Linear Gyrokinetic Stability Analysis of ST40 Hot Ion Plasmas

Y. Ren[1], S. Kaye[1], M.S. Anastopoulos Tzanis[2], M. Sertoli[2], A. Dnestrovskii[2], M. Romanelli[2]

1 Princeton Plasma Physics Laboratory, Princeton, NJ 08543

2 Tokamak Energy Ltd, 173 Brook Drive, Milton Park, Oxfordshire OX14 4SD

PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

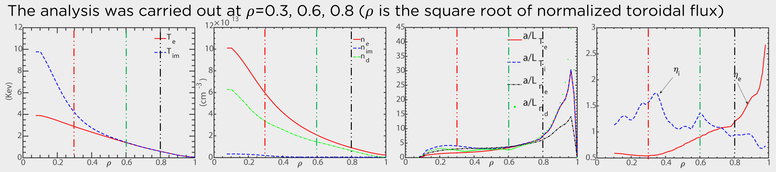
Tokamak Energy

Introduction

- ST40 is the first high-field spherical tokamak, achieving $I_p \approx$ 0.4-0.8 MA, on-axis $B_T \approx$1.5-2.2 T, and pulse durations ≈0.2 s in the most recent operations.
  - 2 MW of neutral beam heating is available: one source at 25 keV for 0.1 second; the other at 55 keV for 1 second
- The high ion temperature ST40 plasmas ($T_i \gg T_e \sim 3\,keV$) were achieved, e.g., with R=0.45 m, κ = 1.5, aspect ratio A=1.65, I_p = 0.6 MA, B_T =1.9 T, and a typical pulse length of 0.1 s.
  - Plasma profiles inferred using in integrated analysis workflow that incorporated the line-of-sight integrated and profile measurements of the electron, ion temperatures and toroidal rotation, the line-of-sight integrated density measurements, and equilibrium constraints.
- It is imperative to explore operating micro-instabilities in ST40 plasmas, particularly in the fusion-relevant hot-ion regime.
  - Micro-turbulence considered to be a major candidate in driving anomalous transport in fusion plasmas, and the energy confinement time of ST40 most likely being limited by micro-turbulence.

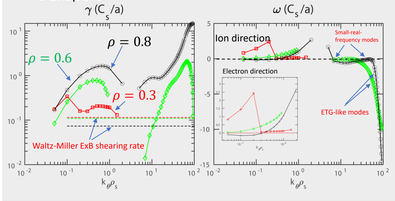
Linear Stability is Studied at Multiple Radii in a ST40 Hot-ion Shot 9831

- B_T~1.8 T, I_p~500 kA and not highly shaped with κ~1.3 and $\delta \sim 0.2$
- Impurity temperature, T_{im}, ~ 10 keV in the core, and ion temperature, T_i, is 1-1.5 keV lower than T_{im} in plasma center, clearly in the hot-ion regime
  - $T_{im} = T_i$ should be well satisfied in the outer half of the plasma.
- $\eta_e = \frac{L_{n_e}}{L_{T_e}}$ decreases from ~1 to ~0.5 from ρ=0.8 to 0.3, showing stabilization of ETG mode towards the plasm core.
- $\eta_i = \frac{L_{n_d}}{L_{T_i}}$ increases from ~1 to ~1.5 from ρ=0.8 to 0.3, indicating ion mode more important towards the plasma core.
- The analysis was carried out at ρ=0.3, 0.6, 0.8 (ρ is the square root of normalized toroidal flux)



Significant Stabilization of Micro-instabilities towards Plasma Core

- Linear growth rates of both ion- and electron-scale ($k_\theta\rho_s \gtrsim 0.2$) modes decrease from the edge towards the core of the plasma
- Complete suppression of electron-scale modes ($k_\theta\rho_s \gtrsim 5$) at $\rho = 0.3$; No-monotonic for $k_\theta\rho_s < 0.2$
- ExB shearing rate < the maximum γ in the ion scale, implying the importance of ion-scale modes in driving transport



- Ion-scale modes are mainly in the ion direction and electron scale modes are mainly in the electron direction
  - At ρ=0.8, there is a change in the propagation direction at $k_\theta\rho_s \approx$ 0.34
- What are these ion-scale modes?
- Small-ω k ranges in the intermediate scale are seen from $k_\theta\rho_s \approx$ 5 to 60 at ρ = 0.8 and from $k_\theta\rho_s \approx$ 5 to 30 at ρ = 0.6 with ω only weakly increasing in amplitude with k
- Typical electrostatic ETG mode dispersion is only seen at higher wavenumbers, $\gtrsim \rho_e^{-1}$ with ω strongly increasing in amplitude with k
- What are these small-ω electron-scale modes?

Ubiquitous Mode (UM) is due to Nonadiabatic Responses of Both Trapped Electrons and Passing Ions

- This branch of solution of the dispersion equation is of TEM at lower k and is of UM at higher k with a purely growing fluid-like mode in the transition
  - Both TEM and ubiquitous mode are driven by wave-particle resonances
  - The fluid-like mode is non-resonantly driven by magnetic drifts of both trapped electrons and passing ions in the bad curvature region
- Nonadiabatic ion response in the electron scale is important
  - Adiabatic ions are usually assumed for electron scale, i.e. for the well-known ETG mode
  - Adiabatic ion response arises from $I_{0,1}(b)e^{-b}$ term in the nonadiabatic ion response where $I_{0,1}(b)e^{-b} \sim 1/\sqrt{b}$ with large b and $b = k_\perp^2\rho_i^2/2$.
  - However, in local approximation, the non-adiabatic part of ion response is:

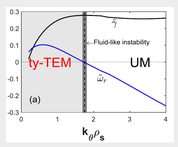
$$\frac{\omega+\omega_{*i}}{\omega+\omega_{Di}} I_0(b)e^{-b}\frac{e\phi}{T_i}n_0$$

where ω_{*i} is the ion diamagnetic drift frequency and ω_{Di} is the ion magnetic drift frequency.

  - If $\omega_{Di} \ll \omega \ll \omega_{*i}$, with large b, the non-adiabatic part of ion response is written as

$$\frac{\omega_{*i}}{\omega}\frac{1}{\sqrt{2\pi b}}\frac{e\phi}{T_i}n_0$$

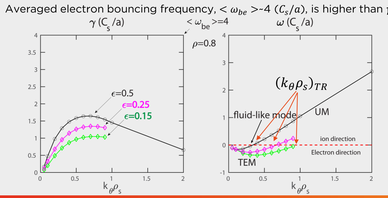
and the $k_\perp$ in ω_{*i} and $\sqrt{b}$ cancel each other, leading to a finite non-adiabatic ion response even in the electron scale (b>>1) (Smolyakov et al., PRL 2002; Hirose and Elia, PoP 2002)

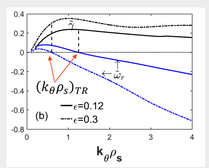


Shen et al., NF 2019

Inverse Aspect Ratio Scans at ρ=0.8 Show Consistent Trend with UM

- The propagation direction changes from the electron direction to the ion direction with increased wavenumber
- The smooth transition (rather than a jump) indicates the same branch of solution of the dispersion relation
- Ubiquitous mode (UM) (Coppi, 1974 and 1977; Shen, 2019) is consistent with these observations
- The transition wavenumber between TEM and UM, $(k_\theta\rho_s)_{TR}$, denotes relative dominance of TEM and UM, i.e., smaller $(k_\theta\rho_s)_{TR}$ meaning more dominant UM in the k spectrum.
- Averaged electron bouncing frequency, $< \omega_{be} >$~4 (C_s/a), is higher than γ and ω at $k_\theta\rho_s < 2$ and the detrapping frequency at ρ = 0.8

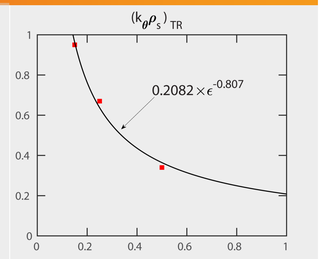




Shen et al., NF 2019

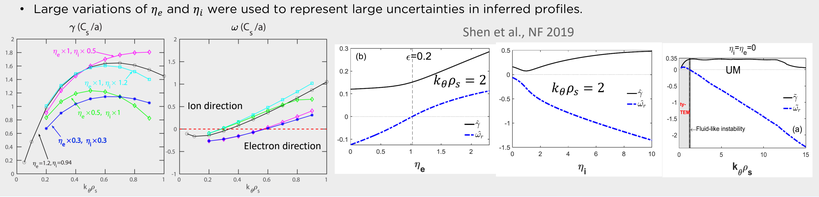
The Transition wavenumber, $(k_\theta\rho_s)_{TR}$, at $\rho = 0.8$ Scales with ϵ Consistently with UM

- $(k_\theta\rho_s)_{TR}$ clearly inversely depends on ϵ, consistent with the UM theory (Coppi, 1974 and 1977).
- $(k_\theta\rho_s)_{TR} \sim \epsilon^{-1/2}$ was found from a cancellation of the density gradient drifts of ions and trapped electrons (Coppi, 1974 and 1977).
- Fit of results from GS2 linear simulations shows $(k_\theta\rho_s)_{TR} \sim \epsilon^{-807}$, having a stronger dependence on ϵ, but in good agreement with Shen et al., NF 2019 where $(k_\theta\rho_s)_{TR} \sim 0.6 \times \left(\frac{1}{\sqrt{2\epsilon}}\right)^{1.6}$ calculated numerically



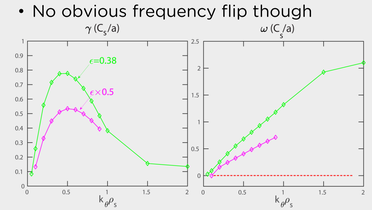
Ion and Electron Temperature gradient Scans at $\rho = 0.8$ Show Consistent Trend with UM

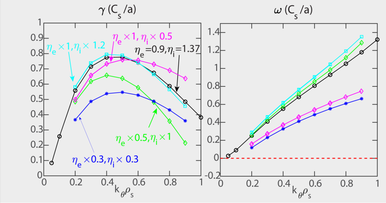
- Reducing η_e (through a/L_{T_e}) by 50% alone leads to reduced γ and more positive ω (except for $k_\theta\rho_s > 0.8$).
  - Smaller $(k_\theta\rho_s)_{TR}$ with reduced η_e, which makes UM more dominant in the k space
- Reducing η_i (through a/L_{T_i})by 50% alone leads to increased γ at $k_\theta\rho_s > 0.4$ and more negative ω overall.
  - Larger $(k_\theta\rho_s)_{TR}$ with reduced η_i, which makes UM less dominant in the k space
- Increasing η_i by 20% alone leads to reduced γ at $k_\theta\rho_s > 0.4$ and more positive ω overall (more dominant UM in the k space).
- The modes are still robustly unstable with a 70% reduction in both η_i and η_e (a/L_{n_e} likely a driving force as shown for UM).
- Large variations of η_e and η_i were used to represent large uncertainties in inferred profiles.



ϵ and Temperature gradient Scans at $\rho = 0.6$ Show Consistent Trend with UM

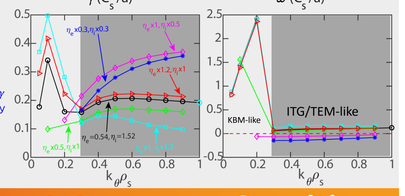
- Reducing ϵ by a factor of 2 leads to reduced linear growth rates and reduced real frequencies, similar to that at ρ = 0.8
- No obvious frequency flip though
- η_e and η_i dependence is very similar to that at ρ = 0.8 (i.e., consistent with UM)
- No obvious frequency flip with the η_i and η_e Scans





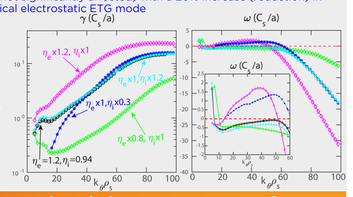
KBM/ITG/TEM are likely the Operating Micro-instabilities at $\rho = 0.3$

- Distinct differences are seen in response to η_e and η_i variations by modes at $k_\theta\rho_s < 0.3$ and at $k_\theta\rho_s \geq 0.3$.
- For $k_\theta\rho_s < 0.3$ modes: either reducing (increasing) η_e or η_i alone being stabilizing (destabilizing);completely stabilized with η_e and η_i both reduced by 70%; γ being more sensitive to η_i than to η_e; ω being in the ion direction
  - KBM likely: modes likely being driven by total pressure, supported by odd parity in $A_{||}$ eigenmode structure (not shown) with much enhanced B fluctuations consistent with the higher β at ρ = 0.3 than at ρ =0.8 (1.2% vs 0.05%)
- For $k_\theta\rho_s \geq 0.3$ modes: γ enhanced with η_e and η_i reduced both by 70% or η_i reduced alone by 50% or η_e increased alone by 20% ; γ reduced with η_i increased alone by 20% or η_e reduced alone by 50%; forming lower-k peak in γ with reduced η_i or η_e
  - Consistent with ITG/TEM hybrid
  - Reducing η_e or increasing η_i alone making modes more ITG-like with lower γ, forming a lower-k γ peaks, and ω in the ion direction
  - Reducing η_i alone leading to significantly enhanced γ and ω switching to the electron direction, consistent with TEM
  - Large reduction of both η_e and η_i leading to significantly enhanced γ and ω switching to the electron direction, clearly evidence of density gradient driven TEM
  - Averaged electron bouncing frequency ~4 (C_s/a), much higher than γ and ω at $k_\theta\rho_s \geq 0.3$ and the detrapping frequency at ρ = 0.3,
- Wide scans in η_e and η_i represent large uncertainties in inferred profiles



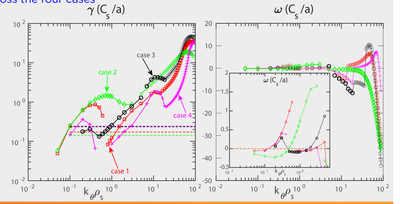
Electron-scale Modes at $\rho = 0.8$ are very Sensitive to η_e

- γ of electron-scale modes at $k_\theta\rho_s > 7$ is very sensitive to η_e (through a/L_{T_e})
  - Up to a factor of 3 increase in γ at $k_\theta\rho_s \approx$ 44 with a 20% increase in η_e; more than 80% decrease in γ in the $k_\theta\rho_s$ range of 23 to 78 with a 20% reduction in η_e
  - T_e gradient is the main free energy driving the unstable modes in the electron scale
  - Much weaker dependence on η_i, only significantly affected at $k_\theta\rho_s < 40$ with a 70% reduction in η_i
- ω of electron-scale modes at $k_\theta\rho_s > 7$ has very different response to η_e in the intermediate k range (between ρ_i^{-1} and ρ_e^{-1}) and in the high k range (ρ_e scale and beyond)
  - Intermediate k range modes having ω flipped to significantly positive values (not significantly affected) with a 20% increase (reduction) in η_e, while high-k modes having more (less) negative ω, consistent with the typical electrostatic ETG mode
  - Much weaker dependence on η_i, with significant changes in mode ω seen at $k_\theta\rho_s < 40$ with η_i reduced by 70%
- Increasing η_i by 20% does not significantly affect either γ or ω
- ω is a continuous function of $k_\theta\rho_s$ at $k_\theta\rho_s$ >7, indicating the same branch of solution of the dispersion relation in the electron scale.
- The Intermediate range small-ω ETG-drive instability has quite different parametric dependence than the typical ETG mode and should be categorized as a different instability.



Identification of UM is Supported with a group of equilibria with different profile combinations

- Four plausible equilibrium combinations (most importantly T_e, T_i and n_e profiles) in another ST40 hot ion plasma, 10014, (similar to shot 9831) were used for GS2 linear gyrokinetic stability analysis at ρ = 0.8 where UM is clearly identified for shot 9831
  - To count for the 20% uncertainties in inferred profiles with different nominal value combinations
  - Having largest variations in T_i/T_e, electron-ion collision frequency across the four cases
- Clear UM-type ω sign switching is seen in the ion scale for cases 1 and 2
  - The existence of UM supported by ϵ and η_e/η_i scans
- Intermediate range small-ω instability and the typical ETG mode still exist
  - Supported by η_e and η_i scans
  - ω discontiuities showing the existence of another ETG-like instability forming a local γ peak in the intermediate scale



Summary

- Linear gyrokinetic stability analysis with GS2 code has been carried out for ST40 hot ion plasmas.
- Linear growth rates of both ion- and electron-scale ($k_\theta\rho_s \gtrsim 0.2$) modes decrease from the edge toward the core of the plasma (ρ = 0.3-0.8).
- Complete suppression of electron-scale modes ($k_\theta\rho_s \gtrsim 5$) is found at ρ = 0.3.
- Ubiquitous mode (UM), ETG and an unidentified low-real-frequency electron-scale instability are found at $\rho \geq 0.6$, with KMB/ITG/TEM most likely at ρ = 0.3, through parametric scans, i.e., temperature gradients and aspect ratio.
- The identification of UM is supported with a group of equilibria with different profile combinations, particularly T_e, T_i and n_e, given the ~20% experimental uncertainty of inferred profiles.