L to H mode Transition: Parametric Dependencies of the Temperature Threshold

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Context

- The L to H mode transition occurs at T threshold which depends on B, n and more [Burrell 89, Suttrop 97, Hubbard 98, Righi 2000, Meakins 2010, etc]
- ExB is stabilizing turbulence [Burrell review 97] more recently observed in AUG [P. Sauter NF2012], JET [Delabie this conf] and dithering transition identified as the result of an interplay between turbulence, zonal and mean E_r flows [Schmitz PRL 2012, Tynan NF 2013]
- The nature of the stabilized turbulence matters: Resistive Ballooning Modes key player in the highly collisional edge [Rogers-Drake-Zeiler 96-97]. Coherent with lower P_{th} observed for lower Z_{eff} in JET [Maggi NF2014, EPS2014, Bourdelle NF Letters 2014], AUG [Neu JNM2013], and earlier [Takizuka ITPA 2004]

Driving idea

Transition when ExB time is shorter than turbulence time, or γ_{turb}/γ_E below a certain number. Account for both the ExB stabilization and the nature of the underlying turbulence.

Nature of Turbulence prior to Transition

- JET-ILW, prior to transition, ρ=0.97, linear stability analysis with GENE: RBM unstable [Bourdelle NF2014]

pulse	ρ	R/L_T	R/L_n	T	n	ν^*	q	s	Z_{eff}	B
82228	0.97	55	9	122	2.6	9.2	3.8	4.3	1.3	1.8

$$\gamma_{turb} = \max(\gamma_{RBM}, \gamma_{ITG-TEM})$$

RBM, fluid limit [Bourdelle PPCF2012]

$$\frac{\gamma_{RBM}}{\gamma_I} = (k_\theta\rho_i)^{4/3}\left(\frac{6\gamma_I\nu}{\omega_{te}{}^2}\right)^{1/3}\left(1+\frac{\tau}{\bar{Z}}\right)^{2/3}(\overline{Z_a}\tau)^{1/3}$$

$$\gamma_I = \sqrt{0.2(1+1.9(s-\alpha))}\frac{c_s}{\sqrt{RL_p}}$$

$$C_s = \frac{\sqrt{2T_e}}{2m_p} \quad \omega_{te} = k_\parallel \rho_i v_{the} \quad k_\parallel = k_\theta/L_s$$

$$\nu = 1.36\times10^5\times\lambda_e\times\frac{n_e(in\ 10^{20}m^{-3})}{T_e(in\ keV)^{3/2}}Z_{eff}$$

At fixed $k_\theta\rho_i$:

$$\boxed{\gamma_{RBM} = f(T,n,q,s,B,L_p,R,A_i,Z_{eff})}$$

ITG-TEM, fluid limit with collisions on TE

$$\gamma_{ITG-TEM}{}^2 = (k_\theta\rho_i)^2\gamma_I{}^2\frac{1}{1-f_t}\sqrt{\left(f_t+\frac{\tau}{\bar{Z}}\right)^2-\left(0.07f_t\frac{\nu}{n\omega_g}\right)^2}$$

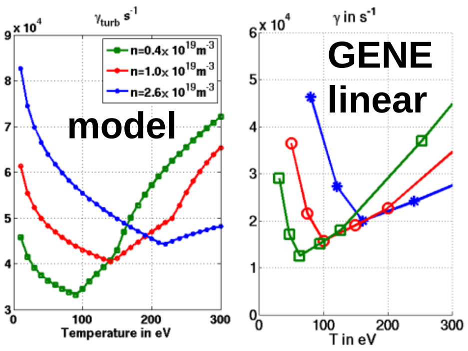
ITG only if: $\left(f_t+\frac{\tau}{\bar{Z}}\right)^2-\left(0.07f_t\frac{\nu}{n\omega_g}\right)^2<\left(\frac{\tau}{\bar{Z}}\right)^2$

$$\gamma_{ITG-TEM}{}^2 = (k_\theta\rho_i)^2\gamma_I{}^2\frac{1}{1-f_t}\frac{\tau}{\bar{Z}} \quad L_s = qR/s$$

$$\bar{Z} = \sum_s\frac{n_e}{n_s} \quad \overline{Z_a} = \sum_s\frac{n_e}{A_s n_s} \quad n\omega_g = k_\theta\rho_i\frac{C_s}{R}$$

At fixed $k_\theta\rho_i$: $f_t = \frac{2}{\pi}\sqrt{2\varepsilon} \quad \tau = \frac{T_i}{T_e}$

$$\boxed{\gamma_{ITG-TEM} = f'(T,n,q,s,B,L_p,R,a,A_i,Z_{eff})}$$

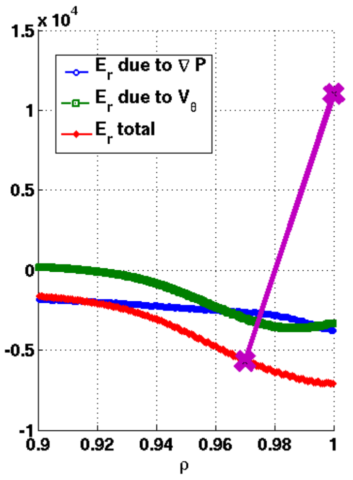


At low T RBM unstable, as T increases ITG-TEM take over Min γ for T in experimental range. NB: α stabilization for T>> T_{exp}

ExB Shear Derivation

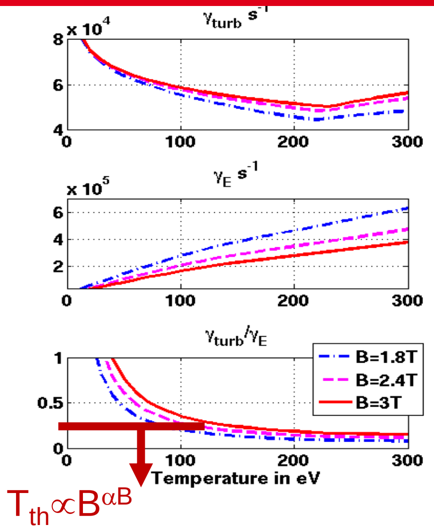
- At ρ=0.97, E_r neo-classical: without V_φ (in JET at low NBI V_φ negligible, [Delabie this conf] in AUG no V_φ gradient in this region [Viezzer, NF13] with V_θ from banana to P-S regimes
- At LCFS, E_r scales (at least) as -3∇T_e, assuming L_T constant across separatrix: $E_r(1) = 3\frac{T(0.97)e^{(0.03a/L_T)}}{L_T}$

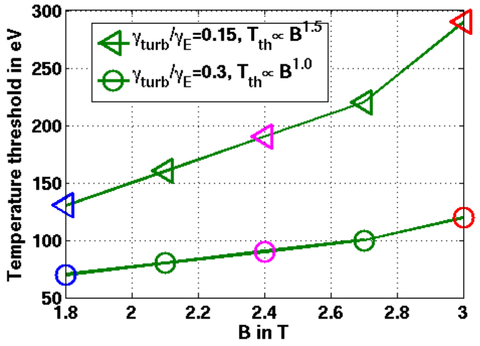
NB: ∇B drift reversal might generate additional residual stress [Fedorczak NF12]



$$\boxed{\gamma_E = \frac{\nabla E_r}{B} = \frac{E_r(0.97)-E_r(1)}{0.03\times a\times B} = g(T,n,Z_{eff},a,R,q,B,Z_i,L_T,L_n)}$$

T threshold ∝ B



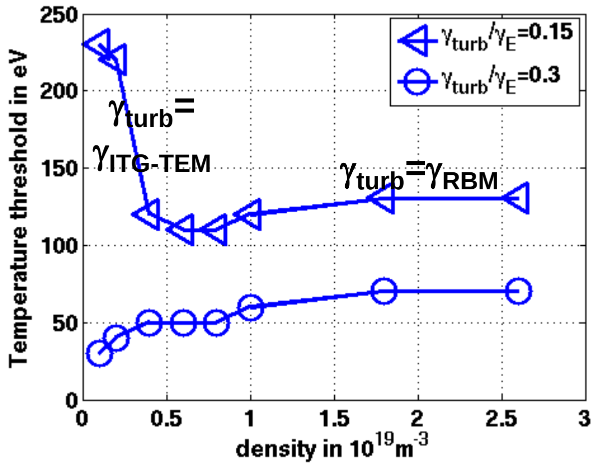


since: P/S = n T V_{perp} [Ryter 96] and $T_{th} \propto$ B [Burrell 89], one gets: P_{th} = n B S V_{perp} as given by [ITPA2004, 2008 and most scaling laws]

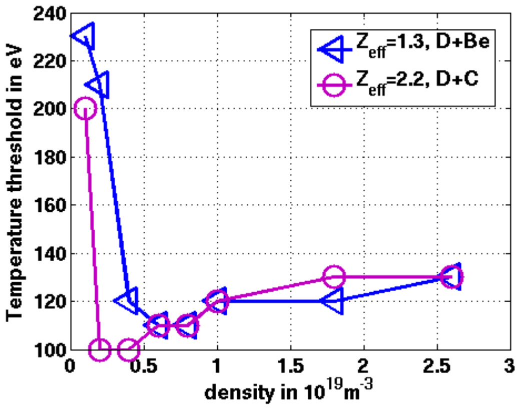
Minimum in density due to modified underlying turbulence

At low density, i.e. lower collisionalities, ITG-TEM dominate over RBM, $\gamma_{ITG-TEM}$ increases as n decreases

At high density, i.e. higher collisionalities, RBM dominate over ITG-TEM, γ_{RBM} increases as n increases

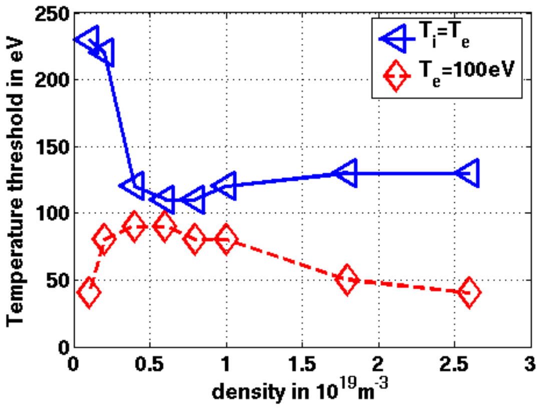


Lower Z_{eff} : min density shifted up



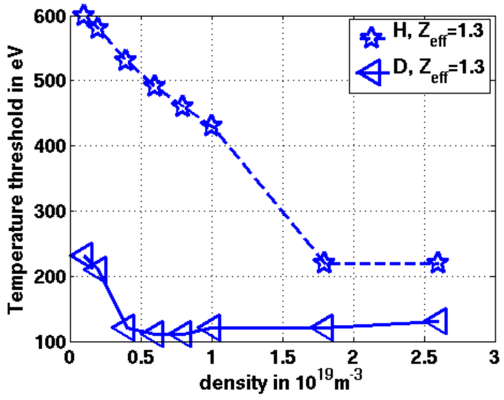
Coherent density min reappearing in JET-ILW with lower Z_{eff} [Maggi NF2014]

T_i increase at fixed T_e: min in density disappears

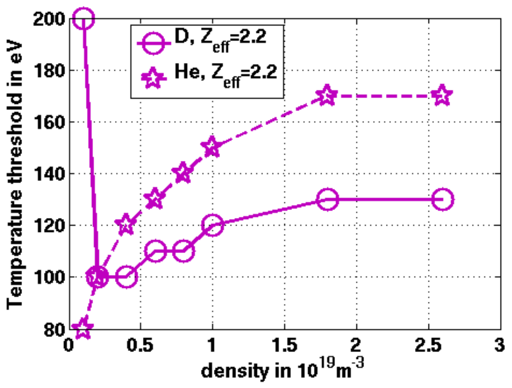


Coherent with AUG key role of ion heat flux at plasma edge [Ryter NF2014]

Higher threshold in H vs D and in He vs D, at fixed Z_{eff}



Coherent with isotope effect seen on P_{th} [Ryter96,Righi99]



Coherent with larger P_{th} in He vs D on DIII-D/Cmod [Gohil13]

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