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Turbulent transport and the plasma edge

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Abstract

In magnetically confined fusion experiments, turbulent transport dominates over collisional transport in the edge gradient region and in the scrape-off layer (SOL). Traditionally concepts as Fick's law are used to describe turbulent transport by effective diffusion coefficients and convective velocities. These concepts are only well founded if the transport exhibits Gaussian statistics. In the last decade it has become increasingly obvious this is not the case [E.T. Lu, Phys. Rev. Lett. 74 (1995) 2511; D. Newman, B.A. Carreras, P. Diamond, T.S. Hahm, Phys. Plasmas 3 (1996) 1858]. Intermittency, long range correlations, and ballistic transport events are widely documented in the plasma edge. The latter are characterized by the radial propagation of coherent structures – usually referred to as blobs – carrying energy, current and particle density across magnetic field lines. This ultimately renders the description of transport by mere use of effective mean transport coefficients useless, as this does not account for the effects of frequent extreme events, which have strong, lasting, and possibly destructive influence on plasma facing components.

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1. Introduction

Turbulence has since long been found to be the dominant reason for the observed limited confinement especially in the edge of fusion devices. The plasma edge being the plasma pressure gradient region in the domain of closed magnetic field lines. While the establishment of an edge transport barrier for a limited time can bring the transport down to neoclassical levels, this so-called H-mode is usually accompanied by large intermittent transport excursions. These are often named ELMs throughout their entire evolution, from the initial instability – which gives rise to the name edge localised mode (ELM) – to the late phase, where the ELM has detached from the plasma and traverses the scrape-off layer (SOL) with open magnetic field lines as a filament, a structure localised perpendicular and extended along the magnetic field lines. The origin of the ELM filaments is ascribed to a number of possible mechanisms, the most accepted at the moment being the Peeling–Ballooning model [3,4]. The SOL is characterized by the flow of plasma towards material surfaces, by the inflow of heat and particles from the plasma core through

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transport, and by the absence of a fully developed equilibrium with associated flows. It is general consensus that both edge and SOL are of utmost importance to the realization of a working fusion machine. The edge sets the overall performance of the plasma, as it is the confining shell through which all transport has to pass. The SOL is, on the other hand, important for the exhaust of plasma and through the SOL the plasma is in contact with the material walls. The properties of the SOL will to a large extent determine the loads on the wall materials, which often are at or above the limits modern materials can withstand. SOL properties also work back on the edge, for example by determining the amount of main chamber recycling and impurity propagation into the core. Consequently, to reach theoretical understanding both regions need to be treated in their interactions. While probe measurements in the SOL routinely reveal high fluctuation levels, only with the arrival of sophisticated spatio-temporal diagnostics, such as fast CCD cameras and multiple probe arrays [5–8], it has become increasingly feasible to perform direct comparisons with results from advanced numerical and theoretical models. This paves the way for developing predictive models, which will be of paramount importance for the design and operation of next generation fusion devices. While over the past decade tremendous progress has been made in that direction, we are still in the infancy of having sufficient understanding of the plasma edge that would allow one the predictive capability that is the foundation of any kind of effective control.

Before reporting on results from theory and simulations in Section 3, Section 2 will review some fundamental properties of turbulence and turbulent transport. In Section 4 challenges to modeling and important ingredients yet lacking in modeling are discussed.

2. Turbulence, turbulent transport and fundamental concepts

When speaking about turbulent transport, which often is used synonymously to anomalous transport, one first has to define what turbulence is. Falkovich gives the following definition: 'Turbulence is a state of a *non-linear* physical system that has energy distribution over *many degrees of freedom* strongly deviated from equilibrium. Turbulence is irregular both in time and in space. Turbulence can be maintained by some external influence or it can decay on the way to relaxation to equilibrium' [9].

A fundamental property of turbulent velocity fields is their capability to advect particles and fields around, leading to mixing and in the presence of gradients to transport.

The distinguishing feature between turbulence and 'chaos' is often asked for, and the above definition clearly separates the turbulence from chaos, the latter which also exhibits complex spatiotemporal behaviour, but can usually be described by a system of n coupled ordinary differential equations, with n being small and slightly larger than the dimension of the attractor of the chaotic system.

In the case of magnetically confined plasmas we are clearly dealing with systems that are far from equilibrium and that are able to constantly drive turbulence as energy stored in gradients is converted to complex plasma motions, consequently leading to a reduction of the driving gradients, which implies transport.

2.1. Is turbulent transport diffusive?

The traditional approach to anomalous transport tries to carry over the concepts of classical and neoclassical collisional transport into the realms of turbulent transport. The fundamental ideas originate, like so many in plasma theory, from fluid dynamics and go back to the concepts of Brownian motion and were first laid out by Taylor [10,11]. The fluctuating velocity field acts as an effective collisionality on the advected quantity. Given a displacement per effective collision proportional to the Lagrangian correlation time τ_L times a typical velocity u, the turbulence leads to an effective diffusion of the form:

$$D_u = \langle u^2 \rangle \tau_L.$$

In practice the Lagrangian correlation time is difficult to measure and moreover, this approach leaves out correlations between turbulent velocity fluctuations and transported quantity. These arise naturally from linear instabilities. Thus, turbulence spectra can be used to express the flux Γ of a quantity, here of the density n with δn being the density fluctuations and $v_r = -\partial_y \phi / B$ the radial electric drift velocity:

$$\Gamma = \int \delta n v_r \, d\vec{x} = -\int \delta n \partial_y \phi / B \, d\vec{x} \approx \sum_{\vec{k}} i k_y \phi_{\vec{k}} / B \delta n_{-\vec{k}} + c.c. \qquad (1)$$

Net transport only occurs for a finite correlation between velocity (potential) fluctuations and transported quantity. As an example regard the relationship between density and potential fluctuations given by drift wave type of turbulence $\delta n_{-\vec{k}} = \phi_{-\vec{k}} - \mathrm{i}\beta \frac{k_y k_\perp^2}{1+k_\perp^2} \phi_{-\vec{k}}$ which leads to a positive net flux $\Gamma \approx \beta \sum_{\vec{k}} \frac{k_y^2 k_\perp^2}{1+k_\perp^2} |\phi_{\vec{k}}|^2 > 0$ [12].

This linear instability reasoning underlies most first principles transport models which parametrize the turbulent transport by effective transport coefficients linking gradient and flux in the form of diffusivities and convective velocities. Turbulence spectra, saturation amplitudes, growth rates and phase relationships all depending on the local properties of the instability regarded determine the transport. Balancing of linear growth rates with the quasilinearly estimate of the flux (1) result in the popular mixing length approach, which has proved to be tremendously successful in many situations. However, spatial and temporal correlations in the turbulence, giving rise to phenomena as intermittency and coherent structures are ignored here. Moreover, this traditional approach excludes non-linear instabilities [13,14] and the advection of turbulence from unstable into linearly stable regions [15,16].

If a significant increase in the fluxes would be all there is to turbulent transport, we would be in a comfortable position. We would largely be able to quantify the transport and predict average transport features with high precision. Our task as fusion physicists would be to develop methods to reduce fluctuation levels or to influence linear instabilities to control transport. But in many situations and almost certainly for the system we are considering, the edge/SOL region, the statistics of turbulent transport are more complex and the simple relation between linear instabilities, gradients and flux is broken. The statistical properties of turbulence, such as heavy tails on the probability density functions (PDFs) of the transport, have been discussed in length in the literature in the past years [1,2,17,18]. I will here concentrate on other, additional, aspects of turbulent transport.

First, I would like to comment on the use of convective velocities and effective diffusion coefficients to describe turbulent transport. Consider a transported scalar quantity θ for which we express the flux in terms of an effective diffusion coefficient D and a convective velocity V:

$$\Gamma = -D\nabla\theta + V\theta. \tag{2}$$

Γ and θ are available in detail in numerical simulations, so that with a scatterplot of Γ/θ versus $\nabla \log \theta$ the alleged linear relation between flux and gradient as well as a finite flux at zero gradient, resulting from a convective net-velocity and showing pinch effects [19], can be evaluated. In edge transport simulations, where assumed fixed or only modestly variable background gradients feed the turbulence, such an analysis of the transport is usually futile, as the necessary variation in the gradients is not achieved. However, the transport of a passive scalar, which does not work back on the turbulent velocity field, is often a good proxy for the bulk plasma transport [20], and – as no fixed gradient for the passive tracer is set beforehand – an evaluation of the flux–gradient relation over a significant range can be performed. Fig. 1 shows on the left side the flux–gradient relation obtained at a fixed poloidal position from a flux tube simulation of

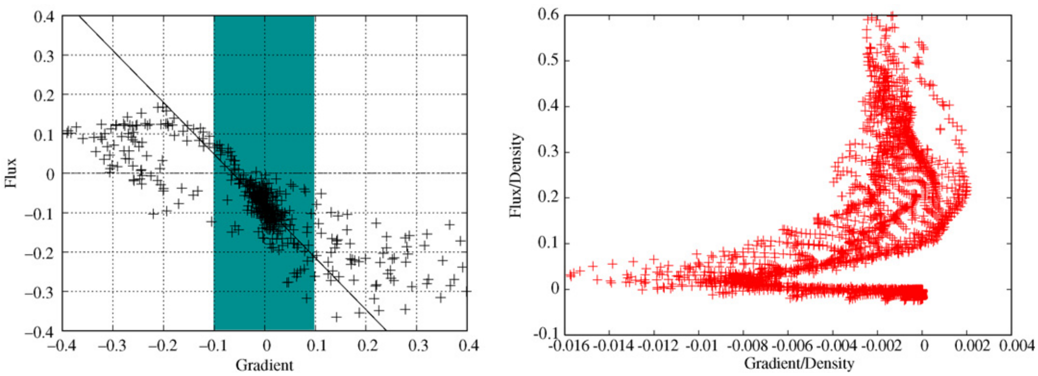


Fig. 1. Scatter of Γ/n versus $\nabla \log n$ for a passive tracer density in a fluctuation based drift-Alfvén turbulence model (left) (from [19]) and for density in a global simple SOL model (right).

drift-Alfvén turbulence [19]. For this system, with clear scale separation between background and fluctuations in length scales as well as in contained energy, the description of transport by just two parameters, effective diffusivity and effective advective velocity, can be justified. The amount of scatter from a linear flux–gradient relationship is weak, despite some complexity in the details of the turbulent transport of the passive scalar field. On the other hand, if we investigate the flux–gradient relation in a simple ESEL interchange model of the SOL at constant temperatures [21–23], we see that the D, V parametrization of the transport no longer makes sense. In these simulations the gradient is freely evolving and the turbulence is driven by a source-sink configuration. As can be seen from Fig. 1 no clear relation between flux and gradient can be reached, high and fluctuating levels of transport are observed even in the absence of a background gradient. This is a manifestation of the highly intermittent nature of transport in the SOL. Self-propelled drifting blobs account for the high transport values destroying the linear flux–gradient relationship. The linear flux–gradient relationship here could match low transport values driven by local fluctuations. Formally, it remains possible to calculate effective diffusion coefficients or convective velocities, at every time or on average. These numbers just have little meaning beyond stating the average gradient and the average flux of the system. While the traditional approaches to transport are justified for a number of weakly turbulent transport processes in the core plasma [24], they in general do not describe the manifold of transport processes active in the edge and strongly intermittent turbulent transport. The traditional picture moreover offers no explanation for observed anomalous pinch effects in plasmas, which play a role in density peaking [25,26] and the penetration of impurities from the edge [27,28].

2.2. Energetics of turbulence and turbulent transport

It is instructive to consider the relation between transport and turbulence by looking at the energetics of the generating processes for the turbulence and their relation to transport. Let us therefore consider a well known paradigmatic model for electrostatic turbulence in the edge, the famous Hasegawa–Wakatani system [29,12], describing magnetized plasma in a straight magnetic field along $\hat{z}$:

$$\partial_t \omega + \{\varphi, \omega\} = \frac{1}{v} \nabla_\parallel^2 (n - \varphi), \tag{3}$$

$$\partial_t n + \{\varphi, n\} + \partial_y \varphi = \frac{1}{v} \nabla_\parallel^2 (n - \varphi), \tag{4}$$

with the Poisson bracket $\{\phi, \cdot\} = \partial_x \phi \partial \cdot - \partial_y \phi \partial_x \cdot = \vec{v}_{E\times B} \cdot \nabla \cdot$ contains the advection with the $E \times B$ drift, and the vorticity $\omega = \nabla_\perp^2 \varphi$. x is in the radial and y in the poloidal direction for a plasma edge setup, and n and ϕ are perturbations in the density and electric potential. This system is known to be driven by a dissipative instability with the growth rate proportional to the parallel resistivity v. The energy theorem for this system reads:

$$\begin{aligned}\frac{\partial}{\partial t} E &= \frac{1}{2} \frac{\partial}{\partial t} \int n^2 + (\nabla \varphi)^2 \, \mathrm{d}V \\ &= -\int n \partial_y \varphi \, \mathrm{d}V - \frac{1}{\delta} \int (\varphi - n)^2 \, \mathrm{d}V.\end{aligned} \tag{5}$$

Here we used the two-dimensional approximation with $\delta = L_\parallel^2 v$ and an effective parallel length $L_\parallel$ of the perturbations. The resistivity provides a sink of energy and the energy in the fluctuations is fed by the $E \times B$ density flux $\Gamma = -\int n \partial_y \varphi \, \mathrm{d}V$. Note that this density flux is zero for an adiabatic electron response ($\delta = 0$) as $n = \varphi$ holds, consistent with a vanishing linear growth rate. Thus, free energy in gradients drives turbulence and turbulent transport simultaneously. It is important to note that in situations where the plasma is only unstable in certain regions, the energy that is transferred from the gradients into the turbulence will not stay at the location of origin, but be advected/transported into the stable regions. This effect known as turbulence spreading [30–32] has more recently obtained attention in plasma physics [33,34,16] with some early ideas to couple this to the evolution of zonal flows [35]. Turbulent transport therefore has not only non-local features, but it can make free energy available in stable regions of the plasma, where linearly modes would be damped. This effect of depositing energy into stable modes, reverses the phase relationship that is necessary to obtain finite down gradient transport, and thus the turbulent energy can in these regions be used to drive an up-gradient transport [36].

3. Results

In this section, we will briefly review some of the more recent results obtained in simulating edge/SOL turbulence and transport.

3.1. Characterization of edge turbulence

Edge turbulence in the closed field line region has been extensively investigated by using fluctuation based turbulence models. Here we would only like to mention the influence of the plasma beta on the nature of the turbulence, which through energy transfer into magnetic field fluctuations influences the dynamics even for relatively low plasma beta [37]. It has been extensively demonstrated that turbulence in the edge has the characteristics of drift-Alfvén turbulence [38–40]. The parallel currents provide most of the coupling between the fluctuating quantities and render the influence of magnetic curvature effects less important. Consequently, most fluctuating quantities show weak ballooning and a transition to stronger ballooning takes place only at rather large plasma beta (see Fig. 3). Recently, the transition from purely edge turbulence to purely SOL turbulence has been investigated within the fluctuation paradigm. It was found that in the SOL the nature of the turbulence changes, becoming interchange mode like [41], implying that the most important energy transfer mechanism in the SOL is due to curvature effects by the inhomogeneous magnetic field.

3.2. Impurity and particle transport in the edge/SOL region

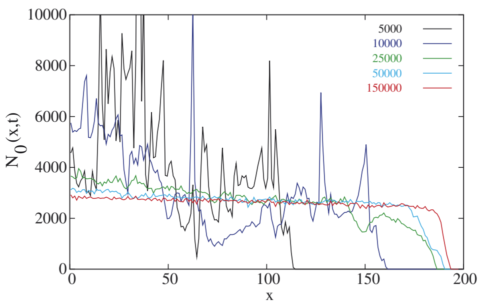
The transport of impurities, characterized by a passive tracer population, has been investigated in ESEL [22] SOL turbulence [29]. Fig. 2 presents the evolution of the impurity density, N_0, averaged over the periodic poloidal direction for the cases where the impurities are released inside the LCFS (left panel) and in the far SOL (right panel). The particles are rapidly mixed and after a few bursts of the turbulence the particles released inside LCFS already have penetrated far into the SOL. The velocity of the fastest of the particles is larger than $0.1c_s$, which is more than twice the typical blob speed [22]. The particles released in the SOL are mixing at a slower rate, but again after only a couple of burst periods they penetrate inside the LCFS. Ultimately the impurity density profile ends up following the same functional shape as the inhomogeneous magnetic field. This final profile is independent of where the particles are released. The transport is certainly not governed by a standard 'Fickian' diffusive process. It can be described by an effective pinch, which may be understood by considering the continuity equation for the impurity particle density N [42,19]. Consider an inhomogeneous magnetic field $B(x)\hat{z}$:

$$\left(\frac{\partial}{\partial t} + \frac{1}{B(x)}\hat{\mathbf{z}} \times \nabla\phi \cdot \nabla\right)\frac{N}{B(x)} = 0, \tag{6}$$

which implies that $N/B(x)$ is a Lagrangian invariant advected by the compressible electric drift $v_{E\times B} = \hat{\mathbf{z}} \times \nabla\phi/B(x)$. Assuming effective mixing of the impurities by the turbulence, this invariant will be uniformly distributed in space and the poloidally averaged impurity density $N_0(x)$ varies like $B(x)$. This corresponds to the so-called inward (curvature) pinch, which is also readily observed in investigating impurity transport in edge turbulence simulations [19], but only has a net inward component if the driving turbulence shows ballooning properties and thus a poloidal dependence in fluctuation level.

3.3. Blobs

Coherent structures such a blobs have been discovered early on [43] and were popular in paradigmatic plasma turbulence models for some time. Only with the recent advent of spatiotemporal fast diagnostics they have received attention again.



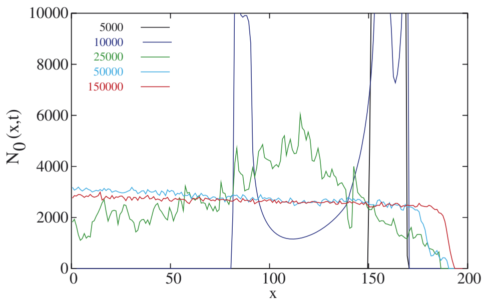


Fig. 2. Evolution of the impurity density N_0 averaged over the y-direction. Impurities are released in a narrow band around $x = 40$ (left panel) and $x = 160$ (right panel).

Since, their theoretical description has been fastly developing [44–47]. For the evolution of blobs in the SOL it is important to understand that the plasma in the SOL is not confined, but streaming off along magnetic field lines toward the divertor target plates. Plasma parameters thus change drastically along as well as across magnetic field lines, opposite to the confined region. In the SOL flux surfaces can still be constructed, but loose their importance as on a SOL flux surface the plasma pressure is not constant. Assuming that plasma is ejected as a blob from the edge into the SOL over a finite parallel extend, in a poloidal window of unfavorable curvature, the blob will be a plasma cloud expanding along magnetic field lines into vacuum while propagating radially across magnetic field lines. Fig. 3 contrasts the blob evolution in the SOL with the drift type dynamics in the edge region. With perpendicular velocities of plasma filaments (V_{Blob}) of a couple of percent of the ion-sound speed c_{s} [6], blobs can move radially across the SOL, which typically is a couple of centimeters wide (Δ_{SOL}), before they expand to the divertor target plates which are meters ($L_{\parallel}$) away: $L_{\parallel}/C_{\mathrm{s}} \approx \Delta_{\mathrm{SOL}}/V_{\mathrm{Blob}}$.

The SOL does not honor the resistive MHD equilibrium existing in the closed field line plasma region. The Pfirsch–Schlüter current system can, for example, not be closed and thus plasma properties are characterized by a balance between parallel and perpendicular transport. Once again the time averaged flow velocities do not reflect the redistribution of energy and particles during intermittent transport events. There is no useful separation between fluctuations and background in the SOL and fluctuations easily exceed the long time average values which define the background. In the SOL fueling from the edge in interplay with losses to the divertor determines the average profiles without any relation to an equilibrium.

The description and simulation of blobs in the SOL has made significant progress in the last few years. Initial models were restricted to the SOL and accounted for sheath dominated parallel losses only [48–50]. Recently, 2D simulations with the parallel losses being due to parallel expansion of an originally poloidally localised structure and encompassing a fueling edge region in addition to the SOL, have had tremendous success in reproducing detailed properties of the SOL, as transport statistics. Predicting the SOL profiles of the Lausanne based TCV Tokamak [51,24] and modeling of the JET SOL profiles appears to be in reach [52].

With ever more detailed simulations available, it should be noted that it becomes increasingly important to also model the experimental diagnostics in the simulations. Fig. 4 shows an ESEL simulated

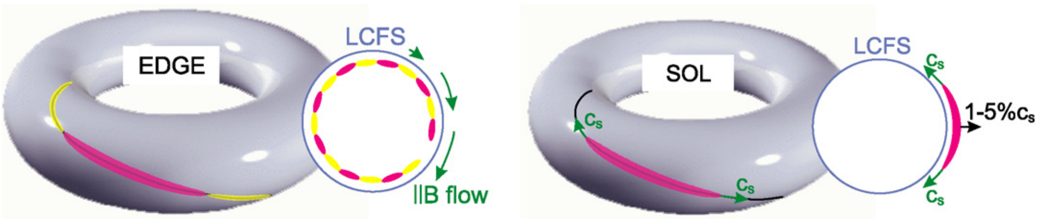


Fig. 3. Difference of drift wave dynamics on closed field lines (left panel) to situation of a blob in the SOL (right panel).

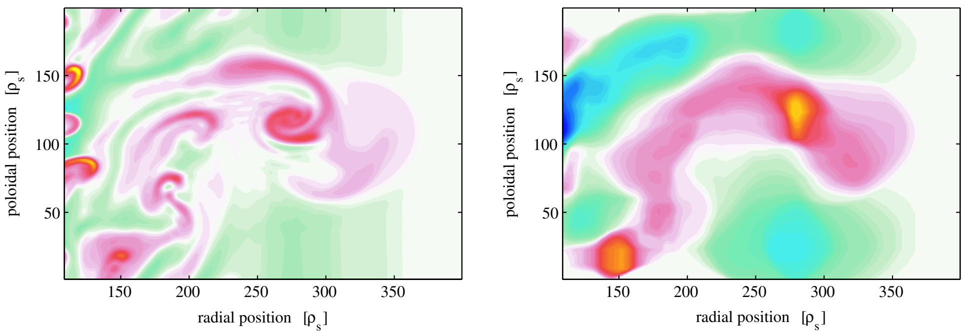


Fig. 4. Blob in the ESEL simulation for Alcator C-Mod (left panel) and inferred D_{α} image of the same structure (right panel) (Figure courtesy of O. Grulke).

blob in the plasma SOL for Alcator C-Mod parameters [53] and correspondingly how that blob would appear to the fast camera detecting D_α. Obviously a larger part of the fine-structure of the blob is lost.

Finally, a few words should be said on the status of modeling of ELMs, which will rely on an accurate modeling of the instabilities in the edge as well as the edge transport barrier. Simulations continue to improve for this phenomena, with results being obtained for the growth phase of an ELM instability [54,55], but the inability, as of yet, to follow the evolution of the ELM self-consistently. In this later phase the ELM sets up high frequency Alfvén waves in addition to low frequency perturbations of the magnetic field, as recently measured at MAST [56]. It seems to emerge a possible picture that in the propagation state of an ELM filament its electromagnetic origin, with magnetic fluctuations and changes in magnetic topology as the main ingredients, is lost. The motion of ELM filaments as they traverse the SOL seems to be governed by the same processes underlying blob transport in the L-mode [57], dominated by electrostatic interchange dynamics [51].

4. Challenges to modeling and simulation

Important for any modeling of plasma dynamics are the timescales in a confined plasma, from electron cyclotron frequency at about 10^{-11} s to the profile evolution timescale in the order of a few hundred milliseconds. Similarly the spatial scales range from 10^{-3} m for the gyroradius to a couple of 10 m in parallel connection length over orders of magnitude. It needs to be noted that for an electromagnetic code that allows for significant changes in magnetic topology, using reduced resolution in one spatial direction seems not to be feasible, as this direction changes locally with the magnetic field evolution. Coupling of 3D turbulence codes with transport codes to overcome time step limitations is pursued [58]. On the other hand 2D modeling of the SOL has clear advantages, as for the foreseeable future it delivers the necessary long simulation times at sufficient spatial resolution [22].

All this puts considerable strain on turbulence modeling of the SOL. Simplifying assumptions made for turbulence in the edge or core cannot be used. Truly integrated global models are needed, which are able to describe the timescales of the turbulence as well as the temporal evolution of the gradients on the same footing including variability in parametrized transport coefficients and usage of realistic dissipative terms, which are not artificially increased and dictated by numerical necessity. Electromagnetic effects with changes to the magnetic field geometry still pose a huge problem for numerical simulations. Even peculiarities in the magnetic field geometry, like the x-point, have until now only been included approximately in turbulence simulations. Neoclassical effects such as the bootstrap-current or magnetic equilibrium evolution are far from being included in simulations, and at some point, turbulence simulations will have to meet up with the detailed simulation of atomic processes build into edge transport models [59].

The ultimate goal is to use SOL modeling for prediction and then for the development of viable mitigation and control mechanisms for edge-SOL turbulence. First results on the latter topic have been obtained in [60,7,61], but as turbulence has significantly more degrees of freedom than low-dimensional chaotic systems, new efficient control schemes have to be developed.

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