Density profile peaking in the presence of ECRH heating in TCV

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Experimental observations in stationary ECRH discharges in TCV show that additional heating has a strong effect on the electron density profile. In the absence of MHD activity or strong internal transport barriers (ITB), additional electron heating generally leads to a broadening of the density profiles with respect to the Ohmic target plasma profiles. In ECRH L-mode and in the presence of weak eITB’s, the density peaking factor depends on the edge safety factor, the power deposition profile and on the ECRH power. Beyond a critical power of some 0.5 MW, the power dependence saturates. The edge safety factor dependence is supportive of turbulent equipartition (TEP) theory, which predicts inward convection in the presence of turbulence. The observation of a reduction of the peaking with central electron heating supports drift wave turbulence theory, which predicts the decrease of inward particle convection in addition to the inward convection by TEP, when trapped electron modes are destabilized, thereby reducing the net inward convection.

Introduction

The transport of particles in magnetically confined plasmas is of great importance for the development of fusion energy. It will determine techniques for fuelling, for controlling impurity concentrations and for the removal of the alpha particles produced by fusion reactions. Recently the study of particle convection in tokamaks has made important progress, providing a fairly consistent picture of its behaviour in several devices and uncovering differences in the behaviour of L-mode and H-mode, allowing for a tentative prediction for ITER [1-3]. Studies performed in TCV Ohmic and in JET L-mode LHCD heated discharges have shown that the electron density peaking depends solely on the current profile peaking [2,3]. In the presence of additional core heating, results from TCV [2] and ASDEX Upgrade [4] show a partial flattening of the density profiles. In this paper we present an extension of earlier work, quantifying the experimentally observed parameter dependencies using the powerful and flexible Electron Cyclotron Resonance Heating (ECRH) and Electron Cyclotron Current Drive (ECCD) systems on TCV and extending observations to electron internal transport barrier (eITB) regimes.

The TCV (R=0.88 m, a<0.25 m, B_T<1.5 T, I_p<1.1 MA) ECRH system includes six gyrotrons for heating at the second harmonic of the electron cyclotron resonance [5]. Operating at 82.7 GHz, these microwave sources can deliver up to 2.7 MW to the plasma for a maximum pulse length of 2 seconds.

The study was performed using a database containing about 600 electron density profiles taken in steady state L-mode ECRH discharges. The database variables include profiles of electron temperature, ECRH power deposition profiles, jacobians and scalar quantities necessary for evaluating transport and equilibrium related quantities. The data in the database cover a wide parameter range of \(0.9 \times 10^{19} \leq n_e(0) \leq 3 \times 10^{19} \text{ m}^{-3}\), \(0.02 \leq V_{75}^* \leq 1\), \(1.2 \leq \kappa_a \leq 2.3\), \(3 \leq q_{95} \leq 20\), \(-0.65 \leq \delta \leq 0.6\), where \(n_e(0)\) is the central electron density, \(V_{75}^*\) is the ratio of pitch angle scattering frequency to the banana trajectory bounce frequency calculated at 75% of poloidal flux, \(k_a\) and \(\delta\) are the elongation and triangularity at the plasma edge, \(q_{95}\) safety factor measured at 95% of poloidal flux. The majority of the discharges presented in the database are on- and off-axis ECRH discharges with a current drive fraction of less than 10% of the total plasma current, as calculated by the linear ray tracing code TORAY-GA [6]. However, we have also included in the analysis some cases with substantial ECCD, both in the co- and counter directions. The electron density and the...
electron temperature profiles were obtained from a repetitively pulsed Thomson scattering system [7]. The measurements were mapped and fitted as smooth functions of the flux surfaces given by the LIUQE equilibrium code [8].

We quantify the density profiles by a profile peaking factor. In order to reduce scatter due to random sampling with respect to the sawtooth cycle, we introduce, instead of traditional peaking factor \( n_e / < n_e > \), “clipped” density peaking as \( n_{e1} / < n_e > \) where \( n_{e1} \) is the electron density at the sawtooth inversion radius, \( n_e = n_{e1} \) for \( \rho < \rho_{inv} \) and \( n_e = n_e \) for \( \rho > \rho_{inv} \). This “clipped” profile is representative of flattened profile just after the sawtooth crash. In the absence of sawtooth oscillations, the “clipped” peaking factor is equivalent to the traditional peaking factor \( n_e / < n_e > \).

**Density profile behaviour in L-mode and weak eITB’s**

An example of the temporal behaviour of the plasma current, ECRH power and density peaking in a TCV L-mode discharge is shown on figure 1. The plasma current and the edge safety factor remain nearly constant during heating phase of the discharge. Variations of the central density do not exceed 20% around the average of \( 2.5 \cdot 10^{-19} \text{ m}^{-3} \). In the Ohmic phases, at the beginning and at the end of the discharge, the density profiles are peaked, in agreement with the scaling previously observed in TCV Ohmic discharges [2,9]. The addition of 1.3 MW of ECRH power with a broad deposition profile (ranging from \( \rho_{pol} \approx 0.1 \) to \( \rho_{pol} \approx 0.7 \) according to TORAY-GA) decreases the peaking by about 30%. The power step up to 2.6 MW at \( t = 0.7 \text{ s} \) with a similar deposition profile increases the central temperature up to 6 keV, but does not lead to a further significant change of the density profile width.

![Figure 1: Temporal behaviour of plasma current, ECRH power, central electron temperature and electron density peaking in ECRH L-mode discharge #18224. Right: Normalized fits of TS electron density profiles at three ECRH power levels.](image)

The overall behaviour shows that the density profiles in the presence of ECRH heating become broader in comparison with the Ohmic target profiles. From figure 1 it is seen that the absolute value of the central temperature, at least above a few keV, has no influence on the density profile, since no major changes of the density peaking are observed when the absolute value of the temperature rises from 4 keV to 6 keV at the second power step. This resilience of the density profile is even more striking in discharges with improved central electron confinement with weak electron internal transport barriers (eITB). In eITB discharges the low (or negative) shear is believed to suppress the turbulence in the plasma core, leading to reduced transport...
and the formation of a transport barrier characterized by steep localized temperature and density gradients [10-12]. The TCV weak eITB regime is characterised [13] by a confinement enhancing factor $H_{RLW} = \tau_e / \tau_{RLW} < 2.5$, where $\tau_e$ is the electron energy confinement time and $\tau_{RLW}$ is confinement time predicted by the semi-empirical Rebut-Lallia-Watkins scaling [14]. Figure 2 presents profiles for a discharge with plasma current $I_p = 0.14 \text{ MA}$, elongation $\kappa \sim 1.56$, triangularity $\delta \sim 0.56$, $q_{95} \sim 8$, preheated with off-axis ECRH ($\rho_{dep} \sim 0.7$, power 1.4 MW, $H_{RWL} \sim 1.4$), which after adding on-axis counter ECCD with a power of 0.7 MW, developed a quasi-stationary, weak eITB with $H_{RWL} \sim 2.2$.

![Figure 2](image)

**Figure 2:** Electron temperature (top) and electron density (bottom) profiles in two phases of discharge #24712. The profiles at 0.9 s correspond to a weak eITB regime. The smaller number of points on the density profiles than number of temperature measurements is due to a loss of absolute calibration for some of channels of the Thomson scattering system.

On figure 2 the profiles of the electron density and electron temperature in the preheating phase are compared to those in the weak eITB phase. The electron temperature profile in eITB phase (triangles on figure 2) is stiff only outside the eITB and is strongly peaked in the centre, with a central temperature exceeding more than 5 times the L-mode temperature. The electron density in contrast, shows a very resilient behaviour, remaining unchanged not only in confinement zone but also in the central region.

A comparison of the different ECRH power steps in the example on figure 1, especially the lack of density response to the power increase from 1.3 MW to 2.4 MW, indicates that the absolute value of the power in this range does not have a noticeable influence on the density profile. Expecting a gradual transition from high density peaking in Ohmic phase to flatter ECRH density profile, we performed a series of power scans in L-mode, changing the ECRH power from 0.18 MW to 2 MW at fixed deposition location ($\rho_{dep} \sim 0.35$) at constant plasma current 0.11 MA, corresponding to $q_{95} \sim 8$, constant shape and density. At such high $q_{95}$, MHD activity such as $m=1$, $n=1$ modes and sawteeth are absent. In each of the discharges power was gradually ramped up during the 1s heating pulse. The resulting dependence of the density peaking factor on the injected ECRH power is shown on figure 3A.
From this figure it is clearly seen that a strong dependence of the density peaking on the ECRH power below 0.5 MW is followed by resilient behaviour in response to a further increase of the heating power. We performed also a series of discharges with power steps of duration 0.5 s, which is longer than the current redistribution time (~0.3 s) and therefore with pronounced steady state phase. No differences in density peaking between these steady state measurements and the measurements performed in power ramps were observed.

Figure 3B represents the values of inverse electron density gradient length $1/L_n(\rho) = \nabla n(\rho)/n(\rho)$ in three radial locations for the discharges presented on figure 3A. It is
seen that central part of the density profile is most sensitive to the ECRH power, showing clear flattening even at lowest levels of the power applied in these experiments. From this point the values of central gradients remain on average constant despite further increase of heating power. The edge gradients decreases more gradually in response to ECRH power and stabilise when the power reaches about 0.5 MW.

It is interesting to compare the changes of the electron density gradients with the changes of the electron temperature gradients in these scans. At the plasma periphery the normalized electron temperature gradients drops with the ECRH power (ρ~0.85 on figure 3C) leading to the flattening of the temperature profile in this region. These temperature profile modifications are similar to the flattening of the density profile. However, as it is seen from figure 3C, the normalized electron temperature gradients at ρ~0.5 increase when ECRH is applied, the behaviour which is in clear contrast with the flattening of the density profile in response to the additional power. One should note however, that a saturation of the normalized temperature gradient changes at ρ~0.5 for high power is very similar to the saturations of the normalized density gradient in this region and therefore a correlation between temperature and density gradients could well exist. This correlation if it exists should however change sign in order to reflect the different behaviour of gradients at ρ~0.5 and ρ~0.8.

The observed independence of the density peaking on the absolute value of the temperature as well as its independence on the absolute level of deposited power above 0.5 MW leads to an important conclusion about the relation between heat and the particle transport. The heat balance shows a significant increase of electron heat conductivity in response to the heating power increase. The resilience of the density profiles to the increase of heat diffusion indicates that, if there is a proportionality of the heat and particle transport diffusivities, $D/\chi_e = \text{const}$, as suggested for example in Refs. [16-18], the pinch velocity must also change in response to ECRH in order to maintain the same steady state density profile, i.e. $\nabla n/n = V/D \equiv \text{const}$ above 0.5 MW.

The study of TCV Ohmic L-mode discharges reported in Ref [2] shows that density peaking scales with the parameter $<j>/((j_0q_0))$:

$$\frac{n_{el}}{n_e} \approx \frac{1}{<j>/(j_0q_0)+0.22}$$

Here $<j>$ is the cross-sectional average toroidal current density and $j_0q_0 = B_0(k_0 + 1/k_0)/\mu_0R_0$, where $j_0$, $q_0$, $k_0$, $B_0$ and $R_0$ are the plasma current density, the central safety factor, the elongation, toroidal magnetic field and major radius respectively at the magnetic axis. The parameter $<j>/((j_0q_0))$ represents a generalization to arbitrary cross sections of the edge safety factor $1/q_e$, and was also found to provide a good scaling parameter for Ohmic sawtooth inversion radii, temperature and pressure profiles [9, 19].

The dependence of the density peaking on the parameter $<j>/((j_0q_0))$ in ECRH discharges is shown on figure 4. The dataset in figure 4 contains only discharges where ECRH powers is higher than 0.45 MW (at least one gyrotron at full power) and the density peaking is practically independent of power (see figure 3). The average peaking of the Ohmic target discharges (obtained from Ref [2]) is plotted as a dashed line. As seen from the figure, ECRH leads in general to a broadening of the density profiles. At fixed $<j>/((j_0q_0))$ the peaking can be as low as 60% of the peaking in the Ohmic target discharge. However in some isolated cases, the ECRH can increase the peaking above the Ohmic target value.
A general dependence of the peaking on parameter $< j > / (j_0 q_0)$ (figure 4) can be expressed as,

$$\frac{n_{el}}{< n_e >} \approx \frac{1}{0.72 < j > / (j_0 q_0) + 0.44}$$

where on average, higher peaking of the density corresponds to the higher edge safety factor values. This dependence of $< j > / (j_0 q_0)$ is similar to the dependence observed in Ohmic TCV discharges (eq. 1). At the same time, the significant vertical scatter of the data at fixed $< j > / (j_0 q_0)$, which is well beyond the errors, estimated to be less than 15%, indicates that $< j > / (j_0 q_0)$ is no longer the only scaling parameter as it was the case for TCV Ohmic discharges [2]. In order to explain this dispersion we checked the dependence of the density peaking on loop voltage $V_{\text{LOOP}} = 2\pi R_0 E_\parallel$ ($E_\parallel$ is parallel electric field and $R_0$ is the major radius), volume average density $< n_e >$, effective collisionality for drift mode growth rate at 75% of the square root of poloidal flux $v_{\text{eff},75} = v_{\text{el}} / \omega_{\text{De}} \approx 10^{-14} R_0 T_e^{-2} n_e Z_{\text{eff}}$ (where $\omega_{\text{De}}$ is the curvature drift frequency [20], $R_0$ is the major radius and $Z_{\text{eff}}$ is the effective charge), inverse temperature “clipped” peaking factor $< T_e > / T_{el}$ and total ECRH power $P_{\text{ECRH}}$. Among the parameters tested using two parameter linear regressions, none was found to provide a statistically meaningful alternative to $< j > / (j_0 q_0)$.

The possibility of a dependence in addition to $< j > / (j_0 q_0)$ dependence was studied using three parameter regression of the form (example for $V_{\text{LOOP}}$)

$$\frac{< n_e >}{n_{el}} = c_1 < j > / j_0 q_0 + c_2 V_{\text{LOOP}} + c_0$$

the results of which are presented in Table 1.

A remarkable decrease of $\sigma$, by more than 25%, is observed when the ECRH deposition radius $\rho_{\text{dep}}$ is chosen as a secondary parameter in these multiple linear regressions (see regression # 4). Here $\rho_{\text{dep}}$ corresponds to the maximum of the deposition profile calculated by TORAY-GA. Only discharges with narrow deposition profiles were included in the regressions, thus $\rho_{\text{dep}}$ is meaningfully representative of the heating location. This particular dependence of the density profile peaking on the deposition location is illustrated on figure 5. In the discharges presented, the density
profiles broadens as the deposition location is moved towards the centre. It is interesting to note that the normalized density gradient outside $\rho_{\text{dep}} = 0.8$ is independent of $\rho_{\text{dep}}$ and the main changes of the profiles occur for $0.4 < \rho_{\text{pol}} < 0.8$.

![Fits of TS electron density profiles normalized to the edge value, together with the profiles of ECRH power density (calculated by TORAY-GA) in three L-mode discharges performed at a plasma current $I_p \approx 0.21$ MA. Discharge #24890 has central density $n_e(0) \sim 2.1 \cdot 10^{19} \text{ m}^{-3}$, #24883 has $n_e(0) \sim 1.2 \cdot 10^{19} \text{ m}^{-3}$ and #16284 has $n_e(0) \sim 2 \cdot 10^{19} \text{ m}^{-3}$.

In order to discriminate the dependencies on $\rho_{\text{dep}}$ in the database, we scaled out the dependence of $n_{\text{ei}} / n_e >$ on $\langle j \rangle / (j_0 q_0)$ by dividing the density peaking by the average density peaking from eq. 2. The relation of this quantity peaking/peaking$_{\text{avg}}$ and the ECRH power deposition location is shown on figure 6. It is clearly seen that the density peaking decreases when deposition becomes more central, depending almost linearly on $\rho_{\text{dep}}$. The lowest peaking in ECRH L-mode discharges is observed for on axis deposition. At the same time, for far off-axis heating, the peaking can be slightly higher than the average Ohmic peaking, although the quality of the data does not allow to unambiguously prove this surplus of peakedness.

The symbols on figure 6 correspond to classes of different central electron temperature. The trend to have a lower peaking at higher temperatures is most likely related to the difficulty of obtaining high central temperatures with off-axis heating rather than to a particular relation between density peaking and central temperature. This is confirmed by the fact that discharges with very different temperatures can have the same density peaking. The density peaking was also found to be independent of the value of the average temperature gradient in the region $0.2 < \rho_{\text{pol}} < 0.5$, where the temperature gradient has maximum changes.

The symbols on figure 4 refer to classes of the central density. It is seen that samples with the same central densities are spaced over the entire range of the observed density peaking. An apparent prevalence of low density discharges at low current is circumstantial and related
to peculiarities of the TCV scientific program. The lack of a relation between the absolute value of the density and density peaking is confirmed by the regression #5 in Table 1. Since, the different absolute densities results in significant differences in the penetration of neutrals originating from the edge, which might be expected to contribute to the density peaking, we can conclude that the observed density peaking must be due to an inward pinch, rather than to the source profile. As expected from figure 3 and confirmed by regression #6 in Table 1, the effect of the power on the density profile in the dataset with ECRH powers above 0.45 MW is negligible.

In the majority of ECRH heated discharges the dominant part of the plasma current is still Ohmic current and the loop voltage, which is proportional to Ware pinch [21], itself correlates to some degree with $<j>/\langle j_0 q_0 \rangle$. The correlation of $n_{ei}/\langle n_e \rangle$ with $V_{LOOP}$ is however significantly lower, indicating the absence of a direct influence of $V_{LOOP}$ on density peaking. In order to quantify the importance of Ware pinch we constructed the parameter

$$\tau \cdot V_{LOOP} \cdot \frac{1}{I_p} \propto \frac{1}{\chi_e} \cdot E_{||} \cdot \frac{1}{B_p} \propto \frac{V_{WARE}}{D}$$

where $V_{LOOP}$ is the loop voltage, related to the parallel electric field $E_{||}$, $I_p$ which is proportional to the poloidal magnetic field $B_p$ and

$$\tau_e = \frac{3}{2} \frac{\int T_e n_e dV}{P_{ECHR} + P_{OH}}$$

is the electron energy confinement time inversely proportional to the electron heat conductivity coefficient $\chi_e$. In eq. 4 we assumed a direct proportionality between $D$ and $\chi_e$ in accordance with theoretical expectations [16, 22]. In steady state the effect of $V_{WARE}/D$ on $\nabla n_e/n_e$ is additive and therefore the dependence of the density peaking on $\tau_e V_{LOOP}/I_p$ is expected to reflect the influence of the neoclassical Ware pinch on the density peaking. The three parameter regression with $\tau_e V_{LOOP}/I_p$ as secondary parameter shows no evidence of an influence of the Ware pinch on the density peaking (regression #3 in Table 1). It is also found in two parameter regression that during ECRH $\log V_{eff75}$ and $n_{ei}/\langle n_e \rangle$ are not directly correlated. The three parameters regression #7 in Table 1 shows a very weak influence of $\log V_{eff75}$, which is at the limit of statistical significance.
Table 1: Results of linear regressions for \( \frac{<j>}{\langle j_0 q_0 \rangle} \) in L-mode ECRH discharges with ECRH power higher than 0.45 MW (at least one gyrotron at full power). The numbers in brackets represents the regressions performed on a dataset of Ohmic targets described in [2]. Intervals are given for the 90\% confidence level. The datasets contain 525 (ECRH) and 313 samples (Ohmic).

Since for high enough power we did not find any important dependencies other than on \( <j>/(j_0 q_0) \) and on \( \rho_{\text{dep}} \) we summarised the observations in the following empirical scaling of the density peaking in ECRH L-mode discharges for ECRH power higher than 0.45 MW

\[
\frac{n_{e1}}{<n_e>} \approx \frac{1}{0.9 <j>/(j_0 q_0) - 0.2 \rho_{\text{dep}} + 0.44}
\]
In order to perform a comparison between Ohmic discharges and ECH discharges we added to table 1 the regressions results obtained on Ohmic target dataset described in [2]. From Eq. 6 and Eq. 2, as well as from the dependencies presented in Table 1 for ECRH and Ohmic (in brackets) phases of the discharges one can note changes of the coefficient for $(< j >/j_0 q_0)$ from 1 to 0.9 and the appearance of the $\rho_{dep}$ dependence during ECRH heating. Note that other minor changes such as the complete disappearance of the dependence on $\tau_e V_{LOOP}/I_p$ or on $<n_e>$ are not reflected in eq. 1 and eq. 6 since the effects of these parameters are at the limit of statistical significance.

It has to be noted that the $\rho_{dep}$ dependence may include effects which we were not able to address in this study. For example, the current profile modifications caused by additional heating cannot be described by a single parameter such as the edge safety factor. In this case, even if the density profile is fully determined by the current profile, a dependence additional to $(< j >/j_0 q_0)$ should appear in the experimental scaling. To determine the origins of the electron density peaking in ECRH discharges, measurements of the current profile would be needed.

**Effects of density pumpout and of strong eITB’s**

In this section we illustrate the consequence of two phenomena which can lead to density profiles which are very different from those discussed above. The detailed analysis of these cases lies outside the scope of this paper.

One of these effects is known as ’density pumpout’ and is observed in a variety of plasma conditions in tokamaks and stellarators [23, 24].

There is some confusion as to the terminology. At ASDEX Upgrade, the word ’pumpout’ is used to describe a reduction of the peakedness with $\nabla n_e \leq 0$ [4]. Consistently with earlier work on TCV we shall here refer to ’pumpout’ only when the net convection is outward over a fraction of the cross section, leading to positive $\nabla n_e$ [23].

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**Figure 7:**
A) Profiles of the electron temperature and the electron density in the discharge with density pumpout #18505 at 1 s. This discharge has quasi-permanent m=1 MHD mode visible on SXR diagnostic.
B) Profiles of the electron temperature...
and the electron density in the discharge with eITB \#26033. Scaling of the density peaking with $<j>/k_j q_0$ (C) and with $\rho_{dep}$ (defined as a maximum of dominant heating deposition) (D). Discharges with eITB’s and with density pumpout are encircled.

The 'pumpout' phenomenon causes inverted sawteeth of the central density in sawtoothing discharges and leads, in the absence of sawteeth, to steady state hollow density profiles. Figure 7A shows a typical example of a stationary TCV electron density and temperature profiles during density pumpout. This discharge, performed at 0.18 MA plasma current, was centrally heated with 2.5 MW of ECRH power. The density profiles in the discharges with pumpout have visibly lower peaking than average ECRH discharges, falling below the general scaling as shown on figure 7C and D. From figure 7D it is seen also that density pumpout is observed on TCV only with centrally deposited electron cyclotron heating or electron cyclotron current drive, in accordance with earlier observations in TCV [23]. Among the proposed explanations for density pumpout, one is based on neoclassical outward thermodiffusion, involving locally trapped particles in the presence of m=n=1 MHD modes [23]. The presence of MHD activity may be responsible for the observed striking difference between the peaking obeying the general scaling and peaking in discharges with pumpout. Another effect, which leads to an increase of the density peaking, is caused by a strong electron internal transport barrier. The presence of strong eITB’s involves a significant reversal of the central magnetic shear. In TCV strong eITB are obtained in low current discharges (usually $I_p < 0.12$ MA) using off-axis co-ECCD [13, 25]. During strong eITB’s in TCV, the confinement enhancement factor $H_{RLW}$ is usually higher than 2.8 [13] in contrast to the weak eITBs described in the previous section for which $H_{RLW} < 2.5$. Figure 7B shows an example of density and temperature profiles in a discharge with a plasma current $I_p = 0.11$ MA in which the combined effect of on-axis ECH and off axis co-ECCD (1.3 MW) created an eITB at $\rho_{pol} \sim 0.5$ with $H_{RLW} \sim 3.5$. A local change of $\nabla T_e$ from $\rho_{pol} \sim 0.5$ during the eITB phase of the discharge is clearly observed. A local change of the density gradient, with increased profile peakedness, although less pronounced, is observed on the electron density profile. Once the eITB is formed, the gradients of the density profiles remain constant for the whole duration of the power pulse, typically over 300 energy confinement times. As in the case of pumpout, the peaking of the density during strong eITB departs from the general scaling for ECRH discharges. As seen from figure 7, discharges with eITB’s are more peaked even than Ohmic target discharges, reaching $n_e / <n_e> \sim 3.5$ in extreme cases. All the points on this scaling which have strong eITB’s, are located in the low current region because of the limitation of the TCV current drive system to produce strong reversal of the shear at high plasma current. The peaking in strong eITB discharges seems to be independent of $<j>/k_j q_0$ or $\rho_{dep}$ and the scatter of the data is most likely related to the eITB strength, controlled by many parameters such as heating power, counter ECCD deposition radius and the toroidal angle of the central heating beams.

**Testing the pinch models**

It is widely accepted that peaked electron density profiles in tokamak plasmas result from an inward particle pinch. However, the nature of this pinch remains unknown. To explain peaked density profile behaviour, usually the three pinch mechanisms, turbulent thermodiffusion (TTD) [26], turbulent equipartition (TEP) [27] and the neoclassical Ware pinch [21] are considered. The former two are predicted to result from electrostatic drift wave turbulence due to unstable trapped electron (TEM) and ion temperature gradient modes (ITG).

The particle balance equation with an anomalous diffusion coefficient $D$ and an effective convective inward pinch velocity $V$ can be written as

$$\frac{\partial n}{\partial t} = -\nabla \cdot (D \nabla n_e + V n_e) + S$$

(7)

where $S$ represents the particle source and $V$ contains all non-diagonal terms of the transport matrix. Assuming all plasma parameters to be constant on the flux surfaces, labelled by $\rho$, equation (6) can be expanded under steady-state conditions into the above three contributions and the source:
\[
\frac{1}{n_e} \frac{\partial n_e}{\partial \rho} = \frac{1}{\rho} \frac{V_{\text{WARE}}}{D} \langle \nabla \rho \rangle - \eta \frac{1}{qH} \frac{\partial qH}{\partial \rho} + \alpha \frac{1}{T_e} \frac{\partial T_e}{\partial \rho} - \frac{1}{\rho} \frac{S_d}{\langle \nabla \rho \rangle} \int \langle \nabla \rho \rangle \right]
\]

where \( V_{\text{WARE}} \) is the neoclassical Ware pinch velocity, \( q \) is the safety factor and \( \langle \cdot \rangle \) means an average over the flux surface. In this equation, \( \eta \) and \( \alpha \) are coefficients for equipartition and thermodiffusion respectively. The coefficient \( \eta \) is positive, whilst \( \alpha \) may be either positive or negative depending on the conditions (ITG or TEM) [20, 28]. The geometrical factor \( H = B_0 dVol / 2R_0 d\rho \), where \( Vol, B_0 \) and \( R_0 \) are the plasma volume, toroidal flux, toroidal magnetic field and major radius at the magnetic axis respectively, is equal to unity in the large aspect ratio limit [29].

Simulations for the particle source were performed using the one dimensional kinetic neutral transport code Kn1D [30] for atomic and molecular deuterium. Results show that the penetration of the neutrals from the edge and their role in the particle balance decreases strongly as the density rises. If the source term was an important contributor to the particle balance, (eq. 7) a strong inverse dependence of density peaking on average density would be expected. The experimental observation presented in the previous section show no evidence for such dependence and therefore the term representing the particle source in eq. 8 can be omitted.

The direct comparison of the convective flux due to the Ware pinch with the outward diffusive flux in several high power TCV ECRH discharges showed that the Ware pinch is too small to compensate for the diffusive outward flux. The diffusion coefficient required to explain peaking by the Ware pinch alone would be of the order of 0.005 m²/s in high power discharges. This value is well below the values of diffusion coefficient observed in L-mode tokamak experiments in the confinement zone [22,31,32]. We do not have the measurements of diffusion coefficient on TCV however, the value 0.005 m²/s is three orders of magnitude below the TCV heat diffusivity calculated from power balance and therefore is implausible. Moreover, peaked density profile in TCV discharges with fully sustained current drive in the absence of core particle source have unambiguously proved the presence of an anomalous inward pinch in TCV ECRH plasmas [2]. Taking into account these facts and the absence of evidence for the role of the Ware pinch in the above regressions, we can safely neglect the Ware pinch term in eq. 8.

A previous study of the TCV Ohmic L-mode discharges showed that predictions of a turbulent equipartition model with \( \eta \sim 1 \) are in good agreement with observations and with the scaling of the density peaking factor with \( \langle j \rangle / (\varepsilon q_{i0}) \) [2]. Figure 8A and figure 8B illustrate that TEP can also provide sufficient peaking in the case of ECRH heating. For the density profiles in TCV ECRH discharges, a good fit of the scaling can be obtained if \( \eta \) is in the range 0.4 – 1 as shown on figure 8B by lines for three values of \( \eta \). High peaking cases, with \( \eta \sim 1 \), are in agreement with the version of TEP proposed by Yankov [33], but is significantly higher than predicted by Isichenko [34], which
corresponds roughly to $\eta \sim 0.3$. Density profiles approaching those predicted by Isichenko are only obtained with high power central ECRH. Since, at fixed $<j>/l(j_0 q_0)$, the density peaking scales with $\rho_{dep}$ it can be suggested that at each fixed $\rho_{dep}$ it is possible to find a corresponding $\eta$, which provides the correct scaling of the profile widths with $<j>/l(j_0 q_0)$ (the lines on figure 8B as an example). In this case $\eta$ has to increase with $\rho_{dep}$ in order to provide broader profiles when the deposition becomes more off-axis. It has to be noted that ECRH density peaking predictions in the framework of TEP based on safety factor profiles derived from equilibrium reconstruction LIUQE can serve only as an indication, since no reversal of shear is allowed by LIUQE.

The role of thermodiffusion (TTD) in TCV ECRH discharges was studied in Ref [2]. The main conclusion was that in ECH discharges, TTD provides sufficient peaking for the majority of the cases, although changes of $\alpha$ along the radius are needed in order to explain the resilience of density profiles to changes in temperature scale length. This observation remains valid for much larger dataset presented here. Connecting these previous results with the $\rho_{dep}$ dependence presented in this work, we can suggest that in order to explain the broadening of the density profiles during on-axis heating, $\alpha$ in the central region would have to depend on $\rho_{dep}$.

We tried also to use interpretations based on combinations of TEP and TTD mechanisms. This mixed model should explain the scaling of the density peaking with $<j>/l(j_0 q_0)$ and predict the profile flattening with central ECRH power. If both, TTD and TEP are important contributors, the flattening of the density profiles in the presence of central ECRH may be attributed to the decrease of the TTD inward contribution (decrease of $\alpha$ at fixed $\eta$) or even to appearance of an outward TTD (negative $\alpha$). This possibility is inspired by the observation of the density flattening in response to strong central electron heating in ASDEX Upgrade [4], [35]. On ASDEX Upgrade the changes of $\alpha$ have been attributed to the destabilisation of TEMs, producing an outward thermodiffusive flux ($\alpha < 0$) proportional to the mode growth rate [4]. At the same time, according to [4], the curvature pinch is expected to exist in any experimental plasma conditions for large enough shear.

The difficulty for a model including TEP combined with inward or outward TTD on TCV is to find the dependence of $\alpha$ on plasma parameters. Experimental observations presented in this paper show no dependence of the density flattening on the value of the central $T_e$ which correlates with $T_e/\nabla T$, on $\nabla T_e/T_e$ or on the value of ECRH power applied for $P_{ECRH} > 0.45$ MW. Since these parameters are supposed to be connected with the strength of TEM instability, the cause for the changes of $\alpha$, necessary to characterise the experimental behaviour, remains unclear.

### Conclusions

The analysis of density profile behaviour in source-free, steady state ECRH L-mode plasmas shows that density peaking correlates with the parameter $<j>/l(j_0 q_0)$, increasing with $<j>/l(j_0 q_0)$. A broadening with respect to the Ohmic target, scaling with deposition location in addition to the $<j>/l(j_0 q_0)$ scaling, is observed. Central power deposition reduces the density peaking. A strong dependence of the density peaking on the level of the ECRH for low power is followed by saturation at power higher than 0.5 MW (for $\rho_{dep} \sim 0.3$). No significant dependencies of the density peaking on the collisionality, central electron temperature, or absolute value of the density were found.

Turbulent equipartion (TEP) and thermodiffusion (TTD) alone are in principle able to match the experimental profiles however a decrease of TEP coefficient $\eta$ is required to follow the flattening of the profiles as deposition of power becomes important and changes of TTD coefficient $\alpha$ along the radius are necessary to explain the stiffness of the density profile in response to the changes of the temperature gradient. It is plausible that TEP and TTD both play a role in ECRH discharges. In this case the general scaling with $<j>/l(j_0 q_0)$ might be explained by a dominant inward pinch provided by the TEP mechanism and the flattening of the density profiles with electron heating would correspond to the decrease of inward TTD. However in order to confirm the capability of the
combination of TEP and TTD to reproduce the experimental scaling, modelling of a significant number of discharges is needed, as well as measurements of the current profiles.

The results presented for L-modes suggest that the core alpha particle heating in ITER may lead to a substantial reduction of the possible peaking factor and the associated performance benefit. We wish however that density profile behaviour in L and H – modes is very different [3] and $T_e/T_i \approx 1$ in ITER, while $T_e/T_i >> 1$ in most of the experiments discussed here. To resolve this matter, experiments with high power electron heating in H-mode with $T_e/T_i \approx 1$ would be required.

References

http://psfcwww2.psfc.mit.edu/people/labombard/