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► **To cite this version:**

Peter Donnel, G. Dif Pradalier, Giannatale G. Di, L. Villard, Grandgirard V., et al.. Gyrokinetic turbulence studies of the transition from open to closed field lines in tokamaks. AAPPS-DPP 2022 - 6th Asia-Pacific Conference on Plasma Physics, Oct 2022, Online Conference (Tokyo), Japan. cea-03949336

HAL Id: cea-03949336

<https://cea.hal.science/cea-03949336>

Submitted on 20 Jan 2023

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Gyrokinetic turbulence studies of the transition from open to closed field lines in tokamaks

P. DONNEL¹, G. DIF-PRADALIER¹, G. DI GIANNATALE²,
L.VILLARD², V. GRANDGIRARD¹, L. NGUYEN³,
K. OBREJAN¹, E. BOURNE¹, X. GARBET¹, P. GHENDRIH¹,
Y.MUNSCHY¹, Y. SARAZIN¹, R. VARENNES¹

1: CEA, IRFM, Saint-Paul-lez-Durance, France

2: SPC, EPFL, Lausanne, Switzerland

3: CEA, DIF, Bruyères-le-Châtel, F-91297 France

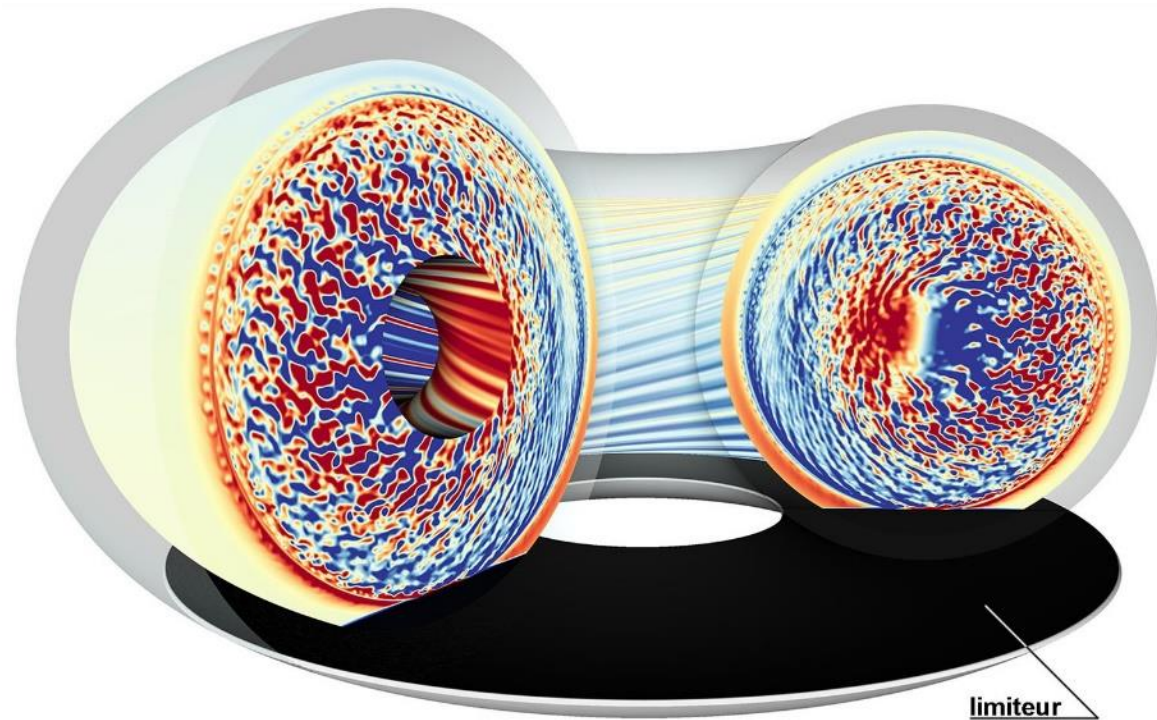
- Transport in the edge is crucial for the global confinement
- LH transition is happening close to the transition between open and closed field lines
- LH transition is related to the deepening of a radial electric field well
- Origin of this radial electric field not fully understood

Objective:

Study the impact of the transition between closed and open field lines with a gyrokinetic code

The GYSELA code is

- Full-F
- Global
- Flux-driven
- Electrostatic
- Possess a limiter boundary condition



Limiter simulated by two terms [Caschera 2018, Dif-Pradalier 2022]:

- A momentum and energy sink via a source term on the Vlasov equation

$$\frac{df}{dt} = C_{coll} + S_{source} - \nu \cdot \mathcal{M}^{mat} (f - ng)$$

- A modification of the quasi-neutrality equation

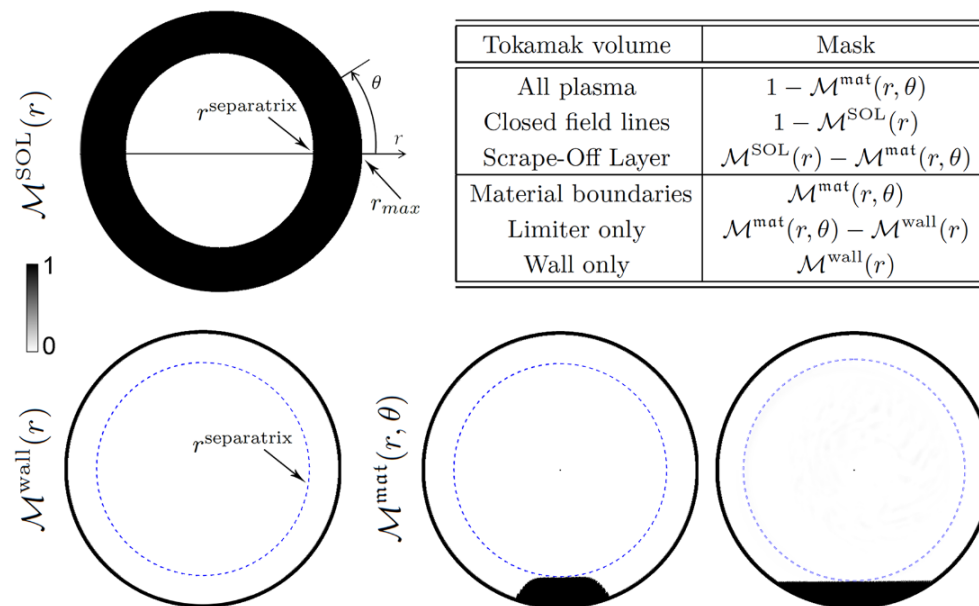
$$\mathcal{L}\phi + \frac{n_{e0}}{Z_0^2 T_e} [\phi - (1 - \mathcal{M}^{SOL}) \langle \phi \rangle_{FS}] = \rho^{LIM}$$

$$\rho^{LIM} = \rho + \frac{n_{e0}}{Z_0^2 T_e} [\Lambda (\mathcal{M}^{SOL} - \mathcal{M}^{mat}) (T_e - T_e^{b.c.}) + (\mathcal{M}^{mat} - \mathcal{M}^{wall}) \phi^{bias}]$$

$$\rho(r, \theta, \varphi) = \sum_s Z_s [n_{G_s}(r, \theta, \varphi) - n_{G_s,eq}(r, \theta)]$$

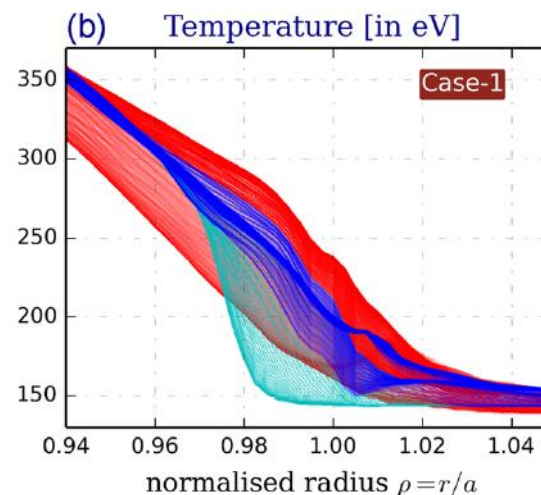
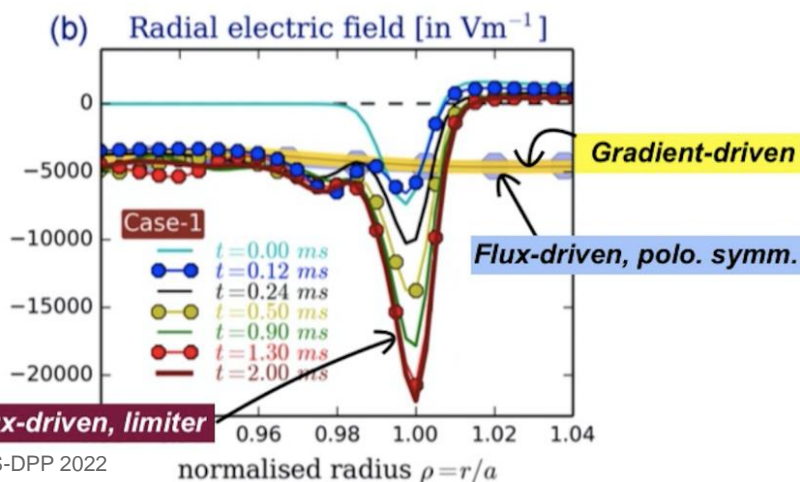
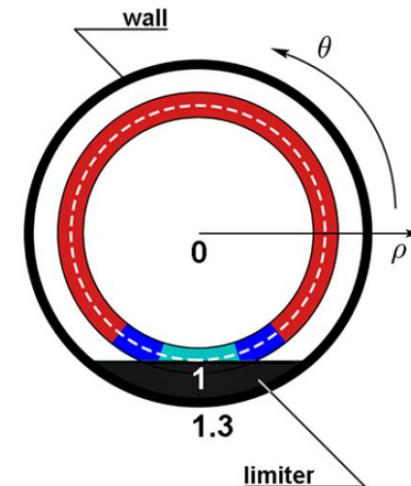
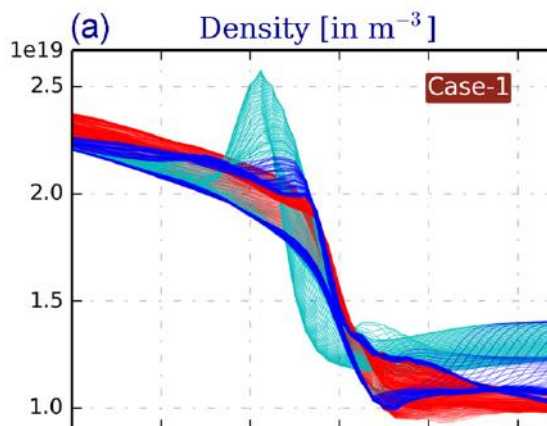
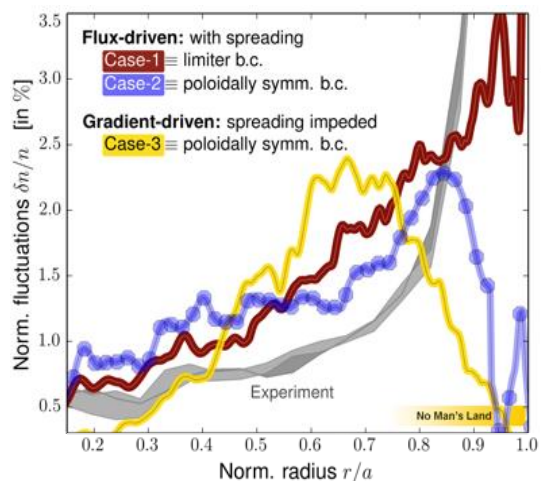
$$\mathcal{L} = - \sum_i A_i \nabla_{\perp} \cdot \left(\frac{n_{i0}(r)}{B_0^2} \nabla_{\perp} \right)$$

$$\Lambda = -\frac{1}{2} \ln \left[2\pi \frac{m_e}{m_i} \left(1 + \frac{T_i}{T_e} \right) \right]$$



Limiter leads to [Dif-Pradalier 2022]

- Level of fluctuations consistent with experimental measurements
- Development of a radial electric field
- Pressure gradient at the transition open/closed field lines



The hybrid electron model [Idomura 2016] treats

- Trapped electrons kinetically
- Passing electrons adiabatically

$$-\sum_i A_i \nabla_{\perp} \cdot \left(\frac{n_{i0}}{B_0^2} \nabla_{\perp} \phi \right) - A_e \nabla_{\perp} \cdot \left(\bar{\alpha}_{t0} \frac{n_{e0}}{B_0^2} \nabla_{\perp} \phi \right) + \bar{\alpha}_{p0} \frac{n_{e0}}{Z_0^2 T_e} (\phi - \langle \phi \rangle_{\text{FS}}) = \sum_i Z_i \delta n_i - \delta n_e^{\text{trap.}}$$

↑ Trapped fraction
 ↓ Passing fraction

The zonal mode is treated fully kinetically as in ORB5 [Lanti 2018]

$$-\sum_i A_i \nabla_{\perp} \cdot \left(\frac{n_{i0}}{B_0^2} \nabla_{\perp} \phi \right) - A_e \nabla_{\perp} \cdot \left(\frac{n_{e0}}{B_0^2} \nabla_{\perp} \phi \right) = \sum_i Z_i \delta n_i - \delta n_e \quad \text{for } n = 0, m_{\star} = 0$$

$$\mathcal{L}\phi_{m,n} + \bar{\alpha}_{p0} \frac{n_{e0}}{Z_0^2 T_e} (\phi_{m,n} - (1 - \mathcal{M}^{SOL}) \langle \phi_{m,n} \rangle_{FS}) = \rho_{m,n}^{TKE,LIM} \quad \forall (m,n) \neq (n=0, m_* = 0)$$

with

$$\rho_{m,n}^{TKE,LIM} = \rho_{m,n}^{TKE} + \bar{\alpha}_{p0} \frac{n_{e0}}{Z_0^2 T_e} [\Lambda (\mathcal{M}^{SOL} - \mathcal{M}^{mat}) (T_e - T_e^{b.c.}) + (\mathcal{M}^{mat} - \mathcal{M}^{wall}) \phi^{bias}]$$

Polarisation term

$$\mathcal{L} = - \sum_i A_i \nabla_{\perp} \cdot \left(\frac{n_{i0}(r)}{B_0^2} \nabla_{\perp} \right)$$

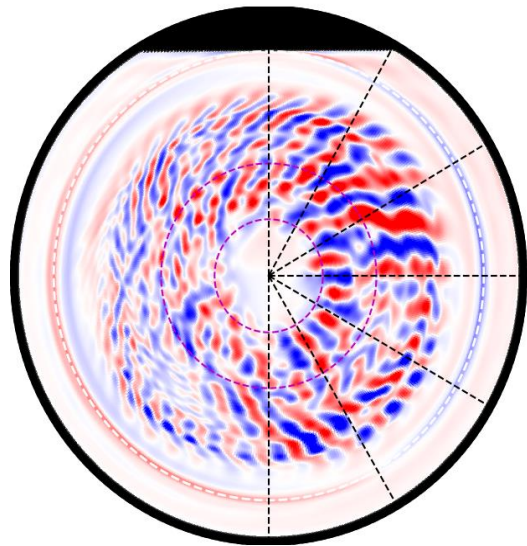
The trapped fraction definition is modified in the SOL:

- Electrons with trajectory that intercept the wall are considered as adiabatic (=passing in the core)
- Other electrons are treated kinetically (= trapped in the core)

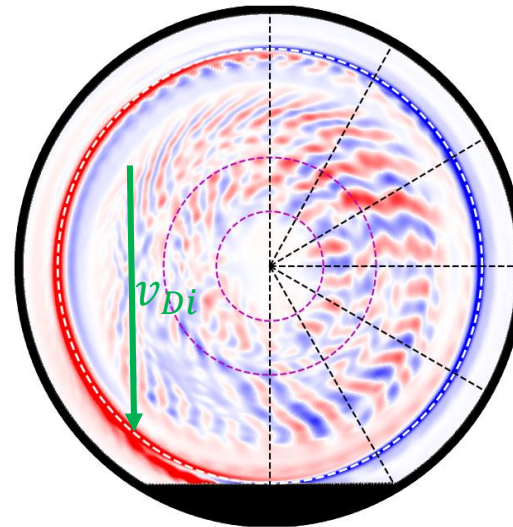
The zonal component is still treated fully kinetically in the core but not in the SOL

$$\phi^{LIM} = \phi^{TKE} + [1 - \mathcal{M}^{SOL}(r)] \left[-\phi_{(m_*=0, n=0)}^{TKE} + \phi_{(m_*=0, n=0)}^{FKE} \right]$$

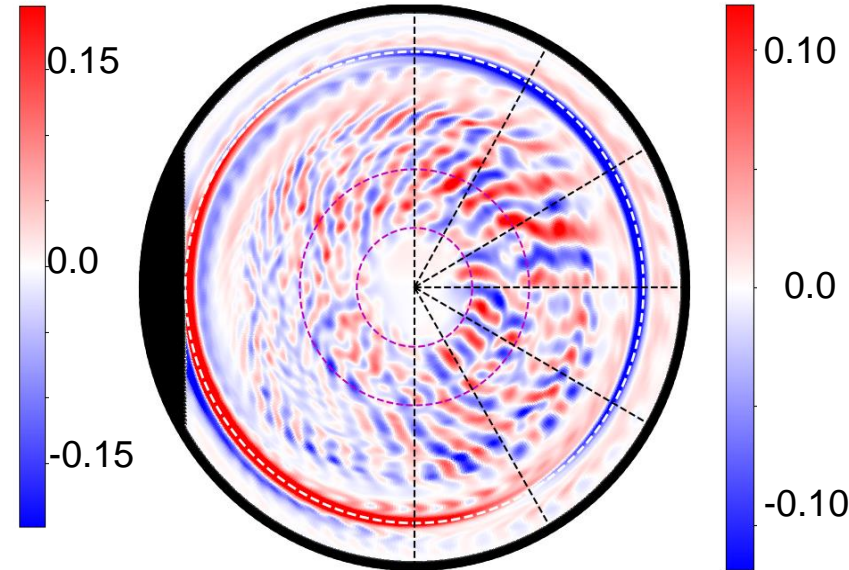
$\Phi - \Phi_{00}$ at time = 25000.0/ ω_c



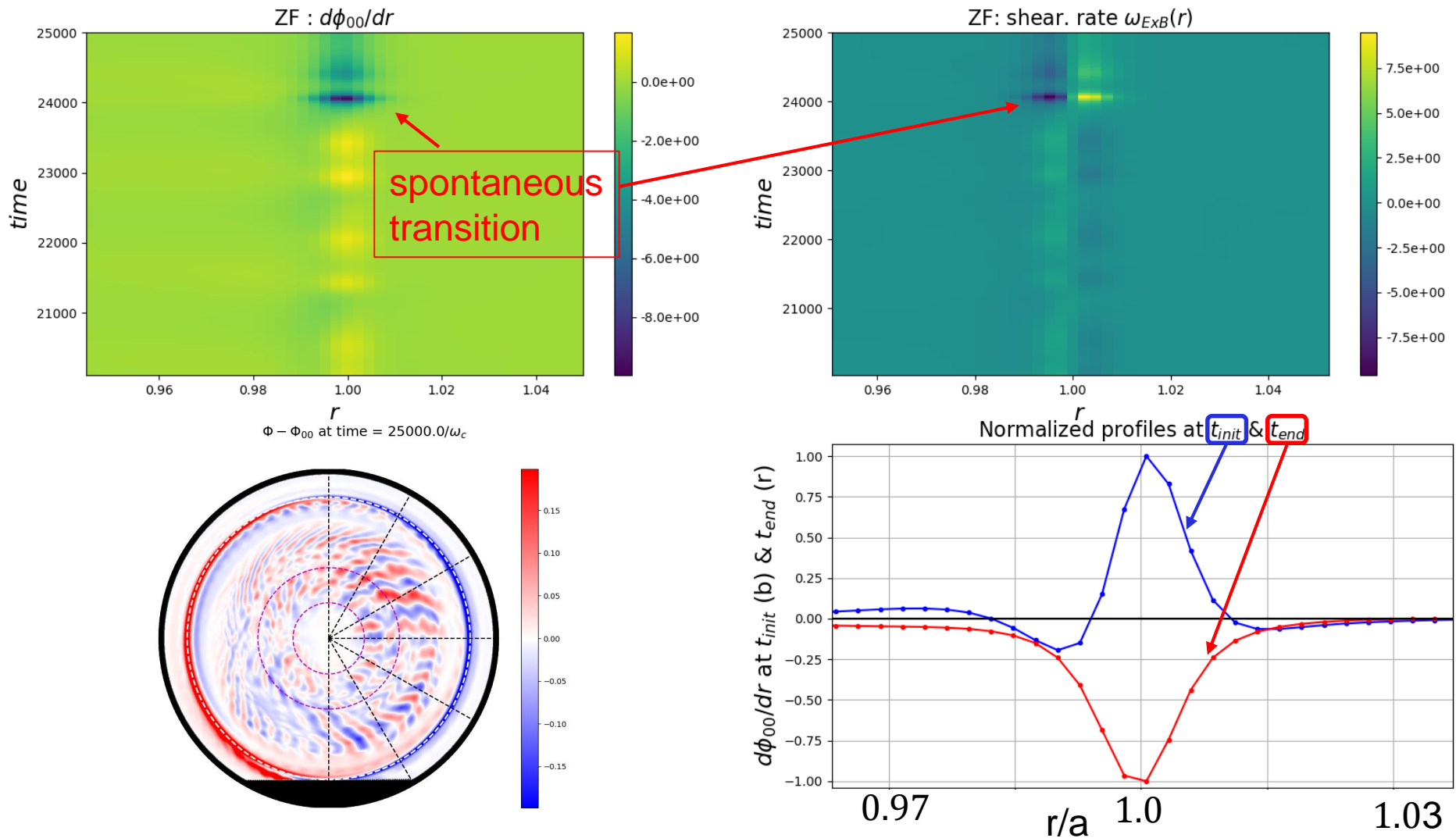
$\Phi - \Phi_{00}$ at time = 25000.0/ ω_c



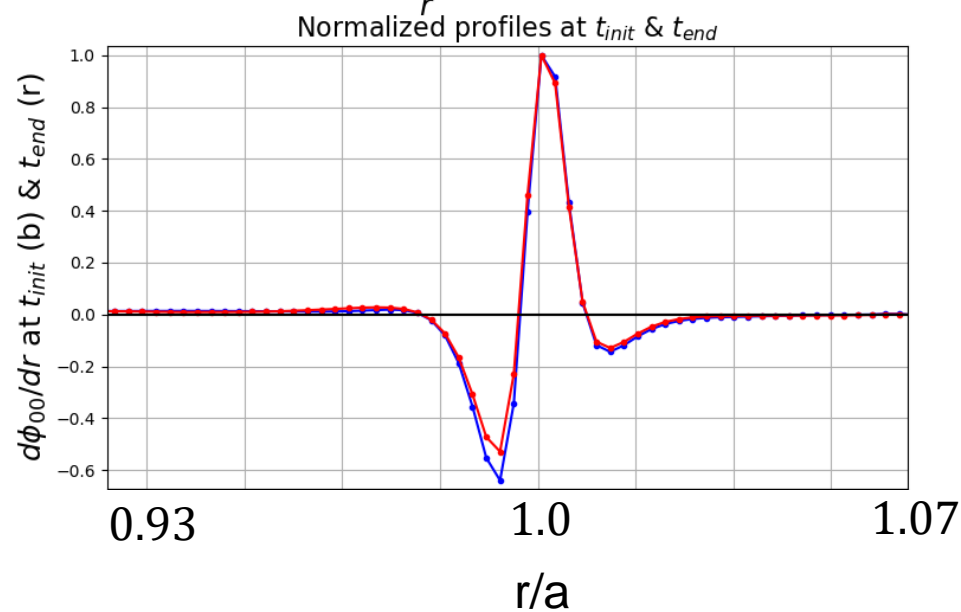
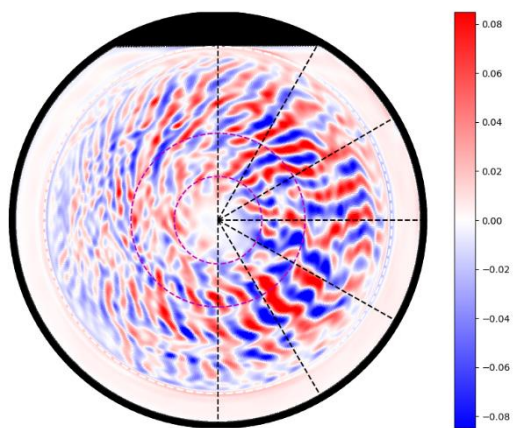
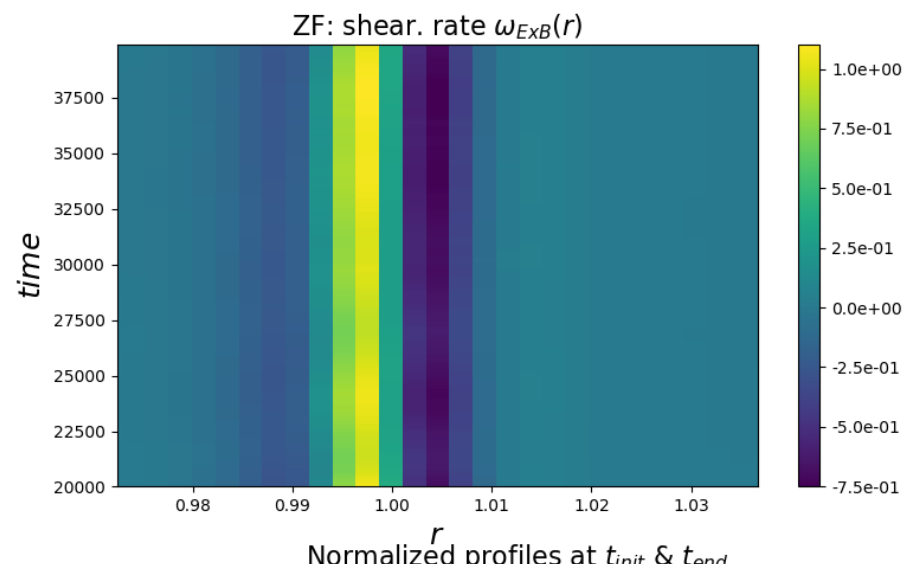
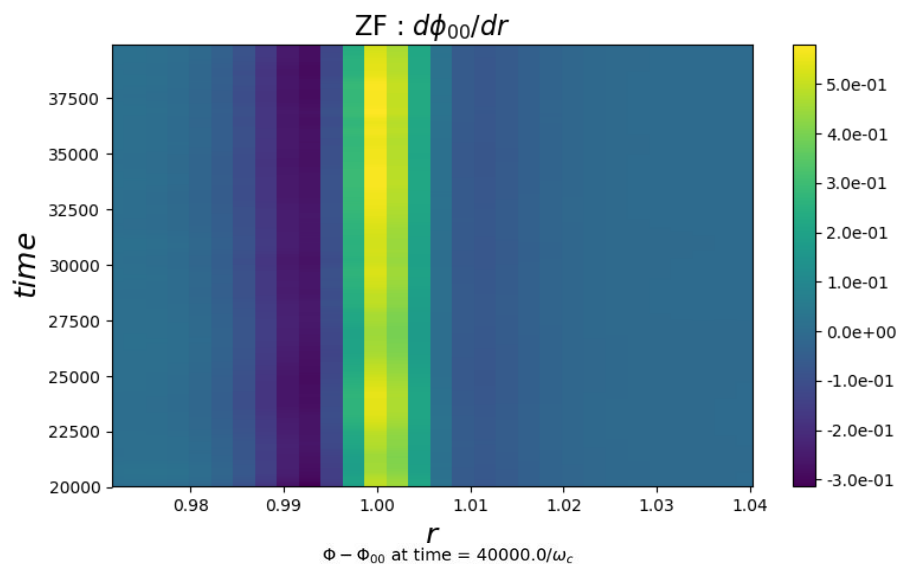
$\Phi - \Phi_{00}$ at time = 25000.0/ ω_c



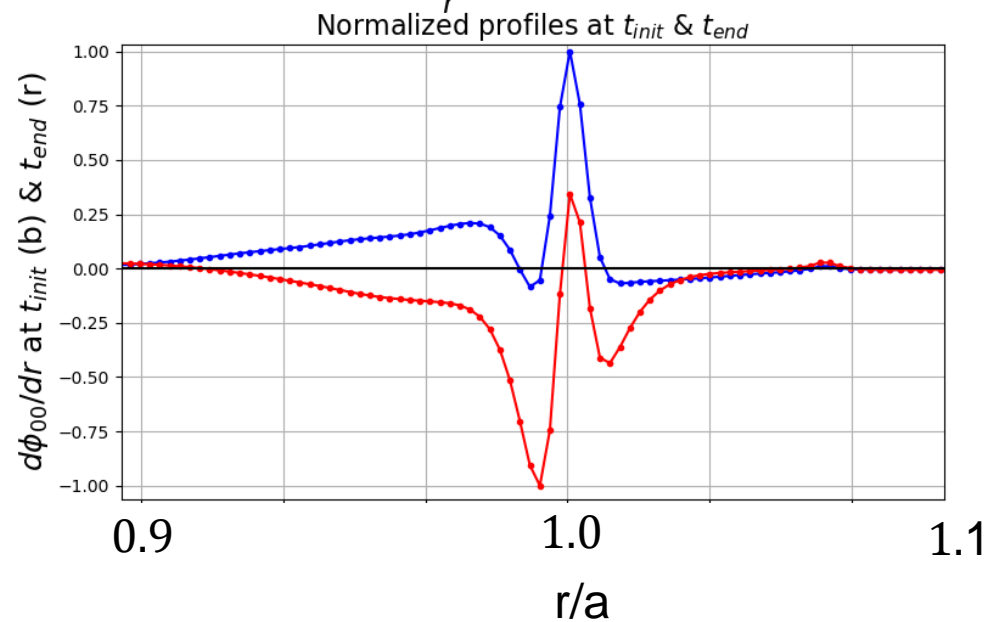
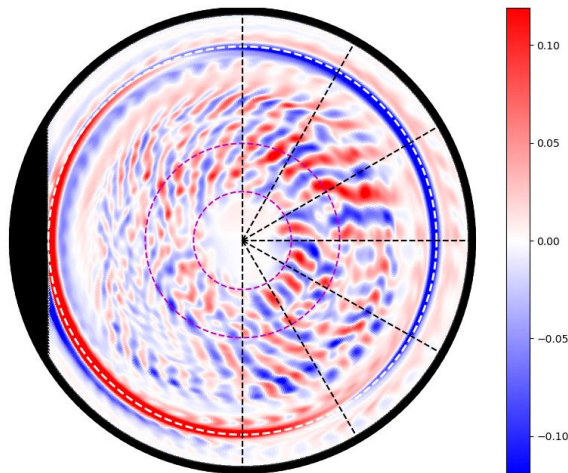
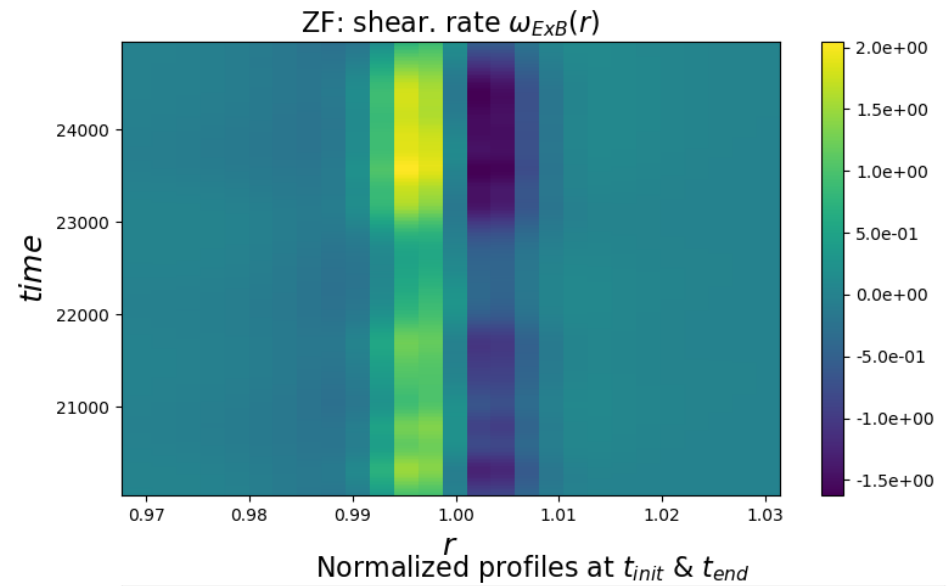
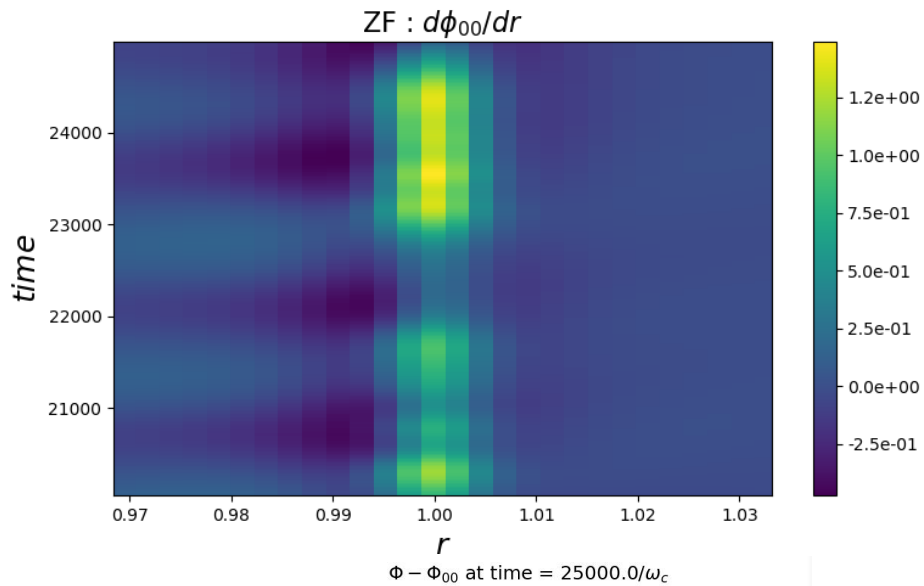
- Small impact of the limiter position in the deep core
- Large impact of limiter position on the poloidal asymmetry of the potential.



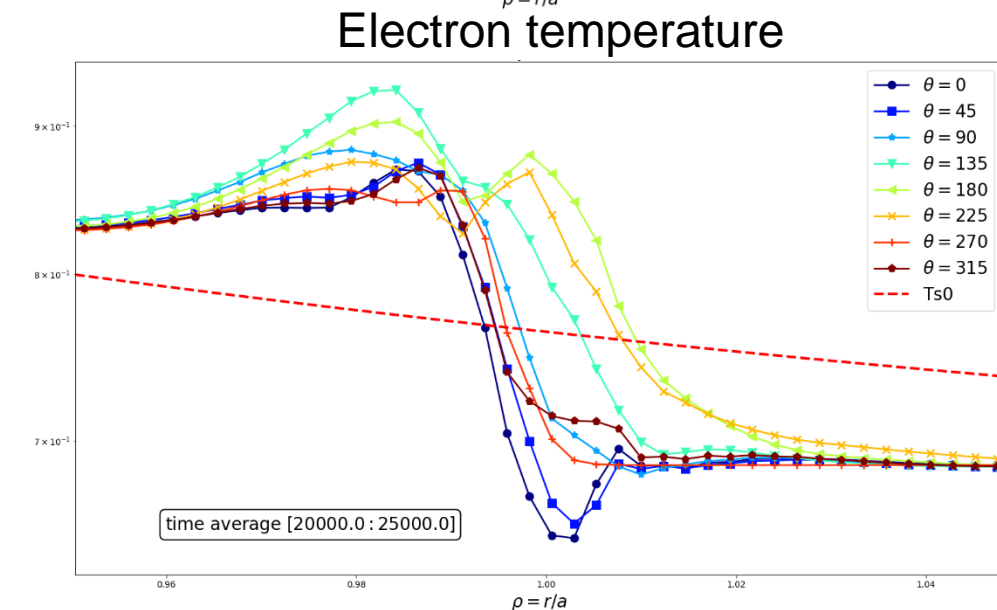
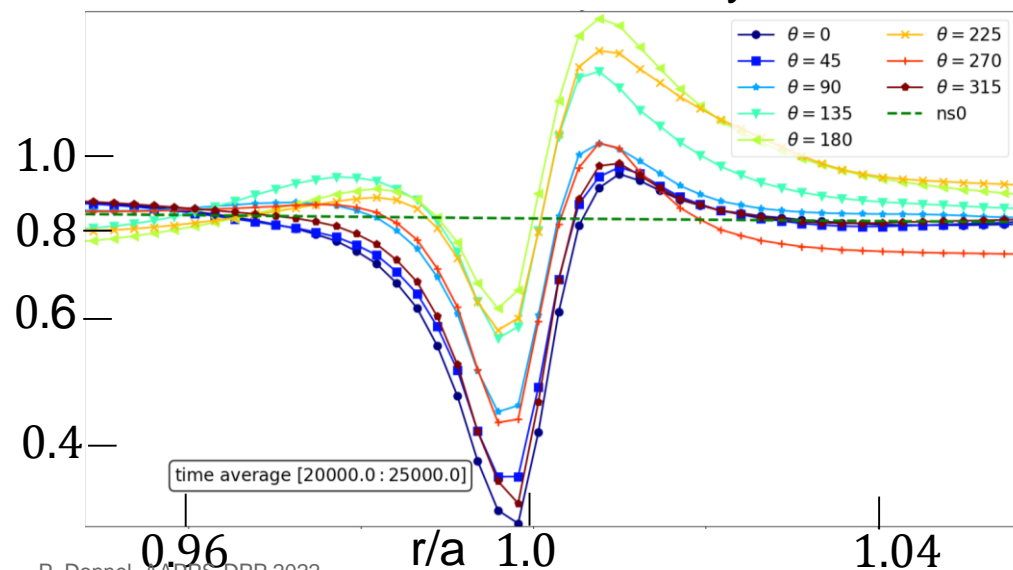
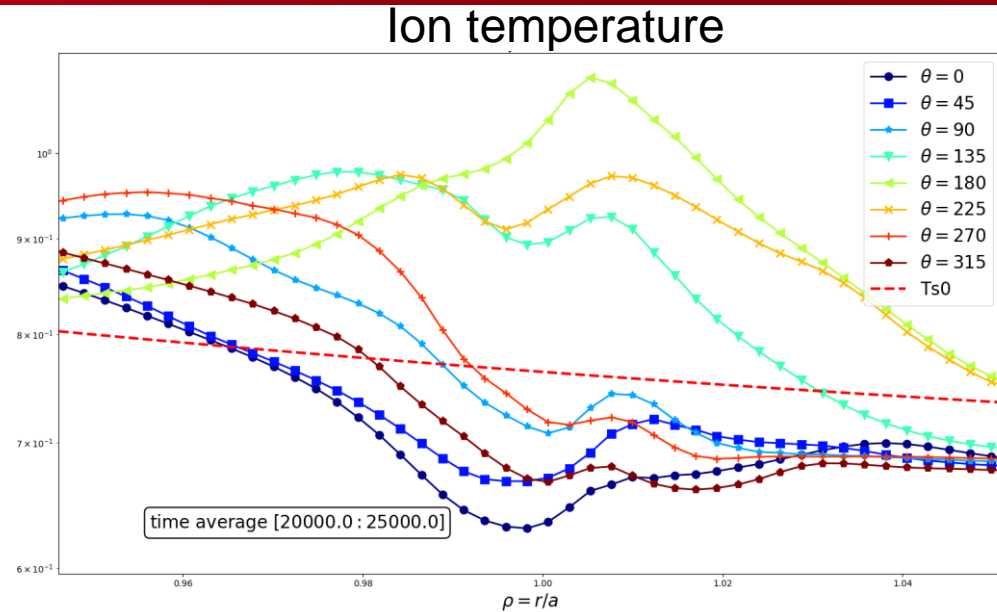
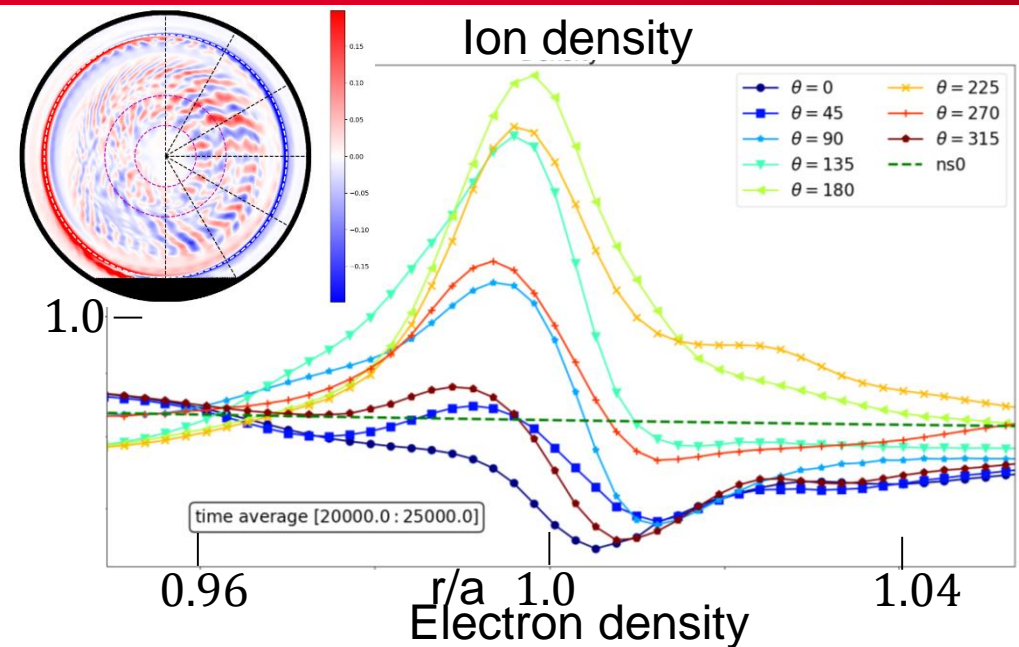
- Spontaneous transition of the edge E_r well. Qualitative agreement with experiments.
- Origin of the transition : physics or numerical?

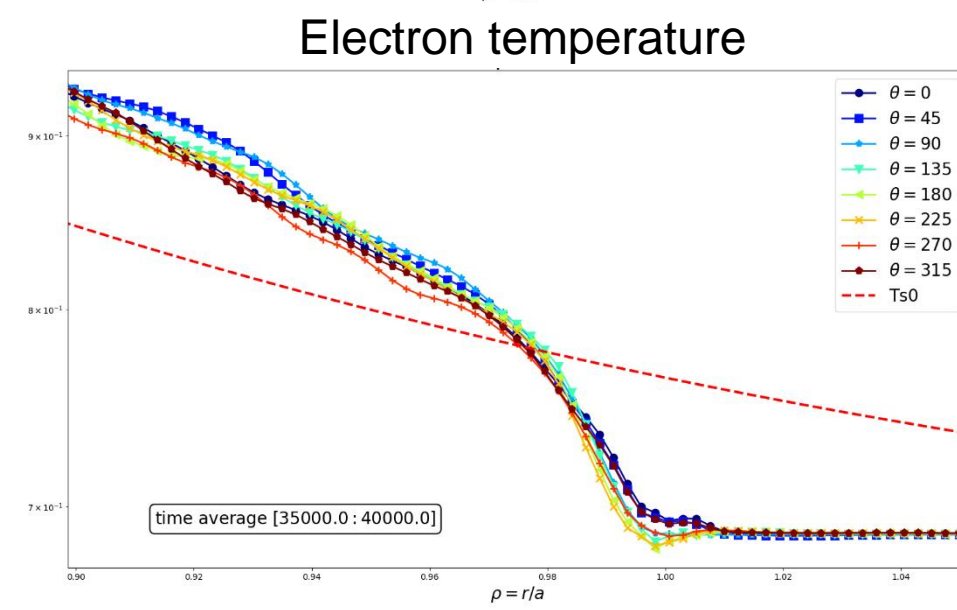
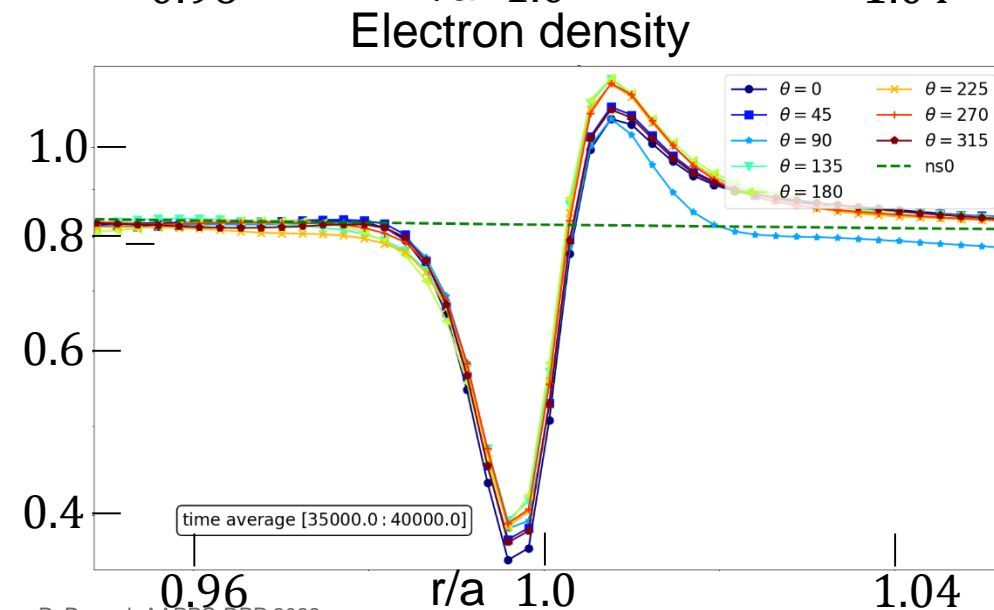
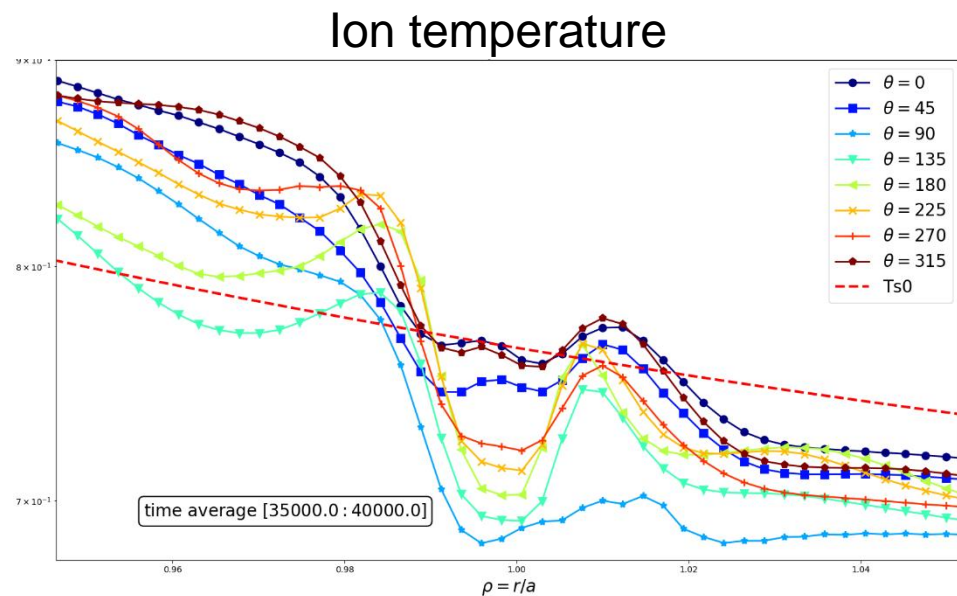
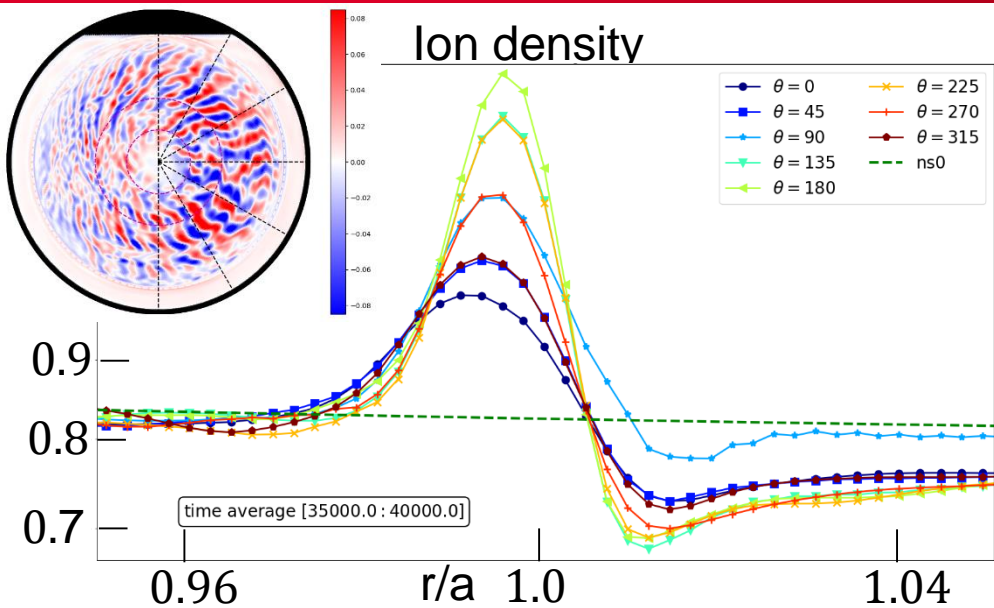


- No large E_r well
- No transition



- Fluctuations of the radial electric field





Polarisation
term

$$\mathcal{L} \phi_{m,n} + \bar{\alpha}_{p0} \frac{n_{e0}}{Z_0^2 T_e} (\phi_{m,n} - (1 - \mathcal{M}^{SO L}) \langle \phi_{m,n} \rangle_{FS}) = \rho_{m,n}^{TKE,LIM} \quad \forall (m,n) \neq (n=0, m_* = 0)$$

with

$$\rho_{m,n}^{TKE,LIM} = \rho_{m,n}^{TKE} + \bar{\alpha}_{p0} \frac{n_{e0}}{Z_0^2 T_e} [\Lambda (\mathcal{M}^{SO L} - \mathcal{M}^{mat}) (T_e - T_e^{b.c.}) + (\mathcal{M}^{mat} - \mathcal{M}^{wall}) \phi^{bias}]$$

Polarisation
term

$$\mathcal{L} = - \sum_i A_i \nabla_{\perp} \cdot \left(\frac{n_{i0}(r)}{B_0^2} \nabla_{\perp} \right)$$

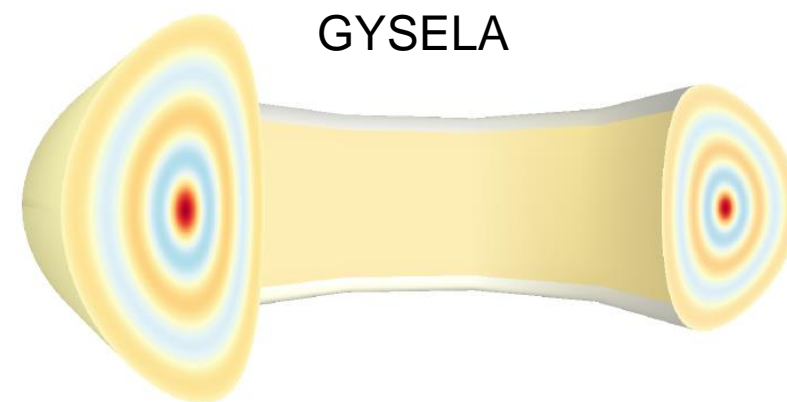
The terms in red are currently functions of the flux surface computed at the initial time.

They need to be functions of the poloidal angle and be dynamically computed

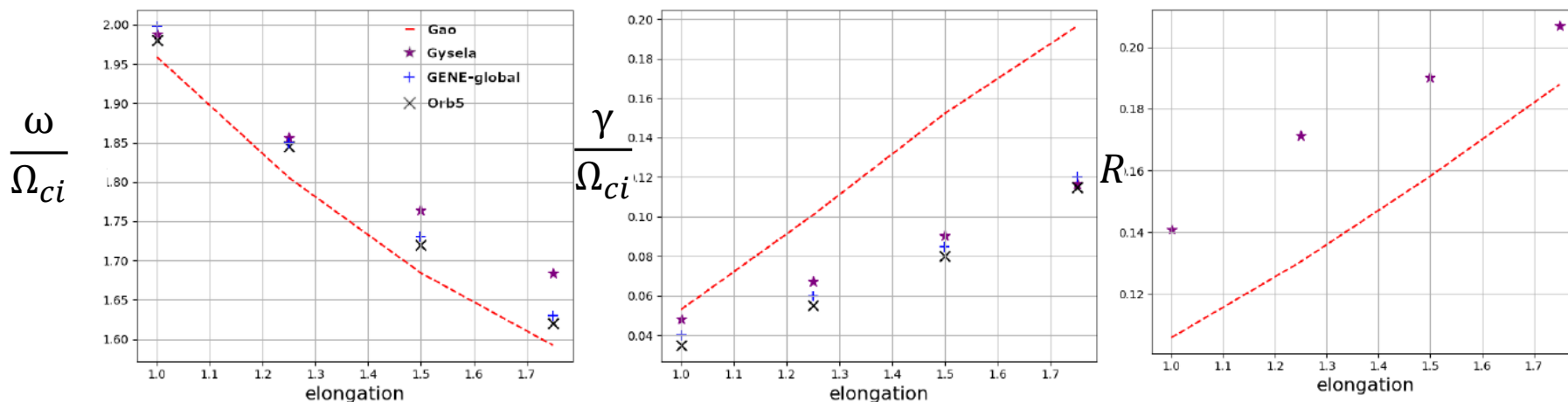
$$-\nabla \cdot (\alpha \nabla \phi) + \beta (\phi - \gamma \langle \phi \rangle_{\text{FS}}) = \text{RHS}$$

- Finite element-like approach to solve the equation in weak form using a gradient conjugate method.
- For the moment, α and β are functions of flux surfaces and do not evolve in time
- Time evolution of the coefficients is easy
- α and β as 2D functions require more work
- This solver already allows generalized geometry [K. Obrejan]

- Culham analytical equilibrium (include aspect ratio, elongation, triangularity)
- No X-point allowed for the moment. Preliminary studies have been done [E. Bourne, submitted]
- GAM dynamic on shaped plasmas and linear growth rate dependence of ITG with respect to elongation retrieved



$$\frac{\Phi(\psi, t)}{\Phi(\psi, t=0)} = R + (1 - R)e^{-\gamma t} \cos(\omega t)$$



[B. Legouix, master thesis]

- A limiter model compatible with the hybrid electron model has been developed and implemented in both GYSELA and ORB5 (not shown)
- A large impact of the position of the limiter is found on the level of poloidal asymmetry and the amplitude of the radial electric field
- The evolution of the density and the generation of large poloidal asymmetries in the SOL imply that the quasi-neutrality equation needs to be generalized. Possible but require more numerical developments
- A spontaneous transition of the electric field well is found in the case of ion magnetic drift pointing in the direction of the limiter, as expected from experiments
 - Is it due to physics or simplifications in the QN equation?

