Impurity Transport in TCV: Neoclassical and Turbulent Contributions

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Abstract. Carbon impurity density profiles in TCV L-modes are studied in detail with respect to the role of sawtooth activity, of plasma current, of central ECH, of collisionality and of plasma shaping by comparing positive and negative triangularity. The carbon transport is compared to electron transport. It is shown that the carbon density profiles can have local normalized gradient much higher than the electron density, by a factor of two. However this is true only in the core of the plasma and outside the sawtooth inversion radius. Indeed, sawtooth activity has a strong influence, which can lead to an apparent dependence on plasma current. However dedicated experiments at different plasma currents I_p show that at radii outside the influence of the sawtooth activity, particle transport does not depend on I_p. Experiments with plasma currents between 105kA and 345kA with an inversion radius varying from 0.2 to 0.6 of the minor radius, have been analysed in details. The local density scale lengths are similar for electrons and carbon outside rho 0.6. They are shown to be very different inside this value except within the area influenced by the sawtooth activity. Adding ECRH in the center flattens both profiles and it is used to study the effect of collisionality. This has also been performed in two types of discharges with different triangularity, positive and negative. It has been shown that the electron heat transport is reduced significantly in negative triangularity and across a large collisionality range. It will be shown that similar results are obtained for both electron and carbon particle transport.

1. Introduction

Impurity transport is an important topic of research in view of burning plasma experiments in order to avoid a significant degradation of the fusion capabilities of a reactor device. Therefore predictions of impurity transport are required and should be validated [2]. Impurity accumulation has been observed in several tokamak scenarios and it is usually related to neoclassical levels of transport ([3]-[7]). It has also been mainly observed in high q_{95} or in the absence of MHD activity. Impurity density measurements in TCV L-modes have also reported cases with very high peaking of impurity profiles [8, 9] which are strongly affected by increased plasma current and/or eclectron cyclotron heating (ECH). The role of plasma shape and collisionality is also important in view of predicting impurity transport in ITER. Gyrokinetic simulations can now be used and tested for such predictions [[10] and references therein]. On the other hand, a fruitful comparison with theoretical predictions can only be performed if the experimental results determine accurately the physics mechanisms at play in determining the impurity transport.

Collisionality has been shown to significantly influence the electron particle transport [11, 2]. Therefore it is required to study if impurity transport depends in the same way on collisionality or if the relative electron to impurity peaking might change with collisionality. On the other hand improved heat transport properties have been observed in TCV plasmas with negative triangularity [12], with a strong dependence on collisionality as well. Therefore TCV experiments have been performed in order to study electron and carbon particle transport in positive and negative triangularity plasmas shapes and the dependence on collisionality.

In this paper we present the study of the influence of plasma current on carbon density profiles in L-mode TCV plasmas, as well as preliminary results on the role of collisionality and of

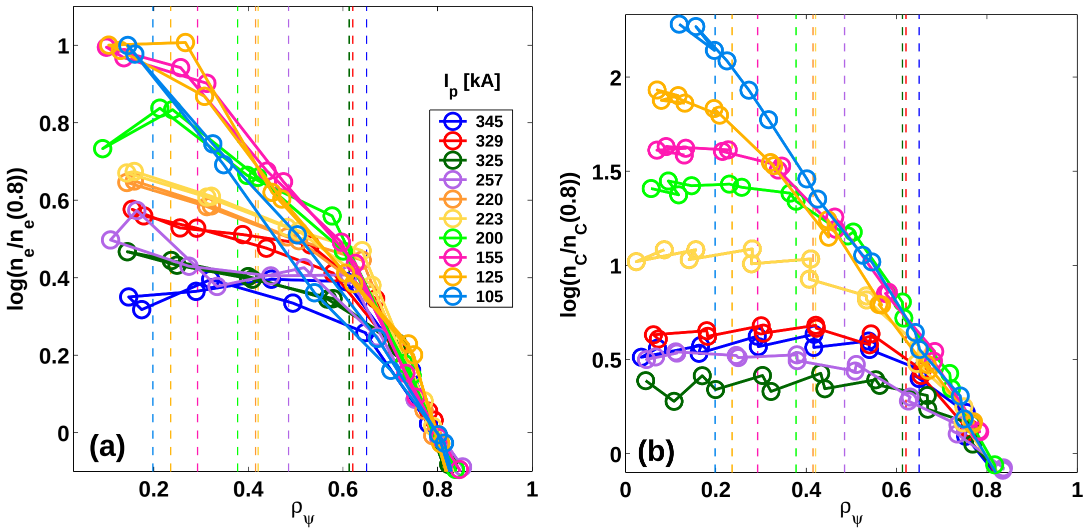

FIG. 1. (a) Electron and (b) carbon normalized density profiles for a scan in plasma current. The corresponding inversion radius is indicated with vertical dashed lines, increasing with increasing plasma current.

positive and negative triangularity. It is shown that one should first determine the contribution of MHD modes, in particular sawteeth, and of turbulence, before comparing with neoclassical transport. In particular the role of central ECH can act on both sawteeth and turbulence to result in a reduction of the impurity density peaking. The results of the dependence on plasma current are presented in Sec. 2 and on collisionality and shaping in Sec. 3.

2. Influence of plasma current on carbon density profiles in L-modes

Accurate carbon density profiles can be measured in TCV plasmas with the CXRS diagnostic. A global dependence of impurity density peaking has been observed on plasma current [8, 9] and a more detailed study is presented here. We have performed several plasma current scan with various plasma shapes and in limited and diverted plasmas. Fig. 1 shows the electron and carbon density profiles as a function of plasma current. Carbon is the main impurity species in TCV. We see that for low plasma current, very peaked carbon profiles are measured. In Fig. 1, we have normalized the density profiles by the value at $\rho = 0.8$, in order to infer information on the local transport properties. We also show the inversion radius for each plasma current and we see that outside the inversion radius, the logarithmic gradient does not change with plasma current. Therefore, the intrinsic carbon transport properties do not change with plasma current, however the sawtooth activity is very efficient in flattening the impurity profile.

The effects of sawteeth is of course well-known but is sometimes neglected if one does not study the whole profile behavior. In addition we shall see that it can influence transport studies in many ways, which is why we have studied its effects in more details. It is shown in [13] that it has a strong effect on momentum transport as well. The effects of sawteeth is actually the effects of the 1/1 internal kink mode responsible for the sawtooth reconnection event. The detailed study around the crash event is out of the scope of the present paper. On the other hand, since the sawtooth period is usually short as compared to impurity and momentum confinement times, frequent sawteeth occur and therefore can determine the average profiles. We show in Fig. 2 the carbon density profiles for the same plasma current scan performed for rotation studies in limited plasmas [13] (Fig. 1). Very peaked carbon profiles are observed, however only for very low plasma current. A preliminary study of this regime has been performed in Ref. [14] and it shows that turbulent transport alone cannot sustain such a large peaking, thus suggesting that the role of neoclassical transport is indeed important. As soon as q_{95} is typically

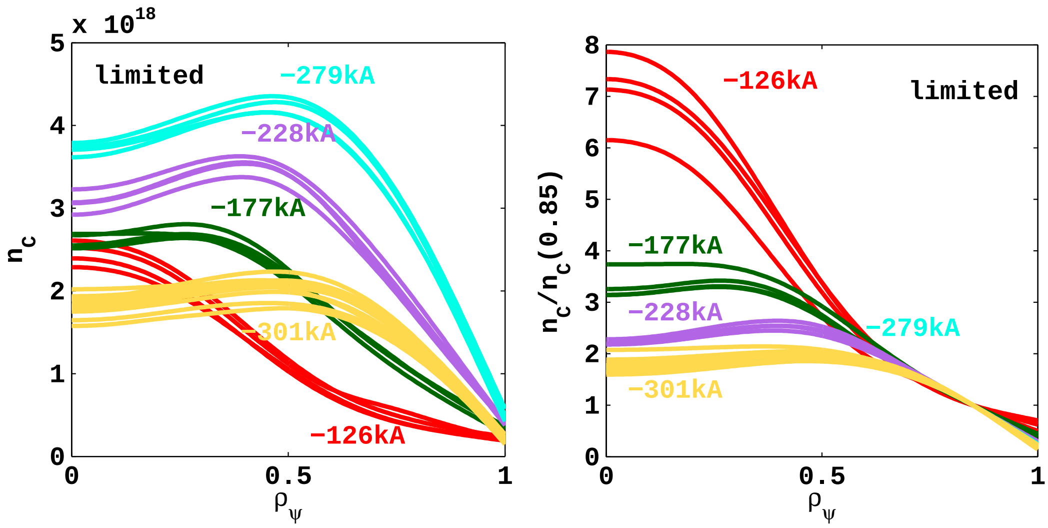

FIG. 2. (a) Carbon density profiles and the same normalized to the value at $\rho = 0.8$ *for a scan of plasma current in a fixed limited plasma shape. It corresponds to the same scan used for rotation studies [13]. Shot/*I_p*: 40117/-126; 40118/-177; 40119/-228; 40130/-279; 41385/-301; 41388/-312; 41386/-325; 41387/-345*

below 4, the profile is flattened up to slightly outside the $q = 1$ radius. A plasma current scan was also performed in diverted plasmas and a similar result is obtained. It indicates that the flattening due to sawteeth is stronger with higher triangularity. Note that this is consistent with impurity accumulation usually observed in ITBs and MHD free discharges.

A scan of the ECH power deposition location from far off-axis to on-axis has been performed during a single discharge for both a positive and a negative triangularity plasma shape. The effects on plasma rotation are described in [13] and the carbon profiles are shown in Fig. 3 and 4. From the soft-X ray measurement, one can infer precisely when the deposition is inside the region affected by the sawtooth activity. Profiles obtained when the EC power is outside the radius are shown with dashed lines, while profiles with central deposition are in solid lines. The central or maximum carbon density value decreases with the EC power deposited more and more on-axis. This could be due to the increase of the particle diffusivity, which in turn reduces the neoclassical contribution. However the normalized profiles show that the main evolution occurs in the very core and mainly once the EC power is deposited inside the mixing radius. Therefore it indicates that it is rather an increase of the effects of sawteeth on carbon that lead to the decrease of the carbon central value. That is an effect similar to an increase in the plasma current and not related to turbulent properties. These results also show that impurity transport properties and the effect of ECH in particular can only be studied with very low plasma current, or rather very small sawtooth mixing radius.

3. Effects of collisionality, ECH and plasma shaping

Two similar plasma shapes have been chosen but with $\delta = +0.4$ and $\delta = -0.4$. The other main parameters are $\kappa = 1.4$, $q_{95} = 4.7$, $I_p = 160$kA and $B_0 = 1.4$T. The aim is to cover a wide range of collisionality by comparing ohmic plasmas at low and high density, as well as EC heated plasmas at different powers and densities. As discussed in the previous Section, a low plasma current should be used. However negative δ plasmas are more MHD unstable and are in particular more difficult to control vertically. This is why we are somewhat limited in the choice of plasma current and elongation, at least for the negative triangularity case.

We show in Fig. 5 the profiles obtained in ohmic plasmas at small and high densities as well as

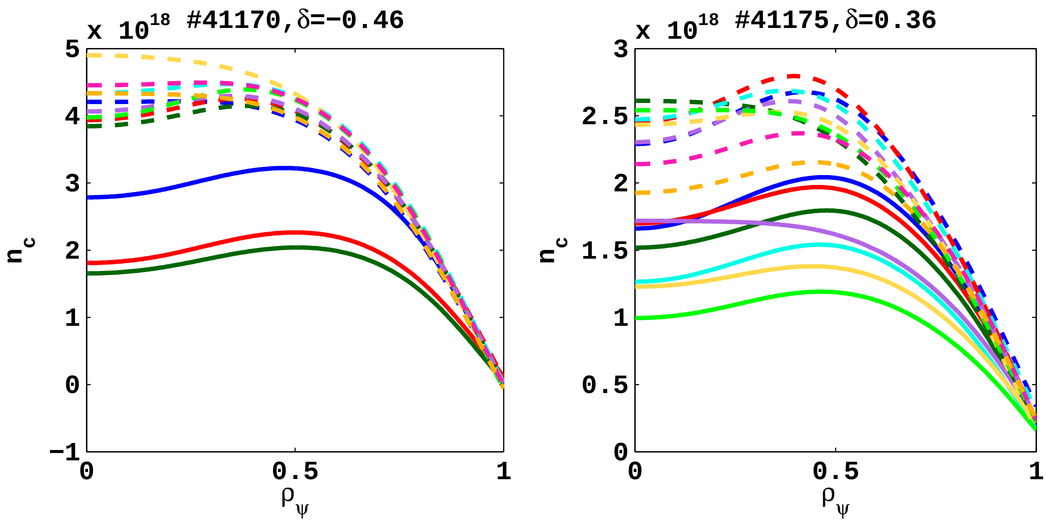

FIG. 3. Carbon density profiles for (a) negative and (b) positive triangularity during a scan of the EC deposition from far off-axis to central values, as described in [13]. Dashed lines correspond to deposition outside the sawtooth mixing radius and solid lines when depositing inside.

one EC heated case. Due to the better confinement observed at $\delta < 0$ [12], half the EC power is injected in that case. The local gradients are shown in Fig. 6. First we see that the electron temperature profiles are very similar in all cases. We also see a higher carbon concentration in the negative triangularity shape. This could be due to plasma wall interaction since these types of plasmas are not often performed. It has however an indirect effect on collisionality through Z_{eff} and leads to similar collisionality for the low density ohmic case at $\delta < 0$ with the high density case at $\delta > 0$. Note that all the ohmic cases have $\nu_{eff} > 2$ which is why similar profiles are observed in both shapes [12], with $\nu_{eff} = 0.1 * R_0 * n_e * Z_{eff}/T_e^2$. Comparing the two ohmic cases, the electron and carbon density profiles are very similar, while the R/L_{ne} and R/L_{nC} values in the ECH case appear to be lower. However a strong flattening is observed on a large core region in Fig. 5 for n_C. This might be due to the sawteeth activity in part as well, since EC does enhance the sawtooth activity. Therefore specific experiments have to be performed, for example scanning the deposition location in order to determine the contribution due to sawteeth, as performed in the previous section, or with even lower plasma current. This is also important in order to avoid measuring an outward pinch due to the EC power through the effect on sawteeth.

4. Conclusions

The dependence of the carbon density profile on plasma current has been clarified in TCV L-modes thanks to detailed I_p and ECH scans. It is shown that very high impurity peaking can be observed, with $L_{ne}/L_{nC} \geq 2$, in the absence of significant sawtooth activity that is at very high q_{95} values. Preliminary theoretical studies [14] suggest that this behavior could be due to neoclassical accumulation in marginal TEM regime. On the other hand the carbon profile is flattened inside the sawtooth mixing radius. Therefore, there is no dependence of the local carbon transport on plasma current in the region outside the sawtooth mixing radius. It has been shown to be the same with respect to ECH power deposition in a medium to low q_{95} case. The main reduction of the central carbon density value is due to the effect of ECH on the sawtooth activity. Thus new experiments need to be performed with ECH central heating with lower plasma current in order to assess the role on turbulent impurity transport.

Electron and carbon transport in positive and negative triangularity plasmas have been analyzed. The comparison of ohmic shots at different plasma density show that very similar behavior is

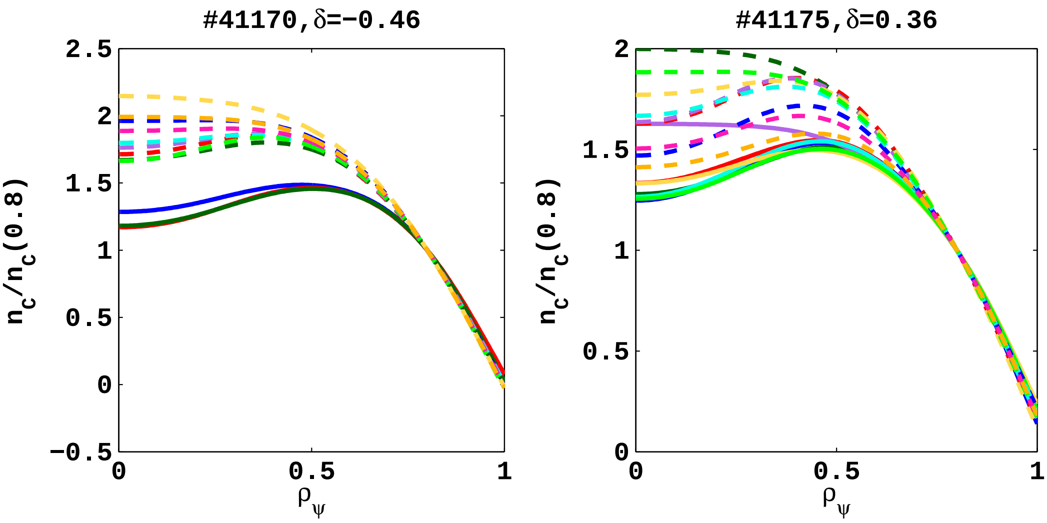

FIG. 4. Same as Fig, 3 but normalized to the value at $\rho = 0.8$*, showing that the main effect of ECH is due to effects on sawteeth.*

observed in positive and negative triangularity. This is due to the relatively high collisionality even at low density in these ohmic plasmas, and to the higher carbon concentration observed with $\delta < 0$. The addition of ECH allows to reach lower values of collisionality. However the preliminary results show that the ECH might have affected the sawtooth activity too much and do not allow to make firm conclusions on the collisionality dependence of electron and carbon density scalelengths. New experiments at lower plasma current or with a scan with the EC deposition location will be performed.

Acknowledgements

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References

[1] S. Coda et al., in Proceedings of the 24th International Conference on Fusion Energy, Seoul, 2010 [International Atomic Energy Agency (IAEA), Vienna, 2010]. (Members of the TCV collaborators appear in the appendix.)
[2] H. Weisen *et al*, Plasma Phys. Contr. Fus. **48** (2006) A457 and references therein.
[3] H. Takenaga *et al*, Nucl. Fus. **43** (2003) 1235
[4] M. E. Puiatti *et al*, Plasma Phys. Contr. Fus. **45** (2003) 2011
[5] R. Dux *et al*, Nucl. Fus. **44** (2004) 260
[6] R. Neu *et al*, Nucl. Fus. **45** (2005) 209
[7] C. Giroud *et al*, Nucl. Fus. **47** (2007) 313.
[8] E. Scavino *et al*, Plasma Phys. Contr. Fus. **46** (2004) 857
[9] A. Zabolotsky *et al*, 33rd EPD Conf., Rome, ECA **30I** (2006) P-1.145.
[10] C. Angioni *et al*, Plasma Phys. Contr. Fus. **51** (2009) 124017.
[11] C. Angioni *et al*, Phys. Rev. Lett. **90** (2003) 205003
[12] Y. Camenen *et al*, Nucl. Fusion **47** (2007) 510
[13] O. Sauter *et al*, this conference, paper EXS/P2-17.
[14] E. Fable, PhD thesis, EPFL-Lausanne, Switzerland **4334** (2009) http://library.epfl.ch/theses/?nr=4334

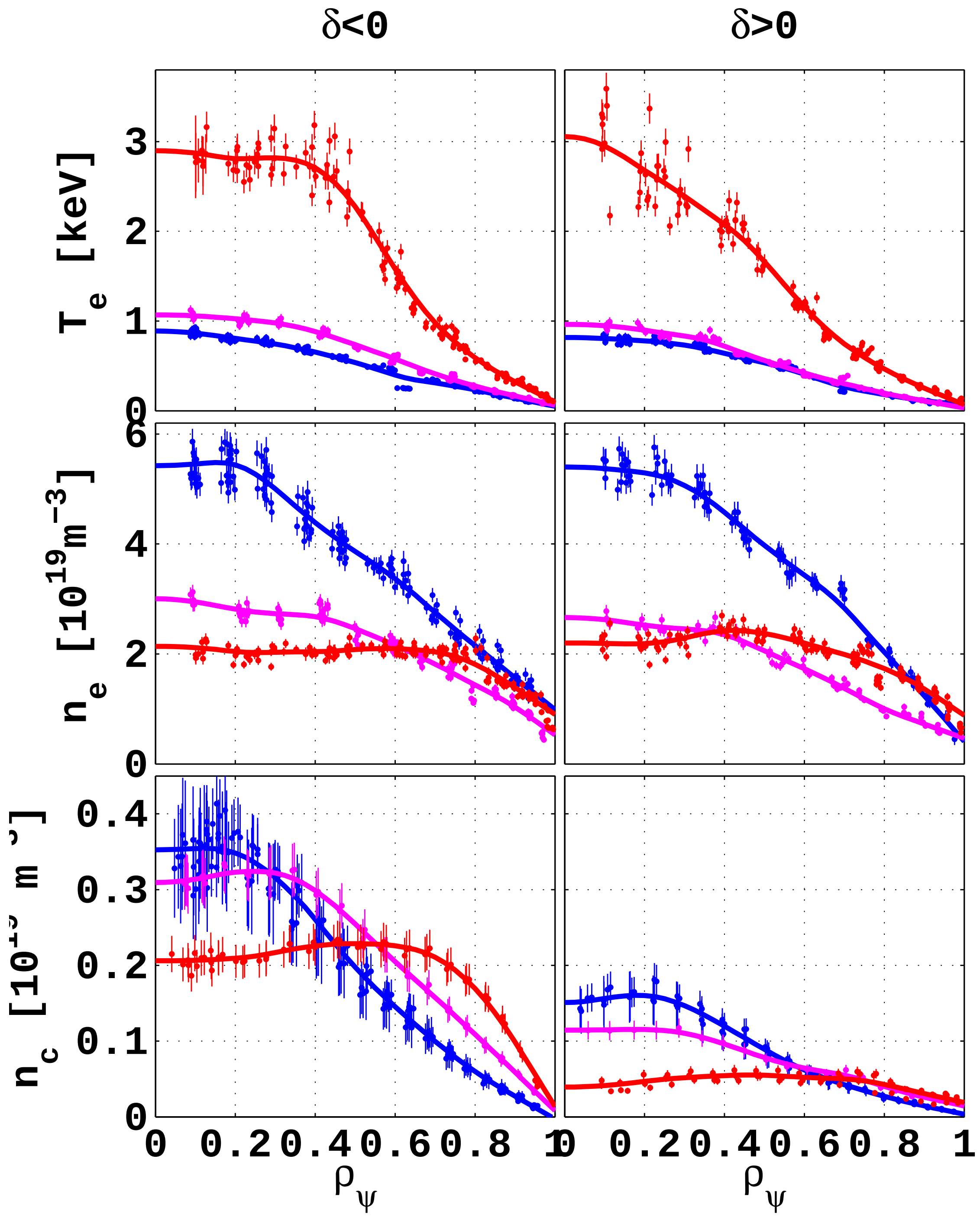

FIG. 5. Electron temperature and density profiles as well as carbon density profiles for two ohmic cases at low and high densities (magenta and blue) and an ECH case (red). Note that half the power is injected in $\delta < 0$ case. (a) $\delta = -0.4$: magenta=#39103, blue=#41144 and red=#38984. (b) $\delta = +0.4$: magenta=#39097, blue=#41137 and red=#39100.

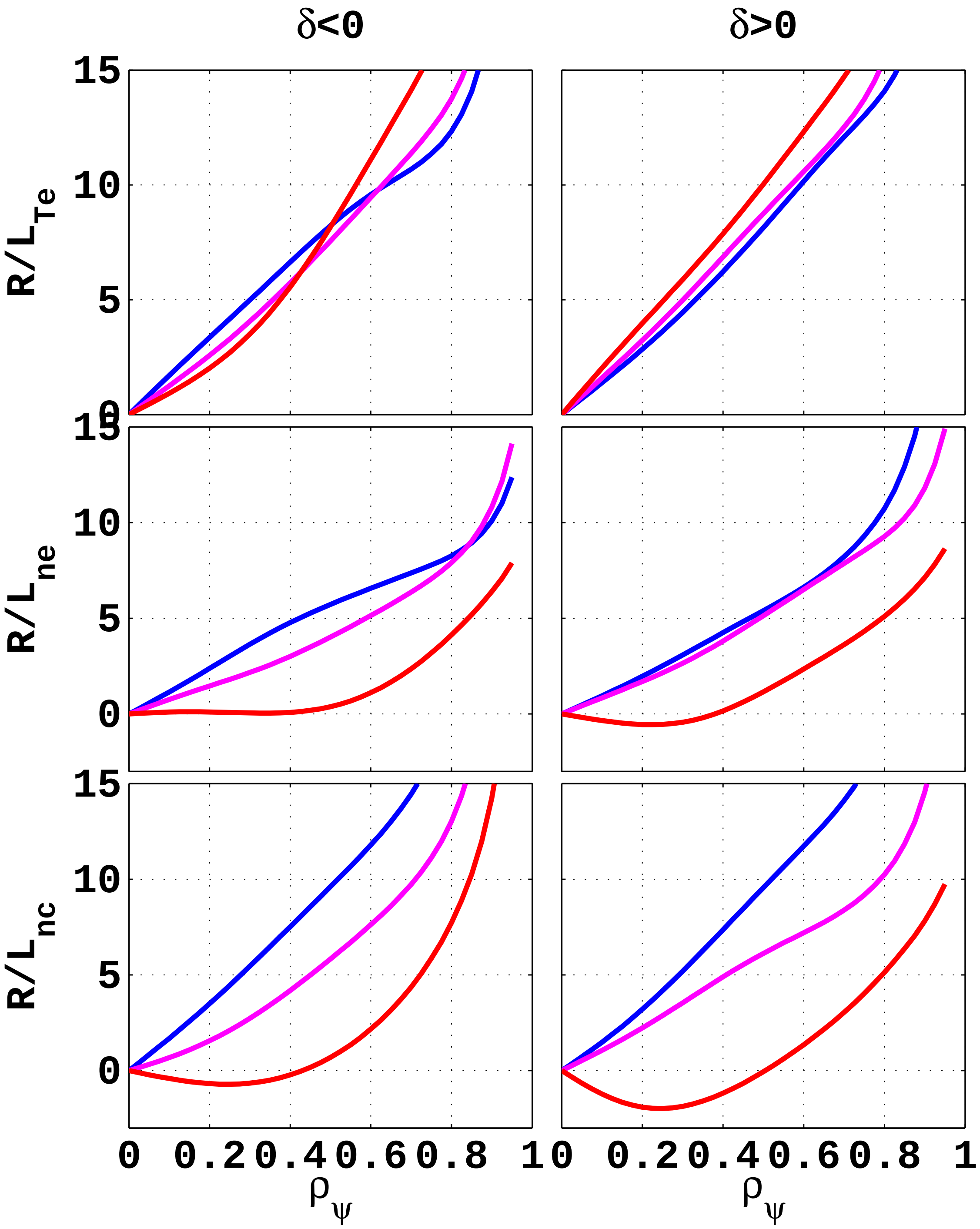

FIG. 6. Scalelengths for T_e, n_e and n_C profiles shown in Fig. 5.