Simulations of Transient Plasma Transport after Injection of High Z Impurity Pellets into T-10 Plasmas

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Introduction

In this paper, we present results on the simulation of fast plasma core cooling observed in the T-10 plasma after injection of high Z (KCl) impurity pellets. These experiments were aimed at studying plasma quench by means of impurity radiation. The interest in the problem arises from a possible mitigation of disruptions in large tokamaks. This so-called 'killer' pellet injection must quench plasma within an appropriate time scale and should not produce additional problems, such as promotion of expected plasma disruptions due to the excess over the density limit [1] or the generation of a large amount of runaway electrons [3]. There are different approaches to this problem: injection of high-Z pellets [2], injection of light impurity pellets [3,4] or even fuel pellets or jets [5].

The injection of high-Z pellets creates a fairly strong radiation source for a small pellet size [2-4]. A possible generation of runaways due to the "avalanche" mechanism could produce an undesirable effect, as was predicted in Ref. [6] using a 1D-code developed for simulations of killer pellet injection into ITER plasmas. The crucial parameter for the avalanche is the ratio $\gamma = E/E_c$ of the toroidal electric field E to the critical electric filed E_c. The runaways can be generated during the current quench phase due to the large increase in E, caused by significant plasma cooling. In the case of light impurity injection, the plasma density after the pellet injection is significantly increased due to a large pellet size necessary to produce an efficient radiation source. At the critical electric field E_c proportional to the plasma density, a higher increase in the parameter γ is expected for the ITER conditions in the case of high-Z impurity deposition compared with that of light materials. As a result, a significant runaway current (comparable with 21 MA plasma current) was evaluated for Xe impurity in Ref. [3]. It should be noted that there are still no studies on the injection of huge light impurity or hydrogen pellets containing the total amount of electrons exceeding 10-50 times that of the plasma particles. The plasma response to this injection into the ITER plasma operating at the density limit, may be a fast plasma disruption before re-radiation of most of the plasma energy.

Recently, several experiments with injection of high Z pellets into tokamak plasmas have been performed [7-11]. It is shown that the injection allows one to quench plasma quickly and effectively within 5-10 msec. No runaways were observed on the Asdex Upgrade [8] after the Ne pellet injection. In the Ne experiments on JT-60U [9], the runaway generation was detected, but the technique of enhancement of magnetic field fluctuations by means of external coils was used successfully to suppress the runaways.

Thus, the conclusion of Ref. [3,4] about disadvantages of high Z pellet injection for the plasma quench is questionable. This problem requires further studies and, first of all, the development of a plasma quench model and its verification in different tokamak experiments. Here, an improved model based on a set of 1D-transport equations [12] is applied for the description of KCl-pellet experiments in the T-10 tokamak [7].

Experimental data and 1D transport model

The main result obtained in Ref. [12] is shown in Fig.1. It is seen that the model suggested can not describe the electron temperature drop in the plasma core registered after the pellet injection at the transport coefficients derived from steady-state plasma simulations. Recently, similar phenomena were observed in hydrogen [13, 14] and impurity [11] pellet experiments ("Non-local Plasma Response" or "Enhanced Transport"). Below, the Enhanced Transport (ET) approach is applied to explain the discrepancy mentioned above.

The experiments [12] were made in the ohmically heated T-10 plasma with the following plasma parameters: the major radius 1.5 m; the minor radius 0.3 m; plasma current 0.24 MA; toroidal magnetic field 2.5 T; central electron temperature 1.1 keV; central line-averaged plasma density $2.5 \cdot 10^{19}$ m^{-3}; loop voltage 1 V; limiter safety factor 3. The KCl pellets of 0.3-0.6 mm in size with 100-150 m/c velocities were injected in the plasma core direction. The pellet size was limited by the inner diameter of the injector barrel, providing the injection of up to $1.5 \cdot 10^{18}$ particles per shot. This amount of impurity was enough to quench of most of the thermal energy but produced no current quench.

The 1D code has been described in Ref. [12]. The measured loop voltage evolution after the pellet injection gives a boundary condition for the electric field. The particle and heat fluxes were used in the form $\Gamma = -D\partial n / \partial t + V_p n$ and $q = -\chi \partial T / \partial t$. The transport coefficients were defined by the Alcator scaling law ($D, \chi = Const/n_e$). This allowed a reasonable description of steady-state electron temperature profile before the pellet injection. The profile of pinch velocity V_p was evaluated from the measured density profile and the V_p/D ratio remained unchanged during the further simulation. The D/χ ratio and the absolute values of D, χ were varied in the simulations.

Results of simulations

In shot #61812, a KCl pellet containing $7 \cdot 10^{17}$ atoms was injected at 670 ms. The transport coefficients χ, D, V_p were equal to their steady-state values. The D/χ ratio was taken to be unity. To solve the problem of the simulation of the core electron temperature drop, we used higher transport coefficients after the pellet injection multiplying their steady-state values by

$$(1 + F \cdot \exp(-t /(0.1 \cdot \tau_E)))\,,$$

where τ_E is the energy confinement time calculated in the model. Fig. 2 shows the simulation results for $F = 5$ and $D/\chi = 1/3$. All other variables are the same as in Fig.1. It is seen that the agreement between the

Temperature evolution [keV] in shot #61812

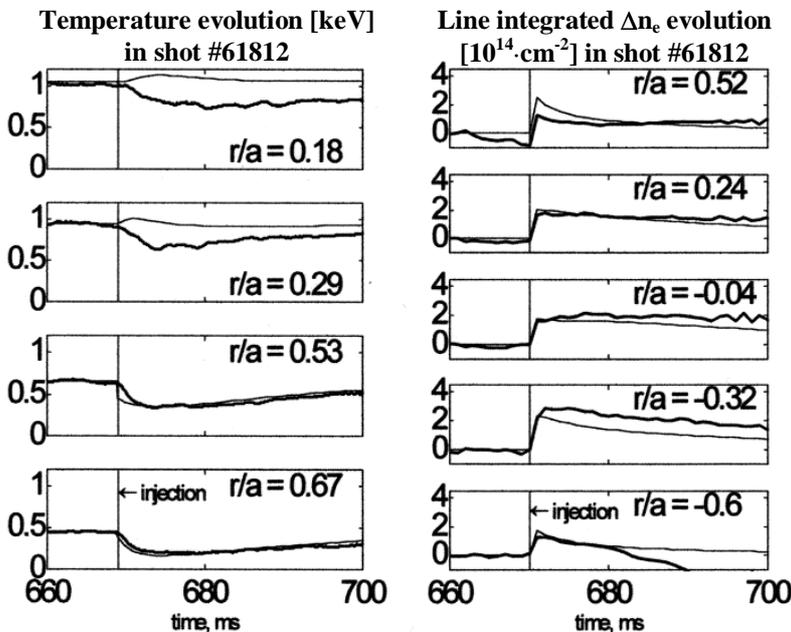**Line integrated Δn_e evolution [$10^{14} \cdot$cm^{-2}] in shot #61812**

Fig. 1. Temporal evolution of the electron temperature (left plots) and the line integrated electron density (right plots) evolution after KCl pellet injection in T-10 shot #61812. Bold lines, experiment; thin lines, simulations without taking into account an ET effect. The positions of measurements are shown in the right corner of the plots. Vertical lines show the injection time.

**Temperature evolution [keV]
in shot #61812**

**Line integrated Δn_e evolution
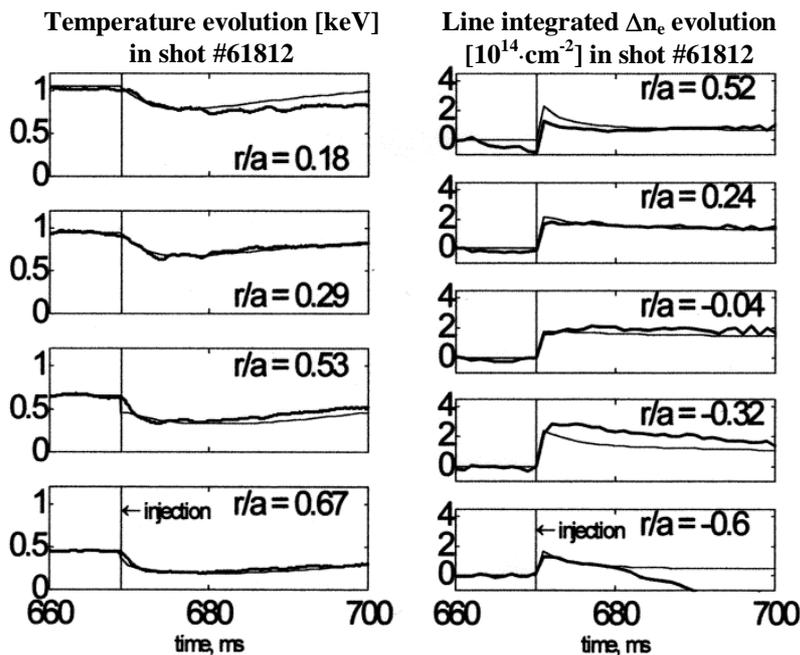[$10^{14}\cdot$cm^{-2}] in shot #61812**

Fig. 2. The electron temperature (left plots) and line integrated electron density (right plots) evolution after KCl injection in shot #61812. Bold lines, experiment; thin lines, simulations with ET effect. The positions of measurements are shown in the right corner of the plots. Vertical lines show the injection time.

**Temperature evolution [keV]
in shot #61905**
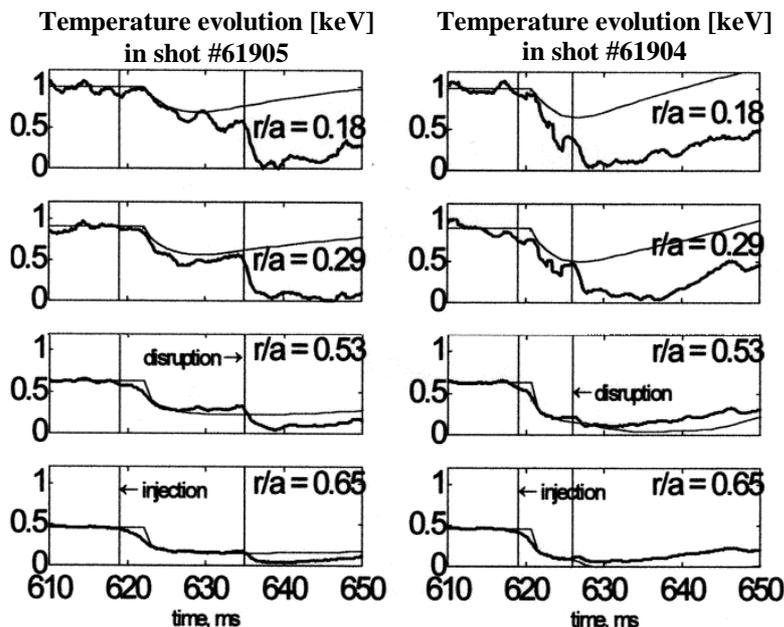
**Temperature evolution [keV]
in shot #61904**

Fig. 3. The electron temperature evolution after KCl injection in shot #61905 (left plots) and #61904 (right plots). Bold lines, experiment; thin lines, simulations with an ET effect. The positions of measurements are shown in the right corner of the plots. Vertical lines show the injection and disruption times.

experiment and simulation becomes much better.

The electron temperature behaviour for shots with a larger amount of impurities injected is shown in Fig. 3. A minor plasma disruption with a well-developed MHD activity and a subsequent drop of the electron temperature is observed after the pellet injection. The moment of disruption is shown in Fig. 3 by the second vertical line. The time delay between the injection and the disruption decreases with the amount of injected impurities, $1\cdot10^{18}$ atoms in #61905 and $1.5\cdot10^{18}$ atoms in #61904. The model cannot describe the disruption evolution, so the comparison should be made within these vertical lines only. All simulation variables were the same as in Fig.2. It is seen that keeping the same factor $F = 5$ as for the smaller amount of injected impurities leads to a growing disagreement between the experimental core temperature evolution and the simulation. This suggests that the values of transport coefficients depend on the perturbation level. It is seen from Fig. 4 that the agreement between the experimental and the simulated core temperature evol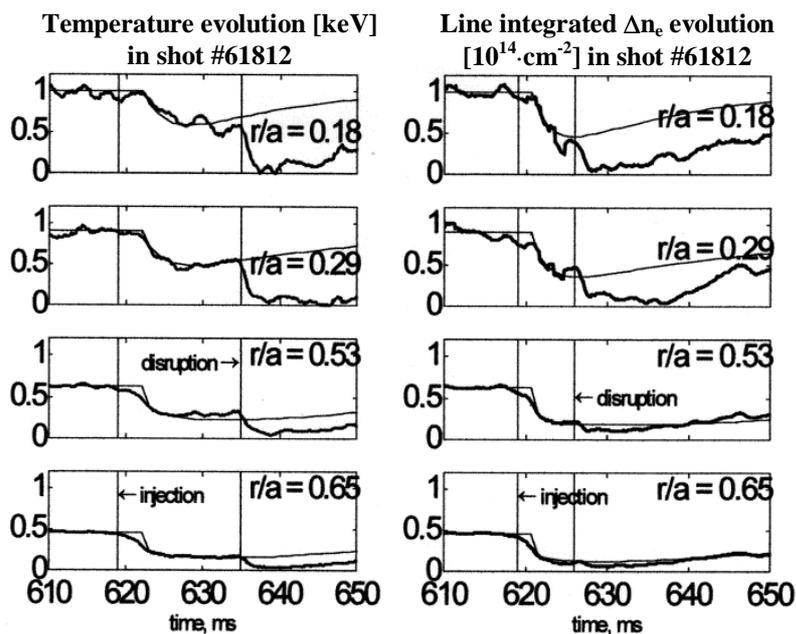utions is much better if this effect is taken into account. The simulations for Fig. 4 were made on an assumption that factor F is proportional to the amount of injected impurities ($F = 7.8$ for #61905 and $F = 11.5$ for #61904).

One cannot exclude fast cooling of the plasma core due to fast impurity drift into this region, as was observed in the "killer" Ne experiments on the D-IIID tokamak [11]. In that

**Temperature evolution [keV]
in shot #61812**

**Line integrated Δn_e evolution
[$10^{14} \cdot cm^{-2}$] in shot #61812**

Fig. 4. *The electron temperature evolution after KCl injection in shot #61905 (left plots) and #61904 (right plots). Bold lines, experiment; thin lines, simulations with the ET effect and the transport coefficients dependence on the total injected impurity. The positions of measurements are shown in the right corner of the plots. Vertical lines show the injection and disruption times.*

experiment, the ablation lasted 0.6 ms and the pellet was fully evaporated at the minor radius *r/a ~ 0.45*. Surprisingly, almost all injected Ne was detected by different diagnostics in the plasma core in less than 1 ms after the injection. At the same time, a detectable increase of magnetic field fluctuations *($\delta B/B$ ~ 0.02)* was observed. The authors of Ref. [11] associate this fast transport with a partial distortion of the magnetic flux map and make an estimation of the effective diffusion coefficient *(D ~ 550 m^2/s)* on the basis of the magnetic fluctuation model [15]. This estimation gives a fairly good agreement with the time of impurity penetration in the plasma core region (~1 ms).

Summary

The use of a temporally enhanced transport initiated by pellets essentially improves simulations of the temperature evolution registered in T-10 KCl killer experiments. The transport is likely to exist within about 0.1 of the energy confinement time, and the transport coefficients are an order of magnitude higher than the steady-state values increasing with perturbation. No clear physical model of the enhanced transport has been suggested.

Acknowledgements

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