A SELFCONSISTENT MODEL OF THE H-MODE PLASMA IMPLEMENTED IN 1-D SIMULATIONS
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Introduction: In the last few years, significant progress has been achieved in the understanding of H-mode plasmas. In particular, many experiments have confirmed the idea that, to a large extent, the H-mode pedestal parameters define the energy confinement in the plasma core via temperature profile stiffness. However, ion energy transport and electron energy transport differ - whereas ions are well described by ITG (Ion Temperature Gradient) turbulence based models, e.g. [1], electrons seem to follow a behaviour resembling RLW (Rebut Lallia Watkins [2]) or in some cases ETG (Electron Temperature Gradient) transport. In addition, a significant magnetic shear dependence can be inferred for electron energy transport, based on observations in e.g. TORE SUPRA low density electron heated plasmas, for which energy transport was generally RLW- or ETG-like but improved with increasing $l_s$, i.e. magnetic shear. Particle transport appears to be related to energy transport. In particular, recent experiments on DIII-D and ASDEX-UP at low heating power (just above the H-mode power threshold) and with careful gas puffing, have yielded significant density profile peaking. This is consistent with a variation of the particle diffusion coefficient $D$ proportional to the heat diffusivities $\zeta_i$, $\zeta_e$, once the Ware pinch is included, i.e. $D$ is probably related to the level of turbulence such as described by the critical gradient models above.

Qualitative understanding of the turbulence stabilisation mechanism in the H-mode pedestal region is derived from several observations. First, the pedestal width, several gyroradii wide, seems to scale roughly in proportion to machine size and to exhibit a poloidal gyroradius like behaviour. Secondly, the narrower pedestal of ELM-free discharges compared to ELMy ones implies a strong influence of the bootstrap current on the pedestal width and height. It seems plausible therefore that magnetic shear contributes significantly to the turbulence stabilisation, in addition to the radial electric field shear. Because the pedestal width is several poloidal gyroradii, the radial electric field shear cannot be produced only by orbit losses and must thus be related to the pressure gradient.

A model based on these observations has been implemented in the ASTRA code [3].

Model description: Due to the strong coupling of the various effects (e.g. pedestal parameters, bootstrap current and shear), a comprehensive model including the core plasma, the H-mode pedestal and a simple scrape off layer (SOL) is required. Even if some parts of the present model are still simplified, a unified treatment of all plasma areas and transport contributions is preferable to other current treatments in which some of these parameters (e.g. pedestal parameters and/or the density profile) are kept constant.

$$C_{ITG}^{\text{Stiffness}} = \text{Stiffness} \left[ \frac{\Delta T_e}{T_i} - \frac{\Delta T_i}{T_i} \right]_{\text{mod}}$$

In our model ion energy transport is neo-classical plus ITG, the latter based on a modified IFSPPL model [1] (e.g. shorter gradient lengths adjusted to a JET discharge).

Electron energy transport is assumed to consist of 5 times electron neo-classical, modified RLW [2] (transport proportional to the difference of the gradient and a critical gradient modified to depend on shear and adjusted to JET), and Alfvén drift dominant at the
plasma edge. As discussed elsewhere [4] this edge-localized instability disappears once a certain edge \( E \) is achieved and thus can trigger the H-mode transition.

\[ c_e^{RLW \cdot mod} = \text{Stiffness} \left( \frac{\Delta T_e - \Delta T_{e, crit}^{RLW \cdot mod}}{\| \Delta T_{e, crit}^{RLW \cdot mod} \|} \right) \text{H} \left( \frac{\Delta T_e / \Delta T_{e, crit}^{RLW \cdot mod}}{1} \right) \]

\[ \Delta T_{e, crit}^{RLW \cdot mod} = \frac{\frac{2}{3} B J B^{-1} \Theta^0.5}{\zeta n T_e^0.5} + \frac{S \Theta e^2}{q \zeta m_e^{0.5}} \]

Only the critical gradients are taken from the IFSPPL and RLW models while the transport coefficients are given by a Heaviside function with a multiplier representing the stiffness. We use 3.5 times the stiffness for ions than for electrons, based on experimental observations.

The particle transport is governed by the Ware pinch and by a diffusion coefficient proportional to the ion and electron heat transport coefficients from the models above everywhere inside the separatrix, with \( D = 0.1(2c_e + c_i) \), i.e. 0.3 times \( c_{\text{eff}} \) if electron and ion transport were equal. The stronger weight of the electron energy transport reflects observations showing an influence of heating on particle transport stronger for electrons than for ions.

At the plasma edge (in the pedestal region), the turbulence is stabilised by a combination of radial electric field shear created by the pressure gradient and magnetic shear. In the model, a stabilisation function (see below) multiplies the relevant heat diffusivities, thereby modifying also the particle diffusion. The pedestal stabilization function is:

\[ c_{E\times B} = c_0 / \left( 1 + \left( v_{E\times B} / g_0 \right)^2 \right)^{0.5} \]

here \( g_0 \) the volume average of \( g_{\text{TG}} \) inside 0.9 of the minor radius, is an estimate for the growth rate in the absence of stabilisation and \( v_{E\times B} \) is the ExB shearing rate. Another possibility may be to increase the power of the stabilizing term in this expression [5]. As the power conducted through the edge rises, the drift Alfven modes disappear, allowing the pressure gradient and its accompanying radial electric field shear to rise. This then stabilises the turbulence where the magnetic shear is high enough, establishing a transport barrier with \( c \) and \( D \) close to ion neoclassical transport and consequently a temperature and density pedestal. The width of the stabilisation depends on the pressure gradient and on the magnetic shear, which in turn is influenced by the developing bootstrap current [6].

In addition to this transport reduction, the particle source function inside the separatrix is important for the pedestal width and the density gradient there, because the radial electric field is defined by the pressure gradient. The particle source inside the separatrix consists of three different mechanisms: thermal neutrals from gas puffing and recycling (temperature of the SOL via charge exchange), neutrals from pellet injection (simulated roughly by assuming a neutral energy for penetration of 2 keV but zero energy gain) and neutrals from beam fuelling. The density gradient in the pedestal is mainly the result of fuelling by the thermal neutrals, and its distribution, together with the pedestal transport, and therefore determines to a large extent the pedestal width. The source rate has been adjusted to agree approximately with B2-EIRENE calculations for each machine investigated (ASDEX-UP, JET). However, for ITER, the source in the ASTRA simulations [6] when central (deep fuelling) and edge sources are equal is more than 3 times the source determined by B2-EIRENE simulations [7], i.e. deep fuelling of more than the edge fuelling will be required for ITER [6].

The pressure gradient in the pedestal is ultimately limited by the ballooning limit using two different ELM models, which are described in more detail elsewhere [6,8]. The model used here is a “continuous ELM model” which means that once the limit is reached the transport parameters are increased such that the pressure gradient stays at the ballooning limit. The bootstrap current was assumed to be half of its calculated value to take account of
loss of the bootstrap current during ELMs. More complex and discrete ELM modes are described in [8,9].

**Results and discussion:** This paper we concentrates on the comparison of the model above to ASDEX-UP and JET discharges as well as on some modelled density and power scans which show a behaviour as observed in the experiments. The predictions for ITER are described elsewhere [6]. The experimental profiles from JET and ASDEX shown in Fig 1 to 4 are the ones used to calibrate and test the model, not necessarily those that match best. The model was also compared to the ITER profile data base and reasonably good agreement to all discharges there was found, i.e. not perfect but similar to other 1-D models However, those models mostly provide the pedestal plasma parameters as a boundary condition (e.g. from experimental data) whereas a self-consistent treatment of the whole plasma is presented here.

Fig. 1 and 2 show reasonably good agreement between the experiment and the modelled electron temperature and density profiles for a 2.5 MA, 8.3 MW heated low triangularity JET H-mode discharge. Also the temperature and density pedestal is well matched. The fuelling in the model is performed by gas puffing and NB injection. The fuelling rate across the separatrix (thermal neutral source term) is broadly consistent with expectations from B2-EIRENE calculations for similar JET discharges. For the discharge shown, the ramp up of density and power, and thus the H-mode transition, was also modelled.

The calculated H-mode transition power shows reasonably good agreement with the H-mode power threshold scaling [10]. The temperature profiles show an initial excursion during this ramp-up and so does energy confinement but after reaching the target density and steady state the energy confinement calculated by the model agrees well with the ITER98y2 scaling relation [10]. A similar level of agreement between model and experiment was found for ASDEX-UP with the same adjustment parameters as for JET (e.g. the ones for the critical gradients). Figure 3 and 4 show reasonably good agreement between modelled and experimental $T_e$ and $n_e$ profiles for a low triangularity ASDEX-UP discharge. Again the source rate inside the separatrix is roughly that predicted by B2-EIRENE for similar discharges. Therefore, a good fit with fuelling only by gas puffing is obtained for JET and ASDEX-UP discharges, whereas ITER [6] certainly requires deep fuelling.
In addition to comparisons with experimental data, a model density and power scan for JET was performed to verify that the general behaviour of plasma parameters and energy confinement is at least qualitatively consistent with experimental observations. As one can see from figures 5 to 7 the drop of energy confinement is consistent (Fig. 6) and the power dependence of energy confinement agrees well with the empirical scaling. The drop of energy confinement with increasing density is due to the changing density gradient in the pedestal caused by a change in the source term when gas puffing is increased (SOL screening).

![Fig. 5: Calculated dependence of energy confinement versus density normalized to ITER98y and y2 [10]](image1)

![Fig. 6: Energy confinement versus density in JET](image2)

![Fig. 7: Calculated energy confinement versus power normalized to ITER98y and y2 [10]](image3)

Generally the model compares rather well to experimental results and also to the general behaviour (e.g. confinement versus density) of H-mode plasmas. Even quantitatively the agreement is reasonably good allowing it to be used as a complimentary predictive tool (to empirical scaling) for ITER as described in more detail in [6]. While certainly several of the transport modules can and will be improved it is important to have a comprehensive model for the whole plasma to make progress in predictions as well as in understanding experimental results and / or to propose dedicated experiments in order to clarify certain physics questions.

This report has been prepared as an account of work performed under the Agreement among the European Atomic Energy Community, the Government of Japan, and the Government of the Russian Federation on Cooperation in the Engineering Design Activities for the International Thermonuclear Experimental Reactor ("ITER EDA Agreement") under the auspices of the International Atomic Energy Agency (IAEA).

[8] O. Zolutukhin, et.al, this conf., (P2.051)