Optimizing the Current Ramp-Up Phase for Hybrid ITER Scenario*)

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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.

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1. Introduction

The current ramp-up phase of ITER is a critical stage: 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 is more critical than for the standard (H-mode) scenario, since the q profile must be shaped carefully: $q_{\min}$ 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 [1]. This paper reports on a systematic effort within the ITER Scenarios Modelling working group (ISM), part of the European Integrated Tokamak Modelling (ITM) Task Force, 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 [2, 3] has shown that both empirical scaling based models and the semi-empirical Bohm/gyro-Bohm model (L-mode version, ITB shear function off, [4]) yield a good reproduction of this phase for considered discharges, in terms of T_e and q profile and l_i. Therefore these two models have been used in the reported work, which was carried out with the CRONOS integrated suite of codes [5].

For the scaling based model a fixed radial shape of the heat diffusion $\chi_{e,i}(\rho, t) = A(t)(1 + 6\rho^2 + 80\rho^{20})$ is used, where $A(t)$ is adjusted at each call of the model such that the plasma thermal energy content W_{th} follows a known scaling expression, e.g. the ITER-97L (L-mode) scaling [6] or the IPB98 (H-mode) scaling [7]. Since confinement during the ramp-up phase is weaker than standard L-mode, a scaling factor smaller than 1 was needed in both cases: the optimal (and similar) agreement between experiment and simulations in the current ramp-up dataset was obtained using $L_{ITER97L} = 0.6$ and $H_{IPB98} = 0.4$, respectively. Here we will use the IPB98 scaling with $H_{IPB98} = 0.4$.

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2. Assumptions Made

Following assumptions were adopted from the ITER team:

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

(ii) A flat Z_{eff} profile is assumed, decreasing in time with increasing density, with an asymptotic value of 1.7 [8].

(iii) A rather low density of $n_e = 0.25 \cdot n_e^{Gw}$ 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 ≃ 1.5 predicted by scaling studies [9].

The total input power should stay below the L-H threshold during the whole ramp-up phase; for the reference case $P_{LHthr} \simeq 29$ MW at end of the current ramp-up. Other assumptions ($T_{e,i}$(edge), initial $T_{e,i}$ and l_i) are based on experimental evidence from e.g. JET, AUG and Tore Supra [2, 3].

The I_p ramp rate is chosen such that $I_p = 12$ MA is reached after 80 s. 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, ECRH from the equatorial launcher deposits very centrally, so is unsuitable for this purpose; ICRF can, due to its wide range of frequencies, deposit on- and off-axis; however, ICRF can only efficiently drive current when deposited on-axis [10], so is also not very useful for this purpose. The remaining heating and CD options are: NBI using the off-axis setting, i.e. with deposition radius $\rho_{dep} \sim 0.3$, LHCD (with $\rho_{dep} \sim 0.4-0.6$ depending on plasma conditions) and the Upper Port Launcher (UPL) of ECCD. The latter has 2 antennas with different ranges of poloidal angles, with $\rho_{dep} \geq 0.4$ and 0.6, respectively. 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 of this.

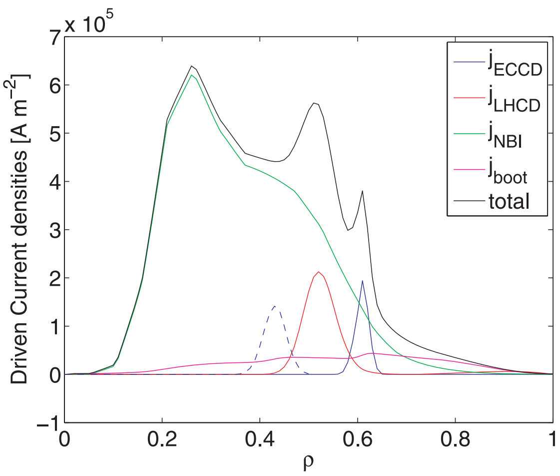

Fig. 1 Driven current density profiles, plotted vs. normalized toroidal flux coordinate ρ for the reference case at 80 s. A balanced mix of sources is used: 8 MW of ECCD from one of the UPL antennas (blue), 3 MW of LHCD (red) and 16.5 MW of NBI (green). Also shown is the bootstrap current density (magenta) and the total non-inductive driven current density (black). If the total input power were allowed to exceed P_{LHthr}, some power from the other UPL ECCD antenna could be added for an even more smooth total driven current density profile; the blue dashed line shows the driven current density for extra 5 MW of ECCD.

4. Reference Case

Figure 2 shows the optimized scenario, as sketched in the previous section, for the reference case using the scaling model (full lines). 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. As seen from Fig. 3 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. Figure 4 shows the currents in the most critical coils.

Since the LHCD system is not foreseen in the ITER baseline, is is important to assess the importance of LHCD for the results. Although LHCD can strongly modify the q profile in the early phase of the ramp-up, its effect on the q profile at the end of the ramp-up is rather modest, i.e. a scenario with LHCD replaced by extra ECCD yields a q profile which is only slightly less flat. However, it

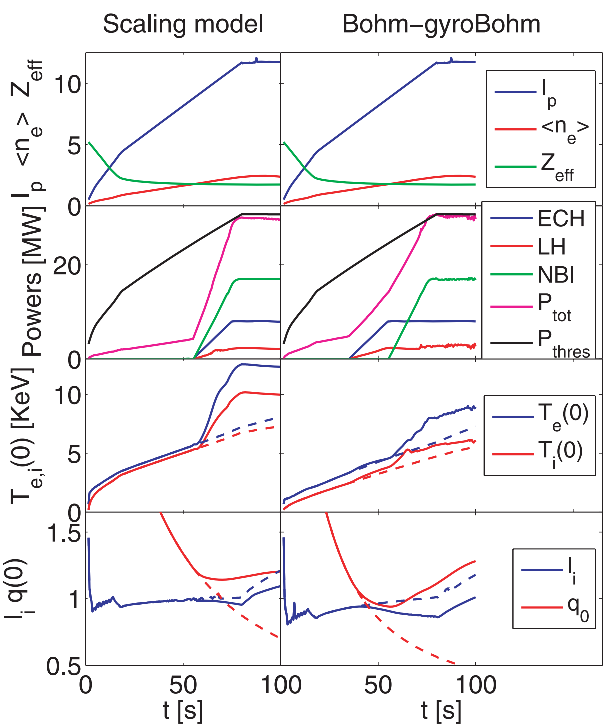

Fig. 2 Time traces of the optimized scenario for the reference case, assuming scaling model (left panels) or Bohm/gyro-Bohm model (right panels). For comparison the figure also shows the time traces of $T_{e,i}(0)$, l_i and $q(0)$ without any additional heating (dashed lines).

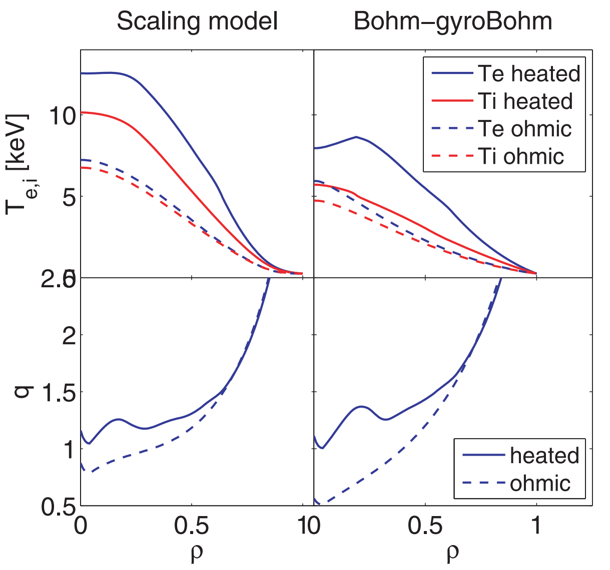

Fig. 3 $T_{e,i}$ and q profiles for the same cases and with the same line coding as the previous figure.

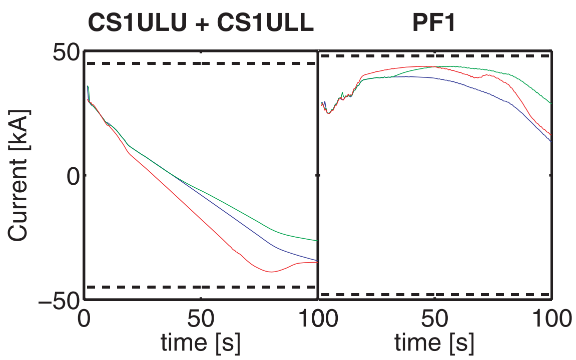

Fig. 4 Some of the coil currents as calculated by FREEBIE. Shown are the currents in the two most critical coils: the central solenoid coils CS1ULU+CS1ULL, and the poloidal field coil PF1, for a typical heating scheme (full red lines) and for a case with only ohmic heating (dashed red lines). The maximum and minimum allowed currents are plotted in black.

should be noted that LHCD is the most effective current drive source. Hence LHCD can play a strong role in reducing the flux consumption during the ramp-up phase; a reduction of ∼15 % can be reached, which would be sufficient to extend the flat top phase by hundreds of seconds.

5. Sensitivity Analysis

Of course the optimized scheme is dependent on the chosen transport model. The Bohm/gyro-Bohm model predicts ∼ 30 % 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 (Fig. 2, dashed lines). As seen from Fig. 3 also in this case a good hybrid q profile is reached at the end of the ramp-up.

Regarding sensitivity of the results to the assumptions,

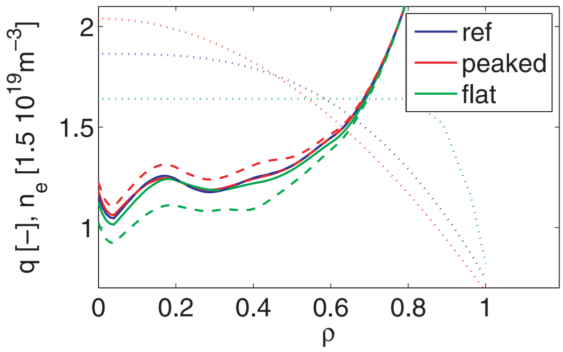

Fig. 5 Effect of flat or extra peaked n_e profile. Plotted are n_e and q profiles at 80 s for the 3 cases (see legend), without (dashed lines) and with adapted heating scheme (full lines).

following parameters were varied: $T_{e,i}$(edge) (by 40 %), n_e (by 40 %), n_e profile shape (parabolic vs. flat) and Z_{eff}. We will consider only the scaling model ($H_{IPB98} = 0.4$) here; the sensitivity of the simulations to these changes when using the Bohm/gyro-Bohm 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 ($\simeq$ 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 ∼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. 5.

(iii) Z_{eff}: A 40 % higher/lower value of Z_{eff} causes a faster/slower current diffusion, and a shift of $t(q_0 = 1)$ of ∼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_{LHthr} is higher by $\simeq$ 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, together with the time traces of l_i and $q(0)$, is shown in Fig. 6. In this way the the flat q profile is restored, see Fig. 7.

Recently the ITER team is considering breakdown at HFS instead of at LFS. The different geometry in the very early phase of the discharge leads to a modified current diffusion. However, the effect on the current density evolution turns out to be negligible after ∼ 40 s, see Fig. 8.

6. Extrapolation to Burn Phase

Since the final goal is to sustain the optimized q profile during the ∼1000 s flat top, two more questions are impor-

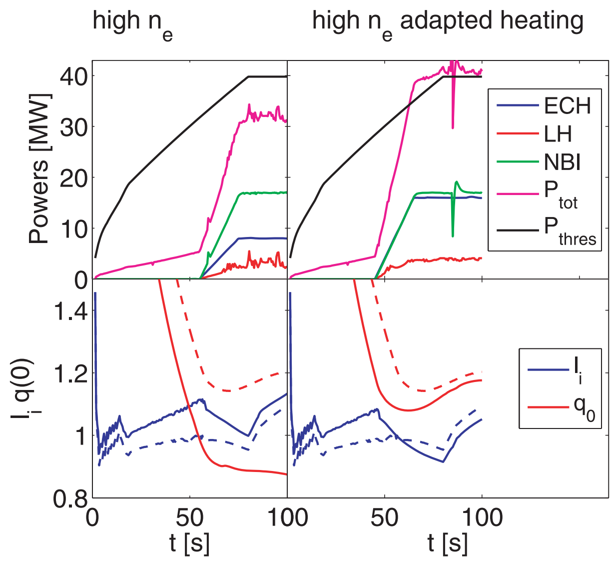

Fig. 6 Time traces of powers, $q(0)$ and l_i for the high n_e case with the heating scheme of the reference scenario (left) and with adapted heating scheme (right). For comparison the lower panels also show the time traces of $q(0)$ and l_i of the reference scenario (dashed lines). Without modified heating scheme, $q(0)$ drops far below 1 and l_i rises too high (i.e. above 1); these unwanted features are avoided with the adapted heating scheme.

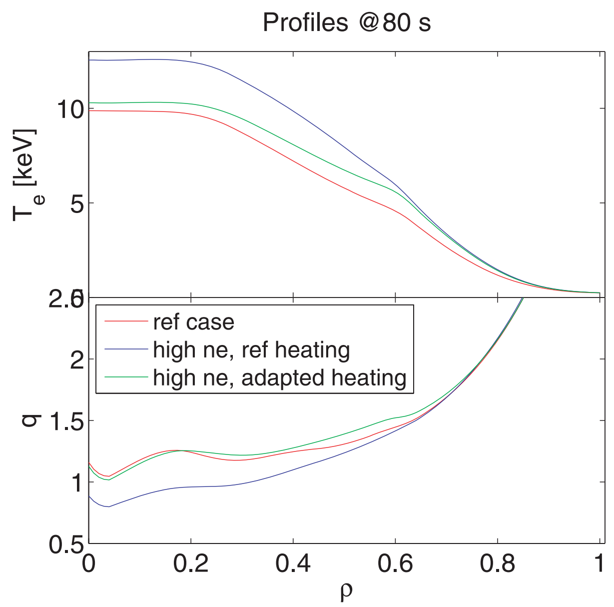

Fig. 7 Profiles of T_e and q at 80 s for the same cases as Fig.6.

tant: how does the q profile react to the L-H transition, and can q be held stationary during the long flat top.

Regarding the first question: based on the reference case, preliminary simulations were done to assess the evolution of the q profile during the L-H transition. To this end, in a time window of 20 s immediately after the end of the current ramp-up, the external (NBI + ECRH) power was raised to 70 MW, i.e. clearly above the L-H threshold, and in the modelling the L-H transition was forced by imposing a pedestal of 4 keV. At the same time the density was raised to the target density for the hybrid scenario ($\sim 9 \cdot 10^{19}$ m^{-3}). It turned out that during this transition the q profile was preserved very well.

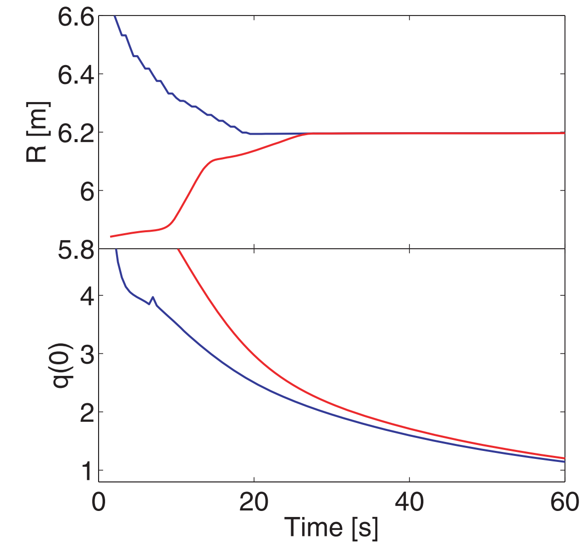

Fig. 8 Time traces of R_0 and $q(0)$ for the normal breakdown at LFS (blue) and for alternative breakdown at HFS (red).

The second question has already been addressed in earlier work, which showed that, under reasonable assumptions for the pedestal, indeed the q be held stationary during the long flat top [1].

7. 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 only slightly less effective the target q profile; however, LHCD can play a crucial role in reducing the flux consumption during the ramp-up phase.

The optimum heating scheme depends on the chosen transport model. Moreover, modified assumptions on n_e peaking, edge $T_{e,i}$ and Z_{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_{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 faster I_p ramp will be the subject of further study.

Acknowledgements

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