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Interpretation of the Observed Radial Electric Field Inversion in TUMAN-3M Tokamak during MHD-activity

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1. Introduction.

During the onset of MHD activity a change of the edge radial electric field from negative (directed inward) to positive (directed outward) values has been observed in Ohmic discharges on TUMAN-3M tokamak [1]-[3]. According to HIBP diagnostic [3] the potential in the central region of TUMAN-3M also changed sign and became positive during MHD events while normally it is negative. There is experimental evidence [1]-[2] that the MHD activity is associated with the rise of a magnetic island at the q=3 flux surface in the core, a few centimeters inside from the last close flux surface (LCFS) and with rise of smaller islands at q=4 and q=2 surfaces. Simultaneously a stochastic layer can be formed in the LCFS vicinity. Below the model for the origin of a positive radial electric field during the rise of MHD activity is put forward. It is based on the assumption of the existence of a strong electron radial flux associated with the formation of an ergodic layer. The radial electron flux requires the same radial flux of ions to provide quasineutrality. To create the positive radial ion current the radial electric field should become more positive.

The radial ion current generates a toroidal rotation in the co-current direction due to the toroidal $\vec{j}\times\vec{B}$ torque. The co-current toroidal rotation should be transported outside the ergodic layer to the core by the turbulent viscosity thus creating the co-current toroidal rotation in the center of the tokamak. The co-current toroidal rotation makes the radial electric field more positive also outside the ergodic layer.

2. Model

We assume that in the vicinity of the LCFS exists a stochastic layer with the width L of the order of few centimeters and with the diffusion coefficient of the magnetic field lines D_{st}. The radial current of electrons in the stochastic magnetic field [4] is:

$$j_r^e = \sigma_{St}\left(E_r + \frac{T_e}{e}\frac{d\ln n}{dr} + \alpha\frac{T_e}{e}\frac{d\ln T_e}{dr}\right), \qquad (1)$$

The stochastic electron conductivity is in the collisional case $\sigma_{St} = \sigma_{\|} D_{st} / \widetilde{L}_k$, where $\sigma_{\|}$ is the Spitzer parallel conductivity and $\widetilde{L}_k$ is of the order of the Kolmogorov length [4] $\widetilde{L}_k \sim qR$;

the coefficient $\alpha = 1.71$. In the collisionless limit ($\lambda_e / \tilde{L}_k >> 1$, where λ_e is the electron mean free path) $\sigma_{St} = i_\sigma n e^2 D_{st} \sqrt{2} / \sqrt{\pi m_e T_e}$ where $i_\sigma \sim 1$; $\alpha = 0.5$.

The current of ions is determined by neoclassical effects [5]. The simplified expression has the form (we assume circular flux surfaces and averaged quantities)

$$j_r^i = \sigma_{NEO} (E_r - E_r^{NEO}) , \tag{2}$$

where the neoclassical radial electric field is

$$E^{NEO} = \frac{T_i}{e} \left(\frac{d \ln n}{dr} + k_T \frac{d \ln T_i}{dr} \right) + B_p U_T . \tag{3}$$

The positive sign of the toroidal velocity U_T corresponds to the co-current direction, B_p is the poloidal magnetic field, and $k_T \sim 1$ is a numerical coefficient, which depends on collisionality. The neoclassical conductivity $\sigma_{NEO} = \frac{3 \mu_{i1}}{2 R^2 B^2}$, μ_{i1} is introduced in [6].

Inside the stochastic layer the radial electric field is determined by the condition $j_r^e = -j_r^i$. For large magnetic field perturbations $\sigma_{St} >> \sigma_{NEO}$ the electric field is positive:

$$E_r^{St} = -\frac{T_e}{e} \left(\frac{d \ln n}{dr} + \alpha \frac{d \ln T_e}{dr} \right) . \tag{4}$$

The toroidal rotation is calculated from the balance of the toroidal component of the $\vec{j}^i \times \vec{B}$ torque and the radial transport of toroidal rotation due to turbulent viscosity:

$$j_r^i B_p = -\frac{d}{dr} \left(\eta \frac{dU_T}{dr} \right) . \tag{5}$$

The viscosity coefficient can be estimated as $\eta = n m_i D$ with D being the turbulent diffusion coefficient. Substituting Eq. (2) into Eq. (5) one obtains the equation for the toroidal rotation

$$\sigma_{NEO} (E_r^{St} - E_r^{NEO}) B_p = -\frac{d}{dr} \left(\eta \frac{dU_T}{dr} \right) . \tag{6}$$

The toroidal rotation enters the l.h.s. of this equation through E_r^{NEO}, Eq. (3). The toroidal rotation velocity depends on the parameter [5] $\kappa = \frac{3 B_p^2}{2 B^2} \frac{\mu_{i1}}{n m_i D} \frac{L^2}{R^2}$. In case $\kappa > 1$ the term in the r.h.s. can be neglected and the toroidal velocity in the stochastic layer is

$$U_T = U_T^{St} = -\frac{T_e + T_i}{B_p e} \frac{d \ln n}{dr} - \alpha \frac{T_e}{B_p e} \frac{d \ln T_e}{dr} - k_T \frac{T_i}{B_p e} \frac{d \ln T_i}{dr} . \tag{7}$$

The suggested model is similar to approach developed for TEXTOR [7].

Outside the stochastic layer in the absence of momentum sources the toroidal rotation is determined by the equation $-\frac{d}{dr}(\eta \frac{dU_T}{dr}) = 0$ with the boundary condition $U_T |_{r=r_{St}} = U_T^{St}$ and zero radial flux of toroidal momentum $-\eta \frac{dU_T}{dr}|_{r=r_{St}} = 0$. The central toroidal rotation in the core in the steady state should reach the value of the rotation at the inner side of the stochastic layer $U_T(r \le r_{St}) = U_T^{St}$. The radial electric field in the core is given by the neoclassical expression Eq. (3). It can become positive if U_T is sufficiently big.

3. Comparison with the experiment

The typical parameters are [1]-[3]: R=53cm, a=22cm, I_p=100-130kA, B=0.7T, $\mathrm{n}|_{\mathrm{r=18cm}} = (0.5 \pm 0.3)\cdot 10^{19} m^{-3}$, $\mathrm{T_e}|_{\mathrm{r=18cm}} = 80 \pm 40 eV$, $\mathrm{T_i}|_{\mathrm{r=18cm}} = 20 \pm 10 eV$. Magnetic islands appear around $r \approx 18cm$ with the width 2-3cm. Radial scale lengths L_n, L_T are $7 \pm 3\,cm$, $D = 2 \pm 1\, m^2/s$. Doppler reflectometry measurements in Ohmic H-mode [1] show that the poloidal rotation during the onset of MHD activity changes from the electron to ion diamagnetic drift direction. The poloidal velocity at r = 18-20 cm during the MHD activity is of the order of $-500 \pm 200\, m/s$ and corresponds to a positive radial electric field $+0.35 \pm 0.14\, kV/m$, while before and after the MHD burst it is of the order of $+1000 \pm 250\, m/s$, and corresponds to a negative electric field $-0.7 \pm 0.18\ kV/m$.

Double Langmuir probe measurements [1]-[2] show that both for L- and H-mode the radial electric field at r = 19-20 cm changes sign from negative to positive whilst the MHD is present. In L-mode the radial electric field changes from $-2 \pm 1.5\, kV/m$ to $+4 \pm 1\ kV/m$, and in H-mode the radial electric field achieves the value $+6 \pm 1\ kV/m$ during the MHD activity. The HIBP method [3] shows that the MHD activity in L-mode is accompanied by a positive shift of the plasma potential in the central region of the order of $600 \pm 50\, V$.

The distance between the 3/1 and 4/1 islands at the plasma periphery is less than the distance between the 3/1 island and LCFS, which is about 4 cm. At the same time the 3/1 island width is about 2-3 cm, so the Chirikov's criteria of ergodization is fulfilled. The periphery plasma is in the collisionless regime $\lambda_e / \tilde{L}_k \approx 20$. The magnetic diffusion coefficient D_{st} is estimated using quasilinear approximation [8] $D_{st} = 2\pi r B / B_\theta (B_{st}/B)^2$. A radial stochastic component of the magnetic field B_{st} is estimated through the island width: $B_{st}/B \approx 3\cdot 10^{-4}$, therefore $D_{st} = 10^{-6} m$. The conductivity is $\sigma_{St} = 3\cdot 10^{-2}\ m^{-1}\cdot Ohm^{-1}$. The neoclassical conductivity $\sigma_{NEO} = 10^{-2}\ m^{-1} \cdot Ohm^{-1}$ is smaller than σ_{St}, therefore the electric field in the stochastic layer should be positive, Eq. (4). The estimate is

$$E_r^{St} \approx \frac{T_e}{eL_n} + 0.5\frac{T_e}{eL_T} = \frac{80eV}{7cm} + 0.5 \cdot \frac{80eV}{7cm} = 1.7\ kV/m\,, \qquad (8)$$

which agrees with the probe measurements. The small values of the electric field obtained with the Doppler reflectometry method can be associated with the influence of phase velocity of fluctuations while qualitatively the change in the rotation corresponds to the rise of the electron conductivity during MHD activity. The Eq.(8) also explains the larger positive electric field in H-mode, where T_e is larger and L_n is smaller. The rise of the positive electric field should lead to the H-L transition, which has been observed [2]-[3]. Estimating the change of the electrostatic potential in the core one should take into account the toroidal acceleration of the bulk plasma and corresponding change in the radial electric field outside the ergodic zone. In TUMAN-3M $k \approx 2$, the toroidal velocity U_T^{st} can be taken for estimations. The overall drop of the potential then can be estimated as $\Delta\varphi = E_r^{St} a \approx 400V$ with the maximum in the center in agreement with the HIBP measurements [3].

4. Conclusions

A theoretical model for the toroidal rotation spin-up and generation of a positive radial electric field during the stochastization of plasma edge is presented. The model takes into account the electron effective conductivity in the stochastic magnetic field and the ion radial current of neoclassical nature which compensates the electron radial current. As the consequence of low m/n MHD a toroidal rotation spin-up in the co-current direction is predicted, as well as a positive radial electric field both in the stochastic layer and in the core. The model is in reasonable agreement with the radial electric field and plasma potential measurements during MHD activity in the TUMAN-3M tokamak.

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