Study of ITER plasma current ramp-down scenarios with DINA and ASTRA codes

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1. Introduction.

Development of the operational scenarios and analysis of conditions influenced the plasma performance in different discharge stages are the important aspects of the ITER design. Results of previous studies of plasma termination in ITER 15 MA DT inductive scenario are presented in [1-3], where the main attention has been focused on the analysis of operation of the Poloidal Field (PF) system. This paper presents results of further complex study of conditions in the termination stage of the reference ITER 15 MA inductive scenario to consider the most important peculiarities of this stage and to optimize plasma parameters behaviour during this stage.

In scenarios under consideration 2D free boundary plasma equilibrium was analyzed with the DINA code [4], taking into account main features of power supplies, 2D model of toroidally conducting structures, as well as feedforward and feedback control systems of plasma current, position and shape. More detailed plasma transport model was used in ASTRA simulations [5], where DINA waveforms of plasma current, position and shape were taken as input data for ASTRA modelling. The ASTRA simulations took into account impurity transport and radiation, as well as different methods of plasma heating and current drive. Some ASTRA modelling results then were tested with DINA code once more.

2. Evolution of plasma parameters during current ramp-down.

Plasma current ramp-down in ITER should be provided sustaining divertor magnetic configuration to as low as possible plasma current (for better control of the plasma density and reduction of heat loads on the first wall) and reducing plasma elongation as fast as possible (for reduction of the plasma vertical instability growth rate). Moreover it is desirable to trigger the H- to L-mode transition at low plasma current and thermal energy, as far as in the opposite case rapid increase of the plasma transport results in strong rise of the heat flux to the divertor plates and large value of plasma inward shift, which may lead to contact with the first wall.

Taking into account these requirements and results of the modelling, the possible strategy of the termination stage can be formulated. It is convenient to perform this stage in two phases. These phases, when plasma current decreases from 15 to 1.4 MA in about 200 s (nominal plasma termination), are illustrated on Fig. 1 (DINA simulation). During the first phase (between 500 s and 600 s in Fig. 1) plasma current is reduced from 15 MA to $\approx$ 10 MA with simultaneous reduction of plasma elongation keeping $q_{95} \approx 3$). The fusion power decreases by about 15-20% owing to reduction of the plasma density simultaneously with the plasma current in the H-mode at small change of plasma temperature (what keeps small loop voltage and resistive flux consumption). It is assumed that plasma density is decreased by a control system reducing the ratio n_e/n_{Gr} from 0.8 to ~ 0.5. Plasma thermal energy decreases in this phase by about a factor of 2. Reduction of the auxiliary power, P_{aux}, is small, which allows to keep total value of the heating power higher than that required for H- to L-mode transition.

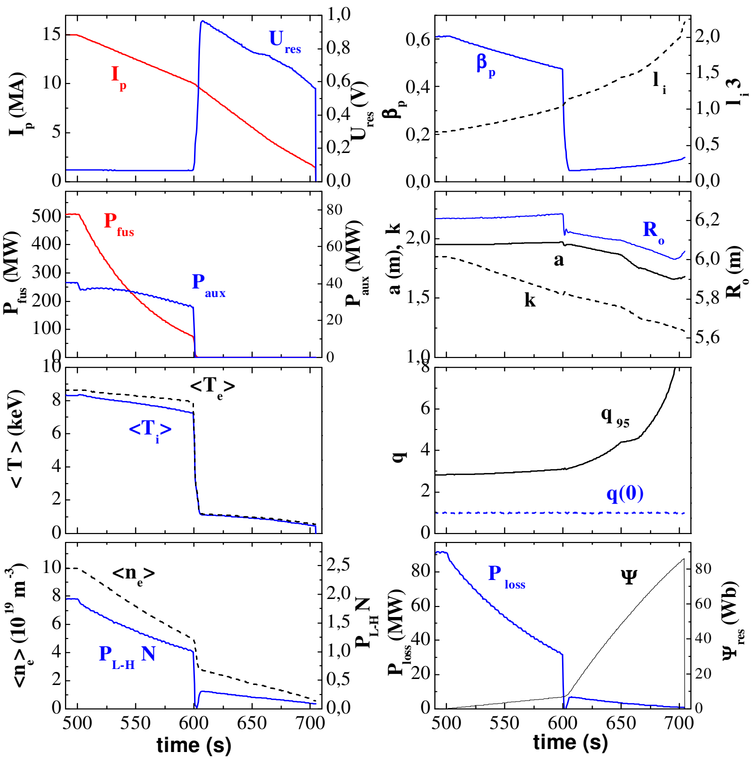

Fig.1 Example of termination stage of reference ITER 15MA scenario

In the second phase ($t > 600$s in Fig.1) plasma current is ramped-down in the L-mode. This phase starts when auxiliary heating is switched off triggering plasma transition to L-mode. By this time the plasma density reduces close to the NBI shine through limit (~ 4×10^{19}m^{-3}) and fusion power reduces by about a factor of 5. Further reduction of the plasma density is assumed performed by a control system keeping about constant value of the n_e/n_{Gr} ~ 0.4.

Examples of ASTRA simulations of scenarios with fast ramp-down of plasma current (in ~ 70 s) are shown in Fig. 2. Left figures illustrate scenario when plasma is keeping in the L-mode till the end of discharge. Right figures illustrate scenario with the plasma termination in the H-mode. In this scenario, requiring higher auxiliary power, the plasma temperature and the internal inductance, l_i, are higher than that during plasma current ramp-down in the L-mode. The scenario of plasma termination in the H-mode has not significant drop of β_p, causing significant inward shift of the plasma, which may results in the plasma contact with the first wall. However, as shows DINA simulations, increase of l_i at the end of discharge leads to loss of plasma vertical stabilization at plasma current ~ 3 MA.

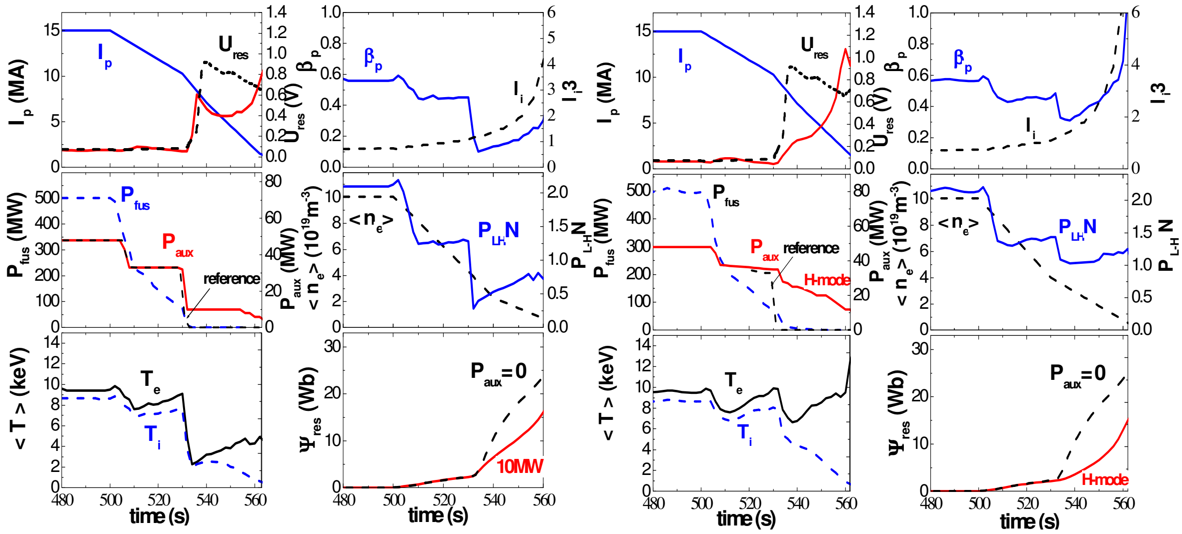

Fig.2 Plasma current fast ramp-down in L-mode (left) and H-mode (right) at the second

Fig.3 shows waveforms of currents in the CS and PF coils in two DINA simulations of plasma current ramp-down in divertor magnetic configuration. Blue lines correspond to simulation with the plasma current ramp-down during 200 s, red lines correspond to the plasma termination during about 70 s. Values of the design limits for the coil currents are shown by the dashed lines. Simulations performed demonstrated the possibility of PF system to control plasma current, position and shape staying within all engineering limits. In

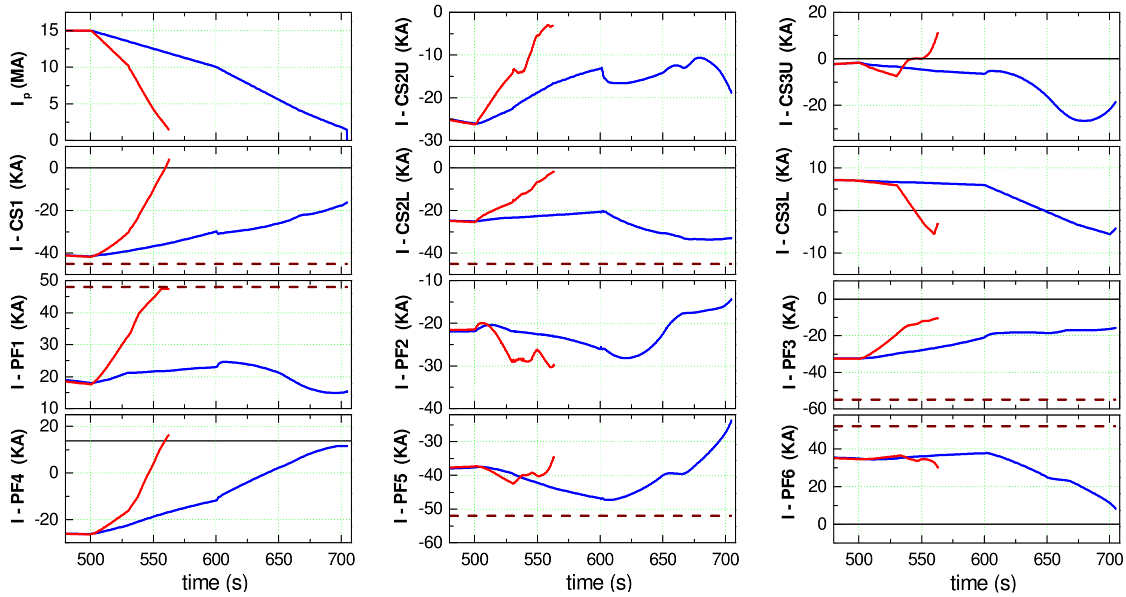

Fig.3 Central Solenoid (CS) and Poloidal Field (PF) coils currents for two ramp down stages of 15 MA scenarios of different duration.

considered scenarios plasma vertical stabilization was done by the feedback voltages varying differential current in the coils PF2, PF3 and PF4, PF5. One can see that faster current ramp-down helps to reduce majority of the coil currents moving them away from their critical values. However currents in PF1 and PF2 rise and PF1 current at the end of the discharge with fast plasma termination is close to its critical value what can define minimal duration of this stage.

3. Summary.

Scenarios of plasma current ramp-down stage in 15 MA DT discharge were studied with the DINA and ASTRA codes. The considered strategy of plasma termination consists of two phases.

The first phase is reduction of plasma current from 15 MA to ≈10 MA in the H-mode with simultaneous reduction of plasma elongation keeping the value of $q_{95} \approx 3$. It is beneficial from the point of view of plasma vertical stabilization. At this phase reductions of the fusion power and the plasma energy are provided in the H-mode basically due to the reduction of plasma density together with plasma current at small change of the power of auxiliary heating and the plasma temperature.

The second phase starts when NB injection is switched off triggering H- to L-mode transition. The further plasma termination is continuing in the L-mode. It was shown that plasma current ramp-down continuing in the H-mode allows avoidance of significant drop of β_p, happening after H- to L-mode transition, (beneficial for control of the plasma-wall inner gap). However increase of the plasma internal inductance at the end of discharge may lead to loss of plasma vertical stabilization (at least in scenarios with fast plasma current ramp-down).

DINA simulations have shown that fast plasma termination can be performed in divertor magnetic configuration during about 70 s. ASTRA modelling confirms waveforms of key plasma parameters of the DINA simulation obtained using simplified plasma transport model.

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