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Calculations of Alfvén Wave Driving Forces, Plasma Flow, and Current Drive in The TCABR Tokamak

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Recently, improvement of energy confinement due to internal transport barriers (ITB) created by different means, such as neutral beam injection and by wave heating in ion cyclotron range of frequencies, has been recently demonstrated in large tokamaks (see, for example, review [1]). The transport barriers appear at a position around half of the plasma minor radius and are associated with negative shear of poloidal magnetic field and sheared plasma rotation.

Here, we consider the use of Alfvén waves as one possible scheme to drive the required hollow current profile and plasma flow to create the ITB. In this case, plasma turbulence can be strongly suppressed[2] and ion banana orbits can be squeezed by radial electric field shear[3, 4]. Two kinds of Alfvén waves are proposed: kinetic Alfvén wave (KAW), which can be excited by mode conversion, and global Alfvén waves (GAW). The energy deposition profile of the KAW has a small radial localization that can help to induce hollow current profiles for reversed magnetic shear configurations and to simultaneously create strongly sheared plasma flows to suppress the plasma turbulence. The attractiveness of these types of waves is that both kinds of effects can be created at the same radial location of the plasma column. Note that current drive and toroidal plasma rotation induced by Alfvén waves were clearly demonstrated[5, 6].

The analyses of the current drive and plasma flow produced by the Alfvén waves is based on a theory of ponderomotive forces[7, 8] modernized for tokamaks with coaxial magnetic surfaces. Time averaged poloidal and toroidal ponderomotive forces $\langle \tilde{F}^{(\alpha)}_{\theta,\zeta} \rangle$ on ions and electrons are calculated from two fluid equations. Any variable $\mathbf{\Phi}$ (density $n^{(\alpha)}$, velocity $\mathbf{V}^{(\alpha)}$, electric $\mathbf{E}$ and magnetic $\mathbf{B}$ fields) is represented as a sum of quasi-stationary (represented as $\mathbf{\Phi}^{(0)}$) and oscillating (represented as $\tilde{\mathbf{\Phi}}$) parts. The oscillating part is supposed to be expanded in Fourier series $\sum_m \tilde{\mathbf{\Phi}}_m \exp(i(m\theta + n\zeta - \omega t))$ where ω is the wave frequency and m, n are the poloidal and toroidal wavenumbers. Two kinds of forces are discussed: one of them $\langle \tilde{F}^{(\alpha)}_{FD,\theta,\zeta} \rangle$ is produced by the fluid dynamic stress, $\mathbf{\nabla}\langle m_\alpha n_\alpha \tilde{\mathbf{V}}^{(\alpha)} \tilde{V}^{(\alpha)}_{\theta,\zeta} \rangle$, and the other $\langle \tilde{F}^{(\alpha)}_{EM,\theta,\zeta} \rangle$ is produced by the electromagnetic stress, $\langle e_\alpha \tilde{n}_\alpha \tilde{\mathbf{E}} + \tilde{\mathbf{j}}_\alpha \times \tilde{\mathbf{B}}/c \rangle_{\theta,\zeta}$, where m_α, e_α are mass and charge of particles, $P^{(\alpha)}$ is the wave dissipation $\tilde{\mathbf{j}}^{(\alpha)} \cdot \tilde{\mathbf{E}}$, and $\tilde{\mathbf{j}}^{(\alpha)}_s$ is the oscillating current, $-(i\omega/4\pi) \sum_p \varepsilon^{(\alpha)}_{sp} \tilde{E}_p$. Averaging the two-fluid equations over time and using the continuity and induction equations, the ponderomotive forces can be calculated. We use the expressions derived in Ref.[7] for the components of the ponderomotive force acting on plasma particles α (electrons or ions) :

$$\left\langle \tilde{F}^{(\alpha)}_\theta \right\rangle \equiv F^{(\alpha)}_{\theta,P} + F^{(\alpha)}_{\theta,\partial} = \frac{m}{r\omega} P^{(\alpha)} + \mathrm{Re} \left\{ \frac{1}{8\pi r^2} \frac{\partial}{\partial r} \left[r^2 \sum_{s=1}^{3} \varepsilon^{(\alpha)}_{rs} \tilde{E}_s \left(\tilde{E}^*_\theta - \frac{4\pi i\omega}{\omega^2_{p\alpha}} \hat{\jmath}^{(\alpha)*}_\theta \right) \right] \right\},$$

$$\left\langle \tilde{F}^{(\alpha)}_\zeta \right\rangle \equiv F^{(\alpha)}_{\zeta,P} + F^{(\alpha)}_{\zeta,\partial} = \frac{k}{\omega} P^{(\alpha)} + \mathrm{Re} \left\{ \frac{1}{8\pi\, r} \frac{\partial}{\partial r} \left[r \sum_{s=1}^{3} \varepsilon^{(\alpha)}_{rs} \tilde{E}_s \left(\tilde{E}^*_\zeta - \frac{4\pi i\omega}{\omega^2_{p\alpha}} \hat{\jmath}^{(\alpha)*}_\zeta \right) \right] \right\}, \quad (1)$$

where the symbols ($s = 1, 2, 3$) are used for the tensor indexes, which mean radial (r), binormal (b), and parallel components ($\|$). In the above equation, the first term is the momentum transfer driving force, $F^{(\alpha)}_{\zeta,\theta,P}$, which acts via wave dissipation, while the second term, $F^{(\alpha)}_{\zeta,\theta,\partial}$, is the gradient force.

Balancing the sum of electron and ion ponderomotive forces $\langle \tilde{F}^{(e,i)}_{\theta} \rangle$ with the neoclassical ion viscosity force, $F^{\pi}_{\theta} = \mu_{neo} V^{(0)}_{\theta}$ (μ_{neo} is viscosity coefficient) we find the quasi-stationary poloidal rotation plasma velocity. Balancing the electron driving force parallel to magnetic field by electron-ion friction force, we obtain the wave driven current

$$j^{RF}_{\|} = \frac{\sigma_{\|}}{e\, n_{e0}} \left[P^{(e)} \frac{k_{\|}}{\omega} + (h_{\theta} F^{(e)}_{\theta,\partial} + h_{\zeta} F^{(e)}_{\zeta,\partial}) \right], \tag{2}$$

where $\sigma_{\|}$ is the plasma parallel conductivity.

To calculate these forces numerically for TCABR (Tokamak Chauffage Alfvén wave heating experiment in Brazil), we use a 2-D kinetic code[9]. The code calculates RF fields and wave dissipation in two ion-species magnetized plasmas with circular magnetic surfaces. It solves the coupled Maxwell equations, posed as a boundary value problem, for the RF fields in plasmas with one sideband poloidal harmonic coupling, which models small toroidicity effects, $\epsilon = r/R_0 \ll 1$. In this case, the toroidal magnetic field is $B_t \approx B_0(1 - \epsilon \cos\theta)$ and the dielectric permeability tensor, $\hat{\varepsilon}^{(\alpha)}_{sp}$, is reduced to its local cylindrical form[9, 10]. Electron Landau, transit time magnetic pumping damping, finite Larmour radius effects, and the poloidal modulation corrections proportional to ϵ are taken into account.

The RF fields are assumed to be produced by a sheet current antenna located on a surface of radius b in a cylindrical limit (one poloidal, M, and one toroidal mode number, N). Surrounding the current surface there is a vacuum region bounded by a conducting wall of radius d. The geometry and plasma parameters of TCABR are: $a = 18\,cm$, $b = 18.5cm$, $d = 23\,cm$, and $R_0 = 61\,cm$; a square parabolic temperature profile is assumed, while the current profile is cubic parabolic, because of Spitzer conductivity. The tokamak safety parameter $q_0 = 1.1$ and the toroidal magnetic field $B_0 = 10\ kG$ in the plasma center. The electron density profile is given by $n_e = n_0(1 - r^2/a^2) + n_a$ with $n_0 = 3 \times 10^{13} cm^{-3}$ and $n_a = 1 \times 10^{12} cm^{-3}$, respectively.

In Fig.1, we present the distribution of the electron driving force parallel to the equilibrium magnetic field, normalized to the maximum value of the momentum transfer force, $P^{(e)}_{max} |k_{\|}|/\omega$. We use the GAW resonance conditions for $m = -1$ (see Ref.[9]) with sideband harmonic mode conversion ($m = 0$) into KAW at the plasma minor radius $r = 0.7a$ in the Alfvén continuum for hydrogen plasmas, $n_0 = 3.0 \times 10^{13} cm^{-3}$. The generator frequency is $f = 4.68 MHz$ and toroidal and poloidal antenna wavenumbers are $-4/-1$, respectively. The electron driving forces are localized around the conversion point r_A and strongly sheared. This force is mainly negative because of negative wavenumbers but current drive is positive. Note that toroidal rotation velocity can be calculated from the balance of the $\sum_i F^{(i)}_{\zeta}$-force with toroidal momentum loss $m_i n_i V^{(0)}_{\zeta}/\tau_E$, where τ_E is the momentum relaxation time.

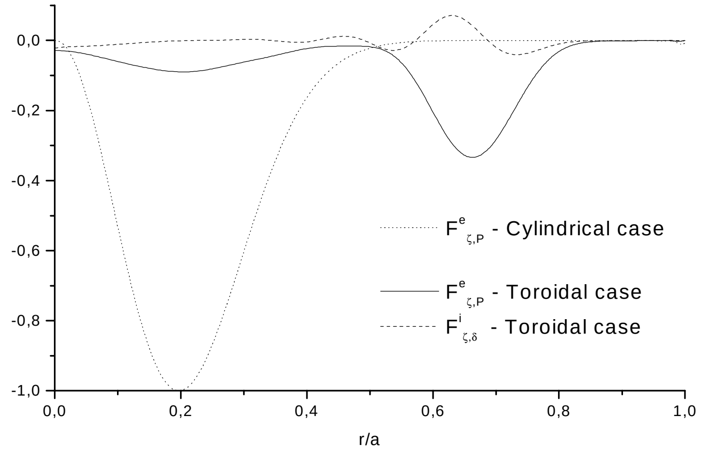


Fig.1. *Distribution of the parallel component of the electron driving force over radius* ($M = -1, N = -4$ *and* $f = 4.7$ *MHz for hydrogen plasma,* $n_{0e} = 3. \times 10^{13} cm^{-3}$, *where the central electron and ion temperatures are* $T_{e0} = 500\ eV$ *and* $T_{i0} = 300\, eV$, *respectively. The curves (dotted, solid and dashed lines) correspond to the electron momentum transfer force for cylindrical case, electron momentum transfer for toroidal case and the ion gradient force for toroidal case, respectively.*

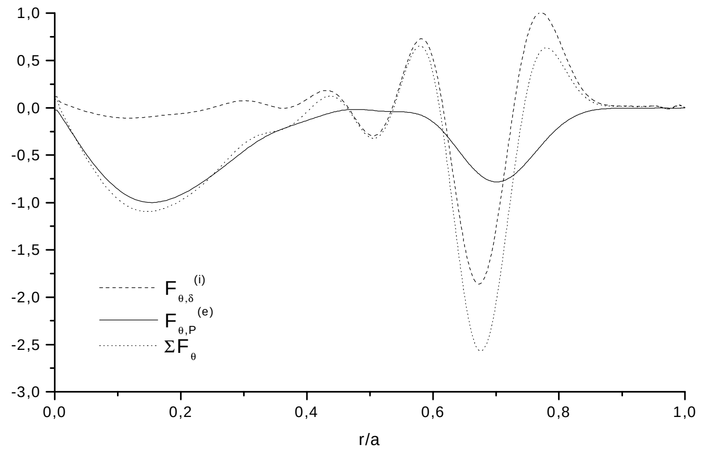
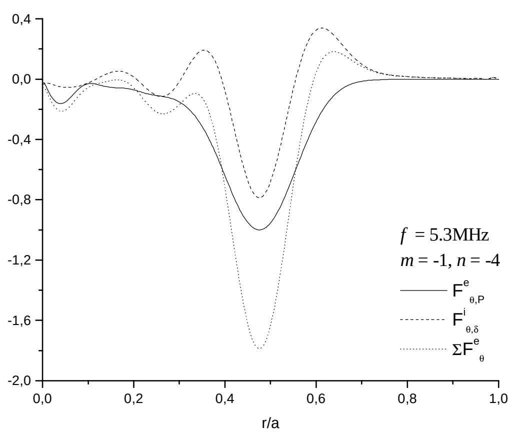
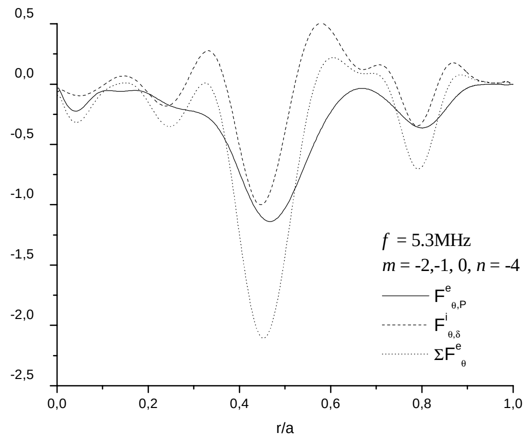


Fig.2. *Distribution of the poloidal component of the driving forces over radius for the parameters of Fig.1, except* $T_e(0) = 300eV$ *and* $T_i(0) = 200eV$. *The forces are normalized to the maximum value of the momentum transfer force,* $P^{(e)}_{max}/\omega r_A$. *The curves (dashed, solid and dotted lines) correspond to the ion gradient force, momentum transfer electron force and the total force upon plasma, respectively.*

In Fig.2 we can observe that ion flow can be driven directly by the gradient force which has opposite signs on the two sides the local Alfven resonance. Note that there is no any dissipation in ions. To compare to the calculations of the ponderomotive forces driven by GAW, we show in Fig.3 the distribution of ponderomotive forces driven by KAW induced by mode conversion effect at the radius $r = 0.5$ for the frequency $f = 5.3MHz$ and electron and ion temperatures respectively equal to 300 and $200eV$, both for cylindrical and toroidal cases.





In conclusion, we can say that:

• A general form of the time-averaged ponderomotive force produced by Alfvén waves in magnetized plasmas has been calculated. The ponderomotive force in the two fluid approximation includes contributions from the momentum transfer force via traveling wave dissipation and the gradient forces, which are related to gradients of the equilibrium plasma parameters and the wave amplitude. These spatial gradient effects (or helicity) may dominate the wave momentum transfer forces.

• Strongly sheared current and plasma flow driven by the kinetic Alfvén waves have been found. Assuming parameters that are characteristics of TCABR, our calculations show that mode-converted KAW can produce an inverted magnetic shear configuration and sheared poloidal plasma flow $dv_\theta/dr \approx 1.6 \times 10^5\,\mathrm{s}^{-1}$(which is bigger than drift frequency ω^* thus enough to suppress main instabilities[2]) about half the minor plasma radius with $400\,kW$ wave dissipated power. The position of the conversion point can be controlled by the generator frequency. This configuration may be appropriate for creation of the internal transport barriers.

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