Current ramp-up in tokamaks: from present experiments to ITER scenarios

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1. Introduction. In order to prepare adequate current ramp-up and ramp-down scenarios for ITER, present experiments from several tokamaks have been analyzed by means of integrated modelling with the aim of determining relevant heat transport models for these operation phases. The results have implications on PF systems, H&CD methods for current profile shaping, and expected flux consumption in ITER.

The main issue is the choice of the heat transport model. Various heat transport models have been tested by means of integrated modelling against experimental data from ASDEX Upgrade, JET and Tore Supra, including both Ohmic plasmas and discharges with additional heating/current drive (NBI, LHCD, ICRH). Validation criteria are the 0D-parameters the plasma internal inductance (l_i) and loop voltage (V_loop), and the 1D-parameters T_e and q. Only energy transport and current diffusion are modelled; density and Z_eff are taken from experiment. Only L mode plasmas are considered. In the first part of this paper the main results of these studies are presented.

In the second part of the paper projections to ITER current ramp-up scenarios are shown, focusing on the baseline inductive scenario (main heating plateau current of I_p = 15 MA).

2. Transport codes and transport models JETTO, CRONOS and ASTRA have been used. It was checked that for the same model, results are independent of the transport code used; therefore the codes are not distinguished in the following.

The l_i prediction and flux consumption are strongly dependent on the T_e prediction in the outer half of the plasma; hence the challenge is to predict T_e up to $\rho = 1$ in L-mode. Models that fail inside $\rho = 0.5$ may still be acceptable for predicting l_i and V_loop.

A variety of transport models was used: *(i)* scaling-based model with a prescribed radial shape of $\chi_\mathrm{e} = \chi_\mathrm{i}$, renormalized to H-mode scaling of global energy content $H_{\mathrm{IPB98(y,2)}} = 0.4$; *(ii)* same, with L-mode scaling $H_{\mathrm{L97}} = 0.6$; *(iii)* the semi-empirical Bohm/gyro-Bohm model [1] (L-mode version, ITB shear function off); *(iv)* the semi-empirical Coppi-Tang model [2]; *(v)* GLF23 [3], either up to $\rho = 1$, or up to $\rho = 0.8$ with large $\chi_\mathrm{edge} = 8$ m^2/s. Regarding the Coppi-Tang model it must be noted that there are ongoing discussions with US colleagues about the definition of the model; therefore results of this model will not be shown here. The effect of sawteeth was not taken into account in the simulations.

* *See the Appendix of F. Romanelli et al., Proceedings of the 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland*

3. Modelling of existing machines Initial conditions, boundary T_e, and n_e profile are taken from experiment. Flat Z_{eff} is assumed, $\langle Z_{eff}\rangle$ taken from experiment (Bremsstrahlung). Toroidal rotation is not taken into account; as no NBI was used in most cases, rotation is low, so no $E \times B$ shear reduction of transport is expected. The prescribed plasma boundary is taken from experiment (EFIT). This paper limits itself to two JET pulses (one slow ohmic ramp, one fast ramp with LHCD), and one Tore Supra pulse with ECCD.

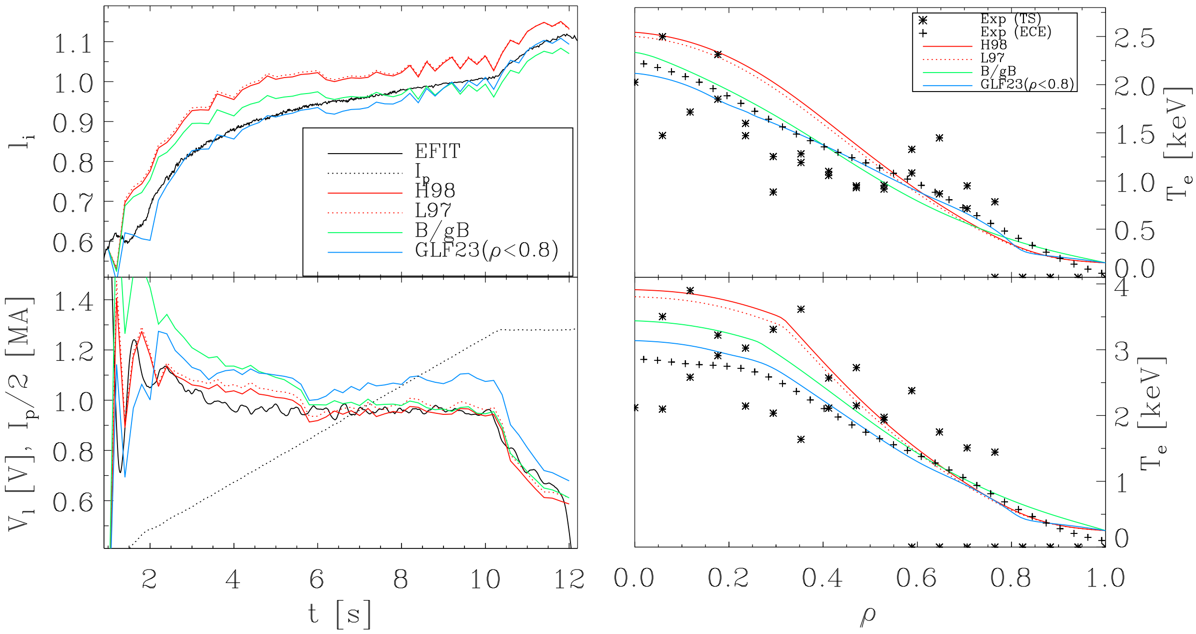

Figure 1: *Ohmic I_p ramp-up phase of JET pulse 71827. Shown are time traces of l_i and V_{loop} (left), and profiles of T_e at 5 and 11 s (halfway and at the end of the I_p ramp-up, right), as calculated by 5 transport models (see legend). For comparison, also experimental data are plotted.*

The modeling of the ohmic JET discharge 71827 is summarized in Fig.1. All models reproduced l_i within 0.1. The B/gB and GLF23 models are most accurate in T_e and l_i; the scaling-based models tend to overestimate T_e in the core; At the end of the ramp-up all models slightly overestimate T_e inside mid-radius, with little impact on l_i.

In the second JET pulse 2 MW of LHCD was applied during the ramp-up phase; moreover NBI blips allowed some q (MSE) and T_i (CXS) measurements. The modeling results are summarized in Fig.2. For this pulse the results of GLF23 both with and without patch at the edge are shown; without patch a large error in l_i is predicted. For the other models again l_i is reproduced within 0.1, apart from the first 0.5 s where too much LH current is predicted. B/gB is the most accurate on l_i, whereas the scaling-based models are better on T_e. Scaling-based on one hand, B/gB and GLF23 on the other, seem to provide a sort of envelope to the experimental data.

Finally, modelling results of Tore Supra pulse 40676, which had Co-ECCD at $\rho = 0.3$ during the I_p ramp, are shown in Fig.3. Again l_i is reproduced within 0.1. GLF23 gives, in spite of a poor reproduction of T_e, an excellent prediction of l_i.

4. ITER projections Projections to the ITER current ramp-up phase were carried out with all models, both ohmic and with up to 20 MW of ECRH at mid-radius from early in the ramp; however, in this paper we only show results of one scaling model (the other one gives practically identical results) and of B/gB for the ohmic case. The ITER inductive scenario was assumed, where I_p is ramped-up to its final value of 15 MA in 100

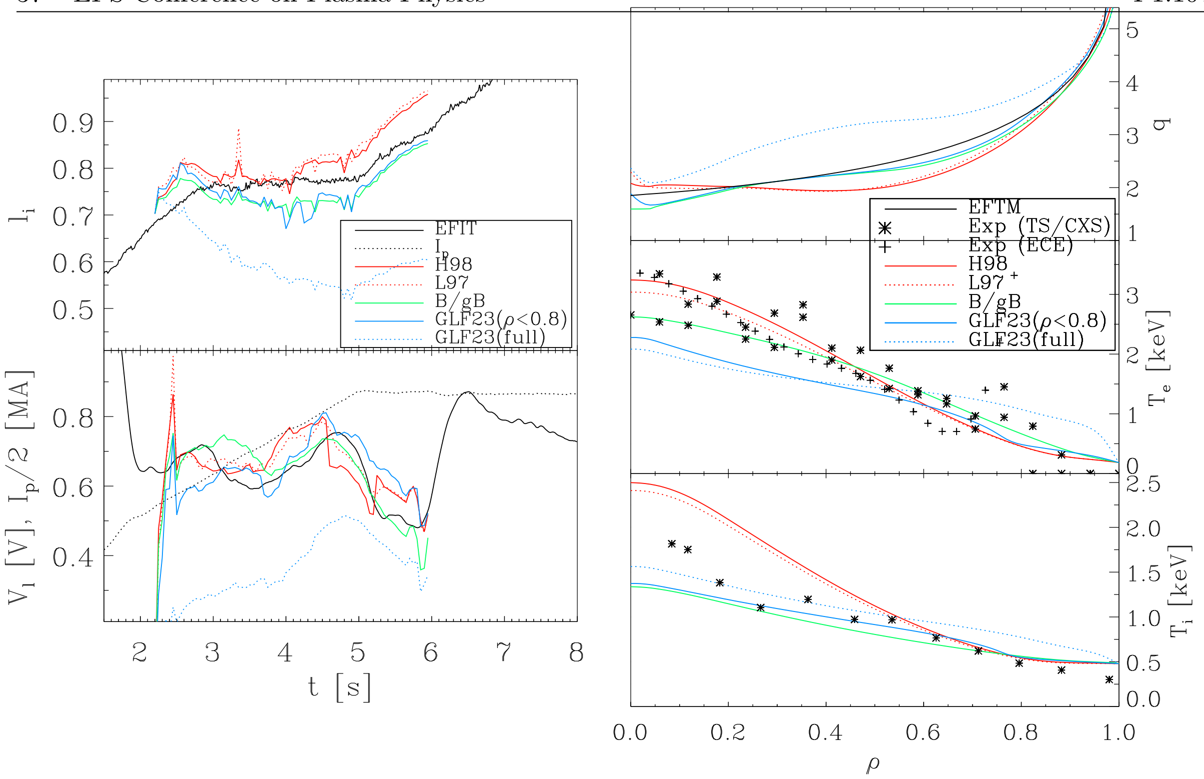

Figure 2: *Ramp-up phase of JET pulse 72823; 2 MW of LHCD was applied after 2 s. Shown are time traces of* l_i *and* V_{loop} *(left), and profiles of* T_e*,* T_i *and q at 5 s (end of ramp-up), as calculated by*

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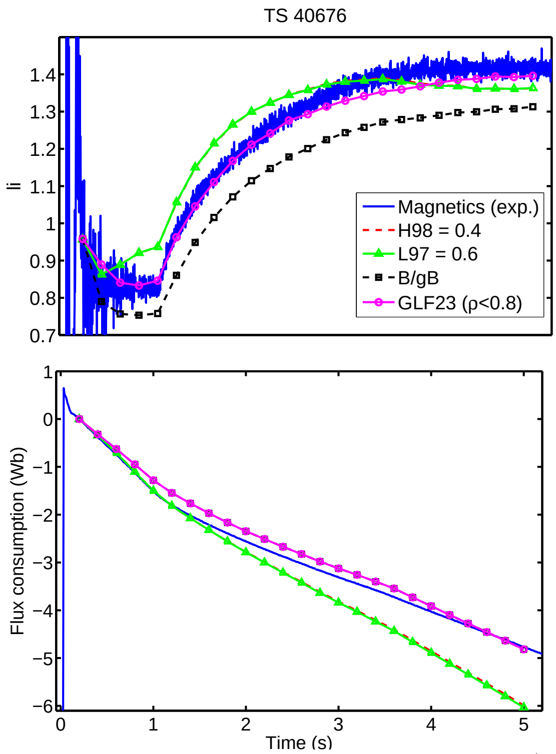

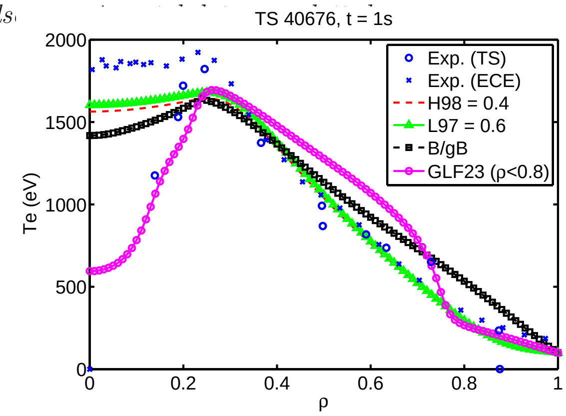

Figure 3: *Ramp-up phase of TS pulse 40676; 0.6 MW of ECCD (deposition at* $\rho = 0.3$*) was applied from 0.5 till 3.5 s. Shown are time traces of* l_i *and* V_{loop} *(left), and profiles of* T_e*, at 5 s (halfway the* I_p *ramp-up), as calculated by 5 transport models (see legend). For comparison, also experimental data are plotted.*

s. The density goes with I_p such that $\langle n_e \rangle = 0.25 n_G$. The standard ITER assumption of a flat density profile up to $\rho = 0.9$ is not very realistic; therefore here a moderately peaked density profile is assumed, as in [5]. The plasma boundary is prescribed. The simulations start at 1.5 s, with $I_p = 0.5$ MA and a small plasma volume. No sawtooth correction model was used in the simulations.

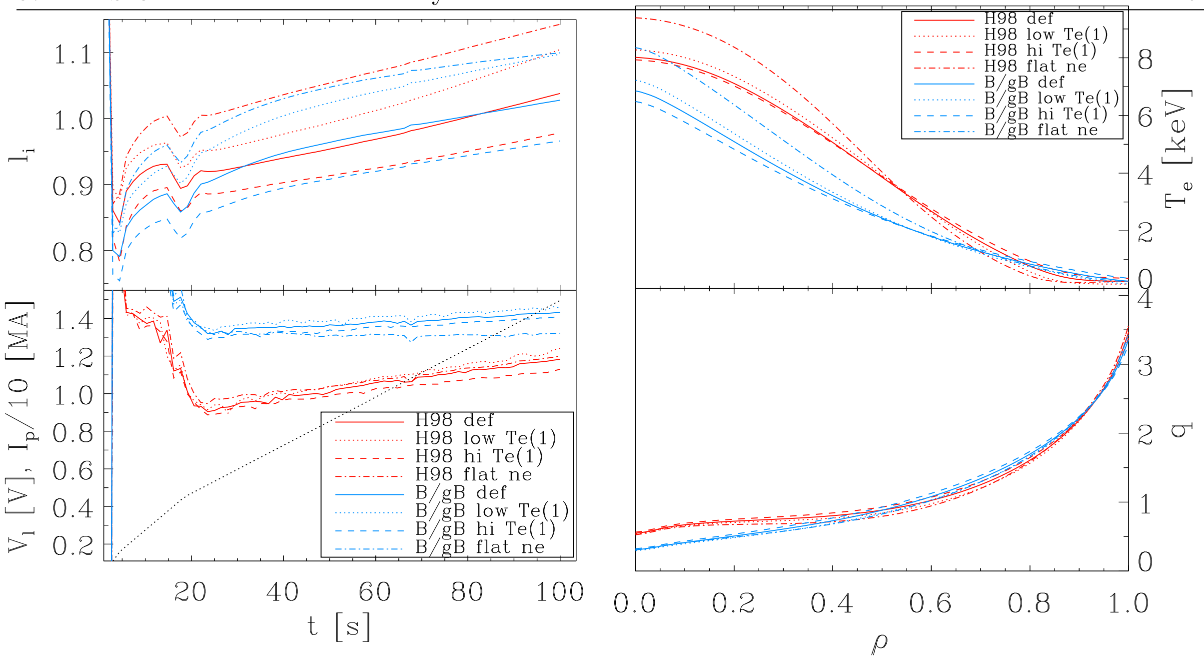

Figure 4: *Ohmic ramp-up phase of ITER. Shown are time traces of* l_i *and* V_{loop} *(left), and profiles of* T_e*, at 100 s (end of the* I_p *ramp-up), as calculated by 2 transport models, under different assumptions regarding* T_e*(edge) and* n_e *profile shape (see legend).*

A sensitivity analysis has been carried out on (a) the boundary T_e, assuming it to be 40% lower or higher than the default value which goes linearly up from 50 to 250 eV during the ramp-up; (b) density profile peaking, by assuming the ITER prescribed flat profile in stead of the moderately peaked one of [5], still with $\langle n_e \rangle = 0.25 n_G$.

Results are summarized in Fig.4. The ordering of models in T_e prediction is the same as on the JET experiments, i.e. the scaling-based model is slightly more optimistic, which also is reflected in a lower V_{loop}. The l_i prediction is remarkably similar for both models. However, l_i is modified significantly (± 0.1 for the parameter scans presented here). Differences in target q profile are small.

5. Conclusions A selection of 4 models has been made, matching present JET and TS current ramp-up experiments in terms of l_i dynamics (within 0.1) for various heating schemes. The same degree of agreement was found for a few other discharges from TS and AUG (not shown here). All models except GLF23 are (semi-)empirical. GLF23 needed a patch recipe outside $\rho = 0.8$. The same models were applied to ITER current ramp-up (ohmic, ECRH). The behavior of models and discrepancies between them are similar as when applied to JET cases. More details, in particular on the sensitivity analysis, will be given in [4].

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