MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Tokamak H-mode edge-SOL global turbulence simulations with an electromagnetic, transcollisional drift-fluid model

ASDEX Upgrade

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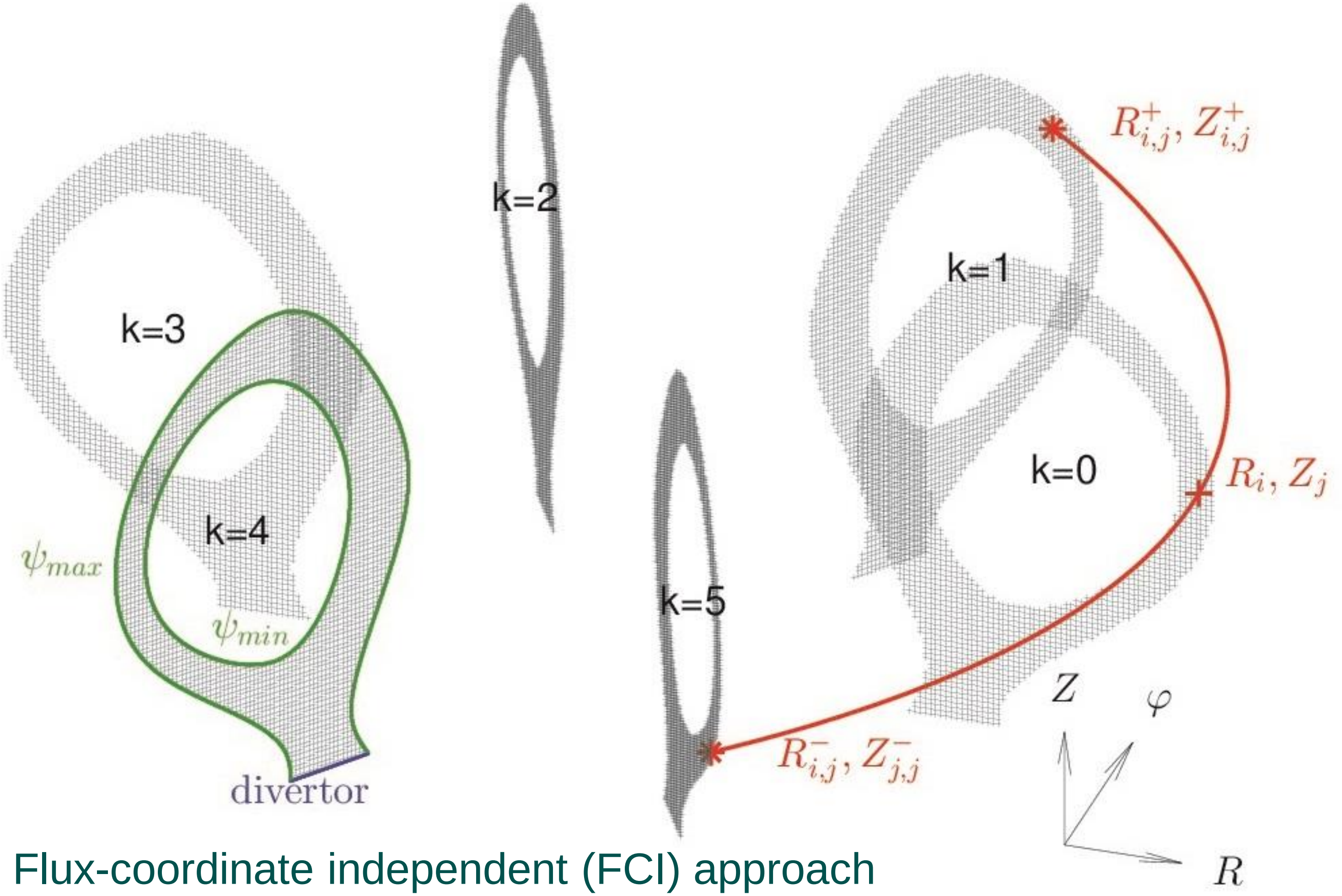
EUROfusion

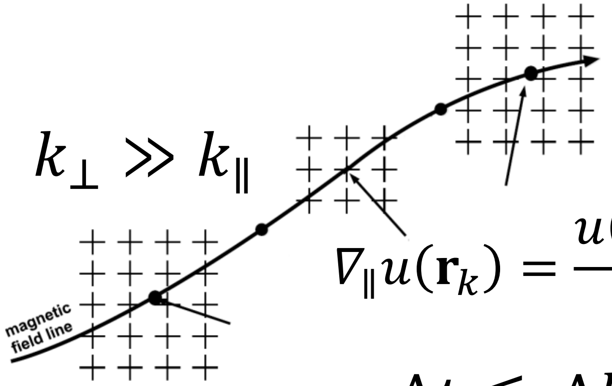
Overview

- **What is GRILLIX**
- H-mode simulations of ASDEX Upgrade
- The radial electric field
- Electromagnetic, transcollisional, global drift-fluid model
- Transport characterisation
- A first L-H transition power scan
- Conclusions

GRILLIX : locally field-aligned discretization

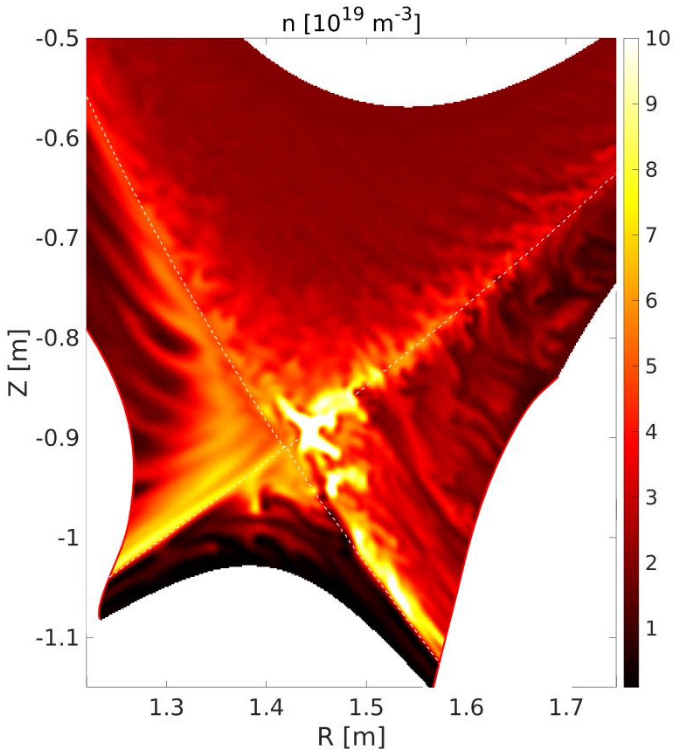


$$k_\perp \gg k_\parallel$$



$$\nabla_\parallel u(\mathbf{r}_k) = \frac{u(\mathbf{r}_{k+1}) - u(\mathbf{r}_{k-1})}{2\Delta l}$$

$$\Delta t \lesssim \Delta l / v_A$$



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)

Drift-fluid equations with diffusive neutrals

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

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

Drift reduction:

$$\mathbf{v}_{e\perp} = \mathbf{v}_E + \mathbf{v}_*^e \qquad \mathbf{v}_E = (\mathbf{B} \times \nabla\varphi)/B^2$$

$$\mathbf{v}_{i\perp} = \mathbf{v}_E + \mathbf{v}_*^i + \mathbf{u}_{pol} \qquad \mathbf{v}_*^{e,i} = \mp(\mathbf{B} \times \nabla p_{e,i})/enB^2$$

$$\mathbf{u}_{pol} = \frac{m_i}{eB^2}\mathbf{B} \times \left(\frac{\partial}{\partial t} + \mathbf{v}_E \cdot \nabla\right)(\mathbf{v}_E + \mathbf{v}_*^i)$$

electromagnetic parallel dynamics

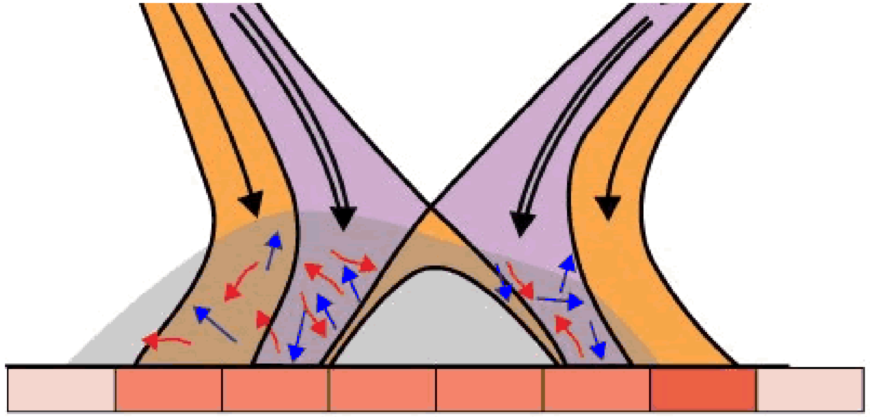
$$\mathbf{E} = -\nabla\varphi - \partial_t A_\parallel \mathbf{b}, \qquad \mathbf{B} = \mathbf{B_0} + \nabla \times A_\parallel \mathbf{b}, \qquad B \approx B_0$$

electron heat

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

ion heat

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



Diffusive neutrals:

$$\frac{\partial}{\partial t}N = \nabla \cdot \frac{1}{nk_{\mathrm{cx}}}\nabla N T_{\mathrm{i}} - k_{\mathrm{iz}}nN + k_{\mathrm{rec}}n^2,$$

N fixed at the divertor.

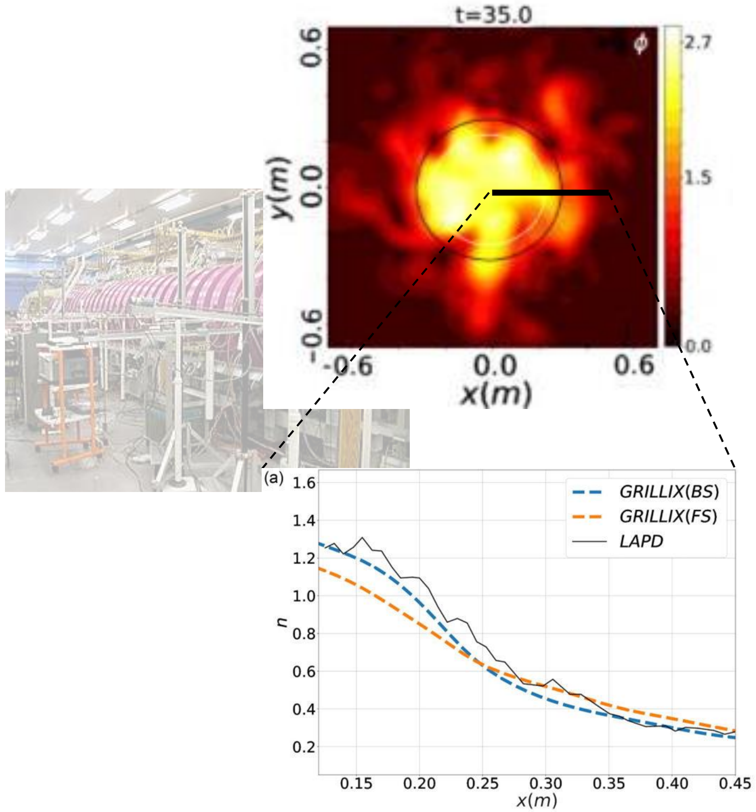
From validation…

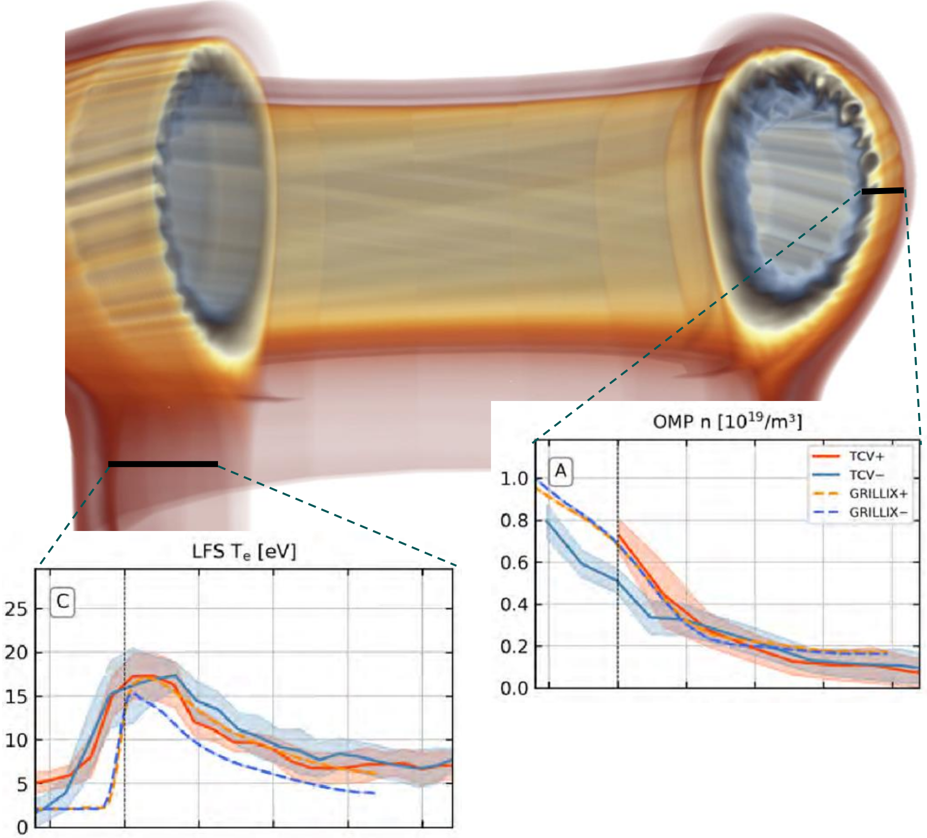
LAPD: 200

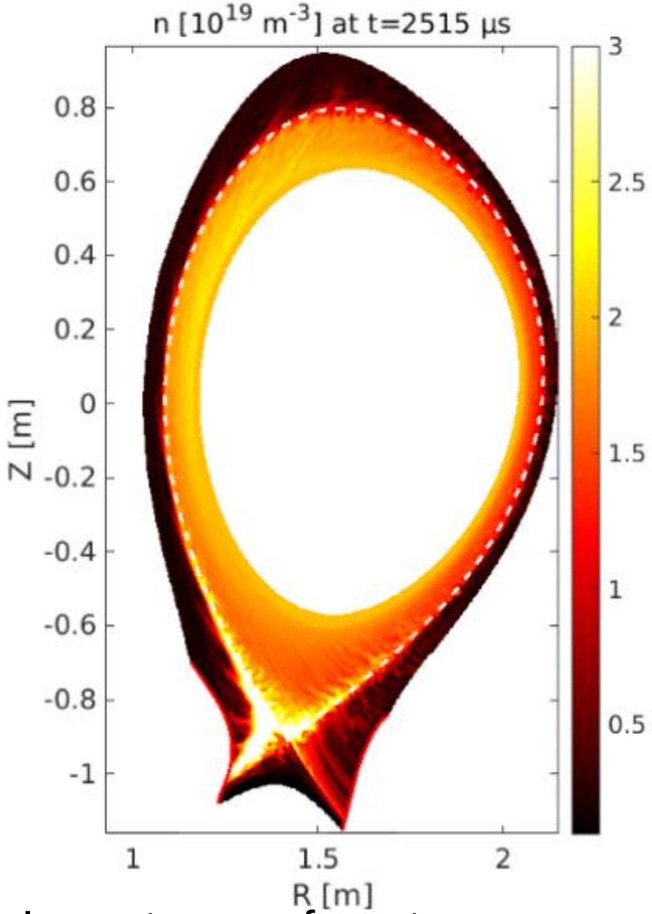
TCV-X21: 900

AUG: 2850

R_0 / ρ_s







- Simple geometry
- cold ions

[A. Ross *et al* 2019 PoP **26** 102308]

- Rigorous validation in diverted geometry for GRILLIX, GBS and TOKAM3X
- Extensive and open experimental dataset

[D.S. de Oliveira, T. Body *et al* 2022 *Nucl. Fusion* in press]

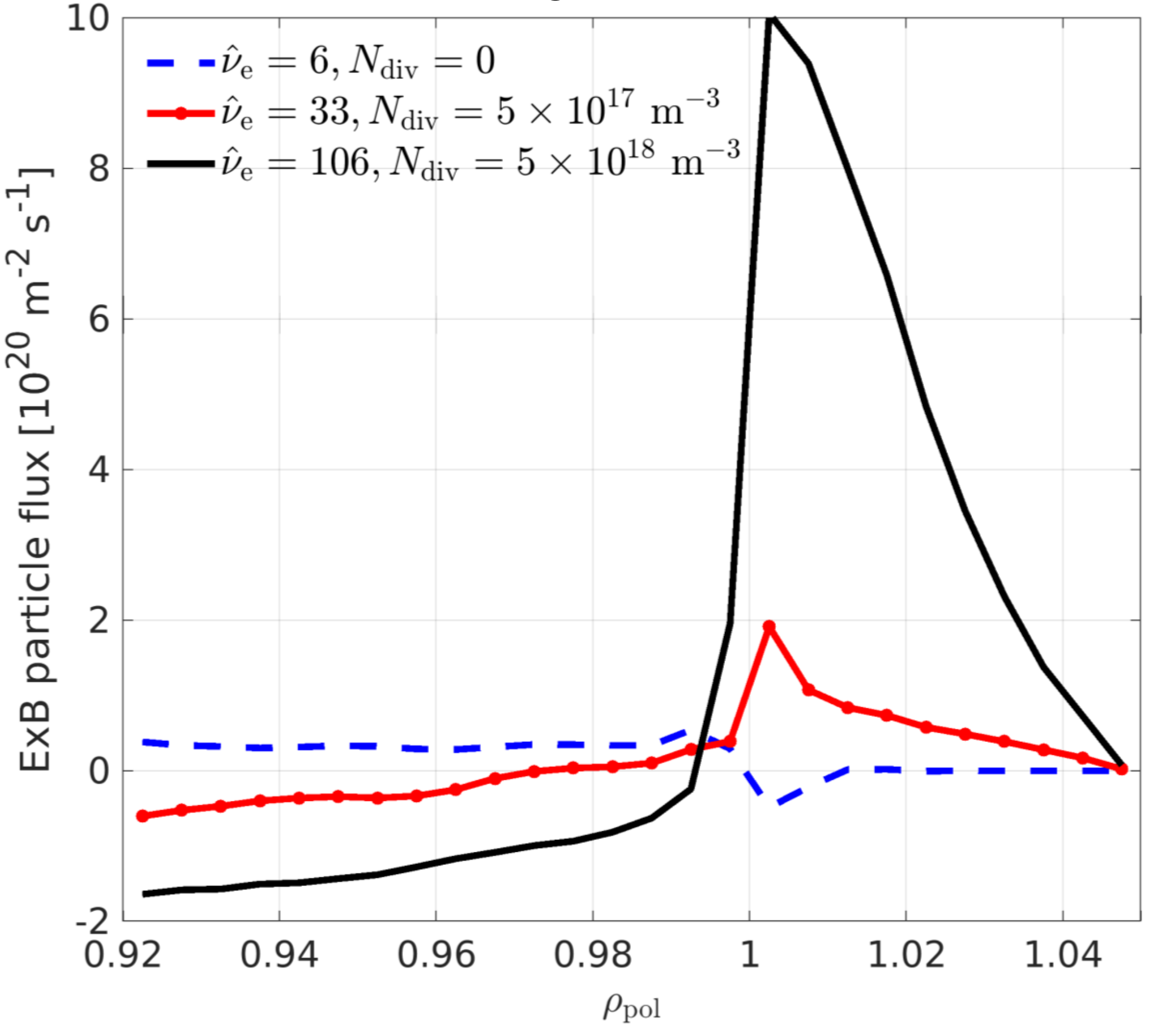
- Importance of neutras
- Formation of radial electric field

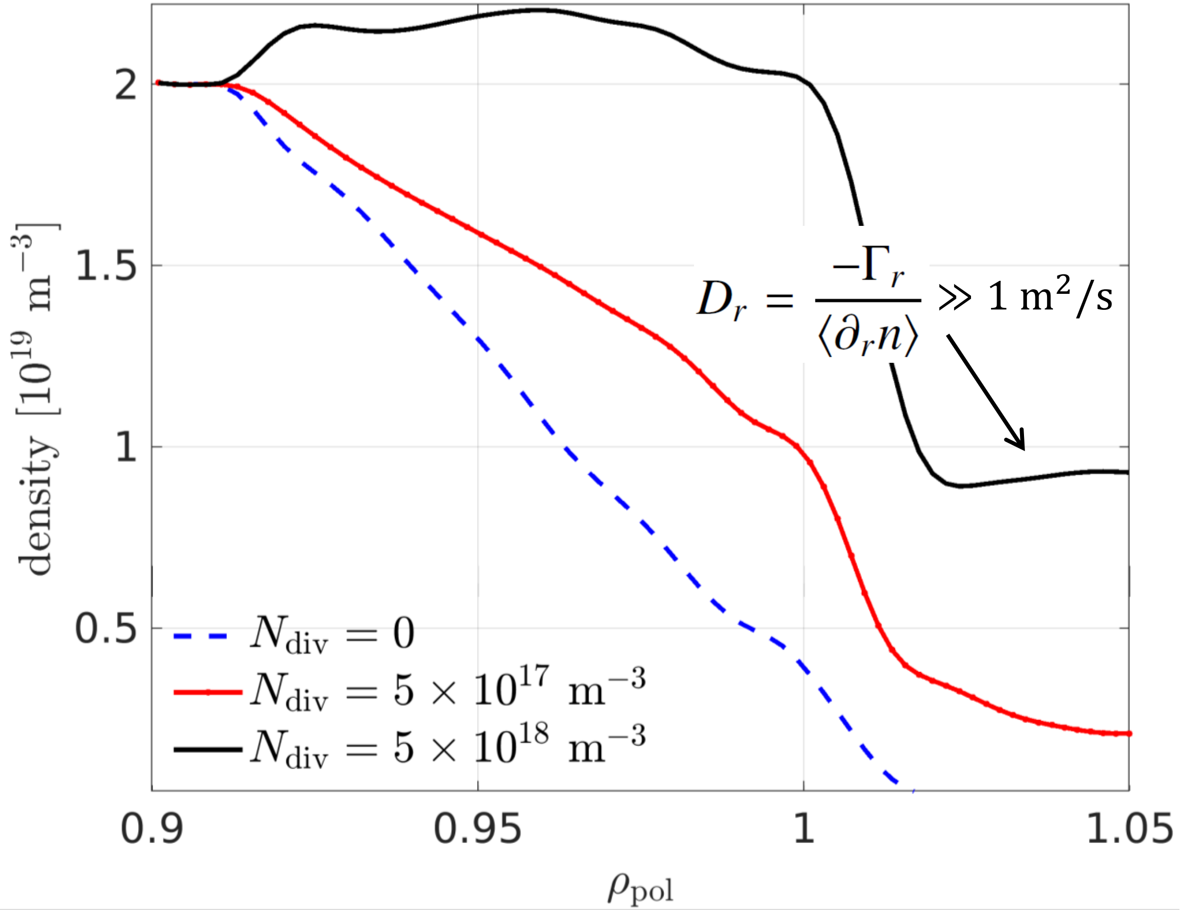
[W. Zholobenko *et al* 2021 NF **61** 116015]

Mean $E \times B$ particle flux at different SOL collisionalities

$$\Gamma_r = \langle \mathbf{v}_E \cdot \mathbf{e}_r n \rangle \qquad \hat{\nu}_e^{sep} = \frac{R_0}{c_{s,e}\tau_e} \approx 5.4 \times 10^{-15} \frac{R_0 n/\mathrm{m}^{-2}}{(T_e/eV)^2} \in (6, 33, 106)$$

flux-surface averaged



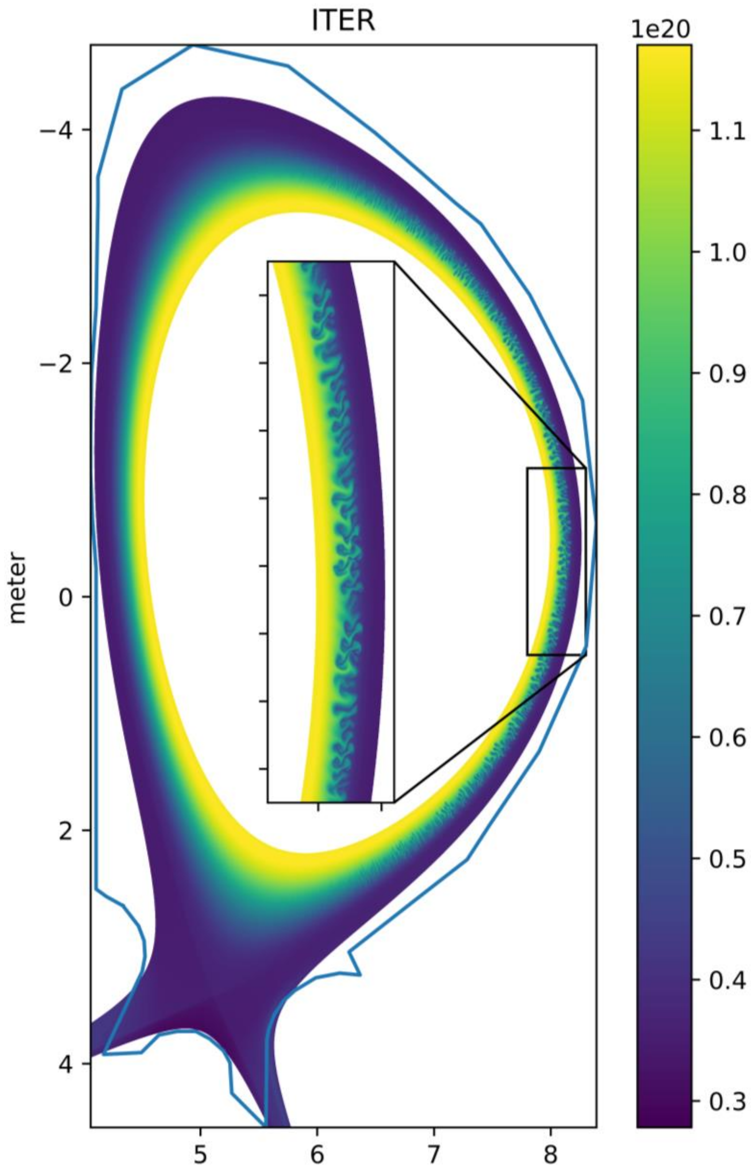


W. Zholobenko *et al.*,
Nucl. Mater. Energy **34**, 101351 (2023)

From validation … to prediction!

R_0 / ρ_s

ITER: 16000



Our goal: predictions for ITER and DEMO!

But first, we need to be able to do:

- Improved confinement (H-mode etc.)
- Detachment (X-point radiator)
- Make reactor scale runs affordable

<u>This talk: H-mode.</u>

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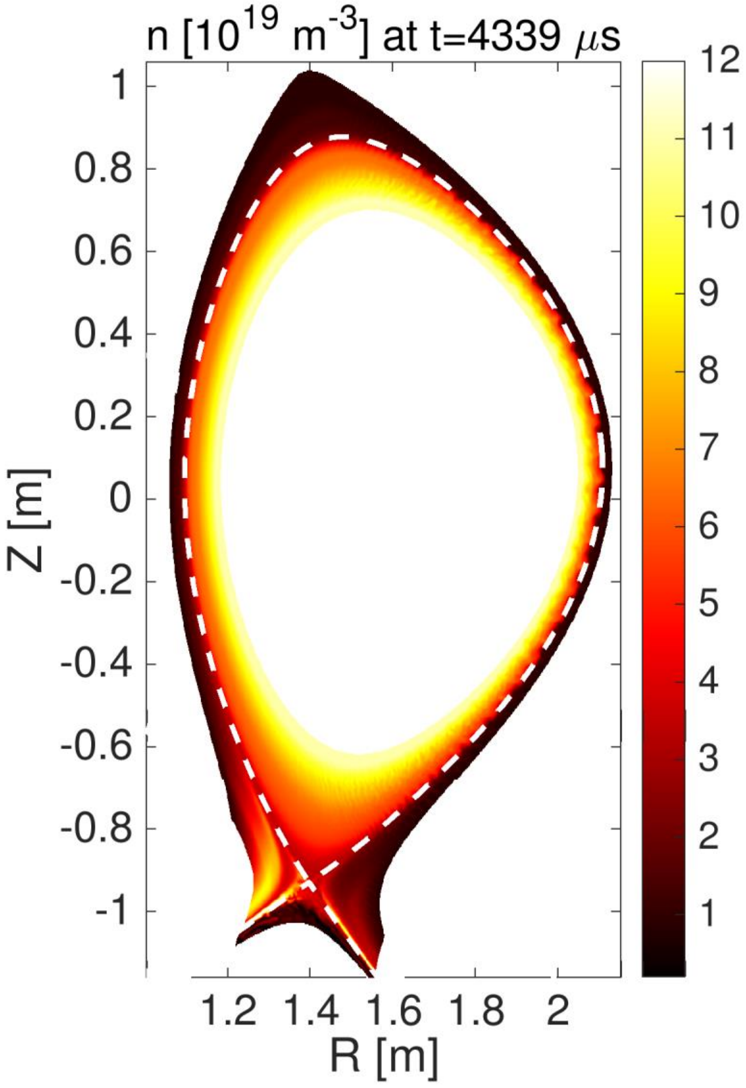
ITER baseline attached type I ELMy H-mode #40411 @ 2.64 s

Decent diagnostics coverage

$B_{\text{tor}} = -1.9$ T,
$I_p = 1.1$ MA,
$q_{95} = 3.3$,
$\kappa = 1.76$,
$\delta = 0.36$ (close to DN),
$Z_{\text{eff}} < 1.5$

Heating:
+1.2 MW - Ohmic,
+4.5 MW - NBI,
+2.4 MW - ICRH,
- 2.5 MW - radiation,
- 0.8 MW - ELMs

= 4.8 MW transport



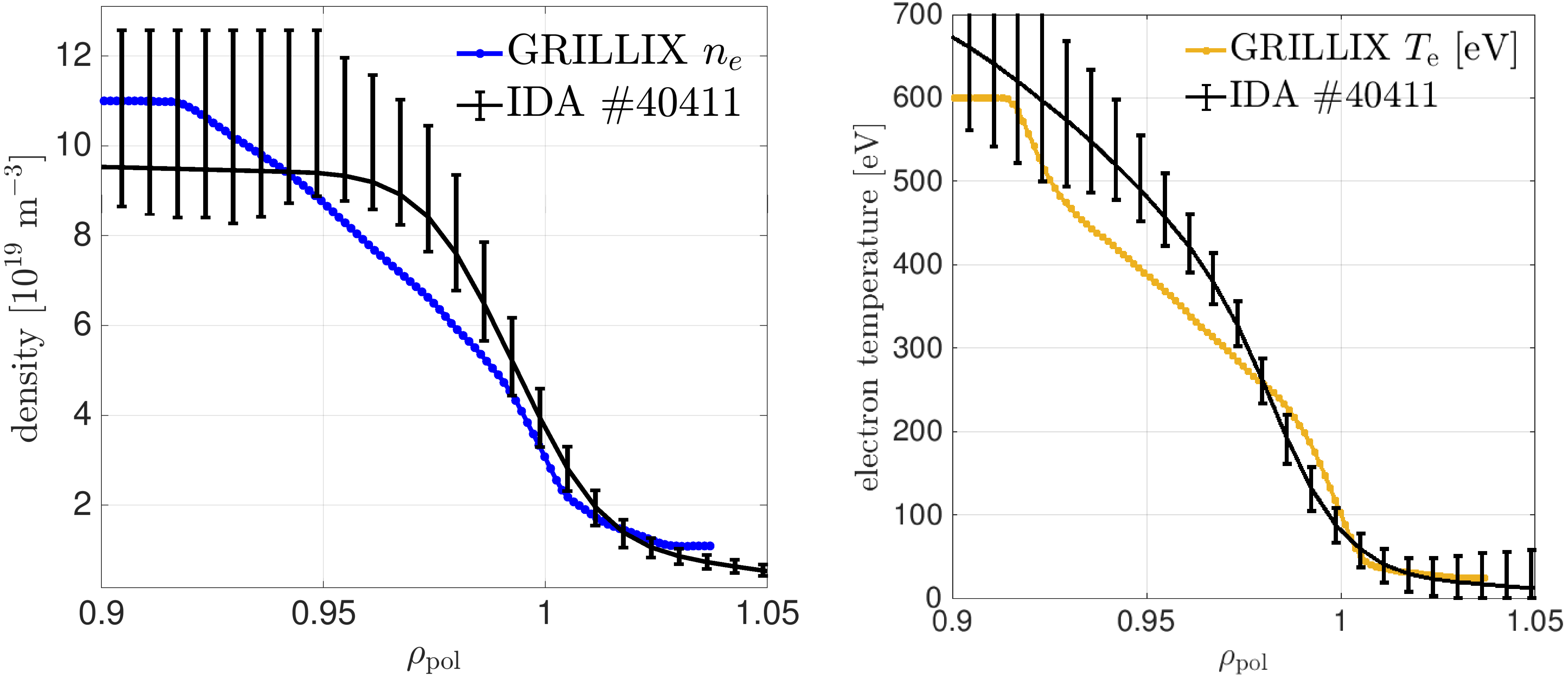
Resolution and type of a run	P_e	P_i
16 planes, $h = 1.9\ \rho_{s0}$, FS	1.6 MW	1 MW
16 planes, $h = 1.9\ \rho_{s0}$, LF	1.5 MW	1.3 MW
32 planes, $h = 1.9\ \rho_{s0}$, FS	1.7 MW	1.2 MW
16 planes, $h = 1.0\ \rho_{s0}$, FS	0.8 MW	0.9 MW
32 planes, $h = 1.0\ \rho_{s0}$, FS	0.7 MW	1.3 MW

$h = 1\rho_{s0} = 0.76$ mm → 42 million grid points

→ 54 days on 768 CPUs

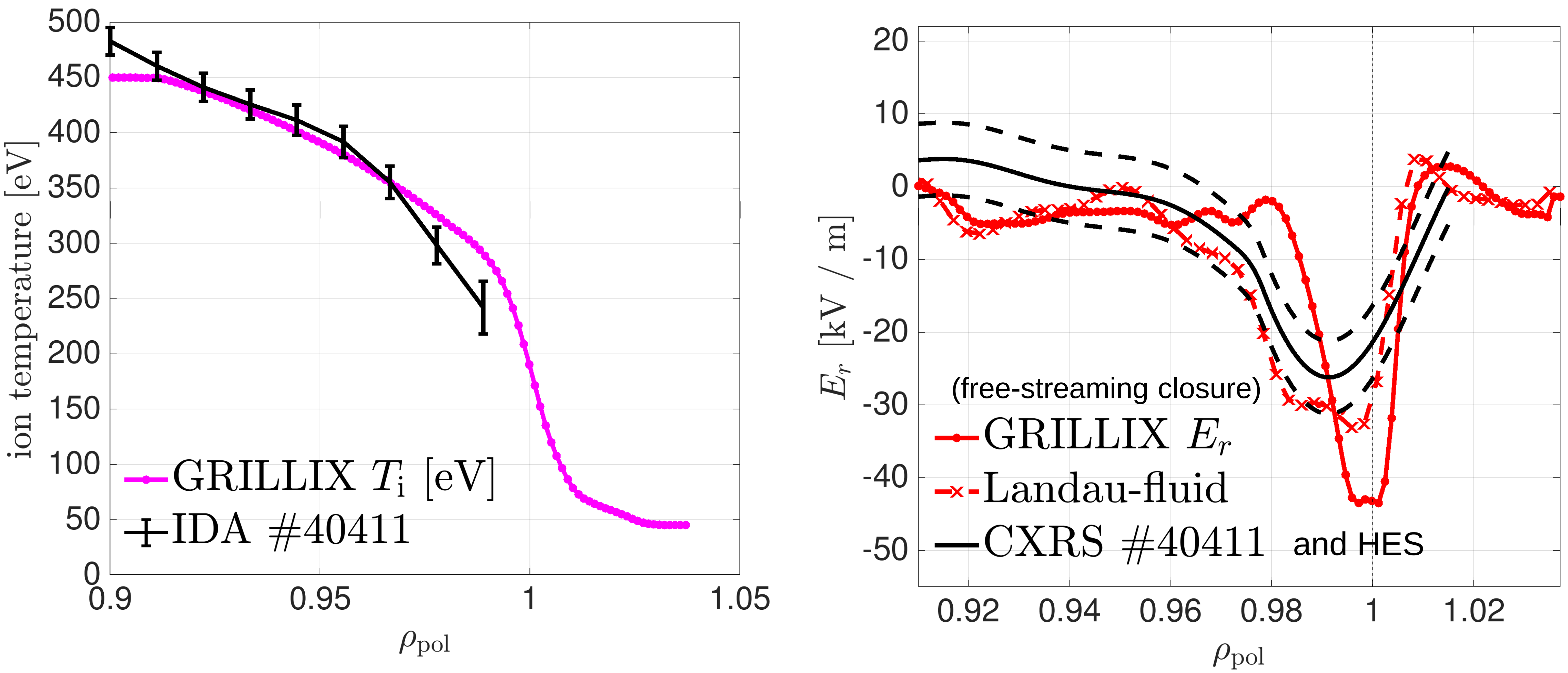
16 planes, $h = 1.9\ \rho_{s0}$ can run in a week!

Outboard mid-plane profiles: density and electron temperature



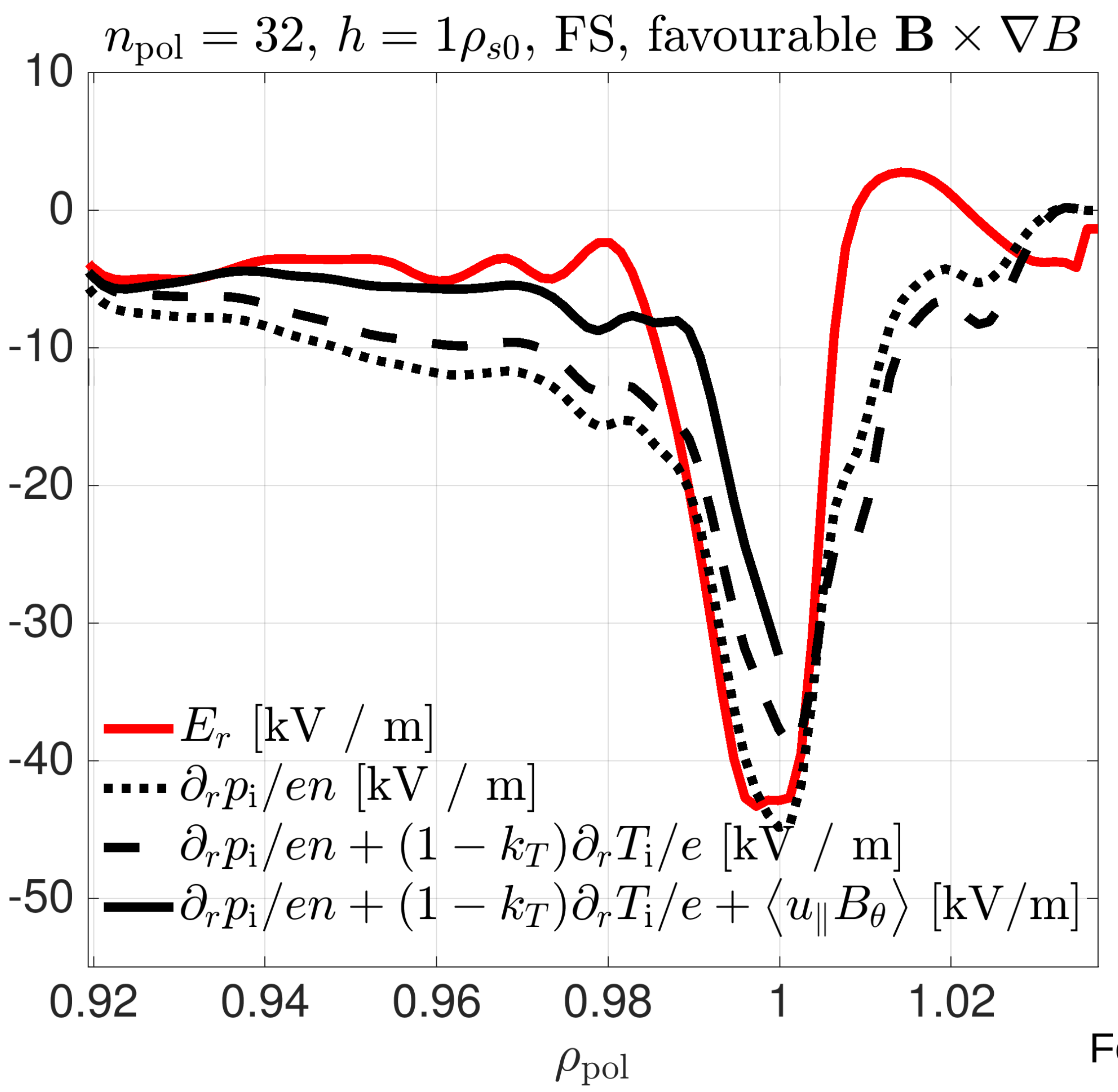
- Satisfactory agreement for electron density and temperature
- At the core, boundary conditions are prescribed, and experimental data are poor – don‘t judge too much
- Shown here only for the highest resolution case, little difference for T_e, n_e improves by up to 2 with resolution

Outboard mid-plane profiles: ion temperature and radial electric field



- Satisfactory agreement for ion temperature
- E_r reasonably matched, particularly with Landau-fluid model (explained below)

Radial electric field composition



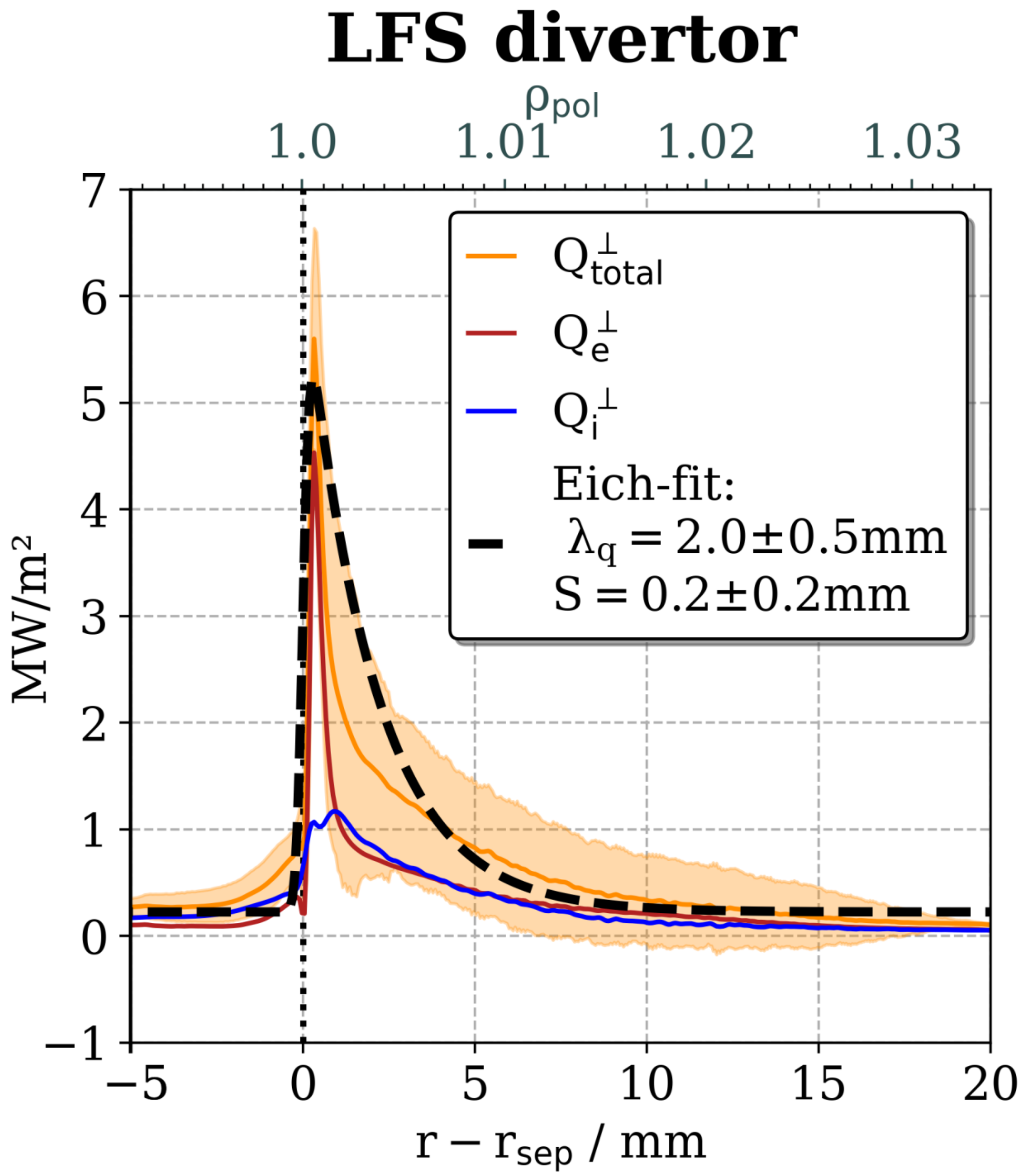
- $E_r \approx \frac{\partial_r p_{\rm i}}{\rm en}$ works very well for the well depth
- But, this is not "neoclassical E_r"!
- Neither poloidal nor toroidal rotation are negligible – they are balanced by the zonal flow!

$$\bar{E}_r \approx \frac{\partial_r \bar{p}_{\rm i}}{e\bar{n}} + (k_T - 1)\frac{1}{e}\partial_r \bar{T}_{\rm i} + \langle u_\parallel B_\theta \rangle_{t,\theta,\phi} + \frac{m_{\rm i}}{\rm e}\langle \mathbf{u} \cdot \nabla \mathbf{u} \rangle_t \cdot \mathbf{e}_r$$

- No geodesic acoustic modes (GAMs)!

For the mechanisms, see W Zholobenko et al 2021 Plasma Phys. Control. Fusion 63 034001

Divertor heat load



- Very small broadening S ≈ 0.2 mm
- Up to 100% fluctuation amplitude
- Total heat flux has double-exponential structure: more narrow in the near-SOL (≈1 mm) and wider in far-SOL (> 2.5 mm), particularly for ions
- Overall comparable to Eich scaling ($B_{\mathrm{pol,MP}} \approx 0.4$ T), no good IR data available for this discharge

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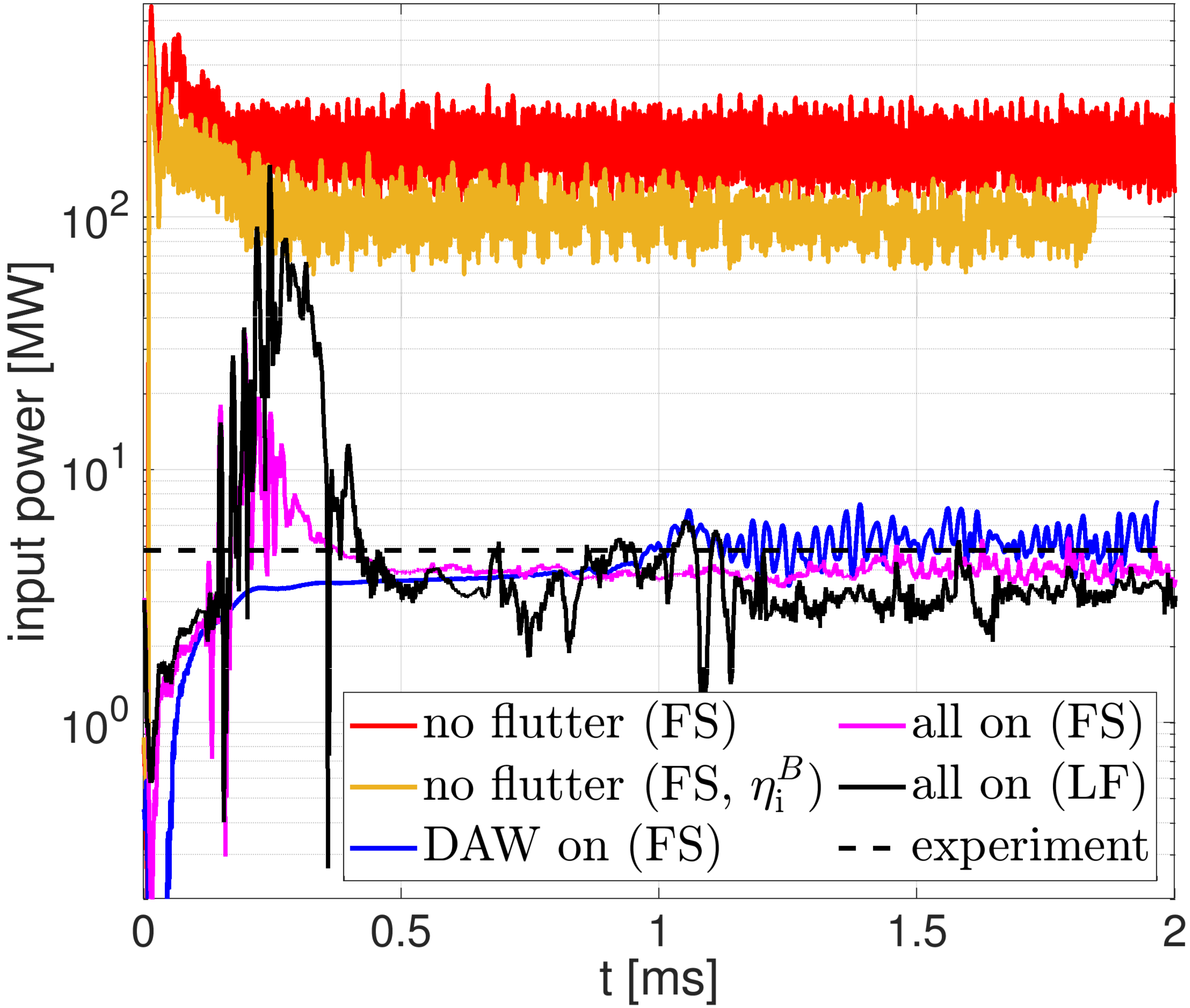
Drift-wave stabilisation by magnetic fluctuations



$$E_\parallel = -\nabla_\parallel \varphi - \partial_t A_\parallel$$

$$\partial_t A_\parallel \sim -\nabla_\parallel \varphi + \frac{1}{en} \nabla_\parallel p_e$$ ⟵ **induction**

$$\tilde{\mathbf{B}} = \nabla \times (A_\parallel \mathbf{b}_0)$$ ⟵ **flutter**

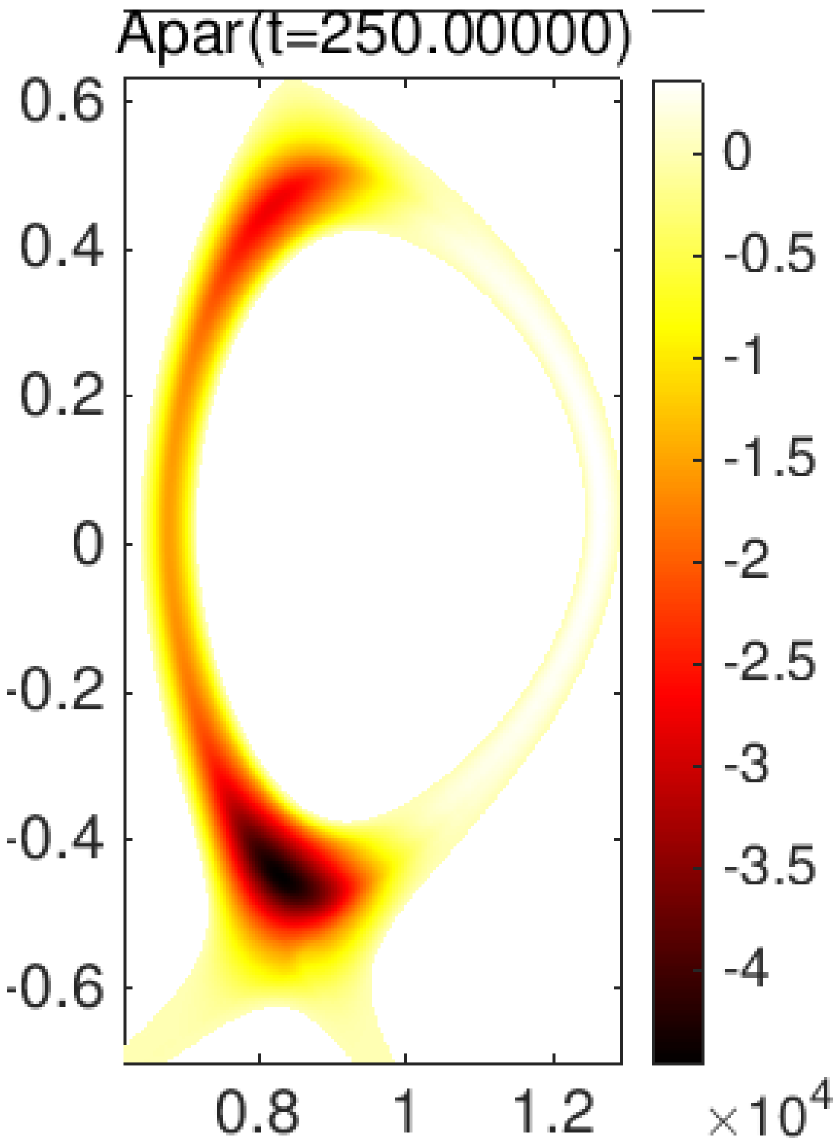
$$\nabla_\parallel = (\mathbf{b}_0 + \tilde{\mathbf{B}}/B_0) \cdot \nabla$$

In L-mode, flutter makes a factor ~2 difference:
Kaiyu Zhang et al 2024 Nucl. Fusion 64 036016

In H-mode, it makes 2 orders of magnitude!

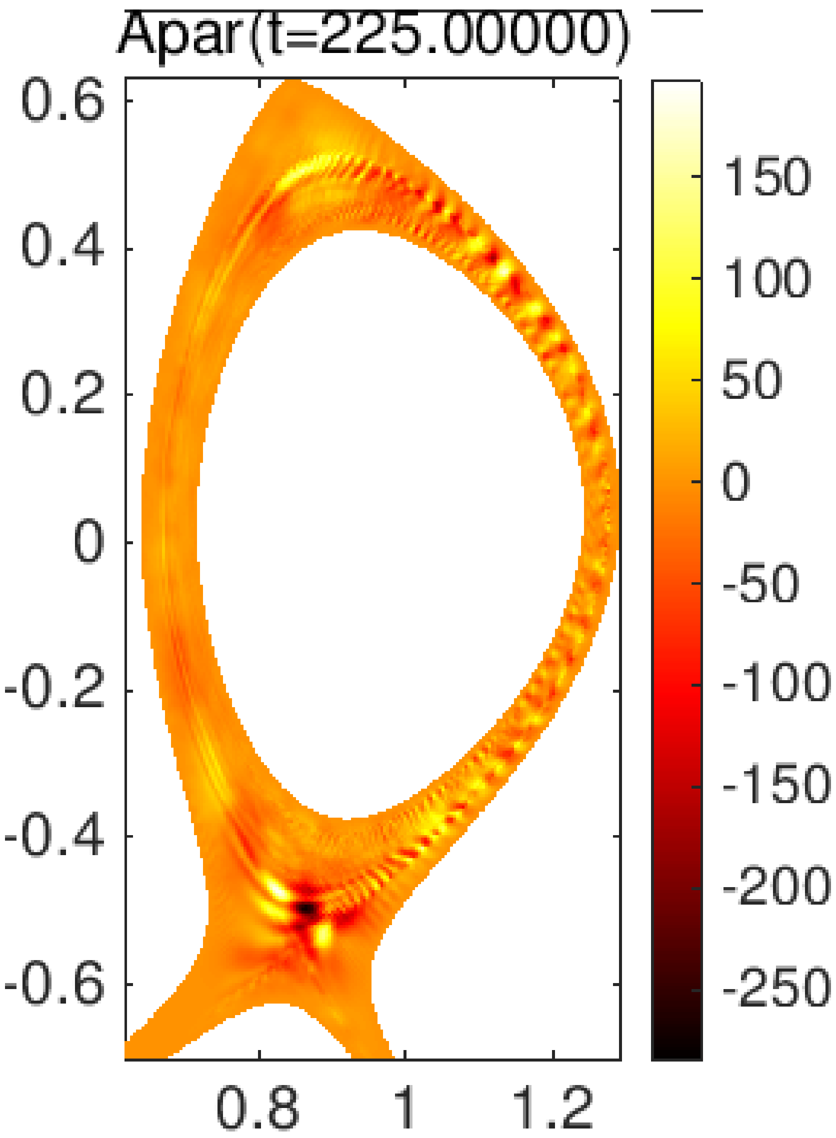
Numerical treatment of the Shafranov shift

$B_1/B_0 \sim 10^{-2}$



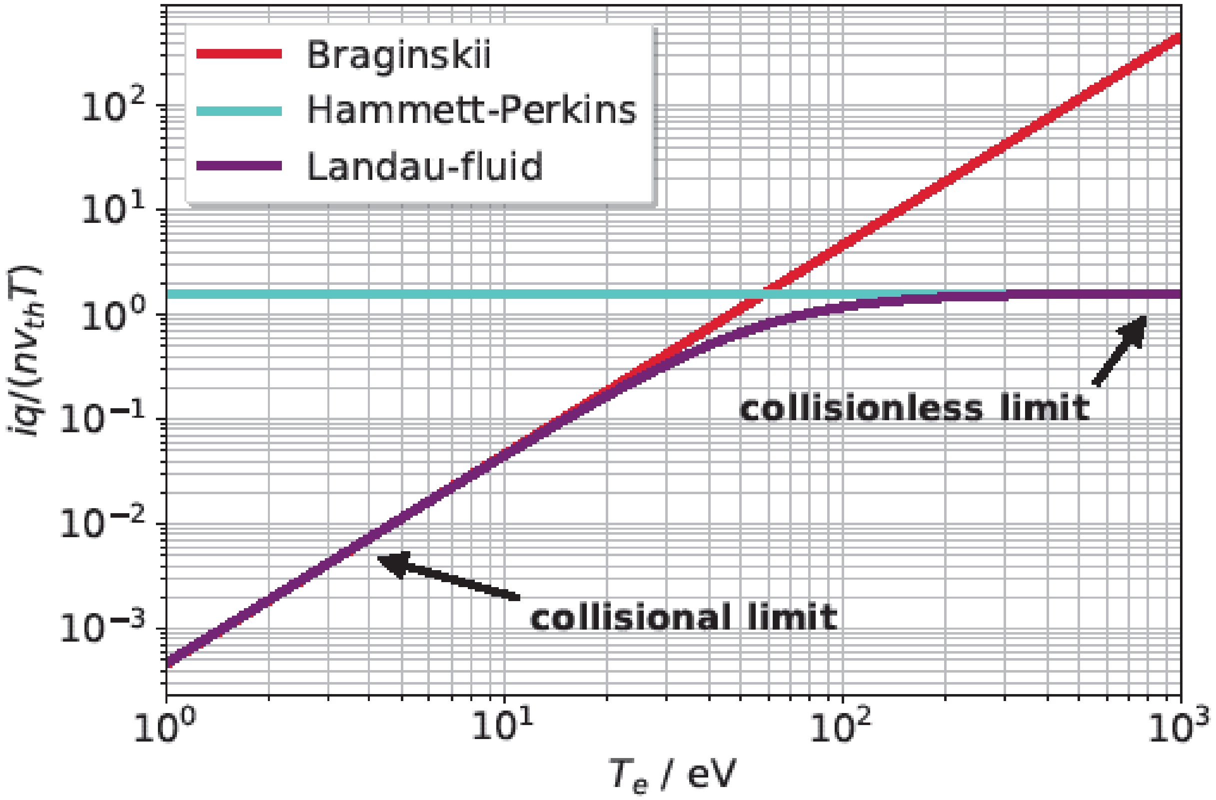
- Locally field-aligned numerics in GRILLIX (and GENE-X) require strong background field B_0, and allow only small perturbations $B_1/B_0 < h/\Delta s \sim \rho_\mathrm{i}/\mathrm{R}_0$
- Global full-*f* models evolve the full plasma pressure, which leads to Pfirsch-Schlüter (and bootstrap) currents and a Shafranov shift
- The Shafranov shift must be removed from parallel operators, it is included in the equilibrium

$B_1/B_0 \sim 10^{-3}$



Landau damping

- Our fluid model requires a closure for the parallel heat flux.
- The Braginskii closure divergence at low collisionality.
- The limiting factor becomes Landau damping.



$$\frac{\partial T}{\partial t} \sim -\frac{1}{n}\nabla\cdot(q_\parallel \mathbf{b})$$

Braginskii: $q_\parallel^B = -\chi_\parallel \nabla_\parallel T$

$$q_{\parallel k}^{\mathrm{LF}} = -A\frac{ik_\parallel}{|k_\parallel| + \delta_j \nu_{\mathrm{e,i}}/v_{\mathrm{th}}}T_k$$

$$\approx -\chi_\parallel^{\mathrm{e,i}}\left(1 + \frac{\chi_\parallel^{\mathrm{e,i}}}{f_{\mathrm{e,i}}^{\mathrm{FS}} n\sqrt{T_{\mathrm{e,i}}/m_{\mathrm{e,i}}}Rq}\right)^{-1}\nabla_\parallel T_{\mathrm{e,i}}$$

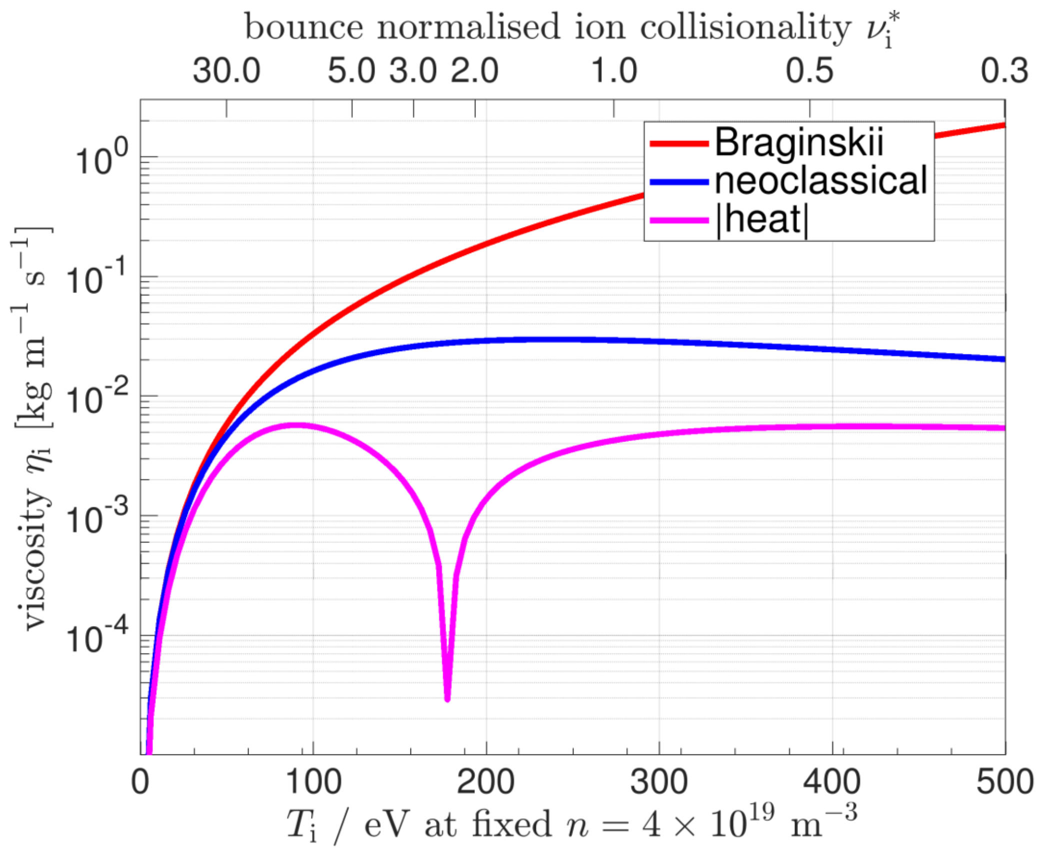
Christoph Pitzal *et al.*, Phys. Plasmas 30, 122502 (2023)

Neoclassical ion viscosity

$$\partial_t u_\parallel \sim \mathbf{B}\cdot\nabla\cdot\Pi,$$
$$\langle \mathbf{B}\cdot\nabla\cdot\Pi_\mathrm{i}\rangle = 3\eta_\mathrm{i}\left\langle(\nabla_\parallel B)^2\right\rangle v_\theta$$

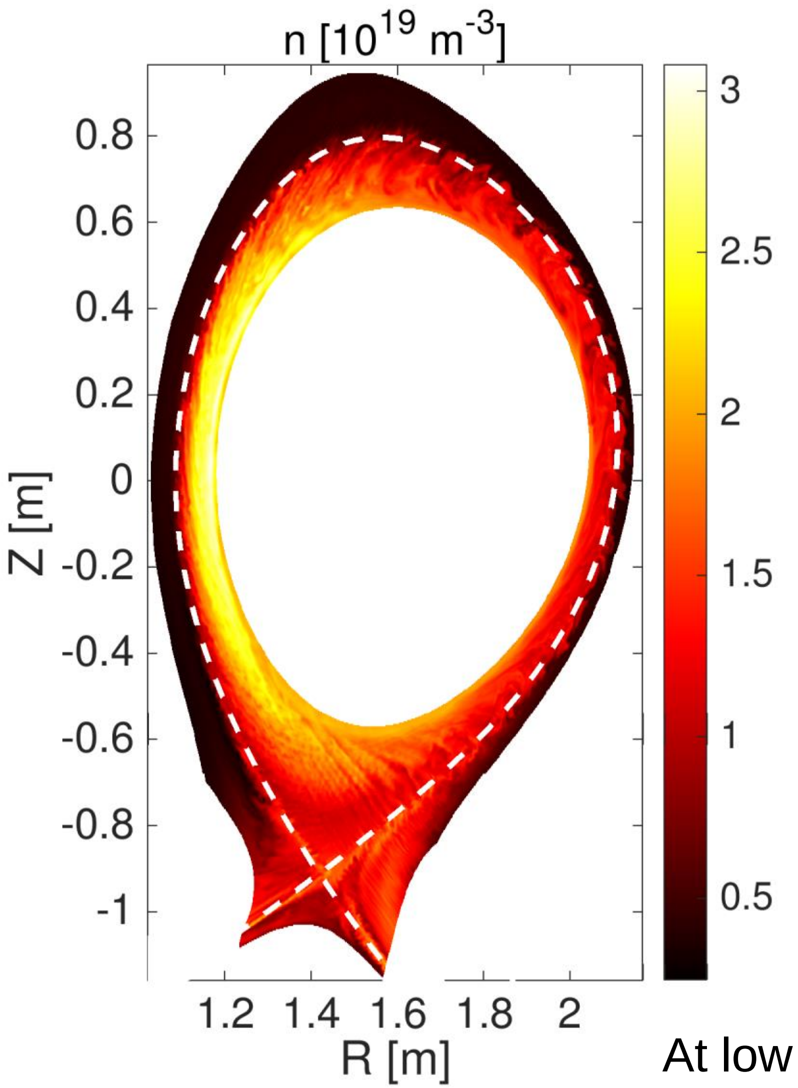
$$\mathbf{B}\cdot\nabla\cdot\Pi = (p_\perp - p_\parallel)\nabla_\parallel B + \frac{2}{3}B\nabla_\parallel(p_\perp - p_\parallel) = \frac{2}{3}B^{5/2}\nabla_\parallel\frac{G}{B^{3/2}}$$

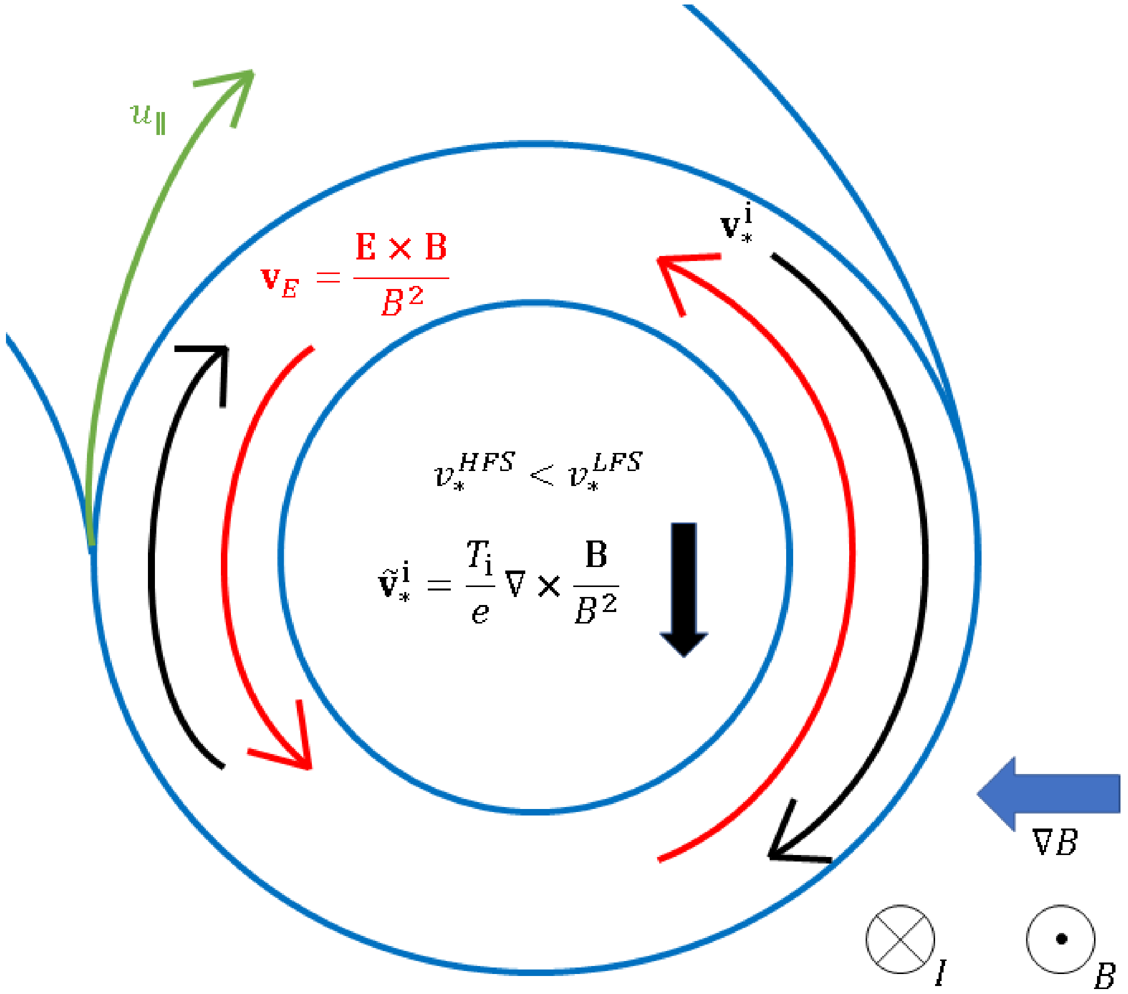
$$G = -\eta_\mathrm{i}\left[\frac{2}{B^{3/2}}\nabla\cdot\left(u_\parallel B^{3/2}\mathbf{b}\right) - \frac{C(\varphi)}{2} - \frac{C(p_\mathrm{i})}{2en}\right] - \eta_\mathrm{i}^\mathrm{heat}\left[\frac{2}{nT_\mathrm{i}B^{3/2}}\nabla\cdot\left(q_{\parallel\mathrm{i}}B^{3/2}\mathbf{b}\right) - \frac{5C(T_\mathrm{i})}{4e}\right]$$



- In drift-fluid models, also the heat anisotropy requires a closure.
- critical for the regulation of poloidal rotation ($E_r, u_\parallel$)
- again, Braginskii expression diverges at low collisionality
- corrected with neoclassical formulae
- Heat viscosity leads to finite mean poloidal rotation

Poloidal asymmetry due to too strong Braginskii flow damping





At low collisionality, the Braginskii viscosity damps out the parallel flow completely. To compensate the compression of poloidal (zonal) flows, density becomes strongly asymmetric.

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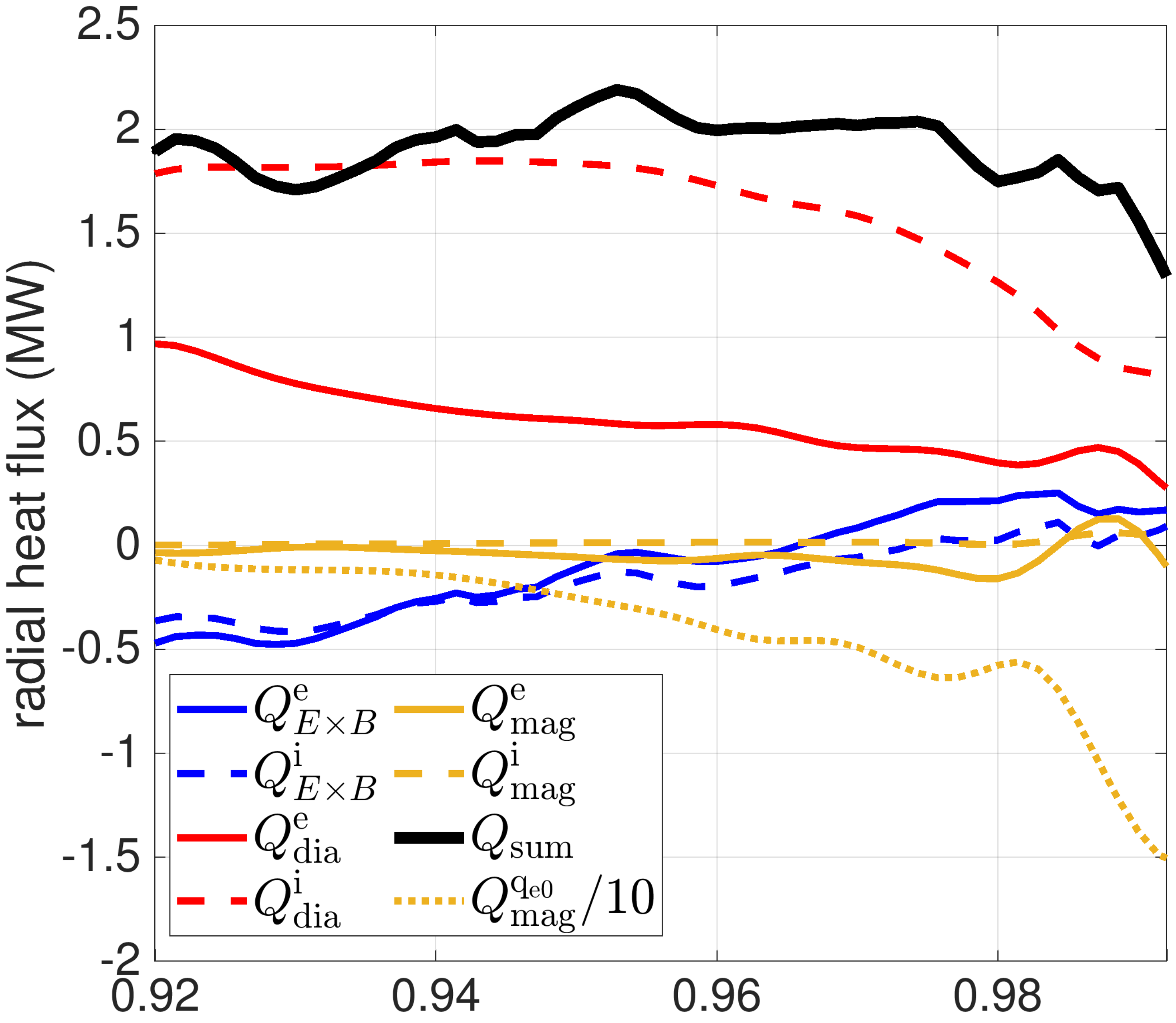
Characterisation of H-mode transport



$$Q^{e,i}_{E\times B} = \frac{3}{2} n T_{e,i} \mathbf{v}_{E\times B} \cdot \mathbf{e}_\rho,$$

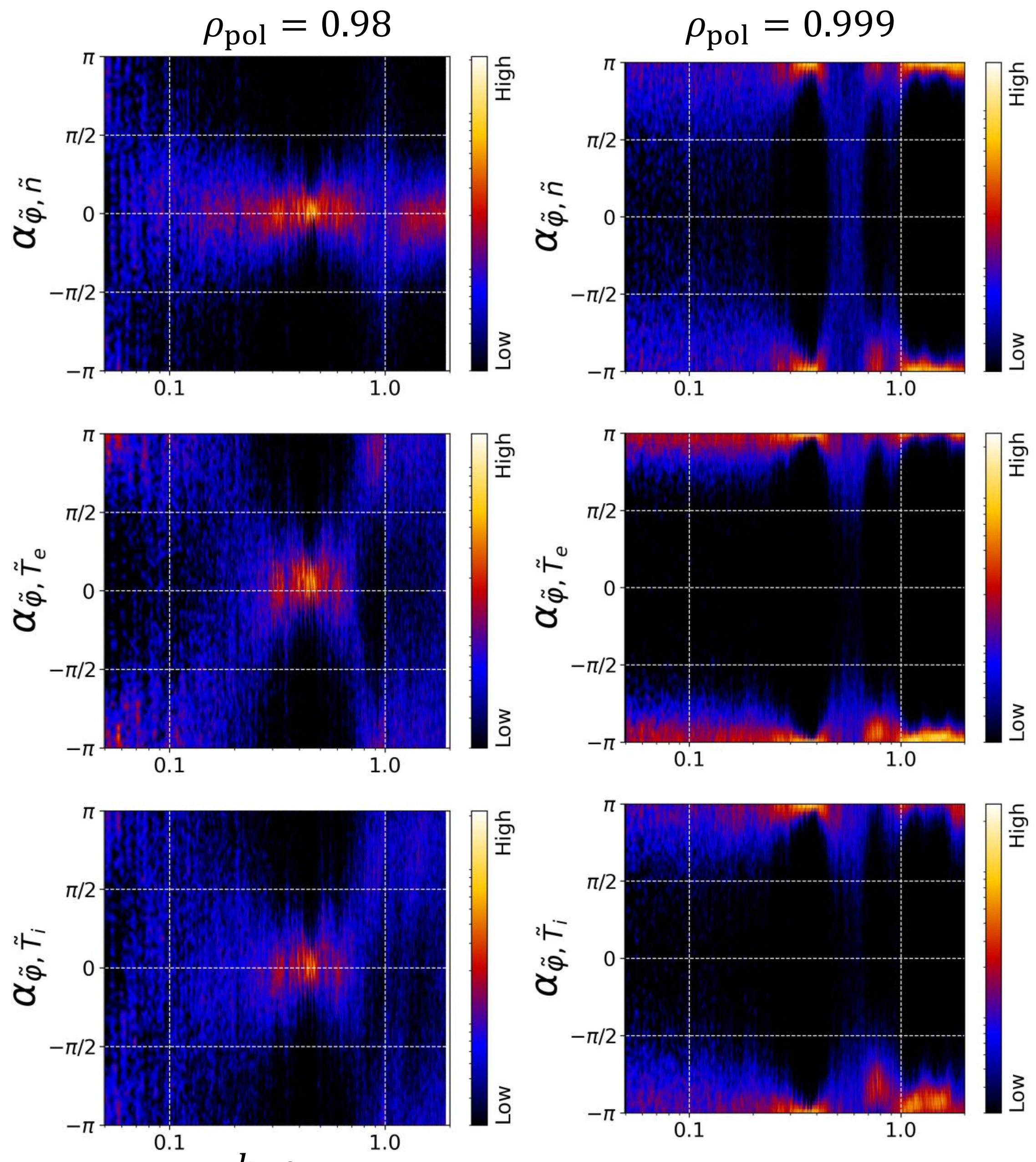
$$Q^{e,i}_{dia} = \frac{5}{2} n T_{e,i} \mathbf{v}^{e,i}_{dia} \cdot \mathbf{e}_\rho = \mp \frac{5}{2} n T^2_{e,i} \left(\nabla \times \frac{\mathbf{B}}{eB^2} \right) \cdot \mathbf{e}_\rho$$

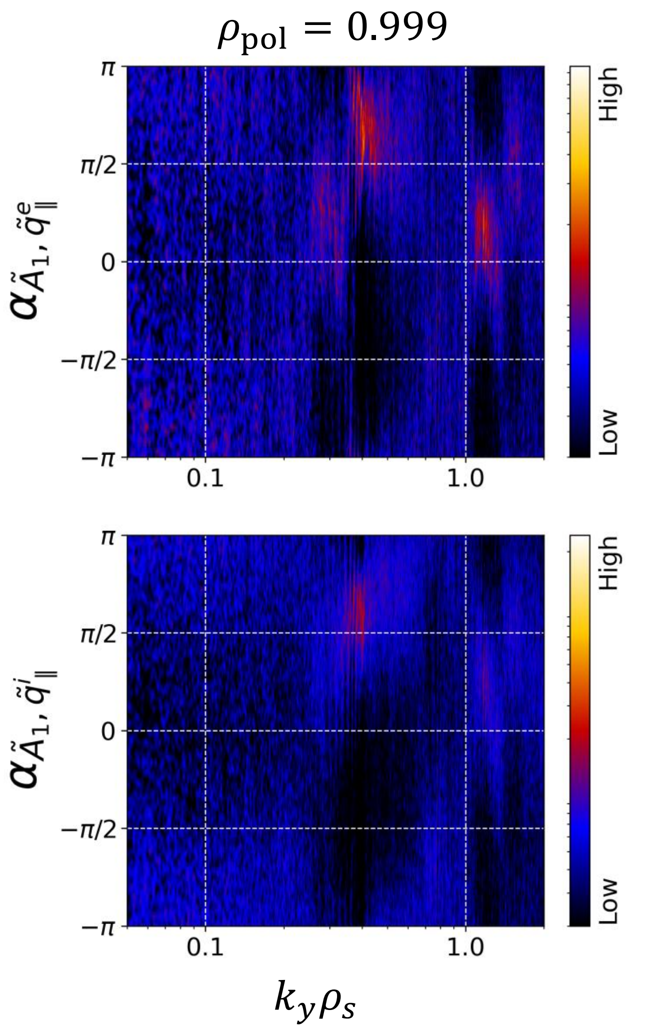
$$Q^{e}_{mag} = \left(\frac{3}{2} n T_e v_\parallel + q_{\parallel e} - 0.71 j_\parallel T_e \right) \mathbf{b}_1 \cdot \mathbf{e}_\rho,$$

$$Q^{i}_{mag} = \left(\frac{3}{2} n T_i u_\parallel + q_{\parallel i} \right) \mathbf{b}_1 \cdot \mathbf{e}_\rho.$$

- Very small $E \times B$ transport due to drift-wave stabilization
- Pedestal top to center, mostly diamagnetic = neoclassical transport (turbulence-enhanced)
- Increasing electromagnetic transport towards pedestal foot

Phase shift analysis





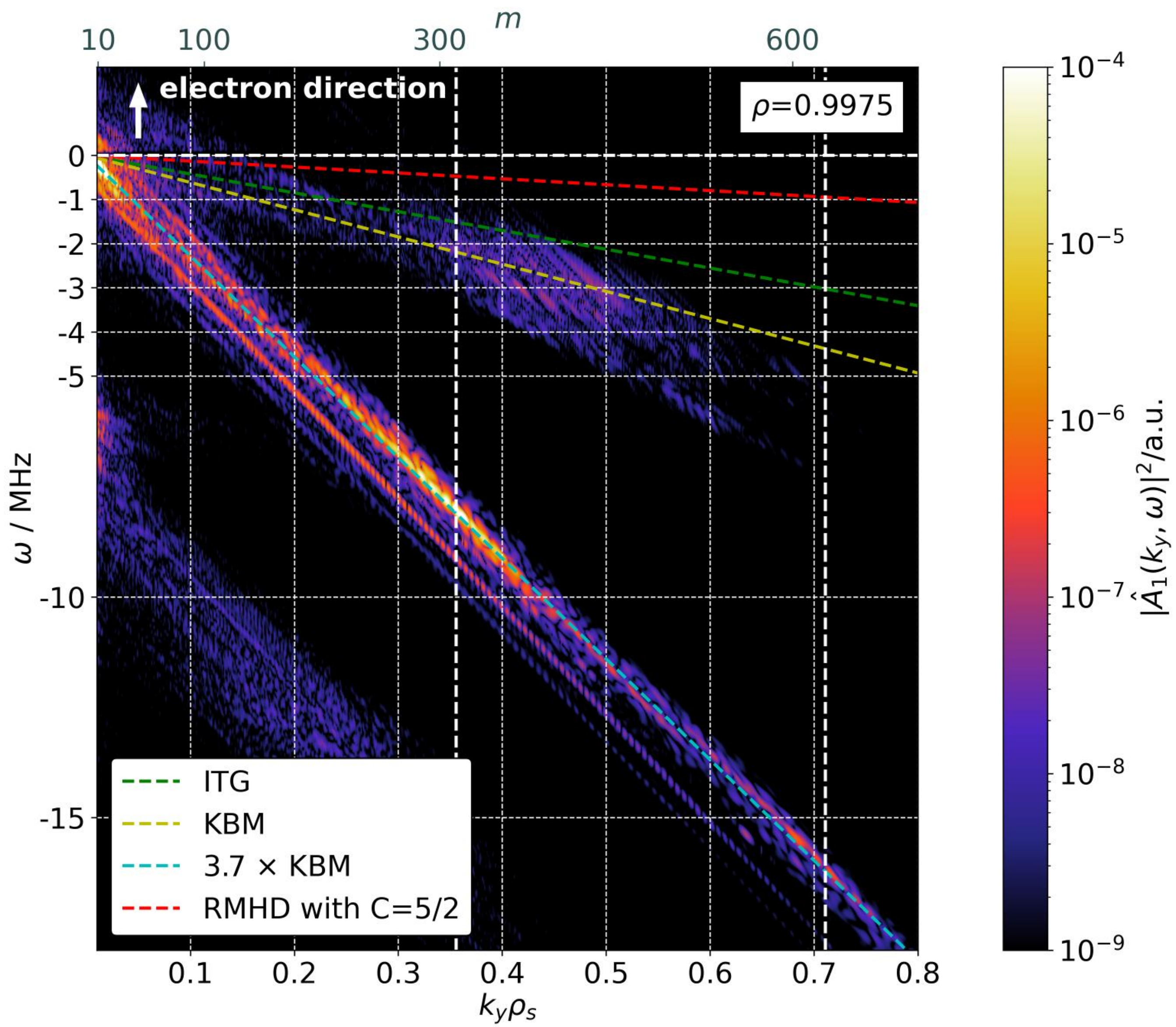
$$\langle \Gamma_r \rangle_y \,(t, \rho_{\text{pol}}, \phi_{\text{tor}}) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} k |\tilde{n}||\tilde{\varphi}| \sin(\alpha_{\tilde{\varphi},\tilde{n}}) \mathrm{d}k$$

$$\alpha_{\tilde{\varphi},\tilde{n}}(k) = \operatorname{Im} \log(\tilde{\varphi} \tilde{n}^*)$$

$$Q_{\text{mag}}^{\text{e,i}} \sim q_{\parallel \text{e,i}} \mathbf{b}_1 \cdot \mathbf{e}_\rho \sim -k |\tilde{q}_{\parallel \text{e,i}}| |\tilde{A}_1| \sin(\alpha_{\tilde{A}_1,\tilde{q}_{\parallel \text{e,i}}})$$

- Drift-waves at $\rho_{\text{pol}} < 0.99$
- Kinetic ballooning modes (KBM) at $\rho_{\text{pol}} > 0.99$

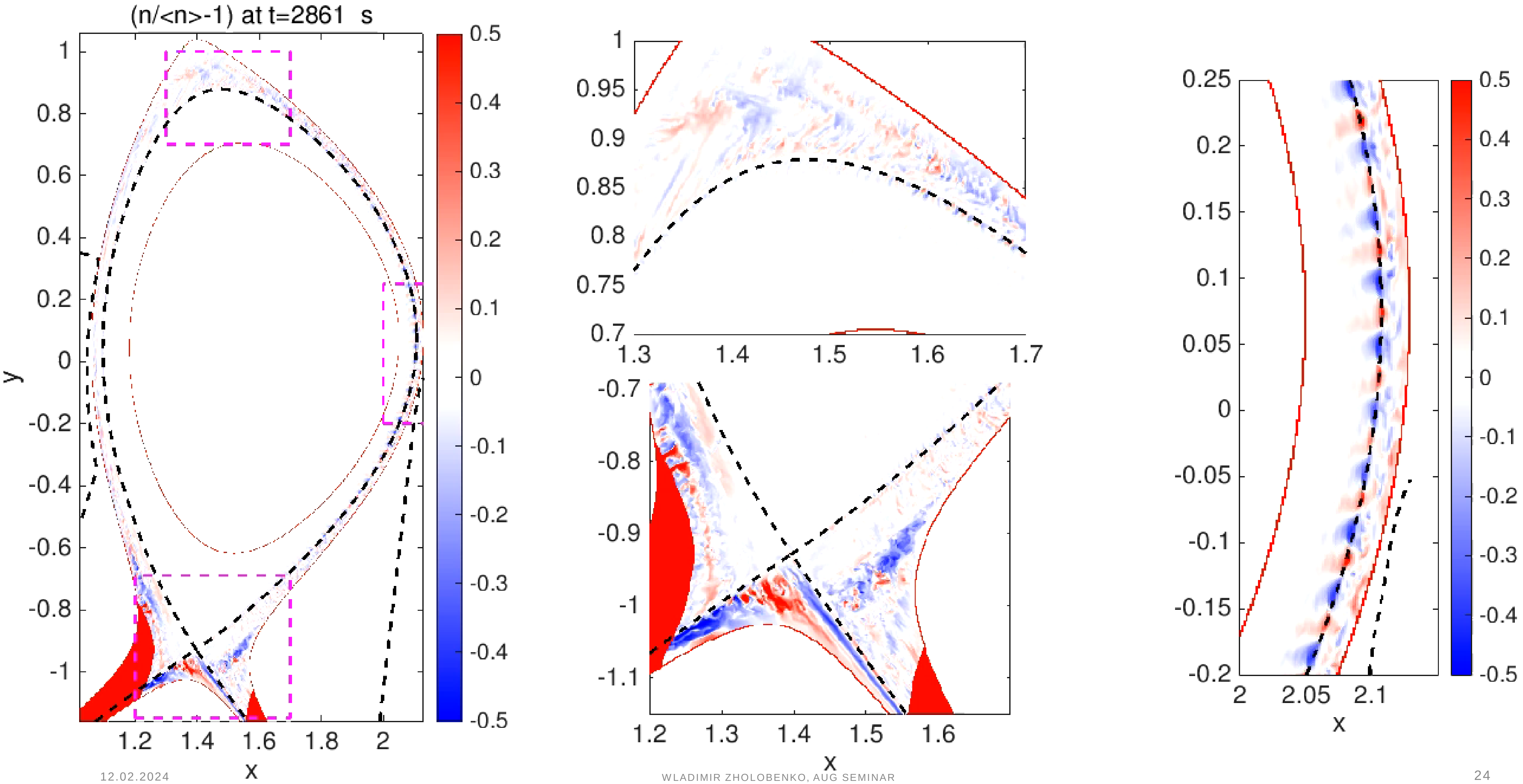
Dispersion relation: kinetic ballooning mode



- Strongly electromagnetic, with $E_{\|} \approx 0$
- Mode propagates in ion diamagnetic direction (excludes MTM)
- Frequency is 4 x flux-tube KBM (deviation possible due to fluid model & geometry)

⇒ Quite clearly a kinetic ballooning mode

Dynamics of density fluctuations



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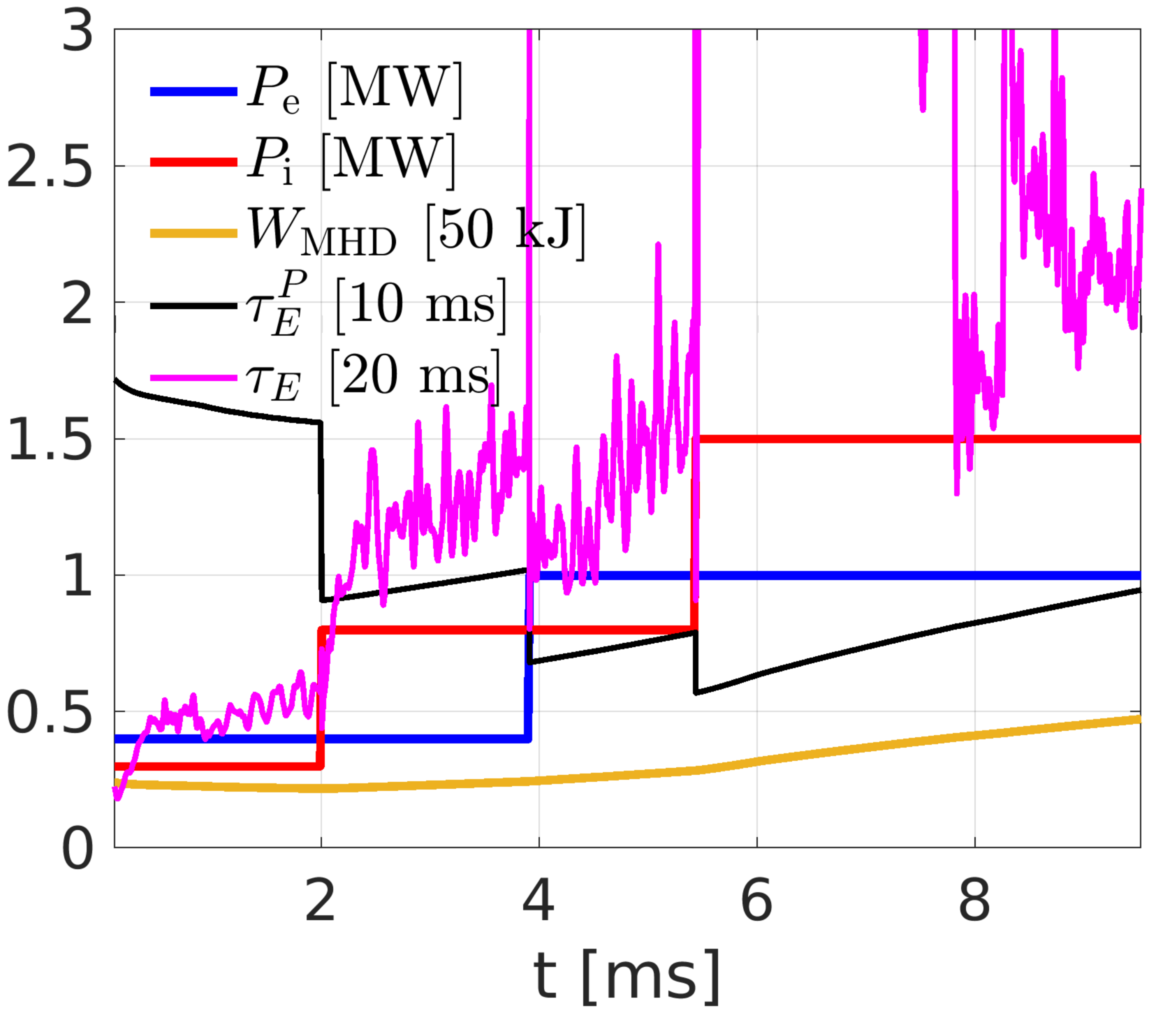
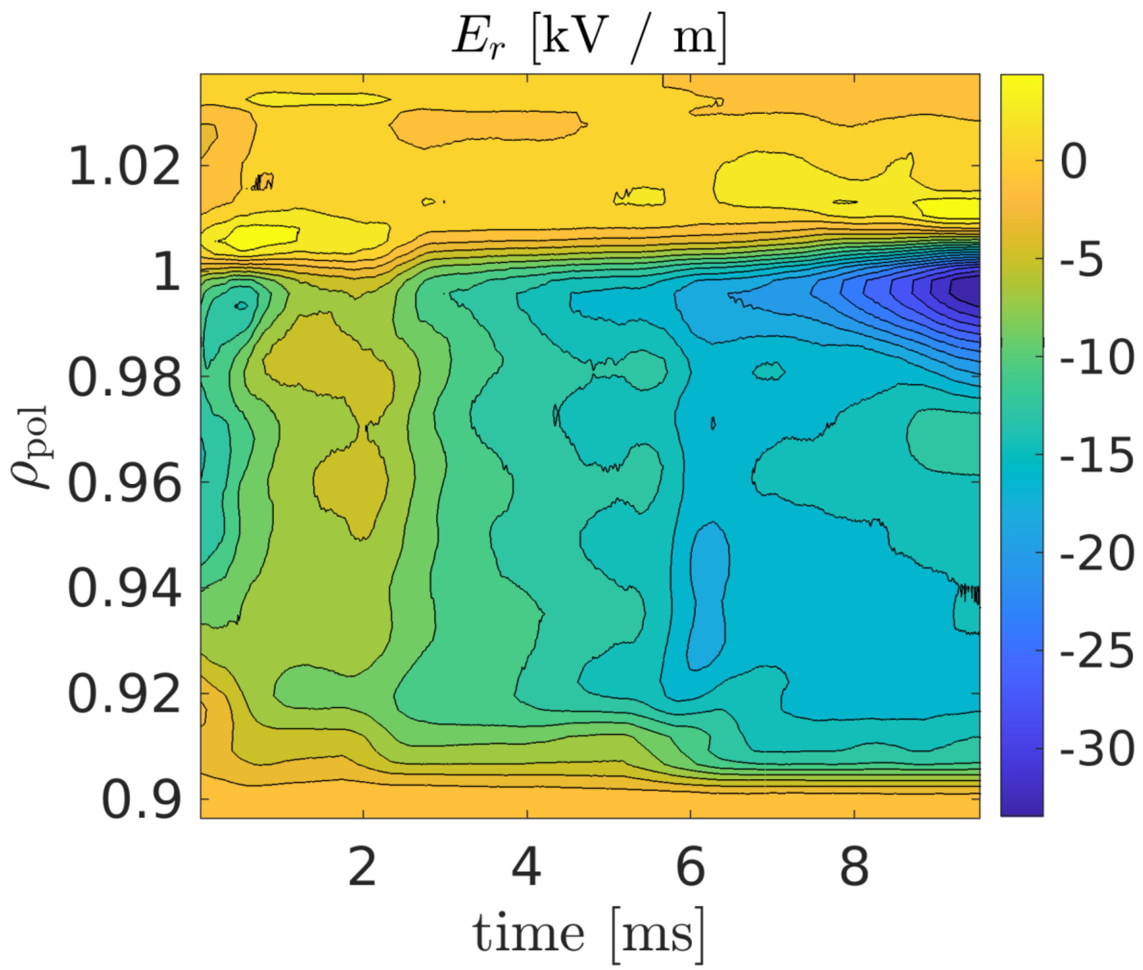
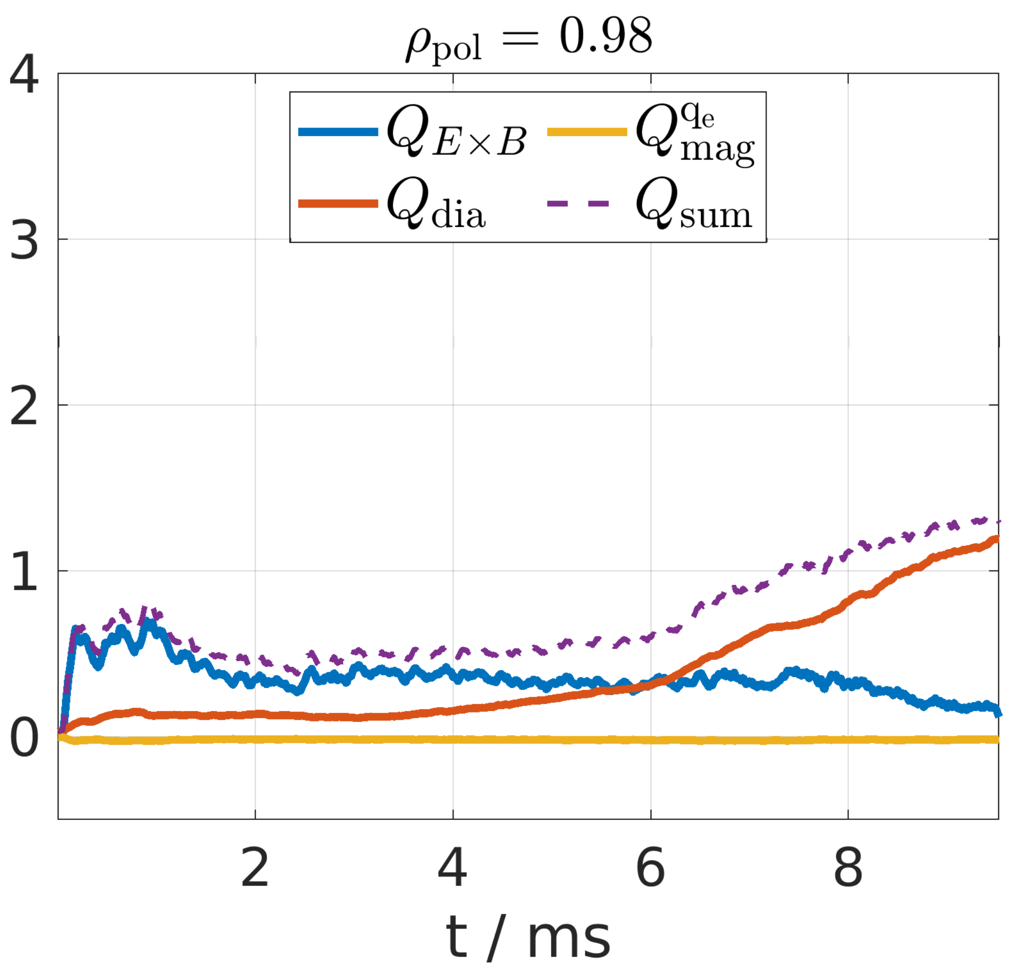
A first L-H transition power scan



- At 2 ms, (nearly) saturated L-mode turbulence
- Stepwise power increase from 700 kW to 2.5 MW
- W_{MHD} only for $\rho_{\mathrm{pol}} > 0.9$, smaller than in experiment
- $\tau_E^P = W_{\mathrm{MHD}}/\mathrm{P}$, $\tau_E = W_{\mathrm{MHD}}/(\mathrm{P} - \dot{W}_{\mathrm{MHD}})$
- Long reaction time, needs better setup

E_r well formation and heat transport evolution





E_r well forms only after t > 6 ms

- Heat propagates radially with significant delay
- $E \times B$ transport decreases, diamagnetic increases

Conclusions

- ✓ H-mode turbulence simulation are now possible with GRILLIX
  - ✓ reasonable OMP profiles
  - ✓ reasonable radial transport, but a factor ~2 below experiment
  - ✓ reasonable divertor heat flux
  - ✓ requires an advanced, electromagnetic, transcollisional model

- ✓ The radial electric field is mostly $E_r \approx \frac{\partial_r p_\mathrm{i}}{\mathrm{en}}$, but only because zonal flows balance poloidal and toroidal rotation ⇒ possible reason why there are no GAMs in H-mode

- ❖ Transport is to a large degree neoclassical: requires investigation of the validity of the fluid model!
  - ❖ Possible missing mechanisms: TEM, ETG, but also just different flow and Landau damping
  - ❖ Need to investigate with GENE-X and GENE
- ❖ At the pedestal foot, electromagnetic kinetic ballooning modes (KBM)

- ○ First L-H transition attempt could be done, but more work is required. Long reaction time of the system. How exactly should we set things up, and how does the expected outcome look like?

- ○ Can investigate advanced collisional H-mode regimes and exhaust solutions.

Thank you for your attention!