Gyrokinetic Turbulence Investigations Involving Ion and Electron Scales

T. Görler, F. Jenko, M.J. Pueschel, D. Told, and H. Lesch

Abstract Plasma microinstabilities are one of the key physics problems on the way to efficient power plants based on nuclear fusion. They cause anomalous heat and particle transport which significantly degrades the plasma confinement quality, thus preventing self-sustaining plasma burning in present-day experiments. Hence, extensive experimental studies are dedicated to understanding and predicting turbulence features. They are accompanied by numerical simulations which are typically based on the gyrokinetic theory. While experimental diagnostics are about to address the role of fine-scale turbulence within a bath of large-scale turbulence, nonlinear gyrokinetic codes are already able to investigate turbulent transport at a wide range of wave numbers simultaneously. However, such simulations covering several space and time scales self-consistently are computationally extremely demanding and thus need to be massively parallelized.

1 Introduction

In the present section, some basic information on plasma turbulence in the context of magnetic confinement fusion will be provided. Furthermore, the underlying theory for theoretical investigations and the requirements for massively parallel computations will be discussed briefly.

1.1 Magnetic Confinement Fusion and Plasma Turbulence

In order to manage an increasing world energy consumption, an important approach is to explore new energy sources whose resources are not running out, or which suf-

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fer from side-effects, such as global warming. A well working example is provided by our star which converts energy mostly by fusing protons to helium. However, efficiency dictates that an artificial, terrestrial sun has to rely on a different but similar reaction where the nuclear fusion involves the hydrogen isotopes deuterium and tritium. During this process, the Coulomb potential barrier has to be overcome which requires temperatures of more than 100 million degrees. At those extreme conditions matter is found to be an (almost) fully ionized gas – a so-called plasma. The most promising way of isolating the hot plasma from the walls of a containing vessel is realized by the application of correspondingly shaped magnetic fields which are often reminiscent of doughnout or floating tire forms. Although motion perpendicular to magnetic field lines is significantly reduced by Lorentz forces, one nevertheless observes outward heat and particle fluxes which degrade the energy confinement in current devices in a way that self-sustained plasma burning cannot be achieved. At present, it is widely accepted that small scale instabilities, i.e. instabilities on scales of the order of the Larmor radius, are responsible for the so-called anomalous transport. Driven by the unavoidably steep density and temperature gradients occurring in fusion devices, they initially grow exponentially in time until the fluctuation amplitudes become sufficiently large for nonlinear effects to come into play. Due to the according redistribution of free energy to stabilizing modes, the system eventually reaches a quasi-stationary state far from thermal equilibrium in which significant core-to-edge transport levels are observed. A general understanding of anomalous transport is therefore crucial to predict and control fusion scenarios. In this context, it is noteworthy that various turbulence types exist which may be distinguished by means of their characteristic wave numbers and frequencies. Three prominent examples are the ion temperature gradient (ITG) driven mode, the trapped electron mode (TEM), and the electron temperature gradient (ETG) mode. While the first two types are typically found on space-time scales associated with to the ion dynamics, the ETG mode resides on electron scales. Obviously, the question arises whether both turbulence scales can be treated independently which is often done due to the enormous computational effort linked to resolving multiple space and time scales. Furthermore, the significance of ETG modes for heat transport fluxes is currently a controversial issue. Namely, mixing length estimates predicting negligible contributions have recently been challenged by new theoretical and experimental findings. A clarification along these line is desperately needed since future fusion devices will exhibit strong electron heating caused by fusion-born α particles.

1.2 Plasma Turbulence Investigations Using Gyrokinetic Theory

It is impossible to solve the equations of motion for each and every plasma particle separately. Additionally, due to the high temperatures and low densities, fusion plasmas are only very weakly collisional which limits the use of fluid models like those known from hydrodynamic turbulence investigations. Instead, a kinetic description is called for. Here, a six-dimensional Vlasov equation for each particle species needs to be solved. Furthermore, they are all coupled via Maxwell's equations. The resulting integro-differential system of equations is extremely difficult to evaluate numerically. However, in strongly magnetized plasmas, the gyromotion around the field line is decoupled from the typical turbulence time scales. The corresponding description can thus be reduced to the dynamics of a charged ring using sophisticated perturbation theories [3]. The most popular and successful such model is the so-called modern gyrokinetic theory [1, 11, 15, 16] which forms the basis for almost all ab-initio simulations of plasma microturbulence in fusion devices. A prominent example of a corresponding implementation is the GENE code which will be further discussed in the next section. With such software, many problems crucial for the next generation fusion devices can be targeted. For instance, turbulent transport contributions originating from scales much smaller than the ion gyroradius can be investigated.

2 The Plasma Turbulence Code GENE

All simulation results which will be presented in the following sections are generated using the nonlinear gyrokinetic GENE code. A brief software introduction shall therefore be given at this point.

Initially developed by F. Jenko [18], the GENE (Gyrokinetic Electromagnetic Numerical Experiment) code has now been maintained and extended at the Max-Planck-Institut für Plasmaphysik and the Garching Computing Centre for about a decade. Some of the most important milestones along this way are reported in [4, 5, 14, 22–25]. Since 2007, regular public releases have been distributed [21], and several significant code extensions have been performed in the context of international cooperations, particularly with the Centre de Recherches en Physique en Plasma at the École Polytechnique Fédérale de Lausanne. By now, GENE is considered to be Open Source, thus encouraging collaborators around the world to extend the physical comprehensiveness.

The discretized nonlinear gyrokinetic equations are solved on a fixed, five-dimensional (three spatial and two velocity space dimensions) grid which is aligned with the magnetic field lines in order to reduce the computational requirements describing highly anisotropic plasma turbulence structures. Furthermore, a so-called δf splitting technique consistent with the ordering used in the derivation of the gyrokinetic theory is employed so that only the fluctuating parts of each distribution function are propagated in time. The phase space and time operators are treated separately, following the so-called method of lines. While the time stepping is typically done with a fourth-order explicit Runge-Kutta scheme in the initial value solver mode, the numerical schemes in the spatial directions depend on the chosen type of operation. Large fusion devices where the gyroradius is much smaller than the machine size may be simulated in the local approximation. Here, all profiles are evaluated at a single radial position which allows for the application of pseudo-spectral methods in both perpendicular space directions. For smaller devices, GENE has been recently enhanced to consider the full radial profile information. Here, finite-element and finite-difference techniques have to be applied in the radial coordinate. The third spatial direction (parallel to the background magnetic field) and the velocity space directions are always discretized via finite difference methods. For an efficient use of high-performance architectures, GENE is hybrid-parallelized, i.e. all core parts can be run in parallel using the OpenMP and/or the MPI paradigm. The latter is achieved through domain composition in the species, in the velocity space directions and in two of the three spatial directions (all three in the nonlocal code, respectively). Very good scaling properties have been demonstrated on up to 32,768 processors [23], and the GENE software package has successfully been ported and used efficiently on various massively parallel systems, for instance IBM BlueGene/P, IBM Power5/6, Cray XT4/5, and of course SGI Altix 4700.

3 Nonlinear Gyrokinetic Simulations Covering Multiple Spatio-Temporal Scales

This section is dedicated to the presentation of one of the first efforts to self-consistently simulate spatio-temporally separated turbulence modes, an attempt which has been made possible by the current and a previous LRZ (DEISA) project. More detailed information can be found in Refs. [12–14].

3.1 Introduction and Context

A large variety of modes involving a wide range of space and time scales may potentially contribute to the heat and particle transport in magnetically confined fusion plasmas. However, based on simple mixing-length estimates, it was often assumed that sub-ion-gyroradius scale turbulent fluctuations do not contribute significantly, e.g., to the heat fluxes. Furthermore, simulations covering all scales involved turn out to be on the verge of today's supercomputing resources. As a remedy, turbulence modes on different scales are often assumed to be decoupled so that investigations of modes e.g. on the ion gyroradius scale become feasible.

In fact, such single-scale simulations [10, 17, 19] provided first evidence for significant electron-scale driven transport. These fluctuations which are spatio-temporally separated from ion-scale turbulence types – for instance, ion temperature gradient (ITG) driven or trapped electron modes (TEMs) – by the square root of the ion-to-electron mass ratio are driven by electron temperature gradients (ETG) and are linearly isomorphic to ITG modes. However, the nonlinear saturation mechanisms turn out to be different. While ITG modes are often dominated by zonal (shear) flows which suppress long, radially elongated structures, ETG modes develop streamer-like vortices which boost the radial heat transport.

In realistic cases where different turbulence types are excited simultaneously, the question immediately arises whether, and if so, how cross-scale coupling potentially alters those findings. Hence, multiscale simulations covering ion and electron space and time scales self-consistently are urgently called for. Corresponding examples will be shown in the next subsection.

3.2 Simulation Details

The physical and numerical parameters chosen in these investigations are detailed in the present section. It is important to avoid including too many effects which have an impact on the turbulent systems under investigation, for that would needlessly complicate a subsequent interpretation and cause significantly more computational effort. Thus, magnetic field fluctuations and collisions are neglected in the following study, even though GENE is able to include them. Furthermore, all of the below simulations were performed in a simplified, so-called $\hat{s}$-α flux tube geometry with vanishing Shafranov shift $\alpha = 0$, which is consistent with the electrostatic limit $\beta \ll 1$ that allows for employing a relatively moderate number of grid points in the parallel direction. Most physical parameters correspond to the so-called Cyclone Base Case (CBC) [9], i.e., the safety factor $q_0 = 1.4$, the magnetic shear $\hat{s} = 0.8$, the inverse aspect ratio $\varepsilon = r/R_0 = 0.18$, as well as equal densities $n_{0i} = n_{0e} \equiv n_0$ and temperatures $T_{0i} = T_{0e} \equiv T_0$ are employed. The density and temperature gradients, $R_0/L_n \equiv R_0 \nabla \ln n$ and $R_0/L_{Tj} \equiv R_0 \nabla \ln T_j$ ($j = e, i$), being normalized to the major tokamak radius R_0 are varied on a case-to-case basis.

Addressing the numerical parameters, the perpendicular box size is chosen to be $(L_x, L_y) = (64, 64)$ in units of the ion gyroradius ρ_s, and $768 \times 384 \times 16$ real space grid points are used in the radial (x), binormal (y), and parallel (z) direction, respectively, complemented by 32×8 grid points in $(v_\parallel, \mu)$ space. Here, $v_\parallel$ is the parallel velocity space direction and μ the magnetic moment. With these settings, one simulation consumes about 100-200 kCPUh. However, at this point, we note that a reduced mass ratio of $m_i/m_e = 400$ is considered. Otherwise, a single multiscale simulation would have exhausted the whole project budget since the computational time roughly scales as $T_{\text{CPU}} \sim (m_i/m_e)^{3/2}$.

Typically, those simulations have been run in a pure MPI mode on 384 cores with an average performance of about 16% of the theoretical maximum value. The memory consumption has been on the order of 100 GB which fits very well within the hardware specifications. To ensure a reasonably well resolved resolved quasi-stationary state of the nonlinear simulations, on the order of 10^5 time steps had to be calculated. At regular intervals which have been adapted to the data size, files containing 1D, 3D, and 6D fields have been written for post-processing reasons.

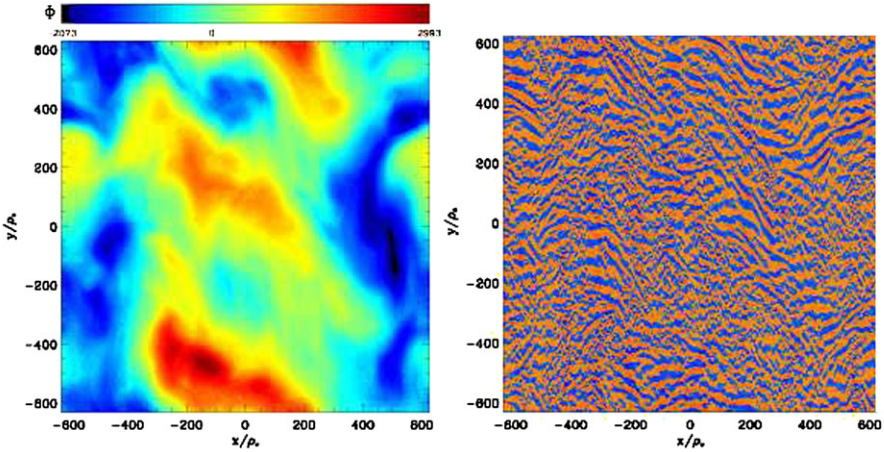

Fig. 1 Snapshot of the electrostatic potential at the outboard mid-plane for $R_0/L_{Ti} = R_0/L_{Te} = 6.9$ and $R_0/L_n = 2.2$, showing a dominance of large-scale, ITG vortices; and the same data with all $k_y\rho_s < 2$ modes filtered out, demonstrating the existence of small-scale ETG streamers which are subject to vortex stretching. Source: [12]

3.3 Simulation Results

The linear driving terms in the gyrokinetic Vlasov equation strongly depend on the temperature and density gradients. In order to be close to an experimentally relevant regime, many simulations thus employ the CBC nominal values, $R_0/L_{Ti} = 6.9$ and $R_0/L_n = 2.2$, which are based on a specific DIII-D tokamak discharge. A snapshot of a corresponding multiscale simulation with $R_0/L_{Te} = R_0/L_{Ti}$ is shown in Fig. 1. In this case, the electrostatic potential is dominated by large-scale vortices which show weak zonal flow behaviour (prevalent orientation in y direction). However, a high-pass filter (in terms of wave numbers) reveals the presence of small-scale streamers whose radial extension seems to be limited by large-scale vortex shearing. The high-k ($k_y\rho_s > 1$) fraction of the electron heat flux is hence quite small (about 10%), see Fig. 2. Both findings imply that single-scale simulations assuming isolated subsystems can, in general, not be applied for transport predicitions. The significance of ETG driven modes, however, depends on the specific parameter set, as will be seen in the following.

Comparing the simulated heat fluxes with the actual experimental values reveals an overestimation of the ion heat flux by almost two orders of magnitude. A likely key reason for this dramatic difference is that the normalized ion temperature gradient R_0/L_{Ti} – on which ITG turbulence depends very strongly but whose extraction from experimental temperature profile data is usually difficult – has been chosen somewhat too large. Therefore, several simulations with smaller values have been performed and analyzed. The ion heat flux is indeed decreased, as can be seen in Fig. 2. But additionally, the high-k contribution to the electron heat flux becomes more and more pronounced with decreasing R_0/L_{Ti} and eventually drives about

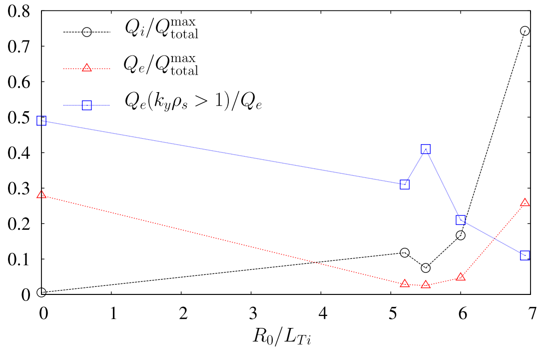

Fig. 2 Ion and electron heat flux Q as functions of the ion temperature gradient, normalized to the maximum total heat transport which is reached for $R_0/L_{Ti} = R_0/L_{Te} = 6.9$ and $R_0/L_n = 2.2$. In addition, the high-k fractions of the electron heat flux are displayed. The default choices for the remaining gradients are $R_0/L_{Te} = 6.9$ and $R_0/L_n = 0.0$. Source: [14]

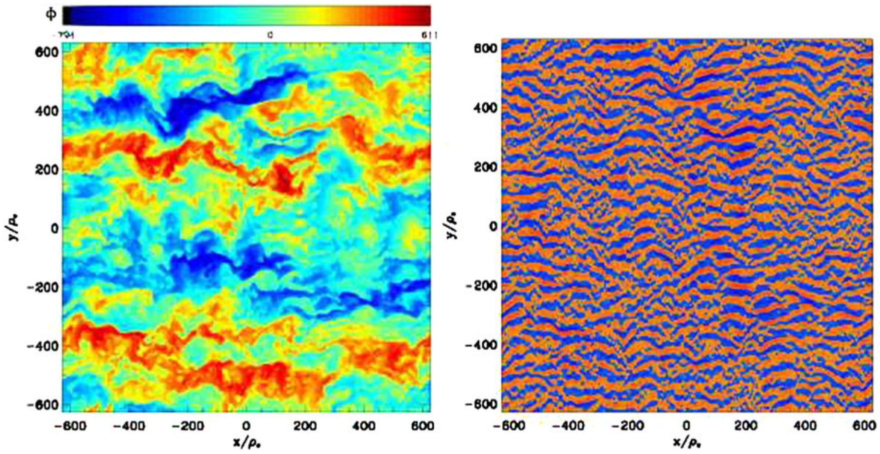

Fig. 3 Electrostatic potential contour at the low-field side for $R_0/L_{Ti} = 0$, $R_0/L_{Te} = 6.9$, $R_0/L_n = 0$, and the same contour neglecting all modes $k_y\rho_s < 2$. Source: [12]

50% when ITG modes are stable. One possible reason can be deduced from Fig. 3 where a contour of the electrostatic potential is shown for the $R_0/L_{Ti} = 0$ case. The character of the remaining large-scale turbulence mode – here, temperature gradient driven TEM – resembles the general behaviour of the small-scale ETG modes. Both seem to develop radially elongated structures so that thin ETG mode streamers may evolve much more easily within thick TEM vortices than in the ITG dominated case.

While heat and particle fluxes and their spectra are typically the quantities of interest in plasma turbulence research, the latter turn out to be hardly measurable in experiments. For spectral comparisons, one thus has to fall back on related quantities as, for instance, densities. Figure 4 shows corresponding examples for different scenarios. Compared to pure ITG, TEM, and ETG mode driven turbulence cases, mixtures exhibit a tendency to flatten density spectra in the $k_y\rho_e \sim 0.1$ region. For experimentalists, such a behaviour may thus serve as a signature for strong ETG activity (note that for a realistic mass ratio of $m_i/m_e = 1836$ or $m_i/m_e = 3675$, the wave numer region corresponds to $k_y\rho_s \sim 4$ and $k_y\rho_s \sim 6$, respectively).

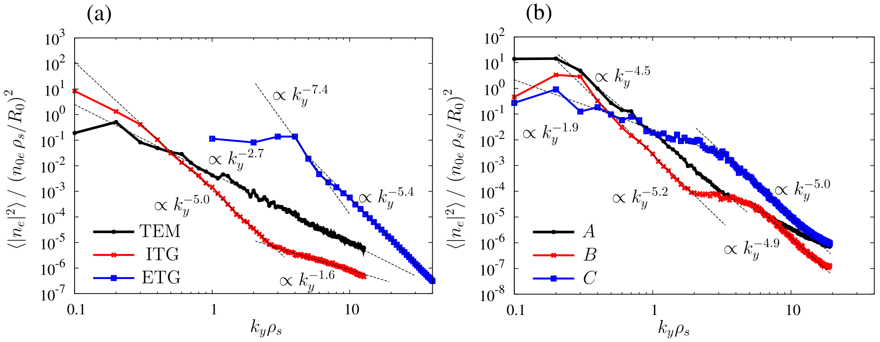

Fig. 4 Squared electron density fluctuations evaluated at $k_x\rho_s = 0$ and averaged over the parallel direction and time for (a) pure turbulence cases and (b) turbulence mixtures. Source: [13]

Summarizing, we have shown that massively parallized multiscale simulations predict a tendency towards a scale separation between ion and electron heat transport. In contrast to its ion counterpart which is only driven by large scales, the electron heat channel may thus exhibit substantial or even dominant high wave number contributions carried by ETG modes and short-wavelength TEMs. Therefore, these investigations might help to understand residual electron heat fluxes in cases where the low-k drive becomes small compared to the ETG drive, as for instance in discharges with dominant electron heating, high β, or transport barriers. Special focus on the latter will be put in the next section.

4 ETG Turbulence in Edge Transport Barriers

Having shown that small-scale ETG turbulence can contribute significantly to the heat transport observed in today's fusion experiments, we now turn to another study which examines ETG turbulence in an edge transport barrier. The formation of such a barrier has been observed for the first time almost three decades ago [26] and has since been found in many other experiments. The physics of its formation, however, is still not fully understood. Experimental measurements show that there are strong shear flows in the plasma edge, which are usually thought to suppress large-scale turbulence. On the other hand, it has been unclear whether ETG turbulence is affected by these flows and what sets the residual transport that is found in the barrier region.

To illuminate this issue, we performed nonlinear GENE simulations with ASDEX Upgrade edge parameters [20], restricting the simulation domain to electron scales and assuming ion turbulence to be suppressed. Under such conditions, it was found that ETG turbulence indeed produces enough heat flux to match the values inferred by transport modeling codes. The simulations furthermore show that the electron heat flux peaks at very small scales of $k_y\rho_s \approx 50$ which corresponds to a physical

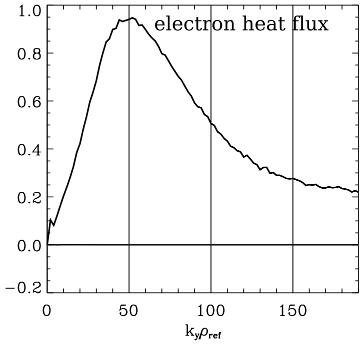

Fig. 5 k_y spectrum of the electron heat flux. As can be seen, most of the transport is produced at wavenumbers around $k_y\rho_s \approx 50$

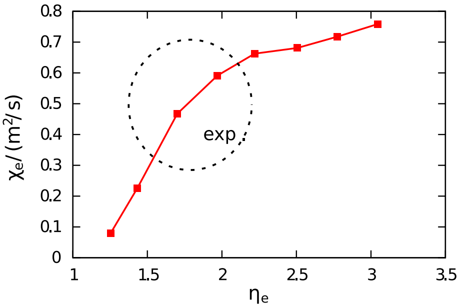

Fig. 6 Electron heat diffusivity at different electron temperature gradients. The obtained diffusivities are of the same order of magnitude as the experimental values

wavenumber of $k_\perp\rho_s \approx 15$ (see Fig. 5). In addition, linear simulations show that the ETG modes examined here are unstable for $\eta_e > 1.2$, where $\eta_e = n_e/T_e \cdot \nabla T_e/\nabla n_e$. This finding, which is confirmed by a nonlinear gradient scan (see Fig. 6), implies that ETG modes are unstable in the edge of ASDEX Upgrade H-mode and even L-mode (low confinement) discharges, since η_e is often around a value of 2. Therefore, ETG turbulence is a chief candidate for the process governing the relation between the electron temperature and density profiles that are found in the experiment.

5 High-β Simulations and Microturbulence in Astrophysics

Most gyrokinetic simulations have been performed either in the electrostatic limit or at low values of the normalized plasma pressure, $\beta = \beta_e = n_e T_e/(8\pi B^2) \ll 1$. At typical experimental values $\beta \sim 0.01$, however, electromagnetic effects become important and can even change the turbulence type completely. Corresponding studies were published in Refs. [6, 25]. There, it was found that for CBC parameters, raising β continuously from zero to values beyond the ballooning threshold had a fundamental impact on the nonlinear transport levels. More specifically, at the experimental value, the transport was suppressed by a factor of ~ 10 compared with the electrostatic limit. Such studies require high parallel resolutions which also has an adverse impact on the time step, resulting in significant computational requirements.

Apart from their importance in understanding tokamak core turbulence, electromagnetic effects are also key to using the GENE code to investigate anomalous transport in magnetized space plasmas. In some astrophysical contexts, density and temperature gradients can occur on scales small enough to drive plasma microinstabilities. Even when the system scale is too big to allow for any such instability to develop, MHD turbulence may create filaments and small structures, and microturbulence is able to enhance the transport by taking over at the end of the MHD cascade (see, e.g., Ref. [7]). Preliminary results regarding turbulence in evaporating clouds around Active Galactic Nuclei (AGN) have been published in Ref. [25]. There, dense, cold gas is immersed in a hot, dilute medium. Since unhindered evaporation would lead to cloud lifetimes much shorter than observations report, mechanisms have to exist which protect the clouds. Primarily, magnetic fields have been considered [8], preventing heat exchange perpendicularly to the field lines. However, microturbulent transport may be strong enough in some of these objects to have a significant impact on the clouds by providing an additional heat transport channel.

6 Conclusions

Employing massively parallel simulations on the HLRB2 machine with the nonlinear gyrokinetic code GENE, we were able to address several key questions concerning plasma microturbulence. First, we investigated whether earlier predictions on the role of sub-ion scale turbulence hold true if such small-scale modes are considered self-consistently with ion-gyroradius-scale turbulence types. It has been found for the first time that ion and electron heat fluxes tend to exhibit a scale separation where the former is only driven by large-scale turbulence whereas the latter may have significant or even dominant electron-gyroradius-scale contributions. Future investigations involving a realistic mass ratio and more physics are thus currently planned. In a second study, we concentrated on pure ETG modes in the edge regime of the Garching experiment ASDEX-Upgrade. It could be shown that such small-scale modes can indeed provide an explanation for the residual transport in edge barriers. Finally, first results of applications to astrophysical plasmas have been discussed which are going to be extended in the near future.

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