Modelling of JET hybrid scenarios with the European Transport Solver

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Introduction

Simulation workflows based on the European Transport Solver (ETS) core transport code have been developed within the Task Force on Integrated Tokamak Modelling (ITM) that can provide a comprehensive description of a tokamak experiment [1–3]. Here, one such 1 ½ D workflow that has recently been benchmarked against other code suites [2] is used to perform integrated simulations of electron and ion densities and temperatures, current diffusion and carbon impurity content for two JET hybrid scenarios [4] at low and high magnetic field, plasma current, NBI power, and electron density. The goal of this exercise is to validate some of the anomalous and neoclassical transport models available in the workflow, particularly H-mode Bohm/gyro-Bohm (BgB) [5] and NCLASS [6], in different plasma conditions.

Experimental scenarios and modelling assumptions

Two pulses have been simulated in their stationary phases: #77922 (2.3 T, 1.7 MA, 0.37/0.37 upper/lower triangularity, 1.65 elongation, $P_{NBI} \approx 18$ MW, $n_e \approx 6\times10^{19}$ m^{-3}, $T_e \approx 6$ keV) from 47.8 s to 48.8 s, and #79635 (1.2 T, 0.8 MA, 0.36/0.36 upper/lower triangularity, 1.7 elongation, $P_{NBI} \approx 6$ MW, $n_e \approx 3\times10^{19}$ m^{-3}, $T_e \approx 3$ keV) from 45.5 s to 46 s. Both plasmas have a similar high triangularity, up-down symmetric shape, $\beta_N = 2.7$ and $H_{IPB98(y,2)} \approx 1.2$, but pulse #79635 has lower plasma current, magnetic field and NBI power, whereby the central densities and temperatures are approximately half in comparison with pulse #77922. The edge pedestal has been simulated assuming constant transport coefficients inside an external transport barrier (ETB), which are much higher than the inter-ELM values previously found in coupled TRANSP-EDGE2D simulations [7], thus compensating for the fact that

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[A] *See the Appendix of F. Romanelli et al., Proc. of the 24th IAEA Fusion Energy Conf., San Diego, USA, 2012*

[B] *See the Appendix of [3]*

ELM-driven transport is not considered here. For pulse #77922 the ETB has been set at $\rho = 0.87$ with $D_i = 0.02$ m^{2}s^{-1}, $\chi_i = 1.0$ m^{2}s^{-1} and $\chi_e = 1.7$ m^{2}s^{-1}. Similarly, for pulse #79635 the ETB has been set at $\rho = 0.86$ with $D_i = 0.02$, $\chi_i = 3.5$ m^{2}s^{-1} and $\chi_e = 5.0$ m^{2}s^{-1}. With these values the simulated profiles match the experimental ones at the top of the pedestal.

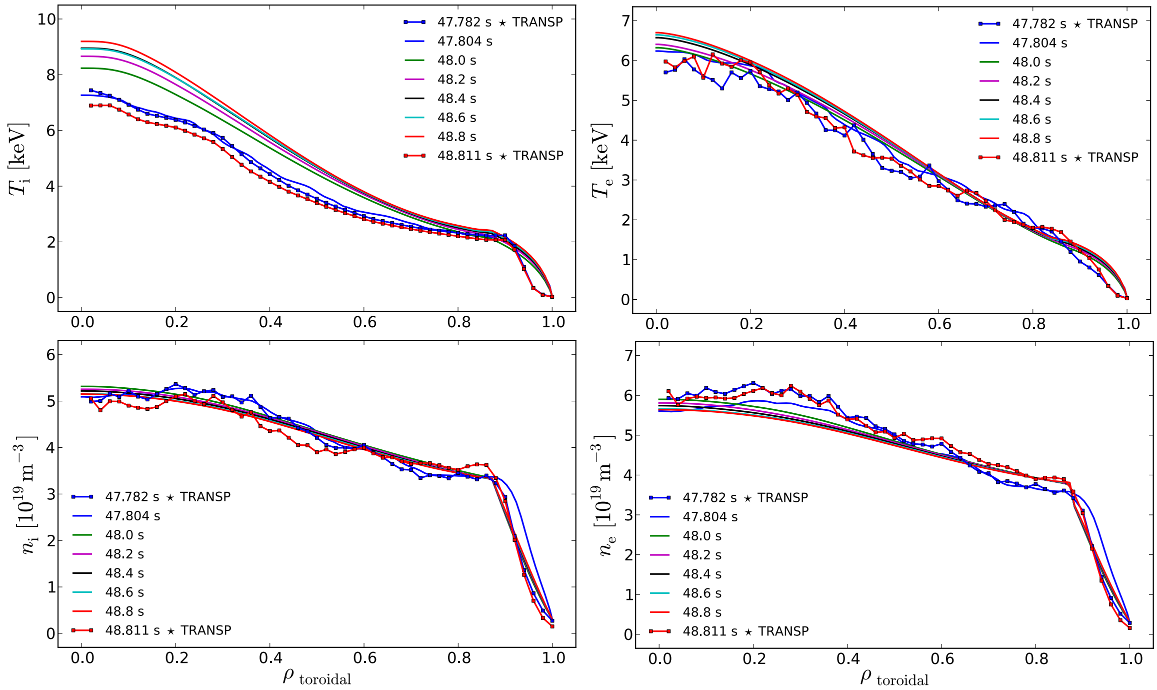

Figure 1. *The simulation of JET pulse #77922 using SPIDER, H-mode BgB and NCLASS shows (upper right) a good agreement between simulated and experimental electron temperatures, with only a small overestimation by the ETS at the plasma center, whereas (upper left) the ion temperatures show a significant discrepancy in the region from ρ = 0.8 to the very core. (Lower left) a good agreement has been found between simulated and experimental ion densities, and (lower right) a satisfactory match of the electron densities has also been obtained.*

The ETS workflow that produced these simulations provides a number of choices for the different types of physical module it uses. Plasma equilibrium has been calculated using the SPIDER [8] and CHEASE [9] codes. The H-mode BgB model used in JETTO [10], which provides anomalous thermal diffusivities and ion diffusion coefficient and has been validated on JET hybrid plasmas [11], has been implemented in the workflow specifically for these simulations. Thermal and main ion neoclassical transport has been provided by NCLASS. The NBI heat and particle sources have been calculated using TRANSP [12] in interpretative mode and stored in an ITM database from which the workflow reads them, together with the experimental[1] density and temperature profiles, which have been processed by TRANSP. Carbon density is evolved by the ETS from an initial profile of the C+6 charge state using the same anomalous transport coefficients of the main ions in the plasma core and considering zero carbon transport inside the ETB. This is a simplified model, which moreover does not consider impurity sources or a pinch. All carbon charge states have been simulated by the ETS and no assumption on coronal equilibrium has been made. Wall neutrals have been ignored in these simulations. A radial grid with 100 points and a 4 ms time step have been

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[1] Ion temperatures and effective charge are not measured for $\rho > 0.85$ and have therefore been set by TRANSP, which also calculated main ion and carbon densities by assuming quasi-neutrality.

used in all simulations. Constant values have been imposed at the edge boundary for densities and temperatures, and the total plasma current has been prescribed.

Modelling results

Figure 1 shows that for pulse #77922 the predicted ion temperature is overestimated at the plasma core — there is a clear separation of the simulated and experimental profiles starting around $\rho = 0.8$ and increasing towards the plasma centre. In contrast, the electron temperature is quite well predicted, despite a small discrepancy at the very core of the plasma. The match between simulated and experimental density profiles is quite acceptable, particularly for ions as can also be seen in figure 1. The calculated densities do not however represent some aspects of the experimental profiles, such as the gradient variations around $\rho = 0.3$ that might possibly have an effect on thermal transport.

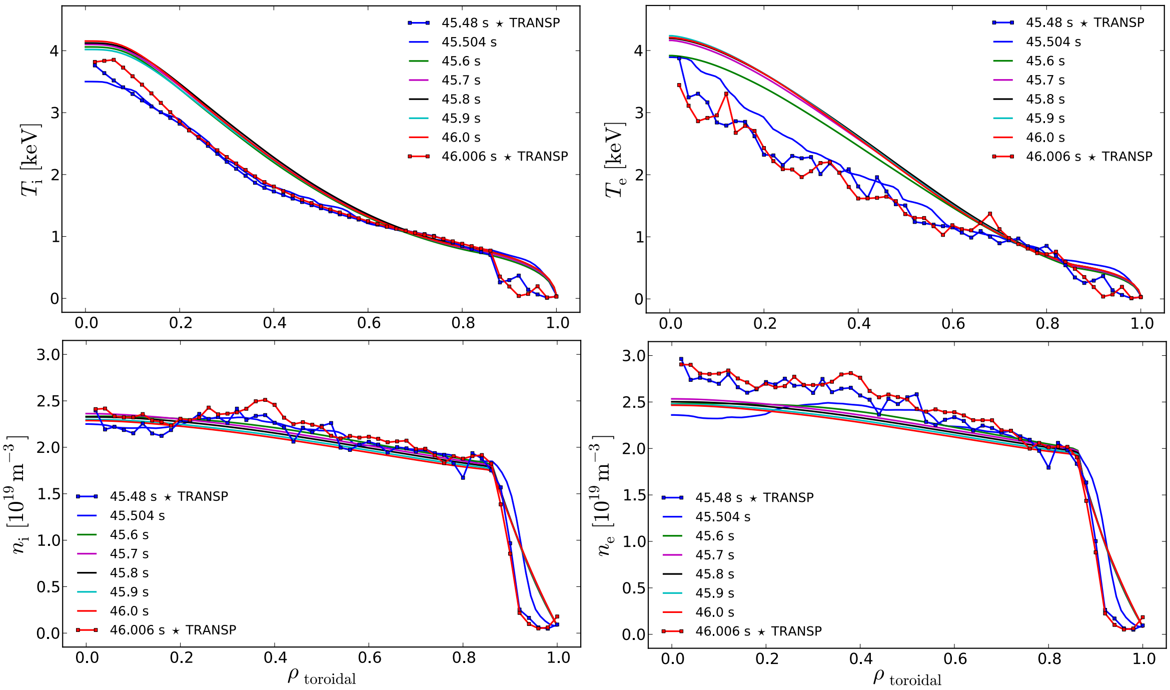

Figure 2. *The simulation of JET pulse #79635 using SPIDER, H-mode BgB and NCLASS shows (upper left) a better agreement between simulated and experimental ion temperatures than for pulse #77922, and (upper right) a significant overestimation of the predicted electron temperature in practically all the plasma core. (Lower left) a good agreement has been obtained between simulated and experimental ion densities, and (lower right) a reasonable match of the electron densities has also been found, despite the moderate underestimation of the experimental electron density in the plasma core.*

The simulation results for pulse #79635 are not very different from those obtained for pulse #77922. However, as can be seen in figure 2, there is a better agreement between predicted and experimental ion temperature profiles, which now start diverging at a deeper radial position close to $\rho = 0.6$, in contrast with a significant difference in the electron temperature profiles starting at the same position and increasing towards the plasma core. Figure 2 also shows that ion densities are again well predicted for pulse #79635, while electron densities are moderately underestimated in the plasma core.

Discussion

A generally good agreement between simulated and measured densities and temperatures has been found for the two hybrid pulses using the H-mode BgB and NCLASS models, despite the fact that the available NCLASS module does not yet provide transport coefficients for impurities. A relatively accurate agreement with the measurements has also been found by replacing NCLASS with NEOS [13], which provides the neoclassical conductivity and bootstrap current density while using a simplified model for the ion thermal diffusivity: parabolic increase from 0.2 m^2s^{-1} at the core to 0.6 m^2s^{-1} at the edge. Ion density has been evolved and well predicted by the ETS, but since electron density is calculated from quasi-neutrality it depends on the calculated carbon distribution, from which a reasonable but not entirely accurate match to the experimental C+6 density and effective charge has been obtained. For example, for pulse #79635 the effective charge in the plasma core is actually overestimated but the predicted electron density is still somewhat lower than the measured density. This mismatch corresponds to a low predicted electron density gradient for pulse #79635, which in turn might also contribute to the electron temperature discrepancy observed in the plasma core for the same pulse. These results should therefore be improved once neoclassical impurity transport is considered and a better model for anomalous impurity transport is used. Concerning temperatures and as could be expected, better accuracy of the predicted temperature profiles has been found in simulations with prescribed electron density and current density profile from EFIT [14]. The predicted ion temperatures have been found to be closer to the experimental profiles in the case of pulse #79635. In contrast, the fact that for pulse #79635 there is a significant difference between simulated and measured electron temperatures, considerably larger than in pulse #77922 for which the ETS prediction is good, suggests that the BgB model might be of limited use in describing electron thermal transport in hybrid scenarios with low plasma current and NBI power.

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