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Towards fully-predictive transport modelling in ASDEX Upgrade H-modes

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To predict energy and particle transport in future tokamaks we cannot use experimental measurements as boundary condition. Therefore, we need integrated modelling from the SOL to the plasma center.
On the other hand, transport in the various plasma regions is known to different degree. In order to increase our confidence on the transport predictions, we need to validate the available transport models or assumptions against existing data, or at least to quantify the impact of the respective uncertainties on the overall confinement performance.
Core transport has been studied with theory-based quasi-linear models for more than two decades, with significant progress both in terms of verification in comparison to nonlinear gyro-kinetic simulations and validation in the description of the main channels of heat and particle transport.
However, detailed aspects of the quasi-linear models can still contain inaccuracies or uncertainties, particularly regarding the precise level of predicted stiffness, or the transport levels approaching the plasma periphery and close to the pedestal. Moreover, effects that can have a predominant non-linear character, such as the stabilization due to fast ions and to beta, are difficult to consistently capture within a quasi-linear description.
In this paper we show recent progress both in integrated modelling \[1\] and in the detailled validation of quasi-linear theory-based transport models in the core, for both electron-heated and ion-heated ASDEX Upgrade H-mode plasmas. The transport characteristics, like the dominant turbulence, are addressed. Two quasi-linear transport model are considered: TGLF \[2\] and QuaLiKiZ \[3\]. The effect of fast ions is retained only in terms of ion dilution.
The ASTRA code \[4\] provides the simulation frame, including theory-based core transport and a pedestal model, which allows us to determine the pedestal pressure for a given pedestal width Δ_{ped} by means of a transport constraint.
The boundary conditions of the density and temperature profiles at the separatrix are derived with a regression-based formula, Eq. (2) in \[1\], depending on the particle fluxes of D and seeding impurity, as well as on the pumping speed. The sensitivity of the predicted plasma thermal energy on the boundary condition is discussed. Multiple parallel ASTRA simulations with different Δ_{ped} are run, then the MISHKA code \[5\] selects the case with highest stable pedestal pressure. The experimental stored thermal energy is predicted significantly better than with the established IPB98(y, 2) scaling, as shown in Fig. 1. for a selected set of stationary plasma phases featuring a heating power scan, a gas puff scan, and a current scan.

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Experiments have been performed featuring a scan of the ion heat flux at constant total heating, by progressively moving from full on-axis to full off-axis NBI heating \[6\]. Two discharges at different levels of central ECRH are selected to assess the profile stiffness with the theory-based models TGLF and QuaLiKiZ.
TGLF-sat1 predicts particle transport very accurately in all cases. T_e and T_i are also close to the experimental profiles in the discharge with low P_{ECRH} ($T_e/T_i \approx 1.3$), whereas they are overpredicted for high P_{ECRH} ($T_e/T_i \approx 1.9$), as summarised in Fig. 2.

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GK simulations show a significant de-stiffening by fast ions for Q_i, so we can conclude that overall TGLF-sat1 is less stiff than the experiment. For electron transport in H and D plasmas, gyro-kinetic simulations indicate a significant role by the ETG at higher collisionality (typically R/L_{T_i}), whereas at lower collisionality the TEM is dominant, leading to the prediction that ITG and TEM will prevail over the ETG for electron heat transport at the low collisionalities of a burning plasma. Modelling with TGLF matches the kinetic profiles with good accuracy, but for a too high sensitivity on $\rho_{tor} = 0.27$. QuaLiKiZ is more accurate at high collisionality.

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\[6\] F. Ryter *et al.*, Nuclear Fusion **59** (2019) 096052

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