

AWECS: A Linear Gyrokinetic δf Particle-in-Cell Simulation Code for the Study of Alfvénic Instabilities in High- β Tokamak Plasmas

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Abstract. A 1-D linear gyrokinetic code called AWECS is developed to study the kinetic excitation of Alfvénic instabilities in a high- β tokamak plasma, with β being the ratio of thermal to magnetic pressure. It is designed to describe physics associated with a broad range of frequencies and wavelengths. For example, AWECS is capable of simulating kinetic ballooning modes, Alfvénic ion-temperature-gradient-driven modes, as well as Alfvén instabilities due to energetic particles. In addition, AWECS may be used to study drift-Alfvén instabilities in the low- β regime. Here, the layout of the code and the numerical methods used are described. AWECS is benchmarked against other codes and a convergence study is carried out.

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1 Introduction

In a tokamak, nested closed toroidal magnetic surfaces are used to confine a high-temperature plasma consisting mainly of ionized Deuterium. Such magnetized plasmas are known to support various kinds of magnetohydrodynamic (MHD) shear Alfvén waves (SAW), the properties of which are determined by the geometry of the magnetic flux surfaces; in particular, the field line curvature and magnetic shear. Resonant and non-resonant interactions between SAWs and plasma particles can lead to excitations of SAW instabilities. These instabilities may, in turn, affect particle confinement. In order

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to optimize the tokamak geometry and operating conditions for thermonuclear fusion applications, a thorough understanding of SAW physics is crucial. For a review of SAW observations and comparison with theory see, e.g., Ref. [1].

In order to investigate the linear instability of SAWs, a linear gyrokinetic particle-in-cell (PIC) simulation code, called AWECS, is developed. The model equations describe the dynamics local to a field-aligned flux-tube using the so-called ballooning formalism. The equations are valid for a broad range of frequencies and wavelengths, with focus on temperature- and pressure-gradient-driven instabilities, while ignoring modes driven by the gradient of the parallel plasma current. For instance, AWECS allows to study electrostatic and Alfvénic ion-temperature-gradient modes (ESITG and AITG) [2, 3], kinetic ballooning modes (KBM) [4], β -induced Alfvén eigenmodes (BAE) [5], toroidicity-induced Alfvén eigenmodes (TAE) [6], α -induced toroidal Alfvén eigenmodes (α TAE) [7], as well as energetic particle modes (EPM) [8]. In addition, AWECS may be used to study drift-Alfvén instabilities in the low- β regime [9]. Here, $\beta = 2\mu_0 P / B_0^2$ is the ratio of thermal to magnetic pressure, and $\alpha = -q^2 R_0 d\beta / dr$ is the normalized pressure gradient, with q being the safety factor (a measure for the field line pitch), R_0 the major radius of the torus, r the minor radial coordinate, and B_0 the field strength at the magnetic axis.

This paper is organized as follows. In Section 2, we describe the physical model and, in Section 3, the numerical methods used to solve the equations. In Sections 4-6, AWECS is benchmarked against other codes, followed by a convergence study in Section 7. Concluding remarks and discussions are given in Section 8.

2 Model

In this section, we describe the physical model used. After providing an overview of assumptions made in the derivation, we describe the equilibrium model, followed by the gyrokinetic equation and the electromagnetic field equations. Then the equations are normalized and cast into a form suitable for numerical solution as an initial-value problem. For convenience, in the first part of this section, all time-dependent variables are Laplace-transformed ($\partial_t \equiv \partial / \partial t \rightarrow -i\omega$).

2.1 Assumptions and formal ordering

We employ the linear gyrokinetic field equations derived by Zonca & Chen [10]. A reduction similar to that described in Ref. [10] is applied, except that finite-Larmor-radius (FLR) corrections for thermal ions are retained in the present paper. The model is valid for Alfvénic instabilities in a wide range of frequencies ω and wave numbers k , provided that

$$(i): \omega \ll k_{\parallel} v_{te}, \quad k_{\perp} \rho_{ce} \ll 1, \quad (ii): \omega \ll \omega_{ci}, \quad (iii): \omega \lesssim \omega_A; \quad (2.1)$$

where $\omega_{cs} = e_s B / m_s$ is the cyclotron frequency and $\rho_{cs} = v_{\perp} / \omega_{cs}$ the Larmor radius for particle species s ($s = e$ for electrons, $s = i$ for thermal ions, and $s = E$ for energetic ions).