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Distribution functions of secondary runaway electrons

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The review of different shapes of runaway electron secondary generation distribution functions are presented. Conditions which lead to different shapes of these functions are considered.

1. INTRODUCTION

The secondary generation of runaway electrons is a fundamental phenomenon. Secondary generation is a process in which already existing high-energy runaway electrons (of the order of 10 MeV or large) kick thermal electrons into the runaway region by close Coulomb collisions (see, e.g., [1]). The knocked out electrons have a significant transverse momentum $p_\perp >> p_{//}$ ($p_\perp$ and $p_{//}$ are the transverse and parallel momenta of the runaways with respect to the magnetic field **B**). The inequality ($p_{cr}^2 = e^3 m n_e L / 4\pi\varepsilon_0^2 E$)

$$p_\perp > p_{\perp cr} \ , \tag{1}$$

where

$$p_{\perp cr} \approx \sqrt[4]{12}\, p_{cr} \sqrt{Z_{eff}+2}\,/\,3$$

determines the runaway region of the knocked out electrons [2], e and m are the charge and rest mass of electrons, n_e the bulk electron density, L the Coulomb logarithm, Z_{eff} the effective ion charge and E the inductive electric field. The knocked out electrons run away in the electric field and in turn make more runaways. The avalanche-like process of runaway generation arises with the avalanching time [3] (c the velocity of light)

$$t_0(E) = \sqrt{12}\, mcL(2+Z_{eff})/9eE \tag{2}$$

Runaway avalanches generated during disruptions in large tokamaks like ITER may have damaging consequences because of the high power generated by their localized deposition on the vessel walls [4].

In the same time the established methods of monitoring the presence of runaway electrons (HXR, photoneutron emission) will be difficult to apply in large machines like ITER because of the high gamma and neutron background and the very thick wall and in vessel shielding thickness. Only the diagnostic based on the runaway electron synchrotron radiation measurements should be possible on ITER [4].

The analysis of the runaway electron distribution function is very important for the understanding of the runaway avalanche formation and for the correct interpretation of synchrotron radiation diagnostic data. That is the reason why the review of investigations of secondary runaway electron distribution functions

$$\bar{f}(p_{//},t) = 2\pi \int_0^\infty p_\perp dp_\perp f(p_\perp, p_{//}, t) \tag{3}$$

are presented in this paper.

2. STEADY STATE PLASMA

For steady state conditions, when plasma parameters n_e, Z_{eff}, E are not changed, the calculations were made on the basis of the integral of close collisions [2]. We assumed that runaways had parallel momenta $p_{//}$ up to the maximum value $p_{//\ max}$. And the time t_{conf} was the time over which an electron undergoes a change in parallel momentum $p_{//}$ from a value close to p_{cr} to a maximum value $p_{//max}$.

In the case when avalanching time t_0 (2) was larger than the confinement time ($t_0 > t_{conf}$) the distribution function of secondary runaways went over to a stationary value [2]. This function had a large peak in region where $p_{//}$ was less or of the order of p_{cr} and a flat distribution outside this region (up to $p_{//max}$). In this situation the avalanching process was suppressed: the density of runaways also went over to a stationary value [5].

In the case when avalanching time t_0 was less than the confinement time ($t_0 < t_{conf}$) the distribution function $\bar{f}(p_{//},t)$ had an exponentially decaying dependence on the parallel momentum [3]. Again a large peak was in the region where $p_{//}$ was less or of the order of p_{cr}. These calculations were carried out for the TEXTOR experimental conditions [6]. In this experiment the secondary runaway generation was first demonstrated.

Few years ago TEXTOR experiments were carried out with the aim of the control of runaway electron secondary generation by changing Z_{eff} [7]. Different amplitudes of neon gas puffs were injected during steady state phases of low density ohmic deuterium discharges in which the runaway electron secondary generation process took place.

In the flat top phase of the discharge an exponential increase of the synchrotron radiation in time was the indication of the avalanching of the runaway electron population with energies higher 15 MeV. With a time detay Δt = 0.6 – 0.75s after start of neon puff the synchrotron radiation signal showed a sufficiently sharp transition from the fast avalanching process to a decay or more slow avalanching processes.

During neon injection the parameter $p_{\perp,cr}$ was increased because of Z_{eff} increase. And from the injection time the number of knocked out electron (and hence $\bar{f}(p_{//},t)$) was decreased in the region where p was of the order or less than p_{cr}. The time of delay Δt is the time over which an electron underwent a change in parallel momentum $p_{//}$ from a value close to p_{cr} to relativistic value of $p_{//}$. From this moment, the synchrotron signal showed a transition to the new regima. In this experiments the evolution of $\bar{f}(p_{//},t)$ took place as it was shown in Fig. 5 of Ref. [7]. Recent TEXTOR experiment [8] also confirmed this interpretation.

3. DISRUPTIONS

During disruptions at the plasma centre the inductive toroidal electric field E strongly changes from values of E ~ (0.1-0.05) V/m up to E ~ (50-100) V/m and then it drops to the typical value of E ~ 5V/m (see, e.g., [9, 10, 11]). The plasma parameters n_e and Z_{eff} also change but not so strong.

The evolution of the runaway parameters strongly influences the avalanching process. During the time when E is very high the parameter $p_{\perp cr}$ Eq. (1) is small. The strong runaway avalanche takes place. The exponentially decaying dependence of distribution $\bar{f}(p_{//},t)$ on the momentum $p_{//}$ (with a huge peak at low energies) occurs.

When E strongly (> 10 times) drops, the parameter $p_{\perp cr}$ strongly increases. The production rate of the secondary generation decreases, a large peak in the knocked out electron distribution function at low energies is now below the runaway region. The enhancement of superthermal electron losses from low energy region arises. The runaway avalanche is reduced. In this stage of disruption the function $\bar{f}(p_{//},t)$ has a gap in the region $p \sim p_{cr}$. And this gap extends from $p \sim p_{cr}$ to larger values of $p_{//}$.

Note that only exponentially decaying dependence of a distribution function on the parallel momentum was considered in Refs. [12, 13].

For the situations reported here the inequality

$$E >> e^3 n_e L / 4\pi\varepsilon_0^2 mc^2 \qquad (4)$$

holds, indicating the possibility of runaway generation [14].

4. CONCLUSIONS

The evolution of the plasma parameters and runaway losses lead to different dependences of runaway electron secondary generation distribution function on the parallel momentum $p_{//}$: an exponentially decaying distributions, flat distributions and distributions with a gap in the region $p \sim p_{cr}$.

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