LOW-FREQUENCY FLUCTUATIONS OF DIVERTED PLASMA FLOW AND THEIR RELATION TO EDGE FLUCTUATIONS IN THE URAGAN-3M TORSATRON

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In the $l = 3/m = 9$ U-3M torsatron with a natural open helical divertor and a plasma produced and heated by RF fields, the joint studies of low-frequency (5–100 kHz) density (ion saturation current) fluctuations at the scrape-off layer (SOL) of the plasma and in the diverted plasma flow (DPF) have been carried out. The knowledge of the relation between fluctuation processes at the boundary and in the divertor region is important as the former are known to induce the anomalous transport, while the level of density fluctuations in some DPF can attain more than 20% of the equilibrium component. The spectral characteristics of DPF fluctuations are compared with those of fluctuations in the SOL, and two characteristic frequency ranges are revealed. Modifications of spectral characteristics due to the spontaneous transition to an improved confinement mode are investigated as well.

1. Introduction

Low-frequency density and potential fluctuations in the edge plasma resulting in the anomalous transport are a subject of research in plasma confinement physics for a long period [1–3]. Changes in the fluctuation behavior are a good indicator of the transition to improved confinement modes. In particular, the investigations of the spontaneous transition to an improved confinement state (hereinafter, the transition) in the U-3M torsatron reveal a distinct decrease of the fluctuation level and radial turbulent particle flux near the plasma boundary with the transition [4, 5]. Naturally, processes near the plasma boundary should be tightly related to processes in the DPF. In particular, it is of interest to study this relationship on the basis of joint measurements of the fluctuation spectral characteristics at the edge and in the DPF.

2. Experimental Conditions and Measurement Techniques

In the U-3M torsatron ($l = 3$, $m = 9$, $R_0 = 1$ m, $\bar{a} \approx 0.12$ m, $\iota(\bar{a}) \approx 0.3$), the whole magnetic system is enclosed into a 5-m-diameter vacuum chamber, so that an open natural helical divertor is realized. The toroidal magnetic field, $B_\phi = 0.7$ T, is produced by the helical coils only, the ion toroidal drift $\boldsymbol{B}\times\nabla\boldsymbol{B}$ is directed upward (Fig. 1). A "currentless" plasma is produced and heated by RF fields ($\omega \lesssim \omega_{ci}$). The RF power irradiated by the antenna is $\lesssim$ 200 kW in a 30–50-ms pulse. The working gas (hydrogen) is admitted continuously into the vacuum chamber at a pressure of $\sim 10^{-5}$ Torr. The line-averaged electron density $\bar{n}_e \sim 10^{12}$ cm^{-3}, and the electron temperature (by the 2nd harmonic ECE) attains $T_e(0) \approx 600$ eV and falls to ~ 50 eV (by probe measurements) near the LCMS.

To study low-frequency density (ion saturation current) fluctuations (hereinafter, fluctuations), plane Langmuir probe arrays in the DPF [6] and a movable four-tip Langmuir probe array in the SOL [4] are used. The dispositions of the divertor probe (DP) arrays in two half field period-separated ($\Delta\phi = 20°$) symmetric

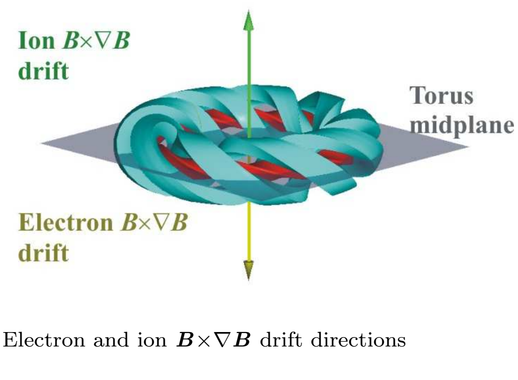

Fig. 1. Electron and ion $\boldsymbol{B}\times\nabla\boldsymbol{B}$ drift directions

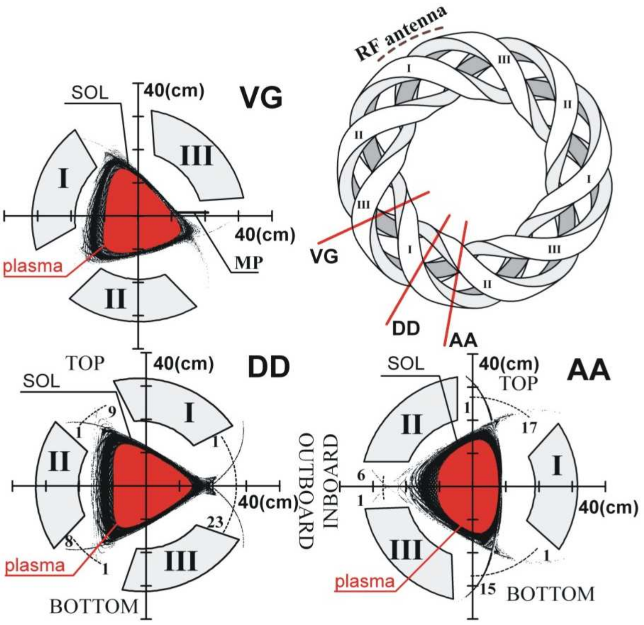

Fig. 2. Disposition of divertor probe arrays 1–17, 1–15, *etc.* (cross-sections AA and DD) and movable probe array (cross-section VG, segment MP) relative to helical coils I, II, and III and the calculated edge structure of field lines. Positions of 4 MP tips are shown in the inset to VG

poloidal cross-sections AA and DD and of the movable probe (MP) array in the cross-section VG ($\Delta\phi = 52.5°$ from AA) are shown in Fig. 2. As a recording facility, a 12-bit ADC with 1.6-μs sampling rate/channel was used.

To obtain the spectral characteristics of fluctuations, methods described in [7] were used.

3. Spectral Characteristics of Fluctuations in SOL and DPF

As an example, the power spectra of fluctuations in the DPF maxima in two divertor magnetic channels (legs) symmetric about the torus midplane in the cross-section DD (top and bottom spacings) are presented in Fig. 3. The evolution of the fluctuation power is traced within 4.8 ms, that is equal to 3000 ADC counts (Fig. 3,*a*,*b*).

The corresponding power spectra averaged over this time period are shown in Fig. 3,*c*,*d*. In combination with the data from the top and bottom spacings of cross-section AA, a conclusion can be made that there are two frequency ranges, where the maximum fluctuation power is observed, namely, one with frequencies less than 30 kHz (over the torus midplane) and one with frequencies exceeding 30 kHz (under the midplane).

It is known [6] that the spatial DPF distributions in U-3M exhibit a strong vertical (up-down) asymmetry with the larger ambipolar flow and the non-ambipolar flow with an excess of ions always outflowing with the ion $\boldsymbol{B}\times\nabla\boldsymbol{B}$ drift (upward, in our case). At the same time, the electrons dominate in the non-ambipolar flow outflowing downward [6]. It is naturally to suppose that the observed vertical asymmetry in the spectral characteristics of fluctuations is related, in some way, to the DPF vertical asymmetry, and the fluctuations with frequencies < 30 kHz are connected with the fast ion loss that is responsible for the DPF asymmetry [6].

Studies of related spectral characteristics of fluctuations near LCMS depending on the radial distance also reveal two frequency ranges with maximum spectral power, as in the DPF case. The results are shown in Fig. 4. With the MP moving toward a smaller radius, the maximal fluctuation power gradually shifts from a frequency range > 30 kHz (Fig. 4,*b*,*d*: $r = 12.0$ cm) to a range < 30 kHz (Fig. 4,*a*,*c*: $r = 10.4$ cm).

In addition to the power spectra, the cross-coherence spectra for fluctuations in the SOL at different distances from the LCMS (last closed magnetic flux surface), on the one hand, and fluctuations in different DPFs, on the other hand, are also investigated. The coherence spectra between fluctuations detected in the bottom spacing of the DD cross-section in the DPF maximum (DP N1) and fluctuations in the SOL for two MP positions, $r = 12.0$ cm and $r = 10.6$ cm, are shown in Fig. 5.

In the case $r = 12.0$ cm, the maximal coherence up to ~ 0.8 in the frequency range 40–60 kHz is observed. As already shown above, the maximum fluctuation power recorded in the SOL (Fig. 4,*b*,*d*) and in the DPF under the torus midplane (Fig. 3,*b*,*d*) belongs to the same frequency range. The coherence gradually decreases with the MP displacing toward the LCMS.

The large coherence apparently can be explained as follows. A bundle of magnetic field lines after crossing the MP tip at the radius $r = 12.0$ cm enters, due to the rotational transform, the divertor region and falls on the DP #1 in the bottom spacing of the DD cross-section [8]. On the other hand, the field lines located closer to the LCMS (e.g., $r = 10.6$ cm) can make a many-fold pass round the torus before deviating to the divertor region. Therefore, the fluctuations in these SOLs should be less correlated with the fluctuations in the DPF.

The fact that the highest fluctuation power in the DPF on the electron $\boldsymbol{B}\times\nabla\boldsymbol{B}$ drift side and the maximum coherence are observed in the same frequency range is an evidence in favor of a common nature of the

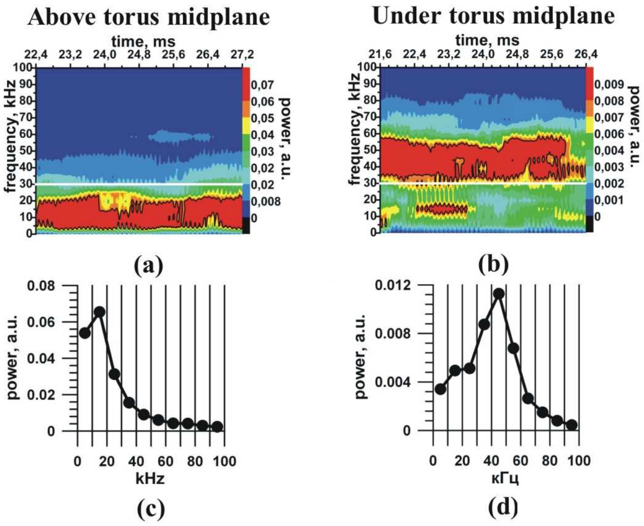

Fig. 3. Time evolution of fluctuation power spectra (a, b) and corresponding time-averaged spectra (c, d) in the top (a, c) and bottom (b, d) spacings of cross-section DD

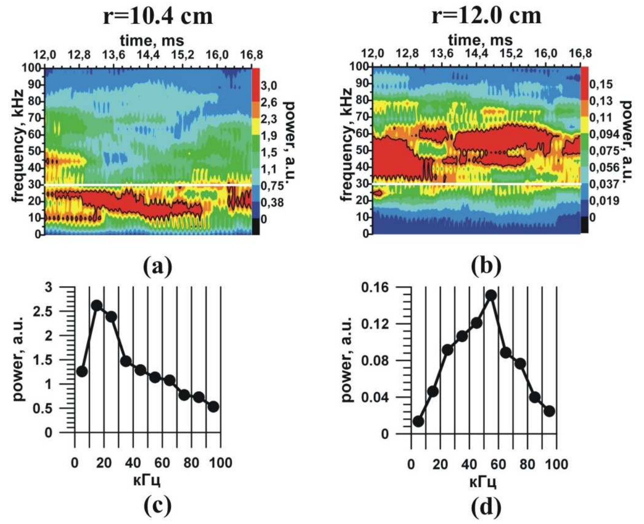

Fig. 4. Time evolution of fluctuation power spectra (a, b) and corresponding time-averaged spectra (c, d) in close vicinity to LCMS, a and c – MP position $r = 10.4$ cm and more distantly; b and d – $r = 12,0$ cm

fluctuations in the SOL at $r = 12$ cm and in the DPF under the midplane.

Thus, two layers can be generally marked out in the SOL. More distantly from the LCMS, the development of fluctuation processes is connected with the electron loss – an electron escape to the divertor region on the electron $\boldsymbol{B}\times\nabla\boldsymbol{B}$ drift side, while the excitation of fluctuations in the layer closer to the LCMS is related to the ion loss. It would be natural to relate the electron loss in the outer layer to a higher field line stochastization in this layer.

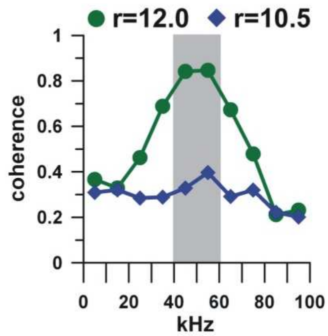

Fig. 5. Cross-coherence spectra for fluctuations in the divertor region (DD, bottom, probe N1, see Fig. 1) and the SOL (movable probe at $r = 12.0$ cm and $r = 10.6$ cm)

4. Changes in Spectral Characteristics with the H-Mode Transition

Like some other plasma parameters, the spectral characteristics of fluctuations change during the transition. The typical fluctuation power spectra taken before and after the transition in DPF maxima in the top and bottom spacings of cross-sections AA and DD and in the inboard spacing of cross-section AA are shown in Fig. 6.

In cross-section AA, the fluctuation power decreases above the torus midplane and increases below the midplane after the transition. In the inboard spacing, the fluctuation power decreases both above and below the midplane.

In cross-section DD, the power spectra change in the opposite way with the transition: the fluctuation power increases above the torus midplane and decreases under it. The same tendency is also observed in the outboard spacing of cross-section DD.

Since the fluctuations with frequencies lower than 30 kHz (higher than 30 kHz) are presumably related to ion (electron) transport processes, the dynamics of particle loss during the transition could be described in the following way, basing on the fluctuation spectral characteristics. In cross-section AA, an insignificant reduction of the ion loss is observed (a slight decrease of the ion outflow to the DPF above the midplane). At the same time, the electron loss insignificantly increases (a slight increase of the electron outflow in the DPF under the midplane). In the inboard spacing of cross-section

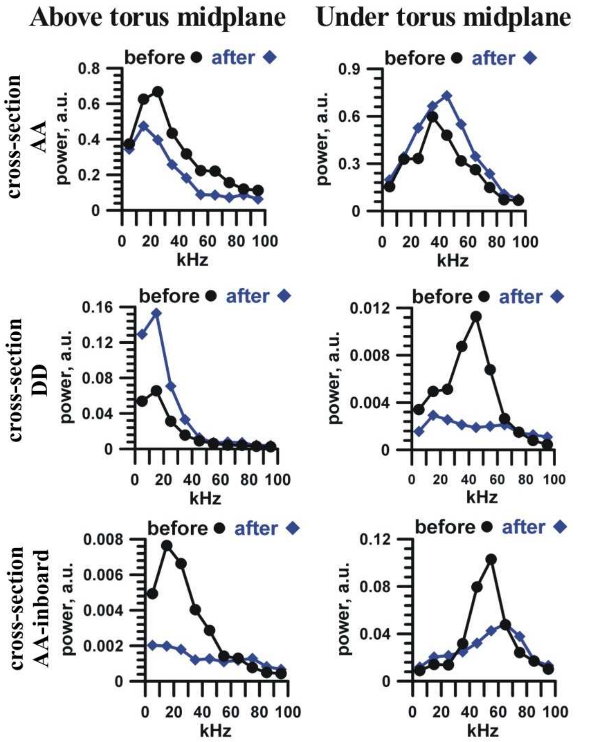

Fig. 6. Power spectra before and after the H-mode transition in two symmetric poloidal cross-sections AA and DD

AA, both the ion and electron losses are significantly reduced. In cross-section DD, a considerable reduction of the electron loss (a sharp drop of the electron outflow to the DPF under the torus midplane) and a considerable rise of the ion loss (a sharp increase of the ion outflow to the DPF) above the torus midplane occur with the transition.

As a whole, these results are in good agreement with those of studies of the H-transition effects on the equilibrium characteristics of the DPF (in particular, on the fast ion outflow to the DPF) in U-3M [9].

5. Summary

As a result of the investigations of DPF fluctuations and the comparison of their spectral characteristics in two symmetric poloidal cross-sections with those in the SOL in the U-3M torsatron, the following conclusions can be made.

A new manifestation of the DPF vertical asymmetry is observed, viz., a difference in the forms of the power and coherence spectra in symmetric divertor channels over and under the torus midplane.

As a result of the studies of the correlation between fluctuations in the SOL and the DPF and their spectral characteristics and the comparison of these data with the distributions of a non-ambipolar DPF [6], two layers of the SOL are defined. The SOL with electron predominance is localized more distantly from the LCMS; the other layer with ion predominance is localized closer to the LCMS.

Basing on the corresponding spectral characteristics, it is shown that the DPF on the ion $\boldsymbol{B}\times\nabla\boldsymbol{B}$ drift side is formed predominantly by particles outflowing from the SOL nearest to the LCMS; on the electron drift side, the DPF is formed predominantly by particles escaping from more distant layers of the SOL.

Changes occurring in the spectral characteristics of fluctuations during the H-mode transition confirm the character of the electron and ion loss dynamics associated with the transition.

1. M. Endler *et al.*, J. Nucl. Mater. **266–269**, 84 (1999).
2. A.J. Wootton *et al.*, Phys. Fluids B **2**, 2879 (1990).
3. H.Y. Tsui *et al.*, Phys. Fluids B **5**, 2491 (1993).
4. E.L. Sorokovoy *et al.*, Probl. At. Sci. and Technol., Ser. Plasma Physics, N 10, 21 (2005).
5. V.V. Chechkin *et al.*, Plasma Phys. Control. Fusion **48**, A241 (2006).
6. V.V. Chechkin *et al.*, Nucl. Fusion **42**, 192 (2002).
7. E.J. Powers, Nucl. Fusion **14** 749 (1974).
8. E.L. Sorokovoy *et al.*, Probl. At. Sci. and Technol., Ser. Plasma Physics, N 1, 60 (1999).
9. V.V. Chechkin *et al.*, in *Proceedings of the Joint Conference of 17th Intern. Tokio Conference (ITC) on Physics of Flows and Turbulence in Plasmas and 16th Intern. Stellarator/Heliotron Workshop (ISHW), Tokio, Japan, October 15-19, 2007.*

НИЗЬКОЧАСТОТНІ ФЛУКТУАЦІЇ ПОТОКУ ДИВЕРТОВАНОЇ ПЛАЗМИ ТА ЇХ ЗВ'ЯЗОК З ФЛУКТУАЦІЯМИ МЕЖОВОЇ ПЛАЗМИ В ТОРСАТРОНІ "УРАГАН-3М"

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Р е з ю м е

На торсатроні "Ураган-3М" з природним гвинтовим дивертором (У-3М; $l = 3$, $m = 9$, $R_0 = 1$ м, $\bar{a} \approx 0{,}12$ м $\iota(\bar{a})/2\pi \approx 0,3$) в умовах ВЧ-створення і нагрівання плазми за допомогою наборів ленгмюрівських зондів проведено дослідження низькочастотних (5–100 кГц) флуктуацій густини у межовій і дивертованій плазмі. Спектральні характеристики флуктуацій в плазмових диверторних потоках (ПДП), що виходять у зазори між гвинтовими котушками, порівнювалися з характеристиками флуктуацій в SOL. Показано, що для плазми, яка більш

(менш) віддалена від КЗМП, типовими є більш (менш) високочастотні флуктуації. Подібне розділення спектра на два піддіапазони спостерігається і в ПДП. При цьому більш низькочастотні флуктуації переважають на стороні іонного тороїдального дрейфу $\boldsymbol{B}\times\nabla\boldsymbol{B}$, а більш високочастотні – на стороні електронного дрейфу. Також були проведені дослідження динаміки спектральних характеристик флуктуацій в SOL і в диверторі при переході в режим з поліпшеним утриманням завдяки створенню внутрішнього і крайового транспортних бар'єрів. Показано, що при переході рівень більш низькочастотних флуктуацій в SOL істотно знижується, а більш високочастотних – практично не змінюється. Що стосується диверторної області, то, залишаючись в тому ж піддіапазоні частот, що й до переходу, максимальна потужність флуктуацій у всіх розглянутих ПДП зростає (спадає) разом із зростанням (зменшенням) відповідної рівноважної складової.