35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-5.034 (2008)

Simulation of the current ramp-up phase of ITER discharges

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1. Introduction. Routine operation of ITER requires a robust current ramp-up phase. Within the narrow operational window of ITER the plasma has to be built up, preferably at low cost in terms of flux consumption, such that at the end of the current ramp-up the temperature (T_i, T_e), density (n_e) and current density (j) profiles have the right shape to run the wanted scenario (H-mode, hybrid mode, etc.). To perform a systematic modelling of this early phase of ITER discharges, a dedicated effort was set up within the ITER Scenarios Modelling working group. This group was formed last year as part of the EU Integrated Tokamak Modelling (ITM) Task Force, which has as long term aim to provide a European suite of software tools for ITER exploitation.

The primary question to be resolved is: what are the most important actuators during the current rise phase (plasma shape, density, heating and current drive profile, etc.), and how can one achieve the profiles of q, T_e, T_i, etc. that are needed to enter the various ITER scenarios.

This paper discusses choices that have been made for the simulations (Sec.2), comparison of the transport codes in use (Sec.3) and calibration of the empirical transport model used so far (Sec.4). Then first results of the simulations are reported (Sec.5), followed by an outlook of future work (Sec.6).

2. Choices Based on results from existing experiments [1] and on ITER reference scenarios, following choices were made for the ITER current rise simulations.:

- For the first results, reported here, the ITER divertor shape is assumed from the start of the simulations. However, recently also simulations with a time-varying plasma shape, i.e. starting from a much smaller plasma volume and interpolating between a given time series of fixed boundary snapshots, were initiated.
- Three groups of simulations have been carried out, using respectively $n_\mathrm{e}/n_\mathrm{e}^\mathrm{Gw} = 0.15, 0.25$ and 0.4. The n_e profile is assumed flat.
- The ITER reference current ramp-up scheme is followed with ramp rate decreasing from 0.35 to 0.1 MA/s during the I_p ramp-up phase; this is not the fastest ramp possible, to limit edge MHD and to give time for the non-inductive actuators to shape the q profile. The current flat-top ($I_\mathrm{p} = 15$ MA) is reached after 100 s.
- A variation of heating schemes is tested: Ohmic, off-axis ECRH/ECCD, LHCD, NBI; the results presented here only use Ohmic and off-axis ECRH.
- For the time being an empirical L-mode heat transport model is used; its calibration against JET start-up plasmas is reported in Sec.3. Later on the usage of theory based transport models is foreseen.
- Carbon is the only impurity and Z_eff follows the empirical prescription $Z_\mathrm{eff} = 1.7 + 2.3(0.5/\langle n_\mathrm{e}\rangle)^{2.6}$.

Initial and edge conditions are based on experimental evidence from existing devices. The break down phase is not treated here; simulations start at 8 s when $I_p = 3$ MA. Current diffusion and heat transport are solved, the other quantities are prescribed.

3. Comparison of Transport Codes The three main transport codes currently in use in Europe (JETTO [2], ASTRA [3], and CRONOS [4]) have been compared under different conditions. Figures 1 and 2 summarize this comparison for a reference case: $n_e/n_e^{Gw} = 0.25$, no additional heating, fixed plasma shape. Various time traces are plotted in Fig.1; the profiles of q, T_e and T_i at various time slices are plotted in Fig.2.

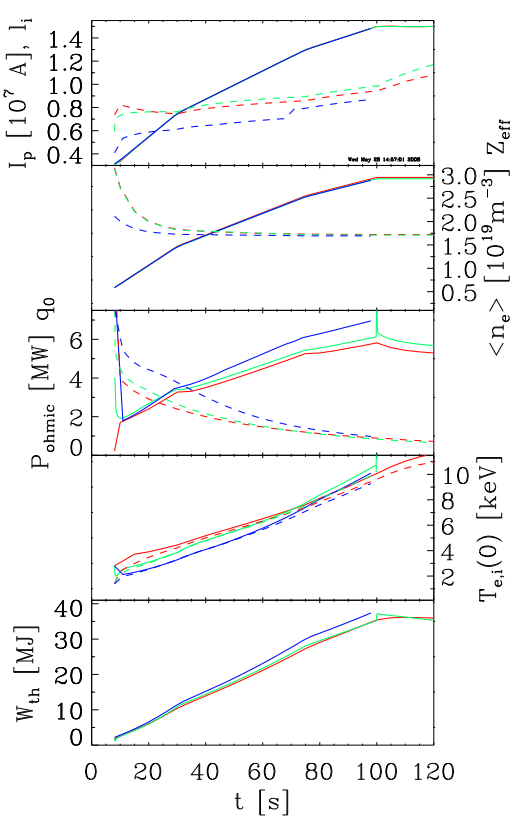

Figure 1: *Comparison of CRONOS (red), JETTO (green) and ASTRA (blue) simulation of standard ITER ramp-up without addition heating. Time traces of global quantities: I_p and l_i (first panel, full/dashed lines); line averaged density and Z_{eff} (second panel, full/dashed); ohmic power and $q(0)$ (3rd panel, full/dashed); $T_e(0)$ and $T_i(0)$ (4th panel, full/dashed) and W_{th} (5th panel).*

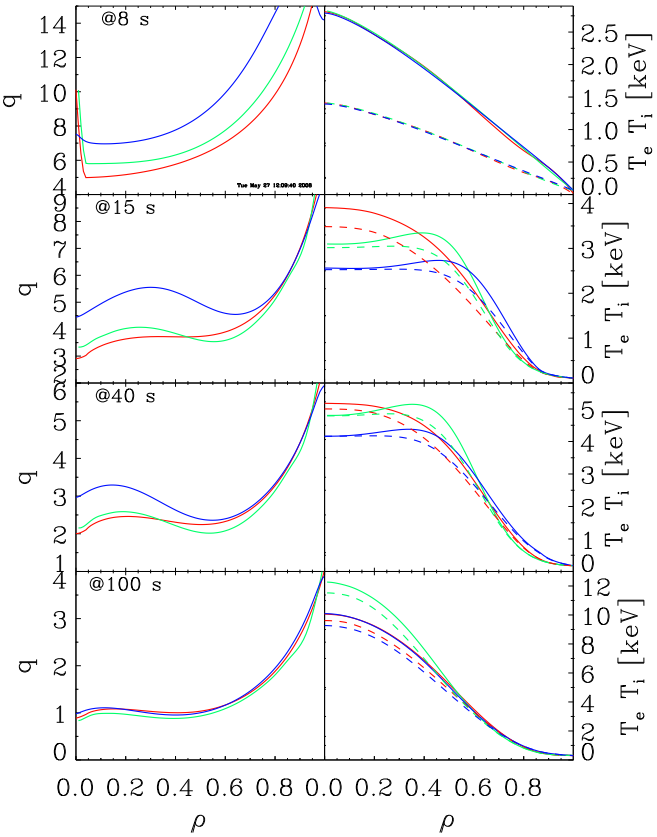

Figure 2: *Profiles of q (left) and T_e (right, full lines) and T_i (right, dashed lines) for the same simulations and with the same colour coding as in Fig.1. The profiles are shown at 8 s (start of the simulations), 15 , 40 and 100 s (end of ramp-up phase).*

Regarding global parameters (Fig.1) there is excellent agreement between JETTO and CRONOS, whereas ASTRA deviates somewhat. The initial q profiles deviate strongly due to a different implementation of the initial plasma parameters; this disagreeable point is currently under investigation. The profiles deviate significantly during the first phase of the current rise; these differences tend to relax towards the end of the current rise phase at 100 s. Therefore we will not address them further here, and we will use both JETTO and CRONOS modelling results in the rest of the paper.

4. Transport calibration In the modelling an empirical formula is used for the heat

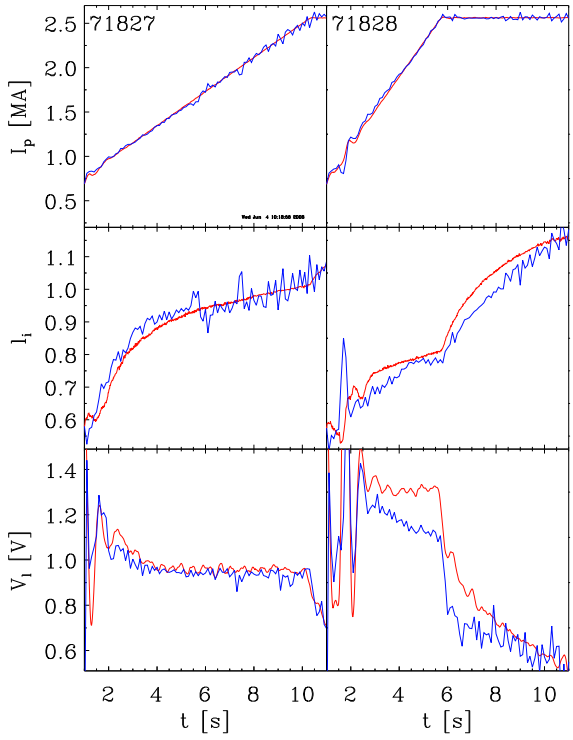

Figure 3: *Comparison of predictive CRONOS simulation of I_p ramp-up phase (blue) of two JET discharges (see text) with experimental data (red). From top to bottom the panels show time traces of I_p, l_i and V_{loop} for JET pulses 71827 (left) and 71828 (right).*

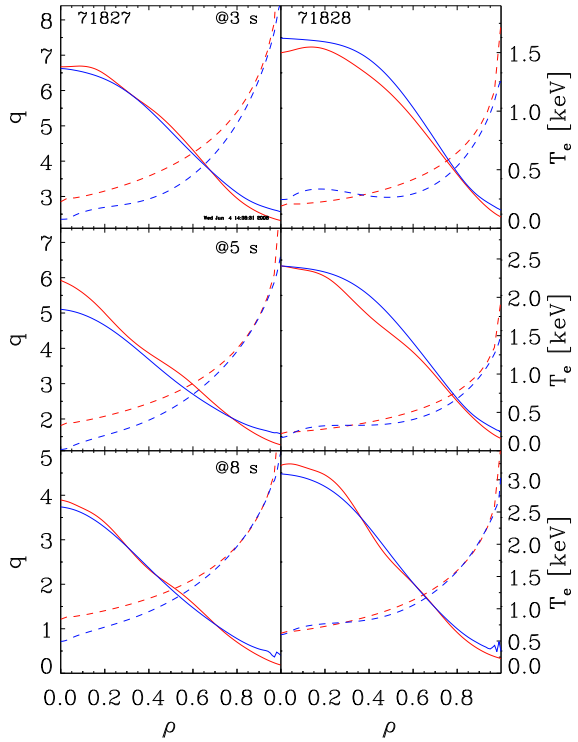

Figure 4: *This plot shows profiles for the same comparison as in Fig.3, and with the same colour coding. Shown are profiles of q (dashed lines) and T_e (full lines) 2, 5 and 8 s after break-down. Experimental data are from the EFIT equilibrium reconstruction (q) and ECE (T_e).*

transport: $\chi_e(\rho) = \chi_i(\rho) = f * (1 + 6\rho^2 + 80\rho^{20})$. where f is dynamically adapted during the run such that the energy content of the plasma (W_{th}) satisfies $W_{th} = H\tau_E^{98}(P_{loss} - dW_{th}/dt)$ where $H = 0.5$ and τ_E^{98} is given by the ITER-H98(y,2) H-mode scaling [5]. This formula has been calibrated against ohmic JET pulses with ITER-like I_p ramp-up phase. Figures 3 and 4 show the results of this calibration for two JET pulses with different I_p ramp rate. Both the current penetration (l_i time trace) and the heat transport (T_e profiles) are very well reproduced by this model.

5. ITER simulations Two important questions to be addressed are: *(i)* How much heating power and current drive is needed and where should it be deposited in order to keep l_i below 1 (required by the available flux of the transformer), and to reach the target q profiles for the various scenarios? *(ii)* How can one minimize the flux consumption?

All three transport codes have been used; here only results from CRONOS will be shown. In Figures 5 and 6 we present the results of two scans: *(a)* an ECH power scan from 0 till 20 MW; the power is assumed to be localized at mid-radius with a narrow Gaussian deposition profile without current drive; *(b)* a n_e scan from 0.15 till $0.4n_G$;

Regarding *(i)*: It is seen that the q profile at the start of the flat-top is flat with Ohmic heating, and is hollow with 10 MW of off-axis ECH; moreover, off-axis heating is crucial to keep l_i below 1. Note that the heat transport model used in the simulations has been tested against ohmic experiments only. Being non-stiff, it may amplify the effect of strongly localized heating methods like ECRH.

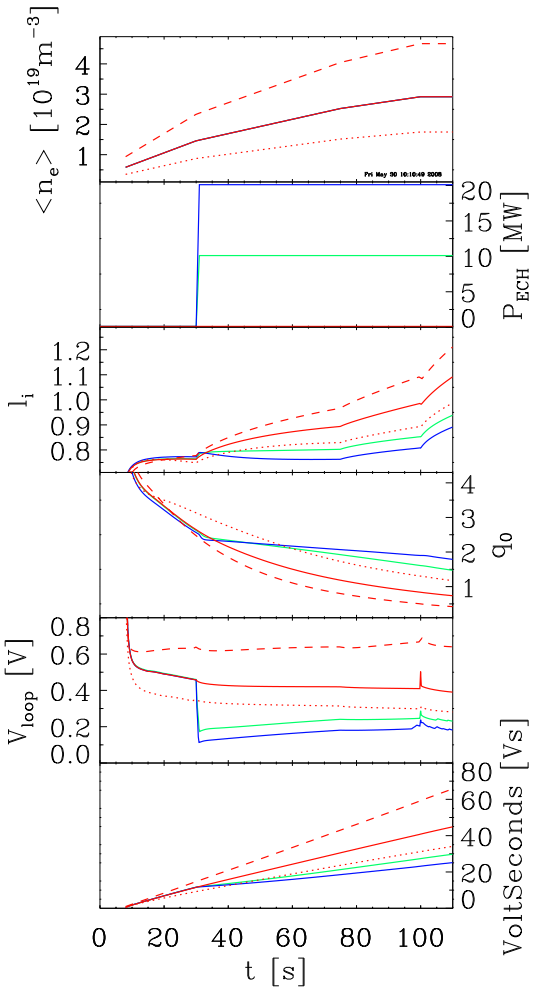

Figure 5: *Effect of varying input power and density during ITER I_p ramp-up. The reference simulation (full red lines) has $\langle n_e \rangle = 0.25 * n_G$, without additional input power. Shown are simulations: (a) with 10 and 20 MW of ECRH power at mid-radius starting at 30 s, at the same density (green and blue, respectively); with $\langle n_e \rangle = 0.15$ and $0.4 * n_G$ without additional input power (dashed, dotted red lines, respectively). The panels from top to bottom give $\langle n_e \rangle$, P_{ecrh}, l_i, $q(0)$, V_{loop} and the flux consumption.*

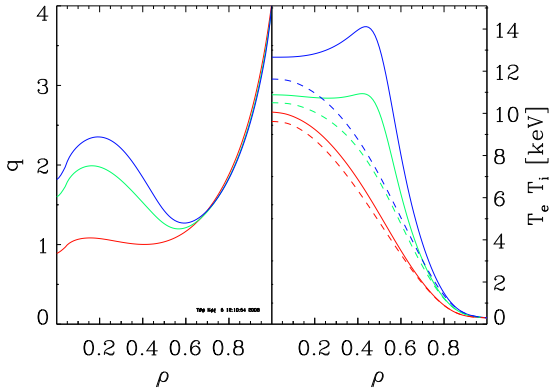

Figure 6: *Final profiles of q (left) and T_e, T_i (right, full/dashed lines) after 100 s for the power scan of Figure 5, with the same colour coding as in Fig.5.*

Regarding *(ii)*: Both lowering the density and applying additional heating lead to a flux saving of 10-20 Wb, which is significant; with a typical loop voltage during the I_p flat-top phase of 0.05 V this would imply an enhancement of this phase by 200-400 s.

6. Discussion and Outlook The ITER start-up modelling effort so far has already yielded some important results, in particular regarding the necessity of off-axis heating already early during the ramp-up phase.

In the near future, in order to be more realistic, these simulations will be repeated starting earlier in the I_p ramp-up phase and addressing the variation of the plasma boundary during the ramp. Moreover, first principle based transport models will be exploited. Finally, other heating and current drive schemes will be used, with more realistic parameters regarding power deposition and current drive profile.

References

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Acknowledgements. This work, supported by the European Communities under the contract of Association between EURATOM/FOM, was carried out within the framework of the European Fusion Programme with financial support from NWO. The views and opinions expressed herein do not necessarily reflect those of the European Commission.