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Runaway effects at the plasma boundary in ISTTOK

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Abstract

Experimental results on minor and major disruption events in discharges with runaway electrons in the small tokamak ISTTOK and corresponding numerical analysis are presented. Using the experimental data from the soft X-ray diagnostic the image of the plasma column in the presence of runaway electron instability and disruptions was reconstructed. The most probable zones of the interaction of energetic electrons with the plasma surrounding surfaces were detected as spots of the soft X-ray emission on the top and bottom parts of the plasma column during the development of the disruptions. Numerical analysis of the runaway instability allowed determining the runaway electrons characteristics, such as energy ($W_{eRA} \leqslant 30$ keV) and density ($n_{RA} \sim (0.001\text{–}0.01)n_e$). On the basis of this analysis the level of electrostatic turbulence due to the instability was estimated.

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Keywords: Tokamak; Disruption; Runaway electrons; Plasma boundary; Runaway instability

1. Introduction

Experimental observations of the runaway electron generation in the ISTTOK tokamak ($R_0 = 0.46$ m, $a_{pl} \leqslant 0.085$ m, $B_0 \leqslant 0.5$ T, $\langle j_{pl} \rangle \cong 0.2\text{–}0.5$ MA/m^2, $n_e \sim (1\text{–}5) \times 10^{18}$ m^{-3}) have been reported briefly earlier [1]. Low-density discharges at the high longitudinal electric fields ($E_0 \geqslant 1$ V/m) revealed substantially unstable character due to the presence of runaway electrons and the instability caused by them. Usually, such instability occurs following the onset of runaway regime at $\omega_{ce} \geqslant \omega_{pe}$ and sufficiently large amount of the accelerated electrons [2]. In the significant amount of the discharges this instability led to minor and major disruptions. Self-consistent model for simultaneous calculations of the plasma power-energy balance and evaluation of the runaway current values was developed for a numerical treatment of the experimental data. The temporal evolutions of the runaway current and the electron temperature were obtained from the measured macroscopic plasma parameters.

In this paper the structure of the discharges in the presence of runaway instability and in the presence of partial and major disruptions was observed using the soft X-ray diagnostic. Analysis of the soft X-rays emission enabled to locate the most probable zones of the interaction of energetic electrons with the plasma surrounding surfaces. These zones were detected as spots of the soft X-ray emission on the top and bottom parts of the plasma column. The main characteristics of the runaways were calculated from the experimental data. On the basis of these calculations and the theory of runaway electron instability the values of the turbulent radial electrostatic fields arisen at the instability excitation were estimated. Determined values of the turbulent electric fields are of the same order of value as those inferred from the analysis of the runaway electrons diffusion in JET [3].

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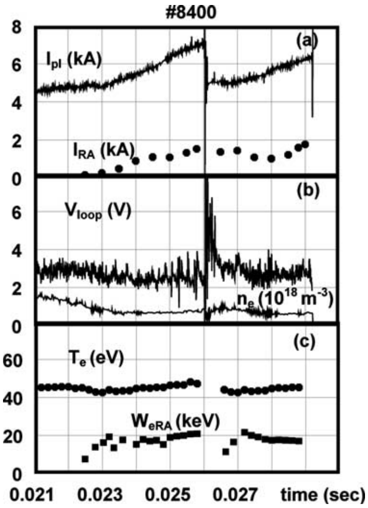

Fig. 1. Temporal evolution of the plasma parameters in the discharge #8400 with runaway generation and minor and major disruptions is presented. In chart (a) plasma current and runaway current are presented, in chart (b) – loop voltage and average plasma density. The average electron temperature T_e calculated by the power-energy balance (chart (c), circles) presented together with estimated runaway electron energy W_{eRA} (squares).

2. Experimental results and discussion

Temporal evolutions of the plasma parameters including the electron temperature $T_e(t)$ in the discharge with runaway generation, and minor and major disruption events are presented in Fig. 1. Experimental data was analysed using the self-consistent numerical model, which includes the calculations of the plasma power-energy balance and the determination of the runaway process characteristics, such as runaway electron current I_{RA}, density n_{RA} and energy W_{RA} [1]. The sequence of measured and numerically modelled events in the discharge #8400 (Fig. 1) is in adequate agreement with the temporal evolution of the discharge image obtained using the soft X-ray diagnostic (Fig. 2). On the first stage of the implementation of this diagnostic in the ISTTOK tokamak experiments the 9-channel system was used for the measurements of spatial and time variations of the soft X-ray emission in the working energy range 1–20 keV. Comparison of the contour plot of the emission structure with the evolution of the loop voltage signal (V_{loop}) reveals obvious coincidence between the broadening of the soft X-ray emission profile (near the plasma periphery) and the regular spikes in V_{loop}, which appeared due to the runaway instability (time between 0.025 and 0.026 s in Fig. 2). During the

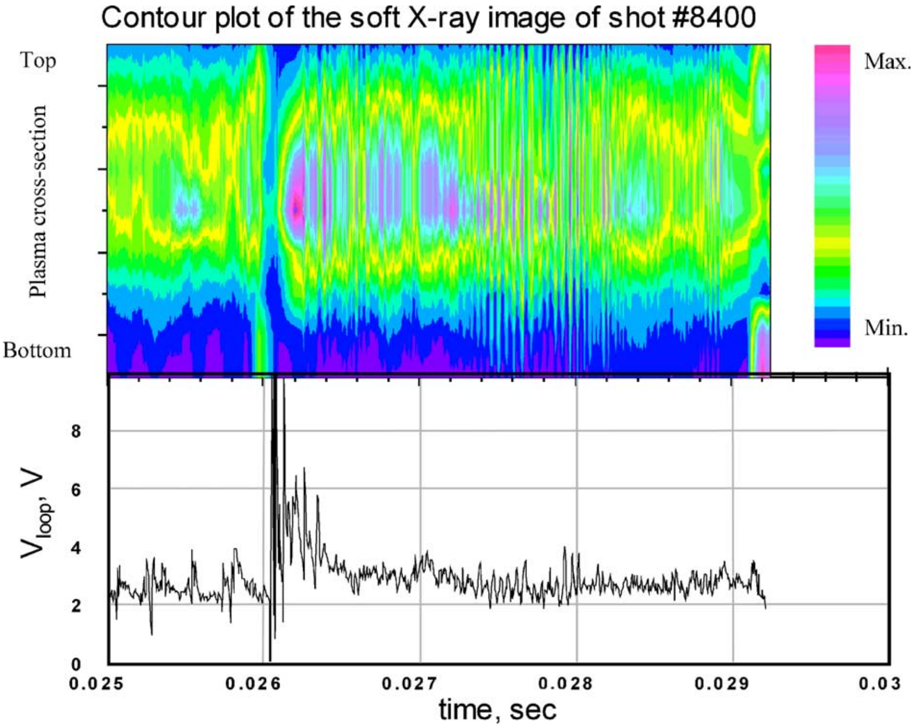

Fig. 2. Soft X-ray image of the discharge #8400. The partial disruption is observed at $t = 0.026$ s. Discharge is finalized by the major disruption. The zones where energetic electrons hit the plasma surrounding surfaces are clearly highlighted on the top and bottom of the plasma column. Runaway instability is identified in a kind of correlated bursts of the soft X-rays and loop voltage spikes.

same time, just prior to the minor disruption ($t = 0.0261$ s), the helical perturbations of the central part of the plasma caused by the MHD activity are clearly distinguished in the soft X-ray image. The similar coincidence between the broadening of the soft X-ray emission profile (now it develops from the plasma core) and $V_{\rm loop}$ spikes is also clearly seen between 0.027 and 0.028 s. The increase of the transverse energy of the plasma electrons during the instability causes this broadening the soft X-ray emission profile, since the plasma density doesn't change remarkably. Analysis of the emission structure during minor ($t = 0.0261$ s) and major ($t = 0.0292$ s) disruptions (Fig. 2) enabled determining the most probable locations, where the runaway electrons interact with surrounding plasma surfaces. These zones are detected as spots of the soft X-ray emission on the top and bottom parts of the plasma column. The energy of the runaway electrons at which they hit the wall was estimated by numerical analysis (Fig. 1). Direct experimental determination of the fast electron energy is still a subject of further study.

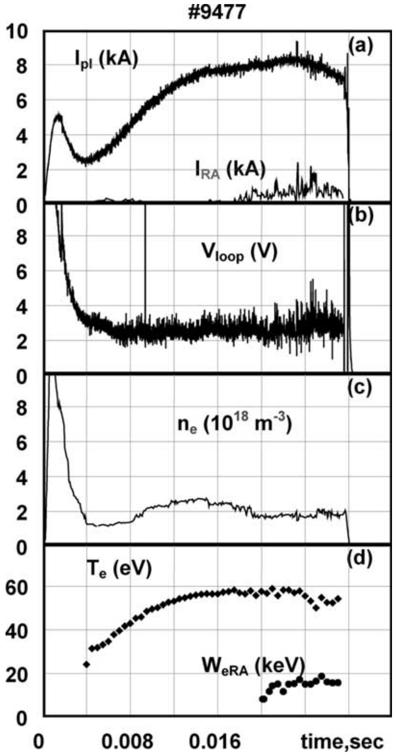

Fig. 3. RA instability in shot #9477 is identified. The instability onset follows the RA regime (at $t = 20$ ms). In chart (a) plasma current and runaway current are presented, in chart (b) – loop voltage, in chart (c) – average plasma density. The average electron temperature T_e (chart (d), diamonds) calculated by the power-energy balance presented together with estimated runaway electron energy $W_{\rm eRA}$ (circles).

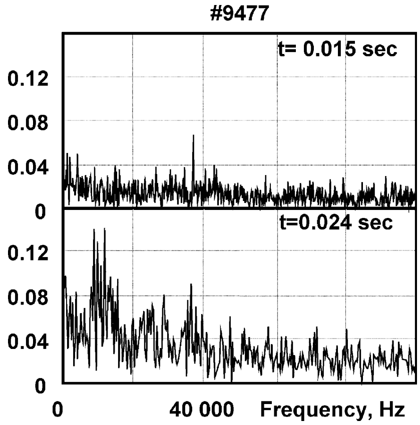

Fig. 4. The evolution of the spectrum of the low frequency magnetic oscillations before and after development of the runaway instability in discharge 9744.

Fig. 3 presents another example of the discharge (#9477) in which the occurrence of the runaway instability at $t \approx 0.023$ s was identified following the runaway regime (started at $t \approx 0.02$ s). The instability itself substantially changes the plasma turbulence level that is noticeably underlined by the data presented in Fig. 4, in which the spectra of the MHD oscillations before and during the instability are presented. This stage of the instability is also characterised by the strong increase of the irregular oscillations in $V_{\rm loop}$ signal. Similarly to earlier observations [1,4], the instability with irregular oscillations (broad spectrum, Fig. 3) didn't provoke the minor and major disruptions, unlike the case of instability with regular relaxations (frequency ~5 kHz, for example, Fig. 1).

The excitation of the unstable plasma oscillations and the increase of effective collision frequency are the main effects associated with the instability driven by the runaway electrons. The magnetized Langmuir oscillations are generated in a plasma by the runaway electron beam if the certain conditions on the runaway electrons velocity and density are satisfied: $v_{\rm beam} > 3v_{\rm cr}(\omega_{\rm ce}/\omega_{\rm pe})^{3/2}$, where $v_{\rm cr} = v_{\rm Te}(E_{\rm CR}/E_0)^{1/2}$ and $E_{\rm CR} = e^3 \ln \Lambda n_{\rm e} Z_{\rm eff}/4\pi\varepsilon_0^2 T_{\rm e}$ – is the critical Dreicer field, and $\nu_{\rm eff} > \nu_{\rm e}$, where $\nu_{\rm e} = 2.91 \times 10^{-6} \ln \Lambda n_{\rm e} Z_{\rm eff} T_{\rm e}^{-3/2}$ and $\nu_{\rm eff}$ is the effective collision frequency, which characterizes the enhancement of collisions due to the plasma oscillations. Actually, $\nu_{\rm eff}$ can be evaluated from the analysis of plasma parameters variation during the instability using the following expression [1,2]: $\nu_{\rm eff} \cong \omega_{\rm pe}(n_{\rm beam}/n_{\rm e})(\omega_{\rm pe}/\omega_{\rm ce})v_{\rm Te}/v_{\rm cr}$, in which $n_{\rm beam}$ and $v_{\rm cr}$ are calculated from the measured plasma parameters. Analysis of the functional dependence of the criterion $\nu_{\rm eff} > \nu_{\rm e}$ on the main plasma parameters shows that in our experiments this criterion is satisfied mainly for the periphery plasma parameters (Fig. 5). Evaluated values of $\nu_{\rm eff}$ and results

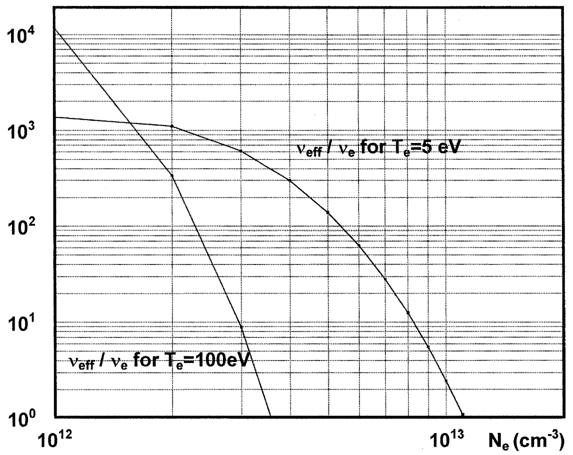

Fig. 5. The ratio $\nu_{\rm eff}/\nu_{\rm e}$ plotted vs. plasma density at the usual electron temperature in the ISTTOK experiments. $\nu_{\rm eff}/\nu_{\rm e} > 1$ is the condition of the runaway instability excitation in discharges.

of Refs. [1,2] were used for estimation of the magnitude of the radial fluctuating electrostatic fields arisen during the instability. For these oscillations: $W_{\rm osc}/nT_{\rm e} \cong (n_{\rm beam}/n_{\rm e})(\omega_{\rm pe}/\omega_{\rm ce})(v_{\rm Te}/v_{\rm cr})$, where $W_{\rm osc}$ is the average energy density of oscillations. At determined values of $W_{\rm osc}$ from known runaway electrons density and energy, at which the instability was observed, the magnitude of the radial fluctuating electric fields was evaluated as $E \cong 1.5$ kV/m. Similar values of the turbulent electrostatic fluctuations were proposed as an explanation of the estimated high values of the diffusion coefficient inferred from the analysis of the experiments with the runaway electrons in JET [3].

3. Summary

The most probable zones of the interaction of fast electron with the plasma surrounding surfaces during disruption in ISTTOK were identified by the analysis of the X-ray emission. These zones were detected as spots of the soft X-ray emission on the top and bottom parts of the plasma column appeared during disruptions. Numerical analysis of the plasma parameters allowed determining the characteristics of the runaway generation process. On the basis of theory of the runaway instability and determined evolution of the plasma parameters the values of turbulent electrostatic fields arisen at the development of the runaway instability were estimated. It is shown that at the easily accessible values of the runaway or supra-thermal electrons density and energy on the plasma periphery the excitation of the intense high-frequency electrostatic plasma oscillations is possible.

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References

[1] V.V. Plyusnin et al., 28th EPS Conference on CFPP, Funchal, Madeira, 18–22 June 2001 ECA vol. 25A, 2001, p. 601.

[2] V.V. Parail, O.P. Pogutse, Nucl. Fusion 18 (1978) 303; Nucl. Fusion 18 (1978) 1357.

[3] B. Esposito et al., Plasma Phys. Controll. Fusion 38 (1996) 2035.

[4] V.V. Alikaev et al., Sov. Phys. Tech. Phys. 20 (3) (1975) (Zh. Tech. Fiz. 45 (1975) 515).