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A STUDY OF RUNAWAY GENERATION IN THE ISTTOK TOKAMAK.

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1. Introduction.

Runaway generation is one of the fundamental physical processes in plasmas being under the action of external electric fields. Usually, the runaways occur in discharges with low density plasmas and relatively high longitudinal electric fields applied. This phenomenon has been intensively studied both experimentally and theoretically (as, for example, [1-4]). Such studies are still actual, because the creation of runaways in disruptions or during fast current ramp-down in reactor-scale tokamaks will lead to unacceptable electromechanical and thermal stresses [5].

Anomalously low plasma resistivity and ion heating are the first experimental evidences of runaways. The analysis of X-ray emission, ECE radiation and measurements performed with the Thomson scattering diagnostic allow to describe quantitavely the runaway process [3,4]. The synchrotron radiation has been detected in TEXTOR-94 with an infrared camera for the direct observation of the runaway beam image [6].

This paper presents the results of a runaway generation study carried out on the ISTTOK tokamak (R_0=0.46 m, $a_{pl}\leq$0.085 m, $B_0\leq$0.5 T) [7]. The runaway-related events, including typical relaxation phenomena were observed in discharges with current density values $\langle j_{pl}\rangle\cong$0.2-0.5 MA/m^2 in the plasma density range (1-5)*10^{18} m^{-3}. Since the diagnostics based on the analysis of radiation from plasmas (X-ray emission, ECE radiation, Thomson scattering) were not available in this study, the runaway process was investigated by the analysis of macroscopic plasma parameters carried out in the frame of runaway theory and numerical modelling. All considerations were carried out in zero-dimensional approximation.

2. Analysis of parameters and detection of runaway regimes.

Due to the high E_0 values (E_0~8-10 V/m) applied for discharge creation, the criterion E_0/p_0>(2-2.5)*10^4 V/m*torr^{-1}, where p_0 is the value of the working gas pressure, taken as the threshold condition for runaway regime on the break-down stage [8], was exceeded in experiments and in some cases after initial break-down the further discharge development was not possible. Therefore, despite of inevitable intensive losses [1,3] a significant runaway production at the earlier stage of discharge can be expected in the ISTTOK experiments.

Another criterion of runaway conditions which can be written in the following form $K\equiv 10^{19}\langle j_{pl}\rangle$[A/m^2]/(1.4x10^6 $\langle n_e\rangle$ [m^{-3}]) $\geq$1 was established in multiple earlier investigations on tokamaks [1,4]. This criterion directly underlines the runaway character of the discharge and can be easily evaluated from the measurements of macroscopic plasma parameters I_{pl} and $\langle n_e\rangle$. The runaway regimes detected in ISTTOK (Fig.1) have the features similar to those commonly observed in runaway tokamak experiments [1,3,4,9]. The increase of plasma current with simultaneous drops in loop voltage and MHD activity were preceeded by the plasma density decrease below the critical value determined from the condition K=1. Usually, the decrease of MHD activity is the consequence of a significant runaway fraction in the total plasma current. The runaway criterion was satisfied for a large amount of obtained experimental data mainly due to the low plasma density at relatively high plasma currents (q(a) ~3-4). The formation of noticeable current plateau at t $\cong$ 500-700 μs after discharge termination which was observed in some shots also should be addressed to the presence of runaways [1,6,9,10].

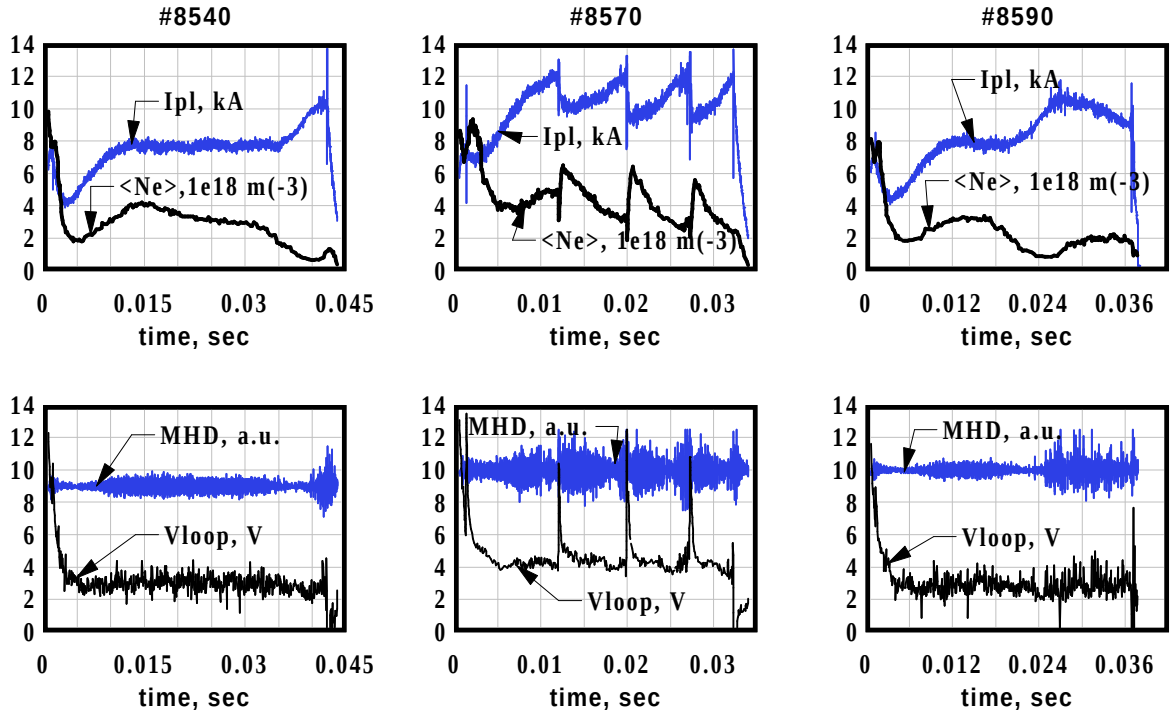

FIG.1. The time traces of the plasma parameters in discharges with runaway generation events.

It is well known that runaway electrons, due to their highly anisotropic distribution function, can be a source of plasma instabilties [1,4,11,12] and, in turn, the development of some instabilities in tokamak discharge enables the runaway generation. The disruptive instability is an example of instability which leads to the creation of runaways together with enhanced impurity release and plasma cooling [13]. The disruptive-like events (DLE) in shot

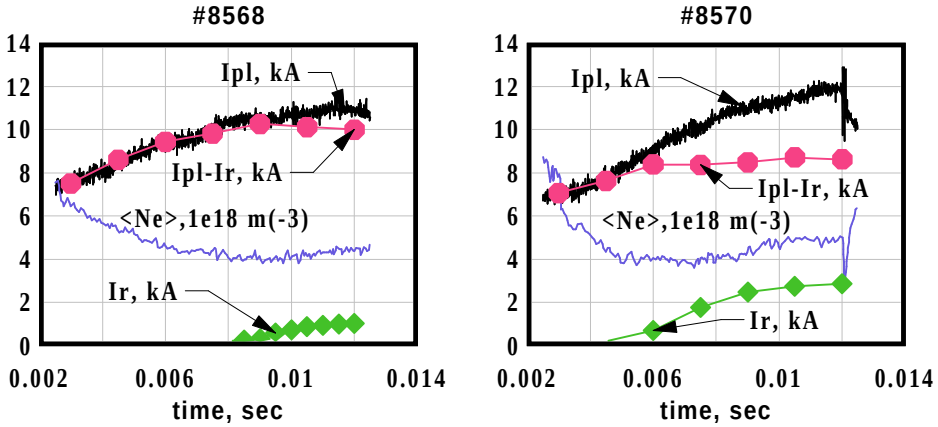

FIG.2. The effect of the runaway currents on the achievement of DLE conditions.

#8570 occured at q(a)≅3.2 (Figs.1,2). In shot #8568 (Fig.2), at the same V_{loop} and B_{vert} values, the plasma current was ~ 7-10% less and the DLE condition was not achieved. After DLEs a significant density decrease enabled the runaway process, which resulted in a voltage drop with simultaneous current increase till the next DLE started. Note, that the incremental increase of MHD activity and oscillations in V_{loop} signal and correlation between bursts of oscillations in both signals are clearly seen and preceeded to the 2nd and the 3rd DLEs. The relaxations are seen also in I_{pl} signal before the 3rd DLE (Fig.3). The observed phenomena are very similar to those detected in tokamak discharges with instability driven by runaway electrons [1,3,4,11].

3. Results on runaway current evaluation and discussion.

The runaway process is very sensitive to the electron temperature and density. Since independent measurements of T_e were not available, the calculation of the runaway current (I_r) from the experimental data was carried out taking into account the results of numerical modelling. In this modelling the evolution of the discharge parameters was simulated including the effect of runaway generation. It was done in the frame of 0-D model which includes the equations of energy balance for electrons, ions and atoms as well as particle balance equations with characteristic confinement times evaluated as $\tau_e \cong (1\text{-}4)10^{-4}$ sec [14]. This set of equations was completed by the equations of electric circuit for capacitor battery driven discharge in equivalent 'perfect transformer' scheme and by an equation of evolution of runaway electron density for calcualtion of I_r in the continuous creation model [9]. The following equations were used in the modelling:

$d V_{loop}/dt = -(I_{pl} + I_r)/C$ $\qquad d(n_a T_a)/dt = P_{cx} - P_{convection\_loss}$

$d I_{pl}/dt = (V_{loop} - I_{pl} * R_{pl})/L_{pl} - dI_r/dt$ $\qquad dn_e/dt = n_e n_a * \langle \sigma v \rangle_{ion} - n_e/\tau_p$

$d(n_e T_e)/dt = P_{OH} - P_{loss} - n_e T_e/\tau_{Ee}$ $\qquad dn_a/dt = - n_e/dt$

$d(n_i T_i)/dt = P_{ei} - P_{cx} - n_i T_i/\tau_{Ei}$ $\qquad dn_r/dt = \lambda_r - n_r/\tau_r$

The runaway current was calculated as $I_r = \pi a^2 e n_r c A_0 * ((ec/m_e)^2 + A_0^2)^{-1/2}$ in numerical modelling and evaluated as $I_r = \int \pi a^2 e \lambda_r c A_0 * ((ec/m_e)^2 + A_0^2)^{-1/2} dt$ from the experimental data, where $\lambda_r \cong const(Z_{eff})(E_{cr}/E_0)^{3(Z+1)/16} n_e \nu_e \exp\{-E_{cr}/4E_0 - sqrt((Z+1)E_{cr}/E_0)\}$ is the runaway particle flux given by [2] and $A_0 = \int E_0 dt$ - the vector potential of the poloidal magnetic field.

The numerical modelling allowed to estimate the reasonable limits of such plasma parameters as electron temperature $\langle T_e \rangle \sim$30-70 eV, $Z_{eff} \sim$2-3 and $I_r \sim$1-5 kA at other macroscopic parameters being choosen close to the experimental ones. These $\langle T_e \rangle$ and Z_{eff} values were used as a starting point in calculations of I_r from the experimental data. The modified Ohm's law: $E_0(t) = E_0(1 - I_r(t)/I_{total}(t))$ and usual formula of the Spitzer's resistivity: $\eta_{pl} = Const * Z_{eff} * f(Z_{eff}) * \ln\Lambda * T_e^{-3/2}$ were used to update in calculations the actual values of I_r and $\langle T_e \rangle$ according to the changes in the Ohmic heating power and other plasma parameters.

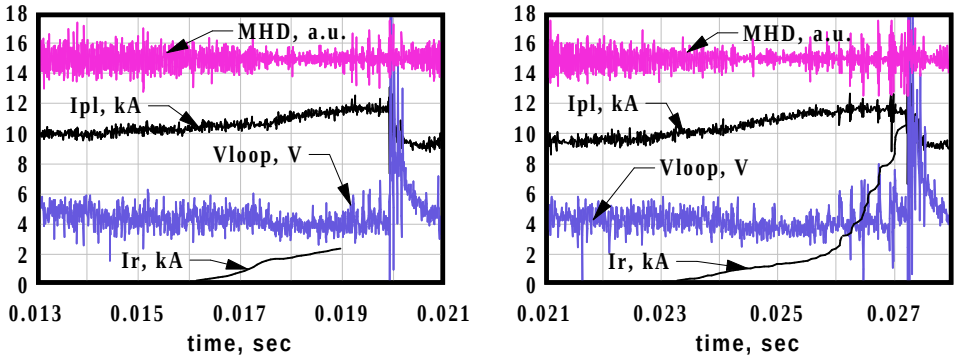

FIG.3.Shot #8570. The evolution of plasma parameters and runaway currents between DLEs.

The best matching of the calculated runaway current to the evolution of macroscopic plasma parameters is found to be at $\langle T_e \rangle$=40 eV and Z_{eff} =2 before the 1st DLE in #8570 and in the same time range in #8568 (without DLE) (Fig.2). It is seen that a higher value of the total plasma current which led to DLEs in #8570 is associated with a higher value of I_r. Such a result can be explained by slightly lower plasma density in #8570 in comparison to #8568, since $E_{cr} \sim n_e/T_e$ in the expression for λ_r. During the transient stage of DLE the plasma parameters strong changed in a very short time: $\Delta I_{pl} \sim 20\%$, $\Delta V_{loop} \cong \pm 10$V, $\Delta \langle n_e \rangle \cong \pm 50\%$ of the

initial value. It is assumed that during instability event the runaway current completely disappears and the process of substitution of the plasma resistive current by the current of runaways [15] is insignificant. That is why the calculation of the runaway current was carried out only during stages between DLEs where the plasma parameters varied slowly. After the 1st and further DLEs the electron temperature slightly decreased, which can be explained by the enhanced impurity release during DLEs.

The analysis of the behaviour of the calculated I_r in latter cases (i.e after the 1st DLE) in comparison to the evolution of measured I_{pl} yields, however, a significant difference in evolutions just before DLEs. The saturation in I_{pl} clearly correlates with the incremental appearance of V_{loop} and MHD bursts, while the continuous creation model yields the step-like I_r increase (Fig.3). Qualitatively such a difference can be exlained by the appearance of an instability driven by the runaway electrons (fan instability) [4,11,12]. This instability tends to isotropize the runaway beam in the velocity space. It appears when the runaway electron beam velocity exceeds the critical value: $V_{beam}>3V_{Te}(E_{cr}/E_0)^{1/2}(\omega_{ce}/\omega_{pe})^{3/2}$ [3,4,11,12]. According to the theory of this instability [11,12] the bursts of V_{loop} are the evidence for the retardation effect of the runaway electron beam. The similar saturation of the plasma current under runaway conditions is clearly seen also in shots #8540 and #8590.

A simple evaluation shows that at the given experimental parameters ($<n_e>$, V_{loop}) and $<T_e>\sim$40 eV the fan instability condition $V_{beam}/V_{Te}\sim10$ can easily be achieved. At the values $I_r\sim3$ kA and $V_{beam}\sim10\ V_{Te}$ the density of runaway electrons is varied in a range of two orders of magnitude depending on the beam radius: $2.5*10^{16}$ [m^{-3}] $<n_r<1.5*10^{18}$ [m^{-3}].

4. Summary.

The runaway regimes were identified in the majority of the discharges in the ISTTOK tokamak. Their characteristic feature is that the runaway electron current is a significant part of the total plasma current. It leads in some cases to the appearance of disruptive-like events due to the temporal loss of equilibrium and stability.

The runaway beam instability was observed in the experiments. This instability led to saturation of the plasma current own by the retardation effect of the runaway fraction in the total current.

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