Princeton Plasma Physics Laboratory

PPPL-4247

PPPL-4247

Full-wave Simulations of LH Wave Propagation in Toroidal Plasma with non-Maxwellian Electron Distributions

E.J. Valeo, C.K. Phillips, P.T. Bonoli, J.C. Wright,
M. Brambilla, and the RF SciDAC Team

July 2007

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

Full-wave Simulations of LH wave propagation in toroidal plasma with non-Maxwellian electron distributions

E. J. Valeo*, C. K. Phillips*, P. T. Bonoli†, J. C. Wright†, M. Brambilla**
and RF SciDAC Team

*Plasma Physics Laboratory, Princeton University
Princeton, NJ
†Plasma Science Fusion Center, MIT
Cambridge, MA
**Max-Planck Institute für Plasmaphysik,
Garching bei München, Germany

Abstract. The generation of energetic tails in the electron distribution function is intrinsic to lower-hybrid (LH) heating and current drive in weakly collisional magnetically confined plasma. The effects of these deformations on the RF deposition profile have previously been examined within the ray approximation [1, 2]. Recently, the calculation of full-wave propagation of LH waves in a thermal plasma [3] has been accomplished using an adaptation of the TORIC [4] code. Here, initial results are presented from TORIC simulations of LH propagation in a toroidal plasma with non-thermal electrons. The required efficient computation of the hot plasma dielectric tensor is accomplished using a technique previously demonstrated in full-wave simulations of ICRF propagation in plasma with non-thermal ions [5].

Keywords: simulation, rf heating, current drive
PACS: 52.50.Sw,52.55.Fa,52.55.Wq,52.65-.y

INTRODUCTION

At the power levels required to significantly heat, or drive current in, MFE plasma the rate of quasilinear diffusion in parallel velocity ($v_\parallel = \mathbf{v} \cdot \mathbf{B}/|\mathbf{B}|$) greatly exceeds the collisional diffusion rate – thus ensuring a nonthermal distribution at velocities $\omega/k_{\parallel,max} \leq v_\parallel \leq \omega/k_{\parallel,min}$ encompassed by the parallel velocity spectrum of the lower hybrid (LH) waves. These modifications will, generally, result in finite changes in the amount and spatial location of absorption. To date, these quasilinear modifications been included in ray-tracing simulations [1, 2]. Results from recent full-wave LH simulations[3] using the TORIC-LH code have characteristics similar to the ray calculations (for example, the evidence of multiple radial pass trajectories) but also suggest full-wave effects such as diffraction can play an important role in determining the spectrum (upon which the absorption and current drive profiles sensitively depend). In order to provide a higher fidelity computational tool, TORIC-LH has been extended to allow the prescription of arbitrary electron distributions $f_e(v_\parallel, v_\perp, \psi)$, using methods developed for the recent extension[5] of the sibling full wave finite ion-larmor-radius TORIC[4] code, valid in the ion cyclotron frequency range. For the initial demonstrations presented here, the electron velocity distribution has been prescribed. The ultimate goal is to compute f_e

self-consistently together with the wave fields–as has been recently accomplished for ICRF simulations[6]–by iterating to self-consistency solutions for the wave fields from TORIC-LH with those for f_e computed from a Fokker-Planck such as CQL3D[7] making use there of the TORIC-LH generated quasilinear diffusion coefficients.

TORIC-LH - CODE DESCRIPTION

TORIC-LH solves the wave equation

$$\nabla \wedge \nabla \wedge \mathbf{E} = \frac{\omega^2}{c^2}\mathbf{E} + \frac{4\pi i}{\omega}(\mathbf{J}^P + \mathbf{J}^A) \tag{1}$$

for the vector electric field $\mathbf{E}(\psi,\theta,\phi)$ in response to plasma (P) and antenna (A) current densities, assuming periodic time and toroidal (ϕ) and poloidal (θ) angular variation $\exp i(n\phi + m\theta - \omega t)$. By virtue of this spectral decomposition in (n,m), the local parallel component of the wavevector is explicitly represented as $k_{\|}(\theta,\psi) \equiv \mathbf{k}\cdot\mathbf{b} = \left(m\nabla\theta + n/R\right)\cdot\mathbf{b}$ with $R(\theta,\psi)$ the major radius. With the assumption that the wave-particle interaction is local in (ψ,θ), the linear tensor plasma susceptibility χ relates the plasma current density to the electric field $\mathbf{J}^P(\psi,\theta,\mathbf{k}) = -(i\omega/4\pi)\chi\cdot\mathbf{E}$. The parallel electron susceptibility $\chi_{zz} = -(\omega_p^2/\omega^2)\int d^3v v_{\|}\partial f/\partial v_{\|}/(\omega - k_{\|}v_{\|})$ contains the essential kinetic response. For a Maxwellian distribution with thermal velocity v_{th}, χ_{zz} can be expressed in terms of the plasma dispersion function $Z(\omega/k_{\|}v_{th})$[9]. More generally, the integration must be done numerically. Efficient evaluation is essential. Our solution[5] is to evaluate f at uniformly spaced points $\zeta_j = j\Delta v$. Given $\omega/k_{\|}$, the susceptibility is evaluated at the surrounding $v_{\|}$ mesh points and the required value is found by interpolation. The computational cost is modest. For a 200 point velocity mesh, the numerical evaluation of χ takes about 4 times as long as its evaluation in terms of the Z function, using library routines.

INITIAL RESULTS

We compare simulation results for a thermal plasma to those for one with an electron distribution containing a prescribed, elevated, tail population. As a precursor to self-consistent calculations, the nonthermal electron distribution was modeled by one which qualitatively includes the effect of strong quasilinear diffusion in parallel velocity, such as would be caused by high phase velocity LH waves. The particular form chosen[1] was

$$f_e(v_{\|}) \propto \exp[-\Lambda/v_{th}^2] \tag{2}$$

with

$$\Lambda(v_{\|}) = 2\int_0^{v_{\|}} \frac{du\,u}{[1 + D_{ql}(u)]}$$

where $D_{ql}(u) = 50$ if $1.6 \le u/v_{th}(\psi = 0) \le 8$ and $D_{ql} = 0$ otherwise.

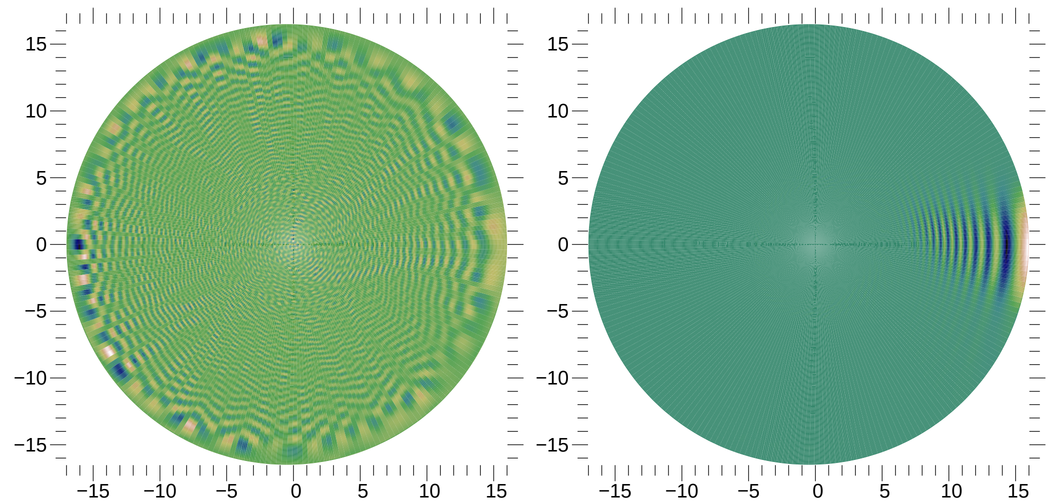

FIGURE 1. Color cell plots of $\mathbf{E}\cdot\hat{\mathbf{b}}$ vs r (horiz.), z (vert.) for Maxwellian (LEFT) and non-Maxwellian Nonthermal $f_e(v_\parallel)$,Eq. (2) (RIGHT).

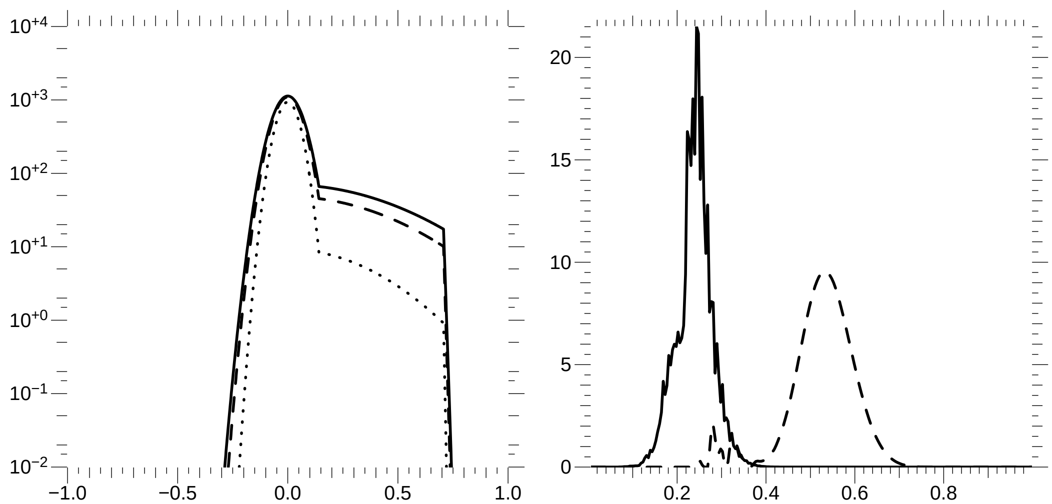

FIGURE 2. LEFT: Nonthermal $f_e(v_\parallel/c)$ at $\psi = 0$ (solid), .25 (dash), and .5 (dot), of the form Eq. (2). RIGHT: $S_{eld}(\psi)$ for Maxwellian (solid) and nonthermal (dashed) electron distributions.

In other respects, the plasma parameters are identical: toroidal magnetic field on axis, $B_T(\psi = 0) = 10$ T; toroidal current $I_T = 170$ kA; safety factor on axis and at the plasma edge $q(0) = 1.1$, $q(1) = 13.3$, respectively; major radius $R_{\mathrm{maj}} = 66$ cm; minor radius $r_{\mathrm{minor}} = 16.5$ cm; central electron density, $n_0 = 5\cdot 10^{13}\,\mathrm{cm}^{-3}$; central electron temperature $T_0 = 1.8\,\mathrm{keV}$. The density and temperature profiles are analytically prescribed with shape $F(\psi) = (1-\psi^2)^2$, $0 \le \psi \le 1$. The waves, launched from the outside midplane, are parameterized by frequency $f = \omega/2\pi = 4.6$ GHz and toroidal wavenumber $n_\phi = 120$ (equivalent $n_\parallel = 1.87$).

For reference, a color cell plot of the parallel component of the electric field $\mathbf{E}\cdot\hat{\mathbf{b}}$ is shown in Fig. 1 (LEFT) for a thermal distribution. The specification of nonthermal f_e, Eq. (2) produces the distribution shown in Fig. 2 (LEFT). With this enhanced tail, the LH waves are much more effectively damped (in a single pass) as shown in Fig. 1 (RIGHT). Absorption occurs at substantially larger ψ as shown in Fig. 2 (RIGHT) where both the thermal (solid) and nonthermal (dashed) electron Landau damping absorption profiles $S_{eld}(\psi)$ are plotted.

In conclusion, The full-wave LH wave simulation code TORIC-LH has been generalized to allow prescription of arbitrary electron distribution functions of the form $f(v_{\|}, v_{\perp}, \theta, \psi)$ in the computation of the plasma susceptibility. Initial results for a model "quasilinear plateau" distribution demonstrated significant modification of the poloidal wave field and absorption patterns as compared to the Maxwellian case for the same macroscopic plasma profiles.

REFERENCES

1. P. T. Bonoli and R. C. Englade, Simulation model for lower hybrid current drive, *Phys. Fluids* 29:2937 1986.
2. D. W. Ignat, E. J. Valeo and S. C. Jardin, Dynamic modelling of lower hybrid current drive, *Nucl. Fusion* 34:837 1994.
3. J. C. Wright, L. A. Berry, P. T. Bonoli, D. B. Batchelor, E. F. Jaeger, M. D. Carter, E. D'Azevedo, C. K. Phillips, H. Okuda, R. W. Harvey, D. N. Smithe, J. R. Myra, D. A. D'Ippolito, M. Brambilla and R. J. Dumont, Nonthermal particle and full-wave diffraction effects on heating and current drive in the ICRF and LHRF regimes, *Nucl. Fusion* 45:1411 2005.
4. M. Brambilla, Quasi-local wave equations in toroidal geometry with applications to fast wave propagation and absorption at high harmonics of the ion cyclotron frequency, *Plasma Phys. Controlled Fusion*, 45:1411, 2005.
5. E. J. Valeo, C. K. Phillips, H. Okuda, J. C. Wright, P. T. Bonoli, L. A. Berry and the RF SciDAC Team, Full-wave Simulations of ICRF heating in toroidal plasma with non-Maxwellian distribution functions, *Bull. Am. Phys. Soc*, 51:7, paper VP147, October 2006.
6. E. F. Jaeger, L. A. Berry, S. D. Ahern, R. F. Barrett, D. B. Batchelor, M. D. Carter, E. F. D'Azevedo, R. D. Moore, R. W. Harvey J. R. Myra, D. A. D'Ippolito, R. J. Dumont, C. K. Phillips, H. Okuda, D. N. Smithe, P. T. Bonoli, J. C. Wright and M. Choi , Self-consistent full-wave and fokker-planck calculations for ion cyclotron heating in non-maxwellian plasmas, *Phys. Plasma*, 13:056101, 2006.
7. R. W. Harvey and M. G. McCoy In *Proceedings of the IAEA Technical Committee Meeting on Simulation and Modeling of Thermonuclear Plasma, Montreal, Canada*, 1992. Available as USDOC NTIS Document No. DE93002962.
8. M. Brambilla, Numerical simulation of ion cyclotron waves in tokamak plasmas, *Plasma Phys. Controlled Fusion*, 41:1 1999.
9. B. D. Fried and S. D. Conte, *The Plasma Dispersion Function*, Academic Press, NY, 1961.

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov