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Synergistic Cross-Scale Coupling of Turbulence in a Tokamak Plasma

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Synergistic Cross-Scale Coupling of Turbulence in a Tokamak Plasma

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For the first time, realistic, nonlinear gyrokinetic simulations spanning both the ion and electron spatio-temporal scales have demonstrated the coexistence of ion ($k_\theta \rho_s \sim \mathcal{O}(1.0)$) and electron-scale ($k_\theta \rho_e \sim \mathcal{O}(1.0)$) turbulence in the core of a tokamak plasma and the possible explanation of a documented discrepancy between simulation and experiment. These cutting-edge, multi-scale simulations utilized the GYRO code [J. Candy and R.E. Waltz, J Comput. Phys. **186**, 545 (2003)] to study the coupling of ion and electron-scale turbulence in the core (r/a = 0.6) of an Alcator C-Mod L-mode discharge shown previously to exhibit an under-prediction of the electron heat flux when using simulations only including ion-scale turbulence. Electron-scale turbulence is found to play a dominant role in setting the electron heat flux level and radially-elongated "streamers" are found to coexist with larger ion-scale eddies in experimental plasma conditions. Inclusion of electron-scale turbulence in these simulations is found to increase both ion and electron heat flux levels by enhancing the transport at the ion-scale while also driving electron heat flux at sub-ρ_i scales. These results suggest that previously observed discrepancies in the electron heat flux may be explained by inclusion of electron-scale contributions in gyrokinetic simulation.

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I. INTRODUCTION

Despite decades of research, anomalous electron heat transport in fusion plasmas is still not well understood and is extremely important to the success of ITER and future fusion reactors. It is generally believed that most anomalous transport observed in magnetic fusion devices is the result of long-wavelength ($k_\theta \rho_s < 1.0$), drift-wave-type instabilities driven unstable by free energy in the plasma's background gradients[1]. Here k_θ is the perpendicular wavenumber, $\rho_s = c_s/\Omega_{ci}$ is the sound speed gyroradius, $\Omega_{ci} = eB/m_i c$ is the ion gyrofrequency, and $c_s = \sqrt{T_e/m_i}$ is the sound speed. Due to their large eddy size and low frequency, the most virulent of these instabilities are identified as Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM). However, recent experimental evidence[234] suggests this paradigm may not be sufficient for describing electron transport in the tokamak core. Using gyrokinetic simulations focused on electron-scale turbulence, Dorland *et al.* demonstrated that short wavelength electron temperature gradient (ETG) driven turbulence could form radially elongated structures known as ETG "streamers"[5] that are capable of driving experimental levels of electron heat transport[6]. However, the actual role of streamers has been unclear, as the presence of ion-scale turbulence has been predicted to shear these structures apart, destroying their impact on the electron heat transport[7]. As a result, ETG is generally thought to be significant in plasma conditions where the role of ion-scale turbulence is limited, i.e. by ExB shear suppression[8,9], electron internal transport barriers[10], or in conditions similar to the H-mode pedestal[11], leaving the origin of electron transport under many more "standard" conditions not well understood.

Investigation of high-k ($k_\theta \rho_s > 1.0$) ETG turbulence using gyrokinetic simulation has, to date, focused predominantly on electron-scale simulation[5,6,9,10,12]. In conditions with unstable low-k ($k_\theta \rho_s < 1.0$) turbulence, such simulations do not provide an accurate representation of reality, as they do not include long wavelength, ion-scale dynamics or the coupling between the two turbulence scales. Research into the cross-scale coupling in plasmas is not limited to fusion devices. Experiment and simulation of ion and electron-scale turbulence coupling is an active area of research in both astrophysical and space plasmas[13,14]. However, due to the extreme computational requirements, examples of multi-scale simulation, which captures coupling of the turbulent scales, are extremely limited[8,11,15–18] in fusion devices. All previous multi-scale work has utilized unphysical values of the electron mass ratio, typically $(m_D/m_e)^{1/2}$ =20.0 or 30.0, to lessen computational demands and generally was performed on model parameters (such as circular geometry and modeled values of turbulence drives). While in some cases, these approximations may yield qualitative understanding of cross-scale coupling, it has also been demonstrated to be insufficient for simulation of some plasma conditions near ITG marginal stability (a common condition in the core of tokamak plasmas)[18], and can not be quantitatively compared with experimental heat fluxes. In this paper we present first-of-a-kind, multi-scale simulations of a magnetically confined fusion plasma performed with all experimental input parameters and realistic electron mass ratio, $(m_D/m_e)^{1/2}$ =60.0. It should be emphasized that the work presented here is not a model validation exercise. Instead, we attempt to answer the question: In realistic plasma conditions that exhibit significant ion-scale turbulence, can electron-scale turbulence drive experimentally relevant levels of electron heat flux? In the sections below these new simulations demonstrate 1.) The coexistence of ion and electron-scale turbulence in the core (r/a=0.6) of a fusion plasma 2.) enhancement of low and high-k driven heat transport by high-k turbulence dynamics and 3.) the first quantitative comparison of multi-scale simulation with experimental heat flux levels which demonstrates that electron-scale turbulence can drive experimental levels of electron heat flux in the presence of ion-scale turbulence and may explain a known discrepancy between simulation and experiment.

II. EXPERIMENTAL AND SIMULATION SETUP

All work in this paper focuses on a low-power Alcator C-Mod L-Mode plasma discharge that has been described previously[18–21]. We emphasize that this plasma possesses no unique characteristics and represents a standard L-mode discharge operated with 1.2 MW of Ion Cyclotron Resonance Heating (ICRH), a core density of approximately 1.4×10^{20} m^{-3}, a plasma current of 0.8 MA, and a magnetic field of 5.4 T. This discharge was chosen for study based on results from previous, ion-scale simulation where agreement between simulation and experiment was identified in the ion heat and impurity particle channels while an under-prediction ($\sim 3\times$) was reported in the electron heat flux[19–21]. In these previous works, scans of the turbulence drive terms a/L_{T_i}, a/L_{T_e}, a/L_n, n_i/n_e, and $E \times B$ shear were performed using ion-scale simulations ($k_\theta \rho_s < 1.3$) to demonstrate that the under prediction of the electron heat flux is robust within experimental uncertainties. It was speculated that the

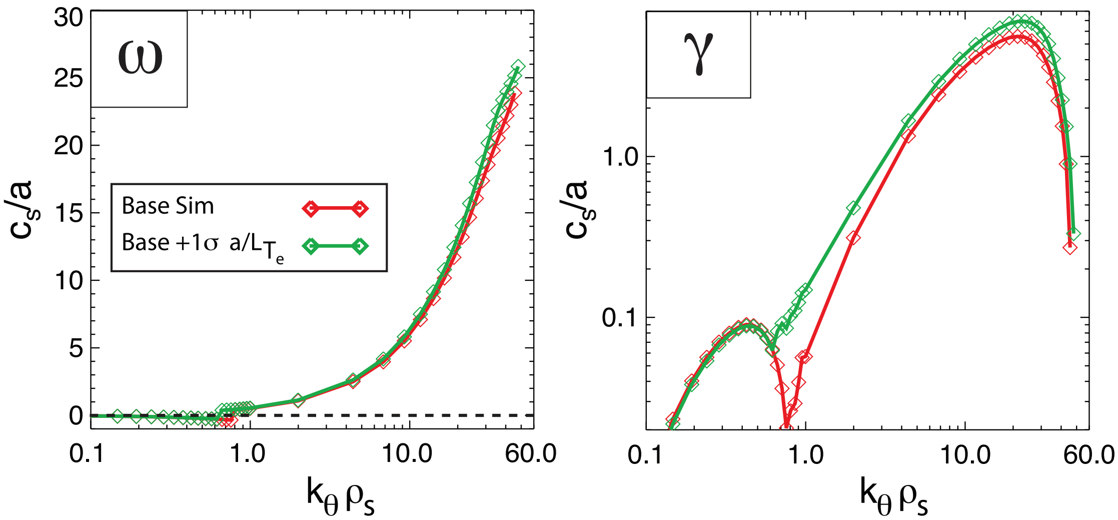

FIG. 1. (Color Online) The linear growth rates of modes spanning the ion and electron scales are plotted for the base case simulation parameters (red) and the base case + 1σ in a/L_{T_e} (green).

discrepancy in the electron heat flux may be due to high-k TEM/ETG contributions that are not captured by standard ion-scale simulation.

III. SIMULATION RESULTS

All linear and nonlinear simulation work is based on massively parallel simulations performed using the GYRO code[22,23]. Due to the low-beta nature of the discharge, all simulations were electrostatic. Each simulation included rotation effects (E×B rotation shear, Coriolis drift effects, and parallel flow gradients) electron-ion collisions, debye shielding effects, Miller geometry parameterization[24], and a standard 128 point velocity space discretization (8 pitch angles, 8 energies, and 2 signs of velocity). Simulations included 3 gyrokinetic species: deuterium ions, electrons, and a single boron impurity species (the dominant impurity species in the experimental discharge). The final simulations presented in this paper were performed as follows: Ion-scale simulation (long wavelength only) used 8 toroidal modes, 32 $\times$ $32\rho_s$ simulation boxes (radial x binormal directions), 134 radial grid points, grid spacing of $0.33\rho_s$, and captured dynamics up to $k_\theta\rho_s = 1.4$. The full multi-scale simulations (coupled short and long wavelengths) used 240 toroidal modes, 32 $\times$ $32\rho_s$ simulation boxes, 1320 radial grid points, grid spacing of $2\rho_e$, and captured short and long wavelength turbulence dynamics up to $k_\theta\rho_s = 48.0 \leftrightarrow k_\theta\rho_e = 0.8$. The choice of maximum simulated value of $k_\theta \rho_s$ was chosen to effectively capture the linearly unstable modes (see Figure 1) and limited by the availability of resources. Given the extreme computational requirements of the multi-scale simulations, convergence tests were performed on the corresponding ion-scale simulations. Ion-scale simulations with a $32 \times 32\rho_s$ box (Q_i = 0.071; Q_e = 0.062) can reproduce time averaged heat fluxes (MW/m^2) obtained from $112\times\ 112\rho_s$ simulation boxes $Q_i = 0.076$; $Q_e = 0.062$). To further ensure accuracy in the results, multi-scale simulations were run well into the saturated state ($\sim 350 - 380\ a/c_s$). Even with optimization of the numerical settings, the multi-scale simulations pushed the limits of current computing and are amongst the most computationally expensive plasma turbulence simulations to date. They utilized approximately 18k processors and required approximately 20 Million CPU hours on the NERSC Hopper supercomputer for the completion of 2 simulations presented.

The input profiles utilized are very similar to previous numerical simulation of this discharge[18], with slight changes due to the choice of profile averaging window (1.0-1.4 sec) and an updated analysis on the rotation profiles. The value of the a/L_{T_i} has been modified from its experimental value, within estimated uncertainty, to match the simulated ion heat flux obtained from ion-scale simulation to the experimental value. The input values for base simulations are summarized here: $r/a = 0.6$, $a = 0.22$ (m), $n_e = 1.07$ (1e20), $T_e = 1.03$ (keV), $\rho_s = 0.65$ (mm), $a/L_n = 1.01$, $a/L_{T_e} = 3.28$, $a/L_{T_i} = a/L_{T_B} = 1.92$, $T_i/T_e = T_B/T_e = 0.98$, $n_D/n_e = 0.875$, $\mathrm{Z_{eff}} = 1.90$, $q = 1.56$, $s = 1.36$, κ=1.24, δ=0.11, $\nu_{ei}(a/c_s)$=0.18, $\gamma_{ExB}(a/c_s)$=0.04, and $a/c_s(\mu s)$=0.99.

To understand the linear instability of ITG, TEM, and ETG in the discharge of interest, initial value, linear gyrokinetic simulations were performed spanning $k_\theta \rho_s = 0.1$ to 60.0 as summarized in Figure 1. For the base simulation parameters, the linear spectra from this discharge is dominated by ITG modes (ion direction (-) and sensitive to a/L_{T_i} variation) below $k_\theta \rho_s < 0.8$. Previous ion-scale analysis of this discharge has revealed its ion heat flux-matched conditions to sit just above the nonlinear critical gradient to ITG, suggesting this plasma condition is marginally stable to low-k ITG turbulence[21]. However, at higher-k, ($> k_\theta \rho_s = 0.8$) electron modes, identified as TEM/ETG, become the dominant linear instability. The simple linear picture indicates that ETG remains unstable up to $k_\theta \rho_s \sim 48.0$ $\leftrightarrow k_\theta \rho_e \sim 0.8$, with only stable linear modes existing above this value. This observation motivates our choice for the maximum simulated $k_\theta \rho_s$ value in the multi-scale simulations.

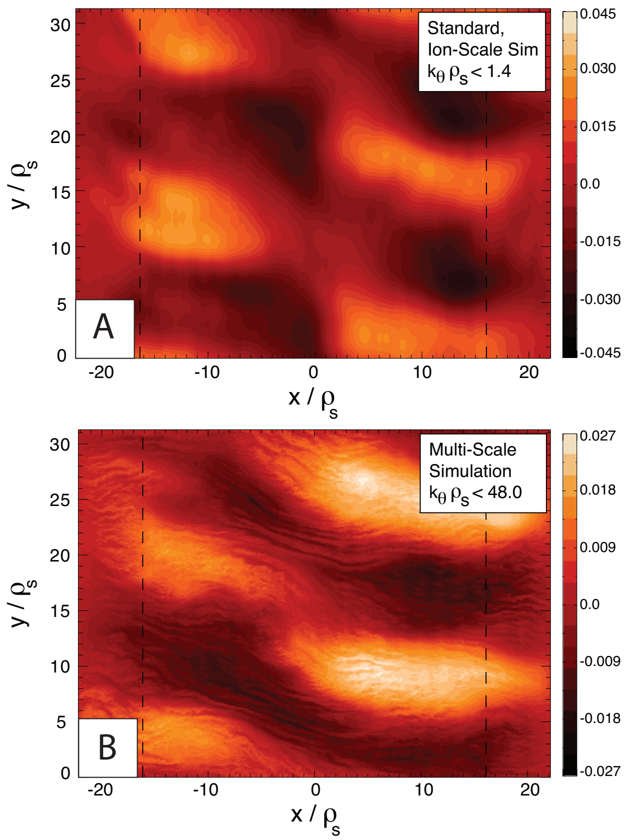

FIG. 2. (Color Online) Snapshots of the potential fluctuations obtained from long wavelength, ion-scale simulation (a) and coupled short and long wavelength, multi-scale simulation (b). The coexistence of ion-scale eddies and the radially elongated ETG streamers is clearly demonstrated in the multi-scale simulation The dotted lines indicate the boundary between the physical simulation domain and buffer regions.

However, to understand the coupling of the ion and electron-scale turbulence and the effects of any subdominant modes not revealed in the linear simulations, we turn to nonlinear simulation of this discharge. Snapshots of the potential fluctuations obtained from nonlinear simulation results corresponding to pure ion-scale ($k_\theta \rho_s < 1.4$) and coupled ion/electron-scale simulation ($k_\theta \rho_s < 48.0$) are shown in Figure 2 in panels a and b respectively.

The snapshot of the potential obtained from ion-scale simulation (Figure 2a) displays the presence of large ion-scale eddies associated with the unstable ITG turbulence in this discharge, while the coupled, multi-scale simulation (Figure 2b) demonstrates coexistence of the ion-scale eddies with clearly defined ETG streamers. The extent of these ETG driven structures is generally quite small in the θ direction with an extent in the radial direction

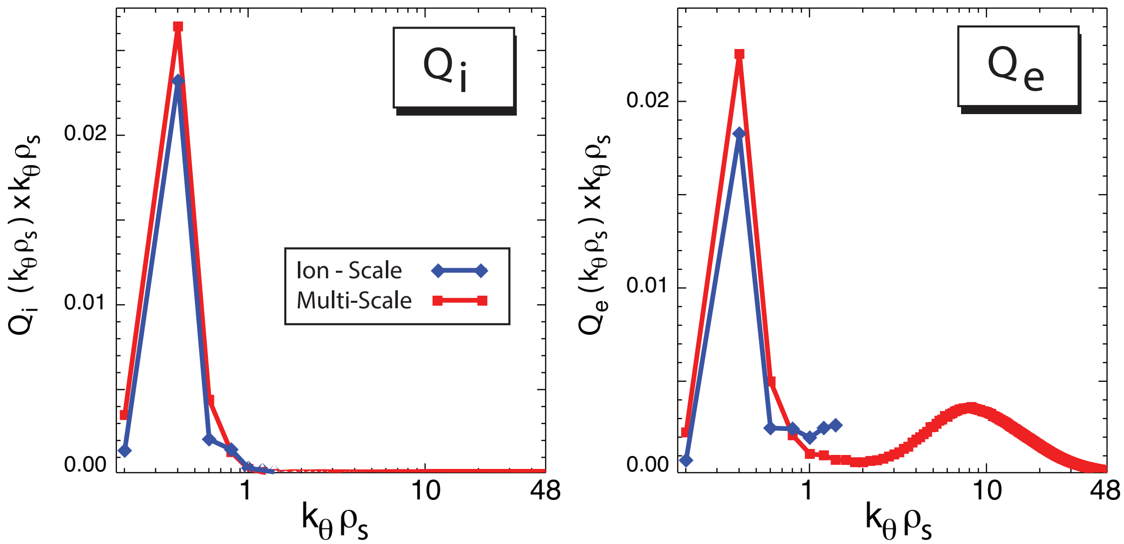

FIG. 3. (Color Online) The heat flux spectra obtained from ion (blue) and multi-scale (red) base simulations are plotted.

of $\sim 6 - 12\rho_s$. However, the visualizations of Figure 2 alone do not provide quantitative insight into the dynamics or relevance of the high-k turbulence. To better quantify the contributions and coupling of the scales, we plot the ion and electron heat flux spectra (see Figure 3) from both the ion-scale and multi-scale base simulations. We adopt a variation of the approach used by Görler and Jenko for plotting of the heat flux spectra such that the area underneath the spectra is approximately representative of the contributions to the heat flux from low and high-k[17].

The ion heat flux spectra obtained from pure ion-scale simulation appears very similar to the multi-scale result, with approximately 99.9% of the total heat flux arising from contributions below $k_\theta\rho_s = 1.0$. In contrast, the electron heat flux spectra indicate a more complicated interaction of the ion and electron scales. The electron heat flux spectra obtained from coupled simulation displays two separate peaks: A low-k peak that occurs around $k_\theta\rho_s = 0.4$, that corresponds to the dominant scale for the ITG turbulence in the simulation and a high-k peak centered around $k_\theta\rho_s = 6.0 \leftrightarrow k_\theta\rho_e = 0.1$ that corresponds to ETG streamers present in the multi-scale simulation. Comparison of the heat fluxes obtained from ion-scale simulation to those obtained via coupled simulation reveals a complicated interaction of the low and high-k turbulence and is summarized in Table I. Despite the fact that all of the ion heat flux is driven at scales below $k_\theta\rho_s = 1.0$ for both the ion and

TABLE I. The ion and electron heat fluxes (MW/m^2) from the ion-scale and multi-scale base simulations are shown.

Quantity	Ion-Scale	Multi-Scale	Change
Q_i (all $k_\theta \rho_s$)	0.071	0.093	+31%
Q_i ($k_\theta \rho_s < 1.0$)	0.071	0.093	+31%
Q_i ($k_\theta \rho_s > 1.0$)	n/a	0.000	n/a
Q_e (all $k_\theta \rho_s$)	0.062	0.111	+79%
Q_e ($k_\theta \rho_s < 1.0$)	0.058	0.079	+36%
Q_e ($k_\theta \rho_s > 1.0$)	n/a	0.032	n/a

multi-scale simulations, the inclusion of the high-k turbulence in the multi-scale simulation is found to increase the total ion heat flux by $\sim$ 31%, indicating that the electron-scale turbulence plays an important indirect role in the determination of the ion heat flux. In the electron channel, the effect of the electron-scale turbulence is significant, increasing the total driven electron heat flux by 79% above the ion-scale result. However, the distribution of this heat flux is even more intriguing as inclusion of the high-k turbulence enhances the electron heat flux driven at long wavelengths by 36% with the remainder of the electron heat flux driven at high-k. In fact, high-k contributions represent $\sim$ 29% of the total multi-scale electron heat flux. It appears as though the role of electron-scale turbulence is both to enhance the low-k turbulence while driving electron heat flux at the high-k in the form of the ETG streamers. The enhancements found in the low-k driven ion and electron heat fluxes have important implications for comparisons of ion-scale turbulence simulation with experiment, as they suggest that quantitative comparison might be significantly altered by inclusion of electron-scale contributions.

In an attempt to understand the enhancement of low-k transport in the multi-scale simulation, the low-k RMS fluctuation levels, radial correlation lengths, and phase angles of the turbulent fluctuations were evaluated from the outputs of both the ion and multi-scale simulations. A comparison of these derived simulation outputs are found in Table II. This analysis reveals increases ($10-15\%$) in the ϕ, T_e, and T_i RMS fluctuation levels with slightly larger relative increases found in the density fluctuations ($\sim$ 25%). With the exception of

TABLE II. The finite-n, low-k ($k_\theta \rho_s < 1.0$) RMS fluctuation levels, radial correlation lengths (l_r), and phase angles (α in radians), obtained from the ion and multi-scale simulations are shown for the main ions and electrons.

Quantity	Ion-Scale	Multi-Scale	Change
$e\tilde{\phi}/T_e$	1.11%	1.27 %	+14%
$l_{r,\phi}(\rho_s)$	8.35	8.50	+2%
$\tilde{T}_e/T_e$	1.01 %	1.14%	+13%
$l_{r,T_e}(\rho_s)$	6.49	7.26	+12%
$\tilde{T}_i/T_i$	1.15 %	1.30%	+13%
$l_{r,T_i}(\rho_s)$	7.27	7.23	-.5%
$\tilde{n}_e/n_e$	.70 %	.87%	+24%
$l_{r,n_e}(\rho_s)$	7.00	7.26	+4%
$\tilde{n}_i/n_i$	.85 %	1.08%	+27%
$l_{r,n_i}(\rho_s)$	7.67	7.46	-3%
α_{n_i,T_i} ($k_\theta \rho_s = 0.4$)	1.77	1.83	+3%
α_{n_e,T_e} ($k_\theta \rho_s = 0.4$)	2.53	2.53	0%
α_{ϕ,T_i} ($k_\theta \rho_s = 0.4$)	1.60	1.69	+6%
α_{ϕ,T_e} ($k_\theta \rho_s = 0.4$)	2.49	2.49	0%

a 12% increase in the radial correlation length of the electron temperature, all other correlation lengths are effectively unchanged between the simulations. The phase angles in Table II were evaluated at $k_\theta \rho_s = 0.4$, the peak in the low-k ion and electron heat fluxes. Again, no significant change in the phase angles is found, suggesting that the observed low-k enhancement of the low-k heat fluxes arises almost exclusively from the combined effect of small increases in the fluctuation levels and not a shift in the phase of the fluctuations.

The presented multi-scale simulation work was motivated by understanding a robust under-prediction of the experimental electron heat flux predicted by ion-scale simulation. Therefore, we wish to asses whether, in the presence of significant ion-scale turbulence, electron-scale turbulence can drive experimentally relevant levels of electron heat transport. To answer this question, we plot a comparison of the heat fluxes obtained from ion-scale and

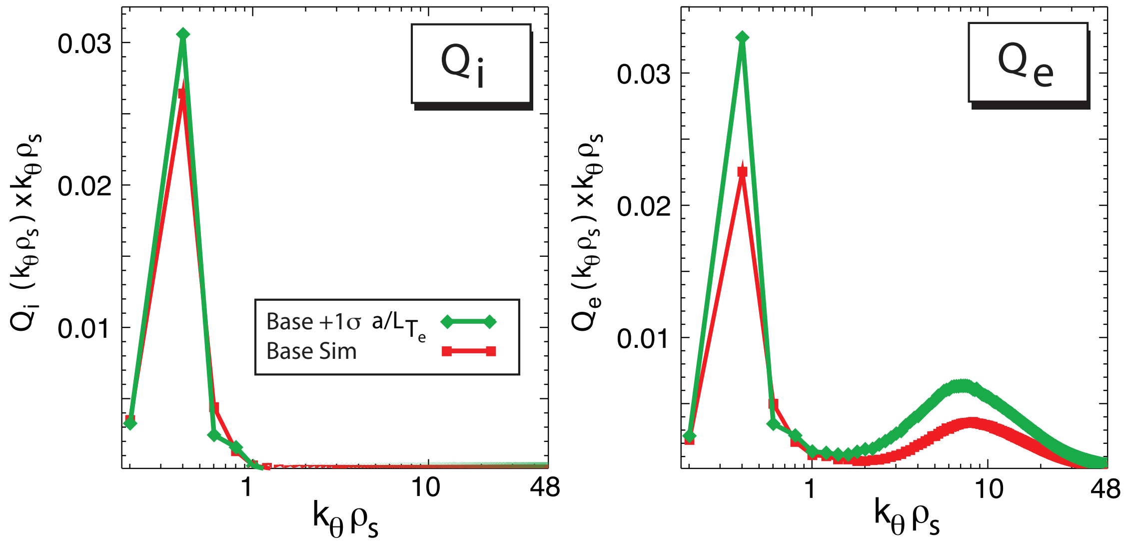

FIG. 4. (Color Online) The ion and electron heat flux spectra obtained from the multi-scale base case simulation and the multi-scale +1 σ simulation are plotted.

multi-scale simulations with experiment in Figure 5. The "base case" simulations referred to below indicate simulations with no modification of the experimental turbulence drive, a/L_{T_e}. The initial ion-scale base case simulation displayed an approximately 3× under-prediction of the electron heat flux while approximately matching the mean of the experimental ion heat flux. Increases in the low and high-k driven heat flux obtained via multi-scale simulation produced ion heat fluxes still in quantitative agreement with experiment and electron heat fluxes significantly closer to matching the experimental levels. The observed (79%) increase in the total electron heat flux originating from the inclusion of electron-scale turbulence motivated an additional multi-scale simulation.

Although it would be desirable to examine the sensitivity of the multi-scale results to all uncertainties in turbulence drive terms, the extreme computational requirements limited our investigation to only a single additional simulation. For an in-depth investigation of the ion-scale simulation sensitivities to experimental uncertainties, the reader is referred to Reference[21]. Here, we attempt to answer a simple question: In realistic plasma conditions that exhibit significant ion-scale turbulence, can electron-scale turbulence drive experimentally relevant levels of electron heat flux? As the high-k contributions are TEM/ETG in nature, this turbulence should respond sensitively to changes in the drive term, a/L_{T_e} (Figure 1) and may have a significant impact on the nonlinear electron heat flux while leaving the ion heat flux relatively unchanged. A second multi-scale simulation was completed with an increase in the ETG drive, a/L_{T_e} within its 1σ experimental uncertainty of 12.5%. A comparison of the heat flux spectra obtained from multi-scale base case and multi-scale $+1\sigma$ simulation is found in Figure 4 and a direct comparison of the ion-scale base, ion-scale $+1\sigma$, multi-scale base, and multi-scale $+1\sigma$ simulations with experimental ion and electron heat fluxes in found in Figure 5.

The heat flux spectra obtained from both multi-scale simulations are similar in shape, with a slight downshift of the high-k electron peak to longer wavelengths ($k_\theta \rho_s \sim 5.2$) in the multi-scale $+1\sigma$ simulation. The total ion heat flux obtained from this simulation remains driven almost entirely at low-k, consistent with the multi-scale base case. Relative to the ion-scale base simulation, the low-k driven electron heat flux increases by $\sim 79\%$ in the multi-scale $+1\sigma$ simulation. Ion-scale simulation with a 1σ increase a/L_{T_e} results in a slightly reduced ion heat flux (-3%) and only a slight increase in electron heat flux (+11%). Therefore, consistent with the multi-scale base case, the enhancement of the low-k electron heat flux is determined to result predominantly from the inclusion of the high-k turbulence. The electron heat flux driven at high-k is found to increase by 80% relative to the multi-scale base case and represents 36% of the total electron heat flux. Overall, relative to the ion-scale base simulation, a 162% increase in the total electron heat flux is found which moves the electron heat flux to experimental levels. When the uncertainty in the experimental and simulated heat fluxes are considered, the multi-scale electron and ion heat fluxes are now found to be in quantitative agreement with the experiment. This result suggest that electron-scale turbulence may explain the robust Q_e under-prediction observed in this discharge[18–21] and demonstrates for the first time that, in realistic plasma conditions with significant ion-scale turbulence, electron-scale turbulence can drive experimentally relevant levels of electron heat flux.

In summary, the simulations presented here demonstrated the coexistence of ion and electron-scale turbulence in the core (r/a=0.6) of a standard tokamak plasma, indicate that low-k turbulence is enhanced by the inclusion of high-k dynamics, and demonstrate that, in the presence of significant ion-scale turbulence, electron-scale turbulence can drive experimental levels of electron heat flux. This mechanism may resolve some known discrepancies between ion-scale simulation and experiment and represents an important step towards a predictive model for fusion plasmas.

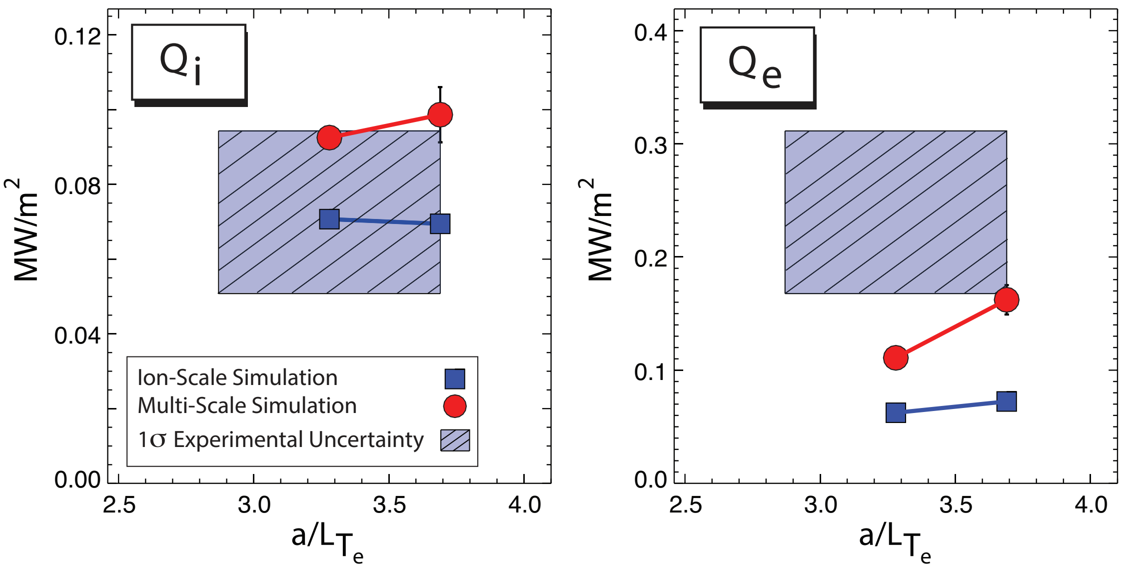

FIG. 5. (Color Online) The ion and electron heat fluxes obtained from ion-scale (blue) and multi-scale base (red) simulations are shown at r/a = 0.6. The shaded region is formed by 1σ uncertainties in the experimental heat fluxes and the turbulence drive a/L_{T_e}. Agreement with experiment is found if the simulation points lie within this region. Representative simulation uncertainties are plotted on the +1σ multi-scale simulation.

IV. ACKNOWLEDGEMENTS

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REFERENCES

[1]W. Horton. Drift waves and transport. *Review of Modern Physics*, **71**(3), (1999).

[2]E. Mazzucato, D. R. Smith, R. E. Bell, S. M. Kaye, J. C. Hosea, B. P. LeBlanc, J. R. Wilson, P. M. Ryan, C. W. Domier, N. C. Luhmann, H. Yuh, W. Lee, and H. Park. Short-scale turbulent fluctuations driven by the electron-temperature gradient in the national spherical torus experiment. *Phys. Rev. Lett.*, 101:075001, Aug 2008.

[3]D. R. Smith, S. M. Kaye, W. Lee, E. Mazzucato, H. K. Park, R. E. Bell, C. W. Domier, B. P. LeBlanc, F. M. Levinton, N. C. Luhmann, J. E. Menard, and H. Yuh. Observations of reduced electron gyroscale fluctuations in national spherical torus experiment h-mode plasmas with largeflow shear. *Phys. Rev. Lett.*, 102:225005, Jun 2009.

[4]T. L. Rhodes, W. A. Peebles, M. A. Van Zeeland, J. S. deGrassie, R. V. Bravenec, K. H. Burrell, J. C. DeBoo, J. Lohr, C. C. Petty, X. V. Nguyen, E. J. Doyle, C. M. Greenfield, L. Zeng, and G. Wang. Response of multiscale turbulence to electron cyclotron heating in the diii-d tokamaka). *Physics of Plasmas (1994-present)*, 14(5):–, 2007.

[5]W. Dorland, F. Jenko, M. Kotschenreuther, and B. N. Rogers. Electron temperature gradient turbulence. *Phys. Rev. Lett.*, 85:5579–5582, Dec 2000.

[6]F. Jenko and W. Dorland. Prediction of significant tokamak turbulence at electron gyroradius scales. *Phys. Rev. Lett.*, 89:225001, Nov 2002.

[7]C. Holland and P. H. Diamond. A simple model of interactions between electron temperature gradient and drift-wave turbulence. *Physics of Plasmas (1994-present)*, 11(3):1043–1051, 2004.

[8]L. Schmitz, C. Holland, T.L. Rhodes, G. Wang, L. Zeng, A.E. White, J.C. Hillesheim, W.A. Peebles, S.P. Smith, R. Prater, G.R. McKee, Z. Yan, W.M. Solomon, K.H. Burrell, C.T. Holcomb, E.J. Doyle, J.C. DeBoo, M.E. Austin, J.S. deGrassie, and C.C. Petty. Reduced electron thermal transport in low collisionality h-mode plasmas in diii-d and the importance of tem/etg-scale turbulence. *Nuclear Fusion*, 52(2):023003, 2012.

[9]W. Guttenfelder, J.L. Peterson, J. Candy, S.M. Kaye, Y. Ren, R.E. Bell, G.W. Hammett, B.P. LeBlanc, D.R. Mikkelsen, W.M. Nevins, and H. Yuh. Progress in simulating turbulent electron thermal transport in nstx. *Nuclear Fusion*, 53(9):093022, 2013.

[10]J. L. Peterson, R. Bell, J. Candy, W. Guttenfelder, G. W. Hammett, S. M. Kaye, B. LeBlanc, D. R. Mikkelsen, D. R. Smith, and H. Y. Yuh. Suppressing electron turbulence and triggering internal transport barriers with reversed magnetic shear in the national spherical torus experiment. *Physics of Plasmas*, 19(5):056120, 2012.

[11]F. Jenko. On the nature of etg turbulence and cross-scale coupling. *Journal of Plasma and Fusion Research*, 11, 2004.

[12]N Joiner, D Applegate, S C Cowley, W Dorland, and C M Roach. Electron temperature gradient driven transport in a mast h-mode plasma. *Plasma Physics and Controlled Fusion*, 48(5):685, 2006.

[13]StevenJ. Schwartz, Timothy Horbury, Christopher Owen, Wolfgang Baumjohann, Rumi Nakamura, Patrick Canu, Alain Roux, Fouad Sahraoui, Philippe Louarn, Jean-Andr Sauvaud, Jean-Louis Pinon, Andris Vaivads, MariaFederica Marcucci, Anastasios Anastasiadis, Masaki Fujimoto, Philippe Escoubet, Matt Taylor, Steven Eckersley, Elie Allouis, and Marie-Claire Perkinson. Cross-scale: multi-scale coupling in space plasmas. *Experimental Astronomy*, 23(3):1001–1015, 2009.

[14]G. G. Howes, J. M. TenBarge, W. Dorland, E. Quataert, A. A. Schekochihin, R. Numata, and T. Tatsuno. Gyrokinetic simulations of solar wind turbulence from ion to electron scales. *Phys. Rev. Lett.*, 107:035004, Jul 2011.

[15]J Candy, R E Waltz, M R Fahey, and C Holland. The effect of ion-scale dynamics on electron-temperature-gradient turbulence. *Plasma Physics and Controlled Fusion*, 49(8):1209, 2007.

[16]R. E. Waltz, J. Candy, and M. Fahey. Coupled ion temperature gradient and trapped electron mode to electron temperature gradient mode gyrokinetic simulations. *Physics of Plasmas*, 14(5):056116, 2007.

[17]T. Görler and F. Jenko. Scale separation between electron and ion thermal transport. *Phys. Rev. Lett.*, 100:185002, May 2008.

[18]N.T. Howard, A.E. White, M Greenwald, C Holland, and J Candy. Multi-scale gyrokinetic simulation of tokamak discharges. *Accepted for Publication in Physics of Plasmas*, 2014.

[19]N. T. Howard, A. E. White, M. Greenwald, M. L. Reinke, J. Walk, C. Holland, J. Candy, and T. Gorler. Investigation of the transport shortfall in alcator c-mod l-mode plasmas. *Physics of Plasmas*, 20(3):032510, 2013.

[20]A. E. White, N. T. Howard, M. Greenwald, M. L. Reinke, C. Sung, S. Baek, M. Barnes, J. Candy, A. Dominguez, D. Ernst, C. Gao, A. E. Hubbard, J. W. Hughes, Y. Lin, D. Mikkelsen, F. Parra, M. Porkolab, J. E. Rice, J. Walk, S. J. Wukitch, and Alcator C-Mod Team. Multi-channel transport experiments at alcator c-mod and comparison with gyrokinetic simulations. *Physics of Plasmas*, 20(5):056106, 2013.

[21] N.T. Howard, A.E. White, M. Greenwald, M.L. Reinke, C. Holland, J. Candy, and J.R. Walk. Validation of the gyrokinetic model in itg and tem dominated l-mode plasmas. *Nuclear Fusion*, 53(12):123011, 2013.

[22] J. Candy and R. E. Waltz. Anomalous transport scaling in the DIII-D tokamak matched by supercomputer simulation. *Phys. Rev. Lett.*, 91:045001, Jul 2003.

[23] J. Candy and R.E. Waltz. An eulerian gyrokinetic-maxwell solver. *Journal of Computational Physics*, 186(2):545 – 581, 2003.

[24] R. L. Miller, M. S. Chu, J. M. Greene, Y. R. Lin-Liu, and R. E. Waltz. Noncircular, finite aspect ratio, local equilibrium model. *Physics of Plasmas*, 5(4):973–978, 1998.