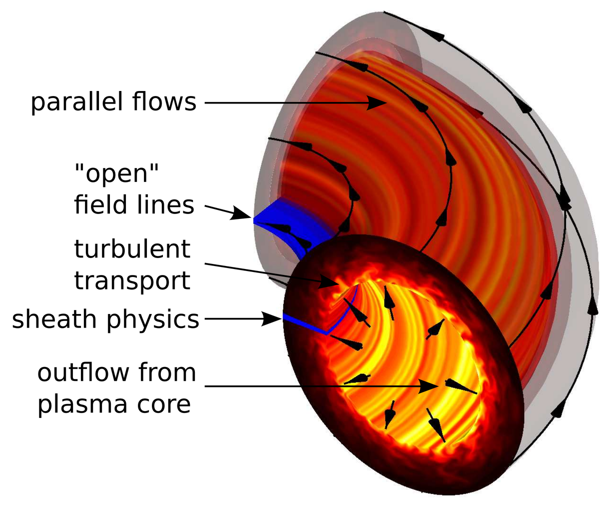
Effects of plasma shaping on tokamak scrape-off layer turbulence

F. Riva, E. Lanti, F. D. Halpern, S. Jolliet, P. Ricci

École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center, CH-1015 Lausanne, Switzerland

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Introduction

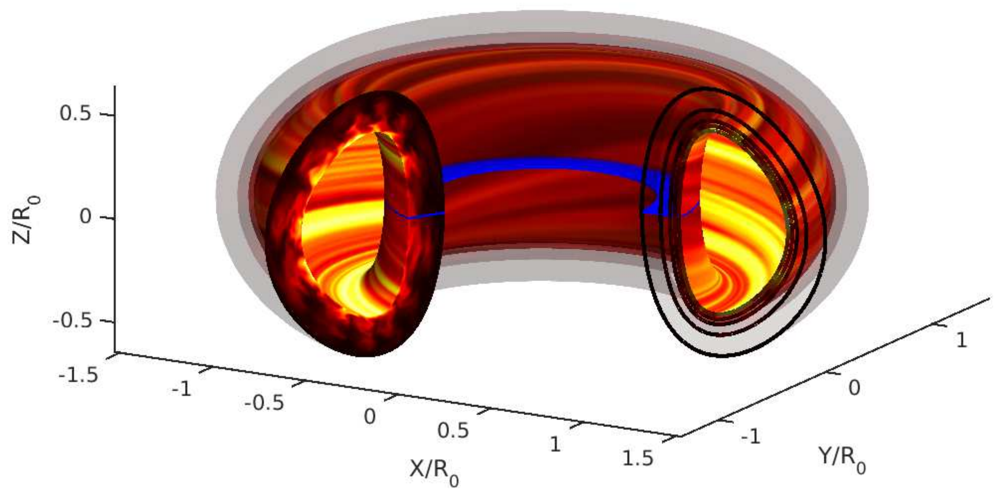


- In Scrape-Off Layer (SOL) of tokamaks, **magnetic field lines intersect the walls** of the fusion device
- **Heat and particles** flow along magnetic field lines and are **exhausted to the vessel**

The **Global Braginskii Solver (GBS) code: a 3D, two-fluid, flux-driven, global turbulence code in limited geometry** used to study **plasma turbulence in the SOL**

Development and achievements of GBS

- Achivements:
  - Non-linear turbulent regimes in the SOL
  - SOL width scaling as a function of dimensionless / engineering plasma parameters
  - Origin and nature of intrinsic toroidal plasma rotation in the SOL
  - Mechanisms regulating the SOL equilibrium electrostatic potential
- In the past: simulations in **circular limited configuration**
- Described here: **generalization** of the GBS **magnetic geometry** to include **Shafranov shift**, plasma **elongation**, and non-zero **triangularity**



The Global Braginskii Solver (GBS) code

- **Two-fluid Drift-reduced Braginskii equations**, $d/dt \ll \omega_{ci}$:

$$\text{Continuity}: \quad \frac{\partial n}{\partial t} = -\frac{\rho_\star^{-1}}{B}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla\cdot(n v_{\parallel e}\mathbf{b}) + S_n$$

$$\text{Charge conservation}: \quad \frac{\partial \omega}{\partial t} = -\frac{\rho_\star^{-1}}{B}[\phi, \omega] - v_{\parallel i}\nabla_\parallel \omega + \frac{B^2}{n}\nabla\cdot(j_\parallel \mathbf{b}) + \frac{2B}{n}C(p_e)$$

$$\text{Ohm's law}: \quad \frac{\partial v_{\parallel e}}{\partial t} = -\frac{\rho_\star^{-1}}{B}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel\phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right)$$

$$\text{Parallel momentum}: \quad \frac{\partial v_{\parallel i}}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p_e$$

$$\text{Electron temperature}: \quad \frac{\partial T_e}{\partial t} = -\frac{\rho_\star^{-1}}{B}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4}{3}\frac{T_e}{B}\left[\frac{C(p_e)}{n} + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2}{3}T_e\left[0.71\frac{\nabla\cdot(j_\parallel \mathbf{b})}{n} - \nabla\cdot(v_{\parallel e}\mathbf{b})\right] + S_{T_e}$$

- Equations implemented in **GBS**, system closed by $\omega = \nabla_\perp^2\phi$ [Ricci *et al.*, PPCF 2012]
- System completed with a set of **first-principles boundary conditions** applicable at the magnetic pre-sheath entrance where the magnetic field lines intersect the limiter [Loizu *et al.*, PoP 2012]
- Note: $L_\perp \to \rho_s$, $L_\parallel \to R_0$, $t \to R_0/c_s$, $\nu = ne^2R_0/(m_i\sigma_\parallel c_s)$ normalization

GBS operators

- The **magnetic geometry** allows to compute **GBS operators**

$$[\phi, A] = \mathbf{b}\cdot(\nabla\phi\times\nabla A) = \frac{1}{\mathcal{J}}\epsilon_{ijk}b_i\frac{\partial\phi}{\partial\xi^j}\frac{\partial A}{\partial\xi^k} \qquad C(A) = \frac{B}{2}\left[\nabla\times\left(\frac{\mathbf{b}}{B}\right)\right]\cdot\nabla A = \frac{B}{2\mathcal{J}}\frac{\partial c_m}{\partial\xi^j}\frac{\partial A}{\partial\xi^k}\epsilon_{kjm}$$

$$\nabla_\parallel A = \mathbf{b}\cdot\nabla = b^j\frac{\partial A}{\partial\xi^j} \qquad \nabla\cdot\mathbf{b} = \frac{1}{\mathcal{J}}\frac{\partial}{\partial\xi^i}(b^i\mathcal{J})$$

$$\nabla_\perp^2 A = -\nabla\cdot[\mathbf{b}\times(\mathbf{b}\times\nabla A)] = \frac{1}{\mathcal{J}}\frac{\partial}{\partial\xi^k}\left[\mathcal{J}\left(g^{ki} - b^kb^i\right)\frac{\partial}{\partial\xi^i}\right]$$

- Note: use of curvilinear coordinates and of Einstein summation, $\mathcal{J}$ is the Jacobian of the metric

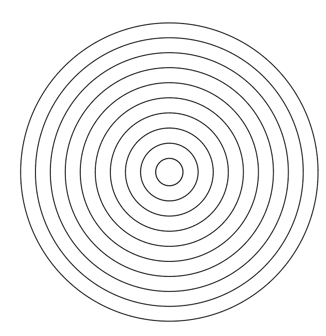
The magnetic field geometry

- Toroic coordinate system (r, θ, φ), general **axisymmetric magnetic field B** $= F(\psi)\nabla\varphi + \psi'\nabla r\times\nabla\varphi$
- GBS uses the (θ_*, r, φ) coordinate system, where $\theta_*(r,\theta) = \frac{1}{q(r)}\int_0^\theta d\theta'\frac{\mathbf{B}\cdot\nabla\varphi}{\mathbf{B}\cdot\nabla\theta'}$ is the straight-field-line angle
- The Grad-Shafranov equation is solved in the $\epsilon = r/R_0 \to 0$ limit to obtain $R(r,\theta)$, $Z(r,\theta)$, and $F(\psi)$ as function of κ, δ, and $q(r)$ [J. P. Graves, PPCF 2013]

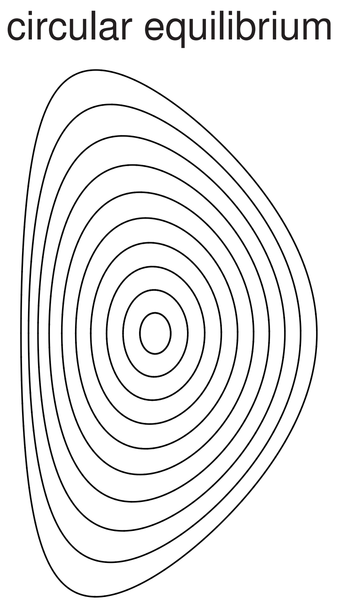
$$R(r,\theta) = R_0\left(1 + \epsilon\cos\theta + \frac{\Delta(r)}{R_0} + \sum_{m=2}^{3}\frac{S_m(r)}{R_0}\cos[(m-1)\theta] - \frac{P(r)}{R_0}\cos\theta\right)$$

$$Z(r,\theta) = R_0\left(\epsilon\sin\theta - \sum_{m=2}^{3}\frac{S_m(r)}{R_0}\sin[(m-1)\theta] - \frac{P(r)}{R_0}\sin\theta\right)$$

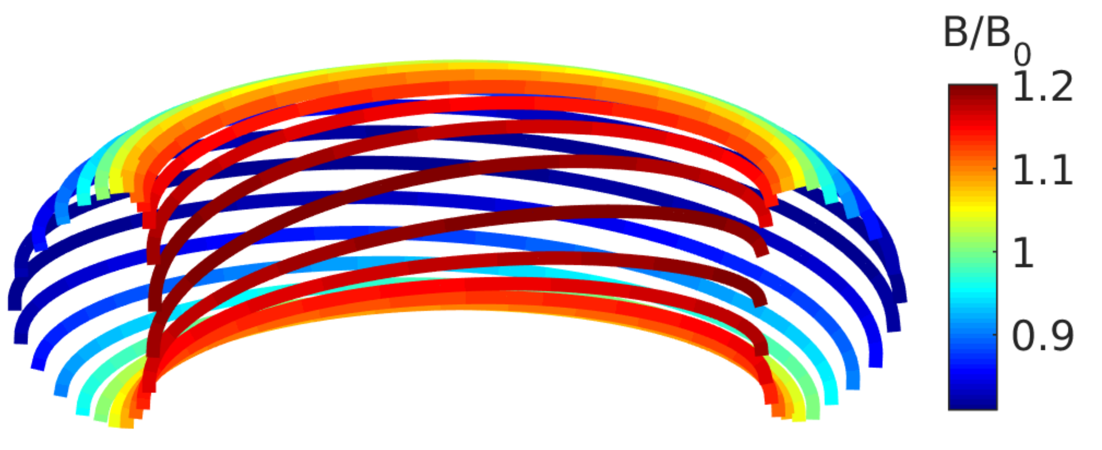
$$F(\psi) = B_0R_0\left(1 - \frac{\epsilon^2}{q(r)^2}\left[2 + \frac{q_e - q_0}{q_0}\left(\frac{r}{a}\right)^2\right]\right)$$



circular equilibrium

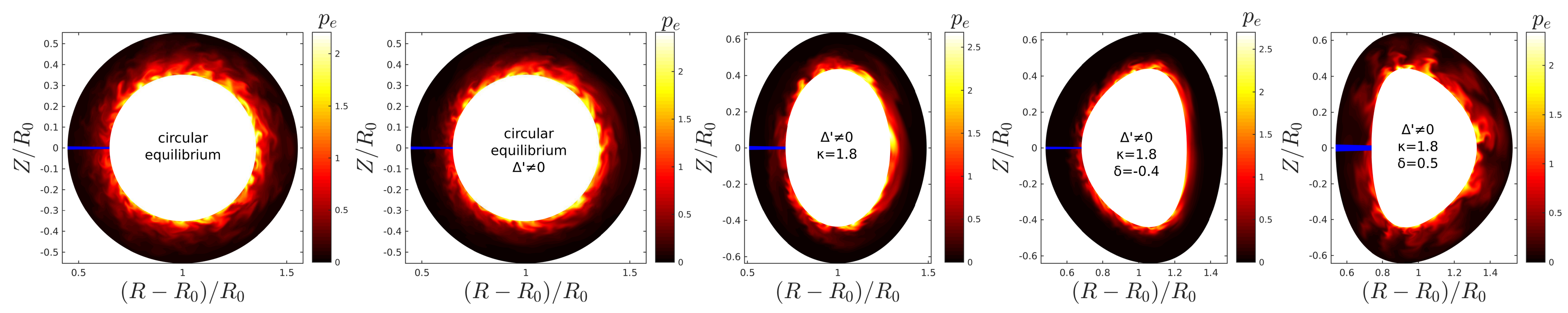


D-shaped equilibrium



Non-linear simulations

- **Fully-turbulent non-linear simulations** with same physical parameters, in **different magnetic geometries**



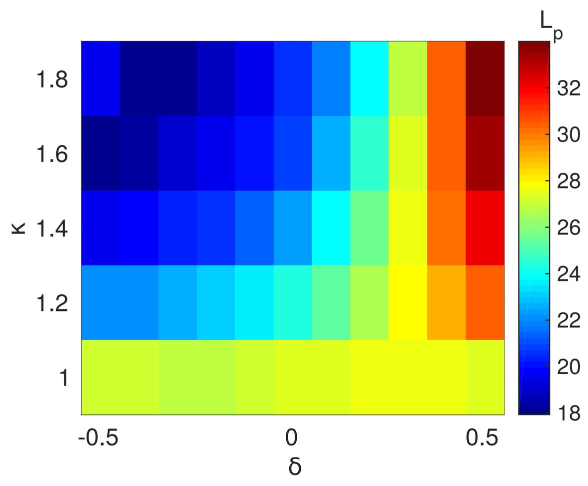
- **Mitigation** of turbulence by $\boldsymbol{\Delta'}$, κ, and **negative** δ; **enhancement** of turbulence by **positive** δ

Gradient removal saturation mechanism

- The radial gradient of the **perturbed** plasma pressure **comparable to** the radial gradient of the **background** plasma pressure $\qquad \partial_r\tilde{p} \sim \partial_r\bar{p} \Rightarrow k_r\tilde{p} \sim \bar{p}/L_p$
- Leading order term of the pressure equation gives the perturbed potential $\qquad \partial_t\tilde{p} \simeq \partial_\theta\tilde{\phi}\partial_r\bar{p} \Rightarrow \tilde{\phi} \sim \gamma\tilde{p}L_p/(\bar{p}k_\theta)$
- **Balance** between **radial flux** $\Gamma_p = \tilde{p}\partial_\theta\tilde{\phi}$ and **parallel losses** $\qquad \partial_r\Gamma_p \sim \nabla_\parallel(\bar{p}v_\parallel) \Rightarrow \Gamma_p/L_p \sim \bar{p}c_s/(qR)$
- Assuming $k_r = \sqrt{k_\theta/L_p}$ and choosing **linear growth rate** γ and **wavenumber** k_θ to **maximize the transport** $\qquad L_p \sim \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$

	circular	circular $\Delta' \neq 0$	$\Delta' \neq 0$ $\kappa = 1.8$ $\delta = -0.4$	$\Delta' \neq 0$ $\kappa = 1.8$ $\delta = -0.3$	$\Delta' \neq 0$ $\kappa = 1.8$	$\Delta' \neq 0$ $\kappa = 1.8$ $\delta = 0.3$	$\Delta' \neq 0$ $\kappa = 1.8$ $\delta = 0.5$
L_p non-linear simulations	31 ± 4	22 ± 4	13 ± 3	14 ± 2	19 ± 2	21 ± 3	27 ± 5
L_p Gradient Removal theory	35	27	18	18	21	27	34

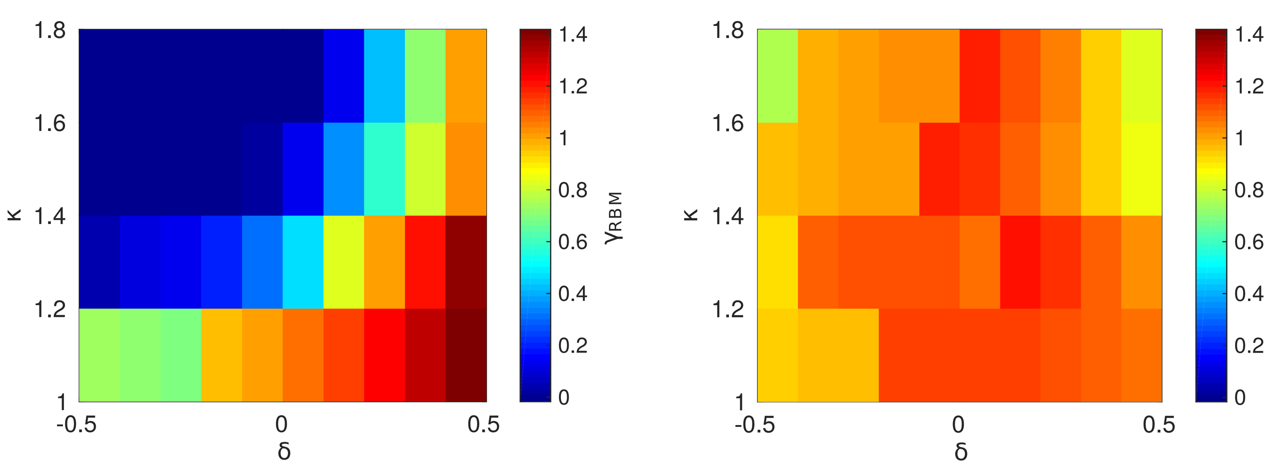
- Good **agreement** between **non-linear simulations** and **Gradient Removal theory**



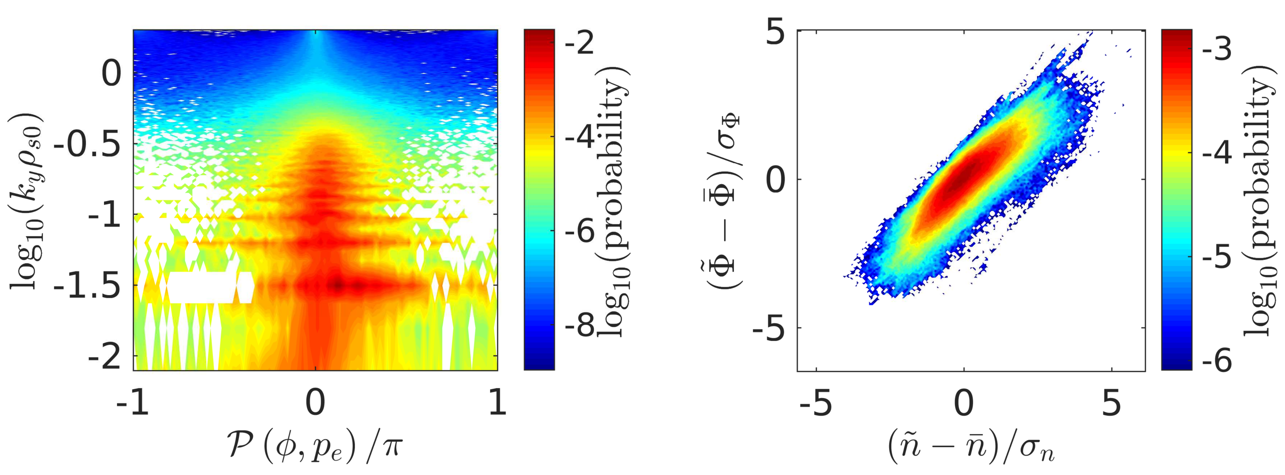
- **Linear scan** over κ and δ **confirms the trend** observed for the non-linear simulations
- Preliminary study indicates the **curvature** as the **most important** operator in setting L_p

Non-linear turbulent regimes

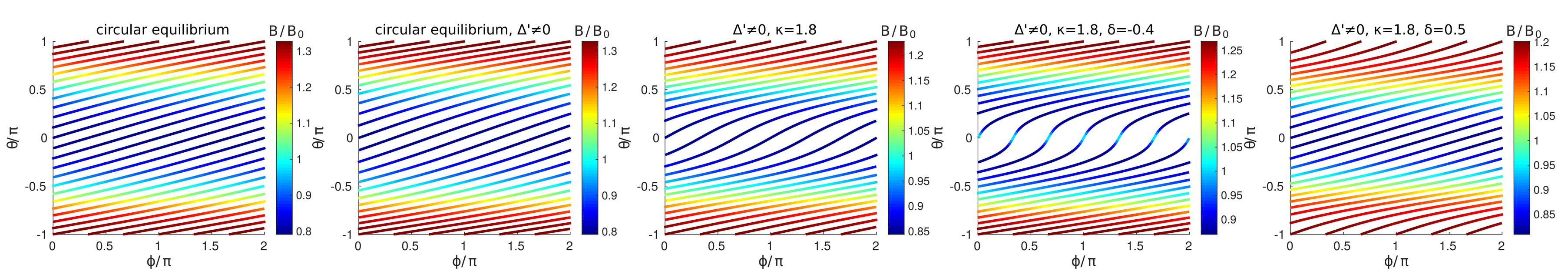
- Investigation of the turbulent regimes to **understand the mitigation of turbulence** by κ and negative δ



- **Resistive ballooning modes mitigated** by κ and negative δ
- **Resistive drift waves slightly affected by shaping** effects



- Non-linear simulations confirm that **turbulence is dominated by drift waves** for negative δ
- **Why** are κ and negative δ mitigating ballooning modes?



- **Shafranov shift**, **elongation** and **negative triangularity stretch magnetic field lines** near the **outer midplane**
- **Positive triangularity compress magnetic field lines** near the **outer midplane**
- Curvature less effective with Shafranov shift, elongation and negative triangularity, and more effective for positive triangularity
- **Ballooning modes strongly mitigated by Shafranov shift, elongation and negative triangularity, enhanced by positive triangularity**

Conclusion

- Simulations of SOL turbulence in shaped plasmas
- Scan of L_p and γ over κ and δ, showing how ballooning modes and drift waves are affected by different magnetic configurations
- Qualitative understanding of the mechanism mitigating/enhancing the ballooning character of turbulence