Progress in simulating SOL plasma turbulence with the GBS code

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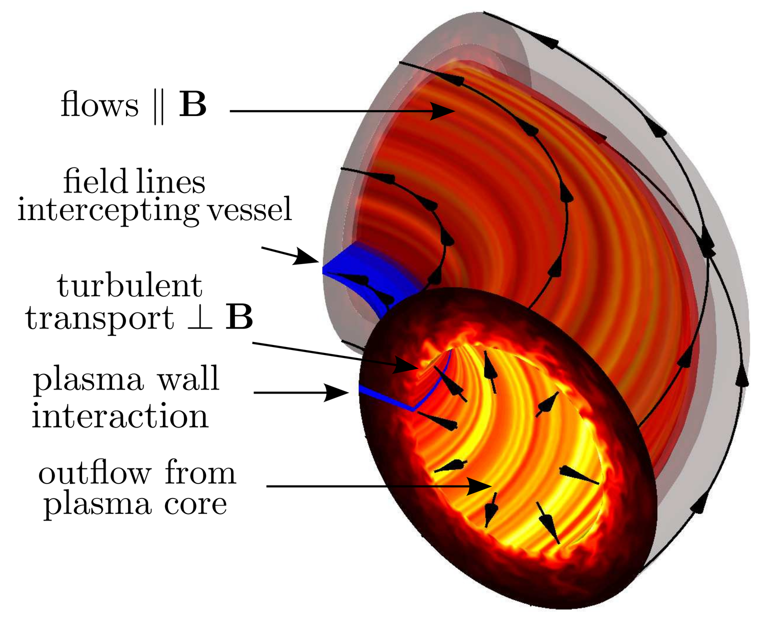
Introduction



- In the tokamak SOL, **magnetic field lines intersect the walls** of the fusion device
- **Heat and particles** flow along magnetic field lines and are **exhausted to the vessel**
- **Turbulence** amplitude and size **comparable** to **steady-state** values
- **Neutral** particles interact with the plasma

The **Global Braginskii Solver (GBS) code: a 3D, flux-driven, global turbulence code** used to study **plasma turbulence in the SOL**
[Ricci *et al.*, PPCF 2012; Halpern *et al.*, JCP 2016]

- GBS solves 3D **fluid equations for electrons and ions**, Poisson's and Ampere's equations, and a **kinetic equation for neutral atoms**.

The Global Braginskii Solver (GBS) code

Two-fluid drift-reduced Braginskii equations, $k_\perp^2 \gg k_\parallel^2$, $d/dt \ll \omega_{ci}$

$$\frac{\partial n}{\partial t} = -\frac{\rho_*^{-1}}{B}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla\cdot(n v_{\parallel e}\mathbf{b}) + \mathcal{D}_n(n) + S_n + n_n\nu_{iz} - n\nu_{rec} \quad (1)$$

$$\frac{\partial \Omega}{\partial t} = -\frac{\rho_*^{-1}}{B}\nabla_\perp\cdot[\phi,\omega] - \nabla_\perp\cdot\left[\nabla_\parallel\left(v_{\parallel i}\omega\right)\right] + B^2\nabla\cdot(j_\parallel\mathbf{b}) + 2BC(p) + \frac{B}{3}C(G_i) + \mathcal{D}_\Omega(\Omega) - \frac{n_n}{n}\nu_{cx}\Omega \quad (2)$$

$$\frac{\partial U_{\parallel e}}{\partial t} = -\frac{\rho_*^{-1}}{B}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left[\frac{\nu j_\parallel}{n} + \nabla_\parallel\phi - \frac{\nabla_\parallel p_e}{n} - 0.71\nabla_\parallel T_e - \frac{2}{3n}\nabla_\parallel G_e\right] + \mathcal{D}_{v_{\parallel e}}(v_{\parallel e}) + \frac{n_n}{n}(\nu_{en} + 2\nu_{iz})(v_{\parallel n} - v_{\parallel e}) \quad (3)$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\frac{\rho_*^{-1}}{B}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{\nabla_\parallel p}{n} - \frac{2}{3n}\nabla_\parallel G_i + \mathcal{D}_{v_{\parallel i}}(v_{\parallel i}) + \frac{n_n}{n}(\nu_{iz} + \nu_{cx})(v_{\parallel n} - v_{\parallel i}) \quad (4)$$

$$\frac{\partial T_e}{\partial t} = -\frac{\rho_*^{-1}}{B}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4T_e}{3B}\left[\frac{C(p_e)}{n} + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2T_e}{3n}\left[0.71\nabla\cdot(j_\parallel\mathbf{b}) - n\nabla\cdot(v_{\parallel e}\mathbf{b})\right] + \mathcal{D}_{T_e}(T_e) + \mathcal{D}^\parallel_{T_e}(T_e) + S_{T_e} + \frac{n_n}{n}\nu_{iz}\left[-\frac{2}{3}E_{iz} - T_e + \frac{m_e}{m_i}v_{\parallel e}\left(v_{\parallel e} - \frac{4}{3}v_{\parallel n}\right)\right] - \frac{n_n}{n}\nu_{en}\frac{m_e}{m_i}\frac{2}{3}v_{\parallel e}(v_{\parallel n} - v_{\parallel e}) \quad (5)$$

$$\frac{\partial T_i}{\partial t} = -\frac{\rho_*^{-1}}{B}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4T_i}{3B}\left[\frac{C(p_e)}{n} - \frac{5}{2}\tau C(T_i) - C(\phi)\right] + \frac{2T_i}{3n}\left[\nabla\cdot(j_\parallel\mathbf{b}) - n\nabla\cdot(v_{\parallel i}\mathbf{b})\right] + \mathcal{D}_{T_i}(T_i) + \mathcal{D}^\parallel_{T_i}(T_i) + S_{T_i} + \frac{n_n}{n}(\nu_{iz} + \nu_{cx})\left[\tau^{-1}T_n - T_i + \frac{1}{3\tau}(v_{\parallel n} - v_{\parallel i})^2\right] \quad (6)$$

$$\rho_\star = \rho_s/R, \quad \nabla_\parallel f = \mathbf{b}_0\cdot\nabla f + \frac{\beta_{e0}}{2}\frac{\rho_*^{-1}}{B}[\psi, f], \quad p = n(T_e + \tau T_i), \quad U_{\parallel e} = v_{\parallel e} + \frac{\beta_{e0}}{2}\frac{m_i}{m_e}\psi, \quad \Omega = \nabla\cdot\omega = \nabla\cdot(n\nabla_\perp\phi + \tau\nabla_\perp p_i)$$

- Equations implemented in GBS, a **flux-driven** plasma turbulence code with limited geometry to study SOL heat and particle transport
- System completed with **first-principles boundary conditions** applicable at the magnetic pre-sheath entrance where the magnetic field lines intersect the limiter [Loizu *et al.*, PoP 2012]
- Parallelized using domain decomposition (MPI and OpenMP), **excellent parallel scalability** up to ∼ 10000 cores
- Gradients and curvature discretized using **finite differences**, Poisson Brackets using Arakawa scheme, integration in time using **Runge Kutta method**
- Code **fully verified** using method of manufactured solutions [Riva *et al.*, PoP 2014]
- 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

The Poisson and Ampere equations

- **Generalized Poisson equation**, $\nabla\cdot(n\nabla_\perp\phi) = \Omega - \tau\nabla_\perp^2 p_i$
- **Ampere's equation** from Ohm's law, $\left(\nabla_\perp^2 - \frac{\beta_{e0}}{2}\frac{m_i}{m_e}n\right)v_{\parallel e} = \nabla_\perp^2 U_{\parallel e} - \frac{\beta_{e0}}{2}\frac{m_i}{m_e}n v_{\parallel i}$
- Stencil based **parallel multigrid** implemented in GBS
- The elliptic equations are separable in the parallel direction leading to **independent 2D solutions** for each perpendicular plane

The kinetic equation for neutral atoms

$$\frac{\partial f_n}{\partial t} + \vec{v}\cdot\frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz}f_n - \nu_{cx}n_n\left(\frac{f_n}{n_n} - \frac{f_i}{n_i}\right) + \nu_{rec}f_i \quad (7)$$

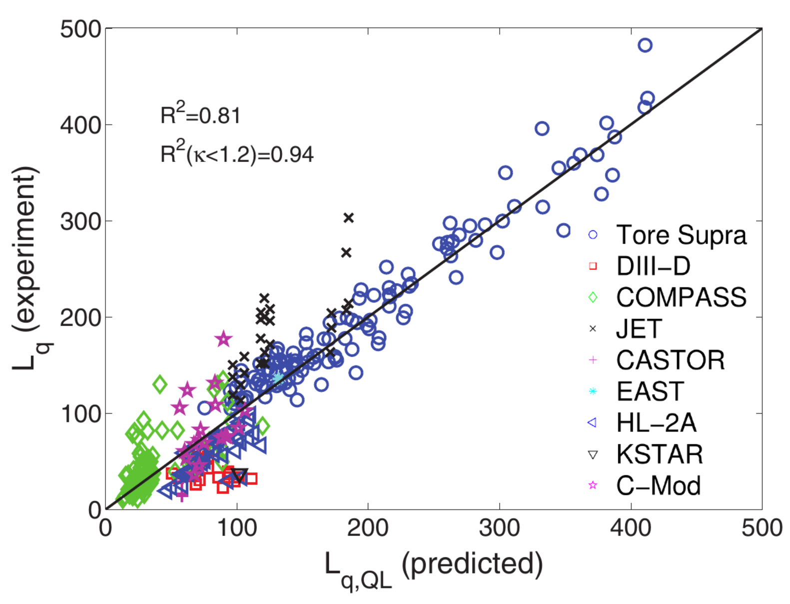
- **Method of characteristics** to obtain the formal solution of f_n [Wersal *et al.*, NF 2015]
- **Two assumptions**, $\tau_{\text{neutral losses}} < \tau_{\text{turbulence}}$ and $\lambda_{\text{mfp, neutrals}} \ll L_{\parallel,\text{plasma}}$, leading to a 2D steady state system for each perpendicular plane
- **Linear integral equation** for neutral density obtained by integrating f_n over $\vec{v}$
- **Spatial discretization** leading to a linear system of equations

$$\begin{bmatrix} n_n \\ \Gamma_{out} \end{bmatrix} = \begin{bmatrix} K_{p\to p} & K_{b\to p} \\ K_{p\to b} & K_{b\to b} \end{bmatrix}\cdot\begin{bmatrix} n_n \\ \Gamma_{out} \end{bmatrix} + \begin{bmatrix} n_{n,rec} \\ \Gamma_{out,rec} + \Gamma_{out,i} \end{bmatrix} \quad (8)$$

- This system is solved for neutral density, n_n, and neutral particle flux at the boundaries, Γ_{out}, with the threaded LAPACK solver.

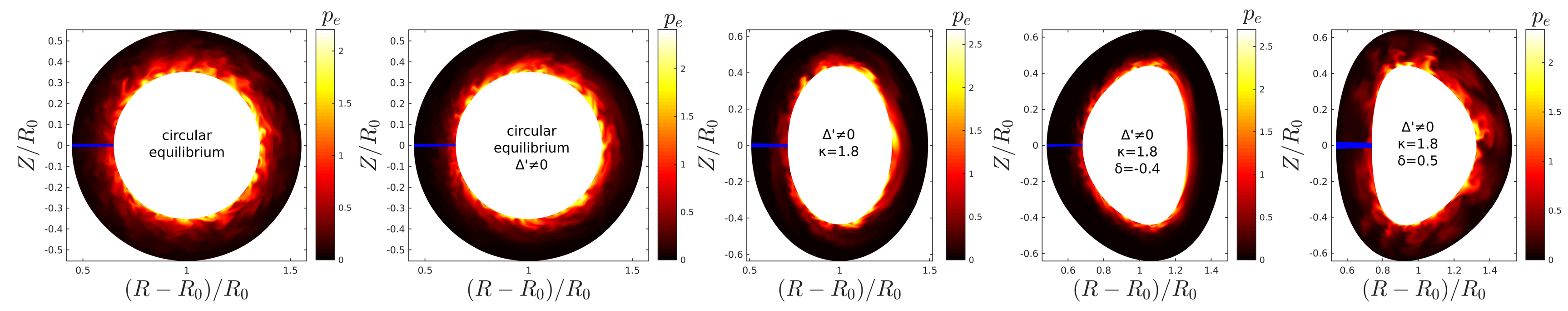
Some of past achievements of GBS

- Characterization of **non-linear turbulent regimes** in the SOL [Mosetto *et al.*, PoP 2015]
- **SOL width scaling** as a function of dimensionless / engineering plasma parameters [Halpern *et al.*, PPCF 2016]
- Origin and nature of **intrinsic toroidal plasma rotation** in the SOL [Loizu *et al.*, PoP 2014]
- Mechanisms regulating SOL **equilibrium electrostatic potential** [Loizu *et al.*, PPCF 2013]



Plasma shaping effects on SOL turbulence

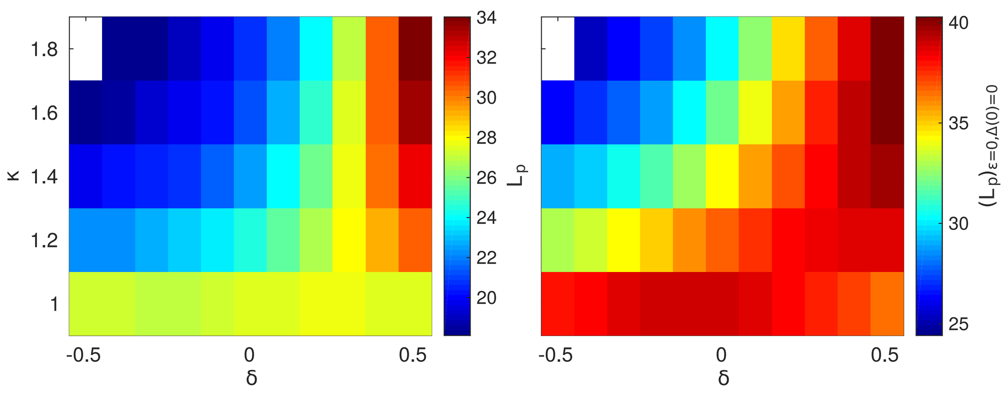
- **Fully-turbulent non-linear simulations** with same physical parameters, in **different magnetic geometries** [Riva *et al.*, PPCF, submitted]



- **Mitigation** of turbulence by Δ', κ, and **negative** δ; **enhancement** of turbulence by **positive** δ
- Good **agreement** between **non-linear simulations** and **Gradient Removal theory**

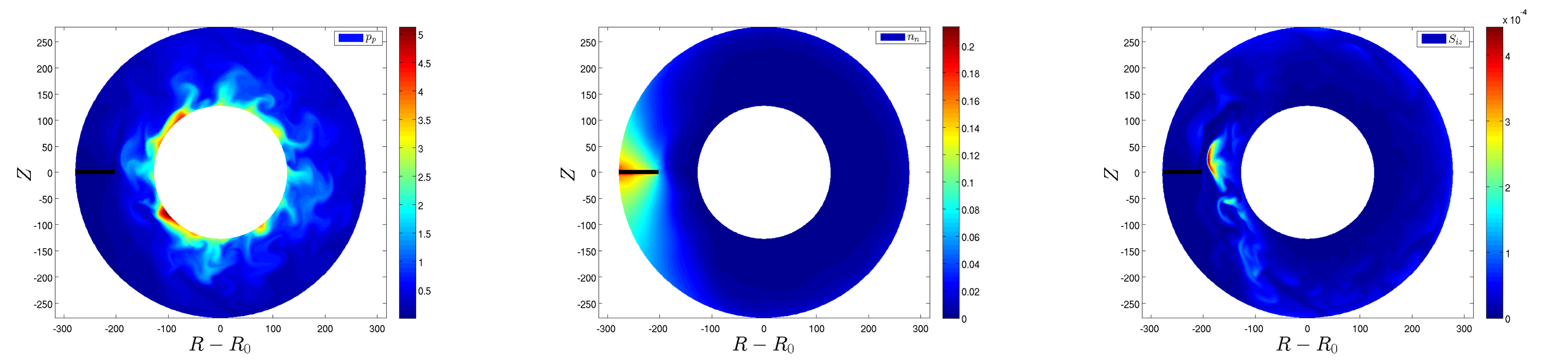
(κ,δ)	Non − linear sim. $\epsilon \simeq 0.25$, $\Delta(0) \simeq 7$	Gradient Removal Theory $\epsilon \simeq 0.25$, $\Delta(0) \simeq 7$	Non − linear sim. $\epsilon = 0$, $\Delta(0) = 0$	Gradient Removal Theory $\epsilon = 0$, $\Delta(0) = 0$
(1.0, 0.0)	25 ± 1	27.4	37 ± 2	38.9
(1.8, 0.0)	20 ± 1	20.7	26 ± 3	30.3
(1.8, −0.3)	15 ± 1	18.1	20 ± 1	26.2
(1.8, 0.3)	23 ± 1	26.8	43 ± 3	36.8

- **Linear scan** over κ and δ allows to predict the **SOL width for non-circular magnetic geometries**
- It is possible to **generalize** the **analytical first-principle** L_p **scaling** to include shaping effects

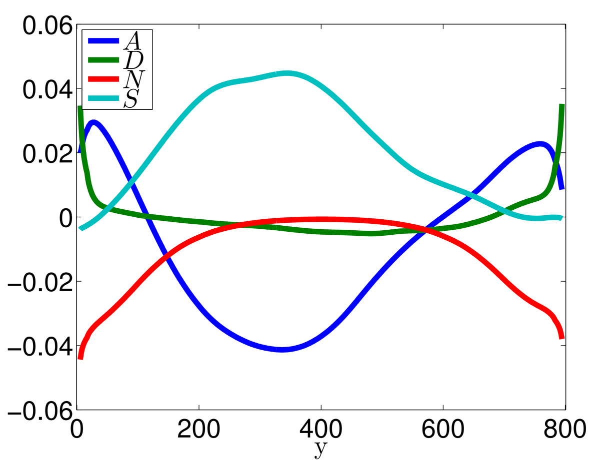


Simulation with neutral atoms and closed flux surface region

- **Self-consistent GBS simulations with neutral dynamics that include closed flux surface region**
- Neutral density peaks around the limiter due to recycling and ionization follows plasma fluctuations

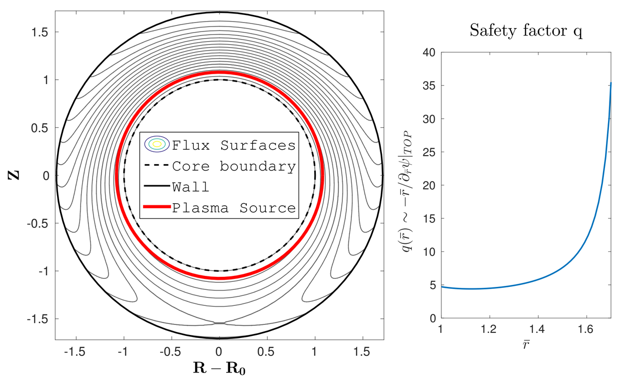


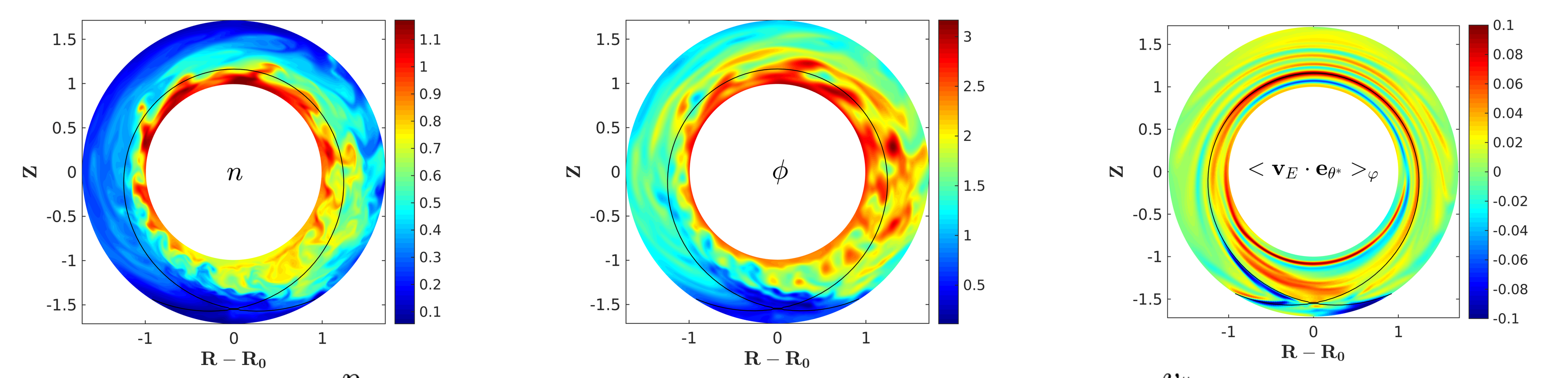
- SOL quasi-steady state balance in the electron temperature equation
- The perpendicular drifts (S) and the neutral interaction terms (N) are balanced by the parallel advection (A) and the parallel diffusion (D) [Wersal *et al.*, NF 2015]

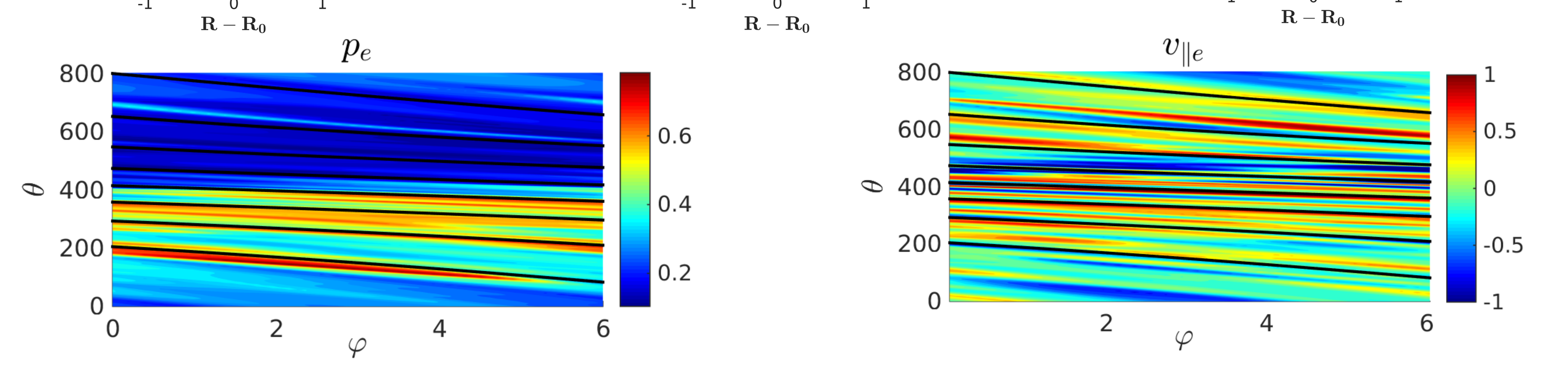


First simulations with X-point

- Development of a numerical algorithm in more flexible coordinates: (r, θ, φ) (not field aligned)
- **X-point equilibrium implemented in GBS**
- Sheath boundary conditions applied at the wall
- Turbulence structures appear field aligned







Summary and Outlook

- GBS is a tool to carry out SOL turbulence simulations of medium size tokamaks
- Recent developments concern the implementation of shaping effects, neutral atom dynamics, the open-closed field lines interface, and implementation of the X-point geometry

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