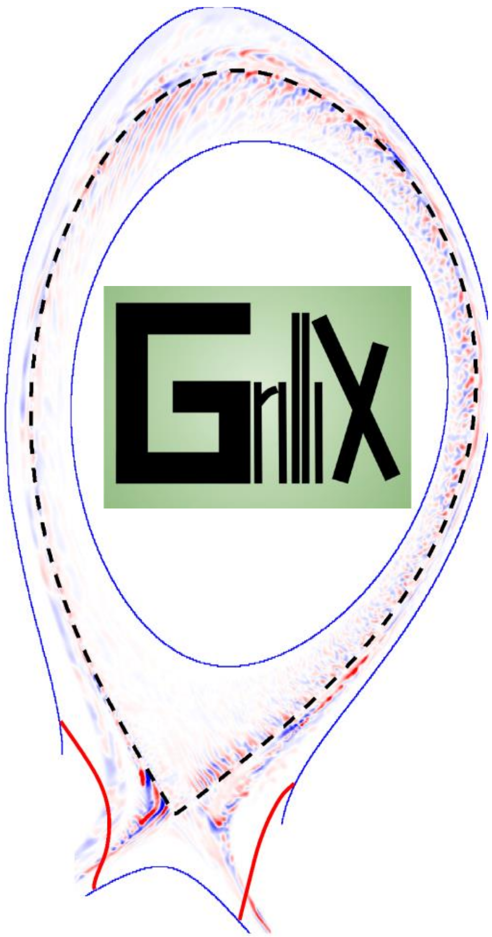
Max-Planck-Institut für Plasmaphysik



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

W. Zholobenko, T. Body, A. Stegmeir, P. Manz, B. Zhu, M. Griener, G. D. Conway, D. Coster, M. Francisquez, B. N. Rogers, E. Wolfrum, F. Jenko and the ASDEX Upgrade Team

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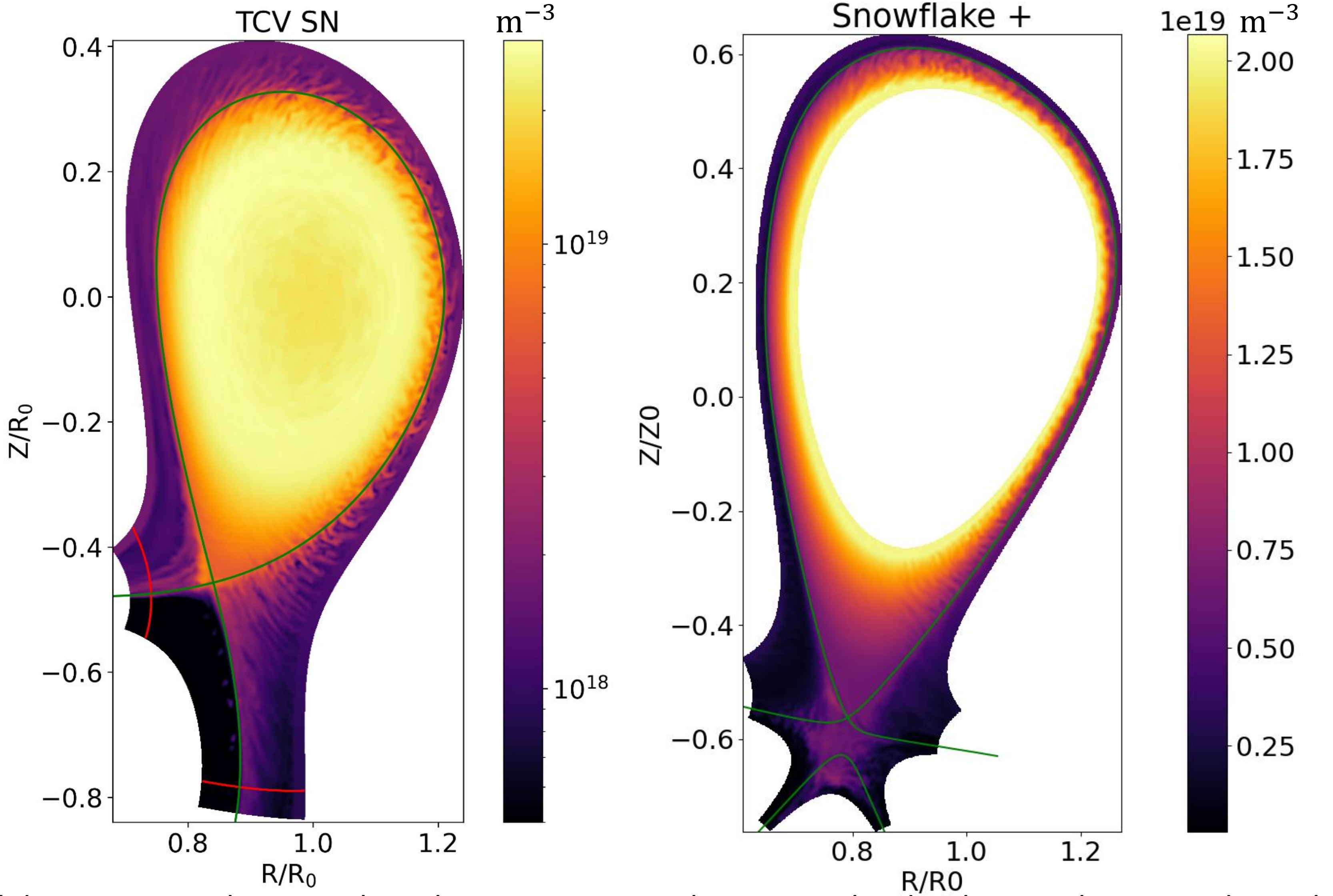
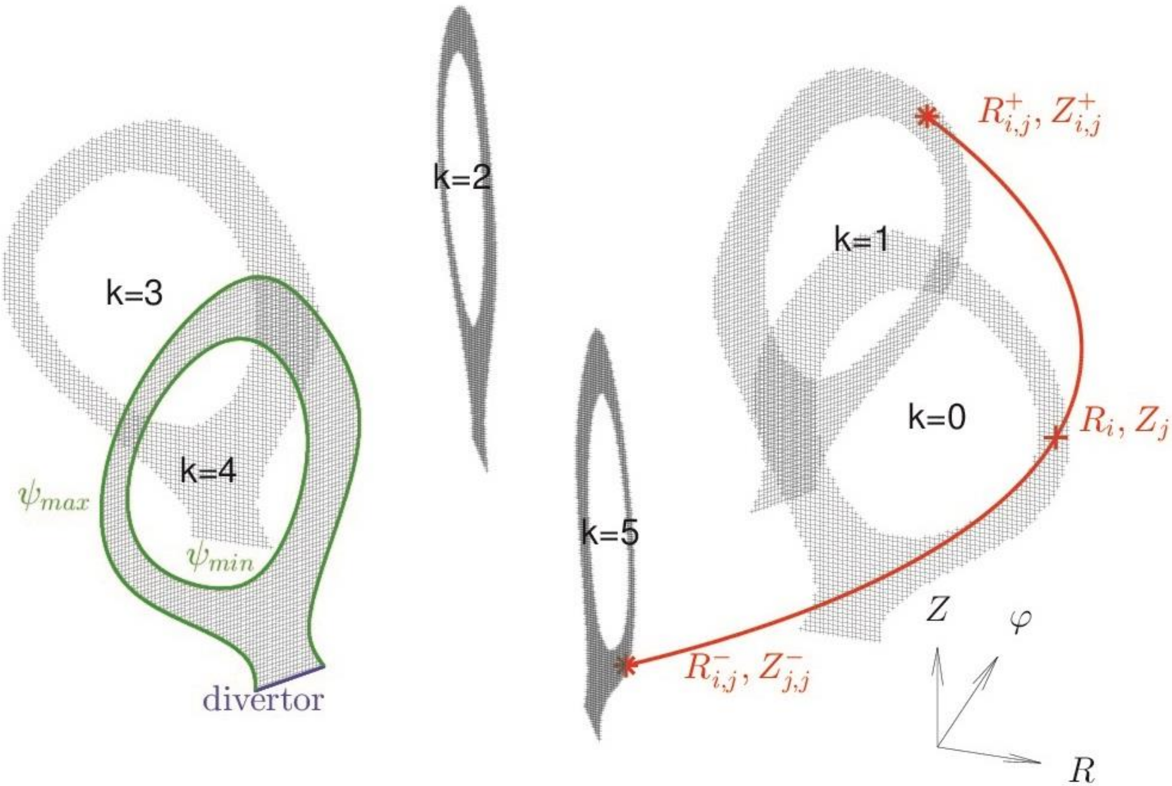
Divertor heat load & confinement optimization



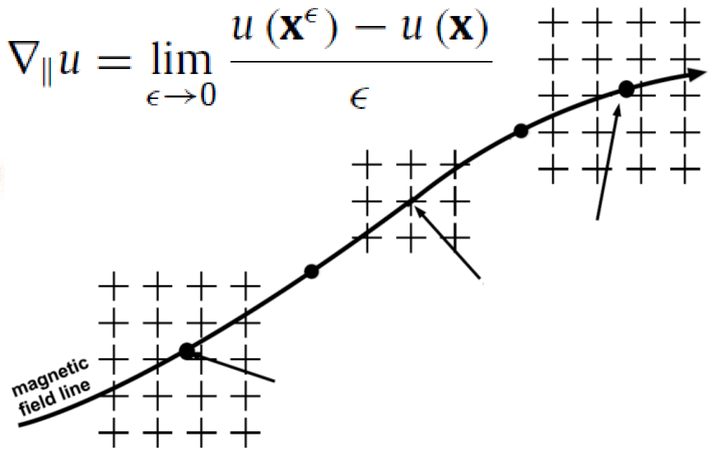
A validation against the TCV tokamak is in preparation by Diego Sales de Oliveira, Thomas Body *et al*

GRILLIX: locally field-aligned discretization



$$k_\perp \gg k_\parallel$$

$$\nabla_\parallel u = \lim_{\epsilon \to 0} \frac{u(\mathbf{x}^\epsilon) - u(\mathbf{x})}{\epsilon}$$



Flux-coordinate independent (FCI) approach

1) F. Hariri and M. Ottaviani, Comput. Phys. Comm. **184**, 2419 (2013)
2) A. Stegmeir *et al*., Comput. Phys. Comm. **198**, 139 (2016)
3) A. Stegmeir *et al*., Phys. Plasmas **26**, 052517 (2019)

Two-fluid Braginskii equations

plasma density
$$\frac{\partial}{\partial t}n + \nabla \cdot (n\mathbf{v}_e) = 0$$

quasineutrality / vorticity
$$\nabla \cdot \mathbf{j} = \nabla \cdot (en\mathbf{v}_i - en\mathbf{v}_e) = 0$$

Drift reduction:
$$\mathbf{v}_{e\perp} = \mathbf{v}_E + \mathbf{v}_*^e \qquad \mathbf{v}_E := c/B^2\mathbf{B} \times \nabla\phi$$
$$\mathbf{v}_{i\perp} = \mathbf{v}_E + \mathbf{v}_*^i + \mathbf{u}_{pol}, \qquad \mathbf{u}_{pol} = \frac{1}{\Omega_i}\mathbf{b} \times \frac{d_i}{dt}[\mathbf{v}_E + \mathbf{v}_*^i] \cdot$$

electron heat
$$\left[\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right] T_e + \frac{2}{3}T_e \nabla \cdot \mathbf{v}_e = -\frac{2}{3n}\nabla \cdot \mathbf{q}_e + \frac{2}{3n}Q_e$$

ion heat
$$\left[\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla\right] T_i + \frac{2}{3}T_i \nabla \cdot \mathbf{v}_i = -\frac{2}{3n}\nabla \cdot \mathbf{q}_i - \frac{2}{3n}P_i : \mathbf{v}_i$$

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + \delta\left(\frac{\mathbf{B}\times\nabla\varphi}{B^2}\right) \cdot \nabla, \qquad C(f) = -\left(\nabla \times \frac{\mathbf{B}}{B^2}\right) \cdot \nabla f \approx -\left(\frac{2}{B^3}\mathbf{B} \times \nabla B\right) \cdot \nabla f$$

Global drift-reduced Braginskii with diffusive neutrals

plasma density

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

quasineutrality / vorticity

$$\nabla\cdot\left[\frac{n}{B^2}\left(\frac{\partial}{\partial t} + \delta_0\left(\frac{\mathbf{B}}{B^2}\times\nabla_\perp\varphi\right)\cdot\nabla_\perp + Nk_{iz} + Nk_{cx} + u_\parallel\nabla_\parallel\right)\left(\nabla_\perp\varphi + \zeta\frac{\nabla_\perp p_i}{n}\right)\right] =$$

$$-C(p_e + \zeta p_i) + \nabla\cdot\left(j_\parallel\mathbf{b}\right) - \frac{\zeta}{6}C(G) + \mathscr{D}_\Omega(\Omega),$$

momentum

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

Ohm & Ampère

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

electron heat

$$\frac{3}{2}\left(\frac{\mathrm{d}}{\mathrm{d}t} + v_\parallel\nabla_\parallel\right)T_e = T_e C(\varphi) - \frac{T_e}{n}C(p_e) - \frac{5}{2}T_e C(T_e) - T_e\nabla\cdot\left(v_\parallel\mathbf{b}\right) + 0.71\frac{T_e}{n}\nabla\cdot\left(j_\parallel\mathbf{b}\right)$$

$$+\frac{1}{n}\nabla\cdot\left[\left(\chi_{\parallel e0}T_e^{5/2}\right)\mathbf{b}\nabla_\parallel T_e\right] - 2\nu_{e0}\mu\left(\frac{n}{T_e^{3/2}}\right)\left(T_e - \zeta T_i\right) + \left(\frac{\eta_{\parallel 0}}{T_e^{3/2}}\right)\frac{j_\parallel^2}{n} + \frac{3}{2}\left(\mathscr{D}_{T_e}(T_e) + S_{T_e}\right),$$

ion heat

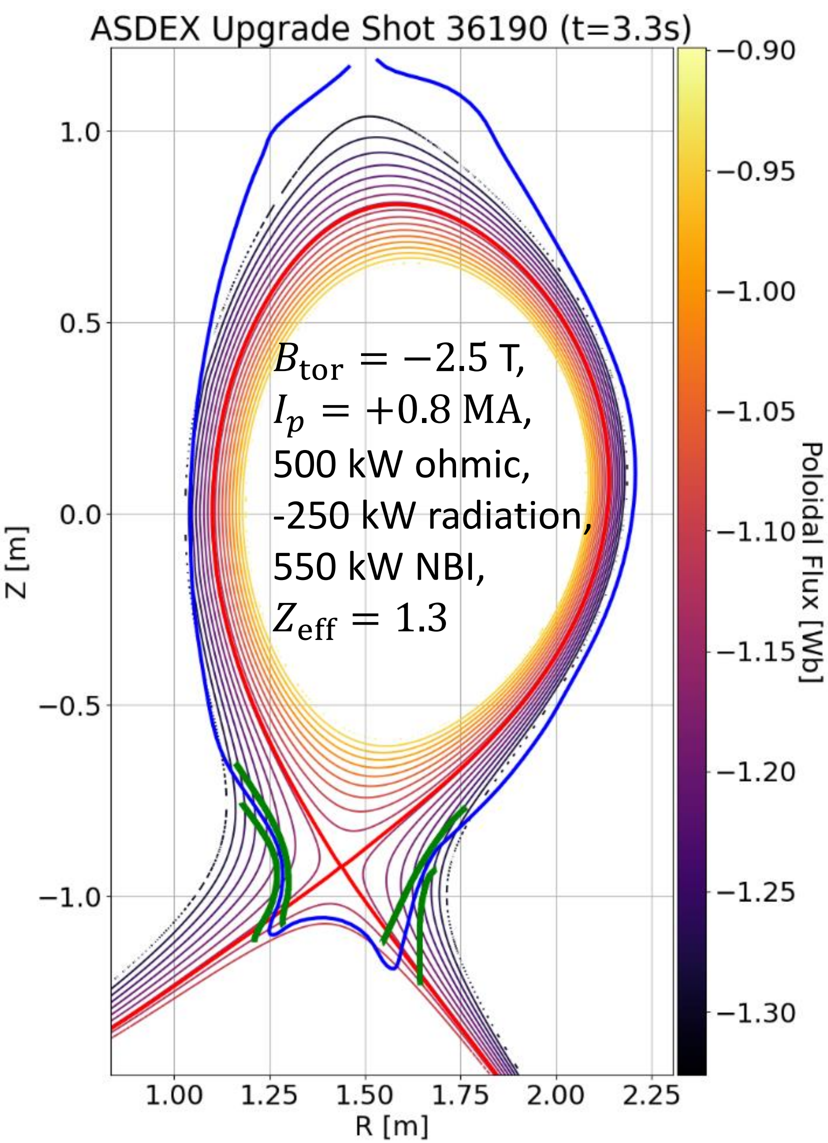
$$\frac{3}{2}\left(\frac{\mathrm{d}}{\mathrm{d}t} + u_\parallel\nabla_\parallel\right)T_i = T_i C(\varphi) - \frac{T_i}{n}C(p_e) + \frac{5}{2}\zeta T_i C(T_i) - T_i\nabla\cdot\left(u_\parallel\mathbf{b}\right) + \frac{T_i}{n}\nabla\cdot\left(j_\parallel\mathbf{b}\right)$$

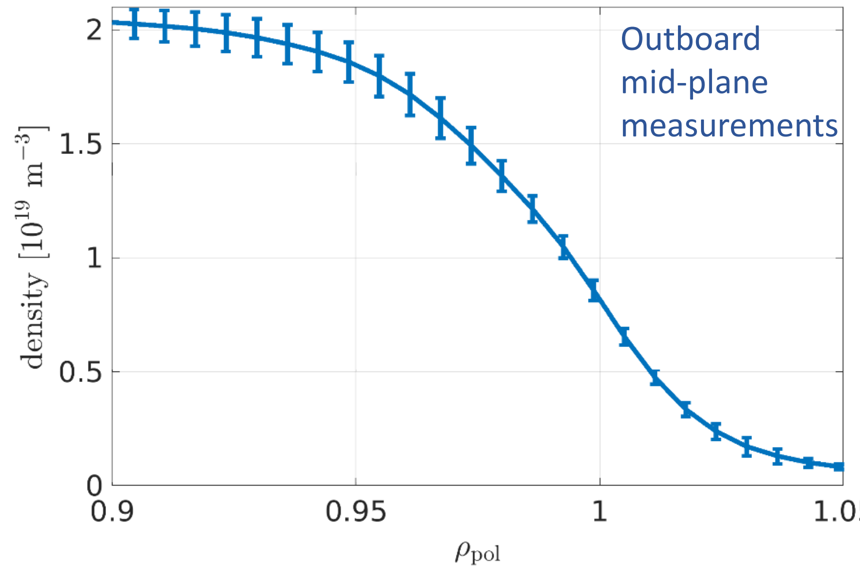
$$+\frac{1}{n}\nabla\cdot\left[\left(\chi_{\parallel i0}T_i^{5/2}\right)\mathbf{b}\nabla_\parallel T_i\right] + 2\nu_{e0}\mu\left(\frac{n}{T_e^{3/2}}\right)\left(\frac{1}{\zeta}T_e - T_i\right) + \frac{2w_{GTi}}{9\eta_{i0}}\frac{G^2}{nT_i^{5/2}} + \frac{3}{2}\left(\mathscr{D}_{T_i}(T_i) + S_{T_i}\right),$$

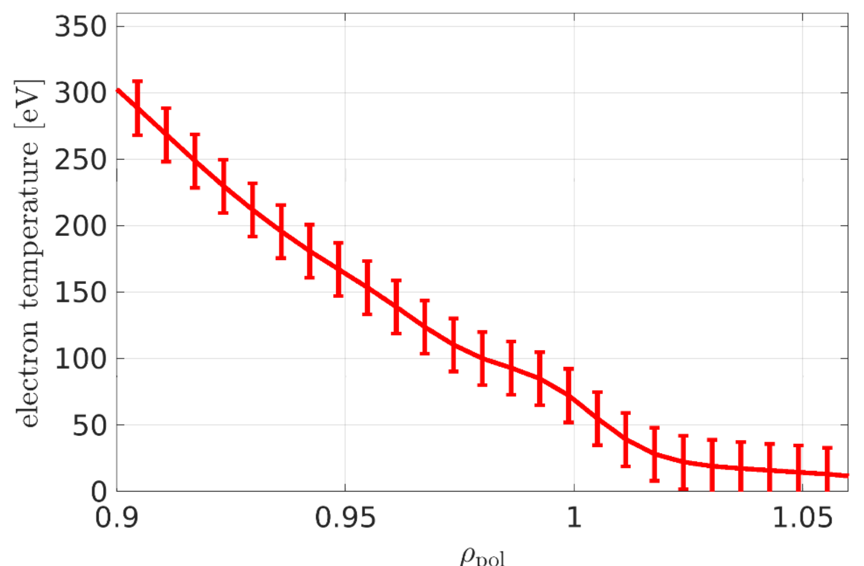
neutral particles

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

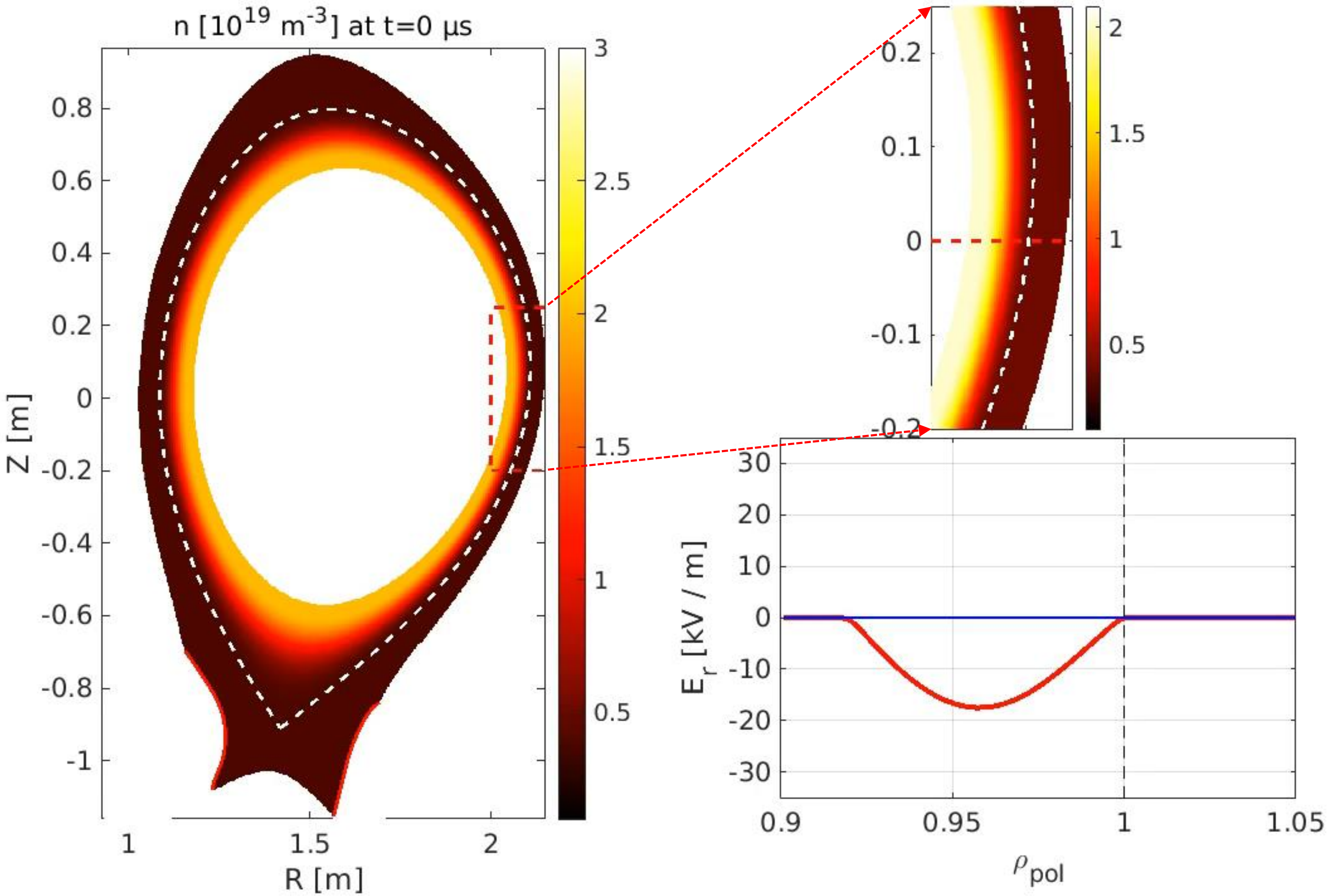
AUG discharge #36190: geometry and parameters





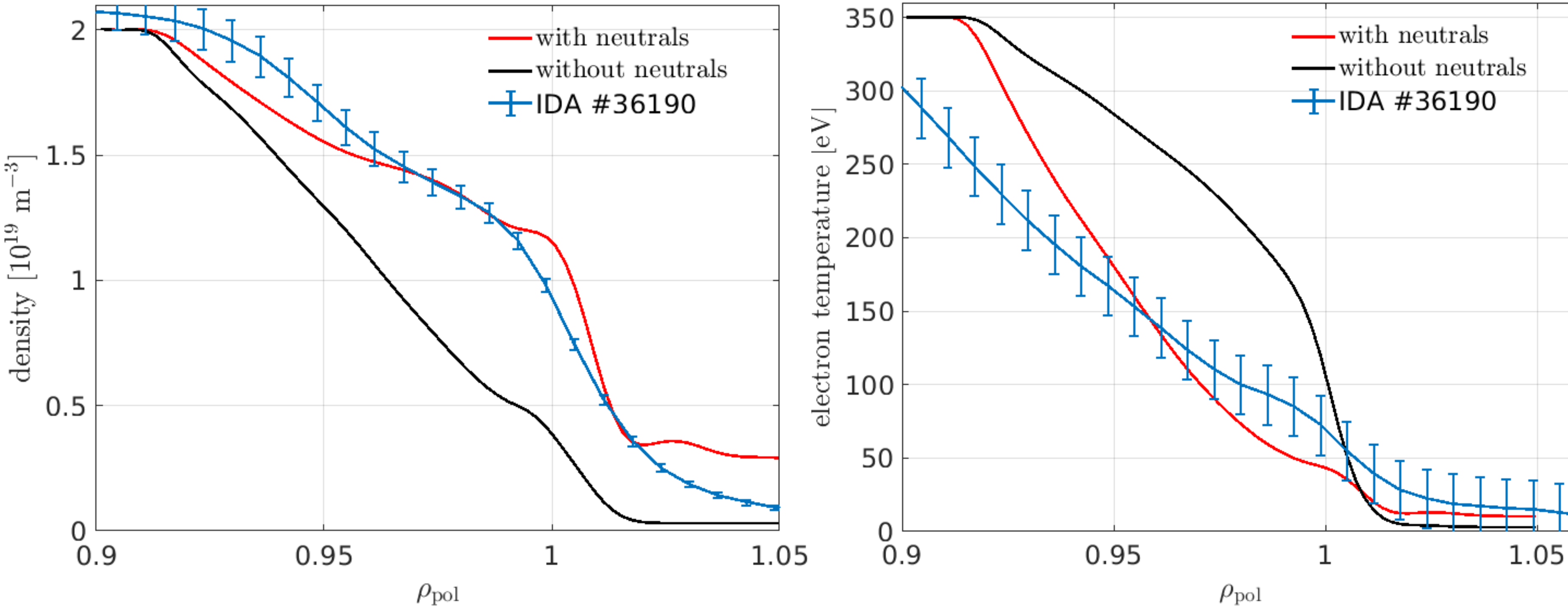


The simulation: density evolution and E_r



Validation driven development (AUG #36190)

outboard mid-plane profiles

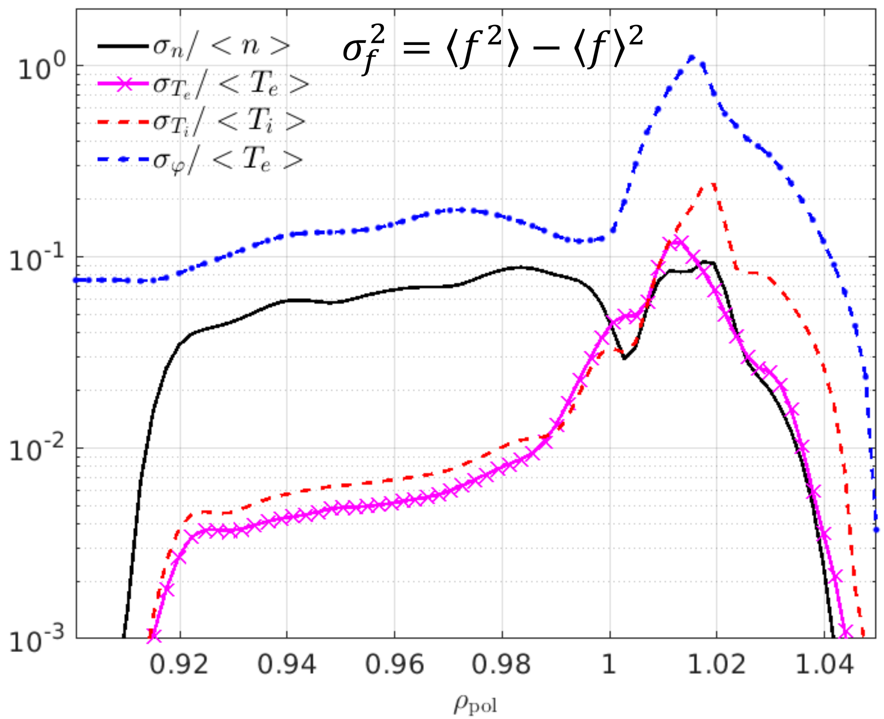


➢ **Neutral gas completely changes the SOL dynamics and edge boundary conditions**

A validation against the TCV tokamak is in preparation by Diego Sales de Oliveira, Thomas Body *et al*

Turbulence characterisation

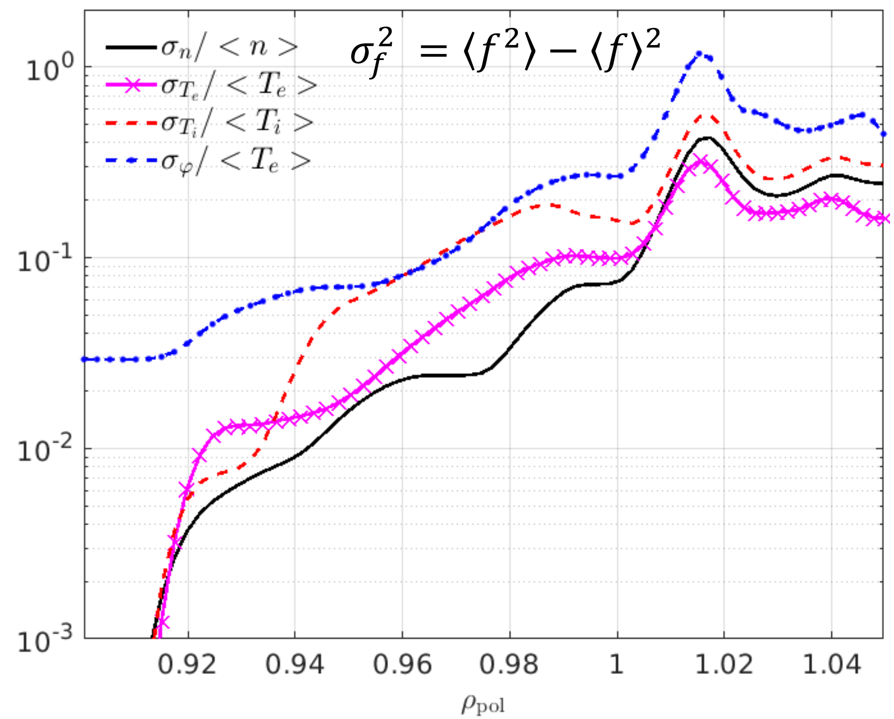
without neutrals (core source)



$$\frac{\sigma_\varphi}{\langle T_\mathrm{e} \rangle} > 2 \frac{\sigma_n}{\langle n \rangle} \gg \frac{\sigma_T}{\langle T \rangle} \quad \Longrightarrow \quad \text{ballooning}$$

$$\chi_\perp^\mathrm{e} = 2/3 D_\perp$$

with neutrals (edge source)

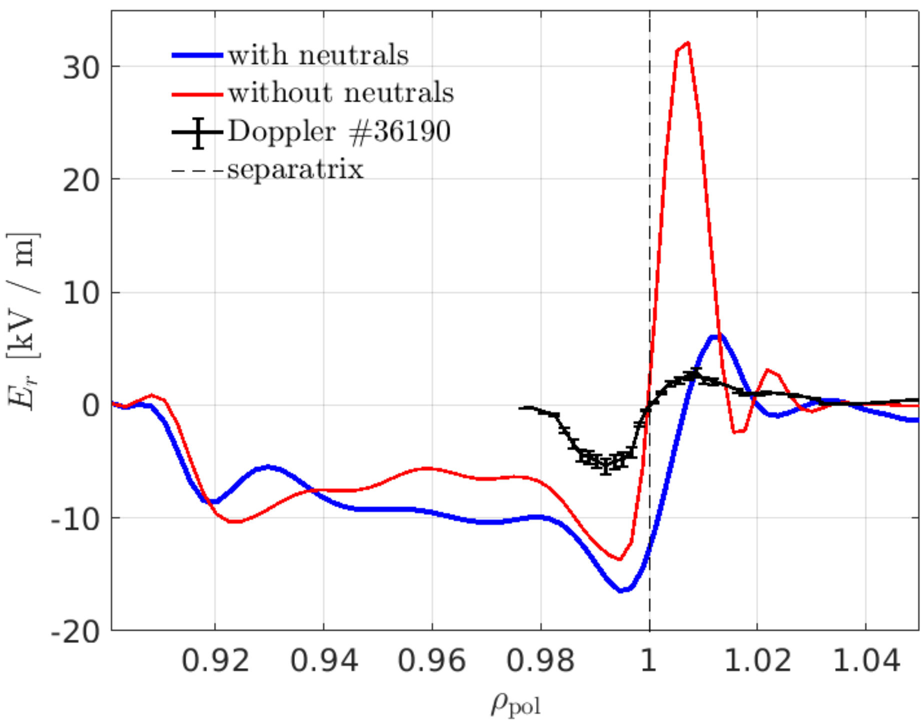


$$\frac{\sigma_\varphi}{\langle T_\mathrm{e} \rangle} \geq \frac{\sigma_{T_\mathrm{i}}}{\langle T_\mathrm{i} \rangle} > \frac{\sigma_{T_\mathrm{e}}}{\langle T_\mathrm{e} \rangle} > \frac{\sigma_n}{\langle n \rangle} \quad \Longrightarrow \quad \textbf{ITG}$$

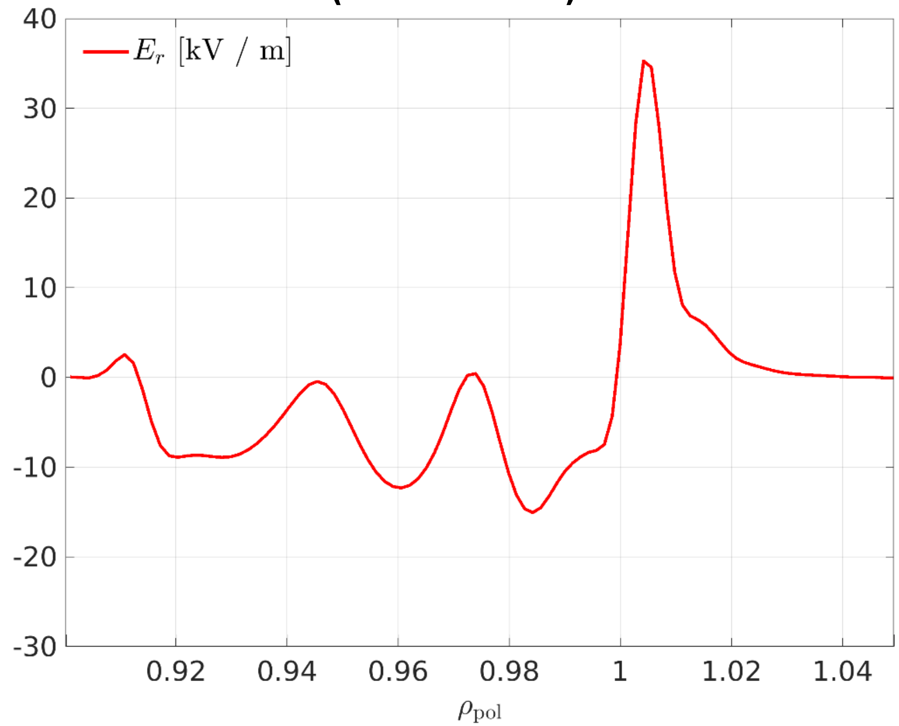
$$\langle D_\perp \rangle \approx 0$$

Radial electric field: validation and physics

validation



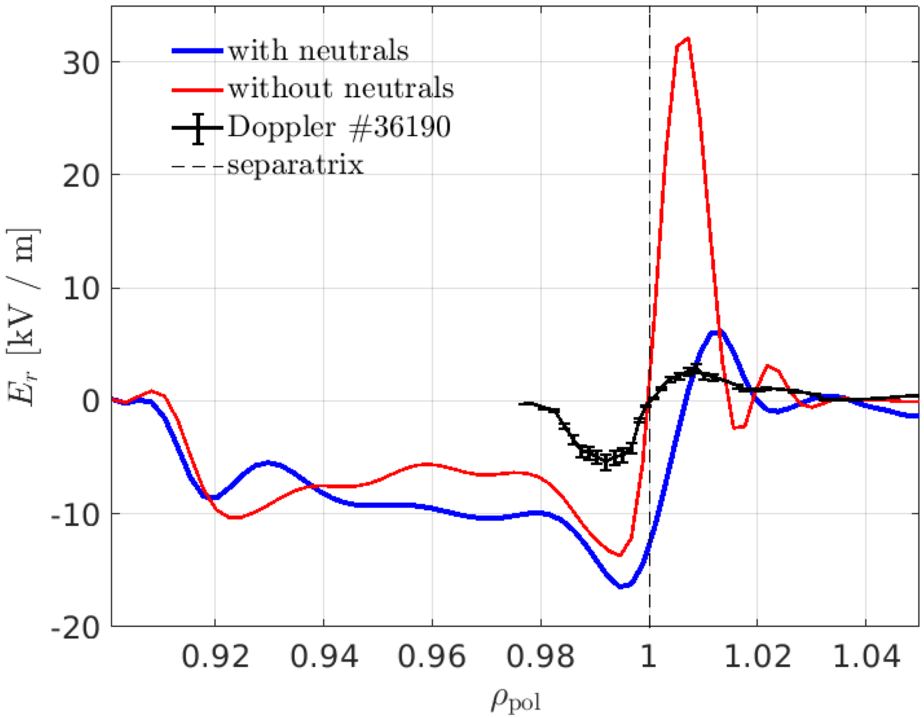
Analysis of contributions (no neutrals)



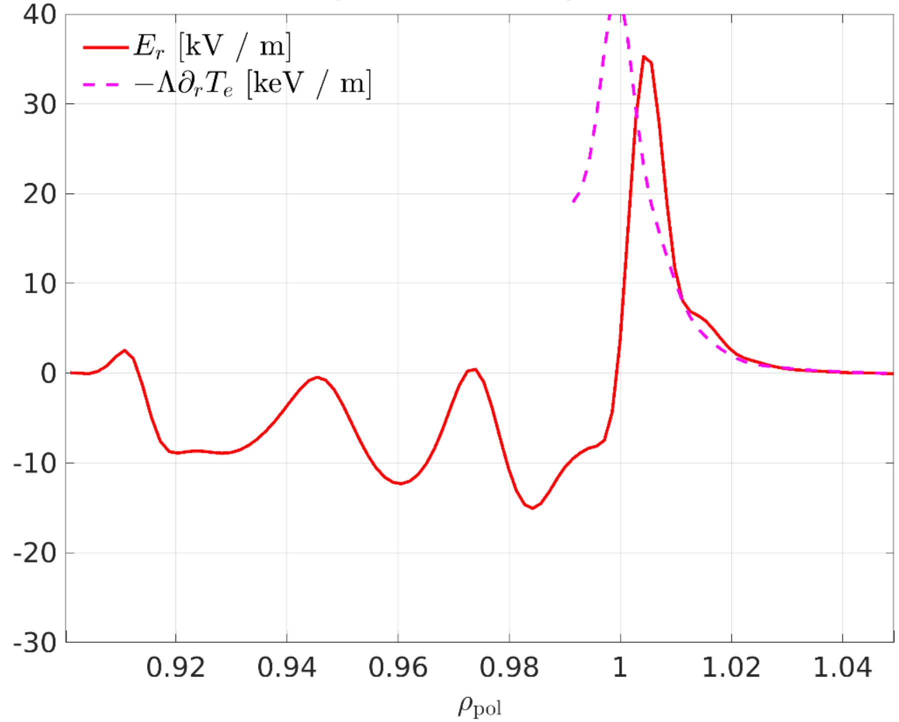
- **right shape, wrong magnitude**
- **Braginskii model inconsistent with neoclassical theory**
- **higher resolution?**

Radial electric field: validation and physics

validation



Analysis of contributions (no neutrals)



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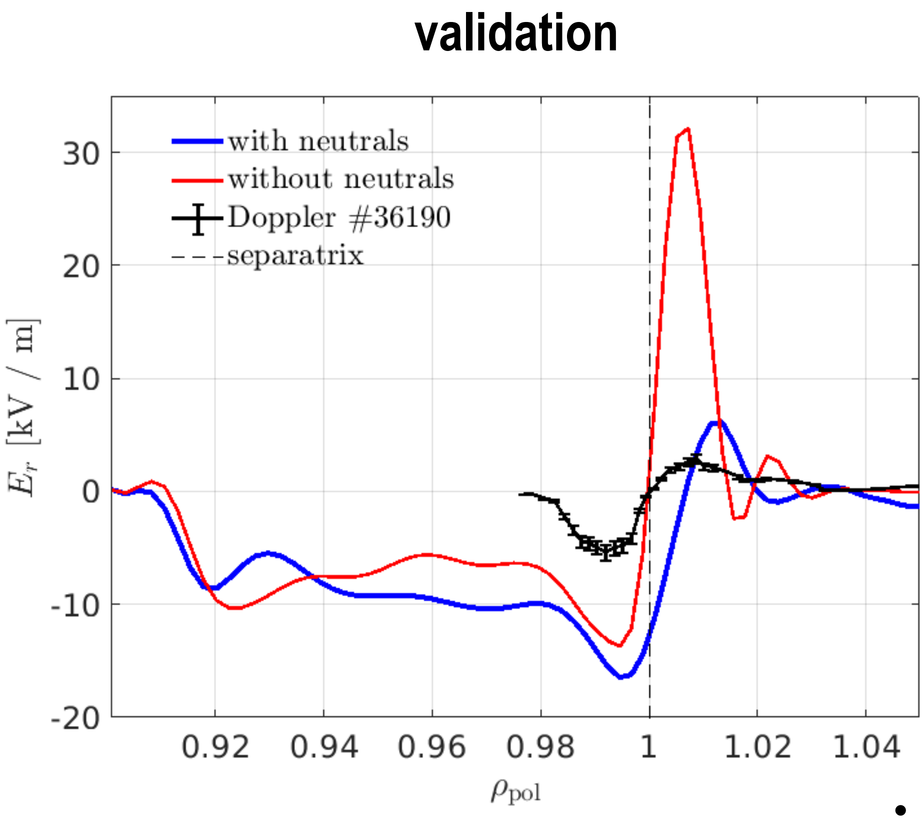
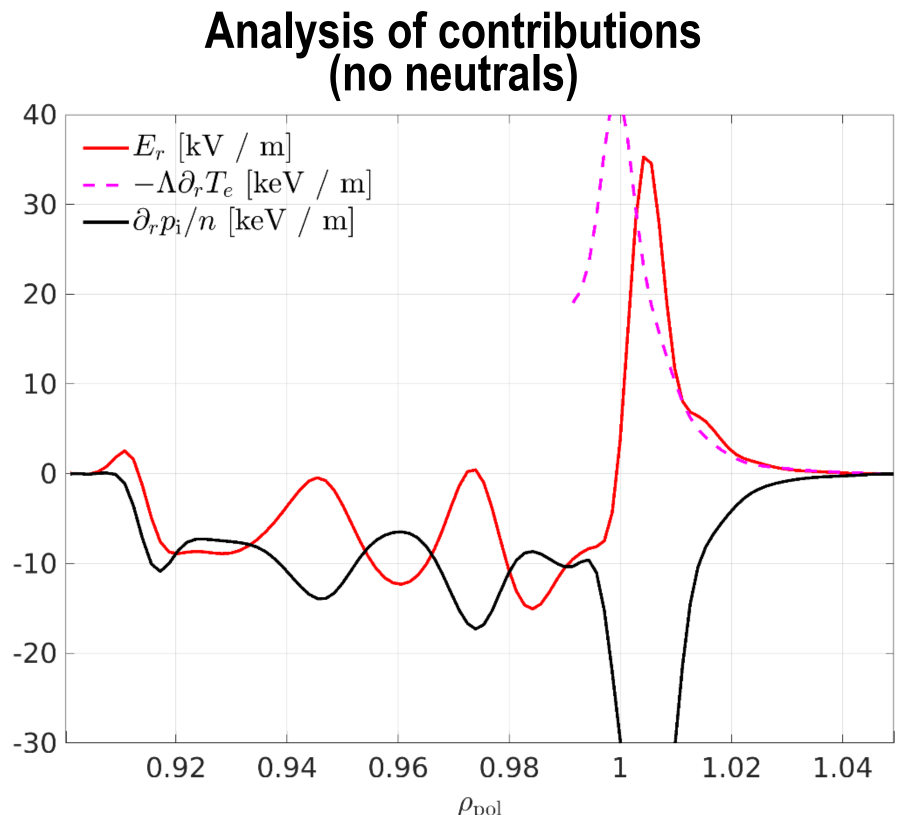
Radial electric field: validation and physics



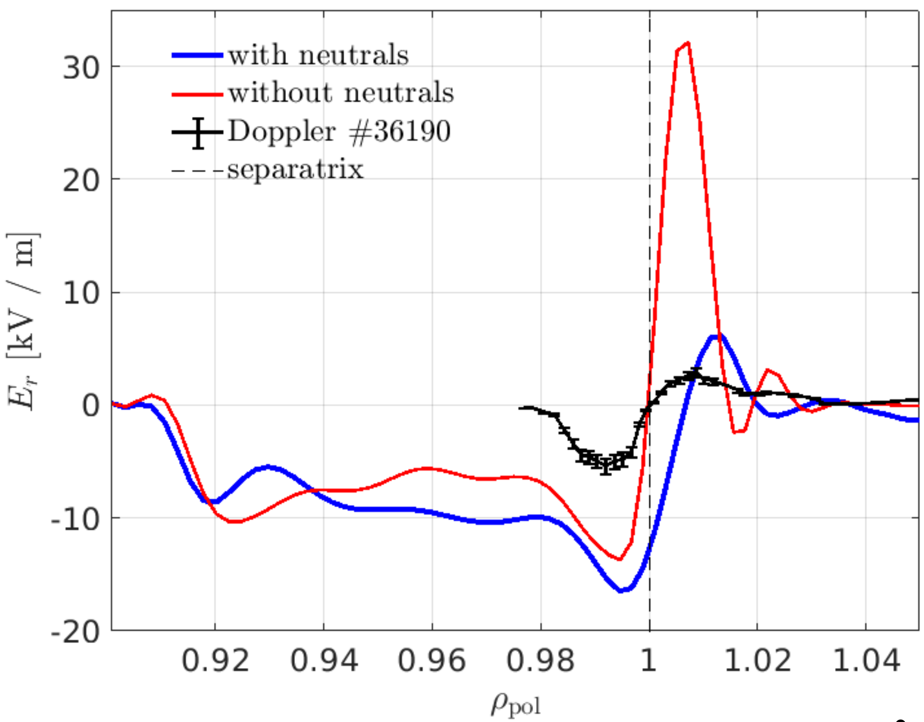


- $\partial_r p_{\mathrm{i}}\ /en$ is the dominant contribution in CR

- right shape, wrong magnitude
- Braginskii model inconsistent with neoclassical theory
- higher resolution?

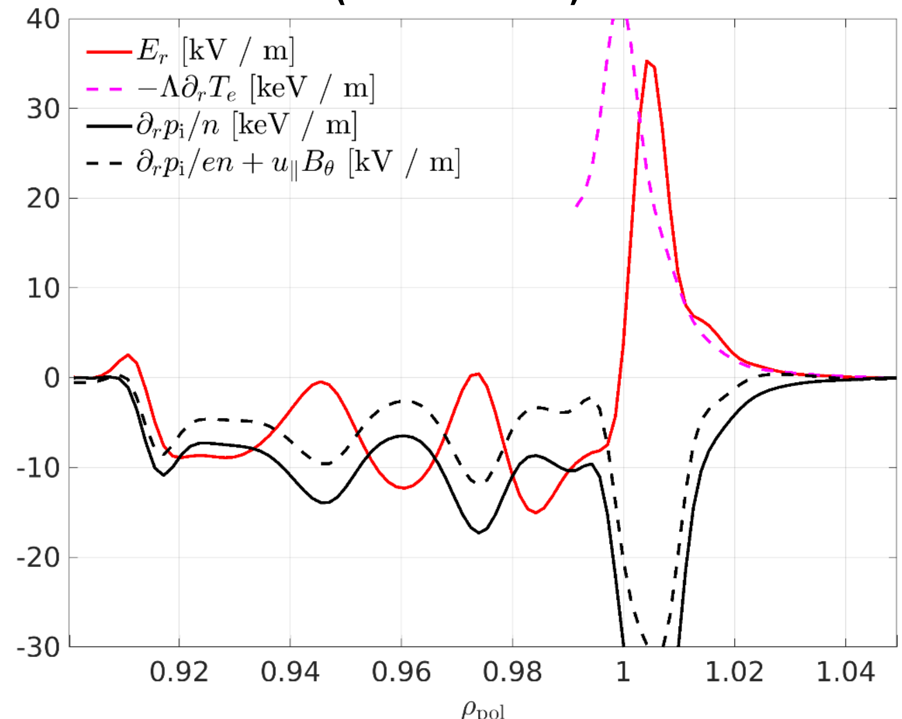
Radial electric field: validation and physics

validation



- ➢ **right shape, wrong magnitude**
- ➢ **Braginskii model inconsistent with neoclassical theory**
- ➢ **higher resolution?**

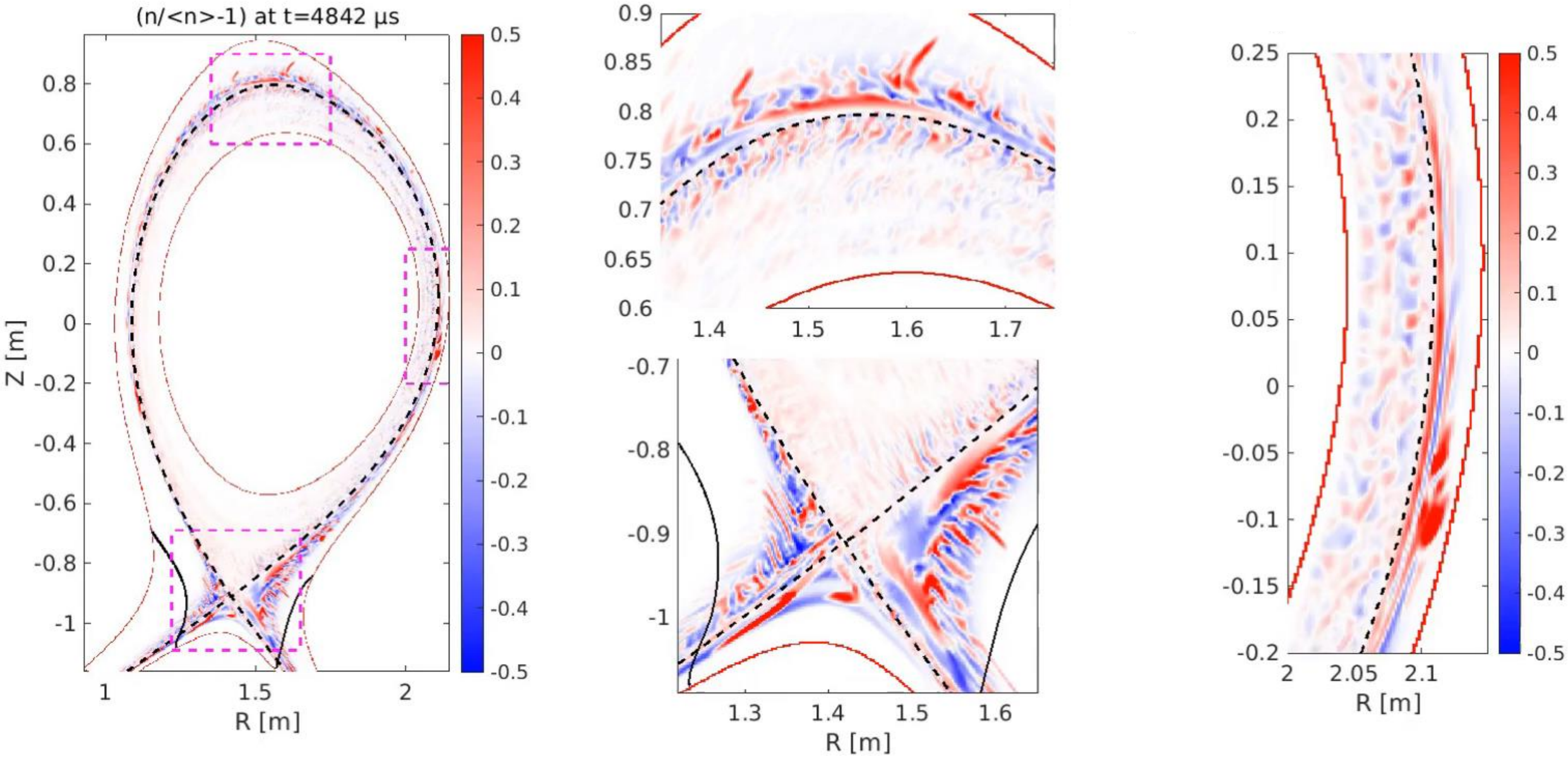
Analysis of contributions (no neutrals)



- $\boldsymbol{\partial_r p_{\mathrm{i}}/en}$ **is the dominant contribution in CR**
- (small) **toroidal rotation (~ 10 km / s)**
- **poloidal rotation** $\langle \mathbf{B}\cdot\nabla\cdot\Pi_{\mathrm{i}}\rangle = 3\eta_{\mathrm{i}}\langle(\nabla_{\|}B)^2\rangle v_\theta = 0$
- **zonal flow** $\langle \mathbf{u}\cdot\nabla\mathbf{u}\rangle$
- $\langle E_r\rangle_t = \left\langle \frac{\partial_r p_{\mathrm{i}}}{en}\right\rangle + \frac{m_{\mathrm{e}}}{e}\langle \mathbf{u}\cdot\nabla\mathbf{u}\rangle\cdot\mathbf{e}_r + \langle u_{\|}B_\theta\rangle$

Turbulence dynamics across the separatrix

simulation without neutrals (core density source)



W Zholobenko *et al* 2021 *Plasma Phys. Control. Fusion* **63** 034001, https://doi.org/10.1088/1361-6587/abd97e, ''Electric field and turbulence in global Braginskii simulations across the ASDEX Upgrade edge and scrape-off layer "

Conclusions and outlook

✓ **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. $\langle E_r \rangle_t^{\mathrm{CR}} = \left\langle \frac{\partial_r p_\mathrm{i}}{en} \right\rangle + \frac{m_\mathrm{e}}{e} \langle \mathbf{u} \cdot \nabla \mathbf{u} \rangle \cdot \mathbf{e}_r + \langle u_\parallel B_\theta \rangle$
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

❖ A lot of work remains **towards predictive, high performance reactor simulations**:

1. Code scalability / speed-up
2. Refining the neutral gas and impurity model
3. Low collisionality and neoclassical corrections to the fluid model

❖ Tackeled in a European effort: see P6 Posters 6 by Patrick Tamain

❖ Gyrokinetic FCI simulations are on their way: Dominik Michels *et al*, accepted by CPC (2021)