# On the role of the edge density profile for the L-H transition power threshold in ASDEX Upgrade

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On ASDEX Upgrade, the carbon tiles were replaced stepwise by tungsten (W) plasma facing components (PFCs) starting from 2003 and ending in 2007 [1]. Since 1999, the so-called 'H-mode standard shot' has been run as the first plasma discharge of each operation day at ASDEX Upgrade. The L-H transition is induced by a power ramp of neutral beam injection (NBI) achieved by beam modulation with increasing duty-cycle. A decrease of the power threshold ($P_{L-H}$) of about 25% for the H-mode standard shots was found when the full tungsten coverage of PFCs was reached [2, 3]. Neoclassical theory predicts that the edge radial electric field ($E_r$) is mainly driven by the main ion species [4, 5]. At ASDEX Upgrade it has been shown that, at fixed $B_T$ and magnetic configuration, the minimum in the neoclassical radial electric field $E_{r,neo}$ at the L-H transition is almost independent of density in the full tungsten wall [6].

The 'H-mode standard shot' was originally run at $|B_T| = 2.0$ T, but this had to be increased to $|B_T| = 2.5$ T when the tungsten coverage of the vacuum vessel increased [3]. The complete dataset at $|B_T| = 2.5$ T consists of 11 carbon wall (69% W coating PFCs) discharges with core line-averaged densities of about $4.5 \times 10^{19}$ m$^{-3}$ (2 shots) and $5 \times 10^{19}$ m$^{-3}$ (9 shots), and 14 discharges with full tungsten PFCs with a core line-averaged density around $5 \times 10^{19}$ m$^{-3}$. The dataset varies in plasma shape and location of gas fuelling (from the main chamber or lower divertor region). By comparing various shapes in both PFCs as well as dedicated experiments in the full tungsten wall discharges, in which we used both main chamber and divertor fuelling, we verified that these variations have no impact on $P_{L-H}$.

In figure 1(a)-(c) we compare the values of edge plasma quantities at $\rho_{pol} = 0.98$ in carbon and full tungsten walls just before the L-H transition by plotting these quantities versus $P_{L-H}$. These quantities are electron densities (taken in a time interval of 40 ms), temperatures (taken in a time interval of $\sim 60$ ms) and pressures. The power threshold values are obtained from

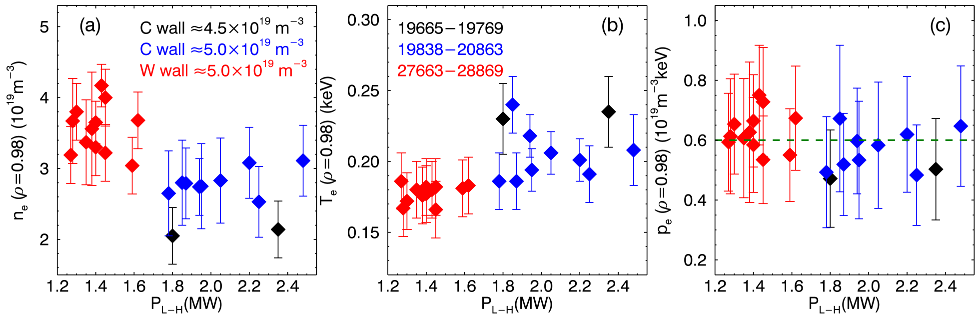


Figure 1: *Edge (a) electron densities, (b) electron temperatures and (c) electron pressures versus power thresholds at* $\rho_{pol} = 0.98$.

the loss power, $P_{loss} = P_{heat} - dW/dt$ at the L-H transition, where $P_{heat}$ is the sum of ohmic and auxiliary heating powers, and $W$ is the plasma stored energy. Figure 1 indicates that $P_{L-H}$ is clearly lower with the full tungsten wall than with the carbon wall. Higher electron densities and lower temperatures at $\rho_{pol} = 0.98$ are found in the discharges with full tungsten PFCs. The pedestal top electron pressures seem comparable in both PFCs.

Figure 2 shows a comparison of typical edge electron density profiles with the same core line-averaged density for two H-mode standard discharges within different plasma facing materials. The time slices for the edge density profile data are taken in a time interval of 20 ms just before the L-H transition. The discharge #28869, run with full metal wall, exhibits a higher $n_e$ at $\rho_{pol} = 0.98$ and a steeper edge density gradient $\nabla n_e$ compared to #20393 with carbon PFCs. The black curves are edge density profiles fitted with a modified hyperbolic tangent (MTanh) function.

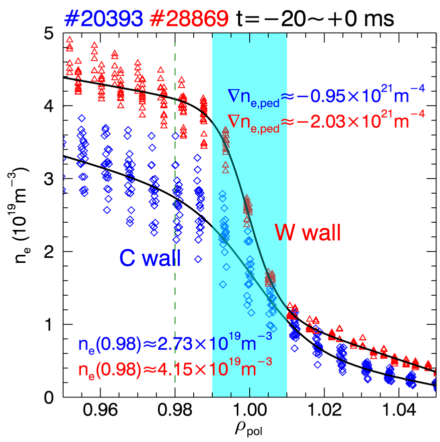


Figure 2: *Edge density profiles comparison of plasmas with the same core line-averaged density but different PFCs.*

Figure 3 shows the edge density gradients taken in a time interval of about 40 ms versus $P_{L-H}$ just before the L-H transition for our dataset. The edge density gradients are evaluated by fitting the edge density profiles applying the MTanh function and then averaging the gradients in $\rho_{pol} = 0.99 - 1.01$ (see the cyan shadowed region in figure 2) (filled diamonds) or applying the least absolute deviation (LAD) function (open circles). The values calculated by these two methods are consistent. With values of about $-1.5 \times 10^{21}$ m$^{-4}$ , steeper edge density gradients are found in the full tungsten wall discharges corresponding to the lower

$P_{L-H}$. In the carbon wall discharges, the edge density gradients are flatter, with values around $-0.95 \times 10^{21}$ m$^{-4}$.

Following the results from reference [6], we investigate whether the minimum in $E_{r,neo}$ just before the L-H transition is the same with the carbon and full tungsten walls in our dataset. The expression of $E_{r,neo}$ is

$$E_{r,neo} = E_{r,dia} - \alpha \frac{\nabla T_i}{e} + \frac{B}{B_t} B_\theta < V_{i\parallel} > . \quad (1)$$

$$E_{r,dia} = \frac{\nabla P_i}{n_i e} = \frac{\nabla n_e}{n_e}\frac{T_i}{e} + \frac{\nabla T_i}{e}. \quad (2)$$

Here, the toroidal field $B_t \approx 1.93$ T and poloidal magnetic field $B_\theta \approx 0.34$ T at the low-field side plasma edge of our dataset is determined by the equilibrium code CLISTE [7]. $\frac{B}{B_t} B_\theta < V_{i\parallel} > \approx 0.35 < V_{i\parallel} >$ and we assume $n_i = n_e$ at the plasma edge in ASDEX Upgrade. Combining equation (1) and equation (2), the neoclassical $E_r$ equation can be written as

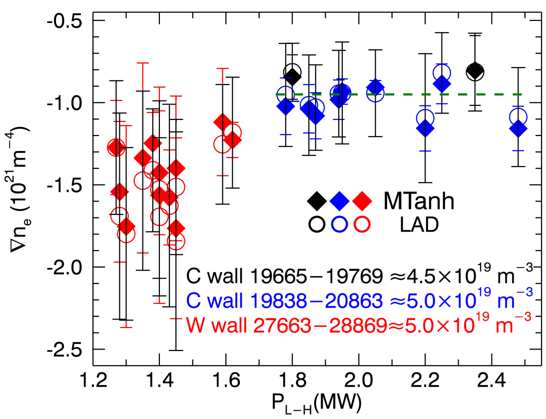


Figure 3: *Edge density gradients versus power thresholds. The edge density gradients are fitted by applying the MTanh function (filled diamonds) and the LAD function (open circles).*

$$E_{r,neo} = \frac{\nabla n_e}{n_e}\frac{T_i}{e} + (1-\alpha)\frac{\nabla T_i}{e} + 0.35 < V_{i\parallel} > . \quad (3)$$

In standard H-mode discharges, the mean impurities parallel velocity is typically $< 10^4$ m/s at the plasma edge before the L-H transition. Thus, the third term $0.35 < V_{i\parallel} >$ in equation 3 is less than $3.5kV/m$. This value is much less than the former two terms and neglected in the following analysis. As the edge CXRS diagnostic was installed in 2009, the direct measurement of the $E_r$ profiles is unavailable for our carbon PFCs dataset. However, $E_{r,neo}$ can be estimated from equation (3) using the routinely measured electron edge density and temperature profiles. According to [8, 9], $E_{r,min}$ is always located just inside the separatrix, therefore $\rho_{pol} = 0.995$ is artificially chosen as the radial position where the minimum of the $E_{r,neo}$ is expected.

The inverse density gradient length $\nabla n_e / n_e$ can simply be calculated by dividing the density gradient values (applying LAD method) in figure 3 by the corresponding edge density at $\rho_{pol} = 0.995$. $T_e$ and $T_i$ at the pedestal top are close to each other for $n_{e,ped} \geq 2 \times 10^{19}$ m$^{-3}$ and heating powers in the range of $P_{L-H}$ [6], but at the separatrix $T_i$ is somewhat larger than $T_e$. Therefore, we assume $T_i = T_e$ at $\rho_{pol} = 0.98$ and $T_i = 0.14$ keV (measured $T_e \sim 0.10$

keV) at the separatrix. The ion temperature profile is almost linear at the plasma edge, thus the edge ion temperature gradients can simply be estimated as $\nabla T_i = \frac{T_i(0.98)-T_i(1.00)}{r(0.98)-r(1.00)}$ and $T_i(0.995) = \frac{T_i(0.98)+3T_i(1.00)}{4}$. Since the collisionality $\nu_{*i}$ [10] at $\rho_{pol} = 0.995$ varies between 1.40 and 4.52 before the L-H transitions in the dataset, the factor $\alpha$ in equation (3) is in the plateau-collisional regime [4]. According to equations (2) and (3) and the terms $\frac{\nabla n_e}{n_e}(0.995)$, $T_i(0.995)$, $\nabla T_i$ and $\alpha$ described above, the minimum radial electric fields $E_{r,dia}(0.995)$ and $E_{r,neo} - \frac{B}{B_t} B_\theta < V_{i\parallel} > (0.995)$ are estimated.

The minimum of the $E_r$ well is plotted in figure 4 versus $P_{L-H}$. The values of the minimum of $E_{r,neo}$ (neglecting the third term $0.35 < V_{i\parallel} >$ in equation 3) are constant around -13 kV/m within the errorbars in a wide range of power thresholds and consistent with $E_{r,neo} \approx -15$ kV/m found for a wide range of pedestal top densities in reference [6]. We also compare the evaluated $E_{r,dia}(0.995)$ taking $T_i = 0.14$ keV at the separatrix ($T_i = T_e$ at $\rho_{pol} = 0.98$) and $T_i = T_e$ at the plasma edge. It shows that when choosing $T_i = 0.14$ keV at the separatrix, the calculated $E_{r,dia}(0.995)$ are much closer in the discharges with both PFCs.

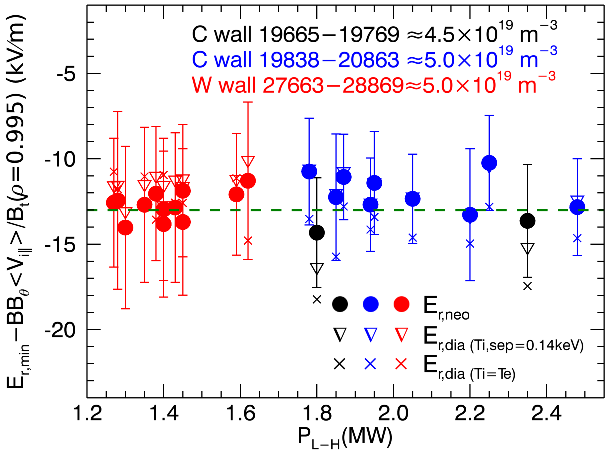

Figure 4: *Radial electric fields at $\rho_{pol} = 0.995$ versus power threshold evaluated according to equations (2) and (3).*

These results suggest that the minimum edge $E_{r,neo}$, just before the L-H transition, seems to be a constant value in different PFCs despite different threshold power. The lower $P_{L-H}$ in full tungsten PFCs can be attributed to steeper edge density profiles.

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