

Impact of electron models on microinstability identification in ITER-relevant plasmas

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In this work, we revisit an ITER pre-fusion-power-operation plasma scenario, referred to as PFPO-2 (IMAS shot 101006) [5], which operates at half-field and half-current conditions (7.5 MA). Energetic particles arise from a negative-ion NBI source of 1 MeV. This scenario was previously analysed in a multiscale study by Ref. [3], where weakly damped toroidal Alfvén eigenmodes (TAEs) and elliptical Alfvén eigenmodes (EAEs) were observed for moderately low toroidal mode numbers ($10 < n < 35$). At higher mode numbers ($40 < n < 70$), unstable Alfvénic modes near rational surfaces were identified as Alfvénic Ion Temperature Gradient (AITG) modes. At even higher toroidal mode numbers ($n \simeq 200$), low-frequency microscale instabilities emerged, but they were only briefly discussed in that earlier work. Building on these prior investigations, the present work conducts a detailed study of the microscale instabilities identified at high toroidal mode numbers, comparing results across four distinct electron models implemented within the global gyrokinetic Particle-in-Cell (PIC) code ORB5 [4].

Moreover, a particular emphasis is placed on the role of the ion-to-electron mass ratio in drift-kinetic electron simulations and on the effect of finite orbit width (FOW) corrections within the hybrid electron model. The relevant equilibrium profiles, including the safety factor q , electron and ion temperature, and density profiles, are shown in Figures 1 and 2 of Ref. [3]. The global gyrokinetic PIC code ORB5 supports multiple electron models of varying physical fidelity and computational cost. In the **adiabatic electron** model, electrons respond

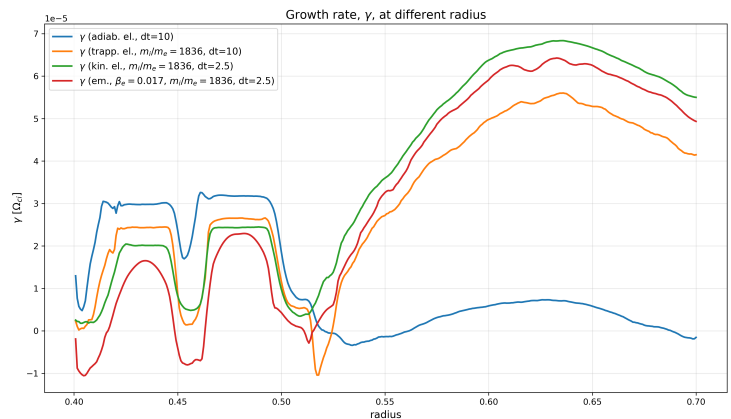


Figure 1: Growth rates as a function of radius for the different electron models, real mass ratio.

instantaneously to electrostatic perturbations according to a Boltzmann relation. This is the simplest and least computationally expensive model, and it is purely electrostatic [1]. It captures ITG-driven turbulence but cannot describe modes driven by electron dynamics, such as the trapped electron mode (TEM). In the **electrostatic drift-kinetic electron model**, electrons are treated as kinetic particles following drift-kinetic orbits, without retaining electromagnetic effects. This model is capable of capturing both ITG and TEM instabilities. The **electromagnetic model** extends the drift-kinetic description by additionally solving the parallel Ampère’s law, thus retaining magnetic flutter effects associated with perturbations of the vector potential A_{\parallel} [6]. The **hybrid electron model** is an electrostatic scheme that treats trapped electrons kinetically while passing electrons are handled adiabatically. This approach reduces the computational cost compared to a fully drift-kinetic treatment while retaining TEM physics [2]. The quasi-neutrality equation in the hybrid model reads:

$$\sum_{s \in \mathcal{I}_{GK}} \frac{q_s^2 n_{0s}}{T_{0s}} [1 - \Gamma_0(b_s)] \phi + f_{p,s}(\psi) \frac{q_s^2 n_{0s}}{T_{0s}} (\phi - \langle \phi \rangle_{FS}) = \sum_{s \in \mathcal{I}_{GK}} q_s \langle \delta n_s \rangle - e \delta n_e^{(\text{trap})}, \quad (1)$$

where $f_{p,s}(\psi) = 1 - \bar{\alpha}_b(\psi)$ is the flux-surface-averaged fraction of passing electrons, and $\langle \cdot \rangle_{FS}$ denotes a flux-surface average. The trapped fraction $\bar{\alpha}_b(\psi)$ is computed explicitly in ORB5 as the flux-surface average of the local trapped particle fraction:

$$\alpha_b(\psi, \chi) = \sqrt{1 - \frac{B(\psi, \chi)}{B_{\text{max}}(\psi, \chi)}}, \quad \bar{\alpha}_b(\psi) = \frac{\int \alpha_b(\psi, \chi) J_{\chi\psi\phi}(\psi, \chi) d\chi d\phi}{\int J_{\chi\psi\phi}(\psi, \chi) d\chi d\phi}, \quad (2)$$

where $J_{\chi\psi\phi}$ is the Jacobian of the coordinate transformation. We perform linear gyrokinetic simulations for a high toroidal mode number ($n = 180$), using each of the four electron models described before. Figure 1 shows the growth rates as a function of radius for the physical mass ratio $m_i/m_e = 1836$. Note that a convergence scan in time step, dt , has been performed separately for the different electron models. The spectrogram of the electrostatic potential for the hybrid model simulation is given in Figure 2. The results indicate that the most unstable mode is a trapped electron mode,

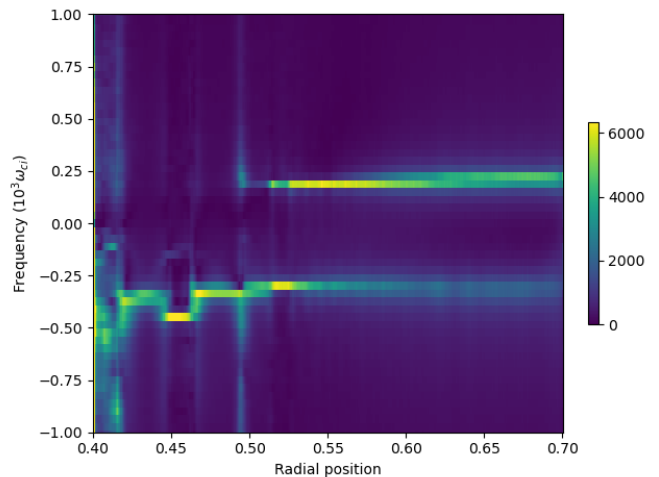


Figure 2: Spectrogram, hybrid model simulation.

localised in the outer region ($s > 0.55$). The globally subdominant mode near the plasma center ($r/a < 0.5$) is an ITG instability. It is important to notice that the hybrid model underestimates the growth rate of the TEM compared to the fully drift-kinetic model.

In order to understand the difference between drift-kinetic and hybrid electron results, the hybrid model has been extended to include finite orbit width (FOW) effects by computing $\bar{\alpha}_b(\psi)$ using the actual marker trajectories rather than a purely geometric criterion. In this approach, a particle is labeled as trapped if and only if its parallel velocity v_{\parallel} changes sign over a full orbit. Trapped markers are then deposited into radial bins to obtain $\bar{\alpha}_b(\psi)$ on a grid. The inclusion of FOW effects leads to an increase in the TEM growth rate within the hybrid model, bringing it closer to the fully drift-kinetic result. However, the discrepancy between the hybrid and drift-kinetic models is not fully resolved by the FOW correction alone, as it is shown in Fig. 3.

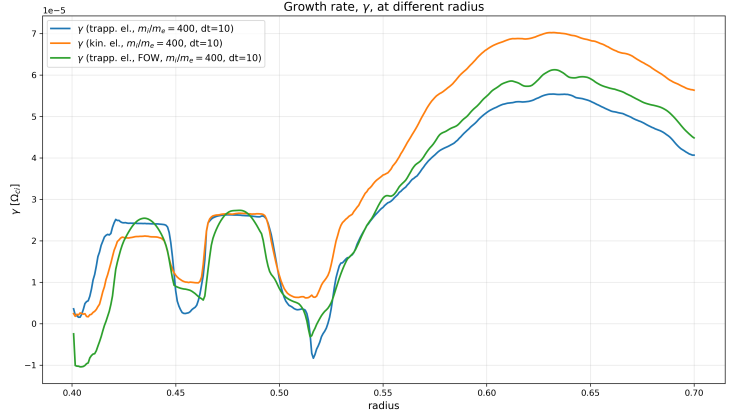


Figure 3: Effect of finite orbit width (FOW) on the TEM growth rate within the hybrid model.

To assess the sensitivity of the growth rates to the ion-to-electron mass ratio, we perform systematic mass scans for both the electrostatic drift-kinetic and the electromagnetic drift-kinetic models. Figure 4 presents the growth rates obtained with drift-kinetic electrons in the electrostatic limit for several values of m_i/m_e . The results demonstrate that the reduced mass ratio has a negligible effect on the TEM growth rate in the electrostatic case, validating the use of reduced mass ratios as a computationally efficient approximation for electrostatic simulations.

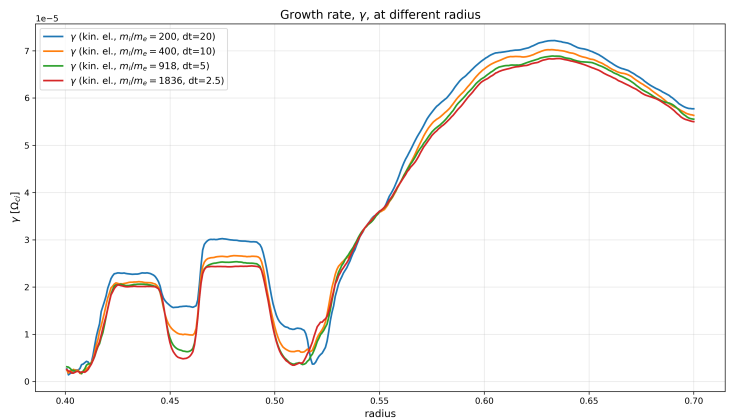


Figure 4: Growth rates for drift-kinetic electrons, for different values of the ion-to-electron mass ratio.

Figure 5 shows the corresponding results for the electromagnetic model at nominal plasma

beta. In this case, the reduced mass ratio is found to reduce the finite-beta stabilisation effect.

The main conclusions of this work are:

1) In the outer plasma region ($s > 0.55$), the dominant microinstability is the Trapped Electron Mode (TEM), while the Ion Temperature Gradient (ITG) mode dominates near the plasma center ($r/a < 0.5$).

2) The hybrid electron model underestimates the TEM growth rate compared to the fully drift-kinetic model, even when finite orbit width effects are included.

3) In the electrostatic limit, a reduced mass ratio $m_i/m_e = 400$ is a reasonable approximation with negligible impact on the TEM growth rate.

4) In the electromagnetic limit at nominal beta, the reduced mass ratio artificially weakens the finite-beta stabilisation of the TEM, highlighting the importance of using the physical mass ratio in electromagnetic simulations.

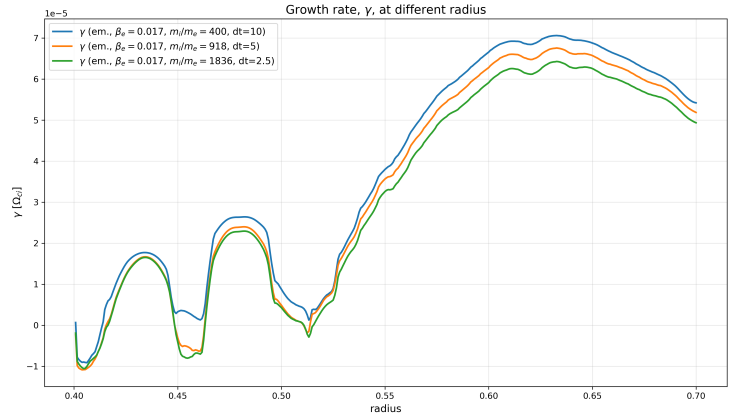


Figure 5: Growth rates for drift-kinetic electrons in the electromagnetic limit at nominal beta, for different values of the ion-to-electron mass ratio.

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