Particle transport in TCV H-modes

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Motivation and experimental observations

Results from a database analysis of H-mode density profiles on the Tokamak à Configuration Variable (TCV) in stationary conditions show that the logarithmic electron density gradient slightly increases with collisionality. By contrast, earlier observations of H-modes at JET [1] and AUG [2] showed that the density profiles tend to flatten with increasing collisionality. The aim of this work is to contribute to the understanding of this experimental behaviour of the density profiles.

The experimental database is built on a representative set of sufficiently diagnosed typical H-mode discharges. The typical parameters of the plasmas in the database are shown in Tab. 1. Purely ohmic and third harmonic electron cyclotron resonance heated (X3 ECH) plasmas are included.

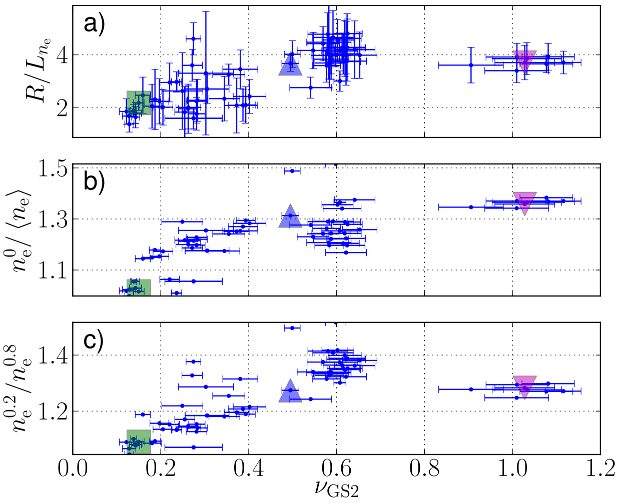

Figure 1: Peakedness of the density profile as the function of the collisionality, measured by the normalized inverse gradient length a), and two common definition of density peaking b), c).

The electron density and temperature profiles are measured via Thomson scattering. Density profile measurements are cross-calibrated with the Far Infrared Interferometer (FIR). The gradient of the profiles are determined by fitting the experimental data with a cubic spline. The local quantities are defined as averages over $0.6 < \rho < 0.8$ region where it was found that the logaritmic gradients are constants and not affected by sawtooth activity. The local quantities are averaged over a stationary phase of the pulse .

Fig. 1 shows the peakedness of the density profile as the function of the collisionality. We adopt the collisionality definition as it is used by the GS2 code [3]. Fig. 1 a) measures the peakedness by the inverse normalized gradient length $R/L_n|_{\mathrm{stat}}$, while b), c) show two other commonly used measures of the peaking factor. Points around $\nu_{\mathrm{GS2}} \approx 1$, high density ohmic heated pulses have a $R/L_n|_{\mathrm{stat}}$ around 4.5. Decreasing ν_{GS2} down to 0.5, $R/L_n|_{\mathrm{stat}}$ stays around 4. The most typical ohmic H-mode pulses fall into this collisionality regime. In the $0.1 < \nu_{\mathrm{GS2}} < 0.5$ range, which is reached by adding 0.5-1.5 MW ECH power, $R/L_n|_{\mathrm{stat}}$ decreases down to 2.

3.7	<	$\langle n_{\mathrm{e}}\rangle_{\mathrm{vol}}\,[10^{19}\mathrm{m}^{-3}]$	<	6.1
0.9	<	T_{e0}[keV]	<	2.5
350	<	I_{p} [kA]	<	420
1.35	<	V [m^3]	<	1.55
150	<	P_{OH} [kW]	<	600
250	<	P_{ECH} [kW]	<	1000
		$\delta_{\mathrm{edge}} \approx 0.45$, $\kappa_{\mathrm{edge}} \approx 1.7$		

Table 1: Typical parameters of the TCV H-modes

Theoretical model

We use the quasi-linear gyrokinetic model presented in [4]. We solve the linear gyrokinetic (GK) equation for electrostatic perturbations with a wavenumber $\mathbf{k} = (0, k_y)$ using shifted - circles $s-\alpha$ equilibria and obtain ω_{R}^k, γ^k, Γ^k, the real and imaginary part of the mode frequency and the particle flux, respectively. $\omega_{\mathrm{R}}^k > 0$ represents a mode turning in the ion diamagnetic (ITG) direction, while $\omega_{\mathrm{R}}^k < 0$ corresponds to the electron diamagnetic direction (TEM).

The results of the linear simulations cannot be applied directly to the fully developed, saturated, turbulent state. ω_{R}^k, γ^k, Γ^k are evaluated on a range of k_y . We then obtain the fluxes and the mode frequency of the turbulent state by a weighted average over the mode spectrum:

$$\omega_{\mathrm{R}}^{\mathrm{QL}} = \frac{\sum_k w_k \omega_{\mathrm{R}}^k}{\sum_k w_k}, \qquad \text{with} \quad w_k = A_0 \left(\frac{\gamma}{\langle k_\perp^2 \rangle} \right)^{\xi} \Delta k_y.$$

Γ^{QL} is obtained in the same way from Γ^k. The w_k weights are usually chosen according to a quasi-linear rule. In our case $\xi = 2$, $A_0 = 1$, Δk_y takes into account the choice of a non-uniform grid in k_y. The GK equation is solved by the initial value flux-tube code GS2 [3].

In the absence of core particle sources the stationary state requires that: $\Gamma^{\mathrm{QL}} = 0$. This condition is used to find $R/L_n|_{\mathrm{stat}}$ i. e. the stationary value of the normalized electron density gradient which can be compared to the experimentally observed values.

Simulation results

We perform our simulations with the following parameters (*standard case*): $\varepsilon = 0.230$, $q = 1.2$, $s = 0.7$, $R/L_{T_e} = 9$, $R/L_{T_i} = 6.5$, $Z_{\mathrm{eff}} = 1$. The Shafranov-shift parameter α is self consistently evaluated with $n_{\mathrm{e}} = 5 \times 10^{19}$ m^{-3} and $T_{\mathrm{e}} = 1$ keV.

A series of simulations has been performed scanning $\nu_{\mathrm{GS2}} = [0.1\ldots 1.2]$ together with a scan in $T_{\mathrm{e}}/T_{\mathrm{i}} = [1.5, 2]$. 3 k_y values used in the range of $[0.08, 1.2]$. The number of k_y values is small in order to obtain the basic trend while reducing the CPU necessity. The results are summarized in Fig. 2 which shows the particle flux Γ^{QL} (multiplied by a factor 5 because of visualisation reasons) and the mode frequency $\omega_{\mathrm{R}}^{\mathrm{QL}}$ as a function of the density gradient R/L_n for different ν_{GS2} (rows) and $T_{\mathrm{e}}/T_{\mathrm{i}}$ (columns).

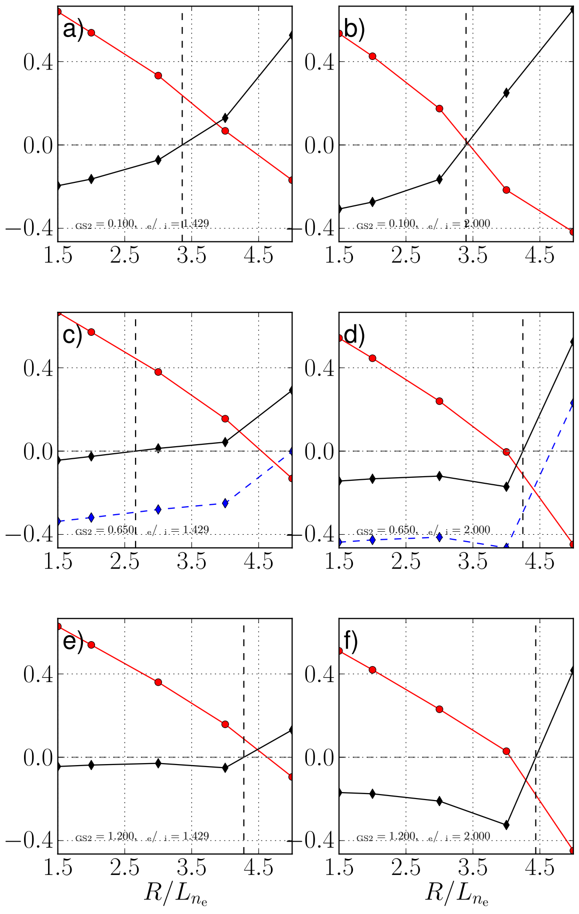

Figure 2: Particle flux Γ^{QL} (black circles), and mode frequency $\omega_{\mathrm{R}}^{\mathrm{QL}}$ (red diamonds) as the function of the density gradient for different ν_{GS2} (0.1, 0.650, 1.2) and $T_{\mathrm{e}}/T_{\mathrm{i}}$ (1.43, 2) values.

At lower density gradients the particle flux points inwards (negative values) when the mode frequency is positive (ITG) it crosses the $\Gamma^{\mathrm{QL}} = 0$ (marked with vertical dashed lines) line when $\omega_{\mathrm{R}}^{\mathrm{QL}} \approx 0$ [4] then going towards larger R/L_n values it points outwards, the mode frequency becomes negative (TEM). Note that when ITG modes are dominant the slope of the particle flux hardly changes with the density gradient. On the other hand, since TEM is driven by the density gradient the particle flux is very sensitive to it. Note that $\omega_{\mathrm{R}}^{\mathrm{QL}} \approx 0$ at $\Gamma^{\mathrm{QL}} = 0$ is consistent with the results of [4].

Increasing the collisionality, ITG modes become dominant (Γ^{QL} flattens), collisions are more stabilizing to TEM. The stationary value of the density gradient corresponding to $\Gamma^{\mathrm{QL}} = 0$ becomes more sensitive to the changes in other parameters for example to the temperature ratio. In this case a finer resolution in k_y is necessary. Increasing $T_{\mathrm{e}}/T_{\mathrm{i}}$ the shape of the Γ^{QL} curve is conserved, the particle flux increases more at higher collisionality.

In ohmic plasmas the neoclassical Ware-pinch can have significant contribution to the density peaking. The strength of this effect depends also on the turbulence regime. In case of the presence of the Ware-pinch one needs to find $R/L_n|_{\mathrm{stat}}$ from: $\Gamma^{\mathrm{QL}} + n_{\mathrm{e}} W_{\mathrm{p}} = 0$. We divide with the turbulent heat flux q^{QL}

$$\frac{\Gamma^{\mathrm{QL}}}{q^{\mathrm{QL}}} + \frac{n_{\mathrm{e}} W_{\mathrm{p}}}{q^{\mathrm{QL}}} = 0,$$

then we rewrite the second term assuming: $q^{\mathrm{QL}} = \lambda Q_{\mathrm{exp}}$, where

$$Q_{\mathrm{exp}} = -\chi_{\mathrm{e}}^{\mathrm{PB}} n_{\mathrm{e}} \nabla T_{\mathrm{e}} = \chi_{\mathrm{e}}^{\mathrm{PB}} \frac{R}{L_{T_e}} \frac{n_{\mathrm{e}} T_{\mathrm{e}}}{R}.$$

Finally

$$\frac{\Gamma^{\mathrm{QL}}}{q^{\mathrm{QL}}} + \frac{R W_{\mathrm{p}}}{\lambda \chi_{\mathrm{e}}^{\mathrm{PB}} \frac{R}{L_{T_e}}} = 0, \tag{1}$$

from which one can find the stationary density gradient value with the Ware-pinch effect included. Note that $W_{\mathrm{p}} < 0$. The first term is evaluated numerically, while the second term comes from the experiments.

In Fig. 2 b), c) the Ware-pinch contribution is added to the particle flux according to Eq. 1. Typical TCV ohmic H-mode parameters used: $\chi_{\mathrm{e}}^{\mathrm{PB}} = 1$ m^2/s, $R/L_{T_e} = 9$, $R = 0.88$ m. The λ parameter was set to 0.5. It can be seen that the shape of the Γ^{QL} curve strongly influences the position of the new value of $R/L_n|_{\mathrm{stat}}$.

Conclusions

The $\Gamma^{\mathrm{QL}} = 0$ stationary condition is set by the subtle balance between ITG and TEM modes as obtained in L-mode simulations [4]. Depending on the turbulence regime the dependence of R/L_n on the collisionality, temperature ratios can be very different. The neoclassical Ware-pinch also can contribute to the peaking in certain conditions typically when the stationary point lies in an ITG dominated regime. Note that $\chi_{\mathrm{e}}^{\mathrm{PB}}$ is larger in ECH H-modes and therefore the Ware-pinch is reduced.

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