Global scrape-off layer electromagnetic fluid turbulence simulations

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Outline

Introduction

Model

Global SOL simulations

Discussion
- Non linear saturation mechanism
- Electromagnetic global mode onset
- Resistive global mode onset

Conclusions

Motivation

- For the development of fusion, it is essential to understand :
  - Instabilities relevant to tokamak scrape-off layer (SOL)
  - Mechanisms responsible for SOL turbulent transport regimes
  - Steady-state profiles and their typical scale lengths

SOL turbulence : interplay between β, ν, and ω_*

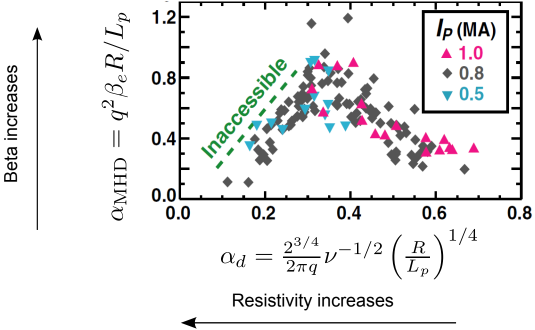
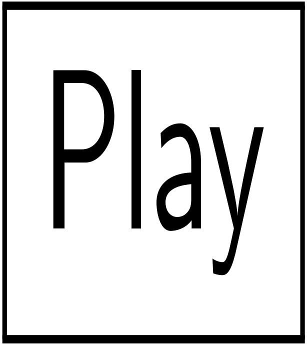


Figure : LaBombard *et al.*, *Nucl Fusion* 45, 1658 (2005)

Our goal : understanding SOL turbulence dependence on β and ν

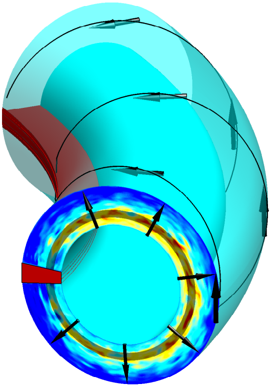
Scrape off-layer turbulence : a challenge for modeling



- Large fluctuations respect to background density
- No separation between equilibrium and turbulent scales
- Parallel losses due to presence of open field lines

Our approach : 3D global fluid electromagnetic simulations

- SOL *global* power balance between
  - Plasma outflow from the core
  - Perpendicular turbulent fluxes
  - Parallel losses at the limiter
- No separation between fluctuations and background quantities
- Gradient length $L_p = -p/\nabla p$ is a simulation result
  - Turbulence drive (R/L_p) is *a priori* unknown



Model equations

Drift-reduced Braginskii equations in $\hat{s}-\alpha$ geometry, $T_i \ll T_e$

$$\partial_t n = -\frac{R}{B}[\phi, n] + \frac{2}{B}\left[\hat{C}(p_e) - n\hat{C}(\phi)\right] - \nabla_\parallel \left(n v_{\parallel e}\right) + S_n$$

$$\partial_t \omega = -\frac{R}{B}[\phi, \omega] + \frac{2B}{n}\hat{C}(p_e) - v_{\parallel i}\nabla_\parallel \omega + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{B}{3n}\hat{C}(G_i)$$

$$\partial_t \chi = -\frac{R}{B}\left[\phi, v_{\parallel e}\right] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{mi}{me}\left\{-\nu\frac{j_\parallel}{n} + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71 n \nabla_\parallel T_e - \frac{2}{3n}\nabla_\parallel G_e\right\}$$

$$\partial_t v_{\parallel i} = -\frac{R}{B}\left[\phi, v_{\parallel i}\right] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p_e - \frac{2}{3n}\nabla_\parallel G_i$$

$$\partial_t T_e = -\frac{R}{B}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4}{3}\frac{T_e}{B}\left[\frac{7}{2}\hat{C}(T_e) + \frac{T_e}{n}\hat{C}(n) - \hat{C}(\phi)\right] + S_{T_e}$$
$$+ \frac{2}{3}T_e\left[0.71\nabla_\parallel v_{\parallel i} - 1.71\nabla_\parallel v_{\parallel e} + 0.71\left(\frac{v_{\parallel i} - v_{\parallel e}}{n}\right)\nabla_\parallel n\right]$$

with ancillary equations $\omega = \nabla_\perp^2 \phi$, $\chi = v_{\parallel e} + \frac{mi}{me}\frac{\beta_e}{2}\psi$, $j_\parallel = n\left(v_{\parallel i} - v_{\parallel e}\right)$, $\nabla_\perp^2 \psi = j_\parallel$,

parallel gradient $\nabla_\parallel a = \hat{b}_0 \cdot \nabla a + \frac{\beta_e}{2}\frac{R}{B}[\psi, a]$, and curvature operator $\hat{C}(a) = \frac{B}{2}\left(\nabla \times \frac{\hat{b}_0}{B}\right) \cdot \nabla a$

BCs consistent with sheath physics are imposed at the limiter

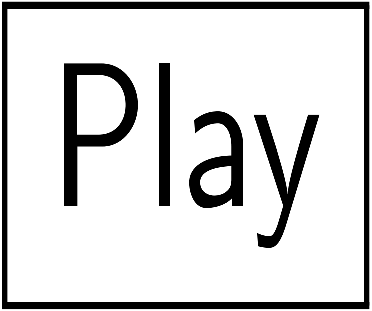
Non-linear simulations

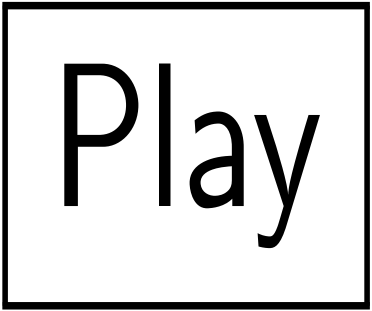
- Simulations carried out using the GBS code
- Typical simulation parameters

$$
\begin{aligned}
L_y &= 2\pi a = \{400, 800\}\rho_s,\ R_0 = \{500, 1000\}\rho_s \\
\nu &= 5 \times 10^{-3} - 0.1,\ m_i/m_e = 200 \\
\beta_e &= 10^{-5} - 3 \times 10^{-3} \\
\hat{s} &= 0,\ q = 4 \\
[nx, ny, nz] &= \{128, 256, 32\}, \{128, 512, 64\}
\end{aligned}
$$

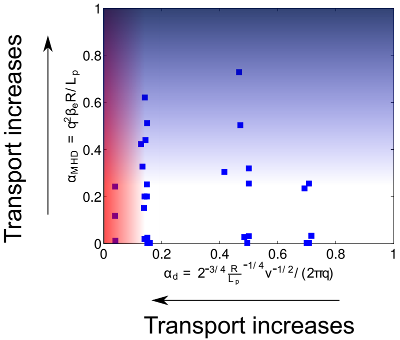
- Typically, in steady state we recover $R/L_p \approx 10 - 20$
  - $\alpha_{\mathrm{MHD}} = q^2 \beta_e R/L_p \approx 0 - 0.7$

Non-linear turbulence driven by RBMs





Scanned parameter space α_{MHD} vs α_d



$\boxed{\text{High } \nu,\ \beta_e \text{ lead to enhanced transport}}$

Equilibrium pressure gradient decreases with high β_e

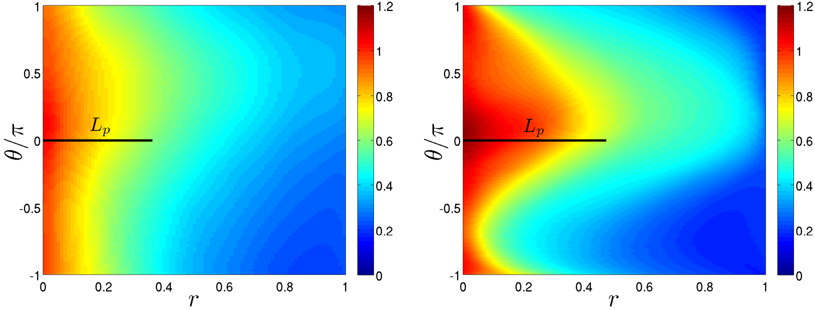


Figure : n_0 for $\alpha_{\mathrm{MHD}} = 3 \times 10^{-3}$ (left) and $\alpha_{\mathrm{MHD}} = 0.7$ (right)

- R/L_p can be computed from toroidal, time average of p_e
- In this case R/L_p decreases $\sim$ %30 at high β_e

Turbulence changes with high β_e

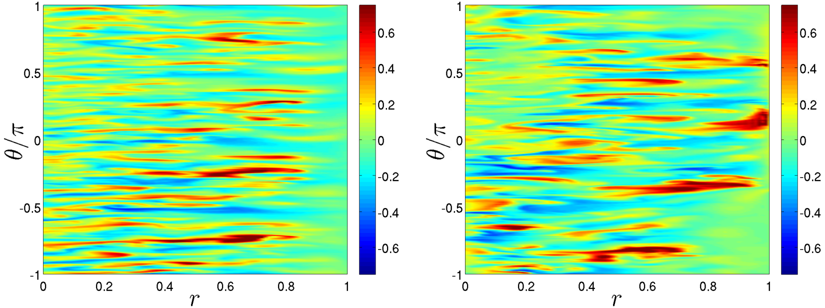


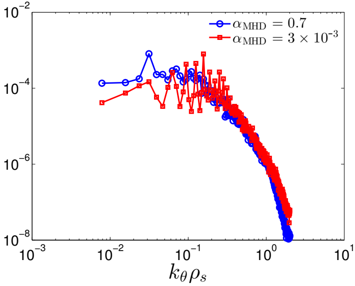
Figure : $n_1 = (n - n_0)/n_0$ for $\alpha_{\mathrm{MHD}} = 3 \times 10^{-3}$ (left) and $\alpha_{\mathrm{MHD}} = 0.7$ (right)

- Density fluctuations of order of $O(1)$
- Radially elongated eddies
- $k_\theta \rho_s$ decreases with increasing β_e

Turbulent spectrum changes with high β_e

Perturbed spectra shift to lower $k_\theta \rho_s$, n (global modes)

- At low β_e, wide spectrum with $k_\theta \rho_s \approx 0.1$ dominant
- As β_e is increased dominant mode acquires smaller n, $k_\theta \rho_s$



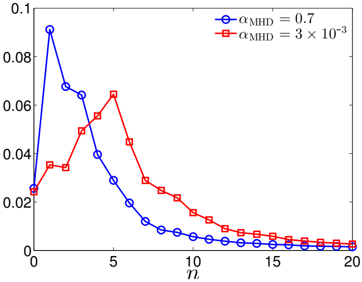
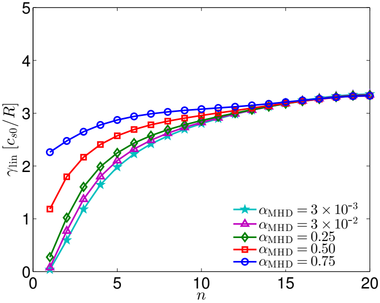


Figure : $k_\theta \rho_s$ (left) and n (right) spectrum

Linear theory does not fully explain global mode onset



- $R/L_p \approx 16$ extracted from GBS non-linear simulation
- Linear growth rates obtained with linear stability code
  - Resistive ballooning modes unstable in electrostatic limit
  - Low n ideal ballooning mode become unstable at $\alpha_{\rm MHD} \approx 0.25$
  - However, low n modes are still linearly sub-dominant

Non linear saturation mechanism

We expect turbulence to saturate when its drive (R/L_p) is removed

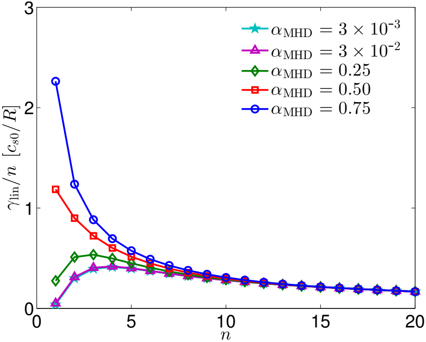
$$\partial p_{e1}/\partial r \sim \partial p_{e0}/\partial r \to p_{e1} \sim p_{e0}/(L_p k_r)$$

Estimating $\phi_1 \sim \gamma_{\rm lin}/(k_\theta k_r)$ and $k_r \sim \sqrt{k_\theta/L_p}$ the radial flux is

$$\Gamma_r = \left\langle p_{e1} \frac{\partial \phi}{\partial \theta} \right\rangle \sim \frac{p_{e0}}{L_p} \frac{\gamma_{\rm lin}}{k_r^2} \sim \frac{p_{e0}}{k_\theta} \gamma_{\rm lin}$$

$$\boxed{\text{Global modes can drive large flux even if } \gamma_{\rm lin} \text{ is small}}$$

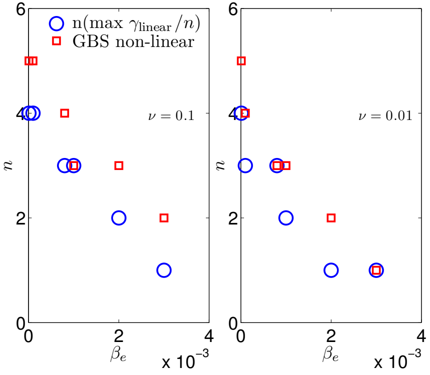
Dominant mode number can be estimated with γ_{lin}/n



- Dominant n decreases as β_e increases

$$\boxed{\Gamma \sim \gamma_{\text{lin}}/n \text{ dominated by } n \sim 1 \text{ for } \alpha_{\text{MHD}} \gtrsim 0.25}$$

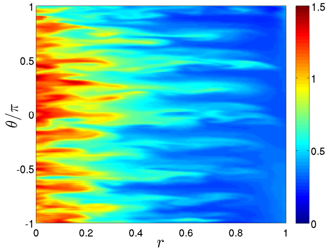
$\Gamma \sim \gamma_{\rm lin}/n$ matches dominant n in GBS simulations

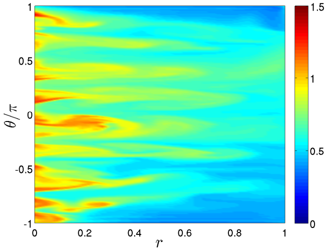


Downward trend can be explained by saturation mechanism

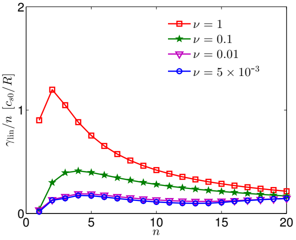
Similar effect can be shown for ν

Low ν





High ν



- RBM unstable at high ν
- $\gamma_{\mathrm{lin}}^2 \sim \frac{2R}{L_p} - \gamma_{\mathrm{lin}} \frac{k_\parallel^2}{k_\perp^2 \nu} \to k_\perp^2 > \frac{k_\parallel^2}{\nu\sqrt{2R/L_p}}$
- Lower n $\rightarrow$global mode

Conclusions

- Global 3-D, E+M simulations of SOL turbulence
  - Recovered $R/L_p \sim 10$–20, turbulent flux dominated by RBMs
  - Large fluctuation amplitude $n_1/n_0 \sim O(1)$
  - Radially extended modes with $k_r \sim \sqrt{k_\theta/L_p}$

$$\boxed{\text{3D non-linear global model required}}$$

- Dominant toroidal mode number vs. β_e or ν consistent with flux estimate due to gradient removal mechanism $\Gamma_r \sim \gamma/k_\theta$
- Shift toward global instability observed at high β_e and ν

$$\boxed{\text{Enhanced transport for high } \nu,\ \alpha_{\mathrm{MHD}} \gtrsim 0.25}$$