Understanding the core density profile in TCV H-mode plasmas

D Wágner, E Fable¹, A Pitzschke, O Sauter, H Weisen and the TCV team

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Station 13, CH-1015 Lausanne, Switzerland

E-mail: david.wagner@epfl.ch

Received 17 October 2011, in final form 26 April 2012
Published 6 July 2012
Online at stacks.iop.org/PPCF/54/085018

Abstract

Results from a database analysis of H-mode electron density profiles on the Tokamak à Configuration Variable (TCV) under stationary conditions show that the logarithmic electron density gradient increases with collisionality. By contrast, usual observations of H-modes showed that the electron density profiles tend to flatten with increasing collisionality. In this work it is reinforced that the role of collisionality alone, depending on the parameter regime, can be rather weak, and in these dominantly electron heated TCV cases, the electron density gradient is tailored by the underlying turbulence regime, which is mostly determined by the ratio of the electron to ion temperature and that of their gradients. Additionally, mostly in ohmic plasmas, the Ware-pinch can significantly contribute to the density peaking. Qualitative agreement between the predicted density peaking by quasi-linear gyrokinetic simulations and the experimental results is found. Quantitative comparison would necessitate ion temperature measurements, which are lacking in the considered experimental dataset. However, the simulation results show that it is the combination of several effects that influences the density peaking in TCV H-mode plasmas.

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years numerous works have been devoted to particle transport studies (see the most recent review [1] and references therein). The experimental observations and the theoretical predictions show a good overall agreement. It is now widely accepted that the electron density profile in the core of tokamak plasmas is mainly tailored by turbulent mechanisms. The turbulent state present in the plasma is intimately related to the density peaking and its dependence on the plasma parameters. In this work we apply a unified quasi-linear theory of ion temperature gradient (ITG) and trapped electron mode (TEM) microinstabilities and turbulence [2] that has emerged in the last years to a very specific problem, namely the density profile behaviour in Tokamak à Configuration Variable (TCV) core plasmas. The success of quasi-linear theory in explaining particle transport in TCV L-mode and eITB plasmas [2, 3] motivates us to test the theoretical predictions against an H-mode dataset as well, using the same methodology. Our goal is to reproduce the observed experimental trends with numerical simulations and understand which transport mechanisms are influential on the density peaking.

Alcator C-Mod internal transport barriers (ITBs) with very strongly peaked density profiles showed density profile flattening with modest electron heating, which was explained by the onset of TEM turbulence, using linear and non-linear gyrokinetic simulations [4]. The density peaking in the C-Mod ITBs was thought to result from the Ware-pinch, with the ITB density gradient during electron heating determined by the balance of Ware-pinch and TEM turbulent fluxes, thus acquiring a strong inverse dependence on temperature. In TCV electron ITBs, where transport barriers are seen mainly on the electron temperature profile [5], the density peaking results from a strong thermodiffusive pinch [6] component which can be explained [3] using the quasi-linear model that will be used in this paper.

The first experiments on TCV with third-harmonic X-mode electron cyclotron resonance heating (X3 ECH) [7, 8]
reported reduction of peakedness of the density profile when intense electron heating was applied. A preliminary study [9] of these plasmas concluded that the density peaking is mainly caused by turbulent processes and suggested that the intense electron heating being favourable for TEM destabilization can possibly lead to profile flattening. In recent experimental campaigns of TCV, new data have been collected on ohmic (OH) and ECH H-modes, repeating the very first experiments and also exploring a wide parameter range. These experiments, where special attention was made to the quality of the collected data, allow us to better explore the experimental dependences and to have more confidence in validation of the theory. The experimental dataset is used to test the quasi-linear model proposed in [2]. Our work is complementary to the recent study with ASDEX-Upgrade (AUG) data [10].

In the next section a brief overview of the TCV H-mode experiments is given with a particular attention to the typical parameter ranges within which these plasmas are sustained. In section 3 the theoretical model that is used for the interpretation of the experiments is summarized. In section 4 the results of the simulations are discussed and compared with the experimental observations. Finally, in section 5, a general discussion and concluding remarks are given.

2. TCV H-mode plasmas

In TCV ($R = 0.88$ m, $a = 0.25$ m, $I_p \leq 1$ MA, $B_t \leq 1.5$ T, $\kappa \leq 2.8$), L-mode to H-mode transitions are obtained with and without additional heating [11, 12]. The additional heating is provided by a powerful third-harmonic electron cyclotron heating system (X3 ECH, 118 GHz, $3 \times 0.5$ MW, 2 s, top launch) [7]. In this work we focus on standard ELMy H-modes with type I and type III ELMs with typical ELM frequencies around 35–100 Hz. Time traces of a typical pulse are shown in figure 1. More ‘exotic’ scenarios such as the quiescent ELM-free [8] and snowflake [13] H-mode scenarios are beyond the scope of this paper and not considered in the analysis.

The experimental database is built on a representative set of sufficiently diagnosed H-mode deuterium pulses. Some typical parameters of these plasmas in the database are shown in table 1. The dataset contains pulses with OH only and those with additional X3 ECH, the different power levels are relatively well covered. The dataset is somewhat less extended in terms of changes in plasma current and contains plasmas with very similar shape.

The majority ion species is deuterium and the most abundant impurity is carbon, originating from the wall tiles. The typical carbon concentration is a few per cent of the total (OH plus bootstrap) current, assuming neoclassical conductivity with the measured $Z_{\text{eff}}$ value, is consistent with the magnetic measurements.

![Figure 1. Time traces of (a) $D_e$ emission; (b) central and peripheral FIR chords; (c) central electron and ion ($C_{\alpha}$) temperature; (d) OH and ECH power. The stationary profiles are taken from the shaded intervals 1.2–1.4 s and 1.46–1.6 s.](image)

Table 1. Typical parameters of the TCV H-modes.

| Parameter | Value |
|-----------|-------|
| $\langle n_e \rangle_{\text{OH}}$ | $10^{20}$ m$^{-3}$ |
| $T_{\text{OH}}$ | 2.5 keV |
| $P_{\text{ECH}}$ | 1000 kW |
| $\delta_{\text{edge}}$ | 0.45, $\kappa_{\text{edge}}$ | 1.7, $q_{95}$ | 2.4 |

2.1. Density and electron temperature measurements

The electron density and temperature profiles are measured via Thomson scattering. Density profile measurements are cross-calibrated with the far infrared interferometer (FIR). Typical temperature and density profiles are depicted in figure 2. The radial flux label throughout this paper is $\rho_\psi = \sqrt{(\psi - \psi_0)/(\psi_b - \psi_0)}$, where $\psi$ is the poloidal flux, $\psi_0$ and $\psi_b$ are the poloidal flux at the magnetic axis and the plasma boundary, respectively. The derivatives of the profiles with respect to $\rho_\psi$ are determined from cubic spline fits. The fit was performed on profiles collected during a stationary phase.
Figure 2. Profiles comparing conditions with OH heating only (diamonds, #38012 1.46–1.6 s) to those with additional 350 kW (squares, #40089, 0.7–1.61 s), 675 kW (triangles, #38012 1.2–1.4 s) ECH. (a) electron density, (b) electron temperature, ion temperature (points, #40089, 0.7–1.61 s). Solid lines show the piecewise polynomial fits which were used to compute the gradients. The shaded areas mark the confidence intervals corresponding to 95% confidence level. The dashed line represents \( T_i(0.8)(T_e/T_e(0.8))^{0.5} \) (#40089, 0.7–1.61 s).

Figure 3. Profiles of the normalized logarithmic gradients calculated from the piecewise polynomial fits depicted in figure 2. The shaded areas mark the confidence intervals corresponding to 95% confidence level.

of pulses, i.e. where the main plasma parameters (plasma current, line-averaged density, internal inductance) do not change significantly. The normalized inverse scale length (normalized gradient) of a profile is defined as \( R/L_X = -R/|\nabla_{\rho\psi}| \delta \log X/\delta \rho\psi \), where \( R \) is the major radius and the \( |\nabla_{\rho\psi}| \) is the Jacobian of the \( r \rightarrow \rho\psi \) coordinate transformation with \( r \) being the distance from the magnetic axis on the outboard midplane. The profiles of the normalized gradients are shown in figure 3.

All the considered pulses exhibited sawtooth patterns. This results in flat average profiles within \( \rho\psi \approx 0.4–0.6 \) surface, depending on \( I_p \).

2.2. Ion temperature measurements

The C6+ ion temperature is measured by charge-exchange recombination spectroscopy (CXRS) [15]. Neutral particle analysers (NPA) [16] provide estimates of the central ion temperature. In these H-mode plasmas, however, due to geometrical constraints, the ion temperature measurements are limited outside \( \rho\psi \approx 0.8 \). This fact, strictly speaking, does not allow us to measure the ion temperature profile in the core.

Figure 2(b) also shows a typical ion temperature profile between \( \rho\psi = 0.8 \) and 1 overlaid on the electron temperature profiles. The ion temperature does not change significantly
when the ECH is applied. From these typical profiles the local value of $T_e/T_i$ at $\rho = 0.7$ ($\rho_{95} \approx 0.6$) is around 1 for phases with OH heating only, and about 2 for phases with ECH.

The present ion temperature data suggest that the ITG form is lower than that of the electrons. Assuming the functional form $T_i(\hat{\rho})(T_e/T_i(\hat{\rho}))^{\nu}$ for the ion temperature profile, the relation $R/L_{T_i} = \nu R/L_{T_e}$ follows. In figure 2(b) the dashed curve, derived from the electron temperature profile of #40089 using $\hat{\rho} = 0.8$ and $\nu = 0.5$, follows rather well the ion temperature measurements outside $\rho_{th} \approx 0.8$. Following these considerations we estimate $R/L_{T_i}$ to be around 3–5 at $\rho_{th} = 0.7$.

### 2.3. Collisionality dependence

Statistical analysis of JET [17] and AUG [18] showed that collisionality is the most important scaling parameter for density peaking in H-modes. Both machines report the flattening of the density profile with increasing collisionality. Note that in these machines collisionality is controlled by the combination of neutral beam injection (NBI) heating and ECH. Despite its complexity, collisionality is a frequently used parameter to map parameter dependences and for inter-machine comparisons. In this subsection the collisionality dependence of the density and temperature profile peaking is presented.

Later (in section 4), the results of the numerical modelling will be presented as a function of the following definition of collisionality:

$$\hat{\nu} = \nu_{ei}/(\nu_{th}/R),$$

where $\nu_{ei}$ is the electron–ion collision frequency, $\nu_{th} = \sqrt{T_i/m}$ the thermal velocity and $R$ the major radius. In order to facilitate the comparison with previous results the experimental dependences are also plotted as a function of an effective collisionality adopted from [19]:

$\nu_{eff} = 0.1 n_e Z_{eff} R/T_e^2 (\approx \nu_{ei}/\nu_{th})$, where $n_e$, $T_e$ are the electron density in $10^{19} \text{m}^{-3}$ and the electron temperature in keV with $Z_{eff} = 2$.

Figure 4 shows the normalized logarithmic gradients of the electron temperature ($R/L_{T_e}$) and density ($R/L_n$) profiles at $\rho_{th} = 0.7$ as a function of collisionality $\hat{\nu}$ and $\nu_{eff}$. Points around $\hat{\nu} \approx 0.02$, the most typical TCV OH H-mode pulses, have $R/L_n$ around 3. Samples from reversed field campaigns with unfavourable ion $\nabla B$ drift direction with somewhat higher density are located at around $\hat{\nu} = 0.03$ having $R/L_n \approx 3.5$. In the $0.008 < \hat{\nu} < 0.02$ range, which is reached by adding 0.5–1.5 MW ECH, $R/L_n$ decreases to about 1.5.

Note that the global trend of $R/L_n$ as a function of the collisionality is very similar to the one observed on FTU fully non-inductive, high density electron heated plasmas [20]. By contrast, H-modes at JET [17] and AUG [10] showed that $R/L_n$ is decreasing with increasing collisionality.

### 3. Theoretical model

In [2] a quasi-linear gyrokinetic framework has been proposed for particle transport with which TCV L-mode plasmas and electron ITBs [3] were studied extensively. In this paper we strive to test this model against TCV H-mode data to understand the density profile behaviour. Although there is no general agreement in the community on the applicability of different quasi-linear models, significant effort has been made to compare various models against non-linear simulations [21–24] and good agreement has been found. It was also shown that the fully developed turbulence preserves many features of the linear evolution [22], therefore with an ad hoc weighting of the linear spectra, non-linear fluxes can be acceptably reproduced [23]. Moreover, quasi-linear predictions fit very well to experimental observations [2, 3, 10]. A relevant exception to this occurs near marginal stability, where a non-linear upshift of the TEM critical density gradient has been found [4], which increases with collisionality [25]. This effect is clearly outside the framework of quasi-linear theory. EC heated experiments are in general not near marginal stability to temperature gradient-driven TEMs [26] with $R/L_{T_e} \approx 8$ [27] but may be near marginal stability to longer wavelength density gradient-driven TEMs [4]. In our dataset, $R/L_n$ ranges from about 1 to approximately 3.5, with the upper value lying above...
We solve the linear gyrokinetic (GK) equation for electrostatic perturbations with a wavenumber $k = (0, k_y)$ to obtain $\omega_k^r$, $\gamma_k$, $\Gamma_k$, the real and imaginary part of the mode frequency and the particle flux, respectively, of the most unstable mode. $\omega_k^r > 0$ represents a mode turning in the ion diamagnetic (ITG) direction, while $\omega_k^r < 0$ corresponds to the electron diamagnetic direction (TEM).

$\omega^r_k$, $\gamma_k$, $\Gamma_k$ are evaluated on a range of $k_y$. We then obtain the quasi-linear fluxes and the average mode frequency of the turbulent state by a weighted average over the mode spectrum:

$$\langle R \rangle = \frac{\int_0^k w_k R^k \, dk}{\int_0^k w_k \, dk},$$

where $R$ can stand for $\Gamma^k$, $q^k$, $\omega^k$. The $w_k$ weights are usually chosen according to a quasi-linear rule of the form

$$w_k = A_0 \left( \frac{\gamma}{k_y^2} \right)^{\xi}.$$
In order to separate the different mechanisms that are responsible for the density peaking, one can decompose the particle flux such as

$$\Gamma = A \frac{R}{L_n} + B \frac{R}{L_T},$$

(4)

which, assuming stationary plasma and using the zero flux condition when no particle sources are present (as is the case in the core of these ECH/OH plasmas), transforms into

$$\frac{R}{L_n} \bigg|_{\text{stat}} = -C_T \frac{R}{L_T} - C_P.$$

The thermodiffusion coefficient $C_T = -B/A$ and the other pinch coefficient $C_P = -C/A$ are evaluated numerically [2, 3].

4. Simulation results

4.1. Setup for the simulations

Linear gyrokinetic calculations have been performed with the initial value flux-tube code GS2 [28]. We introduce two model cases representing TCV OH and ECH H-mode pulses. For both $R/L_T = 9$, $R/L_n = 6$, $Z_{\text{eff}} = 2$. For the OH reference case $T_e/T_i = 1.0$, $\nu = 0.024$, for the ECH case $T_e/T_i = 2.0$, $\nu = 0.008$ (see section 2.1).

The magnetic equilibrium of a representative discharge (see figure 1) was calculated by the equilibrium code CHEASE [29]. The $\rho_0 = 0.7$ flux surface with $q = 1.2, s = 0.7$ was used for flux-tube simulations. For the collisions both pitch angle scattering and energy diffusion are taken into account. 13 $k_y$ values are used in the range [0.08, 1.6] distributed in a logarithmic way. All growth rates and frequencies are normalized to $v_{\text{th}}^2/R$. The binormal wavenumber $k_y\rho_0$ is normalized to $\rho_0$, the normal wave number is always zero ($k_x = 0$). Note that on the outboard midplane the normal direction is radial. The timestep was fixed to $\Delta t = 0.05$ in units of $R/v_{\text{th}}^2$, 32 grid points for each $2\pi$ turn in $\theta$, and 12 poloidal periods were used. The parameters are then scanned according to the various simulation results presented in the next subsections.

4.2. Finding the stationary density gradient

In the absence of core particle sources, as is the case in the TCV OH/ECH H-modes [30], the stationary value of the density gradient $R/L_n|_{\text{stat}}$ corresponds to the $\Gamma = 0$ condition. Here we only consider the particle flux ascribed to turbulence, we shall deal with neoclassical contributions later, in section 4.5. Other contributions to the total particle flux (e.g. MHD, ripple losses, etc) are neglected. It is also assumed that these approximations hold under both OH and ECH conditions. $R/L_n|_{\text{stat}}$ is obtained by making a set of simulations for different values for $R/L_n$, keeping all the other input parameters fixed. At each $R/L_n$, $\langle \Gamma \rangle$ is evaluated with equation (2). Then the zero point is found by linear interpolation.

In order to understand the relationship between the linear and quasi-linear fluxes, in figure 5 we show the different contributions in equation (2) together with the mode frequency and growth rate of the most unstable mode as a function $k_y\rho_0$ for the OH reference case. First we note that the quasi-linear rule gives small weight at large wavenumbers (short scales), therefore $\langle \Gamma \rangle$ and $\langle \omega_0 \rangle$ are mainly determined by the $k_y\rho_0 < 0.4-0.5$ wavenumber range (ITG and TEM range).

When the density gradient $R/L_n$ is small (figures 5(a) and (b)), the most unstable modes are ITGs (positive $\omega_0$), the $w_{\|}\Gamma^k$ contributions to $\langle \Gamma \rangle$ throughout the covered wavenumber range is negative (inwards), making $\langle \Gamma \rangle$ pointing unambiguously inwards. Increasing $R/L_n$ (figures 5(c) and (d)), the growth rate of the most unstable modes decreases and at low $k_y\rho_0$, $w_{\|}\Gamma^k > 0$ contributions appear, making $\langle \Gamma \rangle = 0$ when $R/L_n = R/L_n|_{\text{stat}}$ is reached. Further increasing $R/L_n$ (figures 5(e) and (f)) the mode frequency changes sign and TEM modes appear at small wavenumbers. When these modes dominate, the particle flux $\langle \Gamma \rangle$ is positive (outwards).

Figure 6 shows the quasi-linear particle flux $\langle \Gamma \rangle$ normalized to the total electron heat flux as a function of $R/L_n$ for the two reference cases. Each point in the figure is a result of 13 simulations (averaged over the $k_y$ spectrum as in figure 5). The average mode frequency $\langle \omega_0 \rangle$ is also plotted showing that, indeed, the zero flux point is found between ITG and TEM type modes [2]. Note the role of ITG–TEM balance at a certain density gradient in the spectrum and also in adjusting the value of $R/L_n|_{\text{stat}}$. It also must be stressed that at the co-existence of different modes, one must certainly account for non-linear effects [4, 24, 25, 31]. It is not expected that the absolute value of $R/L_n|_{\text{stat}}$ from the quasi-linear estimate of the particle flux instantly matches the experimental values; however, its parametric dependence on the plasma parameters is remarkably well retained [2, 3, 10].

4.3. $v_{\text{eff}}-T_e/T_i$ scan

We endeavour to reproduce the collisionality dependence reported in section 2.3 with numerical simulations. Since in TCV H-mode experiments collisionality is mainly controlled by intense electron heating, the $T_e/T_i$ ratio certainly increases with additional ECH. It is expected that the temperature ratio has a significant effect on the nature of the dominant instabilities and hence on the particle flux. We also want to explore the effect of the electron–ion collisions at each considered temperature ratio. Therefore, we perform a double parameter scan in the range $\nu = [0.008, 0.012, 0.016, 0.020, 0.024]$ together with a scan in $T_e/T_i = [1, 1.5, 2]$. The results are summarized in figure 7(a), which shows the predicted value of the density gradient $R/L_n|_{\text{stat}}$ as a function of the collisionality $\nu$. Each point is obtained from a scan over $R/L_n$ to determine $R/L_n|_{\text{stat}}$ where $\langle \Gamma \rangle = 0$. Therefore, each point in figure 7 is the result of about $10 \times 13$ linear simulations. When $T_e/T_i = 1.0$ the predicted density gradient is decreasing with collisionality. As the temperature ratio is increased, this trend is reversed and at $T_e/T_i = 2.0$ an increase in $R/L_n|_{\text{stat}}$ is predicted with increasing $\nu$. These results show a clearer trend (figure 7(b)) if one now plots $R/L_n|_{\text{stat}}$ as a function of $\langle \omega_0 \rangle$ which characterizes the nature of the background turbulence
Figure 6. Quasi-linear particle flux $\langle \Gamma \rangle$ (diamonds) and average mode frequency $\langle \omega_r \rangle$ as a function of $R/L_n$; (a) OH reference case ($T_e/T_i = 1.0$, $\nu = 0.024$), (b) ECH reference case ($T_e/T_i = 2.0$, $\nu = 0.008$).

Figure 7. Predicted values of $R/L_n$ for different values of the temperature ratio $T_e/T_i$, as a function of (a) the collisionality $\nu$ and (b) the average mode frequency $\langle \omega_r \rangle$.

and orders very well the predicted values of $R/L_n|_{\text{stat}}$ [2, 10] and also clearly shows that the change in the dominant instabilities alters the collisionality dependence. Therefore, an explanation of the different behaviour of TCV H-modes with respect to JET/AUG plasmas can be due to the different $T_e/T_i$ ratios and hence a different collisionality dependence.

Collisionality provides a purely convective term to the particle flux [1] which is directed outwards for ITG and inwards for TEM modes and increases with increasing collisionality. Intuitively one expects that increasing $\nu$ tends to push $\omega_r$ towards more positive values [1] (towards ITG type turbulence) due the stabilizing effect of collisions on TEM turbulence [4, 32]. The net effect of collisionality on $R/L_n|_{\text{stat}}$ stems from these two effects: $\nu$ influences the turbulence regime and, depending on the turbulence regime, the particle flux. Since an increase in collisionality implies an increase in the real mode frequency, the effect of the collisionality on the TEM mode-driven outward flux is expected to be weak [1]. Indeed, in figure 7 we observe almost no collisionality dependence at $T_e/T_i = 1.5$, where $\langle \omega_r \rangle \approx 0$. Moving away from this point towards either more positive or more negative $\langle \omega_r \rangle$, the net particle flux is less inwards, and $R/L_n|_{\text{stat}}$ is found at a lower gradient. The increase in $T_e/T_i$ at fixed $T_i$ is destabilizing for ITG and enhances the TEM [33] activity as well. Their interplay is such that TEM takes over rapidly with increasing $T_e/T_i$, in particular with ECH, i.e. by increasing $T_e$ [34]. Indeed, starting from the OH reference point in the ITG instability domain, with increasing $T_e/T_i$ and decreasing...
\( \hat{\nu}, \langle \alpha_i \rangle \) decreases and the predicted value of \( R/L_n|_{stat} \) is increasing. In the transition region between ITG and TEM, the largest \( R/L_n|_{stat} \) is obtained, then moving towards the TEM domain the density peaking decreases, leaving the point corresponding to the ECH reference case with a very similar \( R/L_n|_{stat} \) value.

We conclude that, although ECH has a significant effect on the values of \( \hat{\nu} \) and \( T_e/T_i \), the change in these parameters only is not sufficient to explain the observed overall experimental behaviour.

**4.4. \( R/L_{T_e} \) and \( R/L_{T_i} \) dependence**

It is expected that the temperature gradients have a large effect on the predicted value of the density gradient. As was pointed out in section 2.2, the ITG is generally lower than that of the electrons even at the high collisionality OH plasmas. The ions are even more decoupled from the electrons when intense electron heating is applied. Thus we expect that \( R/L_{T_e} \) does not change significantly in these plasmas (more precisely it does not increase). The experimental data are more clear on the \( R/L_{T_i} \) dependence; however, it is useful to study the dependences on the parameter, as well.

Two scans of \( R/L_{T_e} \) in the range [6, 7.5, 9, 10.5, 12] have been performed: the first with OH only parameter set \( (T_e/T_i = 1.0, \hat{\nu} = 0.024) \); the second with ECH parameter set \( (T_e/T_i = 2.0, \hat{\nu} = 0.008) \). The other parameters were kept fixed (see section 4.1). In the same way, we change the value of \( R/L_{T_i} \) in the range [4, 5, 6, 7.5, 9].

In figure 8 we present the results of these four scans in terms of \( \eta_{ei} = (R/L_{T_e})/(R/L_{T_i}) \). Figure 8(a) shows that the change in \( R/L_{T_e} \) has a different effect on the OH and the ECH reference cases. Indeed, starting with the OH reference case (triangles), increasing \( R/L_{T_e} \) predicts smaller \( R/L_n \). On the other hand, this parameter has the opposite effect on the predicted peaking for the ECH case. In figure 8(b), it is shown that increasing \( R/L_{T_i} \) increases \( R/L_n \) for the OH case, while the density peaking is rather insensitive to the change in the electron temperature gradient for the ECH case.

In figure 9 we decompose the predicted \( R/L_n \) in terms of \( C_T \) and \( C_P \) as in equation (5) in order to identify the change in the thermodiffusive and the other contributions. We see that the larger contribution is always the thermodiffusive pinch \( C_T R/L_{T_i} \) and usually the two pinches change in the opposite direction and a complicated interplay between the two yields the predicted \( R/L_n \). This means that the parametric dependence of the density peaking is largely determined by the starting reference parameters as mentioned above.

In figure 10(a) we plot these results against \( \langle \alpha_i \rangle \) which, again, orders very well the simulation results [2, 10]. As was already shown in section 4.3, the OH reference (shaded triangle) case is in the ITG regime \( \langle \alpha_i \rangle > 0 \), while the ECH (shaded square) reference case is predicted to be more TEM \( \langle \alpha_i \rangle < 0 \). Increasing the electron temperature gradient results in moving to the left on the \( \langle \alpha_i \rangle \) axis (towards negative values), while the ITG pushes towards larger \( \langle \alpha_i \rangle \) values. The density peaking is maximal around \( \langle \alpha_i \rangle \approx 0 \) and the predicted value decreases towards both ITG and TEM regime as predicted for eITB and L-mode parameters [2, 3].

As mentioned in section 2.2, the ion temperature measurements indicate that \( (R/L_{T_e})/(R/L_{T_i}) \approx 0.5 \), although we do not have measurements near \( \rho_i = 0.7 \), where we have based our analysis. If this ratio is further decreased in the simulations, moving left in figure 10(a), the value of \( R/L_n|_{stat} \) decreases, following the trend seen previously. However, the range of \( k_y \rho_i \) where the ITG is the most unstable mode (typically \( k_y \rho_i = 0.1–0.6 \)) shrinks and slab-like electronic
modes very elongated along the magnetic field lines appear as seen in [35, 36]. Although their contribution to the particle flux is small, so is that of the remaining ITG and TEM. This domain requires non-linear simulations and the role of non-adiabatic passing electrons to be studied in detail, which is left for further analyses.

4.5. Effect of the Ware-pinch

In OH plasmas, the neoclassical Ware-pinch can have a significant contribution to the density peaking [4, 37]. The strength of this effect depends also on the heating scheme applied [4, 10]. In the presence of the Ware-pinch, one needs to find $R/L_n|_{\text{stat}}$ from: $\Gamma + n_e W_p = 0$ [4]. In order to cancel normalization factors, it is more convenient to use the $\Gamma/Q_e$ ratio; therefore, we divide by the electron heat flux $Q_e$:

$$\frac{\Gamma}{Q_e} + \frac{n_e W_p}{Q_e} = 0.$$  

We evaluate the first term using the ratio of the normalized fluxes $\langle \Gamma \rangle / \langle Q_e \rangle$ (which is proportional to $T_e \Gamma/Q_e$) from numerical simulations, while the second term is computed from experimental measurements using $Q_e = Q_{e,\text{exp}}$ and power balance (PB) arguments assuming a stationary plasma, where

$$Q_{e,\text{exp}} = -\lambda_c^{\text{PB}} n_e T_e = \lambda_c^{\text{PB}} \frac{R}{L_T} \frac{n_e T_e}{R}.$$  

![Figure 9](image9.png)

Figure 9. Thermodiffusive $-C_T R/L_T$ and the other pinch $-C_P$ contributions to the predicted value of $R/L_n$ (see figure 8) as a function of the temperature gradient ratio $L_T/L_e$, changing $R/L_T$ (solid) and $R/L_e$ (dashed). Different symbols indicate different heating phases, with OH only (triangles) and ECH (squares). The larger shaded symbols show the reference cases.

![Figure 10](image10.png)

Figure 10. The predicted value of $R/L_n$, the thermodiffusive $-C_T R/L_T$ and the other pinch $-C_P$ contributions as a function of the average mode frequency $\langle \omega_r \rangle$ changing $R/L_T$ (solid) and $R/L_e$ (dashed). Different symbols indicate different heating phases, with OH only (triangles) and ECH (squares). The larger shaded symbols show the reference cases.
We find
\[
\frac{\langle \Gamma \rangle}{\langle Q_e \rangle} + \frac{R W_p}{\chi_e^{PB} R/L_T} = 0, \tag{8}
\]
from which one can find the stationary density gradient value with the Ware-pinch effect included. Note that $W_p < 0$. Note also that for any consistent normalization of $\langle \Gamma \rangle$ and $\langle Q_e \rangle$, $T_e$ of equation (7) cancels in equation (8).

We compare the Ware-pinch contribution for the OH and ECH reference cases substituting typical values of $W_p$ and $\chi_e^{PB}$ in equation (8), assuming that the intense ECH does not directly drive significant particle flux that must be countered by the turbulent flux to restore the total flux to zero. In figure 11 the ratio of the normalized fluxes $\langle \Gamma \rangle/\langle Q_e \rangle$ without (symbols), and with (no symbols) the Ware-pinch contribution are shown as a function of $R/L_n$. (a) shows the OH reference case with $\chi_e^{PB} = 0.3$ m$^2$ s$^{-1}$, (b) is the ECH reference case with $\chi_e^{PB} = 1$ m$^2$ s$^{-1}$. For both cases, $W_p = -0.3$ m s$^{-1}$. It can be seen that the shape of the $\langle \Gamma \rangle$ curve around $R/L_n|_{stat}$ can influence the position of the new value of $R/L_n|_{stat}$. The addition of the Ware-pinch results in a vertical downshift of the curve. At the OH reference case $\langle \Gamma \rangle$ is almost linear with $R/L_n$. Due to its modest slope, the upshift in $R/L_n|_{stat}$ can be as large as 1. For the ECH case the slope of the $\Gamma$ curve is somewhat reduced which would imply a larger change in $R/L_n|_{stat}$. However, for the ECH case the contribution of the Ware-pinch is negligible mainly for two reasons. First, the loop voltage decreases as the electron temperature increases at constant current [4]. This reduces the absolute value of $W_p$. Second, due to the profile stiffness the value of $\chi_e^{PB} R/L_T$ is larger in ECH plasmas, which makes the contribution of the second term in equation (8) much smaller.

### 4.6. Choice of the quasi-linear rule

Our analysis is consistent with the observed experimental data. However it is based on a specific quasi-linear rule (equation (3) with $\xi = 2$). Other similar studies reported successful interpretations with different quasi-linear theory [3, 10, 21–23, 38] using different summation rules, or even using only one $k_y$ mode. A question arises as to whether the results reported here are strongly dependent on the choice of the $w$ weights in equation (2).

We evaluated the quasi-linear fluxes and $R/L_n|_{stat}$ with several different choices of $w$ for the parameter scans discussed previously. In figure 12 we show again the results of the temperature gradient scans (see figure 10) summing many modes with the power law used throughout this paper and in [2] (squares), summing with the classical mixing-length estimate (diamonds), summing with an exponential rule (triangles) motivated by fluctuation measurements [23], using one mode where the mixing-length transport is maximal (circles) [3] and using one mode with $k_y \rho_i = 0.3$ (stars) [10]. Although the differences in the predicted absolute value of $R/L_n|_{stat}$ can be as large as 1.5, the relative changes in $R/L_n|_{stat}$ and the parametric dependences are nearly identical, independent of the choice of the quasi-linear rule. Figures 12 and 10 show that the main trends do not depend so much on the quasi-linear rule but rather on the main dependence of the underlying most unstable modes. However, it is safer to use the whole spectrum in order to be sure to capture both the effects of ITG and TEM modes. The importance of the most unstable modes explains why similar trends can be expected in nonlinear simulations [22, 24, 31] and in the experiments.

### 5. Conclusions

The collisionality dependence of the local logarithmic electron density gradient $R/L_n$ has been investigated in ohmic and
electron cyclotron resonance heated H-mode plasmas on TCV. The density profile flattens when ECH power is added, the normalized density gradient \( R/L_{n,\text{stat}} \) at \( \rho_i \approx 0.7 \) decreases from about 3 to approximately 1.5. The dependence of \( R/L_{n,\text{stat}} \) on collisionality is rather unusual: the density peaking increases with increasing collisionality. With local quasi-linear gyrokinetic simulations it was shown that the change in collisionality alone cannot reproduce the observed experimental behaviour. The simulation results show that the most important parameter is the ion temperature gradient \( R/L_T \), which was not available in these experiments. Using \( R/L_T = 6 \) puts the OH and the ECH reference case in the ITG and the TEM regime, respectively, with predicted \( R/L_T \approx 2.5 \) and 3. For the OH case the contribution of the Ware-pincho can be as large as \( \Delta R/L_T \approx 1 \), resulting in a peaking around 3.5 which is in good agreement with the experiments. However, the flat ECH profiles are not recovered.

If a lower ion temperature gradient \( R/L_T = 4 \) is assumed, the predicted OH density gradient increases to around 4 (with the Ware-pincho included) and that of the ECH case decreases to 2. The experimental trends are, therefore, qualitatively explained. The edge ion temperature data suggest that \( R/L_T \) is about 3–5; however, new experimental data are required to compare with our simulation results. We have also seen that at very low \( R/L_T \), below 3–4, electron modes with large \( k_y \rho_i \) are seen to play a role, therefore new simulations are also required in this domain with non-adiabatic passing electrons and a non-linear model. The quasi-linear simulations predict that \( R/L_{n,\text{stat}} \) for the OH and the ECH reference case decreases as \( R/L_T \) is decreased; however, dedicated experiments are needed to explore how the \( T_i \) profile changes between the OH and ECH phases.

The simulation results, where the parameters can be changed individually, also show that the collisionality dependence can actually be due to a change in \( T_e/T_i \) and \( (R/L_T)/(R/L_T) \) rather than the collisionality itself. Table 2 summarizes the change in \( R/L_{n,\text{stat}} \) due to the considered parameters.

The \( (\Gamma) = 0 \) stationary condition is set by the balance between ITG and TEM modes as obtained in L-mode simulations [2]. Depending on the turbulence regime, the dependence of \( R/L_{n,\text{stat}} \) on the collisionality, temperature ratios and temperature gradients can be very different, but in all cases the average mode frequency \( \langle \omega_r \rangle \) as a figure of merit of the background turbulence clarifies the simulation results. This property of real mode frequency of the most unstable modes was observed in the study of L- and H-mode AUG plasmas [10, 19], L-mode and eITB TCV plasmas [2, 3], and now has been confirmed for TCV H-mode parameters as well. The neoclassical Ware-pincho can also contribute to the peaking under certain conditions typically when the stationary point lies in an ITG dominated regime and when the electron heat flux is not very large.

It is interesting to relate the present results to those of AUG reported recently in [10]. The density peaking in those considered H-mode plasmas increases with increasing additional ECH power, mainly due to the increase in the ratio of the logarithmic electron temperature gradient to the logarithmic ion temperature gradient and partly also from the increase in the electron to ion temperature ratio. Figure 7(a) in [10] can be directly compared with the curve with stars in figure 12. In purely NBI heated AUG H-mode plasmas ITG modes are the most unstable modes, positioned on the right part of the plot with positive frequencies. Adding ECH destabilizes the TEMs and \( R/L_{n,\text{stat}} \) increases as the mode frequency decreases. It is predicted that even larger amounts of ECH would result in decreasing peaking [10]; however, this could not be validated by those experimental results. According to our interpretation, the TCV OH plasmas are positioned very close to the ITG–TEM boundary and the additional ECH moves \( R/L_{n,\text{stat}} \) down on the left branch of the curve in figure 12. Therefore, our results combined with AUG observations [10] recover the full non-monotonic \( \langle \omega_r \rangle \) dependence.

In these TCV H-mode plasmas, the local behaviour of the density profile can be well explained in a unified

**Figure 12.** Same as figure 10(a), using different quasi-linear rules: (a) \( R/L_T \) scan, (b) \( R/L_{T_i} \) scan. Different symbols show different prescriptions for the \( \omega \) weights in equation (2). The larger shaded symbols mark the reference cases as in figure 10: the OH case for \( \langle \omega_r \rangle > 0 \) and ECH case otherwise.
quasi-linear gyrokinetic theory of ITG and TEM instabilities and turbulence. This work confirms that the model used to understand particle transport in L-mode [2] and eITB [3] plasmas is also able to reproduce the main trends observed in H-modes. The results of a quasi-linear theory used in this work can be further improved and validated by nonlinear simulations and also global codes are expected to predict more precise values of $R/L_{ni,stat}$. For a better test of this theory, systematic and precise ion temperature profile measurements are desirable. The systematic study of the dependence of local density peaking on the plasma parameters such as collisionality, electron to ion temperature ratio, electron and ion temperature gradient and Ware-pinch shows that the values of the plasma parameters from which these scans are performed are important in order to understand their effects on the stationary value of the density gradient. This complex interdependence is found to be considerably simplified when analysed in terms of the quasi-linear real mode frequency of the most unstable modes.

Acknowledgments

The authors thank M Kotschenreuther and W Dorland for having made available the GS2 code. The GS2 simulations have been run on the PLEIADES2 cluster EPFL, Lausanne. This work has been supported in part by the Swiss National Science Foundation.

© Euratom 2012.

References

[1] Angioni C, Fable E, Greenwald M, Maslov M, Peeters A G, Takenaga H and Weisen H 2009 Particle transport in tokamak plasmas, theory and experiment Plasma Phys. Control. Fusion 51 124017
[2] Fable E, Angioni C and Sauter O 2010 The role of ion and electron electrostatic turbulence in characterizing stationary particle transport in the core of tokamak plasmas Plasma Phys. Control. Fusion 52 015007
[3] Fable E, Angioni C and Sauter O 2008 Gyrokinetic calculations of steady-state particle transport in electron internal transport barriers Plasma Phys. Control. Fusion 50 115005
[4] Ernst D R et al 2004 Role of trapped electron mode turbulence in internal transport barrier control in the Alcator C-Mod tokamak Phys. Plasmas 11 2637
[5] Coda S et al 2007 The physics of electron internal transport barriers in the TCV tokamak Nucl. Fusion 47 714
[6] Fable E, Sauter O, Coda S, Goodman T P, Henderson M A, Weisen H, Zabolotsky A and Zucca C 2006 Inward thermodiffusive particle pinch in electron internal transport barriers in TCV Plasma Phys. Control. Fusion 48 1271
[7] Alberti S, Arnoux G, Porte L, Hogge J P, Marletaz B, Marmillod P, Martin Y, Nowak S and the TCV team 2005 Third-harmonic, top-launch, ECRH experiments on TCV tokamak Nucl. Fusion 45 1224
[8] Porte L et al 2007 Plasma dynamics with second and third-harmonic ECRH and access to quasi-stationary ELM-free H-mode on TCV Nucl. Fusion 47 952
[9] Maslov M, Weisen H, Zabolotsky A, Porte L, Angioni C, Beurskens M and the TCV team 2006 Density peaking in TCV and JET H-modes Proc. 2006 33rd EPS Conf. on Plasma Physics (Rome, Italy) vol 301 O–3.005
[10] Angioni C, McDermott R M, Fable E, Fischer R, Püttnerich T, Ryter F, Tardini G and the ASDEX Upgrade team 2011 Gyrokinetic modelling of electron and boron density profiles of H-mode plasmas in ASDEX Upgrade Nucl. Fusion 51 023006
[11] Hofmann F et al 1994 Creation and control of variably shaped plasmas in TCV Plasma Phys. Control. Fusion 36 B277
[12] Martin Y et al 2003 Accessibility and properties of ELMy H-mode and ITB plasmas in TCV Plasma Phys. Control. Fusion 45 A351
[13] Piras F, Coda S, Duval B P, Labit B, Marki J, Medvedev S Y, Moret J M, Pitzschke A and Sauter O 2010 ‘Snowflake’ H-mode in a tokamak plasma Phys. Rev. Lett. 105 155003
[14] Weisen H, Pasini D, Weiler A and Edwards A W 1991 Measurement of light impurity densities and $Z_{el}$ in JET using x-ray tomography Rev. Sci. Instrum. 62 1531–8
[15] Bortolon A 2009 Plasma rotation and momentum transport studies in the TCV tokamak based on charge exchange spectroscopy measurements PhD Thesis EPFL no 4569
[16] Karpushov A N, Duval B P, Schlatter C, Afanasiev V I and Chernyshov F V 2006 Neutral particle analyzer diagnostics on the TCV tokamak Rev. Sci. Instrum. 77 033504
[17] Weisen H, Zabolotsky A, Maslov M, Beurskens M, Giroud C and Mazon D 2006 Scaling of density peaking in JET H-modes and implications for ITER Plasma Phys. Control. Fusion 48 A457
[18] Angioni C et al 2007 Scaling of density peaking in H-mode plasmas based on a combined database of AUG and JET observations Nucl. Fusion 47 1326
[19] Angioni C et al 2005 Relationship between density peaking, particle thermodiffusion, ohmic confinement, and microinstabilities in ASDEX Upgrade L-mode plasmas Phys. Plasmas 12 040701
[20] Romanelli M et al 2007 Parametric dependence of turbulent particle transport in high density electron heated FTU plasmas Plasma Phys. Control. Fusion 49 935
[21] Casati A et al 2009 Validating a quasi-linear transport model versus nonlinear simulations Nucl. Fusion 49 085012
[22] Merz F and Jenko F 2010 Nonlinear interplay of TEM and ITG turbulence and its effect on transport Nucl. Fusion 50 054005
[23] Bourdelle C, Garbet X, Imbeaux F, Casati A, Dubuit N, Guirlet R and Pariset T 2007 A new gyrokinetic quasilinear transport model applied to particle transport in tokamak plasmas Phys. Plasmas 14 112501
[24] Lapillonne X, Brunner S, Sauter O, Villard L, Fable E, Görlé T, Jenko F and Merz F 2011 Non-linear gyrokinetic simulations of microturbulence in TCV electron internal transport barriers Plasma Phys. Control. Fusion 53 054011
[25] Ernst D R, Basse N, Dorland W, Fiore C L, Lin L, Long A, Porkolab M, Zeller K and Zhurovich K 2006 Identification of TEM turbulence through direct comparison of nonlinear gyrokinetic simulations with phase contrast imaging density fluctuation measurements Proc. 21st Int. Atomic Energy Agency Fusion Energy Conf. (Chengdu, China), number IAEA-CN-149/TH/1-3 http://www-pub.iaea.org/MTCD/Meetings/FECD2006/6b_1-3.pdf
[26] Ernst D R, Lang J, Nevins W M, Hoffman M, Chen Y, Dorland W and Parker S 2009 Role of zonal flows in trapped electron mode turbulence through nonlinear gyrokinetic particle and continuum simulation Phys. Plasmas 16 055906
[27] Ryter F et al 2001 Experimental studies of electron transport Plasma Phys. Control. Fusion 43 A323
[28] Kotschenreuther M, Rewoldt G and Tang W M 1995 Comparison of initial value and eigenvalue codes for kinetic toroidal plasma instabilities Comput. Phys. Commun. 88 128–40
[29] Lutjens H, Bondeson A and Sauter O 1996 The CHEASE code for toroidal MHD equilibria Comput. Phys. Commun. 97 219–60

[30] Zabolotsky A, Weisen H and Karpushov A N 2006 Influence of particle sources on electron density peaking in TCV and JET Nucl. Fusion 46 594

[31] Görler T et al 2011 Flux-and gradient-driven global gyrokinetic simulation of tokamak turbulence Phys. Plasmas 18 056103

[32] Angioni C, Peeters A G, Jenko F and Dannert T 2005 Collisionality dependence of density peaking in quasilinear gyrokinetic calculations Phys. Plasmas 12 112310

[33] Lang J, Chen Y and Parker S E 2007 Gyrokinetic δf particle simulation of trapped electron mode driven turbulence Phys. Plasmas 14 082315

[34] Bottino A, Sauter O, Camenen Y and Fable E 2006 Linear stability analysis of microinstabilities in electron internal transport barrier non-inductive discharges Plasma Phys. Control. Fusion 48 215

[35] Hallatschek K and Dorland W 2005 Giant electron tails and passing electron pinch effects in tokamak-core turbulence Phys. Rev. Lett. 95 55002

[36] Angioni C, Dux R, Fable E and Peeters A G 2007 Non-adiabatic passing electron response and outward impurity convection in gyrokinetic calculations of impurity transport in ASDEX upgrade plasmas Plasma Phys. Control. Fusion 49 2027

[37] Stober J et al 2003 Dependence of particle transport on heating profiles in ASDEX Upgrade Nucl. Fusion 43 1265

[38] Maslov M, Angioni C and Weisen H 2009 Density profile peaking in JET H-mode plasmas: experiments versus linear gyrokinetic predictions Nucl. Fusion 49 075037