Microturbulence studies in RFX-mod

Outline of the talk

ˇ The Past

Why microturbulence studies in RFX-mod

Established results 2008-2011: a brief review of the different kinds of microturbulence investigated (ITG, TEMs, MTs, eta-g) and assessment of their stability properties

A comprehensive report is provided in [Cappello et al NF 51, 103012 (2011)]

ˇ The Present and the Future

Current lines of investigation

Open issues
Why microturbulence studies

- Onset of SHAx or DAx states with low-magnetic-chaos core in RFX-mod as standard operational scenarios has triggered interest towards transport mechanisms other than the classical magnetic field line diffusion due to overlapping of MHD tearing modes.

- Internal Temperature transport barriers provide strong gradients, potentially free energy sources for driving instabilities.

- Is microturbulence \( k_\perp * \rho \sim 1 \) unstable? What is its impact upon confinement and transport?

- Numerical investigations carried out using gyrokinetic and gyrofluid approaches

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FIG. 1 (color online). (a),(d) Poincaré plot for a SHAx and DAx case, respectively. (b) Safety factor profile for a SHAx state (continuous) and \( q_{\text{axi}} \) (e) \( q \) for DAx case. Continuous (respectively, dashed) line represents the \( q \) computed with respect to the \( O \) point \( O \) (respectively, former axisymmetric axis A). (c) (f) Thomson scattering profile for a SHAx and a DAx case respectively, measured along the diameter shown with a horizontal line in (a) and (d).
Ion Temperature Gradient Modes/1

ITGs are a major instability in tokamaks: Electrostatic drift modes driven by temperature gradients.

Several investigations concur in assessing that, in RFX-mod, ITGs are stable, or at most marginally unstable in extreme temperature barriers [Guo 2008 PoP 15 122510, Predebon 2010 PoP 17 012304, Sattin 2010 PPCF 52 105002], see also [Tangri, PoP 18, 052310 (2011)]

Reason: Landau damping more effective in RFPs


\[
\left( L_{T_i} \right)^{-1} \equiv \nabla T_i / T_i
\]

Roughly a factor \( R/a \)

[Predebon I. et al 2010 PoP 17 012304]
Impurities (mostly Carbon and Oxygen) are ubiquitous in RFX-mod, with $Z_{\text{eff}} > 1.5$.

Possible coupling between ITGs and impurities:

Impurity gradients may help destabilize ITGs $\leftrightarrow$ unstable ITGs shape impurity density profiles

**Role of the impurities on ITGs**

Impurities help destabilizing ITGs when their gradient is opposite to main gas’ since this condition alleviates the effect of the Landau damping.

The effect grows with the content of impurities in the plasma. Significant enhancements of the growth rate take place for impurity concentrations of several %

**Role of ITGs on impurities**

Assuming ITGs are destabilized, gyrokinetic simulations point it out that their role on transport is driving an inward convection of impurities. However, transport modelling of spectroscopic data hints to an outward convection

*ITGs do not look the main transport mechanism as far as impurities are concerned*

Refs: [Predebon et al, submitted; Carraro et al poster P1.129 EPS 2011; Liu et al, NF 2011]
Trapped Electron Modes

RFPs have a fraction of trapped electrons comparable to tokamaks [Gobbin et al, J plasma Fus Res Ser 8 (2009)]

Possible onset of instabilities related to this population (Trapped Electron Modes)

Study of linear stability performed via integral gyrokinetic equation and GS2 code. [Guo-Predebon-Wang EPS 2010]

Overall conclusion:
TEMs can be triggered by relatively large density gradients, $L_B/L_n \geq 3$, and moderate temperature gradients, $a/L_T < 4$

These conditions are hardly met in the core. Could be attained at the edge
Resistive-g modes

Interchange modes driven by pressure gradients.

MHD instabilities, characterized by high wavenumbers (\(n >> 10\)): may be monitored using the same tools as other microinstabilities.

Positively identified in edge plasmas. Unstable at ITBs, too? not yet observed (investigations underway)

(a) Theoretical growth rate (ETAW,MARS) for different toroidal mode numbers, corresponding to two \(q(a)\). Different symbols mark the two different plasma pressure profiles used for the simulation.

(b) Experimental \(S(n)\) spectra under the same \(q(a)\) conditions of (a)

[Zuin et al PPCF 51 (2009)]

[Zuin et al NF 50 (2010)]
Microtearing modes

- EM instability, high wavenumber \((m,n \gg 1)\). Driven by temperature gradients, not magnetic field like its MHD counterpart, thus possibly unstable on the barrier.
- Found in GS2 linear stability calculations.
- Provide a source of stochastic transport via mode overlapping.

Temperature profiles (black squares) and MT linear growth rates for two RFX-mod discharges

[Predebon et al, PRL 105, 195001 (2010); Sattin et al, J Phys Conf Series 260, 012018 (2010)]
Effect of collisionality over MT stability

- It is acknowledged that MT are linearly stable at zero collisionality [Drake PRL 1980]. For this reason they are traditionally dismissed as turbulence sources in high-temperatures devices but...

- …linear gyrokinetic calculations suggest another result: MT linearly unstable even at $\nu = 0$. Some evidences found in tokamak simulations [refs. In Doerk-Bendig 2009], then in RFX-mod.

- If confirmed, potentially important consequences for high-temperature devices confinement

- Why this discrepancy? Terms neglected in simplified analytical treatment, lack of convergence in numerical gyrokinetic calculations, …?

[H. Doerk-Bendig, Physical and Mathematical Challenges in Light of ITER, Marseille 2009 – GENE]


[D.R. Smith et al, PPCF 53,035013 (2011) – GS2 NSTX sub-ion-radius gyroscale]

Counter-example ?
Up to now, most experimental evidence of MT’s has been indirect: usually, the heat conductivity is estimated theoretically and then compared against power-balance estimates [Predebon et al, PRL 105, 195001 2010; K.L. Wong et al, PRL 99, 135003 2007].

In RFX-mod, thanks to the system of sensors for magnetic measurements, some activity has been recorded that could be related directly with the onset of MTs.

Magnetic probes used: same U-probe as for g-modes (low n resolution), plus 2 others at the GPI location (high n resolution)

Figure 1. Schematic of the insertable probe and pictures of the total assembly and of a three-axial magnetic coil.
Bursts of magnetic activity in the 100-300 kHz frequency range are observed with the U-probe.

Alfven eigenmodes

A peak in the power spectrum forms during QSH phases: related to temperature gradients?
Toroidal and poloidal mode numbers

By using 2-points correlation technique, extremely high $m$ and $n$ mode numbers are measured.
Other evidences from the comparison between experiment and gyrokinetic simulations:

- GS2 predicts instability when probes measure magnetic signal (same shots and times)
- Phase velocity of the signal = electron diamagnetic velocity (expected for MT rotation)

... but problems, too:

- Appearance of a branch of non-MT modes at shorter wavelengths: likely same modes reported in [Hallatschek& Dorland, PRL 95 (2005) 055002]. Growth rates peak at \((m,n)\) numbers larger than experiment
- Mismatch between magnetic and thermal analysis? Thermal island’s lifetimes (hence instabilities triggered by \(T\) gradients) something shorter than magnetic signal’ (Ruzzon’s talk)

...issue still open to investigations...
Perspectives: Helical effects in the Numerical Codes

Up to now, studied

- ITGs
- TEMs
- MTs
- $\eta$-g modes

in cylindrical geometry. Not the best choice for helical SHAx states.

Past studies already highlighted shear q relevance in microturbulence excitation ...
Need to take into account true helical geometry

Next step: From GS2 to GENE

GENE code can be easily fed with arbitrary magnetic topology (for example via VMEC output or PIXIE3D MHD computations).

Allows revisiting all of the previously investigated physics

END - thank you
U-Probe: technical details

Sampling frequency 10 MHz

Bandwidth 3 MHz

Max $n$ measured = 85.

Poloidal numbers $m$ measured by rotating 90° the probe. Max $m$ achieved = 16.
RFPs are more resilient than Tokamaks to this kind of instability.

The rationale for this behaviour stays in the different level of Landau damping due to the different connection length $L_c$ of magnetic field lines between the two devices.

Waves with helicity defined by the angular numbers $(m, n)$ are damped through energy exchange to those particles that are close to the resonance condition

$$v_{||} = \omega k_{||}^{-1} \quad k_{||} = 2\pi \times (m - nq) \times L_c^{-1}$$

$v$ is the parallel component of the particle velocity, $k$ the parallel wavenumber of the mode, $\omega$ its angular frequency, and $q$ the safety factor.

In RFPs, by virtue of their geometry, $L_c$ is shorter than in Tokamaks by about a factor (minor radius)/(major radius), accordingly, $k$ is larger by the same amount. Landau damping of the wave is the most effective the more resonant particles are present. If the velocity distribution function $f(v)$ is close to a Maxwellian, the smaller $v$, the more resonant particles are available.
Case study: ITB beyond ITG marginal stability conditions + ohmic heating + background diffusivity.

Without ITGs, ohmic heating raises the temperature in the low-chaos core region; how does the final profile relax by including ITGs?

An instance of nonlinear simulation using TRB code

An initially ITG-unstable ion temperature profile (red curve) fed by ohmic heating is let to evolve (blue curves) under self-generated turbulent transport and additional background diffusivity (solid piecewise curve).

Conclusions: ITGs relax the profiles onto their marginal stability curve, regardless of other transport mechanisms and sources.
**Phase velocity and diamagnetic velocity**

**Diamagnetic velocity:**

\[ V_{de} = \nabla \times B (en_e B^2) \sim \nabla T_e / (eB) \]

\[ \approx 400 \text{ eV} / (10 \text{ cm} \times 0.5 \text{ T}) = 8 \times 10^3 \text{ m/s} \]

**Toroidal phase velocity:**

\[ V_\phi = 2\pi f / (n/R) \approx 10^4 \text{ m/s} \]
GS2 numerical simulations

Runs carried out on the same database as measurements

Measurements are sensitive only to the left part of the whole profile

[Hallatschek & Dorland, PRL 95 (2005) 055002]