Study of burn duration in ITER with reduced internal stress in the bottom module of the central solenoid

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1. INTRODUCTION

The maximum value of the internal stress (Lorentz force) in the conductors of ITER central solenoid (CS) can be characterised by a parameter $max(I\times B_{\max})$, where I is the coil current and $B_{\max}$ is the maximum value of magnetic field on the coil conductor. For the nominal CS conductor the allowable value of this parameter is 530 kAT. The plasma scenarios reported in this paper were designed and simulated with the DINA code [1-4] assuming the maximum value of this parameter in the bottom module, CS3L, is reduced by about 30% (375 kAT). The conductors of other CS modules were assumed to perform at the nominal level (530 kAT). The studies reported here were carried out as part of an ongoing R&D program to qualify the ITER CS superconductor.

It should be noted that maximum value of the internal stress in the coil CS3L is achieved only at plasma initiation. Taking into account that at the plasma initiation distribution of currents among the CS coils is rather up/down symmetrical, a limit on the maximum value of the internal stress in the bottom coil, CS3L, leads, in practice, to a similar limit for the top coil, CS3U.

The study of the central-inboard plasma initiation performed with the TRANSMAK code [5] has shown that the value of magnetic flux at the CS initial magnetization with the reduced by 30% internal stress in the coils CS3 is ≈ 115 Wb vs. ≈ 118 Wb obtained previously in the scenarios of plasma initiation designed assuming the nominal value of the internal stresses in all CS coils. This small difference (≈ 3 Wb) can be achieved by increasing the maximum voltages on CS, PF1 and PF6 coils from 1.05 kV (one converter) to ≈ 2.1 kV (two converters). In this case special efforts for reduction of the total converter power are necessary. The maximum value of the total converter power of about 260 MW can be obtained by a proper choice of the resistances of Switching Network Units in the circuits of CS modules, PF1 and PF6.

The simulations of 15 MA DT scenarios ($Q \approx 10$) with the reduced (by 30%) internal stress in the CS3 coils has been performed using the DINA code from the start of the CS discharge (as described in [4]) till the end of plasma termination. The scenarios were simulated with feedback control of plasma current, position and shape taking into account axisymmetric model of the conducting structures, all engineering limits imposed on the coil operation, models of the coil power supplies (the switching network units and converters) and other input data as they are in the ITER design 2011 [6]. Plasma vertical displacements were stabilized by the outer PF coils (PF2 – PF5 using the VS1 feedback loop). The Bohm-gyroBohm L-mode plasma transport model [7] was assumed during the current ramp-up.

The paper has two parts. The 1st part (Section 2) presents results of the study of the burn duration in the nominal 15 MA DT scenarios (with burn during the plasma current flattop). The 2nd part (Section 3) presents a modified 15 MA DT scenario, where the burn is significantly extended beyond the plasma current flat-top, allowing increase of the neutron fluence by more than a factor 2.4 relative to that in the nominal scenarios.

2. DURATION OF BURN IN NOMINAL 15 MA SCENARIOS

15 MA DT scenarios starting from plasma initiation with $max(I_{CS3L}\times B_{CS3L}) \leq 375$ kAT were studied with the DINA code assuming during the current ramp-up three options of Z_{eff} (illustrated in Fig. 1). Different rates of the plasma current ramp-up and two assumptions on the power of EC heating, P_{aux}, during the current ramp-up (after X-point formation) were used in this sensitivity study: 1) $P_{aux} = 5$ MW, from $I_p = 4.3$ MA till $I_p = 15$ MA, 2) P_{aux} linearly increases with the increase of I_p from 5 MW at 4.3 MA to 20 MW at 15 MA.

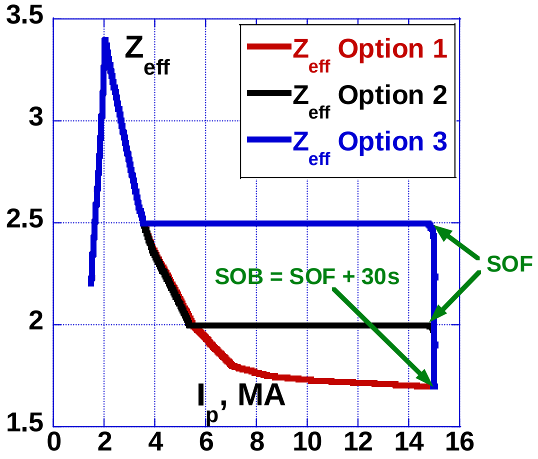

FIG. 1 *Different assumptions on* Z_{eff} *vs. plasma current during current ramp-up*

In the simulations all engineering parameters (coil currents, voltages, magnetic fields, forces, etc.) and plasma-wall gaps were within the design limits [6]. The end of current flattop was defined as the state when current in the CS1 coils is 44.2 kA (the engineering limit is 44.5 kA). This allows reliable plasma control in the case of "unplanned" H-to-L mode

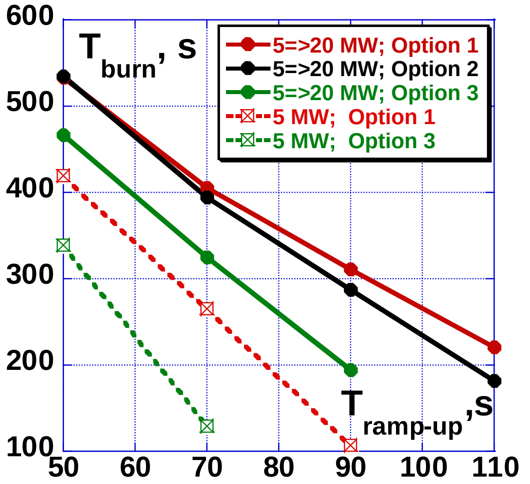

FIG. 2 *Duration of burn vs. current ramp-up time for different assumptions on* Z_{eff} *and* P_{aux}

transition at the end of current flattop.

The burn duration obtained at different rates of the plasma current ramp-up is shown in Fig. 2 for different assumptions on the power of EC heating and Z_{eff}. One can see that the burn duration increases strongly with decrease of the plasma current ramp-up time, achieving 530 s, assuming Z_{eff} option 1 in scenarios with the fastest current ramp-up (during 50 s, limited by the power supply voltages) and linear increase of the ECH power from 5 MW to 20 MW. It is also shown that the fastest current ramp-up allows more than 300 s of burn during the 15 MA current flattop ($Q \approx 10$) for a wide range of Z_{eff} and ECH power.

3. SCENARIO WITH BURN EXTENDED BEYOND THE CURRENT FLATTOP

The described above scenario, demonstrating 530 s of burn during the current flattop, was continued in DINA simulation with the goal of extending the burn beyond the current flattop. This scenario has two phases of the plasma current ramp-down, starting at 610 s, when current in the CS1 coils achieves 44.2 kA. The 1st phase is a slow current ramp-down (during 1400 s, full bore divertor configuration) with "natural" decay of the plasma current (feedback control of plasma current is switched off) from 15 MA to 7.7 MA. Auxiliary heating is increased to 73 MW keeping. The 2nd phase is a fast current ramp-down from 7.7 MA to 1.8 MA (during 84 s) in L-mode and divertor configuration with progressively reduced elongation and minor radius (feedback control of plasma current is switched on).

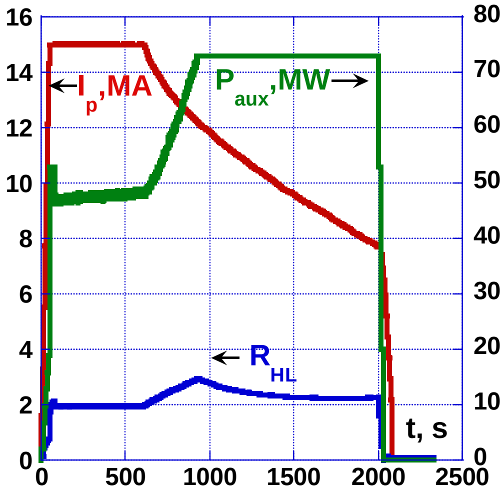

FIG. 3 *Time traces of* I_p, P_{aux} *and* R_{HL} *in the scenario with extended burn.*

Fig. 3 shows time traces of I_{p}, P_{aux} and R_{HL} – the ratio of the total heating power to the threshold value for L to H mode transitions [8]. Fig. 4 shows the fusion power P_{fus}, Q and the neutron fluence G_{fus} (in MW·h). The plasma elongation k, internal inductance $l_{\mathrm{i}}(3)$ and β_{p} are presented in Fig. 5. One can see that during the 1st phase the value of R_{HL} is more than 2, i.e. the plasma stays deeply in H-mode. From

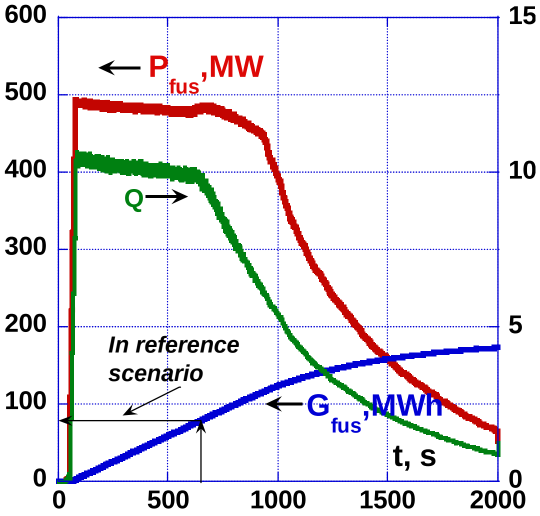

FIG. 4 *Time traces of fusion power* P_{fus}, Q *and neutron fluence* G_{fus} *in the scenario with extended burn.*

the beginning of the current ramp-down (610s) till 2020 s the value of *k* is slightly decreases by the control system, from 1.83 to 1.7, preventing loss of the plasma vertical stability and formation of configuration with upper X-point (due to the growth of l_i). During the 2nd phase of the current ramp-down, the plasma elongation is reduced to 1.2 by the same reasons.

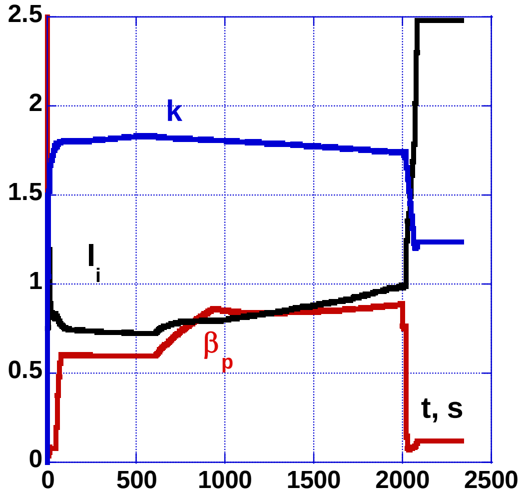

FIG. 5 *Time traces of* β_p, l_i(3) *and k in the scenario with extended burn.*

During the 2nd phase of current ramp-down the feedback control of the plasma current is switched on again and the back transition to L-mode is produced in three steps: 1) at 2000 s, 20 MW of ICH is turned off (plasma is still in H-mode), 2) at 2020 s, two NBIs are switched off (33 MW) triggering the H to L mode transition and 3) at 2030 s, 20 MW of ECH is turned off. After the H to L mode transition the plasma current ramp-down takes 54 s. During this phase of the current ramp-down the value of l_i(3) increases from ≈ 1 at 7.7 MA to ≈ 2.5 at the last divertor configuration controlled by the PF system (1.8 MA).

4. CONCLUSION

Reduction by 30% of the internal stress in conductor of the bottom module of the central solenoid results in only minor modifications of the 15 MA DT scenarios with Q ≈ 10. The total flux swing (more than 240 Wb) is reduced by only 3 Wb relative to the case with the nominal conductor. Studies performed with the DINA code have shown that the fastest current ramp-up (during 50 s) allows more than 300 s of burn during the current flattop for a wide range of Z_{eff} and ECH power. In the proposed modified 15 MA DT scenario, the burn is significantly extended beyond the plasma current flat-top allowing increase of the neutron fluence by more than a factor 2.4 relative to that in the nominal scenarios.

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

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