UDC 533.9

Disruption generated secondary runaway electrons in present day tokamaks

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An analysis of the runaway electron secondary generation during disruptions in present day tokamaks (JET, JT-60U, TEXTOR) was made. It was shown that even for tokamaks with the plasma current I ~ 100 kA the secondary generation may dominate the runaway production during disruptions. In the same time in tokamaks with I ~ 1 MA the runaway electron secondary generation during disruptions may be suppressed.

1. INTRODUCTION

One of the important problems of a tokamak fusion reactor is the possible damage caused by disruption generated runaway electrons. The avalanching process of runaway electron secondary generation was recognized to dominate the runaway production during major disruptions in large tokamaks like ITER [1]. But for present day tokamaks the role of the runaway electron secondary generation during disruptions is under discussion up to now. That is the reason why this paper is presented.

Remind that the secondary generation is the process in which already existing high energy runaway electrons kick thermal electrons into the runaway region by close Coulomb collisions.

2. RUNAWAY GENERATION

The importance of the runaway electron secondary generation in a disruption can be investigated on the base of two equations.

The inductive toroidal electric field E(t) at the center of the plasma is given by

$$E(t) = -\frac{1}{2\pi R}\frac{d\Phi}{dt} , \qquad (1)$$

where

$$\Phi(t) = \int \mathbf{B}\, d\mathbf{S} \qquad (2)$$

is the magnetic flux across the surface bounded by the circular contour with radius R, R is the major radius of the runaway beam center. Note, that experiments show that the runaways are generated at the plasma center in a region with small minor radius (see, e.g., [2]).

The runaway production is given by [2]

$$\frac{dn_r}{dt} = n_e(t)\nu_e(t)\lambda(t) + \frac{n_r(t)}{t_0(E)} - \frac{n_r(t)}{t_l} \qquad (3)$$

The first term in the right side of Eq. (3) describes the primary (Dreicer) generation (see, e.g., [3]). Here $n_r(t)$ is the density of runaways,

$$\nu_e = e^4 n_e(t) L / 4\pi\varepsilon_0^2 m^2 v^3 , \quad \varepsilon(t) = E(t)/E_D(t), \qquad (4)$$

$$\lambda(t) = K(Z_{eff})\,\varepsilon^{-3(Z_{eff}+1)/16} e^{-1/4\varepsilon - \sqrt{(Z_{eff}+1)/\varepsilon}} , \qquad (5)$$

$n_e(t)$ - is the bulk plasma density, e, m and v are the charge and the rest mass and the velocity of the electron, L is the Coulomb logarithm, Z_{eff} is the effective ion charge number, $E_D(t) = e^3 n_e(t) L / 4\pi\varepsilon_0^2 T_e(t)$, T_e – is the bulk electron temperature, $K(Z_{eff})$ is a weak function of Z_{eff} (K(1) = 0.32, K(2) =0.43).

The second term in the right side of Eq.(3) describes the secondary generation with the avalanching time [4] (c the velocity of light)

$$t_0(E) = \sqrt{12} mcL(2 + Z_{eff}) / 9eE \qquad (6)$$

The last term in the right side of Eq. (3) describes the losses of runaways.

From Eqs. (1), (3) we obtain the runaway current density $j_r(t) = ecn_r(t)$ (t = 0 is the start of the runaway generation)

$$j_r(t) = ec\exp[-(s(t) + t/t_l)]\int_0^t \{dt\, n_e(t)\lambda(t)\nu_e(t)\exp[s(t) + t/t_l]\} + j_r(0)\exp[\Delta s(t) - t/t_l], \qquad (7)$$

where

$$s(t) = \frac{3\sqrt{3}}{2}\frac{e}{mcL(2+Z_{eff})}\frac{\Phi(t)}{2\pi R} , \qquad (8)$$

$$\Delta s(t) = s(0) - s(t) \qquad (9)$$

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The second term in Eq.(7) describes the secondary generation of runaway electrons, the necessary condition of this process is

$$\Delta s(t) > 0 \qquad (10)$$

Or in the more suitable form (I_A = 0.017MA is the Alfven current):

$$\Delta s \approx \frac{2.6}{2+Z_{eff}} \frac{e}{mcL} \frac{1}{2pR} [I(0)L_{\hat{O}}(0) - I(t)L_{\hat{o}}(t)] = = \frac{2.6}{2+Z_{eff}} \frac{1}{I_A L} [I(0)h_i(0) - I(t)h_i(t)] > 0 \qquad (11)$$

We introduce the flux inductance of the plasma current I(t) (see, e.g., [5]),

$$\hat{O} = L_{\hat{o}} I, \qquad (12)$$

where

$$L_{\hat{o}} = m_0 R h_i / 2 , \qquad (13)$$

h_i is the normalized flux inductance of the plasma column. Note that h_i differs from the normalized energy self inductance l_i. In Eq. (11) the evolution of the current density profile during disruptions is taken into account.

To estimate the value of h_i we consider the simple model of the current density profile j(r)

$$j(r) = j_1, \ r < r_c , \qquad (14)$$
$$j(r) = j_2, \ r_c < r < r_p , \qquad (15)$$

where r_c is the minor radius of the central part of a plasma, r_p is the minor plasma radius ($r_c^2 \ll r_p^2$), $I_1 = \pi r_c^2 j_1$ is the current in the central part of a plasma, $I_2 = \pi (r_p^2 - r_c^2) j_2$ is the current outside the plasma center. Using Eqs. (2), (12) – (15) we find that

$$h_i = 1 + \frac{2\ln(r_p/r_c)}{I_1 + I_2} (I_1 - \frac{I_2 r_c^2}{r_p^2 - r_c^2}) \qquad (16)$$

If $j_1 = j_2$ from Eq. (16) we have $h_i = 1$. In the case $I_1 >> I_2$

$$h_i \approx 1 + 2\ln(r_p/r_c) \qquad (17)$$

Note, that the value of the normalized energy self inductance l_i for our simple model of the current density profile Eqs. (14), (15) is given by

$$l_i = \frac{0.5}{(I_1+I_2)^2} [I_1^2 + I_2^2 + 4(I_1 - \frac{I_2 r_c^2}{r_p^2 - r_c^2})^2 \ln\frac{r_p}{r_c} + + 4I_2 (I_1 - \frac{0.5 I_2 r_c^2}{r_p^2 - r_c^2})] \qquad (18)$$

If $j_1 = j_2$ from Eq. (18) we have $l_i = 0.5$. In the case $I_1 >> I_2$

$$l_i \approx 0.5 + 2\ln(r_p/r_c) \qquad (19)$$

3. DISCUSSION

In this section we estimate the role of the runaway electron secondary generation during disruptions in JET, TEXTOR and JT-60U tokamaks.

In JET the density limit disruption # 42155 [6] had all the usual disruption characteristics such as the negative voltage spike and therefore a flat current profile may be assumed in the initial current quench phase. The runaway generation was observed after a small delay of (4-6) ms after the thermal quench ($I(0) \approx$ 1,5 MA), the runaway beam was located in the central part of a plasma with the radius of the runaway beam $r_{beam} \approx$ 15 cm ($r_p \approx$ 1m). In the current plateau stage the runaway current was $I_{run}(t) \approx$ 0.6 MA ($I(t) \approx$ 1MA) and $r_{beam} \approx$ 0.3 m.

At the start of runaway generation (t = 0) $r_c \approx$ 0.2 m and $I_2 > I_1$, hence $h_i(0) \approx 2.5$. In the plateau stage $r_c \approx$ 0.35m and $I_2 \cong I_1$, hence $h_i(t) \approx 2$. Note that the value $h_i \approx 2 - 2.5$ is in good agreement with $L_{\hat{o}} = 4.5$ μH of Ref. [5]. For Δs (L = 12; Z_{eff} = 3) we have approximately

$$\Delta s \cong 4.5.$$

This estimate is in good agreement with calculation of Ref. [7].

The TEXTOR disruption # 55860 [2, 8] was a result of a huge gas puff in a low density discharge. Contrary to usual disruptions no negative voltage spike was observed in the thermal quench and a flattening of the current profile did not occur. After a delay (4-6)ms after the thermal quench ($I(0) \approx$ 100 kA) a strong runaway generation in the central part of the plasma started. The $r_{beam} \approx$ (5-7)cm was small compared to the plasma minor radius r_{beam} = 46 cm. The runaway current was $I_r \approx$ (20-30)kA about 30% of the total current in the plasma I(t) ≈ 75kA when the runaway plateau is formed.

In this shot at the start of runaway generation a strongly peaked current profile took place: $I_1 >> I_2$, $r_c \approx$ ≈ 0.1 m and hence $h_i(0) \approx 4$. In the plateau stage $I_2 > I_1$ ($r_c \approx$ 0.1m) and $h_i(t) \approx 2$. For Δs we have from Eq. (11) (L = 10, Z_{eff} = 3)

$$\Delta s \approx 0.75.$$

This estimate shows that even for tokamaks with I ~ 0.1 MA secondary generation can dominate the runaway production during disruption.

The investigation of the runaway generation during disruptions in JT-60U (see, e.g., [9]) shows that the secondary generatuon process does not play the principal role here. In the same time in these experiments a very high value of the plasma internal energy unductance $l_i \approx$ 3,5 (and hence $h_i \approx 4$), was observed. It means that the last term in Eq. (11)is large for this case and it was the reason (in addition to a high level of magnetic perturbations) why the runaway avalanches were suppresed during disruptions in JT-60U.

It is necessary to underline that in all considered here disruptions the strong inequality [10]:

$$E >> e^3 n_e L / 4pe_0^2 mc^2 \qquad (20)$$

holds, indicating the possibility for runaway generation.

4. CONCLUSIONS

Up to now to estimate the role of runaway electron secondary generation during disruptions in tokamaks the next expression [11] was used

$$g_{RA} t \cong I / I_A L \qquad (21)$$

From Eq. (21) it is possible to wait the strong runaway avalanche in JT-60U and no avalanche in TEXTOR disruptions. But experiments show that these conclusions are not correct.

As it is shown in the present paper that for the correct analysis of runaway avalanches during disruptions it is necessary to take into account not only the plasma current value, but also the evolution of the current density profile.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. T. Dolan for useful discussion.

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