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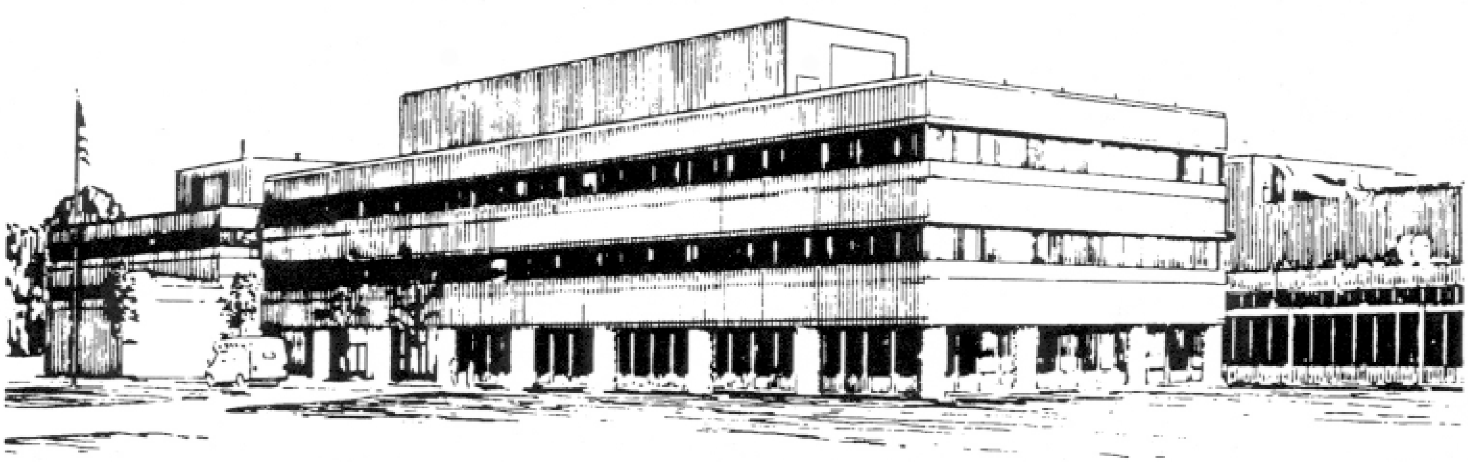

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Effects of Radial Electric Fields on ICRF Waves

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Abstract. Equilibrium considerations infer that large localized radial electric fields are associated with internal transport barrier structures in tokamaks and other toroidal magnetic confinement configurations. In this paper, the effects of an equilibrium electric field on fast magnetosonic wave propagation are considered in the context of a cold plasma model.

INTRODUCTION

In recent years, enhanced confinement regimes characterized by large localized pressure gradients and sheared rotational velocity profiles have been observed in many tokamaks. Equilibrium considerations indicate that large localized radial electric fields are associated with these internal transport barrier (ITB) structures. In particular, if the pressure and rotational velocity profiles for a given species are known, then the equilibrium electric field can be inferred from:

$$\vec{E} + \vec{v}\times\vec{B} = \nabla p. \tag{1}$$

In experiments on TFTR in which an ITB was formed using co-dominated neutral beam-driven toroidal rotation, significant localized radial electric fields on the order of 7 X 10^4 V/m were inferred [1]. These equilibrium electric fields were localized to a region centered near r/a ~ 0.3, with a radial extent of ± 20% of the minor radius. Radially-varying equilibrium electric fields on the order of 3 X 10^4 V/m have also been inferred in the core of H-mode discharges on C-Mod which were heated with fast magnetosonic waves in the ion cyclotron range of frequencies (ICRF) [2]. In the Electric Tokamak (ET) device at UCLA, radial electric fields generated by rf-induced fast ion loss will be utilized to drive poloidal rotation and thereby induce the formation of a “global H-mode” [3]. Based on gyrokinetic simulations, radial electric fields with magnitudes on the order of 3 X 10^3 V/m should be sufficient to suppress ion temperature gradient turbulence in ET and improve confinement [4]. Preliminary calculations indicate that equilibrium electric fields on the order of those observed in tokamaks may be present in some NSTX discharges [5].

The propagation and absorption of radio frequency waves in quasineutral plasmas has traditionally been determined assuming that there are no significant equilibrium electric fields present in the plasma. However, in the presence of equilibrium electric fields, the particle orbits are modified and equilibrium velocity flows arise. Hence, the dielectric properties of the plasma may be altered. It has been shown previously by Ganguli, Lee and Palmadesso using kinetic models that nonuniform electric fields perpendicular to ambient uniform magnetic fields can drive electrostatic ion cyclotron instabilities in the earth's ionosphere and magnetosphere [6]. In this paper the effects of an equilibrium radial electric field on fast magnetosonic wave propagation in toroidal magnetic confinement devices will be considered in the context of a locally uniform cold plasma model. Kinetic corrections and effects of nonuniform electric fields will be considered in future work.

MODIFIED COLD PLASMA DIELECTRIC TENSOR

The simplest model that can be used to examine effects of an equilibrium electric field on electromagnetic wave dynamics in quasineutral plasmas is a locally uniform cold plasma description. With the equilibrium magnetic field oriented in the $\hat{z}$ direction and the equilibrium electric field oriented in the $\hat{x}$ direction, the linearized cold fluid equation of motion for species, s, can be written in the form [7]:

$$n_s m_s \frac{d\vec{v}_s}{dt} = n_s\Big(q_s\vec{E}_0 + \frac{q_s}{c}\vec{V}_d \times \vec{B}_0 + q_s\vec{E}_1 + \frac{q_s}{c}\vec{v}_{1s} \times \vec{B}_0 + \frac{q_s}{c}\vec{V}_d \times \vec{B}_1\Big) , \qquad (2)$$

where $\vec{B} = B_0\ \hat{z} + \vec{B}_1$, $\vec{E} = E_0\ \hat{x} + \vec{E}_1$, and $\vec{v}_s = \vec{V}_d + \vec{v}_{sl}$. The perturbed wave fields and particle velocities are assumed to have a wave-like dependence in the form $\vec{E}_1 = \vec{E}_1\ e^{i(\vec{k}\cdot\vec{x}-\omega t)}$, and similarly for $\vec{B}_1$, $\vec{v}_1$. In the unperturbed steady state, the first two terms on the right hand side of Equation (2) must balance, indicating that the unperturbed plasma is drifting with the $\vec{E}\times\vec{B}$ velocity:

$$\vec{V}_d = \frac{c\vec{E}_0 \times \vec{B}_0}{{B_0}^2} = V_d\ \hat{y} = -\frac{cE_0}{B_0}\ \hat{y} . \qquad (3)$$

For the simple uniform plasma model considered here, the equilibrium drift speed is a constant, so a transformation to a moving coordinate system could be utilized. However, in general the experimentally observed equilibrium electric fields are nonuniform, so inclusion of this non-uniformity would entail the use of spatially dependent frame transformations. Hence, in order to apply this model locally to a radially inhomogeneous tokamak plasma, the wave dynamics will be calculated in the "laboratory" frame to avoid these complications.

By combining the first order terms in Equation (2) with the linearized Maxwell equations, the perturbed velocity for each species can be expressed in terms of equilibrium quantities, wave parameters, and the wave electric field. Finally, the perturbed plasma current, which constitutes the response of the plasma to the applied wave fields, can be constructed from two terms, one arising directly from the wave-driven velocities and one arising from the zeroth order flow:

$$\vec{j} = -\frac{i\omega}{4\pi}\sum_s \vec{\vec{\chi}}_s \cdot \vec{E}_1 = \sum_s \left[n_{s0} q_s \vec{v}_{s1} + n_{s1} q_s V_d \ \hat{y} \right] \quad . \tag{4}$$

In this expression, the perturbed density, n_{s1}, obtained from the continuity equation, is given by:

$$n_{s1} = n_{s0} \frac{\vec{k} \cdot \vec{v}_{s1}}{\omega_*}, \text{ where } \omega_* = \omega - k_y V_d . \tag{5}$$

Solving Equation (4) for the susceptibility for each species, one finds:

$$\vec{\vec{\chi}}_s = \begin{bmatrix} \left(\frac{\omega_*}{\omega}\right)^2 A_1 & \left(\frac{\omega_*}{\omega}\right) A_1 \left(\frac{i\Omega_{0s}}{\omega_*} + \Phi_x\right) & 0 \\ \left(\frac{\omega_*}{\omega}\right) A_1 \left(\frac{-i\Omega_{0s}}{\omega_*} + \Phi_x\right) & A_1(1+\Phi_x^2) - \left(\frac{\omega_{ps}}{\omega_*}\Phi_z\right)^2 & -\left(\frac{\omega_*}{\omega}\right)\left(\frac{\omega_{ps}}{\omega_*}\right)^2 \Phi_z \\ 0 & -\left(\frac{\omega_*}{\omega}\right)\left(\frac{\omega_{ps}}{\omega_*}\right)^2 \Phi_z & -\left(\frac{\omega_{ps}}{\omega}\right)^2 \end{bmatrix}, \tag{6}$$

where $A_1 = -\frac{\omega_{ps}^2}{\omega_*^2 - \Omega_{0s}^2}$, $\Omega_{0s} = \frac{q_s B_0}{m_s c}$, and $\Phi_i = \frac{k_i V_d}{\omega}$, for i = x, y, z. The cold plasma dielectric tensor, generalized to include the effects of the equilibrium electric fields, is finally given by $\vec{\vec{\varepsilon}} = \vec{\vec{1}} + \sum_s \vec{\vec{\chi}}_s$. Note that the modified susceptibility reduces to the conventional form [7] when the electric-field induced equilibrium drift speed vanishes.

DISCUSSIONS AND FUTURE WORK

The modified cold plasma dielectric tensor given in Equation (6) is hermitian for real ω, $\vec{k}$ so no new damping or instability mechanisms have been introduced in this approximation. However, the modified dielectric tensor elements now depend on the wave vector components. Furthermore, in some of the terms that lead to resonances and cutoffs in the conventional cold plasma model, the wave frequency appears in the Doppler-shifted form, $\omega_* = \omega - k_y V_d$. The equilibrium magnetic field in a tokamak has both poloidal and toroidal components, so the equilibrium $\vec{E} \times \vec{B}$ drift velocity also has both poloidal and toroidal components. In TFTR and C-Mod, typical toroidal rotation speeds are on the order of 10^5 m/s [1, 2] and typical toroidal wave vector components are on the order of 10 m^{-1}. For these experiments, the electric field induced Doppler shift is on the order of 1 MHz – a value small compared to the launched wave frequencies of 30 – 80 MHz in these devices. Hence, corrections to the cold plasma wave dynamics due to an equilibrium electric field appear to be small in conventional tokamaks. However, the corrections in low magnetic field devices such as NSTX or ET could prove to be larger, since the ion cyclotron frequency is on the order of a few MHz in these devices. Finally, spatially localized electric fields perpendicular to ambient magnetic fields have been shown to destabilize electrostatic ion cyclotron waves [6]. Therefore, in future studies, the effects of spatially localized electric fields on the propagation and absorption of fast magnetosonic waves will be explored using kinetic models.

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