Nonlinear Particle Simulation of Radio Frequency Waves in Fusion Plasmas

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Outlines

• Motivation
• Linear electrostatic RF physics
• Linear electromagnetic RF physics
• Nonlinear electron trapping physics
• Discussions & Summary

✓ Need for a nonlinear toroidal radio frequency (RF) (LHW, ICW, IBW) code
Scheme

- Ion- Fully kinetic (FK) using Vlasov equation
- Electron-Drift-kinetic (DK) for $\omega \ll \omega_{ce}, \lambda \gg \rho_e$ (LHW, ICW, IBW)

Gyrokinetic Toroidal Code (GTC)

- GTC current capability for kinetic-MHD simulation:
  - General 3D toroidal geometry & experimental profiles
  - Microturbulence & EP: Kinetic electrons & electromagnetic fluctuations
  - MHD: Equilibrium current, resistive and collisionless tearing modes
  - Neoclassical transport
  - RF: fully kinetic ions
  - Ported to GPU (titan) & MIC (tianhe-2)

http://phoenix.ps.uci.edu/gtc
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✓ Verification of Debye length for ion plasma wave, Ion Bernstein wave, and lower hybrid wave in cylinder
✓ Linear propagation of LH wave in cylinder and tokamak
✓ Mode conversion
Electrostatic mode verification

- Normal modes

Ion plasma oscillation frequency as a function of normalized wavelength

Ion Debye shielding effect as a function of normalized radius

Comparison of ion Bernstein wave dispersion relation between analytical solution and GTC simulation

Kuley et al., POP-2013
Verification of Electrostatic Lower hybrid wave

(a) Time evolution of the LH wave (m=4, n=60) amplitude excited by an artificial antenna in the cylinder, (b) radial profiles of LH waves from the GTC simulation and from the theory. (c) and (d) are poloidal mode structures of LH waves obtained from the theory and from the GTC simulation, respectively. The color scale represents the normalized electrostatic potential.

(a) $e\phi/T_e$ vs $\omega_0 t$

(b) $e\phi/T_e$ vs $r/a$

(c) Theoretical eigenmode

(d) GTC simulation

$X(m)$ vs $Z(m)$

$X(m)$ vs $Z(m)$
Verification of Linear Landau Damping of LHW

(a) Time history of the LH wave amplitude due to linear electron Landau damping. The dashed line is the numerical fitting. (b) Comparison of damping rates of LH waves obtained from the GTC simulation and the theoretical calculation in different regimes.
Linear lower hybrid wave propagation

- Lower hybrid wave packet which initially a standing wave is launched at the edge.
- Lower hybrid wave propagate as two counter propagating wave.
- Poloidal mode number is not constant due to the poloidal asymmetry of the magnetic field.
- Mode structure is formed by the coupling of different mode number.
- Wave packet propagate faster in the high field side compare to the low field side.
- Poloidal mode number does not change due to the poloidal symmetry of the magnetic field.
- Wave packet propagate only in the radial direction.
- Mode structure give well agreement between theory and GTC simulation.

- Lower hybrid wave packet which initially a standing wave is launched at the edge.
- Lower hybrid wave propagate as two counter propagating wave.
- Poloidal mode number is not constant due to the poloidal asymmetry of the magnetic field.
- Mode structure is formed by the coupling of different mode number.
- Wave packet propagate faster in the high field side compare to the low field side.
LH wave propagation in toroidal geometry comparison with WKB solution

- Wave packet moves faster toward the magnetic axis in the high field side.
- Radial and poloidal group velocity are strong in the high field side compare to the low field side.
- WKB solution is consistent with the GTC simulation

Bao et al., PPCF 2014
Verification of EM slow and fast modes excitation using antenna

- Simulation model
  - Ion: Fluid
  - Electron: Drift Kinetic
  - System is closed with Poisson’s equation, Ampere’s law and electron force balance equation

Mode history of LH wave slow branch

Mode structure of LH wave slow branch

Mode history of LH wave fast branch

Mode structure of LH wave fast branch
Mode conversion between slow and fast wave in tokamak

Launched slow wave from antenna at $\theta = 0.25\pi$

Mode converted fast wave
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✓ The wave amplitude becomes oscillatory with a frequency equal to the trapped electron bounce frequency
Nonlinear Physics : Electron trapping: Demonstration of capability for NL simulation

![Graph showing linear and nonlinear excitation of LH wave using antenna.]

<table>
<thead>
<tr>
<th>Antenna amplitude</th>
<th>Amplitude from field time history</th>
<th>No of oscillation in the amplitude envelope</th>
<th>Bounce frequency from theory</th>
<th>Bounce frequency from simulation</th>
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<td>4* antenna envelope</td>
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Summary and Discussions

Linear physics

- Dispersion relation and mode structure of the electrostatic modes (LH, IBW) and electromagnetic modes (slow and fast wave) are verified.
- Linear simulation of LH wave propagation are carried out in both cylindrical and toroidal geometry.
- Linear mode conversion of LH wave into slow and fast modes branch are verified in toroidal geometry

Nonlinear Physics

- Electron trapping in the LH wave in cylindrical geometry is verified.

Future work

- Parametric decay instabilities of LH wave