Modeling of EBW CD in spherical tokamaks

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Motivation

- For heating and current drive in high-density core plasmas of spherical tokamaks, electromagnetic waves with electron cyclotron (EC) waves are used.
- Difficult to cyclotron harmonics higher than the third order.
- Applicable parameter range is limited: fast wave, traveling wave.
- Plasma dispersion function.
- Kernel Function and its integral:
  - Boundary-value problem of Maxwell’s equation with fixed current.
  - Solution obtained with quasi-linear velocity diffusion coefficients.
  - Anisotropic Maxwellian distribution correlations are localized within several Larmor radii.

Full Wave Analysis

- Fast wave approximation:
  - Estimate k∥ from fast wave k∥ in cold plasma approximation.
  - Applicable parameter range is limited: fast wave, traveling wave.
- Differential operator approach: k∥ = ω/c = iω/c.
- Expansion in k∥ not applicable for |k∥| > 1.
- Difficult to cyclotron harmonics higher than the third order.
- Spectral approach: Fourier transform in the inhomogeneous direction.
- This approach can be applied to the case k∥ > 1.
- All the wave field spectra are coupled with each other.
- Solving a dense matrix equation requires large computer resources.
- AODSA code (Jawor, ORNL).
- Integral operators: ∫ (v(−t) + v(t)) E(x,t) dx.
- This approach can be applied to the case k∥ > 1.
- Correlations are localized within several Larmor radii.
- Necessary to solve a large band matrix.
- Sauter (1952), TASK9/1

Finite Larmor Radius Effects in Full Wave Analysis

- General form of diocotron tensor:
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  - Electric field, electron momentum distribution function required for evaluating the power absorption profile.
- Particle orbit:
  - Perturbation distribution from Vlasov equation:
  - Induced current:
  - The integral form of the conductivity tensor is defined by
  - Variable transformation:

Integral Formulation of Wave-Particle Interaction

- Transformation of integral variables:
  - Transformation from velocity space variables (v∥, v⊥) to particle position r and guiding center position r∥.
- Jacobian: J = det(r∥, r⊥).
- Expressions of v∥ and v⊥ by the use of (v∥, v⊥) = (r∥, r⊥)
  - Integral over r⊥:

Equilibrium Velocity Distribution Function

- For arbitrary velocity distribution function:
  - Numerical integration with respect to v∥ and v⊥ is necessary.

Anisotropic Maxwellian distribution:

- Perpendicular temperature: T⊥, parallel temperature: T∥
- Integral over v∥.
- Reduced to four types of kernel functions.
  - Kernel Function and its integral:

Kernel Functions

- Transformation from velocity space variables.
- Differential operator approach.

Evolution of Momentum Distribution Function

- Full wave analysis for arbitrary velocity distribution function:
  - Dielectric tensor:
  - Fokker-Planck analysis including finite Larmor radius effects.
- Quasi-linear operator:
  - First-order distribution function:
  - Second-order Vlasov equation:

Consideration on Quasi-Linear Diffusion Coefficient

- Ordering:
- Vlasov equation:
- Particle motion in a local orthogonal coordinates:

Coefficient Matrix \( \mathbf{H} \)

- One-Dimensional Analysis:

O-X-B excitation

- Major radius: 0.22 m, minor radius: 0.15 m.
- Central magnetic field: 0.08 T.
- Toroidal mode number: 24.
- Central electron density: 3 x 10^{19} m^{-3}.

Summary

- For the analysis of heating and current drive by the electron Bernstein waves, integral formulation of full wave analysis and Fokker-Planck analysis in an inhomogeneous plasma has been developed.
- Implementation of integral form of diocotron tensor for one-dimensional full wave analysis has been done for TASK9/1.
- The O-X-B mode conversion of EC waves was successfully described.
- Future work:
  - Completion of integral form of quasi-linear velocity diffusion coefficients.
  - Two-dimensional full wave analysis including finite Larmor radius effects.