MODELLING OF PLASMA MOTION RESPONSE INDUCED BY AN EXTERNAL ROTATING HELICAL PERTURBATION IN THE HYBTOK-II TOKAMAK

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In addition to the analysis of magnetic perturbation amplitudes [2] a detailed investigation of the plasma motion affected by this external helical magnetic perturbation is carried out near the HYBTOK-II main resonance surface.
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1. INTRODUCTION

Direct observations of tokamak plasma responses to an externally applied rotating helical magnetic perturbation have been performed on a small tokamak HYBTOK-II (R=0.4m, a=0.11m) in order to clarify the process of penetration of this external magnetic perturbation into tokamak plasmas [1]. The radial profiles of the radial and poloidal magnetic components of the penetrating external field were measured using a small magnetic probe inserted into the plasma. A comparison of the theoretical treatment [2] with these HYBTOK-II experiments shows a good qualitative agreement. In the present paper a more detailed theoretical study of the HYBTOK-II experiments is made.

2. MODEL

A model of a current carrying cylindrical plasma, whose axis is taken as the *z* direction, is used. The external axial magnetic field B_{z0} is large in comparison with the poloidal magnetic field $B_{\theta 0}$ produced by the axial current. The perturbation values depend on the azimuthal angle θ , the coordinate *z* ($k=n/R$) and the time *t* as $\exp\left[i\left(m\theta-kz-\omega t\right)\right]$, *m* and *n* are poloidal and toroidal numbers, respectively, R plays the role of the tokamak major radius, ω is the frequency of the external perturbation. The investigation is based on the equations for perturbations of radial components of plasma velocity $V_r^{\sim}$ and magnetic field $B_r^{\sim}$ (see [2])

$$\frac{d}{dr} r\,\omega' \,\rho \frac{d}{dr}\left(rV_r^{\sim}\right)-\left(\omega' m^2\rho+i\frac{r^2}{\delta^2}\frac{F^2(r)}{\mu_0\omega}\right)V_r^{\sim} = \left(i\frac{r^2}{\delta^2}\frac{\omega'}{\omega}F(r)+r^2\frac{d^2F}{dr^2}+3r\frac{dF}{dr}\right)\frac{B_r^{\sim}}{\mu_0}, \quad (1)$$

$$\frac{d}{dr} r \frac{d}{dr}\left(rB_r^{\sim}\right)-\left(m^2-i\frac{r^2}{\delta^2}\frac{\omega'}{\omega}\right)B_r^{\sim}=-i\frac{r^2}{\delta^2}\frac{F(r)\,V_r^{\sim}}{\omega}, \quad (2)$$

where

$$\omega'=\omega+(m/r)\left(E_{r0}/B_{z0}\right)+kV_{z0}\,,\qquad \delta=1/\sqrt{\mu_0\sigma_{||}\omega}\,, \quad (3)$$

$$F(r)=k\cdot B_0=\frac{m}{r}B_{\theta 0}-kB_{z0}\,. \quad (4)$$

In Eqs. (1), (2) the terms $kV_z^{\sim}$ and $kB_z^{\sim}$ ($kr<m$) are neglected, ρ is the plasma mass density and $\sigma_{||}$ is the parallel conductivity. We included the poloidal plasma rotation connected with an equilibrium radial electric field E_{r0} and the toroidal plasma rotation with a homogeneous velocity V_{z0} . We assume that the equilibrium quantities are slowly varying. Recall that the ion gyroviscosity tensor π_i compensates the drift diamagnetic effect (see, e.g., [3,4]).

In this paper only the main HYBTOK-II resonant mode (*m/n*=6/1) is investigated, when the value of $F(r)$ is equal to zero, $F\left(r_{res}\right)=0$, on the main resonance surface $r_{res}=8.5\ cm$, where $q\left(r_{res}\right)=6/1$ ($q(r)=rB_{z0}/RB_{\theta 0}$).

The typical HYBTOK-II parameters are used: the toroidal magnetic field B_{z0} = 0.27 T, the plasma current I_p = 5 kA, the edge electron density $n_e=1.5\times10^{18}\,m^{-3}$ and the electron temperature T_e = 25 eV.

3. RESULTS AND DISCUSSION

Recall [2] that for the considered HYBTOK-II experiments the resistive effects dominate in a broader region than that defined by the Alfven resonances.

In Eqs. (1), (2) we neglect the ion diamagnetic drift. As a result, Eqs. (1), (2) contain only the Doppler shifted frequency ω' as a key parameter. In Figs. 1-3 the results of calculations for three Doppler shifted frequencies f' = 10, 30 and 40 kHz are presented. For *f*=30 kHz we take the skin depth value δ =1 cm. Note, that results of the calculations depend on the local values of Z_{eff}

In Figs.1a,d, 2a,d, 3a,d the radial profiles of $B_{r,\theta}^{\sim}$ amplitudes and their phases $\psi_{B_{r,\theta}}$ are shown. These results are in a good qualitative agreement with HYBTOK-II experimental measurements ([1], Case I). The gap in the profile of $\left|B_\theta^{\sim}\right|$ is clearly visible near $r\approx r_{res}$. The minimum value of this gap is shifted to the plasma depth from the surface $r=r_{res}$. Some attenuation of $\left|B_r^{\sim}\right|$

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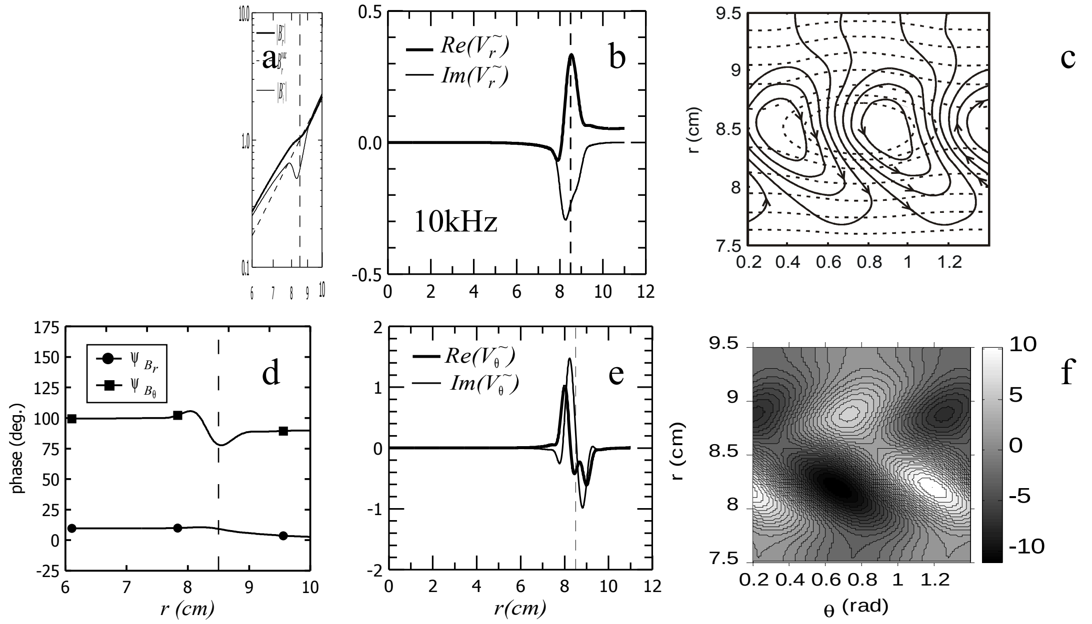

Fig.1. The resonant zone size, ┌ 1 cm, is approximately two times magnetic island width. Two vortexes are observed per one poloidal period of the magnetic perturbation

and amplification of $|\tilde{B_\theta}|$ for $r > r_{res}$ may be explained by not only sideband modes occurring, but also by the non-resonant $\tilde{J_z}$ excitation.

Figs. 1b,e, 2b,e, 3b,e show the radial profiles of the velocities $\tilde{V}_{r,\theta}$. Because $|\tilde{B_r}|$ grows towards the antenna, $|\tilde{V_r}|$ has a finite value at the plasma edge.

In Figures 2b, 3b $|\tilde{V_r}|$ ~0.4 km/s at r>10 cm.

In Figures 1e, 2e, 3e the maximum values of $|\tilde{V_\theta}|$ are max $|\tilde{V_\theta}|$ ~2-3 km/s. The value of $|\tilde{V_\theta}|$ grows, when f' drops. For example, max $|\tilde{V_\theta}|$ ~10 km/s for f' =1 kHz.

Figs. 1c, 2c, 3c show the magnetic island *m/n*=6/1 position and contour plots of the plasma fluxes (the arrows show the direction of motion) in the poloidal cross-section ($\Delta\theta = \pi/3$) near the main resonance surface $r_{res} = 8.5\ cm$ for a certain moment of time. In time this picture rotates as a unit. The calculated width of the magnetic island is approximately 0.5 cm. When the Doppler shifted frequency ω' increases, the resonant zone (resistive layer) size increases with respect to the magnetic island width. The plasma vortexes occur. The plasma moves across the resonant surface inwards (outwards) of the discharge near O-point (X-point) of the magnetic islands (compare with [5]). The last statement is not concerned with the plasma inside four vortexes. Sideband modes of *m/n*=5/1 and *m/n*=7/1 are resonant at $r_{res} = 7\ cm$ and $r_{res} = 9.5\ cm$, respectively. For the wide resonant zone in a toroidal plasma a strong coupling between *m* and $m \pm 1$ modes through the plasma

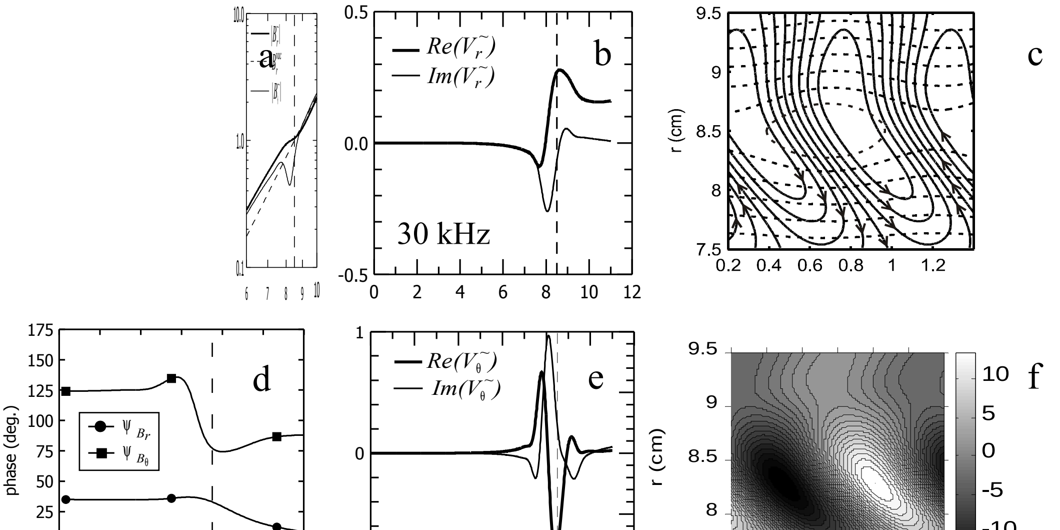

Fig.2. The resonant zone size, ┌ 2 cm, is approximately four times magnetic island width. Two vortexes are still observed per one poloidal period of the magnetic perturbation

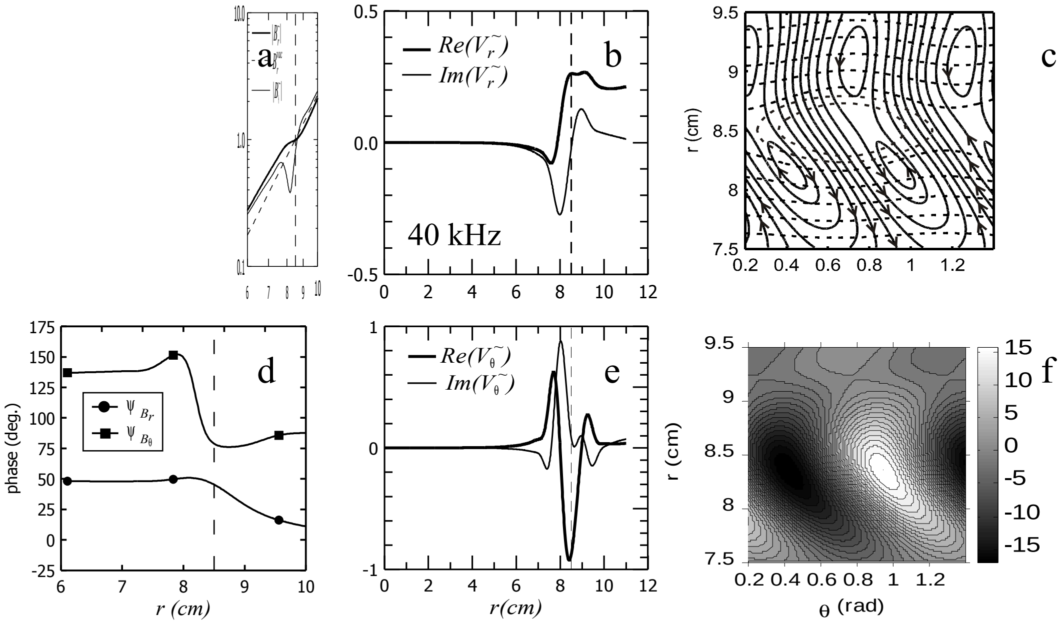

Fig.3. The resonant zone size, ┌ 3 cm, is approximately six times magnetic island width. Formation of four vortexes is observed per one poloidal period of the magnetic perturbation. Note, four vortexes per one period were also observed during the stability analysis of the resistive tearing eigenmodes (see, e.g. [8])

motion is possible (see, e.g.,[6]). The effect on the poloidal rotation profile of an external rotating helical magnetic perturbation was observed near resonant surfaces in the HYBTOK-II experiment [7], but more detailed experiments are needed.

In Figs.1f, 2f, 3f the 2-D profiles of the perturbed current density $J_z^{\sim}$ are presented. Here $J_z^{\sim}$ ~10-15 kA/m^2.

In the figures the values of $B_{r,\theta}^{\sim}$, $V_{r,\theta}^{\sim}$ and $J_z^{\sim}$ are normalized to the values $B_r^{vac}(r_{res})$, $V_{rA}=B_r^{vac}/\sqrt{\mu_0\rho}\,|_{r=r_{res}}$ and $B_r^{vac}(r_{res})/\mu_0 r_{res}$, respectively.

In Figs.1-3 the situation f' >0 is presented. For f' <0 (Eq.(3)) the same radial profiles of $|B_{r,\theta}^{\sim}|$ are observed, the values of *Re* $V_r^{\sim}$ and *Im* $V_\theta^{\sim}$ change the sign, and the phases $\psi_{B_{r,\theta}}$ decrease now towards the plasma depth.

4. CONCLUSIONS

The present calculations reproduce not only the radial profiles of amplitudes [2] but also the phase radial profiles of externally induced magnetic perturbations in the HYBTOK-II experiments.

The plasma vortexes with opposite direction of rotation are found per one poloidal period of the external perturbation ($\Delta\theta=\pi/3$). The cases with two vortexes and the formation of four vortexes per one poloidal period are considered.

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МОДЕЛИРОВАНИЕ ОТКЛИКА ПЛАЗМЫ, ИНДУЦИРОВАННОГО ВНЕШНИМ ВИНТОВЫМ ВОЗМУЩЕНИЕМ В ТОКАМАКЕ HYBTOK-II

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Дополнительно к анализу амплитуд магнитных возмущений [2] выполнено детальное исследование движений плазмы под воздействием этого внешнего винтового магнитного возмущения вблизи главной резонансной поверхности в HYBTOK-II.

МОДЕЛЮВАННЯ ВІДГУКУ ПЛАЗМИ, ІНДУКОВАНОГО ЗОВНІШНІМ ОБЕРТОВИМ ГВИНТОВИМ ЗБУРЕННЯМ У ТОКАМАЦІ HYBTOK-II

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Додатково до аналізу амплітуд магнітних збурень [2] виконано детальне дослідження руху плазми, що викликано цим зовнішнім гвинтовим магнітним збуренням поблизу головної резонансної поверхні в HYBTOK-II.