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ANOMALOUS AND NEOCLASSICAL TRANSPORT SUPPRESSION IN TCABR TOKAMAK BY ALFVÉN WAVES

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Radio frequency waves, used in tokamak plasmas, can solve many problems of interest for controlled nuclear fusion. These waves, adequately chosen, can convert into kinetic or slow Alfvén waves near an appropriate magnetic surface in tokamaks, and were used to investigate plasma heating and current drive in the TCA and Phaedrus - T tokamaks[1,2]. In the latter, current drive and plasma rotation induced by Alfvén waves were clearly demonstrated at low densities[3]. Kinetic or slow Alfvén waves have a small radial localization and, consequently, can be used to create radial electric fields and strongly sheared plasma rotation. Theoretical calculations have indicated that the formation and maintenance of edge and internal transport barriers are possible with Alfvén Waves.[4–8].

These topics will be investigated in the forthcoming experimental research program of the TCABR tokamak[9]. This machine, called previously TCA in Lausanne, Switzerland is, presently, in operation at the Laboratory of Plasma Physics (LFP) of the University of São Paulo, Brazil. It was originally designed and constructed aiming at the investigation of Alfvén wave (AW) heating and current drive, and its effect on plasma stability and transport. These objectives are still at the frontier of research in magnetically confined plasmas, and were maintained and expanded for TCABR. For the work to be performed in TCABR an advanced antenna system was developed. It consists of 4 sets of antennae displaced toroidally at 90^0 to each other and each one composed of 3 pairs of poloidal loops. By changing the phase of the loop currents it is possible to obtain the excitation of almost pure helical modes with M = ±1, N = ±2, ±4 and ±6. According to the calculations the best mode for excitation is M = -1, N = -4, contrary to the modes used in Lausanne experiments M = ±1, N = ±2. Wall conditioning and boronization will be used as well to control impurities. One module of the antennae system was designed, constructed, tested, and is scheduled to be installed in the machine in the second semester of 1999. It will be fed by a RF four-phase generator of 1 MW pulsed power, duration of 20 ms and frequency of 2 to 8 MHz. The system was designed for the study of plasma heating and current drive, extending the demonstration of the feasibility to densities above 10^{13} cm^{-3}. This will be important to verify the feasibility of using Alfven waves for heating and current drive at densities closer to those needed for fusion reactors and the expectation that the efficiency is not dependent on the density. Transport barrier formation can also be studied with the same antenna system. In initial experiments on TCABR ohmic currents of up to 80 kA and duration of 100 ms have been achieved.

In this paper, we consider in more detail the suppression of anomalous and neoclassical transport and the formation of transport barriers in tokamaks by Alfvén waves. Previously, we provided simple estimates to evaluate the appropriate absorbed power of KAW to suppress anomalous[5] and neoclassical[8] transport both in edge and internal regions of tokamaks.

It is possible to suppress anomalous transport in tokamak plasmas by sheared plasma rotation produced by quasistationary sheared radial electric field[6]. Simple estimates to find the required radial electric field give:

$$\gamma_E = \frac{cB_\theta R}{B} \frac{\partial}{\partial r} \frac{E_r}{RB_\theta} \geq \gamma_{max}, \tag{1}$$

where γ_{max} is the maximum linear growth rate of instabilities in edge tokamak plasmas. We consider the case of subsonic velocities, $c_s > U_{i\theta} > \{h_\theta U_{i\zeta}; U_{ip}\}$, where $c_s = \sqrt{(T_e + T_i)/M_i}$, $U_{ip} = (1/e_i n_0 B)\, \partial p_i/\partial r$. Then, we can use the approximate relation

$$E_r \approx -BU_{i\theta}/c. \tag{2}$$

The ion and electron poloidal velocities U_θ can be found from the poloidal component of the momentum equation[8]

$$F^\pi_{\theta i} + F^\pi_{\theta e} + F^h_\theta = 0, \quad F^\pi_{\theta\alpha} \approx -\mu_{\theta\alpha} U_{\alpha\theta}, \quad \alpha = i, e. \tag{3}$$

The forces F^π_θ and F^h_θ are the magnetic surface averaged viscous forces, neglecting the plasma residual rotation, and rf forces, respectively, acting along the poloidal θ direction of tokamak. In the banana region, the viscosity coefficient $\mu_{i\theta}$ can be expressed via the squeezing parameter S by means of the relation

$$\mu^*_{\theta i} \approx \frac{1}{\mid S \mid^{3/2}}, \qquad \mu^*_{\theta i} = \frac{\mu_{\theta i}}{\mu_{\theta i0}}, \qquad \mu_{\theta i0} \approx n_0 M_i \frac{\nu_i q^2}{\epsilon^{3/2}}, \qquad S = 1 - \frac{e_i B^2_\zeta}{M_i \omega^2_{ci} B^2_\theta} \frac{dE_r}{dr}, \tag{4}$$

where ω_{ci} is the ion gyrofrequency.

In our previous papers[5,8], we have made approximate estimates of ion viscosity dependences on the KAW absorbed power P_w, substituting the radial derivative of the quasistationary radial electric field dE_r/dr by the expression $E_r/\Delta r$. The parameter Δr is the halfwidth of the radial dependence curve of the rf electric field parallel component $E_\parallel$. We choose to model the radial distribution of $E_\parallel$ in the form

$$E_\parallel \approx E_A \exp[-\frac{1}{2} \mid x \mid^{3/2}], \; x \approx 2^{5/3}(\ln 2)^{2/3} \frac{(r - r_0)}{\Delta r}, \; \Delta r \approx 1.8 \left(a \frac{c^2}{\omega^2_{pe}} \frac{v^4_{Te}}{V^4_A} \right)^{1/3}, \tag{5}$$

where r_0 is the radial coordinate of the conversion point. For kinetic Alfvén waves, the absorbed power P_w can be expressed via the parallel component $E_\parallel$

$$P_w \approx \Omega \mathrm{Im}\epsilon_\parallel \left| E_\parallel \right|^2 /8\pi \approx P_{wA} \exp[- \mid x \mid^{3/2}], \; P_{wA} = \Omega \mathrm{Im}\epsilon_\parallel \left| E_A \right|^2 /8\pi. \tag{6}$$

Here, Ω is the KAW frequency, $i\mathrm{Im}\epsilon_\parallel$ is the anti Hermit part of the dielectric permittivity tensor parallel component. In the case of KAW, the poloidal forces, affecting ions, can also be expressed via the absorbed power[5,8]

$$F^h_\theta \approx mP_w/r\Omega, \tag{7}$$

where m is the poloidal wave number. From Eqs. (2),(3),(6),(7), one find the quasistationary radial electric field E_r as a function of absorbed power P_w

$$E_r \approx -\frac{\omega_{ci}}{\Omega} \frac{mM_i}{re_i(\mu_{\theta i} + \mu_{\theta e0})} P_w, \; \frac{\mu_{\theta e0}}{\mu_{\theta i0}} \approx \sqrt{\frac{M_e}{M_i}}. \tag{8}$$

Using Eqs. (4),(6),(8), we find the remarkable situation when, in the presence of kinetic Alfvén waves, the radial dependence of the ion viscosity, in the tokamak banana region, is governed by the following differential equation

$$\mu^*_{\theta i} \approx \mid 1 + \frac{d}{dx} \frac{P^*_w \exp(-x^{3/2})}{(\mu^*_{\theta i} + \sqrt{M_e/M_i})} \mid^{-3/2}, \; P^*_w = \frac{2^{5/3}(\ln 2)^{2/3} m}{r \mu_{\theta i 0} \omega_{ci} \Omega} \frac{B^2_\zeta}{B^2_\theta} \frac{P_{wA}}{\Delta r}. \quad (9)$$

In Eq. (9), it was supposed that all macroscopic plasma parameters are smooth functions of the radial coordinate except of the absorbed power and ion viscosity. It was solved numerically, and the solution $\mu^*_{\theta i}(x, P^*_w)$ is shown in Fig.1.

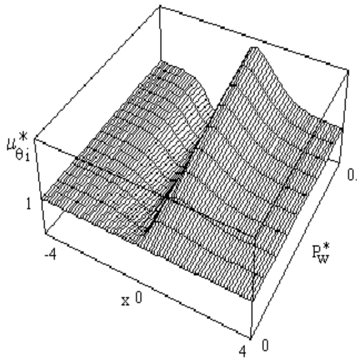

Fig.1

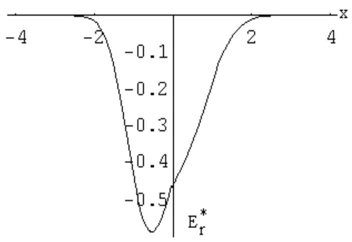

Fig. 2

Fig.1 shows that the normalized ion viscosity in the tokamak banana region is equal to 1 far from the conversion point where the absorbed power of KAW is exponentially small, and that close to the conversion point, the ion viscosity is increased or decreased depending on the sign of the normalized absorbed power P^*_w and of the coordinate x. If the sign of P^*_w is changed, i.e., the sign of poloidal wave number m is changed, Fig.1 will be the same, but it is necessary to transform $x \to -x$. From this plot, we can find the radial dependence of $\mu^*_{\theta i}(x)$ at $P^*_w \approx 0.75$. When $P^*_w > 0$, the ion viscosity decreases approximately twofold for $r < r_0$, and increases a factor ≈ 1.7 for $r > r_0$.

The estimates of the appropriate absorbed power for suppression of anomalous and neoclassical transport by Alfvén waves in tokamaks, given in the sequence, should be more favorable than those given in Ref.8.

From Eqs. (4),(6),(8), one sees that the radial and absorbed power dependence of the function $\mid S \mid^{-3/2}$is the same as the normalized ion viscosity $\mu^*_{\theta i}$. Therefore, the neoclassical heat conductivity in the tokamak banana region χ_i, depends on the radial coordinate and absorbed power in the same way as shown in Fig.1.

It is also very interesting to find the radial dependence of the quasistationary radial electric field E_r, induced by KAW close the conversion point r_0. Combining Eq. (8) and the solution of Eq. (9), one has the dependence shown in Fig.2 of the function E^*_r

$$E^*_r \approx -\frac{P^*_w}{\mu^*_{\theta i} + \sqrt{M_e/M_i}}, \qquad E^*_r = \frac{2^{5/3}(\ln 2)^{2/3} e_i}{\omega^2_{ci} M_i} \frac{B^2_\zeta}{B^2_\theta} \frac{E_r}{\Delta r}, \quad (10)$$

At first, we compare the obtained results with our previous results from Refs. 5 and 8. As in these references, we offer some estimates for DIII-D tokamak assuming the core plasma parameters[10]: $T_i \approx 2 \cdot 10^4$eV, $n_0 \approx 5.7 \cdot 10^{13}$ cm^{-3}, $B_0 = 2.1$ T, $r = 62$ cm, $R = 168$ cm. We take the case $\Omega \approx 10^7$ s^{-1} and $m = 1 - 3$, and with $P_w^* = 0.75$ we obtain for the absorbed power averaged over the conversion layer, the value $P_w^{av} \approx 1$ W/cm^3. This power provides a twofold suppression of ion viscosity and heat conductivity in the banana region at $r < r_0$ close to the conversion point r_0. These values of the absorbed power P_w^{av} are higher or at the level of those used in existing experiments[1-3]. From Eq. (10) and Fig.1, the maximum value of the radial electric field, induced by KAW, is estimated as $E_r \approx 10^2$ V/cm.

To find the absorbed power to suppress the anomalous transport in weakly collisional plasmas with ion banana orbits squeezed by Alfvén waves, the sheared electric field to be used in Eq. (1) can be found using the values given in Eq.(4) for S and $\mu_{\theta i}^*$. Then, the extremes values of $\mu_{\theta i}^*$, obtained from the numerical solution of the differential Eq.(9), and shown in Fig.1 can be used to find the extremes of dE_r/dr. In the range $0 \leqslant P_w^* < 1$, the maximum and minimum of $\mu_{\theta i}^*$ are given respectively by:

$$\mu_{\theta i}^{*(\max)} \approx 1 + 0.9P_w^*, \qquad \mu_{\theta i}^{*(\min)} \approx 1 - 0.6P_w^*. \tag{11}$$

and the maximum of the radial derivatives of the radial electric field on both sides of the conversion point r_0 by:

$$\frac{dE_r}{dr} \approx \frac{M_i \omega_{ci}^2 B_\theta^2}{e_i B_\zeta^2}[1 - (1 + 0.9P_w^*)^{-2/3}], \; \frac{dE_r}{dr} \approx \frac{M_i \omega_{ci}^2 B_\theta^2}{e_i B_\zeta^2}[1 - (1 - 0.6P_w^*)^{-2/3}]. \tag{12}$$

One can estimate the appropriate absorbed power of KAW, using the second equation in Eq.(12) because the radial derivative is larger than in the first equation. As in Ref. 5, we consider the maximum increment of the ion-temperature-gradient instability

$$\gamma_{max} \approx k_b c T_i \sqrt{\epsilon} / \left(e_i r B\right), \tag{13}$$

where k_b is the binormal component of the wave vector. From Eqs. (1), (12), one finds the anomalous transport suppression condition to read

$$(1 - 0.6P_w^*)^{-2/3} - 1 \geqslant \frac{k_b T_i \sqrt{\epsilon}}{r M_i \omega_{ci}^2} \frac{B_\zeta^2}{B_\theta^2}, \qquad r < r_0. \tag{14}$$

Using parameters of DIII-D tokamak[10], we obtain from Eq.(14), $P_w^{av} \gtrsim 1 W/cm^3$. Estimates for the plateau region of tokamaks shows that the absorbed power needed to suppress the anomalous transport is approximately the same.

References:

[1]G.A. Collins et al. Phys. Fluids, **29**, 2260 (1986)

[2]N. Hershkovitz et al. Proc. 15th IAEA Conf. on PPCF, Seville, **2**, 245, (1994)

[3]S. Wukitch et al. Phys. Rev. Lett. **77**, 294 (1996)

[4]G.G.Craddock and P.H.Diamond. Phys. Rev. Lett. **67**, 1535 (1991)

[5]V.S.Tsypin, A.G.Elfimov, M.Tendler et al. **5**, 7 (1998)

[6]K.H. Burrell. Phys. Plasmas. **4**, 1499 (1997)

[7]K.C. Shaing, R.D. Hazeltine. Phys. Fluids B, **4**, 2547 (1992)

[8]V.S.Tsypin, R.M.O.Galvão, I.C.Nascimento et al. Phys. Rev. Lett. **81**, 3403 (1998)

[9]I.C. Nascimento, TCABR team. Proc. Xth Conf. on PPCF. Brazil, **1**, 69 (1996)

[10]E.J. Strait et al. Phys. Rev. Lett. **75**, 4421 (1995)