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Simulations of turbulence and profile evolution across the edge and scrape-off layer of the ASDEX Upgrade tokamak

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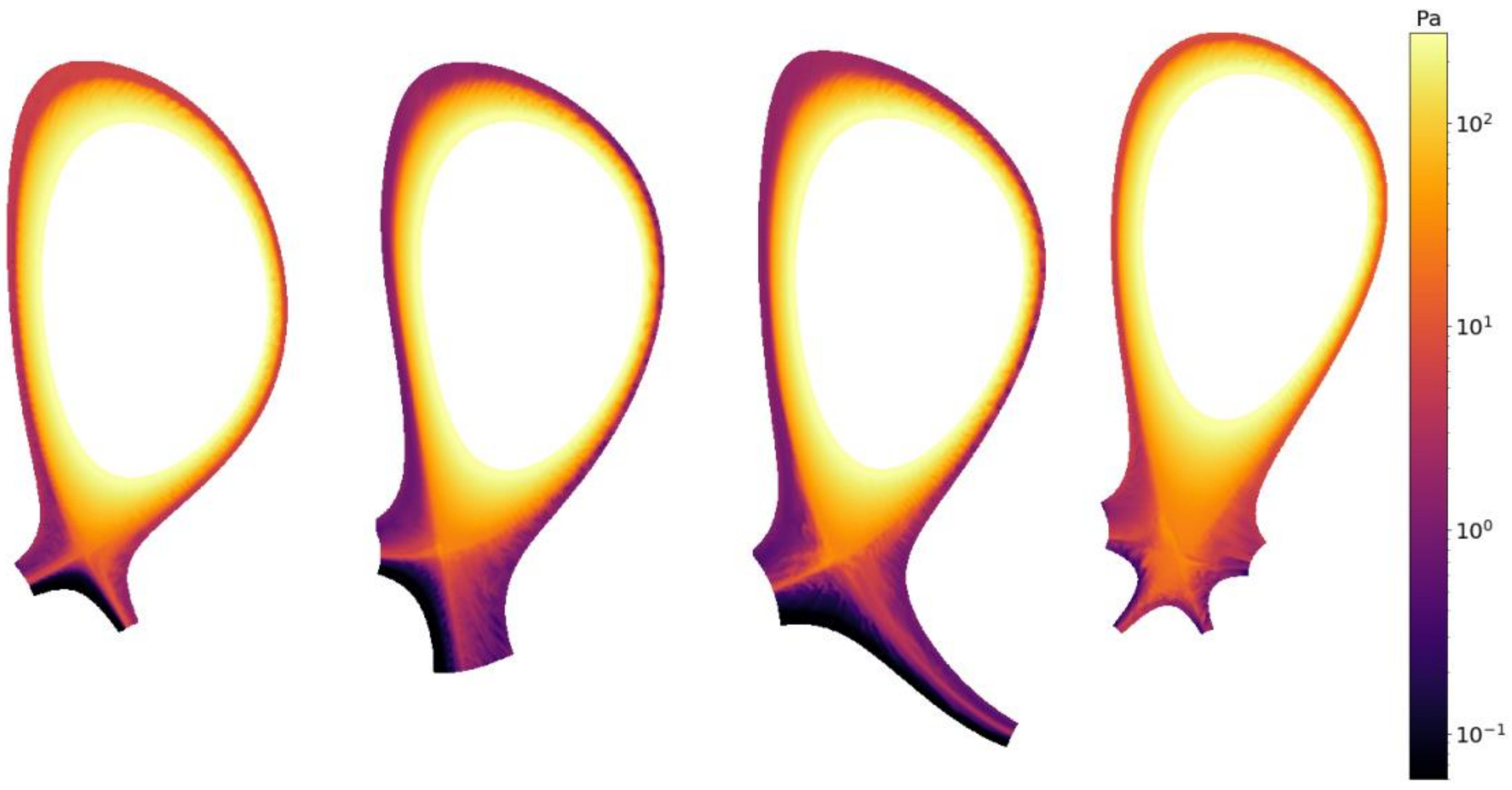
Abstract / Motivation

- The development of predictive modelling for the edge and SOL is essential to solving the heat exhaust problem, which arises in tokamaks at reactor scale (ITER, DEMO)
- The GRILLIX code [1,2] can simulate multi-scale turbulence and transport in complex magnetic and wall geometry, including advanced divertor concepts (ADCs)
- The code is validated against the TCV and ASDEX Upgrade experiments
- The interaction of turbulence and the mean radial electric field is investigated [3]

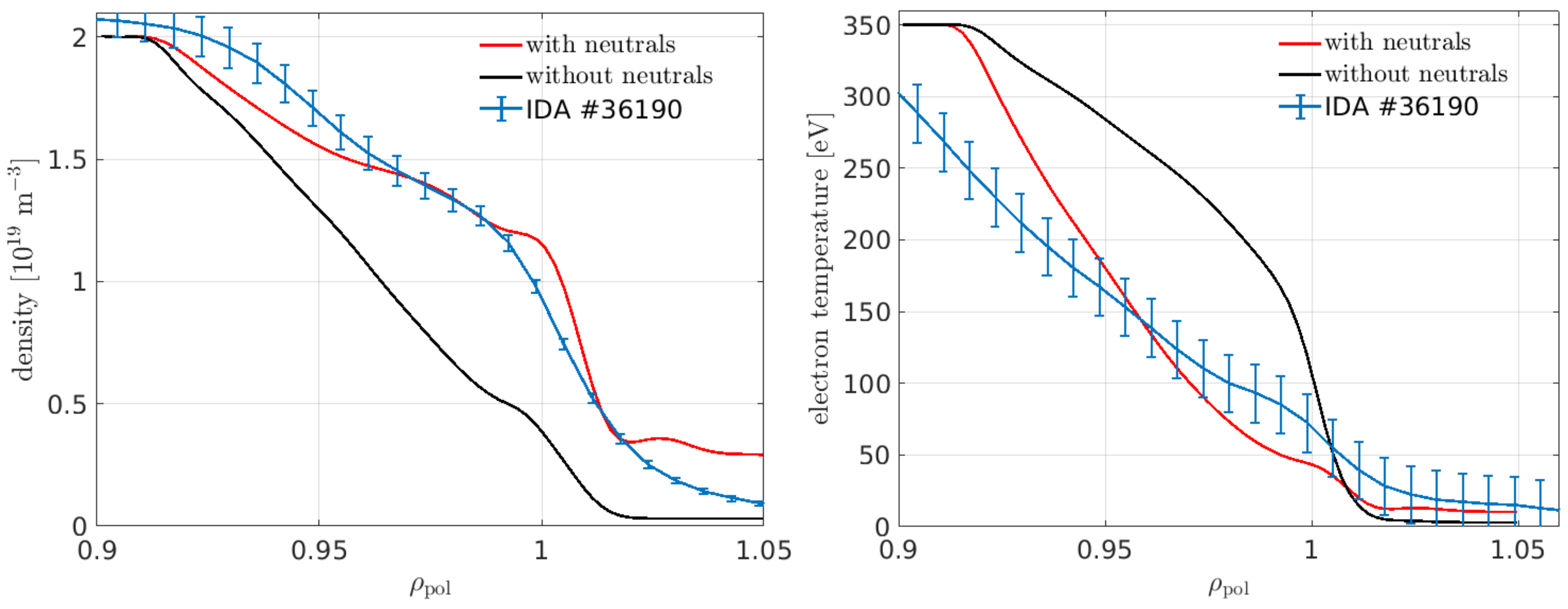
Advanced Divertor Concepts (ADCs)

For the DEMO design it is investigated how dedicated shaping of the divertor magnetic field could help increase the wetted area and reduce heat loads on target plates through flux expansion and long divertor legs [4]. To support the ADC design by simulations of turbulent transport, GRILLIX was extended to run in arbitrary axisymmetric equilibria [5]. Shown below are electron pressure snapshots in saturated state of a TCV size simulation in single-null, X-divertor, Super-X and snowflake configuration (left to right).



Validation driven development (e.g. ASDEX Upgrade)

GRILLIX was developed with the goal to perform affordable predictive turbulence simulations in relevant diverted geometry and at relevant parameters. On the way to reactor scale simulations, the development is driven by continuous validation: here shown are outboard mid-plane density and electron temperature profiles compared to integrated data analysis in ASDEX Upgrade discharge #36190 from ECE, Thomson, He and Li beam measurements.



The black lines show results from a simulation with core density and energy sourcing. The red lines are with density sourced by neutral gas ionization. Even a very simple diffusive neutrals model improves the agreement with the experiment drastically.

Conclusion

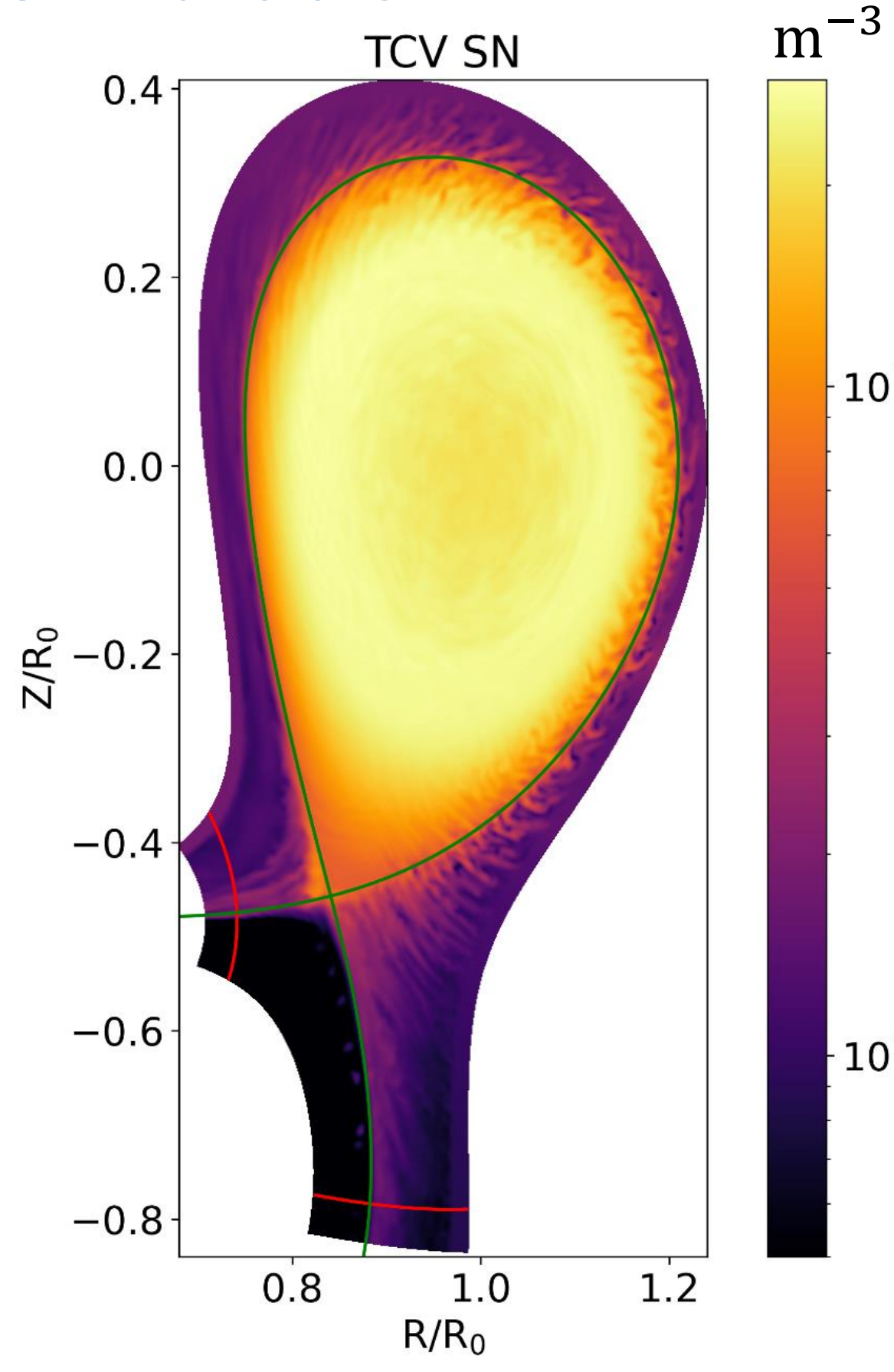
Global electromagnetic turbulence simulations across ASDEX Upgrade edge & SOL show

1. **transport** dominated by large scale **interchange** modes,
2. **zonal flows**, driven by drift waves on Larmor radius scale,
3. $\langle E_r\rangle_t = \left\langle\frac{\partial_r p_\mathrm{i}}{en}\right\rangle + \frac{m_\mathrm{e}}{e}\langle\mathbf{u}\cdot\nabla\mathbf{u}\rangle\cdot\mathbf{e}_r + \langle u_\parallel B_\theta\rangle$ in confined region and $\langle E_r\rangle \sim -3\partial_r T_\mathrm{e}$ in SOL,
4. $\boldsymbol{E}\times\boldsymbol{B}$ **shear** peaks at separatrix, driving both vortex breaking and zonal flows,
5. **neutral gas** recycling is crucial in setting the profiles.

Simulations are validated against attached L-mode AUG and TCV experiments.

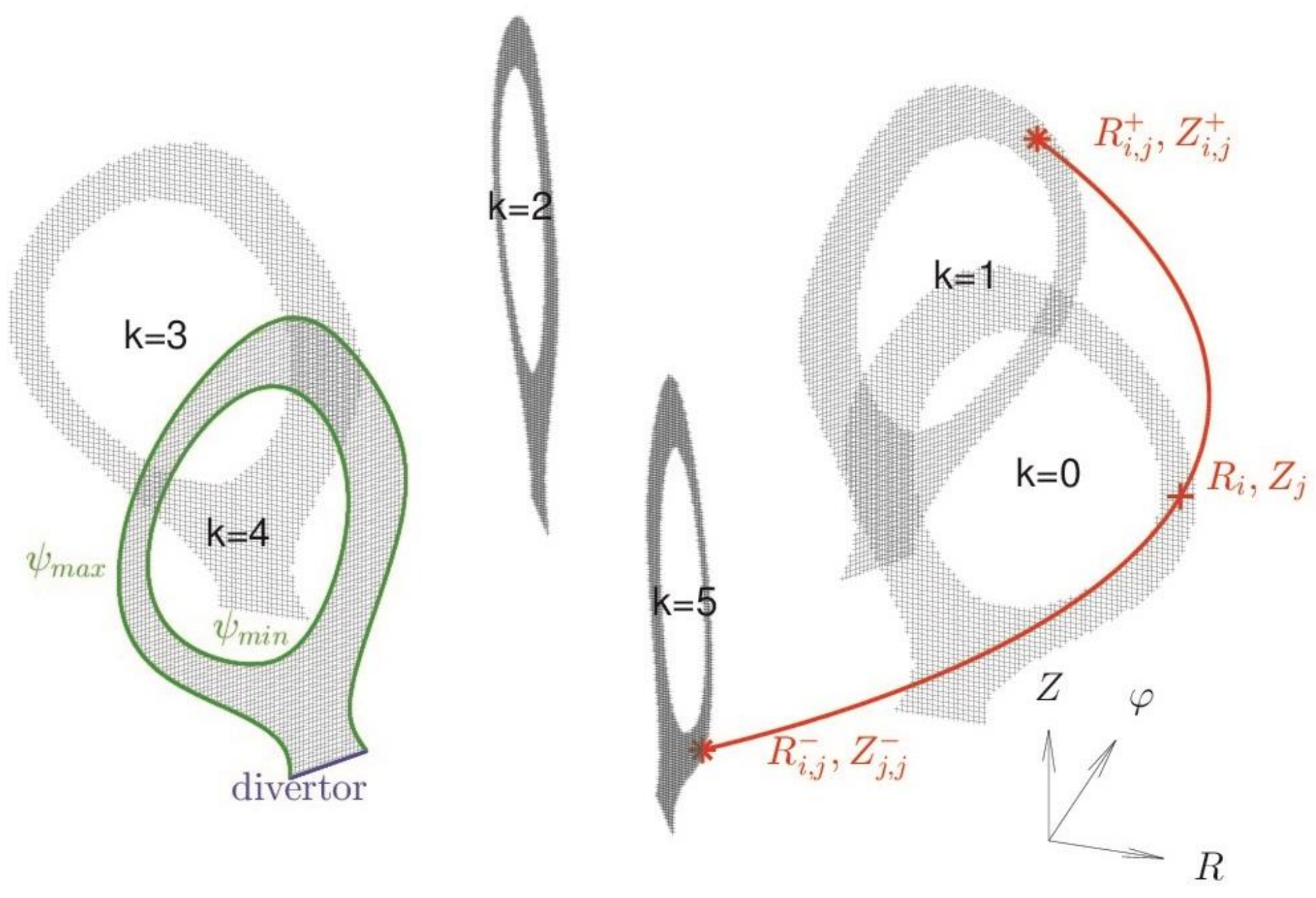
Work remains towards predictive reactor scale simulations, tackled in a European effort: see P6 Posters 6 by Patrick Tamain.

A full device TCV simulation

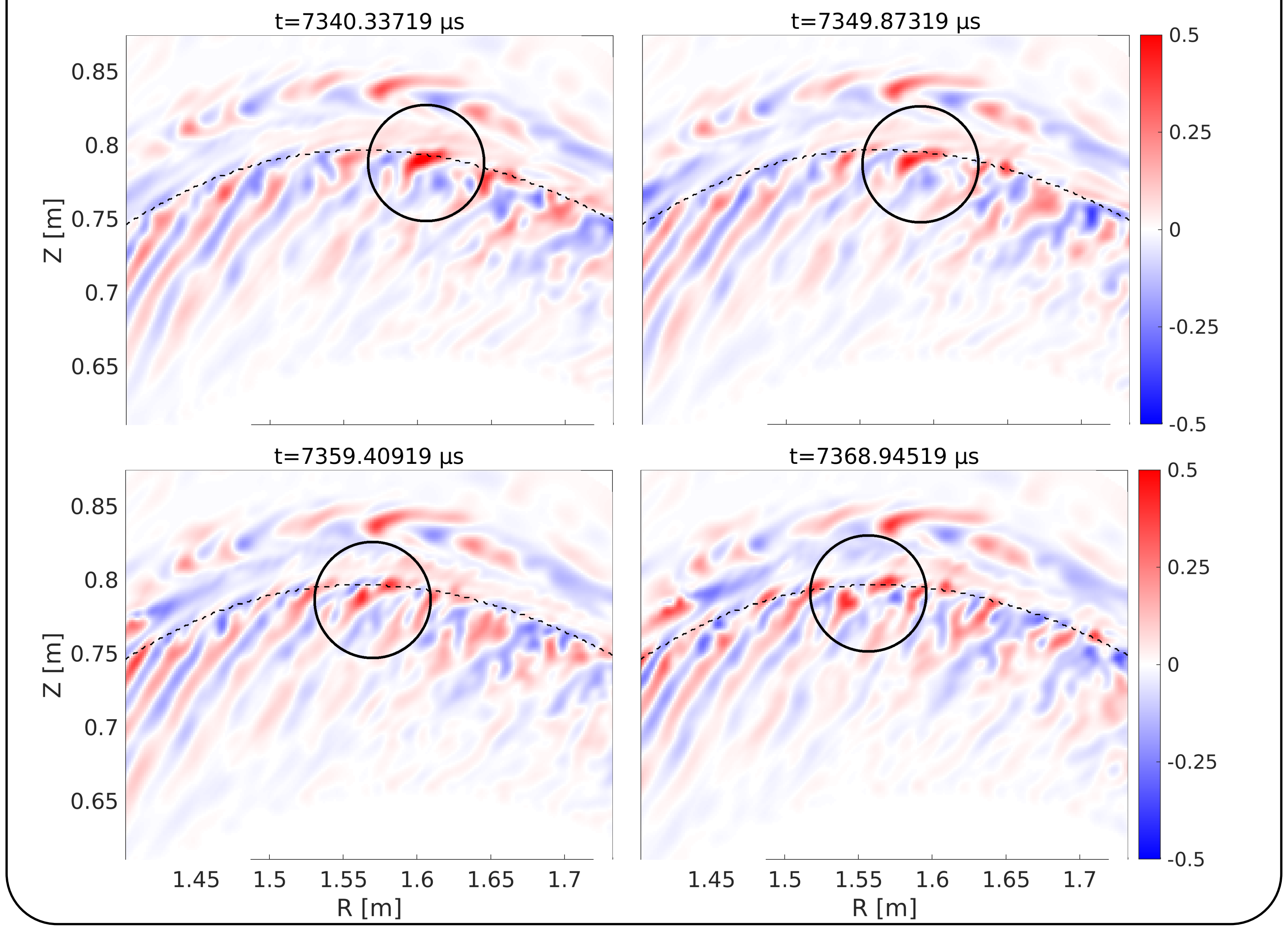


Locally field-aligned discretization

The flux-coordinate independent (FCI) approach [1] allows GRILLIX to simulate turbulence efficiently in arbitrary diverted equilibria.



Vortex breaking and straining-out at the separatrix [3]



Global drift-reduced Braginskii [3] with diffusive neutrals

$$\frac{\mathrm{d}}{\mathrm{d}t}n = nC(\varphi) - C(p_\mathrm{e}) + \nabla\cdot\left[\left(j_\parallel - nu_\parallel\right)\mathbf{b}\right] + \mathscr{D}_n(n) + k_\mathrm{iz}nN + S_n,$$

$$\nabla\cdot\left[\frac{n}{B^2}\left(\frac{\partial}{\partial t} + \delta_0\left(\frac{\mathbf{B}}{B^2}\times\nabla_\perp\varphi\right)\cdot\nabla_\perp + Nk_\mathrm{iz} + Nk_\mathrm{cx} + u_\parallel\nabla_\parallel\right)\left(\nabla_\perp\varphi + \zeta\frac{\nabla_\perp p_\mathrm{i}}{n}\right)\right] =$$
$$-C(p_\mathrm{e}+\zeta p_\mathrm{i}) + \nabla\cdot(j_\parallel\mathbf{b}) - \frac{\zeta}{6}C(G) + \mathscr{D}_\Omega(\Omega),$$

$$\left(\frac{\mathrm{d}}{\mathrm{d}t} + u_\parallel\nabla_\parallel\right)u_\parallel = -\frac{\nabla_\parallel(p_\mathrm{e}+\zeta p_\mathrm{i})}{n} + \zeta T_\mathrm{i}C(u_\parallel) - \frac{2}{3}\zeta\frac{B^{3/2}}{n}\nabla_\parallel\frac{G}{B^{3/2}} + \mathscr{D}_u(u_\parallel),$$

$$\beta_0\frac{\partial}{\partial t}A_\parallel + \mu\left(\frac{\mathrm{d}}{\mathrm{d}t} + v_\parallel\nabla_\parallel\right)\frac{j_\parallel}{n} = -\left(\frac{\eta_{\parallel 0}}{T_\mathrm{e}^{3/2}}\right)j_\parallel - \nabla_\parallel\varphi + \frac{\nabla_\parallel p_\mathrm{e}}{n} + 0.71\nabla_\parallel T_\mathrm{e} + \mathscr{D}_\Psi(\Psi_m), \qquad \nabla_\perp^2 A_\parallel = -j_\parallel,$$

$$\frac{3}{2}\left(\frac{\mathrm{d}}{\mathrm{d}t} + v_\parallel\nabla_\parallel\right)T_\mathrm{e} = T_\mathrm{e}C(\varphi) - \frac{T_\mathrm{e}}{n}C(p_e) - \frac{5}{2}T_\mathrm{e}C(T_\mathrm{e}) - T_\mathrm{e}\nabla\cdot(v_\parallel\mathbf{b}) + 0.71\frac{T_\mathrm{e}}{n}\nabla\cdot(j_\parallel\mathbf{b})$$
$$+\frac{1}{n}\nabla\cdot\left[\left(\chi_{\parallel\mathrm{e}0}T_\mathrm{e}^{5/2}\right)\mathbf{b}\nabla_\parallel T_\mathrm{e}\right] - 2\nu_{\mathrm{e}0}\mu\left(\frac{n}{T_\mathrm{e}^{3/2}}\right)(T_\mathrm{e}-\zeta T_\mathrm{i}) + \left(\frac{\eta_{\parallel 0}}{T_\mathrm{e}^{3/2}}\right)\frac{j_\parallel^2}{n} + \frac{3}{2}\left(\mathscr{D}_{T_\mathrm{e}}(T_\mathrm{e}) + S_{T_\mathrm{e}}\right),$$

$$\frac{3}{2}\left(\frac{\mathrm{d}}{\mathrm{d}t} + u_\parallel\nabla_\parallel\right)T_\mathrm{i} = T_\mathrm{i}C(\varphi) - \frac{T_\mathrm{i}}{n}C(p_e) + \frac{5}{2}\zeta T_\mathrm{i}C(T_\mathrm{i}) - T_\mathrm{i}\nabla\cdot(u_\parallel\mathbf{b}) + \frac{T_\mathrm{i}}{n}\nabla\cdot(j_\parallel\mathbf{b})$$
$$+\frac{1}{n}\nabla\cdot\left[\left(\chi_{\parallel\mathrm{i}0}T_\mathrm{i}^{5/2}\right)\mathbf{b}\nabla_\parallel T_\mathrm{i}\right] + 2\nu_{\mathrm{e}0}\mu\left(\frac{n}{T_\mathrm{e}^{3/2}}\right)\left(\frac{1}{\zeta}T_\mathrm{e} - T_\mathrm{i}\right) + \frac{2w_{GTi}}{9\eta_{\mathrm{i}0}}\frac{G^2}{nT_\mathrm{i}^{5/2}} + \frac{3}{2}\left(\mathscr{D}_{T_\mathrm{i}}(T_\mathrm{i}) + S_{T_\mathrm{i}}\right),$$

$$\frac{\partial}{\partial t}N = \nabla\cdot\frac{\zeta\nabla NT_\mathrm{i}}{nk_\mathrm{cx}} - k_\mathrm{iz}nN, \qquad N \text{ fixed at the divertor.}$$

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[5] T. Body *et al.*, Contrib. Plasma Phys. **60,** e201900139 (2019)

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