Turbulence simulations in diverted geometry

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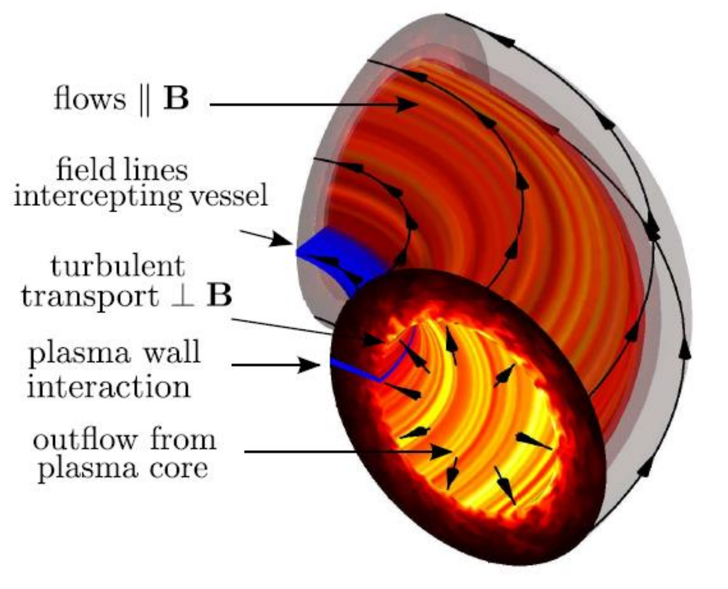
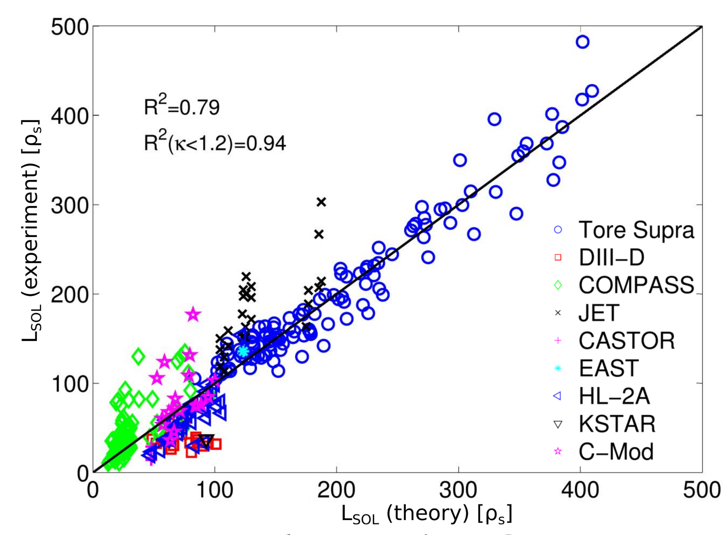
The tokamak periphery and GBS code



- The **tokamak periphery** is dived in two parts: the plasma **edge** and the **Scrape-Off Layer (SOL)**
- The **edge** is the plasma region between the core and the last closed flux surface (**LCFS**)
- The **turbulence across the LCFS** determines the **confinement**
- The **SOL** is the plasma region **outside the LCFS**
- In the **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**
- **Global Braginskii Solver (GBS) Code** is a 3D, flux-driven, global turbulence code in **limited** and **diverted X-point** configurations used to study plasma **turbulence in the tokamak periphery** [Halpern et al., JCP 2016], [Ricci et al. PPCF 2012]
- GBS solves 3D fluid equations for electrons and ions, Poisson's and Ampere's equations, and a kinetic equation for neutral atoms

Some of the past GBS achievements

- Characterization of non-linear turbulent regimes in the SOL [Mosetto *et al.*, PoP 2013]
- 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 the SOL equilibrium electrostatic potential [Loizu *et al.*, PPCF 2013]



[Halpern *et al.*, PPCF 2016]

A new version of GBS for diverted geometry

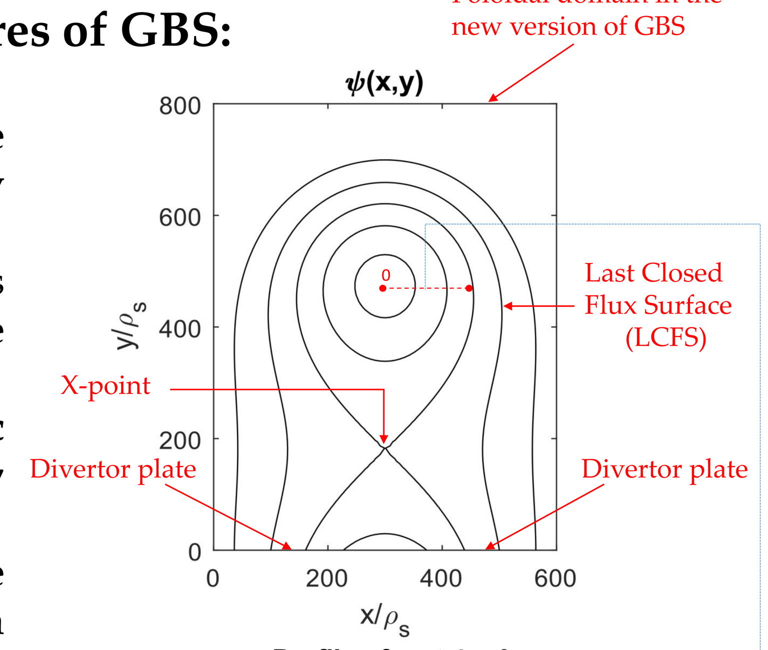
Numerical implementation in GBS:

[Paruta et al., submitted to PoP]

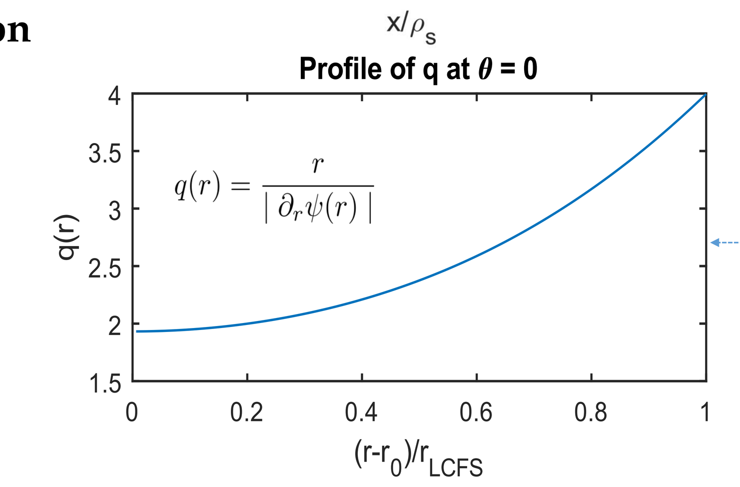
- Spatial accuracy: **4th order centered finite differences** scheme with the grid **staggered in the toroidal and vertical direction**
- An extension to the **4th order of the Arakawa algorithm** is used for the Poisson bracket operator $[\phi, f]$
- Time evolution: **4th order Runge-Kutta** time stepping method
- **Non-field-aligned coordinate system** is used to treat diverted configurations

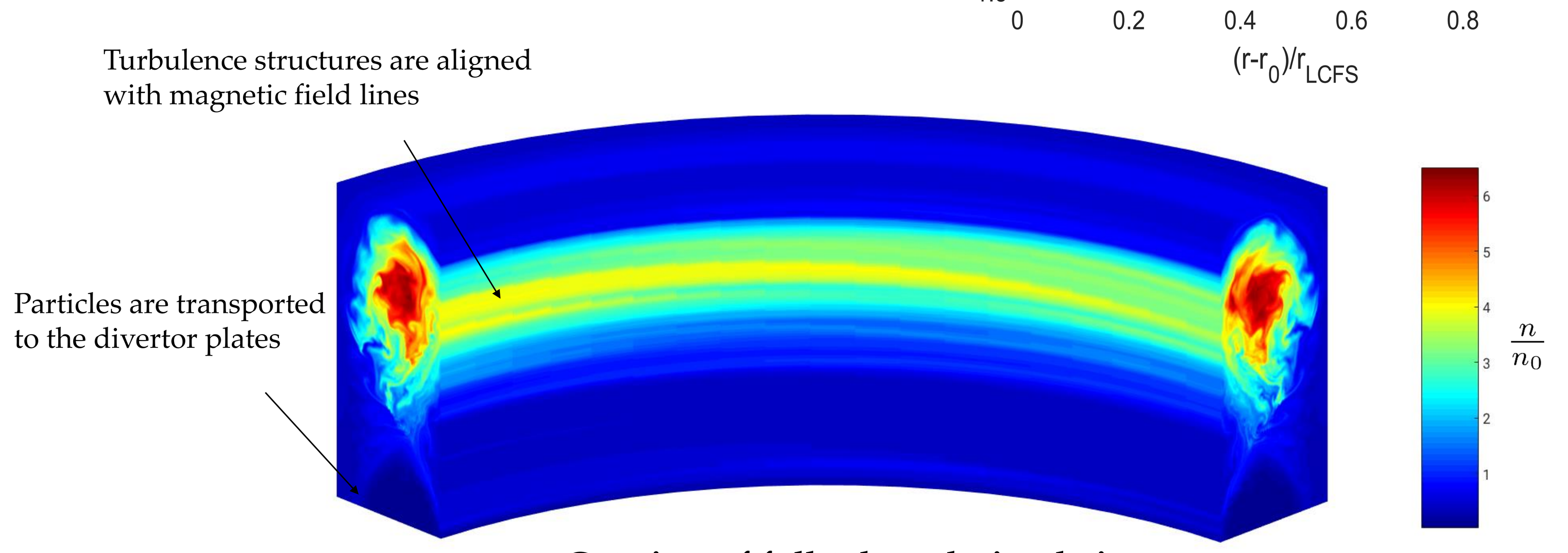
The new main features of GBS:

- **Full-tokamak simulations** to investigate the interaction between core and edge: **boundary conditions at the core are no longer needed**
- Rectangular poloidal domain guarantees much **more flexibility on the geometry** size (it reduces computational domain in SOL)
- **More flexibility** in choosing the **magnetic poloidal flux** as a function of x and y cartesian coordinates
- Proper boundary conditions are applied to the **divertor plates**. A **Robin boundary condition** for the **electric potential** is used



$$\phi + \frac{T_e}{n c_s \nu}\frac{\partial \phi}{\partial y} = \Lambda T_e + \frac{T_e^2}{n c_s \nu}\left(\frac{1}{n}\frac{\partial n}{\partial y} + 1.71\frac{1}{T_e}\frac{\partial T_e}{\partial y}\right)$$





Cut view of full-tokamak simulation

Conclusion and future plans

Conclusion

- **Full-tokamak** simulations used to investigate **the core-edge turbulence transport**
- Analysis of the **electric potential** in the tokamak (**SOL, edge and core**)
- Formation of $\boldsymbol{v_{E\times B}}$ **shear** and preliminary study of the **L-H mode transition**.

Next steps

- Expand the **analysis** with the simplified **time and toroidal averaged equation**
- Determination of the **heat flux** impacting on the **divertor plates**
- Effect of core-edge **turbulence** transport on **SOL width**

Drift-reduced fluid equations implemented in GBS

- GBS evolves the **drift-reduced Braginskii equations** with ordering $k_\parallel \ll k_\perp$ and $d/dt \ll \omega_{ci}$
- Plasma and heating outflowing from the wall is mimicked by localized plasma and heat sources S_n , S_{T_e} and S_{T_i}

$$\frac{\partial n}{\partial t} = -\frac{1}{B}\frac{R_0}{\rho_{s0}}[\phi, n] + \frac{2}{B}\Big[C(p_e) - nC(\phi)\Big] - \nabla_\parallel(n v_{\parallel e}) + D_n \nabla_\perp^2 n + S_n$$

$$\frac{\partial \omega}{\partial t} = -\frac{1}{B}\frac{R_0}{\rho_{s0}}[\phi, \omega] - v_{\parallel i}\nabla_\parallel \omega + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{2B}{n}C(p_e + \tau p_i) + \frac{B}{3n}C(G_i) + D_\omega \nabla_\perp^2 \omega$$

$$\frac{\partial v_{\parallel e}}{\partial t} = -\frac{1}{B}\frac{R_0}{\rho_{s0}}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\Big(\nu j_\parallel + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e - \frac{2}{3n}\nabla_\parallel G_e\Big) + D_{v_\parallel e}\nabla_\perp^2 v_{\parallel e}$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\frac{1}{B}\frac{R_0}{\rho_{s0}}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel(p_e - \tau p_i) - \frac{2}{3n}\nabla_\parallel G_i + D_{v_\parallel i}\nabla_\perp^2 v_{\parallel i}$$

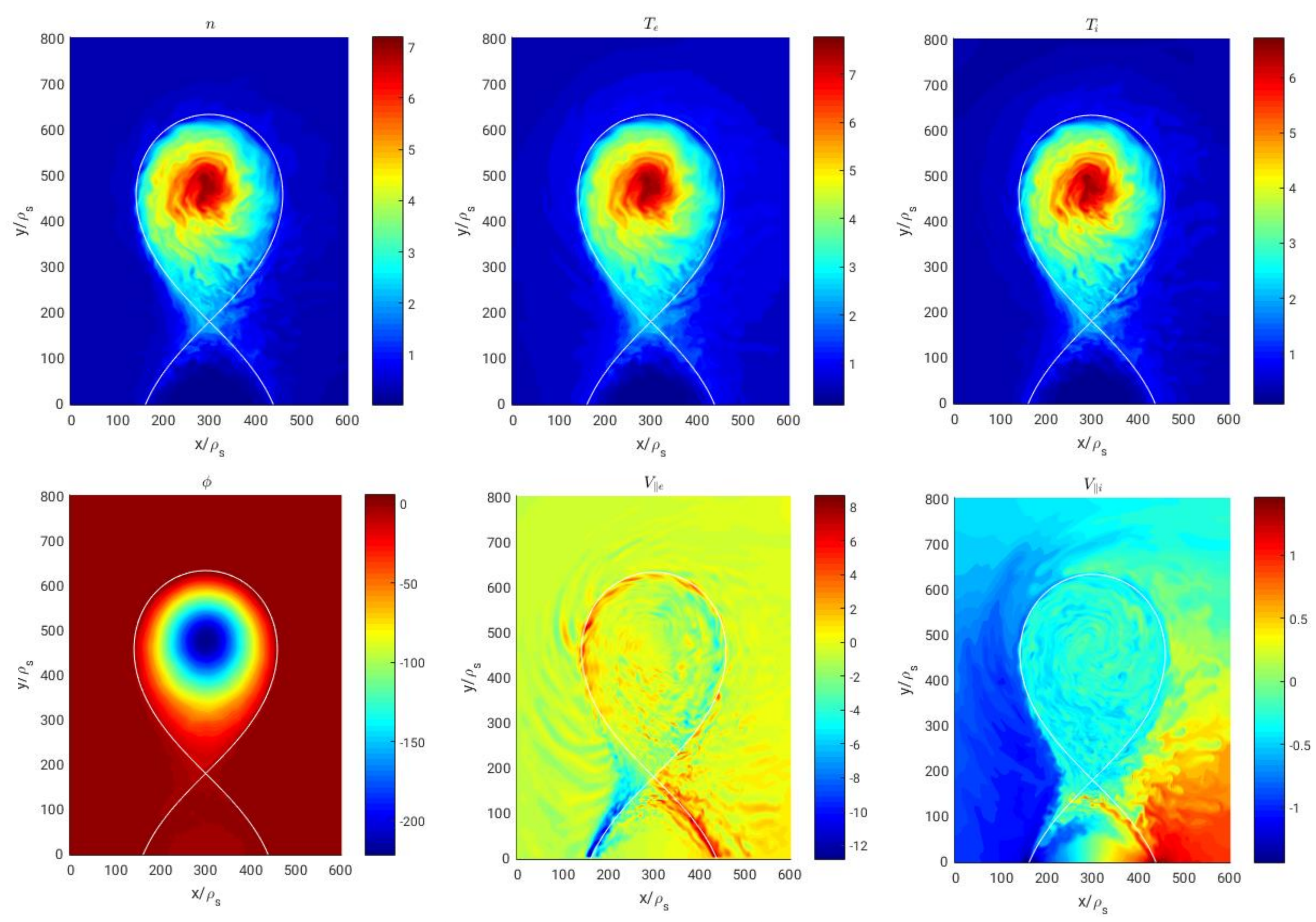
$$\frac{\partial T_e}{\partial t} = -\frac{1}{B}\frac{R_0}{\rho_{s0}}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4}{3}\frac{T_e}{B}\Big[\frac{7}{2}C(T_e) + \frac{T_e}{n}C(n) - C(\phi)\Big] + D_{T_e}\nabla_\perp^2 T_e + \chi_{\parallel e}\nabla_\parallel^2 T_e$$
$$+ \frac{2}{3}T_e\Big[0.71\nabla_\parallel v_{\parallel i} - 1.71\nabla_\parallel v_{\parallel e} + 0.71(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n}\Big] + S_{T_e}$$

$$\frac{\partial T_i}{\partial t} = -\frac{1}{B}\frac{R_0}{\rho_{s0}}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4}{3}\frac{T_i}{B}\Big[C(T_e) + \frac{T_e}{n}C(n) - C(\phi)\Big] + \frac{2}{3}T_i(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n}$$
$$- \frac{2}{3}T_i\nabla_\parallel v_{\parallel e} - \frac{10}{3}\frac{T_i}{B}C(T_i) + D_{T_i}\nabla_\perp^2 T_i + S_{T_i}$$

$$\omega = \nabla_\perp^2 \phi \,, \quad [\phi, f] = \vec{b}\cdot(\nabla\phi \times \nabla f)\,, \quad C(f) = \frac{B}{2}\Big(\nabla \times \frac{\vec{b}}{B}\Big)\cdot \nabla f\,, \quad \vec{b} = \frac{\vec{B}}{B}$$

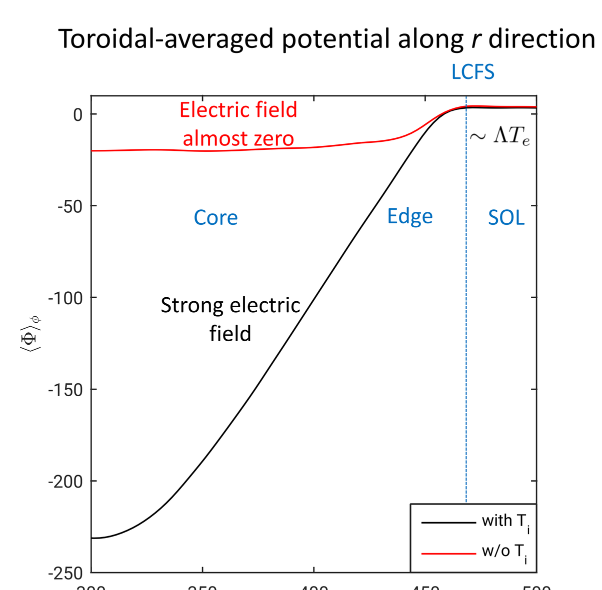
- System completed with **first-principles boundary conditions** applicable at the magnetic pre-sheath entrance [Loizu et al., PoP 2012]
- Normalized units used throughout: $L_\perp \to \rho_{s0}$, $L_\parallel \to R_0$, $t \to R_0/c_{s0}$, $\nu = n_0 R_0 e^2/(m_i c_{s0} \sigma_\parallel)$

Preliminary results



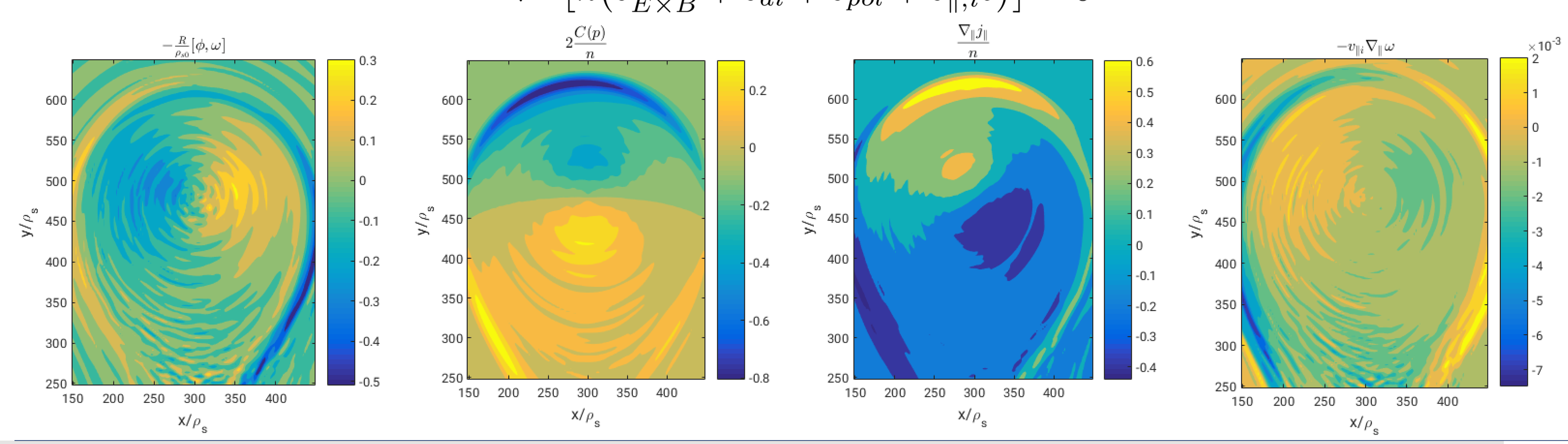
Electric potential in the tokamak

- In the **SOL**, the **electric potential follows the electron temperature** and it does not depend on the cold ion approximation.
- In the **edge** and **core**, the electric potential strongly depends on the ion temperature: in the **cold ion approximation no electric field** is generated
- The electric field leads to an $\vec{\boldsymbol{E}} \times \vec{\boldsymbol{B}}$ **shear** that **improves the plasma confinement**
- The analysis points out the importance of **ion heating** to reach a better confinement (**H-mode**). This result has been seen experimentally [F. Ryter *et al.*, NC 2014]



- The $\vec{\boldsymbol{E}} \times \vec{\boldsymbol{B}}$ **velocity** is **self-generated** by the plasma when the ions are heated up: **the ion pressure gradient increases** as well as **the diamagnetic ion velocity** which is **balanced by** an increase of the $\vec{\boldsymbol{E}} \times \vec{\boldsymbol{B}}$ **velocity**
- By retaining only the dominant terms, the **time and toroidal averaged vorticity equation** (figures below) is $-\frac{R_0}{\rho_{s0}} n[\phi, \omega] + C(p_e + \tau p_i) + \nabla_\parallel j_\parallel \approx 0$
- By combining this equation with the **time and toroidal averaged density equation**, the **continuity equation for the ions is retrieved**, where $\vec{v}_{pol}$ is the polarization velocity and it **comes from the non-negligible term** $-\frac{R_0}{\rho_{s0}} n\,[\phi, \omega]$

$$\nabla \cdot \left[n\left(\vec{v}_{\vec{E}\times\vec{B}} + \vec{v}_{di} + \vec{v}_{pol} + v_{\parallel,i}\vec{b}\right)\right] = 0$$



EUROfusion

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