge is shown by 3, the direction of electron poloidal motion along the outer banana part is shown by arrow

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, $p_\perp > p_\|$. Note, for fixed maximum runaway energy the amount of the knocked-on electrons decreases with plasma density increasing [7].

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. [8]. Detail investigations of such instabilities for suprathermal electrons are planned in the future.

If trapped knock-on electrons are created far enough from the magnetic axis (the DIII-D case), they may be detrapped and run away [9] because of these trapped electrons drift radially inwards due to the Ware pinch effect [10]. Analysis of the time it takes for initially trapped electrons to become runaways [9]

$$dt_W = \frac{B_\theta}{E_\|} R \cdot \Delta\varepsilon \tag{12}$$

shows that for the DIII-D quiescent runaway experiments [2,3] this time dt_W is the order of 0.7s. ($E_\| = 50$ mV/m, $B_\theta \approx 0.2$ T, $R = 1.67$ m, $\Delta\varepsilon \approx 0.1$). Here $\Delta\varepsilon = \varepsilon(r) - \varepsilon(r')$, r is the radial position where the electron was trapped and r' is the radial position where the electron stay detrapped and run away. For $E_\| = 5$ V/m (disruption case) this time will be the order of 7 ms. For electric field 40 V/m this time will be about 870 µs which gives up to 200 banana turns before detrapping.

The inequality $3E_{CH} < E_\| < 5E_{CH}$ holds in the DIII-D case [2], where $E_{CH} = e^3 n_e L / 4\pi\varepsilon_0^2 m_e c^2$ [11]. 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.

CONCLUSIONS

The analysis of electron trajectories in the 2D runaway region ($p_\|$, $p_\perp$) are carried out for parameters close to the DIII-D experiments [2, 3]. The formation population of trapped suprathermal electron with $p_\| < p_\perp$ is shown during gas puffing, when plasma density n_e and Z_{eff} are changed in time. This phenomenon is strong for knocked-on electrons. 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 knocked-on suprathermal electrons (banana orbits) in non-uniform magnetic field must be taken into account. The avalanching (secondary runaway generation) process may be suppressed in part.

-The effective collision frequency is much smaller in comparison with the oscillation frequency of the bounce motion of trapped suprathermal electrons.

-The ECE signal must be strongly enhanced due to existence of the suprathermal electron population with a high value of transversal momentum, 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.

-Additional losses of such electrons may take place from outer part of discharge.

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АНАЛИЗ В ИМПУЛЬСНОМ ПРОСТРАНСТВЕ ГЕНЕРАЦИИ НАДТЕПЛОВЫХ ЭЛЕКТРОНОВ ПРИ НАПУСКЕ ГАЗА В РАЗРЯДЫ ТОКАМАКА С УБЕГАЮЩИМИ ЭЛЕКТРОНАМИ

И.М. Панкратов, В.Ю. Бочко

Проведен анализ генерации надтепловых электронов в токамаке DIII-D при параметрах, близких к квазистационарному разряду с убегающими электронами #152895, в условиях напуска рабочего газа. Использованы уравнения движения пробной частицы на двумерной фазовой плоскости с учетом ускорения ее тороидальным электрическим полем и столкновений с частицами плазмы. Показано, что в результате близких кулоновских столкновений образуется популяция надтепловых электронов, захваченных неоднородным магнитным полем токамака.

АНАЛІЗ В ІМПУЛЬСНОМУ ПРОСТОРІ ГЕНЕРАЦІЇ НАДТЕПЛОВИХ ЕЛЕКТРОНІВ ПРИ НАПУСКУ ГАЗУ В РОЗРЯДИ ТОКАМАКА З ЕЛЕКТРОНАМИ-ВТІКАЧАМИ

І.М. Панкратов, В.Ю. Бочко

Проведено аналіз генерації надтеплових електронів у токамаці DIII-D для параметрів, близьких до квазістаціонарного розряду з електронами-втікачами #152895, за умов напуску робочого газу. Були використані рівняння руху пробної частинки на двомірній фазовій площині з урахуванням прискорення тороїдальним електричним полем та зіткнень із частинками плазми. Показано, що в результаті близьких кулонівських зіткнень утворюється популяція надтеплових електронів, захоплених неоднорідним магнітним полем токамака.