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LFS/HFS edge density profile dynamics on ASDEX-Upgrade

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Introduction

Next generation fusion devices are required to operate in regimes with high energy confinement and high density in order to achieve large fusion power. They will explore new regimes of boundary plasma physics with competing needs of plasma performance and plasma facing components. A reduction of the power loads on the plasma facing components will be required due to the narrow width of the scrape-off layer (SOL) power flux profile characteristic of the H-mode. This necessitates high density and low temperature SOL plasmas detached from the divertor. The development of a High Field Side High Density Front (HFSHD) associated with the inner divertor detachment has been reported [1, 2], which is located in the SOL at the height of the X-point. In these regimes the edge plasma and the plasma-wall interaction exhibits a complex dynamic that needs to be understood.

In this work the dynamics of the midplane edge electron density profiles and its relation to divertor detachment is studied on ASDEX-Upgrade (AUG) both in L- and H-mode, taking advantage of the high resolution High-Field-Side (HFS)/Low-Field-Side (LFS) O-mode reflectometry measurements.

L-mode density ramp discharges

It was previously shown[1] that as plasma density increases, divertor detachment undergoes three distinct states: onset state (OS), fluctuating state (FS) and complete detachment state (CDS) [1]. Figure 1a,b shows the temporal evolution of the HFS/LFS iso-density contours from reflectometry together with other relevant plasma parameters. Gas fuelling was ramped up leading to an increase in the plasma density until the density limit occurs. Transition to the FS is observed at 2.5s (determined by the onset of X-point fluctuations), while the CDS (characterized by the end of the X-point fluctuations and density and temperature reduction at the outer strike-point) occurs at 3.2s. As illustrated in Figure 1a,b, at low densities (below $3.5 \times 10^{19} \text{ m}^{-3}$) edge density profiles measured by reflectometry at the midplane are roughly HFS/LFS symmet-

ric. However, around $t=2.2$ s, well before the transition to the FS, a density increase is observed in front of the inner wall leading to strong poloidal asymmetries in the SOL density. Divertor plasma is often observed to oscillate back and forth between the OS and the FS [3]. Around 2.5 s, these oscillations reach the HFS midplane leading to a strong modulation of the HFS density profiles but are not detected in the LFS. At the transition to the FS the HFS/LFS density asymmetry decreases, increasing again for $t > 2.8$ s when the CDS is approached. Even in the presence of resonant magnetic perturbations, seen in Figure 1c as I_{RMP1} and I_{RMP2} , density profiles change little until core density starts to increase, half a second later.

The high density at the midplane may be related to the so-called HFSHD observed on the HFS far-SOL divertor region. The divertor HFSHD, characterized by high density in the divertor volume measured by Stark broadening, is seen to move upwards from the strike-point to the X-point as detachment develops (Figure 1d). The HFS high density region observed at the midplane continues to develop as the gas fuelling is ramped up and the density limit is approached, suggesting that the HFSHD reaches the midplane. However, the AXUV measurements do not indicate the existence of a significant radiation outside the divertor region. The evolution of the LFS profiles is significantly different from that at HFS. As the gas fuelling is ramped, the LFS edge density increases across the entire region scanned by the reflectometry diagnostic and particularly outside the separatrix leading to a broad SOL. This broad density profile at the LFS is most probably a result of an increased radial transport at the LFS [4]. Note that the midplane HFSHD is formed before any significant SOL broadening is observed at the LFS.

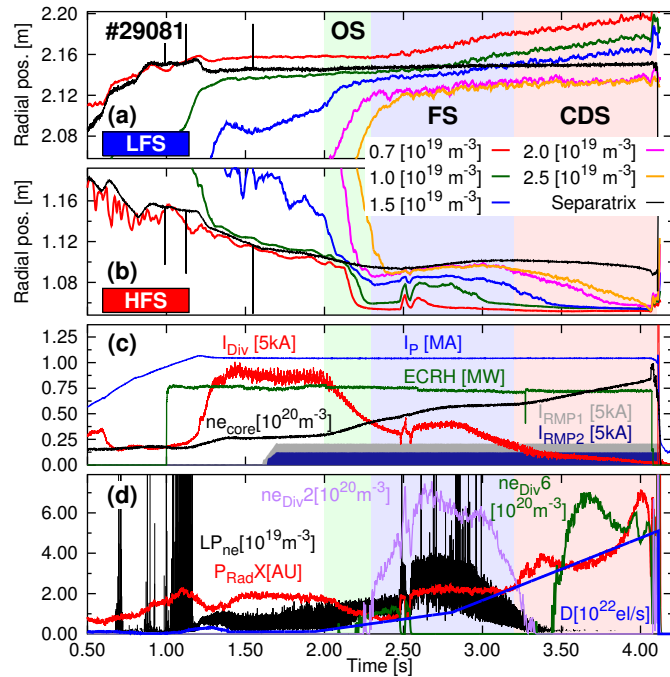


Figure 1: Temporal evolution of the radial position of different density layers for an L-mode (29081) at the LFS (a) and HFS (b) obtained from reflectometry density profiles, together with plasma current, applied ECRH power, divertor shunt current, core line-averaged density (c), divertor target density LP_{ne} , volume density at lower (ne_{Div2}) and upper (ne_{Div6}) inner divertor, radiated power in the X-point region and D fuelling (d).

H-mode discharges

In high power H-mode discharges at AUG, a high density front also develops in the far SOL of the HFS divertor. Figure 2 shows the temporal evolution of the HFS/LFS iso-density contours of an H-mode discharge with nitrogen seeding together with the time traces of relevant plasma parameters. In the first phase (up to 2.8 s) moderate NBI power and gas fuelling are applied resulting in large amplitude low frequency ELMs. In a second phase (3–3.5 s) both NBI power and gas fuelling rate are increased, leading to faster ELMs. Finally, at 3.5 s, nitrogen is puffed at constant rate to cool the divertor. The behaviour of the HFSHD changes strongly despite the roughly constant line-averaged core density. The increase of both heating power and fuelling leads to the development of the HFSHD that is then reduced when nitrogen is injected.

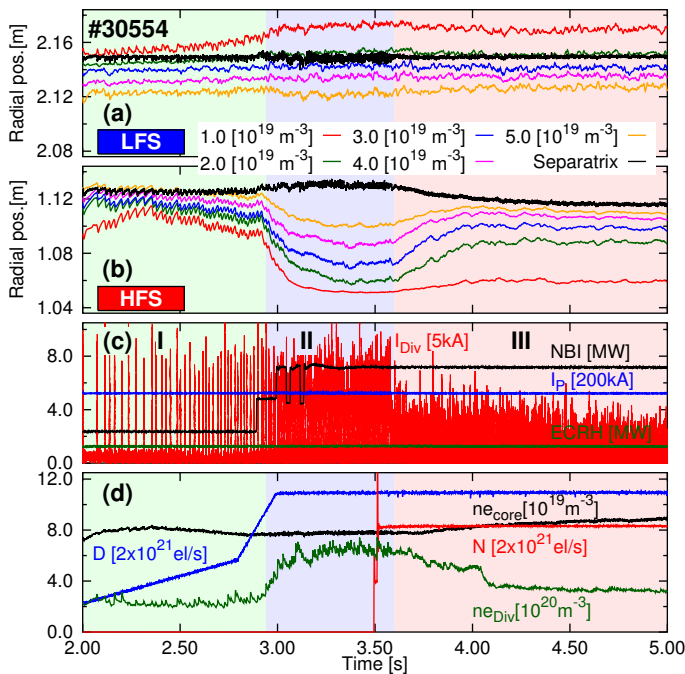


Figure 2: Temporal evolution of the radial position of different density layers along a H-mode discharge (30554) for LFS (a) and HFS (b). Plasma current, applied ECRH and NBI power, divertor shunt current (c), core line-averaged density, divertor volume density and D and N fuelling (d).

Reflectometry data shows the HF-SHD extending all the way up to the HFS midplane, but not to the LFS, leading to strong poloidal asymmetries in the edge density profiles. At the mid-plane, the HFSHD is located in the SOL just in front of the inner wall with densities greater than $6 \times 10^{19} \text{ m}^{-3}$ (diagnostic limit at the HFS). A delay ($\approx 25 \text{ ms}$) is observed between the density increase in the divertor volume (HFSHD formation) and that seen at the midplane. The ELM dynamics are found to be strongly influenced by the HFSHD. The conditional averaging of edge density profiles to study their evolution during ELMs can be seen in Figure 3 for the first and second discharge phases. In the case of low frequency Type-I ELMs (Figure 3a-c) the pre-ELM density profile is recovered after 2 ms at the LFS, while at the HFS a HFSHD is observed during the ELM that then persists for about 5 ms. During this period the particle flux to the inner divertor is reduced, as confirmed by divertor probes.

The power radiated in the inner divertor is also reduced as indicated by divertor AXUV measurements. These results suggest that in the period just after the ELM no HFSHD exists in the divertor region. The divertor target density and temperature are observed to increase when the

midplane HFSHD disappears 5 ms after the ELM. Both inner and outer divertor shunt currents show an ELM signature lasting 2 ms, compatible with LFS profile data. In the second discharge phase (Figure 3d-f), the ELM frequency increases and the HFSHD is continuously observed at the midplane although the density in front of the inner wall increases further during ELMs. The formation of the midplane HFSHD during ELMs may be related with an enhancement of the plasma-wall interaction at the inner wall caused by the broadening of the plasma profiles.

Summary

The formation of a HFSHD at midplane has been observed with reflectometry in both L- and H-mode regimes associated with divertor detachment. In L-mode, the midplane HFSHD develops continuously as the discharge density is increased while in H-mode, the midplane HFSHD is essentially observed during ELMs for low ELM frequency and it is continuously observed when the ELM frequency is increased. Results indicate that for low frequency ELMs the HFSHD builds up at the midplane while it vanishes in the divertor region.

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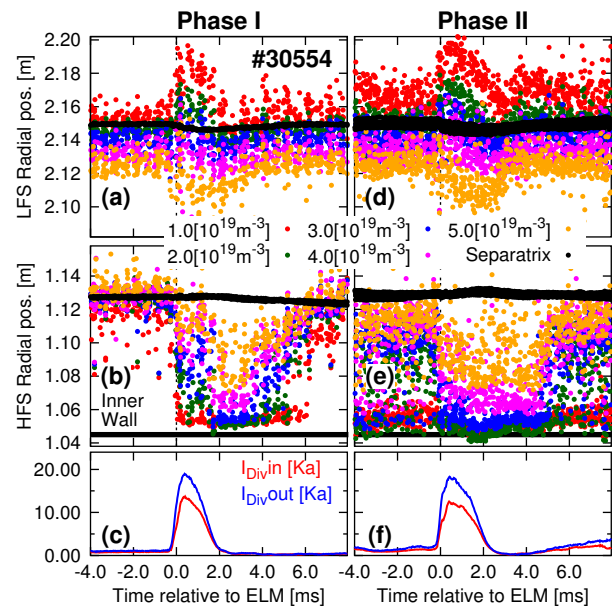


Figure 3: Temporal evolution of the radial position of different density layers during low (1.7–2.8 s) (a,b) and high (3.0–3.5 s) (d,e) frequency Type-I ELMs obtained using Conditional Averaging, together with the divertor shunt current (c,f).