Electron temperature evolution during mitigated ELM regimes in ASDEX Upgrade

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Introduction.   High confinement mode or H-mode will be the baseline scenario for ITER. This scenario is characterized by an edge transport barrier formed in the pedestal region, just inside the last closed flux surface. The high pressure gradients formed in this region, lead to periodic relaxation, called edge localized modes (ELMs), expelling particles and heat towards the divertor and the plasma facing components. The particle losses associated with type-I ELMs have on one hand the beneficial effect of reducing the impurity accumulation, but on the other hand the heat loads will dramatically reduce the lifetime of the divertor target for ITER [1].

For this reason, strong efforts to mitigate or suppress type-I ELMs have been made during the last decade. In ASDEX Upgrade, a new set of 16 saddle coils creating a magnetic perturbation (MP) with toroidal mode number of n=1, 2 and 4 has been installed. Recent experiments have shown that type-I ELMs are replaced by another benign edge relaxation with higher frequency. The transition from type-I ELMs to mitigated ELMs occurs at high collisionality or plasma pedestal density (65% of the Greenwald density n_{gw}) [2], maintaining the pedestal pressure and the confinement energy [3].

The underlying mechanism leading to the ELM mitigation is still not clear, and efforts to understand possible changes in the particle or heat transport are needed. The analysis of the electron temperature dynamics in mitigated ELM regimes is presented in this paper.

Heterodyne Radiometer.   The heterodyne radiometer measures the ECE radiative temperature with 60 channels at fixed frequencies and bandwidth of 300 or 600 MHz (spatial resolution <2 cm). The gain of the individual channels can be optimized depending on the expected measured temperatures, optimizing therefore the SNR of the data, which is especially relevant for channels measuring at the plasma edge. Thus, drop of the electron temperature profile caused by small ELM crashes can be resolved with this diagnostic. The small spatial and time scales involved in the crash of the ELM (from several tens of microseconds to few milliseconds) can be well defined with this diagnostic. The upgraded fast acquisition system has a sampling rate of up to 1 MHz. For this analysis the data was down sampled to maximize the SNR (64μs temporal resolution, enough to resolve the ELM crash).

Transition from type-I to mitigated ELMs.   Figure 1 shows the transition from big type-I to small ELMs, for a pair of H-mode discharges with B_T=-2.5 T, I_p=0.8 MA and dominant ICRH heating (P_{ICRH}=5 MW, see figure 1a).

By increasing the gas puff (figure 1b), the density is continuously rising. The time evolution of the edge and core line integrated density are shown in figures 1c (with resonant MP coils n=2 in the time interval shadowed) and 1d (without MP). The transition to small ELMs for the discharge with MP occurs at 65%n_{gw}, while for the discharge without MP coils this transition occurs at 77% n_{gw}. This observation is in agreement with previous experiments which were made with dominant NBI heating power [2, 4]. Figure 1e shows the time evolution of the divertor current -I_{div}-. At times where the heat load reaches the divertor, a big increase in the thermo current is observed. This diagnostic is used as an indicator for occurrences of ELMs.
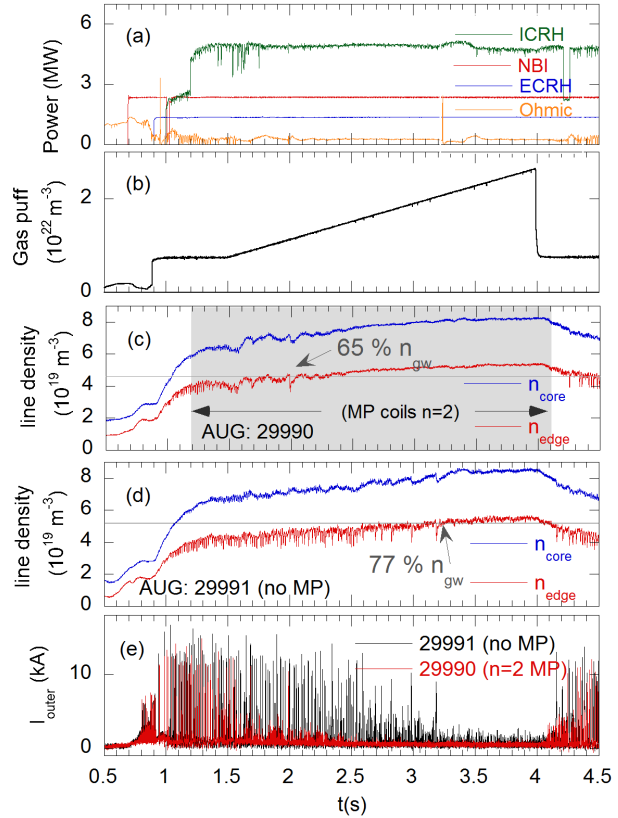

Figure 1: *Overview of the discharges 29990 and 29991. Heating power (a), gas fuelling (b), core (red) and edge (blue) integrated density for discharges 29990 (c) and 29991 (d), outer divertor current for the discharges 29990 (red) and 29991 (black).*

Small ELM regimes. In the presence of MP coils, the frequency of the big type-I ELMs diminishes before they are completely eliminated. During the transition from big type-I to mitigated ELMs, smaller and faster periodic heat pulses are observed in the divertor current. Figure 2d shows its evolution in a short time interval before the last big ELM crash. Figure 2c depicts the evolution of an ECE channel located at the pedestal top. At the time of the collapse of the ELM, the pedestal temperature $T_{e,ped}$ drops, I_{div} start to rise and the stored energy (figure 2a) decreases. Few hundreds of microseconds after $T_{e,ped}$ shows a minimum - considered in this analysis as t_{ELM}-, the divertor current shows a peak. This delay is considered as the duration of the divertor ELM power pulse. The drop of the edge density $n_{e,edge}$ is measured with the edge interferometer channel (figure 1b). Several milliseconds after t_{ELM}, a decrease in the density ($\sim 2\%n_{edge}$) is also observed. The energy loss due to those small ELMs is $\sim 2\%$, in contrast to the $\sim 10 - 20\%$ energy loss for big type-I ELMs.

Using the ELM average technique [5], the ELM affected area and the average T_e drop in the pedestal region are calculated. The selected time windows have from 5 to 40 ELMs (whose frequency varies from 80 to 500 Hz). The drop of the temperature at the ELM crash is calculated as $\Delta T_e = T_{e,before}(t_{ELM} - 1ms) - < T_{e,after} >$. The duration of the $T_{e,ped}$ crash for the small ELMs was observed to be ~ 150-$300\mu s$, therefore we calculate $< T_{e,after} >=< T_e(t_{ELM} : t_{ELM} + 320\mu s) >$.
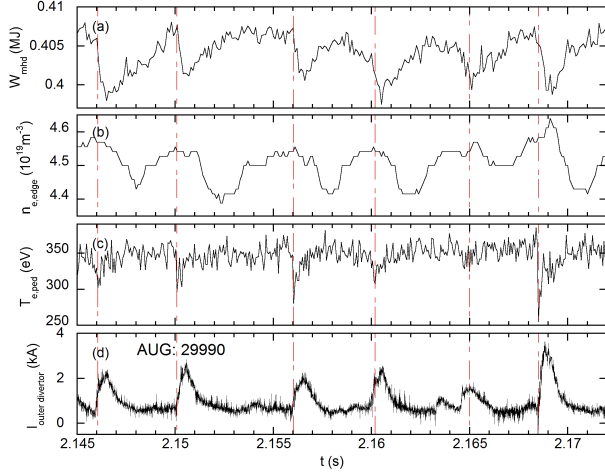
Figure 2: *(a) Plasma stored energy, (b) line integrated density at the edge, (c) T_e at the pedestal top, (d) outer divertor current for discharge 29990 in a time interval of mitigated ELMs. Red lines show the time of T_e crash (t_{ELM}).*

For certain intervals, the time traces of the pedestal ECE channels measure sharp spikes of T_e at the time of the ELM crash, and the calculated drop at those times -$\Delta T_e(t_{ELM})$- results to be $\sim 50\%$ higher than the average value. As the presence of filament structures could affect the ECE radiation collected by the antenna, the results presented here consider only average values. The region affected by the ELM crash for most of the cases analysed here is approximately 20% of the normalized minor radius, and the drop of the electron temperature varies from $\Delta T_e \sim 10$ to 50 eV for mitigated ELMs. The recovery time of the pedestal temperature varies from 0.5 to 2 ms, depending on how much the electron temperature drops.
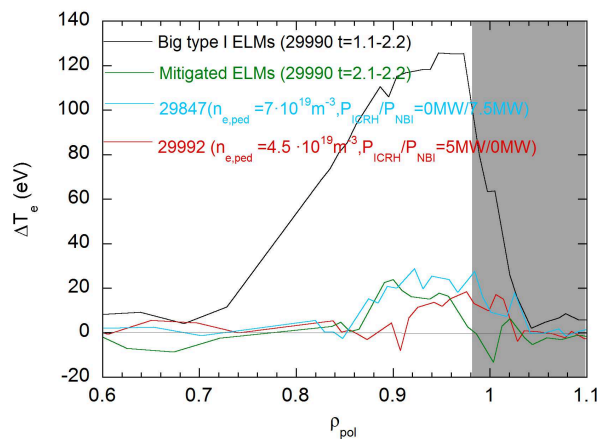
Figure 3 shows four different cases of the electron temperature drop versus the normalized minor radius $\Delta T_e(\rho)$. The ELM affected area for a time interval including the ELMs showed in figure 2 is represented in green line. The blue line depicts $\Delta T_e(\rho)$ for a time interval with dominant NBI heating and mitigated ELMs. For comparison, the case of big type-I ELMs for the discharge 29990 before the mitigation is also shown (black line). Its ELM affected area is bigger and the electron temperature drop is $\Delta T_e \sim 130$ eV (37 %$T_{e,ped}$). A case for a type III ELM (with low density and low temperature) is shown in red. In this case,

$\Delta T_e \sim 20$ eV and the ELM affected area is $\sim 10\%$ of the normalized minor radius. The shadowed area in the figure shows the region of low optical thickness. Due to the shine through effect, only channels located at $\rho_{pol} < 0.98$ provide local electron temperature[6].

Electron temperature drop dependency. A data base with mitigated ELMs using resonant n=2 MP coils has been analysed. The discharges had B_T=-2.5 T, I_p=0.8 MA and differ in the heating power and plasma density. The range of the pedestal density values was $n_{e,edge} = 6 - 8 \cdot 10^{19} m^{-3}$ and the pedestal

Figure 3: *Average drop of the electron temperature profile versus rho poloidal. The traces represent four different time intervals analysed: black for big type-I ELM, red for a type III ELM, and green and blue for typical mitigated ELMs with MP (n=2).*

top temperature $T_{e,ped}$=300-600 eV. Figure 4 shows the electron temperature drop calculated with the ELM average technique versus the pedestal density. Closed symbols represent data points with discharges with resonant n=2 MP, while open symbols represent data points without MP. Cyan symbols are data points with dominant NBI heating ($P_{ICRH}/P_{tot,eff}$<0.3). Those points have the higher $T_{e,ped}$ ($\sim$500 eV) and the steepest T_e profiles in the analysed data base. Green and red symbols correspond to data points with mix heating and $P_{ICRH}/P_{tot,eff}$ >0.6 respectively. Squared and triangle symbols distinguish ELM of different sizes (I_{div}>1.4 kA or I_{div}<1.4 kA respectively). With MP coils, the minimum ΔT_e observed occurs for high denisty and low temperature. For dominant ICRH heating, $T_{e,ped}$ have the lowest values in the analysed data base. It was observed that for those cases the T_e drop is minimal (ΔT_e <20 eV) and the relative drop of the temperature $\Delta T_e/T_{e,ped}$ is lower as well. Among the analysed data base with MP, there is evidence of a second transition from small ELMs to grassy ELMs, ocurring at $n_{e,ped} > 7 \cdot 10^{19} m^{-3}$ and $T_{e,ped} < 450$ eV.

Summary and Discussion. The present results of mitigated ELM support previous experiments made at ASDEX Upgrade. The electron temperature drop associated to big type-I ELMs is typically ΔT_e >100 eV, while for mitigated ELMs the temperature crash is faster ($\sim 100\mu$s) and smaller ΔT_e <20-50 eV. The drop of the pedestal temperature ΔT_e, and the relative drop $\Delta T_e/T_e$ depends on density and temperature, diminishing the drop for higher density or lower temperature. For the cases with lower temperature values and MP n=2, when the plasma density keeps rising, the mitigated ELMs become smaller (ΔT_e <
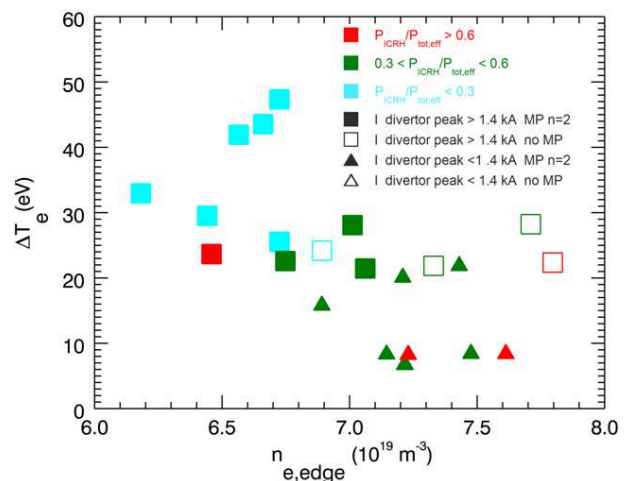

Figure 4: *Electron temperature drop for small ELMs versus the density at the plasma edge.*

20 eV) and a second transition from mitigated ELMs to grassy ELMs occurs.

The recovery time of the T_e profile for mitigated ELMs varies from 0.5 to 2 ms, depending on how big ΔT_e is. The duration of the divertor ELM power pulse for mitigated ELMs is $\sim$200-600 μs, which is correlated with the typical time of the ion parallel transport from the pedestal to the divertor target $\tau_\| = 2\pi R q_{95}/c_{s,i}$ (as observed for typical type-I ELM [1]).

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