ITER 15 MA DT scenarios with maximum expansion of poloidal magnetic flux on divertor target plates

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Introduction

High values of heat loads on the ITER divertor target plates is an issue for high power plasma operation. An increase of the poloidal flux expansion near the plates reduces these loads. Expansion of the poloidal flux on the divertor plates can be characterized by the distance between the separatrix (blue lines in Fig. 1) and "1 cm SOL" (green lines in Fig. 1) near the outer (Δ_{out}) and inner (Δ_{in}) strike points. Here "1 cm SOL" is the poloidal magnetic flux surface passed through the point with coordinates $R \approx R_{max}$+1 cm, $Z = Z_{Rmax}$, where R_{max} and Z_{Rmax} are the co-ordinates of the plasma outermost point in the poloidal cross section (Fig. 2). The goal of the study reported here is the design and simulation with the DINA code [1] of a 15 MA DT scenario (Q = 10, fusion power 500 MW), whose magnetic configuration during the burn has maximum values of Δ_{out} and Δ_{in}.

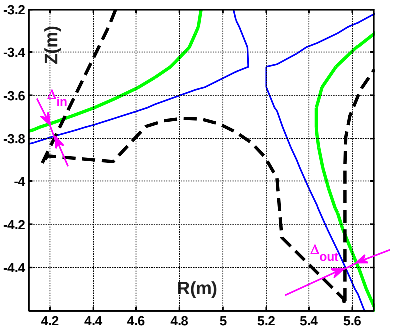

Fig. 1. Magnetic configuration in the divertor area. Blue lines – separatrix, green lines "1 cm SOL", black dashed line – the divertor plasma facing line.

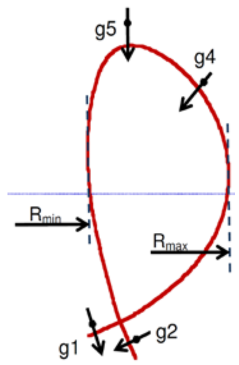

Fig. 2. Six plasma shape parameters (plasma–wall "gaps") controlled in divertor magnetic configuration in DINA simulation.

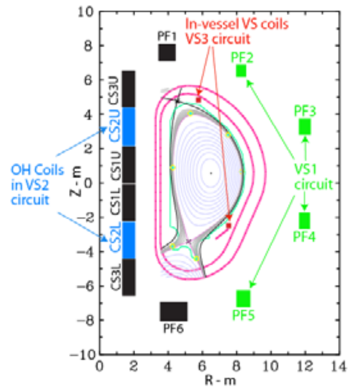

Fig. 3. Plasma, vacuum vessel, CS and PF coils, and circuits used for plasma vertical stabilization (VS).

Standard feedback controller used in DINA simulations

The DINA code [1] comprises a two-dimensional free boundary plasma equilibrium solver and one-dimensional model describing transport of the poloidal magnetic flux and the plasma temperatures (electrons and ions), taking into account eddy currents in the vacuum vessel, models of the power supplies and the plasma control system. DINA simulations of ITER scenarios are performed with feedforward and feedback plasma magnetic control. In DINA simulations, the standard feedback controller controls the following parameters:

1) the plasma-wall "gaps" $g1$, $g2$, $g4$ and $g5$ (Fig. 2),
2) the R-coordinates of the plasma outermost and innermost points in the poloidal cross section (R_{max} and R_{min} in Fig. 2),
3) the plasma current (I_p),
4) the currents in CS and PF coils (shown in Fig. 3).

The errors between the values of these parameters and their target waveforms are inputs to the Multiple-Input Multiple-Output (MIMO) controller used at the divertor phase of scenario simulations. The outputs of the controller are the voltages requested from the main converters of the CS and PF coils. In the scenario simulations, feedback stabilization of the plasma vertical displacements is performed by the VS in-vessel coils (the VS3 circuit in Fig. 3), using as input the speed of plasma vertical displacements, dZ/dt. A low frequency noise with uniform spectrum and a given RMS value, $\langle dZ/dt \rangle$, in the frequency band [0, 1 kHz] is “injected” in the “diagnostic” signal dZ/dt used in the feedback loop. In the simulations considered below, $\langle dZ/dt \rangle = 0.2\ \mathrm{ms^{-1}}$.

Simulations of ITER scenarios with the DINA code are performed complying with all engineering limits imposed on the CS and PF coils (currents, magnetic fields, forces) and their power supplies, as well as on the quality of control of the plasma-wall gaps and divertor strike points.

Feedback control of Δ_{out} and d_{sep}

A new MIMO controller has been designed for simulations of 15 MA DT scenarios for reduction of heat loads on the divertor target plates during the burn phase. The new controller includes feedback control of the parameter Δ_{out} simultaneously with feedback control of the nominal set of plasma parameters (six plasma-wall “gaps” and plasma current). The parameter Δ_{in} is not controlled. In the simulations, the plasma control is switched from the standard controller to the new controller at the start of the plasma current flattop. This controller operates approximately until the middle of the plasma current ramp-down phase, but after the end of burn, the error in Δ_{out} control was set to zero. At the second part of the plasma current ramp-down phase, the plasma control is switched from the new controller to the standard one.

The increase of Δ_{out} requires higher currents in the PF4 and CS1 coils. The maximum value of Δ_{out} is limited by the engineering limit of current in PF4 (55 kA·170 turns). The increase of current in CS1 reduces the duration of burn, limited by the engineering limit of current in the CS1 coils (45 kA·554 turns).

Moreover, the increase of outer divertor flux expansion Δ_{out} can only be obtained by increasing the plasma upper triangularity as well. This leads to the decrease of the parameter d_{sep} - the distance between the inner (with lower X-point) and outer (with upper X-point) separatrices near the outermost point on the poloidal cross section. The preliminary study has shown that the value of d_{sep}, during the plasma current flattop, mainly depends on the value of the controlled plasma-wall gap $g4$ (see Fig. 2). Therefore, adjusting the target values of this parameter, we can control the gap $g4$ and d_{sep}. Decrease of the gap $g4$ increases d_{sep}. The following algorithm of d_{sep} control was used in the DINA simulations at the plasma current flattop. The input to the MIMO controller for parameter $g4$ (difference between the $g4$ value and its target value) at n–th time step is:

$$error_n(g4) = g4_n - g4_{n,targ}(d_{n-1,sep}), \text{ where } g4_{n,targ}(d_{n-1,sep}) = g4_{n-1,targ} + k_{dsep}\cdot(d_{n-1,sep} - d_{sep,min}).$$

Here $g4_{n,targ}$, $g4_{n-1,targ}$ are the target values of the gap $g4$ at n and $(n - 1)$ time steps, respectively, $d_{n-1,sep}$ is the distance d_{sep} at $(n - 1)$ time step, $d_{sep,min}$ is the minimum target value of the parameter d_{sep} (in the simulation reported here it was 4.5 cm), k_{dsep} is a tuned coefficient. If $d_{n-1,sep} > d_{sep,min}$, $k_{dsep} = 0$ (there is no control of d_{sep}, when its value is higher than $d_{sep,min}$), otherwise k_{dsep} is some constant value. It should be noted that the increase of d_{sep} is limited by the allowed minimum distance between the plasma and first wall for high-power plasma operation to ensure acceptable power fluxes to the first wall.

Simulation results

Two scenarios simulated with the DINA code are considered here. Scenario 1 is an example of a 15 MA DT scenario without control of Δ_{out} and d_{sep}. Scenario 2 is a modification of Scenario 1 with the control of d_{sep} during the burn at the level higher than 4.5 cm and with the control of Δ_{out} at the maximum value. In preliminary simulations of Scenario 2, the target value for Δ_{out} was progressively increased, increasing `the peak value of the current in the coil PF4. The scenario, when the current in PF4 hits its engineering limit (55 kA), was considered as Scenario 2.

The simulations include the following phases of the PF system operation: 1) initial magnetisation with fully charged CS, plasma breakdown with ECRF assist and inboard plasma initiation, 2) plasma current ramp-up during 65 s with early formation of a divertor configuration (at about 3.2 MA), 3) plasma current flattop and burn (the flattop is stopped when the current in the CS1 coils hits its engineering limit, 45 kA) with the fusion power 500 MW and Q = 10, 4) plasma current ramp-down in a divertor configuration. Fig. 4 shows waveforms of the plasma current and fusion power in Scenarios 1 and 2. One can see that the duration of burn in Scenario 2 is 250 s shorter than in Scenario 1. Fig. 5 shows currents in the coils PF4 and CS1. In Scenario 2, the current in PF4 hits the engineering limit (55 kA) during the burn at t > 200 s. In Scenario 2, the current in CS1 hits the 45 kA limit 250 s earlier than in Scenario 1, reducing the current flattop and burn duration by 250 s. It should be noted that in the scenarios considered, the plasma current ramp-up time is 65 s, which corresponds to a peak magnetic field on the PF6 conductor of 5.4 T (the engineering limit is 6.4 T). In modified Scenario 2 with the fastest plasma current ramp-up - during 50 s (limited by 6.4 T of the magnetic field on PF6 conductor), the duration of burn is 330 s without taking into account the NBI current drive. The NBI current drive (≈1 MA) increases this value to 386 s.

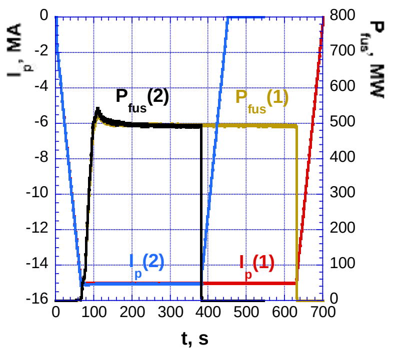

Fig. 4. Plasma current, I_p, and fusion power, P_{fus}, in Scenarios 1 and 2.

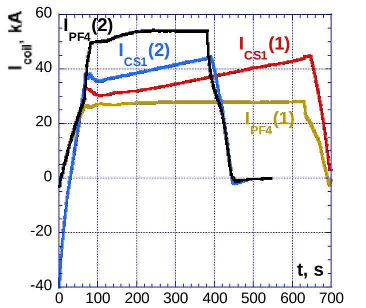

Fig. 5. Currents in the coils CS1, I_{CS1}, and PF4, I_{PF4}, in Scenarios 1 and 2.

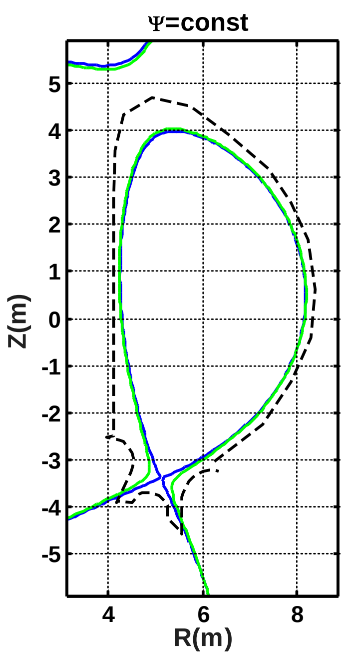

Fig. 6a. Magnetic configuration in Scenario 1 during the burn (at t = 380 s): **blue** line – inner separatrix, **red** line – "1 cm SOL", **black** dashed line – contour of the first wall and divertor.

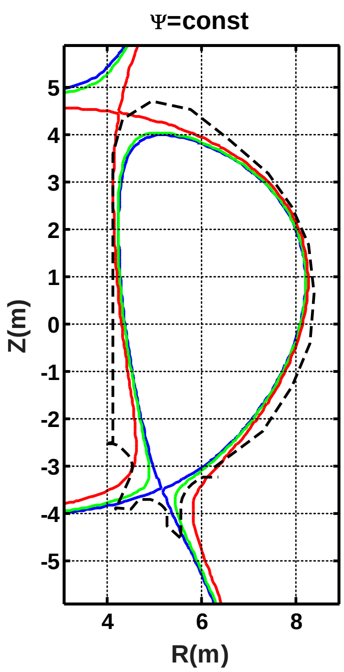

Fig. 6b. Magnetic configuration in Scenario 2 during the burn (at t = 380 s): **blue** line – inner separatrix, **green** line – "1 cm SOL", **red** line – outer separatrix, **black** dashed line – contour of the first wall and divertor

Figs. 6a and 6b show the magnetic configurations in Scenario 1 and Scenario 2, respectively, during the burn (at t = 380 s). One can see that an increase of the poloidal magnetic flux expansion on the divertor target plates requires an increase of the plasma upper triangularity. Fig. 7 illustrates the evolution of the parameters Δ_{out} and Δ_{in} in three simulations: blue lines – Scenario 1, magenta lines – Scenario 2 (control of Δ_{out} with the target value 6.5 cm and control of d_{sep} with $d_{sep,min}$ =4.5 cm), red line – simulation of Scenario 2 without control of d_{sep}. One can see that the distances between the separatrix and "1 cm SOL" near the outer (Δ_{out}) and inner (Δ_{in}) divertor target plates in Scenario 2 are about 6.2 cm and 6.7 cm, respectively. In Scenario 1, these parameters are about 3.5 cm and 4.5 cm. The increase of plasma upper triangularity in Scenario 2, not only requires higher currents in the CS1 coils (reducing the burn duration), but also reduces the distance d_{sep} between the inner and outer separatrices. Fig. 8 illustrates the evolution of the parameter d_{sep} in the simulations considered.

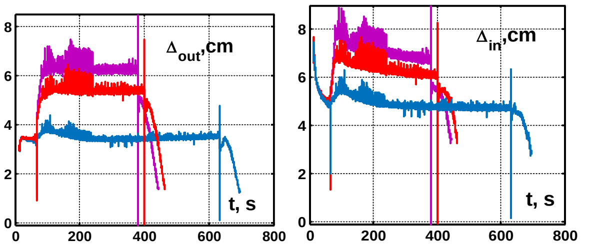

Fig. 7. Evolution of Δ_{out} (left figure) and Δ_{in} (right figure): **blue** lines – Scenario 1, **magenta** lines – Scenario 2, **red** lines – Scenario 2 without d_{sep} control.

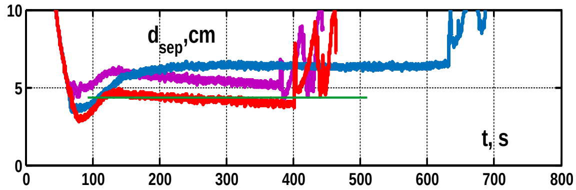

Fig. 8. Evolution of d_{sep}: **blue** line – Scenario 1, **magenta** line – Scenario 2, **red** lines – Scenario 2 without d_{sep} control. **Green** line - the target value $d_{sep,min}$ = 4.5 cm for d_{sep} control in Scenario 2.

Conclusions

MIMO feedback control of the poloidal magnetic flux expansion near the divertor outer target plates allows an increase in the values of Δ_{out} and Δ_{in} during the burn in 15 MA DT scenario (Q = 10, fusion power 500 MW) by about 80% and 50%, respectively, relative to those in a scenario without Δ_{out} control. The calculations indicate a reduction in the peak heat flux to the outer target by ≈40% [2]. However, the increase of Δ_{out} and Δ_{in} requires higher current in the CS1 coils and reduces the value of d_{sep}.

The increase of Δ_{out} and Δ_{in} is limited by the allowable current in the PF4 coil (55 kA). The increase of current in CS1, required for the magnetic configurations with the maximum Δ_{out} and Δ_{in}, leads to a decrease of the burn duration (limited by the allowable current in the CS1 coils, 45 kA) by about 250 s relative to a scenario without control of Δ_{out}. The maximum duration of burn in the scenario with maximum Δ_{out} and Δ_{in} is about 386 s, if the plasma current is ramped-up during 50 s and taking into account about 1 MA of current driven by the NBIs.

The increase of Δ_{out} and Δ_{in} leads to a decrease of the distance between the inner and outer separatrices, d_{sep}. A feedback control algorithm was developed for keeping d_{sep} during the plasma current flattop above a given value $d_{sep,min}$, varying the target value of the plasma-wall gap g4 in MIMO control of the plasma-wall gaps. In the Scenario 2 simulations, $d_{sep,min}$ = 4.5 cm.

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Reference

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