Characteristics of type I and type III ELM precursors in ASDEX Upgrade
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1. Introduction

So far, steady state H-mode has been achieved only with the presence of edge localized modes (ELMs) providing an efficient particle density and impurity control [1,2]. Following the classification based on the ELM frequency $f_{ELM}$ dependence on the energy flux across the separatrix $P_{sep} = P_{heat} - P_{rad} - dW_{MHD}/dt$, where the radiated power $P_{rad}$, the heating power $P_{heat}$ and the stored kinetic energy in the plasma $W_{MHD}$ are considered [1], the ELM types observed in the ASDEX Upgrade tokamak are of type I ($dP_{sep}/df_{ELM} > 0$) and of type III ($dP_{sep}/df_{ELM} < 0$). It has been shown, that in ASDEX Upgrade type III ELMs are stabilized at edge electron temperatures somewhat above 300 eV [3]. Therefore their mechanism might be governed by resistivity. Type I ELMs on the contrary are found to be triggered at critical edge pressure gradients close to the ideal ballooning limit.

In this paper we will show, that an edge pressure gradient close to the ideal ballooning limit is not sufficient to trigger a type I ELM. In order to understand the ELM mechanism the MHD characteristic must be investigated further. The following discussion concentrates on the ELM precursor oscillation, as this phase of an ELM is not perturbed by turbulence emerging during the enhanced transport phase. Therefore the characteristics and experimental phenomenology of both types of ELM precursors observed in the ASDEX Upgrade tokamak (major radius $R_0 = 1.65$ m, minor radius $a = 0.5$ m, elongation $\kappa = 1.6$, triangularity $\delta = 0.1$) are presented.

2. Experimental observations

2.1 Temporal evolution of the edge pressure gradient

First the temporal evolution of the edge electron pressure gradient $\nabla p_{e,edge}$ taken at $r = a = 2$ cm is investigated before and after a type I ELM. The electron pressure gradient shown in Fig. 1 is obtained from measurements of the electron density by means of DCN-Laser interferometry and Li-beam injection, and the electron temperature detected with the ECE-diagnostic. All data have been taken at the low-field side.

![Fig. 1: The temporal evolution of the edge electron pressure gradient taken at $r = a = 2$ cm during a type I ELM shows that the pressure gradient recovers continuously from the drop caused by the preceding type I ELM (not shown). Several milliseconds before the next type I ELM occurs (solid vertical line at $t = 1.814$ s) and well before the precursor oscillation arises (dashed vertical line at $t = 1.813$ s) $\nabla p_{e,edge}$ saturates.](image)

It can be observed, that $\nabla p_{e,edge}$ recovers continuously from the drop caused by the preceding type I ELM (not shown). Several milliseconds before the next type I ELM occurs (solid vertical line at $t = 1.814$ s) and well before the precursor arises (dashed vertical line at $t = 1.813$ s), $\nabla p_{e,edge}$ saturates at $\nabla p_{e,edge} = 136$ kPa/m (dashed horizontal line). Thus, $\nabla p_{e,edge}$ remains approximately constant for a significant time period prior to the type I ELM. The normalized pressure gradient $\alpha = -2\mu_0 R_0^2/B^2 \cdot \nabla p$ equals 2.57 at this time ($p = p_e + p_i \approx 2p_e$ is assumed).
Infinite-n ideal ballooning mode calculations (carried out with the help of the HELENA-code [4]) show that this value lies with an uncertainty of 30% close to the critical value $\alpha_{\text{crit}}$ given by the ideal ballooning limit. The main sources of error are the unknown ion pressure $p_i$ and the uncertainty of the relative position of the profile. Another indication for ideal ballooning is the $P^2$-scaling of $\nabla p_{\text{crit}}$ found in the experiment [5]. Thus, in the considered case, the critical value of the edge pressure gradient is reached within the experimental accuracy well before the type I ELM occurs without immediately triggering a type I ELM. This indicates, that proximity to the ideal ballooning limit is not a sufficient to trigger a type I ELM, as suggested in [1]. Thus the MHD characteristic of ELMs must be further investigated. As the precursor phase of an ELM is not deteriorated by turbulence or non-linear effects, the following discussion is focused on their phenomenology as observed in ASDEX Upgrade.

2.2 Frequency of the ELM precursors

In Fig. 2 the result of a wavelet analysis (temporal evolution of the frequency spectrum) of a type I (Fig. 2a) and a type III ELM (Fig. 2b) together with their corresponding precursor oscillations during a discharge with counter-injection ($I_p = 1$ MA, $P_{\text{NB1}} = 5$ MW $D^0 \rightarrow D^+$) and the toroidal magnetic field ($B_t = 2.5$ T) in the unfavourable field direction (ion-$\nabla B$-drift away from the X-point) is shown. It can be seen, that in both cases the ELM precursor oscillation starts to grow about 1 ms before the transport increases (type III ELM precursors sometimes grow much faster). On the other hand the frequency of both types of ELM precursor oscillations differs considerably. Whereas type I ELM precursors exhibit a frequency of the order of 20 kHz, type III ELM precursors show a frequency of the order of 100 kHz during counter-injected discharges. Both frequency spectra exhibit quite a narrow band in contrast to the enhanced transport phase of the ELMs, which has a broad band spectrum.

In the case of co-injection the frequencies change significantly. The frequency of type III ELM precursors is then shifted to lower frequencies of the order of 60 kHz and type I ELM precursors are not observed. Despite the absence of a clear magnetic type I ELM precursor a slow electron temperature fluctuation around 5 kHz is detected by ECE channels resonant near the separatrix [6]. Here the question arises, whether the magnetic type I ELM precursor is indeed absent or only undetectable with magnetic probes.

Another feature of the ELM precursor oscillation, which can been seen for instance in Fig. 2b, is the presence of two apparently periodically alternating frequencies (100 kHz and 120 kHz in this example). The observation of two clearly separated frequencies in the Fourier spectrum appears sometimes also during type I ELM precursor oscillations and is also reported from the COMPASS-D experiment [7].
2.3 Mode structure of the ELM precursors

The mode structure of the ELM precursors can be inferred from an analysis of the magnetic signal [8]. In ASDEX Upgrade three pick-up coils each measuring $B_r$ (a maximum sampling rate of 500 kHz is provided) are installed in different toroidal positions in the midplane ($z = 0$), thus enabling the determination of the toroidal mode number. A mode analysis of many ELM precursors of both types reveals that the toroidal mode number varies in the range of $n = 5 - 10$ for type I ELM precursors, whereas for type III ELM precursors $n = 10 - 15$ is found. Despite the obvious variation of $n$ there is a significant global difference in the toroidal mode structure between both types of ELM precursors.

Since the type III ELM precursors are not detected by the poloidal Mirnov coil array positioned at the inside of the vacuum vessel and the radial pick-up coils are only available for one poloidal position (outer midplane), no reliable statement about the poloidal mode structure ($m$-number) can be given yet. But as a very rough approximation $m$ can be estimated by the decay of the radial magnetic field $B_r$. As the three additional pick-up coils also have different radial positions ($R_1 = 2.267$, $R_2 = 2.301$, $R_3 = 2.386$) the decay of $B_r$ can be measured. In cylindrical and circular approximation $B_r(r) \sim (r_{res}/r)^{m+1}$ holds, where $r_{res}$ denotes the radius of the resonant surface at which the mode is located. Thus, the following expression for the poloidal mode number $m$ can be derived: $m = \left\{ \ln(B_{i}/B_{j})/\ln(r_{j}/r_{i}) \right\} - 1$, where $i$ and $j$ subscripts different pick-up coils located at different radial positions. Note, that this method is not very exact and therefore afflicted with a significant uncertainty due to the poloidal variation of the pitch. Furthermore, the $m$-numbers are underestimated in this approximation, since only coils at the low-field side are used. Applying this method we find $m$ varying from 10 to 15 for type I ELM precursors and $m$-numbers between 15 and 20 for type III ELM precursors.

The result that type I ELM precursors show significantly lower $m$-numbers compared to type III ELM precursors is also confirmed indirectly by the observation that these modes are also faintly visible on the coils mounted further away from the plasma. Thus the poloidal $m$-numbers of type I ELM precursors have to be smaller than for the type III ELM precursors, consistent with their lower $n$-numbers and reduced signal frequency.

Furthermore, both ELM precursor modes rotate in the electron diamagnetic drift direction consistent with observations from other experiments.

The radial extent of the layer in which the precursor oscillation occurs can be estimated from the time resolved measurement ($\Delta \tau = 4$ ms) of the $T_e$ at different radial positions in the plasma edge region. Such an investigation shows that the extent of the type I ELM precursor is restricted to a thin layer ($\Delta r \approx 1 - 2$ cm) close to the plasma edge as the precursor oscillation cannot be seen on the channels resonant deeper inside the plasma [6].

3. Discussion

The detected significant variation of the ELM precursor frequency can partly be understood by the different spatial structure of the ELM precursors. In the lab frame, MHD modes roughly rotate corresponding to the present radial electric field $E_r$, i.e. with the sum of the mainly poloidal diamagnetic frequency $\omega^* = 1/(\pi Brn) \cdot \nabla p$ and the frequency due to toroidal fluid rotation $\omega_{tor}$ driven by the tangential component of the neutral beam injection [8]. Thus, the detected signal frequency equals $\nu_{Mirnov} = (m \cdot \omega^* \pm n \cdot \omega_{rot})/2\pi$ ($+/-\omega$ for counter/co-injection). Consequently, the oscillation frequencies are generally higher in the case of counter-injection, consistent with the higher radial electric field $E_r$ observed in these discharges ($E_r$ is measured via the charge exchange flux [9]) [3].

However, the different $n$-numbers cannot fully explain the frequency difference between type I and type III ELM precursors. The frequencies differ by about a factor of $4 - 5$, whereas for the corresponding mode numbers only a factor of $2 - 3$ is found. This might point to a finite frequency of one of the modes in the fluid frame. In the case of type I ELMs with co-injection
(the usual case in ASDEX Upgrade), the effect of $\omega^{*}$ and $\omega_{rot}$ almost cancel (note the minus sign in this case in the above equation). Thus the fact that type I ELM precursors are not clearly visible under these circumstances is due to the resulting low frequency yielding a low Mirnov amplitude. Actually, the type I ELM precursor may also grow locked and therefore not be detected by magnetic probes at all. In these cases, they have a very high growth rate (on the sub-ms timescale), whereas the rotating precursors grow on a ms timescale. This may be due to the stabilizing effect of the wall on the rotating mode, which is absent for the locked precursor mode. In co-injected cases, where $E_r$ vanishes in the steep pressure gradient region, the mode will be most unstable at this position, whereas in counter-injected discharges, $E_r$ does not vanish in the region of high pressure gradient. This difference can explain why in ASDEX Upgrade generally, discharges with counter-injection have a significantly reduced ELM frequency (about a factor 10) compared to discharges with co-injection.

4. Summary
In this paper, we have shown that proximity of $\nabla P_{edge}$ to the critical value given by the ideal ballooning limit is not sufficient to trigger a type I ELM. In order to get more information about the ELM mechanism the MHD characteristic of ELMs is investigated. The present discussion is focused on the experimental phenomenology of type I and type III ELM precursor oscillation as observed in ASDEX Upgrade. Both types of precursor have a significant different oscillation frequency in co- ($f_l \leq 5$ kHz, $f_{III} \approx 60$ kHz) as well as in counter-injected discharges ($f_l \approx 20$ kHz, $f_{III} \approx 100$ kHz). The mode numbers found for type I ($m, n = 10 - 15, 5 - 10$) and type III ELM precursor ($m, n = 15 - 20, 10 - 15$) are consistent with the observed precursor frequencies, thus providing a third criterium, besides the ELM frequency scaling with $P_{dis}$ and the peak power load on the diverter plates, to distinguish between type I and type III ELMs at ASDEX Upgrade. Furthermore, it has been shown, that the type I ELM precursor oscillation originates from a thin layer ($\Delta r \approx 1 - 2$ cm) close to the plasma edge.

5. Conclusions
From our point of view, it seems to be likely, that a coupling between the mode responsible for the ELM precursor oscillation and an ideal ballooning mode can trigger a type I ELM. A possible candidate for this ELM precursor mode would be the current-driven peeling mode, which has been shown can couple to an ideal ballooning mode at high plasma pressure and create a hybrid mode [10]. However, the major lack of this model is that the ELM-free regime experimentally found at ASDEX Upgrade is located right in the parameter space, which is calculated to be peeling unstable (compare Fig. 2 in Ref. 10). Further hints about the ELM mechanism may also be given by an observation recently reported from the TCV tokamak showing toroidally asymmetric precursor oscillations [11].

References