H-MODE OPERATION IN ITER: DETERMINATION OF TRAJECTORIES IN EDGE OPERATIONAL SPACE

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Introduction
The transport model developed to analyse H-mode operation, whose details are described elsewhere [1], is applied to ITER with the 1.5D transport code ASTRA [2], in order to trace out the n-T trajectories in edge operational space. For this study, the effect of edge-localised-modes (ELM's) is treated in a time-averaged manner. The model is calibrated to JET discharges so as to reproduce the global L- and H-mode confinement times, as well as the H-mode power threshold. The H-mode profiles then agree well with the profile shapes obtained experimentally for both JET and Asdex-UG, as does the time evolution of the discharge. When the model is applied to ITER, appreciable core fuelling is required to obtain edge fuelling rates consistent with B2-Eirene modelling and Q=10 operation is then obtained.

Calibration of the model
Anomalous core transport is described by critical gradients for both electrons and ions. The factors in front of the critical gradient expressions, as well as the stiffnesses when the critical gradients are exceeded, are adjusted so as to reproduce JET and Asdex-UG ion and electron temperature profiles. For electrons, the Rebut-Lallia-Watkins critical gradient expression is used, but its value is increased in proportion to the magnetic shear for shear values larger than unity. The critical ion temperature gradient is that appropriate for ITG instabilities.

In the L-mode phase the plasma edge is dominated by Drift-Alfven modes. The size of the associated transport coefficient is one of the factors which is adjusted to give confinement consistent with L-mode scaling. As the power is increased, these modes are suppressed with increasing temperature, leaving only neoclassical transport for ions (and enhanced neoclassical transport for electrons), thus allowing edge gradients to build up. The resulting pressure gradients give rise to ExB shear stabilization of the instabilities in the plasma edge and thus to a transition into ELM-free operation with a further increase of the edge gradients.

The effect of type I or type II ELM s is implemented as a time-averaged ELM model, which limits the pressure gradient to the ballooning limit by increasing transport equally for both electrons and ions when this limit is reached. The associated convective transport coefficient is taken as 30% of the heat transport coefficients.

The details of our transport model, as well as our comparison with experiment, are discussed in another paper at this conference [1]. The time-dependent simulation of ELM s is presented in [3].
ExB shear stabilization and pedestal widths

The anomalous transport coefficients are divided by the expression \(1 + \left(\omega_{E\times B} / \gamma_{ITG}\right)^2\), where \(\gamma_{ITG}\) is estimated as the volume average over the inner 90% of the minor radius. This stabilization is appreciable only in the outer region of the plasma, and is applied to all transport coefficients except neoclassical (and the time-averaged ELM transport). This approach results in a pedestal width calculated self-consistently. The pedestal widths for electron temperature and total pressure in steady state ELMy H-mode are shown in the table.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Experiment</th>
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</thead>
<tbody>
<tr>
<td>Asdex UG</td>
<td>3.8</td>
</tr>
<tr>
<td>JET</td>
<td>4.3</td>
</tr>
<tr>
<td>ITER</td>
<td>10.5</td>
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</tbody>
</table>

JET edge operational space

The model was first applied to the JET scenario presented in [1], where the input power was first ramped up at intermediate densities, resulting in a rapid transition from L to H-mode, followed by a density rampup to the final desired density \(0.6 \times 10^{20} \text{ m}^{-3}\). Reasonable agreement with experimental H-mode profiles was obtained. The trajectories in edge operational space are shown in fig.1 for three different initial densities. The points during and at the end of the transition indicate a boundary in \(n_{ped} T_{ped}\) space for the transition, in good agreement with experiment [5]. The longest scenario shows a rise to the ballooning limit at high \(T\) and low \(n\) after the transition, followed by a trajectory along the ballooning limit to higher density and lower temperature. The limit is low in this case because of the plasma current is low in the chosen discharge (2.55 MA rather than 3.5 MA in [5]).

![Fig.1 Edge operational space for JET](image1)

![Fig.2 Edge operational space for ITER](image2)

Application of the model to ITER

The edge operational diagram for ITER was traced out in the same fashion as for JET, with an external power ramp to 100 MW and no alpha-particle heating. The location of the LH transition is indicated in fig.2, as is the edge parameter regime at the ballooning limit.

For a realistic ITER simulation limited to the available heating power, but including self-consistent alpha particle heating, the transition to H-mode required ramping both the input beam power (initial value 20 MW) and the density (initial value \(0.3 \times 10^{20} \text{ m}^{-3}\)) at the same time, in order to suppress the Drift-Alfven instability by the combined effect of edge...
density and temperature. A well-established H-mode was obtained at $n \approx 0.6 \times 10^{20} \text{ m}^{-3}$ with $P_{\text{beam}} \approx 40 \text{ MW}$.

![Graph](image1)

![Graph](image2)

**Fig. 3** *ITER scenario with edge fuelling only before $t=35s$*

In the first part of the scenario of fig.3, the discharge is fuelled exclusively by gas puffing and by recycling neutrals in the scrape-off layer: this would require a steady-state neutral flux of $\sim 9-10 \times 10^{22} \text{ atoms/s}$ at the final density ($0.9 \times 10^{20} \text{ m}^{-3}$), almost a factor of ten larger than the neutral inflow consistent with B2-Eirene simulations [6]. This large neutral inflow would result in large charge exchange losses from the plasma periphery, depressing the edge ion temperature and would limit the $Q$ to approximately 7 for these conditions because of the stiffness of the ITG transport. This situation is considerably improved if deeper fuelling is provided. At $t=35 \text{ s}$, a core fuelling source is introduced which provides half of the total required particle source with a penetration depth of about 30 cm measured at the midplane. As a result, the pedestal ion temperature rises, allowing an increase of the average temperature which, along with the increased central density, raises $Q$ above 10. This process is accompanied by a decrease in the total required fuelling rate and both core and edge fuelling drop to less than $3 \times 10^{22} \text{ atoms/s}$ ($\sim 50 \text{ Pa-m}^3/\text{s}$ each) for the same average density. Consistency with B2-Eirene edge modelling would require a further decrease of edge fuelling, which should be possible if core fuelling can be increased. The result of fuelling with equal core and edge fluxes throughout the rampup is shown in fig.5, which avoids the high fuelling peak of the scenario of fig. 3.

**Discussion and Conclusion**

Further work requires a detailed comparison of L-mode profiles with experiment, as well as an extension of the comparisons in H-mode to more experimental shots. The detailed
L-mode comparison, as well as the comparison of the dynamics of the L-H transition, will be appropriate once a type III ELM model is included in the simulation. At the present time, the transition by ExB stabilization begins at about 90% of the minor radius and then propagates outward to the separatrix vicinity, illustrated on fig. 4. This behaviour is expected to be modified by type III ELMs.

![Fig. 4](image)

**Fig. 4**  Edge profiles during LH transition in ITER for $T_e$, $j$, and ExB shear reduction factor. The time slices are (increasing $T_e$) before, during, and at end of transition, one-half the density rampup, final state without core fuelling ($Q=7$), and final state with core fuelling ($Q=10$).

The pedestal widths obtained in H-mode, as well as the threshold power for the transition, and the edge operational space are consistent with experimental results. Simulations carried out for ITER show an LH transition with the available input beam power if the density is increased during power rampup to facilitate the transition. The model predicts $Q=10$ operation in ITER (fig.5) if core fuelling is at least as large as edge fuelling.

![Fig. 5](image)

**Fig. 5**  ITER scenario with equal core and edge fuelling

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