Controlled emergency plasma termination in ITER

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1. Introduction

Studies of plasma magnetic control in ITER 15MA DT scenarios are being extensively performed with the DINA code [1-10]. The code uses models describing transport of the electron and ion temperatures and a 1D model describing diffusion of the poloidal magnetic flux (evolution of l_i), which are integrated with a 2D plasma free boundary equilibrium solver, implementing feedback and feedforward control of the plasma current, position and shape (plasma-wall gaps), taking into account eddy currents in the vacuum vessel and models of the coil power supplies. Moreover, DINA simulations take into account numerous engineering limits imposed on the coils, their power supplies and plasma–wall gaps.

The studies performed have shown that, in 15MA DT scenarios, the nominal plasma termination in a divertor configuration with nominal requirements on the precision of plasma-wall gap control can be performed with the maximum rate of plasma current ramp-down of 0.21 MA/s, limited by the power supply voltages. This paper presents results of design and simulation of controlled emergency plasma termination scenarios performed with higher rates of the current ramp-down in expense of degradation of the precision of plasma-wall gaps control.

The most recent description of the ITER PF system is given in [9, 10]. The PF system data and location of the first wall used in the simulations presented here correspond to the 2015 ITER design. The stabilization of plasma vertical displacements is performed using the VS3 circuit (in-vessel coils) in combination with the VS1 circuit (varying the differential current in the coils PF2, PF3 and PF4, PF5). The VS1 circuit is used to reduce the current in the in-vessel coils [10]. The simulations took into account a low frequency noise in the diagnostic signal of the plasma vertical speed, dZ/dt, used in feedback stabilization of plasma vertical displacements. A low frequency noise with a uniform spectrum on the frequency band [0, 1 kHz] with a root mean square value 0.6 m/s was "injected" in the signal *dZ/dt*.

2. Simulation results

Plasma emergency terminations were simulated after an H to L mode transition at the end of burn with 500 MW of fusion power when the current in the CS1 coil is close to the design limit (45 kA). Three scenarios of plasma current ramp-down were considered: 1) from 15 MA to 10 MA, 2) from 15 MA to 7.5 MA and 3) from 15 MA to 5 MA. In these scenarios, the maximum rates of the current ramp-down were limited by the following conditions: i) the plasma stays in a divertor configuration (without precise control of the plasma shape and a minimum value of the plasma-wall gaps), ii) the separatrix strike points stay on the divertor vertical plates, and iii) the CS and PF coil currents and voltages are within the design limits.

It has been shown that for controlled emergency termination:

1) the maximum rate of plasma current ramp-down from 15 MA to 10 MA is 0.83 MA/s (more than 6 s is required),
2) the maximum rate of plasma current ramp-down from 15 MA to 7.5 MA is 0.77 MA/s (more than 10 s is required),
3) the maximum rate of plasma current ramp-down from 15 MA to 5 MA is 0.58 MA/s (more than 17 s is required).

In each scenario of plasma emergency termination, further plasma current ramp-down with the same rate leads to the loss of plasma magnetic control (e.g. the plasma touches the first wall or the separatrix forms an upper X-point). As it was mentioned above, in the nominal plasma termination (with precise control of the plasma-wall gaps and separatrix strike points) the rate of plasma current ramp-down is less than 0.21 MA/s. Variation of plasma parameters in these scenarios of the plasma emergency termination is given in Fig. 1.

An important parameter is the power requested from the electric grid by plasma axisymmetric magnetic control. This power is defined as follows:

$$P_{\mathrm{grid}}(t) = \sum_{n=1}^{11} I_n(t) V_n(t) + I_{\mathrm{VS1}}(t) V_{\mathrm{VS1}}(t) + P_{\mathrm{VS3\,rg}}(t),$$

$$P_{\mathrm{VS3\,rg}}(t) = \begin{cases} 5\ \mathrm{MW}, & \text{if } P_{\mathrm{VS3}}(t) \geq 5\ \mathrm{MW}, \\ P_{\mathrm{VS3}}(t), & \text{if } 0 < P_{\mathrm{VS3}}(t) < 5\ \mathrm{MW}, \\ 0, & \text{if } P_{\mathrm{VS3}}(t) < 0. \end{cases} \qquad P_{\mathrm{VS3}}(t) = I_{\mathrm{VS3}}(t) V_{\mathrm{VS3}}(t),$$

where I_n, V_n are the current and voltage of each power supply in the CS or PF coil circuit with the number *n*; $I_{\mathrm{VS1}}, V_{\mathrm{VS1}}$ and $I_{\mathrm{VS3}}, V_{\mathrm{VS3}}$ are the current and voltage of the VS1 and VS3 power supplies, respectively. The upper figures in Fig. 2 show variations of power requested from the electric grid by the plasma axisymmetric magnetic control in the scenarios of plasma emergency termination. For comparison, the lower figure in Fig. 2 shows the variation of the power in the scenario with the fastest nominal plasma termination (0.21 MA/s).

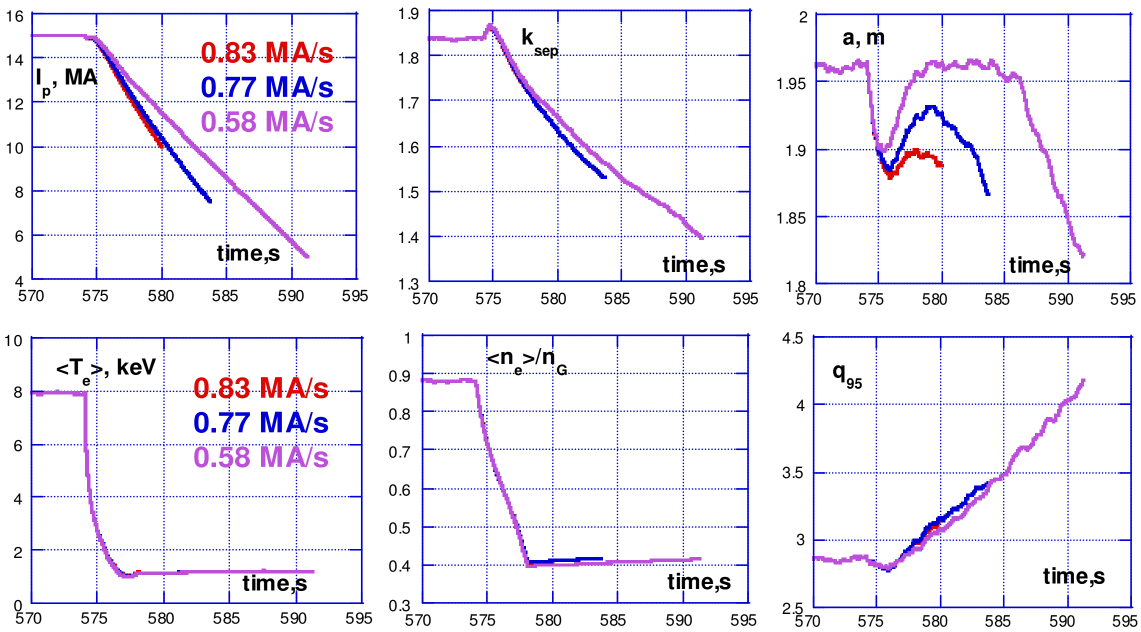

Fig. 1 Variations of plasma current (I_p), elongation (k_{sep}), minor radius (a), volume averaged electron temperature ($<T_e>$), ratio of the volume averaged electron density ($<n_e/n_G>$) in the scenarios of plasma emergency termination.

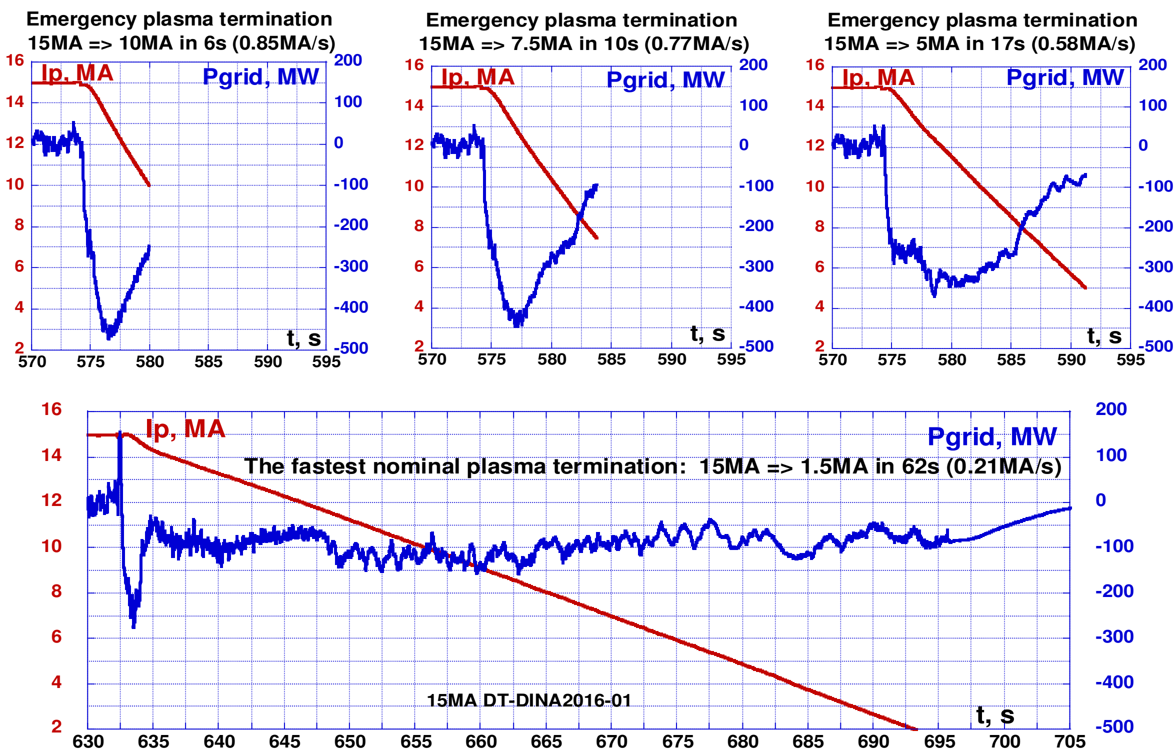

Fig. 2 Variations of plasma current (I_p) and power requested from the electric grid by plasma axisymmetric magnetic control (P_{grid}) in the scenarios of plasma emergency termination (upper figures), and in scenario with the fastest nominal plasma termination (lower figure).

For emergency plasma terminations with a plasma current ramp-down rate of 0.83MA/s, the peak of the absolute value of the total power requested from the grid is 470 MW. This value is significantly higher than that in the case of the fastest nominal plasma termination, where it is 270 MW. It should be noted that the absolute limit on the power request is ± 500 MW, however additional limits on waveforms of the power request need to be studied.

In the scenarios considered, at the end of the plasma current ramp-down to 10 MA, 7.5 MA and 5 MA, the plasma state is close to the upper limit of the plasma MHD stability in the li-q diagram with (q_{95}, $l_i(3)$) equal to (3.2, 1.2), (3.5, 1.5), (4.2, 1.9), respectively. The final plasma equilibria have been analysed with respect to the ideal and resistive MHD stability limits using the MISHKA-1 [11] and CASTOR [12] linear MHD stability codes. These plasmas are stable except for the internal kink instability, related to sawteeth.

3. Conclusion

In the controlled emergency termination of 15 MA DT plasmas in divertor configuration with as fast as possible reduction of the plasma current and elongation (allowing degradation of the plasma-wall gaps control): 1) a minimum of 6 s is required for the plasma current reduction to 10 MA, 2) a minimum of 10 s is required for the plasma current reduction to 7.5 MA, and 3) a minimum of 17 s is required for the plasma current reduction to 5 MA.

The absolute value of the peak total power requested from the grid at the plasma emergency termination can reach 470 MW. This is significantly higher than in the nominal plasma termination (less than 270 MW). The limits on waveforms of the power request need to be studied.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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