ELM ion energies in the ASDEX Upgrade far scrape-off layer

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1. Introduction. Type I ELMs carry a significant fraction of their energy $\Delta W_{\text{ELM}}$ across the scrape-off layer (SOL) and are the dominant source of the first wall thermal load and impurity sputtering. In ITER, $\Delta W_{\text{ELM}}$ will be considerably larger compared to present tokamaks and the ELM-wall interaction may be an issue for the first wall lifetime and impurity production.

New measurements of the ELM ion energies by a retarding field analyzer (RFA) in the ASDEX Upgrade (AUG) far SOL are presented. Type I and, for the first time, mitigated ELMs are captured by a RFA at different $\Delta W_{\text{ELM}}$ and the outer midplane separatrix distance $\Delta r_{\text{sep}}$. A fluid model of the ELM filament parallel transport [1] is employed to obtain the characteristic range of the ELM-averaged filament radial propagation speeds $v_r$.

2. Experimental setup. RFA measurements were obtained in lower single null divertor H-mode discharges with the representative magnetic equilibrium shown in Fig. 1. Edge plasma parameters of these discharges are compiled in Tab. 1. Type I ELMs were measured at a neutral beam heating power $P_{\text{NBI}} = 2.5$ MW. Mitigated ELMs, produced by new in-vessel magnetic perturbation (MP) coils [2], were measured at $P_{\text{NBI}} = 5$ MW with the mode number $n = 2$ resonant MPs with the coil current of 900 A. In all discharges $B \times V_B$ points downwards, $I_p = 1$ MA, $q_{95} = 4.7$, $R \approx 1.67$ m. The separatrix parallel collisionality $v_c^* \approx 2-4$.

A bidirectional RFA is mounted on the horizontal scanning probe drive 31 cm above the outer midplane, Fig. 1. Each analyzer consists of semi-permeable grids and a collector, separated from the plasma by a thin plate in which a narrow slit is cut. A standard ion retarding voltage scheme is applied to both analyzers [3]. The slit plate measures the ion current density $j_{\text{sat}}$. A collector measures the current of ions ($I_c$) that have enough kinetic energy to overcome the positive bias voltage applied to one of the grids $V_{B1}$. $j_{\text{sat}}$ and $I_c$ are sampled at 2 MHz. In this paper we present the data measured by the analyzer connected magnetically to the outer divertor (Fig. 1) and viewing the outer midplane around which the ELM filaments are typically ejected into the SOL.

3. Experimental results. Fig. 1 shows the time traces of $j_{\text{sat}}$ and $I_c$ measured in similar Type I ELMs for different $V_{B1}$. $\Delta r_{\text{sep}} = 35$ mm. $j_{\text{sat}}$ and $I_c$ feature synchronized bursts lasting several tens of $\mu$s, separated by up to several hundred microseconds, interwoven with smaller spikes. The

\begin{tabular}{|c|c|c|c|c|}
\hline
Set & $T_{\text{ped}}$ [eV] & $T_{e,\text{ped}}$ [eV] & $n_{e,\text{ped}}$ [$10^{19}$ m$^{-3}$] & $\Delta W_{\text{ELM}}$ [kJ] & $\Delta W_{\text{ELM}}$ [%] \\
\hline
1 & 350 & 300 & 7.3 & 36±7 & 23 \\
2 & 300 & 250 & 6.9-7.1 & 28±10 & 22 \\
3 & 300 & 350 & 6.8-7.0 & 34±12 & 22 \\
4 & 400 & 400 & 6.8-7.1 & 56±7 & 31 \\
5 & 350 & 350 & 7.6-7.8 & 27±6 & 19 \\
6* & 450 & 350 & 7.6-7.8 & 24±5 & 1 \\
\hline
\end{tabular}

\textbf{Table 1.} From left to right: set index, ion and electron temperatures and plasma density at the pedestal top (~1.5 cm inside the separatrix), plasma energy lost per ELM (absolute and relative to the pedestal energy). * Mitigated ELMs.
same ELM filamentary structure was observed in other tokamaks (e.g. references in [1]). Qualitatively similar filamentary structure is observed in mitigated ELMs. The filaments measured by the RFA were found to be well correlated with the time traces recorded by the fast visible light camera viewing the probe head. We recall that only ions striking the RFA with energies exceeding \( eV_{g1} \) (in electron volts) can be measured by the collector. High ELM ion energies in the far SOL were observed earlier by a RFA in AUG [4]. The ELM ion current to the collector \( I_{c, ELM} \) decreases with increasing \( V_{g1} \) and almost vanishes at \( V_{g1} = 325 \) V. \( I_{c} \) is absent between ELMs meaning that most background ions are repelled and do not contribute to \( I_{c, ELM} \).

![Figure 1](image1.png) **Figure 1.** RFA signals measured in similar Type I ELMs at \( \Delta r_{sep}=35 \) mm (set #1 from Tab. 1). The current to the inner divertor \( I_{div} \) serves as an ELM marker. \( V_{g1} \) is the ion repelling voltage applied at a given ELM. Right: Representative magnetic neutral line of the database discharges with the AUG vessel structures and the RFA. Arrow indicates the poloidally-projected direction from which the RFA collects the data presented in this paper.

The information about the radial expansion of ions in ELM filaments and their characteristic temperature can be estimated from the ELM-averaged ion current density \( \langle j_{sat} \rangle \) and the collector current \( \langle I_c \rangle \). \( j_{sat} \) values above \( 3\sigma \) threshold are selected from the time trace measured during an ELM. \( \langle j_{sat} \rangle \) equals the mean of these data points. \( \langle I_c \rangle \) equals the mean of the collector signal for the same time points. High \( V_{g1}^* \) makes it reasonable to expect that ELM ions have a drifting Maxwellian distribution of parallel speeds. Selecting from each discharge set ELMs measured at constant \( \Delta r_{sep} \), the ELM ion temperature \( T_{i, ELM} \) can be obtained from the exponential fit to \( \langle I_c \rangle \) plotted against \( V_{g1} \), \( \langle I_c \rangle \propto \exp(-V_{g1}/T_{i, ELM}) \), which is the standard RFA model. ELM ion current-voltage characteristics (\( \langle I_c \rangle \) versus \( V_{g1} \)) are illustrated in Fig. 2.

Measurements of \( T_{i, ELM} \) are shown in Fig. 3. \( T_{i, ELM} \) decreases with increasing \( \Delta r_{sep} \) (\( e \)-folding length of \( \lambda_{T_i} \approx 10 \) mm) and increases rather strongly with \( \Delta W_{ELM} \). The same trend persists if \( \Delta W_{ELM} \) is normalized to the total plasma or the pedestal energy. Smallest \( T_{i, ELM} \) is measured in mitigated ELMs. The decrease of \( T_{i, ELM} \) with increasing \( \Delta r_{sep} \) is easily explained by the energy loss along the field lines to the solid surface as the ELM filaments propagate across the SOL. Strong dependence of \( T_{i, ELM} \) on \( \Delta W_{ELM} \) might have two possible interpretations:
filaments of larger ELMs (i) are ejected into the SOL with higher initial temperatures and thus arrive hotter into the far SOL or (ii) they propagate faster radially and have less time to lose their energy along the field lines (or (iii) a combination of both). (i) would be surprising, given that hotter ELM filaments are also subject to stronger parallel energy loss because of larger sound speed $c_s$. A large variation of the initial ELM filament temperature would, therefore, result in relatively small changes in the far SOL $T_{i,\text{ELM}}$. (ii) is addressed in what follows.

![Figure 3](image)

*Figure 3.* From left to right: The ELM-averaged ion temperature plotted against the midplane separatrix distance as well as the energy lost per ELM, e-folding length of the ELM ion current density and the radial ELM-averaged filament propagation speed estimated from RFA measurements of $T_{i,\text{ELM}}$ and $\lambda_i$. Arrows indicate mitigated ELMs.

A balance between the characteristic parallel loss time and the perpendicular transport time is used to estimate from the RFA measurements the ELM-averaged filament radial propagation speed $v_r \approx \lambda_i c_s / L_{\|}$ [5]. $c_s / L_{\|}$ accounts for the parallel sink rate. $c_s$ is approximated by $(eT_{i,\text{ELM}} / m_i)^{1/2}$ assuming $T_{i,\text{ELM}} > T_{e,\text{ELM}}$. $T_{i,\text{ELM}}$ and $\lambda_i$ (the radial e-folding length of $\langle j_{\text{sat}} \rangle$) are taken from Fig. 3. Note that $T_{i,\text{ELM}}$ measured values in similar ELMs at different $\Delta r_{\text{sep}}$ correspond to a single $\lambda_i$. Since the filaments are connected to a solid surface at each end of the flux tube, $L_{\|}$ equals one half of the harmonic mean of the length of the field lines between either side of the filament and the nearest surface. However, in the frame of a toroidally rotating filament, $L_{\|}$ can vary in the far SOL due to toroidally discrete structures such as the limiters. This makes the evaluation of the “effective” $L_{\|}$ cumbersome. In the far SOL of the present discharges, $L_{\|}$ obtained from the field lines tracing at the outer midplane at a random toroidal location is at most a few meters. We assume $L_{\|} \approx 1$ m, so that we might overestimate $v_r$. As seen from Fig. 3, $v_r$ tends to increase with $\Delta W_{\text{ELM}}$ which (assuming that the same trend holds in the near SOL) would be consistent with (ii) and could explain the inverse scaling of the JET divertor ELM energy fraction [5] as well as increase of the JET limiter ELM loading with $\Delta W_{\text{ELM}}$ [6]. No radial variation of $v_r$ is observed within the uncertainty of the measurements.

### 4. Modelling the ELM filament transport.

A fluid model of the parallel ELM filament transport developed in [1] is used to reconcile the observations from Sec. 3. Once the initial filament temperatures and densities are specified, their time evolution due to parallel transport to the nearest surface is calculated. $T_{i,\text{ped}}$ and $n_{e,\text{ped}}$ for Tab. 1 determine the initial filament parameters (with $T_{e,\text{ped}} = T_{i,\text{ped}}$ for simplicity). Temporal and radial evolution of a filament is coupled through $v_r$, which is assumed to be radially constant. $v_r$ is adjusted to bring modelled ELM filament ion temperature into exact agreement with the RFA measurements, as illustrated in Fig. 4. The error bar of $v_r$ is obtained by matching the confidence interval of $T_{i,\text{ELM}}$. $T_{i,\text{ELM}} > T_{e,\text{ELM}}$, a general trend, is because of the higher parallel conductivity of electrons compared to that of ions. $\lambda_{Ti} \approx 10\text{-}20$ mm in the far SOL is in a good agreement with measured $\lambda_{Ti} \approx 10$ mm.
The range of \( v_i \) from the simulations is plotted against \( \Delta W_{ELM} \) in Fig. 4. The range of \( v_i \) as well the dependence on \( \Delta W_{ELM} \) is very similar to RFA measurements in Fig. 3, suggesting that we have chosen reasonable \( L_{fil} \). For the reasons mentioned earlier, \( v_i \) obtained from the simulations is insensitive to the initial filament temperatures. \( v_i \) would vary at most by 11% if \( T_{i,ped} = T_{e,ped} = 350 \text{ eV} \) were assumed in all simulations. Also shown in Fig. 4 is the filament stored energy \( W' \) at \( \Delta r_{sep} = 40 \text{ mm} \), normalized to its initial value at the pedestal top. \( W' \) is proportional to \( \Delta W_{ELM} \), which is a simple consequence of larger \( v_i \) required in the simulations to match \( T_{i,ELM} \) measured at higher \( \Delta W_{ELM} \). Filaments of the largest ELMs arrive at \( \Delta r_{sep} = 40 \text{ mm} \) with up to 40% of their initial energy. Therefore, larger ELMs might be associated with smaller relative thermal loads to the divertor in exchange of larger first wall loading. This is consistent with the thermographic observations in JET [6,7]. \( W' \) in Fig. 4 agrees with an earlier energy balance study in AUG in which 15% of \( \Delta W_{ELM} = 25 \text{ kJ} \) was found on the outboard limiters in the Type I ELMMy discharge with a separatrix-wall gap of 5 cm [8].

5. Summary. First systematic measurements of ion energies in Type I and mitigated ELMs were carried out in the far SOL of AUG using a RFA. The ELM-averaged ion energies \( T_{i,ELM} \approx 20-200 \text{ eV} \), which corresponds to 5-50% of the ion temperature at the pedestal top, were observed 35-60 mm outside the separatrix (i.e. 15-25 mm in front of the outboard limiters). \( T_{i,ELM} \) decreases with the separatrix distance with an e-folding length of \( \sim 10 \text{ mm} \). Lowest \( T_{i,ELM} \) was observed in mitigated ELMs. The increase of the energy lost per ELM is associated with the increase of \( T_{i,ELM} \) and the flattening of the ELM ion current density profile. This suggests that on average the filaments in larger ELMs might propagate faster across the SOL and thus deposit larger fraction of their energy on the first wall in exchange for smaller relative divertor loading.

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