*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.097 (2002)*

EFFECT OF MICRO-INSTABILITIES ON RUNAWAY GENERATION IN TOKAMAK DISRUPTIONS.

V.V. Plyusnin

Association Euratom/IST, Centro de Fusão Nuclear, Instituto Superior Técnico, Av. Rovisco Pais, 1049 – 001 Lisboa PORTUGAL

1. Analysis of the runaway generation parameters in the presence of instability.

High-energy runaway electrons are often observed during disruptions in large tokamaks, such as JET, JT-60, TORE SUPRA [1], while in medium size tokamaks (like TEXTOR) their appearance in post-disruptive plasmas was detected in few cases only [2]. Some recent experiments, including JET results [1,3] revealed the absence of the runaways in disruptions, if magnetic field was $B_0 \leq$ 2-2.2 T. Some models proposed to explain this phenomenon underline the role of the magnetic turbulence in the prevention of the generation of high-energy runaway electrons due to enhancement of diffusion, but they do not explain the effect of the magnetic field. Indeed, the generation rate of the primary runaways includes the dependencies on the values of plasma density, electron temperature, ratio $\varepsilon=E_0/E_{CR}$ ($E_{CR}=e^3\ln\Lambda_e n_e Z_{eff}/4\pi\varepsilon^2 T_e$ – is the critical Dreicer field) and doesn't have any dependence on the magnetic field. The only known runaway-related phenomenon, which has dependence on the magnetic field value, is the kinetic instability driven by the runaway electrons (fan instability) [4,5] that arises due to the anomalous Doppler effect. The magnetized Langmuir oscillations are generated in plasma by the runaway electrons if the certain conditions on the runaway beam velocity and density are satisfied:

1. $\omega_{ce} > \omega_{pe}$;
2. $V_{beam} > 3V_{cr}*(\omega_{ce}/\omega_{pe})^{3/2}$, where $V_{cr}=V_{Te}\varepsilon^{-1/2}$; and
3. $\nu_{eff} > \nu_e$, where $\nu_e=2.91*10^{-6}\ \ln\Lambda_e\ Z_{eff}T_e^{-3/2}$ and ν_{eff} is the effective collision frequency, which characterizes the enhancement of collisions due to the excitation of the plasma electrostatic oscillations: $\nu_{eff} \approx \pi^{1/2}\omega_{pe}(\omega_{pe}/\omega_{ce})K(Z_{eff})*\varepsilon^{-3(Z+1)/16-1.5}\exp\{-1/4\varepsilon-((Z+1)/\varepsilon)^{1/2}\}$, which in turn depends on the density of electrons diffused into runaway regime. To analyse the conditions (1)-(3) the runaway production rate and density of runaways were calculated and used. Conditions (1)-(3) are plotted in Fig.1 (a-b), where the values of V_{beam} for different toroidal magnetic fields are shown as functions of plasma density. As it follows from this picture the runaway instability can't be excited while $V_{beam}>c$ (such velocity is not accessible) and at plasma density values where the condition (1) is not more held (V_{beam} dependencies are truncated in these points in Fig.1a). In Fig.1b the condition (3) clearly highlights the density ranges in which fan instability can be excited for different values of the electron temperature. Thus, the plasma parameters ranges, in which the absence of the runaway generation during disruptions was observed, practically completely correspond to those ranges in which the runaway instability can be excited with high probability. Another instability, which can enhance the runaway electrons loss, preventing their acceleration is the current driven ion acoustic instability (the classical examples of electrostatic turbulence). Instability can appear if $V_{curr} \sim V_{te}$ during the quench.

2. Thermal quench and runaway generation.

The main mechanism responsible for the runaway production in disruptions is considered to be an avalanching of the high-energy electrons due to close electron-electron collisions between existing runaway and thermal electrons. The secondary avalanching is not possible without the primary generated runaways that can exist in the pre-disruptive plasma, or they can be produced during the thermal quench. Thermal quench still be the most unknown transient stage since the strong plasma perturbations do not allow measuring in detail the plasma parameters evolution. Meanwhile, the large increase of the electric field in plasma due to electron temperature decrease should be expected during the quench [6]. This should lead to the noticeable generation of the super-thermal or runaway electrons. Runaway electrons also can be generated during the magnetic reconnection at the pre-disruption stage due to local electric fields increase. The sequence of very complicated transient events during disruption doesn't allow reliable extrapolation of the present time results on disruption-generated runaways for the ITER case. Experimental data on disruptions makes possible only to estimate and extrapolate the duration of different stages of the disruption, usually distinguished as several steps of the thermal quench. Characteristic times of these stages are the delay time between first temperature decrease (T_e~1keV) and complete quench, and duration of the fast thermal collapse (usually ~100-500 μsec) [7].

Calculations performed in frames of simplest model of the single test particle acceleration and 0-D calculations of the runaway density predict a strong increase of the longitudinal electric field and the creation of the RA electrons with substantial energy and density due to the Dreicer mechanism for the case of 1 keV thermal quench in a large-scale tokamak (a_{pl}=1-1.2 m, 2 MA<I_{pl}<6 MA, $\langle n_e \rangle = 10^{20}$ m^{-3} and temperature decay within ~100-500 μsec). Analysis of calculation results shows that RA electrons increase their energy and density mainly during the stage when electron temperature decreases below 100 eV. Duration of this phase has to be considered as the most critical parameter, since even for τ_{fast} ~200 microseconds, the energy of the runaways can achieve up to 7-10 MeV at a density of ~10^{11}-10^{12} m^{-3} (Fig.2). Creation of runaways with such parameters obviously [1-3,7] can cause the process of secondary runaway electrons avalanche, which leads to abrupt increase of the runaway electrons density at the energy ≥ 10 MeV (Figs.3, 4). Calculations performed for the different values of the fast quench (τ_{fast}) in medium and large tokamak experiments show that in medium scale tokamaks (TEXTOR, ASDEX-U) the duration of the thermal quench and evolution of plasma parameters during disruption don't allow significant runaway generation (Fig.5). Meanwhile, calculation performed for the ITER case (I_{pl} =24 MA and τ_{fast}=1 msec) predicts very large runaway electron density produced before avalanching starts (Fig.5).

Taking into account these results the experimental facts, that disruptions with runaways not always observed in JET even in similarly disrupted discharges, small quantity of runaway disruptions were observed in TEXTOR and disruptions without runaway generation are usually observed in ASDEX-Upgrade tokamak, can be plausibly explained, at least in the frames of the following model. This model establishes the correlation between efficiency of the primary generation mechanism on the stage of electron temperature drop and consequent appearance of conditions for further runaway generation including the secondary avalanche during disruption. From the other hand, if the density of runaway will exceed certain threshold (in certain ranges of magnetic field, see part 1) the appearance of instability can stop the acceleration process serving like mitigating mechanism.

Summary.

Analysis of the plasma evolution during thermal quench, in which the core electron temperature evolution was represented by a fast decaying function of time, was carried out in 0-D approximation for the evaluation of the main characteristics of runaway electrons produced during the temperature quench, such as runaway density and kinetic energy. The calculations have demonstrated that runaway electrons with density up to ~ 10^{11}-10^{12} m^{-3} and energy up to 10 MeV can be generated in the case of the large-scale tokamak. At these runaway parameters the secondary runaway avalanching becomes dominating process in the RA production.

However, the performed analysis didn't reveal significant runaway generation for the case of the medium size tokamak disruptions that can explain the absence of runaways in experiments. Results of the numerical modelling predict the decrease of the runaway electron energy and density for less peaked profiles of the plasma current and temperature, and for shortest time of fast quench stage.

Acknowledgement.

This work has been carried out in the frame of the Contract of Association between the European Atomic Energy Community and Instituto Superior Técnico and has also received financial support from "Fundação para a Ciência e a Tecnologia" (FCT). The content of the publication is the sole responsibility of the authors and it does not necessarily represent the views of the Commission of the European Union or FCT, or their services.

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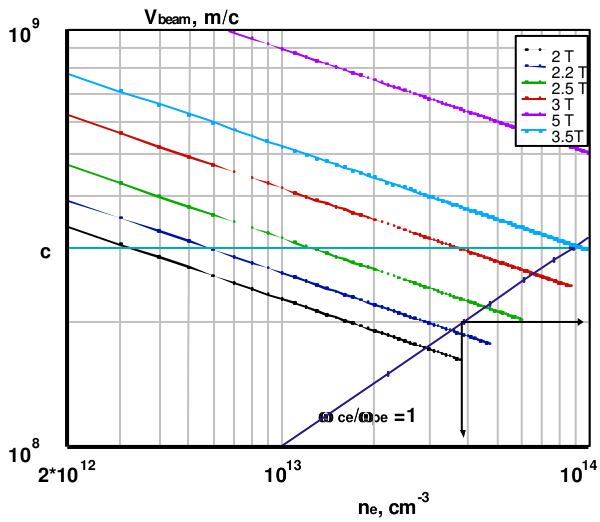


Fig.1a. The runaway instability criterion (2) on the accessible values of the Vbeam plotted vs. plasma density.

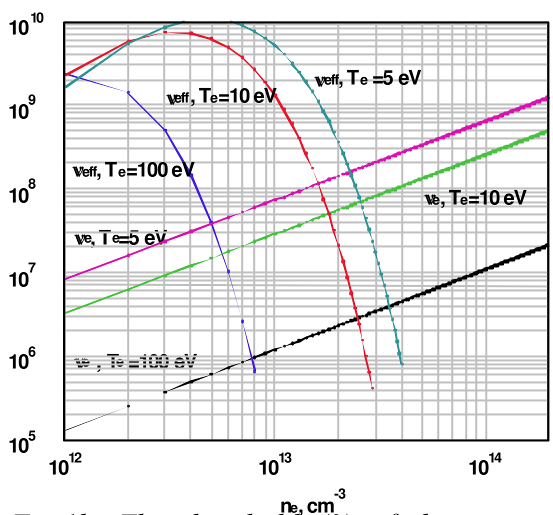
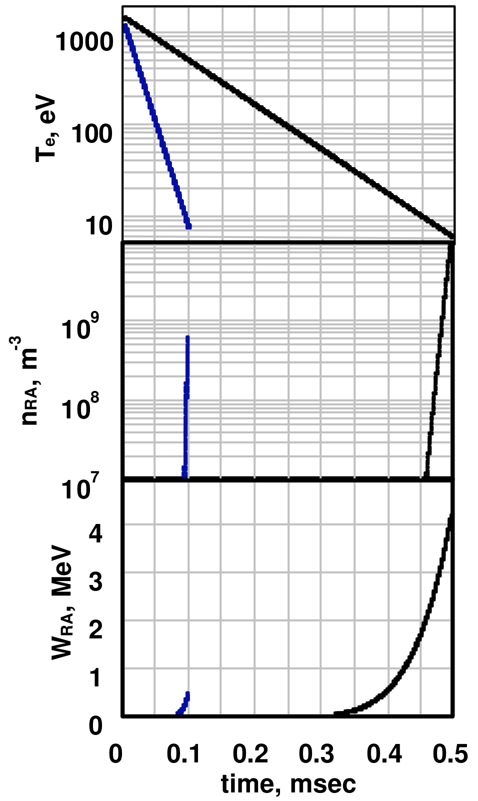


Fig.1b. The threshold (3) of the runaway instability excitation for different electron temperatures plotted vs. plasma density.



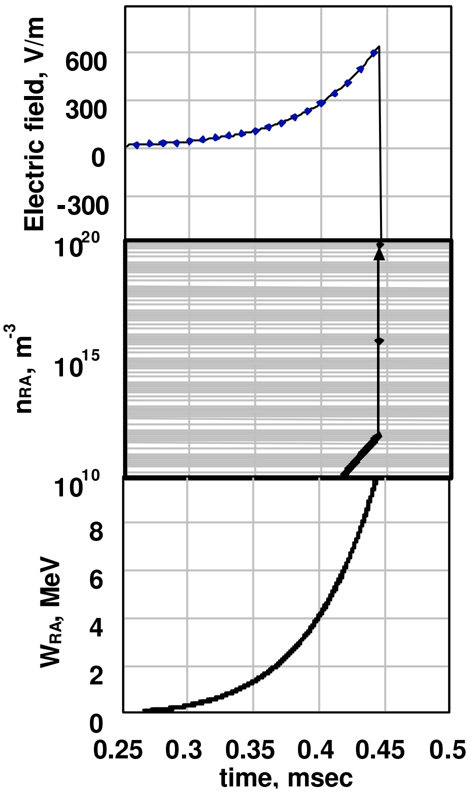
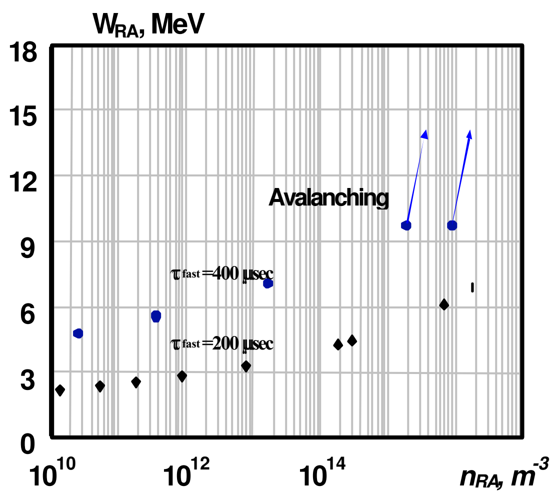


Fig.2. The runaway generation in the thermal quenches with different times of fast quench for medium size tokamak experiment

Fig3. The runaway generation in the thermal quench with inclusion of the secondary avalanching (time points marked by arrow) in large tokamak.



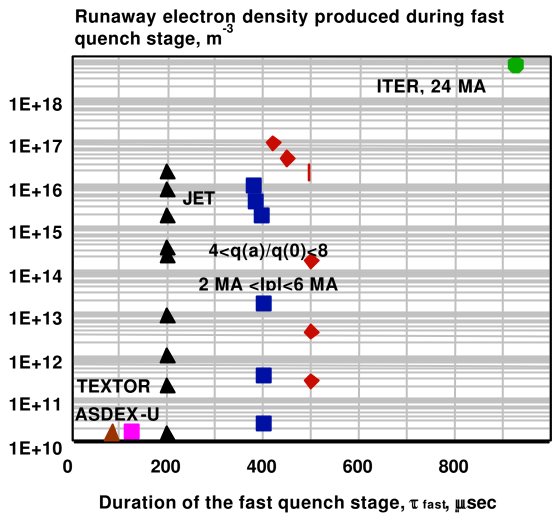


Fig.4. The runaway generation in the thermal quenches with different times of fast quench in large tokamak (JET, 4<q(a)/q(0)<8, 2 MA< I_{pl} <6 MA, < n_e >= 10^{20} m^{-3})

Fig5. The runaway generation in the thermal quench without inclusion of the secondary avalanching (upper values of the runaway density are pre-avalanche values for JET and ITER