PLASMA ROTATION DIAGNOSTICS AT THE FT-2 TOKAMAK BASED ON THE UPPER HYBRID RESONANCE BACKSCATTERING ENHANCED DOPPLER EFFECT

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Observations of enhanced Doppler frequency shift effect of the highly localized microwave backscattering in the upper hybrid resonance are reported. The experiment is performed at FT-2 tokamak, where a steerable focusing antenna set, allowing off equatorial plane plasma extraordinary wave probing from high magnetic field side, was installed. A separate line less than 1.5 MHz wide and shifted by up to 2 MHz is routinely observed in the backscattering spectrum under condition of accessible upper hybrid resonance. The enhanced frequency shift is explained by the growth of poloidal wave number of the probing wave in the resonance. Development of a new scheme for local diagnostics of fluctuations poloidal rotation based on this effect is started.

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1. INTRODUCTION

Inhomogeneous plasma rotation, according to the present day understanding, can play a substantial role in energy confinement in toroidal plasmas, suppressing drift micro turbulence and thus reducing anomalous heat and particle fluxes. The Doppler frequency shift of Back Scattering (BS) signal at oblique microwave plasma probing is often used for diagnosing of poloidal plasma velocity in magnetic fusion devices. The typical value of frequency shift of BS microwave of several hundred kHz in the "Doppler reflectometry" diagnostics based upon this effect is usually substantially smaller than its broadening, which complicates interpretation and reduce the accuracy of measurements. Recently a possibility of a drastic increase of the Doppler frequency shift of microwave BS signal in toroidal devices, based on the Upper Hybrid Resonance (UHR) BS was demonstrated experimentally [1].The microwave BS experiment was performed at FT-2 tokamak with a new steerable focusing double antennae set, allowing off equatorial plane plasma X-mode probing from high magnetic field side.

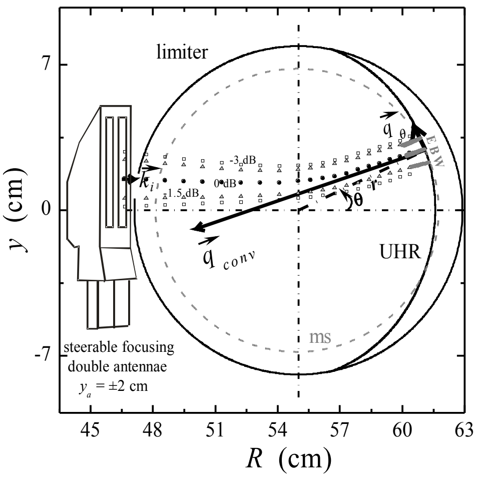

Fig.1. Poloidal FT-2 tokamak cross section with antennae set. $\vec{k}_i$ – incident wave vector, $\vec{q}_{conv}$ and $\vec{q}_\theta$ – fluctuation wave vector at BS efficiency maximum and it's poloidal projection, circles – central ray of the probing beam, triangles and squares – probing beam at 1.5 dB and 3 dB power suppression levels, ms – magnetic surface(dashed curve)

The spatial distribution of the focused probing beam, computed using the beam tracing code [2], is shown in Fig. 1. The maximal vertical displacement of antennae center is $y_a = \pm 2$ cm, whereas the diameter of the wave beam at the position of UHR, where the probing frequency satisfies condition $f_i^2 = f_{ce}^2(R) + f_{pe}^2(r)$, as computed by the code, was close to the values measured in vacuum (1.5 – 1.7 cm, depending on the probing frequency in the range 52 – 69 GHz). According to theoretical predictions [1, 3] and beam tracing

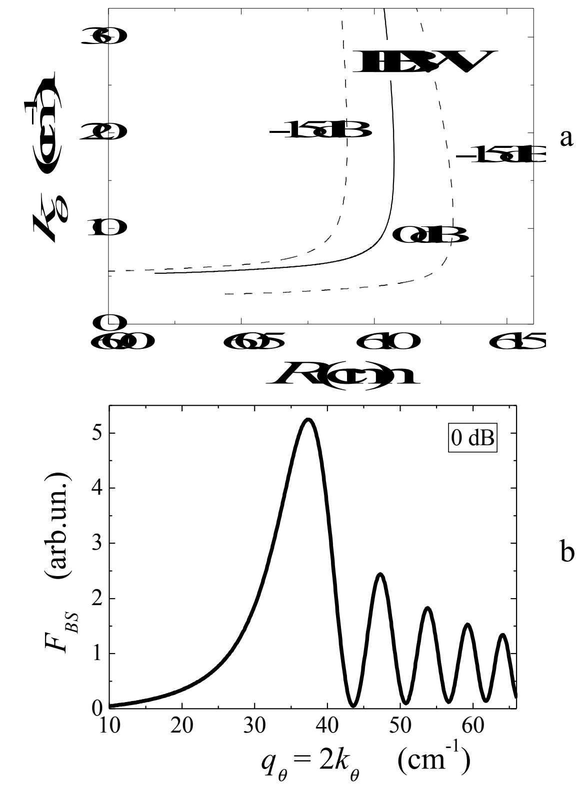

Fig.2. (a) Poloidal probing wave number near UHR, (b) BS efficiency for central probing ray

computation shown in Fig. 2a, the probing poloidal wave number grows rapidly in the vicinity of the UHR linear conversion point, where the BS cross section $F_{BS}(q_\theta)$ possesses sharp maximum, as demonstrated in Fig. 2b. This projection, which can be much larger than the poloidal component of wave vector at the antenna, can lead to substantial enhancement of the Doppler frequency shift of the microwave BS by fluctuations moving with poloidal plasma flow. The frequency shift corresponding to fluctuation radial wave number q is given by

$$f_D = 2\left[k_{\theta 0} + \frac{q}{2}\,\frac{\vec{e}_\theta \vec{e}_R f_{ce}^2}{R\left|\nabla(f_{pe}^2 + f_{ce}^2)\right|}\Bigg|_{UHR}\right] V_\theta \, , \qquad (1)$$

where V_θ is the fluctuation poloidal velocity; $k_{\theta 0}$ gives the probing extraordinary mode poloidal wave number out of the UHR zone, $\vec{e}_\theta$ and $\vec{e}_R$ are unit vectors in poloidal and major radius directions; R gives the major radius in the UHR. In agreement with theoretical predictions a separate line less than 1.5 MHz wide and shifted by up to 2 MHz, was reliably observable in the BS spectrum under condition of accessible UHR [1].

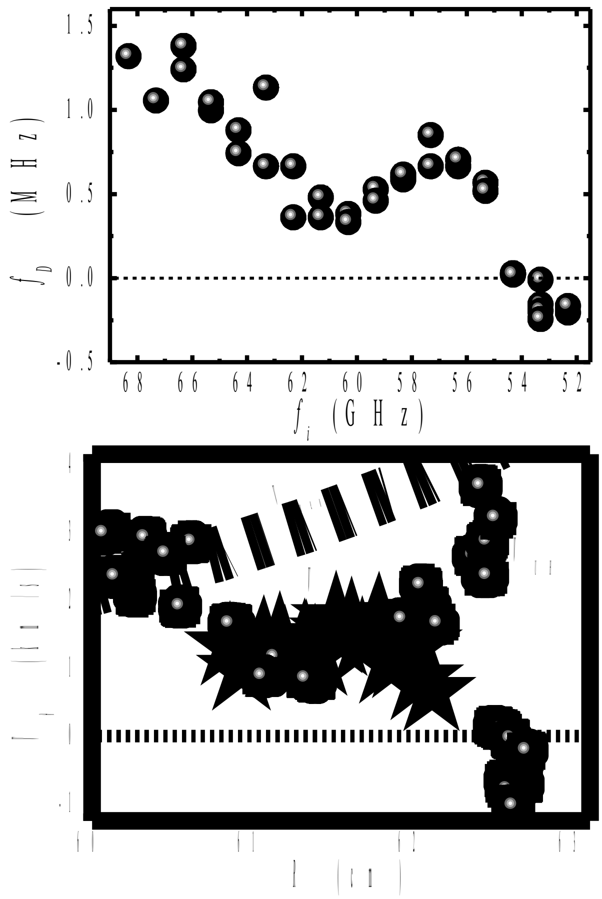

*Fig.3. (a) Doppler frequency shift versus incident frequency (y_a = +15 mm).**(b)** Poloidal velocity profiles for I_p = 35 kA. Circles – UHR BS, stars – O-mode Doppler reflectometry, dashed curve - neoclassical dependens*

2. ROTATION IN OHMIC REGIME

In this paper, the recently observed giant Doppler frequency shift effect of the highly localized microwave BS in the Upper Hybrid Resonance (UHR) [1] is applied to FT-2 tokamak plasma rotation diagnostics in ohmic and LH heating regimes. The obtained profiles of plasma poloidal velocity are benchmarked against the Doppler reflectometry data. The experiment is performed at research FT-2 tokamak (R = 55 cm, $a \approx$ 8 cm, $B_T \approx$ (1.7 ÷ 2.2) T, $I_p \approx$ (19 ÷ 37) kA, $n_e(0) \approx (0.5 \div 5)\times10^{19}$ m^{-3}, $T_e(0) \approx$ 500 eV), where the RF power up to 120 kW at frequency 918 MHz is launched into the plasma by a two-waveguide grill.

Very different poloidal rotation profiles are measured in ohmic discharges for plasma current values of 19 kA and 35 kA. The dependence of BS frequency shift on the probing frequency in the high current case is shown in Fig. 3a. The important feature of this dependence is complicated behavior resulting in minimum at f_i = 60.3 GHz and very steep variation at f_i = 57.3 GHz. The corresponding poloidal rotation profile, determined using (1) under supposition that the BS spectrum maximum corresponds to the maximum of BS efficiency, situated at $q_{conv} \equiv 2\left(2\pi f_i / c\right)\sqrt{c/V_{Te}}$, is given in Fig. 3b by circles. As it is seen, the poloidal plasma velocity increases towards LCFS, where it possesses discontinuity in agreement with expectations of neoclassical theory (the corresponding estimation is shown in Fig. 3b by dashed curve). The corresponding velocity values determined using the UHR BS technique fit well those obtained by the O-mode Doppler reflectometry, which are shown by stars in Fig. 3b. Out of the LCFS the rotation velocity changes sign, which indicate the dominant role of electron losses to the limiter along the magnetic field lines.

In the lower current regime no poloidal rotation discontinuity at the LCFS was observed. As it is shown in Fig. 4, at current less than 30 kA the rotation velocity decreases continuously towards the LCFS, where it changes sign, which is not consistent with the neoclassical

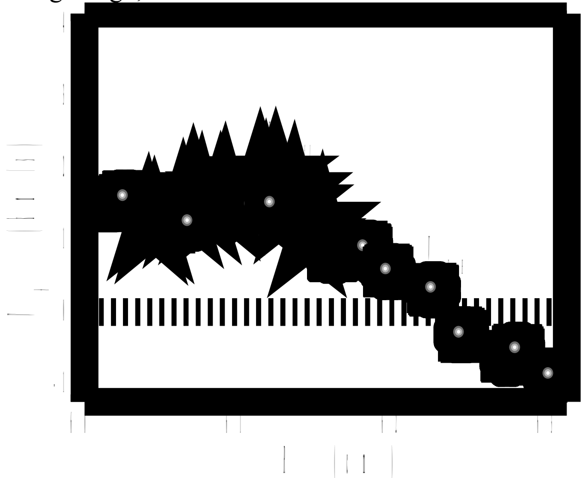

Fig.4. Poloidal velocity profiles for I_p < 30 kA circles – UHR BS, stars – O-mode Doppler reflectometry

theory expectations and indicates important role of anomalous electron losses mechanism in formation of plasma potential in this region. It should be stressed that in this regime as well the poloidal rotation velocity obtained by Doppler reflectometry and UHR BS diagnostics are in nice agreement. It should be underlined that in spite of the fact both microwave BS techniques provide information on fluctuation rotation, the wave length of those fluctuations differs by two orders of magnitude. It is very unlikely that the phase velocities for such a different fluctuations coincide, which gives an argument in favor of plasma rotation origin of the frequency shift measured by both diagnostics. It is important to note that the calculated electron diamagnetic drift velocity all over the measurement region exceeds the experimental values of poloidal rotation velocity by a factor of 3 – 5. This result provides additional confirmation to our assumption that the Doppler frequency shift is rather associated with the plasma flow than with fluctuation phase velocity, which is quite natural because the fluctuations producing BS in the UHR possess radial wave number much higher than the poloidal one and thus are not similar to the drift wave eigen-modes.

3. PLASMA ROTATION SUPPRESSION AT LH HEATING

In the present paper a specific regime of LH heating at densities $2\cdot10^{13} < n_e(0) < 3\cdot10^{13}$ cm^{-3} , at which the LHCD and electron heating terminates and wave – ion interaction and ion heating starts, was investigated. The wave forms of the discharge are shown in Fig.5. As it

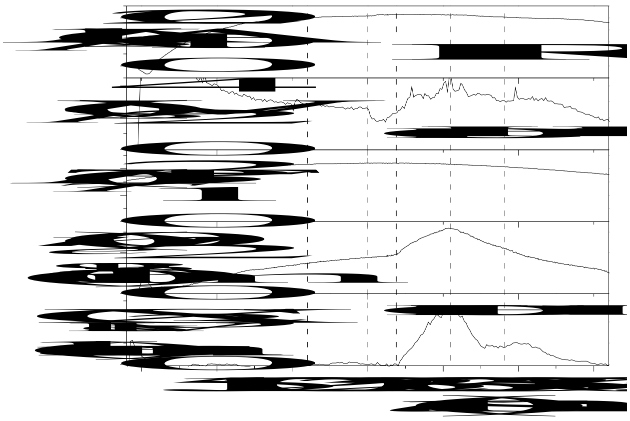

Fig.5. Discharge wave forms

is seen there, just at the onset of RF pulse at *t=30 ms* an evident decrease is observable in the loop voltage signal indicating the LHCD effect. This effect is accompanied by the plasma density growth, leading to the LHCD termination at *t=31 ms*. Soon after that, at *t=32 ms,* the steep increase of fast ion population at energy in 1 keV range is observed in the discharge by the charge exchange diagnostic, indicating transition to the LH Ion Heating (LHIH) regime. Under these conditions excitation of small scale component of plasma turbulence was observed at FT-2 tokamak by CO_2 and UHR scattering diagnostics [4, 5]. Here we study the reasons and consequences of this effect.

The temporal evolution of the UHR BS spectrum at probing frequency f_i=62 GHz during the RF pulse is shown in Fig.6. As it seen at *30 ms <t<31 ms*, the BS spectrum remains similar to that observed in ohmic heating. The fast reduction of the Doppler frequency shift and the spectrum narrowing starts simultaneously with the fast neutral flux growth. This evolution of the BS spectrum is accompanied by steep increase of its amplitude. The relaxation of the BS spectrum to that, observed in the ohmic discharge, starts just after the RF power switch off. The poloidal velocity profiles, determined from the Doppler frequency shift of the UHR BS spectra are shown in Fig.7 for three typical moments.

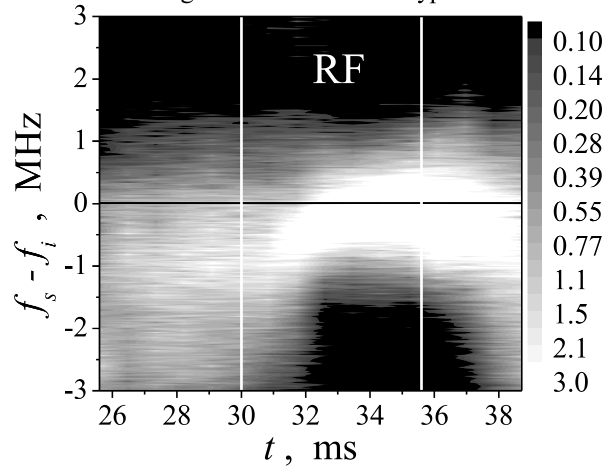

Fig.6. UHR BS spectrum evolution (62 GHz)

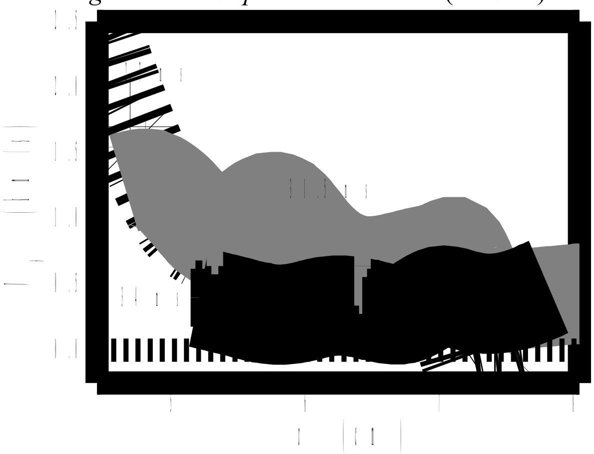

Fig.7. Fluctuation poloidal velocity profiles (UHR BS)

Before the RF pulse the velocity profile is typical for measured by this technique in the low current regime. The velocity monotonically decreases when approaching the plasma edge and change sign in the vicinity of LCFS (dashed curve in Fig.7). At the LHCD phase the velocity increases slightly, however its shear remains unchanged during the first millisecond after RF power onset (light curve in Fig.7). The dramatic variation of the velocity profile is observed only after transition to the LHIH regime at *t> 32 ms*. As the result, at *t= 34 ms* poloidal velocity is substantially reduced and its profile in the edge region become flat (solid curve in Fig.7). In *2 ms* after RF power switch off the rotation profile relaxes to the initial state. It is important to note that the flattening of the rotation profile and related decrease of the poloidal velocity shear results in strong growth of the BS signal, proportional to the level of small scale density fluctuations, as it is shown by dependences of BS signal on the UHR position, plotted by filled and empty points in Fig.8 for the LHCD and LH ion heating phase of RF pulse correspondingly. Similar observations were made also by the Doppler reflectometry technique. Suppression of poloidal rotation was measured by this diagnostic during the RF pulse, which resulted in decrease of the velocity shear at the plasma edge, by the end of the RF pulse.

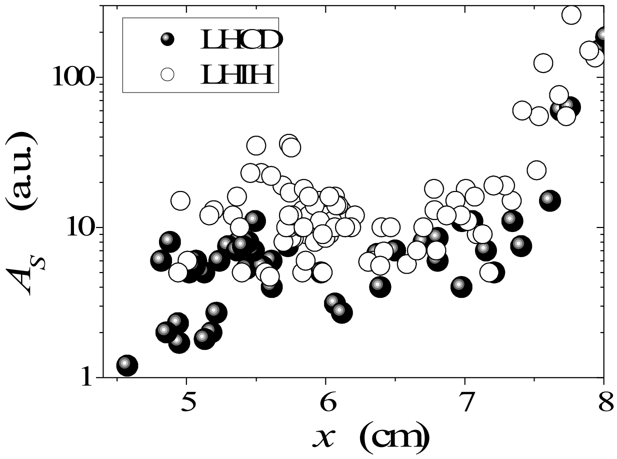

Fig.8. UHR BS spectrum amplitude profile

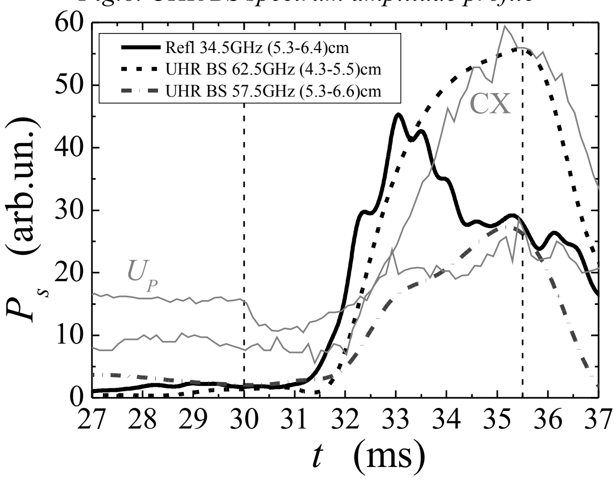

Fig.9. Scattered power evolution

It should be mentioned that the velocity value, as well as the profile form, measured by this two microwave diagnostics do not coincide, which is probably explained by contribution of wave numbers smaller than those corresponding to the BS cross section maximum. The level of the Doppler reflectometry signal at the plasma edge also experienced substantial growth at the transition from the LHCD regime to the LHIH, as it is shown in Fig.9 for Doppler reflectometry probing frequency 34.5 GHz. This growth is only partly associated with the outer shift of the cut off layer and indicates the growth of long scale component of tokamak micro turbulence. The dependence of the UHR BS signal at probing frequency 62.5 GHz (dash) and 57.5 GHz (dash dot) is shown in Fig.9 for comparison. The drastic increase of the turbulence level initiated by the rotation shear suppression is accompanied by substantial cooling of the electron component at the plasma periphery, which occurs at the background of growing density (see Fig.10).

The typical feature of the plasma rotation at the very edge (out of the LCFS), observed by the UHR BS technique at RF power onset was quick change of velocity direction. This effect, well pronounced in all regimes of interaction and at different grill antenna phasing is illustrated by Fig.11 in which the temporal variation of the BS spectrum is shown. The possible explanation robust effect taking place in the vicinity of the LH grill, which is situated in the UHR BS diagnostics poloidal cross section, is based on the improvement of electron confinement along magnetic field due to their trapping in ponderomotive potential

$$\Phi_{RF} = \frac{f_{pe}^2}{f_{RF}^2}\frac{\tilde{E}_z^2}{16\pi}$$

produced by two LH wave resonance cones, shown in Fig.12. ($\tilde{E}_z$ here is the toroidal component of RF field).

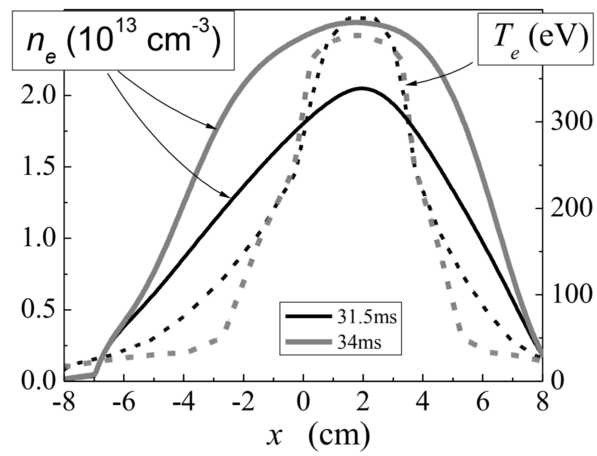

Fig.10. Electron density and temperature profiles

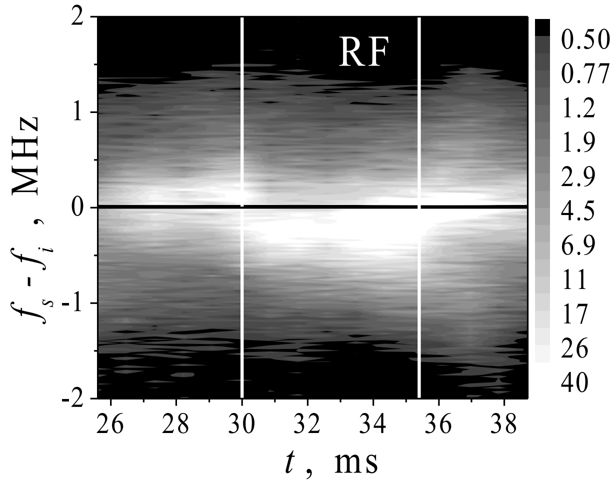

Fig.11. UHR BS spectrum evolution (53 GHz)

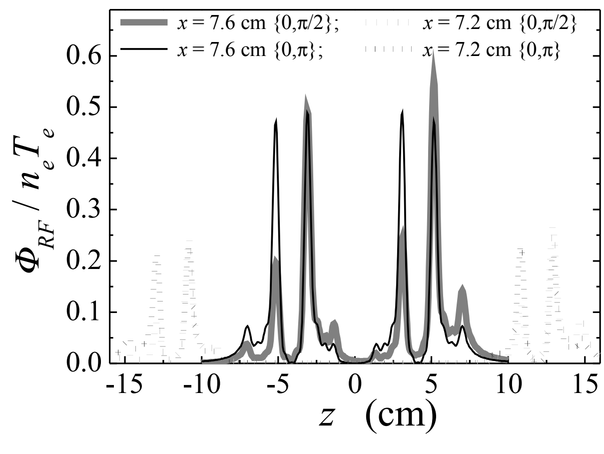

Fig.12. The ponderomotive potential in the LH grill vicinity

4. CONCLUSIONS

Based upon the robust Enhanced Doppler effect observed in the off equatorial plane microwave UHR BS experiment at FT-2 tokamak a new scheme for precise diagnostics of plasma fluctuations poloidal rotation in tokamaks and stellarators possessing high spatial and temporal resolution has been developed. The new diagnostic is successfully benchmarked against the Doppler reflectometry technique data and than applied to study of plasma rotation and turbulence behavior in ohmic and RF heated plasma. Two types of poloidal rotation profiles are observed at FT-2 tokamak in ohmic regime at plasma currents 20 kA and 35 kA. Suppression of fluctuation poloidal rotation and growth of their amplitude is observed at transition from LHCD to ion heating.

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REFERENCES

1. A.B. Altukhov, A.D. Gurchenko, E.Z. Gusakov et al. Observation of Enhanced Doppler Effect in the Upper Hybrid Resonance Backscattering Experiment at the FT-2 Tokamak//*Proc. Of the 30-th EPS Conf. on Control. Fusion and Plasma Phys., St.Petersburg, 7-11 July, 2003/* ECA 27A, 2003, P-4.170pd.

2. A.N. Saveliev, A.D. Piliya. The Method of Virtual Beams for Microwave Radiation in Toroidal Plasmas//*Proc.of the 30-th EPS Conf. on Control. Fusion and Plasma Phys., St.Petersburg, 7-11 July, 2003/* ECA 27A, 2003, P-2.20.

3. D.G. Bulyiginskiy, A.D.Gurchenko, E.Z.Gusakov et al. RADAR upper hybrid resonance scattering diagnostics of small-scale fluctuations and waves in tokamak plasmas// *Phys. Plasmas (8)*. 2001, p.2224.

4. V.N. Budnikov et al. Microturbulence behaviour study during LH heating in FT-2 tokamak by CO_2-laserscattering//*Proc.of the 23-th EPS Conf. on Controll. Fusion and Plasma Phys., Kiev, 24-28 June,1996/* ECA 20C, 1996, P.855.

5. V.N. Budnikov et al. Study of Plasma Turbulence by Microwave Backscattering Technique in Lower-Hybrid Heating Experiments on the FT-2 Tokamak// *Plasma Phys. Rep. (24)*. 1998, p. 233.

ДИАГНОСТИКА ВРАЩЕНИЯ ПЛАЗМЫ НА ТОКАМАКЕ ФТ-2 НА ОСНОВЕ УСИЛЕННОГО ЭФФЕКТА ДОПЛЕРА ПРИ РАССЕЯНИИ НАЗАД В ВЕРХНЕМ ГИБРИДНОМ РЕЗОНАНСЕ

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В статье описываются наблюдения усиленного эффекта Доплера в спектре сигнала рассеянного назад в верхнем гибридном резонансе зондирующей волны. Эксперимент выполнен на токамаке ФТ-2, на котором недавно были установлены подвижные антенны, позволяющие осуществлять зондирование плазмы электромагнитными волнами в необыкновенной поляризации со стороны сильного магнитного поля. При условии доступного верхнего гибридного резонанса в спектре рассеяния наблюдалась линия шириной менее 1.5 МГц, сдвинутая до 2 МГц. Эффект объяснён ростом полоидального волнового числа зондирующей волны в резонансе. Начато развитие новой схемы локальной диагностики вращения плазменных флуктуаций, основанной на этом эффекте.

ДІАГНОСТИКА ОБЕРТАННЯ ПЛАЗМИ НА ТОКАМАЦІ ФТ-2 НА ОСНОВІ ПОСИЛЕНОГО ЕФЕКТУ ДОПЛЕРА ПРИ РОЗСІЮВАННІ НАЗАД У ВЕРХНЬОМУ ГІБРИДНОМУ РЕЗОНАНСІ

А.Б. Алтухов, В.В. Буланін, В.В. Дьяченко, Л.А. Єсипов, М.В. Горохов, А.Д. Гурченко, Є.З. Гусаков, М.А. Іржак, М.Ю. Кантор, Д.В. Купрієнко, С.І. Лашкул, О.В. Петров, А.Н. Савєльев, А.Ю. Степанов, С.В. Шаталін, Є.О. Векшина

У статті описуються спостереження посиленого ефекту Доплера в спектрі сигналу розсіяного назад у верхньому гібридному резонансі зондувальної хвилі. Експеримент виконаний на токамаці ФТ-2, на якому недавно були встановлені рухливі антени, що дозволяють здійснювати зондування плазми електромагнітними хвилями в незвичайній поляризації з боку сильного магнітного поля. За умови доступного верхнього гібридного резонансу в спектрі розсіювання спостерігалася лінія шириною менш 1.5 МГц, зрушена до 2 МГц. Ефект пояснений ростом полоідального хвильового числа зондувальної хвилі в резонансі. Почато розвиток нової схеми локальної діагностики обертання плазмових флуктуацій, заснованої на цьому ефекті.