Demonstrating the Multiscale Nature of Electron Transport through Experimentally Validated Simulations

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New experimentally validated simulations demonstrate for the first time that the turbulent transport that sets tokamak confinement is robustly multiscale across a variety of reactor-relevant regimes, with significant nonlinear cross-scale couplings that must be accurately described to correctly predict ITER performance. These gyrokinetic and gyrofluid simulations of electron transport dominated experiments performed on the Alcator C-Mod and DIII-D tokamaks consistently find that over half of the electron thermal transport arises from short-wavelength electron-scale ($k_{\theta}\rho_i > 1$) fluctuations not resolved by conventional ion-scale ($k_{\theta}\rho_i \leq 1$) microturbulence simulations. It is found that only by including these short-wavelength fluctuations can the turbulence simulations simultaneously match the measured temperature gradients, incremental electron thermal diffusivity, and independent power balance calculation energy fluxes within experimental uncertainties. Significant transport contributions from electron-scale streamers are found to persist even in discharges with low rotation and input torque, where they coexist with nonnegligible ion-scale eddies that drive the ion thermal transport. The multiscale simulations show complex nonlinear interactions between the electron- and ion-scale fluctuations, such that the intensity of electron-scale fluctuations can depend upon the ion-scale fluctuation intensity, and vice versa. Therefore, the resulting transport cannot be assumed to be a simple sum of separate ion- and electron-scale dynamics. Taken together, these simulations provide the clearest evidence to date that electron-scale turbulence will be prevalent in burning plasma conditions, and that the nonlinear multiscale dynamics and cross-scale couplings of this turbulence must be accurately described to confidently predict the performance of those regimes.

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Demonstrating the Multiscale Nature of Electron Transport Through Experimentally Validated Simulations

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Abstract. New gyrokinetic and gyrofluid simulations demonstrate that turbulent transport is robustly multiscale across a variety of reactor-relevant regimes, with significant nonlinear cross-scale couplings that must be accurately described to correctly predict ITER performance. These simulations of electron transport dominated experiments performed on the Alcator C-Mod and DIII-D tokamaks consistently find that over half of the electron thermal transport arises from short-wavelength electron scale \( (k \rho_i > 1) \) fluctuations not resolved by conventional ion-scale \( (k \rho_i \leq 1) \) microturbulence simulations. Moreover, it is found that only by including these short-wavelength fluctuations can the turbulence simulations simultaneously match measured temperature gradients, independent power balance calculation energy fluxes, and measured incremental electron thermal diffusivity within experimental uncertainties. Significant transport contributions from electron-scale streamers are found to persist even in discharges with low rotation and input torque, where they co-exist with non-negligible ion-scale eddies that drive the ion thermal transport. The multiscale simulations show complex nonlinear interactions between the electron- and ion-scale fluctuations, such that the intensity of electron-scale fluctuations can depend upon the ion-scale fluctuation intensity, and vice versa. Therefore, the resulting transport cannot be assumed to be a simple sum of separate ion- and electron-scale dynamics. Taken together, these experimentally validated simulations provide the clearest evidence to date that electron-scale turbulence will be prevalent in burning plasma conditions, and that the nonlinear multiscale dynamics and cross-scale couplings of this turbulence must be accurately described to predict the performance of those regimes with confidence.

1. Introduction

In magnetically confined fusion energy (MFE) plasmas, the turbulent cross-field transport of particles, energy, and momentum is often the primary determinant of the overall level of confinement achieved. It is therefore essential to fully understand the underlying physics of the turbulence, in order to build validated predictive models of the transport processes that can be confidently extrapolated to burning plasma regimes and used to design future MFE reactors. This turbulence forms from the nonlinear interactions of various small-scale instabilities driven by the equilibrium temperature and density gradients of the plasma, resulting in collective behavior- the cross-field transport- that works to relax the driving gradients [1]. In high-temperature tokamak plasmas, the most prevalent of these instabilities are the ion temperature gradient (ITG) mode, the trapped electron mode (TEM) and the electron temperature gradient (ETG) mode. To date, most theoretical and computational work has focused on long-wavelength (low-\( k \)) ion-scale \( (k \rho_i \leq 1) \) ITG and TEM turbulence, since significant ion thermal transport generally cannot be driven at smaller scales due to finite Larmor radius (FLR) effects. Here \( k_i = n q / r \) is the binormal wavenumber of the fluctuations (with \( n \) the toroidal mode number, \( q = r B_t / R B_p \) the plasma safety factor, \( r \) the midplane minor radius, and \( R \) the major radius), and \( \rho_i = v_{ti} / \Omega_i \) is the ion gyroradius. Advances in computing power over the last decade have enabled direct numerical simulation of the gyrokinetic-Maxwell equations to directly predict ion-scale turbulent fluxes and fluctuation levels for a variety of experimental conditions with ever-increasing physical fidelity. While a full summary of these results is beyond the scope of this work, a common result is for these ion-
scale simulations to underpredict the electron thermal transport, particularly at larger radii in electron-transport dominated plasmas.

Resolving this discrepancy is particularly important for prediction of burning plasmas, which are expected to be electron transport dominated due to fusion α-particles predominately heating the electron population. In this paper, we investigate the ability of gyrokinetic simulations to correctly predict energy transport in reactor-relevant conditions, using data from plasma discharges performed in the Alcator C-Mod [2] and DIII-D [3] tokamaks. Each discharge considered is electron transport dominated, has little or no injected torque or core fueling, \( T_i \approx T_e \), and \( q_{95} \leq 4.5 \). The Alcator C-Mod discharge is a low-confinement (L-mode) plasma with core plasma conditions qualitatively consistent to those expected in the plasma current ramp-up/down phase of ITER. The DIII-D discharge is a high-confinement (H-mode) plasma run in an “ITER-similar shape”, with a combination of electron cyclotron heating (ECH) and modest neutral beam injection (NBI) operated in feedback mode to match target parameters of the ITER inductive baseline scenario.

For both experimental conditions considered, we find that ion-scale gyrokinetic simulations predict ion energy fluxes \( Q_i \) in agreement with independent power balance calculations for density, temperature and rotation gradients consistent with the measured profiles, but systematically underpredict the electron energy fluxes \( Q_e \). However, multiscale simulations of these conditions, which resolve short-wavelength (high-\( k \)) electron-scale fluctuations (\( k \rho_s > 1 \)) as well as the ion-scale turbulence, are able to simultaneously match the power balance values of \( Q_i \) and \( Q_e \) for measured gradient values. Here, \( \rho_s = c_s/\Omega_{ci} = (T_i/T_e)^{1/2} \rho_i \) is the ion-sound speed gyroradius. For both conditions, low but finite levels of relatively isotropic ion-scale turbulence (with typical values of \( k \rho_s \sim 0.3-0.4 \)) are found to co-exist with a broad spectrum of radially elongated electron scale “streamers” that peaks in the range of \( k \rho_s = 8 \) – 10. Despite their small scale, these electron-scale fluctuations contribute over half of the total \( Q_e \) in both conditions. Moreover, it is found that only by including the high-\( k \) fluctuations can the simulations match the measured incremental electron thermal diffusivity \( \chi_e,inc = -d(Q_e)/d(n_edT_e/dr) \) in the C-Mod discharge. These simulations show complex nonlinear interactions between the ion- and electron-scale fluctuations, such that the intensity of electron-scale fluctuations can depend upon the ion-scale fluctuation intensity, and vice versa. Therefore, the resulting transport cannot be assumed to be a simple sum of separate ion- and electron-scale dynamics. Most notably, inclusion of electron-scale turbulence can lead to enhanced levels of ion-scale turbulence and \( Q_e \) through a variety of linear and nonlinear energy transfer processes, including changes to the strength of the long-wavelength zonal flows. Taken together, these simulations provide the clearest evidence to date that electron-scale turbulence will be prevalent in burning plasma conditions, and that the nonlinear multiscale dynamics and cross-scale couplings of this turbulence must be accurately described to predict the performance of those regimes with confidence.

2. Multiscale gyrokinetic simulations of Alcator C-Mod L-mode discharges

The first plasma conditions considered were obtained in a pair of Alcator C-Mod L-mode discharges with on-axis electron density \( n_e(0) \sim 1.5 \times 10^{20} \) m\(^{-3} \), \( I_p = 0.8 \) MA, \( B_T = 5.4 \) T, elongation \( \kappa = 1.6 \), and either 1.2 MW or 3.5 MW of applied ion cyclotron resonance (ICRH) heating. Additional experimental details can be found in Ref. 4, along with the results of local ion-scale gyrokinetic simulations performed with the GYRO code [5] at multiple radii in the outer half of the plasma for each discharge. For these cases, the ion-scale simulations were able to match \( Q_e \) at all radii considered (\( \rho_{tor} = 0.53, 0.63, \) and 0.73, where \( \rho_{tor} \) is the square root
of the normalized toroidal flux enclosed within the flux surface it labels). However, while these simulations were able to match $Q_i$ in the high-power (3.5 MW ICRH) discharge, they systematically underpredicted $Q_e$ in the low-power (1.2 MW ICRH) case. In order to resolve this discrepancy, and motivated by the observation of strongly unstable ETG modes in the discharges (Fig. 1), a series of seven multiscale simulations for $\rho_{tor} = 0.53$ in the low-power discharge, and one for $\rho_{tor} = 0.53$ in the high power discharge, were performed. The results of these simulations were published in Refs. 6-9, and are summarized here. The multiscale simulations were also performed with the GYRO code, and like the ion-scale simulations were local and included magnetic shaping (via a generalized Miller parameterization [10]), equilibrium rotation effects, ion-electron collisions, and three gyrokinetic species- electrons, deuterium, and a single boron impurity species (the dominant impurity in the discharge). Due to the low-$\beta$ ($\beta_i \sim 0.1\%$) nature of the plasmas, magnetic fluctuations were not included. A standard 128-point velocity-space grid was used (8 energies, 8 pitch angles, and 2 signs of velocity) in all simulations. To resolve both ion and electron scale dynamics, the multiscale simulations use 342 complex toroidal modenumbers to span $0 \leq k_\rho \rho_s \leq 48$ (equal to $k_\rho \rho_s = 0.8$) with resolution $\Delta k_\rho \rho_s = 0.14$ ($\Delta n = 18$). Physical binormal simulation box sizes were $44 \rho_s \times 44 \rho_s$, with additional 8 $\rho_s$ wide radial buffer regions as the simulations are not radially periodic to allow inclusion of equilibrium $E \times B$ shearing, and 1800 radial grid points are used such that the radial resolution $\Delta r = 0.033 \rho_s = 2 \rho_s$. All results are obtained using time-averaging windows of 150-200 $a/c_s$ during the saturated phase. Each simulation used approximately 17,000 cores for several hundred hours on either the NERSC Hopper or Edison machines, such that approximately 120,000,000 core-hours were required to complete all of the multiscale simulations. To our knowledge, these simulations are the first realistic mass-ratio simulations of experimentally observed plasma conditions. Earlier multiscale simulations [11-15] all used idealized input parameters and/or reduced ion-to-electron mass ratio, which has been shown to lead to both quantitative and qualitative differences in predicted results [7].

Predictions of $Q_i$ and $Q_e$ from ion-scale and multiscale simulations as a function of $a/L_{ni} = -(aT_i) dT_i / dr$ (where $r$ is the midplane minor radius and $\alpha$ its value at the separatrix) for the low-power discharge are compared to power balance calculations performed with the TRANSP code [16] in Fig. 2. Because these fluxes are obtained from independent (of the gyrokinetic simulation) power balance modeling calculations with their own set of inherent uncertainties and assumptions [17], and are not measured quantities, we intentionally do not refer to them as the “experimental” fluxes as is commonly done. While the ion-scale simulations can match either $Q_i$ or $Q_e$ for values of $a/L_{ni}$ within the experimental uncertainties, there is no point at which both fluxes are matched simultaneously. However, for values of $a/L_{ni}$ where the ion-scale simulations are consistent with the power balance $Q_i$ calculation, but underpredict $Q_e$, the multiscale simulations predict both ion and electron energy fluxes consistent with the TRANSP results. At these gradients ($a/L_{ni} = 1.75$ or 1.92), we find that not only do the high-$k$ fluctuations contribute significantly to the total $Q_e$, but that their inclusion also leads to a modest increase in $Q_i$ as well. In Ref. 6, it was shown that this increase is due to increased power in the low-$k$ fluctuations, rather than a change in cross-phase or correlation lengths. Reflecting this change, the low-$k$ contributions to $Q_e$ in the multiscale simulations are also larger than the corresponding ion-scale simulation fluxes. Examination of cross-bispectra
exhibits the formation of instability, collapse in the predicted values of gyrokinetic simulations have generally had the greatest success noted that the low turbulence by low theoretical predictions and earlier simulation results \[ Q_e \] drive creates enough low only a very small residual contribution to \( a/L \). Important when ion multiscale effects are not unique to a single plasma condition, and can be important even presented in Refs. 8 and 9 shows that there is a rich set of nonlinear cross-scale couplings between low-\( k \) and high-\( k \) electron temperature fluctuations, including both local (in wavenumber) forward and inverse cascade processes, as well as nonlocal transfer processes, and that the relative strength of these processes depends upon \( a/L_{T_i} \). Moreover, it was found that the magnitude of the long-wavelength zonal flow shearing rate to turbulent intensity levels was weaker in the multiscale simulations at these gradients relative to ion-scale simulations, also consistent with increased low-\( k \) fluctuation power in the multiscale simulations. These results are consistent with those of Maeyema et al. [18], who observe finite electron-scale turbulence reduces zonal flow generation in multiscale simulations of CYCLONE base case hydrogen plasmas. Similar enhancement of both \( Q_i \) and \( Q_e \) in a multiscale simulation of the high-power discharge is also observed [9], indicating that these multiscale effects are not unique to a single plasma condition, and can be important even when ion-scale simulations are able to match power balance \( Q_i \) and \( Q_e \) calculations.

Important insights into multiscale physics also come from examining the two extremes of the \( a/L_{T_i} \) scan shown in Fig. 2. At the highest value of \( a/L_{T_i} (= 2.25) \), the multiscale simulation yields essentially the same flux predictions as the corresponding ion-scale simulation, with only a very small residual contribution to \( Q_e \) from high-\( k \) fluctuations. At this point, the ITG drive creates enough low-\( k \) turbulence to suppress the high-\( k \) fluctuations, consistent with theoretical predictions and earlier simulation results [12,13]. This suppression of high-\( k \) turbulence by low-\( k \) fluctuations can also be seen at smaller values of \( a/L_{T_i} \), as time traces of the low-\( k \) and high-\( k \) turbulence intensity are often strongly out-of-phase. It should also be noted that the prediction at this point is essentially \( Q_i \approx Q_e \), which corresponds to the situation often observed in plasmas with moderate NBI heating for which conventional ion-scale gyrokinetic simulations have generally had the greatest success [17]. More surprising are the results from the lowest value of \( a/L_{T_i} \) considered (\( a/L_{T_i} = 1.58 \)), for which there is a strong collapse in the predicted values of \( Q_i \) and \( Q_e \), relative to their values at \( a/L_{T_i} = 1.75 \). While the collapse in \( Q_i \) can be readily understood in terms of reducing \( a/L_{T_i} \) below it’s critical value for instability, the collapse in \( Q_e \) was unexpected. For this condition, the simulation initially exhibits the formation of strong, well-extended streamers and significant values of \( Q_e \).
A scan of an ion-scale simulation displays experimental observations. Multi-scale simulation displays a significant electron stiffness and resistive relaxation times. Experimentally, the electron temperature profile demonstrates that multi-scale simulations are shown in Fig. 3. Scaling of $Q_e$ predicted by (●) ion-scale and (■) multi-scale GYRO simulations as a function of $a/L_{Te}$ for the low-power Alcator C-Mod case. Only the incremental diffusivity $\kappa_{e,inc}$ calculated for the multi-scale simulations matches the experimentally measured value.

Finally, we note that while demonstrating consistency between the gyrokinetic flux predictions and the power balance calculations for measured gradient levels can be viewed as sufficient for validation of the gyrokinetic model, additional comparisons of code predictions to experimental measurements is desirable for more robust validation. While fluctuation measurements are not available for the discharges studied, a recent analysis of partial sawteeth crashes in the low power discharge [20] yielded a determination of the incremental electron thermal diffusivity $\kappa_{e,inc} = - \frac{d(Q_e)}{dn_e dT_e} = 1.6 \pm 0.4 \text{ m}^2/\text{s}$. By performing an additional sensitivity analysis in which $a/L_{Te}$ rather than $a/L_{NI}$ is varied, a predicted value of $\kappa_{e,inc}$ can be derived. The results of this scan for both multi-scale and ion-scale simulations are shown in Fig. 3. While the ion-scale simulations show essentially no response to increasing $a/L_{Te}$ (and so are inconsistent with the measured $\kappa_{e,inc}$), the multi-scale simulations predict a value of $\kappa_{e,inc} = 1.4 \text{ m}^2/\text{s}$, in agreement with the observations. Thus, not only do the multi-scale simulations reproduce the power balance $Q_e$, they also capture the observed scaling with $a/L_{Te}$, further supporting the need for including multi-scale effects in predictions of turbulent transport in tokamaks.

3. Multiscale gyrokinetic simulations of DIII-D ITER baseline discharge

The results reported in the previous section clearly demonstrate that electron-scale fluctuations can play a significant role in determining thermal transport in electron-transport dominated L-mode plasmas. However, it is generally envisioned that any tokamak-based fusion reactor will operate in H-mode, and so it is important to determine whether multi-scale effects will play an important role in that regime as well. Towards this end, a number of studies investigating turbulent transport in scaled ITER baseline scenario (IBS) plasmas are now underway within the DIII-D program. Here, we report on investigations of turbulent transport in one particular discharge, chosen because it sustains many of the core plasma conditions and parameters expected for the $Q_{fusion} = 10$ baseline inductive scenario for multiple resistive relaxation times. In particular, the plasma was run in an ITER-similar-shape with
$q_{95} = 3.3$, $\beta_N = 1.8$, normalized confinement factor [21] $H_{98y2} = 1$, $T_i \approx T_e$, and 3.4 MW of steady electron cyclotron heating (ECH) deposited at $\rho_{out} = 0.5$. DIII-D’s highly flexible neutral beam system was operated in feedback mode to maintain these parameters while providing an additional 2.8 MW of heating, but only 0.6 N · m of torque. Additional experimental details, including discussions of stability and transport dependences on rotation and heating mix, are given in Ref. 22. Time-averaged equilibrium profiles for this discharge are shown in Fig. 4.

Previous integrated core-edge transport modeling of this discharge using the quasilinear gyrofluid TGLF model [23] for core transport and the EPED model [24] to predict pedestal parameters yielded predictions of density and temperature profiles consistent to within 10% of the experimental observations [25]. Transport modeling of a similar discharge with TGLF [26] yielded similar levels of agreement. A key finding of these studies is that for electron-transport dominated IBS discharges, TGLF predicts high-$k$ fluctuations will contribute significantly to both the electron thermal transport and to the particle transport at larger radii in the plasmas. In particular, it was shown in Ref. 26 that switching from pure NBI heating to a mixture of NBI+ECH heating (thereby increasing the ratio of $Q_e$ to $Q_i$) leads to an increase in high-$k$ fluctuations that contribute a significant fraction of the total electron thermal transport. These fluctuations are also shown to drive a particle pinch, thereby leading to increased density peaking. The high-$k$ fluctuations and resulting transport contributions are predicted to persist in ITER conditions, with the magnitude of the particle pinch becoming stronger as collisionality decreases from values observed in the DIII-D IBS discharges to those expected in ITER itself. This dependence manifests as a strong peaking of the density profile in predictive simulations of the ITER inductive scenario, leading to up to a 30% increase in predicted $Q_{fusion}$ relative to predictions for flat density profiles. Despite the strong electron density peaking, only modest tungsten peaking was predicted due to turbulent transport dominating neoclassical processes at all radii in ITER. Wavenumber spectra of the TGLF-predicted electron particle and energy fluxes for both the DIII-D and ITER discharges are shown in Fig. 5.

Motivated by these findings, a series of local ion-scale and multiscale gyrokinetic simulations were performed using the GYRO code, for parameters corresponding

![Equilibrium profiles for a low torque electron-transport dominated IBS DIII-D plasma operated at $\beta_N = 1.8$, $H_{98y2} = 1$ averaged over 800 ms.](image1)

![TGLF-predicted electron flux spectra for (a,b) DIII-D IBS discharges and (c,d) an ITER inductive scenario plasma. In both cases high-$k$ fluctuations drive a pinch in (a,c) particle flux $\Gamma_e$ and contribute significantly to (b,d) $Q_e$.](image2)
to $\rho_{\text{tor}} = 0.65$ of the plasma profiles shown Fig. 4. The simulation setup and resolution are similar to those used for the Alcator C-Mod case, but now include perpendicular magnetic fluctuations and use carbon, rather than boron, as the impurity species. The simulations utilize an approximately $50 \rho_s \times 50 \rho_s$ binormal box size, with $6.4 \rho_s$ wide radial buffers on either edge. The multiscale simulations include 368 toroidal modes with a spacing $\Delta n = 14$, corresponding to $\Delta k_\theta \rho_s = 0.12$ and spanning the range $0 \leq k_\theta \rho_s \leq 45$, 1536 radial grid points yielding $\Delta r = 0.04 \rho_s$ and an integration timestep $h = 0.001 a/c_s$. The ion-scale simulations use 8 toroidal modes to resolve $0 \leq k_\theta \rho_s \leq 0.86$, and 180 radial grid points ($\Delta r = 0.32 \rho_s$), and $h = 0.01 a/c_s$.

Linear growth rates calculated for this condition are plotted in Fig. 6, and show coexisting ITG and ETG instabilities very similar to what was observed for the C-Mod plasmas. Microtearing modes \[27\] are also observed to be linearly unstable at the longest resolved wavelengths, but no significant contributions to $Q_i$ from these modes are observed in the nonlinear simulations. The predictions of $Q_i$ and $Q_e$ from nonlinear ion- and multiscale simulations as a function of equilibrium $E \times B$ shearing rate $\gamma_{E\times B}$ are compared to power balance results in Fig. 7. The scan was performed with respect to $\gamma_{E\times B}$ rather than $a/L_{Ti}$ or $a/L_{Te}$ because of the much larger experimental uncertainty in the shearing rate. As in the C-Mod simulations, ion-scale simulations are able to match the power balance $Q_i$ calculation within the experimental uncertainty on $\gamma_{E\times B}$, but systematically underpredict $Q_e$; multiscale simulations match both. However, we emphasize that these results should be treated as preliminary because the simulations exhibit significant temporal variations and additional time-averaging (currently in progress) is needed. The $Q_e$ wavenumber spectra of the multiscale simulations are shown in Fig. 7c; in both cases high-$k$ fluctuations contribute more than half of the total $Q_e$. Also shown in Fig. 7a and 7b are predictions of $Q_i$ and $Q_e$ from ion-scale simulations with $100 \rho_s \times 100 \rho_s$ box sizes. These simulations predict systematically

**FIG. 6.** Linear growth rates of (●) MTM, (○) ITG, and (□) ETG modes at $\rho_{\text{tor}} = 0.65$ of the DIII-D IBS discharge shown in Fig. 4.

**FIG. 7.** Scaling of (a) $Q_i$ and (b) $Q_e$ predicted by $50 \rho_s \times 50 \rho_s$ (●) ion-scale and (□) multiscale GYRO simulations of the DIII-D IBS discharge, as a function of $E \times B$ shearing rate $\gamma_{E\times B}$ normalized to the experimental value. Results from a corresponding $100 \rho_s \times 100 \rho_s$ ion-scale simulation (○) show higher levels but the same general trend as $50 \rho_s \times 50 \rho_s$ case. Low-$k$ (●) and high-$k$ (▲) contributions to the multiscale $Q_e$ show more than 50% of total flux comes from high-$k$ fluctuations. (c) Wavenumber spectra of $Q_e$ for multiscale simulations shown in (a) and (b).
higher fluxes than the 50 ρs x 50 ρs ion-scale simulations, as well as weaker temporal variability, but exhibit the same response to variations in γE×B. Moreover, the larger box-size simulations predict the same ratio of \( \frac{Q_e}{Q_i} \approx 1.1 \) as the smaller simulations for all values of \( \gamma_{E\times B} \), which is inconsistent with the power balance result of \( \frac{Q_e}{Q_i} = 2.1 \). Larger box-size multiscale simulations would be desirable, but are not yet practically feasible with current machine memory limitations and GYRO performance levels. To address this limitation, the new CGYRO code [28] is currently being optimized to enable more computationally efficient multiscale simulations on next-generation mixed architecture platforms. Nonetheless, while the multiscale may not be fully converged in domain size, we believe they provide clear evidence for high-k fluctuations contributing significantly to electron thermal transport levels in reactor-relevant conditions.

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