

Understanding the impact of the divertor configuration on the L-H transition in the ASDEX Upgrade tokamak

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Introduction

In future tokamak reactors, the high confinement mode (H-mode) is a promising operational regime to achieve sufficient plasma confinement for net energy production. Tokamak plasmas initially form in a low confinement mode (L-mode) and require a minimum heating power to make the transition into H-mode. This is known as the L-H power threshold (P_{LH}), which defines the minimum heating power crossing the separatrix required to trigger the confinement transition. Consequently, P_{LH} directly influences the operational power requirements of a tokamak reactor, and therefore it has an impact on the overall machine cost. While the P_{LH} scaling laws depend on global parameters like line-averaged electron density ($n_{e,\text{lav}}$), magnetic field strength (B_t), and the machine size, historically a factor describing the divertor configuration was not included [1]. This can introduce a large uncertainty for the predictive scaling, as previous results from different devices such as JET, DIII-D, and MAST have demonstrated that the divertor configuration can affect the P_{LH} by up to a factor of two [2, 3, 4]. To include this divertor configuration effect in scaling laws for future devices, we need a better understanding of how divertor configuration modifies edge and scrape-off layer (SOL) conditions.

The goal of this work is to demonstrate the impact of the divertor configuration on the P_{LH} in the ASDEX Upgrade tokamak and to investigate the underlying physics mechanisms driving this effect.

Experimental Setup

The analysed experiments were done in the ASDEX Upgrade tokamak using upper single null (USN) discharges in a favorable ion drift configuration. Global plasma parameters were kept constant throughout the study with a plasma current of 800 kA and $B_t = 2.55$ T. The two divertor configurations compared in this study are shown in Figure 1.

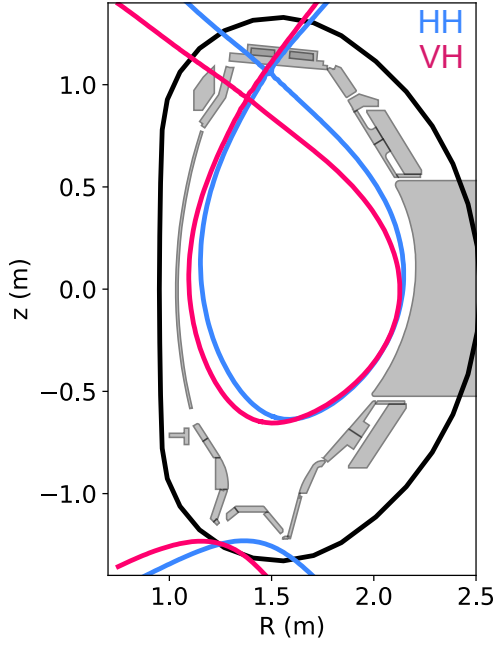


Figure 1: Comparison of the VH and HH divertor configurations on the ASDEX Upgrade tokamak.

In the vertical-horizontal (VH) configuration, the inner strike point is positioned on the vertical target while the outer strike point is on the horizontal target. In the horizontal-horizontal (HH) configuration, both the inner and outer strike points are on the horizontal target. Because the P_{LH} follows a parabolic density dependence, we repeated the experiments in both the low-density regime ($n_{e, \text{lav}} = 2.5 \times 10^{19} \text{ m}^{-3}$) and the high-density regime ($n_{e, \text{lav}} = 4.8 \times 10^{19} \text{ m}^{-3}$), selecting these two values based on reference lower single null (LSN) L-H transition studies [5]. To accurately identify the heating power crossing the separatrix at the time of the L-H transition, we used a fine-stepping Electron Cyclotron Resonance Heating (ECRH) scheme by increasing the heating power by 150 kW every 200 ms in the 2024 campaign and 200 kW every 150 ms in the 2025 campaign.

The L-H transition time (t_{LH}) is determined using a combination of different diagnostic signals. The L-H transition indicators are the increases in the $n_{e, \text{lav}}$ and stored energy resulting from improved edge confinement, the appearance of L-H dithers in magnetic fluctuations measured by Mirnov coils, and a deepening of the radial electric field (E_r) well near the separatrix. The P_{LH} is then evaluated as the net heating power crossing the separatrix at t_{LH} .

L-H Power Threshold

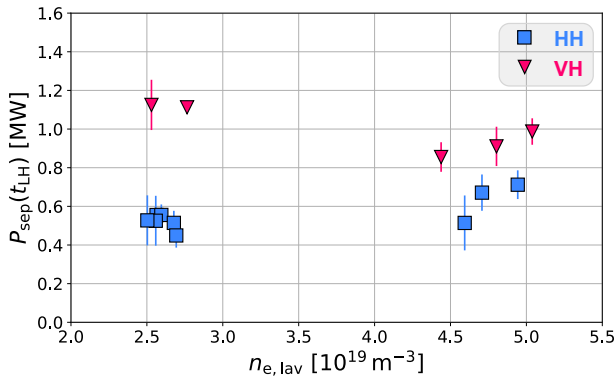


Figure 2: Comparison of $P_{\text{sep}}(t_{LH})$ for VH and HH configurations.

As shown in Figure 2, the evaluated P_{LH} depends strongly on the divertor configuration. Across the studied parameter range, the HH configuration consistently requires lower heating power to trigger the L-H transition than the VH configuration. This dependency holds across both density branches. The VH P_{LH} is approximately a factor of 2 higher in the low-density regime and a factor of 1.4 higher in the high-density regime. These observations on the ASDEX Upgrade tokamak USN plasmas align with previous findings from other major devices (JET [2], MAST [4], and DIII-D [3]), confirming that divertor configuration

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plays a significant role in setting the minimum power requirement for H-mode access.

Local Divertor Conditions Prior to the L-H transition

To understand the difference in P_{LH} , local divertor electron temperatures ($T_{\text{e,div}}$) from Langmuir probe measurements were analyzed for both configurations prior to the L-H transition. By fitting an Eich function to the probe data, the maximum $T_{\text{e,div}}$ was extracted and compared.

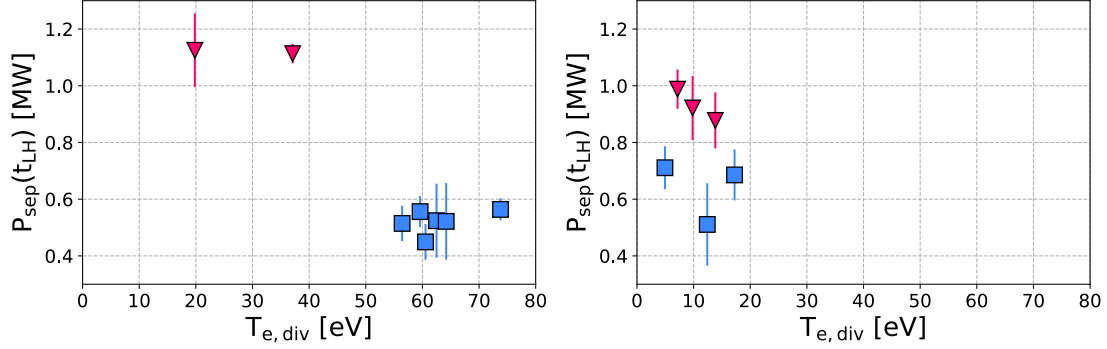


Figure 3: $T_{\text{e,div}}$ prior to the L-H transition. Left: Low density. Right: High density.

In the low-density branch (Figure 3: Left), a clear correlation can be seen between the peak $T_{\text{e,div}}$ and the P_{LH} . The HH configuration, which has a lower P_{LH} , exhibits a significantly higher maximum $T_{\text{e,div}}$ on the divertor tile. In this low-density regime, the plasma is in a low-recycling regime, which means that this higher divertor temperature can directly impact the outer mid-plane plasma potential ($\phi_{\text{pl,OMP}}$) via the sheath potential [6]. Consequently, this higher midplane potential can result in an increased E_r in the SOL. In the high-density branch (Figure 3: Right), the divertor plasma is colder, resulting in low and scattered $T_{\text{e,div}}$ measurements. For this regime, no clear difference in the maximum $T_{\text{e,div}}$ is observed between the HH and VH configurations.

Edge Radial Electric Field (E_r) Profiles prior to the L-H transition

One of the leading physics theories explaining the L-H transition relies on the formation of an edge E_r well, which creates a strong sheared flow that suppresses turbulent transport. Consequently, modifying the E_r shear can have an influence on the P_{LH} . Using helium spectroscopy measurements, the E_r profiles prior to the L-H transition were evaluated via the impurity radial force balance equation, which is strongly dominated by the measured poloidal velocity term near the separatrix. In the low-density regime, the HH configuration shows a higher SOL E_r (aligning with higher $T_{\text{e,div}}$) and a deeper E_r minimum. The inner and outer E_r gradients are similar for both configurations prior to the L-H transition. At high density, the SOL E_r is identical, but VH shows a slightly steeper inner E_r gradient. Since the helium spectroscopy diagnostic reliability diminishes inside $\rho_{\text{pol}} = 0.975$, this inner gradient steepening requires further confirmation by other diagnostics.

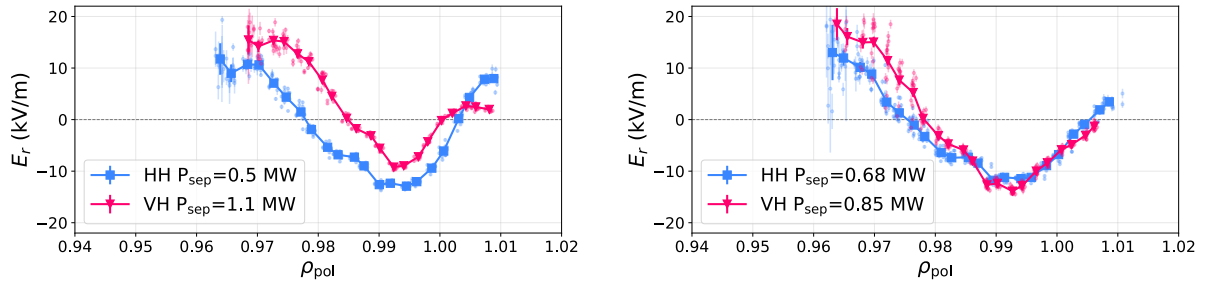


Figure 4: Edge E_r profiles prior to the L-H transition. Left: Low density. Right: High density.

Summary and Conclusion

In this work, we demonstrated that the P_{LH} in the ASDEX Upgrade tokamak depends on the divertor configuration, with the HH configuration requiring less heating power than the VH. The underlying physical drivers seem to be different depending on the density regime. In the low-density regime, the lower P_{LH} in the HH configuration appears to be linked to a higher $T_{e,div}$, which can increase the E_r in the SOL via the sheath potential. This change in the SOL could act as a boundary condition, potentially making it easier to build the outer E_r gradient required to trigger the L-H transition. At high densities, the $T_{e,div}$ and SOL E_r are similar across configurations, but the VH configuration has a slightly steeper inner E_r gradient prior to the L-H transition. This difference in the inner gradient suggests that the critical E_r shear required to achieve the transition might be different between the two configurations in this regime.

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