

## Study of ELM density crash in ASDEX Upgrade

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### Introduction

This paper studies the behaviour of the H-mode edge density profiles in ASDEX Upgrade for type I ELMs. The density profiles analyzed in these studies are measured by simultaneous high-field side (HFS) and low-field side (LFS) swept frequency reflectometry, with high temporal ( $35\mu\text{s}$ ) and spatial resolution ( $\leq 1\text{cm}$ )[1]. This diagnostic allows the determination of the density evolution during the edge localized mode (ELM) crash as well in the inter-ELM period. This study concentrates on the comparative analysis of the density profile evolution at the inboard and outboard side of the plasma and its relation with the time needed for ions to stream (with ion sound speed) from HFS to the LFS. Preliminary results are also shown for type III ELMs.

### Profile dynamics: HFS/LFS delays at the onset of the ELM

From the density profile dynamics study, three phases of the ELM are identified: precursor, MHD and recovery phases [2]. During the ELM event, a crash in the pedestal density and a rapid rise in the scrape-off layer (SOL) is observed at both HFS and LFS at the onset of the ELM. HFS/LFS density profile comparison shows a smaller effect of the ELM at the HFS where the affected depth, and particle losses are smaller than at LFS [3]. Although a symmetric behaviour is observed on the dynamics of the density profiles after the MHD phase of the ELM, a delay ( $\Delta t_{LFS/HFS}$ ), is measured between the start of the density profile perturbation at the LFS and the HFS, at the onset of the ELM. Here we will show that this delay is consistent with the crash of the density profiles being initiated at the low-field side and propagating to the high-field side along the field lines. The observed  $\Delta t_{LFS/HFS}$  is comparable with the time,  $\tau_{||}$  needed for the ions to stream with the ion sound speed,  $c_s$  from LFS to HFS. The streaming time is given by  $\tau_{||} = \pi Rq/c_{s,ped}$  where  $c_{s,ped} \approx \sqrt{((T_{e,ped} + T_{i,ped})/m_i)}$  and  $(\pi Rq)$  is the connection length from the LFS to HFS midplane across the plasma top (opposite to the X-point, figure 5). Here,  $q$  is approximated by  $q_{95}$ , the safety factor at 95% of the last closed flux surface. Therefore,  $\tau_{||}$  depends on the pedestal temperature and on the connection length. To study the dependence of the observed delay with  $\tau_{||}$ , several discharges with different plasma parameters were analyzed. At the onset of the ELM, the signal measured by the reflectometer is highly perturbed, as shown in figure 1, where a series of density profiles during the three phases of the ELM event for both HFS and LFS are shown. The delay of the ELM onset between LFS and HFS is defined as the time lag between the start of the profile perturbation at LFS and HFS as shown in figure 2. The minimum time interval between successive reflectometry profiles sweeps is  $35\mu\text{s}$ , hence there is a degree of uncertainty in determining  $\Delta t_{LFS/HFS}$  for short delays. This is particularly evident for  $\Delta t_{LFS/HFS} < 70\mu\text{s}$  where a large scatter is observed. In figure 2 two contour plots with the time evolution of the density

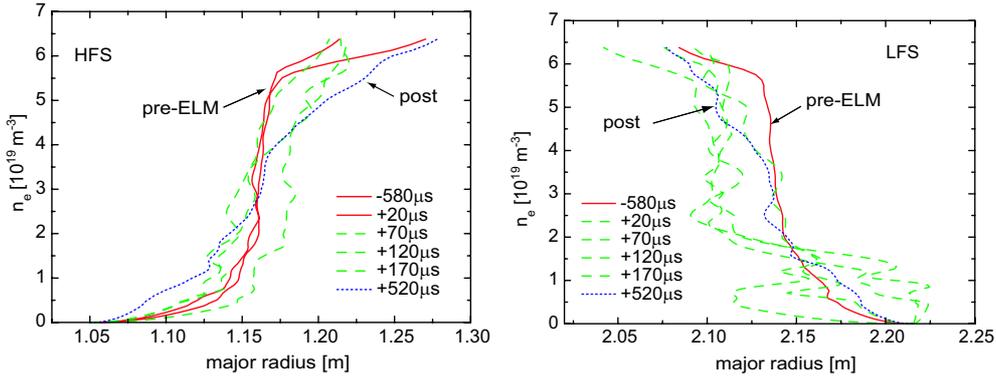


Figure 1: Density profiles before (full red), during (dash green) and after (dot blue) the ELM for HFS and LFS. The onset of the ELM is considered to be at  $t = 0$ s.

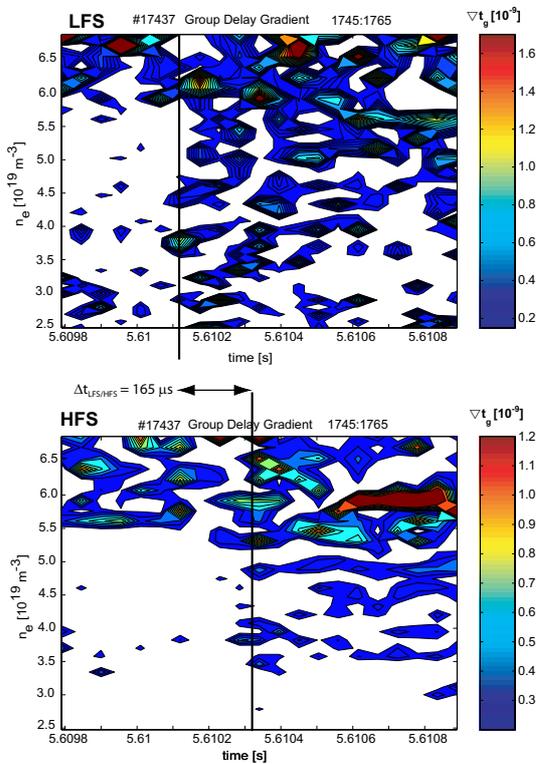


Figure 2: Contour plot of the gradient of the group delay curves showing the different onset of the density profile perturbation

perturbation for discharge #17437(2)<sup>1</sup> are shown. The perturbation is inferred from the change on the local gradient of the group delay,  $\tau_g$  curve calculated for each instant, where the colors show the value of the gradient. Before the ELM event, one observes that below the pedestal density ( $\approx 5.5 \times 10^{19} \text{m}^{-3}$ ) there is almost no change in the local gradient. Above this density the density profile flattens which explains the change of value of the local gradient. At the onset of the ELM the density profiles show a highly perturbed curve (for example, for  $\Delta t_{ELM} = +120 \mu\text{s}$ , as shown in figure 1) and changes on the gradient values are observed for all the densities. This perturbation is clearly observed to start first at the LFS and only  $\approx 165 \mu\text{s}$  after at the HFS (figure 2).

### LFS/HFS delay dependence on the ion parallel transport time

Figure 3 shows the delay on the density profile crash as a function of  $\tau_{\parallel}$  for several discharges. It is found that the delay of the crash of the density profile for these discharges is increasing linearly with  $\tau_{\parallel}$ . Pedestal temperature and connection length dependence were analyzed separately. To test the temperature dependence, two discharges #16201 and #16164 with  $I_p = 1\text{MA}$ ,  $B_T = 2\text{T}$ ,  $\delta = 0.15$ ,  $q_{95} = 3.25$  and a pedestal temperature of 750 and 1150 eV were analyzed. The  $\tau_{\parallel}$  for a pedestal temperature of 750

<sup>1</sup>Index 1 and 2 mean that this discharge has two different levels of gas

eV is  $67 \mu\text{s}$  and  $50 \mu\text{s}$  for  $1150 \text{ eV}$ , respectively, and the observed LFS/HFS delay is in most cases  $70 \mu\text{s}$ . A change of  $\approx 400 \text{ eV}$  in the pedestal temperature leads only

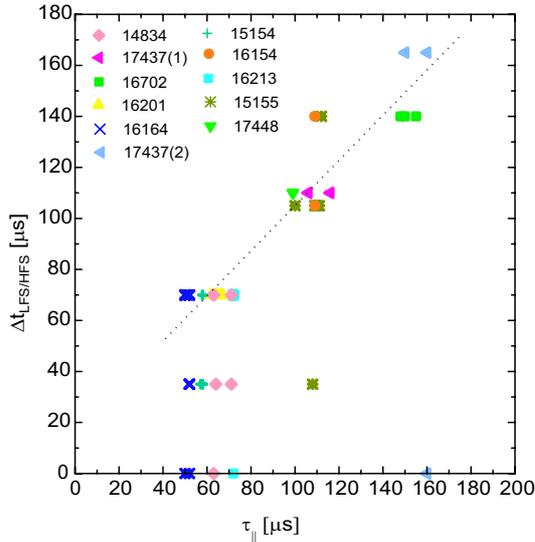


Figure 3: Observed time delay of the density profiles as a function of the ion parallel transport time where a line was drawn to guide the eye.

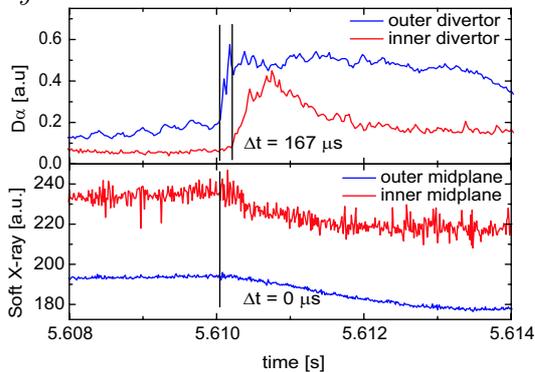


Figure 4:  $D\alpha$  signals at the divertor showing a delay of  $167 \mu\text{s}$  and soft X-ray signals at the midplane where no delay is observed.

$\tau_{||}$ ). The dynamic of the particle flow during an ELM event occurs in two phases: first, fast electrons are ejected establishing a new sheath at the SOL [4]. During this phase the flux to the divertor remains unchanged because of the characteristic time for ions to flow along the field lines from the midplane to the divertor ( $>100 \mu\text{s}$ ). In the second phase a flux of ions starts to arrive onto the divertor target which leads to an increase of the  $D\alpha$  signal [5,6]. The soft X-rays measure the radiated emission from the interaction of the fast electrons with the wall and hence show no delay between LFS and HFS, since this happens in a very fast time scale (few  $\mu\text{s}$ ) [7]. On the other hand, the  $D\alpha$  measuring the ion flux arriving onto the divertor show asymmetries between inboard and outboard divertor due to the different connection length from the pedestal to the

to a change of  $\tau_{||}$  of  $3 \mu\text{s}$  and hence the scaling with  $T_e$  is weak. For the connection length dependence study, three similar discharges of a current scan (#14834, #17437(1) and #16702 with  $B_T = 2\text{T}$  and  $I_p = 1, 0.8, 0.55 \text{ MA}$  and  $q_{95} = 3.14, 4.85, 7.09$  respectively), where the pedestal temperature for the three discharges is between  $600$  and  $700 \text{ eV}$ , were analyzed. It is found that the delay of the crash of the density profile for these discharges is increasing linearly with  $\pi R q_{95}$ , showing that the dominant factor of the  $\tau_{||}$  is the connection length while the dependence of  $T_e$  is less significant. Figure 3 also includes several other ASDEX Upgrade plasma ELM H-modes, randomly selected. Globally, a linear dependence of the LFS/HFS delay with estimated  $\tau_{||}$  is observed, and one can conclude that the measured time delays are correlated with the ion parallel transport. It should be noted that, for some cases, in consecutive ELMs, a zero delay on the density profiles crash is observed, although these ELMs have similar pedestal parameters and  $D\alpha$  signatures to those having a finite delay. The understanding of these particular cases requires further study. The results from reflectometry are compared with measurements from the inboard and outboard divertor  $D\alpha$  and the soft X-ray emission, with sight lines intersecting LFS and HFS as shown in figure 5. Figure 4 shows both signals for the discharge #17437(2) (case with higher

divertor target. In the given example, the delay between outboard and inboard divertor is of  $\approx 167\mu\text{s}$ , close to  $\Delta t_{LFS/HFS} = 165\mu\text{s}$  measured by the reflectometer. Note that for the  $D\alpha$  signals, the connection length from LFS midplane to the inboard divertor is  $(3/4)\pi Rq$  and to the outboard divertor is  $(1/4)\pi Rq$ , while the reflectometer is placed at both LFS, HFS midplane where the connection length is  $\pi Rq$  on the plasma top (see figure 5). Figure 6 shows the time evolution of the density profile gradient for two type III low  $q_{95}$  case. An in/out delay of the ELM density crash is also observed, about  $\approx 110\mu\text{s}$  which is in good agreement with  $\tau_{\parallel}$  ( $115\mu\text{s}$ ). Further study is necessary in order to assess the behaviour of the type III ELM pedestal density crash for a wider range of plasma parameters. The study of the LFS/HFS delays for type III ELMs has so far been limited to a few cases, due to the lack of available data with high  $q_{95}$ .

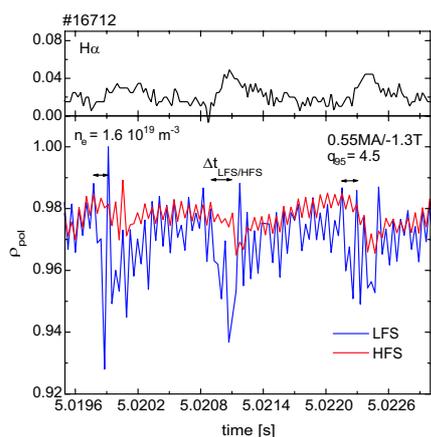


Figure 6: *Density profile gradients for a type III ELM discharge where a very clear delay between LFS/HFS is observed.*

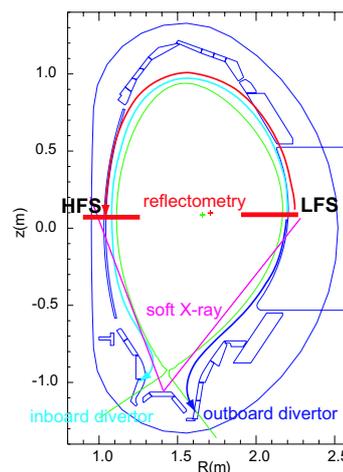


Figure 5: *Schematic of the connection length for the diagnostics here compared.*

## Summary and Discussion

Clear evidence of the ELM particle losses starting at the outboard and propagating to the inboard side is shown by the delay observed at the density profile crash. In this paper it has been shown that for type I ELMs the observed delay of the density profile crash from LFS to HFS is consistent with the parallel transport time. The analysis of several discharges with different plasma parameters shows a good agreement between measured delays and calculated ion parallel transport time. This phenomenon is consistent with a ballooning character for type I ELMs. In the case of type III ELMs, more experimental results are needed to assess if a dependence with the connection length is also observed.

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[1] A. Silva *et al*, *Rev. Sci. Instrum.*, **67** (1996), 4138 [2] I. Nunes *et al*, *Proceedings of the 29th EPS Conference*, Montreux, **26B** (2002) [3] I. Nunes *et al*, *9th EU-US Transport Workshop*, Cordoba, Spain (2002) [4] P. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*, (Bristol: Institute of Physics Publishing) [5] A. Loarte *et al*, *Proceedings of the 18th IAEA Fusion Energy Conf.*, Sorrento, Italy (2002) [6] G. Janeschitz *et al*, *J. Nucl. Mater.*, **290 293** (2001) 1 [7] A. Loarte *et al*, *Plasma Phys. and Control. Fusion*, **44**, (2002) 1815