Trapped-electron modification of kinetic ballooning instabilities in general geometry

Alessandro Zocco[1], Eduardo Rodríguez[1] and James Edmiston[1,2,3]
[1] *Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, D-17491 Greifswald, Germany*
[2] *Cambridge University, 19 JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[3] *Rudolf Peierls Centre for Theoretical Physics, Parks Road, Oxford OX1 3PU, United Kingdom*

Our understanding of the physics of trapped electrons [1] is mostly based on electrostatic results [2]. These have been extremely important in the description of particle transport both in tokamaks [3, 4] and stellarators [5], and in the assessment of the properties of turbulence in optimised stellarators [6, 7]. However, the persistence of trapped-electron effects at finite β in gyrokinetic simulations, and the high-β requirements in a stellarator like Wendelstein 7-X to achieve good trapped-electron properties [8] (for the so-called max-$\mathcal{J}$ configurations) put in doubt any electrostatic analysis.

Analytical studies of electromagnetic trapped electron instabilities are extremely rare in the literature [9]. Rosenbluth and Sloan [9] proved an electromagnetic stabilization of trapped-particle microinstabilities. Their result is based (but surely does not depend) on a peculiar choice for the electromagnetic gauge, which renders the analysis opaque. The Rosenbluth-Sloan formulation was put in relation to what then became the standard approach in kinetic ballooning mode studies by Tang, Connor, and Hastie (TCH) [10], who, however, overtly admit that: "If trapped particles contributions are retained, it becomes considerably more complicated to obtain a single eigenmode equation" for the kinetic ballooning mode. Nevertheless, the authors provide one. Their result, however, remained somehow *in fieri* and not fully explored, in particular if is considered in relation to ideal magnetohydrodynamic (MHD) short-wavelength instabilities.

Kinetic effects on ideal (MHD) instabilities have been investigated in a number of highly influential works [11, 12] in which several modifications of a variational MHD principle, first proposed by Mercier [13], were put forward. Within these theories, the role of trapped particles was emphasized by Connor and Hastie [14].

The advent of gyrokinetics in toroidal geometry [10, 15] allowed for considerable analytical progress. It is clear that while high-order corrections in a perturbative expansion for small magnetic drifts are necessary to reproduce ideal MHD results [10, 16], it is not obvious to predict: i) what is the electromagnetic trapped-electrons resonant contribution when no fluid (non-resonant) effect can provide destabilization, like for the regular strongly-driven kinetic ballooning mode [16] and/or ideal ballooning modes [17] ii) what are the actual constraints on the plasma pressure that determine the validity of the TCH trapped-electrons-modified KBM equation, iii) how do electrons participate to the interchange physical mechanism that drives kinetic ballooning modes unstable, iv) what is the impact of the symmetries of magnetic curvature, for different families on confining devices, in relation to the destabilisation of finite$-\beta$ trapped-electron modes. In this work, we address these problems.

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