Optimization of the current ramp-up phase for hybrid ITER discharges

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1. Introduction. During the current ramp-up phase of ITER MHD instabilities have to be avoided, flux consumption has to be minimized, and this has to be achieved within the narrow operational window of ITER. Ramp-up for the hybrid scenario moreover requires that the \( q \) profile is shaped: \( q_{\text{min}} \) should stay near or slightly above 1 and, for an optimized fusion performance, the \( q \) profile should have the typical hybrid shape with a wide flat region \cite{1}. This paper reports on a systematic effort to optimize the current ramp-up phase for the ITER hybrid scenario, and to assess the sensitivity of the results to the assumptions made.

Validation on the ramp-up phase of JET, AUG and Tore Supra \cite{2,3} has shown that both empirical scaling based models (H-mode scaling with H-factor \( H=0.4 \); L-mode scaling with factor 0.6 gives the same result) and the semi-empirical Bohm/gyro-Bohm model (L-mode version, ITB shear function off) yield a good reproduction of this phase for considered discharges, in terms of \( T_e \) and \( q \) profile and \( l_i \). Therefore these models have been used in the reported work, which was carried out with the CRONOS integrated suite of codes \cite{4}.

2. Assumptions made

Following assumptions for the baseline scenario were adopted from the ITER team:

\textit{(i)} An expanding ITER shape is used, starting on the LFS of the torus, with initial plasma volume \( \simeq 50\% \) of the final plasma volume. X-point formation takes place after 15s, when \( I_p = 3.5 \) MA.

\textit{(ii)} A flat \( Z_{\text{eff}} \) profile is assumed, decreasing in time with increasing density, with an asymptotic value of 1.7 \cite{5}.

\textit{(iii)} A rather low density of \( n_e = 0.25 \cdot n_{\text{Gw}} \) is taken.

The \( n_e \) profile is assumed to be parabolic with a moderate peaking factor \( n_e(0)/\langle n_e \rangle = 1.3 \). This is a compromise between the (unrealistic) flat \( n_e \) profile often used in ITER scenario predictions and the peaking factor of \( \simeq 1.5 \) predicted by scaling studies \cite{6}.

The total input power should stay below the L-H threshold during the whole ramp-up phase; for the reference case \( P_{\text{LH thr}} \simeq 29 \) MW at end of the current ramp-up.

The \( I_p \) ramp rate is chosen such that \( I_p = 12 \) MA is reached after 80 s. Other assumptions \( (T_{e,i}(\text{edge}), \text{initial } T_{e,i} \text{ and } l_i) \) are based on experimental evidence.

The simulations start 1.5 s after breakdown, when \( I_p = 0.5 \) MA.

3. Choice of heating and current drive scheme

The ITER design and limitations are used, e.g. the designed geometries of the heating systems are used; NBI is only allowed if \( \langle n_e \rangle \geq 2 \cdot 10^{19} m^{-3} \); NBI can only be applied at half or full power (i.e. 16.5 or 33 MW).

The logical way to get at the hybrid \( q \) profile is as follows: let the discharge evolve without additional heating until \( q(0) \) close to 1, and then apply off-axis heating and CD to clamp \( q(0) \) and broaden the \( q \) profile. For the typical plasma conditions during the ramp-up phase, both ECRH from the equatorial launcher and ICRF deposit very centrally, so...
are unsuitable for this purpose. Hence the remaining heating and CD options are: NBI (using the off-axis setting), LHCD and the Upper Port Launcher (UPL) of ECCD. The latter has 2 antennas with different ranges of poloidal angles, i.e. of power deposition radius ($\rho_{dep}$). Table 1 gives an overview of the options.

<table>
<thead>
<tr>
<th>CD method</th>
<th>$\rho_{dep}$</th>
<th>width</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPL ECCD 1st antenna</td>
<td>$\geq 0.4$</td>
<td>narrow</td>
<td>depends on poloidal angle</td>
</tr>
<tr>
<td>UPL ECCD 2nd antenna</td>
<td>$\geq 0.6$</td>
<td>narrow</td>
<td>depends on poloidal angle</td>
</tr>
<tr>
<td>LHCD</td>
<td>0.3 - 0.6</td>
<td>narrow</td>
<td>depends on plasma parameters</td>
</tr>
<tr>
<td>off-axis NBI</td>
<td>0.3</td>
<td>wide</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Overview of CD methods; the $\rho_{dep}$ given here are for the plasma parameters during the $I_p$ ramp-up phase.

Since ECCD and LHCD have quite narrow power deposition profiles, excessive use of one of these as only current drive source would yield a very localized net CD profile, leading to locally a strong negative shear, which should be avoided because of the risk of triggering unwanted MHD. Therefore it is better to use a combination of CD sources in such a way that the CD is spread over a wide off-axis zone, thus compensating for the peaked ohmic drive. Figure 1 gives an example if this.

4. Reference case Figure 2 shows the optimized scenario, as sketched in the previous section, for the reference case, using the scaling model ($H=0.4$) and the Bohm-gyroBohm model. Figure 3 shows the profiles of $T_{e,i}$ and $q$ at the end of the $I_p$ ramp-up. For reference the figures also show the result without any additional heating.

The Bohm-gyroBohm model predicts $\sim 40\%$ lower temperatures than the scaling model, and therefore a faster current penetration; this is accounted for by switching on ECCD and LHCD 20 s earlier. As seen from fig.3 in both cases a good hybrid $q$ profile is reached at the end of the ramp-up.

By post processing the simulation results with the free boundary equilibrium code FREEBIE, run in Poynting mode, it has been checked that the reference case, both with and without additional heating, is safely within the boundaries put by ITER coils.

5. Sensitivity analysis Regarding sensitivity of the results to the assumptions, following parameters were varied: $T_{e,i}(edge)$ (by 40%), $n_e$ (by 60%), $n_e$ profile shape (parabolic vs. flat) and $Z_{eff}$. We will only consider the scaling model ($H=0.4$) here; the sensitivity of the simulations to these changes when using the Bohm/gyroBohm model is quite similar and can be accounted for in the same way.
(i) varying edge $T_e$ gives only a modest change of $l_i$ ($\sim 0.04$) and a tiny change of $q$, so poses no problem.

(ii) $n_e$ peaking: A more peaked $n_e$ profile would cause a decreased peaking of $T_e$, hence a faster current diffusion. Indeed in an ITER ramp-up without additional heating, in this case the time that $q(0)$ reaches 1 ($t(q_0 = 1)$) is shifted forward by $\sim 10$ s. This can be compensated for by a corresponding earlier start of the additional heating. The opposite trend applies in case of a flatter $n_e$ profile and is accounted for in a similar way by delaying the heating. See Fig. 4.

(iii) $Z_{\text{eff}}$: A 40% higher/lower value of $Z_{\text{eff}}$ causes a faster/slower current diffusion, and a shift of $t(q_0 = 1)$ of $\sim 10$ s, which can be compensated for like the previous case.

(iv) $n_e$: We only consider the effect of a 40% higher $n_e$. Again this causes (due to lower $T_e$) faster current diffusion. Since now also $P_{\text{LH thr}}$ is higher by $\sim 10$ MW, the applied power can be higher by this amount; moreover higher $n_e$ allows earlier application of NBI. The thus adapted heating scheme restores the flat $q$ profile; see Figs. 5 and 6.
5. Conclusions and Outlook

The heating systems available at ITER allow, within the operational limits, the attainment of a hybrid $q$ profile at the end of the current ramp-up. This is reached by a combination of NBI, ECCD (UPL) and LHCD. A heating scheme with only NBI and ECCD is less effective (not shown in the paper).

The optimum heating scheme depends on the chosen transport model. Moreover, modified assumptions on $n_e$ peaking, edge $T_e,i$ and $Z_{\text{eff}}$ can be easily accounted for by a shift in time of the heating scheme. A higher density during the ramp-up phase can be accounted for equally well, and might even be profitable because it gives more freedom in the application of the heat sources.

The sensitivity of the current diffusion on parameters that cannot be controlled, shows that development of real time control is important to reach the target $q$ profile. On the positive side, this paper also shows that the effect of a deviation of the assumed plasma parameters, like $Z_{\text{eff}}$ or peaking of $n_e$, can be accounted for in a straightforward way, i.e. in a way suitable for a controller.

The effect of breakdown on the HFS instead of on the LFS, as considered by the ITER team, will be considered in future sensitivity studies. Also the effect of faster $I_p$ ramp will be the subject of further study.

References


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