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Measurements of the FT-2 tokamak edge plasma fluctuations in improved confinement regimes.

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Numerous experiments demonstrate that the presence of peripheral wideband microscopic fluctuations is a common property of toroidal devices with magnetic plasma confinement. Fluctuations in the particles' density, in the potential, electric and magnetic fields are detected by means of various diagnostics, while the characteristics of these fluctuations (localization at the periphery of the plasma cord, range of frequencies, fluctuation levels, etc.) in different devices appear to be fairly similar. The microscopic plasma turbulence is generally considered to account for the anomalous energy losses in tokamaks [1].

Experimental investigations of peripheral processes in a tokamak plasma are necessary to create a reliable theoretical model of the anomalous transverse particle and energy transport. These investigations take on particular interest in the light of the discovery and intensive studies of regimes with improved plasma confinement (H-regimes), that have emphasized a close relationship between peripheral processes (specifically the nature of the peripheral microturbulence and particle fluxes attributed to it) and plasma parameters in the main part of a tokamak (see, e.g., [2]).

In the FT-2 tokamak (R=0.55 m, a=0.08 m, B_{tor}=2.2 T, I_{pl}=22 kA) the transition to an improved confinement regime was discovered in experiments on the additional plasma heating by lower hybrid electromagnetic waves (*f*=920 MHz, P ≤150 kW). The transition was most neatly recorded after the lower-hybrid heating (LHH) pulse switch off [3]. Obtaining experimental data concerning the transition accompanying processes in the peripheral zone of the tokamak has been the goal of the present investigations. The greatest attention has been paid to the study of the behaviour of fluctuation-induced particle drift fluxes and the evolution of the characteristics of fluctuations. Particle flux in the edge region of the tokamak is an additive effect of the diffusion flux

$\Gamma_d = - D \text{ grad } n$

(D – effective diffusion coefficient, n – particles' density) and the flux related to the charged particles' drift in crossed electrical (**E**) and magnetic (**B**) fields, which in its turn can be presented as a sum of the quasistationary

$\Gamma_0(t) = cn(t)[\mathbf{E}_0(t),\mathbf{B}]/B^2$

and the fluctuation-induced components. Fluctuation-induced fluxes result from the correlation between fluctuations in the plasma density $n^{(\sim)}$ and the electric field $\mathbf{E}^{(\sim)}$:

$$\Gamma_{fl}(t) = \frac{c}{B^2}\left[\left\langle n^{(\sim)}(t)\mathbf{E}^{(\sim)}(t)\right\rangle,\mathbf{B}\right], \qquad (1)$$

where angle brackets denote the time averaging.

Fluctuation-induced fluxes represent one of the main mechanisms of transverse particle transport in the peripheral regions of toroidal devices. Thus, in particular, experiments on the FT-2 tokamak have demonstrated that in the ohmic regime these fluxes can account for up to (60…100)% of the total radial particle flux [4]. Investigation of the characteristics of the edge plasma fluctuations and measurements of particle fluxes and their contribution to the integral radial transport in LHH experiments required the application of a new probe diagnostic improved in comparison with [4].

The updated measuring circuit has enabled the important requirements to be met such as the wide range of operating frequencies and the capability of making reliable measurements during the LHH pulse. Measurement technique is based on the use of three movable five-electrode Langmuir probes [4, 5], located in the same transverse cross-section of the chamber, allowing to obtain data in the limiter shadow region inclusive of the whole poloidal bypass of the torus. The noise-immunity of the circuits during the LHH pulse is achieved by a careful balancing of the input impedances and by the use of wideband differential amplifying sections. The diagnostic allows to measure the time evolution of local electron temperature, plasma density and plasma potential, register the fluctuations of these parameters in the frequency band up to 500 kHz; and also to determine the local quasistationary and fluctuation-induced drift flux densities. The fluctuation-induced component of the flux can be measured by either analog or digital equipment. Analog processing module performs the multiplication of fluctuating components of the probe ion saturation current signal and the potential difference between the two symmetrically located floating electrodes followed by averaging. Digital equipment allows recording the initial probe signals with the sampling frequency of 1 MHz.

In the course of experiments local fluctuation-induced drift flux densities have been measured by a step of (20…30)° in poloidal angle and a step of 1 mm along minor radius (r). Most data have been obtained by analog equipment. The integral radial flux Q_{rad} at r=8 cm calculated from these data is shown in Fig. 1. One can see that the transition to the improved confinement regime after the additional heating switch off is accompanied by a reduction in this flux nearly in half in comparison with the ohmic regime. In Ref. [6] an approximately double increase in the energy confinement time in the improved confinement mode compared to the ohmic regime was pointed out. One of the dominant reasons for this may well be the observed decrease in fluctuation-induced fluxes.

Spectrum and cross-correlation characteristics of fluctuations in plasma density and electric field have been studied by means of the digital equipment. A statistical coefficient of correlation $C_{n^{(\sim)}E^{(\sim)}}$ between $n^{(\sim)}$ and $\mathbf{E}^{(\sim)}$ fluctuations determined by (2) describing the time evolution of the fluctuation-induced particle flux and also the cross-coherence function $\gamma^2(f)$ determined by (3) describing the contribution of different harmonics were calculated.

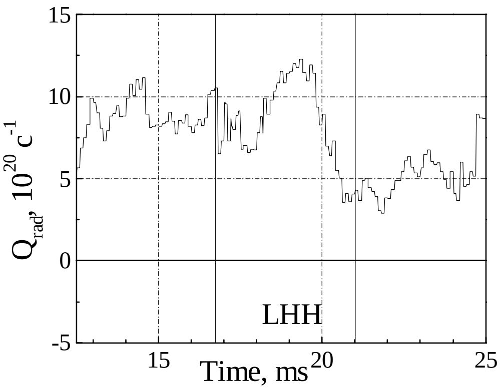

fig.1

Time evolution of the integral radial fluctuation-induced particle flux. Solid vertical lines designate the time position of the lower hybrid heating (LHH) pulse.

$$C_{n^{(\sim)},E^{(\sim)}} = \frac{\langle n^{(\sim)}E^{(\sim)}\rangle - \langle n^{(\sim)}\rangle\langle E^{(\sim)}\rangle}{\sqrt{\langle n^{(\sim)2}\rangle - \langle n^{(\sim)}\rangle^2}\sqrt{\langle E^{(\sim)2}\rangle - \langle E^{(\sim)}\rangle^2}} \qquad (2)$$

$$\gamma^2(\mathrm{f}) = \frac{\left|n^{(\sim)}(\mathrm{f})E^{(\sim)}(\mathrm{f})\right|^2}{\left|n^{(\sim)}(\mathrm{f})\right|^2\left|E^{(\sim)}(\mathrm{f})\right|^2} \qquad (3)$$

Here $n^{(\sim)}(f)$ and $E^{(\sim)}(f)$ stand for Fourier-components of plasma density and electric field fluctuations.

For $C_{n^{(\sim)}E^{(\sim)}}$ and $\gamma^2(f)$ calculation $n^{(\sim)}$ and $\mathbf{E}^{(\sim)}$ fluctuations were measured in the 10…500 kHz range of frequencies. These measurements were made on the outer side of the toroidal plasma cord within the symmetric poloidal angle range ±60° in respect of the equatorial plane with a step of 30°. The correlation coefficient behaviour is depicted in Fig. 2. Coefficient of correlation between the electric field and plasma density fluctuations in the ohmic regime typically amounts to about 0.3 and decreases practically to zero after the LHH pulse. This tendency is exhibited at all poloidal angular positions where the measurements have been made.

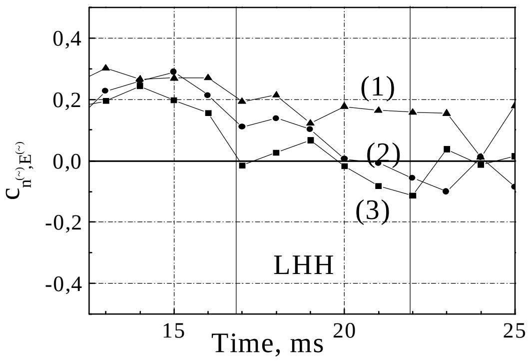

fig. 2

Time evolution of the correlation coefficient between $n^{(\sim)}$ and $\mathbf{E}^{(\sim)}$ fluctuations in the limiter shadow for three angular positions: (1) - Θ = 0°, (2) - Θ = 60°, (3) - Θ = 30°. The poloidal angle Θ is measured from the outer perimeter of the torus in the direction of the toroidal drift of electrons.

The behaviour of the cross-coherence function is also uniform within this spatial region. As an example its time evolution at the spatial position on the outer perimeter of the torus is presented in Fig. 3. In the steady state of the discharge in the ohmic regime the cross-coherence function typically equals about 0.5 within the 10…200 kHz range of frequencies and it is about 0.1…0.2 for the harmonics above 200 kHz. The transition to improved confinement after the LHH pulse corresponds to the decrease of the cross-coherence function to about 0.1 for all observed frequencies.

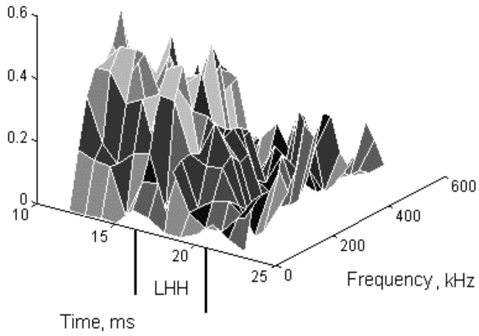

fig. 3

Time evolution of the local cross-coherence spectrum of $n^{(\sim)}$ and $\mathbf{E}^{(\sim)}$ fluctuations in the limiter shadow at the position Θ = 0°.

The effect of the reduction in the intensity of plasma parameter fluctuations in the H-regime has also been observed in the experiments but this did not take place at all values of the poloidal angle. On the inner poloidal bypass a substantial reduction in the fluctuation levels was registered whereas on the outer side of the torus the intensity of the fluctuations did not undergo any significant changes or even indicated an increase at some spatial positions. It should be noted that a similar behaviour of the peripheral plasma turbulence after the LH heating pulse switch off was observed by reflectometry [7]. In such a way, the effect of the suppression of fluctuations is of local nature, while the decrease in the cross-coherence and correlation coefficient has been registered at all points were the measurements were made.

Fig. 4 presents the radial electric field (E_r) profiles for several angular positions at the outer perimeter of the torus. X axis starts from the limiter rim. Those dependences were obtained from the electron temperature and floating potential smoothed radial distributions. One can see that the transition to the improved confinement regime is accompanied by appearance of significant inhomohenity of E_r (both poloidal angle and radial).

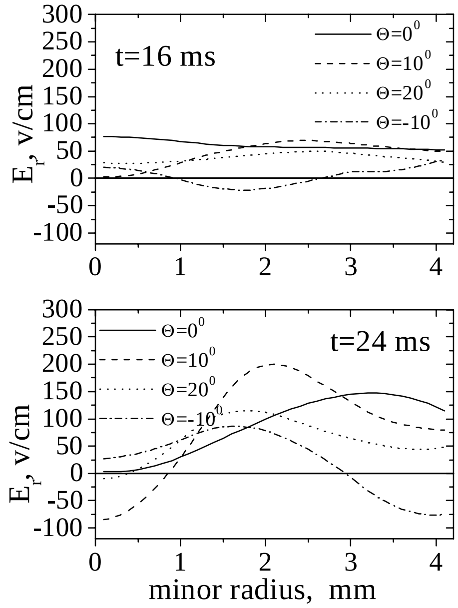

Fig. 4

Radial dependence of radial electric field. Upper picture refer to time 16 ms (ohmic regime), lower picture – 24 ms (improved confinement regime). Dependence brings for several angular position.

Thus, the transition to the improved confinement regime in the FT-2 tokamak after switching off the LHH pulse is accompanied by a considerable reduction in the transverse particle transport caused by fluctuation-induced drift fluxes in the peripheral zone. This reduction for the most part is due to the effect of the suppression of correlation between fluctuations in the electric field and plasma density and the reduction in their cross-coherence. Possible reason for it is essential E_r inhomogenity which leads to the chaotic structure of drift particle fluxes. Experimental observations allow of making a supposition that the above-enumerated effects play an important role in the mechanism of the transition to the improved confinement regime.

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