LETTER

Multi-scale gyrokinetic simulation of tokamak plasmas: enhanced heat loss due to cross-scale coupling of plasma turbulence

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Measured ion and electron heat fluxes in fusion plasmas have been observed for decades to exceed predictions from collisional transport theory [2]. As a result, sophisticated nonlinear gyrokinetic [3] codes have been developed that capture the dynamics of plasma turbulence [4] and are now commonly used to interpret tokamak experiments. Given the success of the established turbulence theory [5] it is now accepted that the observed levels of transport in tokamak plasmas are the result of drift-wave turbulence driven by the free energy available in the plasma pressure gradients [2]. However, despite many instances of the model’s success, disagreements between simulated and experimental heat fluxes, particularly in the electron channel, still remain unresolved [1, 6], and thus the ability to predict the outcome of one of the world’s largest scientific endeavors, ITER\(^5\) [7], remains lacking. It is generally accepted that a handful of turbulent instabilities are primarily responsible for the observed heat fluxes [4]. These instabilities are classified by their primary driving mechanism and by the spatial scales of their associated turbulent eddies. Driving mechanisms are traditionally parameterized as the logarithmic gradients in density, electron temperature, or ion temperature normalized to the plasma minor radius, e.g. \(\ln(\nabla x)\), where \(x = n_e(r)\), \(T_e(r)\) or \(T_i(r)\), \(r\) is the radial coordinate of the plasma and \(a\) is the midplane minor radius. Eddy sizes are characterized by

\(^5\) www.iter.org
the values of $k_\theta \rho_i$, where $k_\theta$ is the poloidal wavenumber of the turbulence and $\rho_i = c_s/\Omega_i$ is the ion sound Larmor radius (with $c_s = (T_e/m_i)^{1/2}$ and $\Omega_i = eB_i/m_i$ for singly charged ions). Turbulence classified as ion-scale ($k_\theta < 1$), has eddy sizes in the range $k_\theta \rho_i < 1.0$, while electron-scale ($k_\theta > 1$) turbulence is associated with spatial scales in the range $1.0 < k_\theta \rho_i < 60.0$. Most research focuses on three modes: At ion scales, the ion temperature gradient (ITG) mode, driven dominantly by $aIL_T$, and the trapped electron mode (TEM), driven by $aIL_m$ and $aIL_e$; while at electron scales, research focuses on the electron temperature gradient (ETG) mode, driven dominantly by $aIL_T$. These candidate turbulent modes and their self-generated zonal flows ($k_\theta = 0$ fluctuations, a principal damping mechanism of the turbulence) [8, 9]) represent the standard model of electrostatic turbulence in fusion plasmas [4].

Experimental evidence for the ITG and TEM has been obtained in a variety of confined plasmas ([5], references therein). In contrast, the challenges of measuring small spatial scales have resulted in more limited evidence for the ETG [10, 11]. The challenge to theories of ETG is that small-scale isotropic eddies imply negligible transport. However, ETG turbulence has been observed in numerical experiments to form radially elongated ($k_\theta \ll k_\theta$) turbulent structures known as ETG streamers [12]. These structures effectively increase the radial step size of the turbulence, allowing for significant transport of heat radially out of confined plasmas [13]. To date, most analysis of ITG and ETG plasma turbulence has utilized single-scale (ion or electron) gyrokinetic simulation, with a sum of the single-scale simulations often used to interpret experiment heat flux levels. However, some work suggests this superposition approach is flawed [14–16] and coupled ion/electron-scale (multi-scale) simulation is required to capture the relevant nonlinear interactions. Due to the wide range of spatial and temporal scales spanned by ITG and ETG turbulence ($k_\theta \rho_i \sim 0.1$ to 60.0), multi-scale simulations have generally not simulated experiment and utilized reduced electron mass [14–19], with artificially ‘heavy’ electrons to reduce the range of scales considered and make the simulation more tractable. The first multi-scale simulations to utilize a realistic ion to electron mass ratio ($m_i/m_e$) were performed recently [20]. Subsequently, the results from Maeyama et al [19] performed multi-scale simulations at a ‘real’ mass ratio. However, these simulations utilized the hydrogen mass ratio ($m_i/m_e = 1836$) to simulate the modeled conditions (CYCLONE base case [21]) roughly extracted from a DIII-D deuterium plasma [22] (where $m_i/m_e = 3600$). As the effects of hydrogen isotope on energy confinement are well documented (references 1–14 in [23]), the gradients used in this simulation are therefore inconsistent with the mass ratio used. Unfortunately, the unphysical approximations made by using modeled parameters and unrealistic mass ratios make experimental comparison inaccurate and can result in incorrect qualitative and quantitative conclusions about the conditions simulated [24].

Critical questions exist that cannot be answered by the usual single-scale approach or by reduced mass multi-scale simulation: Does the ETG alter the energy transfer and the well-established feedback between zonal flows and the ITG? How does ion and electron-scale turbulence couple and collectively drive heat flux in experiment? Can these collective effects explain the origin of ‘anomalous’ electron heat transport in tokamak plasmas? We present a set of realistic, multi-scale simulations of an experimental discharge that reveal a rich tapestry of new physics. The relative strength of ITG and ETG turbulence is found to dictate the direction of energy cascades, modify the zonal flow shear generation, and ultimately enhance heat fluxes at both the ion and electron turbulence scales. For the first time, these simulations are compared quantitatively against experimental ion and electron transport in tokamak plasmas. The first multi-scale simulations to utilize a realistic ion to electron mass ratio ($m_i/m_e = 1836$) to simulate the modeled conditions (CYCLONE base case [21]) roughly extracted from a DIII-D deuterium plasma [22] (where $m_i/m_e = 3600$). As the effects of hydrogen isotope on energy confinement are well documented (references 1–14 in [23]), the gradients used in this simulation are therefore inconsistent with the mass ratio used. Unfortunately, the unphysical approximations made by using modeled parameters and unrealistic mass ratios make experimental comparison inaccurate and can result in incorrect qualitative and quantitative conclusions about the conditions simulated [24].

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heat fluxes and electron profile stiffness resolving a longstanding disagreement between simulation and experiment, and establishing the applicability of the newly discovered physics to experiment.

The analysis reported here focuses on a low confinement mode, radiofrequency heated plasma in the MIT Alcator C-Mod tokamak [25]. This discharge has been studied extensively revealing a robust under-prediction of the experimental electron heat flux levels by standard, ion-scale gyrokinetic simulation [26, 27]. All the simulations reported here utilize the GYRO code [28], a Eulerian gyrokinetic code with an extensive history of comparison with experiment [29–32]. The simulations in this paper were performed with extremely high physics fidelity: Three gyrokinetic species (ions, electrons, and a boron impurity), rotation and $E \times B$ shear effects, realistic geometry, electron–ion collisions, a realistic electron mass ratio ($m_e/m_i$)$^{1/2}$60.0, and all the inputs obtained from dedicated experiments. The multi-scale simulations presented span both the ion and electron spatial scales to capture turbulence with up to $k_{θρ} = 48.0$ with physical simulation boxes of nominally $44 \times 44 \rho_s$ in the radial and binormal directions. All the simulation details, including resolutions, input and output values, and convergence details are provided in supplementary methods 1 and supplementary tables 1 and 2 (stacks.iop.org/NF/56/014004/mmedia). We present here the results from six simulations. These simulations comprise scans of the input parameters $aL_T$ and $aL_T$, which are the dominant ion and electron-scale turbulence drivers, respectively. To maintain experimental realism, we scan the inputs ($aL_T$ and $aL_T$) only within the approximate 1-sigma experimental uncertainties. Performed almost exclusively on the NERSC Edison supercomputer, each simulation required 17 000 processors and ~37 total days (~15 M CPU hours) for completion with a total of approximately 100 M CPU hours used in this study.

A three-point scan of the ITG drive term ($aL_T$) was performed using multi-scale simulation. At a fixed value of $aL_T = 3.69$ (chosen based on the flux-matched conditions reported in [20]), simulations were performed with $aL_T$ values 32.0, 12.0, and 3.0% above the ITG critical gradient ($aL_T = 1.7$; see supplementary methods 2 (stacks.iop.org/NF/56/014004/mmedia)). These simulations will be referred to as Simulations #1, 2, and 3 throughout this text. This scan displays a transition from long wavelength, ITG-dominated plasma conditions (large eddies: Simulation #1) to short wavelength ETG streamer dominated conditions (large ion-scale eddies coexisting with ETG streamers: Simulation #3) with the intermediate condition represented by Simulation #2. The transition in turbulence is clearly demonstrated in snapshots of the electrostatic potential fluctuations plotted in figure 1.

As Simulations #1 and #3 represent the largest variation in the dominant turbulence, we quantified the nonlinear energy transfer, and zonal flow shear generation in these simulations. In tokamak plasmas, the transfer of internal fluctuation energy (density, temperature, etc) is generally assumed to take the form of a local, forward cascade from an injection range at large scales to a dissipation range at small scales [33]. Energy transfer between the three coupled waves ($k_3 = k_1 + k_2$; with $k = k_0$) can be quantified using techniques of higher order spectral analysis and have been applied previously to analysis of plasma turbulence [34, 35]. The total energy transfer, $T(k_3,k_1)$, from the gradients of a fluctuating field, $f$, at a wavenumber, $k_1$, into fluctuations with a wavenumber of $k_3$, due to $E \times B$ velocity fluctuations at wavenumber, $k_2$, was evaluated for temperature fluctuations in figures 2(a) and (b) (see supplementary methods 3 for details) (stacks.iop.org/NF/56/014004/mmedia). In figures 2(a) and (b), the transfer of energy into a wavenumber, $k_3$, from $k_1$ and $k_2$, is denoted by lighter colors (yellow to red-orange) while the energy transfer out of $k_3$ to the wavenumber $k_1$ is denoted by darker colors (shades of purple/blue). Additional details on interpretation can be found in [35].

Figure 2(a) shows the results from Simulation #1, where a local forward energy cascade spans from the ion to electron scales in the wavenumber range $0.14 < k_3,\theta ρ_s < 3.5$ and a local inverse cascade occurs in the electron-scale range above $k_3,\theta ρ_s = 5.0$. The local inverse cascade is found to span the peak in the ETG streamers ($k_3,\theta ρ_s = 10.0$), which exist, but play a negligible role in this condition. Figure 2(b) plots the results from Simulation #3. In contrast to the ITG dominated condition, the local forward energy cascade at lower wavenumbers reverses to become an inverse cascade in the wavenumber range, $1.0 < k_3,\theta ρ_s < 4.5$. Even more striking is the
presence of a nonlocal inverse cascade from ETG streamer wavenumbers ($3.0 < k_{3,p1} < 7.0$) to wavenumbers in both the ITG and ETG turbulence range, $0.14 < k_{1,p1} < 3.0$, not observed in Simulation #1. One common feature of both conditions is a nonlocal forward transfer of energy from near the peak in the ITG wavenumbers, $k_{3,p1} \sim 0.4$, to the peak of the ETG streamer wavenumbers. These results are clear evidence of cross-scale coupling in both conditions with qualitative differences existing between conditions exhibiting dominant (Simulation #3) and negligible (Simulation #1) ETG streamers.

In the standard paradigm, the saturation of ion-scale turbulence relies on a well-established feedback between turbulence and self-generated zonal flows ($k_0 = 0$ potential fluctuations). The radial variation of zonal flows has been demonstrated to effectively shear apart turbulent eddies, reducing transport levels, and resulting in a saturation of the turbulence level [8]. To study how ETG turbulence fits within this paradigm, we evaluated the efficiency of zonal flow shear generation across the transition from ITG dominated to ETG streamer dominated conditions. The efficiency is quantified as the ratio of the total long wavelength ($k_{s} < 1.0$) zonal flow shear divided by the total power in the finite-$k_0$ potential fluctuations (see supplementary methods 4 for details) (stacks.iop.org/NF/56/014004/mmedia). The results obtained from the ion and multi-scale simulation are plotted in figure 2(c), as the input $aL_{Ti}$ value is scanned. Multi-scale simulations display a less efficient generation of zonal flow shear than the corresponding ion-scale simulation at all values of $aL_{Ti}$. Therefore, we find that the inclusion of electron-scale turbulence results in the less efficient generation of zonal flow shear. The largest difference between the ion and multi-scale results occurs in Simulation #3, where the ETG streamers are most significant, while the zonal flow efficiency obtained from ion and multi-scale simulation are almost identical in conditions where the ITG is dominant (Simulation #1). Given the standard paradigm for turbulence/zonal flow interactions, inefficient zonal flow shear generation will allow the ion-scale turbulence to saturate at a higher level for a given value of driving gradient, presumably driving higher levels of transport.

Despite the ability of ion-scale simulation to reproduce experimental ion and electron heat fluxes ($Q_i$ and $Q_e$) in many conditions, significant disagreements have been documented between simulated and experimental electron heat fluxes [26, 36]. After 50 years of plasma physics transport research, a full understanding of the origin of electron heat flux remains elusive. As for ITER, the question is absolutely critical because in a burning fusion plasma electron heat flux will dominate energy loss [37]. To validate the newly discovered cross-scale couplings (energy transfer and zonal flow shear modification), and to assess their effect on the driven heat flux levels, we compare the predicted ion and electron heat fluxes from multi-scale simulations directly with experimental values, and we compare the predicted ion and electron heat fluxes from multi-scale simulations directly with experimental values, and contrast these results with the ion-scale simulation. Figure 3 plots the simulated ion ($a$) and electron ($b$) heat flux versus $aL_{Ti}$, using ion-scale (red diamonds) and multi-scale (blue squares) are plotted.

turbulence is strongly unstable, driven approximately 32% above its critical gradient ($aL_{Te, cri} = 1.7$). The heat fluxes predicted by the corresponding ion-scale simulation are in close agreement to those predicted by the multi-scale simulation, unsurprising since ETG streamers play a negligible role, driving only 10% of the total electron heat flux. This is consistent with previous analytic theory [38] and simulation [15, 16] of ETG streamer suppression by strong ITG turbulence and the associated zonal flow shear. However, the ion heat flux in this simulation condition is in quantitative disagreement with the experimental level. Simulation #2 represents conditions where ITG is moderately unstable (12% above the critical gradient). Unexpectedly, the ion heat flux and electron heat flux at low-$k$ ($k_0/\rho_s < 1.0$) exceeds the corresponding ion-scale
prediction by \(\sim 45\%\), suggestive of strong nonlinear interaction between the ion and electron scales. The total electron heat flux in Simulation \(\#2\) is a combination of a significant high-\(k\), ETG streamer driven heat transport, and enhanced long wavelength turbulence due to reduced zonal flow shear generation and energy cascades (figure 2). These mechanisms result in a 120\% increase in \(Q_e\) above the ion-scale simulation and heat flux levels that are simultaneously consistent with the experimental levels of ion and electron heat fluxes within diagnosed experimental and simulation uncertainties \((Q_{i,exp} = 0.07 \pm 0.021, Q_{e,exp} = 0.23 \pm 0.069, \sim 10\%\) error bars on simulation; see supplementary methods 5 and supplementary table 2 for details) (stacks.iop.org/NF/56/014004/mmmedia).

Simulation \(\#3\) has marginally unstable ITG turbulence \((3.0\%\) above the critical gradient). Strikingly, in this condition the ion heat flux exceeds the corresponding long wavelength simulation by nearly a factor of three and the total electron heat flux exceeds the ion-scale prediction by nearly a factor of ten. In this condition the ITG is weakly unstable and the zonal flow shearing rate is small. As a result, ETG streamers are able to form and dominate the electron heat flux, driving \(\sim 70\%\) of the total, with the remainder coming from substantially enhanced low-\(k\) turbulence. The simulated heat flux values in this case best reproduce the experimental heat flux in the ion and electron channels within experimental uncertainties, definitively explaining the disparity between ion-scale simulation and experiment [26, 27].

In multi-scale simulations the response of the ion and electron heat fluxes to \(a/L_T\) variation is due to the collective effects associated with cross-scale turbulence coupling. For the ion heat flux, \(Q_i\), there are two new observations: Reduced stiffness \((S = dQ_i/d(a/L_T))\) in the ion heat flux, \(Q_i\), and an apparent downshift of the nonlinear ITG critical gradient \((a/L_T = 1.7 \text{ to } 1.6)\) relative to the ion-scale simulation. Both of these effects are the direct result of the enhanced low-\(k\) heat fluxes observed in conditions exhibiting ETG streamers. For the electron heat flux, a ‘U’-shaped dependence of \(Q_e\) on \(a/L_T\) is found to occur as the plasma transitions from being ETG dominated to ITG dominated. The response of the electron heat flux to \(a/L_T\) in multi-scale simulations is entirely different from ion-scale simulation, calling into question predictions for ITER that are based on ion-scale simulations [39]. This behavior has never been simulated before, and it is a unique signature of significant cross-scale coupling between ITG and ETG turbulence. Simulations \(\#2\) and \(\#3\) are the only simulations able to obtain quantitative agreement with ion and electron heat fluxes, exhibiting heat fluxes up to a factor of ten above standard ion-scale simulation. These results indicate that conditions with significant ETG streamers and significant cross-scale coupling are consistent with experiment, thus establishing the applicability of the new physics to realistic conditions.

Using a variety of approaches [40–42], electron profile stiffness has been studied experimentally in tokamak plasmas worldwide, revealing highly stiff electron transport in the core of most plasma conditions. In simulation, electron profile stiffness can be investigated by probing the response of \(Q_e\) to changes in \(a/L_T\) [43], with a strong response consistent with stiff transport. To further validate multi-scale simulation against experiment, additional multi-scale simulations scanned the electron-scale turbulence (ETG) drive \((a/L_T)\). We plot the results from a three-point scan in figure 4. Figure 4(A) shows that the enhancement of the ion heat flux and low-\(k\) electron heat flux increases with increased ETG turbulence drive. Hence, changes in cross-scale coupling and zonal flow shear generation will occur either by weakening the ITG turbulence (as in figure 3) or by more strongly driving the ETG turbulence (figure 4). Standard ion-scale simulation (figure 4(B)), displays no response of \(Q_e\) to changes in \(a/L_T\) (low stiffness), qualitatively inconsistent with experiment. In contrast, multi-scale simulation responds strongly to changes in \(a/L_T\) (high stiffness), qualitatively consistent with experiment. The simulated and experimental electron profile stiffness can be quantified and compared by defining the incremental thermal diffusivity \((\chi_{inc} = dQ_i/d(n_e V^2 T))\). We find that evaluation of this quantity for multi-scale simulation \((\chi_{inc,multi} = 1.39 \text{ m}^2 \text{s}^{-1})\)
yields values in agreement with those obtained experimentally in this discharge \( <x_{\text{inc,exp}} = 1.61 \pm 0.36 \text{ m}^2 \text{s}^{-1}> \) \( [44] \) (see supplementary methods 6) \( (stacks.iop.org/NF/56/014004/mmedia)\).

Overall, the results from this set of realistic mass, multiscale simulations of experimental fusion plasmas reveal rich new physics. The balance of ITG and ETG turbulence is found to dictate the direction of energy cascades and to adjust zonal flow shear generation, ultimately enhancing heat fluxes at both the ion and electron turbulence scales. For the first time, experimental ion and electron heat fluxes and electron profile stiffness can be quantitatively matched by simulations, resolving a longstanding disagreement and establishing the applicability of the newly discovered physics to experiment. We conclude that cross-scale turbulence coupling is likely the origin of ‘anomalous’ electron heat transport in tokamak plasmas.

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