Role of Trapped Electrons on Global Gyrokinetic Linear Stability of Collisionless Microtearing Modes

Aditya K Swamy, R Ganesh
Institute for Plasma Research, Bhat, Gandhinagar, India
E-mail: ganesh@ipr.res.in

J. Chowdhury
Dept of Physics, University of Colorado, Boulder, CO, 80309, USA

S. Brunner, J. Vaclavik, L. Villard
CRPP, EPFL, 1015 Lausanne, Switzerland

Abstract. Unstable collisional MicroTearing Mode (MTMs) have been found in experiments of high-$\beta$ Spherical Tokamaks and are believed to be driven by drift resonance of trapped electrons. It has been recently shown that at large aspect ratio, the magnetic drift resonance of highly passing electrons is a minimal mechanism to drive the collisionless MTM unstable. In this work, a preliminary study of inclusion of trapped electrons in large aspect ratio tokamaks indicate that for the reference parameters investigated, the collisionless MTM retain their essential mode structures, while growth rates are only moderately affected.

1. Introduction

Microtearing modes (MTMs) are low frequency, high-$n$ electromagnetic microinstabilites in Tokamak plasmas. The mode draws free energy from the electron temperature gradient and is excited above a threshold gradient. Thus, if found unstable, it is envisaged to open up an important channel of electron transport. These modes exhibit tearing parity, i.e. odd parity in electrostatic potential and even parity in parallel magnetic vector potential and rotate in the electron diamagnetic direction. Early analytical work predicted these modes to be unstable only in collisional plasmas [1, 2, 3]. Recent gyrokinetic simulations have found unstable collisional MTMs in various magnetic confinement configurations such as spherical tokamaks with very high $\beta$ values in collisional or semi-collisional regime [4, 5, 6, 7, 8], standard tokamaks, such as ASDEX-Upgrade [9, 10], and weakly collisional Reversed Field Pinch plasmas [11, 12]. These linear gyrokinetic simulations, using a local flux-tube implementation, have thrown light on several characteristics of the mode, typically for high $\beta$ and relatively moderate electron temperature gradient length scales. The connection to experimentally observed
heat fluxes in devices through linear and nonlinear simulations is only beginning to be explored [8, 9, 5, 13].

Recent investigations have found that MTM is unstable in the absence of collisions as well [12, 14, 15], triggering a need to understand collisionless drive mechanisms. In the work of Ref. [14] pertaining to a spherical tokamak with high-β plasma, the magnetic drift resonance of trapped electrons is found to drive the collisionless MTM instability. At larger aspect ratios, the fraction of trapped particles is relatively small, and it has been found that collisionless MTM is driven unstable by the magnetic drift resonance of highly passing electrons [15]. Ions dynamics, on the other hand, do not affect the mode significantly. For typical β in tokamaks, it has been shown that the mode requires a high temperature gradient threshold to be unstable, and that the threshold is downshifted at higher β. For the ρ* (ρ/a, normalized ion radius) value considered, the global mode structure is found to be sensitive to profile variations in Ref. [15]. The trapped fraction was ignored with a view to gain insight into the nature of MTMs. As the trapped population (\( \sim \sqrt{2e} \)) constitutes a significant fraction, it is pertinent to study the role of trapped electron dynamics in the MTM instability mechanism.

Such a study is carried out using the linear global gyrokinetic electromagnetic microstability code EM-GLOGYSTO, for a circular flux surface, axisymmetric equilibrium in toroidal coordinates \((r, \theta, \phi)\). The model assumptions and formulation are detailed in Refs. [15, 16, 17, 18, 19, 20] and references thereof. In this work, many of the recent results described in Ref. [15] will be elaborated, where it is shown that passing electron alone suffice to drive MTM unstable in large aspect ratio tokamaks. In the later part, the effect of trapped electrons is addressed. As before, Shafranov shift is neglected for simplicity, while the \( B_\parallel \) fluctuations, which become important at very high β are also neglected in the present work. Section 2 contains the various profiles and input parameters used for the study, and the discussion mentioned above. Section 3 contains the important conclusions and future directions.

2. Results & Discussion

2.1. Input Parameters

The equilibrium profiles and plasma parameters used in this work are as in Table 1, Ref. [15]. For details, the reader is referred to Section IIA therein. The corresponding profiles are plotted in Fig. 1. The radial position where \( \eta_i \) peaks is represented as \( s = s_0 \) and \( \beta(s_0) \) as \( \beta_0 \). Frequencies and growth rates are normalized to \( \omega_0 = c_s/a \). For parameters throughout this work, we have \( T_{i0} = T_{e0} \), thus \( c_s = v_{th}, \omega_0 \approx 1.7 \times 10^6 \text{ s}^{-1} \). Studies in the range \( 0.0 < \beta_0 < 0.1 \) and \( 1 < a/L_T < 12.5 \) relevant to the operational regimes in tokamaks [22, 23, 24, 25] show that, qualitatively, the nature of the mode in the poloidal cross-section, including the tearing parity of the eigenmode structures, radial extent etc. remain similar across the parameter space, within both cases viz. (i) excluding the trapped electrons, (ii) including the trapped electrons.
2.2. Mode Structures excluding trapped electrons

The MTM instability typically has been thought to require a collisional drive and thus studies have focused more in high-\(\beta\) spherical tokamaks that allow for relatively high density and have strong toroidal effects. The scattering of trapped electrons in the trapped-passing boundary in velocity space increases the effective drive mechanism according to the model of Catto-Rosenbluth, thus accentuating the instability. On the other hand, in lower-\(\beta\) large aspect ratio plasmas, the trapped electron fraction is relatively smaller. Thus passing electron dynamics, in particular, the resonance of the
higher harmonics of transit frequency, magnetic drift resonance of passing electrons are more at play in destabilizing the collisionless MTM. The global mode characteristics are described in Ref. [15]. The mode shows a clear tearing parity, and is electromagnetic since it grows more unstable with $\beta$. The mode is seen to be most unstable at short, sub-ion scale wavelengths. Toroidal mode number $n = 23$ is seen to be the most unstable from Fig. 2.

![Fourier space plots for MTM fluctuations](image)

**Figure 3.** Fourier space plots for MTM $\tilde{\phi}$ fluctuations $n = 8, 12, .., 33$, excluding trapped electrons.

In Figs. 3, 4 the Fourier space plots for $n = 8, 12...33$ are shown (For the real space plots, see Figs. 7-11, Ref. [15]). Figs. 5, 6 show the contours of $\tilde{\phi}$ and $\tilde{A}_\parallel$, respectively. It is found that, typically, about 20 poloidal modes $m$ couple to form the converged global mode. The symmetry of the poloidal components of $\tilde{\phi}$ in reciprocal space with a zero amplitude for $n_r = 0$ translates to the odd symmetry, whereas the maximum for $\tilde{A}_\parallel$ to even symmetry, in radial direction. It is interesting to note that the amplitude for $\tilde{A}_\parallel$ has a sharper fall with $n_r$, indicating that the number of Fourier modes are more than sufficient and the eigenmode is well resolved. The $\tilde{\phi}$ spectrum is broad, whereas that of $\tilde{A}_\parallel$ is relatively narrow. In real space, $\tilde{\phi}$ is localized and $\tilde{A}_\parallel$ more extended, (See. Ref. [15]) consistent with similar results reported in Ref. [10]. The fluctuations arise from very short scale dynamics of electrons, such as in Trapped Electron Mode [21] and requires high resolution and computational resources for convergence, particularly for higher $n$. MTM mode characteristics are known to be complex, because of the dependence on different parameters. In Fig. 7, the $n = 10, 12$ modes are seen to remain more unstable at lower $\beta$. The critical $\beta$ is seen to be different for different $n$, with $n = 12$ having threshold near 2.5% and $n = 10$ having a threshold less than 2.5%
2.3. Mode Structures with trapped electrons

Inclusion of the non-adiabaic contribution of trapped electron is addressed here. In Figs. 8, 9 the radial Fourier spectrum of $\tilde{\varphi}$ and $\tilde{A}_||$ for each of the poloidal Fourier
components $m$ of the eigenfunctions are plotted. Figs. 10, 11 show the corresponding contour plots. The non-adiabatic response of the trapped electrons increases the amplitude of higher radial harmonics in $\tilde{\varphi}$ resulting in a broader spectrum in the radial direction and sharper structures on the mode rational surfaces, as seen from the contours.
in Figs. 10 and more clearly noticed in the plot for \( n = 8 \).

On the other hand, the eigenfunction \( \tilde{A} \parallel \) is unchanged with the inclusion of trapped electrons. This is expected since \( \tilde{j} \parallel \) is not changed by the trapped electron population. The trapped electrons do not seem to affect the overall mode structures of \( \tilde{\phi} \) and \( \tilde{A} \parallel \) and preserve the parities. For the fastest growing mode \( n = 23 \), the eigenfrequency \((\omega_r, \gamma)\) (in units of \( c_s/a \)) without trapped electrons is (0.96, 1.17), whereas the inclusion of trapped electrons leads to (1.03, 1.23). Similarly, for \( n = 12 \), the eigenfrequency is (0.59, 0.92) without and (0.58, 0.83) with trapped electrons. The radial and poloidal extent, poloidal variation of the amplitude envelopes are nearly the same, with and without the trapped electrons.

3. Conclusions

For large aspect ratio, collisionless tokamak plasmas, we have presented a high resolution 2D global gyrokinetic stability study of MTM considering passing ions and electrons and the effect of inclusion of the trapped electrons on the mode structures. The model is electromagnetic in nature but neglects parallel magnetic field perturbations, which are important only at very high \( \beta \). Completely collisionless Microtearing Modes were recently found unstable in large aspect ratio hot tokamaks in the finite temperature gradient region with a finite-beta plasma. The magnetic drift resonance of the passing electron population provides the main destabilizing mechanism, even though the trapped
Figure 9. Fourier space plots for MTM $\tilde{A}_||$ fluctuations $n = 8, 12, \ldots, 33$, with trapped electrons.

Figure 10. Contour plots for MTM $\tilde{\varphi}$ fluctuations $n = 8, 12, \ldots, 33$. For clarity, only the first quadrant is shown. Sharp radial structures are seen in $\tilde{\varphi}$ due to trapped electrons. The odd symmetry with respect to $\theta$ is preserved. As $n$ increases, the modes are seen more localised in $r$.

electron population constitutes a significant proportion. For MTM with trapped electrons neglected, global calculations showed that $n = 23$ is the most dominant mode,
at $\beta_0 = 5\%$ and $a/L_T \sim 5.0$, and has a critical $\beta$ value of about $3.3\%$. Importantly however, the dependence of the growth dates on $\beta$ is distinct for different toroidal modes $n$.

The tearing parity of $\tilde{\psi}$ and $\tilde{A}_\parallel$ are preserved with the inclusion of trapped electrons. The nonadiabatic response of the trapped electrons is observed to excite higher radial Fourier harmonics of $\tilde{\psi}$ fluctuations, leading to sharp structures in the radial direction. The structure of $\tilde{A}_\parallel$ is not strongly affected by the inclusion of trapped electrons, as can be expected. The contribution from trapped electron dynamics moderately affects the linear growth rates of the instability, changing by about $10\%$. A more detailed study of the influence of trapped electron dynamics and other plasma parameters on MTM will be communicated elsewhere.

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