Integrated modelling for tokamak plasma: physics and scenario optimisation

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Recent (2010-2012) studies dedicated to the analysis and modeling of Hybrid Scenarios (HS) performed within the EFDA ITM-TF by the ITER Scenario Modelling (ISM) group are summarized here including the core transport physics, pedestal stability, transport model validation on existing experiments and projection to ITER.

I. Hybrid scenarios on JET and ASDEX-Upgrade (AUG): physics and model validation.

16 JET discharges performed within a broad density ((2.5-5)10^{19} m^{-3}) and NBI power (6-19 MW) range have been analysed including the whole pulse scenario (current ramp up, main heating phase and current ramp down). This database has been completed with 2 AUG hybrid discharges (main heating phase only) [1].

a) current diffusion

Hybrid scenarios are characterised by a nearly flat q profile within a broad central region with $q_0 \geq 1$ during the main heating phase. In JET HS such profiles are sufficiently well reproduced in interpretative simulations started with the first measured q profile (EFIT) at the main heating phase when the neoclassical current diffusion (NCLASS) is assumed (Fig. 1 left) while in AUG the simulated q_0 reduces well below the CLISTE reconstructed value using MSE constraints. The current ramp up and ramp down phases are not sufficiently well diagnosed for a proper validation of current diffusion models. Still the simulated (NCLASS) l_i evolution during the current ramp down is consistent with the EFIT l_i (Fig. 1b) [2]. During the current ramp up an agreement between the simulated q_0 and the time of the 1st observed sawtooth crash can be achieved by adjusting the profile of Z_{eff} constrained by its measured line averaged value.

b) GLF23-based modelling: physics of core confinement improvement

Three field simulations (ion (T_i) and electron (T_e) temperature, and electron density (n_e)) of the JET and AUG HS with the GLF23 model examining the effect of q-profile tailoring on core confinement show that s/q shaping at outer radii may be responsible for a significant proportion of core confinement improvement [3]. The effect of the ExB rotation shear on anomalous transport described here in more detail has been studied in the four field modelling (T_e, T_i, deuterium density n_D and toroidal angular frequency ω) of eight JET discharges performed at various triangularities δ, n_e, NBI powers P_{NBI}, magnetic fields and plasma currents. The wall particle source (deuterium neutral influx through the separatrix) used in the predictive modelling has been estimated in the self-consistent TRANSP-EDGE2D simulations for two selected discharges performed at P_{NBI} =6 MW (79635) and 17 MW (77922), and extrapolated to other pulses. The GLF23 model applied with the *ExB* shear calibration factor α_E=1, which usually gives a satisfactory prediction for the JET H-mode plasmas and high β_N scenarios, over-predicts the density and toroidal rotation in hybrid pulses while T_e and T_i are in a good agreement with measurements (Fig. 2, left). By reducing the *ExB* shear factor in the GLF23 model by factor 2 (i.e. α_E=0.5) a more accurate density prediction has been achieved while the simulated temperature and rotation were weakly affected by this change of α_E. Trying to improve the prediction of toroidal rotation, the simulations have been performed assuming that the momentum diffusivity χ_φ is a fraction of the thermal ion diffusivity χ_i where χ_i has been computed with the GLF23 model. The Prandtl number $P_r=\chi_\varphi/\chi_i$ had to be adjusted separately for low and high triangularity pulses to match the measured ω. With this adjustment (P_r=0.3 at low δ and P_r=0.5 for two high δ discharges) an essential improvement in the prediction of the toroidal rotation has been achieved while the density and temperatures remains within 20% deviation from the measurements (Fig.2 right and Fig.3). However the *Pr* number has to be reduced to 0.2 in the high δ pulse 75590 where a steep ("ITB-like") T_i gradient has been observed.

A good agreement between the measured and simulated n_D and T_i has been obtained also in simulations with the TGLF [4] model applied with reduced strength of the *ExB* shear (α_E =0.5, Fig. 3). It should be mentioned that the GLF23 simulated density is weakly sensitive to α_E in the low NBI power high δ discharge (Fig. 3) while an important density over-prediction at high power clearly indicates that the *ExB* shear effect in the GLF23 model should be weakened to achieve an accurate density prediction in hybrid scenario.

c) validation of the Bohm-gyroBohm transport model

Self-consistent three field simulations (n_e, T_e and T_i) performed with the H-mode Bohm-gyroBohm (BgB) transport model also show an over-peaking of the density profile during the main heating phase in the JET hybrid pulses [5]. The electron and ion temperature in the JET [5] and two AUG pulses is well predicted with the BgB model. When applied to the whole discharge simulation the BgB model accurately predicts the temperature evolution during the current ramp up as well as the n_e and T_e evolution during the current ramp down performed at different densities and ramp down rates [2].

d) micro-turbulence stability analysis

Linear stability analysis performed with GYRO [6], QuaLiKiz [7] and GLF23 [8] shows that the ITG driven mode is the dominant instability in selected JET discharges, although the operational point is very close to the KBM dominant domain in GYRO simulations performed for #77922 (Fig. 4). The stabilising effect of the *ExB* shear on the ITG mode is very weak while the onset of KBM is sensitive to the *ExB* shear. Strong stabilising effect of β_e on the ITG mode in JET HS has been found (Fig. 4).

e) particle confinement

First self-consistent TRANSP-EDGE2D simulations performed here for two JET pulses allow an estimation of the particle confinement time τ_p. In these pulses the τ_p value exceeds the energy confinement time τ_E nearly by factor 2, with a longer τ_p in the high power pulse ($\tau_p\approx$0.4 s and $\tau_E\approx$0.16 s in #79635, $\tau_p\approx$0.54 s and $\tau_E\approx$0.25 s in #77922).

g) pedestal transport, MHD stability and ELMs

Deuterium particle transport in the pedestal region estimated between ELMs in the interpretative TRANSP-EDGE2D simulations for two JET pulses is much lower than the electron heat transport ($\chi_e/D_d\approx$6 in #77922 and $\chi_e/D_d\approx$11 in #79635). Similar estimation of pedestal χ_e/D_d ratio for #77922 has been obtained in [5]. In both pulses the deuterium particle diffusion D_d and χ_i are close to their neoclassical values while χ_e exceeds the neoclassical transport by more than factor 10. The pedestal height in JET pulses is in a good agreement with the EPED model prediction (within 20% discrepancy with the data) in a broad range of measured pedestal pressures (5-15 kPa) [9] indicating that the pedestal constraint based on the peeling-ballooning (PB) stability combined with an onset of KBM is consistent with measurements. An ideal MHD stability analysis performed with MISHKA code for a low δ HS shows that the 1st ELM occurring after the current overshoot is triggered by the PB mode with n=10-14. An integrated modelling approach combining the free boundary equilibrium (CREATE-NL), core-pedestal (JETTO) and SOL (EDGE2D) codes has been applied in the simulations of type I ELMs, similar to ELMs observed in HS, investigating the possibility of ELM mitigation [10]. This approach applied to the ELM mitigation by kicks in H-mode plasmas properly predicts the observed density depletion, measured T_e, thermal energy and H-factor with an increase of ELM frequency [10].

II. From existing experiments to ITER: performance and scenario optimisation

The transport models validated on JET and AUG hybrid discharges have been applied in the simulations of ITER HS. It has been shown that the heating systems available at ITER (NBI, ECCD (UL) and LHCD) allow the attainment of a hybrid q profile at the end of the current ramp up, although the optimum heating scenario depends on the chosen transport model [11]. Based on a sensitivity analysis a real-time adaptive determination of auxiliary power start time has been proposed for the current ramp up phase [11]. Assuming the GLF23 computed transport during the burn phase the auxiliary heating and current drive mix has been optimised (33 MW of NBI and 37 MW of ECCD peaked at ρ=0.3) resulting in a fusion performance $P_{fus}\approx$350 MW and $Q\geq$5 [12]. Hybrid scenarios simulated with the experimentally validated models are used for the development of the real time profile control on ITER using an integrated profile control strategy ARTAEMIS [13].

III. Summary

Simulations of JET and AUG HS with the GLF23 model show that the observed core confinement improvement can be partly explained by the beneficial s/q effect on the ITG driven transport while the effect of the ExB shear stabilisation is weaker than in H-mode plasmas. Strong stabilising effect of β_e on the ITG turbulence has been found, but the transport reduction due to this effect can be limited by the onset of the KBM mode at high β_e. The simulations of toroidal rotation in HS with the GLF23 model give an indication of the toroidal momentum pinch (P_r<1).

Use of H-mode parameters in the GLF23 and BgB models results in the over-peaking of the density profile while the temperatures are sufficiently accurately predicted. Based on the performed analysis a re-tuning of the BgB [7] and GLF23 models which enables a more accurate prediction for the main heating phase of HS is suggested. An impact of the models modifications on the predictions for ITER HS is to be assessed. The current ramp up and ramp down [2] phases are satisfactorily predicted with the original L-mode version of the BgB model. During the main heating phase the pedestal height and width are in a good agreement with the EPED model [9]. The modelling of ITER HS based on the results presented here, as well as the scenario optimisation will be discussed in Ref. 14.

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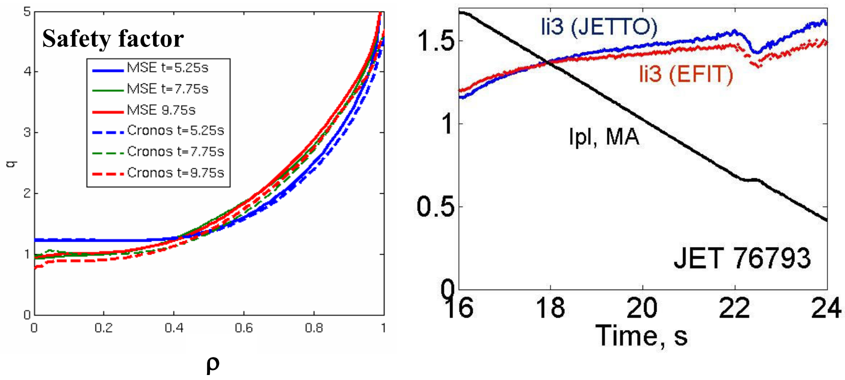


Fig. 1. Current diffusion in HS: simulated (CRONOS) and reconstructed (MSE/EFIT) q-profile during the main heating phase in JET discharge 75225 (left); simulated (blue) and reconstructed (red) l_i during the current ramp down [2] (right).

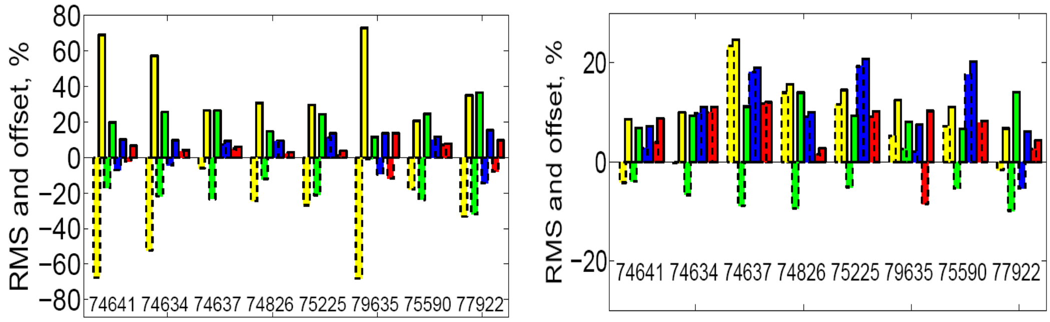
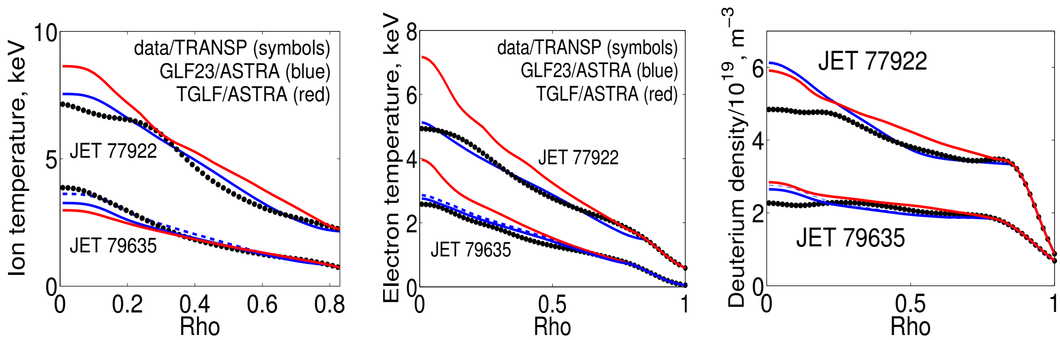
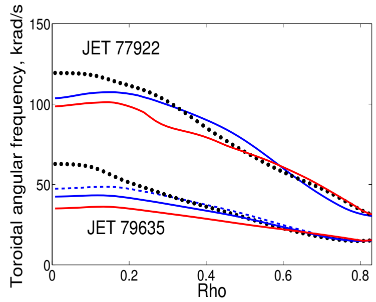


Fig. 2. RMS (solid contour bars) and offset (dashed contour bars) estimated for T_e (red), T_i (blue), n_D (green) and ω (yellow) using α_E=1 and GLF23 computed χ_φ (left), and α_E=0.5 and χ_φ=Pr·χ_i with Pr=0.3 (low triangularity) and 0.5 (high triangularity) discharges (right). Pulse 75590 showing the ITB-like steep Ti gradient has been simulated using Pr=0.2. The H-mode pulse 74826 has been simulated using α_E=1.





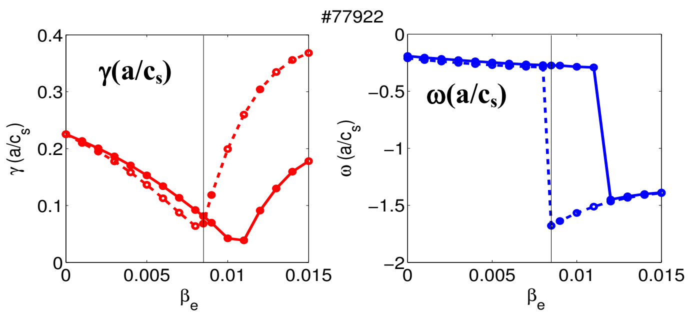


Fig. 3. Simulations with GLF23 and TGLF models performed with α_E=0.5 and Pr=0.5 (solid curves) for JET HS. Dashed blue curves show the GLF23 simulations performed with α_E=1 for low power

Fig. 4. Linear electromagnetic GYRO simulations for # 77922: growth rate (left) and frequency (right) simulated with (dashed) and w/o (solid) ExB shear using the plasma parameters measured at ρ=0.5. Experimental β_e value is shown by vertical line.