Modelling of Tokamak Discharges with the Fast Central Response to the Boundary Plasma Perturbations

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Abstract. Results of the modelling of a series of tokamak discharges with the fast central response to the boundary plasma perturbations of different nature are presented. The main attention is attended to the behaviour of the neutral plasma component which propagation time across the plasma column is sufficiently short (less than 100μs) owing to the effect of multiple charge exchange. It is shown that the effects under consideration can be explained without the assumption on the non-local character of transport processes in tokamaks and may be attributed to the behavior of the neutral plasma component. In particular, the rapid electron temperature rise in the plasma core after the fast L-H mode transition can be explained by the reduction of the cold electron source and charge exchange losses caused by the decrease of neutral flux in plasma. An opposite effect of fast drop of the core electron temperature after deuterium pellet injection (faster that the pellet penetration) may be explained by the rise of deuterium atom density in the plasma core induced by charge exchange. Increase of the electron temperature in the central region of plasma in the experiments with impurity laser ablation can be attributed to the decrease of neutral density in the plasma core due to the drop of the characteristic energy of warm neutrals from the boundary and associated reduction of their penetration. Thus, the neutral plasma component can be responsible for the visible coupling of the plasma edge and the core in considered experiments at least during the time interval just after the edge plasma perturbations.

1. Introduction

One of the fundamental and important phenomena in tokamak plasmas is the fast propagation of electron temperature perturbations from the boundary to the plasma core (faster than the characteristic transport time). This phenomenon has been observed in different tokamak (and stellarator) experiments: fast cold pulse propagation to the plasma center after deuterium pellet injection [1-3], fast plasma core response to the L-H mode transition [4-5], fast propagation of the electron temperature perturbation after impurity injection by laser ablation [6-9] and many other experiments. Standard diffusive model of local turbulent transport fails to describe so fast perturbation propagation. Even more contradictive to the simple diffusive model is that there were experiments demonstrating the reverse of perturbation polarity in propagation from the edge to the plasma core. In the series of works the rapid, compared with characteristic diffusive time, changes in the plasma core along with the absence of visible variations in local plasma parameters there, were taken as a proof of the non-local nature of transport in tokamaks. In addition, no significant changes in the core density fluctuations ($f > 5kHz$, $k \leq 2cm^{-1}$), their spectra and plasma potential were observed in some experiments [6,7] in which such measurements have been done. No evidence of fluctuation propagation has been detected in these experiments. In some experiments the approximately diffusive perturbation propagation is observed together with the non-local responses. As a rule, this was in the vicinity of the primary perturbation and transition to the non-diffusive transport remains unclear. In a series of experiments the MHD activity could be taken into account for some explanation but these instabilities were absent in other experiments. Fundamental and robust character of these phenomena and absence of clear explanations requires more detailed analysis.

In the interpretation of these experiments it was taken into account that the measured variations of the plasma radiation, which can provide the non-local energy transport, were small and not enough for explanation. However, there is a plasma component that can ensure a rapid propagation of a signal into the plasma core. This is *the plasma neutral component* whose propagation time across the plasma column is sufficiently short (t < 100μs). Deuterium atoms due to the charge-exchange propagate into the plasma core with the velocity of the order of plasma ion thermal velocity. Their propagation time is very close to the delay time of perturbation in the considered experiments. In many discharges, the neutrals play a noticeable role in the plasma energy balance, being responsible for energy losses through the charge exchange and convection. The ionization of neutrals is a source of cold electrons in the major part of the plasma column. Neutrals can change ionization state of impurities and, consequently, the plasma radiation. Hence, a rapid change in the neutral flux into the plasma column or in their energy spectrum (which influence the neutral penetration into the plasma core) may somewhat affect the plasma energy balance in the whole plasma cross section almost simultaneously. Moreover, in some experiments with the fast responses considerable variations parameters of neutral component are the specific feature of the process. In particular, in the experiments with the L-H mode transition appreciable reduction of neutral density is detected by the drop of the D_{α} deuterium spectral line intensity and is considered as one of the principal characteristic indicating this transition. Considerable increase of deuterium atom density takes place at the ablation of the deuterium pellet in plasma too.

The behaviour of the neutral plasma component has some peculiarities, effect of which on the bulk plasma is not sufficiently investigated. As a rule the main attention is attracted to its behaviour in the divertor. However its behaviour in the SOL and in the region near the separatrix can strongly influence the properties of the total plasma column. In particular, many specific characteristics of the L-H mode transition were described in [10] with use of the model based on the dynamics of the particle source and neutral component in the peripheral layers of the plasma column. The decisive role of the neutral component in the explanation of the fast L-H mode transition has been shown in [11]. Effect of the charge exchange atoms on the penetration of perturbation after deuterium pellet injection has been discussed in [1,3].

In the presented paper we continue investigations of the role of neutral plasma component and attendant effects in the characteristic experiments with the fast plasma responses on the boundary perturbations of different nature. Results of detailed simulations of discharges with the fast L-H transition (section 2), discharges with the deuterium pellet injection (section 3), discharges with impurity injection by laser ablation (section 4) are presented. For the modelling we selected discharges without pronounced MHD activity effect of which is beyond of the scope of the present work and must be studied separately.

Modelling was performed with use of the ASTRA transport code [12]. Impurity transport and radiation were simulated by the ZIMPUR code [13]. The behavior of the neutral component was described by the kinetic equation in the slab approximation. This approximation seems to be quite applicable to describe the atoms arriving from the plasma periphery in large size tokamaks with high plasma thickness with respect to charge exchange and ionization lengths. The model takes into consideration recycling of the neutrals at the wall [14]. It was assumed that the atomic flux into the plasma consists of the fluxes of cold and warm atoms. The cold atoms are produced in the dissociation of deuterium molecules. Flux of warm atoms is the sum of the flux of fast atoms produced via molecule dissociation and the atomic flux reflected from the first wall and limiters. The main attention was focused to the first several milliseconds (or several tens of milliseconds) after events when changes in plasma parameters and radial profiles were small and their influence on plasma confinement was negligible. At present, there is no completely satisfactory physical model which can explain transient transport properties of toroidal plasma during this short time interval. To more clearly display the role of neutral plasma component we use time-independent transport coefficients: $\chi_e = D = k_i \cdot \chi_i = k \cdot [1+\alpha \cdot (\rho/\rho_{max})^{\beta}]$, $V_p = - k_p \cdot D \cdot \rho/\rho_{max}^2$. The radial dependences of the transport coefficients and the normalization factors were chosen to reproduce unperturbed experimental radial profiles of the plasma parameters (in particular, the *Te*(*r)* profile) before events and then were fixed. The atomic influxes were chosen to provide a density growth rate consistent with the experiment under consideration.

2. Fast L-H Mode Transition

Before the analysis of the fast L-H mode transition it is necessary to discuss briefly the neutral component and the particle source dynamics in these discharges. One of the characteristic features of the L–H transition, by which this transition is now detected, is a sudden fast drop in the D_α deuterium spectral line intensity indicating the reduction of the atomic flux into the plasma column. It is accompanied by an increase in the average plasma density. It is usually interpreted as the improvement of the plasma confinement at decrease of the particle source. However, in the general case it is not so due to the complex structure of the particle source. Dynamics of the neutral component and the particle source in the L and H discharges and effect of the source on the formation of these discharges have been analyzed in[10]. Results of this work can be briefly formulated as follows.

The main part of the hydrogen from the plasma facing components comes into the plasma column as molecules. This is indicated by the existence of the main component of Franck-Condon atoms with the energy of ~ 2 eV in the atomic spectra. At low electron temperatures ($T_e \leq 20$eV) hydrogen molecules dissociate into two atoms. In hotter plasma the dissociation of molecules into atom and ion becomes more important. *FIG. 1*

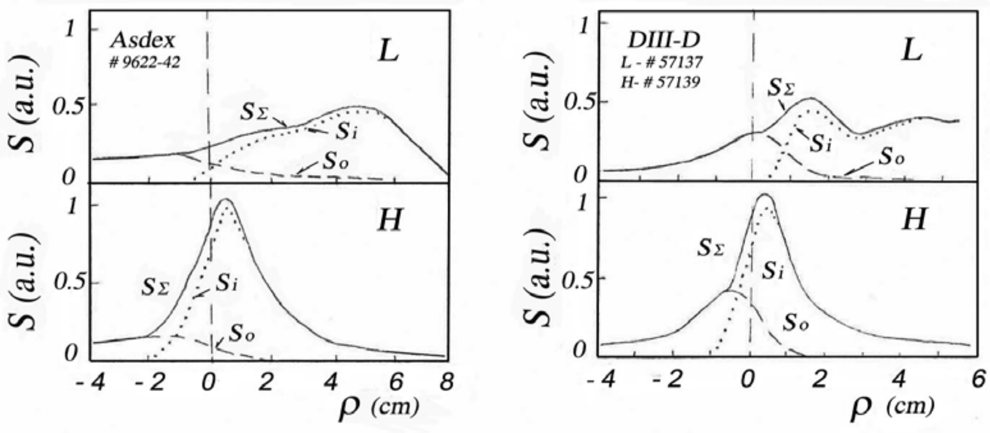

FIG. 1. Radial dependencies of the particle source rates taking account of the molecular dissociation for Asdex and DIII-D tokamaks in L- and H-mode regimes: S_o - source from the atomic ionization, S_i -ion source from dissociation , S_Σ -the total particle source.

demonstrates results of simulation of the particle source in the L- and H- discharges for Asdex and DIII-D tokamaks using the experimental profiles of the peripheral plasma parameters in these devices [15,16]. The radial position in these figures $\rho = 0$ corresponds to the separatrix location. In the L-mode the SOL is not transparent for molecules which dissociate in the SOL in the region with low plasma temperature. In this case the channel of molecular dissociation into two atoms is prevailing. At sufficiently strong auxiliary heating plasma temperature increases providing enhanced particle losses from the SOL to the divertor and to the wall. It induces decrease of plasma density accompanied by associated weakening of molecular dissociation and further density decreasing. Thus a new stable state of SOL parameters, typical for the H-mode, is formed. In this state with decreased plasma density and enhanced SOL opacity for molecules, the region of molecular dissociation shifts to the separatrix (see *FIG.1*) Due to higher temperature near the separatrix, the dissociation of molecules into atom and ion becomes more efficient. This results in decreasing of atomic flux and reduction of D_α light intensity without changing the total particle source (ions from dissociation which replace some atoms do not contribute to the D_α emission). In addition, the particle source moves to the layer limited by separatrix and ions, which previously were lost to the divertor, are now confined in the closed magnetic surfaces. It induces density rise inside the separatrix and formation of pedestal on the density profile. This, in turn, leads to the improvement of energy confinement in regions with enhanced density and formation of thermal barriers. At the variation of the radial profiles the process gradually propagates into the plasma core. Modelling realized in [10] provides rather good description of the plasma parameter dynamics and evolution of their radial profiles in considered Asdex and DIII-D discharges with the L-H mode transition.

Considered model shows that pedestal formation starting just after the L-H mode transition is not necessary coupled with the enhancement of plasma confinement but can be induced by the dynamics of the particle source. The necessity to analyze plasma reaction on the reduction of the atomic flux into the plasma column is appearing. Modelling shows that this reduction can result in the rise of the electron temperature in the plasma core. Results of the simulation of the typical JET discharge with the fast L-H transition [4,5] have been presented in *FIG.2* by solid blue lines. Experimental data are shown in this figure by dotted lines. One can see that at the discharge stage we are interested, just after the L-H transition, simulations fairly well reproduce the dynamics of the electron temperature. The ion temperature shows similar behaviour and slightly increases in the outer plasma regions with the maximal changes of the neutral density. Simulations show that the electron and ion temperature variations during the L-H transition in the considered experiments may be explained at the constant transport coefficients by the

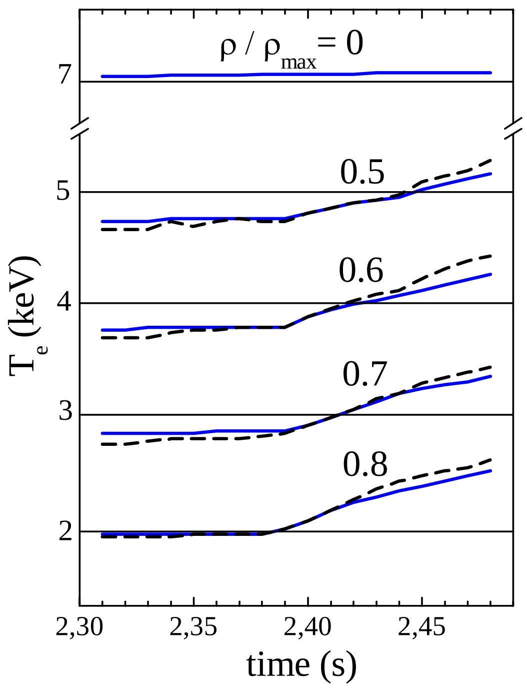

FIG. 2. Evolution of electron temperature at different radii ρ/ρ_{max} during fast L-H mode transition for JET short # 26021. Solid blue lines – simulation, dashed lines- experiment.

reduction of the cold electron source intensity related to the ionization of deuterium neutrals in the plasma core and the reduction of ion charge exchange losses when the atomic flux in the plasma column decreases. Rise of the ion temperature in these experiments with NBI heating when T_i is higher than T_e also assists in T_e increase by the rise of ion-electron energy transfer. The charge-exchange losses of the decelerated ions of the injected beams also slightly decrease what can contribute in temperature rise but this effect in considered experiments comprises only several percent. At the reversed H-L transition the opposite effect of the reduction of temperatures simultaneously with the increasing of the atomic flux takes place.

3. Deuterium Pellet Injection

An opposite effect of fast drop of the core electron temperature, which is observed after deuterium pellet injection, also may be caused by the rise of deuterium atom density in the plasma core with corresponding increase of cooling rate of cold electrons ionization source. Figures 3, 4 present the results of the simulation of the Tore-Supra tokamak discharge with the injection of deuterium pellet with the velocity of 1.82 km/s and a total content of $8 \cdot 10^{20}$ atoms [3]. Calculation of the pellet ablation rate has been performed using model [17]. *FIG. 3* shows simulated temporal evolution of neutral density $n_o(\rho)$ radial profile after the pellet injection. Time intervals after the injection are shown near the curves. Maximums on each

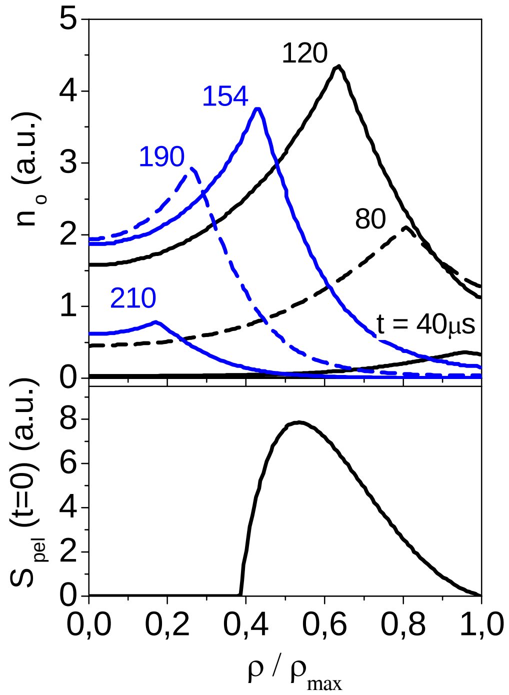

FIG. 3. Temporal evolution of atomic density profiles in the experiment with deuterium pellet injection and curve of pellet ablation on unperturbed profiles.

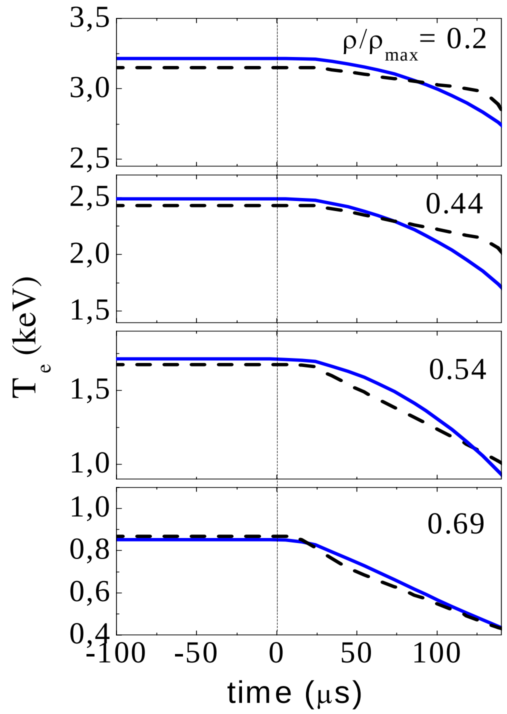

FIG. 4. Temporal evolution of electron temperature at different radii for TORE SUPRA pellet injection experiment: dashed line- experiment, solid blue line –simulation

curve correspond to the current position of the pellet. Bottom figure shows radial dependence of the pellet ablation rate on the unperturbed plasma parameter profiles before the pellet injection. This curve shows that pellet must be evaporated before reaching the radial position ρ/ρ_{max}= 0.4 on unperturbed profiles. However, as demonstrated by the top curves in *FIG. 3,* at changing the profiles pellet can penetrate to the plasma center. *FIG. 4* shows nearly simultaneous reduction of the electron temperature in different radial positions after the pellet injection owing to the rise of the atomic density in the plasma central regions. This cooling promote smaller pellet evaporation rate and deeper its penetration into the plasma column. As one can see, rapid variations of the electron temperature in the initial stage of this process can be well described by the using model.

4. Laser Ablation Injection of Impurities

The cases when variations of hydrogen atoms density in the plasma column were attracted to explain fast response of the plasma core to the plasma periphery perturbations were considered in the previous sections. The experiments with the fast edge cooling by the impurity injection induced by laser ablation are considered in this section. These experiments are in stronger contradiction with the standard diffusive model because of central response has in many cases the inversion polarity. At first sight, it seems, that neutral component cannot help in the explanation of these experiments. Moreover, in some experiments only small variations of the hydrogen spectral line intensity were registered [6,7]. However, one must take into account that at the fixed total neutral flux into the plasma its spectrum can vary due to the influence of the peripheral plasma cooling. This can change penetration of atoms into the plasma core. In particular, the group of atoms reflected from the wall has the effective energy of some tens or hundreds eV which is closed to the average energy of escaping plasma atoms determined by the temperature of the peripheral plasma. In the experiments with the plasma periphery cooling by impurity injection, average energy of the escaping plasma atoms and, hence, of the atoms reflected from the wall should be reduced decreasing their penetration into the plasma core.

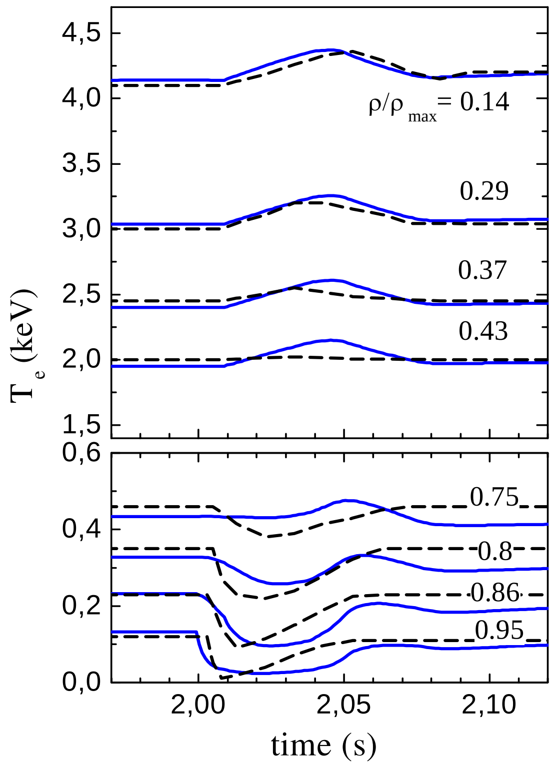

FIG. 5. Temporal evolution of T_e at different radii for laser ablation injection of aluminium in TFTR plasma: dashed line – experiment, solid blue line – simulation.

The modelling of the TEXT [6,7] and the TFTR [8,9] experiments with the laser impurity injection was performed to test possible effects from the variation of atomic spectra. Result of the modelling of the TFTR discharge # 31889 [8,9] is presented in *FIG. 5*. It has been difficult to reproduce such a strong and sharp plasma periphery cooling as in the experiments. With a rise of the impurity flux the very strong cooling and plasma column contraction were started. In simulations together with the impurity flux, which cools the periphery but did not yet results in the plasma column contraction, the energy of the warm atoms which enter the plasma column has been reduced for TFTR from 150 eV to 50 eV and for TEXT from 100 eV to 30 eV. *FIG. 5* demonstrates good agreement between the simulation results and the TFTR experimental data. The similar agreement was found for TEXT results also. The model allows describing the change of the perturbation polarity in its approaching the plasma center. In reality there are two perturbations: the negative one originated from the plasma boundary and the positive one, caused by the reduction of neutral density in the plasma core. Simulations reproduce with an acceptable accuracy change polarity of perturbation and variation of the amplitude of the positive perturbation and its temporal evolution.

5. Conclusions

The main goal of the present study is to attract attention to the investigation of the behaviour of the neutral plasma component in the experiments with the fast central core response to the boundary plasma perturbations. Simulations indicate that taking into account the dynamics of this component one can describe many peculiarities of the experiments with boundary perturbations of different nature. Estimations of possible effects are presented. Modelling shows that effect of fast penetration of perturbations into the plasma core right after the events in discharges under consideration can be explained without assumptions on the non-local character of transport processes in the bulk tokamak plasma. The acceptable coincidence with the experimental results would be obtained even with the time-independent transport coefficients. Effect of the non-locality may be attributed to the behavior of the neutral plasma component, which is responsible for the visible fast coupling of the plasma edge and the core due to short time of propagation (less than 100μs) of the charge exchange atoms to the plasma core.

-- For example, the rapid electron temperature increase in the plasma core after the fast L-H mode transition can be explained by the reduction of the cold electron source and charge exchange losses caused by the reduction of the neutral influx to the plasma during the L-H mode transition time.
-- Fast cooling of the plasma core after deuterium pellet injection can be explained by the fast penetration in the plasma core of the atoms after charge exchange of primary atoms from the pellet ablation (with the velocity of the order of the plasma ion thermal velocity).
-- Increase of the electron temperature in the central region of plasma in the experiments with the impurity laser ablation also can be attributed to the decrease of neutral density in the plasma core. It can be caused by the reduction of their penetration owing to drop of the characteristic energy of warm neutrals from the boundary stimulated by the boundary cooling.

Presented simulations demonstrate different possible cases with different mechanisms which influence the atomic density in the plasma column: change of the neutrals influx as at the deuterium pellet injection; dynamics of the particle source near the plasma edge as in the L-H mode transition; change of the atomic energy spectrum with corresponding variation of neutral penetration depth as at the plasma edge cooling by laser ablation of impurities. In all considered cases expounded approach was productive and provides clear reasons for the description of peculiarities of these phenomena. We considered the simple cases but in the real experiments one can investigate more complicated combinations. For example, in the experiments with the tangent pellet injection when pellet penetration is worse, the possible neutral density rise in the plasma core due to the pellet ablation can be reduced by the periphery cooling and periphery density rise which reduce the penetration of atoms in the plasma core and so on.

All these results show that the neutral plasma component can be responsible for the visible coupling of the plasma edge and the core in considered experiments. Therefore, conclusions of some previous works analyzing experiments with the fast responses about the non-local character of total plasma transport in tokamaks demand further investigation with proper accounting for the dynamics of the neutral plasma component. Behaviour of this component gives robust and important effects and must be included in consideration at the analysis of the experiments with the fast core responses to the boundary perturbations and at the development of the accurate models of tokamak transport.

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