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

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Abstract

The common way to predict energy confinement in future devices such as ITER is to use scaling laws, based on parameters regression of large cross-machine databases. However, this approach is limited: the regression variables are not purely engineering parameters, physics quantities such as the plasma density n_e are also input; power regressions fail to capture important physics such as regime transitions; profile effects such as T_i/T_e or reverse magnetic shear are not retained. As a consequence, the scatter is large, but even some dependences are known to be of limited validity, such as the n_e or P dependences of the IPB98(y, 2) scaling. Dimensionless physics, if validated, provides a reliable basis for predicting confinement in a future device. However, there are no experimental data to use as boundary condition, nor empirical knowledge based on that device. Also, the use of full gyro-kinetic codes with all relevant ingredients is computationally unfeasible for a full-radius modelling.

In this paper we present a workflow for modelling transport from the separatrix to the plasma center, the core being predicted with theory-based quasi-linear models, the pedestal with a new ansatz combining peeling-ballooning stability and a heuristic constraint for the pedestal width. Moreover, we further validate the most established quasi-linear models TGLF and QuaLiKiZ in different regimes and experimental conditions. As a result, we obtain a much more accurate prediction of the thermal energy content of ASDEX-Upgrade H-mode plasmas than just using scaling laws, without using any direct experimental input, and we assess the validity limits of the current quasi-linear transport models for further development.

1. Introduction

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. Transport in the various plasma regions is understood to different degree. In order to increase our predictive confidence, we need to validate the available transport models or assumptions against existing data, or at least to quantify

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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 just inside the pedestal. Moreover, effects with 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][2] and in the detailed validation of quasi-linear theory-based transport models in the core, for both electron-heated and ion-heated ASDEX Upgrade H-mode plasmas. Two quasi-linear transport model are considered: TGLF [3] and QuaLiKiZ [4] The effect of fast ions is retained only in terms of ion dilution.
The ASTRA code [5] provides the simulation frame for the Integrated Modelling with Engineering Parameters (IMEP), 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 experimental stored thermal energy is compared to the established IPB98(y, 2) [6] and to the recent ITPA20-IL scaling [7].
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 [8]. Two discharges at different levels of central Electron Cyclotron Resonance Heating (ECRH) are selected to assess the profile stiffness with the theory-based models TGLF and QuaLiKiZ at different T_e/T_i. The same models are validated over a database of plasmas with dominant electron heating, in particular their sensitivity to T_e/T_i [9].

2. IMEP workflow for full-radius modelling of the kinetic profiles

In this section we describe the newly developed IMEP workflow [1][2], for full-radius modelling of H-mode plasmas. The method has been applied so far to ASDEX-Upgrade discharges, but it does not make use of any experimental input and it is portable to any tokamak, as the input from empirical device-related information is minimised. If it has to be predictive for future devices, the IMEP workflow should not just to capture the resulting thermal energy content W_{th} , but it should be accurate in all different plasma regions.
In the following we summarise the main assumptions used in the integrated modelling.

2.1. T, n at the separatrix

The boundary condition of the IMEP workflow in ASTRA is set to the separatrix. Since the pedestal constraints refer to gradients, it is crucial to have an accurate description of the plasma temperature and density at the separatrix. For $T_{e,sep}$ and $n_{e,sep}$ we use the formulas in [10], equations (5) and (8), respectively. For ions we simply assume $T_{i,sep} = 2^*T_{e,sep}$, a robust observation in ASDEX Upgrade, associated to the parallel heat conductivity in the Scrape Off Layer (SOL), which is smaller for the ions than for the electrons. This is valid at least for attached divertor, which is the case in the discharges in [1][2], whereas $T_{e,sep}$ and $T_{i,sep}$ become closer in the case of detached divertor. The formula for $n_{e,sep}$, equation (1) in [1], depends on the particle fluxes of deuterium and of the seeding impurity, as well as on the pumping speed. At this stage we do make use of machine-related information, as we combine the effects of momentum losses, power losses and divertor heat flux broadening into a coefficient, derived by regression analysis of ASDEX Upgrade measurements. The main dependence is found to be the divertor neutral pressure. Note that the IMEP workflow does not use any direct input from the specific plasma discharge, as it is the case for instance in the EPED model by assuming e.g. $n_{e,sep} = 1/4\ n_{e,top}$.

2.2. Pedestal modelling

For the pedestal transport we apply an original approach which does not rely on any experimental input, neither for the pedestal width nor for its height, for any kinetic profile. We assume the electron heat conductivity $\chi_{e,ped}$ to be constant across the pedestal region, moreover $\chi_{i,ped} = \chi_{e,ped} + \chi_{i,NC}$ and $D_{ped} = 0.03\chi_{e,ped} + D_{NC}$. A priori we do not know the pedestal width, therefore we run, for a given discharge, several ASTRA full simulations with different pedestal widths. These ASTRA runs do model also core transport with the TGLF model, because we need realistic heat fluxes (including thermal exchange between electrons and ions) and the Shafranov shift. The χ_e value is adjusted to fulfill the average condition $< \nabla T_e > / T_{e,top}$ = -0.5 cm^{-1}, which is the main constraint of the IMEP workflow in the pedestal region. This relation is regularly observed in ASDEX Upgrade H-mode plasmas, as documented in Fig. 2(a) of Ref. [11]. For each pedestal width, a different χ_e level is found. We analyse a posteriori the linear stability of each pedestal pressure profile with the MISHKA code [12]. The IMEP workflows prescribes the selection of the simulation with the highest stable pedestal pressure profile. Note that, due to our constraint, the pedestal pressure gets steeper with increasing pedestal width, as shown in Fig. 1 of Ref. [1].

2.3. Other assumptions

The core transport is predicted with the theory-based quasi-linear model TGLF [3], using the saturation rule sat1. The particle and heat sources are calculated self-consistently with the TORBEAM code [13] and the NBI module included in ASTRA. The boundary condition is given by the pedestal values derived with our workflow (see Section 2.2).

In the refined version of the IMEP workflow [2], the toroidal velocity v_{tor} is derived by assuming the Prandtl number to be 1, combined to a boundary condition based on existing formulas [2]. However, the energy confinement predicted with TGLF is not

too sensitive to the v_{tor} profile [2]. The effective charge Z_{eff} is assumed to be 1.3, constant in space and time, a typical value for ASDEX-Upgrade since the completion of the tungsten wall. The corresponding light impurity is chosen to be Boron. Again, the predicted confinement is not significantly sensitive to Z_{eff} in a range 1.1-1.8. A heuristic tungsten concentration $c_W = 210^{-5}$ is assumed, providing core radiation.
Fast ions are retained only for the dilution effect.

2.4. Performance of the IMEP workflow

The most basic parameter to compare is the plasma thermal energy W_{th} , which at steady-state is just proportional to the energy confinement time τ_E . However, a good validation should assess the accuracy of each modelling region separately, in order to gain confidence on the predictive capability of the IMEP approach for future devices. Also, well-known experimental trends and dependences should be captured, before extrapolating to larger devices. A comparison of the global confinement prediction with respect to the IPB98(y,2) [6] and ITPA20-IL [7] scaling laws is shown in Fig. 1. Hereby,

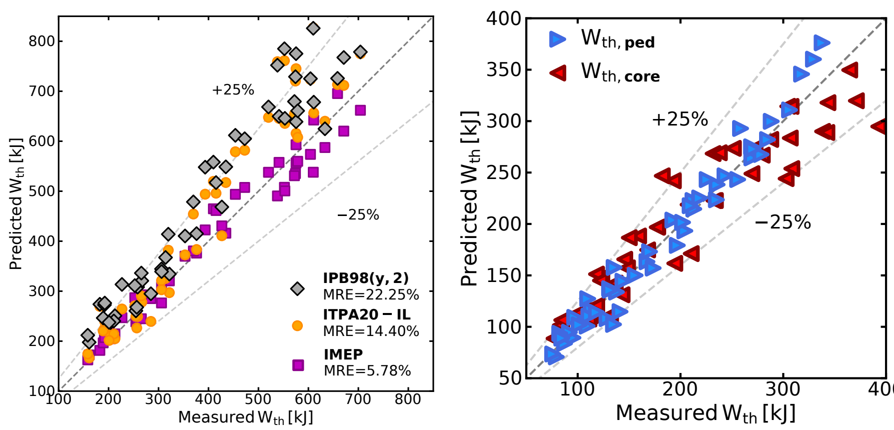

Figure 1. Left: predicted versus experimental W_{th} ; IMEP (magenta squares), IPB98(y,2) (grey diamonds), ITPA20-IL (yellow circles).
Right: IMEP versus experimental $W_{th,ped}$ (blue) and $W_{th,core}$ (red).

W_{th} is the average of two independently derived estimates: the volume integral of the kinetic profiles between ELMs, and $W_{MHD} - W_{fast}$, where W_{MHD} is the total plasma energy from equilibrium reconstruction and W_{fast} is the fast ion energy calculated by the NBI module of ASTRA. As Fig. 1 (left) shows, the IMEP prediction fits significantly better than the two scaling laws. The Mean Relative Error (MRE) is less than 6%, compared to 14% of ITPA20-IL and 22% for IPB98(y,2). Both scaling laws, moreover, exhibit a clear systematic trend to over-predict confinement at high W_{th} , whereas IMEP keeps well-balanced in the whole range.
Looking into more detail, it is useful to separate the predictions of the pedestal energy $W_{th,ped}$ and the core energy $W_{th,core}$. The former is defined as the volume integral of a pressure profile which is constant from the pedestal top inward and equal to the

simulated one in the pedestal region. The latter is just $W_{th,core} := W_{th} - W_{th,ped}$. Interestingly, as seen in Fig. 1 (right), the core energy exhibits a larger deviation from the experimental value, with a systematic trend to under-predict towards higher energies.

3. Assessing profile stiffness with an ion heat flux scan

Although quasi-linear models are believed to predict core transport with reasonable accuracy, there are many experimental conditions where they are not fully validated, such as impurity seeding, dominant electron heating, improved confinement, isotopes or in regions close to pedestal top. As Fig. 1 shows, there are still uncertainties and systematic trends, larger than for the simple pedestal model, of course with the important remark that there is no heuristic adjustment nor tuning for such theory-based models. Recently, the TGLF model was optimised to fix the so-called "transport-gap" just inside the pedestal top, where temperature gradients were predicted to be significantly higher than for the measured profiles.

A key feature of quasi-linear models is profile stiffness, i.e. the tendency of kinetic profiles to clamp (to a lower or higher degree) to a critical gradient length, despite increasing the heat flux.

We performed two H-mode discharges, one with low $P_{ECRH} = 0.65$ MW, resulting in $T_e/T_i \approx 1$, and a second one with $P_{ECRH} = 2.7$ MW, resulting in $T_e/T_i \approx 2$ in the plasma core. In each discharge, the NBI deposition (2 sources, 5 MW) was moved from fully on-axis, to one source on-axis and one off-axis, to entirely off-axis, taking advantage of the tangential NBI at ASDEX Upgrade [8]. As a result, the ion heat flux was varied by a factor ≈ 2.5 around $\rho_{tor} = 0.4$, safely out of the sawteeth mixing radius.

These plasmas were modelled with the TGLF [3] and QuaLiKiZ [4] models. The boundary condition was pushed far outside, at $\rho_{tor} = 0.82$, which is just inside the pedestal top for these plasmas. A special routine was used to mimic the effects of sawteeth, which were present in both discharges, also to prevent spurious predicted transport coefficients due to the wrong local values of the safety factor and magnetic shear. The T_e, T_i and n_e profiles were modelled simultaneously, while the source terms were computed with the NBI code RABBIT [14] and the ECRH code TORBEAM [13], also self-consistently with the evolving kinetic profiles.

For TGLF we used the recent sat2 option for the saturation rule (units 'CGYRO'), while for QuaLiKiZ we used a collisionality multiplier of 0.1, following the developers' recommendation, as otherwise the predicted T_e results far too high. A refined collisionality model should be distributed soon with a new QuaLiKiZ version. A sensitivity scan on the collisionality factor is discussed in Section 4.

Figure 2 displays the simulated kinetic profiles on top of the experimental ones for the case with low ECRH ($T_e/T_i \approx 1$), both the NBI on-axis phase (top row) and off-axis (second row). The corresponding plots for the case with strong ECRH ($T_e/T_i \approx 2$) are contained in Fig. 3. The case with $T_e/T_i \approx 1$ (Fig. 2) is matched with high accuracy by

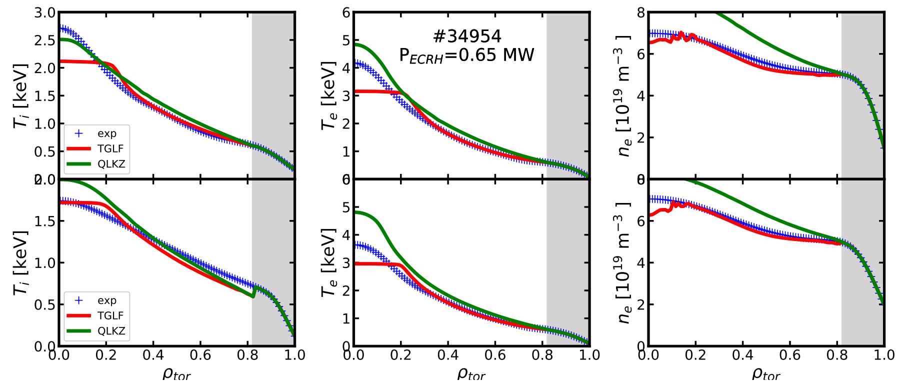

Figure 2. Kinetic profiles: experimental (blue dots), TGLF (red), QuaLiKIZ (green) for discharge #34954 ($T_e/T_i \approx 1$). On-axis NBI (first row), off-axisNBI (second row).

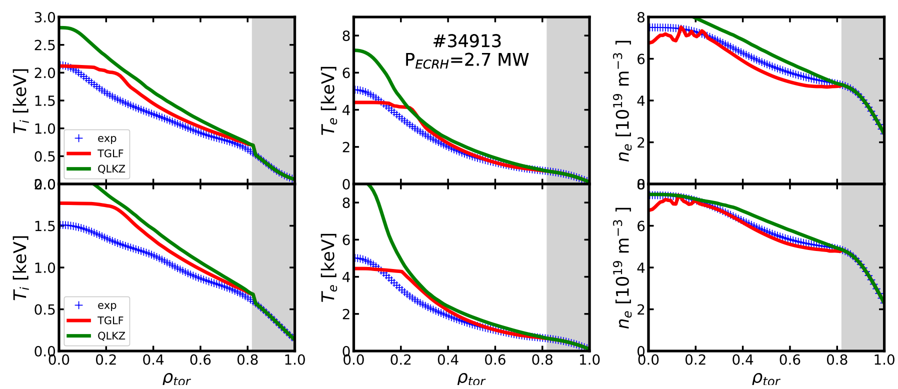

Figure 3. Symbols and colors like in Fig. 2, for discharge #34913 ($T_e/T_i \approx 2$).

the TGLF model, while QuaLiKiZ predicts temperatures nicely but the density profile exhibits a stronger peaking than the experimental one. At higher T_e/T_i, however, both models overestimate the temperature gradient in the core, for both T_e and T_i, whereas the density peaking is predicted correctly.

The extent of profile stiffness is summarised in Fig. 4. Note that the ion heat flux (y-axis) is not identical in experimental and modelling, due to the self-consistent calculation of the heat deposition profiles, which depend on the simulated kinetic profiles. Also, we are discussing an "effective" stiffness, because increasing the heat flux does change also the temperature profiles and their ratio, which can shift the critical gradient length. It appears that the quasi-linear models predict the correct stiffness when $T_e/T_i \approx 1$ (black symbols in Fig. 4), whereas they tend to under-predict it when electron heating gets stronger (red symbols). As gyro-kinetic calculations show a strong de-stiffening due to fast ions when $T_e/T_i \approx 1$, and this effect is not retained in the quasi-linear models, one can interpret these results as an overall under-predicted stiffness by TGLF and QuaLiKiZ.

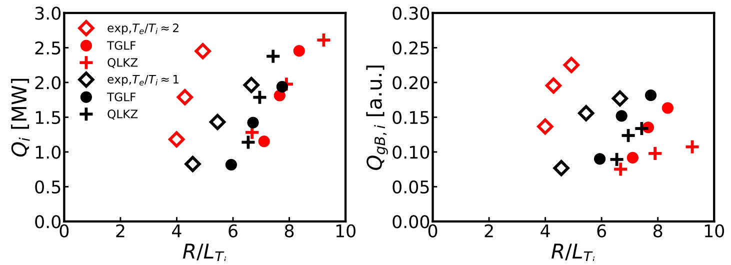

Figure 4. Ion heat flux versus R/L_{T_i} at $\rho_{tor} = 0.4$, in MW (left) and with Gyro-Bohm normalisation (right); $T_e/T_i \approx 1$ (black) and ≈ 2 (red). The highest fluxes correspond to on-axis NBI.

4. Quasi-linear transport modelling with dominant electron heating

A more systematic validation has been performed over a database of ASDEX-Upgrade discharges with strong electron heating [9]. We restrict here to H-modes, where T_e/T_i ranging from 1 to 5, as Fig. 5 (right) shows. TGLF is used here with the SAT1-geo saturation rule, which has been optimised to predict transport just inside the pedestal top. In fact, the boundary condition could be pushed out to the pedestal (in L-mode even up to $\rho_{tor} = 0.95$ [9]). The TGLF model features a good prediction of core transport, with a moderate trend towards underestimated T_e with increasing T_e/T_i, as shown in Fig. 5. The QuaLiKiZ model is reliable only when transport is dominated by the ITG (Ion Temperature Gradient driven) mode, with a too strong stabilisation of trapped electron turbulence when the Trapped Electron Mode (TEM) becomes dominant. The new collision operator, currently developed, could solve this issue.

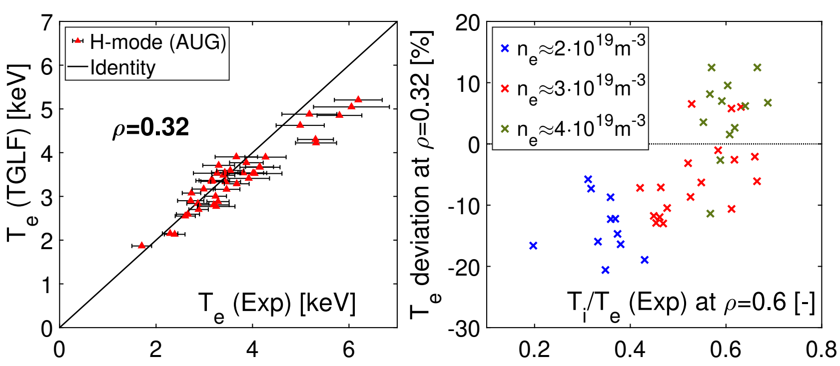

Figure 5. Modelling T_e with TGLF SAT1-geo in AUG H-mode plasmas with dominant electron heating. Left: core T_e, model vs experiment. Right: T_e deviation as a function of T_i/T_e; a clear trend is observed.

5. Conclusions

The IMEP workflow has been established, allowing full-radius predictive transport modelling without any experimental input. It also minimises heuristic input which applies only to a specific tokamak device. The workflow proves to predict the plasma thermal

energy more accurately than the established and refined scaling laws IPB98(y,2) and ITPA-IL, with a significantly smaller mean residual error and no systematic trend to over-predict W_{th} at high stored energy, although the scaling laws do have the line averaged density as input from the experiment. The pedestal model, based on the heuristic constraint $< \nabla T_e > /T_{e,top} = 0.5$/cm and on peeling-ballooning stability analysis, is shown to deliver good predictions for the pedestal, even more accurate than the core, predicted with the theory-based TGLF model.
The quasi-linear models TGLF and QuaLiKiZ are validated in a variety of experimental conditions, with a boundary condition as far outside as the pedestal top, modelled density profile and self-consistent heat and particle sources.
A dedicated ion heat flux scan in ASDEX Upgrade shows that profile stiffness and overall the kinetic profiles are predicted with high accuracy with TGLF in the case $T_e/T_i \approx 1$, and reasonably well with QuaLiKiZ (after reducing artificially the collisionality), albeit with an over-predicted density peaking. At $T_e/T_i \approx 2$, instead, both models over-predict the temperature profiles. Modelling extensively plasmas with dominant electron heating reveals overall good predictions by TGLF, with some trend to under-predict T_e for very high values of $T_e/T_i = 3-5$, whereas QuaLikiZ works fine as long as transport is mainly due to the ITG mode, but it over-predicts T_e very strongly when the TEM is dominant, due to the too strong TEM stabilisation, even when putting the collisionality artificially to zero. Summarising, TGLF is applicable for integrated modelling in a variety of scenarios and experimental conditions, in particular for several ITER scenarios, although it still shows some trends. QuaLiKiz is applicable in ITG plasmas, and it could soon improve overall, with a new collision operator currently under development.

Acknowledgment
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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