L-H transition and pedestal studies on MAST

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Abstract. On MAST studies of the profile evolution of the electron temperature ($T_e$), electron density ($n_e$), radial electric field ($E_r$) as well as novel measurements of the ion temperature ($T_i$) and toroidal current density ($j_\phi$) in the pedestal region allow further insight into the processes forming and defining the pedestal such as the H-mode access conditions and MHD stability. This includes studies of fast evolution of $T_e$, $n_e$ and $E_r$ with $\Delta t = 0.2$ ms time resolution and the evolution of $p_e$ and $j_\phi$ through an ELM cycle. Measurements of the H-mode power threshold, $P_{L-H}$ revealed that about 40% more power is required to access H-mode in $^4$He than in D and that a change in the Z-position of the X-point can change $P_{L-H}$ significantly in single and double null configurations. The profile measurements in the L-mode phase prior to H-mode suggest that neither the gradient nor the value of the mean $T_e$ or $E_r$ at the plasma edge play a major role in triggering the L-H transition. After the transitions first the fluctuations are suppressed, then the $E_r$ shear layer and the $n_e$ pedestal develops followed by the $T_e$ pedestal. In the banana regime at low collisionality ($\nu_\star \nabla T_i \approx 0$ leading to $T_i > T_e$ in the pedestal region with $T_i \sim 0.3$ keV close to the separatrix. A clear correlation of $\nabla T_i$ with $\nu_\star$ is observed. The measured $j_\phi$ (using the Motional Stark Effect) $T_e$ and $n_e$ are in broad agreement with the common peeling-ballooning stability picture for edge localised modes (ELM) and neoclassical calculations of the bootstrap current. The $j_\phi$ and $\nabla p_e$ evolution $\Delta t \approx 2$ ms as well as profiles in discharges with counter current neutral beam injection raise questions with respect to this edge stability picture.

1. Introduction:

Type-I ELM My H-mode [1] with a transport barrier at the plasma edge (ETB) is the baseline operating regime for ITER [2]. Predicting the performance of magnetically confined plasmas in future devices in the presence of the edge pedestal [3–5] due to the ETB is difficult, since the access criterion, the barrier formation and the pedestal stability are not fully understood. Hence, in the absence of predictive theory empirical scalings are used to extrapolate the
performance leading to large uncertainties in particular for the transition from L-mode to H-mode (L-H transition), although heuristic models for these quantities with some predictive capability start to emerge [6, 7]. With respect to the edge localised modes (ELMs) [8, 9] the unmitigated type-I ELM is likely to be intolerable in ITER or other future devices [10]. Hence, a better understanding of the L-H transition and pedestal physics is needed, calling for even better measurements to guide theory.

For both, H-mode access and the pedestal structure $E_r$ may play an important role, since $E \times B$ flow shear stabilisation of turbulent transport [11] is believed to be the underlying physics of transport barriers. This is consistent with the general observation of a strong radial electric field during H-mode [1, 12–15]. In case of the L-H transition, there is clear evidence for the fact that an applied electrical bias to the plasma can generate an H-mode transition [13]. However, looking at naturally occurring transition the demands on the temporal and spatial resolution are extremely high, in order to understand the causality of the L-H transition. Only a few experiments have sufficiently good measurements to study this. A further complication is that one needs to distinguish between $E_r$ fluctuations, $\tilde{E}_r$, and the mean equilibrium field. New results from the TJ-II stellarator suggest that it is $\tilde{E}_r$ rather than $E_r$ that is important for the L-H transition [16]. MAST is equipped with a good set of edge diagnostics at high spatial and temporal resolution. The most important for the pedestal physics being the $T_e$ and $n_e$ measurements ($\Delta R = 1$ cm) using Thomson Scattering (TS)[17, 18], the $E_r$ and $T_i$ measurements ($3 \text{ mm} \leq \Delta R \leq 6 \text{ mm}$) using active Doppler spectroscopy [15] and the current profile measurement ($\Delta R \approx 2$ cm) using the Motional Stark Effect (MSE)[19]. The edge $T_i$ profile uses charge exchange recombination spectroscopy between C$^6+$ and D$^+$ on a thermal gas puff. This technique has not been used before. Recent findings using this suite of edge diagnostics are discussed below.

2. H-mode access:

During the non-activation phase of ITER the planned auxiliary power will be limited. Measurements on current devices suggest that the installed power will not be enough to access H-mode in H or $^4$He since $P_{L-H} \propto A_{\text{eff}}^{-1}$ ($A_{\text{eff}} = \sum_\alpha M_\alpha n_\alpha / \sum_\alpha n_\alpha$) [20]. However, recent results from ASDEX Upgrade show no difference of $P_{L-H}$ between $^4$He and D discharges [21], however there is no broad experimental basis for the L-H transition in $^4$He discharges.

To study the isotope dependence on MAST discharge to discharge scans have been performed in similar $^4$He and D plasmas (see Fig. 1). The L-H transition in $^4$He is at $t_{L-H} = 0.22$ s. The D discharge enters H-mode at $t_{L-H} = 0.19$ s, despite the much lower injected power of $P_{\text{NBI}} = 1.8$ MW compared to $P_{\text{NBI}} = 2.7$ MW in $^4$He. Therefore, the core temperature (Fig. 1d) is higher in $^4$He than in D, although the D discharge has a longer H-mode phase.

The power flowing over the separatrix, $P_{\text{loss}} = P_{\text{abs}} + P_{\Omega} - \partial W_{\text{pl}}/\partial t - P_{\text{rad}}$ (terms connected to the change in plasma shape that are relevant for a spherical tokamak), has to be calculated with care using TRANSP. This is for several reasons. Firstly, the $^4$He discharge still has some
D inventory due to the NBI fuelling and the D captured in the wall (e.g. $D_\alpha$ emission in Fig. 1e). Secondly, the ratio of absorbed to injected power is lower in $^4$He compared to D. The charge exchange process between $^4$He$^{2+}$ and D is less efficient than the process between D$^+$ and D. Thirdly, at high power there is evidence for enhanced ion losses/“diffusion”, $D_{FI}$, due to the MHD driven by the fast-ion density gradient [22, 23]. Studying the sensitivity of these unknowns with TRANSP the best match with the experimental data is achieved with $^4$He to D concentration of $c_{^4He}/c_D \approx 0.85/0.15 \Rightarrow A_{eff} \approx 3.7$ and $D_{FI} \approx 1 \text{ m}^2/\text{s}$ leading to a correction of $P_{loss}$ by 20% in $^4$He (see Fig. 1g). This analysis results in threshold powers of $P_{L-H}^D = (1.45 \pm 0.15)$ MW and $P_{L-H}^{^4He} = (2.0 \pm 0.15)$ MW for D and $^4$He respectively.

With the same excess power $P_{loss} - P_{L-H} \approx 0.3$ MW the profiles of $T_e$ and $n_e$ are remarkably similar in deuterium and helium plasmas (black circles and blue squares in Fig. 2). Even at higher excess power of $P_{loss} - P_{L-H} \approx 0.7$ MW similar profiles are encountered in $^4$He (red diamonds in Fig. 2). The density in $^4$He discharge seems to be a slightly lower than in the D discharge. The temperatures are almost the same within the error bars of the measurement, although the slope towards the core seems to be higher in $^4$He. As a result the $^4$He discharge has a slightly higher core temperature (Fig. 1d and Fig. 3b). Fitting the pedestal profiles with a modified tanh fit [24] in normalised flux space gives a pedestal width for $T_e$ and $n_e$ in $^4$He that is a factor of 1.6 narrower than in D. These fitted values have to be taken with caution, since the density fit needs to be corrected for the presence of the ear, and there is also a well known correlation between the fitted width and the core slope in the function used for these fits. A higher core slope leads to a narrower pedestal. The pedestal $\beta_{pol}$ is very
similar if calculated from the experimental profile data at the same flux surface directly. This is interesting since in $^4$He there $^4$He$^+$ and $^4$He$^{2+}$ are dominantly present in the edge region rather than only D$^+$. Furthermore, the velocity distributions is different, since dissociation is absent for $^4$He.

With respect to the energy confinement both discharges have the same electron pressure (see Fig. 3c) and also the same stored energy evolution around $t = 0.24$ s (see Fig. 1c) despite a difference of about a factor of 1.8 in $P_{\text{loss}}$. Hence the confinement time in $^4$He is about $\tau_{E,\text{He}}^D \approx 30$ ms compared to $\tau_{E,\text{D}}^D \approx 52$ ms in D. The TRANSP analysis for a similar deuterium discharge and the $^4$He discharge with the same excess power as the deuterium discharge ($#22653$, blue circles in Fig. 2) confirm this rough estimate giving thermal confinement times for D and $^4$He of $\tau_{E,\text{th},D}^D \approx 52$ ms and $\tau_{E,\text{th},\text{He}}^D \approx 27$ ms respectively, albeit with a large error bar since the discharges are not stationary. This difference $\tau_{E,\text{He}}^D / \tau_{E,\text{D}}^D \approx 0.54$ is more than the 0.68 one would expect from the ITER IPB98(y,2) scaling talking the different power, average mass and slightly different discharge conditions into account. As a result the D discharge has an H-factor of about $H_{\text{IPB98(y,2)}}^D \approx 1$ and the $^4$He discharge $H_{\text{IPB98(y,2)}}^\text{He} \approx 0.7$. The difference in the density pedestal would be sufficient to account for the difference in confinement, but more stable discharges and more statistics would be needed to substantiate this statement. Generally the influence of the pedestal on the global confinement on MAST is small. The pedestal energy is only of the order of 20% of the full energy [25].

Profiles of the edge radial electric field, $E_r$, during the power scan in D are shown in Fig. 4 as a function of normalised poloidal flux $\psi_N = (\psi - \psi_0)/(\psi - \psi_a)$ where $\psi_0$ and $\psi_a$ denote the poloidal flux at the magnetic axis and separatrix respectively. The $E_r$ profile is derived from the leading terms of the impurity force balance of He$^+$ ions [14, 15]. The poloidal and toroidal velocities as well as the temperature of the impurities are directly

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**Figure 4.** Average “L-mode” edge $E_r$ for different $P_{\text{NBI}}$ approaching $P_{\text{L-H}}$.

**Figure 5.** Loss power for L-mode (open) and H-mode (full) discharges with different height of the X-point in single null (red circles) and double null (blue squares) configuration. The configurations are shown in the sub figures.
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provided by active edge Doppler spectroscopy. The impurity density gradient is derived from the impurity emission profile using atomic data from ADAS [26] and $T_e$ and $n_e$ from TS [17]. The measurements were averaged between $0.31 \, s < t < 0.33 \, s$, since the dithers present during this phase can not be resolved by the $\Delta t = 4 \, ms$ individual measurement period. As H-mode is approached with increasing power little change is observed in the $E_r$ profiles, and hence in $\nabla E_r$. The only real difference is seen with $P_{\text{loss}} = 1.6 \, MW$, which samples a sustained dithering H-mode. Here, $E_r$ starts to become more negative. This data suggest that the DC $\nabla E_r$ may not play a key role for the L-H transition. This is supported by several data discussed below including fast measurements through a L-H transition. It should be noted however, that these mostly L-mode discharges already show a considerable $\nabla E_r$.

On JET it was found that the distance between the X-point and the strike points sensitively affects H-mode access [27]. On MAST also a sensitive dependence on the distance between the outer strike point and the X-point was observed [28] in single null (SN) plasmas. Initial power threshold measurements in a pair of down shifted lower SN discharges ($I_p = 0.8 \, MA, \bar{n}_e = (2.4 \pm 0.1) \cdot 10^{19} \, m^{-3}, B_t = -0.55 \, T$) with $Z_{\text{mag}} = -0.2 \, m$ and $Z_{\text{mag}} = -0.1 \, m$ show a difference in $P_{L-H}$ of about a factor 1.7 with $P_{L-H} = (1.5\pm0.2) \, MW$ and $P_{L-H} = (2.5\pm0.2) \, MW$ for the lower and upper discharge respectively (see red circles in Fig. 5). Unfortunately, these lower SN discharges experience small sawtooth crashes every $20 \, ms < \Delta t < 30 \, ms$ with slightly different characteristics. In both cases the L-H transition is triggered by a sawtooth crash. This increases the power by $\Delta P \approx (4/3)n_e\Delta T_eV_{q=1}/\tau \approx 0.2 \, MW$ estimated from the core electron temperature $\Delta T_e = 0.2 \, keV$ change inside the $q = 1$ surface at $\psi_N < 0.4$ and a typical heat transport time scale $\tau \approx 20 \, ms$ of the order

Figure 6. Comparison of typical time traces between two discharges with different $\kappa$ at the same input power.

Figure 7. Comparison of edge $E_r$ for high (red/gray) and low $\kappa$ (black) in L-mode close to the L-H transition.
of a volume corrected the energy confinement time. $P_{L-H}$ is chosen between the two values of $P_{\text{loss}}$ that lead to a sustained H-mode after the crash. This effect on H-mode access with X-point height is also present in double null (DN) as can be seen from the blue squares in Fig. 5. Here the elongation needs to be changed to change $Z_x$. As can be seen from Fig. 6 the higher $\kappa$ discharge has a clear L-H transition at $t_{L-H} = 0.3$ s at a power level where the lower $\kappa$ discharge is still in L-mode, albeit close to H-mode. In order to get an H-mode of similar quality in the lower $\kappa$ shape the power has to be increased by $\Delta P_{\text{NBI}} = 0.2$ MW. Parameters at the L-H transition for the 4 different shapes are given in table 1.

<table>
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<th>$Z_{\text{mag}}$ (m)</th>
<th>$R_c$ (m)</th>
<th>$Z_x$ (m)</th>
<th>$P_{L-H}$ (MW)</th>
<th>$\bar{n}_e$ ($10^{19}$m$^{-3}$)</th>
<th>$S_{\text{pl}}$ (m$^2$)</th>
<th>$\delta_l$</th>
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<th>$\phi_{95}$</th>
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Table 1. Discharge parameters for X-point $P_{L-H}$ scan ($\delta_{l,u}$: lower/upper triangularity, $S_{\text{pl}}$: plasma surface, $L_c$: SOL connection length from inner to outer strike point in SN and upper to lower strike-point in DN).

A comparison of the L-mode $E_r$ at lower power shows no significant change between low and high $\kappa$ (Fig. 7) supporting the notion that the mean $E_r$ is not the driving factor in the L-H transition. During the application of resonant magnetic perturbations (RMP) $P_{L-H}$ is increased and $E_r$ becomes more positive [29]. This would be consistent with a decreased $E \times B$ leading to a loss of H-mode with RMPs. However, increasing the power to regain H-mode access does not change $E_r$. There is also no change of $n_e$ or $T_e$ close to the edge prior to the L-H transition as can be seen from the lower two panels in Fig. 6 showing the values at $R - R_{\text{sep}} = -4$ cm. Hence, there is no evidence for a critical $T_e$ needed to access H-mode as favoured by many L-H transition theories (see also Fig. 9).

Surprisingly both SN discharge have similar connection length, $L_c$, due to the slight differences in shape close to the separatrix, although $L_c$ further out in the SOL is slightly higher for the high X-point discharge. It is unlikely that such a small change in $L_c$ is responsible for the large difference in $P_{L-H}$. The change in $L_c$ with $\kappa$ is also small. It is remarkable how small changes in the shape can sensitively influence the conditions to access H-mode. A close examination of all profiles as well as the fluctuations is needed to see which local parameters may be responsible for these changes.

3. Pedestal Formation:

To improve the understanding of the H-mode access and the pedestal formation fast measurements $\Delta t = 0.2$ ms of $E_r$, $T_e$, and $n_e$ have been performed. Using the dependence of the H-mode access on the magnetic configuration [28] a sequence of L-H, H-L, and L-H transitions were triggered in synchronisation with the 8 TS profiles 0.2 ms apart every 33 ms ($\Delta t_{\text{las}} \approx 10$ ns). This lead to a natural jitter of the individual transitions of less than 3ms
greatly improving the statistics. \( E_r \) was measured at four radial positions and the development during the L-H transition and through an ELM can be seen in Fig. 8. The shaded regions mark data where no \( T_e \) or \( n_e \) data is present to correctly evaluate the diamagnetic correction to \( E_r \). Each L-H transition starts with 1 to 3 dithers. Prior to the transition there is no discernible change in \( E_r \). In detail, the Lorentz term \( E^L_r = u_\phi B_\theta - u_\theta B_\phi \) seems to correlate with the drops in \( D_\alpha \) that indicate the better confinement, whereas the diamagnetic term \( E^D_r = \partial_r p/(eZn) \) seems to show an anti-correlation. This is until the last dither when \( E^D_r \) becomes more positive close to the separatrix and more negative further inward. \( E^L_r \) becomes more negative over the whole measured region. In total this leads to an increased positive gradient in \( E_r \) with the shear layer forming around \( R - R_{sep} \approx -1.2 \) cm. The increase of \( \partial_r E_r \) happens on similar time scales as the decrease of \( D_\alpha \) with \( \tau_{D_\alpha} \approx 0.6 \) ms (\( \tau_f := |f \Delta t/\Delta f| \) is the linear approximation for the characteristic time scale) for the innermost chord. The dynamic of the \( E^L_r \) differs slightly from \( E^D_r \) in the sense that the more inner radii show larger changes than the outer radii with \( E^D_r \), showing, if at all, the opposite behaviour. For the transport physics, however, only the evolution of the total \( E_r \) is of relevance since the different parts of the force balance may behave differently depending on the observed species. The ELM completely destroys this shear layer during its rise time (Fig. 8b). It should be noted that the time points are marked at the end of the acquisition interval.

As can be seen from Figures 9 and 10 there is a clear increase of \( n_e \) and \( |\nabla n_e| \) after the L-H transition at the edge with a typical rise times of \( \tau_{n_e} \approx 3 \) ms and \( \tau_{\nabla n_e} \approx 0.6 \) ms. \( T_e \) hardly changes, but \( |\nabla T_e| \) seems to increase as well although the statistical uncertainty indicated in the plot (bottom left in Fig. 10) is large. Such behaviour could be either due to the initial formation of a particle barrier rather than a thermal barrier, or by the formation of an ion barrier with \( n_i(t) \) reflecting the evolution of \( n_i \). Analysis of the visible light fluctuations show that the edge turbulence is suppressed in less than 100 \( \mu s \), which is at least 5 times faster than the evolution observed in \( E_r \), \( T_e \) or \( n_e \). This suggests that the measured profiles...
evolve as a consequence of the suppressed turbulent transport rather than the changes causing the turbulence suppression. Further statistical analysis is needed to verify this. In Figs. 9, 10, $t_{L-H}$ is defined at the top of the last dither to get a unique time for multiple shots corresponding to $t - t_{L-H} \approx 0.5$ ms in Fig. 8.

Novel Charge exchange measurements using the reaction $C^{6+} + D^* \rightarrow C^{5+} + D^+$ in a thermal $D_2$ beam provides $T_i$ on a 10 ms – 20 ms time scale with high spatial resolution $3 \ mm < \Delta R < 6 \ mm$. Fig. 11 shows $T_i$ profiles for a dedicated collisionality scan for confinement studies, where all other global dimensionless parameters were kept constant. At low collisionality $\partial_r T_i$ is very flat, and high temperatures similar to the pedestal temperature $T_i < 0.3 \ keV$ (see Fig. 11) are measured right up to the separatrix. At high collisionality $T_i \approx T_e$. Note, that the measurements at high collisionality are ELM averaged, whereas the data a low collisionality are collected in an ELM free period. A good correlation of $\nabla T_i$ with collisionality is observed on MAST as can be seen from Fig. 12 showing the $T_i$ gradient length $L_{T_i} = 1/\nabla \ln T_i$ normalised by the poloidal Larmor radius $\rho_{pol,i}$ as a function of collisionality close to the separatrix. This is consistent with the fact that in hot MAST pedestals the ions are in the banana regime with $\rho_{pol,i} \approx 15 \ mm$ of the order of the width of the $T_e$ pedestal. According to a very general argument about the conservation of entropy in the pedestal one expects $\rho_{pol,i} \nabla \ln T_i \ll 1 \Rightarrow \rho_{pol,i} \ll L_{T_i}$ [30]. For the leading order ion velocity distribution to approach a Maxwellian distribution as required in local thermodynamic equilibrium the entropy needs to be conserved. At low collisionality trapped ions following Banana orbits link neighbouring flux surfaces together with respect to entropy production. Hence, the entire pedestal volume acts as a closed system preventing strong $T_i$ gradients to develop. As the plasma becomes more collisional ions become more and more de-trapped such that the coupling between flux surfaces becomes less important and entropy is conserved within each flux surface allowing for stronger gradients in $T_i$. This is supported by the MAST measurements shown in Fig. 12.
4. Pedestal Stability

The most common model for the trigger of type-I ELMs is the onset of peeling-ballooning modes [31] with experimental points often sitting close to the stability boundary calculated numerically from the pedestal profiles. Here, generally $p_e = p_i$ is assumed and the bootstrap current is calculated according to neoclassical theory [32]. The new $T_i$ measurements on MAST suggest that $p_e = p_i$ is only viable at high collisionality, where the pedestal is typically far from the MHD stability boundary. At low collisionality $T_i > T_e$ in the pedestal pressure gradient region. The impact of this, however, is probably small since $\nabla p_i = k_B n_i \nabla T_i + T_i \nabla n_i$ with the first term decreasing, whilst the second term increases. Large ELM like bursts are encountered in MAST H-mode discharges with counter current NBI, although there is hardly a pedestal formed [33]. The instability – structurally indistinguishable from a type-I or type-III ELM – ejects $2 \text{kJ} \leq \Delta W \leq 6 \text{kJ}$ of the stored energy. This is $\Delta W/W_{\text{pl}} < 7\%$ with respect to the total stored energy and $\Delta W/W_{\text{ped}} < 30\%$ ($W_{\text{ped}} \approx 20 \text{kJ}$), which more like the energy loss observed during type-I rather than type-III ELMs. Stability analysis of these plasmas has shown that the edge is stable with respect to peeling-ballooning modes.

A more fundamental question for pedestal stability is if the edge current is calculated correctly. Unfortunately, the edge current density $j_\phi$ usually derived from a pitch angle, $\gamma_m = \arctan(B_\theta/B_\phi)$, measurement is very hard to measure, since generally the integrated quantity $\gamma_m$ is not only small at the tokamak edge where $B_\phi \gg B_\theta$, but the change due to the edge current is minimal. Furthermore, the few existing measurements of the local $B_\theta$ have to poor a time resolution to resolve the ELM cycle [34]. In the ST, the strong field line pitch on the low field side leads to measurable changes in $\gamma_m$ [35] using the Motional Stark Effect (MSE) measurement ($\Delta t = 2 \text{ ms}, \Delta R \approx 2 \text{ cm}$) [19].

Consistent with the picture of pressure driven edge current, strong edge currents are observed in H-mode as can be seen from Fig. 13 showing the comparison between the MSE data and the neoclassical calculation of the bootstrap current according to Sauter et.al. [32]. Again the assumptions $T_i = T_e$ and $n_i = n_e$ are used. Figures a) and c) show the derived current profiles $j_\phi$ whilst figures b) and d) show a direct comparison of the pitch angle $\gamma_m$. Profiles are shown a), b) just after an ELM at $t - t_{\text{ELM}} = 3 \text{ ms}$ ($t = 0.347 \text{ s}$) and c), d) well into an ELM-free period $t - t_{\text{ELM}} = 39 \text{ ms}$ ($t = 0.383 \text{ s}$). Well into the ELM free period the pitch angle as well as the magnitude of the current density in the confined plasma region agrees with neoclassical theory. However, the MSE measurements show also an apparent finite current density in the SOL. This is probably due to the finite spatial resolution of the measurement that leads to a spatial smearing of a narrower profile of $j_\phi$ with a higher maximum.

Indeed a different derivation of the edge pitch angle by the analysis of 2-D electron Bernstein wave emission (EBE) [36] shows a much narrower and higher profile during ELM free H-mode (see Fig. 14). This measurement was done using a prototype system and is shown in comparison with the MSE measurement. The good localisation of the EBE measurement is given by the steep $\nabla n_e$ at the edge measured with TS. Both measurements are consistent with each other if their different spatial resolution is taken into account. This data suggests that $j_\phi$ in MAST could be much higher than can be accounted for by standard neoclassical
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Figure 13. Comparison of a), c) $j_\phi$ and b), d) pitch angle $\gamma_m$ from MSE with the neoclassical calculation according to Sauter et.al. [32]. Data are shown immediately after a large ELM crash a), b) and well into the ELM free period c), d).

theory. Of particular interest is that the $\gamma_m$ profile requires a negative current sheath close to the separatrix. Such a current sheath may suppress the turbulence [37]. The large pitch angle changes would account for a significant fraction of the plasma current of the order of $|\Delta I_p/I_p| \approx 25\%$ in each direction within a two centimetre layer. The time resolution of this prototype system is poor and the proof of principle measurements were taken over $\Delta t_{E}B_{E} \approx 40$ ms of an ELM-free period with slightly rising density. It is unclear how such large opposing current layers should be stable for this amount of time and faster measurements are needed. For such faster measurements currently a 36 antenna imaging system with 8 active antennas has been installed on MAST. In principle this should be able the measure $\gamma_m$ on sub ms timescales, possibly resolving ELMs.

Shortly after the ELM also the MSE measurement clearly disagrees with the neoclassical equilibrium picture (see Fig. 13a,b). This could be simply due to the finite current diffusion time that prevents the edge current to change within the time period the measurement was taken and therefore requires a dynamic calculation of the current density evolution. Simple modelling of ASDEX Upgrade data [38] shows that current diffusion prevents the current from decaying to the levels expected from the bootstrap drive, but it also suggests that this difference only persists on time scales of the order of $1$ ms. On MAST $T_e^{ped} \approx 0.2$ keV in this discharge. This is roughly a factor two to three lower than on ASDEX Upgrade at similar pedestal densities of $n_e^{ped} \approx 6 \cdot 10^{19}$ m$^{-3}$ giving a factor three to five faster current diffusion according to Spitzer or even faster when the neoclassical resistivity is considered. Hence, $2$ ms to $3$ ms after the ELM one would expect the current to be fully diffused through the edge and $j_\phi$ should be well represented by the neoclassical bootstrap current. The ELM itself
expels current. On MAST one filament typically carry a current of the order of 200 A [39] and there are around 10 filaments during one ELM. The resulting current change of $\Delta I_p \approx 2 \text{kA}$ would change the pitch angle only by $\Delta \gamma_m \approx \arctan \left\{ \frac{B_\phi \mu_0 \Delta I_p [2\pi a (B_\phi^2 + B_\theta^2)]}{2\pi a (B_\phi^2 + B_\theta^2)} \right\} = 0.02^\circ$, which is below the accuracy of the measurement. A full account of the analysis techniques and the dynamics of the current diffusion would go beyond the scope of this paper and will be presented in a future publication [35].

Despite the caveats of both measurement techniques (spatial resolution for MSE, temporal resolution for EBE) the data suggest that the neoclassical expression derived from modelling may be incomplete. It is by no means clear that neoclassical theory applies in the steep gradient zone of the H-mode pedestal. For example, the edge $E_r$ could lead to an enhancement of $j_\phi$ [40], or the assumption that $\rho_i \ll L_\perp$ (with $\rho_i$ the ion gyro radius and $L_\perp$ the gradient length) could account for the discrepancies. Also, a bootstrap calculation assumes the plasma to be in equilibrium, which, especially just after the ELM crash, might not be the case and time dependent ab initio calculations may be needed to get the time scales correct.

![Figure 15. Measured trajectory of $\max(j_\phi)$ versus $\max(|\nabla p_e|)$ in comparison with the stability limits calculated with ELITE [31].](image)
pedestal with just two parameters), we assume that qualitatively these stability boundaries can represent all the other time points as well. In Fig. 15 the values of $\max(j_\phi)$ and $\max(|\nabla p_e|)$ of the entire H-mode period are plotted with the stability boundaries. No unstable peeling modes were found in the stability calculations for the two experimental equilibria. To guide the eye a dotted line is added to the figure indicating where the peeling boundary is expected.

It should be said that the stability calculation on MAST depends sensitively not only on the full profiles of $T_e$, $n_e$ and $j_\phi$, but also $T_i$ and $Z_{\text{eff}}$. Here $Z_{\text{eff}} = 2.4$ as measured in the gradient region by visible bremsstrahlung [41] and $T_e = T_i$ was used in the stability calculation. This, as well as the maximum current density may not be quite right. $Z_{\text{eff}}$ for example falls to $Z_{\text{eff}} \approx 1$ towards the pedestal top and the analysis at the edge is complicated by molecules. Also the data shown in Fig. 11 suggests that $T_i(\psi_N) = T_{\text{ped}}$ in the pedestal rather than $T_i = T_e$. Using different assumptions may shift the stability boundary with respect to the measured point. During the type III ELMy phase of the discharge the edge plasma is deep in the stable region against edge instabilities. In the long ELM free period the increase of $\max(|\nabla p_e|)$ brings the data points to the ballooning boundary. As $\max(|\nabla p_e|)$ increases $\max(j_\phi)$ shows an initial decrease, but it recovers when $\max(|\nabla p_e|)$ stabilises. Interestingly it is not just the data point right before the ELM crash that lies on the stability boundary; the plasma lingers around the stability boundary for several ms before the ELM crash. At the ELM crash $\max(|\nabla p_e|)$ drops while $\max(j_\phi)$ stays more or less the same. The second ELM free period is similar to the first one: a sudden increase of $\max(|\nabla p_e|)$, with a slight drop in $\max(j_\phi)$, followed by an increase of both $\max(|\nabla p_e|)$ and $\max(j_\phi)$. This time the data points even cross the ballooning boundary well before the ELM crash. However, the position of the ballooning boundary is almost within the errors bars of $\max(j_\phi)$ and $\max(|\nabla p_e|)$ (see top left of the figure). In conclusion the measurements in general support the edge stability picture as the ELM crash occurs very close to the instability boundary, but the evolution itself raises questions since the profiles are equally close to the boundary well before the actual ELM crash.

5. Conclusions

The MAST studies of H-mode access, pedestal formation and stability give unique insight into the underlying physics. The L-H power threshold in $^4$He on MAST is about 50% higher than in D. H-mode access is greatly influenced by the vertical position of the X-point in single null and double null (change of $\kappa$). It is not likely, that the small changes of the outer scrape-off-layer connection length are responsible for the observed differences. When H-mode access conditions are improved by increasing the input power or changing the elongation no detectable changes of $\nabla E_r$ are observed on transport time scales ($\Delta t = 20 \text{ ms}$), whilst the plasma is mostly in L-mode. Measurements on a faster time scale ($\Delta t = 200 \mu\text{s}$) through the L-H transition also show no consistent increase in $\nabla E_r$ during the L-mode phase. This strongly suggests that the mean $E_r$ field is only a secondary player for the transition. However, in special cases a correlation with the mean $\nabla E_r$ and H-mode access potentially exist. For example with the application of resonant magnetic perturbations $E_r$ becomes more positive.
and also more power is needed to access H-mode [29], although the behaviour of $E_r$ with input power is similar with and without perturbations.

In MAST $T_i > T_e$ in the pedestal with flat gradients at low collisionality, since the large banana orbits couple the flux surfaces in the pedestal together with respect to entropy conservation. With increasing collisionality this coupling is broken and $|\nabla T_i|$ increases. No clear change in $n_e$, $T_e$, and $E_r$ or their gradients is observed prior to the L-H transition. Comparing the evolution of $E_r$, $n_e$, $\nabla E_r$, $\nabla n_e$ and $\nabla T_e$ after the transition with that of the fluctuations suggest that the profiles react on a relatively sudden change in the transport rather than causing the transition.

Measurements of the detailed time evolution ($\Delta t = 2$ ms) of the edge current density, $j_\phi$ in inter ELM periods using the Motional Stark Effect (MSE) suggest that the peeling-balloonning model for the type-I ELM onset may be incomplete, although the measurements are in broad agreement with ideal MHD stability calculations. This is supported by the edge stability in counter current NBI H-modes that show large ELM like instabilities with almost no pedestal. Well into an ELM free period the measured pitch angle agrees well with those predicted by neoclassical theory, although the profile is somewhat wider and hence the total edge current is somewhat larger. After an ELM crash there is a large disagreement, which is unlikely to be resolved by current diffusion alone. The analysis 2-D electron Bernstein wave emission (EBE), a novel technique, suggest that there may be an even more complex current profile with a sign change close to the separatrix, which would be in disagreement with neoclassical predictions. This profile would not be resolvable with the spatial resolution of $\Delta R = 2$ cm of the MSE measurement, but needs further confirmation with EBE data on a faster time scale. These measurements will be provided by an innovative improvement of the EBE system (currently collecting initial data) that may even allow the measurement through an ELM.

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**References**

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