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Three-Dimensional Full-Wave Modeling of Waves in the Ion Cyclotron Range of Frequencies on LHD

LHDにおけるICRF波動の3次元全波計算

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Waves in the ion cyclotron range of frequencies (ICRF) are widely used for heating fusion plasmas. Because of the existence of various resonances and mode conversion layers, full-wave modeling is often necessary. In this study, we have performed a 3D modeling of the actual experimental condition of Large Helical Device (LHD) using the full-wave code AORSA (Phys. Plasmas 9 (2002) 1873). The result was compared with the reflectometer measurement through a synthetic diagnostic technique. The simulated signal amplitude was within an order of magnitude of the measurement.

1. Introduction

Waves in the ion cyclotron range of frequencies (ICRF) are widely used to heat fusion plasmas. Because of the existence of various resonances and mode conversion layers, a full-wave simulation is often necessary to accurately describe wave propagation and absorption in a realistic toroidal geometry. To use the simulation code as a reliable predictive tool, it is important to validate the code against the actual experimental measurements.

In this study, the full-wave code AORSA [1] was used to model the ICRF waves in the Large Helical Device (LHD). LHD has three ICRF antennas [2] which can inject about 1.2 MW each. The frequency is 38.47 MHz. Usually, He-4(H) minority heating (minority species in parentheses) is performed.

A reflectometer is installed near the HAS antenna [2], and is capable of measuring the ICRF waves. The AORSA simulation was compared with the reflectometer measurement quantitatively through a synthetic diagnostic technique, which will be described in the following sections.

2. ICRF Wave Modeling

AORSA [1] is a full-wave simulation code for rf waves in a plasma. The code is able to model a three-dimensional equilibrium with the hot plasma dielectric. The field is spectrally represented in cylindrical coordinates. The model is valid for arbitrary $k_\perp \rho_L$ ($k_\perp$: perpendicular wavenumber, ρ_L: Larmor radius), and for arbitrary number of cyclotron harmonics under the local approximation.

The VMEC equilibrium and experimentally measured density and temperature profiles are used to simulate the ICRF waves. The minority hydrogen distribution function is assumed to be Maxwellian. Figure 1 shows the electric field amplitude simulated by AORSA for a typical LHD discharge. The antenna is located on the lower edge where the field strength is the strongest. Absorption is modest and the wave field spreads toroidally somewhat.

3. The Synthetic Reflectometer Diagnostic and Comparison with the Measurement

Evaluating density fluctuations from reflectometer measurements is a rather complicated exercise [3]. When a realistic simulation of the actual experiment is available, it is often easier and more accurate to “synthesize” the diagnostic signal from the simulation results and compare it directly with the measurement.

A commercial software COMSOL (www.comsol.com) was used to model the plasma and the reflectometer. Since the reflectometer uses O-mode, the cold unmagnetized dielectric was used in this study. The wave electron density fluctuations predicted by AORSA was added to the background electron density profile, and introduced to the COMSOL model. The fluctuating component of the density was assumed to be stationary and the electric field inside the receiving waveguide was evaluated. The calculation was repeated for different phases of the wave fluctuations to evaluate the phase and amplitude perturbations of the

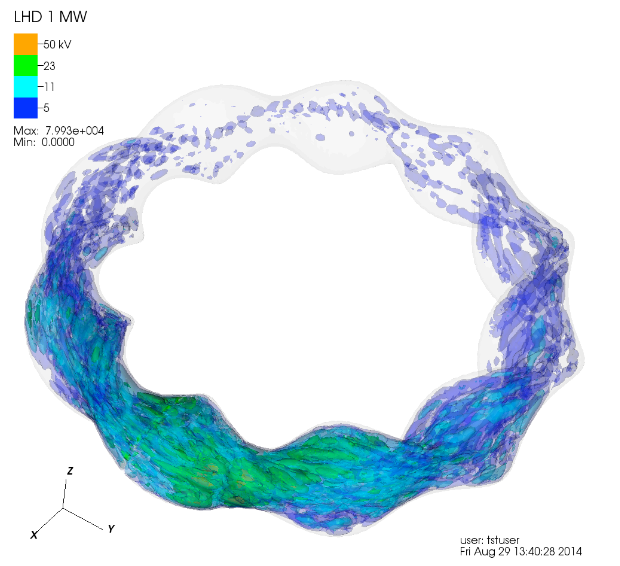

Fig. 1. The right-hand circularly polarized component of the electric field simulated by AORSA.

reflected beam. Since the three-dimensional calculation of the microwave beam was computationally too expensive, the analysis was performed on a two-dimensional slice that includes the beam trajectory.

The simulation was performed for a typical LHD discharge with the central electron temperature 3 keV, central electron density 2×10^{19} m^{-3}, n_H/n_e of 0.04, and 0.2 MW rf power. The results are shown in Fig. 2. The simulated reflectometer signal amplitudes are shown for various toroidal angles. The full-wave calculations are shown for frequency down-shifted and up-shifted signals. The difference between them is due to the existence of the beam amplitude perturbations as well as the phase perturbations. The WKB estimate is also shown for comparison. Since the ICRF wavelength is appreciably longer than the probe beam wavelength, it is expected that the phase perturbations are mostly due to the movement of the cutoff layer. Since this effect is captured in the WKB approximation, it can give a reasonable estimate of the reflectometer signal.

The asterisk symbols show the measured signal amplitude for the down-shifted and up-shifted sidebands. The simulated amplitude is about 30% weaker than the measured value, but the agreement is reasonable considering the fact that the ICRF wave field has a complicated spatial structure and that this is only a single comparison.

4. Discussion

Since the local wave measurements are sensitive to small changes in the plasma parameters, many similar discharges need to be analyzed and sensitivity study of the simulation needs to be performed. There are also parts of the present modeling that may need further improvement. For the AORSA modeling, the perfectly conducting wall of the simulation boundary is rather close to the plasma edge, and the edge electric field may be under-predicted. Since the reflectometer cutoff layer is close to the edge, this may be one of the reasons for the discrepancy. Inclusion of magnetization in the reflectometer beam propagation analysis may also be necessary considering the complicated three-dimensional geometry of the LHD device.

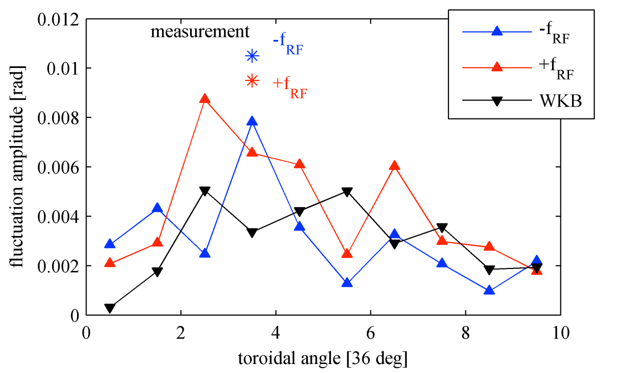

Fig. 2. Comparison of the simulated and measured reflectometer signals at various toroidal angles. Asterisks: measured down-shifted (blue) and up-shifted (red) signal amplitude. Blue upward triangle: full-wave simulation (down-shifted). Red upward triangle: full-wave simulation (up-shifted). Black downward triangle: WKB estimate.

6. Summary

Full-wave modeling of ICRF waves was performed for the hydrogen minority heating scenario on the three-dimensional LHD equilibrium. The result was compared with the reflectometer measurement through a synthetic diagnostic technique. The simulated fluctuation intensities were about 30% weaker than the measured value for this initial comparison. More cases will be analyzed and ICRF and reflectometer modelings will be improved.

Acknowledgments

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