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GLOBAL WAVE MODELING OF ELECTRON INTERACTIONS WITH FAST MAGNETOSONIC WAVES*

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INTRODUCTION

Electron interactions with fast magnetosonic waves are of interest for both direct electron heating and fast-wave current drive (FWCD) in tokamaks. Here we apply the full-wave ICRF code PICES¹ to examples of both of these applications. To realistically account for the actual D-shaped magnetic geometry of present-day tokamaks, PICES is interfaced with the 3-D MHD equilibrium code VMEC.² Likewise, to correctly model the real toroidal structure of both source and image currents in ICRF current drive antennas, PICES is interfaced with the 2-D recessed antenna impedance code RANT.³ Both current drive and electron heating by fast waves can be strongly altered through modification of the $k_{\parallel}$ -spectrum by the poloidal magnetic field. A poloidal mode expansion in PICES allows such variations in $k_{\parallel}$ to be included correctly. In this paper, comparisons are made to observations of the direct electron heating profile on TFTR⁴ and to the FWCD efficiency on DIII-D.⁵ We also extrapolate to make predictions for future tokamaks such as TPX and ITER.

THE PICES FULL-WAVE CODE

The PICES (Poloidal Ion Cyclotron Expansion Solution) code was designed specifically to treat electron interactions with fast magnetosonic waves. Poloidal and toroidal mode expansions are used to solve the reduced-order⁶ wave equation in full toroidal geometry using general flux coordinates:

$$-\nabla \times \nabla \times \vec{E} + \frac{\omega^2}{c^2} \left(\vec{E} + \frac{i}{\omega \epsilon_0} \vec{J}_p \right) = -i\omega \mu_0 \vec{J}_{ext} \quad (1)$$

In Eq. (1) $\vec{J}_{ext}$ represents the antenna current, and $\vec{J}_p$ is the plasma current as determined by the constitutive relation $\vec{J} = \vec{\sigma} \cdot \vec{E}$, which is expressed as a sum over poloidal and toroidal harmonics of the electric field.⁷ Because the plasma conductivity $\vec{\sigma}$ is expanded to second order in Larmor radius, only harmonic resonances up to second order are retained to lowest order. However, higher-order resonances are still included in the wave solution and power absorption by adding additional terms to σ_{xx} and σ_{xy} that are obtained from a selective series expansion of the modified Bessel function, I_ℓ , for small argument.

The calculation includes a full (nonperturbative) solution for $E_{\parallel}$ and uses the reduced-order form of the plasma conductivity tensor⁶ to eliminate numerical

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problems associated with resolution of very short wavelength ion Bernstein waves.⁷ By solving the wave equation in two spatial dimensions (ρ, ϑ) , PICES calculates the wave electric field, $\vec{E}$, the wave plasma current, $\vec{J}_p$, and the power absorbed per unit length. The poloidal mode expansion in ϑ allows variations in $k_{\parallel}$ to be included correctly, while the ρ dimension is treated by finite differences. Variations in the toroidal dimension ζ are included by summing toroidal harmonics weighted by a particular antenna spectrum. Toroidal harmonics are uncoupled because of the azimuthal symmetry and can therefore be calculated individually. Poloidal harmonics, on the other hand, are tightly coupled by the toroidal $(1/R)$ dependence of $\vec{B}$ as well as by the noncircularity of the magnetic flux surfaces and must therefore be calculated simultaneously.

DIRECT ELECTRON HEATING ON TFTR

Recently, direct electron heating experiments have been carried out by Murakami et al.⁴ on NBI-heated supersonic deuterium plasmas in TFTR. Modulation of the rf power allows direct measurement of the electron power deposition profile, q_e . Experimental results in Fig. 1(a) show that q_e is strongly peaked in the plasma core, and the total integrated power, P_e , is about 72% of the applied power, $P_{rf} \sim 1.65$ MW. The magnitude and profile shape agree well with those predicted by PICES in Fig. 1(b). For hydrogen plasmas, PICES predicts a very different heating profile due to Alfvén wave heating of electrons in a narrow band located at the shear Alfvén resonance.⁸

FAST-WAVE CURRENT DRIVE ON DIII-D

In addition to providing an alternative to minority ion cyclotron heating (but without the associated ion tails), direct electron heating provides the basis for FWCD in tokamaks. The first evidence of this process in a large tokamak has been reported by Pinsker et al.⁵ on DIII-D, where about 25% of the total plasma current was sustained by fast waves launched from a directionally phased four-strap antenna array. Figure 2 (from Ref. 5) shows the observed dependence of current drive efficiency on electron temperature for co-FWCD in $B_0 = 1$ T discharges. Circles and squares indicate normal and ECH preheated discharges, respectively. For $Z_{eff} = 3.5$, the efficiency predicted by PICES (shown by the solid and dashed lines for co- and counter-FWCD, respectively) agrees quite well with the observed values.

FUTURE EXPERIMENTS ON TPX AND ITER

A good model for electron interactions with fast waves should not only describe present observations but should also make definite predictions about future observations. In this section, we consider predictions for future experiments on TPX and ITER. Figure 3 shows a frequency scan for TPX parameters. The toroidal mode number is varied with frequency to match the wave's phase velocity to the electron thermal velocity at plasma center. Peaks in the current drive efficiency γ (solid line) occur at frequencies $f \sim 45$ MHz and 75 MHz, where parasitic ion absorption by deuterium (P_D), hydrogen (P_H), and neutral beam deuterium (P_{beam}) are minimum. The remaining fraction

which is absorbed by electrons (P_e) is maximum at these same frequencies. More detailed calculations at 45 MHz suggest that about half of the total required plasma current in TPX can be sustained by FWCD, the remaining fraction being provided by the bootstrap current. As expected, the resulting current profile is centrally peaked and gives a self-consistent q -profile that is less than unity on axis.

Such steady-state operating points do not appear to be practical in the latest designs for ITER-R, where average wall loading (W) is 1 MW/m^2 and plasma current (I_p) is about 25 MA. However, if the critical electron temperature gradient model for power balance holds, there appear to be some low current scenarios ($I_p \sim 5 \text{ MA}$ and $q_{95} \sim 14$) where steady-state operation may be practical.⁹ These cases exhibit reduced wall loading $W \sim 0.2 \text{ MW/m}^2$ with $Q \sim 10$. An example is shown in Fig. 4(a) where 34 MW of fast-wave power at 21 MHz drives about 2 MA of current with 3 MA of bootstrap current. The equilibrium plasma assumes $T_{e0} = 33 \text{ keV}$ with $n_{e0} = 0.7 \times 10^{20} \text{ m}^{-3}$. In this case the current drive efficiency $\gamma \sim 0.29 \text{ A/W} \cdot \text{m}^2$ is limited only by the $k_{||}$ -upshift, and the resulting current profile is quite broad. An alternate scenario in Fig. 4(b) at 69 MHz gives a more centrally peaked current profile with $\gamma \sim 0.31 \text{ A/W} \cdot \text{m}^2$, but in this case, one-third of the power is lost to tritium ions at the second harmonic resonance. This parasitic absorption increases if a tritium tail develops. Less than 1% of the rf power is lost to fast alpha absorption.

SUMMARY AND CONCLUSIONS

The full-wave ICRF code PICES appears to be a good model for electron interactions with fast waves. By this we mean that it describes a large class of present observations on TFTR and DIII-D with only a few adjustable parameters. In addition, it makes definite predictions about observations on future tokamaks such as TPX and ITER. There are still problems which require work, however. A better current drive calculation is needed to calculate electron fluxes directly from a solution to the quasilinear equation rather than from fits to such solutions, as is now the case. Likewise, a self-consistent ion tail calculation would eliminate much of the present uncertainty involving parasitic ion losses.

REFERENCES

1. E. F. Jaeger, D. B. Batchelor, and D. C. Stallings, Nucl. Fusion **33** (1993).
2. S. P. Hirshman, and D. K. Lee, Comput. Phys. Commun. **31**, 161 (1986).
3. D. B. Batchelor et al., Fusion Technology **21**, 1214 (1992).
4. M. Murakami et al., Paper to be presented at the 10th Topical Conference on Radio Frequency Power in Plasmas.
5. R. I. Pinsker et al., IAEA-CN-56/E-2-3 (1992).
6. D. N. Smithe, P. L. Colestock, R. J. Kashuba, and T. Kammash, Nucl. Fusion **27**, 1319 (1987).
7. M. Brambilla, and T. Krucken, Nucl. Fusion **28**, 1813 (1988).
8. R. Majeski, personal communication, December 14, 1992.
9. W. M. Nevins, personal communication, January 18, 1993.

Fig. 1. Direct electron heating in TFTR.

Fig. 2. FWCD efficiency vs electron temperature in DIII-D. Experiment: Pinsker et al., IAEA-CN-56/E-2-4.

Fig. 3. Frequency scan in TPX for $V_{ph} = V_{th}$.

Fig. 4. Current profiles in ITER-R (reduced wall loading $W = 0.2 \text{ MW/m}^2$ and $Q \approx 10$).
 (a) $I_{bs} = 3.16 \text{ MA}$, $I_{fw} = 2.16$; (b) $I_{bs} = 3.16 \text{ MA}$, $I_{fw} = 2.28$.

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