Influence of temperature fluctuations on plasma turbulence investigations with Langmuir probes

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\textbf{Abstract.} The reliability of Langmuir probe measurements for plasma-turbulence investigations is studied on GEMR gyro-fluid simulations and compared with the results from conditionally sampled $I-V$ characteristics as well as electron-emitting probe measurements close to the last closed flux surface of the tokamak ASDEX Upgrade. In this region, simulation and experiment consistently show coherent in-phase fluctuations in density, plasma potential and also electron temperature. Ion-saturation current measurements turn out to reproduce density fluctuations quite well. Fluctuations in the floating potential, however, are strongly influenced by temperature fluctuations and, hence, are strongly distorted compared to the actual plasma potential. These results suggest that interpreting floating as plasma-potential fluctuations while disregarding temperature effects is not justified near the separatrix of hot fusion plasmas. Here, floating potential measurements led to corrupted results on the $E \times B$ dynamics of turbulent structures in the context of, e.g., turbulent particle and momentum transport or turbulence characterization on the basis of density–potential phase relations.
1. Introduction

In the boundary region of magnetically confined fusion plasmas, micro-instabilities determine a major part of transport losses across the last closed flux surface (LCFS) into the scrape-off layer (SOL) and, therefore, play a key role in the global confinement quality. In order to understand the mechanisms degrading or even improving confinement via vortex-flow interactions, the involved dynamical processes are addressed by measurements of, e.g., correlations between density ($\tilde{n}$) and plasma-potential ($\tilde{\Phi}_{pl}$) fluctuations as well as average radial turbulent transport of particles ($\Gamma = \langle \tilde{n} \tilde{v}_r \rangle$) with radial $E \times B$ velocity fluctuations $\tilde{v}_r = \tilde{E}_\theta / B$) and momentum (perpendicular Reynolds stress $R_s = \langle \tilde{v}_\theta \tilde{v}_r \rangle$); see, e.g., [1–10], among others.

The acquisition of local plasma-potential fluctuations as required for these studies is mostly based on Langmuir probe measurements. The measured floating potential of the probe is related to the plasma potential via

$$\tilde{\Phi}_{fl} = \tilde{\Phi}_{pl} - \Lambda \frac{\tilde{T}_e}{e}$$

(1)

with $\Lambda \approx 3$. Electron-temperature fluctuations ($\tilde{T}_e$) are rarely available in experiments and are usually neglected such that, for simplicity, $\tilde{\Phi}_{fl} = \tilde{\Phi}_{pl}$ is used. The simplifying assumption that temperature fluctuations are negligible has been proven valid in a toroidally confined low-temperature plasma [11]. However, in the boundary of several high-temperature plasmas, significant temperature fluctuations have been found by fast sweeping Langmuir probes [12–15], triple probes [14, 16, 17], swept double probes [18], a harmonic probe technique [3, 19, 20] and Thomson scattering [3, 21].

In this work, the influence of temperature fluctuations on Langmuir probe measurements of density and potential fluctuations in a high-temperature plasma is investigated. To this end, simulations of plasma-edge turbulence are carried out with the gyro-fluid code GEMR. Synthetic probe data from the simulations are analyzed with respect to temperature effects. The results are compared with probe measurements near the LCFS in the tokamak ASDEX Upgrade [22]. For the comparison, two independent sophisticated approaches are employed to resolve $\tilde{T}_e$ experimentally: one is based on electron-emitting probe measurements and the other on conditionally sampled probe characteristics. It will turn out that temperature fluctuations near the LCFS of high-temperature plasmas strongly distort floating-potential measurements, and an interpretation of $\tilde{\Phi}_{fl}$ as $\tilde{\Phi}_{pl}$ is tenuous.

This paper is organized as follows. A short description of the GEMR code is given in section 2. Section 3 presents the analysis of the synthetic probe data from the simulations and...
temperature effects will be identified. The results are compared with experimental data from both electron-emitting probe measurements and conditionally sampled probe characteristics, in sections 4 and 5, respectively. In section 6, the results are discussed with respect to possible consequences for the interpretation of probe data and the conclusion is presented.

2. GEMR simulations

This section gives a brief summary of the model used for the plasma turbulence simulations and provides the basic reasons that motivated such a choice. The details of the model given here, for the sake of completeness, are not crucial for understanding of the results presented in the following sections.

The three-dimensional (3D) gyro-fluid model GEMR [23] solves the first six moments [24, 25] (density, parallel velocity, parallel and perpendicular temperatures and the associated parallel/parallel and perpendicular/parallel heat flux) of the gyro-kinetic equation [26], for ions and electrons. The corresponding conservation equations are derived using a consistent treatment of the energy conservation [27]. The plasma species are connected through the quasi-neutrality condition obtained from the gyro-kinetic polarization equation [28] and the induction obtained from Ampère’s law.

The number of moments retained in the model enables GEMR to capture typical tokamak edge regimes, where realistic density and temperature gradients yield a mixture of drift-Alfvén [29] and ion-temperature-gradient (ITG) turbulence [30] that can be faster than both species’ collision frequencies (especially for the ions where the difference is about two orders of magnitude). This weakly collisional regime lies outside the Braginskii assumptions [31] and requires a different closure to the hierarchy of moments of the gyro-kinetic equation. Namely, the time-dependent response of the parallel heat flux to the temperature gradients, or the parallel viscosity to flow divergences and the nonlinear advection must be taken into account [32]. As the drift wave component reaches below ion Larmor radius scales (assuming comparable species’ temperatures $T_i \sim T_e$) [33], the gyro-fluid formulation guarantees that the entire dynamical spectrum is captured. Furthermore, an established correspondence between the model used and the Braginskii model [34] justifies its use.

GEMR is a global code in the sense that no geometrical flux-tube approximation is invoked. The geometry is allowed to vary both poloidally and radially. A circular cross-section with toroidal axisymmetry is assumed. The coordinate system is aligned with the equilibrium magnetic field to take computational advantage of the strong spatial anisotropy of magnetized plasmas [35]. Global consistency in the angles is ensured, even for toroidally truncated domains [36]. Namely, the present simulations were performed in a quarter of the full torus, with a resolution of $128 \times 512 \times 16$ in the $x$-, $y$- and $s$-directions, respectively. The coordinate system consists of the flux label $x$, the field line label $y$ and the coordinate parallel to the magnetic field $s$. It is linked to the polar coordinates $(r, \theta, \phi)$ by the unit Jacobian transformation rules

$$ x = 2\pi^2 R_0 r^2, \quad y_k = (q_s \theta - \phi - \alpha_k) / (2\pi), \quad s = \theta / (2\pi). \quad (2) $$

ASDEX Upgrade parameters were chosen for the tokamak major and minor radii of $R_0 = 1.65$ m and $r_0 = 0.5$ m, respectively. The magnetic field line pitch, also termed the safety factor, measures the number of turns in the toroidal direction necessary to complete one poloidal loop. Its nominal value was set to $q_s = 4.6$ and the magnetic field strength to $B = 2.6$ T.

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A toroidal shift \( \alpha_k(r) \) is also included to remedy the numerical grid deformation stemming from the magnetic shear caused by the radial dependence of the safety factor. This is referred to in the literature as the shifted metric procedure [37]. The deuterium ion to electron mass ratio was \( m_i/m_e = 3670 \).

The radial (or zonal) profiles of the state variables (densities, temperatures and field potentials), obtained by zonal averaging of the corresponding quantities over the angles, are evolved together with the fluctuations. This is demanded by the vigor of SOL turbulence. Still, the spatial scales of the fluctuations are assumed to be much smaller than the scale of the background profiles and the homogeneous assumption is invoked, i.e. the normalizing parameters of the model are yield constant across the full domain. The normalizing parameter set used in the simulations reflects typical ASDEX Upgrade L-mode edge parameters. For the density \( n_0 \) and temperature \( T_0 \), the values were \( T_0 = T_i = T_e = 60 \text{ eV} \) and \( n_0 = n_i = n_e = 1.2 \times 10^{19} \text{ m}^{-3} \), respectively. The linear drive terms are included in the gradients of the evolving profiles. Profile maintenance is achieved with source/sink zones at each radial boundary. The zonal components of the densities and temperatures are feedback dissipated towards an initially specified profile [38]. The radial profile scale lengths of temperature \( L_T = |\nabla_r \ln T|^{-1} \) and density \( L_n = |\nabla_r \ln n|^{-1} \) have been chosen as \( L_T = L_n/2 = 3 \text{ cm} \) [39, 40]. The inner half of the radial box corresponds to a 3 cm wide edge region and the outer half corresponds to the SOL, with a limiter cut located at the bottom of the flux surfaces.

The SOL is implemented with a change in the parallel boundary conditions according to a linearized sheath model [38, 41], consistent with the formulation of GEMR, which retains only quadratic nonlinearities. In the SOL, the field lines intersect material plates, allowing the existence of modes with parallel and perpendicular wave numbers \( k_{||} = 0 \) and \( k_{\perp} \neq 0 \) [41], respectively, which are suppressed in the edge region through the field line connection constraint [36]. This changes substantially the behavior of heat and particle fluxes down the gradients by affecting the nonlinear balance between the instabilities within the model [41]. Within the local approximation of homogeneous normalization parameters, the code gives a consistent description of the turbulence from the confinement region across the LCFS into the SOL.

The following section compares 4 ms of turbulent fluctuations from a saturated phase of the GEMR simulation with simultaneous measurements of a synthetic Langmuir probe at the same position.

### 3. Synthetic-probe results

Synthetic Langmuir probes have been implemented in GEMR to extract measurements from the simulated data. The ion-saturation current fluctuations are calculated according to the linearized equation

\[
\tilde{I}_{sat} \approx A_p n_0 c_{s0} \left( \tilde{n}_e - \frac{1}{n_0} \frac{\tilde{T}_e}{T_0} \right)
\]

assuming \( T_e = T_i \), to be consistent with the GEMR model. The electron density \( \tilde{n}_e \) and temperature fluctuations \( \tilde{T}_e \) evolve with time, while \( n_0 \) and \( T_0 \) are constant normalization parameters. The current is averaged over the parallel projection area \( A_p \) of an ASDEX Upgrade pin probe. The constant ion-sound velocity \( c_{s0} \) is calculated using \( T_0 \). The results do not change

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Figure 1. Comparison of simulated plasma fluctuations with synthetic probe data. Shown are details of the raw time series (left) and the conditionally averaged fluctuations (right) at the LCFS. Top: density and ion-saturation current (dashed) fluctuations; middle: plasma and floating (dashed) potential fluctuations; and bottom: electron-temperature fluctuations from GEMR.

significantly if the common expression

$$I_{\text{sat}} = \alpha A e n_e \sqrt{\frac{T_e + T_i}{m_i}}$$

(4)

is used instead with $\alpha = 0.61$ to account for the reduced density at the sheath edge. The floating potential fluctuations are approximated by equation (1) with $\Lambda = 3.4$ for a cold Langmuir probe in a deuterium plasma. Different models predict similar values for $\alpha$ and $\Lambda$ [42–44]. The differences are small, especially when compared with the experimental uncertainties arising from secondary electron emission, effective particle collection areas and deviations of the particle energy distribution functions [45]. However, the exact values are not decisive for the nature of turbulent fluctuations in the present analysis even if the absolute values change.

The left-hand side of figure 1 compares the simulated plasma fluctuations $\tilde{n}_e$ (top), $\tilde{\Phi}_{\text{pl}}$ (middle) and $\tilde{T}_e$ (bottom) in a 100 $\mu$s time window with the synthetic probe data of $\tilde{I}_{\text{sat}}$ and $\tilde{\Phi}_f$. All signals are taken from the LCFS at the outboard midplane of the circular simulation domain. Good agreement is found between fluctuations of plasma density and ion-saturation current. This indicates a minor influence of the temperature fluctuations and justifies the common experimental assumption $\tilde{I}_{\text{sat}} \propto \tilde{n}_e$ in the simulation. In contrast, no agreement is found
between fluctuations of plasma and floating potential (figure 1(c)). $\Phi_1$ rather follows the inverse temperature behavior as shown in figure 1(e), which according to equation (1) indicates the dominance of $T_e$ in the measured floating potential.

In order to study the correlation between the fluctuating quantities systematically, the coherent part of the fluctuations is extracted by means of the conditional averaging technique [46]. The ion-saturation current was used as the reference signal with a trigger threshold of $2\sigma$ (the upper horizontal dashed line in figure 1(a)), where $\sigma$ is the standard deviation. The right-hand side of figure 1 shows the conditional average of 660 independent series of fluctuations in density and ion-saturation current (top), plasma and floating potential (middle) and temperature (bottom). The average temporal behavior of coherent structures in the synthetic ion-saturation current and that in the density are again found to agree very well. However, the synthetic floating potential is clearly anti-correlated with the simulated plasma potential fluctuations (figure 1(d)). This can be attributed to significant coherent temperature structures as depicted in figure 1(f), which show up in phase with the structures in $\tilde{n}$ and $\Phi_{pl}$.

The analyses carried out on data from turbulence simulations suggest that close to the LCFS in high-temperature plasmas, floating-potential fluctuations measured with probes are strongly affected by temperature fluctuations and, therefore, do not even qualitatively reflect the plasma potential. This reflects the experimental situation if two assumptions hold: (i) The turbulent fluctuations calculated by the gyro-fluid simulation are comparable to plasma fluctuations in the boundary of a real tokamak. (ii) In hot magnetized plasmas, the behavior of Langmuir probes is sufficiently well described by the sheath model. Hence, the presence of significant temperature fluctuations would have severe consequences for the interpretation of fluctuations from probe measurements, as will be discussed in section 6. In the next two sections, it will be shown that the above assumptions are indeed supported by experimental observations.

4. Emissive-probe measurements

In order to test the validity of the simulation results from the previous section, probe measurements were carried out in the tokamak ASDEX Upgrade [22]. The experiment was conducted in an L-mode deuterium plasma, kept in lower single null divertor configuration with a constant toroidal magnetic field of 2.5 T (clockwise) and a plasma current of 800 kA (counterclockwise from the top). A relatively low auxiliary electron cyclotron heating power of 600 kW was centrally absorbed and it led to an edge plasma density of $4.0 \times 10^{19} \, \text{m}^{-3}$.

A Langmuir probe array penetrated the plasma horizontally 0.31 m above the outer torus midplane [47]. Eight freestanding carbon pins on the top level measured alternately floating potential and ion-saturation current, as shown in figure 2 (white background). The $I_{sat}$ probes were biased with $-180 \, \text{V}$ and the floating-potential signals were amplified directly at the manipulator exit to minimize low-pass filtering by cable capacity and plasma impedance. The data were sampled at 2 MHz with 14 bit resolution and 800 kHz cut-off frequency of the anti-aliasing filter. The recorded fluctuation frequencies are far below the ion-plasma frequency of about 300 MHz, i.e. the probe is always in equilibrium with the plasma [42]. For the investigation of only the turbulent dynamics against a stationary background, fluctuations below 10 kHz have been digitally removed from the signals.

For comparison with simulation results from the previous section, fluctuations in the ion-saturation current and density, floating and plasma potential as well as temperature are deduced.
Figure 2. Photograph (left) and sketch (right) of the multi-pin probe head as seen from the plasma in the tokamak ASDEX Upgrade. The shaded areas in the sketch are retracted by 4 and 8 mm (probe 13).

Figure 3. Measurements of the ion-saturation current (top) and potential (bottom) during a stroke of Langmuir probes in ASDEX Upgrade. Due to the high heat load in the plasma, one probe emits electrons during the outward motion and measures a more positive potential (red line).

from the probe signals in two different, independent ways: the first method—presented in this section—involves measurements of the plasma potential with an electron-emissive probe. The next section is dedicated to the second method, which is based on conditionally sampled probe characteristics. Both methods are applied to data from discharge no. 26530.

Figure 3 shows raw data from three Langmuir probes moving into and out of the plasma. The ion-saturation current ($I_{\text{sat}}$, top) increases and the floating potentials ($\Phi_{\text{fl}}$, bottom) decrease while the probes approach the LCFS ($t < 3.57$ s). At $t \approx 3.582$ s, probe 10 (red line in figure 3) reaches a critical temperature due to the heat flux from the plasma onto the probe and starts
emitting electrons. The emitted electron current is space charge limited after a fast transition within 2 $\mu$s. Now, the probe floats at the potential

$$\Phi_{se} = \Phi_{pl} - \lambda \frac{T_e}{e}, \quad \text{with } \lambda = 0.6,$$

(5)

of the sheath edge that separates the sheath and the presheath. This was shown in previous investigations with electron-emitting probes in ASDEX Upgrade [48]. Generally, the factor $\lambda$ depends on the electron temperature. However, for sufficiently high plasma electron temperatures, as in the present situation, the temperature dependence of $\lambda$ could be shown to be negligible [49, 50]. The electron emission of probe 10 is maintained during the entire backward motion of the probes ($t > 3.59$ s). Probe 9 is less heated and measures the floating potential of a cold probe

$$\Phi_{fl} = \Phi_{pl} - 3.4 \frac{T_e}{e}$$

(6)

during the entire discharge. During the slower outward motion, the average potential difference between hot and cold floating probes is decreasing in proportion to the radial decrease of the electron temperature. The decrease of the density and electron temperature profile is indicated by the decreasing ion-saturation current at the top of figure 3.

Electron cyclotron resonance heating can modify the electron energy distribution function. This might lead to deviations in the probe coefficients $\Lambda$ and $\lambda$. However, in the present experiment, the heating power is absorbed in the center of the plasma, far from the measurement position. Consequently, the plasma in the vicinity of the probes can be expected to be thermalized with a Maxwellian electron energy distribution function.

Combining equations (5) and (6) the electron-temperature dynamics can be deduced from the simultaneous measurements of $\Phi_{fl}$ and $\Phi_{se}$ with a temporal resolution of 0.5 $\mu$s. The plasma density was calculated according to equation (4) from nearby measurements of the ion-saturation current and the electron temperature assuming $T_e \approx T_i$. Similar to figure 1, figure 4 shows short time traces of the results on the left-hand side and the conditional average of 28 independent large-amplitude events with $I_{sat} > 2\sigma$ on the right-hand side. The stationary fluctuations are taken from a 4.1 ms time interval at $t = 3.625$ s, which corresponds to the radial range 14–18 mm outside the LCFS. An anti-correlation is observed between floating and plasma potential (figure 4(d)), similar to the simulation result in figure 1(d). Electron temperature fluctuations with a significant amplitude (figures 4(e) and (f)) are found in phase with plasma-potential fluctuations. Fluctuations in the density are almost coincident with those in $I_{sat}$ (figures 4(a) and (b)), i.e. the temperature fluctuations do not carry significant weight. In comparison, good agreement between the simulation and experimental results is found, which confirms the crucial role of temperature fluctuations in interpreting probe data. It can be shown that the experimental findings are not distorted by the probe separation, which introduces additional phase delays between the signals due to the perpendicular propagation of turbulent structures. Structures propagating with typically 1 km s$^{-1}$ would show a phase shift of 5 $\mu$s over a distance of 5 mm. This might explain a small phase delay and a corresponding error of the absolute values, but cannot account for the coherent fluctuations and the anti-correlation of floating and plasma potentials. Nevertheless, a different method, which does not suffer from the probe distances, is used in the next section to verify the experimental results given here.
5. Conditional sampling of probe characteristics

In this section, previous results from emissive probes are verified via an alternative method, which resolves fluctuations in potential, electron temperature and density quasi-instantaneously at the same position. This method has been proposed recently and is based on the conditional sampling of characteristics from a slowly swept Langmuir probe \[51\]. Here, it is applied for the first time to the high-temperature plasma in ASDEX Upgrade. Figure 5 shows time windows of the high-frequency ion-saturation current fluctuations \(I_{\text{sat}}\), top) together with the raw current \(I\), middle) and voltage \(V\), bottom) of a slowly swept Langmuir probe near the \(I_{\text{sat}}\) measurement. Complete probe characteristics are obtained with a rate of 1 kHz using the data acquisition system described in section 4. After conditional sampling, a full characteristic is available every microsecond within a short time window around the trigger time \(\Delta \tau = 0\) s. The trigger condition is 1.5 times the standard deviation \(\sigma\) of the \(I_{\text{sat}}\) fluctuations on probe 2 and is indicated as a dashed red line at the top of figure 5. Around each trigger event at \(t_i\), a short \(I-V\) trace is collected from the neighboring probe 6. From several trigger events, a complete \(I-V\) characteristic can be reconstructed at each time lag \(\Delta \tau\) with respect to
the trigger times $t_i$, since the trigger is not phase locked to the sweeping bias voltage. In the present case, 510 trigger events have been detected within a 40 ms time interval. During this time, the probe was located in the SOL 8–15 mm outside the LCFS. The temporal resolution is reduced from 0.5 to 1 $\mu$s, i.e. 1020 $I$–$V$ pairs are combined to one conditionally sampled $I$–$V$ characteristic. This is sufficient to obtain reasonable fits to the characteristics providing $T_e$, $\Phi_0$ and $I_{\text{sat}}$ every microsecond. The presence of a small fraction of high-temperature electrons could lead to an overestimation of the electron temperature [52]. However, the electron energy distribution function can be expected to be Maxwellian in the present experiments, as discussed in the previous section.

Figure 6 shows the fluctuations obtained from fits to the conditionally sampled $I$–$V$ characteristics, together with the plasma density and potential calculated according to equations (4) ($T_e \approx T_i$) and (6), respectively. The results are qualitatively the same as those from emissive-probe measurements: density, plasma-potential and temperature fluctuations are essentially in phase. The ion-saturation current does not substantially deviate from the density. The floating potential, however, is seriously affected by the temperature fluctuations, resulting in anti-correlation between floating and plasma potentials. Moreover, the experimental results confirm once more those from the numerical simulations in section 3. This means that (i) the plasma fluctuations in the boundary region of ASDEX Upgrade are sufficiently well represented by the gyro-fluid simulation and (ii) the sheath model is appropriate for describing Langmuir probes under the present conditions. It turned out that great care has to be taken in interpreting the data from Langmuir probes when strong temperature fluctuations are present.
6. Discussion and conclusions

The objective of this paper was to study the influence of electron-temperature fluctuations on turbulence investigations with Langmuir probes in high-temperature plasmas. To this end, gyro-fluid simulations of plasma turbulence were carried out for fusion edge plasmas comparable to that in ASDEX Upgrade. Synthetic Langmuir probes were implemented to mimic the experimental diagnostics. From the simulations, coherent structures could be expected in the fluctuations of plasma density, plasma potential and electron temperature near the LCFS of a real tokamak. For comparison, Langmuir-probe measurements were carried out in the near SOL of ASDEX Upgrade. The simulation results were confirmed using two independent experimental approaches, one based on electron-emitting probe measurements and the other on conditionally sampled probe characteristics. The temporal evolution of the plasma potential fluctuations in this work is consistent with previous results from TJ-K [53], DIII-D [3] and ASDEX Upgrade [54]. The observed coincidence of density and electron-temperature fluctuations is consistent with the findings from the experiments TEXT, Phaedrus-T, TJ-I, W7-AS and Repute-I [55].

In investigations on plasma dynamics, probe measurements of ion-saturation current and floating-potential fluctuations are widely used interchangeably for density and plasma-potential fluctuations, respectively. In this paper, it was shown that density fluctuations are well reproduced in ion-saturation current measurements, i.e. the influence of $\tilde{T}_e$ is marginal. Plasma and floating potentials, however, show different behavior. The floating potential is seriously altered by coherent temperature fluctuations and anti-correlated with the plasma potential in the here presented experiments and simulations. An effect of $\tilde{T}_e$ on $\Phi_{fl}$ was also observed elsewhere [56, 57].

If floating potential measurements do not reflect plasma potential fluctuations, as in the presented case, this has far-reaching consequences for probe-based turbulence investigations. For example, the density structure in figure 4(b) is accompanied by a negative signal in the floating potential although the plasma potential is positive (figure 4(d)). As a result, the deduced local electric field and the resulting $E \times B$ drift of the plasma are inverted. This has consequences for a number of drift measurements: (i) turbulent transport in the radial direction.
$\Gamma_r$ is altered if temperature fluctuations are not taken into account. It is typically measured with two floating probes $\Phi_{fl,1}$, which are poloidally separated by a small distance $\Delta$, and a negatively biased probe in between, measuring the ion-saturation current $I_{sat}$. The turbulent transport is calculated according to $\Gamma_r = \tilde{n} \tilde{v}_r$, with density fluctuations $\tilde{n} \propto \tilde{I}_{sat}$ and fluctuations of the radial drift velocity $\tilde{v}_r = \tilde{E}_\theta / B$ and the local fluctuations of the poloidal electric field $\tilde{E}_\theta \approx -(\tilde{\Phi}_{fl,2} - \tilde{\Phi}_{fl,1}) / \Delta$. Contrary to the common assumption, temperature fluctuations do not cancel out, since they are spatially correlated with potential fluctuations. (ii) The phase between plasma and floating potentials is governed by the potential-temperature cross phase. This may modify the phase relation between the density and plasma potential fluctuations, which is indicative of the character of the turbulence [58]. Hence, interpretations of the turbulent character must take into account temperature fluctuations. (iii) Furthermore, estimates of the perpendicular Reynolds stress $R_s = \tilde{v}_\theta \tilde{v}_r$ as a measure of vortex tilting in turbulence can be affected qualitatively if temperature fluctuations deform the topology of the floating compared to the plasma potential.

In conclusion, plasma fluctuations near the LCFS of L-mode plasmas in ASDEX Upgrade are similar to those found in GEMR gyro-fluid simulations. Experimental measurements and simulations showed that large and coherent temperature fluctuations influence floating-potential measurements with Langmuir probes and have to be taken into account to derive plasma-potential fluctuations. Great care must be taken when interpreting floating-potential measurements with respect to, e.g., cross-phase relations and turbulent transport of particles or momentum. The results obtained near the LCFS of hot fusion plasmas similar to ASDEX Upgrade are likely to be corrupted if the effect of temperature fluctuations is disregarded. In this work, methods based on electron-emitting probe measurements or conditionally sampled probe characteristics proved useful in circumventing such temperature effects.

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