Flow Shear Suppression of Turbulence Using DE92 001834 Externally Driven Ion Bernstein and Alfvén Waves

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Abstract

The utilization of externally-launched radio-frequency waves as a means of active confinement control through the generation of sheared poloidal flows is explored. For low-frequency waves, kinetic Alfvén waves are proposed, and are shown to drive sheared $\mathbf{E} \times \mathbf{B}$ flows as a result of the radial variation in the electromagnetic Reynolds stress. In the high frequency regime, ion Bernstein waves are considered, and shown to generate sheared poloidal rotation through the ponderomotive force. In either case, it is shown that modest amounts of absorbed power ($\sim$ few 100 kW) are required to suppress turbulence in a region of several cm radial width.

I. INTRODUCTION

The suppression of edge turbulence by sheared plasma flows (and consequently, the radial electric fields associated with them) has emerged as the leading paradigm to explain the improvement of confinement in the transition from L - to H -mode.¹ The basic idea is that in the presence of rotational $\mathbf{E} \times \mathbf{B}$ shear, fluctuations experience enhanced decorrelation and are shorn apart before they have had time to grow to large amplitudes. The criterion for turbulence suppression is roughly given by

$$\left| \frac{d\langle v_\theta \rangle}{dr} \right| > C_0 \frac{\Delta\omega_{k'}}{k'_\theta \Delta x_{k'}}, \quad (1)$$

where $\langle v_\theta \rangle = -c\langle E_r \rangle/B_0$ is the $\mathbf{E} \times \mathbf{B}$ flow, k'_θ , $\Delta\omega_{k'}$, and $\Delta x_{k'}$ are the poloidal wavenumber, decorrelation frequency, and radial correlation length of the ambient turbulence, respectively, and $C_0 \lesssim 1$ is a model-dependent parameter that accounts for how much the general criterion $\langle v_\theta \rangle' > (\Delta\omega_{k'}/k'_\theta \Delta x_{k'})$ overestimates the velocity shear needed for turbulence suppression. As the sign of the shear is irrelevant to this argument, it is possible to effect a transition to an improved state of confinement with either sign of the electric field, a prediction of the theory that has been experimentally corroborated.² Indeed, observations of locally reduced turbulence in the vicinity of shear layers even in non- H -mode discharges³ suggest that this mechanism is robust and of general applicability. One is therefore naturally led to inquire whether it is possible to *actively* control plasma confinement quality through the generation of sheared flows by *external*, *non-intrusive* means (thus, for example, dodging the inherent limitations associated with electrode insertion²). Given the wall-sputtering disadvantages associated with neutral beam injection,⁴ the utilization of externally-launched radio-frequency waves in this capacity lends itself as an intriguing possibility which we consider in this work. For low-frequency waves, we propose kinetic Alfvén

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waves (KAW), which are shown to drive sheared $\mathbf{E} \times \mathbf{B}$ flows as a result of the radial variation in the electromagnetic Reynolds stress.⁵ In the high frequency regime, we consider ion Bernstein waves (IBW), and show that they generate sheared poloidal rotation through the ponderomotive force. In either case, it is shown that modest amounts of absorbed power ($\sim$ few 100 kW) are required to suppress turbulence in a region of several cm radial width.

II. KINETIC ALFVÉN WAVE FLOW DRIVE

We first consider the application of kinetic Alfvén waves in connection with sheared flow drive and turbulence suppression at the plasma edge.⁵ To minimize losses due to radial attenuation, the location of the Alfvén resonance r_A [where $\omega = k_{\parallel}(r_A)v_A$] is taken to be very close to the plasma edge. The time evolution of the average poloidal flow, in the low-frequency, cylindrical approximation, is driven by the electromagnetic Reynolds flux and damped by neoclassical magnetic pumping:

$$\frac{\partial \langle v_{\theta} \rangle}{\partial t} = \frac{d \langle \mathcal{S} \rangle}{dr} - \mu_{neo} \langle v_{\theta} \rangle, \quad (2)$$

where $\langle \mathcal{S} \rangle = v_A^2 \langle \tilde{B}_r \tilde{B}_{\theta} / B_0^2 \rangle - \langle \tilde{v}_r \tilde{v}_{\theta} \rangle$ is the electromagnetic Reynolds stress (or equivalently, ponderomotive pressure), $\mu_{neo} = \alpha \nu_{ii}$ is the magnetic pumping frequency ($\alpha \simeq \epsilon = r/R$ in the plateau regime and $\sim \omega_{ti}^2 / \nu_{ii}^2$ in the Pfirsch-Schlüter regime), and $(\tilde{\mathbf{v}}, \tilde{\mathbf{B}})$ are the KAW velocity and magnetic field fluctuations. Equation (2) indicates that for rotational flow to be generated, one must have *i)* radially propagating waves (since for standing waves, the cross-correlations are identically zero), and *ii)* an imbalance between the fluid and magnetic stresses. These criteria are satisfied by KAW's, for which the radial wave vector is complex, and ion inertia introduces an imbalance between electric and magnetic fluctuations. Thus, $k_r = k_r^R + i k_r^I$, where $k_r^R \rho_s = [(\omega^2 / k_{\parallel}^2 v_A^2) - 1]^{1/2}$ characterizes the radially propagating component of the wave vector ($\rho_s = c_s / \Omega_i$, $c_s^2 = 2T_e / m_i$ is the sound speed, and $\Omega_i = eB_0 / m_i c$), and $k_r^I / k_r^R = \delta_e / 2$ characterizes the evanescence scale length, where δ_e is electron dissipation. For a collisionless ($\omega_{te} \gg \nu_e$) plasma, $\delta_e = \pi(\omega / |\omega_{te}|) \exp(-\omega^2 / \omega_{te}^2)$, and for a collisional ($\omega_{te} \ll \nu_e$) plasma, $\delta_e = \omega \omega_{te}^2 / \nu_e [\omega^2 + (\omega_{te}^2 / \nu_e)^2]$, where $\omega_{te} = k_{\parallel} v_{te}$. Using $\tilde{A}_{\parallel k} = (1 + k_{\perp}^2 \rho_s^2) (k_{\parallel} c / \omega) \tilde{\phi}_k$ as appropriate for KAW's, we obtain $\langle \mathcal{S} \rangle = k_r^R k_{\theta} \rho_s^2 k_{\perp}^2 \rho_s^2 c_s^2 \langle |e\tilde{\phi} / T_e|^2 \rangle$, and for steady flows,

$$\frac{\langle v_{\theta} \rangle}{c_s} = \delta_e \frac{\omega^2}{\mu_{neo} k_{\theta} c_s} \left\langle \left| \frac{\tilde{\xi}_r(r_A)}{\rho_s} \right|^2 \right\rangle \left(\frac{\omega^2}{k_{\parallel}^2 v_A^2} - 1 \right)^2 \exp(-2k_r^I |r - r_A|), \quad (3)$$

where $\tilde{\xi}_r = d\tilde{v}_r / dt$ is the radial displacement vector. Substituting this expression into Eq. (1), we obtain the amount of absorbed power required to suppress turbulence over a radial width Δr :

$$P_{abs} > \frac{\pi^2}{2} m_i n_i a R \rho_s c_s^2 \delta_e^{-2} \frac{C_0 \Delta \omega_{k'}}{k'_{\theta} \Delta x_{k'}} \frac{\omega \mu_{neo}}{\Omega_i k_{\theta} c_s} \frac{\rho_s}{L_n} \left(\frac{\omega^2}{k_{\parallel}^2 v_A^2} - 1 \right)^{-5/2} \exp(2k_r^R \Delta r), \quad (4)$$

where $L_n^{-1} = -d \ln n_i / dr$ is the density scale length, and a and R are the plasma minor and major radius, respectively. In deriving Eq. (4), $\tilde{\xi}_r$ was eliminated in terms of the absorbed power to which it is related by⁶ $P_{abs} = (\pi/4) a R \omega (|\tilde{\xi}_r|^2 / k_{\theta}^2) d(4\pi m_i n_i \omega^2 - k_{\parallel}^2 B_0^2) / dr$. As an example, assuming drift wave-like turbulence ($\Delta \omega_{k'} \sim \omega_{*e} = k_{\theta} c T_e / e B L_n$, $k'_{\theta} \Delta x_{k'} \sim 1$, and $k'_{\theta} \rho_s \sim 0.2$), for TEXT

edge parameters ($B_0 = 20$ kG, $n_0 = 5 \times 10^{12} \text{ cm}^{-3}$, $T_e = 30$ eV), $P_{abs} = 300$ kW is required for a 3 cm wide zone of enhanced confinement. Similar estimates for the edge of DIII-D ($B_0 = 21$ kG, $n_0 = 10^{13} \text{ cm}^{-3}$, and $T_e = 150$ eV) indicate that $P_{abs} = 300$ kW will result in a 4 cm wide turbulence suppression zone.

III. PONDEROMOTIVE FLOW GENERATION BY ION BERNSTEIN WAVES

One of the dilemmas of thermonuclear fusion research is that confinement quality in the plasma core must be simultaneously high enough to allow for the possibility of ignition, yet low enough so as to allow for the rapid removal of helium ash. An *active* knob with which confinement quality in the plasma core could be regulated would therefore be a major boon to the fusion program. It is with this motivation in mind that we now turn to the possibility of using high-frequency RF waves to suppress *core* plasma turbulence through the generation of sheared rotation. The proposed RF scheme must *i*) be able to access the high-temperature plasma interior, *ii*) have very short perpendicular wavelength (as shall become clear momentarily), *iii*) have high power density, and *iv*) not adversely affect plasma confinement in other ways. As a working paradigm, we consider here the utilization of ion Bernstein waves in this regard. These quasi-electrostatic waves, for which $n_\perp^2 \gtrsim K_{zz} \gg n_\parallel^2 \sim K_{xx} \sim K_{xy}$, and $\tilde{E}_x \gg \tilde{E}_z \gg \tilde{E}_y$, satisfy the dispersion relation

$$\frac{n_\perp^2}{K_{zz}} + \frac{n_\parallel^2}{K_{xx}} \simeq 1, \quad (5)$$

where $\mathbf{n} = c\mathbf{k}/\omega$, $\mathbf{k} = k_\perp \hat{\mathbf{e}}_x + k_\parallel \hat{\mathbf{e}}_z$, and K_{xx} , K_{xy} , and K_{zz} are the elements of the hot plasma dielectric tensor⁷ and incorporate cyclotron damping on the minority species (in K_{xx}) and electron Landau damping (in K_{zz}). The total power absorbed comes predominantly from the sloshing energy of the ions and given by $P_{abs}/A \simeq (v_{ph\perp}/4\pi) |\tilde{E}_x|^2 \partial K_{xx}/\partial \ln b_i$, where $v_{ph\perp} = \omega/k_\perp$, and $b_i = k_\perp^2 \rho_i^2/2$. The perpendicular ion flow pattern associated with the wave is

$$\begin{pmatrix} \tilde{v}_x \\ \tilde{v}_y \end{pmatrix}_i \simeq i \frac{\omega \Omega_i}{\omega_{pi}^2} \begin{pmatrix} K_{xx} \\ K_{xy,i} \end{pmatrix} \frac{c \tilde{E}_x}{B_0}, \quad (6)$$

where the subscript ‘*i*’ refers to ions. The nonlinearly-generated, ponderomotive ion poloidal flow at steady state is then given by

$$\langle v_y \rangle \simeq \mu_{neo}^{-1} \langle \tilde{\mathbf{v}} \cdot \nabla \tilde{\mathbf{v}}_y \rangle \simeq \left(\frac{\omega \Omega_i}{\omega_{pi}^2} \right)^2 \frac{k_\perp^R}{\mu_{neo}} K_{xx} |K_{xy,i}| \left\langle \left| \frac{c \tilde{E}_x(r_0)}{B_0} \right|^2 \right\rangle \exp(-2k_\perp^I |x - r_0|), \quad (7)$$

where $(k_\perp^R, k_\perp^I)$ represent the radially propagating and evanescent components of the perpendicular wavenumber, and r_0 is the radial location of the resonance layer. Eliminating the field amplitude in terms of the absorbed power and substituting into Eq. (1), we obtain the power requirement to suppress turbulence over a layer of radial width Δr :

$$P_{abs} > \frac{r_0 R B^2}{4} \frac{c^2 v_{ti}^2}{v_A^4} \frac{\mu_{neo}}{\omega} \frac{C_0 \Delta \omega_{k'}}{k_\theta' \Delta x_{k'}} \frac{n_\perp^2 - K_{zz}}{n_\parallel^2 K_{zz}} \frac{\partial \ln K_{xx}/\partial b_i}{|K_{xy,i}|} \frac{\exp(2k_\perp^I \Delta r)}{k_\perp^I}, \quad (8)$$

A simple estimate of the (cyclotron) damping decrement $k_\perp^I$ can be obtained from the field fall-off, i.e., $(k_\perp^I R)^{-1} \sim \Delta B/B \sim (\omega - \Omega_{i,m})/\omega \sim 3k_\parallel v_{ti,m}/\omega$, where the subscript ‘*m*’ denotes the

minority ion species. Again, assuming drift wave-like turbulence for the case of PLT ($B_0 = 30$ kG, $n_0 = 3 \cdot 10^{13} \text{ cm}^{-3}$, $T_i = 1$ keV, $R = 132$ cm, $r_0 = 40$ cm), we find $P_{abs} > 300$ kW for confinement enhancement over a 7cm wide radial zone. It is interesting to note that there have been a number of experiments which have observed confinement improvement, turbulence suppression, and/or poloidal rotation generation in connection with IBW heating. On PLT,⁸ for example, the energy confinement time with the application of 650 kW IBWH yielded a factor 1.7 improvement over the value associated with neutral beam-heated L -mode discharges at the same density. Furthermore, the electrostatic density fluctuations, as measured by microwave scattering, were observed to drop in magnitude by a significant factor relative to the *equivalent-density* ohmic phase, while the frequency spectrum was Doppler-shifted, suggesting a net increase of the poloidal rotation velocity. Further evidence of confinement improvement with the application of IBWH comes from JIPPTII-U,⁹ where transport analysis shows that the ion thermal diffusivity, χ_i , decreases with the application of 400 kW of IBW in the vicinity of the core plasma region where the wave is deposited. The reduction in transport coefficients is accompanied by a sharp steepening of the density profiles.

In summary, our calculations indicate that RF waves afford a promising means of actively controlling plasma confinement quality. We have found that modest amounts ($\sim$ several hundred kW) of power are required to cause a local suppression of turbulence and consequent confinement improvement either at the plasma edge or in the plasma core. The possibility of helicity injection current drive has also been explored and will be presented elsewhere.

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