THE ANALYSIS OF TURBULENCE AND ROTATION U-3M TORSATRON PLASMA DURING TRANSPORT BARRIERS FORMATION

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The analysis of plasma density oscillations and E×B rotation of U-3M torsatron plasma was performed by UHR correlation reflectometry during the transport barrier formation. The connections between these characteristics and the phenomenon of inner and edge transport barrier formation were determined experimentally at the different values of HF power and plasma density.

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INTRODUCTION

The possibility of spontaneous transition to mode characterized by increase of density temperature and confinement time of plasma in torsatron U-3M was shown earlier [1]. Such mode is caused by formation of the internal transport barrier (ITB) at the vicinity of rational magnetic surfaces with the stochastic character of magnetic field lines. The existence of the edge transport barrier (ETB) was proved by Langmuir probe measurements in the out-of–separatrix area [2] and by correlation reflectometry in the near-separatrix area. The occurrence of such barrier was usually linked with the formation of increased electric field in plasma. The definition of ITB and ETB formation conditions will help to determine an optimal regime of plasma confinement in torsatron. As it was noted in works [3] the reaching of a high confinement mode is usually accompanied by a large shear of rotation velocity in crossed E×H fields, by reduction of fluctuations correlation length with following them decorrelation. An important role in the transport processes belong to a different types of oscillations excited in plasma. Plasma turbulence is usually defined by a set of different oscillatory processes that could studied by means of microwave correlation reflectometry.

In the present work, the results of experimental study of oscillation processes and E×H rotation character in the different regime of a high-frequency discharge including ITB and ETB are considered.

EXPERIMENT

The experiments were carried out on U-3M device, which is an l = 3, m = 9 torsatron with and opened divertor (R = 100 cm, a = 13.5 cm). Plasma creation and heating in U-3M is provided by a high-frequency method in the range of frequencies $f \le f_{ci}$ ($f \approx$ 8.5…8.8 MHz). High-frequency power was introduced into plasma using the antennas placed inside the helical winding near the last closed magnetic surface.

Experimental measurements were provided at the intensity of magnetic field B_0 = 7.2 kE and introduced high-frequency power P_{rf} = 150…200 kW when the average plasma density was n = 1…1.4×10^{12} cm^{-3} and 3…4×10^{12} cm^{-3}. Used scheme of correlation reflectometry is shown on Fig.1. This method is the most suitable for obtaining the plasma rotation velocity on U-3M [1,4]. The application of correlation reflectometry method is suitable under the certain conditions: the long-wave length fluctuation dominate in the turbulence spectrum, the reflection occur in cut-off layer, the turbulence correlation time is smaller then correlation shift caused by rotation, the oscillation characteristics do not change appreciable at layer motion between antennas [4]. Taking into account [5] that reflection takes place in the cut-off layer if the fluctuation wave number: $k_\varphi \le 2\cdot k_A = 1.26\cdot k_0^{+2/3}\cdot L^{-1/3}$, where $k_0 = 2\pi/\lambda$ and k_A, λ, L are the Aire wave vector, probing wavelength and the gradient length this inequality is satisfied for given experimental conditions. Since the average density in studied regime is n ~ 10^{12} cm^{-3}, to obtain a reflection near edge of the confinement area (n < 10^{12} cm^{-3}) the probing may be provided by X-waves.

From outer side of the torus the plasma probing was provided by X-waves f = 18.5…25.5 GHz (electron cyclotron frequency on the separatrix was f_{ce} = 17 GHz and on the axis of magnetic field f_{ce} = 19.2 GHz) in neighbor cross-sections distanced on Δl = 50 cm. from each to other and from the inner side plasma location was provided by O-wave in same plasma density layer. Such probing set-up allowed using X-waves location at a single frequency and near values of magnetic field, near the density gradient.

The shift of the cross-correlation function is the result of poloidal and toroidal rotation. Since a period of toroidal rotation is equal to nine periods of poloidal rotation, the main contribution in measured CCF period is made by poloidal rotation. This assumption was proved by comparing data from toroidally (2, 3) and poloidally (2, 4) shifted channels Fig.2. Low-frequency oscillations correspond to layer rotation, high-frequency components are connected with oscillatory processes. The reflection radius was inferred from reflectometry.

Oscillations excited in plasma were studied by using spectral and correlation analysis of the backscattered microwave signals. To observe the radiation at the area of electron cyclotron waves a superheterodyne microwave signal analyzer was used.

EXPERIMENTAL RESULTS AND DISCUSSION

The density oscillations spectrums were studied over the analyzing of autocorrelation functions (ACF) for three reflectometrical channels and its spectrums. Such spectrums for one of the channel (N 2) are shown on

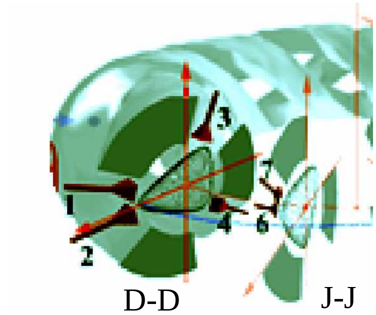

Fig.1. Setup of reflectometry UHF antennae for cross-section D-D and J-J

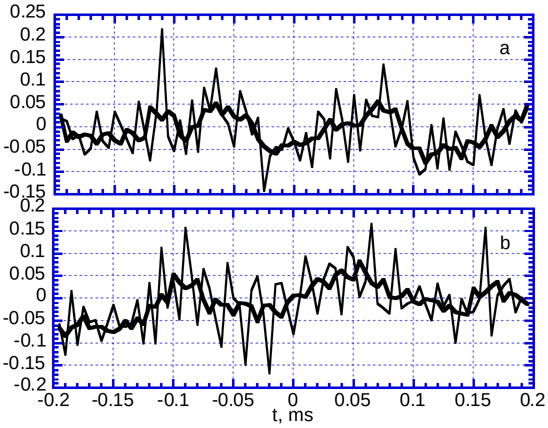

Fig.2. Cross-correlation functions of toroidal (2-6) and poloidal (2-3) distanced channel for time 15-16 ms

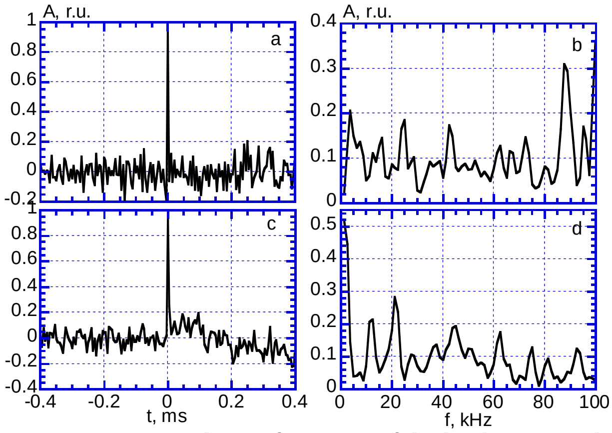

Fig.3. Auto-correlation functions of the back-scattered UHF signals and their spectrums in time intervals 21…22 ms (a, b) and 37…38 ms (c, d)

Fig.3. ACF shows that these oscillations have a stochastic character with separate maximums, which are shifting towards a low frequency when higher density regime put an end. A high-frequency component here corresponds to high-frequency ACF on Fig.2. The analysis of poloidal rotation velocity temporal evolution was made at $B_0 = 7.2$ kE and high-frequency generator anode voltage 7.5 kV and 9 kV with the hydrogen pressure 7.42×10^{-6} Torr and $n \approx 1\ldots4\times10^{12}$ cm^{-3}. Fig.4 displays $V_{pol}(t)$ at $r_{ref}^{(1)} = r/a$ (corresponds to the area of magnetic islands) and $r_{ref}^{(2)}$ (near the separatrix). The decreasing of high-frequency power or the average density increasing leads to reduction of $|V_{pol}|$ and its maximum shifts to the end of the high-frequency energy impulse. On Fig.5 one could observe the dependence: $E(t)=V_{pol}(t)B\times10^{-8}$ [V/cm], where V_{pol} corresponds to displayed on Fig.4 and B is the vacuum intensity of magnetic field corresponding to layer with V_{pol}. By comparison of $V_{pol}(t)$ and E(t) in the area of magnetic islands and in the border area one could make a conclusion about decorrelation of the electric field in ITB and ETB layers. As the ITB mode terminates the field intensity reduces at the middle of the radius and increases on the edge. Spatial and temporal behavior of ITB and ETB layers may be monitored by observation of the *nl* and reflected microwave signals level evolution (Fig.6).

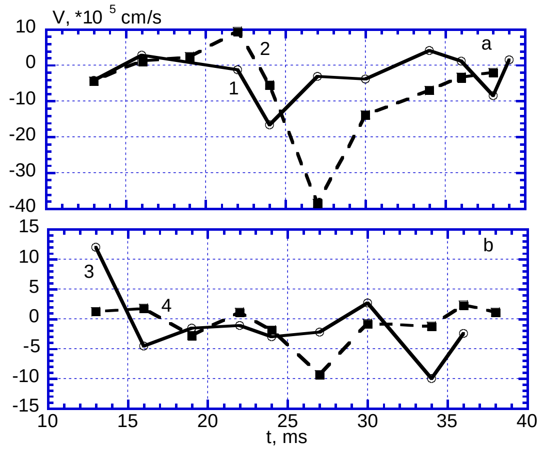

Fig.4. Temporal dependencies of poloidal velocity at HF generator voltage U=9 kV (a) and U=7.5 kV (b):1,3– near separatrix; 2, 4 – in vicinity of rational magnetic surfaces

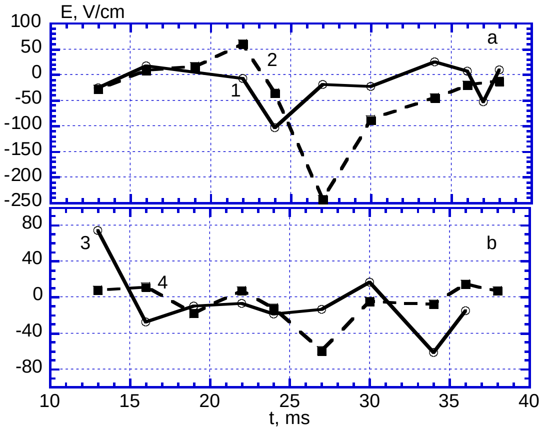

Fig.5. Temporal dependencies of $E = V_p \cdot B \cdot 10^{-8}$ *V/cm for data of mode on Fig.4*

The signals of reflectometers exhibited phase oscillations in the reflected wave before the formation of ITB and ETB. These oscillations correspond to periodical shifting of the reflecting layer and damps after the transport barrier establishment.

ITB occurs at the rational surface vicinity and occupies a wider segment of confinement area. However this barrier is more stable in the inner layers ($r_{ref}/a = 0.1\ldots0.5$). In the outer layers such barrier is formed later and exists over the smaller time interval.

Before the formation of ETB there was an intensive ejection of ions in the out-of-separatrix area [3]. Such ejection results in creation of negative electric potential at the edge of plasma (Fig.5).

Sometimes before the establishing of the increased density mode the superthermal radiation of plasma was registered in the range of electron cyclotron frequency ($f_{ce} \approx 17.5$ GHz) near the plasma edge (Fig.7).

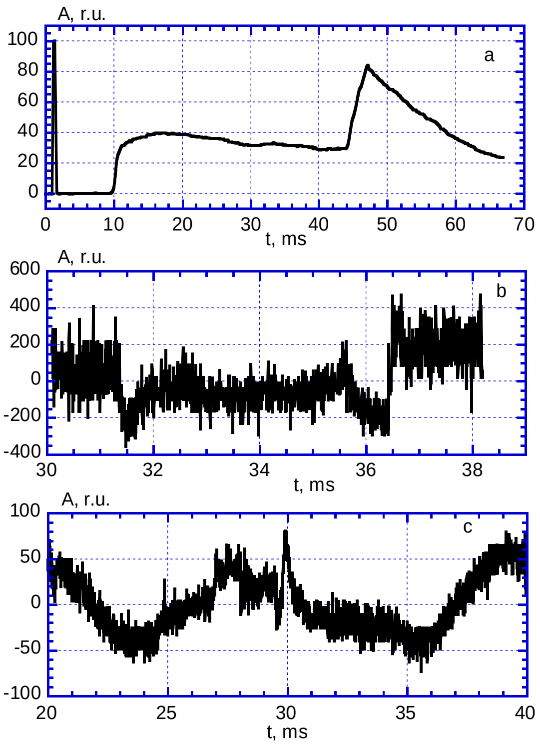

Fig.6. Time behavior of integral density nl (a) and the fragments of back-scattered signals of X-wave from the outer side at n_e=0.4·10^{12} cm^{-3} (b) and O-wave from the inner side at n_e=1.17·10^{12} cm^{-3} (c)

The measurements by means of CXH neutral energy analyzer showed the increase of supra-thermal ion temperature in this phase of the discharge. These effects may be connected with the input of RF power at the plasma periphery.

The peculiarities of the density fluctuation spectra (Fig. 3) may be connected with the transport barrier formation: high-frequency oscillations correspond to short-wave fluctuations during the transport barrier existence. When the barriers disappear these oscillations transform into low-frequency long wave ones. Such confirmation corresponds to conclusion from similar measurements on T-10 tokamak: coherent oscillations in the turbulence spectrum correlates with the discharge transition into a high confinement mode.

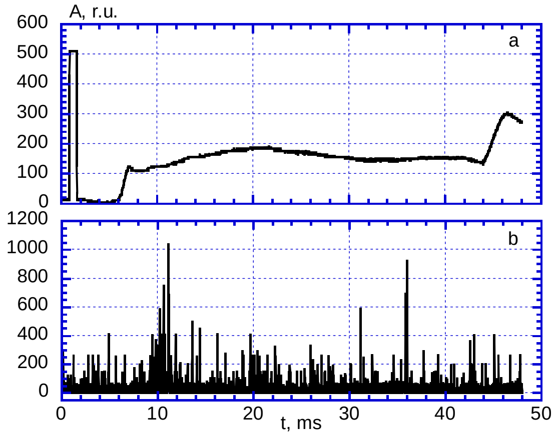

Fig.7. Time behavior of integral density nl (a) and the signal of EC emission, f = 17.5 GHz (b)

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АНАЛИЗ ТУРБУЛЕНТНОСТИ И ВРАЩЕНИЯ ПЛАЗМЫ В ТОРСАТРОНЕ У-3М ПРИ ОБРАЗОВАНИИ ТРАНСПОРТНЫХ БАРЬЕРОВ

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На основе СВЧ-корреляционной рефлектометрии проведен анализ колебаний плотности и E×B вращения плазмы в торсатроне У-3М при формировании транспортных барьеров. Была установлена связь между этими характеристиками и явлением формирования внутреннего и краевого транспортных барьеров при различных уровнях вводимой ВЧ-мощности и плотности плазмы.

АНАЛІЗ ТУРБУЛЕНТНОСТІ Й ОБЕРТАННЯ ПЛАЗМИ У ТОРСАТРОНІ У-3М ПРИ УТВОРЕННІ ТРАНСПОРТНИХ БАР'ЄРІВ

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На основі НВЧ-кореляційної рефлектометрії проведено аналіз коливань густини та E×B обертання плазми торсатрона У-3М при формуванні транспортних бар'єрів. Встановлений зв'язок між цими характеристиками й утворенням внутрішнього та краєвого транспортних бар'єрів при різних рівнях ВЧ-потужності і густини плазми.