STUDY OF DISRUPTION GENERATED RUNAWAY ELECTRONS IN TEXTOR-94

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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 secondary generation was recognized to dominate the runaway production in an ITER disruption [1,2]. Secondary generation is the process in which already existing high-energy runaway electrons (of the order of 10 MeV or larger) kick thermal electrons into the runaway region. The avalanche-like process of runaway generation arises with the avalanche-time t_0 [3]:

$$t_0 = \sqrt{12} m_e c L \left(2 + Z_{eff}\right) / (9 e E_{//}) . \qquad (1)$$

Here e and m_e are the charge and rest mass of the electron, c the velocity of light, L the Coulomb logarithm, Z_{eff} the effective ion charge and $E_{//}$ the inductive electric field.

Only the combination of the data of the infrared synchotron radiation (IR), electron cyclotron emission (ECE), hard and soft X-ray (HXR,SXR), photoneutron emission (N), MHD activity and Z_{eff} diagnostic allows to study runaway electrons successfully. Previously in TEXTOR-94 the time evolution of runaway electrons with energies of the order of 20 MeV was analyzed using their IR [4,5] for the steady state phase of the discharge. But for the fast runaway avalanche during disruptions the runaway ECE signal is more suitable and it is used in these experiments.

All types of disruptions have a similar evolution: a precursor phase (as noted by MHD activity), the thermal quench (observed as a strong drop on the ECE signal), the plasma current decay phase with an enormous increase in the inductive electric field. In this latter phase the runaway generation is thought to take place. On the same time each disruption has individual features which are very important for the runaway electron generation. In this paper three ohmic TEXTOR-94 (limiter tokamak with major radius R_0=1.75 m, minor radius a=0.46 m and circular cross-section) disruptions are presented with different runaway characteristics: strong runaway avalanching, weak avalanching and no avalanching.

2. Runaway Electron Generation in TEXTOR-94 Disruptions

2.1 Disruption with strong avalanching process

In Fig. 1 data are shown of shot 55860 with B_ϕ=2.25 T, I_p=275 kA. This discharge exhibited no infrared radiation in the stable phase before the disruption. Application of a huge deuterium puff resulted in a disruption. The central density increased in this phase from $n_e(0)=2\cdot10^{19}$ m^{-3} at t=2.845 s to $n_e(0)=(7\text{-}8)\cdot10^{19} m^{-3}$ at t=2.853 s. Strong MHD (m=1,2) activity was observed from t=2.843s on. After the ECE signal (thermal resonance at R=1.70 m) drop the plasma current I_p dropped and the loop voltage V_{loop} increase took place at t=2.846 s. At this moment huge SXR and neutron bursts showed the pre-disruptive runaway electron losses. No negative voltage spike and a small temporary increase of I_p were observed. It is possible if a strong stochasticity of the magnetic field lines was lacking in this shot.

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The ECE signal started increasing again from t=2.852 s on some 6 ms after the thermal quench. The IR radiation (r_{beam}≈6 cm, $p_{\perp}/p_{//}$ ≈ 0.15, $I_{runaways}$≈18 kA) was observed with a small delay Δt=(0.9±0.2) ms relatively to this part of the ECE signal. Since the electron cyclotron emission is emitted by runaways with rather low energy (Γ ≥ 1) and the IR radiation by high energetic electrons with Γ ≥ 35, this delay is the time during which electrons reach the high energy region with Γ ≈35, Γ is the relativistic factor. From this observation we can estimate the average parallel electric field over this Δt: $<E_{//}>≈m_e c\Gamma/e\Delta t$≈65 V/m. The saturation of the neutron detector here confirmed the existence of high energy runaway electrons.

The exponential rise of this ECE signal from t=2.852 s to t=2.854 s is a clear indication for the occurrence of the secondary generation process. The effective rise time of this signal t_{eff}≅0.6 ms can be interpreted as the avalanching time, for which Eq. (1) gives t_0≈0.6 ms (where $E_{//}$=65 V/m and Z_{eff}=3 has been inserted). The good agreement of t_{eff} with t_0 is another indication for the secondary generation.

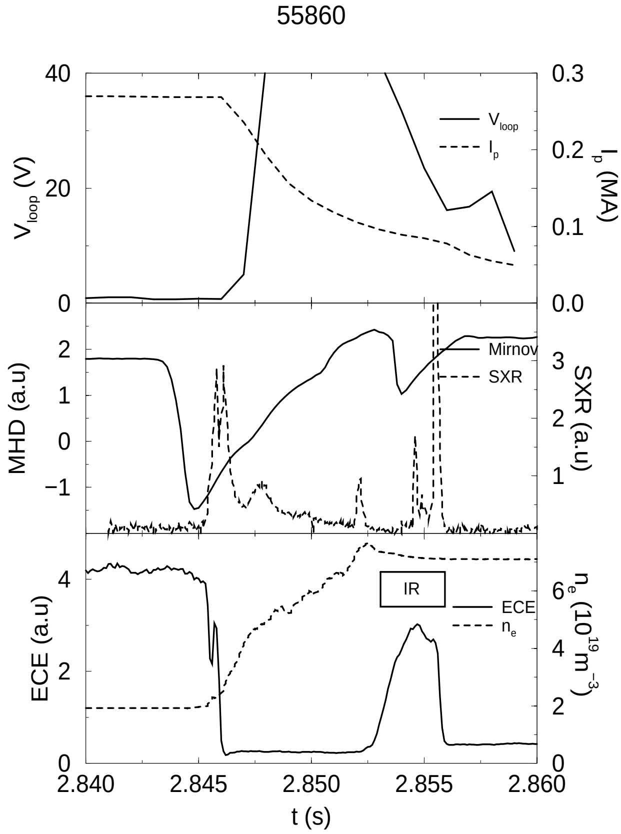

Fig. 1: *Time traces of V_{loop} (not measured above 40 V), I_p, Mirnov coils, SXR, ECE and n_e (might be wrong after disruption due to fringe jumps). The avalanching is recognized on the ECE signal. The IR time-window is indicated.*

Note also the fact that the ECE signal (and the IR signal as well) does not increase further after t=2.855 s and even decreases slowly. This could be the results of the fact that the electric field in the plasma center might have become very low since the large runaway population will carry an appreciable part of the plasma current wit a low resistance and hence a low electric field will result [1]. The strong runaway avalanche like in this case is a serious issue for large tokamaks [2].

2.2 Disruption with weak avalanching process

Fig. 2 shows the disruption data from shot 64845, with B_ϕ=2.25 T and I_p=360 kA. This discharge exhibited no IR radiation before the disruption. The average plasma density decreased smoothly from $\overline{n_e} \approx 1.2\cdot10^{19}$ m^{-3} at t=0.5 s to $\overline{n_e} \approx 0.6\cdot10^{19}$ m^{-3} at t=1.465 s. The plasma current was sufficiently large for sawtooth activity in the plasma center with the following transition to strong MHD activity at t=1.465 s (first m=2, then m=1,2). At t=1.467 s the ECE signal dropped and a strong increasing V_{loop} and I_p-drop were observed. Similar as in the previous example no negative V_{loop} spike and I_p increase were observed. Because of the strong sawtooth activity the magnetic field reconnections took place for r ≤ 15 cm before the disruption. As a result the flattening of the current profile was before the thermal quench.

A large IR spot with r_{beam}≈20-25 cm was observed at t=1.496 s and then on the subsequent frame of the IR camera at t=1.512 s, after strong losses of runaway electrons, a smaller IR spot with r_{beam}≈10-15 cm was seen. (Note that the IR information was missing in between subsequent frames because of the camera scanning principle).

The V_{loop} was equal to 1.5-2 V just before the disruption. This combined with the low density in that phase makes it plausible that the runaway generation took place already before the disruption. The initial value of Z_{eff} was sufficiently large as indicated by the high V_{loop} before the disruption. Moreover, because of the impurity influx after the thermal quench we estimate Z_{eff}≈5.

It was deduced after accurate analysis that runaway ECE became visible from t=1.462 s (before the strong MHD activity) up to t=1.52 s although on a very low level. The increasing part of this signal from t=1.467 s to t=1.475 s indicates the secondary generation avalanching process on the low level with t_0≈t_{eff}≈20 ms. Analysis of the IR radiation shows the delay Δt≈22 ms from t=1.462 s. Hence, $<E_{//}>$≈3V/m over this Δt, corresponding to $<V_{loop}>$≈30 V and maximum V_{loop}≈60 V as seen in Fig. 2.

During this disruption $Z_{eff}(0)$ strongly increased to $Z_{eff}(0)$ ≈5 and as a result from this the avalanche process was reduced (see also [5]). But the initial density and energy of primary generated runaways were so large, that the avalanche process started even before the disruption and became visible just after the thermal quench.

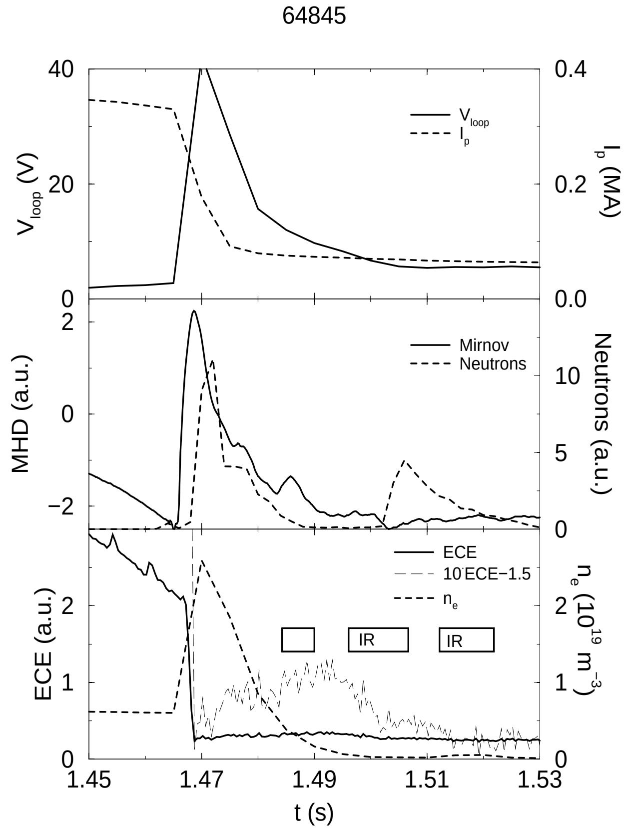

Fig. 2: *Time traces of V_{loop}, I_p, Mirnov coils, neutrons, ECE and n_e. The IR time-windows are drawn. Note, there is only a very small ECE left after the thermal quench indicating a very weak secondary generation process.*

2.3 Disruption without runaway electron avalanche

In Fig. 3 data from shot 71238 (B_ϕ=1.964 T, I_p=257 kA) are presented after deuterium injection. The density increased almost linearly from $\overline{n_e} \approx 2{\cdot}10^{19}$ m^{-3} at t=1.5 s until the density limit at $\overline{n_e} \approx 3.6{\cdot}10^{19}$ m^{-3} was reached at t=2.5 s and a disruption occurred. During this discharge no IR radiation was observed both in the stable phase and during the disruption.

A first increase in MHD activity was recorded at t=2.523 s and the thermal quench took place at t=2.528 s. Now the negative V_{loop} spikes and the small increases in I_p are visible in Fig. 3 during t=2.528-2.530 s, then V_{loop}≈7 V; between t=2.538-2.540 s, then V_{loop} increased to 14 V and between t=2.545-2.548 s after this V_{loop} strongly increased to approximately 100 V. $Z_{eff}(0)$ as obtained from bremsstrahlungs-emission varied between 2 and 3 in this phase. The neutron signal, which represents the high energy runaway loss, did not show these losses during the disruption except for a small peak in the signal at the thermal quench was observed.

From this we conclude that there was no or only a very small runaway population generated during the disruption. From Eq. (1) we calculate t_0≈20-40 ms for the first two disruption and t_0≈3 ms for the last disruption. So in principle this last value is small enough for the secondary process to become effective. However, a simple estimate shows that the (low level of) primary runaway electrons have an energy of less than 14 MeV. And a prerequisite for strong avalanche is to have higher energetic electrons. So an avalanche process was not observed in this case.

It is necessary to underline that in all TEXTOR-94 disruptions the strong inequality [6]:

$$E_{//} >> e^3 n_e L / (4\pi\varepsilon_0 m_e c^2) \qquad (2)$$

holds, indicating the possibility for runaway electron generation.

3. Conclusions

For the process of runaway avalanching to become clearly visible during a disruption several conditions have to be fulfilled: a) the presence of high energetic (~20 MeV) primary runaway electrons, b) a value for t_0 small compared with the current quench time scale, i.e. a low value for Z_{eff} or a sufficiently high $E_{//}$, c) some intact magnetic surfaces, such that the generated runaway electrons can be confined for a time longer than t_0 and finally d) suitable diagnostics, such as the IR synchrotron radiation and ECE diagnostics.

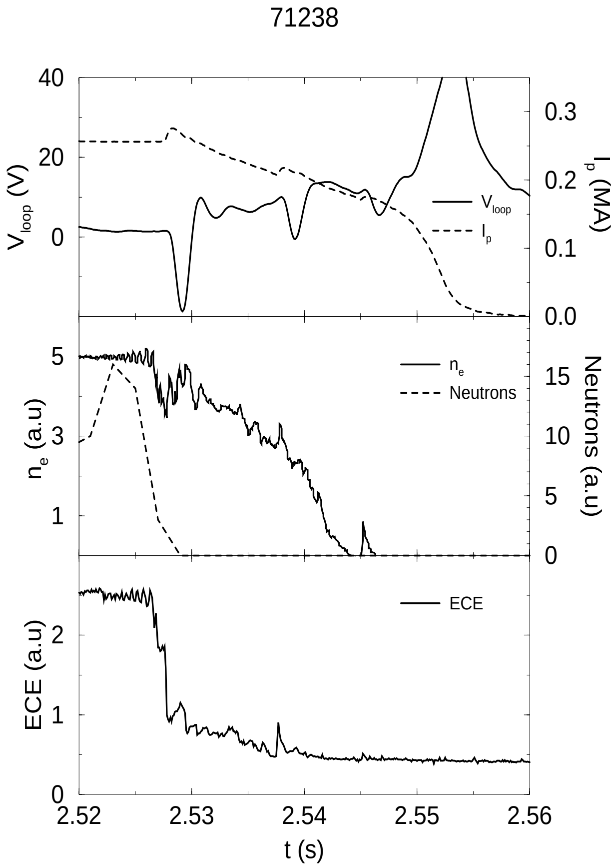

Fig. 3: *Time traces of V_{loop}, I_p, neutrons, n_e and ECE. No evidence for runaway production during the disruption is found.*

In this paper we considered two examples of runaway avalanche during a disruption, when the above mentioned conditions were satisfied. In present day large tokamaks (JET, JT-60U, DIII-D, Tore Supra, ASDEX-U, TEXTOR-94) the current quench time τ_{cq} is of the order of 10 ms or less, with an electric field $E_{//}$ of the order 5V/m or less. It is unreal to observe strong avalanche in these disruptions, when the avalanching time t_0 is close to this τ_{cq}.

Another situation will be on ITER, where τ_{cq}=(1-2) s and $t_0 << \tau_{cq}$. Moreover, the TEXTOR-94 experiment of #55860 shows that in fact the strong secondary generation reduced the time during which $E_{//}$ was high. In spite of this the avalanche was sufficiently huge.

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