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# Simulations of ITER Plasma Limiter Start-Up Conditions

O. Zolotukhin[1], G. Federici[1], A. Tanga[1], A. Loarte[2], L. Horton[3],
A. Portone[2], Y. Gribov[4], A. Polevoi[4], M. Shimada[4]
[1] *ITER Garching JWS, Boltzmannstraße 2, 85748 Garching, Germany*
[2] *EFDA-CSU Garching, Boltzmannstr. 2, D-85748 Garching, Germany*
[3] *Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, 85748 Garching, Germany*
[4] *ITER JWS Naka Co-centre, 801-1 Mukouyama,Naka-machi,Naka-gun,Ibaraki-ken,Japan*

**1. Introduction.** Analysis of the current ramp-up phase of plasma discharges in ITER is an important part of the design. Among other things, good accuracy is required to determine the fraction of power flowing to the plasma boundary and intercepted by the start-up limiter(s), and the resulting heat flux distribution, throughout the limiter phase of the discharge, for all anticipated limiter start-up scenarios.

This paper summarizes the results of a recent modeling effort conducted with the plasma transport code ASTRA to simulate typical limiter start-up sequences proposed for ITER.

**2. Transport model.** This study was conducted by using the plasma transport code ASTRA [1] which is a 1.5-dimensional time dependent simulation code that comprises of a system of 1-D diffusion equations for densities and temperatures of ions and electrons, a 2-D equilibrium equation, and, a variety of other modules to describe additional heating, current drive and other non-diffusive processes in tokamak plasmas.

The heat transport of electrons and ions is evaluated assuming that the properties of the plasma confinement during the current ramp-up are close to those during the steady state ohmic discharges. Several calibration runs were performed by using either one of the Ohmic $\tau_{E,Ohmic} = 0.14 \cdot B_{tor,[T]}^{1.1} \cdot R_{[m]} \cdot a_{[m]} \cdot k_x \cdot n_e / n_G \Big/ \left(1 + 0.63 \cdot B_{tor} k_x^2 (n_e/n_G)^2\right)$ or L-mode $\tau_{E,L89} = 0.048 \cdot I_{p,[MA]}^{0.85} \cdot R_{[m]}^{1.2} \cdot a_{[m]}^{0.3} \cdot k_x^{0.5} \cdot \overline{n}_{[10^{20} m^{-3}]}^{0.1} \cdot B_{[T]}^{0.2} \cdot A_i^{0.5} \cdot P_{[MW]}^{-0.5}$ energy confinement scalings [2] or a combination of them according to the formulation recommended by Shimomura-Odajima [3] in cases with additional heating. In these models, the electron heat flux and the ion heat flux depend only on their own respective temperature gradients. The values of the heat conductivities have been derived from the knowledge of the plasma cross section. The ion transport is assumed to be purely neoclassical.

The particle transport is governed by the Ware pinch and by a diffusion coefficient proportional to the ion and electron heat transport coefficients with $D = 0.2 \cdot (\chi_e + \chi_i)$. For simulation of ITER ramp-up, gas puffing was adjusted to keep a volume-averaged electron density at the level a Greenwald limit fraction $\langle n_e \rangle / n_G$ .

It is supposed that the main ions are deuterium and tritium ions ($n_D = n_T$) and the impurity concentration (in our case, ions of beryllium and carbon) is proportional to the plasma density, i.e., the fraction of impurity species *k* in the plasma, $f_k = n_k / n_e$ was assumed to be a constant. For the calculations discussed here, the concentration of impurities has been fitted to provide the experimentally measured effective charge $Z_{eff}$ in the range 2-3.The radiated power profile is calculated in a coronal approximation. The effect of the finite residence time of impurities on the radiation in the plasma, which enhances radiation compared to the corona model, was taken in account by using of a normalization factor to provide the global value in agreement with the empirical scaling described in Refs. [4,5], which gives a reasonable match (within a factor of 2.5) of the experimental results of JET and ASDEX Upgrade. The total radiation losses are described in the form $P_{rad} = C_{noncor} \cdot P_{rad,\exp} \cdot P_{rad}^{corona} / \langle P_{rad}^{corona} \rangle + P_{bremss} + P_{synchr}$, where parameter $C_{noncor}$ variation from $C_{noncor}$ = 2.5 for low densities n ~ $10^{19}$ m$^{-3}$ to $C_{noncor}$ = 1 for moderate densities n ~ 2.5 $10^{19}$ m$^{-3}$ is required to fit the experimental data $P_{rad,exp}$ by experimental scaling dependence $P_{rad,\exp} = 10^{-3} \cdot A_{pl} \cdot \bar{n}_e^2 \cdot (Z_{eff} - 1)$. Here $A_{pl}$ is plasma surface area in m$^2$, $\bar{n}_e$ is line-averaged electron density in $10^{19}$m$^{-3}$. As one can see a range of uncertainty in the applied model is determined by the numerical coefficient 1-2.5 (Figure 2).

**3. A validation of the model against experimental data.** The model has been first calibrated against two well diagnosed standard ohmic limiter discharges in existing tokamaks (i.e., JET: shot # 27884 with 7 MA, and ASDEX Upgrade: shot # 11492 with ~1 MA).

Details of these simulations are discussed elsewhere [7, 8]. Here, we show only some selected results for the JET case (Figs 1 and 2). In the Fig.1a-d radial profiles of electron and ion temperatures as well as electron density are presented for the JET case at *t=45s* and *t=49s* .

Fig.2 shows time evolution of the ohmic power $P_\Omega$, average electron temperature $T_e$ and radiation power $P_{RAD}$ in comparison with the experiment. Although, preliminary results for global parameters at the final phase of the current ramp-up look satisfactorily, the applied model need to be developed further to include effects of radial impurity distribution on plasma density and radiation profiles and provide betted fit to the low density range. It is also necessary to validate the model vs the JET data with radiative catastrophic behavior.

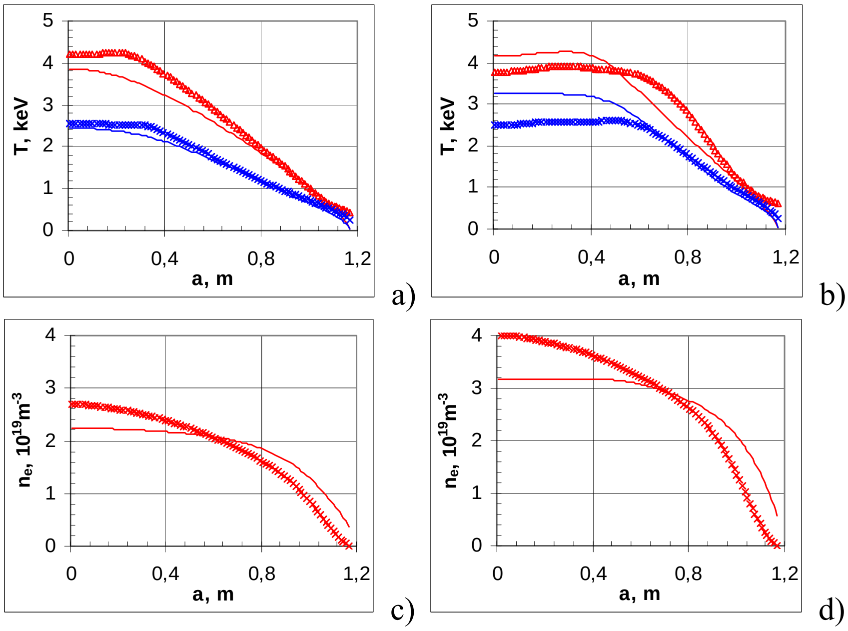


*Fig.1. Electron (red) and ion temperature (blue) and electron density radial profiles (solid curves) for the JET case in comparison with experimental results (×) for t=45 s (a, c)and t=49 s (b, d). Transport model here is based on L-89 scaling.*

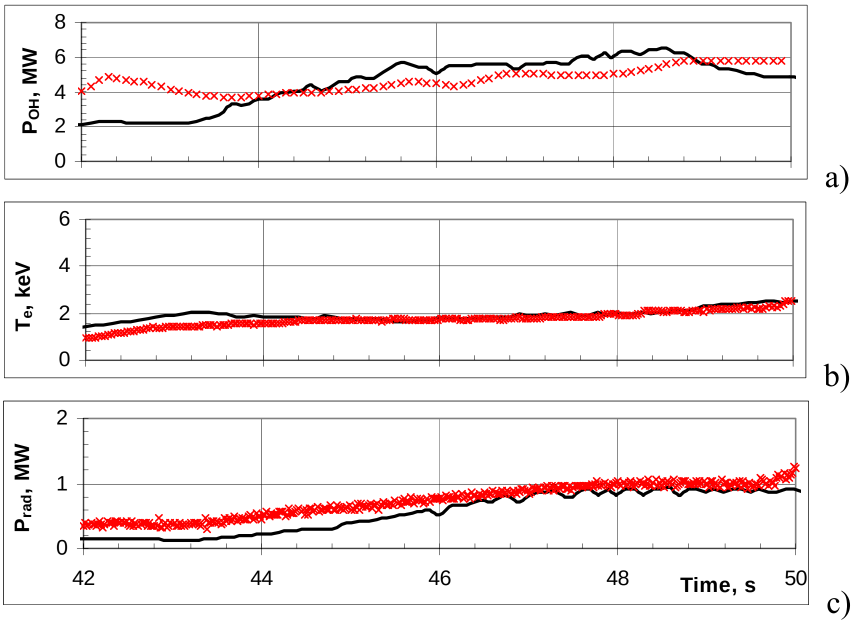


*Fig.2. Comparison of time histories of experimental (red × 's) and calculated values (solid) for ohmic power (a), average electron temperature (b), radiated power (c). Transport model here is based on L-89 scaling.*

**4. ITER limiter star-up simulations.** The transport model has been applied to simulate limiter start-up in ITER for the reference start-up scenario 2 (15 MA inductive scenario, fusion power 500 MW and Q=10) [6]. It was found that for the ramp-up at relatively low plasma density (e.g., $n/n_G$ ~0.2, i.e., <1x$10^{19}$ $m^{-3}$, which is about a factor of 2 lower than in current experiments), the power to the limiter is moderate (≤3 MW). Operating at this very low density causes problems in present experiments (e.g., onset of slideway / runaway effects, lock-modes, runaway erosion effects), but it is not completely clear what are the risks arising for ITER. A sensitivity study with respect to density, impurity concentration and the level of auxiliary heating to study the physics trade-off issues and explore possible ranges of parameters and window of operation has been carried out. In all simulations the most optimistic value $C_{noncor}$ = 1 is suggested. The results of these runs are compared in Table, where maximal values of $P_{\Omega}$, $P_{RAD}$, total power to the limiter $P_L$ are presented for both L-89 and ohmic scaling transport model (L89/ohmic) to show reliable "error bars" for the applied model. It is seen that the predictions are close, however, ohmic scaling gives somewhat lower confinement. Supplementary heating early during the limited discharge is required to avoid radiation collapse, which is predicted by our modeling at higher densities (e.g., 0.4-0.5$n_G$) due to the strong contribution of $P_{rad,\exp} = 10^{-3} \cdot A_{pl} \cdot \overline{n}_e^2 \cdot \left(Z_{eff} - 1\right)$ term. The power to the limiter for the cases analyzed could increase up to <4 MW. Taking into account the observed difference of the model predictions we assume a factor of 2.5 uncertainty in the present estimates. In this case the upper bound of $P_L$ should be about 6 MW.

| $n_e/n_G$ | $Z_{eff}$ | $P_{aux}$,MW | $P_{\Omega,max}$,MW | $P_{rad,mx}$,MW | $P_{L,max}$,MW | $t_{run}$, s |
|---|---|---|---|---|---|---|
| 0.2 | 2 | 0 | 3.1/3.3 | 0.5/0.5 | 2.4/2.6 | >$t_{ramp\text{-}up}$ |
| 0.2 | 3 | 0 | 3.6/3.9 | 0.9/0.9 | 2.5/2.8 | >$t_{ramp\text{-}up}$ |
| 0.3 | 2 | 0 | 4.1/4.3 | 1.1/1.1 | 2.9/3.1 | >$t_{ramp\text{-}upp}$ |
| 0.3 | 3 | 0 | 4.8/5.0 | 1.9/1.9 | 2.6/2.9 | >$t_{ramp\text{-}up}$ |
| 0.4 | 2 | 0 | 4.9/5.2 | 1.8/1.9 | 2.8/3.1 | ≤50/$t_{ramp\text{-}up}$ |
| 0.4 | 3 | 0 | 5.6/6.0 | 3.3/3.3 | 2.1/2.5 | ≤30/50 |
| 0.4 | 2 | ≤10 | 4.8/- | 1.8/- | 2.9/- | >$t_{ramp\text{-}up}$ |
| 0.4 | 3 | ≤10 | 5.2/5.6 | 3.2/3.4 | 2.5/2.8 | >$t_{ramp\text{-}up}$ |
| 0.5 | 2 | 0 | 4.3/5.3 | 2.4/2.6 | 1.4/2.5 | ≤20/27 |
| 0.5 | 3 | 0 | 3.7/4.7 | 2.4/3.2 | 1.1/1.3 | ≤15/20 |
| 0.5 | 2 | ≤10 | 4.5/5.8 | 3.3/3.3 | 3.3/2.9 | >$t_{ramp\text{-}up}$ |
| 0.5 | 3 | ≤10 | 4.1/4.9 | 4.5/3.8 | 1.5/1.4 | ≤17/23 |

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