Abstract. The ITER machine is reaching a stage in which the design is in large part frozen. Nevertheless design changes are necessary in the procurement phase due to additional constraint linked to manufacturing techniques and/or cost containment. In this framework, the reference ITER scenario and the control system strategy are in continuous evolution. The aim is preserving the final goal of a 15 MA Q=10 burning plasma in ITER, which will require a careful optimization of the scenario in order to fully exploit the machine capabilities within the engineering limits which define and restrict the operational space available.

This paper presents a summary of the activities carried out within the EU-DA on the engineering optimization of the ITER plasma scenarios and of the magnetic plasma position control system strategy.

1 Introduction
As the construction of ITER proceeds, the detailed design of its components evolves to comply with additional constraints arising from the choice of a particular supplier, manufacturability issues, the need of cost containment or following an optimization process often based on a fruitful collaboration with suppliers.

Following such evolution of the project, it is necessary to review the analyses of plasma controllability in order to ensure that the operational space of ITER is preserved. The design of ITER plasma scenarios is also in evolution benefiting from progress in simulation capabilities and influenced by new experimental results in present experiments.

The present paper summarizes recent activities carried out within the EU-DA on ITER plasma control and scenario optimization. In particular, section 2 summarizes the recent changes to the ITER design [1] affecting plasma controllability. Section 3 presents a review of analyses of the ITER vertical stabilization system taking into account the most recent design of in-vessel coils and including the effect of noise. Section 4 presents the analysis of shape control, discussing in detail the achievable performances with the present ITER baseline design, the use and optimization of feed-forward to counteract the most demanding disturbances and the discussion of a proposal of an XSC type controller [2] for ITER. Section 5 presents the results of the analysis of the ITER operational space and, in particular, the impact on breakdown of recent changes to the poloidal field coils power supplies system and, finally section 6 draws some general conclusions.

2 Relevant design changes
The main design changes to the ITER machine [1] with respect to the previous baseline (2007) and having an impact on plasma controllability regard the Poloidal Field (PF) power supply system, the internal coils and the central solenoid.

The new design of the PF power supply system [3] is summarized in terms of voltage ratings and compared to the previous configuration in Table 1. The main features are:

- Adoption of a basic unit with 1.05 kV output voltage for the main CS and PF converters, instead of a 1.5kV main converter unit.
- Cancellation of booster converters. To compensate for this, the maximum voltage on PF2-4 is increased from 1.5 to 3.15 kV (on load). While booster converters can be used only at start-up when the coils current is below 10 kA, the main converters are available throughout the whole discharge.
- Staging of the power supplies procurement: the PF power supplies are planned in two stages: phase one with a substantially reduced power supply voltage on CS and PF1 & 6 (from 1.5 to 1.05 kV) and 2kV instead of 6kV on VS1, and phase 2 with 2.1 kV on CS and PF1 & 6 and 6.3 kV on VS1.
Phase 1 is not considered in this study since previous analysis show that such configuration does not allow to operate ITER in any of the reference design scenarios [4];

<table>
<thead>
<tr>
<th>2001 STAC</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I (kA)</td>
<td>V (kV)</td>
</tr>
<tr>
<td>CS</td>
<td>45</td>
<td>1.5</td>
</tr>
<tr>
<td>PF1, PF6</td>
<td>55</td>
<td>1.5</td>
</tr>
<tr>
<td>PF2,3,4,5</td>
<td>55</td>
<td>1.5</td>
</tr>
<tr>
<td>PF2,3,4,5</td>
<td>10</td>
<td>4.2</td>
</tr>
<tr>
<td>Booster</td>
<td>VS1</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Table 1: Power supply configurations (on load voltages)

The adoption of smaller units is advantageous for the control of the reactive power. However, the discussion of this issue is out of the scope of this paper which concentrates on the EU analyses of the impact of the proposed voltage ratings and of the cancelation of the booster converters on machine operation and plasma control.

As for the internal coils, the novelty of the present design [1] is a radially asymmetric position due to space constraints. Furthermore the limitation in effective current has been substituted by a limitation in the maximum coolant temperature which results in a more relaxed constraint [1].

The design of the Central Solenoid has seen a reduction of the overall radius from 1.722 to 1.696 m reducing by approx. 4Wb the maximum flux linked to the plasma.

3 Plasma Vertical stabilization system analysis

The vertical stabilization system has been studied in detail with open loop and closed loop Best Achievable Performances (BAP) analyses. The influence of noise has also been evaluated. In order to define the performance boundaries of the system, the BAP analysis has been performed with two machine configurations, namely with only external or only internal coils.

3.1 Open loop analysis

Two equilibria are considered in the analyses [5]:
- Case 1 Scenario, L-mode @ Start Of Flattop (I_p=15 MA, li=0.88, β_pol =0.06)
- Case 1 Scenario, H-mode @ End Of Burn (I_p=15 MA, li=0.80, β_pol =0.75)

Tables 3.1.1 gives the values of the main indicators useful to describe the open loop behaviour of the "plasma– circuits" system for the 2 equilibria described above: the growth rate γ of the unstable mode x_u, the growth time τ_g=1/γ, the stability margin m_s(EFDA) computed as the largest real part of the eigenvalues of the matrix Ms = −L* L_0⁻¹ [6], the stability margin computed as m_s(CREATE) = −(x_uᵀ L* x_u)/(x_uᵀ L_0 x_u), where x_u is the unstable (right) eigenvector.

<table>
<thead>
<tr>
<th></th>
<th>Growth rate</th>
<th>Growth time</th>
<th>Stability margin</th>
<th>Stability margin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>γ (s⁻¹)</td>
<td>τ_g (ms)</td>
<td>m_s(EFDA)</td>
<td>m_s(CREATE)</td>
</tr>
<tr>
<td>L mode</td>
<td>10.75</td>
<td>93</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>@ SOF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H mode</td>
<td>6.05</td>
<td>165</td>
<td>0.61</td>
<td>0.42</td>
</tr>
<tr>
<td>@ EOB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1.1: Open loop analysis: growth rate and stability margins.
3.2 Closed loop analysis

The closed loop analysis of the VS system has been carried out with reference to the most critical equilibrium for vertical stabilization, i.e. Case 1 Scenario, L-mode @ SOF in different configurations.

3.2.1 Configuration (a: External coils)

The VS control scheme considered for this case is the standard VS1 (6 kV) driven in feedback by the plasma vertical velocity $\dot{z}$ using a dynamic controller with transfer function:

$$C(s) = \frac{15000 \cdot (1+s/18)}{(1+s/60)^2}.$$

The values of the standard performance indicators [7] are given in Table 3.1.1: $VDE_{\text{max}}$ i.e. the maximum initial ($t=0$) offset (along the unstable mode) that can be stabilized with the available voltage, phase margin ($m_\phi$), crossover frequency ($\omega_t$), upper gain margin ($m_{GU}$), lower gain margin ($m_{GL}$). The control system stability margins have been calculated at the output of the controlled system, namely the plasma vertical velocity. The indicators show that controllability of the plasma with internal coils is marginal. An initial displacement greater than 34 mm would cause a loss of vertical control.

<table>
<thead>
<tr>
<th>$VDE_{\text{max}}$(mm)</th>
<th>$m_\phi$</th>
<th>$\omega_t$ [rad/s]</th>
<th>$m_{GU}$ [dB]</th>
<th>$m_{GL}$[dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>22°</td>
<td>13</td>
<td>5.6</td>
<td>-4.0</td>
</tr>
</tbody>
</table>

Table 3.1.1: Best Achievable Performance (BAP) with VS1

3.2.2 Configuration (b: Internal coils)

The controller has the following form:

$$V(s) = -8000 \cdot \frac{1+s/40}{1+s/6} \left( Z_{\text{dort}}(s) - 1.2 \times 10^{-5} \times I_{s3}(s) \right),$$

$Z_{\text{dort}}(s)$ being the Laplace transform of the plasma current centroid vertical velocity and $I_{s3}$ the current in the VS3 stabilization circuit. The VS controller was tested in non-linear simulations and optimized in order to eliminate undesired oscillations. The values of the performance indicators are given in Table 3.2.1. The control system stability margins have been calculated at the input of the controlled system, namely the VS3 voltage. The indicators show that controllability of the plasma with internal coils is reliable allowing vertical control of the plasma in presence of large initial vertical displacements due to instabilities.

<table>
<thead>
<tr>
<th>$VDE_{\text{max}}$(mm)</th>
<th>$m_\phi$</th>
<th>$\omega_t$ [rad/s]</th>
<th>$m_{GU}$ [dB]</th>
<th>$m_{GL}$[dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;200</td>
<td>65°</td>
<td>78</td>
<td>13</td>
<td>-18</td>
</tr>
</tbody>
</table>

Table 3.2.1: Best Achievable Performance (BAP) with internal coils.

3.3 Simulations in presence of noise

Table 3.3.1 gives the $VDE_{\text{max}}$ which can be tolerated in the presence of a band limited white noise with bandwidth of 1 kHz, zero mean, and standard deviation $\sigma=210$ mm/s and $\sigma=430$ mm/s.[1]. The values of $VDE_{\text{max}}$ have been calculated by considering the most critical realization of the noise, and applying the VDE at 400 different time instants. The calculation accuracy for $VDE_{\text{max}}$ is 1 mm.

<table>
<thead>
<tr>
<th>Noise level</th>
<th>$\sigma = 210$ mm/s</th>
<th>$\sigma = 430$ mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>$VDE_{\text{max}}$(mm)</td>
<td>$VDE_{\text{max}}$(mm)</td>
</tr>
<tr>
<td>VS1 (6 kV)</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>VS3 (2.3 kV)</td>
<td>148</td>
<td>141</td>
</tr>
</tbody>
</table>

Table 3.3.1: BAP in the presence of noise
The machine configuration with internal coils (VS3) for the vertical stabilization is quite resilient to noise. At the noise level considered, a negligible deterioration of the VS system performance is observed in terms of $VDE_{\text{max}}$ (148 mm with $\sigma = 210$ mm/s, and 141 mm $\sigma = 430$ mm/s instead of 171 mm in absence of measurement noise).

The analyses confirm that the vertical stabilization of the target equilibria in the ITER 2010 machine configuration using only the VS1 circuit shows critical values in terms of maximum controllable VDE and stability margins. On the contrary, the performance indicators using the VS3 circuit give adequate confidence of a robust and reliable stabilization of the plasma.

4 Plasma Shape Control analysis

Apart from the design changes reported in section 2, an additional motivation for a revision of the ITER plasma shape control system performance comes from the additional requirement introduced in [1], consisting in a minimum plasma-wall distance to be respected at a set of points on the First Wall (FW). Previous versions of [1] relied on the respect of a minimum plasma-wall distance at the six control points to ensure the avoidance of plasma wall interaction but it has been shown in simulations [8,9] that during transients the plasma can deform in such a way that it touches/approaches the wall, while the tolerance on the six control gaps are respected. To avoid this risk, the requirements to the control system now include a set of 24 FW points where a minimum distance needs to be respected.

4.1 XSC like Shape Control

To overcome this limitation, a novel approach is proposed which allows to better exploiting the available degrees of freedom and to control the overall plasma shape. The controller is based on the eXtreme Shape Controller (XSC) [2] concept tested successfully on the JET machine.

A new scheme is proposed for the implementation of the control system of ITER plasmas. Most plasma shape and current controllers, used in present experiments and in past ITER analyses [8,9,10], drive directly the PF coil voltages and consist of a feedback component, rejecting disturbances, plus a feed-forward component driving the plasma along the desired parameters trajectory. The feed-forward component is computed offline, starting from a series of snapshot equilibria describing the scenario.

This is a well-proven system, however is has some important drawbacks:
- The computation of feed-forward voltages is affected by significant errors, mainly during plasma formation because of the uncertainty on the initial configuration; this error propagates in the subsequent phases requiring a feedback correction over the pulse, even in absence of main disturbances;
- ad-hoc schemes are needed to protect coils from overcurrent, whereas the current controller can directly saturate the commands;
- voltage control does not allow implementing high performance controllers such as the XSC scheme, here proposed for ITER.

In scheme proposed here, the shape and plasma current controller calculates, in real time, the required deviation from the scenario PF coil currents. An additional loop is needed to control the PF coil currents. Such scheme allows the implementation of controllers better exploiting the available degrees of freedom and furthermore makes it easier to implement specific controllers for abnormal
terminations of the pulse along pre-decided trajectories (so-called soft terminations). The resulting control scheme is shown in figure 4.1.1. Although, in principle, the introduction of an additional control loop might cause a loss of performance in terms of total time response of the control systems, in practice, in the ITER case the active response time is mainly determined by the PF coil voltage limits, so that no performance deterioration was observed in simulations. The XSC like controller for ITER is designed to minimize the overall shape deformation by controlling a high number of geometrical parameters, e.g. gaps 1:19, 21, 24 from the set described in [1].

A set of simulations has been carried out to assess the performance of the designed control system in rejecting the set of nominal disturbances for ITER [9]. The simulations have been carried out using:
- the CREATE_L model of Case 1 Scenario, L-mode 15 MA plasma at SOF;
- the CREATE_L model of Case 1 Scenario, H-mode 15 MA plasma at EOB;
- the simplified models for the diagnostics and the power supplies proposed in [1].

A summary of the simulation results is shown in Table 4.1.1

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>Uncontrolled ELM</th>
<th>Minor Disruption</th>
<th>Fast H-L transition</th>
<th>L-H transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power [MW]</td>
<td>SOF</td>
<td>SOF</td>
<td>SOF</td>
<td>EOB</td>
</tr>
<tr>
<td>Max.</td>
<td>40.6</td>
<td>166.5</td>
<td>32.9</td>
<td>204.5</td>
</tr>
<tr>
<td>shape variation after 10 s [mm]</td>
<td>12.4 @ gap 10</td>
<td>99.5 @ gap 15</td>
<td>42 @ gap 9</td>
<td>99.6 @ gap 19</td>
</tr>
</tbody>
</table>

Table 4.1.1: Summary of the simulation results

A benchmark campaign was performed under the same conditions with a controller feeding back only the six nominal control gaps and optimized for the equilibria considered. The results reported in [8] show that the XSC approach reduces by 30% the maximum separatrix deformation.

![Figure 4.2.1 Plasma shape sequence during L to H transition](image1)

![Figure 4.2.2 Controlled gaps evolution compared to reference signals](image2)
4.2 Feedforward component

For the most demanding transients, namely the L-H and H-L transitions, the control system performance are still not fully compliant with the requirements set in [1] for the plasma-wall clearance with an inner radial displacement of 15 cm. Since rising the feedback controller gains causes a large overshoot in the radial position (>20 cm), an approach considering the addition of a feedforward component was analysed to keep the plasma deformation within the set limits.

To evaluate the performance of a feedforward plus feedback control scheme a first nonlinear simulation of a L-H transition taking place at 80s and at Ip = 15 MA in the reference Q=10 scenario was performed with the proposed control scheme. The results of the simulation are summarized in figures 4.2.1 and 4.2.2. The control system is able to keep the plasma deformation within the limits set in [1] while respecting the power supplies limits.

The same approach has been tested extensively for the H-L transition in different conditions. In particular, since the possibility of triggering the feed-forward component at the right instant is clearly a questionable assumption, the impact of a delay in the trigger has been evaluated together with the impact of different update frequencies of the feed-forward component. An alternative strategy consisting in a real-time computation of a feed-forward component based on the measurement of the poloidal beta has also been developed and tested in simulation.

A wide set of simulations has been performed. Below only the results relative to a fast H to L transition are reported for the different cases considered:
- **HL2.a** Feedforward control updated with T = 1s;
- **HL2.b** Feedforward control updated with T = 5s;
- **HL2.c** Feedforward control updated with T = 1s just after the transition and then T= 9s;
- **HL2.d** Feedforward control updated with T = 1s and a delay of 0.2s;
- **HL2.e** Feedforward control updated with T = 5s applied 1s in advance.

From the simulation results, shown in figure 4.2.3, the following conclusion can be derived:
- The update at 1s is more efficient than any other during the beta poloidal drop (case a)
- T = 5s in not a suitable updating period (case b)
- The effect of slowing down the feedforward control action after 1s helps in avoiding overshoot toward the external wall (case c)
- The delay of 0.2 has a minor effect on radial displacements (case d).
- An anticipation of the feedforward control action by 1 s is not beneficial (case e)

![Fig. 4.2.3 Radial Inner and Outer Gap evolution in the different cases simulated.](image)

Figure 4.2.4 shows the comparison of the results obtained with the following approaches
- **HL7.a** Feedforward control updated with T = 1s;
- **HL7.f** Feedforward computed as a function of beta poloidal

The application of a feedforward action computed as a function of beta poloidal gives even better results than the approach relying the most on a a-priori knowledge (Update of preprogrammed currents every second). The feasibility and performance of such control along the whole scenario evolution should be further investigated.
The results of the analyses show that, while the increased voltage ratings have brought higher performance in the plasma controllability with respect to the ITER 2007 baseline design, some issues are still open such as control of the plasma in a fast H-L transition at full current. Nevertheless the solutions proposed for the shape control system are able to overcome the problem and guarantee respect of the requirements set to avoid damage to the First Wall during transients.

5 Operational space analysis and Breakdown

The impact of the design changes described in chapter 2 on the ITER operational space has been assessed.

The configuration changes to the PF Power supplies bring a 30% increase in the maximum achievable Ip change rate in ramp-up and ramp down. As far as the design of the Central Solenoid is concerned, the change in the maximum available flux linked to the plasma due to the reduction of the CS diameter is 4 Wb. When exploring the high flux equilibria (high Ip at End Of Burn) a second effect is observed linked to the shaping capability of the CS which are slightly reduced due to the greater distance from the plasma. Such effect causes an additional loss of linked flux of approximately 4 Wb, reaching a total loss of 8 Wb with the 2010 CS design cfr. the 2007 baseline.

As far as the breakdown (BD) is concerned, the analysis has shown that the parameter space for ohmic start-up is strongly reduced by the withdrawal of the booster converters because the maximum applicable $V_{\text{loop}}$ is limited by the capability to control the subsequent plasma current rise for high $dI_p/dt$. Furthermore, the additional voltage on the outer coils provided by the booster converters would balance the power demand on the other coils and allow reducing the power step at breakdown. In absence of booster converters, the size of the power step required to obtain the maximum $V_{\text{loop}}$ becomes an additional limiting factor for ohmic breakdown. The simulations presented in [4] were repeated using a refined model which allows to compute a self-consistent evolution for the plasma current according to [11]. The simulation was performed for a fully charged CS and with 2 MW of applied EC power. At the initial time ($t = 0$), the poloidal field coil system produces about 115 Wb of poloidal magnetic flux. This corresponds to an initial $I_{\text{CS1}}$ current value of 38kA. The requirements in terms of null quality [1] at $t_{\text{BD}} = 0.9$ s are satisfied, having a large region under 1 mT. The resulting flux loss at BD is about 8 Wb. The achievable loop voltage at the center point of the BD region is around 12 V and the plasma current ramp-rate after BD is achieved is 1 MA/s. The voltage on P3-P5 is fully saturated and a power step of about 400 MW is required around the breakdown time. Forces and maximum fields in coils remain within the imposed limits.

The results reported in [4] indicate that a reliable start-up is achievable at low $V_{\text{loop}}$ using EC assist both for the breakdown and avalanche phase provided that the target low stray field is achieved. This means that EC assist is mandatory to operate ITER.

6 Conclusions

The results of the analyses performed within the EU-DA on plasma control and scenario analysis confirm the need of internal coils in order to ensure reliable plasma operation. At the same time, the analyses confirm the validity of the present proposal for the internal coils system design.
The higher voltage ratings for the PF power supplies also bring enhanced plasma controllability with respect to the 2007 design. Nevertheless, some issues are still open, in particular for the control of the plasma in case of an unexpected H-L transition at full plasma current. The alternative control system design proposed in this paper has the potential for overcoming these problems and ensuring the respect of the plasma wall clearance required to avoid plasma-wall interaction and machine damage. Some of the strategies proposed need, though, to be further investigated in order to prove their feasibility such as the application of a feedforward component computed on the basis of the measured $\beta_p$.

The revised simulations of breakdown confirm that the cancelation of booster converters has reduced strongly the operational space for Ohmic BD and confirm the need of EC assist in order to ensure a reliable breakdown ad burn-through phase, consistent with the strategy envisaged for ITER.

References


[8] G. Ambrosino et al., Task on the study of control of plasma current, position and shape, September 2011, Private communication available at request from the authors.

