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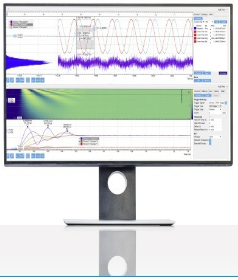

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Quasilinear Evolution of Multiple Non-thermal Ion Distributions in ICRF Heating

E. F. Jaeger[a], L. A. Berry[a], R. W. Harvey[b], C. K. Phillips[c], J. R. Myra[d], D. N. Smithe[e], D. B. Batchelor[a], P. T. Bonoli[f], M. D. Carter[a], M. Choi[g], E. D'Azevedo[a], D. A. D'Ippolito[d], E. J. Valeo[c], J. C. Wright[f]

[a]*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6169, USA*
[b]*CompX, P.O. Box 2672, Del Mar, CA 92014-5672, USA*
[c]*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543, USA*
[d]*Lodestar Research Corporation, 2400 Central Avenue P-5, Boulder, CO 80301, USA*
[e]*Tech-X Corporation, 5621 Arapahoe Avenue, Boulder, CO 80303, USA*
[f]*Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[g]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*

Abstract. Self-consistent full-wave and Fokker-Planck simulations of wave heating in tokamaks have been generalized to include multiple energetic ion populations. To simplify the problem, it is assumed that, because of their low densities, the individual ion tails do not interact with each other in the Fokker-Planck solution. They do, however, interact self-consistently in the wave solution. Preliminary results are presented for DIII-D at 60 MHz and 116 MHz.

Keywords: Full-wave, ICRF heating, Fokker-Planck, plasma simulation.
PACS: 52.50.Qt, 52.55.Fa, 52.65 Ff

INTRODUCTION

An important problem for ITER [1], as well as present day tokamaks [2], is the creation and evolution of energetic particle populations due to wave heating, neutral beam injection, and fusion reactions. These energetic populations, or "ion tails" can significantly alter wave propagation and absorption in the ion cyclotron range of frequencies (ICRF). In some cases, more than one non-thermal ion population can exist simultaneously in the plasma. Previous self-consistent full-wave and Fokker-Planck simulations [3] of wave heating in tokamaks using AORSA [4] and CQL3D [5] have included only one such non-thermal ion distribution at a time. In this work, these calculations are generalized to include multiple non-thermal ion distributions. To simplify the problem, it is assumed that, because of their low densities, the individual energetic tails do not interact with each other in the Fokker-Planck solution. They do, however, interact self-consistently in the full-wave solution.

For rapidly oscillating, time harmonic wave fields, Maxwell's equations reduce to a generalization of the Helmholtz equation,

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$$-\nabla\times\nabla\times\mathbf{E}+\frac{\omega^2}{c^2}\left(\mathbf{E}+\frac{i}{\omega\varepsilon_0}\mathbf{J}_p\right)=-i\omega\mu_0\mathbf{J}_{ant}, \tag{1}$$

where $\mathbf{J}_{ant}$ is the externally driven antenna current, and $\mathbf{J}_p$ is the fluctuating plasma current which can be written as a non-local, integral operator on the wave electric field,

$$\mathbf{J}_p(\mathbf{r},t)=\sum_s\int d\mathbf{r}'\int_{-\infty}^{t}dt'\sigma\left(f_s^0(E),\mathbf{r},\mathbf{r}',t,t'\right)\cdot\mathbf{E}(\mathbf{r}',t'), \tag{2}$$

where $\sigma(f_s^0, \mathbf{r}, \mathbf{r}', t, t')$ is the plasma conductivity kernel.

Bounce-averaged energetic ion distribution functions f_0 are obtained from the bounce-averaged Fokker-Planck equation,

$$\frac{\partial}{\partial t}(\lambda f_0)=\nabla_{\mathbf{u}_0}\cdot\Gamma_{\mathbf{u}_0}+\langle\langle R\rangle\rangle+\langle\langle S\rangle\rangle, \tag{3}$$

where f_0 is evaluated at the outer equatorial plane, and $\langle\langle S\rangle\rangle$ is a bounce-averaged particle source/sink operator. The radial diffusion operator $\langle\langle R\rangle\rangle$ is set to zero for calculations in this paper. The divergence term in Eq. (3) contains two parts: the collision operator $C(f_0)$ and the quasi-linear operator $Q(f_0,\mathbf{E})$ [5] which describes the diffusion of f_0 in velocity space due to the wave electric field. Equations (1) and (2) are solved by AORSA [4], a 2-D all-orders spectral wave solver, and Eq. (3) is solved by CQL3D [5], a 3-D, bounce-averaged Fokker-Planck solver that assumes particle orbits are tied to a flux surface (zero orbit width approximation).

SELF-CONSISTENT ITERATIVE SOLUTIONS WITH TWO NON-MAXWELLIAN ION POPULATIONS

Self-consistent wave fields and particle distribution functions are calculated by iterating between the full-wave and Fokker-Planck solutions given by AORSA and CQL3D, respectively. For two non-Maxwellian ion species, we alternate the iterative steps between the two species. For example, AORSA and CQL3D are first iterated for ion species #1, assuming that the distribution function for species #2 remains fixed. Then, the iteration is repeated for species #2, assuming that the distribution function for species #1 remains fixed. This process neglects collisions between the two developing energetic tails, but as long as the density of the tails is low, this should be an accurate approximation. Both ion tails are included self-consistently in the wave solution, and both contribute to the total power absorption. Figure 1 shows an example of this iteration procedure for H and D ions in DIII-D shot 122080 assuming a 2% fraction of H with 1.1 MW of wave power at 60 MHz. Only a single iteration between AORSA and CQL3D is used for each step in the solution. When multiple iterations between steps are used, there is no significant change in the solution.

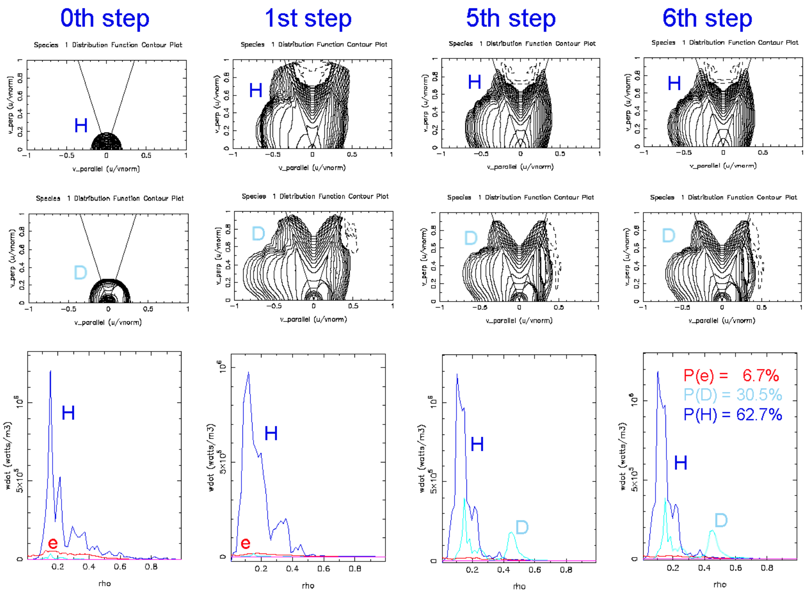

FIGURE 1. Six steps in the iterative solution for non-Maxwellian H and D ion populations in DIII-D shot 122080 at 60 MHz. (2% H is assumed)

From Fig. 1, it is clear that energetic tails form simultaneously on both the H and D distributions, and both contribute significantly to the power absorption. By the 6th step in the solution, approximate convergence is achieved, with about 63% of the wave power absorbed by H and 30% absorbed by D. This is in contrast to previous calculations [3] where Maxwellian hydrogen accounted for only 31% of the wave power at convergence.

Figure 2 shows a similar calculation for the same shot, but at a frequency of 116 MHz. Although qualitatively similar to Fig. 1, the result in Fig 2 shows relatively less power absorbed by the hydrogen. This appears to be due to a more extended tail on the D distribution function compared to the lower frequency in Fig. 1. Although there is an additional 5th harmonic resonance present for H directly in front of the antenna at 116 MHz, it appears to absorb little power due to the lower ion energies in this region. Reducing the H fraction by a factor of two (to 1%) reduces the hydrogen absorption at both frequencies by a similar fraction.

CONCLUSION

Self-consistent full-wave and Fokker-Planck simulations of wave heating in tokamaks have been generalized to include multiple non-thermal ion distributions. Energetic tails form simultaneously on both the H and D distributions in DIII-D, and both contribute significantly to the power absorption. However, there is no indication that the hydrogen absorption is stronger at higher frequencies, and it is therefore unlikely that this absorption could account for the reduced deuterium absorption observed at high frequencies [2].

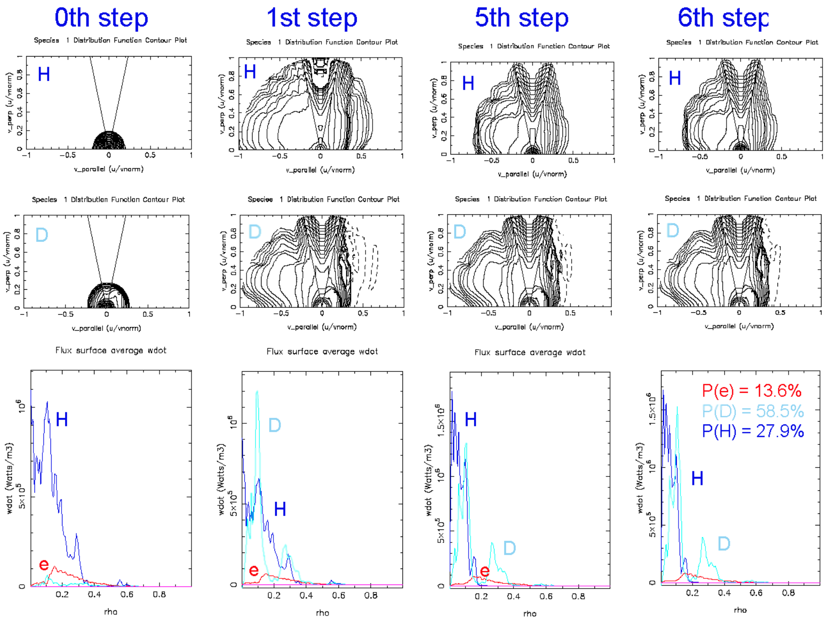

FIGURE 2. Six steps in the iterative solution for non-Maxwellian H and D ion populations in DIII-D shot 122080 at 116 MHz. (2% H is assumed)

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