Time Dependent evolution of RF-generated non-thermal particle distributions in fusion plasmas

J.C. Wright[1], P.T. Bonoli[1], A.E. Schmidt[1], E.J. Valeo[2]

[1] *MIT, Cambridge-MA, USA*

[2] *PPPL, Princeton-NJ, USA*

Introduction

Lower hybrid (LH) waves have the attractive property of damping strongly via electron Landau resonance on relatively fast tail electrons at $(2.5-3)\times v_{\rm te}$, where $v_{\rm te}=\sqrt{T_e/m_e}$. The velocity at which damping occurs depends on the non-linear balance between quasilinear diffusion and collisions. For high efficiency current drive, a low parallel index of refraction, $n||$, corresponding to a high phase velocity, is chosen. Depending on the plasma electron temperature this may put the wave propagation in a multi-pass regime. In cases of low parallel refractive index, ray tracing with no scrape off layerd has been shown to have differences with experiment [3] and collisional effects in the scrape off layer may be important [6]. Using a coupled model of the full wave code, `TORLH` [8], and the Fokker-Planck code, `CQL3D` [2], the importance of full wave effects in weak and strong absorption regimes are studied.

In this paper, we describe fully self-consistent time dependent simulations of RF-generated electron distributions in the lower hybrid range of frequencies (LHRF) using combined Fokker-Planck and full-wave electromagnetic field solvers. The non-thermal particles distributions have been used in synthetic diagnostic codes to simulate hard x-ray diagnostic measurements from experiment, thus providing validation of the simulation capability. The computational intensive simulations require multiple full wave code runs that iterate with a Fokker-Planck code.

In previous work [5, 7] we have developed the tools for solving self-consistent RF electric fields in the lower hybrid frequency regime. The full wave code `TORLH` , a modified version of the `TORIC` ICRF code [1], has been made more efficient with a new parallel solver using a more efficient three dimensional parallel decomposition [8]. In addition, advanced algorithms that have been implemented to accelerate the iteration with the Fokker-Planck distribution code.

Numerics and Iteration

The ratio of scales between the LH wavelength and the system size is of the order of 1/100 to 1/1000 requiring very high resolutions. The LH `TORLH` simulations used in this paper were done with 980 radial finite elements and 1023 poloidal modes (2048 theta mesh points). For efficient parallel scaling, we have extended our processor mesh from a 2D decomposition of the blocks in the resulting discrete system of a block tri-diagonal matrix to a 3D decomposition including radius. The resulting algorithm scales to 10 000 or more processor cores efficiently [8]. Even with run times of only a few hours on 256 cores, the numerous iterations required for convergence are burdensome. Equation 1 describes the normal fixed point iteration technique used to iterate between a wave equation(WE) as described by Eqs. (2) and Fokker-Planck(FP) equation. This technique is known to converge slowly in many instances. It can also be unstable in cases of weak ($n_\parallel^2 < 40/T_e$) absorption unless used carefully (small time steps in the Fokker-Planck code and ramping up of power slowly.) A vector extrapolation method [4] that permits Jacobian free acceleration of the traditional fixed point iteration technique is used to reduce the number of iterations needed between the distribution and wave codes to converge to self-consistency. This method only requires the solutions resulting from the iterations of the fixed point method and refines the solution to much higher accuracy at negligible cost as shown in Figure 1.

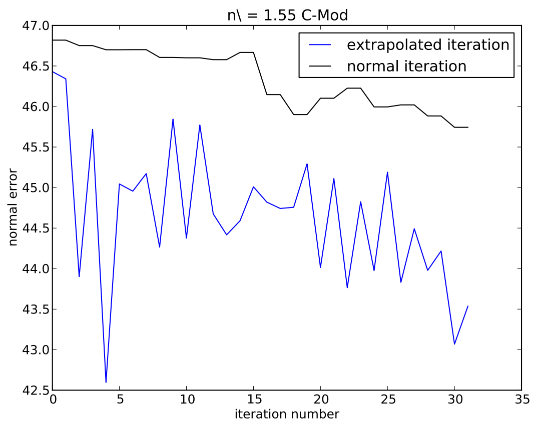

Figure 1: Acceleration of high phase velocity LH iteration reduces error 30× Implemented in python. The L2 norm of the difference of Dql between successive iteration steps is plotted on a $\log_{10}$ scale. Results have not been normalized to vector length. Refinement of solution takes less than 10 minutes with gain in accuracy of more than 100 times ($10^{2.0}$).

$$\begin{aligned} f_{n+1} &= FP(f_n, Dql_n) \\ Dql_{n+1} &= WE(f_n) \end{aligned} \tag{1}$$

$$\nabla \times \nabla \times \mathbf{E} = \frac{\omega^2}{c^2}\left\{\mathbf{E} + \frac{4\pi i}{\omega}\left(\mathbf{J}^{\mathrm{P}} + \mathbf{J}^{\mathrm{A}}\right)\right\} \tag{2a}$$

$$\mathbf{J}^{\mathrm{P}}(\mathbf{x}) = \sum_i \overleftrightarrow{\sigma}_c\left(\mathbf{k}^{(i)}, \mathbf{x}\right) \cdot \mathbf{E}_i(\mathbf{x}) \tag{2b}$$

$$\Re\hat{z}\hat{z}\cdot\overleftrightarrow{\sigma}_c = -(\omega/4\pi)\alpha\int_0^\infty du_\perp^2 J_0^2\left(\frac{k_\perp c}{\Omega_0}u_\perp\right)(1+u_\perp^2)^{1/2}\frac{\partial f_0(\mathbf{u_0})}{\partial p_\parallel} \tag{2c}$$

$$\alpha \equiv \pi^2\left(\frac{\omega_{pe,0}}{\omega}\right)^2 (m_0 c)^4 (n_\parallel^2 - 1)^{-3/2} n_\parallel \tag{2d}$$

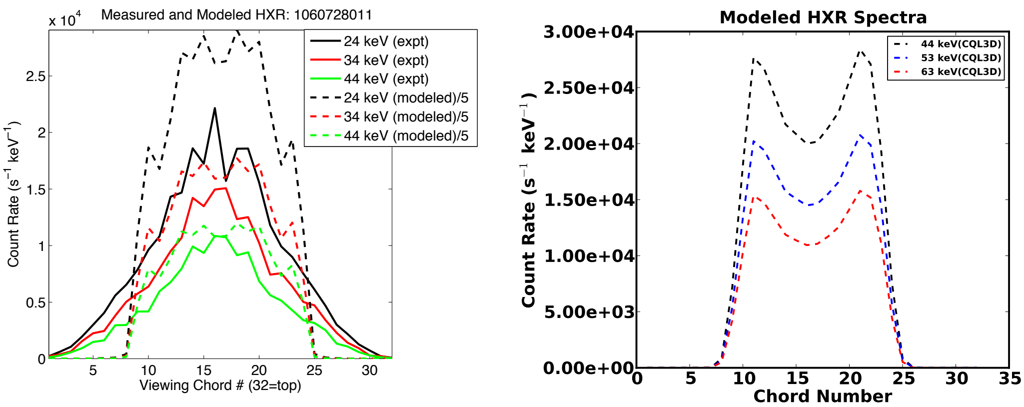

Figure 2: Comparison of measured and modeled HXR profiles for shot 1060728011. Modeled profiles from ray tracing (left panel) have been scaled by a factor of 1/5 and those from full wave (right panel) have not been scaled. The HXR camera views horizontally with chord 1 (32) corresponding to the bottom (top) of the tokamak. Full wave simulations assume 500kW coupled LH power. The plasma parameters are [B_0=5.36 T, $n_{e0}=7\times10^{19}m^{-3}$, T_{e0}=2.33 keV].

HXR Modeling Results

When the absorption strength is weaker, the LH waves are in a multi pass regime where interference of crossing waves, reflections from the cutoff and caustic formation must be treated properly. In this case, we expect full wave results to diverge from ray tracing. In Figure 2, we compare the HXR predictions for multi pass using self-consistent TORLH /CQL3D simulations for the evolution of $f_e(\mathbf{v})$ and calculation of the HXR signal.

The HXR signal from ray tracing in Figure 2 is a factor of five larger than the experiment, in contrast to the HXR signal from the full wave analysis. This may be due to the differences in the reconstructed Dql from the two approaches, since the Dql from full wave includes phase interference effects which can lead to a reduction in the energy density that are absent in first order WKB ray tracing.

Conclusions

We have presented simulation results from a combined LH full-wave / 2-D $(v_\parallel, v_\perp)$ Fokker Planck calculation for parameters characteristic of the weak damping regime in the Alcator C-Mod device. Accurate treatment of the evolution of the distribution function consistent with the wave fields was necessary to achieve these results. We employed advanced numerical algorithms to accelerate the convergence of the required iteration procedure and showed that the computational burden can be reduced a factor of four to five or and accuracy can be increased a factor of approximately 30. Simulated HXR spectra have been computed from the converged electron distributions predicted by CQL3D and validated against experimentally measured spectra.

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