Microstability Analysis of Low-Z Impurity Doped Tokamak Plasmas

Gábor Szepesi[1,2], Michele Romanelli[1]

[1]EURATOM/CCFE Fusion Association, Culham Science Centre
[2]Centre for Fusion, Space and Astrophysics, University of Warwick

michele.romanelli@ccfe.ac.uk
g.szepesi@warwick.ac.uk

FTU Collaborators: M.L. Apicella, D. Frigione, M. Marinucci, G. Mazzitelli and C. Mazzotta

GKW Group: A.G. Peeters, Y. Camenen, F. Casson, W. Hornsby, A. Snodin

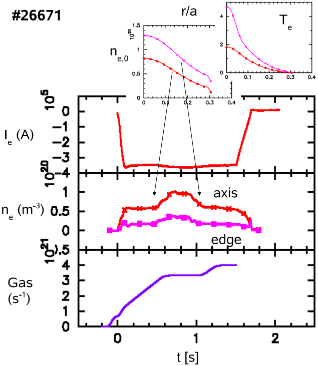
Contents

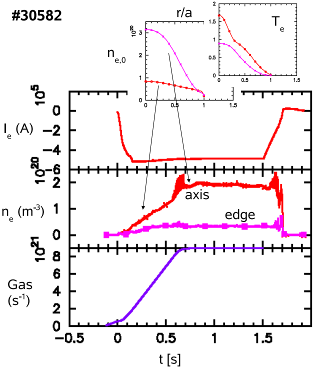
LLL discharges in FTU

G. Mazzitelli et al., submitted to Nuclear Fusion.

- reference discharge: #26671
- **metallic limiter**, Ohmic and ECRH heating

- LLL discharge: #30582
- improved recycling + density follows gas injection **in the core**

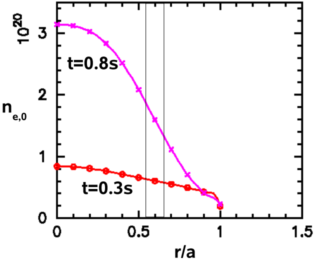




Contents

Parameters, FTU #30582, $r/a = 0.6$

- Linear microstability analysis at: $r/a = 0.6$, $t = 0.3\mathrm{s}$ and $t = 0.8\mathrm{s}$
- GKW: Peeters et al. CPC 2009



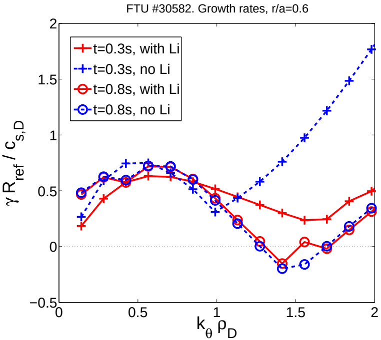
$t = 0.3\mathrm{s}$

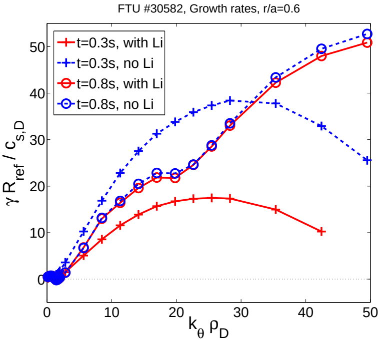
	$n[10^{19}\mathrm{m}^{-3}]$	$T[\mathrm{keV}]$	$-\frac{a\nabla T}{T}$	$-\frac{a\nabla n}{n}$
D^+	3.21	0.47	2.14	0.89
e^-	6.03	0.57	3.07	0.89
Li^+	0.94	0.47	2.14	0.89

$t = 0.8\mathrm{s}$

	$n[10^{19}\mathrm{m}^{-3}]$	$T[\mathrm{keV}]$	$-\frac{a\nabla T}{T}$	$-\frac{a\nabla n}{n}$
D^+	15.50	0.26	4.61	3.12
e^-	15.95	0.24	4.94	3.12
Li^+	0.15	0.26	4.61	3.12

Linear Results: Growth Rate





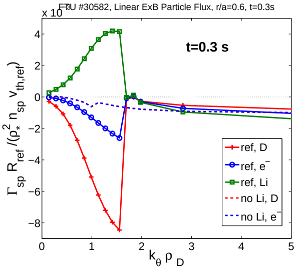
Low-k spectrum

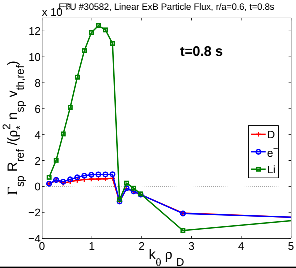
- $t = 0.3$s: weak stabilization by Li at the largest wavelength ITG modes, **drive of Li-TG modes at intermediate wavelengths**.
- $t = 0.8$: low Li concentration, negligible effect on ITG growth rate (circles).

High-k spectrum

- ETG and TEM modes stabilised by large lithium concentration (crosses), see M Reshko, C M Roach, PPCF **50** 2008
- Li concentration low, negligible effect on ETG growth rate (circles)

Linear Results: Particle Flux





Linear fluxes

- reflect the phase difference of ϕ_1 and n_1
- **magnitude carries no information**
- the sign indicates inward (-) or outward (+) flux
- abrupt change at transition from ITG to TEM

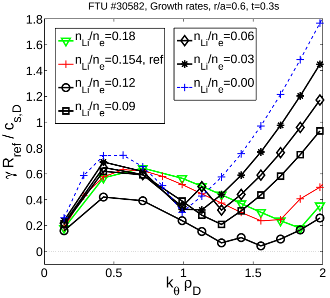
$t = 0.3\mathrm{s}$ (top)

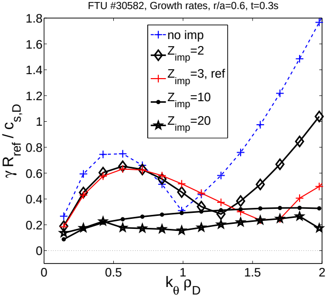
- **with Li:** ITG modes drive inwards D^+ and e^-, and outwards Li^+ fluxes
- **no Li:** most of the spectrum drives inward flux

$t = 0.8\mathrm{s}$ (bottom)

- D^+ and e^- fluxes driven by ITG are outward.

Impurity Parameter Scan





Li Density Scan

- Transition from ITG to TEM modes depends on n_{Li}.
- Inward flux of main species and outward impurity flux even at $n_{\mathrm{Li}}/n_{\mathrm{e}} = 0.3$

Z_{imp} Scan

- TEM (and ETG) stabilization observed with various low-Z impurities.
- Collisions play an important role in stabilization of ITG modes.

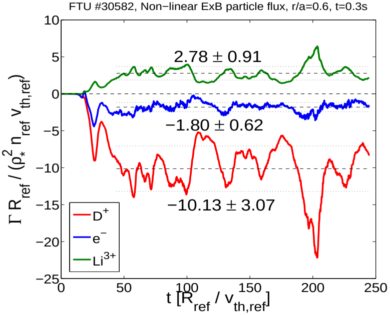
Summary of Linear Simulations

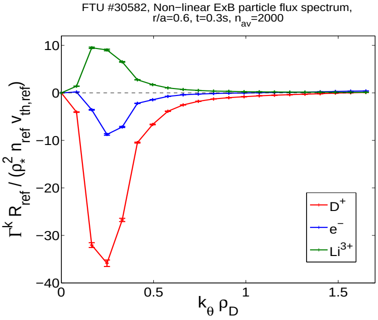
Presence of impurities ($n_{\mathrm{Li}}/n_{\mathrm{e}} > 0.01$):

- gives rise to Impurity-TG driven modes (depending on collisions),
- stabilizes TEM and ETG modes (Reshko, Roach, PPCF 2008),
- decouples ion and electron density fluctuations allowing different phase shifts compared to the potential fluctiation,
- drives inward flux of main species via ITG modes while impurity ions are being transported outward.

Do these characteristics persist in the non-linear phase?

Non-Linear Results: Experimental Case

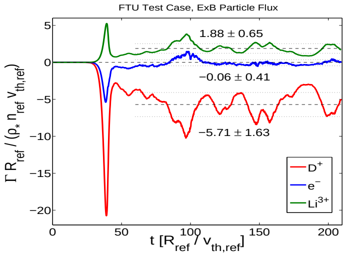


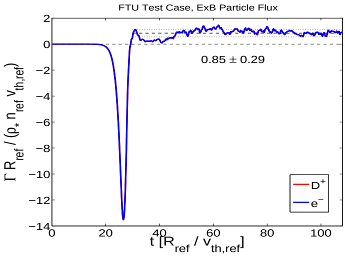


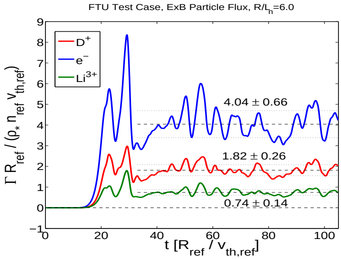
Non-Linear Fluxes

- Non-linear simulation of the ITG modes (up to $k_\theta \rho_D \sim 1.6$)
- Linearly predicted flux direction remains in the saturated phase.
- Flux level comparable to experimentally obtained values.
- Mode amplitude and flux dominated by the fastest growing modes.

Non-linear Results: Test Case







- Lower drive ($R/L_{T,i} = 6.0$), lithium density ($n_{\mathrm{Li}}/n_{\mathrm{e}} = 0.1$) and safety factor ($q = 2$)
- Lithium changes the direction of D^+ and e^- fluxes.
- Increased density gradient ($R/L_n = 3.0 \rightarrow 0.6$) changes flux.

Contents

Particle Transport

Theoretical study of turbulent particle transport (non-complete list):

- Turbulent particle flux in gyro-kinetic and quasi-linear theory (role of ITG, TEM): Fable, Angioni, Sauter PPCF 2008, 2010
- Effects of collisionality: Peeters, Angioni, PoP 2003
- Electromagnetic effects on trace impurity transport: Hein, Angioni, PoP 2010

Effect of non-trace impurities on main species has not yet been addressed.

Collisional multi-fluid model

- Braginskii-equations for ions, trapped electrons and impurities
- adiabatic passing electrons: $n^{\mathrm{p}}_{\mathrm{e},1}/n^{\mathrm{p}}_{\mathrm{e},0} \sim \mathrm{e}\phi_1/T_{\mathrm{e},0}$
- isotropic fluctiations: $\pi_{ab} = 0$
- low collisionality: $\frac{\nu}{\omega_{\mathrm{c}}} \sim \delta \ll 1$
- standard linearization: $f = f_0 + f_1 + O(\delta^2)$, $\frac{f_1}{f_0} \sim \delta$, $f_1 \sim \exp(-i\omega t + i\mathbf{k}\cdot\mathbf{x})$
- quasi-stationary ions and trapped electrons: $\frac{v_{\mathrm{i},0}}{v_{\mathrm{th}}} \sim \frac{v^{\mathrm{t}}_{\mathrm{e},0}}{v_{\mathrm{th}}} \sim \delta^2$
- gradients: $\nabla_\perp f_0 \sim f_0/a$, $\nabla_\perp f_1 \sim kf_1$, $\nabla_\| \sim \delta^2/a$ (parallel dynamics neglected)
- low Mach-number: $\frac{v_1}{v_{\mathrm{th}}} \sim \delta \ll 1$
- **Result:** only thermal effects in the source terms (q,Q,R)

Linearized, first order equations

- continuity: $-i\omega n_{s,1} + \nabla n_{s,0} \cdot \mathbf{v}_{s,1} + i n_{s,0} \mathbf{k} \cdot \mathbf{v}_{s,1} = 0$
- momentum:

$$-i\omega m_s n_{s,0} \mathbf{v}_{s,1} + i\mathbf{k}(n_{s,1} T_{s,0} + n_{s,0} T_{s,1}) + \nabla n_{s,0} T_{s,1} + n_{s,1} \nabla T_{s,0}$$
$$+ i\mathbf{k} Z_s e n_{s,0} \phi_1 - Z_s e n_{s,0} \mathbf{v}_{s,1} \times \mathbf{B} - Z_s e \frac{n_{s,1}}{n_{s,0}} \nabla p_{s,0} + \mathbf{R}_{s,0} = 0$$

- energy balance:

$$-i\omega \frac{3}{2} n_{s,0} T_{s,0} + \frac{3}{2} n_{s,0} \mathbf{v}_{s,1} \cdot \nabla T_{s,0} + i p_{s,0} \mathbf{k} \cdot \mathbf{v}_{s,1} + \nabla \cdot \mathbf{q}_{s,0} - Q_{s,0} = 0$$

- quasi-neutrality: $e\phi_1 = \frac{T_{\mathrm{e},0}}{n^{\mathrm{p}}_{\mathrm{e},0}} \left(Z_{\mathrm{i}} n_{\mathrm{i},1} + Z_{\mathrm{imp}} n_{\mathrm{imp},1} - n^{\mathrm{t}}_{\mathrm{e},1} \right)$

An analytical expression for $\mathbf{v}_{\mathrm{i},1}$ has been obtained.

Contents

Conclusions

- Impurity induced profile peaking observed in several experiments, including FTU LLL plasmas.
- Microstability analysis has been carried out to assess the role of turbulent transport.
- Both linear and non-linear simulations based on an FTU LLL discharge confirm that the presence of impurities can lead to inward turbulent flux of the main plasma species.
- A multi-fluid description has been developed to estimate the effects of plasma parameters on the particle flux (still in progress).

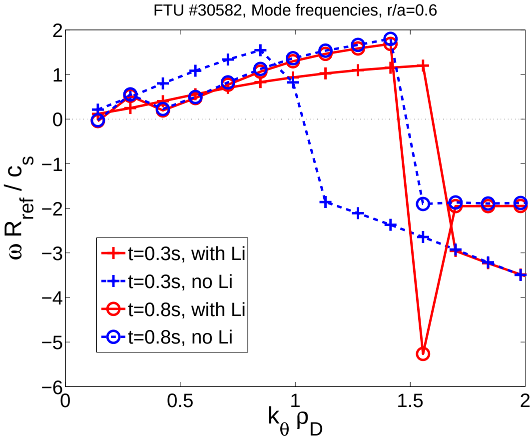
Main references

Thank you for your attention.

Main references:

- A.G. Peeters et al., Computer Physics Communications 180, 2650 (2009)
- G. Mazzitelli et al., submitted to Nuclear Fusion
- M. Reshko, C.M. Roach, Plasma Phys. Control. Fusion 50 115002 (2008)
- E. Fable, C. Angioni and O. Sauter, Plasma Phys. Control. Fusion 52 015007 (2010)
- G.R. McKee at al., Phys. of Plasmas 7 5 (2000)

Real Frequencies



Simulation Parameters

Linear:

- parallel gridpoints (ns) per period: 24, number of periods: 11
- parallel velocity gridpoints (nvpar): 36
- magnetic moment gridpoints (nmu): 10

Non-Linear (experimental case):

- parallel gridpoints (ns): 16-24
- parallel velocity gridpoints (nvpar): 36-48
- magnetic moment gridpoints (nmu): 10
- circular geometry
- number of perpendicular modes: 21 bi-normal (NMOD), 83 radial (NX)
- maximum bi-normal wavenumber: $(k_\theta \rho_D)_{max} = 1.65$
- $\hat{s} = 0.97$, $q = 2.76$, $\epsilon = 0.18$
- perpendicular box size: $L_Y/\rho_D = 76.2$ (bi-normal), $L_X/\rho_D = 74.7$ (radial)