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Full Wave Simulations of Lower Hybrid Waves in Toroidal Geometry with Non-Maxwellian Electrons

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Abstract. Analysis of the propagation of waves in the lower hybrid range of frequencies in the past has been done using ray tracing and the WKB approximation. Advances in algorithms and the availability of massively parallel computer architectures has permitted the solving of the Maxwell-Vlasov system for wave propagation directly [Wright et al., Phys. Plasmas (2004), 11, 2473-2479]. These simulations have shown that the bridging of the spectral gap (the difference between the high injected phase velocities and the slower phase velocity at which damping on electrons occurs) can be explained by the diffraction effects captured in the full wave algorithm - an effect missing in WKB based approaches. However, these full wave calculations were done with a Maxwellian electron distribution and the presence of RF power induces quasilinear velocity space diffusion that causes distortions away from an Maxwellian. With sufficient power, a flattened region or plateau is formed between the point of most efficient damping on electrons at about 2-3 $v_{\rm the}$ and where collisional and quasilinear diffusion balance. To address this discrepancy and better model experiment, we have implemented [Valeo et al., "Full-wave Simulations of LH wave propagation in toroidal plasma with non-Maxwellian electron distributions", 18th Topical Conference on Radio Frequency Power in Plasmas, AIP Conference Proceedings (2007)] a non-Maxwellian dielectric in our full wave solver. We will show how these effects modify the electron absorption relative to what is found for a Maxwellian distribution.

AMS subject classifications: 35Q60, 65L60, 74J05, 82D10
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1 Introduction

The wave equation finds much relevance in plasma physics. In this work we deal with externally driven radio frequency (RF) waves in the lower hybrid (LH) range of frequencies.

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This range is between the ion and electron cyclotron frequencies and is approximately given by $\omega_{\rm lh} \approx \sqrt{\Omega_{\rm e}\Omega_{\rm i}}$ where $\Omega_{\rm i,e} \equiv qB/m_{i,e}c$ are the electron and ion cyclotron gyration frequencies in a magnetic field of strength B. Because of the large mass ratio of protons to electrons, $Am_p/m_e \approx A1836$, this results in a hybrid frequency that is much less than the electron cyclotron frequency and much greater than that of the ions', $\Omega_{\rm ci} \ll \omega \ll \Omega_{\rm ce}$. At these frequencies, the wavelengths are on the order of a few millimeters for parameters typical of fusion research devices, i.e., the magnetic field of the order of several Tesla and the electron density several times 10^{20} per m^3. The waves also have a high phase velocity on the order of 3-7 times the electron thermal velocity. This results in a high efficiency for driving toroidal current in the plasma [1, 2] which is needed for steady state stability of tokamak plasmas. For this reason, these waves have been proposed as a method of edge current profile control for the International Tokamak Experimental Reactor (ITER) [3]. LH experiments on Alcator C-Mod have achieved over 80% of the needed steady state current for the duration of the discharge, which represents several times that needed for current relaxation [4]. These experiments are at ITER relevant plasma parameters but the machine is about 10 times smaller than ITER making for more tractable sized simulations. Validation of our code on C-Mod LH experiments would support its use for predictive studies of LH on the ITER device now under construction.

The short wavelength relative to machine sizes of the order of a meter have encouraged the use of ray tracing as the primary method for calculating the power and current drive deposition in the plasma. The wavelengths are much shorter than the gradient scale length of the dielectric tensor, and so the Wentzel, Kramers and Brillouin (WKB) method would seem to be appropriate. While it can capture features such as broadening of the launched spectrum due to toroidicity [5] and the propagation path, it breaks down in cases where the rays undergo multiple reflections from cutoffs and caustics and form a stochastic field. Extended ray tracing techniques such as the Maslov method popular in seismology [6] and the wave-kinetic method [7], are valid at the caustic surfaces; but because the LH cutoffs in tokamak plasmas occur in the plasma edge where the gradients are very large, they violate the WKB approximation where the plasma is changing on the same scale as the wavelength [8].

A more serious challenge to traditional ray tracing is the importance of diffraction in LH wave propagation [9, 10]. Although in LH experiments, frequencies are chosen to avoid the presence of any mode conversion, components of the wavenumber vector vanish at the caustics, and significant diffraction can occur there. There are other methods of dealing with high frequency waves that attempt to account for finite frequency effects such as diffraction [11] within the ray tracing picture. We have chosen to simulate the lower hybrid waves directly with the full wave code, `TORIC` [12], to account for these effects.

The outline of this paper is as follows. In Section 2 we describe the `TORIC` code and its discretization of the wave equation. In Section 3 the changes to the plasma model for the dielectric in the lower hybrid range of frequencies (LHRF) are given. We next discuss the inclusion of non-Maxwellian electrons in the plasma dielectric response in Section 4 -