

Composition of electron temperature gradient driven plasma turbulence in JET-ILW tokamak plasmas

B. Chapman-Oplopoiou¹,¹ J. Walker,² D. R. Hatch,³ T. Görler,⁴ and JET contributors⁵

¹UKAEA, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom

²University of Wisconsin-Madison, Madison, Wisconsin 53706, USA

³Institute for Fusion Studies, University of Texas at Austin, Austin, Texas 78712, USA

⁴Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

⁵See the author list of “Overview of T and D-T results in JET with ITER-like wall” by CF Maggi et al. to be published in Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, United Kingdom, 16-21 October 2023)



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This letter reports on new fundamental insights into small scale plasma turbulence that is responsible for confinement degradation on the JET tokamak. We compare the structure of electron temperature gradient (ETG) driven turbulence in the edge region of two JET ITER-like-wall (ILW) high-confinement-mode discharges operating at different levels of gas fuelling. By artificially removing the toroidal drifts from our gyrokinetic turbulence simulations, we demonstrate that the high gas pulse has a substantial component from the toroidal branch of ETG turbulence whilst the low gas pulse is completely driven by slab ETG turbulence. This enables us to explicitly answer *why* increased gas puffing on JET-ILW leads to confinement degradation.

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Introduction. The JET tokamak stands at the forefront of fusion science in several areas. First, *Size*—as one of the two largest tokamaks to have ever operated (the other being the recently commissioned JT60-SA) it closely approximates ITER parameter regimes in terms of size and the closely related dimensionless parameter, $\rho_* = \rho/a$, where ρ is the gyro radius and a is the minor radius. Second, *Fuel*—JET is the only experiment currently harnessing the reactor fuel, tritium. Third, *Plasma facing components (PFCs)*—for the last several years, JET has operated with an ITER-like wall (ILW) which consists of a tungsten divertor and beryllium wall [1]. This makes JET-ILW the *only* magnetic fusion device to have operated with both Tritium and a metal wall. JET’s *size* and *fuel*, among other things, enabled the recent demonstration of record fusion power production [2]. However, this achievement was only possible after several years of optimization to overcome the degraded confinement caused by the *PFCs*, manifest as a severe anomalous limitation on the edge temperature. Given its capabilities, JET therefore presents an entirely unique opportunity to examine the fundamental nature of plasma turbulent transport. This letter reports on new insights into the nature of the turbulent transport produced by the electron temperature gradient (ETG) instability and how this relates to confinement on JET-ILW. We demonstrate that one branch of the ETG instability—the slab branch—is manifest in scenarios representative of high performance pre-ILW operation. We show that a separate branch—the toroidal branch—additionally arises under

conditions engendered by the ILW and is responsible for the strong limitation on the edge temperature. This elucidates an important mechanism by which confinement may be degraded in reactor scenarios and informs strategies to enable high confinement in future burning plasma experiments like ITER.

Crucial for increasing thermal confinement and therefore the efficiency of operation of future tokamak fusion reactors is the edge transport barrier [3], in which cross field turbulent transport is strongly suppressed. The formation of this transport barrier, known as the pedestal, is thought to be due to the suppression of turbulence due to increased equilibrium flow shear [3]. Despite the formation of the pedestal and transition to high confinement mode (H mode), heat and particle transport through the pedestal cannot be explained solely by neoclassical transport. The presence of steep equilibrium gradients in the pedestal provides a large source of free energy and a mechanism for the growth of microinstabilities such as the aforementioned ETG modes, ion temperature gradient modes, trapped electron modes, micro tearing modes, and kinetic ballooning modes, which manifest as turbulence in their nonlinear saturated state [4].

In particular, there have been extensive efforts recently to develop our understanding of ETG turbulence in the pedestal, largely motivated by the transition of JET from a carbon wall to an ITER-like-wall. In JET-ILW, increased molecular deuterium (D_2) gas puffing is needed to prevent tungsten contamination in the core. This drastically degrades the pedestal top temperature $T_{e,ped}$, a key measure of plasma performance, meaning increased input power is therefore needed to sustain robust temperature pedestals. Such a reduction in pedestal temperature is thought to be due to an increase in ETG driven turbulent heat transport associated with the increased gas puffing.

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The work described in Ref. [5] provided evidence of ETG turbulence in JET-ILW pedestals, finding that it was required to explain the experimental heat flux. This turbulence was noted to be slablike and isotropic, in contrast with the streamer dominated core ETG turbulence. A targeted investigation of the effects of power and gas on ETG turbulence was subsequently carried out by ourselves and others [6], and pedestal ETG turbulent heat flux scalings were found and were in agreement with similar pedestal ETG scalings in the DIII-D tokamak [7].

Pedestal ETG turbulence. We now demonstrate how the nature of pedestal ETG turbulence in JET-ILW responds to changes in the gas rate by revisiting and extending the analysis carried out in Ref. [6] and focusing more on the fundamental aspects of the turbulence. In this work, the GENE gyrokinetic code [8,9] was applied to a deuterium JET-ILW experimental data set [10] comprising four type I ELMy H-mode discharges from scans in the neutral-beam-injected (NBI) power (P_{NBI}) at two levels of D_2 gas fueling rate ϕ_e . All pulses have a low triangularity plasma shape, plasma current $I_p = 1.4$ MA, toroidal magnetic field $B_T = 1.7$ T, and have been well characterized experimentally [10–12]. Presently, we consider only the two “high power” ($P_{NBI} \simeq 15$ MW) pulses of the four described in Ref. [6], one of which has a “low” gas rate of $\phi_e \simeq 2.7 \times 10^{21} \text{ es}^{-1}$ and the other with a “high” gas rate of $\simeq 18.0 \times 10^{21} \text{ es}^{-1}$. Henceforth we refer to these pulses as LG and HG, respectively, consistent with the nomenclature in Ref. [6]. We use GENE in its local flux-tube mode of operation, which is appropriate for studying ETG turbulence which has length scales much smaller than the width of the pedestal.

The density n_e and electron temperature T_e profiles as a function of flux surface (radial) coordinate ρ_t for these two pulses, along with the corresponding normalized temperature ($\omega_{T_e} = \nabla T_e / T_e$) and density ($\omega_{n_e} = \nabla n_e / n_e$) gradients and $\eta_e = \omega_{T_e} / \omega_{n_e}$ are plotted in Fig. 1. All simulations are local, fully electromagnetic, collisional, and include full toroidal effects unless stated. The numerical equilibria are calculated self-consistently with the pre-ELM Thompson scattering profiles shown in Fig. 1 using the HELENA code [13]. We assume $T_i = T_e$ throughout, neglect the effect of impurities (relaxing both these assumptions would result in a minor quantitative but not qualitative change to some of our results [6]), and use a small level of equilibrium flow shear ($\gamma_{E \times B} \approx -0.67$ for all simulations) consistently, which has been estimated from a neoclassical formula [14] by setting the parallel flow $V_{||}$ to zero. Some important simulation parameters are shown in Table I. All the quantities in Table I were subject to extensive resolution tests and convergence was found to be satisfactory with these values. We refer the reader to our previous manuscript [6] for a detailed discussion of our simulation inputs. All nonlinear simulations are run until all flux quantities are completely saturated and capture multiple linear growth times of the modes that we resolve.

In Fig. 2 we reproduce the ETG heat flux scalings for these two pulses which we found previously [6] and we briefly recount our findings here. Figure 2 plots the Gyro-Bohm heat flux normalized to the temperature gradient scale length in the pedestal as a function of η_e . Here η_e is varied in two ways for both the low gas pulse and the high gas pulses: it is increased via increases in ω_{T_e} and decreases in ω_{n_e} around the

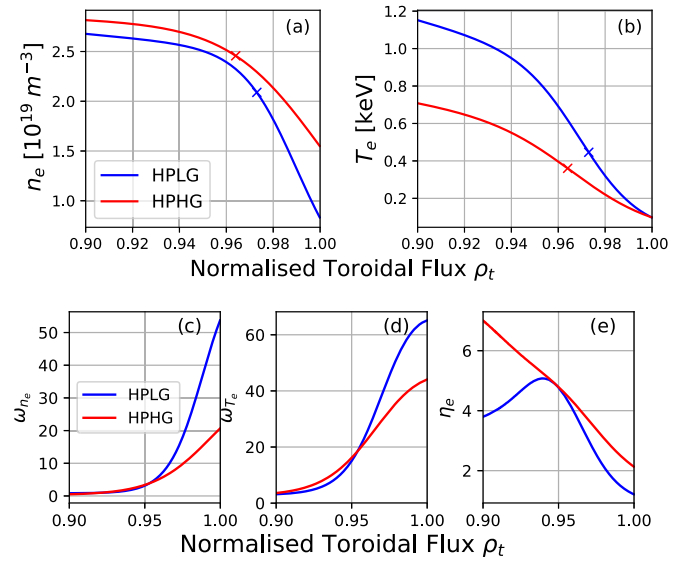


FIG. 1. Thomson scattering n_e (a) and T_e (b) “high power” profiles used in the GENE simulations throughout. Blue (red) lines denote low (high) gas pulses. Crosses denote the locations of flux surfaces on which the simulations reported were performed. (c) Normalized density gradient ω_{n_e} , (d) Normalized temperature gradient ω_{T_e} , and (e) $\eta_e = \omega_{T_e} / \omega_{n_e}$ profiles.

nominal point denoted by the black stars. We observe that both pulses display similar trends in the heat flux and are in good agreement with the DIII-D pedestal results [7] shown in the green line (extrapolated). These results reinforce the following paradigm with regards to the impact of ETG turbulence in JET-ILW:

“Gas puffing flattens the density profile $\rightarrow$ reduces $\omega_{n_e} = a/L_{n_e} \rightarrow$ increases $\eta_e = L_{n_e}/L_{T_e} \rightarrow$ more (slab-)ETG turbulence $\rightarrow$ higher power needed to sustain temperature pedestal”.

However, Fig. 2 shows that (i) The HG pulse turbulent heat transport is more responsive to changes in the driving gradients (it is more “stiff”, larger rate of change of the heat flux with the driving parameter η_e , $dQ_e/d\eta_e$) than the LG pulse. (ii) While the heat flux variation with η_e in the LG pulse is the same regardless of the manner in which η_e is varied, the HG pulse displays different heat flux dependencies depending on whether η_e is varied via ω_{T_e} or ω_{n_e} . This prompts the question: *Is the ETG turbulence of a different nature in these two pulses?*

To answer this, we now repeat some of the scan points in Fig. 2 but without the toroidal drifts in the simulation such

TABLE I. Selected parameters for the simulations presented throughout. Other simulation parameters can be found in Ref. [6].

	HPLG	HPHG
$k_{x,\min} \rho_s$	~ 1.4	~ 1.3
$k_{x,\max} \rho_s$	~ 92	~ 70
$k_{y,\min} \rho_s$	5.0	2.5
$k_{y,\max} \rho_s$	407.5	317.5
n_z	480	240

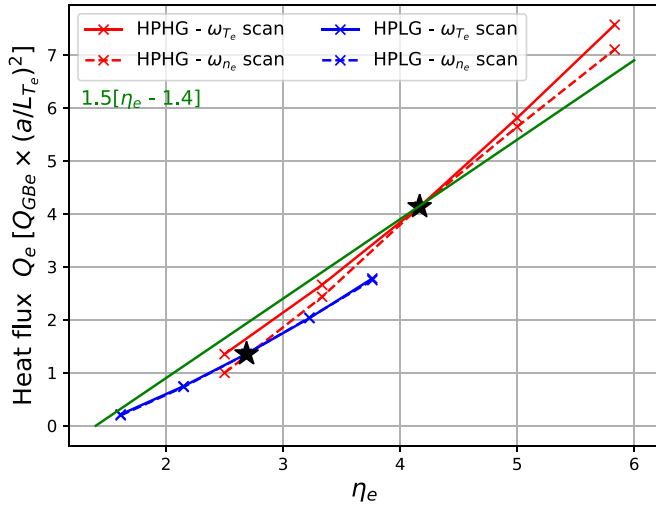


FIG. 2. Reproduction of Fig. 13 of Ref. [6] Copyright 2022 UKAEA. CC BY 3.0. Normalized ETG heat flux as a function of η_e . Red and blue traces correspond to data from the HG and LG pulses, respectively, and black stars denote the operational points. The solid green line shows the trend $Q_e/Q_{GBE} = 1.5[\eta_e - 1.4]$, details of which can be found in Ref. [7]. We point out to the reader that there are two blue HPLG traces, solid ω_{Te} scan and dashed ω_{ne} scan, that perfectly overlay each other. This is due to the exclusively slab nature of the turbulence which we discuss below.

that only slab modes are present. This is done for both the ω_{ne} and ω_{Te} scans in both the high gas and low gas pulses and the results are shown with diamond shaped markers in Fig. 3. Considering the low gas simulations first (blue traces), we see that removing the toroidal drifts has had no effect on the heat flux scaling. We assure the reader that there are four

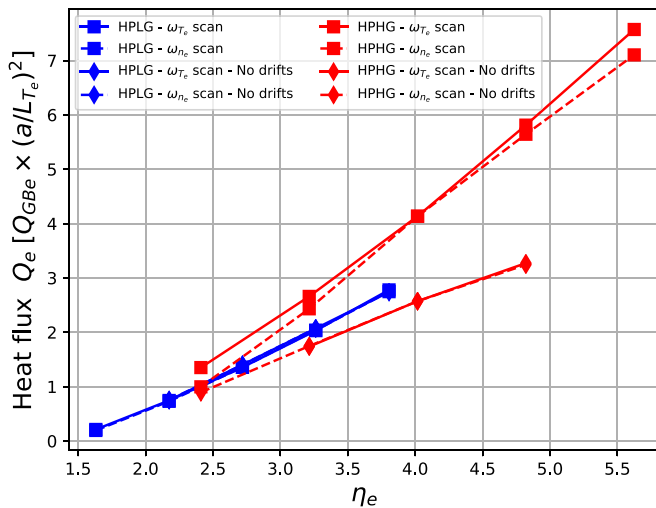


FIG. 3. Data from Fig. 2 showing ω_{Te} scans (solid) and ω_{ne} scans (dashed) is replicated (squares). Additionally, for each pulse there are data with (squares) and without (diamonds) the magnetic drift terms in the gyrokinetic equation. Note the four LG data sets obscure each other and appear as one solid line. This is due to the turbulence being driven by slab-ETGs only, and is discussed further in the main text. The HG solid ω_{Te} scan and dashed ω_{ne} scan traces from simulations without drifts also obscure each other for the same reason.

blue traces in Fig. 3 which all obscure each other due to the similarity in the heat flux scaling. This further demonstrates that the heat flux scaling for these low gas pulses is almost entirely due to slab-ETG modes. The results of this exercise for the high gas pulse are more complex and are shown in the red traces of Fig. 3. Firstly, without the toroidal drifts the nominal heat flux decreases substantially to $\sim 65\%$ of its initial value. Secondly, without toroidal drifts there is no difference in the heat flux scalings of the ω_{Te} and ω_{ne} scans (the dashed and solid lines with diamond markers lie on top of one another). This is expected as removing the toroidal drifts leads to purely slab modes driven by η_e alone; as is the case in the low gas (blue) scans regardless of the toroidal drift terms. The resulting HG-No-drifts scaling is much closer to that of the low gas simulations, the remaining small differences could be due to slightly different equilibrium parameters as well as minor differences in the simulation resolutions. Finally, we see that at the lowest value of η_e in the high gas scan, corresponding to the highest value of ω_{ne} , the simulations with and without drifts agree with each other, and lie on top of the low gas heat flux scaling. This is because this scan point is at a high enough value of ω_{ne} such that the turbulence is predominantly slablike. These results demonstrate that the turbulence in the HG pulse is of a different nature to that of the LG pulse, this can be explained in terms of the different driving frequencies. For ETG turbulence, there are three relevant frequencies: (i) The diamagnetic frequency: $\omega_{*e} = k_y \rho_s c_s (\frac{1}{L_{ne}} + \frac{1}{L_{Te}})$, (ii) the drift frequency due to toroidal and curvature effects: $\omega_d = \mathbf{k}_\perp \cdot \mathbf{V}_d$, and (iii) the parallel drift frequency: $\omega_\parallel = k_\parallel v_\parallel$. For the slab resonance to dominate, we require $\omega_{*e} \sim \omega_\parallel \gg \omega_d$, which is usually well satisfied in steep gradient region. In JET-ILW, as fueling is increased to counteract the detrimental effect of Tungsten accumulation, $1/L_{ne}$ reduces in the steep temperature gradient region and ω_{*e} decreases. This results in the toroidal resonance $\omega_{*e} \sim \omega_d$ becoming more accessible. In JET-C, the values of $1/L_{ne}$ in the steep temperature gradient region are, generally larger, much like the LG pulse, meaning the slab resonance dominates.

To gain a better understanding of the differences in the turbulence between these two pulses, we perform proper-orthogonal-decomposition (POD) analysis [15–18] on the nonlinear simulations that comprise Fig. 2. POD analysis is a means of decomposing data into a set of constituent modes, ordered by their “variational-content”, or “energy.” This is particularly useful when dealing with a nonlinear, turbulent system that cannot be described by a few linear eigenmodes. Here, we perform POD analysis on the electrostatic potential ϕ , the parallel temperature $T_\parallel$, the perpendicular temperature $T_\perp$, and the density. We then use this decomposition to calculate the contribution of each POD mode to the heat flux. In Fig. 4 we examine the heat flux POD spectrum for the nominal HG simulation at $k_y \rho_s = 30$, which is near the peak in the k_y flux spectrum. The red trace plots the heat flux for each POD mode, while the blue trace plots the average parallel wave number estimated from the weighted derivative of the electric potential of the POD mode $\Phi(t, z)$ as

$$\langle k_z \rangle \equiv \left[\frac{\int dt \int dz J(z) \|\nabla_\parallel \Phi(t, z)\|^2}{\int dt \int dz J(z) \|\Phi(t, z)\|^2} \right]^{1/2}, \quad (1)$$

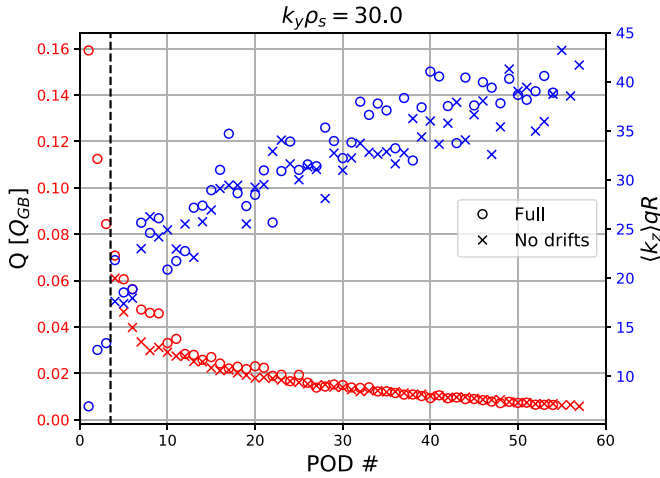


FIG. 4. Heat flux (red) and normalized average parallel wave number (blue) as a function of POD number evaluated at $k_y \rho_s = 30$ for the nominal HG simulation both with (circles, “Full”) and without (crosses, “No drifts”) the magnetic drift terms in the gyrokinetic equation. We have made the ansatz, which we subsequently justify in the main text, that the “No drifts” data set approximately corresponds to all but the first three of the “Full” POD modes. We have shifted the “No drifts” dataset by +3 on the x axis to highlight this.

where $J(z)$ is the Jacobian associated with the magnetic coordinates. We do this for both the “Full” simulation with all physical effects, and the “No drift” simulation in which the toroidal drifts have been artificially suppressed. The first three “Full” POD modes (circle markers) are clustered at $\langle k_z \rangle qR \lesssim 15$ and are predominately toroidal in nature. Evidence of which can be seen in the upper panels of Fig. 5 in which we plot the electrostatic potential structure along the field line of the first and fourth “Full” POD modes, respectively. The first three POD modes (only the first is shown) do not have much parallel structure and look ballooning in nature, as is the case with predominantly toroidally driven modes.

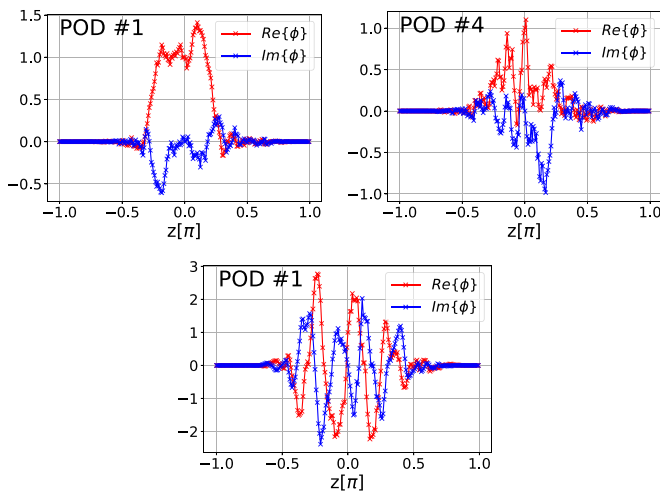


FIG. 5. Upper: Electric potential structure along the field line of the first (left) and fourth (right) “Full” HG POD modes at $k_y \rho_s = 30.0$ shown in Fig. 4. Lower: Electric potential structure along the field line of the first “No drift” HG POD mode at $k_y \rho_s = 30.0$.

The fourth POD mode has more parallel structure (a higher $\langle k_z \rangle$), which is associated with modes that are predominantly slablike. We make the ansatz that the “No drift” data will approximately correspond to all but the first three POD modes of the “Full” case, and shift the “No drifts” data by +3 POD modes along the x axis. Note, we have not removed the first three POD modes from the “No drifts” system, we are simply shifting all “No drift” POD modes by three places along the axis. Upon doing so the two data sets overlap remarkably, the only notable difference between them being the first three “Full” POD modes to the left of the vertical dashed black line. Indeed, the structure of the first POD mode of the “No drift” case shown in lower panel of Fig. 5 is clearly slablike, and is not dissimilar to the structure of the fourth “Full” POD mode shown in the upper panel of Fig. 5. Thus, in this simulation, at $k_y \rho_s = 30$, the primary consequence of switching off the toroidal drifts is to remove the first three POD modes from the system, thereby removing a substantial proportion of the heat flux. Finally we note that at this value of $k_y \rho_s$, the first three POD modes account for $\sim 25\%$ of the heat flux. This is strikingly similar to the $\sim 35\%$ reduction in heat flux throughout the entire simulation (when summed over all $k_y \rho_s$), providing further evidence that these three POD modes are the primary contributors to the toroidally driven portion of the heat flux.

Conclusions. We have shed new light on the nature of ETG turbulence in JET-ILW pedestals by extending the work of Ref. [6] with further analysis and simulations which have enabled us, for the first time, to understand why the performance is reduced in JET-ILW pedestals compared to JET-C pedestals.

By artificially removing the toroidal drifts from the simulations we were able to examine the relative contribution of slab and toroidal ETG turbulence. We found that this had almost no impact on the low gas heat flux, which, combined with ω_{n_e} and ω_{T_e} scans displaying identical results, confirms that the turbulence in this pulse (at this flux-surface) is almost entirely due to slab-ETG modes. However, removing the toroidal drifts from the high gas pulse led to a significant reduction in the electron heat flux in both the ω_{n_e} and ω_{T_e} scans ($\sim 35\%$ at the nominal scan point). Additionally, without toroidal drifts the high gas ω_{n_e} and ω_{T_e} scans display the same heat flux scaling with η_e , which is similar to that of the low gas scans. This was subsequently elaborated upon using proper-orthogonal-decomposition (POD) analysis. We demonstrated that a variety of POD modes with different parallel structures contribute to the total heat flux, and the impact of structures with small parallel wave number is severely diminished when toroidal drifts are artificially removed.

Thus, the answer to our earlier query “Is the turbulence of a different nature in these two pulses?” is yes. At these flux surfaces, the low gas pulse is almost entirely slab-ETG dominated while the high gas pulse has important contributions from both toroidal and slab ETG turbulence. Knowing this enables us to reconcile the mismatch in the η_e scaling of the high gas and low gas pulses, and we are now in a position to revise our understanding of JET-ILW pedestal ETG turbulence from:

“Gas puffing flattens the density profile $\rightarrow$ reduces $\omega_{n_e} = a/L_{n_e} \rightarrow$ increases $\eta_e = L_{n_e}/L_{T_e} \rightarrow$ more (slab-)ETG turbulence $\rightarrow$ higher power needed to sustain temperature pedestal”.

to:

*“Gas puffing flattens the density profile $\rightarrow$ reduces $\omega_{ne} = a/L_{ne} \rightarrow$ **Addition of toroidal-ETG turbulence in the steep region of the pedestal alongside slab-ETG turbulence $\rightarrow$ higher power needed to sustain temperature pedestal**”.*

Armed with this knowledge, it may be possible to optimize future pedestal scenarios to ameliorate the detrimental impact of toroidal-ETG turbulence in the pedestal. For instance, optimization of the geometry (in particular aspect ratio and elongation), safety factor q , and magnetic shear $\hat{s}$, in the pedestal so as to increase the critical gradient for the onset of toroidal-ETG modes [8]. It may also be possible to optimize the level of equilibrium flow shear, the details of the ion temperature profile, and the impurity mixture, all of which are known to impact ETG transport levels. Such investigations are left to future work.

The preceding discussion has necessarily omitted the possibly important role that nonlinear interactions between toroidal and slab modes may play in setting the final turbulent transport levels, as well as the role of multiscale interactions between the low k_y (high k_x) toroidal ETG modes discussed in Ref. [19] and the high k_y ETG modes discussed here.

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Author contributions were as follows. B.C.-O.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, resources, visualization, writing (original draft). J.W.: investigation, methodology, software, resources, writing (review and editing). D.H.: investigation, methodology, writing (review and editing). T.G.: methodology, software, writing (review and editing). JET contributors (see Ref. [21] for full author list): resources.

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