Investigation of the influence of edge parameters on L-H-mode transitions on COMPASS-D


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1 Introduction

The transition of a magnetically confined plasma from L-mode to H-mode is still not well understood. Although many theories have been developed in recent years [1] none of them is completely satisfactory. In particular the influence of neutral particles and the causality of events are controversial subjects. It is widely believed that a sheared perpendicular electric field and the associated sheared poloidal (and toroidal) plasma flows observed in the H-mode phase account for the reduction of turbulent cross field transport. However due to the lack of detailed experimental data many problems still remain unsolved. To obtain good experimental data a fast time resolution is required because of the fast time scales associated with ELMs or an abrupt L/H transition as well as spatial profiles of the main plasma parameters such as electron density $n_e$, electron temperature $T_e$, ion temperature $T_i$, poloidal velocity $v_{\theta}$, toroidal velocity $v_{\phi}$, and neutral (atomic) density $n_D$.

Most of the above parameters have been measured in recent experiments on COMPASS-D using a combined diagnostic consisting of a thermal helium beam diagnostic (HELIOS) [2] and a high resolution spectrometer (CELESTE) [3]. Both diagnostics observe the same spatial region at the plasma boundary with shared optics. To investigate the evolution of the plasma edge profiles during L/H-transitions ELM-free H-modes were generated in ohmic SND discharges by shutting off the gas fuelling. Within this ELM-free phase a stepped gas puff was applied to trigger a transition back into L-mode followed by a subsequent second L/H transition.

2 Diagnostic

The evolution of the radial profiles of $T_e$, $n_e$, $n_D$, $v_{\theta}$, $T_z$, and the relative impurity density $\tilde{n}_z$ was measured on COMPASS-D ($R = 0.56$ m, $a = 0.17$ m) using the recently implemented novel HELIOS/CELESTE diagnostic observing the plasma boundary at the outboard mid-plane. HELIOS is a thermal helium beam diagnostic providing $n_e(r)$, $T_e(r)$ from Hel line ratios and the absolute $D_\alpha$-intensity on 10 spatial points with a time resolution of $\Delta t = 2$ ms → 5 ms. CELESTE is a multi-chord Doppler-spectrometer delivering $I_z(r)$, $v_{\theta}(r)$, and $T_z(r)$ for the chosen impurity $Z$ (19 chords, $\Delta t = 1$ ms → 2.5 ms). For the experiments here CELESTE recorded the HeII resonance line emission at $\lambda_0 = 468.67$ nm. HeII is locally produced by the thermal helium beam ($\lambda_{\text{ion}}(0 \rightarrow 1^+) \approx 3$ mm). These ions are further ionized after $\lambda_{\text{ion}}(1^+ \rightarrow 2^+) \approx 3$ m which is smaller than the toroidal perimeter $2\pi R \approx 4.6$ m on COMPASS-D. Hence, the HeII emission detected is essentially localized to the beam. The neutral density profile $n_D$ was deduced from the absolutely calibrated $D_\alpha$-intensity. Since the intensity is a line integrated quantity the measured profile has to be inverted to obtain radial profiles of the emissivity. The information provided by HELIOS is not sufficient for a full tomographic reconstruction. However, assuming that $D_\alpha$-emissivity is constant on flux surfaces in the region of interest the radial profile of $n_D$ can be calculated using a maximum entropy fit [4] for the $D_\alpha$ inversion and applying a collisional radiative model to the inverted profiles [5].
3 Shot preparation

Figure 1 shows time traces for the shots 28443 (red; without gas puff), and 28447 (black; with gas puff) of (a) plasma current $I_p$, (b) line averaged density $\bar{n}_e$, (c) averaged $D_{\alpha}$-intensity through the X-Point, and (d) the driving voltage of the piezo valve $U_{\text{Piezo}}$ controlling the inlet of deuterium. The sudden drop of the $D_{\alpha}$-intensity at $t \approx 0.16$ s (trace b) indicates the transition to an ELM-free H-mode 3 ms after termination of the gas fuelling. In ohmic discharges on COMPASS-D usually a gradual transition between L-mode and ELM-free H-mode through a “dithering” ELMy phase is observed and the $D_{\alpha}$ traces (c) show type III ELMs before the ELM-free phase. However, as indicated by the detail in Fig. 1 the plasma is close or even in full L-mode just before the transition, due to the sustained fuelling and the increasing density. In shot 28447 a stepped gas puff was applied at $t_3 = 0.18$ s (trace d). The bigger first-part ($\Delta t = 10$ ms) triggers an H-L-transition which then is sustained by the slightly smaller second-part ($\Delta t = 10$ ms). After the gas is shut-off the plasma enters again into an ELM-free H-mode.

4 Results

Parameters are analysed using flux-coordinates $(\psi, \theta, \phi)$ [6], with $\psi = \Psi_p/2\pi$ being the poloidal flux function calculated with the equilibrium code EFIT [7], $\theta$ the usual poloidal angle and $\phi$ the toroidal angle defined in the opposite direction to the toroidal angle in the cylindrical machine coordinate system $(R, \phi, Z)$.

Fig. 2 shows time traces of the poloidal velocity along surfaces of constant normalized flux $\psi_N = (\psi - \psi_0)/(\psi_S - \psi_0)$ where $\psi_0$, and $\psi_S$ denote the flux on the magnetic axis and the separatrix respectively. To illustrate the different phases of the shot the $D_{\alpha}$-intensity and $U_{\text{Piezo}}$ are also depicted. Note, that the time points are chosen to be at the end of the integration interval to avoid confusion with the causality of events.

The most striking feature is that there is no evidence for change in velocity shear prior to the L-H transitions within the observed region. But, after the plasma has entered the H-mode a considerable shear develops. This can also be seen from Fig. 3 showing $E_\psi$. Nevertheless, the importance of the velocity shear becomes evident on the H/L-transition where the velocity shear starts to decrease coincident with the onset of the gas puff. The plasma undergoes the transition only when the shear has fallen to a low value. The Hetti velocity can however differ substantially from the plasma ion velocity. A more fundamental quantity is the radial electric field $E_\psi = \mathbf{E} \cdot \nabla \psi/|\nabla \psi|$.

We derive the electric field from the momentum balance equation for the impurity species $\alpha = \text{He II}$. Only the contributions from the Lorentz force $-\mathbf{v}_\alpha \times \mathbf{B}$ and the pressure gradient $\nabla p_z/(Z_\alpha e n_z)$ have to be considered since the other terms, normalized to the pressure gradient...
term, scale as follows: inertia $\propto M_z^2 \approx 0.04$, perpendicular viscosity $\propto M_zp_c/L_\perp \approx 0.07$, neutral friction $\propto M_zL_\perp/\lambda_e \approx 3 \cdot 10^{-6}$, coulomb friction $\propto M_zL_\perp/\lambda_e \approx 5 \cdot 10^{-5}$ where $M_z = v_\theta/v_\text{th}$, $p_c$ the Larmor radius, $L_\perp$ the typical pressure gradient length, and $\lambda_e$ the mean free path for collisions between particles of species $\alpha$ with $\beta$. The contribution arising from the toroidal velocity $v_\theta$ can be neglected. This is because on COMPASS-D the toroidal velocity is usually smaller than $v_\theta$ [8]. Hence, being weighted with $B_0/B_\theta \approx 0.1$ it is negligible. Therefore, the radial electric field can be reasonably approximated by

$$E_\psi = \frac{\nabla p_e \cdot \nabla \psi}{Z_e n_e |\nabla \psi|} - v_\theta B_\psi. \quad (1)$$

In the following we show contour plots of the evolution of analysed parameters from the example shot 28448. This shot was similar to shot 28447 apart from a longer triggered L-mode phase due to a higher second part of the gas puff. In Figures 4 to 6 the abscissa is $\sqrt{\psi_N} \sim r/a$ and the vertical lines correspond to the 90%, 95%, and 100% (separatrix) flux surfaces as indicated. The horizontal lines mark the transition times as can be seen from the $D_\alpha$-traces at the right edge of the graphs.

**Figure 3:** Evolution of the radial electric field for shot 28448.

**Figure 4:** Evolution of $\partial E_\psi / \partial \psi_N$ relative to the shear during the first L-mode phase for shot 28448.

The evolution of the electric field $E_\psi$ is shown in Fig. 3. Within the confined region $E_\psi$ points inwards with higher values in the H-mode phase and a maximum change of $\Delta E_\psi \approx -12$ kV/m. Although the velocity clearly has a maximum around the 92% flux surface (see Fig. 2) no minimum of $E_\psi$ occurs.

The maximum shear in the electric field of $\partial E_\psi / \partial r \approx 2 \cdot 10^3$ kV/m$^2$ is around the 96% flux surface as can be seen from Fig. 4 showing the change of $\partial E / \partial \psi_N$ with respect to the first L-mode phase. Note, that even in the L-mode phase the electric field already exhibits shear in this region. But, after the L/H-transition this shear increases. Correlated with the gas puff, the shear decreases before the H/L-transition.

Figures 5, and 6 show the evolution of $n_e$, and $n_D$ respectively. As expected, the electron density inside the separatrix is higher in the H-mode than in L-mode. But, interestingly, the opposite is true outside the separatrix in the SOL. This is more pronounced in the triggered L-mode from $t = 0.18$ s to $t = 0.19$ s. The neutral density (Fig. 6) shows an opposite behaviour. Here, in L-mode the neutral density profile extends further into the plasma than in H-mode. However, the changes of the neutral density seem to follow the transition whereas the $n_e$-evolution is more correlated to the $E_\psi$-evolution. The fact that both electron and neutral density decrease at the separatrix suggests that the mean energy of the influx neutrals has decreased in H-mode compared to L-mode.
5 Conclusions

At this stage of the analysis no change in any of the analysed quantities was found prior to the transition into ELM-free H-mode. We find, however, that on COMPASS-D at least, the velocity and electric field shear build up around the 95% flux surface only after the L/H-transition. On the other hand the H/L-transition is preceded by a decay of the shear in this region corresponding to onset of the gas puff. Whether this decay is caused by a change in the local neutral density or not can not be deduced from our data. However, we regard this as unlikely since our data indicates that the evolution of \( n_D \) at the mid-plane follows the L/H and H/L-transition. The neutral density at the separatrix was found to be rather high \( n_D \approx 2.5 \cdot 10^{17} \text{ m}^{-3} \) in L-mode and \( n_D \approx 1.7 \cdot 10^{17} \text{ m}^{-3} \) in H-mode. The gradient lengths of both, \( n_D \) and \( n_e \) are shorter in H-mode than in L-mode and both quantities are reduced at the separatrix in H-mode suggesting that the mean energy of the influx neutrals is reduced in H-mode.

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References