Recent progress in core/edge integrated plasma wave modeling based on FEM

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Abstract

We explored the possibility of using FEM (finite element method) to plasma wave simulation in LH/ICRF frequency regimes. A FEM based full wave lower hybrid wave simulation code, LHEAF (Lower Hybrid wavE Analysis based on Fem) code is connected to 3D Fokker-Planck code to evaluate LHCD profile. In the Fokker-Planck analysis, the quasi-linear diffusion is evaluated based on the transit-acceleration during one bounce time. The comparison of the calculated current profile on Alcator C-Mod shows reasonable agreement with the equilibrium reconstruction which is constrained both by kinetic and motional Stark effect (MSE) pitch angle measurements. In addition, a method to integrate edge/antenna simulations using FEM with a core plasma code is sought, showing interesting possibility (presented in the poster).

Introduction

We have explored the possibility of using finite element method (FEM) to plasma wave simulation in LH/ICRF frequency [1]. Our goal is a plasma wave simulation which treats core plasma, edge plasma and antenna regions seamlessly. FEM allows to have a complicated geometry without an extreme simplification of geometry and it has also an advantage of producing numerically sparse matrix. It can handle a cold plasma with collisions without a special difficulty, providing a possibility of developing a wave modeling tool particularly in the edge/antenna regions. However, introducing non-local hot plasma effects, while keeping the numerical sparsity of the matrix, are not trivial for FEM. In the LHEAF (Lower Hybrid wavE Analysis based on Fem) code, we addressed this issue by treating an non-local term as an perturbation term [2]. This technique transforms the Vlasov-Maxwell's equations to usual partial differential equations. By iterating a Maxwell equations solver and an electron Landau damping term calculation, which is expressed as an line integration along the magnetic field line, a self-consistent solution was obtained. Also, LHEAF simulations have been compared with other codes, ray-tracing and TORIC-LH spectral solvers [3], showing good agreement. The comparison has been done in the single pass absorption regime, using a Maxwellian plasma. To compare LHEAF simulations with experiments, it is important to take into account the fast electron population generated by the LH waves. Presently, LHEAF is coupled with a 1D (parallel velocity) Fokker-Planck module. We are working on integrating it with a newly written 3D (parallel/perpendicular momentum + radial) Fokker-Planck module to evaluate plasma parameters which can be directly compared with experiments, such as the LHCD current profile. This report presents the first results of the current profile analysis using the 3D Fokker-Planck module.

3D FP module for LHEAF

The 3D Fokker-Planck module solves the following bounce-averaged Fokker-Planck equation

$$\frac{\partial \tau_B p_\parallel f_0}{\partial t} = \nabla_{\rm p}\Gamma_{\rm p} + \nabla_{\rm r}\Gamma_{\rm r} + \langle S(f_0)\rangle, \quad (1)$$

where Γ_p includes a quasi-linear flux in momentum space due to collisions, LH waves and the Ohmic electric field. $\langle S(f_0)\rangle$ is a source term including the first order non-linear correction to Belaiev-Budker linearized relativistic collision operator and the compensation of particle loss in order to keep the total number of particle constant in the computation domain.

Expressions of these terms can be found in literature (for example see Ref.[4]), except for the LH waves. Previous works of coupling a full wave simulation with a Fokker-Plank code have been done on spectral basis functions. Instead, we evaluate the transit-time acceleration of electrons during one bouncing time, and calculate the quasi-linear diffusion coefficient using $D_{\parallel\parallel} = (\delta p)^2/\delta t$. In LHEAF this approach is more convenient to implement, since the code works in the configuration space, not in the spectral space. The obtained diffusion coefficient is by definition always positive. The module discretizes Eq.1 into a fully implicit form and solves it by means of the MUMPS (MUltifrontal Massively Parallel Sparse direct Solver) direct solver. This way, the stationary solution can be obtained by a few time steps.

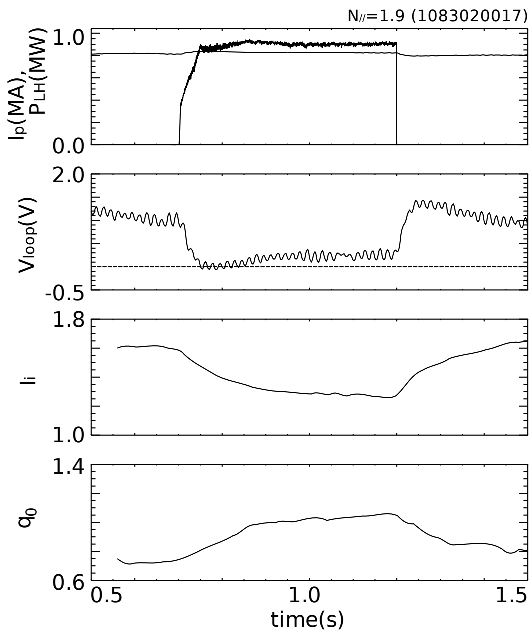

Figure 1: Time evolutions of the plasma current, the LH power, the internal inductance $l_{\rm i}$, and the safety factor at the magnetic axis q_0 of the discharge 1080320017. The main peak of LHCD spectrum is $N_\parallel = 1.93$. $l_{\rm i}$ and q_0 in this figure are evaluated by MSE constrained EFIT described in Ref. [6].

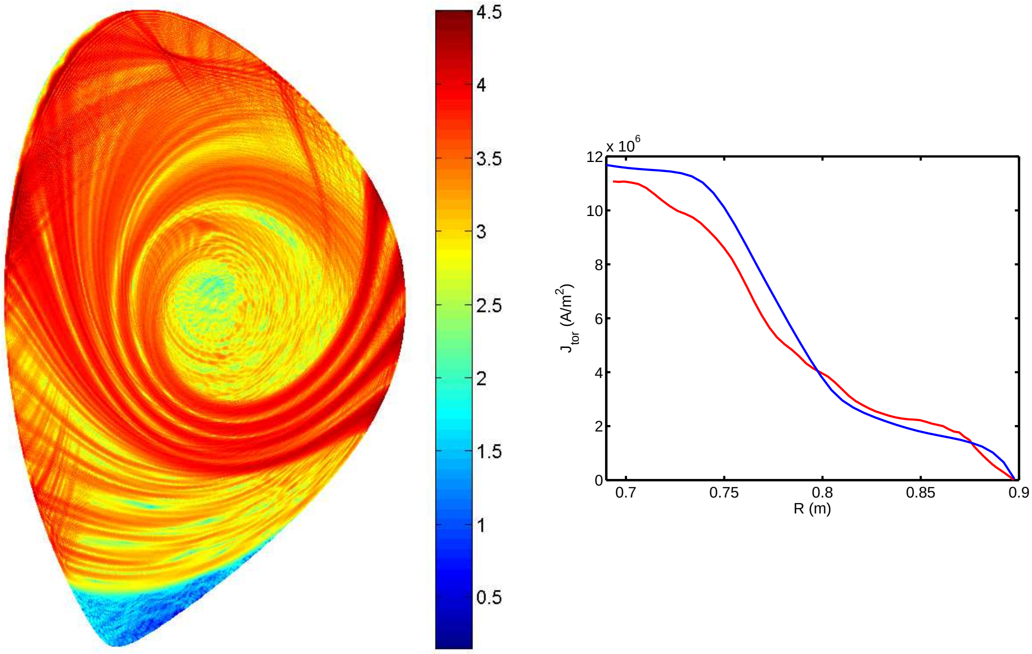

Figure 2: (right) The profile of logarithmically compressed parallel electric field amplitude ($\log(|E_{\parallel}|+1)$), and (left) the toroidal current profile evaluated by Fokker-Planck analysis (red) and kinetic-MSE constrained EFIT (blue) on the low field side mid-plane.

Results

We applied this module to LHCD experiments on Alcator C-Mod [5]. The discharge waveforms are shown in Fig. 1. LHCD power of 900kW at 4.6GHz was injected to a plasma having a plasma current of 800kA from 0.7 s. Upon the LHCD turn-on, significant reduction of the loop voltage (close to zero) occurred, and then it saturated to be 0.25 V. The broadening of current profile can be seen in the decrease of internal inductance and the increase of the safety factor. We applied the Fokker-Planck analysis to the LHEAF simulation result at 1.1 s, when the loop voltage penetrated fully to the magnetic axis. In this analysis, the full wave calculation was integrated with 1D Fokker-Planck calculation so that the modification of the distribution function in the parallel direction is taken into account self-consistently. The new 3D module was used as an interpreter of the LHEAF simulation output. Although the distribution function in the perpendicular direction is not self-consistent, the power deposition profiles from 1D Fokker-Planck and 3D Fokker Planck calculations are already quite similar, since the electron Landau damping is determined by the gradient of distribution function in the parallel direction.

Figure 2 shows the parallel electric field profile of LHEAF simulation and the current profile evaluated by 3D Fokker Planck module. From fig. 2 left, it can be seen that the waves launched from the top waveguide are in single pass regime (or close to). These waves are well absorbed before they pass through the core plasma and hit the plasma edge. On the other hand, the waves launched from the lower waveguides undergo multiple reflections before being absorbed by the plasma. Due to this difference of wave propagation patterns, the power absorption profile spreads very widely inside $r/a \sim 0.8$.

Figure 2 right shows the comparison of current profile evaluated by the Fokker-Planck module and the equilibrium reconstruction. In this reconstruction, both MSE pitch angle measurements and kinetic measurements are used to allow a flexible parametrization of current profile using spline functions. In the Fokker-Planck analysis, $D_{\|\|} = 0.02\mathrm{m}^2/\mathrm{s}$ was assumed, although the power deposition profile and resultant driven current were already broad and did not sensitively change due to $D_{\|\|}$. The shape of current profile shows very good agreement with the reconstruction, and the total current calculated by the Fokker-Planck module was 750 kA, while it was 800 kA in the experiment.

Summary

We introduced the 3D Fokker-Planck module to the LEHAF full wave LHCD simulation code. Initial application to a stable LHCD discharge shows good agreement between the measured and calculated current profiles. Further analysis of discharges with different LHCD antenna phasing and the comparison with other measurements such as Hard X-ray spectrum is planned.

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