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Comparison of ETG model for the electron pedestal temperature profile across isotope mix and gas fuelling rate scans in JET-ILW H-mode plasmas

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[*]See the author list of *'Overview of T and D-T results in JET with ITER-like wall'* by C F Maggi *et al* to be published in Nuclear Fusion Special Issue: *Overview and Summary Papers from the* 29th *Fusion Energy Conference (London, UK, 16–21 October 2023)*

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Abstract.

Predictions of the pedestal temperature profile calculated using a model for ETG turbulent electron heat transport [A R Field *et al* 2023 Phil. Trans. Royal Soc. A **381** (2242) 20210228] are compared with the pedestal structure of JET-ILW ('ITER-like wall') H-mode plasmas over scans of the deuterium-tritium (D:T) isotope mix and hydrogenic gas fuelling rate [L Frassinetti *et al* 2023 Nucl. Fusion **63** 112009]. The model predictions for the electron temperature at the location of the density pedestal top $T_e(\psi_N^{n_{e,top}})$ are found to agree well with the measured values over both scans across the full range of D:T ratio. However, the pedestal top temperature $T_{e,ped}$, which is typically located somewhat inside the density pedestal top, is under predicted by as much as a factor ~ 2. This discrepancy implies that the ETG heat flux scaling appropriate for the steep-density gradient region, on which the model is based, is not applicable where the density gradient is weak. This difference might be attributed to a difference between the physics of the ETG turbulence in regimes where the density gradient either strong or weak, which are thought to be dominated by either the 'slab' or 'toroidal' branches of ETG turbulence. Other branches of turbulence might also play a role in the electron heat transport, particularly in the weak density gradient region at the pedestal top. As in the experiment, the predicted T_e across the pedestal is found to decrease with the ratio of separatrix to pedestal density $n_{e,sep}/n_{e,ped}$, which increases with the gas fuelling rate. Results from three models combining the ETG heat flux model with the EPED pedestal model [P B Snyder *et al* 2009 Phys. Plasmas **16** 056118] are also presented, including one which also incorporates the density pedestal prediction mode of Saarelma *et al* [S Saarelma *et al* 2023 Nucl. Fusion **63** 052002], providing a complete prediction of the pedestal profiles .

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1. Introduction

In a high-confinement 'H-mode' tokamak plasma [1], an edge transport barrier (ETB) (a narrow region of reduced particle and heat diffusivity) forms spontaneously at the plasma periphery, resulting in much stronger gradients of density and temperature, known as the H-mode 'pedestal' just inside the last closed flux surface (LCFS) or 'separatrix'. This pedestal increases the total particle and energy content of the plasma and thereby the overall energy confinement. Hence, for predictions of the performance of future devices, it is crucial to be able to predict the electron density $n_{e,ped}$ and temperature $T_{e,ped}$ at the top of the pedestal, which provide the boundary conditions for calculation of the density and temperature profiles across the confined 'core' plasma and thereby total stored thermal energy W_{pl} of the plasma.

Future fusion devices designed to demonstrate the conditions of a burning D-T plasma, e.g. ITER, DEMO or STEP [2–4], will be run with plasmas formed from a 50:50 D-T mixture for thermonuclear operation, so it is important to understand the effect of the relative isotope mass, $A_{eff} = \sum A_i / \sum (c_i A_i)$, where $A_i \equiv m_i/m_p$ is the mass number and $c_i = n_i/n_e$ the concentration of each hydrogenic isotope (H, D and T), on confinement and heat transport across the core and pedestal regions of the plasma. Hence, any model, either theory-based, a reduced model or a simulation of turbulent heat transport, to be used for prediction of the pedestal temperature $T_{e,ped}$ must be able to model its dependence on the effective mass A_{eff}.

Many studies using gyrokinetic codes have now demonstrated that electron-scale turbulence due to electron-temperature-gradient (ETG) driven modes and/or micro-tearing modes (MTMs) frequently dominates the heat transport across the H-mode pedestal [5–13], especially at high heating power and when the pedestal density gradient is steep.

Notably, in the study by Told on ASDEX Upgrade, reported in Ref. [5] it was found that, while MTMs were found to dominate in the region just inside the pedestal top, small-scale, ETG modes with maximum amplitudes near the 'x'-points were found to dominate in the steep-gradient region and it was also pointed out (and also in Ref. [6]) that the measured values of the parameter $\eta_e \equiv L_{n_e}/L_{T_e} \sim 2$, where $L_{n_e} = n_e/(dn_e/dr)$ and $L_{T_e} = T_e/(dT_e/dr)$ are the electron temperature and density scale lengths, were about a factor of 1.6 above the linear threshold for ETG modes.

This observation of values of $\eta_e \sim 2$ across the pedestal was also reported in the earlier study on ASDEX Upgrade by Neuhauser *et al* [14], in which it was suggested this might be related to the threshold behaviour of drift waves, and in Ref. [15] by Horton *et al* it was shown that by assuming a constant value of $\eta_e \sim 2$ across the pedestal, the measured T_e profile could be reconstructed from the n_e profile, leaving the electron temperature and density at the separatrix, $T_{e,sep}$ and $n_{e,sep}$, as the only other free parameters.

Several other studies have also revealed the importance of η_e in governing the electron heat flux q_e across the pedestal region [16–18] and have proposed several, rather similar scaling expressions for the gyro-Bohm normalised heat flux $q_e/q_{e,gB}$ with the parameters η_e and R/L_{T_e}. Here, the gyro-Bohm electron heat flux is defined as $q_{e,gB} = n_e \chi_{e,gB} T_e/R$ where the associated heat diffusivity $\chi_{e,gB} = v_{th,e}\rho_e^2/R$, $v_{th,e}$ is the electron thermal velocity and ρ_e is the electron Larmor radius.

A simplified heat flux scaling (or, alternatively, modified quasi-linear expressions for the ETG heat flux as proposed in Ref. [18]) can be used to form the basis of numerical models for the pedestal T_e profile. Such an approach is taken to construct the numerical model of pedestal structure presented in Ref. [16], which is based on a combination of ETG heat transport governed by η_e and particle transport due to pressure-gradient limited, kinetic-ballooning modes (KBMs) – consistent with the mechanisms for pedestal transport proposed in Ref. [8].

Such a simplified, semi-numerical model for the pedestal T_e profile, based on a scaling for the electron-temperature gradient (ETG) driven turbulent heat transport proposed in Ref. [17], appropriate for the steep-density gradient region of the H-mode pedestal, is presented in Ref. [19]. Here, this model is used to predict the T_e profile across the pedestal of a set of 2 MA H-mode pulses, run in the JET-ILW ('ITER-like wall') tokamak device, in which the effective isotope mass A_{eff} was varied from pure D to pure T, as well as pulses in D and T at higher and lower rates of gas fuelling [20]. Hence, the predictive capability of the model is tested both across the A_{eff} scan and at a different plasma current I_p to that for which the scaling was determined, i.e. 2 MA rather than 1.4 MA, by comparing the predicted values of T_e with those measured at two locations at the top of the T_e and n_e pedestals.

The resulting agreement between the predicted and measured values of T_e at the top of the density pedestal provides strong evidence that the electron heat transport across the steep-density gradient region of the pedestal conforms to the assumed scaling for $q_e/q_{e,gB}$ with η_e, which is independent of the ion mass and hence of A_{eff}. Furthermore, the applicability of this model also highlights the importance of the pedestal boundary conditions at the separatrix, i.e. $n_{e,sep}$ and $T_{e,sep}$ in governing the pedestal temperature $T_{e,ped}$, which is a consequence of the assumed electron heat flux dependence on η_e.

The EPED model [21] for prediction of the total pressure at the pedestal top p_{ped} is based on two assumptions: (A) that the pressure pedestal width Δ_p is determined by the stability of kinetic ballooning modes (KBMs), which limit the pressure gradient p', yielding the relation $\Delta_p \propto \beta_p^{1/2}$‡; and (B) the pedestal height is determined by increasing p_{ped} until the MHD stability limit set by peeling-ballooning instabilities [22] is reached, above which an ELM would be triggered. Hence, in order to determine $T_{e,ped}$, using EPED it is necessary to assume a prescribed pedestal density $n_{e,ped}$.

Typically, equal electron and ion temperatures ($T_e = T_i$) and equal widths for the electron density, temperature and pressure pedestals ($\Delta_{n_e} = \Delta_{T_e} = \Delta_p$) are assumed. As an attempt to improve upon this aspect of the EPED model, we have incorporated the ETG model of Ref. [19] for the pedestal T_e profile into a modified version of EPED, which has been applied to the JET-ILW isotope mass scan dataset discussed above [20]. As a further step, the ionisation/diffusion model of Ref. [49] has also been used to predict the pedestal n_e profile. This, in combination with the EPED prediction of the total pressure p_{ped}, also allows the pedestal T_i profile to be determined.

The remainder of this paper is structured as follows: The ETG model for the pedestal T_e profile is outlined in §2, then the experimental §3 describes the pedestal data set used for this comparison in §3.1, followed by an explanation of how the data is prepared for input to the model in §3.2. The resulting comparisons of the predicted and measured T_e profiles are then presented in §4, followed by a discussion of these comparisons in terms of current understanding of the underlying physics of turbulent electron heat transport across the pedestal in §5. Results from attempts to combine the ETG model for the pedestal T_e profile with the EPED [21] model for the pedestal height and width are presented in §6. The overall conclusions of the study are then summarised in §7.

‡ The poloidal beta β_p is the pedestal pressure normalised to the energy density of the poloidal magnetic field, defined as: $\beta_p = 2p_e/(2\mu_0 \bar{B}_p^2)$, where $\bar{B}_p$ is the flux-surface averaged poloidal magnetic field.

2. ETG heat transport model for pedestal T_e profile

This model is based on a scaling for the gyro-Bohm normalised turbulent electron heat flux $Q_e^\star \equiv q_e/q_{e,MgB}$ with the parameter $\eta_e = L_{n_e}/L_{T_e}$. Here, the modified gyro-Bohm normalisation $q_{e,MgB} = q_{e,gB}(R/L_{T_e})^2$ is defined in terms of the local L_{T_e} at the simulated flux surface within the pedestal region, rather than the usual definition in terms of a macroscopic length scale such as the major radius of the plasma R.

The $Q_e^\star(\eta_e)$ scaling was determined as a fit to saturated, turbulent electron heat flux q_e data from a set of local, non-linear, electromagnetic, electron-scale simulations [17] performed using the gyrokinetic (GK) code GENE [23]. The simulations were run at a flux surface in the steep-density gradient region of the pedestal, half way between the density pedestal top (defined here in terms of the normalised poloidal flux as $\psi_N^{n_{e,top}}$) and the separatrix ($\psi_N = 1$§.)

Two sets of pedestal profiles were considered from 1.4 MA JET-ILW deuterium plasmas at high and low rates of gas fuelling ($\Gamma_{D2} \sim 0.3$ & 1.8×10^{22} e/s) with 16 MW of heating power [24, 25], for each of which a set of simulations were run with the normalised density and temperature gradients R/L_{n_e} and R/L_{T_e} scanned around their nominal experimental values [17]. It was found that by defining $Q_e^\star \equiv q_e/q_{e,MgB}$ in terms of the local L_{T_e} rather than the major radius R, the q_e data from all four gradient scans could be fitted approximately by the same $Q_e^\star(\eta_e)$ scaling:

$$Q_e^\star = \alpha(\eta_e - \eta_{e,cr})^\beta \tag{1}$$

, where $\alpha = 0.85$, $\eta_{e,cr} = 1.28$ and $\beta = 1.43$. Here, the threshold $\eta_{e,cr}$ is somewhat higher than the linear threshold of 0.8 found, e.g. in Ref. [26] for ETG turbulence. This scaling is derived from analysis of JET-ILW pedestals [24, 25] and is used as the basis for the numerical model described in Ref. [19]. Note that it is similar to that found in Ref. [16] from a set of non-linear GK simulations using CGYRO [27] for the steep-density gradient region of a set of DIII-D pedestals, which is also used there for numerical calculation of the pedestal T_e profile.

Numerical calculation of the pedestal T_e profile is performed as follows: First, assuming a linear form of Eq. (1), i.e. $\beta = 1$, this can be expressed in the form of the cubic polynomial in R/L_{T_e}:

$$(R/L_{n_e})^{-1}(R/L_{T_e})^3 - \eta_{e,cr}\,(R/L_{T_e})^2 - q_e/(\alpha q_{e,gB}) = 0 \tag{2}$$

, which can be solved for R/L_{T_e} at any flux surface given values of q_e, T_e, the magnetic field B and n_e and R/L_{n_e}. This provides an initial estimate of R/L_{T_e} for a more accurate, numerical solution of the non-linear form of Eq. (1) with $\beta = 1.43$. The electron heat flux q_e is determined from $q_e = P_{e,sep}/S$, where $P_{e,sep}$ is the loss power conducted across the pedestal by the electrons and S is the area of the LCFS. The T_e profile is calculated by iteration, starting at the separatrix, where $T_e = T_{e,sep}$, using the prescribed, fitted experimental density profile to provide n_e and R/L_{n_e} and taking T_e from the previous iteration step. A more detailed explanation can be found in Ref. [19].

3. Experimental data set and data preparation

3.1. Isotope mix and gas fuelling rate scans at constant β_N

The experimental data set used for this comparison is from a series of type-I ELMy H-mode plasmas with plasma current $I_p = 2$ MA at a toroidal field $B_t = 2.25$ T in JET-ILW, over

§ The normalised poloidal flux is defined as $\psi_N = (\psi - \psi_0)/(\psi_a - \psi_0)$, where ψ, ψ_0 and ψ_a are the values of poloidal flux at an arbitrary flux surface, the magnetic axis and the separatrix respectively.

which the effective mass A_{eff} was scanned from pure deuterium (D) to pure tritium (T) [20]. The equilibrium configuration positioned the inner strike point on the vertical target and outer strike point on the horizontal target with a plasma cross-section of low average triangularity ($\delta \sim 0.24$).

Over the scan, the key parameters that affect the pedestal behaviour (normalized pressure $\beta_N \sim 1.5$, ratio of the separatrix density to the pedestal density $n_{e,sep}/n_{e,ped}$, pedestal ion Larmor radius $\rho_i \sim 2.1 - 2.3 \times 10^{-3}$, pedestal electron collisionality $\nu_e^\star \propto n_e/T_e^2$ and toroidal rotation rate Ω_ϕ^{ped}) were kept as constant as possible. Feedback control of the neutral beam heating (NBI) power was used to maintain $\beta_N \sim 1.44-1.58$, while the ion-cyclotron-resonance (ICRH) heating was maintained at 2 MW. It was not possible to maintain a constant value of pedestal collisionality $\nu_e^\star$, which varied from ~ 0.8 in D to ~ 1.8 in T [20].

The A_{eff} scan, comprising six pulses (two in pure D, three in mixed D and T and one in pure T), was performed at a gas fuelling rate $\Gamma_{gas} \sim 1.7 \times 10^{22}$ e/s, injected from divertor. In all pulses, a small H concentration ($c_H \sim 1\%$) was used for the minority ICRH heating. At this fuelling rate, the ratio of density at the separatrix to that at the pedestal top was maintained at $n_{e,sep}/n_{e,ped} \sim 0.5$.

In order to investigate the role of the ELM frequency f_{ELM} on the pedestal structure, in particular the density ratio $n_{e,sep}/n_{e,ped}$, further pulses (referred to as the 'extended data set' in Ref. [20]) were run at higher and lower gas fuelling rates (two in D and two in T), the higher gas rate promoting more frequent ELMs. The importance of $n_{e,sep}/n_{e,ped}$ in determining the cross-pedestal transport is discussed in detail in Ref. [28]. The parameters of the full set of pulses used for this study are summarised in Table A1.

3.2. Input data and data preparation

Required inputs for calculation of the pedestal T_e profile using the model described in §2 are: the nominal toroidal magnetic field B_t, the separatrix loss power during the inter-ELM periods P_{sep}^{iELM} and the fraction of this power carried by the electrons $f_{cnd,e}$, and the measured n_e profile across the pedestal, together with the corresponding T_e profile for comparison with the predicted profile.

The pre-ELM, pedestal kinetic profiles used for these comparisons are fits of mtanh() functions [29] to an ensemble of n_e and T_e profile data measured by the JET-ILW high-resolution Thomson scattering (HRTS) system [30]. The finite spatial resolution of the HRTS measurements is taken into account in the fitting procedure as described in Ref. [31]. The ensemble of measurements are for HRTS laser pulses (with 50 ms) repetition rate) that fall within the last 20% of the ELM cycle, i.e. the fraction 0.8-1.0 of the relative inter-ELM period τ_{ELM}, which occur during the averaging time windows $t_0 - t_1$ specified in Table A1.

The resulting fitted profiles and the measured profile data are stored, together with the parameters of the mtanh() fits and their uncertainties, in the JET processed-pulse files (PPFs), also specified in Table A1. These files form a subset of the JET-processed, EUROfusion Pedestal Database [28]. The fitted profiles, e.g. as shown in Fig. 1 (a-c) are reconstructed from the parameters of the mtanh() function using a Monte-Carlo method to calculate uncertainties on the profiles and also on the derived gradient parameters R/L_{T_e}, R/L_{n_e} and η_e. In order to set the temperature at the separatrix $T_{e,sep}$ at a prescribed value, the T_e profiles are shifted radially in ψ_N, with the same shift applied to the n_e and p_e profiles.

The separatrix temperature is a rather 'stiff' parameter, scaling approximately as $T_{e,sep} \propto P_{e,sep}^{2/7}$ [32] and is found, e.g. from calculations using a SOL model to vary only within a rather limited range of $80-110$ eV on JET-ILW for a wide range of $P_{e,sep}$ [33]. Hence, the fixed value

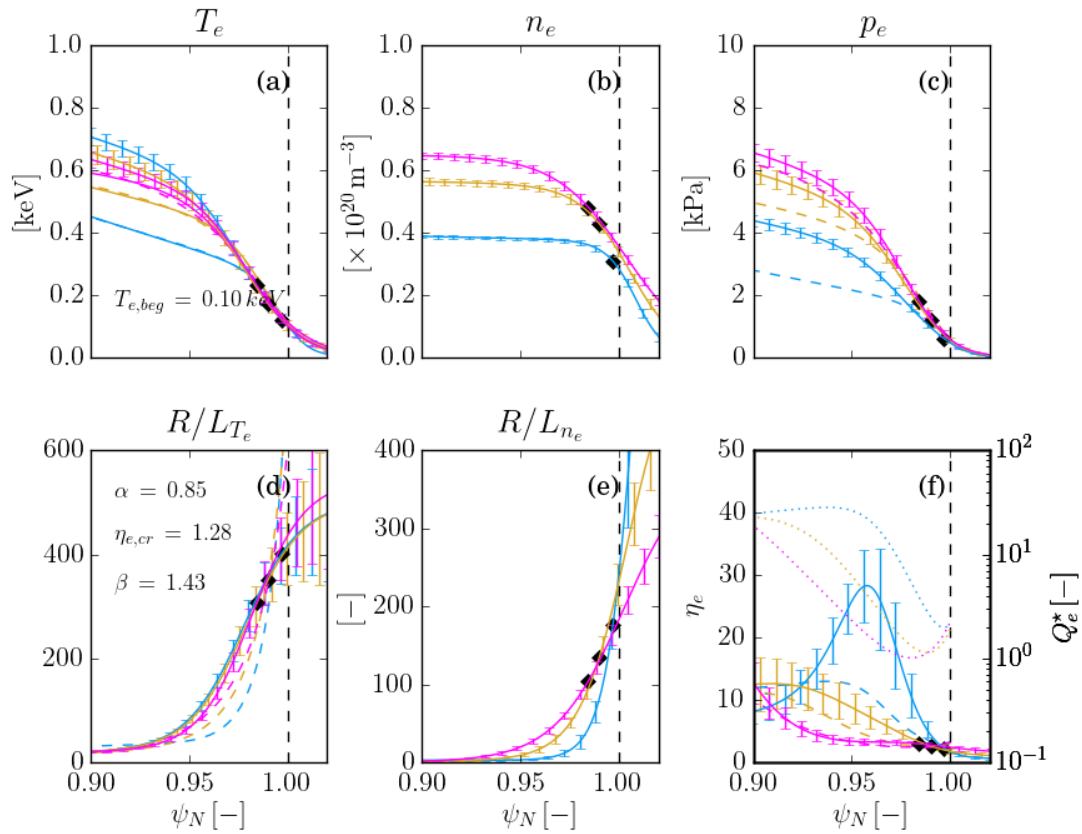

Figure 1: *Pre-ELM averaged ($\sim 80-100\%$ of the inter-ELM period) pedestal profiles for three* 2 MA *JET-ILW H-mode pulses in pure D (#99208, blue), pure T (#99491, magenta) and a D:T isotope mixture with an effective mass $A_{eff} \sim 2.4$ (#100247, gold) at a nominal hydrogenic gas fuelling rate of $\Gamma_{gas} \sim 1.6 \times 10^{22} e/s$, with other pulse parameters given in Table A1, showing (with error bars): (a) electron temperature T_e, (b) density n_e, (c) pressure p_e, their normalised gradients (d) R/L_{T_e}, (e) R/L_{n_e} and (f) the parameter η_e (solid/dashed) and the locally gyro-Bohm normalised electron heat flux $Q_e^\star$ (dotted) vs' normalised poloidal flux ψ_N. Profiles in (a, c, d and f) calculated using the ETG model assuming the scaling: $Q_e^\star = 0.85(\eta_e - 1.28)^{1.43}$ are shown dashed with* mtanh() *fits to the calculated profiles (dotted). The ♦symbols indicate the 'mid-pedestal' positions.*

of $T_{e,sep} = 100$ eV is assumed for all of the cases considered here.

Calculation of the time-averaged, conducted loss power across the pedestal during the inter-ELM periods P_{sep}^{iELM} requires subtracting the radiated power from the confined plasma P_{Rad}^{iELM} and the time-averaged ELM loss power $\langle P_{ELM}\rangle$ from the absorbed heating power P_{abs} i.e., $P_{sep}^{iELM} = P_{abs} - P_{Rad}^{iELM} - \langle P_{ELM}\rangle$. Here, the absorbed heating power P_{abs} is the sum of the injected NBI power, the ICRH heating power and the ohmic power minus the shine-through power $P_{abs} = P_{NB} + P_{RF} + P_{OH} - P_{sh}$, the radiated power P_{Rad}^{iELM} is determined from tomographic reconstructions of multi-channel bolometric measurements of the total radiation and the ELM loss power from the rate of change of the total stored energy of the plasma dW_{pl}/dt between the ELMs determined from magnetic equilibrium reconstructions. The methodology of this analysis of the loss power is exactly the same as used in Ref. [34], to which the reader is referred for further details.

The results presented here have been calculated assuming that the total heat flux conducted across the pedestal during the inter-ELM periods $q_{cond} = P_{sep}^{iELM}/S$, where S is the area of the LCFS, is carried by the electrons, i.e. $f_{cnd,e} = 1$. For the JET-ILW equilibria used here, the area of the LCFS formed by the separatrix $S \sim 140\,\mathrm{m}^2$. Calculated values of P_{abs}, P_{Rad}^{iELM}, $\langle P_{ELM}\rangle$ and the resulting P_{sep}^{iELM} are given for each of the cases in Table A1. It is interesting to note that, while the variation of heating power P_{abs} required to maintain constant β_N is quite small, i.e. $\sim 12 - 18\,\mathrm{MW}$ ($\pm 20\%$), the ranges of $P_{Rad}^{iELM} \sim 3 - 7\,\mathrm{MW}$ ($\pm 40\%$)) and $\langle P_{ELM}\rangle \sim 0.5 - 9\,\mathrm{MW}$ ($\sim \pm 50\%$)) are much larger and roughly compensate one another, resulting in a smaller variation of $P_{sep}^{iELM} \sim 5 - 8\,\mathrm{MW}$ ($\sim \pm 33\%$).

Note that the predicted pedestal temperature from the model scales approximately as $(T_{e,ped}^{ETG} \propto (P_{sep}^{iELM} B_t^2)^{1/3}$, so is rather insensitive to the loss power, i.e. $\delta T_{e,sep}/T_{e,sep} \sim (\delta P/P)/3$. It has been found that $T_{e,ped}$ is much more sensitive to other input parameters, in particular the assumed temperature at the separatrix $T_{e,sep}$ and the non-linear threshold $\eta_{e,cr}$ of the assumed ETG heat flux scaling. Hence, uncertainties in P_{sep}^{iELM} are not quoted in Table A1 or propagated to give uncertainties on the predicted $T_{e,ped}^{ETG}$.

4. Comparisons of predicted and measured T_e profiles

A comparison of the measured pedestal profiles for cases in pure D and T and an mixed D:T case with ~ 2.4 at the same gas fuelling rate of $\Gamma_{gas} \sim 1.6 \times 10^{22} e/s$ is shown in Fig. 1 (a-c) (solid), from which it can be seen that the pedestal density $n_{e,ped}$ increases with A_{eff}, while the temperature $T_{e,ped}$ only slightly decreases with A_{eff}, resulting in an overall increase in $p_{e,ped}$, as is discussed in Ref. [20]. This result is also consistent with other isotope mass scans in JET-ILW [35].

Both the normalised temperature and density gradients increase strongly with radius to values $\mathcal{O}(100)$ at the separatrix from much lower values $R/L_{T_e} \sim \mathcal{O}(10)$ and $R/L_{n_e} \sim \mathcal{O}(1)$ inside the pedestal top. In the steep-density gradient region close to the separatrix, the parameter η_e has a value ~ 2, increasing strongly at and inside the density pedestal top, where the n_e gradient is weak.

For this data set, which is based on performing mtanh() fits to the HRTS data only, as well as $n_{e,ped}$ increasing, the width of the density pedestal also increases and shifts inwards with increasing effective mass A_{eff}. However, it should be noted that the pedestal profile data presented in presented in Ref. [20] was obtained by fitting a revised form of the mtanh() function [37] also incorporating a finite slope in the outer (LFS) SOL region as well in as the core (HFS) region of the pedestal to n_e profile data obtained by combining that from both the HRTS and the Li-beam diagnostic [38], as described in Ref. [37].

The Li-beam provides more detailed, reliable n_e measurements than available from the HRTS system over the SOL region, where the scattered signal is weak. This change primarily affects the fits in the SOL region, in particular for the cases at high gas fuelling rates, for which the outward relative shift of the n_e profile is largest, decreasing the fitted pedestal width Δ_{n_e} and slightly increasing the n_e gradient inside the separatrix in comparison to the values obtained with the standard mtanh() fit. For this reason, the reader is referred to Ref. [20] for definitive statements regarding the depedence of the pedestal structure on A_{eff}.

The density at the separatrix $n_{e,sep}$ varies similarly to $n_{e,ped}$ with A_{eff}, so the density ratio $n_{e,sep}/n_{e,ped}$ remains approximately constant. These trends are also plotted explicitly for the full data set in Fig. 2, in which the color scale represents the fuelling rate Γ_{gas}.

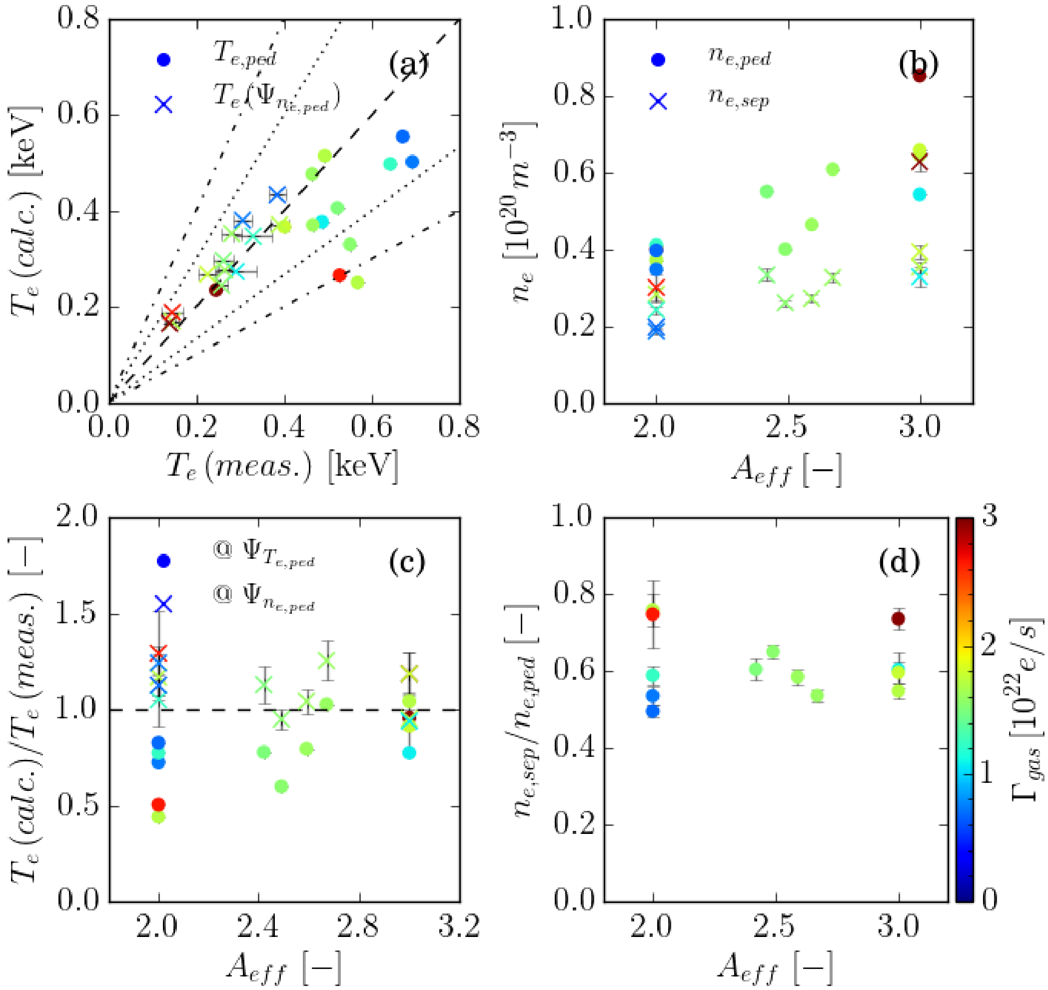

Figure 2: *Calculated and measured pedestal parameters corresponding to the cases for the isotope mix and fuelling rate scans for the* 2 MA *H-mode pulses listed in Table A1, showing: (a)* $T_{e,ped}$ *from the* mtanh() *fit* (•) *and* T_e *at the location of the density pedestal top* $T_e(\psi_N^{n_{e,top}})$ ($\star$)*, both calculated using the ETG model, vs' the equivalent experimental values (calculated values of* T_e *at factors of 1.5 and 2 higher/lower than the measured values are represented by the dotted and dot-dashed lines respectively); (b)* $n_{e,ped}$ (•) *and* $n_{e,sep}$ ($\star$) *vs' the effective isotope mass ratio* A_{eff}*; (c) the ratios of* T_e *calculated using the ETG model to the measured values at* $\psi_N^{T_{e,top}}$ (•) *and at* $\psi_N^{n_{e,top}}$ ($\times$)*; and (d) the separatrix to pedestal density ratio* $n_{e,sep}/n_{e,ped}$ *vs'* A_{eff}*, where the color represents the gas fuelling rate* $\Gamma_{gas}e/s$*.*

The predicted T_e and p_e profiles, calculated using the ETG model described in §2 are shown in Fig. 1 (a, c) (dashed). Comparing the measured and predicted profiles, it can be seen that these match well in the steep-density gradient region between the separatrix and the density pedestal top, while further inwards, where the density gradient is weak and η_e is large, the predicted T_e under predicts the actual value.

At the mid-pedestal location, half-way between the density pedestal top and the separatrix (indicated in the figure by the ♦), for which the heat flux scaling of Eq. (1) was determined from the non-linear GENE simulation results, the predicted value of R/L_{T_e} closely matches the actual value, while further outwards R/L_{T_e} is over predicted and under predicted further inwards. In other words, the electron heat flux q_e determined from the $Q_e^\star$ scaling is too high inside the mid-pedestal location and too low further outwards, requiring too low and too high a temperature gradient T_e' to match the prescribed q_e.

In Fig. 2 (a), the predicted pedestal temperature $T_{e,ped}^{ETG}$ (indicated by the $\bullet$) is plotted as a function of the measured $T_{e,ped}$ for the full data set from both the effective mass and gas rate scans. From this, it is evident that, for most but not all cases, the model under predicts $T_{e,ped}$ compared to the measured values, in some cases by over a factor ~ 2. The degree of agreement appears to be independent of the particular gas fuelling rate Γ_{gas} used.

The position of the T_e pedestal top $\psi_N^{T_{e,top}}$ is generally located further inwards to that of the density pedestal top $\psi_N^{n_{e,top}}$, i.e. there is a relative inward shift of the T_e profile, $\delta_{n-T} = \psi_N^{n_{e,top}} - \psi_N^{T_{e,top}}$, which has been well documented in previous studies [28] and found to be well correlated with the increasing density ratio $n_{e,sep}/n_{e,ped}$ resulting from higher rates of gas fuelling. A consequence of this inward shift of the T_e pedestal top relative to that of the density is that an increasing portion of the T_e pedestal is coincident with the region of weak density gradient inside the density pedestal top, i.e. in this inner region of the pedestal R/L_{T_e} well exceeds R/L_{n_e} and η_e is consequently large.

It is sometimes stated as an explanation of the lower $T_{e,ped}$ resulting from the relatively high gas fuelling rates for sustained, high-power operation on JET-ILW [39], that the resulting higher values of η_e across the region of weak density gradient at the pedestal top drives more turbulent heat transport and hence cools the pedestal [40]. However, the loss power conducted across the pedestal $P_{e,sep}$ is prescribed, the T_e gradient at a particular location adjusting to drive the corresponding turbulent electron heat flux q_e. Furthermore, we learn from the above discussion that our $Q_e^\star$ scaling for the electron heat flux determined for the steep-density gradient region actually over predicts q_e in this region of weak density gradient, so whatever branch of turbulence is prevalent there requires a higher rather than lower driving T_e gradient to match the prescribed heat flux. This point is discussed further in §5 below.

Values of the predicted T_e at the location of the density pedestal top $T_e(\psi_N^{n_{e,top}})$ are also plotted (as the $\times$'s) in Fig. 2 (a) as a function of the corresponding measured values at the same location. It is evident that there is a much better agreement between the model prediction and the measured values at this location than at the T_e pedestal top, with only a slight over prediction of $T_e(\psi_N^{n_{e,top}})$ by factor $\lesssim 1.2$. This is to be expected because the $Q_e^\star$ scaling on which the model is based was determined from the non-linear GENE simulations for the steep-density gradient and prediction of $T_e(\psi_N^{n_{e,top}})$ requires calculation of T_e over this region but not further inwards of the density pedestal top where the density gradient is weak.

The effect of increasing the gas fuelling rate Γ_{gas} in both the pure D and pure T pulses is shown in Fig. 3 and Fig. 4 respectively. For the D pulses, increasing Γ_{gas} by a factor of ~ 3.5 results in only a small increase in $n_{e,ped}$, i.e. the gas fuelling is rather inefficient at fuelling the confined plasma. In fact, the increased fuelling results in a higher ELM frequency and these then expel the additional particles deposited inside the separatrix at an increased rate, almost balancing the additional influx.

The main effect of the increased gas rate is to increase the density at the separatrix and hence the density ratio $n_{e,sep}/n_{e,ped}$, as is also shown in Fig. 2 (c). This has the effect of shifting the n_e profile outwards with respect to the T_e profile, thereby narrowing the steep-density gradient region just inside the separatrix and increasing η_e at the pedestal top, as is also discussed in [40].

In the case of the two D pulses #96208 and #96201 shown in Fig. 3 at the two higher fuelling rates of $1.7 \,\&\, 2.7 \times 10^{22}$ e/s for which f_{ELM} is particularly high ($\gtrsim 70$ Hz), the degree of agreement between the predicted value of $T_{e,ped}$ and the measured value is particularly poor.

Similar trends are observed for the T as for the D pulses, except that the pulse #100183 at the highest fuelling rate of 3.0×10^{22} e/s has an anomalously high pedestal density, increasing more strongly for a similar increase in Γ_{gas} than in the case of the D pulse #96201 shown in Fig. 3. This increase can be attributed to the low ELM frequency in pulse #100183 of $f_{ELM} \sim 7.5$ Hz, which is much lower than in the other pulses in the data set.

Hence, in the T pulses, the effect of increasing the gas fuelling is not to increase but to decrease f_{ELM}. In the case of the T pulses, increasing Γ_{gas} increases the radiated power P^{iELM}_{Rad} and hence the rate at which the pedestal energy $W_{e,ped}$ can increase between the ELMs, thereby decreasing f_{ELM} and the ELM power loss $\langle P_{ELM} \rangle$. However, for the D pulses, increasing Γ_{gas} has the opposite effect of reducing P^{iELM}_{Rad}, which increases rather than decreases f_{ELM}.

These observations support the notion that the narrower the steep-density gradient region, the worse the predictive capability of the model, which is not applicable to the weak density gradient region inside the density pedestal top. The particularly poor agreement for the T pulse #100183 at the highest fuelling rate also follows this trend. Note that the dependencies of the loss power components due to radiation, ELMs and inter-ELM heat transport across this data set are discussed in more detail in Ref. [20].

Generally, as is evident from Fig. 2 (a), the higher gas fuelling rates, with the correspondingly higher density ratios $n_{e,sep}/n_{e,ped}$ exhibit the lowest values of $T_{e,ped}$ and

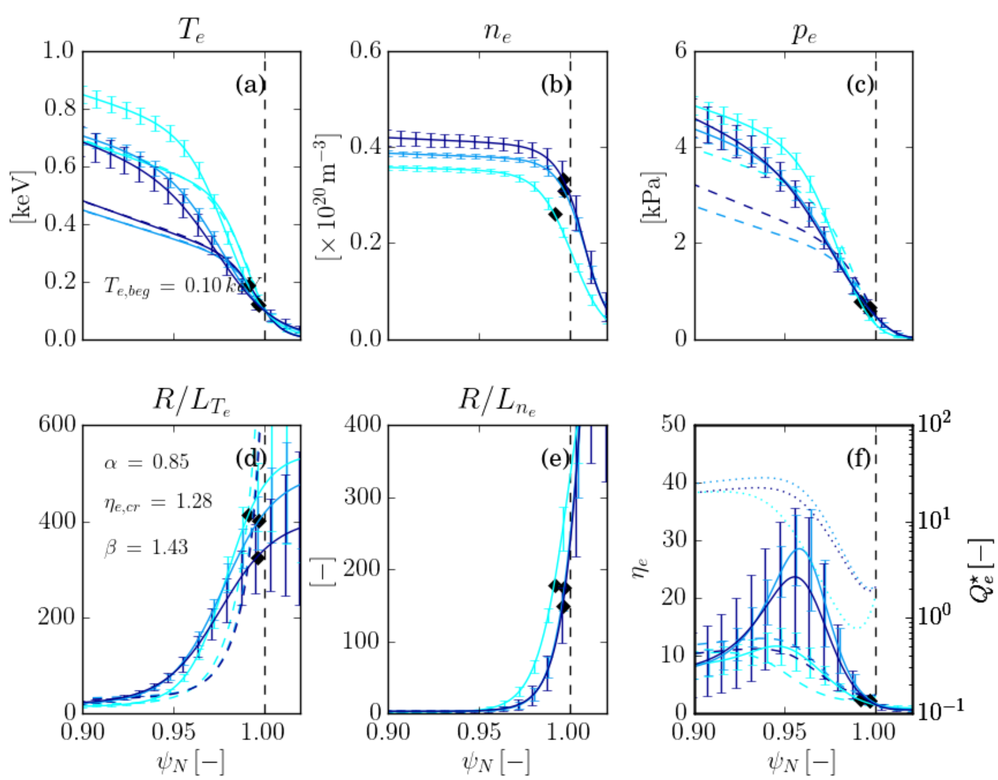

Figure 3: *Pedestal profiles for the three* 2 MA *JET-ILW H-mode deuterium pulses ($A_{eff} = 2$) from Table A1 #96202 (cyan), #96208 (mid-blue) and #96201 (dark-blue) with gas fuelling rates of* $\Gamma_{gas} \sim 0.74, 1.7 \,\&\, 2.7 \times 10^{22}$ e/s *respectively, with the plotted quantities as defined in Fig. 1.*

$T_e(\psi_N^{n_{e,top}})$, in agreement with several previous studies on JET-ILW, e.g. as in Ref. [28, 40]. An alternative interpretation of this observation to that proposed in Ref. [40], i.e. increased turbulent transport due to higher resulting values of η_e across the pedestal, is presented in §5.

5. Discussion

5.1. On the role of the separatrix boundary conditions

An extreme simplification of the model for the pedestal T_e profile presented in §2 gives insight into the important role that the density ratio $n_{e,sep}/n_{e,ped}$ plays in governing the resulting pedestal temperature, in particular its value at the density pedestal top $T_e(\psi_N^{n_{e,top}})$. As reported in Ref. [34], values of the parameter η_e averaged over the steep density gradient region of the pedestal is often observed to saturate at a value $\langle\eta_e\rangle_{ped} \sim 2$ in JET-ILW. This observation is also supported by results presented in Ref. [20].

It is also discussed by W. Guttenfelder in Ref. [16], that values of $\langle\eta_e\rangle_{ped}$ in the range 1-2 have been reported on several other devices and it is explicitly mentioned in Ref. [6] that values of $\eta_e \sim 2$ measured across the steep-density gradient region in ASDEX Upgrade pedestals lie at $\sim 1.6\times$ the linear threshold and that this observation might be attributable to the 'stiffness' of turbulent ETG driven heat transport. Similar observations from ASDEX Upgrade were also reported earlier by Neuhauser *et al* [14] and in Ref. [15] by Horton *et al* it was shown that the

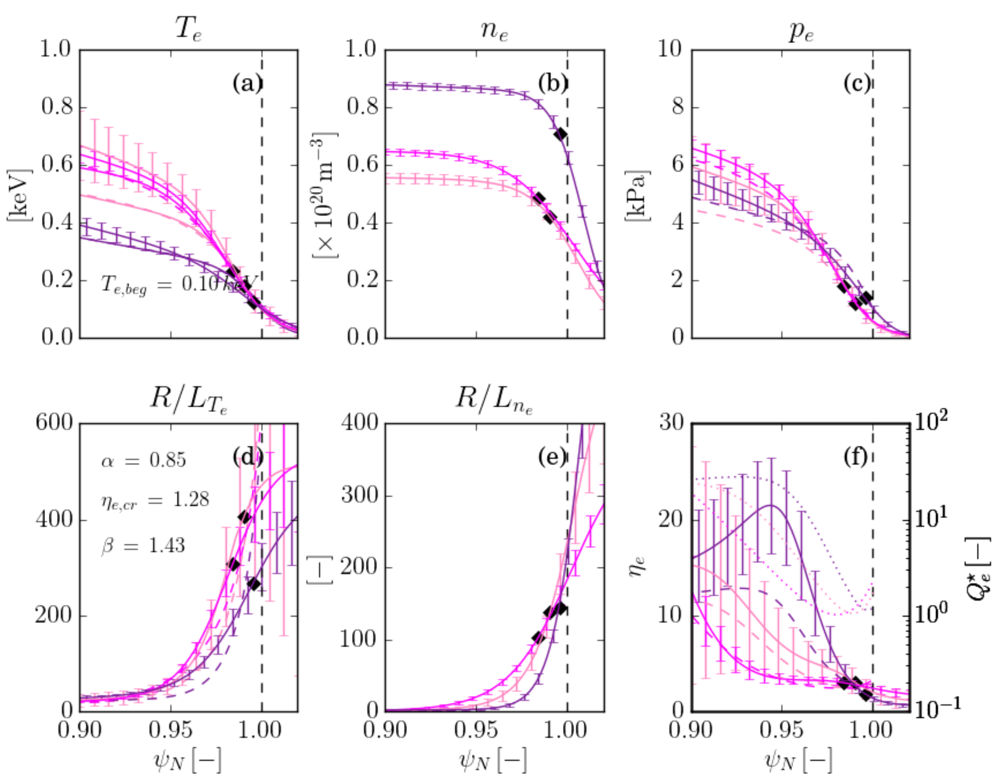

Figure 4: *Pedestal profiles for the three* 2 MA *JET-ILW H-mode tritium pulses (A_{eff} = 3) from Table A1 #100185 (pink), #100247 (magenta) and #100183 (purple) with gas fuelling rates of* $\Gamma_{gas} \sim 1.1, 1.7$ & 3.0×10^{22} e/s *respectively, with the plotted quantities as defined in Fig. 1.*

pedestal T_e profile could be reconstructed from the n_e profile by assuming a constant $\eta_e \sim 2$, in accordance with the following discussion.

In Ref. [34], the consequences of assuming that infinitely 'stiff' electron heat transport clamps η_e to a constant, critical value $\eta_{e,cr}$ across the pedestal are discussed. Under this assumption, the definition of $\eta_e \equiv L_{n_e}/L_{T_e}$ represents a first-order differential equation $T_e'/T_e = \eta_{e,cr}(n_e'/n_e)$, where the prime $' = d/dr$. On integration inwards from the separatrix, this yields the following simple relation for T_e at the top of the density pedestal:

$$T_e(\psi_N^{n_{e,top}}) = T_{e,sep}\left(\frac{n_{e,ped}}{n_{e,sep}}\right)^{\eta_{e,cr}} \tag{3}$$

This highlights the importance of the boundary conditions at the separatrix for the case of stiff heat transport, i.e. that $T_{e,ped}$ is then proportional to $T_{e,sep}$ and increases strongly with the density ratio $n_{e,ped}/n_{e,sep}$, conversely decreasing with the inverse ratio $n_{e,sep}/n_{e,ped}$. This can be understood from the n_e in the denominator on the RHS of the initial differential equation, which results in a larger value of T_e' for given values of R/L_{n_e} and T_e at the separatrix, this increase then propagating inwards as the temperature profile is integrated.

Hence, taken together, the observation that across the steep-density gradient region of the pedestal $\langle\eta_e\rangle_{ped} \sim 2$ and the simplifying assumption of infinitely stiff electron heat transport, offer and explanation of the decreasing dependence of $T_{e,ped}$ on the density ratio $n_{e,sep}/n_{e,ped}$.

5.2. Influence of the effective isotope mass A_{eff} and B-field

The heat flux scaling of Eq. (1) on which the model described in §2 is based is only dependent on the electron mass m_e appearing in the gyro-Bohm normalisation $q_{e,gB} \propto \rho_e^2 \propto m_e$, so is independent of the isotopic mass A_{eff} of the plasma ions. However, the predicted pedestal T_e profile does depend on the density profile, which does vary with A_{eff}, as is described in detail in Ref. [20]. Across the data set used here and in Ref. [20], $n_{e,ped}$ increases by $\sim 50\%$ when changing isotope from pure D to T, i.e. with A_{eff} increasing from 2 to 3, while $T_{e,ped}$ decreases by $\sim 25\%$. As shown in Fig. 2 (b & c), $n_{e,sep}$ increases with A_{eff}, although less than $n_{e,ped}$, resulting in an almost constant density ratio $n_{e,sep}/n_{e,ped}$.

The effect of these changes to the density profile is that the model predictions for $T_{e,ped}$ broadly reproduces the observed trends. As described above, the effect of increasing the assumed $n_{e,sep}$ is to decrease the initial T_e gradient at the separatrix, so results in lower predicted T_e across the whole pedestal. At each flux surface, the predicted R/L_{T_e} adjusts to give the appropriate η_e required to match the prescribed electron heat flux q_e, accounting for the predicted, local value of the gyro-Bohm normalisation $q_{e,MgB}$.

As can be seen from Fig. 2 (a), the predicted T_e at the density pedestal top $T_{e,ped}^{ETG}(\psi_N^{n_{e,top}})$ typically agrees quite well with the measured values. The ratios of the calculated to measured values shown in Fig. 2 (c) show that the predicted values typically overestimate the measured values by up to a factor ~ 1.2. This indicates that, at least across the steep-density gradient region of the pedestal, the electron heat transport is probably independent of A_{eff}.

As is also evident from Fig. 2 (c), the degree of agreement between the predicted and measured values of $T_{e,ped}$ improves with increasing A_{eff}, i.e. is better for the T pulses with lower $T_{e,ped}$ than for the D pulses. This indicates that the underlying scaling for the electron heat transport across the weak density gradient region must depend to some extent on A_{eff}.

This trend is consistent with the electron heat flux across the weak-density gradient region having a significant component due to to ion-scale turbulence, which does exhibit a dependence on isotope mass. For example, the ion gyro-Bohm normalisation $q_{i,gB}$ scales with A_{eff}. So, should the heat transport require a relatively constant normalised heat flux $q_e/q_{i,gB}$, this alone would result in the predicted $T_{e,ped}$ decreasing with A_{eff}. Furthermore, the ion mass can affect the growth rates of TEM turbulence by changing the electron-ion collision frequency, which increases with $A_{eff}^{1/2}$. This would reduce the trapped electron fraction for otherwise similar parameters and hence decrease the linear growth rates of TEM modes.

Global linear GK simulations using GENE, discussed in Ref. [20] performed without flow shear, yielded lower growth rates for ion-scale turbulence with $k_y\rho_i \lesssim 0.4$ and a significant TEM component for the T pulse #100247 compared to the D pulse #96208, while in simulations with flow shear, the ion-scale turbulence is completely suppressed in the T pulse but not in the D pulse. As TEM turbulence is thought responsible for electron particle transport [11], this change is consistent with the higher $n_{e,ped}$ of the T pulse. In this case there would be an indirect effect of increasing A_{eff} on $T_{e,ped}$. Should the pedestal heat transport be dominated by ETG turbulence, as it is across the steep-density gradient region, the increased pedestal density would then result in a reduction of T_e across the pedestal.

Ref. [41] presents results of a recent detailed GK study by Predebon *et al* of the isotope mass dependence of pedestal transport in three 1.4 MA, low-triangularity ($\delta \sim 0.2$) JET-ILW pulses, two in D and one in H at similar fuelling rates. Local ρ_e-scale GK simulations using GENE revealed that heat transport due to ETG turbulence dominates near the pedestal top, decreasing in significance outwards towards the separatrix. Swapping the isotope mass in the simulations, resulted in a negligible change in the predicted heat fluxes, showing that ρ_e-scale ETG turbulence is unable to explain the isotope effect on the heat transport. Also, as expected for ETG turbulence, the predicted particle and ion heat fluxes were negligibly small.

In the global ρ_i-scale GK simulations, the turbulent ion heat transport was found to be mostly due to ITG modes and to be characterized by an anti-gyro-Bohm heat-flux scaling due to different normalised $E\times B$ shearing rates in species units $\tilde{\omega}_{E\times B}(H) = A_D^{-1/2}\tilde{\omega}_{E\times B}(D)$, relevant for flow-shear stabilisation of the ion-scale turbulence. Here, the normalised $E\times B$ shearing rate is defined as $\omega_{\tilde{E\times B}} = /(c_i/a)$, where c_i is the ion sound speed and a is the minor radius. As the NC component of the ion heat flux is instead characterised by an gyro-Bohm scaling, overall this resulted in no net isotope dependence of the ion heat transport.

Turning to particle transport, whereas the NC component is not expected to be affected by the isotope mass, the global ρ_i-scale GK simulations showed the turbulent particle transport to largely dominate the NC transport and to exhibit a clear anti-gyro-Bohm scaling, this providing an efficient mechanism to explain the increased density gradient observed with increasing isotopic mass.

Regarding the dependence of the model predictions on the magnetic field, the gyro-Bohm normalisation $q_{e,gB}$ in the heat flux scaling of Eq. (1) scales with B^2. Hence, as mentioned in §3.2 above, the predicted T_e across the pedestal is expected to scale approximately with $B^{2/3}$. Hence, the higher toroidal field of the pulses considered here of 2.25 T compared to the 1.7 T of the pulses for which the q_e scaling was determined [17], would result in a factor ~ 1.52 increase in the predicted $T_{e,ped}$, provided other pulse parameters where held constant. The fact that at least the predicted T_e at the density pedestal top $T_e(\psi_N^{n_{e,top}})$ agrees well with experiment, indicates that the electron heat flux, at least across the steep-density gradient region of the pedestal, likely does scale with the expected electron gyro-Bohm normalisation.

5.3. On the critical threshold for ETG turbulence

Here, we discuss the conditions under which ETG driven turbulence is expected to exhibit a threshold, normalised temperature gradient $R/L_{T_e,cr}$ or a threshold in the parameter η_e, the latter implying that an increased density gradient would require a larger temperature gradient to destabilise the turbulence. In which regions of the pedestal these different thresholds are expected to apply gives insight into their role in determining the pedestal structure.

A study by F. Jenko of the linear threshold temperature gradient for the destabilisation of ETG turbulence is reported in Ref. [26]. A series of linear stability calculations were performed using the gyrokinetic code GENE, scanning a number of parameters over ranges representative of the core of a typical tokamak plasma equilibrium, to determine the scaling of the critical, normalised electron temperature gradient $R/L_{T_e,cr}$ required for finite growth rate of the most unstable linear mode, i.e. at which its growth rate $\gamma_m > 0$.

By separately fitting the scaling of $R/L_{T_e,cr}$ obtained for each parameter, e.g. the normalised density gradient R/L_{n_e}, the temperature ratio parameter $\tau = Z_{eff}(T_e/T_i)$, safety factor q, magnetic shear $\hat{s} = r/q(dq/dr)$, the overall scaling could be summarised by an expression of the form:

$$R/L_{T_e,cr} = \{(1+\tau)(\mathcal{A}+\mathcal{B}\hat{s}/q), \mathcal{C}R/L_{n_e}\}_{max} \tag{4}$$

where the fit coefficients are $\mathcal{A} = 1.33$ $\mathcal{B} = 1.91$, $\mathcal{C} = 0.8$ (see Eq. 4 of Ref. [26]). A more complete scaling, accounting for finite aspect ratio and non-circular plasma geometry is given by:

$$R/L_{T_e,cr} = \{(1+\tau)(1.33+1.91\hat{s}/q)(1-1.5\epsilon)(1+0.3\epsilon(d\kappa/d\epsilon)), 0.8R/L_{n_e}\}_{max} \tag{5}$$

where the inverse aspect ratio $\epsilon = r/R_0$ and $\kappa = b/a$ is the elongation of the flux surfaces (see Eq. 7 of Ref. [26]).

The first and second terms in Eq. (4) and Eq. (5) represent the linear thresholds for what are known as the 'toroidal' and 'slab' branches of linear ETG modes, which we denote hereafter as T-ETG and S-ETG modes. For the slab modes, which dominate at high R/L_{n_e}, the parallel dynamics dominates over perpendicular drifts, while toroidal modes, which are driven by perpendicular drifts, are dominant at low R/L_{n_e} [26, 42].

The behaviour of this threshold is made up of two parts, the constant $R/L_{T_e,cr}$ branch at low R/L_{n_e}, where the first term in Eq. (5) is largest and the branch at high R/L_{n_e} where $R/L_{T_e,cr} = 0.8R/L_{n_e}$. It is this second branch, corresponding to the dominance of S-ETG modes, that is appropriate at the high values of $R/L_{n_e} \sim \mathcal{O}(100)$ typical of the steep density gradient region of the pedestal. With the definition of the parameter $\eta_e = L_{n_e}/L_{T_e}$, this branch corresponds to the threshold $\eta_{e,cr} = 0.8$ for a finite linear growth rate of these modes.

The set of non-linear, GENE simulations, over which the electron temperature and density gradients were scanned about nominal values of R/L_{T_e} and R/L_{n_e}, performed for the study of Ref. [17], were run only for the mid-pedestal location in the steep-density region. These showed that the ETG turbulence prevalent there exhibits a threshold in $\eta_{e,cr}$, with the threshold R/L_{T_e} increasing linearly with R/L_{n_e}, as expected for slab-ETG modes. The saturated electron heat fluxes q_e from these simulations were found to decrease linearly with increasing R/L_{n_e} and increase with $(R/L_{T_e})^3$ for values well above threshold, these trends captured by the expression:

$$Q_e^\star = (R/L_{n_e})^{-1}(R/L_{T_e} - R/L_{T_e,cr}) \equiv (\eta_e - \eta_{e,cr}) \tag{6}$$

Here, the dependence of the threshold η_e on the density gradient $\eta_{e,cr} = (R/L_{T_e,cr})(R/L_{n_e})$ is consistent with that found from the linear scans with GENE in Ref. [26], represented by the second term in Eq. (5).

In Ref. [17], two expressions for the electron heat flux q_e were used to fit the data from the non-linear GENE simulations from the temperature gradient scan, i.e.: Eq. (i)

$q_e \propto (\omega_{T_e} - \alpha\omega_{n_e,0})^{\beta}$ and Eq. (ii) $q_e \propto (\omega_{T_e} - \delta\omega_{n_e,0}))^{\epsilon}\omega_{T_e}^2$, where $\omega_{T_e} \equiv a/L_{T_e}$, etc. Only the latter expression can be transformed algebraically into Eq. (6). The fit found using Eq. (i), yielded a threshold $\alpha \equiv \eta_{e,cr} \sim 0.8$ and an exponent $\beta \sim 3$, while the fit using Eq. (ii) yielded a higher threshold $\delta \equiv \eta_{e,cr} \sim 1.28$ and an exponent $\epsilon \sim 1.43$.

It is interesting to note that fitting the q_e data using Eq. (i) yielded a threshold much closer to the linear threshold $\alpha \equiv \eta_{e,cr} \sim 0.8$, while the fitted exponent $\beta \sim 3$ is consistent with the prediction of critical balance theory [43], even for values of not far above threshold. In contrast, the higher threshold found by fitting to Eq. (ii) instead, results in a slightly stronger dependence of $q_e \propto (R/L_{T_e})^{3.4}$ only far above threshold. The similar uncertainties on the fit parameters found with either expression, meant that it was impossible to distinguish which of the two forms better fits the heat flux data. It therefore remains an open question whether $\eta_{e,cr}$ lies at the linear threshold or whether there is an upward, non-linear Dimits' shift to the threshold η_e for ETG turbulence in the pedestal region [44].

5.4. On the structure of turbulence across the pedestal

The structure of turbulence across the pedestal of selected JET-ILW type-I ELMy H-modes at 1.4 MA/1.7 T with varying input power and gas injection rates, from the weak density region inside the pedestal top across the steep-density gradient region to the separatrix, is investigated in detail using both linear and non-linear, electromagnetic GK simulations using GENE in Ref. [17]. For the cases studied there, the heat flux was found to be carried predominantly by turbulent electron heat transport across most of the pedestal, except in one case for a pulse at lower heating power, in which neo-classical ion heat transport carried most of the heat flux across this region.

For the innermost flux surface considered, mid-way between the temperature and density pedestal top positions, the dominant modes were found to be ITG/TEM turbulence at low $k_y\rho_i$ and 'core-like' ETG turbulence (with growth rates peaking at the outboard mid-plane, i.e. $\theta_0 = 0$) at high $k_y\rho_i$. There, the electron heat flux spectra were found to peak at larger scales, over the range of $k_y\rho_i \sim 10 - 20$, than in the steep-density gradient region.

At the mid-pedestal flux surface in the steep-density gradient region, the heat flux was found to be carried predominantly by S-ETG turbulence, the spectrally-resolved electron heat flux peaking at $k_y\rho_i \sim 60$, i.e. where $k_y\rho_e \sim \mathcal{O}(1)$. Linearly, these modes were found to have a high parallel wave number k_z, indicating the importance of the parallel resonance ($\omega \sim k_z v_{th,e}$, where $v_{th,e}$ is the electron thermal velocity and k_z the wave number parallel to B) in their dynamics, thus confirming the S-ETG character of this turbulence.

A tendency for ETGs to exist also at smaller $k_y\rho_i$ in the steep-density gradient region was particularly noticeable for the high power pulses. At $k_y\rho_i \lesssim 5$, the dominant form of ETG were found to be T-ETG modes, requiring large values of R/L_{T_e} to exist and with growth rates peaking at $\theta_0 \neq 0$, in contrast to the high k_z S-ETG modes present at high $k_y\rho_i$, which were found to carry the overwhelming fraction of the electron heat flux.

The cases studied with low gas fuelling rates also exhibited kinetic-ballooning modes (KBMs) present close to the separatrix at $k_y\rho_i \sim 0.2$, characterised by their vanishing parallel electric field $E_{\parallel}$ and transport fingerprints [8, 11].

Recently the GK study of JET-ILW pedestal heat transport reported in Ref. [17] has been extended by performing a more detailed study of the morphology of the ETG turbulence [45], with the aim of investigating why the cases with a higher gas fuelling rate exhibit a somewhat 'stiffer' $q_e(\eta_e)$ scaling than the low-gas cases. Here, the term 'stiffness' refers to the rate of increase of q_e with η_e, i.e. $dq_e/d\eta_e$. The relative importance of the toroidal and slab resonances could be investigated by comparing the resulting heat fluxes obtained from non-linear GK simulations performed both with and without the toroidal drifts active. For the low-gas case, no difference was found between the cases with and without the toroidal drifts, indicating that the ETG turbulence is purely slab-like in character.

In contrast, for the high-gas case, which consequently has a higher ratio of separatrix to pedestal density $n_{e,sep}/n_{e,ped}$ (and hence lower normalised density gradient ω_{n_e} at the mid-pedestal flux surface) than the low-gas case, disabling the toroidal drifts significantly reduced the heat flux (by $\sim 35\%$ at the nominal gradients), resulting in quantitatively very similar $q_e(\eta_e)$ scaling to the low-gas case. Hence, with a weaker density gradient, an increasing relative contribution from T-ETG modes is found to be the underlying cause of the increased stiffness of the heat flux scaling. As expected, the T-ETG modes were of a ballooning character, peaking at $k_z \sim 0$. Furthermore, it was found that, while variation of ω_{n_e} did not affect the $q_e(k_z)$ spectrum, increasing ω_{T_e} caused a pile up of the heat flux at high values of k_z at the limit of the parallel resolution of the GK simulations, as was also documented for S-ETG modes in Ref. [46].

In the detailed GK study by J. Parisi in Ref. [47] of the pedestal of the 1.4 MA/1.9 T JET-ILW pulse #92174 with 17.4 MW of heating power, the turbulence for a flux surface in the steep-density gradient region was found to be dominated by ETG turbulence for all $k_y\rho_i > 0.1$, with a novel type of T-ETG instability found often to be the fastest growing mode for $k_y\rho_i \geq 1$. These modes exhibited such large radial wave numbers for electron Larmor radius effects to be important, i.e. $k_x\rho_e \sim 1$. This mode was found to be driven far away from the outboard mid plane, i.e. $\theta_0 \neq 0$, and to exist at large spatial scales, where $k_y\rho_i \sim (\rho_i/\rho_e)(L_{T_e}/R) \sim 1$, which is consistent with the results reported earlier by Told et al. in Ref. [5].

The T-ETG modes were found to co-exist with S-ETG modes, with the latter dominant at $\theta_0 = 0$ for $k_y\rho_i \geq 5$. Quasi-linear, mixing-length arguments indicated that both the T-ETG and S-ETG modes were expected to make comparable contributions to the electron heat transport. While growth rates of the S-ETG modes were found to decrease with R/L_{n_e}, the T-ETG modes were insensitive to R/L_{n_e} but strongly driven by R/L_{T_e}. At all scales, ITG modes were found to be subdominant and KBMs were shown to be suppressed by $E\times B$ shear.

In another recent study by L. Leppin *et al* reported in Ref. [48], the structure of turbulence across a typical pedestal in ASDEX Upgrade was determined using a combination of linear and non-linear, global electromagnetic GK simulations performed using GENE. Trapped-electron driven mode (TEM) turbulence with electromagnetic components due to micro-tearing modes (MTMs) was found to be dominant at the pedestal top/shoulder, while a combination of linear stabilisation and $E\times B$ shear was found to suppress such ion scale turbulence towards the steep gradient region, where the electron heat flux was instead carried by small-scale ETG modes and the ion channel reduced to neo-classical levels.

Of particular relevance to this present work is the finding of each of the studies discussed above that small-scale ETG turbulence carries the dominant fraction of the electron heat flux across the steep-density region of the pedestal. This turbulence predominantly has a 'slab' structure, with high parallel wave number k_z and a threshold in η_e close to or somewhat above the linear threshold, although there is an increase in the relative contribution from T-ETG modes, driven by toroidal drifts, as the density gradient weakens. Furthermore, across the weak density gradient region inwards of the density pedestal top, other larger scale ITG/TEM modes or electromagnetic MTMs are found to carry a significant fraction of the electron heat flux.

It is across this inner region of the pedestal that the model for the temperature profile of §2 breaks down, as here the heat flux scaling for the steep-density gradient region on which it is based is invalid. Further sets of non-linear GK calculations scanning the temperature and density gradients are required to determine the appropriate electron heat flux scaling to adopt for this region, which would have to be global to capture the ion-scale modes. Ideally, other parameters as appear in Eq. (5) for the threshold R/L_{T_e}, e.g. $\hat{s}/q$ should also be scanned to further parameterise the heat flux scaling. Note that estimates of the magnitude of $R/L_{T_e,cr}$ obtained from the first term of Eq. (5) using typical values of the parameters for the region at the pedestal top give too low values for $R/L_{T_e,cr}$ of $\mathcal{O}(1)$ compared to the observed values which are of $\mathcal{O}(10)$ in this inner region of the pedestal.

6. Predictions using EPED combined with an ETG critical heat flux model

The ETG critical heat flux model for the pedestal T_e profile, described in Ref. [19], has been combined with the standard EPED model within Europed by implementing three different models, which are described in §6.1 below. Results from applying these models to the isotope mass scan pulses are presented in the following §6.2.

6.1. Combined EPED and ETG critical heat flux pedestal models

The standard EPED model [21] for prediction of the total pedestal pressure p_{ped} functions in the following way: a range of pedestal widths Δ_p are assumed from which profiles of the total pressure p_{ped} are constructed using the relation $p_{ped} \propto \Delta_p^2$, which derives from the KBM pressure gradient constraint $\Delta_p = 0.076\,\beta_p^{1/2}$; 2D equilibria, constructed for each pressure profile, are tested for MHD stability using the MISHKA code [36], with that which is marginally stable giving the EPED prediction of p_{ped}. The marginal stability criterion on the growth rate γ used here is $\gamma > \omega^{\star}_{p_i}/2$, where $\omega^{\star}_{p_i}$ is the ion diamagnetic frequency.

The ETG critical heat flux model for the pedestal T_e profile, described in Ref. [19], allows calculation of the T_e profile across the pedestal, given the n_e profile and the loss power across the pedestal P_{sep} as input. This model has been combined with the standard EPED model within Europed in various ways, forming the models M1-3 described below.

The first two models still take $n_{e,ped}$ as an input and use the ETG model to calculate the associated T_e profile. A consequence of this is that the resulting $T_{e,ped}$ is extremely sensitive to the ratio $n_{e,sep}/n_{e,ped}$, increasing values of this ratio causing $T_{e,ped}$ to decrease strongly. This sensitivity causes the first model M1, which does not use the KBM constraint to determine the total pressure p_{tot}, to fail in some cases at the experimental value of this density ratio.

M1) With $n_{e,ped}$ given, assuming $T_i/T_e = const$ but without EPED KBM constraint:

- i) A range of pedestal widths Δ_p are generated, which together with the experimental value of $n_{e,ped}$, gives a range of pedestal n_e profiles;
- ii) For each of these n_e profiles a corresponding T_e profile is calculated using the ETG critical heat flux model, as explained in §3 of Ref. [19];
- iii) The total pressure $p_{tot} = p_i + p_e$ is calculated, assuming a fixed ratio of $T_i/T_e = const$ and taking account of ion dilution using the measured Z_{eff} and a representative impurity charge state Z_I;
- iv) The resulting p_{tot} profiles are used to generate a range of self-consistent equilibria, each of which are tested for stability to ideal MHD peeling-ballooning modes using the MISHKA code;
- v) The profile which is found to be marginally stable then yields a prediction of p_{tot} and the corresponding $n_{e,ped}$ and $T_{e,ped}$.

M2) With $n_{e,ped}$ given, determine: p_{tot} from EPED, T_e from ETG model and T_i by matching p_{tot} from the KBM constraint:

  i) A range of pedestal widths Δ_p are generated and for each the given value of $n_{e,ped}$, gives a range of pedestal n_e profiles;
  ii) For each of these n_e profiles the corresponding T_e profile is calculated using the ETG critical heat flux model, as explained in §3 of Ref. [19];
  iii) For each Δ_p the corresponding p_{tot} profile is calculated using the KBM constraint, i.e. $p_{ped} \propto \Delta_p^2$;
  iv) The resulting p_{tot} profiles are used to generate a range of self-consistent equilibria, each of which are tested for stability to ideal MHD peeling-ballooning modes using the MISHKA code;
  v) The profile which is found to be marginally stable then yields a prediction of p_{tot} and the corresponding $n_{e,ped}$ and $T_{e,ped}$.
  vi) To satisfy the KBM constraint, the T_i profile is determined from p_{tot}, i.e. $T_i = (p_{tot} - p_e))/n_i$.

M3) The density pedestal prediction model of Ref. [49] combined with the ETG critical heat flux model and the EPED KBM constraint ($\Delta = 0.076\sqrt{\beta_{p,ped}}$):

Using this combined model, both the n_e and the T_e profiles can be predicted simultaneously using an iterative procedure, where the predicted n_e profile is used as input to the ETG model to predict the T_e profile and then this is used as input in the density pedestal prediction model. As this model uniquely constrains the profiles, it would completely eliminate the need for both the MHD stability and KBM constraints. Hence, to ensure that the predicted profiles are marginally stable, the T_i profile is used as a free parameter. The T_i profile is calculated by matching p_{tot} to that predicted using the EPED KBM condition ($p_{tot} \propto \Delta_p^2$). For a full prediction, the set of profiles and the associated equilibrium that is marginally MHD peeling-ballooning mode stable are selected. The principle inputs to this model, which provides a full prediction of the pedestal strucure are: the boundary conditions $n_{e,ped}$ and $n_{e,sep}$, the loss power across the separatrix P_{sep} and the assumed ratio of electron particle diffusivity to electron heat conductivity (D_e/χ_e) across the pedestal.

6.2. Results of applying combined EPED+ETG pedestal models to isotope scan pulses

M1) The strong inverse dependence of the value of $T_{e,ped}$ predicted using the ETG model on the density ratio $n_{e,sep}/n_{e,ped}$, which is a result of the stiffness of the ETG heat flux clamping η_e to values not far above $\eta_{e,cr}$ as discussed in Ref. [19], causes the model to fail, i.e. never reaching marginal MHD stability, for some cases with higher values of this ratio. For this reason, this model, which does not use the EPED KBM constraint, has not been explored further.

M2) Results from applying model M2 to one of the pulses from the isotope mass scan dataset discussed here (#96202), at a low gas fuelling rate of $\Gamma_{gas} \sim 0.74 \times 10^{22}$ e/s, are shown in Fig. 5 (a-d). Both the predicted T_e profile from the standard EPED and from the combined model M2 are shown for four different density profiles with the same $n_{e,ped}$, which explore the dependence of the predicted $T_{e,ped}$ on the density ratio $n_{e,sep}/n_{e,ped}$.

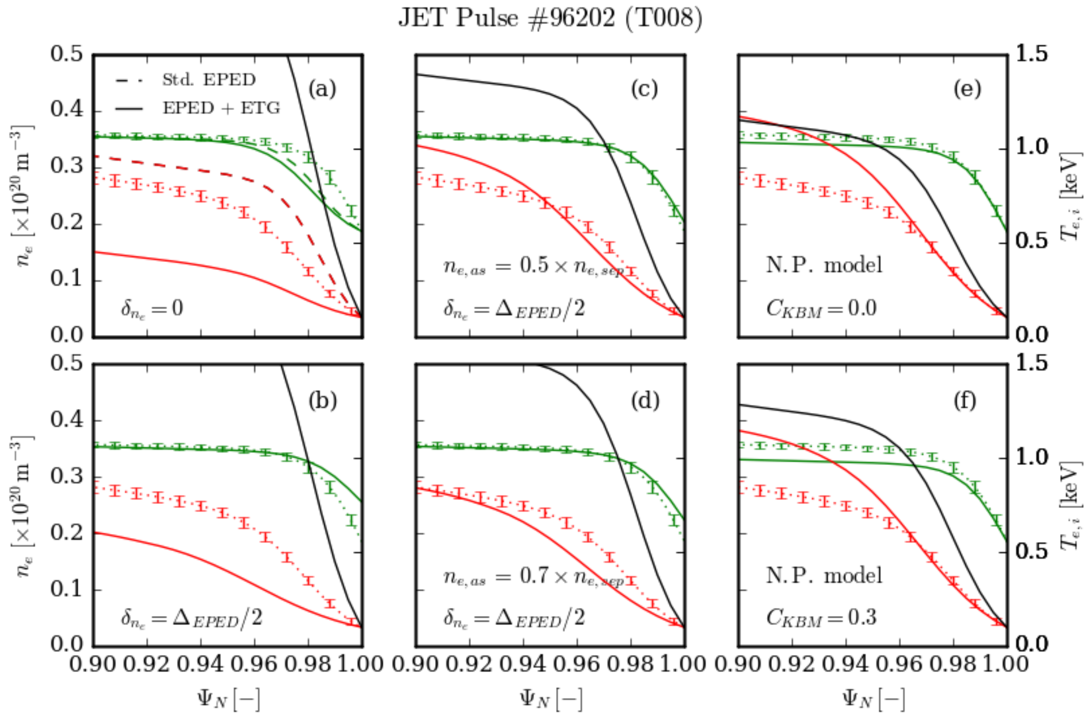

Figure 5: *Pedestal profiles for D pulse #96202 at the low fuelling rate of* $\Gamma_{gas} \sim 0.74 \times 10^{22}$ e/s *showing* n_e *(green),* T_e *(red) and* T_i *(black) vs' normalised poloidal flux* ψ_N *from various EPED based models, where the experimental profile fits are shown with error bars: calculated using (a) standard EPED (dashed) and standard EPED with* T_e *from the ETG model (solid); (b, c & d) EPED with* n_e *profile shifted outwards by* $\delta_{ne} = \Delta_p/2$ *with* T_e *from the ETG model; (c) with* n_e *asymptotic to* $0.5 \times n_{e,sep}$ *outside separatrix; (d) with* n_e *asymptotic to* $0.7 \times n_{e,sep}$ *outside separatrix; (e, f) with* n_e *from the neutral-penetration model [?],* T_e *from the ETG model and* T_i *for consistency with the EPED prediction of* p_{tot}*; (e) with coefficient* $C_{KBM} = 0$ *and (d) with* $C_{KBM} = 0.3$.

For the first case (a) following the standard EPED, the n_e profile position is at $\Delta_{n_e}/2$ inside the separatrix and the profile asymptotes to the experimental $n_{e,sep}$ outside the separatrix. This results in too low a predicted T_e from the ETG model, which is has to be compensated by too high values of T_i required to match the predicted p_{tot} from EPED. Note that for the pulses in the dataset discussed here, the experimental values of $T_i \sim T_e$ in the pedestal region, although relatively large uncertainties preclude a detailed comparison with our predictions.

For the other cases (b-c), the n_e profiles are shifted outwards by $\Delta_{n_e}/2$ from the standard EFIT case (a), i.e. the centre position is located at the separatrix. In case (b), this shift increases the ratio $n_{e,sep}/n_{e,ped}$, resulting in similarly too low values of T_e and too high values of T_i, as for case (a). In case (c & d), the asymptotic value of n_e outside the separatrix is reduced to $0.5 \times n_{e,sep}$ and $0.7 \times n_{e,sep}$, respectively. For the lowest resulting ratio $n_{e,sep}/n_{e,ped}$ of case (c), the predicted T_e profile is the closest to the experimental profile and the predicted T_i profile closest to T_e, although still considerably higher.

Results from applying model M2 to the full isotope mass scan dataset are shown in Figs. 6-8, which compare the calculated $T_{e,ped}$, $n_{e,ped}$ and Δ_p from the standard EPED and from the various combined models with the experimental values, respectively. The most

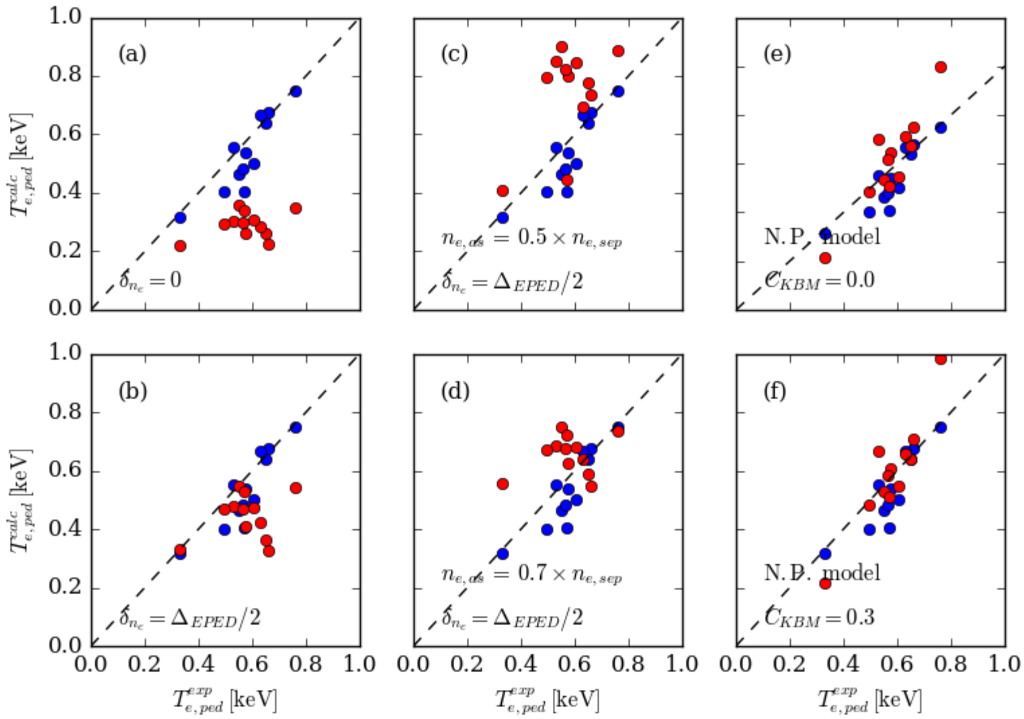

Figure 6: *Predicted values of the pedestal electron temperature $T^{calc}_{e,ped}$ vs' experimental values $T^{exp}_{e,ped}$, with $T^{calc}_{e,ped}$ calculated using the standard EPED (•) model and from each of the various EPED based pedestal models (•) corresponding to the same model cases as in Fig. 5 (a-f) above, each for all of the* 2.0 MA *pulses from the isotope mass and fuelling rate scans in Table A1.*

accurate predictions of $T_{e,ped}$ are for case (d). However, for this case, the predicted pedestal widths Δ_p are wider than the experimental values. For these pulses, the standard EPED predicts quite constant values of Δ_p, which are mostly narrower than the experimental widths. Note that the values of $n_{e,ped}$ shown in Fig. 7 (a-d) from model M2, which takes $n_{e,ped}$ as an input, differ slightly from the experimental values because the former are obtained from a fit to the analytic model profile rather than from a fit to the experimental data.

M3) Results from applying model M3, which combines the density pedestal prediction model of Ref. [49], the ETG critical heat flux model and the EPED KBM constraint, to profiles from pulse #96202 are shown in plots (e,f) of Fig. 5 and to the full dataset of pulses in Table A1 in plots (e,f) of Figs. 6-8.

The difference between the two cases is the value of the KBM coefficient C_{KBM}, which is set to 0 and 0.3 for plots (e) and (f) respectively. This coefficient is a multiplier on the contribution to the particle diffusivity from KBM modes ($D_{KBM} = C_{KBM}(\alpha - \alpha_{cr}), \alpha > \alpha_{cr}$). Hence, for $C_{KBM} > 0$, KBM modes can contribute to particle transport if $\alpha > \alpha_{cr}$ but not if $C_{KBM} = 0$. The similarity between the results shown for these two cases show that KBM modes are not predicted to contribute significantly to particle transport across the pedestal for these cases.

The overall agreement between the predicted pedestal T_e profiles from model M3 and the experimental profiles is the best of those from the three combined models, with a slight

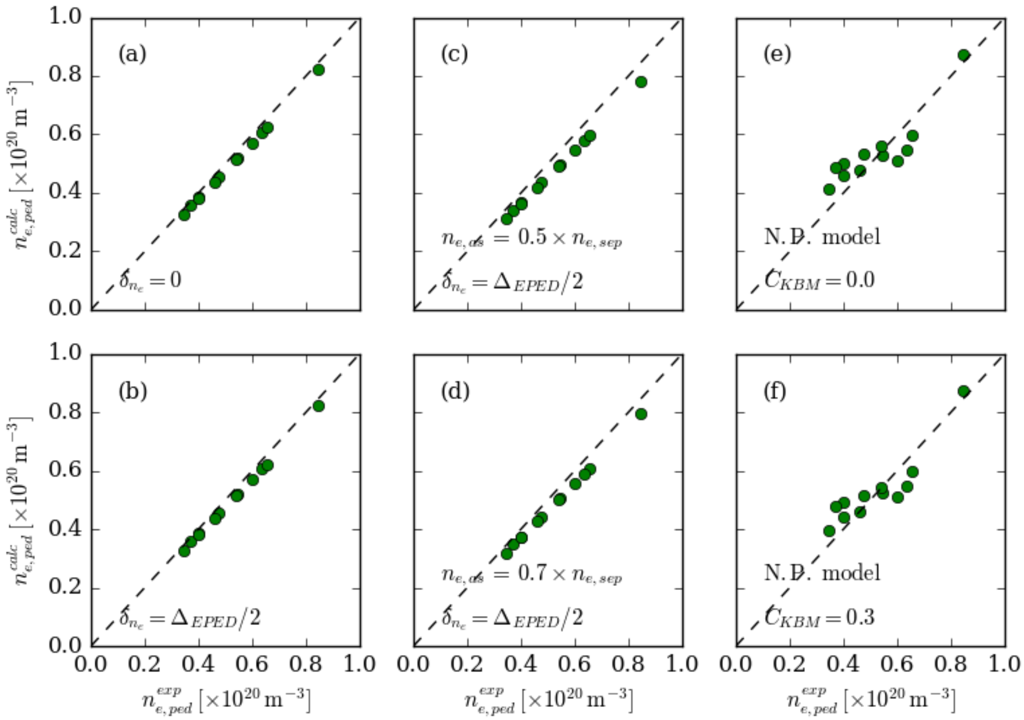

Figure 7: *Predicted values of the pedestal density $n^{calc}_{e,ped}$ vs' experimental values $n^{exp}_{e,ped}$ from each of the various EPED based pedestal models (•) corresponding to the same model cases as in Fig. 5 (a-f) above, each for all of the* 2.0 MA *pulses from the isotope mass and fuelling rate scans in Table A1.*

improvement over the standard EPED predictions. Both the predicted $n_{e,ped}$ and $T_{e,ped}$ generally agree well (within $\sim \pm\%10$) with the experimental values. Although both the predicted $n_{e,ped}$ and $T_{e,ped}$ increase with the experimental values, the predicted values of $T_{e,ped}$ tend to increase faster than linearly, while the predicted $n_{e,ped}$, increase more slowly. The predicted pedestal widths Δ_p are of approximately the correct magnitude, however, these exhibit an opposite trend to the experimental values, i.e. smaller widths are predicted for wider experimental pedestals.

7. Conclusions

The fact that the model described in §2 for the pedestal electron temperature profile is able to predict the electron temperature at the top of the density pedestal $T_e(\psi_N^{n_{e,top}})$ with reasonable veracity across these scans of effective isotope mass A_{eff} and gas fuelling rate, supports the underlying assumption of the model that the electron heat transport across this region of the pedestal is dominated by turbulent heat transport due to ETG modes. The slab-ETG turbulence prevailing in a regime with a strong density gradient exhibits a critical threshold in the parameter η_e, rather than of R/L_{n_e}, which results in the T_e profile being intimately related to the n_e profile.

Currently, the model is based on the simple scaling of the gyro-Bohm normalised electron heat flux of Eq. (1) with η_e alone. As the electron gyro-Bohm normalisation depends only on the local T_e gradient scale length L_{T_e}, the magnetic field B and the electron mass m_e,

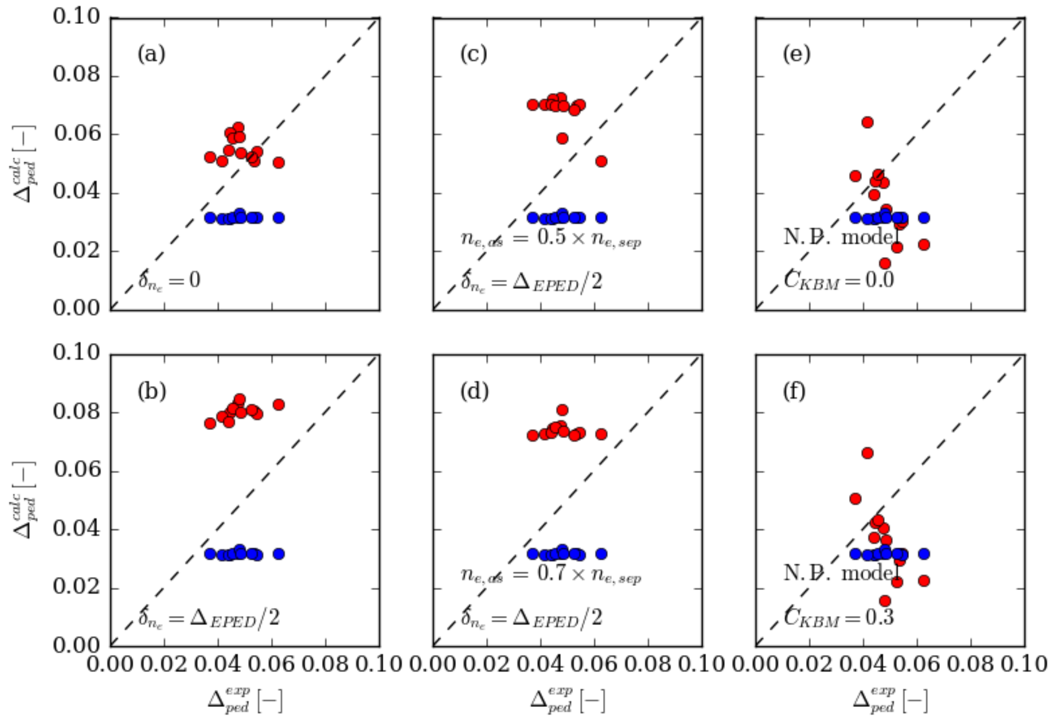

Figure 8: *Predicted values of the pedestal width Δ_p^{calc} vs' experimental values Δ_p^{exp}, with Δ_p^{calc} calculated using the standard EPED (•) model and from each of the various EPED based pedestal models (•) corresponding to the same model cases as in Fig. 5 (a-f) above, each for all of the* 2.0 MA *pulses from the isotope mass and fuelling rate scans in Table A1.*

this scaling is independent of the ion mass and hence exhibits no dependence on A_{eff}. The agreement of the predicted T_e at the top of the density pedestal $T_e(\psi_N^{n_{e,top}})$ across the effective isotopic mass A_{eff} scan data set results purely as a consequence of the electron heat transport responding to changes to the density profile occurring with the change in A_{eff}, which can affect the relative level of electron particle compared to heat transport, e.g. as has been found in the recent study by Predebon *et al* of Ref. [41].

As can be seen e.g. from Fig. 1 (d), the adopted electron heat flux scaling tends to over/under predict R/L_{T_e} outside/inside the mid-pedestal location for which the scaling was derived. Although these effects largely compensate, resulting in a reasonable prediction of $T_e(\psi_N^{n_{e,top}})$, this indicates that this scaling is probably over simplified. It is likely that other parameters are also relevant in controlling the electron heat transport, e.g. the magnetic shear $\hat{s}$, which increases strongly towards the separatrix.

The value of $T_{e,ped}$, which is determined from the mtanh() fit to the T_e profile, is always higher than that at the density pedestal top $T_e(\psi_N^{n_{e,top}})$, which in turn is a consequence of the inward shift of the pedestal T_e profile with respect to the n_e profile. This shift is actually a consequence of the underlying turbulent electron heat transport requiring that η_e exceed a value $\mathcal{O}(1)$ to be able to carry the imposed heat flux q_e across the pedestal. Note that for $\eta_e = 1$, the profiles of R/L_{T_e} and R/L_{n_e} are identical and there is no relative shift between the T_e and n_e profiles, while for $\eta_e > 1$ the resulting T_e profile is shifted inwards with respect to the n_e profile and vice versa.

The higher values of $T_{e,ped}$ than $T_e(\psi_N^{n_{e,top}})$ are a consequence of T_e continuing to increase across the weak density gradient region inside the density pedestal top. In this region, the assumed heat flux scaling of *Eq.* (1) is invalid, resulting in an under prediction of R/L_{T_e}, i.e. an over prediction of the resulting electron heat flux. The findings of several of the pedestal GK studies discussed in §5 that other modes than slab-ETG modes are dominant in this region, implies that the electron heat transport is unlikely to be governed by η_e. This hypothesis is consistent with the expression proposed by Jenko et al. [26] for the critical threshold for ETG turbulence, which implies that $R/L_{T_e,cr}$ is independent of R/L_{n_e} when the density gradient is weak.

The critical role of the pedestal density profile in largely determining the electron temperature profile, means that in order to be able to predict $T_{e,ped}$, any stand-alone model for the T_e profile must provide also include a model for the density profile. A recent model for the pedestal density profile is presented in Ref. [49], which is a refinement of the ionisation/diffusion model of Groebner et al. [50], extended to include a self-consistent population of charge-exchange neutral atoms. This model has been tested against the EUROFusion Pedestal Database [28] and is found, in particular, to be able to reproduce the observed increase in $n_{e,ped}$ with isotope mass A_{eff}. This arises primarily from the strong sensitivity of the predicted $n_{e,ped}$ to the assumed value of $n_{e,sep}$, which is an input to the model, the former increasing with the latter. However, to reproduce the observations, it is also necessary to adjust the assumed ratio of electron particle diffusivity to electron heat conductivity (D_e/χ_e), by decreasing this ratio with increasing A_{eff} (from 1 in H to 0.5 in D and 0.25 in T) [49], broadly consistent with the trends found in the study by Predebon *et al* of Ref. [41].

Hence, the boundary conditions at the separatrix, $T_{e,sep}$ and in particular $n_{e,sep}$, are critical for determining both the electron density and temperature profiles across the pedestal, which are determined by heat and particle transport in the SOL, rather than details of transport processes within the confined plasma. The main control parameters determining $T_{e,sep}$ and $n_{e,sep}$ are the heat and particle fluxes into the SOL, although these also depend on the geometry of the SOL, i.e. the plasma shape and on the divertor configuration. Hence, as is well appreciated by machine operators, the plasma heating and fuelling are the principle means for influencing the pedestal parameters.

Three different numerical pedestal models, combining EPED with the ETG heat flux model of Ref. [19] discussed here, have been tested against the isotope and fuelling rate scan dataset discussed here. The first two models take $n_{e,ped}$ as an input, while the third combines EPED, the ETG heat flux model and the density prediction model of Ref. [49]. The first model, which does not use the EPED KBM constraint, fails on many cases due to the strong dependence of the predicted $T_{e,ped}$ from the ETG model on $n_{e,sep}/n_{e,ped}$. The second model, which uses the KBM constraint ($p_{tot} \propto \Delta_p^2$), provides predictions of both the T_e profile from the ETG model and the T_i profile by matching the total pressure p_{tot}. The third model, which provides a full prediction of the pedestal profiles, exhibits a reasonable agreement between the model predictions and experiment, implying that this model encapsulates the main physics underlying the pedestal structure.

It is illuminating to determine the scaling of $n_{e,sep}$ with the power crossing the separatrix in the electron channel $P_{e,sep}$ and the electron particle fuelling rate into the SOL Γ_e for the admittedly grossly over simplified case of a a collisionless SOL, which is sheath-limited at the divertor target. This can be derived from a simple two-point model [32] as described in §Appendix B, which predicts that $n_{e,sep}$ should increase with isotope mass $\propto A_{eff}^{1/2}$ and also with the particle fuelling rate into the SOL $\propto \Gamma_e^{3/2}$ and decrease with the loss power across the separatrix $\propto P_{sep}^{-1/2}$. Note that an extension of this 2-point model to incorporate the temperature dependence of the parallel electron heat conductivity $\kappa_{\|} \propto T_e^{5/2}$ predicts a very weak power scaling for $T_{e,sep} \propto P_{sep}^{2/7}$. Hence, the influence of the loss power on the pedestal due to changes to the separatrix boundary conditions is stronger through its effect on $n_{e,sep}$ than through its effect on $T_{e,sep}$. Note that modelling of JET-ILW plasmas with neon impurity seeding described in Ref. [33] demonstrated agreement between the scaling $T_{e,sep} \propto P_{sep}^{2/7}$ with the results of simulations using the EDGE2D-EIRENE code [51], provided the dependence of λ_q on the density and radiation in the SOL was taken into account.

This over-simplified scaling would predict an increase in $n_{e,sep}$ by a factor ~ 1.2 changing isotope alone from D to T, which is less than the observed increase of a factor ~ 1.6 at constant Γ_{gas} as shown in Fig. 2 (b). However, this toy model does illustrate how SOL physics can influence the boundary conditions at the separatrix and hence indirectly govern the pedestal structure. Of course, realistic simulations require much more complex 2D models, such as the coupled fluid and Monte-Carlo neutrals simulation code EDGE2D-EIRENE [51], to account for the complex processes occurring in a high-density, recycling SOL and particularly with a detached divertor where impurity and molecular radiation and charge-exchange heat and momentum losses play a dominant role.

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Appendix A.

Pulse	**PPF**	$t_0 - t_1$	A_{eff}	Γ_{gas}	P_{abs}	P_{Rad}^{iELM}	$\langle P_{ELM} \rangle$	P_{sep}^{iELM}	f_{ELM}
#	#	[s]	[-]	[10^{22} e/s]	[MW]	[MW]	[MW]	[MW]	[Hz]
96201	T008	51.4-52.1	2.0	2.7	18.2	2.6	**9.1**	**6.5**	**72**
96202	T008	52.4-54.1	2.0	0.73	14.2	3.7	4.5	5.0	39
96208	T058	51.6-52.8	2.0	1.7	17.3	2.8	**6.9**	**7.6**	**83**
99480	T003	48.0-49.4	2.6	1.8	15.7	2.5	6.2	6.9	54
99490a	T005	48.3-49.7	2.7	1.6	15.6	6.2	2.7	6.7	27
99490b	T007	50.1-51.3	2.6	1.6	14.8	4.2	4.7	5.9	54
99491a	T003	48.3-49.4	2.4	1.5	16.3	5.2	4.2	6.9	40
99491b	T005	50.1-51.8	2.5	1.5	14.9	3.6	**6.5**	**4.8**	**72**
100247a	T003	47.8-49.1	3.0	1.7	12.6	4.8	1.9	5.8	18
100247b	T004	49.7-50.9	3.0	1.8	12.7	5.9	1.5	5.4	32
100183	T003	48.4-49.5	3.0	3.0	12.4	7.0	0.5	4.9	7.5
100185	T004	47.6-48.0	3.0	1.1	11.5	2.9	3.7	4.9	43

Table A1: *Parameters of the* 2.0 MA *JET-ILW H-mode pulses and the corresponding fitted pedestal profile data files (PPFs): pulse number, PPF number, averaging time period $t_0 - t_1$, effective isotope mass A_{eff}, gas fuelling rate Γ_{gas}, absorbed heating power P_{abs}, radiated power from confined plasma P_{Rad}^{iELM}, time-averaged ELM loss power $\langle P_{ELM} \rangle$, averaged conducted power across the pedestal between ELMs P_{sep}^{iELM} and average ELM frequency f_{ELM}. Note that for some pulses the multiple PPFs correspond to different time periods during the pulse.*

Appendix B.

For a collisionless, isothermal SOL, assuming that $T_i = T_e$, we have for the temperature $T_u = T_t$ and density $n_u = 2n_t$, where the subscripts u and t denote upstream (mid-plane) and target values respectively [32]. Also assuming a constant SOL power decay length λ_q implies that the parallel electron heat flux in the SOL is proportional to the loss power across the separatrix $q_\parallel \propto P_{sep}/S\lambda_q$, where S is the area of the LCFS.

Expressions for the particle and heat fluxes at the target are then: $\Gamma = \frac{1}{2} n_t c_s \propto n_t T_t^{1/2}/A^{1/2}$ and $q = \gamma T_t \Gamma \propto n_t T_t^{3/2}/A^{1/2}$, where c_s is the sound speed and $\gamma \sim 5/2$ is the sheath transmission factor. By elimination of n_t from these two expressions, we have $T_t \propto q/\Gamma$, which can be substituted into the expression for Γ to yield the following scaling for the upstream density $n_u \propto \Gamma^{3/2} A^{1/2}/q^{1/2}$.

Hence, even this simple-as-possible model predicts that $n_u \equiv n_{e,sep}$ should increase with isotope mass $\propto A_{eff}^{1/2}$ and also with the particle fuelling rate into the SOL $\propto \Gamma_e^{3/2}$ and decrease with the loss power across the separatrix $\propto P_{sep}^{-1/2}$.