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Co-counter Asymmetry in Fast Wave Heating and Current Drive and Profile Control in NSTX

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1. Introduction

Different plasma responses to neutral beam injection in directions co and counter to the plasma current have long been accepted as well understood in neutral beam heating of tokamak plasmas [1]. Similar differences have now been observed in electron heating and current drive experiments with toroidally phased antenna arrays in the ion cyclotron range of frequencies (ICRF) on the DIII-D tokamak [2]. Initially, such differences are puzzling because almost all radio frequency (RF) heating models are based on the homogeneous plasma dielectric tensor [3], which exhibits no obvious asymmetry for propagation in different longitudinal directions. But coupling of power between the antenna and the plasma is also a critical part of the problem, and it is here that the asymmetries become apparent. First, even for the homogeneous case, there are up-down (i.e., poloidal) asymmetries in wave propagation caused by the direction of Hall currents with respect to the applied magnetic field. This is observed as a shift in the poloidal spectrum of power radiated from the antenna in a magnetized plasma column with straight magnetic field lines [4]. The shift is symmetric in the longitudinal wave number, but symmetry is broken when a poloidal magnetic field is applied. This was first noticed in the ST tokamak [5] when split eigenmodes were observed for each value of the toroidal wave number.

In this paper, full-wave ICRF coupling models are applied to understand the difference in plasma response when antenna arrays are phased to drive currents co and counter to the plasma current. The source of this difference lies in the natural up-down asymmetry of the antenna's radiated power spectrum caused by Hall currents. When a poloidal field is applied, this up-down asymmetry acquires a toroidal component. The result is that plasma absorption (i.e., antenna loading) is shifted or skewed toward the co-current drive direction, independent of the direction of the magnetic field. When waves are launched to drive current counter to the plasma current, electron heating and current profiles are more peaked on axis, and this peaking becomes more pronounced at lower toroidal magnetic fields.

2. Symmetry of the Cold Plasma Wave Equation

Consider a two-dimensional (2-D) slab plasma in Cartesian coordinates with an external magnetic field B_0 aligned along the z axis. Assuming that the component of the RF electric field parallel to B_0 is zero (zero electron mass limit, [6]) and periodic dependence of the RF fields in the z direction, a simple wave equation can be written for B_z, the RF magnetic field in the longitudinal direction:

$$\left(\frac{\omega}{c}\right)^2 B_z + i\left[\frac{\partial B_z}{\partial y}\frac{\partial}{\partial x}\left(\frac{K_x}{(K_\perp - n_\zeta^2)^2 - K_x^2}\right) - \frac{\partial B_z}{\partial x}\frac{\partial}{\partial y}\left(\frac{K_x}{(K_\perp - n_\zeta^2)^2 - K_x^2}\right)\right] + \nabla\cdot\left(\frac{(K_\perp - n_\zeta^2)\nabla B_z}{(K_\perp - n_\zeta^2)^2 - K_x^2}\right) = 0 \qquad (1)$$

The second term (in square brackets) results from Hall currents that flow from the $\boldsymbol{E}\times\boldsymbol{B}$ force and is proportional to density and magnetic field gradients through the dielectric tensor element K_x. When K_x and $K_\perp$ are real, Eq. (1) is invariant under the transformation $B_z(x,y) \Rightarrow B_z^*(x,-y)$ or equivalently for the RF electric fields: $E_x(x,y) \Rightarrow E_x^*(x,-y)$ and $E_y(x,y) \Rightarrow -E_y^*(x,-y)$, where * denotes complex conjugate. The condition that K_x and $K_\perp$ are real is consistent with the usual cold plasma assumption of no collisions and therefore no absorption of wave energy. When collisions are included, K_x and $K_\perp$ become complex, and the up-down symmetry of Eq. (1) is destroyed.

These conclusions are borne out by full-wave calculations with the PICES [7] global wave code including a finite parallel RF electric field and warm plasma effects. The result in Fig. 1 is for a single toroidal harmonic, $n_\zeta = 10$, with 32 poloidal (ϑ) harmonics and 100 radial (ρ) mesh points. The geometry is that of a tokamak similar to DIII-D with no poloidal magnetic field and $B_0 = -2.0$ T (into page), $R_{axis} = 1.8$ m, $\kappa = 1.9$ (elongation), $R_{plasma} = 2.31$ m, $f = 60$ MHz, and $n_{e,0} = 3.0\times10^{19}$ m^{-3}. The majority ion species is deuterium with a 2% minority fraction of hydrogen. Results are calculated for (a) zero temperature and (b) finite temperature. E_ρ and E_ϑ correspond to E_x and E_y, respectively, in the slab model. Note the perfect up-down symmetry of E_ρ in (a) without absorption. When absorption is included in (b) through finite temperature, the up-down symmetry is destroyed. A plot (not shown) of the radiated power spectrum in front of the antenna shows that the direction of energy flow in (b) is down. Reversing the sign of B_0 reverses the direction of energy flow.

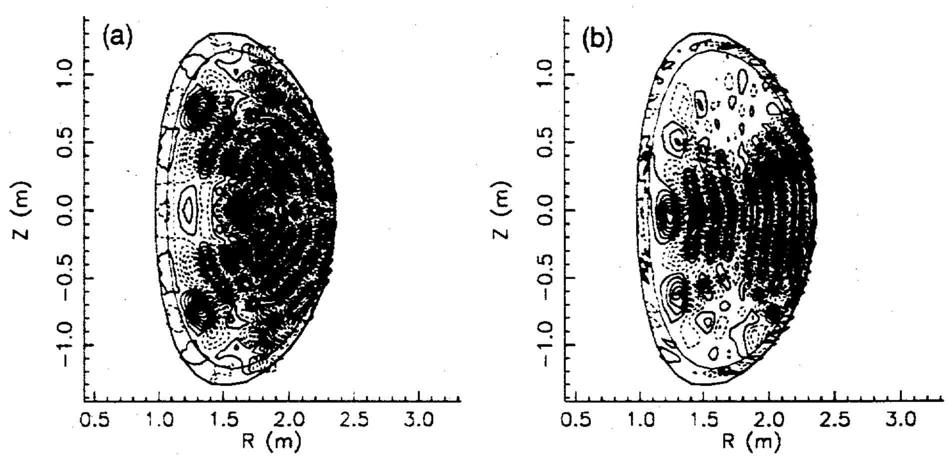

Fig. 1. Wave electric field $Re(E_\rho)$ from the PICES code [7] for no poloidal magnetic field with (a) zero temperature and (b) finite temperature ($T_e = 20$ keV, $T_i = 8$ keV).

3. Co-counter Asymmetry

When a poloidal magnetic field is introduced, the up-down asymmetry acquires a toroidal component. In this case, the plane of the magnetic field in front of the antenna is tilted due to the pitch of the field lines. For a positive plasma current, the downward direction of energy flow in Fig. 1(b) has a toroidal component in the $-\zeta$ or "co current" drive direction. (Note that because of the negative electron charge, waves traveling in the $-\zeta$ direction drive current in the

+ ς direction). Thus, an antenna that is phased to launch waves in the $-\varsigma$ direction transfers more energy to the plasma (loads better) than the same antenna phased to launch waves in the $+\varsigma$ direction. This is shown in Fig. 2(*a*) where the spectrum of absorbed power is plotted vs toroidal mode number for $B_\varsigma < 0$ and $B_\vartheta > 0$. The calculation includes 100 uniformly excited toroidal modes. Parameters are those expected for the National Spherical Tokamak Experiment (NSTX) [8]: $B_0 = -0.30$ T, $R_0 = 0.8$ m, $I_p \approx 1$ MA, $\kappa = 2.0$ (elongation), $R_{wall} = 1.39$ m, $f = 41$ MHz, $n_{e,0} = 3.0 \times 10^{19}$ m^{-3}, $T_{e,0} = 2.0$ keV and $T_{i,0} = 1.0$ keV. In NSTX, the co-counter asymmetry is particularly strong because of the large poloidal magnetic field near the antenna.

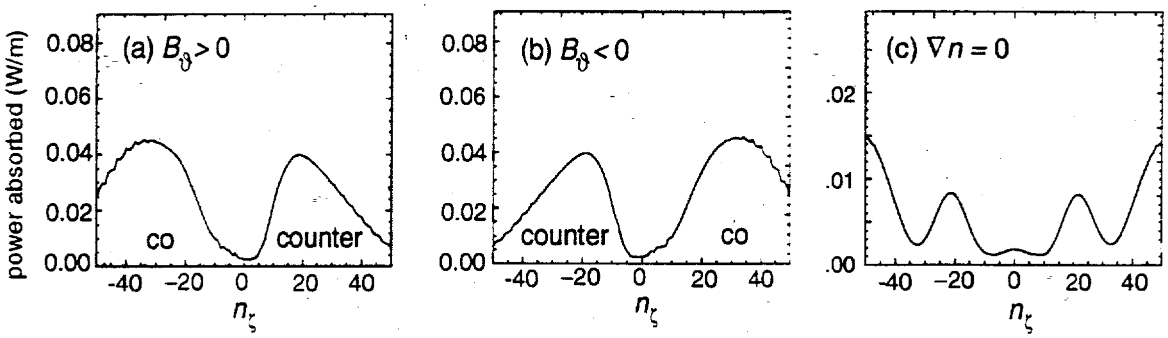

Fig. 2. Spectrum of absorbed power in NSTX with $B_\zeta < 0$ and (a) $B_\vartheta > 0$. In (b) $B_\vartheta < 0$, and in (c) the density gradient is set to zero.

When the sign of B_ϑ is reversed in Fig. 2(b), the asymmetry is also reversed. But in this case, the plasma current also changes sign so that co and counter directions reverse, and loading remains highest for the co direction. The general conclusion is that plasma absorption and hence antenna loading are always shifted or skewed toward the co-current drive direction independent of the direction of the applied magnetic field. When density gradients are forced to zero as in Fig. 2(c), both up-down and co-counter asymmetries are eliminated because the Hall terms in Eq. (1) are proportional to density gradients.

Current drive efficiency is also affected by the direction that waves are launched relative to the plasma current. Figure 3 shows radial profiles of the driven current density $J(\rho)$ and integrated current $I(\rho)$ for the example of Fig. 1, but includes a positive poloidal magnetic field.

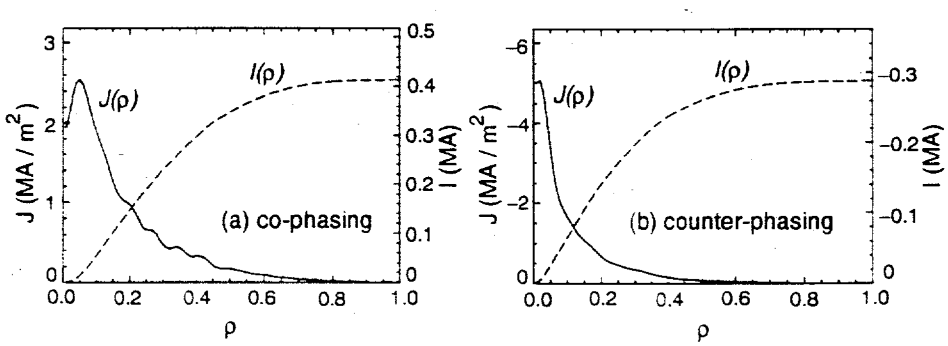

Fig. 3. Driven current profiles for the case of Fig. 1 but with a positive poloidal magnetic field and a smaller toroidal magnetic field ($B = -1.7$ T): (a) co-phasing; (b) counter-phasing.

Although the total current is slightly higher for co-phasing in (a), the current density profile is more peaked near the axis for counter-phasing in (b). This peaking is more pronounced at low toroidal magnetic fields because the Hall terms in Eq. (1) are proportional to the magnitude of the $E \times B$ drift velocity (E/B).

4. Current Profile Control in NSTX

The ideas in this paper suggest new ways for optimizing antenna performance in advanced tokamaks such as NSTX. The discussion in Secs. 2 and 3 suggests that poloidal phasing and/or poloidal positioning of the antenna could be used to partially cancel or reinforce the natural up-down shift of the antenna's radiation pattern. Also, RF power can be used to control the total current profile shape by driving current co or counter to the bootstrap current. An example is shown in Fig. 4 where a fast wave current of about 100 kA is used to partially cancel or reinforce the bootstrap current (≈ 200 kA) in NSTX. The ohmic current is adjusted in both cases to keep the total plasma current constant at about 1 MA. Depending on the direction of the fast wave current relative to the bootstrap current, two distinctly different current profiles are obtained in Fig. 4. This provides a unique opportunity to use RF power in advanced tokamaks to influence turbulence and stability properties as well as to control transport barriers.

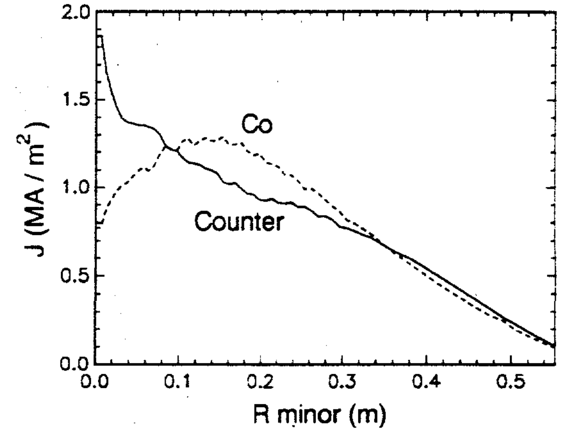

Fig. 4. Total current density profile in NSTX for the case of Fig. 2(a). The RF power is phased co and counter to the bootstrap current. Integrated current is 1 MA for both cases.

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References

[1] J. A. Rome, J. D. Callen, J. F. Clarke, Nucl. Fusion **14** 141 (1974).

[2] C. C. Petty, et al., "Direct Electron Absorption of Fast Waves on the DIII-D Tokamak" in *Radiofrequency Heating and Current Drive of Fusion Devices,* (Proc. Euro. Top. Conf., Brussels, 1992) Vol **16E**, EPS, p. 177 (1992).

[3] T. H. Stix, *Waves in Plasmas* (American Institute of Physics, New York, 1992)

[4] A. M. Messiaen, et al., Nucl. Fusion **15** 75 (1975) .

[5] J. Adam, et al., "Wave Generation and Heating in the ST-Tokamak at the Fundamental and Harmonic Ion Cyclotron Frequencies", in *5th Conf. on Plasma Physics and Controlled Nuclear Fusion Research*, Tokyo, IAEA-CN-33/A3-2, 1974.

[6] E. F. Jaeger, D. B. Batchelor, H. Weitzner, J. H. Whealton, Comput. Phys. Commun. **40,** 33 (1986).

[7] E. F. Jaeger, D. B. Batchelor, D. C. Stallings, Nucl. Fusion **33** 179 (1993) .

[8] M. Ono, Phys. Plasmas **2** 4075 (1995) .