The influence of plasma density, heating power and plasma shape on type-I ELM energy and particle losses in ASDEX Upgrade

H. Urano, W. Suttrop, L. D. Horton, A. Herrmann, J. C. Fuchs and ASDEX Upgrade Team  
Max-Planck-Institut für Plasmaphysik, D-85748, Garching, Germany

1. Introduction

The existing design of ITER requires ELMy H-mode as the reference regime for inductive operation with favourable energy confinement at steady state. However, the energy loss produced by ELM bursts can increase erosion of the divertor targets to the point where component lifetime becomes unacceptably short. A basic observation in several devices is that the ELM energy loss can generally become larger with increasing pedestal stored energy and is reduced with increasing plasma density [1,2]. When the pedestal pressure is limited by type-I ELMs, plasmas with high pedestal temperature \( T_{\text{ped}} \) or low pedestal density \( n_{\text{ped}} \) are expected to generate a large ELM energy loss. In a situation of stiff temperature profiles, higher energy confinement is accompanied by higher \( T_{\text{ped}} \) [3-6]. Mitigating the heat load onto the divertor target simultaneously without deterioration of the energy confinement is a crucial issue in recent ELM studies. In this study, we examine the characteristics of ELM energy and particle losses in type-I ELMy H-modes in ASDEX Upgrade.

2. Experimental data

ELMy H-mode phases in ASDEX Upgrade are selected, which provide maximum variation of upper triangularity \( \delta_u \), plasma current \( I_p \), toroidal magnetic field \( B_t \), auxiliary heating power \( P_{\text{aux}} \) and gas fuelling rate \( \Gamma_0 \). The dataset is restricted to single-null divertor configuration discharges with ion \( VB\)-drift direction towards X-point. All discharges are fuelled by deuterium gas puffing. All time intervals used in the dataset are selected from stationary phases.

3. ELM energy losses

3.1. Effects of plasma density and shape

Plasma density and shape dependence of ELM energy losses are examined at \( I_p = 1 \, \text{MA}, \ B_t = 1.5\sim2.5 \, \text{T} \) and the power crossing the separatrix \( P_{\text{sep}} = 4 \, \text{MW} \). At fixed \( P_{\text{sep}} \), the ELM frequency \( f_{\text{ELM}} \) and the ELM energy loss \( \Delta W_{\text{ELM}} \) are roughly inversely proportional (see figure 1(a)). While \( f_{\text{ELM}} \) becomes higher when the pedestal density \( n_{e,\text{ped}} \) is raised, \( f_{\text{ELM}} \) decreases with increasing triangularity \( \delta_u \) at a given \( n_{e,\text{ped}} \) (see figure 1(b)). From the relation between \( f_{\text{ELM}} \) and \( \Delta W_{\text{ELM}} \), one can expect that \( \Delta W_{\text{ELM}} \) increases with increasing triangularity at a given \( n_{e,\text{ped}} \).

Figure 2(a) and (b) show the normalised ELM energy loss \( \Delta W_{\text{ELM}}/W_{\text{ped}} \) as a function of the pedestal electron density normalised to the Greenwald density.
(n_{ped}/n_{GW}) and the normalised pedestal collisionality (\nu_{ped}^{*}) for the same discharges as in figures 1, respectively. It can be seen that at fixed I_p, P_{sep} and \delta_0, the ELM size (\Delta W_{ELM}/W_{ped}) decreases with n_{ped}/n_{GW} or \nu_{ped}^{*}. However, we also find an explicit difference of \Delta W_{ELM}/W_{ped} between lower and higher \delta_0 at fixed n_{ped}/n_{GW} or \nu_{ped}^{*}. The higher triangularity plasmas obviously produce larger ELM energy losses by a factor of 3-4 than the lower triangularity plasmas at a given n_{ped}/n_{GW} or \nu_{ped}^{*}. Note that since \Delta W_{ELM} is normalised to W_{ped}, the increase of \Delta W_{ELM} with the elevated triangularity is stronger than the increase of W_{ped}. We select two cases for comparison that are marked (A) and (B) in figure 2(a) and (b). These two discharges have different \delta_0 but similar n_{ped}/n_{GW} ~ 0.45 or \nu_{ped}^{*} ~ 0.15. Both cases (A) and (B) are also near T_{e ped} ~ 1 keV (\beta_{ped} ~ 0.01). Figure 2(c) plots the relative changes of the T_e profiles due to an ELM measured with the ECE radiometer for the discharges with T_{e ped} in the range of 0.8-1.2 keV. In figure 2(c), profiles of \Delta T_e/T_e have a peak near the plasma boundary for all discharges with similar relative change. The higher triangularity discharge (A) shows that the ELM perturbation extends radially inward to \rho_{pol} < 0.7, while in the lower triangularity discharge (B) the ELM-affected area extends from the separatrix to \rho_{pol} ~ 0.8, inside which the perturbation rapidly becomes negligibly small. Therefore, the increased ELM energy loss at higher triangularities cannot merely be explained by the increased pedestal pressure but also involve the extended width of the ELM-affected area.

3.2. Effects of heating power

The power dependence of ELM energy losses are also investigated for discharges performed at I_p ~ 1 MA and B_t ~ 2 T. In order to analyse the effects of the power crossing the separatrix P_{sep} on ELMs, we select two possible power scans at low (A \rightarrow B) and high triangularity discharges (C \rightarrow D) in which P_{sep} is varied over a wide range at a fixed \Gamma_0. In the discharges (A) and (B) performed at \delta_0 = -0.05 and \Gamma_0 ~ 1\times10^{21} s^{-1} (n_{e ped} ~ 0.3n_{GW}), P_{sep} is varied from 2 to 5 MW, while in the discharges (C) and (D) conducted at \delta_0 = 0.20 and \Gamma_0 ~ 3\times10^{22} s^{-1} (n_{e ped} ~ 0.6n_{GW}), P_{sep} is varied from 5 to 10 MW. Figure 3(a) shows f_{ELM} as
a function of $P_{\text{sep}}$ for the two power scans (A)-(B) and (C)-(D). We observe that for each case $f_{\text{ELM}}$ increases in proportion to $P_{\text{sep}}$. Figure 3(b) shows $\Delta W_{\text{ELM}}/W_{\text{ped}}$ as a function of $P_{\text{sep}}$ for the discharges (A)-(D). The increased power does not change the ELM energy loss for each of the two configurations. From figure 3(a) and (b), one sees that at fixed gas fuelling rate $P_{\text{ELM}}/P_{\text{sep}}$ remains constant ($P_{\text{ELM}} = f_{\text{ELM}} \Delta W_{\text{ELM}} \propto P_{\text{sep}}$) because $f_{\text{ELM}} \propto P_{\text{sep}}$ and $\Delta W_{\text{ELM}} \sim \text{const.}$ The relation between $f_{\text{ELM}}$ and $\Delta W_{\text{ELM}}$ for the discharges (A)-(D) is plotted in figure 3(c). The data point in each power scan is simply shifted towards larger $f_{\text{ELM}}$ by the factor of the increased $P_{\text{sep}}$ while $W_{\text{ELM}}$ is not changed.

Note that the discharges (B) and (C) are performed at the same $P_{\text{sep}}$ of ~5 MW with variations of $\Gamma_0$ and $\delta_{\text{in}}$. If $P_{\text{ELM}}$ was simply proportional to $P_{\text{sep}}$, then $f_{\text{ELM}}$ and $\Delta W_{\text{ELM}}$ would be inversely proportional at fixed $P_{\text{sep}}$. However, figure 3(c) shows that despite of the same $P_{\text{sep}}$ the data points (B) and (C) do not follow the expected inverse proportionality. This indicates that there are residual parameters controlling the ELM loss power so that $P_{\text{ELM}}/P_{\text{sep}}$ is not constant. There is a correlation between $\nu_{\text{ped}}^*$ and $P_{\text{ELM}}/P_{\text{sep}}$ as shown in figure 3(d). The fraction of ELM loss power is reduced when $\nu_{\text{ped}}^*$ is increased since the data points (A)-(D) can be laid on a single trend with the pedestal collisionality. Shown in figure 4 is $P_{\text{ELM}}/P_{\text{sep}}$ as a function of $\nu_{\text{ped}}^*$ for the discharges shown in figure 1(a). Regardless of wide ranges of $\delta_{\text{in}}$ and $\Gamma_0$, we observe the reduction of $P_{\text{ELM}}/P_{\text{sep}}$ along a single trend with increasing $\nu_{\text{ped}}^*$. The pedestal collisionality therefore seems to be playing a key role controlling the ELM loss power $P_{\text{ELM}}$. This finding has implications for the inter-ELM perpendicular transport losses. The dimensionless quantity $P_{\text{ELM}}/P_{\text{sep}}$ represents the fraction of ELM loss power assigned from the power crossing the separatrix. It follows that the inter-ELM perpendicular transport losses $(1 - P_{\text{ELM}}/P_{\text{sep}})$ also depends on $\nu_{\text{ped}}^*$. Figure 4 amounts to saying that with increasing $\nu_{\text{ped}}^*$ the inter-ELM perpendicular transport at the plasma edge is enhanced and the ELM transported loss power is reduced.

4. ELM particle losses

At a fixed $P_{\text{sep}}$ an inverse proportionality between $f_{\text{ELM}}$ and $\Delta N_{\text{ELM}}$ is found with varying $\Gamma_0$ in which $P_{\text{ELM}}$ remains roughly constant within a finite range (see figure 1(a)). Figure 5 shows the relation between $f_{\text{ELM}}$ and $\Delta N_{\text{ELM}}$ for the same data set in figure 1(a). In figure 5, the data points are classified into two groups of discharges with relatively low $\Gamma_0 (< 1.5 \times 10^{22} \text{ s}^{-1};$ squares) and high $\Gamma_0 (> 1.5 \times 10^{22} \text{ s}^{-1};$ circles). It is then seen clearly that the data points with the low $\Gamma_0$ exist in the region of low ELM particle flux $\Gamma_{\text{ELM}} (= f_{\text{ELM}} \Delta N_{\text{ELM}})$ bounded by $\Gamma_{\text{ELM}}$ of $2.0 \times 10^{21} \text{ s}^{-1}$, while those with the
high $\Gamma_0$ are located inside the region above $\Gamma_{ELM}$ of $2.0 \times 10^{21}$ s$^{-1}$. Thereby, $\Gamma_{ELM}$ rises with increasing $\Gamma_0$. This feature is analogous to the ELM loss power $P_{ELM}$ which rises with increasing $P_{sep}$. For detailed analysis of the particle balance at the plasma edge, it is desirable to evaluate the particle flux crossing the separatrix $\Gamma_{sep}$. Nevertheless, it seems reasonable to use the global parameter $\Gamma_0$ as an ordering parameter subsequently. At a fixed $\Gamma_0$, $f_{ELM}$ and $\Delta N_{ELM}$ in type-I ELMs are roughly inverse proportional to each other in spite of a wide variation of $P_{ sep}$.

5. Discussion and conclusions

The prediction and control of ELM energy loss in type-I ELMs are of significant concern because it is not clear as yet how ELMs of tolerable size can be obtained in a reactor. Integrating the results obtained in this study enables us to identify a scaling for the energy and particle transport of ELMs. Assuming steady state condition, we split energy and particle losses across the separatrix into proportional to each other in spite of a wide variation of $P_{ sep}$.

Taking it into account that $f_{ELM}$ is a function of $\Gamma_{sep}$ ($f_{ELM} \propto G(\Gamma_{sep})$), we obtain $f_{ELM} = P_{sep} \cdot G(\Gamma_{sep}) \cdot K$, where $K$ is a function of the other parameters such as $\delta_0$. Then, since $P_{ELM} = f_{ELM} \cdot \Delta W_{ELM}$, $\Delta W_{ELM} = P_{sep} \cdot G(\Gamma_{sep}) \cdot K$ and $P_{ELM} / P_{sep} = H(\nu_{ped}^*)$, the ELM energy loss $\Delta W_{ELM}$ can be expressed as:

$$\Delta W_{ELM} = \frac{H(\nu_{ped}^*)}{G(\Gamma_{sep}) \cdot K}$$

This formula shows why $\Delta W_{ELM}$ does not just depend on $\nu_{ped}^*$ but also explicitly on plasma shape even if $P_{ELM}$ is a function of pedestal collisionality only. Empirically, $H(\nu_{ped}^*)$ is given to scale approximately as $\nu_{ped}^{*-0.3}$. Knowledge of the functional form of $G(\Gamma_{sep}) \cdot K$, which can be controlling $\Delta W_{ELM}$ at a given $\nu_{ped}^*$, is of significant concern and thus will be obtained in a future study.

References