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Overview of multiscale turbulence studies covering ion-to-electron scales in magnetically confined fusion plasma

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OVERVIEW OF MULTISCALE TURBULENCE STUDIES COVERING ION-TO-ELECTRON SCALES IN MAGNETICALLY CONFINED FUSION PLASMA

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Abstract

Turbulent transport in magnetically confined fusion plasma has conventionally been analyzed at the ion gyroradius scale based on the microturbulence theory. However, ion-scale turbulence analysis sometimes fails to predict the turbulent transport flux observed experimentally. Microturbulence at the electron gyroradius scale and cross-scale interactions between disparate-scale turbulences are possible mechanisms to resolve this issue. This overview discusses the recent progress in multiscale turbulence studies and presents future perspectives from recent experimental, theoretical, and numerical investigations. The following aspects are highlighted: (1) the importance of electron-scale effects in experiments, (2) the physical mechanisms of cross-scale interactions, (3) modeling electron-scale effects in quasilinear transport models, and (4) the impacts of cross-scale interactions on burning plasmas. Understanding multiscale turbulence is necessary to improve performance prediction and explore optimal operations for future burning plasmas.

1. INTRODUCTION

Turbulent transport in magnetically confined plasma is inherently governed by multiscale physics. The associated microinstabilities have a wide spatial range from electron-to-ion gyroradius scales, separated by a factor of the square root of the ion-to-electron mass ratio if their temperatures are equal. Large-scale turbulence tends to cause large transport in a random walk diffusion process. Hence, ion-scale instabilities, such as ion temperature gradient (ITG) and trapped electron modes (TEM), are the leading causes of turbulent transport. However, electron-scale turbulence is still considered a candidate for electron heat transport because electron temperature gradient (ETG) modes can cause extreme heat transport by creating radially elongated eddies called streamers [1], [2]. Due to the wide spatiotemporal separation between electron-scale and ion-scale instabilities, their turbulent transport has long been analyzed separately in theoretical and numerical studies.

For more than ten years, gyrokinetic simulations, with the aid of flagship supercomputers and the development of high-performance computing techniques, have enabled the analysis of multiscale turbulence covering both electron and ion scales. Since direct numerical simulations of multiscale turbulence are computationally expensive, initial attempts were limited to cases with reduced mass ratios. Subsequently, it was observed that cross-scale interactions between electron- and ion-scale turbulence exist even under the real ion-to-electron mass ratio [3], [4]. Although the aforementioned studies focused on the interaction between the ion-scale ITG and the electron-scale ETG turbulence, the analyses have been gradually extended to different instabilities, such as the microtearing mode (MTM) or TEM, as well as to various devices, such as Alcator C-Mod, DIII-D, JET, TCV, and ASDEX Upgrade (AUG). The core plasma turbulent transport in existing devices is being discussed, and future burning plasma and its application to edge transport are also being considered. This is an excellent opportunity to review the present multiscale turbulence studies, extract the generic features of cross-scale interactions, and establish a common understanding of multiscale turbulent transport. It is also a good starting point for clarifying the research issues to be addressed in future multiscale turbulence studies.

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This overview paper is organized as follows. Section 2 compares numerical simulations and experimental results. Section 3 discusses a theoretical understanding of multiscale interaction is discussed. Section 4 explains the efforts to implement electron-scale effects in quasilinear transport models. Section 5 summarizes recent studies that predict cross-scale interactions in future burning plasma. Section 6 presents the concluding remarks and some perspectives for future studies.

2. IMPORTANCE OF ELECTRON-SCALE EFFECTS IN THE EXPERIMENTS

This section highlights some comparisons between numerical simulations and experiments, which indicate the importance of electron-scale effects. Electron-scale turbulence has two impacts. Firstly, it can directly lead to a considerable electron heat flux in some cases. Secondly, it can cause cross-scale interaction between ion and electron-scale turbulence, which can either enhance or reduce turbulent transport depending on the underlying physical mechanisms underlying the process. This section discusses the impact of electron-scale turbulence in the core and pedestal, starting with heat fluxes in tokamaks, and spherical tokamaks, followed by an examination of recent fluctuation measurements in a nonaxisymmetric torus device.

2.1. Historical background

Plasma turbulence at the ion or electron gyroradius scale is now widely considered to be responsible for anomalous transport of magnetically confined fusion plasma. Experimental studies of the internal transport barrier have shown that ion thermal transport is suppressed while electron transport remains high, indicating separation of the ion and electron transport channels [5], [6]. The first nonlinear gyrokinetic simulations of ETG turbulence reported that a radially elongated ETG streamer could be responsible for electron thermal transport, even in an ion transport barrier [1], [2]. Experimental measurements using varying electron cyclotron heating (ECH) revealed the relevance of electron thermal transport and electron-scale fluctuations [7], [8]. The subsequent gyrokinetic simulation studies have encountered difficulties in the nonlinear saturation of ETG turbulence, the role of the nonadiabatic ion model and large simulation domain [9], and the importance of cross-scale interactions between ETG and ion-scale turbulence. Owing to these numerical difficulties, direct comparisons between experiments and simulations have only progressed in recent years.

2.2. Electron heat flux in multi-channel transport

Several comparisons of gyrokinetic simulations with experiments have shown that ion-scale turbulence simulations failed to explain the experimentally observed turbulent heat fluxes. Fig. 1 is an example from an Alcator C-Mod L-mode plasma [10]. In ion-scale simulations, the ion and electron heat fluxes increase as the ion temperature inverse gradient scale length $a/L_{Ti} = (a/T_i)\mathrm{d}T_i/\mathrm{d}r$, where a and r are the minor radius of the torus and the generalized radial coordinate, respectively, increases within experimental uncertainty. At low a/L_{Ti}, the electron heat flux is too small, whereas the ion heat flux exceeds the experimental value at high a/L_{Ti}. Therefore, the ion-scale simulation failed to explain the experimental ion and electron heat fluxes simultaneously. Meanwhile, multiscale turbulence simulations resolving from the ion-to-electron scales successfully yielded ion and electron heat fluxes comparable to experimental values around $a/L_{Ti} = 1.8$. In addition to the consistency with experiments, the comparison between ion-scale and multiscale simulations provides interesting implications. First, the contribution of heat flux at low wavenumbers (low-k) appears to be greater than that observed in the ion-scale simulation. This indicates a potential increase in ion-scale turbulent transport due to the coupling with electron-scale turbulence. Second, in multiscale simulations, the contribution at high wavenumbers (high-k) is diminished as a/L_{Ti} increases. This is contrary to the negligible impact of a/L_{Ti} on linear ETG stability. Therefore, it can be inferred that ion-scale turbulence has a stabilizing effect on electron-scale turbulence. The importance of multiscale turbulence to electron heat transport has also been reported in an Alcator C-Mod, ELM-y H-mode plasma [11], and a DIII-D ITER baseline discharge [12], [13]. The finding in this section is significant because electron-scale turbulence can compensate for the lack of electron heat transport in ion-scale turbulence simulations by contributing to direct electron heat transport.

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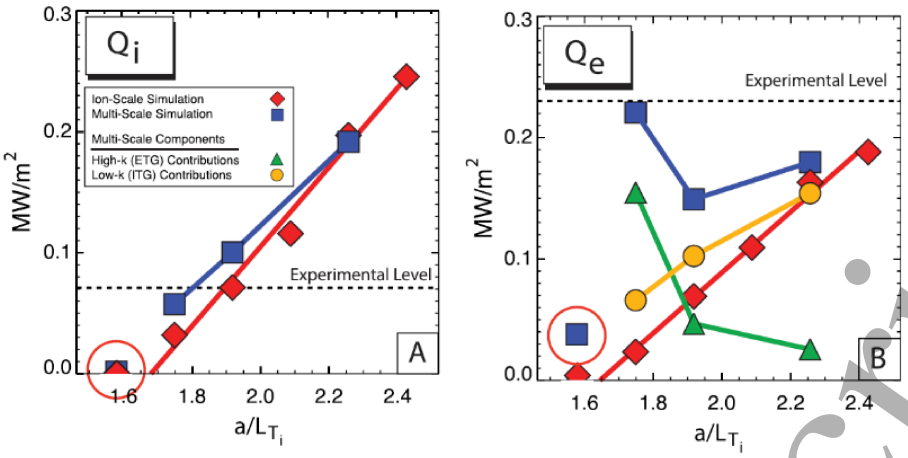

FIG. 1. (a) Ion and (b) electron heat fluxes Q_i and Q_e vs. ion temperature inverse gradient length a/L_{Ti} for the Alcator C-Mod experiments. Results from ion-scale (red) and multiscale (blue) simulations are compared with experimental heat flux levels (dashed). High-k and low-k contributions in multiscale simulations are represented by green and yellow dots in panel (b). Reprinted with permission from [10].

2.3. Electron temperature stiffness

The electron temperature stiffness observed in Alcator C-Mod [10], JET [14], [15], AUG, and TCV [16] experiments can also be understood as a signature of ETG turbulent transport. The stiffness of a profile refers to the extent to which the radial temperature profiles change in response to changes in the applied heat flux. When the electron temperature profile is stiff, it does not peak over a certain threshold even when the applied electron heat flux is increased, which limits the peaking of electron temperature. Fig. 2 shows the electron temperature gradient stiffness observed in an AUG H-mode discharge [16]. The heat flux scan and ECH power modulation, which probe the response of turbulent transport versus the electron temperature gradient, suggest a highly stiff response in the experiment. Ion-scale simulations did not reproduce the rapid increase of the electron heat flux against the electron temperature gradient. The multiscale simulation with ETG physics shows a rapid rise in the electron heat flux. This is attributed to the rapid enhancement of the electron-scale contribution in conjunction with an increase in ion-scale transport. This suggests that stiffness due to ETG turbulent transport can limit electron temperature peaking. Advanced fusion devices such as ITER rely on electron heating such as ECH and fusion-born alpha particle heating to achieve optimal fusion performance. The ions in these devices must be efficiently heated through collisional heat exchange from electrons. However, electron temperature stiffness may pose a challenge in achieving high efficiency. Therefore, this subsection implies that accurately assessing the impact of ETGs on the electron temperature stiffness is critical to the success of future burning plasmas.

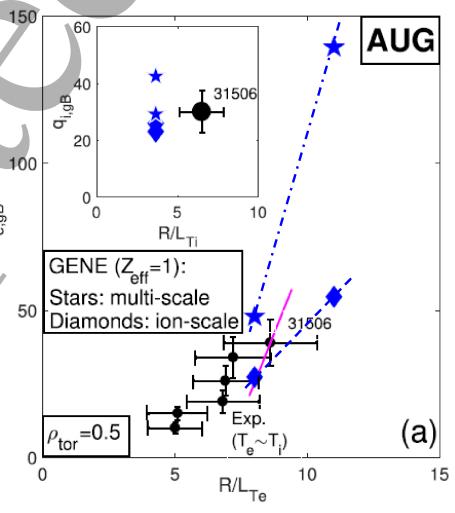

FIG. 2. Electron heat flux $q_{e,gB}$ vs. electron temperature inverse gradient length R/L_{Te} for ASDEX Upgrade experiments (black circles plot a heat flux scan, and the pink solid line shows ECH modulation), ion-scale simulations (blue diamonds),

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and multiscale simulations (blue stars). Blue dashed and dotted-dashed lines are drawn as guides to determine the different slopes in ion-scale and multiscale simulations. Reprinted with permission from [16].

2.4. Electron heat flux in the H-mode pedestal

For the turbulence in an H-mode pedestal of a tokamak plasma—an edge region of steep pressure gradients in high-performance discharge—ITG/TEM is suppressed by equilibrium E × B flow shear. Therefore, ETG turbulence is considered to contribute significantly to the pedestal heat flux [17]. ETG turbulent transport combined with ion-scale turbulence and neoclassical transport can yield heat fluxes comparable to those observed in experiments [18], [19]. A recent global nonlinear gyrokinetic simulation reported a multi-channel, multiscale character of turbulent transport throughout the pedestal, with the dominant contribution transitioning from ion-scale TEM/MTM at the pedestal top to electron-scale ETG in the steep gradient region [20]. Fig. 3 shows an analysis of electron-scale turbulent transport at the H-mode pedestal in JET ITER-like-wall (ILW) experiments [21], [22]. Although pulse with low gas puffing makes slab-type ETG modes unstable, pulse with high gas puffing, which has a flatter density profile, shows the characteristics of both toroidal-type and slab-type ETG modes. The dependence of the electron heat flux Q_e on the electron temperature-to-density gradient ratio $\eta_e = L_{ne}/L_{Te}$ qualitatively agrees with the trend found in the DIII-D experiments $Q_e/Q_{GBe} = 1.5\ (\eta_e - 1.4)$. Gyrokinetic simulations for DIII-D, JET, Alcator C-Mod, and AUG [21], [23], [24] predict a simple dependence of ETG pedestal transport on η_e, motivating the construction of a simple predictive transport model.

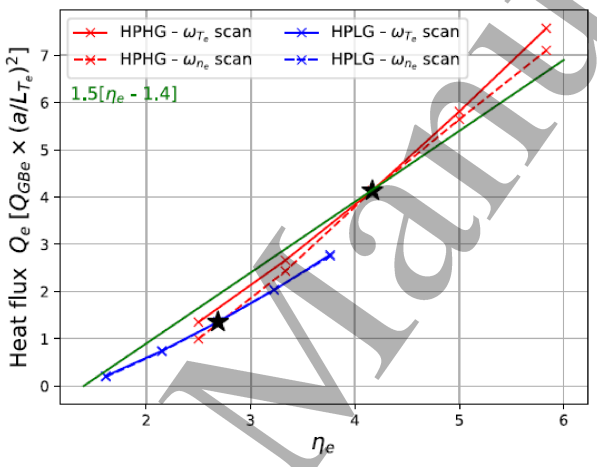

FIG. 3. Electron heat flux Q_e vs. electron temperature-to-density gradient ratio $\eta_e = L_{ne}/L_{Te}$ for the JET experiments. The red trace shows single-scale ETG simulation results corresponding to a high-power and high-gas pulse discharge (HPHG), whereas the blue trace corresponds to a high-power and low-gas pulse discharge (HPLG). The solid green line shows the trend $Q_e/Q_{GBe} = 1.5(\eta_e - 1.4)$. Reprinted with permission from [21].

Although most analyses of turbulent transport in the H-mode pedestal were based on single-scale simulations, several recent publications reported multiscale turbulence simulation results, e.g., the coupling of MTM and ETG [25], ion-scale ETG (due to a pedestal profile) and electron-scale ETG [26], and hybrid drift mode and ETG modes [27]. Partial suppression of electron-scale turbulence by ion-scale turbulence is commonly observed. In summary, based on previous gyrokinetic turbulence simulations, ETG appears to play a role in electron heat transport in H-mode pedestals. However, there seems to be a gap between the report that the sum of transport obtained by single-scale turbulence simulations separately treating electron and ion scales agrees with experimental data and the report of suppression of electron-scale turbulence by multiscale turbulence simulations. Further research is needed to understand multiscale turbulence in H-mode pedestals better in order to quantitatively evaluate turbulent transport up to the electron scale.

2.5. Electron-scale turbulence in spherical tokamaks

A spherical tokamak is characterized by a low aspect ratio R/a, where R is the major radius of the torus. Compared with conventional tokamaks, spherical tokamaks have a more extreme toroidicity (reducing so-called bad curvature region), higher plasma current (allowing access to high normalized plasma pressure β), and larger E × B flow shear. These features tend to suppress ion-scale electrostatic drift wave instabilities, such as ITG and TEM. Therefore, spherical tokamaks are more prone to ion-scale electromagnetic instabilities with both MTM and kinetic ballooning modes as well as electron-scale ETG modes. Heat transport occurs mainly through the

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electron channel in the present generation of spherical tokamaks. Under certain conditions, MTM or ETG modes have been reported to significantly contribute to heat transport [28], [29]. We refer to a topical review paper [30] for a more comprehensive understanding of spherical tokamaks.

A distinctive feature of spherical tokamaks is that the normalized energy confinement time scales nearly inversely with the collisionality. This scaling is much stronger than that of conventional tokamaks, making it favorable for future high-temperature plasma burning conditions. One possible explanation is the dependence of the MTM on collisionality. According to previous theoretical studies, the growth rate of MTM peaks at a specific electron–ion collision frequency. As the collisionality decreases below this peak, the growth rate of the mode decreases. A nonlinear gyrokinetic simulation study of NSTX has shown that the reduction of MTM turbulent transport with decreasing collisionality is consistent with experimental observations [28]. Another candidate to consider is the ETG modes. Fig. 4 shows the collisionality dependence of nonlinear gyrokinetic simulations of single-scale ETG turbulence in MAST plasma [31]. The study discovered that the linear dependence of the electron heat flux on the electron collision frequency was consistent with the experimental observations. The mechanism behind this phenomenon is the interaction between ETG and electron-scale zonal flows. At early simulation time, the ETG streamer dominates with no strong dependence on collisionality. However, the zonal fluctuations slowly grow, leading to a new saturated state dominated by zonal flows. The collisional damping of zonal flows causes the heat flux to be proportional to the collision frequency. Recent studies of both NSTX and MAST indicate significant ETG turbulent transport and MTM [32], [33]. ETG has also contributed to turbulent transport in the pedestal of spherical tokamaks [34]. For NSTX pedestal transport, an attempt is being made to develop a simple predictive transport model depending on η_e, similar to that done in tokamaks, with the effect of the Shafranov shift added [[35]. It should be noted that, to the best of our knowledge, all MTM and ETG turbulence studies of spherical tokamaks are based on single-scale simulations. A nonlinear multiscale simulation of MTM and ETG at tokamak core parameters reported the suppression of MTM by ETG turbulence [36]. Therefore, multiscale turbulence analyses of spherical tokamaks are required to clarify the possible impact of cross-scale interactions.

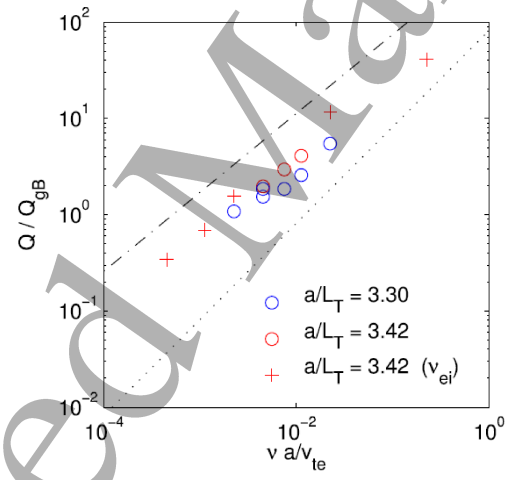

FIG. 4. Electron heat flux Q_e vs. normalized electron collisionality ν for the MAST experiment. The circle and cross points plot the single-scale ETG simulation results. The dotted-dashed line shows the experimental scaling, and the dotted line shows the linear scaling. Reprinted with permission from [31].

2.6. Fluctuation measurement of the interplay between the electron and ion scales

In addition to the validation studies that compare heat fluxes, the novel density fluctuation measurements on the LHD enable the direct observation of the interplay between ion-scale and electron-scale fluctuations, providing a basis for discussing the physical mechanisms of cross-scale interactions. Fig. 5 shows a fluctuation measurement of the response of an LHD plasma to the change in the ECH power [37]. The ion-scale turbulence intensity was estimated from the perturbation amplitudes of the frequency spectrum in the Doppler backscattering signal integrated over 30–150 kHz around the wavenumber $k_\perp\rho_i$ ~ 0.5. The perturbation amplitude of the frequency spectrum of the millimeter wave backscattering signal integrated over 150–490 kHz at $k_\perp\rho_e$ ~ 0.13 was used as an index of the electron-scale turbulence intensity. The results show a negative correlation between them, i.e., the electron-scale turbulence amplitude decreases when the ion-scale turbulence amplitude increases and vice versa. The linear ETG growth rate tends to stabilize as the electron-to-ion

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temperature ratio T_e/T_i increases. Thus, it shows a trend opposite to that of the electron-scale fluctuation amplitude. Therefore, linear physics alone cannot explain the observed correlation, suggesting an interplay between ion-scale and electron-scale turbulence. This trend can be interpreted as mutually exclusive interactions between ion-scale and electron-scale turbulence, as discussed in subsections 3.4 and 3.5. However, there is a need for a detailed investigation comparing experiments and simulations. Because the LHD is a nonaxisymmetric device employing a heliotron magnetic configuration, cross-scale interactions are not limited to axisymmetric tokamaks but are considered ubiquitous features of multiscale turbulence.

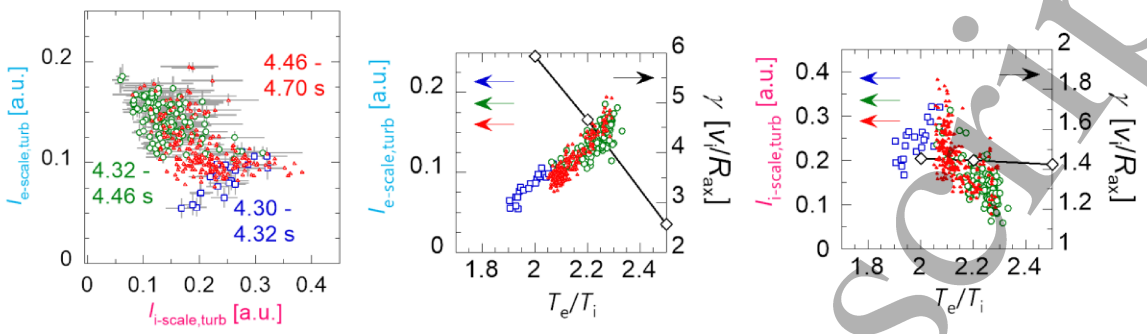

FIG. 5. (Left) Evolution of ion-scale and electron-scale turbulence intensities $I_{amp,ion}$ and $I_{amp,electron}$ for an LHD experiment just after the ECH power increased during time durations from blue (4.30–4.32s) via green (4.32–4.46s) to red (4.46–4.70s) points. (Middle) Electron-scale and (Right) ion-scale turbulence intensities plotted against the electron-to-ion temperature ratio T_e/T_i. The linear growth rates in local gyrokinetic analyses are also shown as black diamonds. Reprinted with permission from [37].

3. UNDERSTANDING THE PHYSICAL NATURE OF CROSS-SCALE INTERACTIONS

Section 2 presented experimental evidence to demonstrate the significance of multiscale turbulence. From a theoretical viewpoint, the fundamental questions are: When is multiscale turbulence necessary for evaluating turbulent transport? What are the physical mechanisms of cross-scale interactions? To answer these questions, theoretical understandings are discussed based on the differences and commonalities in cross-scale interactions among several types of multiscale turbulence simulations. Theoretical approaches also provide physical interpretations of cross-scale interactions.

3.1. Historical background

Although coexisting microinstabilities at ion and electron gyroradius scales have been known since the 1960s, the conventional approach has long been based on single-scale analysis, neglecting the other scale in the assumption of scale separation. Ref. [38], which predicted competitive interaction between disparate-scale turbulence, was the first theoretical literature directly discussing the cross-scale interaction between ion-scale and electron-scale turbulence. Another study using wave kinetic equations discusses the role of relatively short-wavelength ion-scale eddies, a weak back reaction from electron-scale turbulence, and the possibility of electron-scale modes destabilization by ion-scale profile corrugation [39]. Direct numerical simulations of multiscale turbulence are required to verify the validity of these theoretical models.

In 2004, a pioneering gyrokinetic simulation including both ITG and ETG modes under edge-like plasma parameters was performed by Ref. [17]. Later in 2007, Refs. [40], [41], [42] reported suppression of ETG turbulence by ITG turbulence using reduced mass (me/mi = 400 or 900) simulations with core plasma parameters. A more recent study has shown the importance of real ion-to-electron mass ratio for cross-scale interactions [3]. Currently, the physical mechanisms of cross-scale interactions between ion- and electron-scale turbulence are investigated based on the nonlinearity of the governing equations [4].

3.2. Criteria for the importance of electron scales

A series of multiscale turbulence simulations have shown that cross-scale interactions can significantly affect turbulent transport, especially when ion-scale instabilities are close to marginal stability, e.g., weak ion temperature gradients [10], [42], equilibrium flow shear stabilization [41], or electromagnetic stabilization [[4]. Otherwise, ion-scale turbulence would dominate. Therefore, near-marginal ion-scale instability is a qualitative signature of the importance of cross-scale coupling with electron-scale turbulence.

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To evaluate the criteria for the impacts of electron-scale effects more quantitatively, some estimations are proposed: a heuristic rule to ETG survives $\gamma_{\text{high-k}}/\gamma_{\text{low-k}} > \sqrt{(m_i/m_e)}$ [10], zonal flow mixing model $(\gamma/k_\theta)_{\text{high-k}} > (\gamma/k_\theta)_{\text{low-k}}$ [43], [44], and parallel-to-field shear model $\gamma_{\text{high-k}} > k_{\text{high-k}}\, \partial_\theta v_{\text{low-k}}$ [45], where γ, k_θ, and v *denote* the linear growth rate, poloidal wave number, and flow velocity of electron-scale (high-k) or ion-scale (low-k) modes, respectively. If we estimate $k_{\text{high-k}} \sim \rho_e$, $k_{\text{low-k}} \sim \rho_i$, and $v_{\text{low-k}} \sim \gamma_{\text{low-k}} / k_{\text{low-k}}$, all three are equivalent. However, even when the criteria $(\gamma/k_\theta)_{\text{high-k}} > (\gamma/k_\theta)_{\text{low-k}}$ are satisfied, strong suppression of ETG turbulence has been reported, e.g., in a DIII-D near-edge L-mode plasma [46] and a JET hybrid H-mode scenario [47]. Further investigations are required to improve the predictability of the criteria for the importance of electron scales.

3.3. Description of cross-scale coupling in the gyrokinetic equations

Cross-scale coupling in the gyrokinetic equation is physically described by the nonlinear advection term of the perturbed distribution function via the perturbed E × B flows or motions along magnetic flutters. Because ions cannot directly feel the high-k fluctuations averaged over the gyration with an ion Larmor radius, cross-scale coupling mainly occurs through electron dynamics. We prefer to use the terms "low-k and high-k" rather than "ion-scale and electron-scale" to avoid confusion regarding their scale and dynamics. The fluctuations of the ion distribution function at low-k and electron distribution function at low-k and high-k, i.e., $f_{\text{i,low-}k}$, $f_{\text{e,low-}k}$, and $f_{\text{e,high-}k}$, are distinguished. When high-k electrostatic potential perturbations exist, the low-k perturbed electron distribution function $f_{\text{e,low-}k}$ is affected by a nonlinear process coupled with the high-k distribution $f_{\text{e,high-}k}$. The change of $f_{\text{e,high-}k}$ is reflected in the low-k electromagnetic potentials and eventually affects the ion dynamics $f_{\text{i,low-}k}$.

A triad interaction is described by the gyrokinetic triad entropy transfer function, which characterizes the transfer process of the perturbed electron distribution function by the quadratic nonlinearity.

$$J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}} = \delta_{\boldsymbol{k}+\boldsymbol{p}+\boldsymbol{q}=0}\frac{\boldsymbol{b}\cdot\boldsymbol{p}\times\boldsymbol{q}}{2B}\,\mathrm{Re}\left[\left\langle\int dv^3\left(\chi_{\boldsymbol{p}}g_{\mathrm{e}\boldsymbol{q}}-\chi_{\boldsymbol{q}}g_{\mathrm{e}\boldsymbol{p}}\right)\frac{T_\mathrm{e}g_{\mathrm{e}\boldsymbol{k}}}{F_{\mathrm{eM}}}\right\rangle\right],$$

where $\chi_{\boldsymbol{k}}$ and $g_{\mathrm{e}\boldsymbol{k}}$ denote the gyrophase-averaged generalized potential and the nonadiabatic part of the electron distribution function of a mode $\boldsymbol{k}$, respectively. F_{eM}, B, and T_e are the equilibrium Maxwellian, magnetic field strength, and electron temperature, respectively. $J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}}$ represents the entropy gain/loss of the mode $\boldsymbol{k}$ via coupling with modes $\boldsymbol{p}$ and $\boldsymbol{q}$ under satisfying the conservation among triplet called the detailed balance, $J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}} + J_{\boldsymbol{p}}^{\boldsymbol{q},\boldsymbol{k}} + J_{\boldsymbol{q}}^{\boldsymbol{k},\boldsymbol{p}} = 0$. The function is symmetrized $J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}} = J_{\boldsymbol{k}}^{\boldsymbol{q},\boldsymbol{p}}$ to uniquely extract the net transfer, as discussed in references [48], [49].

To evaluate the cross-scale interactions, particularly the effects from high-k fluctuations to low-k fluctuations, it is necessary to extract the collective contribution via anisotropic and nonlocal interactions in wavenumber space. Therefore, the subspace transfer function is defined in [50] as

$$J_{\boldsymbol{k}}^{\Omega_p,\Omega_q} = \sum_{\boldsymbol{p}\in\Omega_p}\sum_{\boldsymbol{q}\in\Omega_q} J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}},$$

where Ω_p, Ω_q are subspaces in wavenumber space satisfying $\sum_{\boldsymbol{k}} = \sum_{\Omega p}\sum_{\boldsymbol{p}\in\Omega p}$ and $\Omega_p \cap \Omega_q = \varnothing$. For example, in Ref. [50], the perpendicular wavenumber space $\boldsymbol{k} = (k_x, k_y)$ is split into three subspaces ($\Omega_p = \Omega_{\mathrm{ZF}}$, Ω_i, and Ω_e) in the analysis: the zonal modes $\Omega_{\mathrm{ZF}} = \{\boldsymbol{k} \mid k_y = 0\}$, the (ion-scale) low-$k$ turbulent modes $\Omega_\mathrm{i} = \{\boldsymbol{k} \mid k_y \neq 0 \cap k\rho_\mathrm{i} \leq 2\}$, and the (electron-scale) high-k turbulent modes $\Omega_\mathrm{e} = \{\boldsymbol{k} \mid k_y \neq 0 \cap k\rho_\mathrm{i} > 2\}$. The subspace transfer represents the entropy gain/loss of mode $\boldsymbol{k}$ via coupling with subspaces. It also satisfies the symmetry $J_{\boldsymbol{k}}^{\Omega p,\Omega q} = J_{\boldsymbol{k}}^{\Omega q,\Omega p}$ and the detailed balance among three subspaces $\sum_{\boldsymbol{k}\in\Omega k} J_{\boldsymbol{k}}^{\Omega p,\Omega q} + \sum_{\boldsymbol{k}\in\Omega p} J_{\boldsymbol{k}}^{\Omega q,\Omega k} + \sum_{\boldsymbol{k}\in\Omega q} J_{\boldsymbol{k}}^{\Omega k,\Omega p} = 0$.

3.4. Effects of ion-scale turbulence on electron-scale

3.4.1. Understanding based on multiscale turbulence simulations

Ion-scale turbulence tends to suppress electron-scale turbulence, which is widely observed in a variety of ion-scale turbulence driven by ITG [4], [10], [40], [42], MTM [36], and TEM [51], and in various devices such as Alcator C-Mod [10] and DIII-D L-mode plasmas [46], a JET hybrid H-mode scenario [47], and an H-mode pedestal of the JET-ILW discharge [26]. This is because shearing by ion-scale turbulent eddies distorts the mode structures in the electron-scale. In Fig. 6, the perpendicular shearing process in ITG/ETG multiscale turbulence

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is analyzed using the gyrokinetic triad entropy transfer function [50]. Fig. 6 (a) plots $J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}}$ for a fixed $\boldsymbol{k}$ as a function of $\boldsymbol{p}$, representing the entropy transfer to the analyzed mode $\underline{\boldsymbol{k}}$ through coupling with modes $\boldsymbol{p}$ and $\boldsymbol{q} = -\boldsymbol{k} - \boldsymbol{p}$. On the other hand, Fig. 6 (b) plots $J_{\boldsymbol{p}}^{\boldsymbol{q},\boldsymbol{k}}$ as a function of $\boldsymbol{p}$ for a fixed $\boldsymbol{k}$, representing the energy transfer to mode $\boldsymbol{p}$ through the coupling with the analyzed mode $\boldsymbol{k}$. Considering Fig. 6 (a), (b), and the detailed balance show that the analyzed streamer $\boldsymbol{k} = (0, 4.4\rho_i^{-1})$ obtains entropy from $k_y\rho_i \leq 4.4$ and gives entropy to $k_y\rho_i \geq 4.4$ through coupling with $k_\perp\rho_i \sim 1$. The coupled mode $k_\perp\rho_i \sim 1$ has negligible entropy gain; therefore, it acts as a mediator. Thus, the electron-scale streamer is governed by the forward entropy cascade from lower $k_\perp$ to higher $k_\perp$ mediated by ion-scale turbulent eddies at relatively short wavelengths $k_\perp\rho_i \sim 1$. The scale separation makes perpendicular shearing by large ion-scale turbulent eddies and zonal flows at $k_\perp\rho_i << 1$ less efficient.

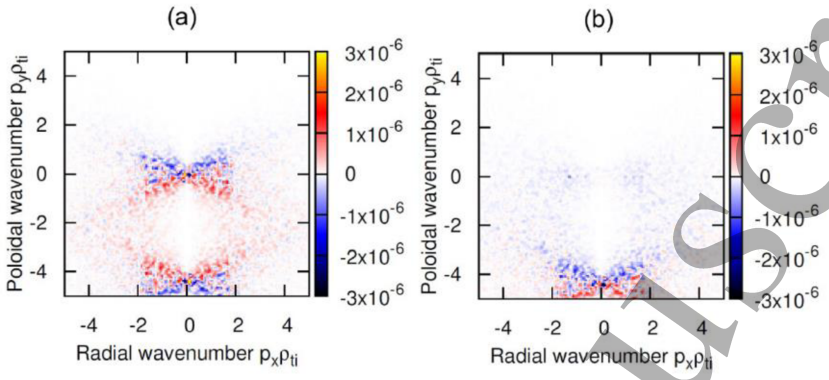

FIG. 6. Analysis of the triad transfer for a streamer of the perpendicular wavenumber $\boldsymbol{k} = (k_x, k_y) = (0, 4.4\rho_i^{-1})$. (a) $J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}}$ represents the entropy gain of the fixed $\boldsymbol{k}$ via coupling with $\boldsymbol{p}$, and (b) $J_{\boldsymbol{p}}^{\boldsymbol{q},\boldsymbol{k}}$ denotes the entropy gain of a mode $\boldsymbol{p}$ via coupling with $\boldsymbol{k}$. Reprinted with permission from [50].

3.4.2. Theoretical approaches for analyzing ion-scale effects on electron-scale instability

When the spatiotemporal scales of ion- and electron-scale turbulence are widely separated, reduced equations can be deduced using the ratio of the electron-scale to the ion-scale as an ordering parameter. A scale-separated approach is derived based on the assumption of scale separation by a large ion-to-electron mass ratio and gyro-Bohm ordering [45]. An important consequence is that the dominant effect of ion-scale turbulence on electron-scale turbulence is parallel-to-field shear. As illustrated in Fig. 7 (left), the ion-scale cross-field turbulent flow $v_E(\theta)$ varies in the field-aligned direction θ, introducing a shorter parallel length scale $k_\parallel$ than the typical ETG connection length qR. This parallel-to-field shearing suppresses the linear ETG growth, as shown in Fig. 7 (right). In addition, the ion-scale corrugation of the density and temperature profiles typically has a stabilizing effect because it is not only a modification of the background gradient drive but also includes its variation along the field line. The above mechanisms survive in the limit of the infinite ion-to-electron mass ratio. In contrast, the perpendicular shearing disappears when the ion and electron scales are entirely separated by the gyro-Bohm ordering $k_\perp\rho_i \sim 1$ and $k_\perp\rho_e \sim 1$.

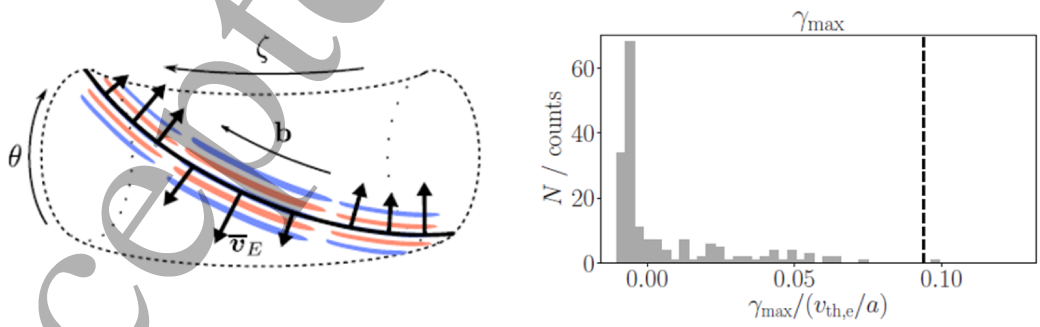

FIG. 7. (Left) Schematic of ETG fluctuations in the presence of ion-scale parallel-to-field shear flow v_E. (Right) Histogram of ETG growth rate in the presence of ion-scale fluctuations with parallel-to-field shear. The dashed line represents the ETG growth rate without cross-scale interaction. Reprinted with permission from [45].

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The scale-separated approach has highlighted the role of parallel-to-field shear in ion-scale turbulence effects on electron-scale instability even at low-$k_\perp\rho_i$ < 1. On the other hand, Fig. 6 in subsection 3.4.1 evaluated only the perpendicular shearing process by decomposing the perpendicular wavenumber space $\boldsymbol{k}_\perp$. To capture parallel-to-field shearing, the parallel wavenumber $k_\parallel$ decomposition is also required as an extension of Fig. 6. The results shown in Figs. 6 and 7 do not necessarily contradict each other. At low-$k_\perp\rho_i$ < 1, where the concerned perpendicular scale is well separated from the electron scale, the parallel-to-field shear will be the dominant interaction path from the ion-scale turbulence to the electron scale. At relatively short (sub-ion-scale) $k_\perp\rho_i \sim 1$, perpendicular shearing by ion-scale turbulence can effectively work on the electron-scale.

3.5. Effects of electron-scale turbulence on ion-scale

3.5.1. Understanding based on multiscale turbulence simulations

Despite the complexity of electron-scale effects on turbulent transport, as discussed later in Section 6, there seems to be a generic feature of the electron-scale role in cross-scale coupling. Fig. 8 exhibits the electron-scale effects on ion-scale fluctuations analyzed in three different multiscale simulations of ITG/ETG [39], MTM/ETG [36], and TEM/ETG turbulence [51]. Collective contributions from electron-scale fluctuations are extracted as the subspace transfer function by splitting the wavenumber space into ion- and electron-scale subspaces. Fig. 8 (top left) shows that the electron-scale effects ($2J_{ek}^{\Omega e,\Omega i} + J_{ek}^{\Omega e,\Omega e}$ plotted as the blue line) have a damping (negative) contribution to the short-wavelength zonal flows, driven by ion-scale turbulence. Fig. 8 (top right) and (bottom) also show electron-scale coupling damping of ion-scale fluctuations ($k_y\rho_a$ < 1 or $k_y\rho_{ti}$ < 1). Since E × B advection nonlinearity dominates the cross-scale coupling, these observations physically indicate that the electron-scale turbulence disturbs ion-scale structures. Relevant ion-scale structures include, for example, short-wavelength zonal flows [50], radially localized current sheets of MTM [36], and trapped electron trajectories resonant with TEM [51]. By satisfying the conservation law described by the detailed balance among triplets, the reduction of the ion-scale structure via electron-scale coupling produces higher $k_\perp$ fluctuations, which eventually damps. Therefore, the electron-scale turbulence effect on ion-scale turbulence is understood as a dissipative effect.

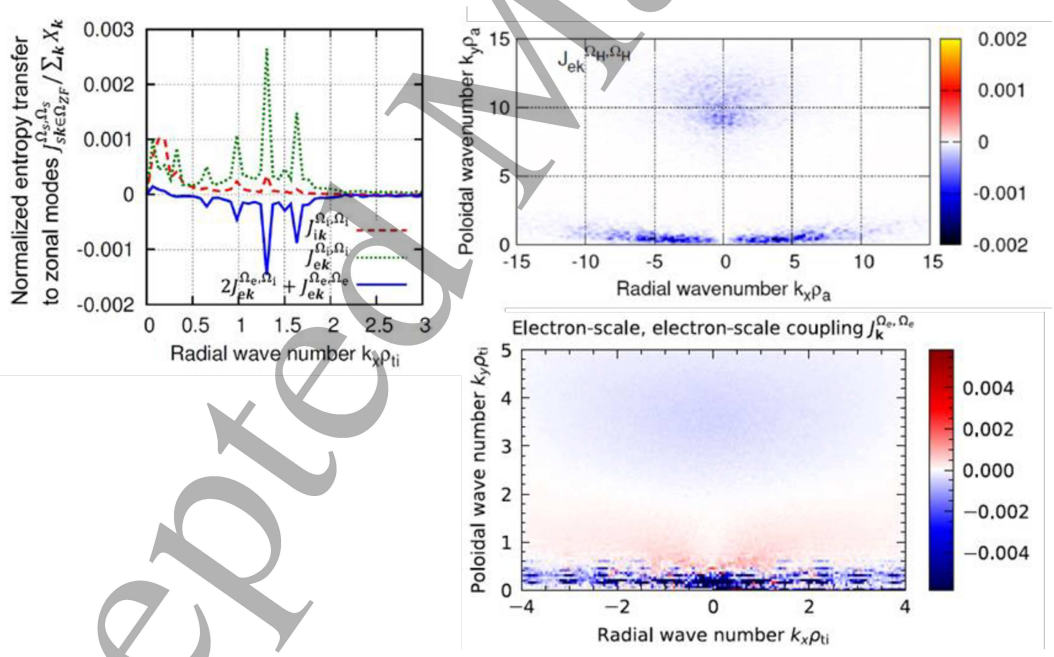

FIG. 8. Spectra of gyrokinetic subspace entropy transfer functions, representing the effects of cross-scale coupling with the electron-scale (Top left) on ITG-driven zonal flows, (Top right) on MTM turbulence, and (Bottom) on TEM turbulence. All gyrokinetic triad transfer functions indicate the damping (negative) effects of electron-scale turbulence on ion-scale fluctuations. Reprinted with permission from [50], [36], [51].

3.5.2. Theoretical approaches for analyzing electron-scale effects on ion-scale instability

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Although the impacts of electron-scale turbulence on ion-scale turbulence have been observed in numerical simulations, the scale-separated approach introduced in subsection 3.4.2 excludes the electron-scale effects on the ion-scale. This contradiction implies that the electron-scale effects observed in numerical simulations cannot be described under a scale separation with isotropic gyro-Bohm ordering for each species $k_r \sim k_\theta \sim \rho_s^{-1}$ [52]. Therefore, it suggests that scale inseparability, e.g., anisotropy of ETG streamers having $k_\theta\rho_e \sim 1$ and $k_r\rho_e << 1$, or cross-scale interaction mediated via sub-ion-scale structures $\rho_i^{-1} \leq k_\perp < \rho_e^{-1}$, plays an essential role. For example, Fig. 8 (left) shows that electron-scale coupling effectively damps the short-wavelength (sub-ion-scale) zonal flows at $k_\perp\rho_i \sim 1$, whereas the long-wavelength zonal flows at $k_\perp\rho_i < 0.5$ are not affected because of scale separation.

Watanabe et al. employed a formulation of quasilinear diffusion and proposed an effective diffusion model of the electron-scale effects D on the ion-scale fluctuation $\bar{f}$,

$$D\bar{f} = \tau_{ac}\nabla_\perp \cdot \left(\overline{\tilde{v}_E \tilde{v}_E} \cdot \nabla_\perp \bar{f}\right),$$

where τ_{ac} and $\overline{\tilde{v}_E \tilde{v}_E}$ denote the autocorrelation time and Reynolds stress tensor of the ETG turbulence, respectively. Because it is a positive definite matrix, the effective diffusion model causes anisotropic dissipation $\int dx^3\, \bar{f} D \bar{f} < 0$. Fig. 9 examines the change in the ion-scale exponential growth rate by electron-scale effective diffusion [53], [54]. The reduction of linear TEM growth rates under ETG turbulence is well represented by the diffusion form $-\delta_{eff}\, k_y^2$. The theoretical estimation of the effective diffusion coefficient $\delta_{eff}^{theory} = \tau_{ac}\left|\overline{\tilde{v}_E \tilde{v}_E}\right| \sim \overline{\tilde{v}_E^2}/\gamma_{ETG}$ gives reasonable agreement within a 50% difference in several case studies.

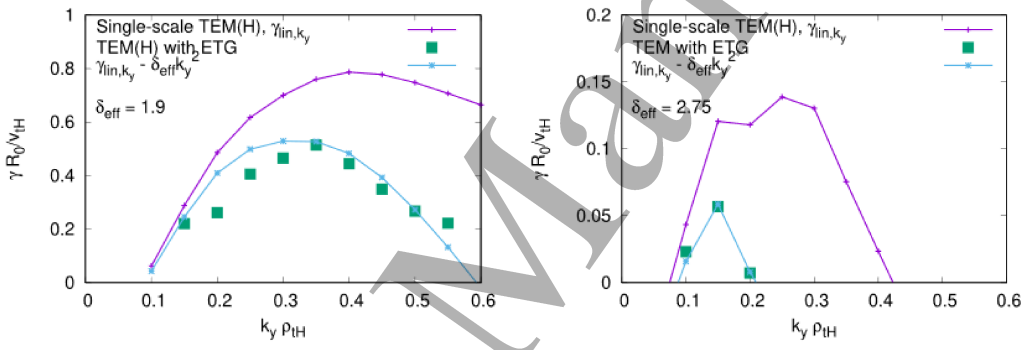

FIG. 9. Linear TEM growth rate (purple) and exponential growth rate of TEM under the presence of ETG turbulence in multiscale simulations (green squares) for (a) hydrogen and (b) multi-ion species (D, T, and He) plasmas. The cyan curve shows the linear growth rate reduced by the effective diffusivity $-\delta_{eff}\, k_y^2$. Reprinted with permission from [53].

Electron-scale effective dissipation is not limited to TEM but to other instabilities such as ITG and MTM. A previous study showed an example of reduced growth rates of ITGs in the presence of ETGs [55]. However, electron-scale turbulence may dissipate both microscopic instabilities and self-organized structures, such as zonal flows, in a nonlinear turbulent state. Depending on the magnitude of each effect, electron-scale effective dissipation can either increase (e.g., the case of ITG turbulence and zonal flows [4]) or decrease (e.g., TEM turbulence without zonal flows [51]) the ion-scale turbulent transport flux. Additionally, note that the dissipation of the perturbed electron distribution function does not always imply a linear growth rate decrease. For instance, resistive drift waves and dissipative trapped electron modes are microscopic instabilities due to finite dissipation.

4. MODELING ELECTRON-SCALE EFFECTS IN QUASILINEAR TRANSPORT MODELS

Based on theoretical and experimental evidence of the importance of cross-scale interactions, quasilinear transport models QuaLiKiz [55], [57] and TGLF (SAT1 and the most recent SAT2 models) [58] have been updated to account for electron-scale effects. In QuaLiKiz, a finite turbulence flux due to electron-scale turbulence is predicted when the suppression of ETG modes by cross-scale interaction with ITG turbulence no longer holds, $(\gamma/k_\theta)_{ETG} > (\gamma/k_\theta)_{ITG}$. The QuaLiKiz ETG saturation level is calibrated to a limited set of multiscale GENE simulations [47]. TGLF incorporates a model of multiscale interactions based on saturation through zonal flow mixing [58] and is calibrated against a more comprehensive set of GYRO simulations.

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Fig. 10 presents a comparative analysis involving experimental data, multiscale GENE simulations, and the TGLF SAT1 and SAT2 simulations for the electron temperature stiffness observed in a JET discharge [59]. There are three variations of TGLF SAT1 cases employing a nominal ion temperature gradient R/L_{Ti} = 5.7, an enhanced ion temperature gradient R/L_{Ti} = 6.5 to align the experimentally observed ion heat flux, and an artificially reduced effective charge Z_{eff} = 1 from experimental Z_{eff} = 1.3. The analysis reveals that the electron stiffness predicted by SAT1 is slightly lower than both the experimental data and GENE multiscale simulations. The SAT2 model further underestimates the electron stiffness. Both models exhibit the onset of electron heat flux by ETG modes at quite high R/L_{Te} values, failing to reproduce the highest experimental data points by a factor greater than 2 in the electron heat flux. The TGLF SAT1 model with an artificially reduced effective charge, Z_{eff} = 1, is closer to the experimental data. In addition, profile evolution simulations using a transport code with the TGLF SAT1 and SAT2 models show overprediction of electron temperature in the core region but good ion temperature prediction [[59]. Therefore, although the inclusion of electron-scale physics into a quasilinear transport model serves to represent the onset of electron heat flux by ETG modes, there are still issues with the model electron stiffness for these plasmas. Since the huge numerical resource requirement prevents an adequate sensitivity study with multiscale gyrokinetic simulations, the use of a quasilinear transport model helps affordable sensitivity studies indicate a strong sensitivity of ETG modes to the effective charge and impurity mix. Therefore, further investigations are required to assess the role of ETG turbulent transport in current and future machines.

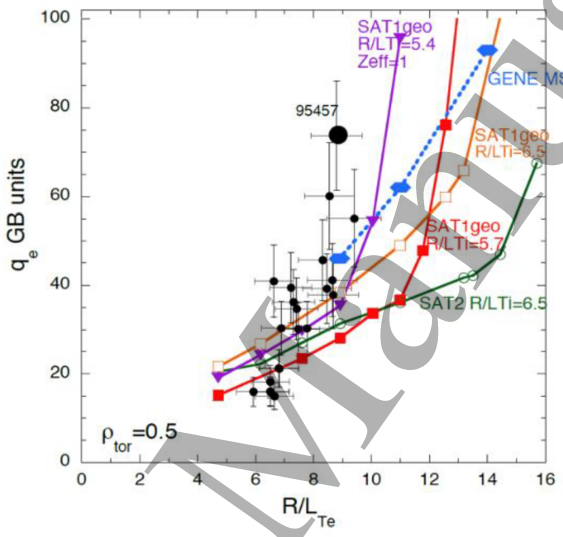

FIG. 10. Electron heat flux q_e vs. electron temperature inverse gradient length R/L_{Te} for the JET experiments (black circles), multiscale simulation (GENE MS), and quasilinear model (TGLF SAT1 or SAT2). Reprinted with permission from [59].

5. PREDICTION OF FUTURE BURNING PLASMAS

The burning plasma is characterized by a mixture of D, T fuel, He ash, and fusion-born alpha particles. ITER is considered to be an electron-heated plasma. The main heating process in the pre-fusion power operation 1 (PFPO-1) phase is ECH. In the case of burning plasma, the fusion-born alpha particle mainly heats electrons. This greatly contrasts most present machines with significant neutral beam injection and ion cyclotron resonance heating. As argued in Ref. [15], ETG modes could have a potentially more dangerous impact in ITER because ions are mainly heated by collisional electron–ion exchange, and T_i cannot exceed T_e. Under these conditions, a limitation to T_e peaking by ETG modes reflects a limitation on T_i peaking and fusion power. Meanwhile, it is known that a higher T_e/T_i ratio tends to suppress the ETG linear growth rate. In other words, although in present ion-heated devices ETG modes are strong but not harmful for fusion performance, in electron-heated future devices ETG modes will likely not be strong but may be potentially more harmful for fusion performance. Therefore, beyond the validation of existing devices, it is crucial to clarify whether cross-scale interactions play a role in future burning plasma.

5.1. Extrapolation for electron-heated plasmas

Since the increase of the electron-to-ion temperature ratio T_e/T_i tends to suppress ETG instability but destabilizes ion-scale instabilities such as TEM and ITG modes, it should be argued whether electron-scale turbulence plays a role in an electron-heated plasma. Fig. 11 plots the dependence of turbulent energy flux on

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the temperature ratio T_e/T_i in multiscale TEM/ETG turbulence simulations with a mixture of electron, D, T, and He ions [51]. ETG turbulence dominates turbulent transport in single-electron-scale and multiscale simulations when T_e/T_i equals 1. However, an increase in electron temperature stabilizes ETG modes and destabilizes TEMs. The multiscale turbulence simulation shows that near-marginal TEM can be suppressed by ETG turbulence in an appropriate T_e/T_i range, which leads to an upshift of the critical temperature ratio for an increase in the TEM-dominated energy flux. From the ITER profile modeling, a reactor-relevant temperature range is considered around $1 < T_e/T_i < 2$. In addition, an analysis of the ITER PFPO-1 phase predicts that the central ratio of T_e/T_i can be even greater than three by ECH operation [60]. Fig. 11 covers these ranges and shows that the ETG contribution could exist in a wide parameter range of $1 < T_e/T_i < 3$, contrary to the previous consideration that ETG has a nonnegligible contribution only when $T_e \sim T_i$ and the electron temperature gradient is sufficiently large. The result also suggests that cross-scale interactions lead to a favorable parameter regime where ETG turbulence suppresses TEM-driven turbulent transport. A similar transport reduction by cross-scale interaction is observed in the analysis of JT-60U L-mode discharge in the outer region [55]. It can also affect the isotope dependence of turbulent transport [54].

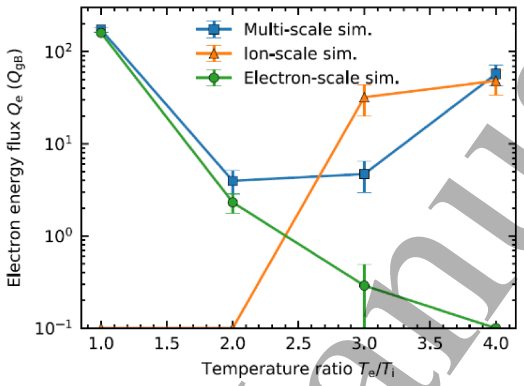

FIG. 11. (a) Electron energy flux Q_e as a function of the electron-to-ion temperature ratio T_e/T_i for multiscale (blue), ion-scale (orange), and electron-scale (green) simulations. Reprinted from [51] (CC BY 4.0).

5.2. Predictions for the SPARC tokamak

To increase confidence in projections of future fusion devices, it is desirable to perform validation and prediction studies by employing dimensionless parameters matched with the concerned operational regimes. Fig. 12 (left) shows the linear growth rate spectrum of the SPARC tokamak's primary reference discharge (PRD) plasma profile [61]. TEM or ITG modes at low wavenumbers and ETG modes at high wavenumbers coexist. Single-scale simulations were conducted separately for ion-scale or electron-scale turbulence to estimate the possible electron-scale impacts. Fig. 12 (right) predicts that electron-scale simulations give smaller turbulent transport than ion-scale turbulent transport, which is about $Q_e = 0.1 \sim 0.4$ MW/m^2. Considering the additional ETG stabilization via cross-scale coupling with ion-scale turbulence, electron-scale turbulence in the SPARC tokamak likely plays a minor role, at least in the profile analyzed. Elucidating the conditions under which the role of electron-scale turbulence diminishes is indispensable to advance the understanding of this phenomenon.

Based on the above estimation that electron-scale turbulence is likely to be minor in a SPARC plasma, predictions using ion-scale turbulence simulations and machine-learning-based surrogate models have been actively investigated for the SPARC burning plasma profile [62]. The same modeling approach was applied for the validation study in the DIII-D ITER-like condition, and predictions for ITER profiles are underway [63].

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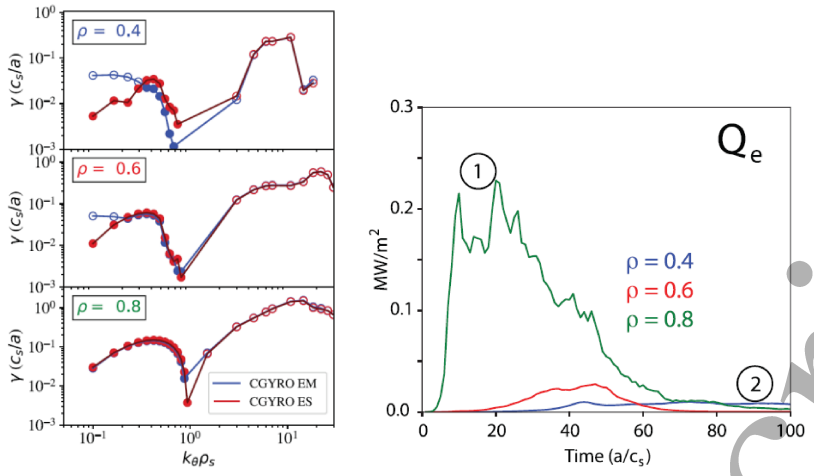

FIG. 12. (Left) Linear growth rate spectrum of the SPARC PRD plasma profile at different radial positions. (Right) Electron energy flux Q_e calculated from single-scale ETG turbulence simulations. Reprinted with permission from [61].

6. SUMMARY AND DISCUSSION

Over the last ten years, multiscale turbulence studies have revealed the critical role of electron-scale turbulence in experiments and deepened the theoretical understanding of cross-scale interactions. The primary physics of the ion-scale turbulence effect is the shearing of electron-scale turbulence by ion-scale eddies, not only perpendicular shear but also parallel-to-field shear. Ion-scale density/temperature corrugations also typically suppress ETG modes. On the other hand, the electron-scale turbulence effect is understood as an effective dissipation on ion-scale structures by small-scale stochastic mixing. Therefore, a mutually exclusive nature between disparate-scale turbulence emerges as a generic physical picture of cross-scale interactions: ion-scale turbulence suppresses electron-scale instabilities by its shearing, whereas electron-scale turbulence disturbs ion-scale structures as an effective dissipation. It is noted that the electron-scale dissipation does not necessarily mean the suppression of ion-scale instabilities and turbulence, as discussed in the next subsection.

6.1. Impacts of cross-scale coupling on turbulent transport

In addition to understanding the physics of cross-scale interactions, their impacts on turbulent transport are of practical interest for evaluating and predicting the confinement properties of magnetic fusion plasmas. Ion-scale effects on electron-scale turbulence are primarily considered to reduce electron-scale turbulent transport. However, the electron-scale dissipative effects on the ion-scale can either enhance or diminish ion-scale transport. For example, the ion-scale heat flux is enhanced when ion-scale zonal flows are damped [4], [10] or diminished when fluctuations of ion-scale instabilities such as TEM or MTM are damped [36], [51]. In addition, direct electron-scale turbulent transport can significantly contribute when ion-scale instabilities are sufficiently weak.

6.2. Future perspectives of multiscale turbulence studies

This overview has reviewed cutting-edge multiscale turbulence studies and identified some issues to be further addressed. First, the impact of multiscale turbulence in future burning plasmas is under active investigation. The fact that electron-scale turbulence is substantially stabilized when ion-scale turbulence is sufficiently strong ensures a certain degree of confidence in performance predictions based on ion-scale turbulence analysis. Therefore, a promising approach is to use ion-scale nonlinear gyrokinetic profile prediction for the computationally expensive profile search and to evaluate electron-scale effects once the profile is determined. Identifying the precise criteria for the importance of electron scales or developing an innovatively efficient computational algorithm for multiscale simulations could be a game changer. It would also be interesting to see if the possible reduction of transport through cross-scale coupling can be used for optimal tokamak operation.

Second, the role of ETG turbulence in H-mode pedestal transport has attracted much attention, although most studies are based on single-scale simulations. As discussed in the latest publications [25], [26], [27], it is important to consider the impacts of cross-scale interaction in pedestal ETG turbulent transport. Similarly, heat transport in spherical tokamaks is understood on the basis of single-scale MTM or ETG turbulence simulations.

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In contrast, a multiscale turbulence simulation in a tokamak core suggests cross-scale interactions between MTM and ETG modes [36], which raises concerns regarding the previous understanding based on single-scale simulations. Note that the standard gyrokinetic ordering, $\rho/L \sim \omega/\Omega \ll 1$, faces challenges when applied to multiscale turbulence in pedestals with a steep gradient scale length approaching the ion gyroradius. Even for ion-scale physics where $k_\perp \sim \rho_\mathrm{i}^{-1}$ and $\omega_{*\mathrm{i}}/\Omega_\mathrm{i} \sim \rho_\mathrm{i}/L \lesssim 1$, there are discussions on the extension of gyrokinetic theory (e.g., higher-order gyrokinetic theory to handle large bootstrap currents associated with steep gradients [64] or extreme E × B shear flows even faster than the so-called large flow ordering [65]) or the application of fully kinetic ions [66]. At the electron scale, where $k_\perp \sim \rho_\mathrm{e}^{-1}$, the gyrokinetic ordering is still satisfied for electrons ($\omega_{*\mathrm{e}}/\Omega_\mathrm{e} \sim \rho_\mathrm{e}/L \ll 1$) but can break down for ions [$\omega_{*\mathrm{e}}/\Omega_\mathrm{i} \sim v_\mathrm{e}/(L\Omega_\mathrm{i}) > 1$]. Thus, the gyro-phase dependence of fully kinetic ions can result in the coupling of ETG modes and ion Bernstein waves.

Finally, recent extensions of quasilinear transport models partially implemented electron-scale turbulence effects, typically a possible electron-scale turbulent transport and its suppression by ion-scale turbulence. Further modeling efforts are required to include the electron-scale effects on the ion-scale, which is a more complicated interaction that enhances or reduces turbulence transport.

In summary, multiscale plasma turbulence research has substantially advanced our understanding of its physical mechanisms and impacts on turbulent transport. Its application expands to turbulent transport in H-mode pedestals, spherical tokamaks, transport modeling, and profile prediction. A comprehensive understanding of multiscale turbulence and transport provides essential implications for improving performance prediction and exploring optimum operation scenarios, contributing to ITER and the early success of developing magnetic confinement fusion.

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