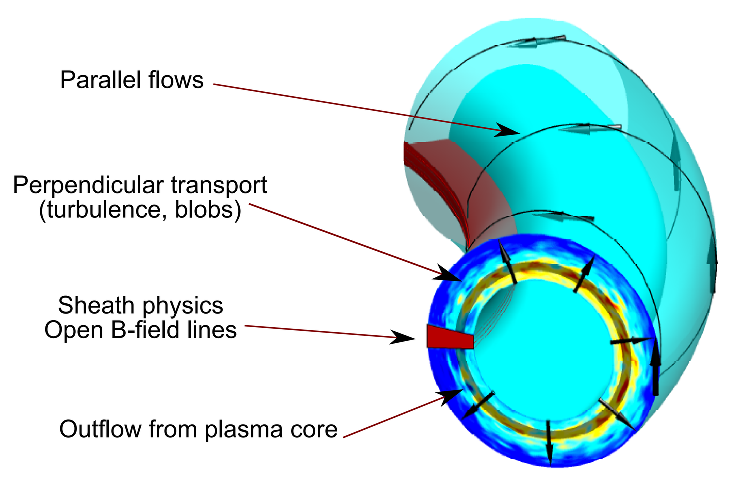
Global electromagnetic simulations of tokamak SOL turbulence

F.D. Halpern, P. Ricci, S. Jolliet, J. Loizu, A. Mosetto

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland

Introduction



Heat load to PFCs, rotation, impurities, L-H transition...

For inner-wall limited tokamak plasmas, we would like to address the following questions:

- What is the mechanism determining the turbulence levels in this simplest configuration?
- What instabilities are present and which one dominates?
- How does the SOL width $L_p = -p/\partial_r p$ change with the plasma parameters?
- Is the influence of parallel dynamics (q, ν, β) important?
- What is the system size ($\rho_\star$) scaling of L_p?

We carry out an extensive non-linear simulation scan which is interpreted using analytical theory

Drift-reduced fluid model for SOL turbulence

- Drift-reduced Braginskii equations with cold ion approximation $T_i \ll T_e$ [Ricci *et al.*, PPCF 2012]:

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - C(\phi)] - \nabla_\parallel \cdot (n v_{\parallel e}) + \mathcal{D}_n(n) + S_n$$

$$\frac{\partial \omega}{\partial t} = -\rho_\star^{-1}[\phi, \omega] - V_{\parallel i}\nabla_\parallel \omega + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{2B}{n}C(p_e) + \mathcal{D}_\omega(\omega)$$

$$\frac{\partial \chi}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right) + \mathcal{D}_{v_{\parallel e}}(v_{\parallel e})$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p_e + \mathcal{D}_{v_{\parallel i}}(v_{\parallel i})$$

$$\frac{\partial T_e}{\partial t} = -\rho_\star^{-1}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4T_e}{3B}\left[\frac{1}{n}C(p_e) + \frac{5}{2}C(T_e) - T_e C(\phi)\right] + \frac{2T_e}{3}\left[0.71\nabla_\parallel j_\parallel - \nabla_\parallel v_{\parallel e}\right] + \mathcal{D}_{T_e}(T_e) + \mathcal{D}^\parallel_{T_e}(T_e) + S_{T_e}$$

$$\nabla_\perp^2\phi = \omega,\ \nabla_\perp^2\psi = n(v_{\parallel i} - v_{\parallel e}) = j_\parallel,\ \chi = v_{\parallel e} + \frac{m_i}{m_e}\frac{\beta}{2}\psi,\ \rho_\star = \rho_s/R$$

$$\nabla_\parallel f = \mathbf{b}_0 \cdot \nabla f + \rho_\star^{-1}\frac{\beta}{2}[\psi, f]$$

- These equations are implemented in GBS, a 3D, flux-driven, global turbulence code with circular geometry including electromagnetic effects
- System is closed with set of fluid boundary conditions applicable at the magnetic pre-sheath entrance where the magnetic field lines intersect the limiter [Loizu *et al.*, PoP 2012]
- Note: normalized units used throughout: $L_\perp \to \rho_s$, $L_\parallel \to R$, $t \to R/c_s$, $\nu = ne^2 c_s/(m_i\sigma_\parallel R)$

Turbulent saturation mechanism

- In GBS non-linear simulations, sheared flows do not contribute significantly to saturation
- We extract the following observations regarding turbulent transport [Ricci and Rogers, PoP 2013]:

(1) Mode saturation caused by local pressure profile flattening

$\partial_r p_0 \sim \partial_r p_1 \to p_1/p_0 \sim \sigma_r/L_p$

(2) Radial extension of the mode given by non-local linear theory

$\sigma_r = \sqrt{L_p/k_\theta}$

(3) Perpendicular turbulent transport driven by **E** × **B** *convection*

$\Gamma_1 = -\rho_\star^{-1}[\phi, p]$

From these observations, we obtain an estimate of Γ_1:

Gradient removal hypothesis

$$\partial_t p = -\rho_\star^{-1}[\phi, p]$$

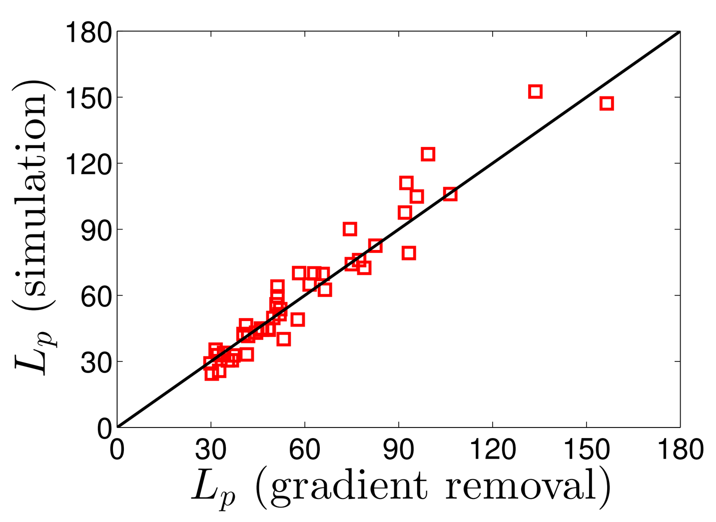
$$\frac{p_1}{p_0} \approx \frac{\sigma_r}{L_p} \qquad \partial_\theta\phi_1 = \gamma\,(p_1/p_0)\,(\rho_\star L_p)$$

$$\Gamma_1 \approx \rho_\star^{-1}\langle p_1 \partial_\theta \phi_1\rangle$$

$$\Gamma_1 \sim p_0\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

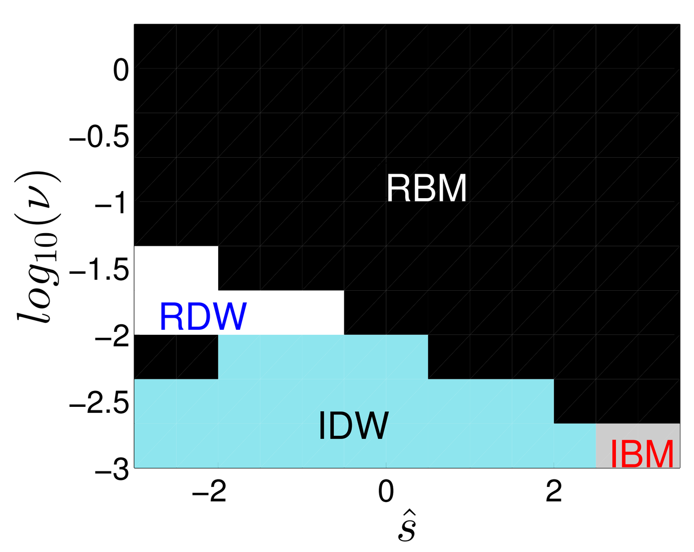
Which results in an estimate of the SOL width:

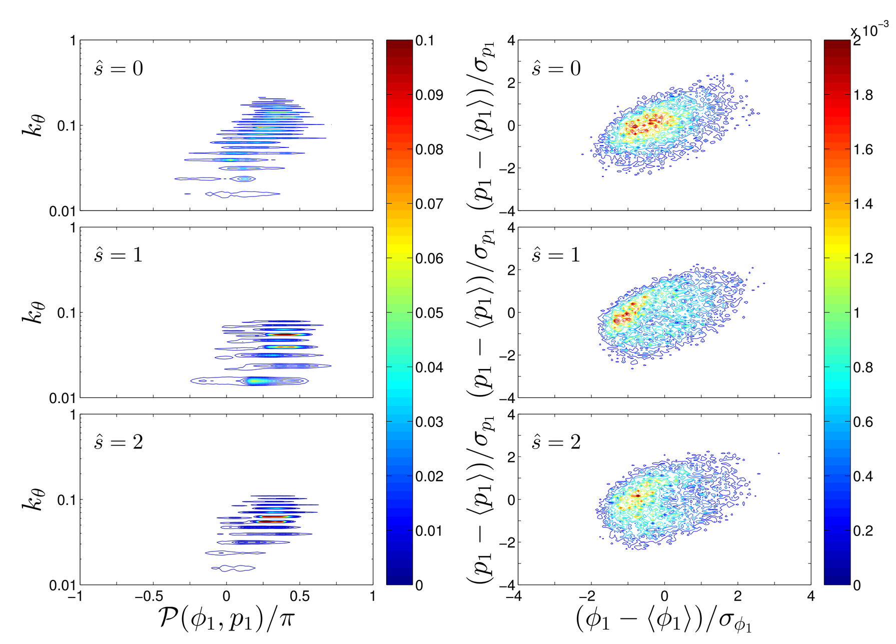
$$L_p = q\frac{\gamma}{k_\theta}$$



Identifying the dominant instabilities

- Reduced linear models combined with saturation theory identify dominant mode [Mosetto *et al.*, PoP 2013]
- In circular, limited plasmas, resistive ballooning modes (RBMs) are dominant in the SOL





- Relevant parameters for inner-wall limited SOL: $q = 3$–10, $\nu \sim 0.01$, $\hat{s} \approx 2$
- Presence of RBMs confirmed in non-linear simulations at realistic parameters for TCV SOL

Scrape-off layer width

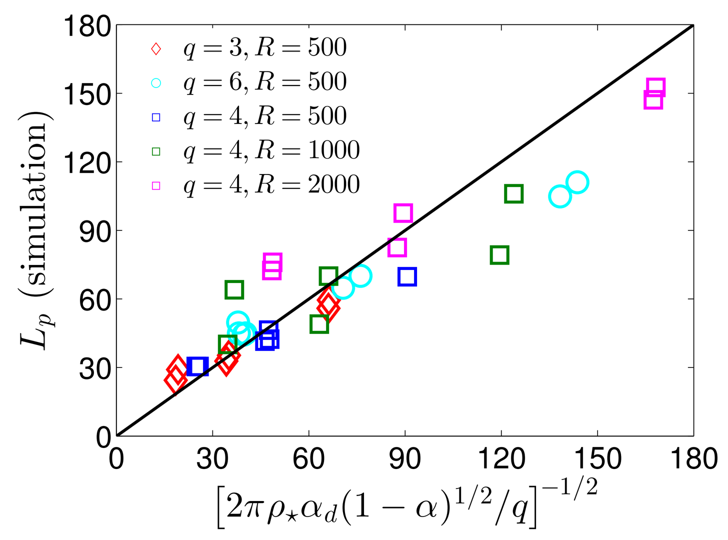
- The SOL width can be obtained analytically by considering *gradient removal saturated RBMs*:

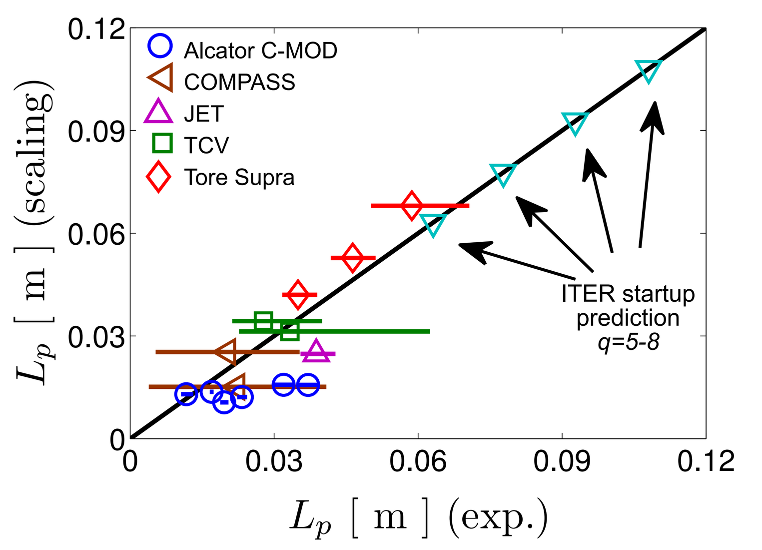
$$L_p = q\frac{\gamma}{k_\theta}, \quad \gamma_b = \sqrt{2/(\rho_\star L_p)}, \quad k_b = \sqrt{(1-\alpha)/(\nu\gamma_b)}/q$$

$$\alpha_d^{-1} = 2^{7/4}\nu^{1/2}(\rho_\star L_p)^{1/4}\pi q, \qquad \alpha = \frac{q^2\beta}{\rho_\star L_p}$$

- Dimensionless and engineering parameter scalings of the SOL width follow [Halpern *et al.*, NF 2013]:

$$L_p = \left[2\pi\rho_\star\alpha_d(1-\alpha)^{1/2}\right]^{-1/2} \qquad L_p \approx 7.2\times10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e0}^{-2/7} n_{e0}^{2/7}(1+T_i/T_e)^{1/7}\ [\mathrm{m}]$$





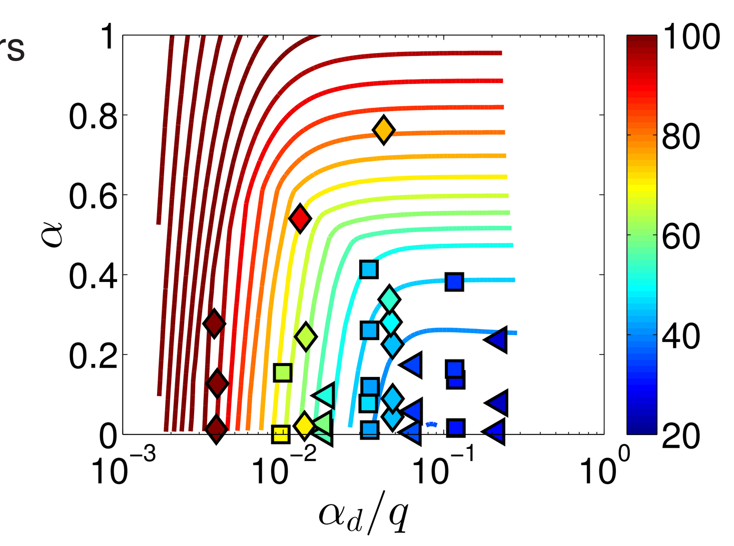
- Scalings obtained from least-squares-fitting of all simulation data verify our theory:

$$L_p = 0.42\,q^{0.55}\rho_\star^{-0.53}\alpha_d^{-0.32}(1-\alpha)^{-0.24}$$

$$L_p \sim q^{0.98}R^{0.63}B^{-0.56}[\mathrm{m}]$$

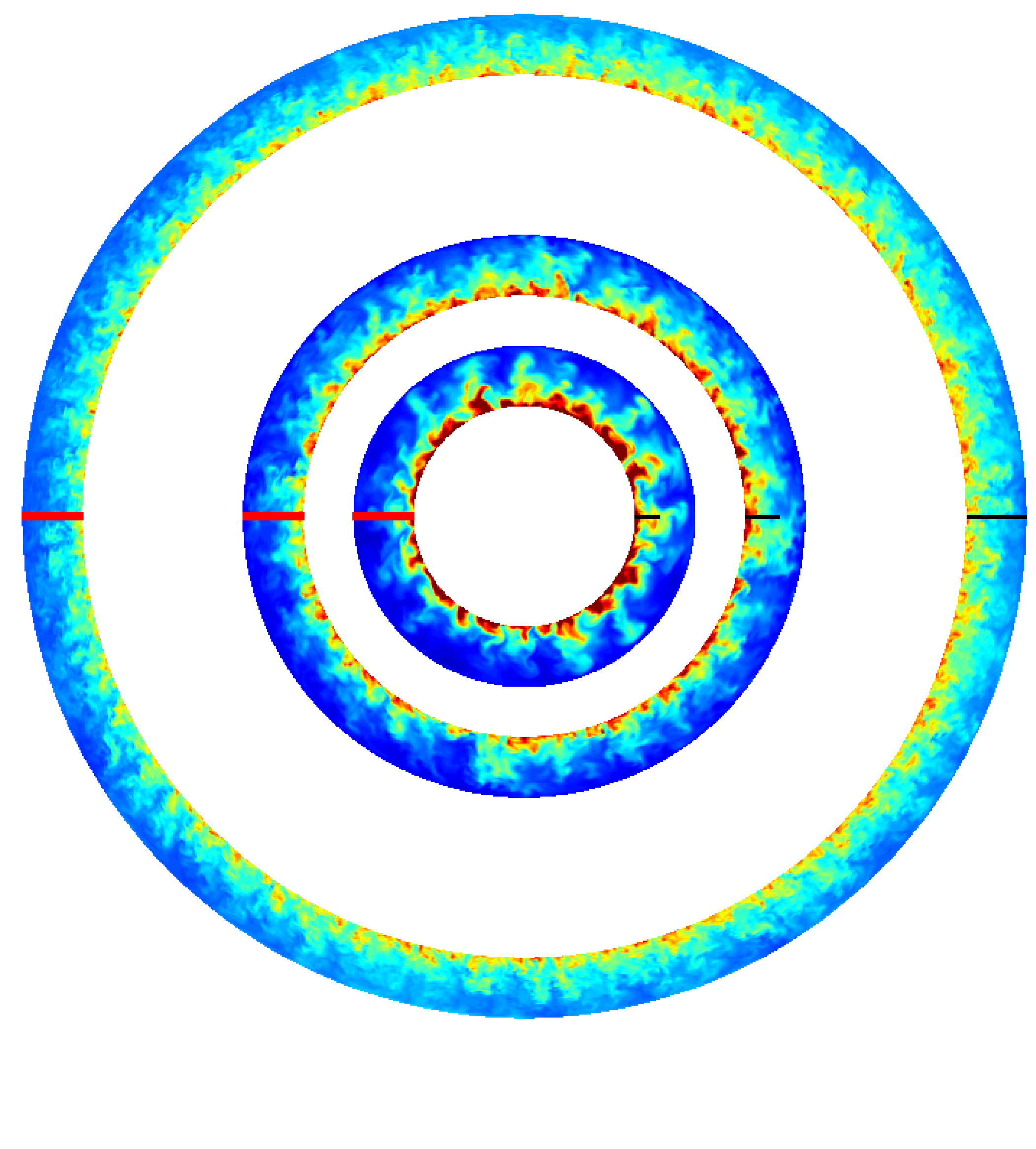
Electromagnetic phase space

- Analytical theory predicts that the dimensionless parameters regulating the SOL width at fixed $\rho_\star$ are α and α_d/q [Halpern *et al.*, NF 2013 (submitted)]
- GBS simulations confirm theory (figure)
- Color contours give L_p obtained from solving $L_p = q(\gamma/k_\theta)_{\max}$ with a linear code
- Symbols give GBS simulation results for $q = 3$ (triangles), $q = 4$ (squares), and $q = 6$ (diamonds).
- Compare to [LaBombard *et al.*, NF 2005] (diverted): α and α_d



System-size scaling

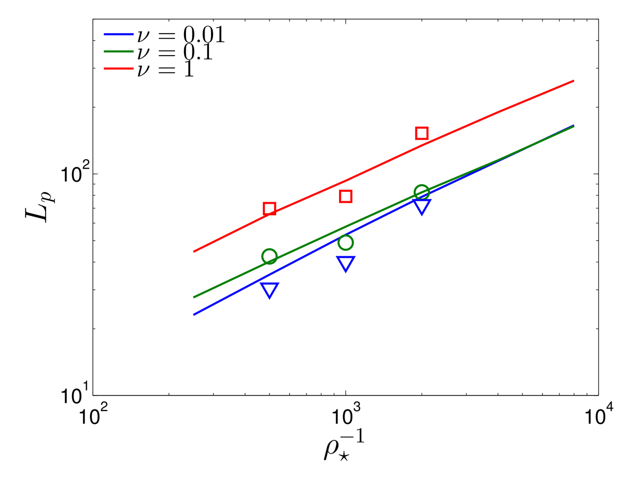
- Crucial to understand $\rho_\star$ scaling of the SOL width (*e.g.* in ITER $\rho_\star \sim 10^{-4}$)
- Carried out dedicated scan at constant $\nu = 0.01, 0.1, 1$, $q = 4$, $\beta =$ [Halpern *et al.*, NF 2013 (submitted)]
- Largest simulations reached $\rho_\star = 2000^{-1}$ (TCV size, flux-driven!)
- Equivalent parameters: $R = 0.85$m, $a = 0.22$m, $T_e = 15$eV, $B_0 = 1.4$T



- System size scaling expected from analytical theory is $L_p \sim \rho_\star^{-3/7}$
- System size scaling retrieved from GBS non-linear simulations

$L_p \sim \rho_\star^{-0.56}$

- Difference arises from combination of effects
  - Artificially large electron mass in GBS non-linear simulations
  - Assumption of full non-adiabaticity not fullfilled in non-linear simulations
- Self-consistent gradient removal flux estimate in good agreement with simulations



Conclusions

- Developed predictive theory for SOL width of inner-wall limited tokamak plasmas
- Local profile flattening from linear modes acts as saturation mechanism
- Non-linear turbulent stage of simulations dominated by RBMs
- Obtained SOL width scaling as a function of dimensionless / engineering plasma parameters
- Theory fully verified using 3D, non-linear, flux-driven SOL turbulence simulations

Thanks to B Labit, I Furno, G Arnoux, J Gunn, J Horacek, M Kočan, B LaBombard, and C Silva for kindly providing their SOL profile measurements