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Optimal modes of gyrokinetic free energy growth with trapped electrons

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Since the development of gyrokinetic theory, a myriad of instabilities, which lead to unwanted turbulent transport in tokamaks and stellarators, have been discovered. A recent series of publications [1, 2, 3] have introduced a novel approach to computing rigorous upper bounds for the growth rates of gyrokinetic instabilities in flux tube geometry. By maximising the growth of a chosen gyrokinetic energy measure through optimal perturbations, known as the optimal modes, these upper bounds represent the fastest-growing instabilities allowed by the sources and sinks of this energy measure. One such choice for the energy is the so-called generalised free energy, which is valid in the electrostatic limit. The generalised free energy has the advantage of containing more information regarding the geometry of the magnetic field than other energies, such as the Helmholtz free energy considered in [1, 2]. The generalised free energy was recently considered in [3] for ion-temperature-gradient instabilities (ITGs) with adiabatic electrons and was found to always give a tighter bound on ITG growth than the Helmholtz energy. However, so far, the impact of trapped particles on the optimal modes has not explicitly been dealt with, and thus, the optimal modes found were largely agnostic to the variation of the magnetic field strength along the field line. In this study we extend the theory of optimal modes to include a population of trapped particles. We consider an electrostatic system with fully gyrokinetic ions and bounce-averaged, drift-kinetic electrons, assuming a bounce time much shorter than the instability timescale. The central result of this work is a system of integral equations that can be solved for a given flux tube. The solutions to this system give the optimal modes of the generalised free energy. The growth rates of the optimal modes in this setting depend on the magnetic field strength, fluxtube metric components, and the curvature of field lines as functions of the field-linefollowing coordinate. We analytically solve this system in a simple square magnetic well, and
numerically solve it for general magnetic field strengths. The resulting optimal modes provide upper bounds on the growth rates of electrostatic instabilities, including ITGs with kinetic electrons, trapped-electron modes, and ion-driven trapped-electron modes. Moreover, the dependence of the upper bounds on magnetic geometry may be exploited in future stellarator optimisation studies.
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