MEASUREMENTS OF FLUCTUATING PLASMA ROTATION VELOCITY BY MEANS OF CORRELATION AND DOPPLER MICROWAVE REFLECTOMETRY IN URAGAN-3M TORSATRON

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Studies of fluctuating plasma rotation by means of correlation and Doppler microwave reflectometry in the Uragan-3M torsatron were carried out. The application of two methods makes it possible to broaden the information about the rotation and structure of poloidal plasma oscillations. The correlation method has an advantage in *l*=3 torsatron, because this one is practically insensitive to the tilt angle of incident mm - ray to the reflecting surface. The pulsation of the poloidal velocity and the position of plasma layer in the region of magnetic islands were observed, that became stable upon the formation of the ITB.

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The measurements of plasma rotation in E×H fields in tokamaks and stellarators are essential in studying the formation of the transport barriers which determine the energy and plasma particles transport [1]. Recently, the transitions to the enhanced mode of the particle and plasma energy confinement, with the formation of the internal transport barrier (ITB), were reported on Uragan-3M (U-3M) torsatron [2]. When studying this phenomenon, the phase, spectral, and correlation measurements of the reflected microwaves were used to determine the plasma profile and characteristics of its fluctuations.

The correlation microwave reflectometry has been used to determine the velocity of plasma rotation in U-3M previously [3]. The method is based on measurement of the time shift/period of cross-correlation function (CCF) of two microwave signals reflected from the layer areas of equal density that are shifted either in toroidal or poloidal direction. The method is practically insensitive to the tilt angle between the mm-ray and the reflecting surface. This is particularly important for the case of probing with X-wave for which the orientation of the reflection surface is defined by density as well as by magnetic field. The direction of rotation is determined by the relation of the obtained CCF shift when CCF_{12} is changed to CCF_{21}: the bigger shift corresponds to the longer distance between the reflecting areas and vice versa.

However the torsatron has a poloidal asymmetry due to the configuration of the magnetic surfaces. The asymmetry shows itself as a poloidal modification of the magnetic field, the radius and the curvature of the reflecting layer. This is the reason why the measured shift, or the CCF period, allows determining the velocity of rotation averaged over the poloidal or toroidal angle.

The UHF Doppler reflectometry (DR) is based on the change in frequency shift of the reflected wave that falls on the tilted moving plasma layer [4-6]. The reflecting layer of fluctuating plasma acts as a reflection grating. The probing antenna that is tilted to the reflecting layer, according to the Bragg's rule, can receive the reflected signal with the diffraction of -1 order on the shifted frequency preferentially, but the zeroth order is suppressed (Fig.1).

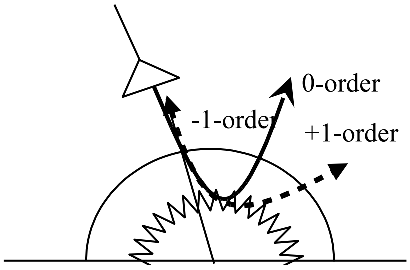

Fig.1. Diffraction of mm-wave in plasma layer perturbation

For the diffraction maximum of -1-st order the wave number of the plasma perturbations is given by:

$$k_{fl}=-2k_i\sin\varphi\simeq-2k_i(r_c)\ , \qquad (1)$$

where k_i is the wave number of the probing wave, φ is the angle of incidence.

The Doppler shift of the reflected wave frequency is:

$$\Delta f_D=-\frac{2f}{c}\mu(r_c)\cdot\upsilon_\theta(r_c)\ , \qquad (2)$$

where μ and υ_θ are the refraction coefficient and the velocity of rotation in the reflection layer. Thus, one can obtain the local value of the rotation velocity by measurement of the Doppler frequency shift.

If density and magnetic field profiles are known than the radius of the beam turning-point r_c and $\mu(r_c)$ are determined by:

$$\mu_{O,X}^{2}(r_c)=\frac{a^2}{r_c^2}\sin^2\varphi\ ,\ \mu_{OW}^2=1-\frac{n(r_c)}{n_c}\ ,$$

$$\mu_{XW}^2=1-\frac{1-\frac{n(r_c)}{n_c}\left(1-\frac{n(r_c)}{n_c}\right)}{1-\frac{n(r_c)}{n_c}-\frac{f_c^2(r_c)}{f^2}}\ . \qquad (3)$$

In the experiment, two methods of determination of the frequency shift of the reflected wave were used: by means of UHF-analyser of the reflected wave and by spectral analysis of the reflected wave fluctuation using fast Fourier transform. The UHF-analyser made it possible to measure shifts of the probing frequencies f = 10-40 GHz; conveniently, it directly determines the sign of the shift (the direction of the velocity). However, the device is designed for analysis of plasma with parameters that change slowly, while the scanning time, Δ t ≥ 2 ms. Besides this device has restrictions in the resolution of the frequency shift.

The method of spectral analysis has no frequency restrictions. The direction of the frequency shift is determined from Fourier transform of the complex signal $U(t)=U_1(t)+iU_2(t)$, where U_1 and U_2 are signals of the same reflected wave, acquired with the phase shift of $\pi/2$. The appearance of a maximum of the power spectral density (PSD) on positive or negative semi-axis corresponds to the direction of the frequency shift. The method was verified on a mechanical model with the rotating corrugated cylinder [3]. The change of the direction of rotation revealed in the change of the position of the PSD maximum (Fig. 2). In the plasma experiment the signal of the microwave detector was digitized with ADC (τ=1.3 mks) and stored.

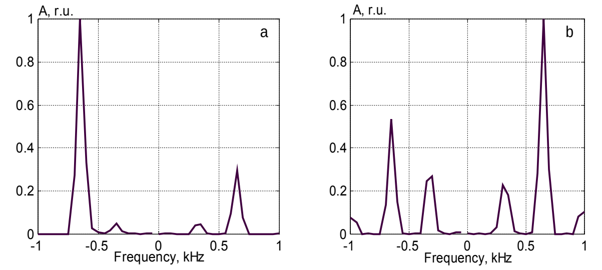

Fig.2. Spectra of complex signals on different direction of rotation

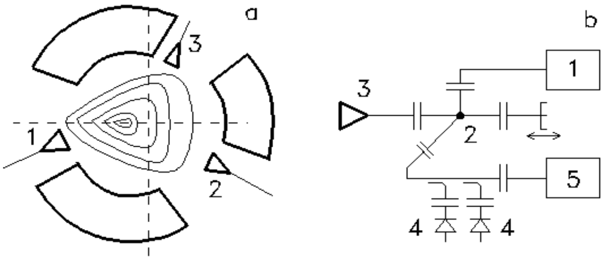

Fig.3

The measurement on U-3M has been fulfilled simultaneously by means the Doppler and the correlation methods at the same torsatron crossection (Fig. 3a). Plasma probing was performed in 3 locations for different direction – X-wave probing (f=18-26 GHz) - both inside and outside and vertical – O-wave probing (f=10 GHz). The receiving-transmitting antenna that were used in the correlation method were put away off each other and were tilted to bounder of plasma so the Doppler frequency shift could be measured by each of them.

The scheme of the measurement of the frequency shift using the analyser and the spectral analysis is given in Fig. 3b. The comparison of the frequency shifts determined using the two methods is given in Fig. 4. The Doppler frequency shift of the reflected wave measured using the two methods gave satisfactory close values.

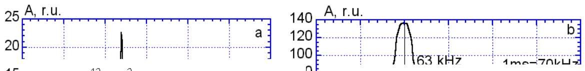

Fig.4. Doppler frequency shift determined by Fourier transform (a) and UHF-analyzer (b)

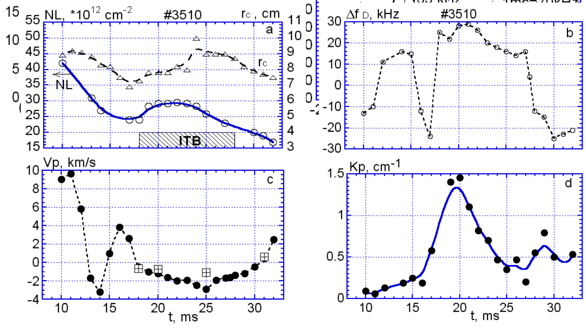

Fig.5. Temporal behaviour of integral density and reflection layer radius (a), Doppler frequency shift (b), velocity of rotation (● - correlation, ⊞ - Doppler reflectometry) (c), poloidal wave number (d)

At determination the velocity of rotation, $\mu(r_c)$ was calculated from equation 3. However, due to variable curvature of magnetic surfaces of the l=3 torsatron during the determining of the angle φ and hence $\mu(r_c)$, significant errors may be present in determining the velocity of rotation. In this case, simultaneous use of the Doppler reflectometry at “U-3M” and the correlation method is expedient for the accurate determination of the direction of rotation. The comparison of the time variation of the Doppler frequency shift and the velocity obtained by using the correlation analysis is presented in Fig. 5 b, c. Obviously, there is an almost synchronous change of the sign of the velocity and the Doppler frequency shift. Measurements of the Doppler frequency shift allow determining the poloidal wave number and a poloidal velocity by using equations 1, 2, 3. The presented results show the change in the direction of rotation (Fig. 5 c) and increase of k_P (Fig. 5 d) to be the precursors of the formation of the ITB, i.e. the wave length of the oscillations decreases. An increase of k_r with a maximum in the range of the magnetic islands chain has been shown on “Uragan-3M” previously [7].

The finite width of probing beam, the finite curvature of wave front and of reflecting layer led to k-space broadening [6]

$$\Delta k_p = \frac{2\sqrt{2}}{w}\sqrt{1+\left(\frac{w^2 k_0}{\rho}\right)^2} \cdot \qquad (4)$$

In these measurements $\Delta k_p \approx 1$ cm^{-1} for $k_i \approx 2$ cm^{-1}, w=2 cm.

In Fig. 6 poloidal velocity is plotted as function of Δf_D. A quasi co-linearity between v_p and Δf_D is observed and confirms that the frequency shift is actually due to Doppler effect.

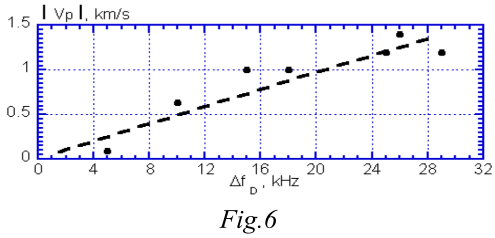

Fig.6

In the time period before the establishing of the ITB mode, the oscillation of the poloidal velocity and Doppler frequency shift has been recorded (see Fig. 5) as well as phase pulsation of the reflected UHF signal (at $\lambda = 3$ cm, $\Delta\phi < \pi$, $\Delta r \approx 1$ cm) with the frequency of ~400 Hz. The pulsation damps after the ITB has been formed (Fig. 7).

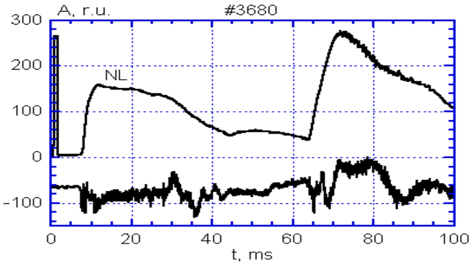

Fig.7

Fig.8

This phenomenon is observed during the reflection of the O- and X- waves provided the reflecting layer is situated in the region of the stochastic magnetic lines that form the “oscillating islands”. The effect of the poloidal rotation of a chain of magnetic island was modelled in work [8]. A similar phenomenon was observed on LHD [9].

Two regions of large rotation shear have been observed: one located at the edge $\rho \approx 0.95$; the second one located in inner region (Fig. 8).

CONCLUSIONS

Simultaneous application of the correlation and the Doppler reflectometry for study of rotation of fluctuating plasma makes it possible to broaden the information about the structure of the poloidal plasma oscillations. The correlation method has an advantage in l=3 torsatron because one is practically insensitive to the tilt angle between the incident mm-ray and reflecting surface. The poloidal wave number as well as the radial wave number increases upon the ITB formation. The pulsations of the poloidal velocity and the position of plasma layer in the region of magnetic islands were observed that became stable upon the formation of the ITB.

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ИЗМЕРЕНИЕ СКОРОСТИ ВРАЩЕНИЯ ФЛУКТУИРУЮЩЕЙ ПЛАЗМЫ С ПОМОЩЬЮ КОРРЕЛЯЦИОННОЙ И ДОПЛЕРОВСКОЙ СВЧ РЕФЛЕКТОМЕТРИИ В ТОРСАТРОНЕ УРАГАН-3М

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Проведено изучение вращения флуктуирующей плазмы методами корреляционной и Доплеровской СВЧ рефлектометрии на торсатроне Ураган-3М. Применение двух методов позволяет расширить информацию о вращении плазмы и полоидальных плазменных флуктуаций. Корреляционный метод имеет некоторые преимущества в l=3 торсатроне ввиду практической нечувствительности к углу падения мм-потока на отражающий слой. Наблюдались пульсации полоидальной скорости и положения плазменного слоя в области магнитных островов, которые стабилизировались при образовании ВТБ.

ВИМІРЮВАННЯ ШВИДКОСТІ ОБЕРТАННЯ ФЛУКТУЇРУЮЧОЇ ПЛАЗМИ ЗА ДОПОМОГОЮ КОРЕЛЯЦІЙНОЇ ТА ДОПЛЕРОВСЬКОЇ НВЧ РЕФЛЕКТОМЕТРІЇ В ТОРСАТРОНІ УРАГАН-3М

А.І. Скибенко, В.Л. Бережний, О.С. Павличенко, В.Л. Очеретенко, І.Б. Пінос, А.В. Прокопенко, І.К. Тарасов, С.А. Цибенко, Є.Д. Волков

Проведено вивчення обертання флуктуїруючої плазми методами кореляційної та Доплеровської НВЧ рефлектометрії на торсатроні Ураган-3М. Застосування двох методів дозволяє розширити інформацію про обертання плазми та полоїдальні плазмові флуктуації. Кореляційний метод має деякі переваги в $l=3$ торсатроні через його практичну нечутливість до кута падіння мм-потоку на відбиваючий шар. Спостерігались коливання полоїдальної швидкості і положення плазмового шару в області магнітних островів, які стабілізуються при створенні ВТБ.