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Statistical properties and radial structure of plasma turbulence in the boundary region of the L2-M stellarator

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Abstract. The structure of fluctuations and turbulent transport have been investigated in the plasma boundary region of the L2-M stellarator. Normalized fluctuation levels are in the range (3–20)% and fluctuations are dominated by frequencies below 300 kHz. In the edge plasma region located inside the last closed magnetic flux surface the radial coherence of fluctuations is due to high-frequency fluctuations (>100 kHz). The poloidal coherence is dominated by low frequencies. Linear coupling of resistive interchange modes is considered a candidate to explain the existence of highly radially correlated fluctuations in the high-frequency range.

1. Introduction

Turbulent transport in the edge plasma region is considered one of the processes that can have an influence on the global plasma confinement properties in fusion devices. Although fluctuations have long been measured in tokamaks and stellarators, so far few experiments have been done to characterize the radial structure of turbulence (Fonck *et al* 1993, Mazzucato and Nazikian 1993, Hidalgo *et al* 1997). Understanding the mechanisms determining the radial structure of fluctuations is considered as a relevant issue to explain the transition between different plasma regimes (e.g. Bohm against gyro-Bohm transport (Romanelli *et al* 1993)) and the phenomenon of fast changes in transport (i.e. a time scale much smaller than the time scale of diffusive transport) (Gentle *et al* 1995). Therefore, the investigation of the radial structure of edge plasma fluctuations is an important issue in the fusion research community.

In this paper, we report on the investigation of the statistical properties and the radial structure of fluctuations and turbulent transport in the boundary region of the L2-M stellarator.

The paper is organized as follows. In section 2 the experimental set-up and the analysis tools are described. The characteristics of edge plasma fluctuations, and, in particular, the spectral behaviour of the radial coherence of fluctuations, are presented in section 3. A discussion of the experimental results on the basis of the influence of coupling effects on fluctuations is presented in section 4. Conclusions are summarized in section 5.

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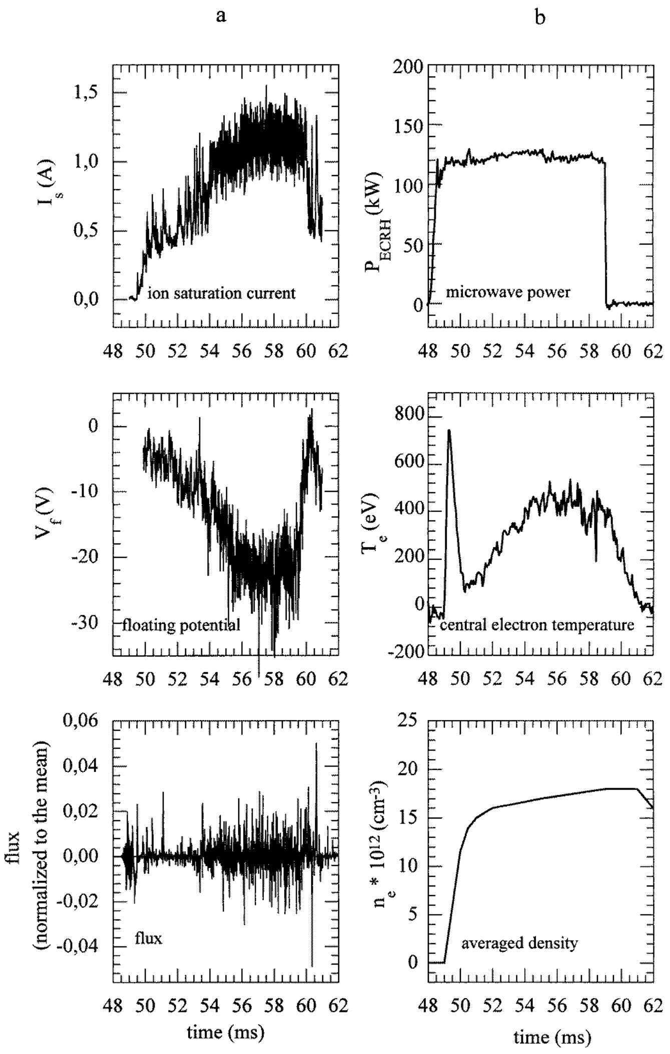


Figure 1. (a) Time evolution of the ion saturation current, floating potential and $E \times B$ turbulent flux in the L2-M plasma edge. 44880 shot. (b) Time evolution of the global plasma parameters: average density $\bar{n}$, central electron temperature $T_e(0)$ and microwave power. 44880 shot.

2. Experimental set-up and analysis tools

The experiments considered in the present work were carried out in the plasma boundary region of the L2-M stellarator (Abrakov *et al* 1995): the major radius $R = 100$ cm, minor radius (the averaged radius of vacuum separatrix) $r_s = 11.5$ cm and the longitudinal magnetic field at the geometrical axis of the torus $B_T = 1.2$–1.4 T. The vacuum rotational transform is created by magnetic fields produced by the currents, flowing over $l = 2$ pairs of helical windings, the total number of the vacuum magnetic field periods $N = 14$. The vacuum rotational transform ι^* for L2-M can be represented in the form

$$\iota^* \approx 0.175 + 0.26(r/r_s)^2 + 0.27(r/r_s)^4 \tag{1}$$

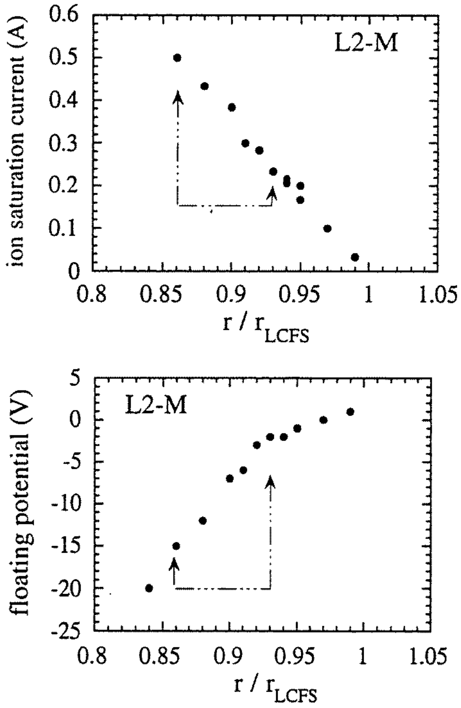


Figure 2. Radial profile of the ion saturation current (I_s) and floating potential (V_f). Arrows show the distance between the tips of probes radially separated by $\Delta r = 0.7$ cm.

where r is the average radius of the magnetic surface and $\iota^* = 1/q$, where q is the safety factor. Shear in the L2-M stellarator is rather high at the plasma edge compared to other existing stellarators, i.e. $r(\iota^{*\prime}/\iota^*)|_{r=r_s} \approx 2.3$ and decreases with a decrease of r_s (for example, up to 1.7 at $r/r_s = 0.8$).

Edge fluctuations were investigated using Langmuir probes in electron cyclotron resonance heated (ECRH) plasmas: $P_{\mathrm{ECRH}} = 100$–200 kW (gyratron pulse duration 12 ms, starting from $t_0 = 49$ ms, t_0 is the time after magnetic field switch on), $\bar{n} \approx 1.5 \times 10^{13}$ cm^{-3} (bar denotes volume averaging), $T_e(0) \approx 400$ eV, H_2 gas. At the plasma edge ($r/r_s \approx 0.8$–0.9) the electron temperature is $T_e \approx 30$–40 eV with electron densities in the range of $n \approx 2$–3×10^{12} cm^{-3}.

To investigate the radial structure of fluctuations and turbulent transport two radially separated ($\Delta r = 7$ mm) and moveable triple Langmuir probes were used (Pedrosa *et al* 1995, Berezhetskii *et al* 1989, Khol'nov *et al* 1991). Two tips of each set of triple probes aligned perpendicular to the magnetic field and poloidally separated ($\Delta\theta = 7$ mm) are used to measure fluctuations of the poloidal electric field, $\tilde{E}_\theta$, deduced from the floating potential and neglecting electron temperature fluctuation effects (i.e. $\tilde{E}_\theta = (\tilde{V}_1 - \tilde{V}_2)/\Delta\theta$). Another tip is biased at a fixed voltage in the ion saturation current regime to measure density fluctuations ($\tilde{I}_s = \tilde{n}$). The turbulent radial particle flux has been computed from the measured values of ion saturation current and electric field fluctuations neglecting $\tilde{T}_e/T_e$ effects.

Signals were digitized at 1 MHz using a 10 bit digitizer. Wavelet analysis tools have been used to characterize the structure of fluctuations (Milligen *et al* 1995). These tools permit us to obtain information about the spatial correlation of fluctuations with time resolution. The experiments reported in this paper were carried out in the plasma boundary region ($r/r_s = 0.8$–1.0) of the L2-M stellarator. A moveable limiter was typically located at $r_L/r_s \approx 1.1$ (r_L being the limiter radius), but in some experiments it was inserted into the plasma up to $r_L/r_s \approx 0.8$.

3. Experimental results

3.1. Plasma profiles and radial structure of fluctuations

Figure 1(a) shows the time evolution of the ion saturation current (I_s), floating potential (V_f) fluctuations and the turbulent flux ($\tilde{\Gamma}$) measured by Langmuir probes located in the plasma bulk side of the last closed flux surface ($r/r_s \approx 0.9$). Figure 1(b) shows the time evolution of the plasma parameters: the average density $\bar{n}$, central electron temperature $T_e(0)$ and microwave power. The flat top of the plasma shot lasted about 5 ms and during this time period both the ion saturation current and the floating potential are stationary. The turbulent flux is bursty and on average is outwards.

The radial profile of ion saturation current and floating potential (taken during the flat top of the plasma discharge) is shown in figure 2. The ion saturation current increases and the floating potential is more negative as the probe is inserted into the plasma edge region. As observed in other devices, the radial electric field is sheared in the proximity of the location of the last closed magnetic surface. In the plasma edge region ($r/r_s < 0.8$–0.9) the level of ion saturation current fluctuations is in the range $\tilde{I}_s/I_s \approx (3$–$6)\%$ and fluctuations are dominated by frequencies below 300 kHz (figure 3). The fluctuation level increases up to 20% in the proximity of the last close flux surface ($r/r_s \approx 1$).

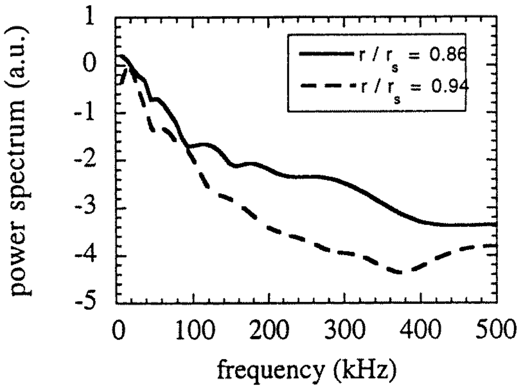


Figure 3. Frequency spectra of ion saturation fluctuation at two different radial locations. Power spectrum, $\log_{10}$ scale.

The power distribution function (PDF) of the computed turbulent local flux (see figure 1(a)) is non-symmetric. Figure 4 shows the PDF of the turbulent flux computed at the plasma edge region. In agreement with previous experiments, large-amplitude bursts account for significant parts of the total local flux (Hidalgo 1995, Carreras *et al* 1996).

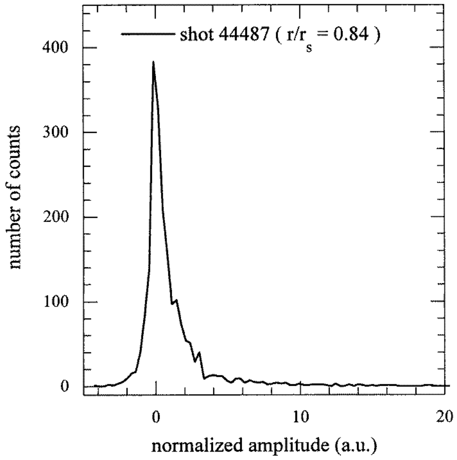


Figure 4. Power distribution function of the turbulent flux in the plasma edge region ($r/r_s \approx 0.84$).

3.2. Cross correlation of fluctuations and turbulent fluxes

Figure 5 shows the frequency resolved radial coherence for ion saturation current fluctuations computed at different radial locations ($0.86 < r/r_s < 1.01$). In the proximity of the separatrix ($r/r_s \approx 1$) the radial coherence is dominated by low frequencies (figure 5(a)). In contrast, at the plasma edge ($r/r_s \approx 0.9$) the radial coherence increases up to 0.9 for high-frequency components (>100 kHz) whereas coherence for the low-frequency components (<100 kHz) is less than 0.5 (figures 5(b) and 5(c)). Similar results were found for the floating potential fluctuations.

These highly radially correlated fluctuations (with frequencies above 100 kHz) do not contribute significantly to the fluctuation spectra dominated by low frequencies (less than 100 kHz shown in figure 3). The radial coherence of the turbulent particle flux is smaller than the radial coherence of fluctuations and the turbulent flux is mainly determined by the low-frequency components.

The structure of density fluctuations is bursty. It is possible to distinguish two kinds of bursts: those with fast rise time (a few μs) and with slow decay time (i.e. asymmetric bursts) and bursts with relatively slow rise time (tens of μs). For example, the time evolution of ion saturation current fluctuations measured simultaneously at two different radial locations ($\Delta r = 7$ mm) in a short time window (2 ms) is shown in figure 6(a). It is interesting to note that I_s-bursts are radially correlated and this correlation is detected in the frequency resolved wavelet cross coherence (figure 6(b)); the I_s burst with fast rise time (this burst is marked with a circle on the picture) coincides in time with an increase in the value of the frequency wavelet coherence at high frequencies.

Wavelet coherences in the poloidal and in the radial directions were investigated for I_s and V_f fluctuations. Figure 7 shows the wavelet coherence in these directions for fluctuations I_s; similar results were obtained for V_f fluctuations. Whereas the radial coherence of fluctuations is dominated by high frequencies (>100 kHz), the poloidal coherence is higher in the low-frequency range (<100 kHz). This result shows that the shape of the frequency resolved radial and poloidal coherence of fluctuations is asymmetric in the plasma edge region of L2-M stellarator.

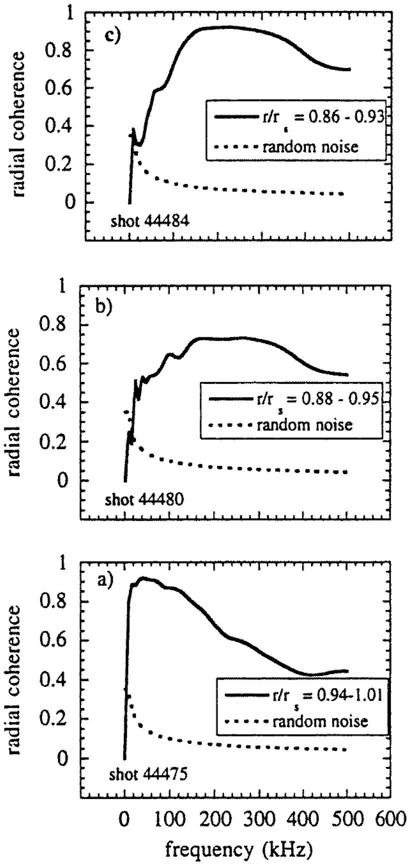


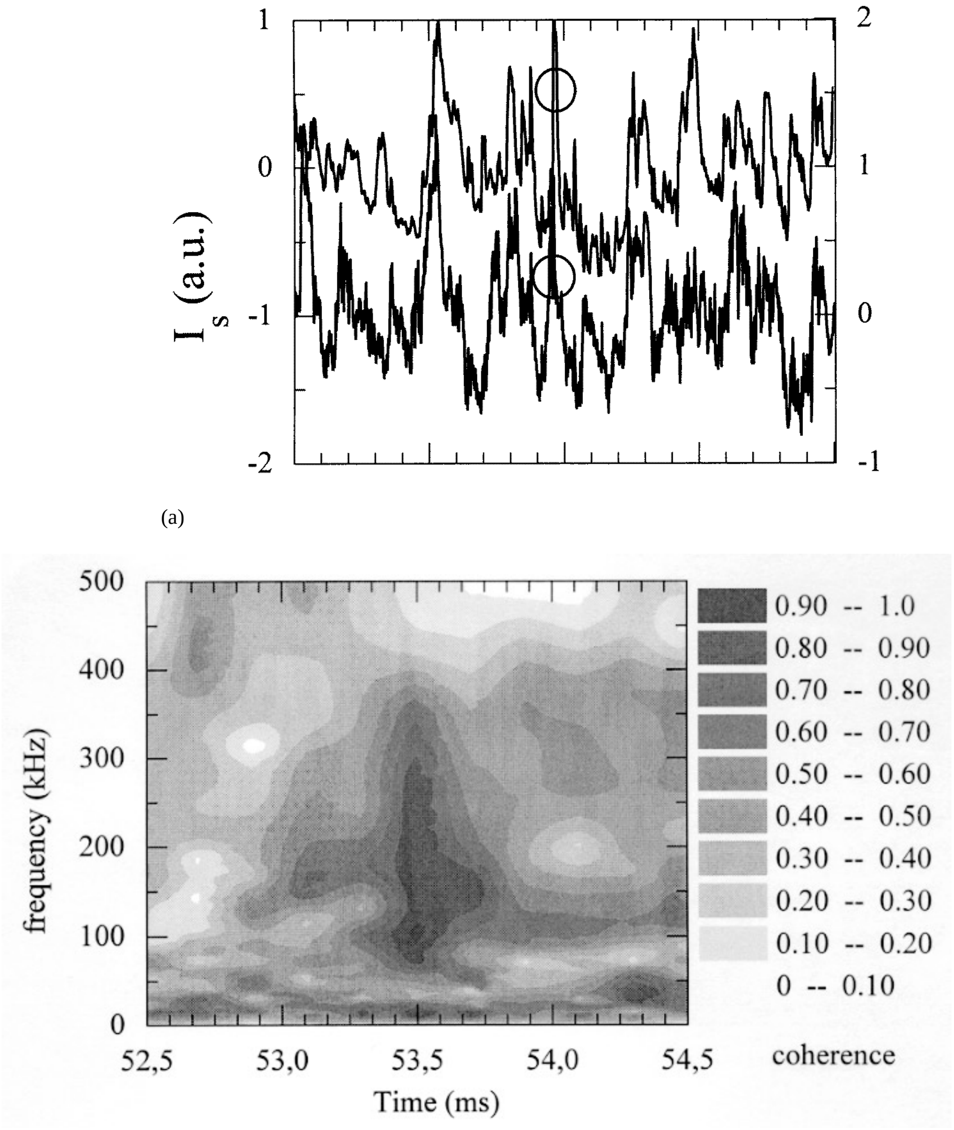
Figure 5. Radial coherence for ion saturation current fluctuations measured at different radial locations.

The influence of the limiter position on the radial structure of fluctuations has also been studied. Interestingly, the radial coherence of high frequencies disappears when the limiter is inserted in the plasma edge ($r_L/r_s = 0.8$) leaving the probes in the shadow of the limiter (figure 8).

It should be noted that the presented wavelet coherence spectra were computed for signals measured by probes radially separated by 7 mm with time delay zero. Increasing the delay time between signals ($\Delta t = 3$ μs), decreases the coherence coefficient remarkably. From the time delay in the maximum of the cross coherence as well as from the dispersion relation (phase against frequency) it was possible to estimate the propagation velocity of the radially correlated fluctuations. It turns out to be close to 4×10^4 m s^{-1}.

4. Discussion

The experimental results presented in the previous section raise a number of questions. In particular, what is the nature of the mechanisms providing a high radial coherence of fluctuations in the high-frequency range in L2-M and why does this correlation decrease in the shadow of the limiter?



(a)

(b)

Figure 6. Raw data for I_s signals and the corresponding wavelet coherence.

As shown in section 3, the burst-like structure of fluctuations has a rise time scale of $\tau_b \sim 10^{-5}$–10^{-6} s. For L2-M edge plasma conditions the resistive skin time (τ_{sk}) and poloidal Alfvén time (τ_A) are given by $\tau_{sk} \approx 10^{-5}\ T_e^{3/2}$ and $\tau_A \approx 3 \times 10^{-8}\ n^{1/2}$, where T_e and n are measured in eV and 10^{12} cm^{-3} units respectively. As $T_e \leqslant 40$ eV and $n \leqslant (2\text{–}3) \times 10^{12}$ cm^{-3} it follows that $\tau_A \ll \tau_b \ll \tau_{sk}$. Therefore, magnetohydrodynamic (MHD) instabilities are candidates to explain edge fluctuations in L2-M.

The present experiments were carried out in low-beta plasmas $\beta(r_s/r = 0) \approx 0.2\%$, where stability calculations show that ideal MHD modes are stable†. The stability criteria

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† β is the ratio of the plasma pressure to the magnetic field pressure.

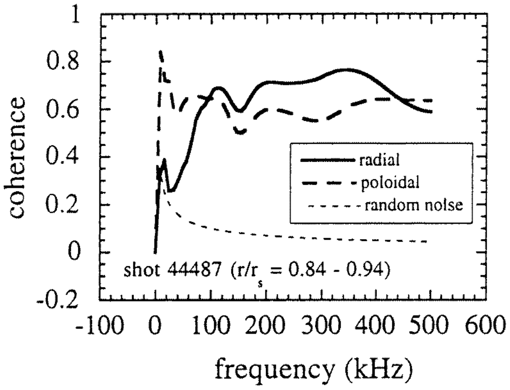

Figure 7. Radial and poloidal coherence of fluctuations.

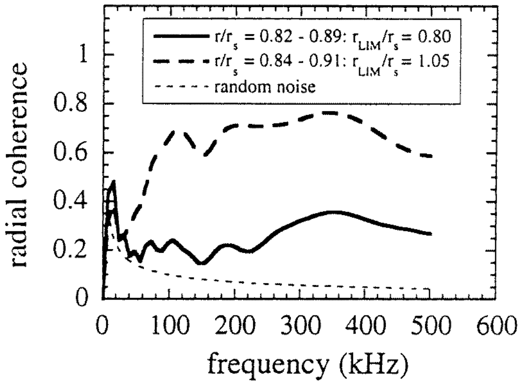

Figure 8. Influence of the limiter position in the frequency resolved coherence of fluctuations.

for pressure-driven-resistive MHD modes with poloidal number $m \gg 1$ and for small beta values is given by (Kovrizhnykh and Shchepetov 1981)

$$\begin{aligned} -U_{\mathrm{S}} = \frac{x\beta'}{2}\Bigg\{ & \frac{N}{l}\frac{(x^4\iota^*)'}{x^3} + A\frac{(x^3(\xi^*/a_{\mathrm{p}})')'}{x^3} - 1 + 2\iota^{*2} \\ & -A\left(\frac{\xi_{\mathrm{p}}}{a_{\mathrm{p}}}\right)\frac{(x^3\iota^{*\prime})'}{x^3} - 2A\left(\frac{\xi_{\mathrm{p}}}{a_{\mathrm{p}}}\right)'\frac{\iota^{*\prime}}{\iota^*}\Bigg\} \geqslant 0. \end{aligned} \qquad (2)$$

In (2) we have taken into account that the relevant experiment is performed under a zero net current regime of operation. Here, ξ_{p} is the average shift of magnetic surfaces caused by Pfirsch–Schlueter currents, ξ^* is the average shift of vacuum magnetic surfaces (in the zero-β case the vacuum magnetic axis in the L2-M stellarator is shifted in distance by ~2.3 cm inside from the geometrical axis of the torus), $A = R/a_{\mathrm{p}}$ is the aspect ratio, $x = r/a_{\mathrm{p}}$ is the normalized radius, a_{p} is the averaged radius of the plasma boundary and ι^* is the vacuum rotational transform. Primes here and later denote derivatives with respect to the dimensionless variable x. In the $\beta \to 0$ limit, plasma in the L2-M stellarator is unstable over all the plasma radius. At finite-β the magnetic well is easily formed in the vicinity of the magnetic axis. The first four terms in (2) characterize the vacuum magnetic hill of the system, while the latter two characterize the influence of the magnetic fields created by Phirsch–Schlueter currents. There are two competing processes; self-stabilization effects in high-shear systems tend to create and deepen the magnetic well, while ballooning-like effects tend to destabilize modes. In the present experimental conditions, L2-M plasma is unstable with respect to resistive pressure-driven MHD modes in the plasma edge region where $0.5 \leqslant x \leqslant 1$.

Taking the driving force for the resistive interchange modes in the form of equation (2) for $1 \ll m \ll S^{\frac{1}{2}}$ (where $S = \tau_{\mathrm{sk}}/\tau_{\mathrm{A}}$, m is the poloidal wavenumber), we obtain the following estimation for the linear growth rate in the well known $\tau_{\mathrm{sk}}^{-1/3}$ regime (Furth *et al* 1963)

$$\gamma = \left[\frac{U_{\mathrm{S}} m}{x \iota^{*'}}\right]^{2/3} \tau_{\mathrm{sk}}^{-1/3} \tau_{\mathrm{A}}^{-2/3}. \tag{3}$$

Considering an upper bound for the rise time of the turbulent burst of 20×10^{-6} s, it implies a characteristic time (γ_m^{-1}) with $m = 30$.

For $m \sim S^{1/2}$ the instability growth rate is a slowly varying function of the mode number m. In the regime with $m \gg S^{1/2}$ the growth rate corresponds to the so-called fast interchange regime with $\gamma_{\max} = U_{\mathrm{S}}^{1/2} \tau_{\mathrm{A}}^{-1}$ which does not depend on resistive time. In the case for L2-M edge plasma conditions $\gamma_{\max}^{-1}$ is of the range 0.5×10^6 s, which is close to the lower bound of the rise time scale of edge plasma turbulent bursts.

In order to explain the large radial correlation of fluctuations in the high-frequency range, the importance of linear coupling processes have been considered (Romanelli and Zonca 1993). A critical ingredient is the degree of overlapping between modes radially localized in the proximity of rational resonant magnetic surfaces. The radial width of the resonant modes as well as the degree of overlapping between adjacent modes depend on the shape of the rotational transform profile. Two neighbouring modes with poloidal wavenumbers m and $(m + 1)$ are radially separated at distance $\Delta x_2 = \iota^*/(m\iota^*)'$. The radial width for resistive pressure-driven modes in the fast interchange regime can be easily obtained after straightforward algebra using the equations derived in Carreras *et al* (1987),

$$\Delta x_1 = [U_{\mathrm{S}}]^{1/4} S^{-1/2} [x \iota^{*'}]^{-1}. \tag{4}$$

Using the condition for mode overlapping, $\Delta x_2 \leqslant 2\Delta x_1$, the minimum poloidal mode number for formation of the coherent zone at the L2-M edge plasma conditions is $m_{\mathrm{c}} \approx 300$.

An estimation of the frequency range of fluctuations with modes with poloidal number $m_{\mathrm{c}} = 300$ is given by $f_{\mathrm{c}} \approx m_{\mathrm{c}} v_{\mathrm{d}}/(2\pi r) \approx 300$ kHz ($v_{\mathrm{d}} = -(BT_{\mathrm{e}}/en)(\partial n/\partial r)$ being the drift diamagnetic velocity, $v_{\mathrm{d}} = 7 \times 10^2$ m s^{-1}). This value is close to the frequency range of highly radially correlated fluctuations observed in the experiment ($f > 300$ kHz). The observed asymmetry in the poloidal–radial coherence of high-frequency fluctuations are consistent with the development of the radially elongated structures due to (linear) coupling effects. Naturally high coherence disappears in the shadow of the limiter due to the break of the coupling.

Let us finally estimate the diffusion coefficient in the edge plasma region of the L2-M stellarator. If we suppose that the experimentally measured time-averaged turbulent flux can be presented in the form $\langle \tilde{\Gamma} \rangle = -D_{\mathrm{turb}} \partial \bar{n}/\partial r$ (angular brackets denote time averaging), where $\bar{n}$ is the stationary plasma density, then $D_{\mathrm{turb}} \approx 10^4$ cm^2 s^{-1} (note that this result must be considered only as a rough estimation, because in order to obtain a more accurate result addition averaging of $\langle \tilde{\Gamma} \rangle$ over the magnetic surface must be performed).

This estimation can be compared to the value of the diffusive coefficient D following from calculations (Grebenshikov *et al* 1996) where both neoclassical and turbulent transport for the L2-M installation under relevant experimental conditions were investigated. The value of the diffusive coefficient D is of the order of $1–2\times10^4$ cm^2 s^{-1}, which is surprisingly close to that estimated from the measured turbulent flux.

5. Conclusions

The statistical properties and the radial structure of edge fluctuations have been investigated in the plasma boundary region of the L2-M stellarator with significant magnetic shear. The obtained results can be summarized as follows.

(a) Normalized fluctuation levels are in the range of (3–20)% in the edge plasma region ($r < r_s$) and fluctuations are dominated by frequencies below 300 kHz.

(b) The structure of fluctuations and turbulent flux is bursty with rise time of turbulent bursts in the range 10^{-5}–10^{-6} s.

(c) In the plasma edge region ($r/r_s = 0.8$–0.9) the radial coherence of fluctuations is due to high-frequency fluctuations (higher than 100 kHz); the poloidal coherence is dominated by low-frequency components (lower than 100 kHz). There are asymmetries in the poloidal and the radial structure of fluctuations.

(d) High-frequency fluctuations ($f > 100$ kHz) are radially correlated in the plasma edge region with a propagation velocity in the range of 4×10^4 m s^{-1}. However, this correlation decreases drastically in the shadow of the limiter.

(e) Resistive interchange MHD instabilities are considered as a mechanism explaining the observed turbulent characteristics in the plasma edge region of the L2-M stellarator.

(f) Mode coupling effects appear as a candidate to explain the existence of highly radially correlated fluctuations in the high-frequency range.

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