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EFFECT OF THE RADIAL ELECTRIC FIELD, INDUCED BY ALFVÉN WAVES, ON TRANSPORT PROCESSES IN TOKAMAKS

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Abstract

We demonstrate that Alfvén waves may be the convenient trigger for the formation and maintenance of edge and internal transport barriers due to their small radial localizations. Kinetic Alfvén waves can also provide a mechanism for squeezing the banana orbits of ions in weakly collisional plasmas of tokamaks. It is shown that the radial electric field, induced by Alfvén waves, at some conditions has a nonlinear dependence on the radio-frequency absorbed power. The dependence of the ion heat conductivity and of the ion poloidal viscosity on the radio-frequency absorbed power is obtained in this paper for tokamak plasmas with ion banana orbits squeezed by Alfvén waves. Estimations of the proper absorbed power of Alfvén waves in some tokamaks is about the level of absorbed power to be used in early fulfilled experiments.

1. INTRODUCTION

Using radio frequency waves in tokamak plasmas can give a possibility to solve multi goal problems. These waves convert into kinetic or slow Alfvén waves near the proper magnetic surface. Plasma heating and current drive by Alfvén waves were thoroughly investigated in the TCA and Phaedrus - T tokamaks Refs[1,2]. In the latter, current drive and plasma rotation induced by Alfvén waves were clearly demonstrated. Kinetic or slow Alfvén waves (KAW or SAW) have a small radial localization, and, consequently, can be used to create strongly sheared plasma rotation and radial electric field. In fact theoretical calculations indicate that Alfvén waves can be used for the formation and maintenance of edge and internal transport barriers (ITB) Ref.[3] and can also provide a mechanism for squeezing the banana orbits of ions in weakly collisional plasmas of tokamaks. This possibility will be investigated in the forthcoming experimental program in TCA/BR Ref.[3].

2. RADIAL ELECTRIC FIELD, INDUCED BY ALFVÉN WAVES

In the L-regime conditions, the plasma parameters have usually smooth radial profiles. The poloidal velocity $U_{i\theta}$ is on the level of drift velocities, $U_{i\theta} = kU_{Ti}$, $U_{Ti} = (c/e_iB)\partial T_i/\partial r$, k is of order unity for all collisional regimes. In the presence of rf forces with the strong radial localizations (for example, of KAW or SAW), the poloidal velocity can substantially exceed the drift velocities in the tokamak plasma and be on the subsonic level.

We further consider the case $c_s > U_{i\theta} > \{h_\theta U_{i\zeta}; U_{ip}\}$. The radial electric field can be found from the ion momentum equation

$$E_r \approx B\left(-U_{i\theta} + h_\theta U_{i\zeta} + U_{pi}\right)/c \approx -BU_{i\theta}/c, \quad U_{pi} = (c/e_i n_0 B)\left(\partial p_i/\partial r\right), \tag{1}$$

where $U_{i\zeta}$ is toroidal components of the ion velocity $\mathbf{V}_i$ respectively. To find the ion poloidal velocity, we proceed from the equations

$$F_\theta^\pi + F_\theta^h = 0, \quad F_\theta^\pi \approx -M_i \mu_{i\theta 0} U_{i\theta}, \quad \mu_{i\theta 0} \approx v_{Ti} q n_0 \nu_i^* / \left[R\left(1 + \nu_i^* \epsilon^{3/2}\right)\left(1 + \nu_i^*\right)\right]. \tag{2}$$

The forces F_θ^π and F_θ^h are the viscous and rf forces respectively acting along the poloidal θ direction of tokamak. Here, $\mu_{i\theta 0}$ is the approximate poloidal viscosity coefficient, $\nu_i^* = qR/\lambda_i \epsilon^{3/2}$, q is the safety factor, $\epsilon = r/R$ is the inverse aspect ratio, R is the torus major radius, $\lambda_i = v_{Ti}/\nu_i$ is the ion mean free path, $v_{Ti} = \sqrt{2T_i/M_i}$ is the ion thermal velocity, and ν_i is the ion-ion collisional frequency.

Expressions for the rf force F_θ^h, connected with KAW or SAW, were earlier found Ref.[5]

$$F_\theta^h \approx mP_w/\left(r\Omega\right), \qquad P_w = \left(\mathbf{E}\cdot\mathbf{j}^* + c.c.\right)/4 \approx \Omega \mathrm{Im}\epsilon_\parallel \left|E_\parallel\right|^2/8\pi, \tag{3}$$

where m is the poloidal wave number, Ω is the frequency of the rf wave, P_w is the rf power, absorbed in the plasma.

Combining Eqs(1)-(3), we express the radial electric field Eq.(1) via absorbed power

$$E_r \approx -m\omega_{ci}P_w/\left(\Omega r e_i \mu_{i\theta 0}\right), \qquad \omega_{ci} = e_i B/M_i c. \tag{4}$$

3. TRANSPORT BARRIERS FORMATION BY ALFVÉN WAVES

At first, we estimate the possibility of the edge plasma turbulence suppression by Alfvén waves. In this case, it is necessary to have the parameter γ_E must be greater than the increments of most dangerous instabilities in tokamak plasmas Ref.[3]

$$\gamma_E = \frac{cB_\theta R}{B}\frac{\partial}{\partial r}\frac{E_r}{RB_\theta} \geq \gamma_{max}. \tag{5}$$

Now, we can estimate the quantity γ_E Eq.(5). We note that all the parameters under the radial derivatives in Eq.(5) are the smooth functions of r except of the absorbed power P_w, which is localized in the narrow radial layer Δr. Thus, we can suppose for weakly collisional plasmas Ref.[5]

$$\frac{\partial P_w}{\partial r} \approx \frac{P_w}{\Delta r}, \quad \Delta r = 1.8\left(a\frac{c^2}{\omega_{pe}^2}\frac{v_{Te}^4}{V_a^4}\right)^{1/3}. \tag{6}$$

Here, a is the plasma minor radius, $V_A = B/\sqrt{4\pi n_0 M_i}$ is the Alfvén speed, $\omega_{pe}^2 = 4\pi n_0 e_e^2/M_e$.

Thus, in Eq.(5) we can only take into account the derivatives of the absorbed power P_w, and Eq.(5) take the form after the using Eqs(4),(6)

$$\gamma_E \approx -\frac{k_b}{M_i\mu_{i\theta 0}\Omega}\frac{\partial P_w}{\partial r} \approx \frac{k_b}{M_i\mu_{i\theta 0}\Omega}\frac{P_w}{\Delta r}. \tag{7}$$

We should compare γ_E with the most dangerous instabilities in tokamak edge plasmas Ref.[3]. Such types of instabilities are electron-drift and ion temperature gradient (ITG) instabilities. Here, we estimate the possibility of the suppressing ITG mode by AW. The dispersion relation of this mode is

$$\omega^2 + \omega_{Ti}^*\omega_d = 0, \quad \omega_{Ti}^* = k_b U_{Ti}, \quad \omega_d = \frac{k_b c T_i}{e_i B}\frac{\partial \ln B}{\partial r}, \quad \gamma_{max} \approx \frac{k_b c T_i\sqrt{\epsilon}}{e_i r B}. \tag{8}$$

Thus, from Eqs(7),(8) one finds the instability suppression condition

$$P_w > \frac{\Delta r}{r}\frac{\mu_{i\theta 0}}{\omega_{ci}}\sqrt{\epsilon}T_i\Omega. \tag{9}$$

Yet, the sheared velocity is usually supposed to be the source of Kelvin-Helmholtz instabilities. Nevertheless, the magnetic shear can suppress this instability, and the stability criterion for the weakly collisional plasma case and the upper limitation on the absorbed power P_w, taking into account Eqs(7),(8), are

$$c\frac{\partial}{\partial r}\frac{E_r}{B} < \frac{V_A}{L_s}, \quad P_w < \frac{\Delta r}{L_s}\frac{\mu_{i\theta 0}}{k_b v_{Ti}}\frac{V_A}{v_{Ti}}T_i\Omega, \tag{10}$$

where L_s is the magnetic shear length. Comparing the inequalities Eqs(9),(10) we see they are in no contradiction, i.e., there is the power range to suppress the ITG mode and not to excite Kelvin-Helmholtz instabilities.

Now, we make estimations for the Tokamak Chauffage Alfvén/Brazil (TCA/BR) plasma parameters Ref.[4] $T_i \approx 2 \times 10^6$K, $n_0 \approx 3 \times 10^{19}\text{m}^{-3}$, $B_0 = 1$T, $a = 0.18$m, $R = 0.61$m, $\omega = 2 \times 10^7\text{rad}^{-1}$, $m = 1 \div 3$, $P_w = (4-8) \times 10^6 W/m^3$. We obtain the evaluation for the absorbed power $P_w > (1-2) \times 10^6$ W/m^3. This quantity is of the same order which was used in experiments Ref.[2], and less than one which will be used in future experiments Ref.[4].

4. ION BANANA ORBIT SQUEEZING BY ALFVÉN WAVES

It is well known that a radial electric field shear can squeeze ion banana orbits Ref.[6]. The squeezing parameter S is given by

$$S = 1 + I^2 e_i \Phi''/M_i\omega_{ci0}^2, \qquad I = R^2\mathbf{B}\boldsymbol{\nabla}\zeta, \tag{11}$$

where $\mathbf{B}$ is the magnetic field, R is the major radius, ζ is the toroidal angle, e_i is the ion charge, M_i is the ion mass, ω_{ci0} is the gyrofrequency in an arbitrary point with the coordinates ψ_0, θ_0, Φ is the equilibrium electrostatic potential, $\Phi' = d\Phi/d\psi$, and ψ is the poloidal flux function. In this paper we analyze the possibility of employing the radial electric field produced by Alfvén waves to modify the size of the banana width of ions.

It follows that in Eq.(4) that we can neglect the radial dependence of all macroscopic quantities except that of P_w. Therefore,

$$\frac{dE_r}{dr} \approx -\frac{\omega_{ci}}{\Omega}\frac{mM_i}{e_i r\mu_{\theta i0}}\frac{dP_w}{dr} \approx -\frac{\omega_{ci}}{\Omega}\frac{mM_i}{e_i r\mu_{\theta i0}}\frac{P_w}{\Delta r}. \tag{12}$$

We estimate next the ion heat conductivity and poloidal viscosity in tokamak weakly collisional plasmas with a strongly sheared electric field, induced by Alfvén waves, taking into account the ion banana orbit squeezing. To estimate the radial electric field in tokamak weakly collisional plasmas with ion banana orbits squeezed by Alfvén waves, one should also take into account electron viscous forces in Eq.(2), because under some special conditions, the ion and electron viscous forces can be of the same order, as shown in Ref.[6]. Thus, Eq.(3) must be modified to

$$F_{\theta i}^{\pi} + F_{\theta e}^{\pi} + F_{\theta}^{h} = 0, \quad F_{\theta\alpha}^{\pi} \approx -\mu_{\theta\alpha}U_{\alpha\theta}, \qquad \alpha = i, e. \tag{13}$$

Indices i, e stand for ions and electrons, respectively. Using inequalities $c_s > U_{i\theta} > \{h_\theta U_{i\zeta}; U_{ip}\}$, we obtain from Eq.(1) that $U_{e\theta} \approx U_{i\theta}$. Thus, in weakly collisional plasmas with ion banana orbits squeezed by Alfvén waves, Eqs(4),(12) should be changed to

$$E_r \approx -\frac{\omega_{ci}}{\Omega}\frac{mM_i}{e_i r\left(\mu_{\theta i} + \mu_{\theta e0}\right)}P_w, \qquad \frac{dE_r}{dr} \approx -\frac{\omega_{ci}}{\Omega}\frac{mM_i}{e_i r\left(\mu_{\theta i} + \mu_{\theta e0}\right)}\frac{P_w}{\Delta r}. \tag{14}$$

Using Eq.(14) and the definition of the poloidal flux function $\psi = \int_0^r RB_\theta dr$ and of the radial electric field $E_r = -d\Phi/dr$, we express the squeezing parameter S via the absorbed power P_w

$$S = 1 - \frac{e_i B_\zeta^2}{M_i\omega_{ci}^2 B_\theta^2}\frac{dE_r}{dr} \approx 1 + \frac{k_b}{\left(\mu_{\theta i} + \mu_{\theta e0}\right)\omega_{ci}\Omega}\frac{B_\zeta^2}{B_\theta^2}\frac{P_w}{\Delta r}. \tag{15}$$

Here, B_θ and B_ζ are the poloidal and toroidal components of the magnetic field respectively. We write the sign "+" before the term with P_w in Eq.(15), taking into account the transport coefficient dependence on $\mid S \mid$ (see Ref.[6]), and focusing on the case $S > 1$.

The ion poloidal viscosity in the core off-axis tokamak region with the squeezed banana orbits can be written in the form

$$\mu_{\theta i}^{*} \approx \mid S \mid^{-3/2}, \qquad \mu_{\theta i}^{*} = \mu_{\theta i}/\mu_{\theta i0}, \qquad \mu_{\theta i0} \approx n_0 M_i \nu_i q^2, \tag{16}$$

where

$$S = 1 + \left[P_w^* / \left(\mu_{\theta i}^* + \mu_{\theta e}^*\right)\right], \quad \mu_{\theta e}^* = \mu_{\theta e0}/\mu_{\theta i0} \approx \sqrt{M_e/M_i}, \quad P_w^* = mB_\zeta^2 P_w / \left(r\mu_{\theta i0}\omega_{ci}\Omega B_\theta^2 \Delta r\right).$$

The analysis of Eq.(16) shows that the ion poloidal viscosity $\mu_{\theta i}$ decreases rapidly with increasing of the absorbed power P_w. The ion poloidal viscosity $\mu_{\theta i}$ becomes of the order of the electron poloidal viscosity $\mu_{\theta e}$ when the parameter P_w^* is about 0.5, $\mid P_w^* \mid \approx 0.5$, corresponding to $S \approx 12.3$. This result is independent on the sign of P_w^* if we consider the case $\mid S \mid > 1$. It can be easily understood as an increase in the absorbed power P_w (and consequently of the squeezing factor $\mid S \mid$) leads to a decrease of the ion poloidal viscosity coefficient $\mu_{\theta i}$ and to a further increase of the squeezing parameter $\mid S \mid$.

The ion heat conductivity χ_i in tokamak off-axis plasmas has been investigated in Ref.[6]. We construct χ_i in the presence of the ion banana orbit squeezing by Alfvén waves analogously to Ref.[6]. We have

$$\chi_i \approx q^2 \rho_i^2 \nu_i (\epsilon \mid S \mid)^{-3/2}, \tag{17}$$

where the squeezing parameter S results from Eq.(16), and $\rho_i = v_{Ti}/\omega_{ci}$. As it follows from the above mentioned analysis, the ion heat conductivity is quickly reduced with the growth of the absorbed power P_w, and, at $\mid P_w^* \mid > 0.5$, the normalized viscosity coefficient $\mu_{\theta i}^*$ can be neglected in the squeezing parameter S in comparison with $\mu_{\theta e}^*$.

To illustrate the point we offer some estimations for DIII-D tokamak assuming the core plasma parameters Ref.[7]: $T_i \approx 2 \cdot 10^8$K, $n_0 \approx 5.7 \cdot 10^{19}\text{m}^{-3}$, $B_0 = 2.1$T, $r = 0.62$m, $R = 1.68$m, $\Omega \approx 10^7 rad^{-1}$, $m = 1 - 3$. Using the inequality $P_w^* > 0.5$, from Eq.(16), we find the absorbed power $P_w > 3 \times 10^6 W/m^3$ to be necessary for a strong suppression of ion transport in the banana region.

5. CONCLUSION

In conclusion, it is demonstrated that a radial electric field can be induced by externally launched radio frequency waves, in the Alfvén wave range of frequencies, which are mode converted into kinetic Alfvén waves. These waves are strongly localized at a given minor radius tokamak plasma, giving rise to induced radial electric fields with large radial derivatives and to sufficiently strong poloidal flow shear. Turbulent eddies get torn apart, thus reducing the fluctuation level. These fields can also squeeze the ion banana orbits in tokamaks. This effect opens the possibility to flexible influence the neoclassical ion transport in tokamak banana regimes by externally excited kinetic Alfvén waves. Absorbed powers, which are necessary to affect the ion transport, are on the level of those used in tokamak experiments with kinetic Alfvén waves.

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