STUDIES OF DISCHARGE QUENCH BY KILLER PELLETS IN T-10

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Fast re-radiation of plasma thermal and magnetic energy is necessary and useful both in emergency and in standard modes of the tokamak-reactor operation [1]. Therefore, studies of the theoretical [2]-[4] and experimental [4]-[6] aspects of the problem for the modern thermonuclear devices are necessary. The results of injection of KCl pellets containing up to $3{\cdot}10^{18}$ atoms into T-10 tokamak for the discharge quench are described in detail in Ref. [7].

This report presents the first investigation of the T-10 tokamak plasma response on injection of the amount of a high-Z impurity KCl, which is by an order greater (~10^{19} atoms) and which causes re-radiation of a considerable part of the discharge current. The KCl pellets were injected into the Ohmically heated plasmas during quasi-steady stage of the discharge with the following basic parameters before injection: plasma current I_p = 280 kA, loop voltage U_l = 1.3 V, magnetic field B_t = 2.1 T, limiter radii a_L = 0.3 m, central electron temperature $T_e(0)$ ~ 1 keV, volume averaged electron density $\overline{n}_e \sim 2{\cdot}10^{19}$ m^{-3}.

Experimental set-up is described in detail in Ref. [8]. Impurity was injected into plasma from top to bottom in the direction of plasma center, by means of several (order of 10) KCl pellets of 0.1-0.3 mm sizes and with velocities V_p = 100-150 m/s. The pellets evaporated at the plasma periphery with minor plasma radii $r \leq 20$ cm. Temporal evolution of signals from basic diagnostics is shown in Fig. 1 for a typical discharge. All signals are normalized by its maximum value over the time interval of interest. Electron temperature at the quarter of minor radius $T_e(a_L/4)$ was measured by the $2\omega_{ce}$-ECE heterodyne receiver; the soft X-ray (*SXR*) signal corresponded to the radiation along the central chord. Signals from the hard X-ray (*HXR*) detector, from MHD m/n=2/1 probes (*MHD*) and from one of the periphery channels of the fast bolometer array (*Bol*) were analyzed as well.

The impurity injection into plasma starts at 812.6 ms, that is well seen from the bolometer signal. The peaks on the signal correspond to the moments of evaporation and ionization of separate pellets. Plasma parameters vary insignificantly approximately up to 821 ms, when a substantial part of impurity enters in the plasma. At this moment (821.2 ms), the bolometer signal reaches its values close to maximum, and keeps at this level during 0.5 ms. At the same time, a sharp collapse of electron temperature occurs simultaneous with decreasing of SXR signals. Temperature drops practically to zero value and remains at this level during all further evolution. Thus, the time interval 813-821 ms corresponds to the removing stage of thermal energy from the plasma (see Ref. [7]).

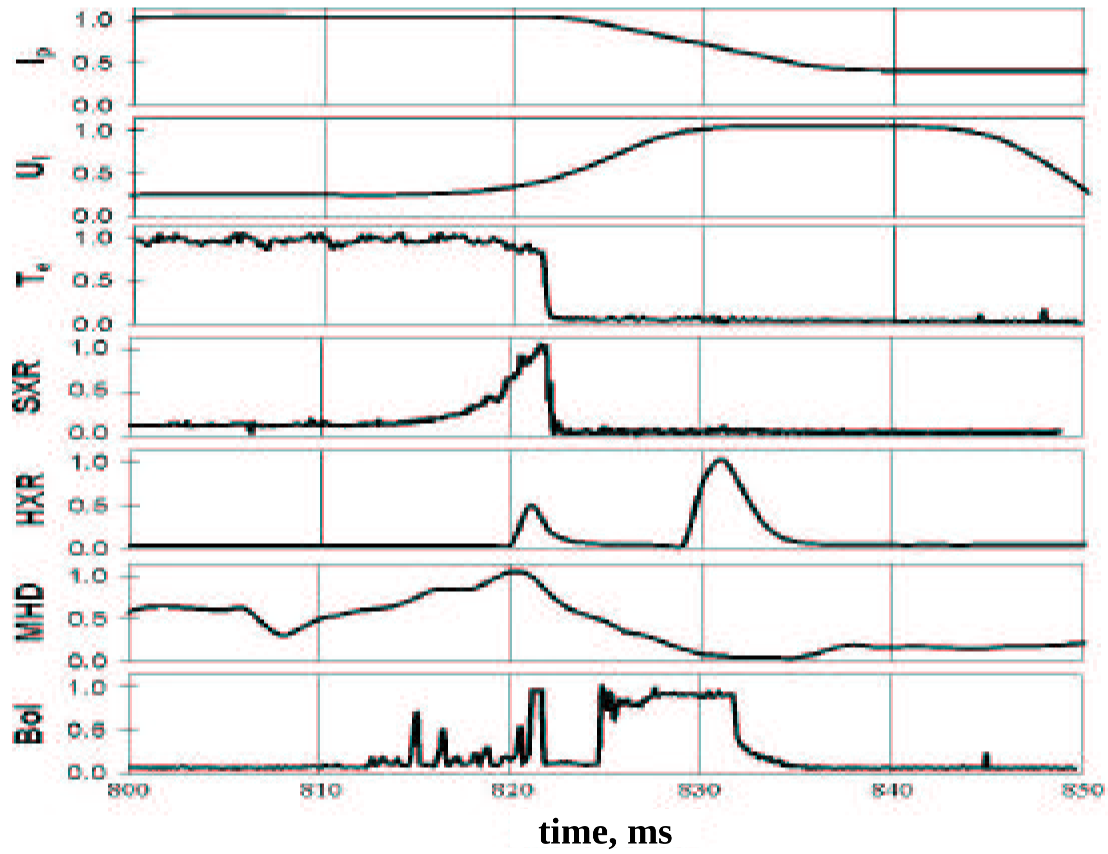

Fig. 1. Temporal evolution of the basic plasma parameters during KCl injection in shot 27528.

Analysis of the electron temperature profile evolution during the phase of its sharp collapse (see Fig. 2) indicates fast impurity penetration into the central area of the plasma column. This follows from a practically simultaneous decreasing of the electron temperature in all channels. Estimations show that the diffusion coefficients values during this phase are at least by an order greater than the quasi-stationary values ($D \sim 1{\cdot}m^2/sec$). This confirms the conclusion made in Ref. [7] that the magnitude of the diffusion coefficients perturbation depends on the injected impurity amount.

When the re-radiation phase of the plasma thermal energy finishes, the current ramp-down stage begins. The current decreases together with growth of loop voltage. The current starts falling down approximately at 822 ms and decreases during 15 ms at an average rate of 12 MA/sec down to values ~ 100 kA (see Fig. 1). The current decreasing in 2.5 times corresponds to more than 75% reduction of the poloidal magnetic field energy.

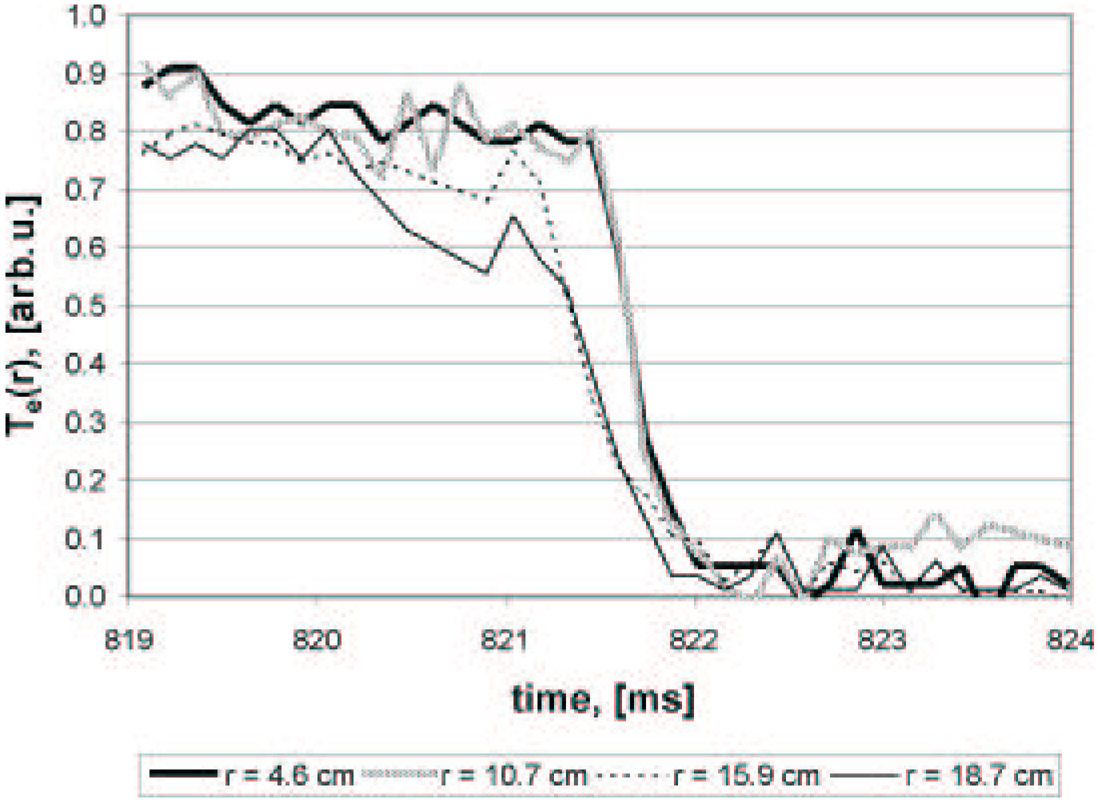

Fig. 2. Temporal evolution of the electron temperature profile during KCl injection in shot 27528.

From 825 ms to 832 ms, the bolometer signal is approximately constant and is close to the maximum value. During this phase, the magnetic field energy of the plasma current is re-radiated by impurity, which is seen from permanent current decreasing. The fairly low bolometer signal (only two - three times greater than the quasi-stationary magnitude just before the thermal quench stage) at the beginning of the current collapse stage (from 822 ms to 825 ms) is interesting. One can assume that the current energy has been transferred to run-away electrons during this time (probably through the avalanche mechanism of generation at close collisions [9]), and is consequently re-radiated in the ranges, where registration by the available hard X-ray detector is impossible (< 0.5 MeV).

In this sense, the hard X-ray burst at 830-835 ms is characteristic. Let's emphases also the earlier burst of hard X-radiation at 820-822 ms (immediately before the sharp electron temperature decrease), which is probably connected with a loss of the runaway electrons population that existed in the discharge before impurity injection. This loss can occur due to large MHD activity that is confirmed by quite good correlation between the moment of the first HXR burst and the maximal plasma MHD activity (See Fig. 1). At the moment of the second HXR burst, the MHD signal is low, and the runaway electrons are apparently lost through another mechanism. Possible explanation is that runaways reach high enough energy

(> 0.5-1 MeV) to intersect the limiter by their orbits shifted from the magnetic flux surfaces where they have been originated [10].

The smooth decreasing of the bolometer signal after 832 ms during the continued current re-radiation can be possibly explained by reduction of the plasma energy content, by the diffusive drift of the radiating impurity to the walls or/and by the continued generation of runaway electrons.

At 840 ms, the current decrease ceases at the level of 100 kA, and the discharge proceeds to a new quasi-stationary stage with minimal energy content. Termination of the current quench, is probably connected with the diffusive going away of impurity from plasma. This is confirmed by the loop voltage decreasing, while the current is constant at the final stage of evolution. Another variant is possible, that runaways carry the main part of the remaining plasma current during the discharge end. Let's mark that the saturation of the loop voltage signal from 835 till 840 ms is obviously determined by the acquisition system registers overflow. The maximum registered signal at the exit of a smoothing filter with the decay time constant of about 30 ms corresponds to loop voltage of 6 V.

The carried out experiments with injection of a large amount of a high-Z impurity KCl into T-10 plasma have demonstrated the complete re-radiation of the thermal component of plasma energy and re-radiation of more than 75 % of the poloidal magnetic field energy. Two hard X-ray bursts during quench have been observed. They indicates that runaway electrons are generated during the discharge quench. Fast penetration of impurity into the central area of plasma column was observed.

Acknowledgments

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