

## Density behavior during electron internal transport barriers in TCV fully non inductive discharges

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### Abstract

Experimental results of particle transport during electron internal transport barriers (eITBs) achieved in the TCV device (Tokamak à Configuration Variable), in fully non inductive discharges, are shown. A database of steady state density profiles is constructed and studied in detail. An interesting relation between density and temperature scale lengths is observed. In the fully non inductive eITB scenario, the density profile is observed to develop a localized gradient, correlated via an almost constant factor with the electron temperature scale length up to the barrier foot. Sensitiveness of this behavior to the degree of the local confinement improvement is demonstrated by the study of the density response in eITBs with applied inductive current perturbations. The results shown have an impact also on the predictions about impurity transport in eITBs, and generally for fully non inductive operations in future machines.

### Introduction

Particle transport observed in Ohmic L-mode and with central electron cyclotron heating has been investigated in several works ([1],[2] and references therein). Understanding the behavior of density profiles in eITB scenarios with fully non inductive current density, is an important issue both experimentally and theoretically. In TCV, thanks to the powerful and versatile electron cyclotron heating system (up to 2.7 MW at 82.7 GHz in X2 mode) high performance eITBs are routinely produced [3]. The fully non inductive discharges presented here are characterized by the total replacement of the Ohmic current with off-axis electron cyclotron current drive (ECCD) and a high fraction of bootstrap current produced thanks to the improvement in the global energy confinement. The resultant current density profile is hollow and peaks off-axis.

### Experimental observations: overview

The database under consideration covers the following parameter range:  $I_p \sim 70 - 100\text{kA}$ ,  $P_{EC} = 0.9 - 2.3\text{MW}$ ,  $\rho_{EC} \sim 0.3 - 0.7$ ,  $q_{95} \sim 8 - 17$  and  $\langle n_e \rangle \sim 0.2 - 1.1 [10^{19}\text{m}^{-3}]$ ; in these plasmas collisionality is low, i.e.  $\nu_{eff} < 0.1$ , where  $\nu_{eff} \equiv \nu_{ei}/(\epsilon c_s/a)$ ,  $c_s$  is the ion sound velocity and  $a$  is the plasma minor radius. If not explicitly shown, estimated error bars on the gradients are about 20%, while for profiles they are 5 - 10%. Radial dependent quantities are averaged in  $0.2 < \rho < 0.6$  where  $\rho$  is the normalized poloidal flux coordinate. Fig. (1a) shows that the normalized electron temperature and density gradients are proportional with a ratio approaching  $\sim 0.5$  as the eITB becomes stronger; the strength of the eITB is defined as simultaneous high  $R/L_{Te} \equiv R_0 \frac{\langle |\nabla T_e| \rangle}{T_e}$  and high  $H_{RLW} \equiv \frac{\tau_E^{exp}}{\tau_E^{RLW}}$ , where  $\tau_E^{EXP}$  is the energy confinement time and it is compared with the Rebut-Lallia-Watkins scaling [4]. In fig. (1b) we compare the ratio of the logarithmic gradients,  $1/\eta_e \equiv L_{Te}/L_{n_e}$ , with the Ohmic phase.

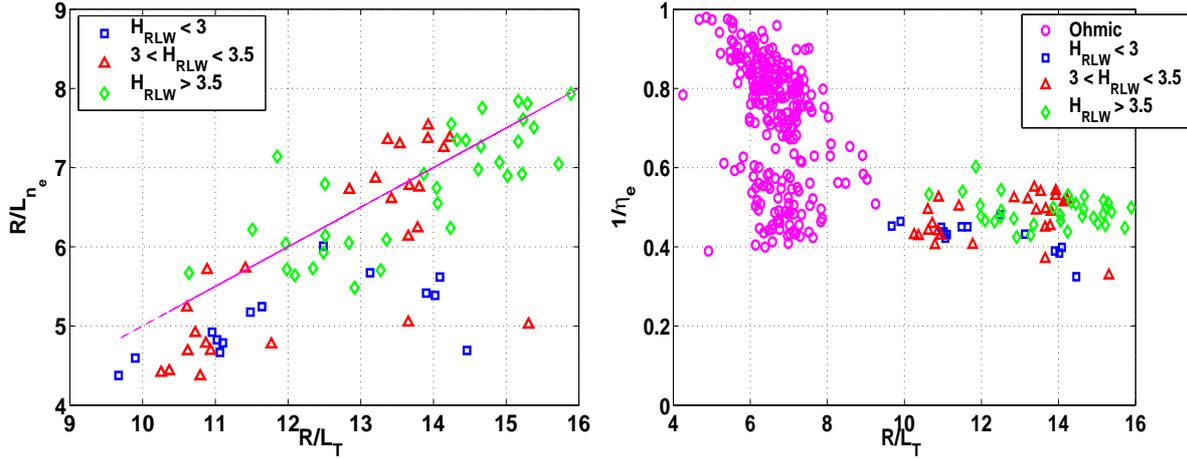


Figure 1: a)  $\frac{R}{L_{n_e}}$  vs  $\frac{R}{L_T}$  for different values of  $H_{RLW}$ , the magenta line has a slope of 0.5; b)  $1/\eta_e \equiv \frac{\partial \ln n_e}{\partial \ln T_e}$  vs  $\frac{R}{L_T}$  for different  $H_{RLW}$ , Ohmic mode values span a much wider range (magenta circles).

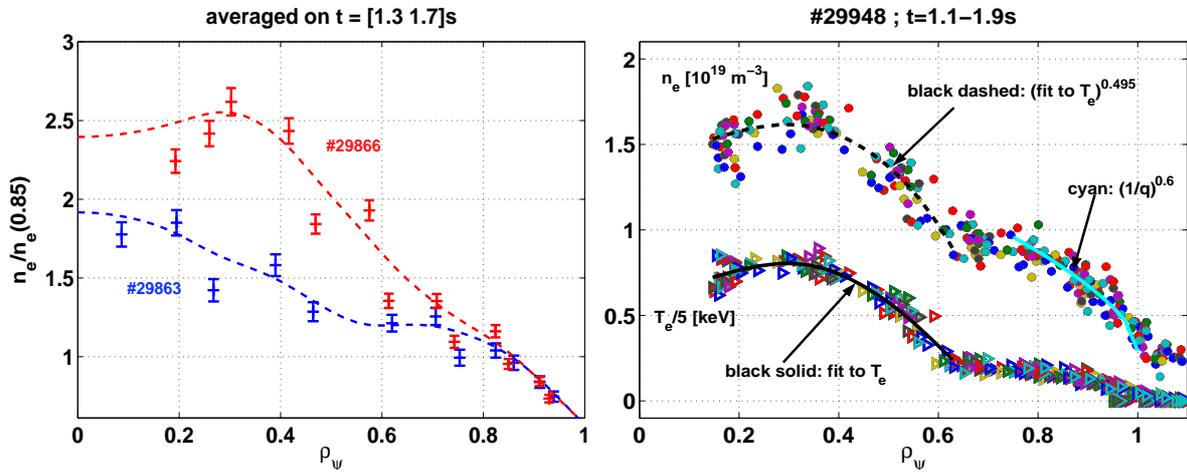


Figure 2: a) Thomson scattering raw data and fit for #29863 and #29866 with the same initial conditions but without (blue) and with strong (red) eITB respectively. Density profiles are normalized to the value at  $\rho = 0.85$ ; b) Thomson scattering data for electron density and temperature taken from a z-scan during a steady state eITB of 800 ms.

### Analysis of profiles

In fig. (2a) we compare raw data and fit for profiles averaged over the steady state phase. Both are normalized to the value of the density at  $\rho = 0.85$ . The two discharges have the same initial conditions in the Ohmic phase, but have an additional small positive or negative  $V_{loop}$  in the ECH/ECCD phase, resulting in a strong (red,  $j_{OH} < 0$ ) or no (blue,  $j_{OH} > 0$ ) eITB case. Fig. (2b) compares electron temperature and density profiles data taken from a steady state eITB of  $\sim 1s$ . Between 1.1s and 1.9s, a fine z scan (3.3cm/s) and a simultaneous ECH/ECCD sweeping has been applied, resulting in an increased spatial resolution for the Thomson points without perturbing the eITB. The dashed black line shows the curve  $n_e \propto T_e^\gamma$ , where the best fit is obtained with  $\gamma = 0.495$  for  $\rho < 0.6$ . The edge density normalized gradient has been found to be proportional to the edge  $q$  profile normalized gradient, indicating mainly a curvature pinch effect [5] as expected in Ohmic L-mode.

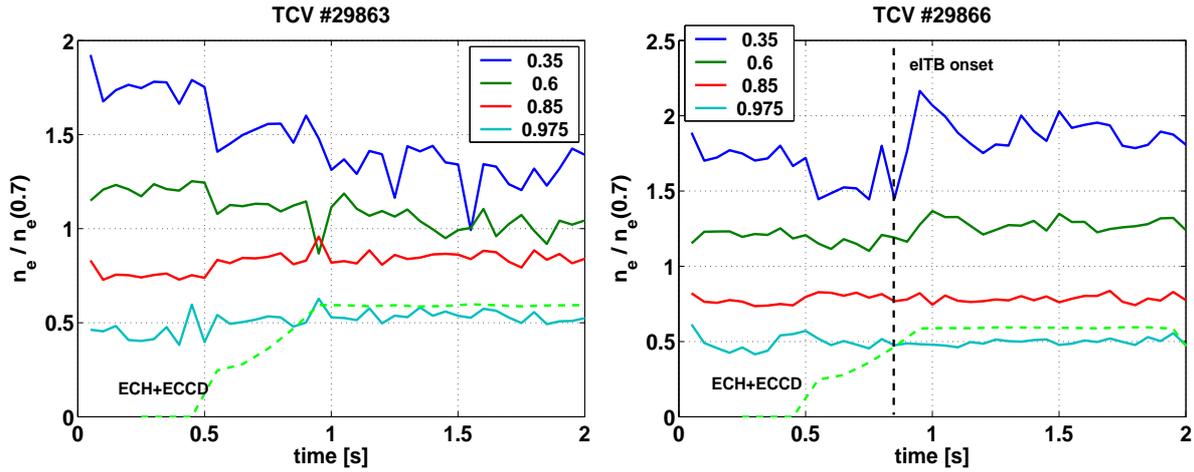


Figure 3: **a)** Time traces at different radial positions of the density profile divided by the value of the density at  $\rho = 0.7$ , for a case without an eITB; **b)** case with a strong eITB. The latter exhibits a clear density peaking while the first has central density decreasing.

### Study of time traces

In fig. (3), time traces at different radial location of the density profile are shown for one discharge with no barrier (3a), and for one with strong barrier (3b). The values are divided by the value of the density at  $\rho = 0.7$ , such that we are observing a measure of the local density peaking factor. It is worth noting that, while in the L-mode no-eITB case the density profile flattens after ECH injection and does not rise again, in the case with strong eITB, after a first phase of flattening, the peaking increases at  $t \sim 1$ s, when the eITB forms, following the increase in electron temperature gradient. Due to the absence of particle source this demonstrates the usual outward convection in non-eITB cases and the presence of a dominant inward pinch in eITBs.

### Inductive current perturbation experiments

Ohmic current perturbation experiments performed in TCV show that it is possible to control the barrier performance with a fine scan in loop voltage [6]. The Ohmic transformer is activated such as to produce a small amount of inductive current to modify the degree of magnetic shear reversal inside the plasma core. The behavior of density respect to the inductive perturbations is shown in fig. (4). In fig. (4a) we see that the presence of an Ohmic component can easily compromise the barrier performance also resulting in a worse particle confinement via a strong flattening effect at positive  $V_{loop}$ . The time traces in fig. (4b) show the enhancement of the eITB with a negative (counter) Ohmic perturbation. The density response is dictated by the electron temperature behavior. On the other hand, if we assume neoclassical diffusivity levels inside the barrier (up to the foot), yet a small inductive perturbation should result in a non negligible Ware pinch effect, contributing with an outward convection in the case with negative current perturbation, but not seen in the cases studied here.

### Conclusions

An overview of experimental results on density behavior during eITBs obtained in fully non inductive discharges in TCV has been presented. In this scenario the density profile becomes strongly coupled to the electron temperature profile almost up to the foot of the barrier. As the eITB becomes stronger, the density naturally evolves toward a profile which replicates temperature such as to have the ratio of the two scale lengths  $1/\eta_e \sim 0.5$ . We mention here that this

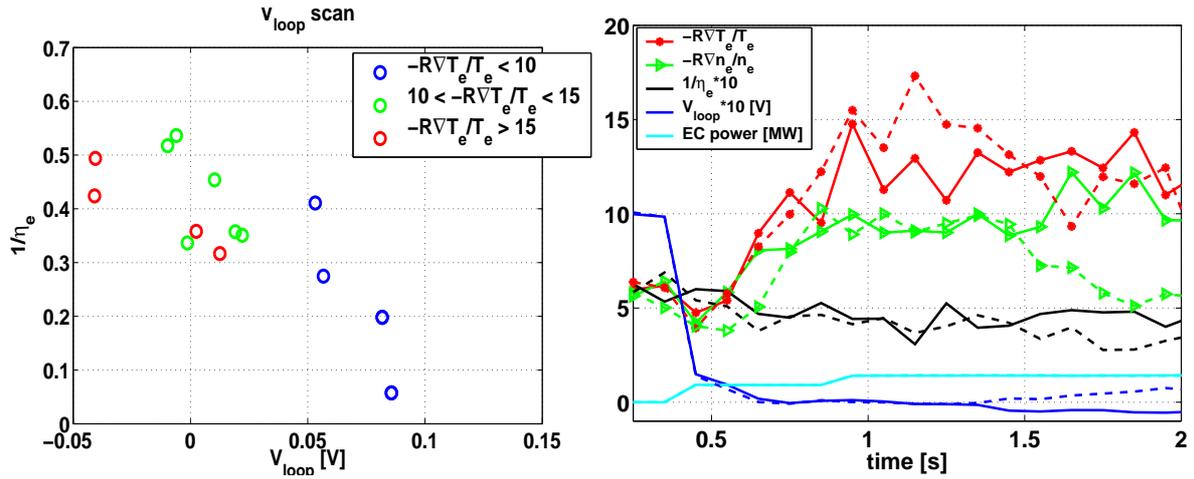


Figure 4: **a)**  $1/\eta_e$  for a  $V_{loop}$  perturbation scan on non-inductive eITBs; **b)** Comparison of time traces for two cases with co (dashed, #29598 with  $V_{loop} \sim 40mV$ ) and counter (solid, #29592 with  $V_{loop} \sim -40mV$ ) Ohmic perturbation. With  $j_{OH}(\rho = 0) > 0$  ( $V_{loop} > 0$ ),  $q$  becomes less reversed, while it becomes more reversed with  $j_{OH}(\rho = 0) < 0$  ( $V_{loop} < 0$ ).

ratio is also predicted by neoclassical theory in the form of an inward thermodiffusion effect (the value has only a weak dependence on the trapped particle fraction and on  $Z_{eff}$ ). This result is supported by the analysis of the static database. The density response observed during experiments assessing the performance of the eITB with inductive current perturbations further demonstrates the result. Theoretical modelling of microinstabilities and global transport might throw some light on the physics of the transition region where the eITB is forming, especially with regard to the role of the magnetic shear in changing the properties of particle and heat transport and the relations between them. Preliminary results indicate a transition from anomalous driven to neoclassical driven thermodiffusion pinch although it is not still clear which level of diffusivity we have inside the eITB. To this purpose, dedicated experiments with deuterium and impurity injection are planned. The role of the Ware pinch in the presence of inductive current perturbations is observed to be negligible but further assessment is required.

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