Optimisation of the ITER baseline scenario

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Introduction:

Based on simulations for the 15 MA ELMy H-mode ITER baseline scenario [1,2] and sensitivity studies that have been made to find potentials of optimisation with respect to neutron yield resp. the fusion energy production per discharge W_{fus}, new scenarios have been developed where all actuators that have been identified to allow an enhancement in W_{fus} have been combined, trying to minimise disadvantageous side effects.

Optimisation techniques:

W_{fus} can be maximised by increasing the fusion reaction rate in the burning phase or by extension of the pulse duration. A summary of techniques for the maximisation of W_{fus} is given in Table 1. Optimisation techniques are not fully exploited if there is a risk that they could lead to the violation of operational constraints (related to heating, fuelling, MHD stability, confinement conditions, PF coil current control etc.). It should be noted that the possible transient exceedance of edge heat flux limits due to ELMs that could lead to an enhanced erosion of the divertor plasma facing components has not been evaluated in this study though.

Simulation conditions:

Current ramp-up: Earliest possible transition to a diverted plasma configuration (at I_{pl} = 4 MA), current ramp at the maximum supportable rate $dI_{pl}/dt \approx 0.3$ MA/s, low fuelling: $n_{e\ lin.\ avg.} \approx 0.25 \cdot n_{GW}$, application of broad on-axis ECRH with additional 16.5 MW of NB power as soon as the density shine through limit is reached, keeping P_{AUX} just below $P_{L\text{-}H}$, L-H transition at the end of current ramp-up.

Flat-top: Low fuelling: $n_{e\ lin.\ avg.} \approx 0.65 \cdot n_{GW}$, application of full available auxiliary heating power, assumed to consist of 20 MW of ECRH, 20 MW of ICRH (both deposited in the central plasma region), and 33 MW of NBI.

Ramp-down: V_{loop} = 0.0 V or close to zero until $I_{pl} \approx 5$ MA, prescribed dI_{pl}/dt for $I_{pl} < 5$ MA, maintenance of H-mode until $I_{pl} \approx$ 7.5-8.5 MA, same fuelling assumptions as for current flat-top: $n_{e\ lin.\ avg.} \approx 0.65 \cdot n_{GW}$, gradual decrease in P_{AUX}, late transition to limited configuration at I_{pl} = 4 MA. (→ Fig. 1)

Three optimised scenarios S1-S3 have been tested and compared to the ITER baseline scenario (referred to as S0, see [1,2]). Differences in the scenario configuration can be summarised as follows:

- Scenario S1: I_{pl} = 15 MA at flat-top, V_{loop} = 0.0 V for I_{pl} = 15→5 MA at ramp-down
- Scenario S2: I_{pl} = 17 MA at flat-top, V_{loop} = 0.0 V for I_{pl} = 17→5 MA at ramp-down
- Scenario S3: I_{pl} = 17 MA at flat-top, V_{loop} = 0.0 V for I_{pl} = 13→5 MA at ramp-down

All three scenarios are not yet fully optimised in the ramp-down phase, where a constant V_{loop} close to 0.0 V has just been applied for reasons of simplicity. The actual flux limits are estimated to allow an additional extension of the ramp-down phase by several hundreds of seconds.

* See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea

As for S0, the simulations have been run with JINTRAC [3] in weak coupling with CREATE-NL [4] in semi-predictive mode (n_e prescribed), using the L-mode Bohm/gyroBohm model [5] for L-mode, the GLF-23 [6] and continuous ELM models [7] for H-mode, and a self-consistent L-H transition model based on the Martin scaling [1,8]. Also, the same source models, impurity assumptions and boundary conditions have been applied.

Simulation results:

Simulation results are shown in Figs. 2-4. It seems to be advantageous to operate at the maximum flat-top current for which a safe and stable operation can be assured, as not only fusion power gets considerably enhanced as expected, but also resistive and sawtooth-induced flux consumption Ψ_{res} and Ψ_{saw} do not increase substantially in the flat-top phase. For a given number of Vs that can be saved, the amount of time by which the flat-top phase could be extended is almost the same for flat-top currents of 15 and 17 MA. Expressed in figures, one Vs is consumed in quasi-steady state flat-top conditions within ≈ 23-25 s for all scenarios S1-S3. Despite the very similar flux consumption properties, the flat-top duration $t_{flat\text{-}top}$ needs to be shortened at higher currents. Comparing scenarios with I_{pl} = 17 MA and I_{pl} = 15 MA with similar flux limit assumptions, the time $\Delta t(I_{pl}>15$ MA) differs by ≈ 120 s. ≈ 60 s of this time are related to the inductive flux consumption Ψ_{ind}, which is higher by ≈ 3 Vs in S3 at the time when I_{pl} starts to drop below 15 MA. One finds that $\Delta\Psi_{ind}$ ≈ -0.5 Vs only if the ramp-down from 17 MA to 15 MA is started 100 s earlier, which leads to the conclusion that the associated reduction in fusion power would overweigh the gain in $\Delta t(I_{pl}>15$ MA), and that the $I_{pl}(t)$ evolution in S3 at I_{pl} > 15 MA must be close to the optimum one.

The flux optimising measures at current ramp-up have the side effect of flattening the current density profile. This leads to a lower s/q in the outer plasma region and a degradation in confinement in accordance with transport theory predictions and experimental observations (see [9] and ref. therein). Nevertheless, it seems to be reasonable to disregard the tailoring of the q profile and instead minimise Ψ_{res} and Ψ_{saw} at ramp-up. Comparing S1 with S0, $\Psi_{res}+\Psi_{saw}$ drops from 17.6 Vs down to 7.4 Vs at the beginning of current flat-top, which corresponds to ≈ 250 additional seconds of flat-top operation that are made available. The fusion energy output can be improved by ≈ 110 GJ (≈ 55% of W_{fus} for S0) that way. s/q is only relevant for the optimisation of W_{fus} as far as it should not drop down to a level where the transition to good quality H-mode could be hindered or delayed. This can happen for instance if one allows the L-H transition to take place at an earlier time during the current ramp-up phase.

Another concern for current density profiles with very small peakedness that could occur if the flux saving techniques are applied too excessively at current ramp-up, is the internal inductance li(3), which may reach very low values that could become a problem for plasma shape control. In S1-3, li(3) temporarily reaches minimum values of ≈ 0.63 in the early phase of flat-top. In dedicated calculations made with CREATE-NL, it was shown, that these very low li(3) values are still manageable. The operation at a flat-top current of I_{pl} > 17 MA may not be possible from a PF coil current control point of view though, as the lower limit in li(3) may be violated. In the current ramp-down phase, a strong rise in li(3) to values > 1.5 appears after the back-transition to L-mode in S1-3 like in S0 at similar I_{pl}, which may become an issue for vertical stability control.

Techniques that help to diminish the rise in Ψ_{res} and Ψ_{saw} at flat-top are particularly important for the optimisation wrt. W_{fus}. In S1-3, the decrease in density and the increase in auxiliary heating and current drive (with slightly more core-localised heat deposition) have helped considerably to keep the flux loss rates at a low level in the burning phase (≈ -45% compared to S0). In this period, only a moderate reduction in n_e can be envisaged though that is within a range where fusion performance remains unaffected and adverse side effects such as an increase in heat flux through the separatrix caused by reduced core radiation as well as higher energies carried by the effluent particles can still be handled.

The current ramp-down phase can also contribute significantly to the maximisation of W_{fus}, provided that H-mode is maintained for as long as possible and flux limits are fully exploited. If Ψ_{tot} is always kept at the allowed maximum for plasma shape and stability control by PF coil currents, one may expect an enhancement in W_{fus} by >≈ +50%.

A comparison between S0 and S1-3 in terms of fusion reactivity and fusion energy production is presented in Fig. 4. The relative importance of various W_{fus} optimisation techniques is depicted for S1-3 in Fig. 5.

Conclusions:

Combining techniques for the increase in fusion energy production per discharge, the ITER baseline scenario could be optimised in a way that might permit an enhancement of W_{fus} by ≈ 150-250%. It may be advantageous to operate at a higher flat-top current of I_{pl} = 17 MA, to increase dI_{pl}/dt at ramp-up, maximise heating and current drive, operate at low to medium fuelling scheme, to maintain H-mode for as long as possible and to stay at the maximum allowed flux level in the ramp-down phase. In the optimised scenarios that have been simulated, the flux limit has not yet been fully exploited, meaning that a further enhancement in W_{fus} could be achieved by a further optimisation of the ramp-down phase.

Acknowledgements:

This work has been funded with support from Fusion for Energy. This publication reflects the views only of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

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Method	Phase	Mechanism	Advantages	Side effects	Limitations
Lower n_e	Ramp-up	Lower η, retarded j_z penetration	Reduced $\Psi_{res} + \Psi_{saw}$	Reduction of s/q	Impurities, lower $P_{L\text{-}H}$
Higher P_{AUX}	Ramp-up	Lower η, retarded j_z penetration	Reduced $\Psi_{res} + \Psi_{saw}$	Reduction of s/q	$P_{L\text{-}H}$
On-axis heating	Ramp-up	Better confinement → lower η	Reduced Ψ_{res}	Earlier start of sawtooth activity	
Early transition to diverted phase	Ramp-up	Possibility of early P_{AUX} application, retarded j_z penetration	Reduced $\Psi_{res} + \Psi_{saw}$		PF coil limits
High dI_{pl}/dt	Ramp-up	Reduced Ψ_{res} integration time and j_z penetration time	Reduced $\Psi_{res} + \Psi_{saw}$	Reduction of s/q	PF coil limits
Early L-H transition	Ramp-up	Lower η, retarded j_z penetration	Reduced $\Psi_{res} + \Psi_{saw}$	Reduction of s/q, sharp li(3) drop after transition	PF coil limit for li(3) after transition
Initial s/q maximisation	Initial flat-top phase	Improved confinement for higher s/q (in the outer region)	Increase in P_{fus}	Earlier start of sawtooth activity, q profile optimisation requires higher $\Psi_{res} + \Psi_{saw}$ at ramp-up	
Increase flat-top current	Flat-top	Improved confinement	Higher P_{fus}	Increase in Ψ_{ind}, higher total power, power fluctuation, and energy per particle for effluent particles, shorter $t_{flat\text{-}top}$	Lower li(3) limit, maximum allowed heat flux to the PFCs
Maximise heating and current drive	Flat-top	Quick transition to good quality H-mode, lower η and inductive j_z	Reduced $\Psi_{res} + \Psi_{saw}$, slightly increased P_{fus}	Lower Q_{fus}	P_{AUX} capacity

Lower n_e	Flat-top	Lower η due to pressure gradient length maintenance	Reduced $\Psi_{res} + \Psi_{saw}$	Higher energy of effluent particles, reduced core radiation	Drop in P_{fus} for $n_{e\ lin.\ avg.} <\approx 0.6 \cdot n_{GW}$ risk of enhanced erosion of PFCs
Minimise $\lvert dI_{pl}/dt \rvert$, staying at the flux limit for PF coils	End of flat-top, ramp-down	Prolongation of discharge, staying at the highest achievable I_{pl} with maximum P_{fus} output	Additional production of fusion energy		Flux limit
H-mode maintenance	Ramp-down	Better confinement with lower η, higher non-inductive current, less peaked j_z	Higher P_{fus}, reduced $\Psi_{res} + \Psi_{saw}$ and Ψ_{ind}		$P_{L\text{-}H}$

Table 1 – Summary of techniques for the maximisation of neutron yield and W_{fus} for the ITER baseline scenario.

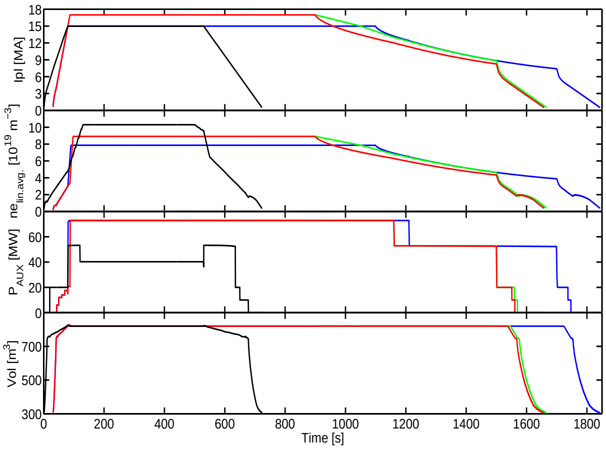

Figure 1 – I_{pl}, $n_{e\ lin.\ avg.}$, P_{AUX} and plasma volume for S0 (black), S1 (blue), S2 (red), and S3 (green).

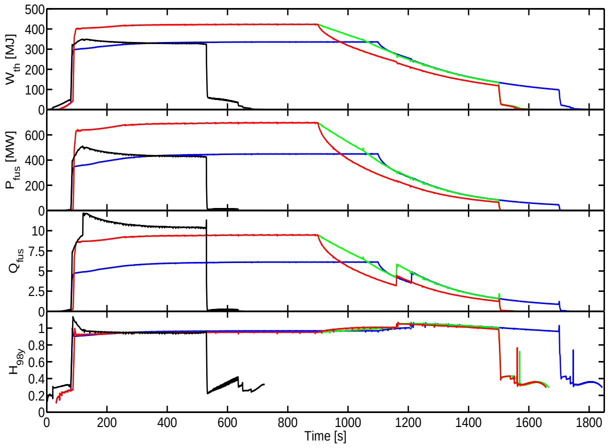

Figure 2 – Thermal energy, P_{fus}, Q_{fus} and $H_{98,y}$ for S0 (black), S1 (blue), S2 (red), and S3 (green).

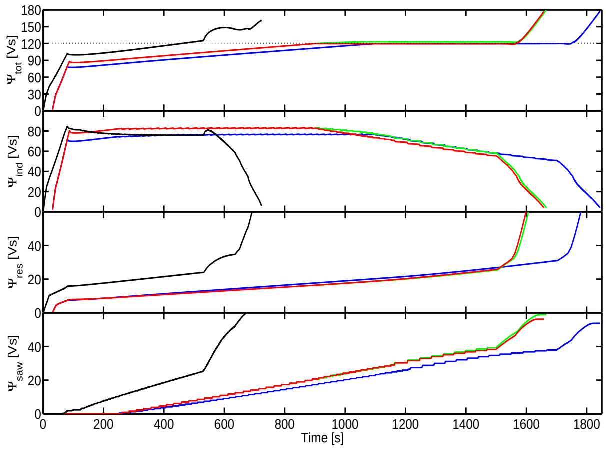

Figure 3 – Ψ_{total}, $\Psi_{inductive}$, Ψ_{res}, Ψ_{saw} for S0 (black), S1 (blue), S2 (red), and S3 (green).

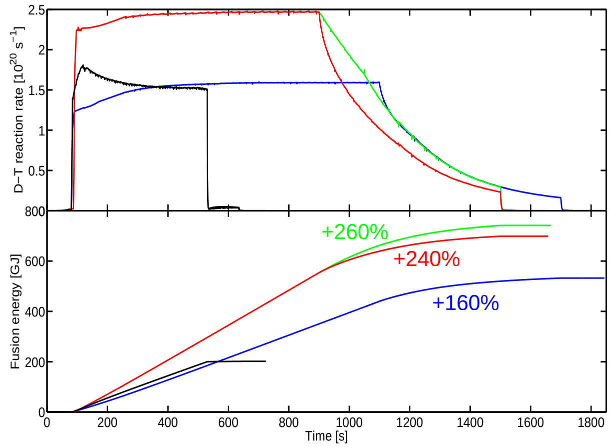

Figure 4 –Fusion reaction rate (top) and W_{fus} (bottom), for S0 (black), S1 (blue), S2 (red), and S3 (green).

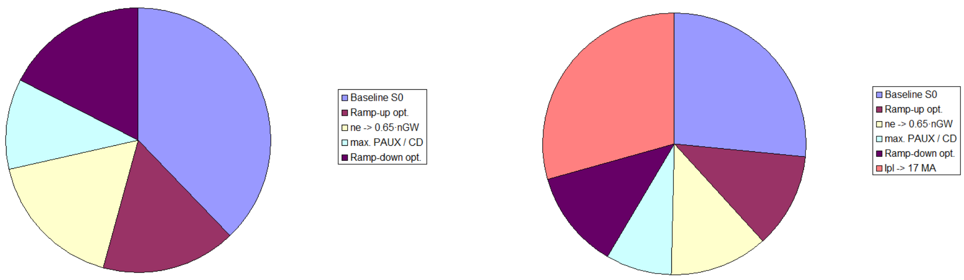

Figure 5 – Contributions from various optimisation attempts to the total neutron yield or fusion energy production in S1 (left) and S3 (right).