Progress in simulating SOL plasma turbulence with the GBS code

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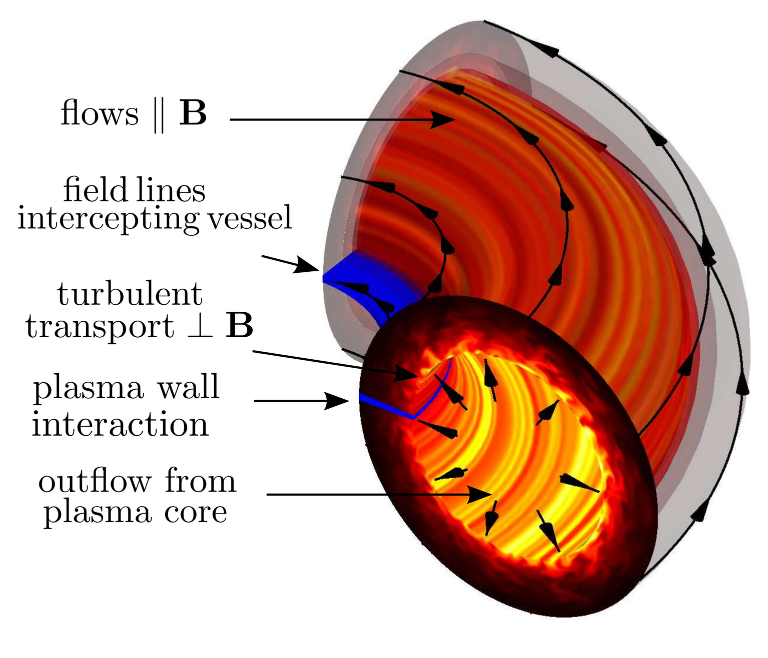
Introduction



- 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 in limited geometry** 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 $\sim$ 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, $\left(\nabla_\perp^2 - \frac{\beta_{e0}}{2}\frac{m_i}{m_e}n\right)v_{\parallel e} = \nabla_\perp^2 U_{\parallel e} - \frac{\beta_{e0}}{2}\frac{m_i}{m_e}nv_{\parallel i}$
- 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 neutral atoms equation

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

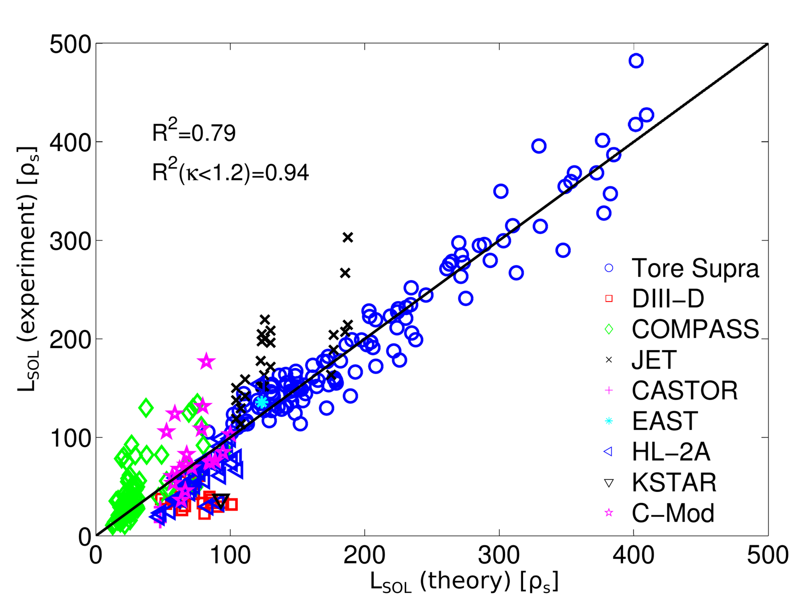
- **Method of characteristics** to obtain the formal solution of f_n [Wersal *et al.*, NF 2015]
- **Two assumptions**, $\tau_{\text{neutral losses}} < \tau_{\text{turbulence}}$ and $\lambda_{\text{mfp, neutrals}} \ll L_{\parallel,\text{plasma}}$, leading to a 2D steady state system for each perpendicular 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.

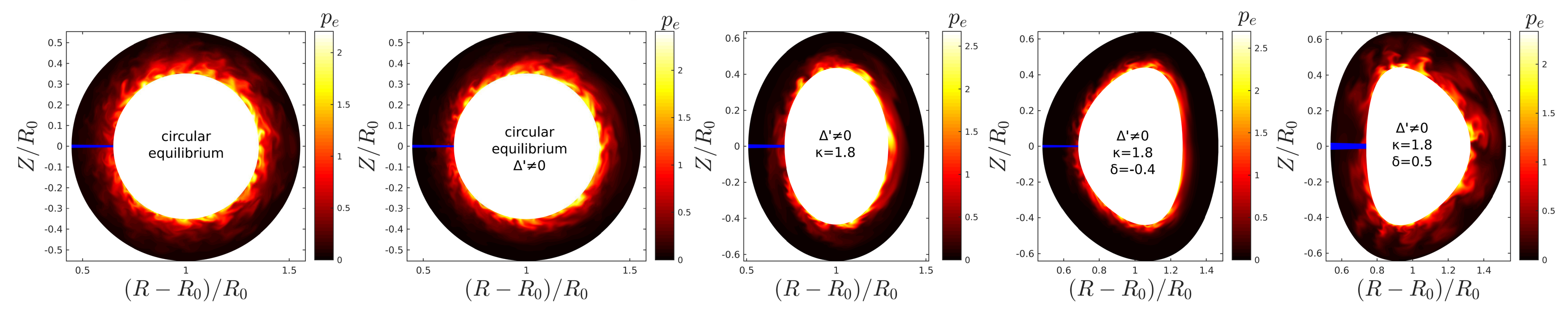
Achievements of GBS

- 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

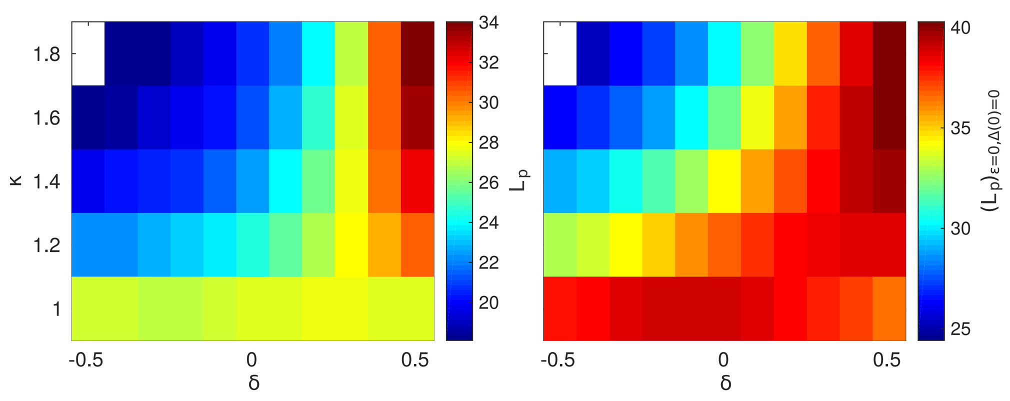
- **Fully-turbulent non-linear simulations** with same physical parameters, in **different magnetic geometries** [Riva *et al.*, PPCF, submitted]



- **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** [Ricci *et al.*, PoP 2013]

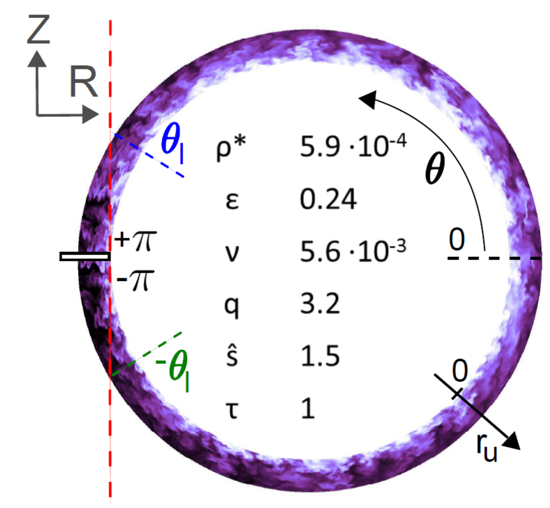
(κ,δ)	Non − linear sim. $\epsilon \simeq 0.25,\ \Delta(0) \simeq 7$	Gradient Removal Theory $\epsilon \simeq 0.25,\ \Delta(0) \simeq 7$	Non − linear sim. $\epsilon = 0,\ \Delta(0) = 0$	Gradient Removal Theory $\epsilon = 0,\ \Delta(0) = 0$
(1.0, 0.0)	25 ± 1	27.4	37 ± 2	38.9
(1.8, 0.0)	20 ± 1	20.7	26 ± 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

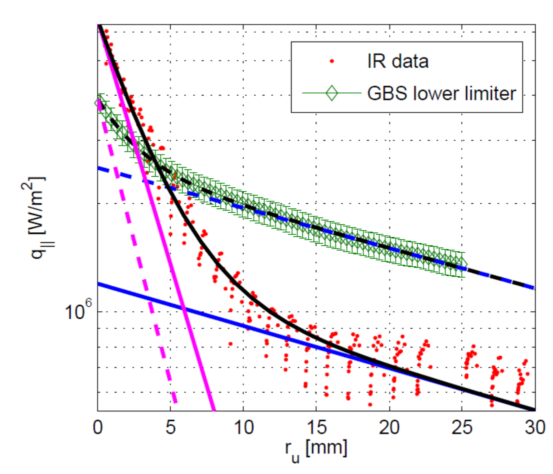
- **Linear scan** over κ and δ allows to predict the **SOL width for non-circular magnetic geometries**
- It is possible to **generalize** the **analytical first-principle** L_p **scaling** to include shaping effects



Simulation of TCV SOL

- **GBS simulation of TCV discharge # 49170**
- Full size simulation with realistic TCV input parameters
- Simulation parameters at the LCFS given by flush-mounted Langmuir probes
- Comparison with infrared imaging of heat flux [Nespoli *et al.*, JNM 2015]

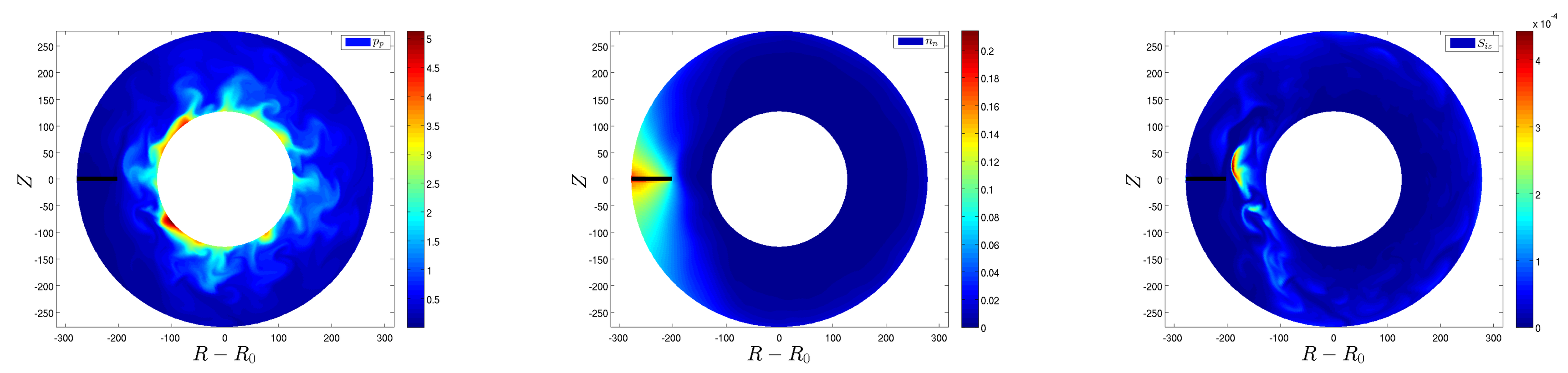




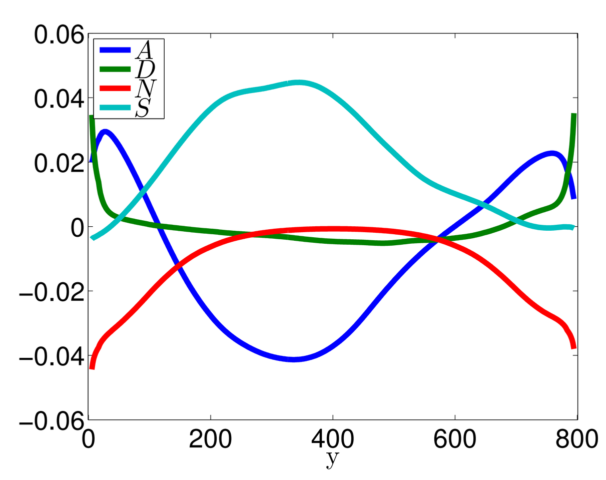
- **Double scale length** in heat flux profile as in TCV measurements
- Good agreement for what concerns the scale lengths
- Heat flux fall-off in the near SOL smaller with respect to experiments
- **Non ambipolar current** at the limiter observed in near SOL as in the experiment

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]



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 validation agains TCV measurements
- A more flexible algorithm to simulate diverted SOL is being implemented

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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