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Turbulent SOL transport in stellarators and tokamaks

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Abstract

Spatially highly resolved Langmuir probe measurements of ion saturation current and floating potential fluctuations in the scrape-off layer (SOL) and edge of several tokamaks and stellarators have revealed the spatial structure of these fluctuations. The knowledge of the phase angle and coherency between the fluctuations of these quantities is important for a comparison with models and for the calculation of the induced radial transport. The fluctuations occur as individual events, causing burst-like E × B flows which are very localised in poloidal position and in time and interchange plasma of different density and temperature radially. The resulting particle transport can account for the confinement time inferred from particle balance considerations and from the observed gradients in the SOL. The role of fluctuations of the electron temperature and our understanding of the instability mechanism acting in the plasma edge is summarised. A brief account is given on the changes of the fluctuations and the resulting transport when discharge parameters are varied. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The interest in plasma turbulence within nuclear fusion research is based primarily on the fact that turbulent convection due to fluctuating E × B velocity is, at least in the edge and scrape-off layer (SOL) of all major fusion experiments on which this has been verified, a major contribution to the observed 'anomalous' radial transport, in limiter [1–4] as well as in divertor devices [5–7]. By investigating the fluctuations of various plasma quantities we hope to understand better the instability mechanisms underlying plasma turbulence and to get insight into how to modify the fluctuation-induced transport. In this paper, I shall summarise our knowledge of the basic properties of fluctuations in the SOL and the related radial transport. These basic properties have been found to be quite the same in devices as different in size, edge and magnetic configuration as tokamaks and stellarators, as limiter and divertor experiments, as JET and 'table-top' tokamaks. I shall restrict myself on the 'electrostatic' fluctuations of plasma density $\tilde{n}$, electron temperature $\tilde{T}_e$ and electric potential $\tilde{\Phi}_{pl}$, as magnetic fluctuations appear to play a minor role for the SOL transport, in agreement between experimental [8–12] and numerical results [13]. Furthermore, I shall not consider fluctuations and transport associated with 'Edge Localized Modes' (ELMs).

Many fluctuation measurements in the SOL rely on the high spatial and temporal resolution of Langmuir probes (see, e.g., Ref. [14–16]), which have the additional advantage that several fluctuating quantities like ion saturation current fluctuations $\tilde{I}_{sat}$ and floating potential fluctuations $\tilde{\Phi}_{fl}$ can be measured. Frequently, for lack of better knowledge, temperature fluctuations are neglected and I_{sat} fluctuations are taken to be $\propto \tilde{n}$, and $\tilde{\Phi}_{fl} \propto \tilde{\Phi}_{pl}$. However, recently $\tilde{n}$, $\tilde{T}_e$ and $\tilde{\Phi}_{pl}$ have been measured simultaneously with Langmuir probes on various devices with slightly different techniques, offering the chance to verify the validity of the conclusions drawn from $\tilde{I}_{sat}$ and $\tilde{\Phi}_{fl}$ measurements [17–19,4,20,21]. Further density fluctuation diagnostics such as the poloidally resolved measurement of the H_α or D_α light [22,23,7], collective scattering [24–26,7], radially resolved measurement of the line radiation emitted by a fast lithium beam [27] and microwave reflectometry [28–30], confirm the results obtained with Langmuir probes. Mirnov coils

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and miniaturised Rogowski coils have been used to detect fluctuations of the magnetic field and electric current.

Reviews on fluctuations and transport in toroidal magnetic confinement devices can be found in [31,32,11,33] and an overview on diagnostic methods for fluctuation investigations is given in [34].

In this paper, I first report on the basic properties of the electrostatic fluctuations in the SOL in Section 2 and then establish their relation with radial transport in Section 3. A very brief account on our theoretical understanding of the instability mechanism in Section 4 will be followed by a discussion of the influence of plasma parameters on fluctuations and transport in Section 5, before I draw conclusions in Section 6.

2. Properties of electrostatic fluctuations in the SOL

Most of the spectral power in fluctuation measurements from the SOL is located at frequencies below 10–50 kHz, and the spectra are decaying towards higher frequencies. Measurements with multiple poloidal channels reveal structures propagating poloidally in the ion diamagnetic drift direction [22,2,7]. This direction of propagation has also been found in nearly all cases where a phase velocity could be determined by two-point measurements. The direction of propagation is consistent with the idea that these structures are convected by the poloidal E × B drift due to the radial electric field in the SOL. No deviation from a random distribution of the structures in time and in poloidal direction has been found, they can be seen to grow and decay again. They have also been called ‘blobs’ [2,35] or ‘events’ [36,37]. The spatio-temporal structure of the fluctuations can be characterised by various data analysis techniques, e.g., by calculating the frequency-wavenumber spectra $S(\vec{k},\omega)$ (either ‘locally’ using a two-point method [1,38] or from the data of multi-tip arrays [39,7]), the spatial-temporal correlation function [40,7], or by biorthogonal decomposition [41]. The diagnostic channels were frequently arranged only in poloidal direction. From the correlation function, parameters like correlation time, poloidal correlation length and poloidal propagation velocity have been extracted on ASDEX [7] and W7-AS [42] to characterize changes in the fluctuations when discharge parameters are varied. A similar analysis has been done for data from different radial positions on TEXT-U [43]. The behaviour of the fluctuations (mostly of the relative fluctuation level) and of the induced E × B flux under discharge parameter variations has also been investigated in other devices, e.g., on TEXT [3], Tokapole II [44] and ASDEX Upgrade [45]. The differences between ohmic and additionally heated or L- and H-mode plasmas have as well been reported (see, e.g., Ref. [46,6,47–49,45]). In addition, conditional averaging has been applied to the fluctuation data [43], as well as an algorithm to identify and parametrise the above mentioned fluctuation events, allowing for advanced statistical analysis and conditional averaging of the events [37,50]. The typical fluctuation parameters obtained are a correlation time (lifetime of the events, not autocorrelation time) of 10–50 μs, a poloidal correlation length of 1–4 cm and a poloidal propagation velocity of a few 100 m/s up to a few 1000 m/s. As a general tendency, the lower values of the velocity are found on experiments with a toroidal magnetic field of 2–3 T such as ASDEX [7] or W7-AS at 2.5 T [36], the higher values on experiments with a toroidal magnetic field of 1–2 T such as Pretext [1], TEXT at 1 T [51], TJ-I [52] or W7-AS at 1.25 T [36].

In radial direction, correlation lengths of the fluctuations have been found to be typically by a factor of 2 smaller than poloidal correlation lengths [2,38,53,54,42]. Due to the poloidal propagation of the fluctuations, a simultaneous poloidal resolution is required to avoid the erroneous interpretation of the measurements: Structures which are oblique in the poloidal-radial plane, together with their poloidal velocity, will show a radial propagation if observed at a single poloidal position, as was recently pointed out by Bleuel et al. [55]. In those cases where fluctuations in the SOL were measured with simultaneous radial and poloidal resolution, very low radial (as compared to poloidal) propagation velocities of ∼100 m/s or below were found [2,35,42].

What has been reported up to now in this section on the spatial and temporal structure is true for the fluctuations of both I_{sat} and Φ_{fl}. The database of simultaneous $\tilde{n}$, $\tilde{T}_{\mathrm{e}}$ and $\tilde{\Phi}_{\mathrm{pl}}$ measurements is much smaller, and nothing at all is known about fluctuations of the ion temperature T_{i}. Density fluctuations behave quit similar to $\tilde{I}_{\mathrm{sat}}$, whereas the poloidal correlation length of $\tilde{T}_{\mathrm{e}}$ was found to be smaller [19]. It is an ongoing effort to establish the same broad basis of knowledge of the spatial structure of $\tilde{n}$, $\tilde{T}_{\mathrm{e}}$ and $\tilde{\Phi}_{\mathrm{pl}}$ as has been achieved for $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$.

The phase angle between the fluctuating quantities is relevant for the calculation of the induced radial transport (see Section 3) and for the comparison with theory (see Section 4). Experimentally, the phase angle between $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ has been found to be in the range $\frac{1}{4}\pi - \frac{1}{2}\pi$ for the frequency range containing most of the power [11,7]. Simultaneous measurements of $\tilde{n}$, $\tilde{T}_{\mathrm{e}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ in the SOL with fast swept Langmuir probes gave phase angles close to zero between $\tilde{n}$ and $\tilde{T}_{\mathrm{e}}$ [56,20,21] and $\frac{1}{3}\pi - \frac{1}{2}\pi$ between $\tilde{\Phi}_{\mathrm{fl}}$ and $\tilde{n}$ [20].

In the direction parallel to the magnetic field, very high correlations (frequently 80–90%) over distances of 6–12 m were found on several devices, both for $\tilde{I}_{\mathrm{sat}}$ [57,58,40,42] and $\tilde{\Phi}_{\mathrm{fl}}$ [59,55,60]. The plasma edge turbulence thus has a ‘two-dimensional’ structure with filaments extending only few cm perpendicular to the magnetic field but many metres in parallel direction (this does not imply that the parallel dynamics may be neglected in models, see Section 4). These filaments are directly visible on high speed movies and videos from ASDEX [61,62], DITE [62], TFTR [63,23] and COMPASS [64]. The parallel correlation measurements were performed with Langmuir probes at different toroidal and poloidal locations, positioned approximately on the same magnetic field line. The maximum correlation was found at time delay zero. To determine the magnitude of the parallel wavevector component $k_\parallel$, magnetic field line tracing codes were used to determine the angle between the magnetic field and the line connecting the two toroidally separated probes at maximum correlation. Both $k_\parallel = 0$ within the errors [59,58,40,55] and small non-zero values of $k_\parallel$ [59,57,60] have been reported for the SOL. In all cases, $k_\parallel / k_{\mathrm{pol}} < 10^{-2}$ was found, and this ratio was smaller when a larger separation between the probes was available.

In contrast, a clear time delay or phase shift could be detected downstream on the same magnetic field line when a driving signal was actively fed into a Langmuir probe, corresponding to a finite $k_\parallel$ of the excited wave [60,65,66]. These data are consistent with an Alfvén-type wave propagating along the magnetic flux tube.

3. Electrostatic fluctuations and transport

Particle and thermal transport perpendicular to the magnetic field results from correlated fluctuations of the plasma drift velocity $\tilde{\vec{v}}_\perp$ and density $\tilde{n}$ and/or temperature $\tilde{T}_{\mathrm{e}}$ or $\tilde{T}_{\mathrm{i}}$. The radial transport due to fluctuations of the radial plasma velocity is

$$\bar{\Gamma}_{\mathrm{r}} = \langle \tilde{n} \tilde{v}_{\mathrm{r}} \rangle \tag{1}$$

for particles and

$$\bar{Q}_{\mathrm{rj}} = \frac{3}{2} \langle \tilde{p}_{\mathrm{j}} \tilde{v}_{\mathrm{r}} \rangle \tag{2}$$

for heat (species j) [67], where $\tilde{p}_{\mathrm{j}} = k_{\mathrm{B}}(\tilde{n}_{\mathrm{j}} \bar{T}_{\mathrm{j}} + \bar{n}_{\mathrm{j}} \tilde{T}_{\mathrm{j}} + \tilde{n}_{\mathrm{j}} \tilde{T}_{\mathrm{j}})$. To measure the turbulent fluxes therefore requires a simultaneous recording of $\tilde{n}$, $\tilde{T}_{\mathrm{j}}$ and $\tilde{E}_\theta$ (or $\nabla_\theta \tilde{\Phi}$) at the same location with sufficient temporal and spatial resolution to resolve the dominant components of the fluctuations in the frequency-wavevector spectra. Except for a few results with a heavy ion beam probe (HIBP) [46], this has so far only been achieved using Langmuir probes. In these measurements, $\tilde{E}_\theta$ is calculated from the difference in $\tilde{\Phi}$ as measured by two probe tips separated a few mm poloidally. The radial particle transport $\bar{\Gamma}_{\mathrm{r}}$ was in most cases calculated from $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$, neglecting the influence of temperature fluctuations. As simultaneous Langmuir probe measurements of $\tilde{I}_{\mathrm{sat}}$, $\tilde{T}_{\mathrm{e}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ were performed [56,20,21], it became evident that $\tilde{T}_{\mathrm{e}}$ and $\tilde{n}$ are nearly in phase for the dominant spectral range of fluctuations and that the relative fluctuation amplitude $\tilde{T}_{\mathrm{e}} / \bar{T}_{\mathrm{e}}$ often is smaller than $\tilde{n}/\bar{n}$. Therefore, $\tilde{n}$ is overestimated by calculating it from $\tilde{I}_{\mathrm{sat}}$ with the neglect of $\tilde{T}$. A more severe error is introduced by the assumption $\tilde{\Phi}_{\mathrm{pl}} \sim \tilde{\Phi}_{\mathrm{fl}}$. However, due to the measured phase between $\tilde{n}$, $\tilde{T}_{\mathrm{e}}$ and $\tilde{\Phi}_{\mathrm{fl}}$, this error does not severely affect the radial transport, Eqs. (1) and (2), as was recently pointed out by Pfeiffer et al. [20].

The coherency between $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ or $\tilde{n}$ and $\tilde{\Phi}_{\mathrm{pl}}$ is usually found to be in the order of 0.5 for the frequency range with significant spectral power, and, together with the phase angles between the fluctuating quantities reported in Section 2, a net transport of particles and heat directed radially outwards results (see, e.g., Ref. [31,11] and references therein). If $\Gamma_{\mathrm{r}}(t) = \tilde{n}(t)\, \tilde{v}_{\mathrm{r}}(t)$ is plotted versus time, its probability distribution function is found to be highly asymmetric, reflected by large values for the third and fourth central moments (skewness and flatness) [7,68]. A large fraction of the transport is due to several high amplitude 'events' during comparatively short intervals of time [7,69]. Likewise in space, the statistical event analysis of the poloidally resolved $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ measurements in the SOL of ASDEX revealed that the poloidal extent of the regions of high outwards transport is smaller than for the underlying $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ signals and that the largest $\tilde{\Phi}_{\mathrm{fl}}$ events do not necessarily contribute most to the transport [50].

The particle fluxes thus calculated from simultaneous $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ measurements at the LCMS and in the SOL have been compared with the global particle balance [1,3,58,70,4] and with the observed density profile in the SOL [2,3,49] on various tokamaks. Although the turbulent particle flux measured locally at one or two positions in the plasma edge had to be taken as valid for the whole surface area of the torus, an agreement within a factor of two usually was found (see also Section 5). Indications to poloidal asymmetries in the particle flux exist where measurements at more than one poloidal position could be performed [71,4,72] – the fluxes always are lower on the high-field side of the torus.

To assess the fluctuation-induced heat flux, $\bar{Q}_{\mathrm{r}}$ from Eq. (2) is subdivided into a 'convective' part $\frac{3}{2} k_{\mathrm{B}} \bar{T} \langle \tilde{n}\, \tilde{v}_{\mathrm{r}} \rangle = \frac{3}{2} k_{\mathrm{B}} \bar{T} \bar{\Gamma}_{\mathrm{r}}$ and a 'conductive' part $\frac{3}{2} k_{\mathrm{B}} \bar{n} \langle \tilde{T}\, \tilde{v}_{\mathrm{r}} \rangle$, neglecting the term $\tilde{n}\tilde{T}$ as of higher order in the fluctuating quantities. Since $\bar{T}_{\mathrm{e}}$ can be estimated fairly well using Langmuir probes, the convective part of the turbulent electron heat flux can be calculated, once the turbulent particle flux $\bar{\Gamma}_{\mathrm{r}}$ is known. In TEXT, the values thus obtained were too low by a factor of the order of two to account for the global energy balance unless unreasonably high contributions from the conductive part were assumed [9]. In contrast, Vayakis concluded that, within the uncertainties of his measurement and invoking a conductive part of the same order of magnitude as the measured convective one, on DITE the global energy balance could be accounted for by the observed electrostatic fluctuations [70]. In an experiment actually measuring electron temperature fluctuations in the Caltech tokamak, Liewer et al. concluded that the observed turbulent fluxes could account for the global energy confinement found in this device, too [8]. In recent simultaneous $\tilde{I}_{\mathrm{sat}}$, $\tilde{T}_{\mathrm{e}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ Langmuir probe measurements in the SOL of the W7-AS stellarator, the particle transport calculated from $\tilde{I}_{\mathrm{sat}}$ and $\tilde{\Phi}_{\mathrm{fl}}$ neglecting $\tilde{T}_{\mathrm{e}}$ was found to be by a factor of 1–2 larger than the value calculated from $\tilde{n}$ and $\tilde{\Phi}_{\mathrm{pl}}$. Furthermore, the conducted heat flux was found to be 0.5–1 times the convected heat flux [20].

No measurements of ion temperature fluctuations are available so far. In the context of turbulent convection due to E × B drift [7] one would, however, expect ion thermal energy $\frac{3}{2}p_{\mathrm{i}}$ to be transported radially in a similar manner and at a similar rate as particles and electron thermal energy.

4. Theoretical understanding

The class of instabilities much discussed to be responsible for the turbulence observed in the plasma edge are drift wave instabilities in a very general sense. In the most simple version of an electrostatic drift wave, as it can be found in textbooks (e.g., Ref. [73]), perturbations of plasma density and electric potential are considered in the presence of a density gradient ∇n_0 perpendicular to the magnetic field. With ∇n_0 in x direction, the magnetic field in z direction and the wavevector of the perturbation chiefly in y direction, E × B drift in x direction due to the potential perturbation occurs, and so do electric currents perpendicular to the magnetic field due to polarisation and diamagnetic drifts. These currents are not divergence-free (for the diamagnetic current this is true only in the presence of a magnetic field gradient) but must be balanced by currents parallel to the magnetic field. These are carried mainly by the electrons due to their higher mobility. In a geometry periodic in z direction, the wavevector of the perturbation must then have a non-zero z component. An analysis of this simple model shows that the electrons tend to establish a Boltzmann distribution

$$\tilde{n} = \frac{e\tilde{\Phi}}{k_{\mathrm{B}}T_{\mathrm{e}}}. \tag{3}$$

If they could move unimpeded parallel to the magnetic field, and if polarization drift and finite Larmor radius effects are neglected, this Boltzmann relation would hold exactly, and density and potential perturbation were in phase. In this case, the drift wave would propagate in y direction but would not be unstable. Every mechanism restricting the motion of the electrons parallel to the magnetic field adds to the phase shift between $\tilde{n}$ and $\tilde{\Phi}$ and drives the drift wave more unstable. The first such mechanisms considered were plasma resistivity (collisional drift wave) and trapping of electrons (see, e.g., Ref. [74] and references therein). For the typical plasma parameters in the edge of fusion experiments the phase shift in such a simple model is still quite small. However, the Boltzmann relation (3) was in general not found to be satisfied experimentally in the plasma edge, neither in amplitude nor in phase between $\tilde{n}$ and $\tilde{\Phi}$ (see, e.g., Ref. [11] and references therein). In more realistic drift wave models and numerical simulations larger deviations from the Boltzmann relation are reproduced (see, e.g., Ref. [75,13,76]). When electron temperature fluctuations are included in the model it becomes evident that it is the radial electron pressure gradient rather than the density gradient which serves as source of free energy [13].

In toroidal geometry, suitable periodic boundary conditions are required in the confinement region, linking the y and z components of the perturbation wavevectors [77]. In contrast, in the SOL by definition each magnetic field line is limited by a target plate. Here, the sheath conditions introduce a new mechanism to impede the electron currents in z direction [78–82,7]. The sheath 'resistivity' scales differently from the bulk plasma resistivity (Spitzer resistivity) and depends also on quantities like the secondary electron emission of the target plates or the average net current to the target plates for each magnetic flux tube [7,83]. This instability can still be called drift instability in the sense that it is derived using the drift approximation for velocities perpendicular to the magnetic field (see, e.g., Ref. [73] or the derivation in [84]) and that particle and energy transport perpendicular to the magnetic field is dominantly due to E × B drift.

A second way in which the target plates and the SOL geometry can influence plasma turbulence is through the formation of a radial electric field: Each magnetic flux tube is charged with respect to the target plates to a potential following the sheath equations (see, e.g., Ref. [85]). In first approximation, this potential is proportional to the electron temperature, but it also depends on the electric current to the target plates and the secondary electron emission coefficient for each flux tube [7,83]. The radial profile of the resulting radial electric field is therefore intimately related to parallel gradients or changes in the connection length to the target plates, in short, to the whole SOL physics including the position of recycling and impurity sources. An additional possibility of influencing the plasma potential is the biasing of parts of the target plates. Examples for the interplay between the SOL geometry, the radial electric field, the radial profiles of Φ_{fl} and I_{sat} and also the fluctuation parameters can be found in Ref. [86,7]. As the radial electric field induces a poloidal E × B drift, the radial shear of this drift velocity depends on the detailed shape of the radial plasma potential profile. The influence of this velocity shear on plasma turbulence and the possible connection with the L–H transition has been discussed extensively ([87,88], and references in the latter). Due to the complex nature of the problem, involving plasma edge geometry, recycling and possibly impurity radiation, no comprehensive model has been presented as yet.

Meanwhile it has become possible to compare the influence of the various terms on the properties of the turbulence simulated in numerical codes. Although the basic dynamics for edge and SOL plasma turbulence appear to be unchanged from a rather simplified model, it seems to be necessary to include all of heat transport and temperature fluctuations, gradients and curvature of the magnetic field, electromagnetic induction, electron inertia, sheath boundary conditions and radial electric field to quantitatively reproduce the observed fluctuation characteristics and induced transport [13,89].

Experimental SOL fluctuation characteristics like amplitudes, poloidal correlation length and lifetime, phases between $\tilde{I}_{\rm sat}$ and $\tilde{\Phi}_{\rm fl}$ and induced radial particle fluxes could be well reproduced by a nonlocal two-dimensional drift-interchange code with target plate boundary conditions [90,42].

5. Influence of the plasma parameters on the SOL fluctuations and on the induced transport

For the comparison of experimental observations with the predictions of plasma turbulence models, the change in fluctuation parameters and E × B transport for variations of the discharge parameters are of particular interest. On the other hand, a comparison between the observed E × B fluxes and global particle and energy confinement time is required to assess the relevance of the measured fluxes for various discharge conditions in addition to the order-of-magnitude agreement reported in Section 3. Only few such parameter scans have been done so far. Rowan et al. measured the E × B particle transport across the LCMS derived from $\tilde{\Phi}_{\rm fl}$ and $\tilde{I}_{\rm sat}$ measurements and compared the particle confinement time calculated from these data with the particle confinement time calculated from H_α measurements of the plasma source. This comparison was done for scans of the plasma density, the toroidal magnetic field and the radial plasma position in TEXT [3]. Endler et al. calculated fluctuation parameters like lifetime, poloidal correlation length, poloidal wavelength and poloidal propagation velocity of the fluctuations from the data of an H_α optical imaging diagnostic for variations of plasma density, toroidal magnetic field, plasma current and vertical plasma position in ASDEX and compared the results with a linear target plate instability model [86,7]. Bleuel calculated fluctuation parameter and radial E × B particle transport profiles from $\tilde{\Phi}_{\rm fl}$ and $\tilde{I}_{\rm sat}$ measurements in the SOL and slightly inside the LCMS for variations of plasma density, ECR heating power, magnetic field and gas species (hydrogen or deuterium) in W7-AS and compared scaling of the E × B flux with the energy confinement time [42].

For the SOL fluctuation parameters (0–2 cm outside the LCMS), the following behaviour has been observed: With increasing average plasma density, the lifetime and the poloidal and radial correlation lengths increase, and the poloidal velocity (in the ion diamagnetic drift direction) decreases [7,42]. In ASDEX, density and separatrix temperature had an inverse scaling in ohmic discharges with constant plasma current and magnetic field [91], so the observed changes in the fluctuation parameters could be due to a decrease of the temperature rather than an increase of the density. In W7-AS, however, the fluctuation parameters in the SOL remained unchanged when the ECR heating power (and thus $T_{\rm e}$ in the SOL) was varied at constant density. It seems therefore to be the plasma density or a related parameter rather than the electron temperature which influences the fluctuation parameters in the SOL. The second discharge parameter strongly affecting the poloidal and radial correlation lengths and the poloidal velocity of the fluctuations is the magnetic field: At low magnetic field, the correlation lengths and the velocity are larger, whereas the lifetime is not significantly changed [7,42]. The strong dependence of the poloidal propagation velocity of the fluctuations in the SOL on the magnitude of the magnetic field becomes also evident when comparing data from different machines (see Section 2 and references given there). A strong variation of the fluctuation parameters with vertical plasma position was found on ASDEX. In such a scan, the SOL configuration changed from single null upper X-point through double null to single null lower X-point [86]. Similarly, strong changes in the SOL turbulence were found upon the insertion of a limiter in the Tokapole II poloidal divertor tokamak [44]. These changes, however not yet understood, emphasize the importance of the detailed SOL and target plate configuration the quantitative behaviour of the fluctuations.

The E × B particle fluxes measured at the LCMS slightly decrease with increasing plasma density in W7-AS. Together with a steepening of the density profiles, a lower anomalous diffusion coefficient is calculated [42]. The same was found in TEXT, where the particle confinement time derived was in good agreement with the values and the scaling obtained from H_α measurements [3]. In W7-AS, likewise, the increase of the energy confinement time with plasma density is in qualitative agreement with the decrease of the turbulent particle flux. The same agreement was found for the increase of particle flux and decrease of energy confinement time when the ECR heating power is increased [42] (assuming again that particle and heat transport are due to the same turbulent convection and hence scale in a similar way). Changes in the magnitude of the magnetic field do not strongly affect the turbulent particle flux both in TEXT and in W7-AS, in contrast to their influence on the size and poloidal propagation velocity of the fluctuation structures.

One of the questions remaining unanswered is whether the SOL fluctuations determine the anomalous transport across the LCMS and thus the global confinement time or whether they just adapt to take over the fluxes passing the LCMS due to processes originating in the confinement region.

6. Conclusions

Many properties of the SOL fluctuations in tokamaks and stellarators can be explained by a drift-interchange instability mechanism, as detailed in Section 4. In addition to the terms used in the early drift wave models, the magnetic geometry (gradients and curvature of the magnetic field), magnetic induction due to fluctuating parallel electric currents, temperature fluctuations, sheath boundary conditions and possibly further effects must be included to account for the observed turbulence quantitatively in a numerical simulation. The interplay between the radial pressure gradients serving as source of free energy for the turbulence, the resulting radial transport flattening the gradients, parallel average electric currents onto the target plates (which are, together with the radial electron temperature gradient, determining the radial electric field), the location of plasma recycling sources or gas puffing and the geometry of the SOL is rather involved and not yet understood in detail.

The radial $E \times B$ particle flux calculated from measured floating potential and ion saturation current fluctuations usually agrees well with the flux inferred from radial profiles and particle balance analysis. The question whether the observed energy confinement and radial temperature profiles are also consistent with the turbulent $E \times B$ heat transport requires further investigation.

The qualitative understanding of the instability mechanism offers the chance to influence the turbulence in the SOL, e.g., by applying DC or AC voltages to target plate sections or probe tips inserted into the SOL [92,93]. The *quantitative* understanding and the modification of SOL turbulence and transport will be the next goals of fluctuation investigations in stellarators and tokamaks.

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