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

Peter Donnel, G. Dif Pradalier, Giannatale G. Di, L. Villard, Grandgirard V., L. Nguyen, Obrejan K., Bourne E., Garbet X., Ghendrih P., et al.

DE LA RECHERCHE À L'INDUSTRIE

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

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MOTIVATION

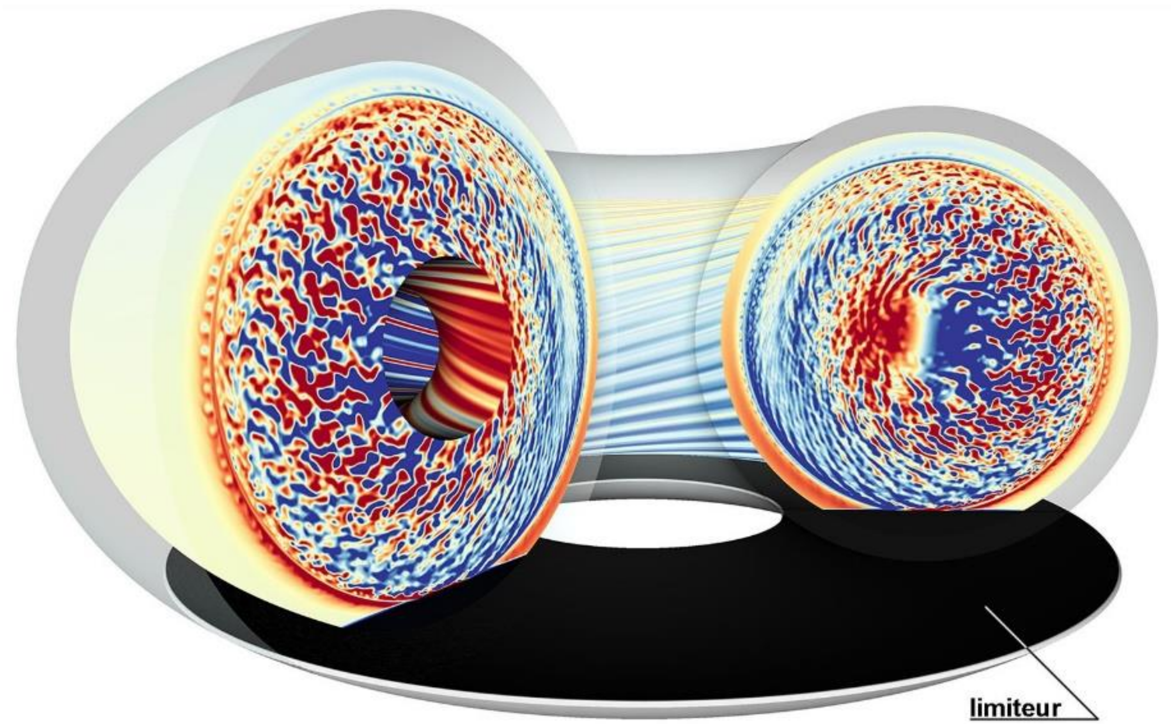
- Transport in the edge is crucial for the global confinement
- LH transition is happening close to the transition between open and closed field lines
- LH transition is related to the deepening of a radial electric field well
- Origin of this radial electric field not fully understood

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

THE GYROKINETIC CODE GYSELA

The GYSELA code is

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



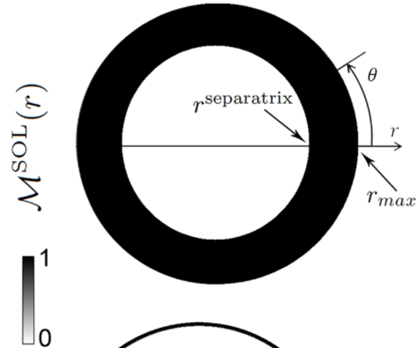
GYROKINETIC SIMULATION WITH A LIMITER AND ADIABATIC ELECTRONS

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

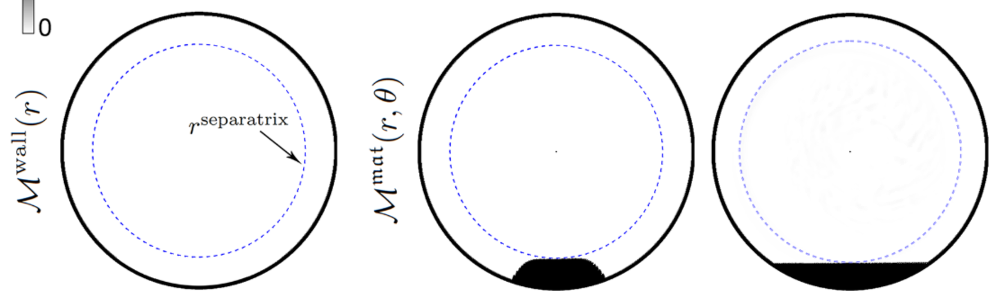
- A momentum and energy sink via a source term on the Vlasov equation

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

- A modification of the quasi-neutrality equation



Tokamak volume	Mask
All plasma	$1 - \mathcal{M}^{\rm mat}(r,\theta)$
Closed field lines	$1 - \mathcal{M}^{\rm SOL}(r)$
Scrape-Off Layer	$\mathcal{M}^{\rm SOL}(r) - \mathcal{M}^{\rm mat}(r,\theta)$
Material boundaries	$\mathcal{M}^{\rm mat}(r,\theta)$
Limiter only	$\mathcal{M}^{\rm mat}(r,\theta) - \mathcal{M}^{\rm wall}(r)$
Wall only	$\mathcal{M}^{\rm wall}(r)$



$$\mathcal{L}\phi + \frac{n_{e_0}}{Z_0^2 T_e}\left[\phi - \boxed{\left(1 - \mathcal{M}^{SOL}\right)} \langle \phi \rangle_{\rm FS}\right] = \rho^{LIM}$$

$$\rho^{LIM} = \rho + \boxed{\frac{n_{e_0}}{Z_0^2 T_e}\left[\Lambda\left(\mathcal{M}^{SOL} - \mathcal{M}^{mat}\right)\left(T_e - T_e^{b.c.}\right) + \left(\mathcal{M}^{mat} - \mathcal{M}^{wall}\right)\phi^{bias}\right]}$$

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

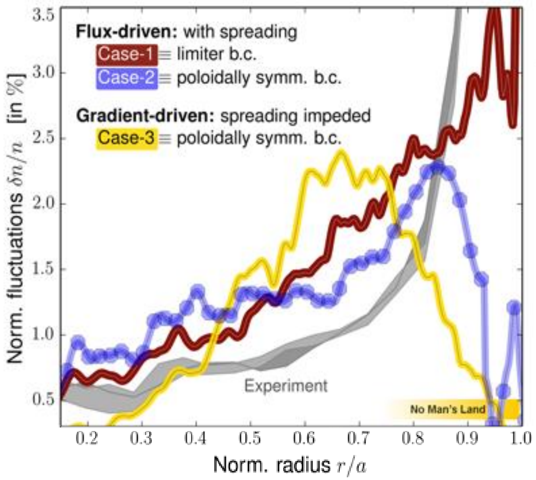
$$\mathcal{L} \;=\; -\sum_i A_i \nabla_\perp \cdot \left(\frac{n_{i_0}(r)}{B_0^2}\nabla_\perp\right)$$

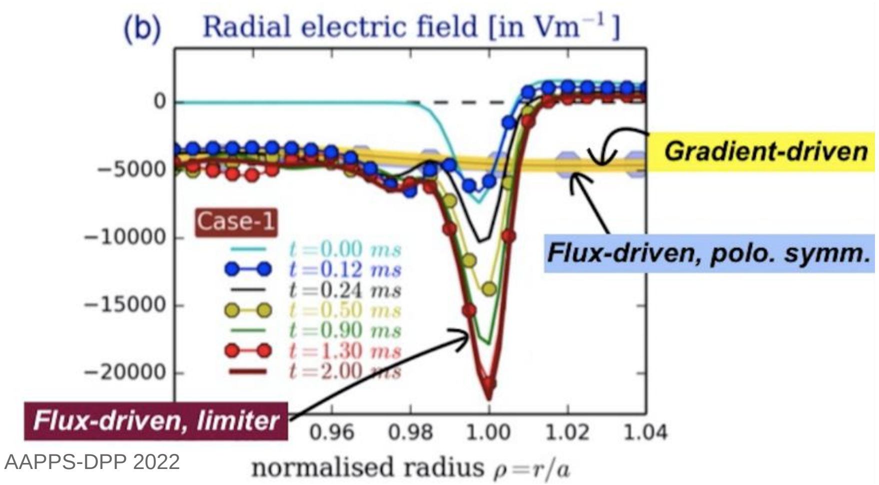
$$\Lambda = -\frac{1}{2}\ln\left[2\pi\frac{m_e}{m_i}\left(1 + \frac{T_i}{T_e}\right)\right]$$

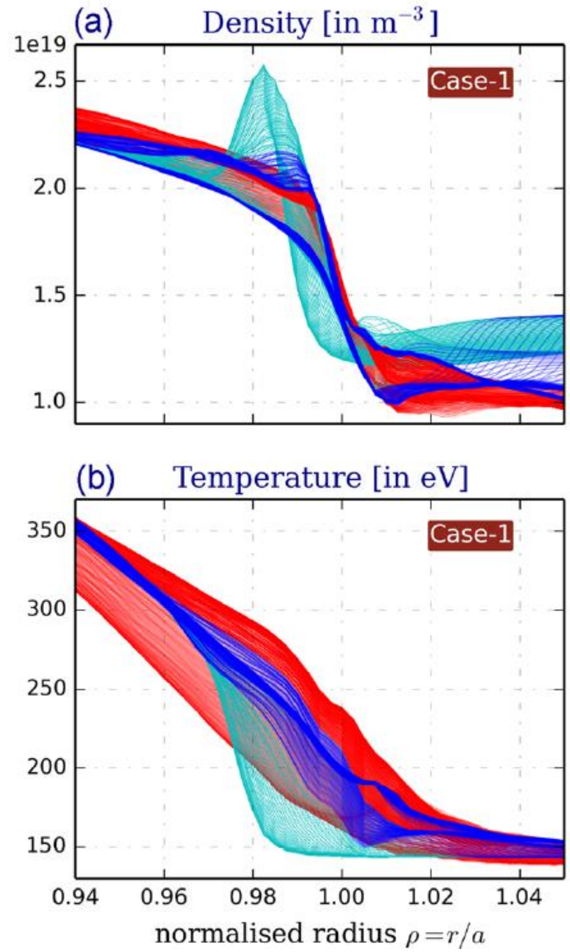
IMPACT OF A LIMITER WITH ADIABATIC ELECTRONS

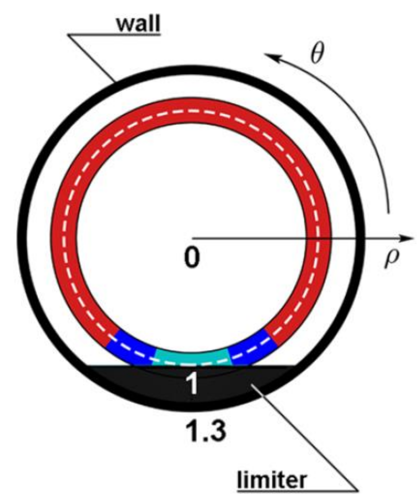
Limiter leads to [Dif-Pradalier 2022]

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









HYBRID ELECTRON MODEL IN THE CORE

The hybrid electron model [Idomura 2016] treats

- Trapped electrons kinetically
- Passing electrons adiabatically

Passing fraction

$$-\sum_i A_i \nabla_\perp \cdot \left(\frac{n_{i_0}}{B_0^2} \nabla_\perp \phi \right) - A_e \nabla_\perp \cdot \left(\bar{\alpha}_{t0} \frac{n_{e_0}}{B_0^2} \nabla_\perp \phi \right) + \bar{\alpha}_{p0} \frac{n_{e_0}}{Z_0^2 T_e} \left(\phi - \langle \phi \rangle_{\mathrm{FS}} \right) = \sum_i Z_i \delta n_i - \delta n_e^{\mathrm{trap.}}$$

Trapped fraction

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

$$-\sum_i A_i \nabla_\perp \cdot \left(\frac{n_{i_0}}{B_0^2} \nabla_\perp \phi \right) - A_e \nabla_\perp \cdot \left(\frac{n_{e_0}}{B_0^2} \nabla_\perp \phi \right) = \sum_i Z_i \delta n_i - \delta n_e \quad \text{for} \quad n = 0, m_\star = 0$$

HYBRID ELECTRON MODEL WITH LIMITER

$$\mathcal{L}\phi_{m,n} + \boxed{\bar{\alpha}_{p0}}\frac{n_{e_0}}{Z_0^2 T_e}\left(\phi_{m,n} - \boxed{\left(1-\mathcal{M}^{SOL}\right)}\langle\,\phi_{m,n}\,\rangle_{\mathrm{FS}}\right) = \rho_{m,n}^{TKE,LIM} \qquad \forall(m,n)\neq(n=0, m_\star=0)$$

with

$$\rho_{m,n}^{TKE,LIM} = \rho_{m,n}^{TKE} + \boxed{\boxed{\bar{\alpha}_{p0}}\frac{n_{e_0}}{Z_0^2 T_e}\left[\Lambda\left(\mathcal{M}^{SOL}-\mathcal{M}^{mat}\right)\left(T_e - T_e^{b.c.}\right) + \left(\mathcal{M}^{mat}-\mathcal{M}^{wall}\right)\phi^{bias}\right]}$$

Polarisation term $\quad \mathcal{L} \;=\; -\sum_i A_i \nabla_\perp \cdot \left(\frac{n_{i_0}(r)}{B_0^2}\nabla_\perp\right)$

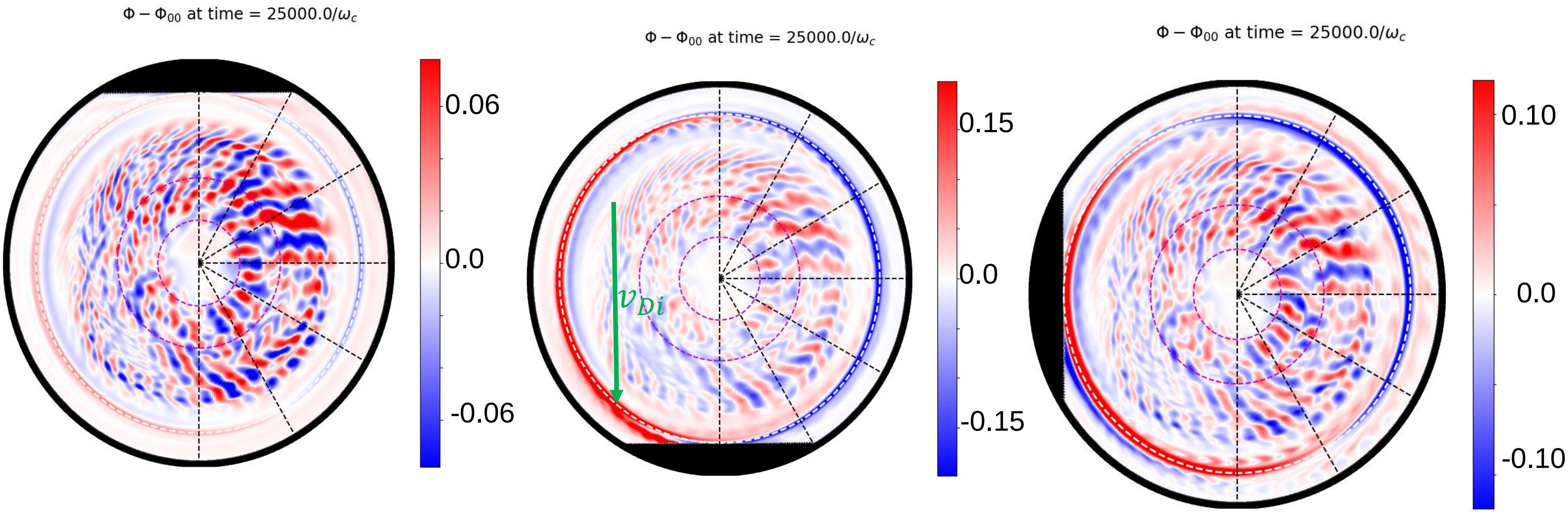
The trapped fraction definition is modified in the SOL:

- 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

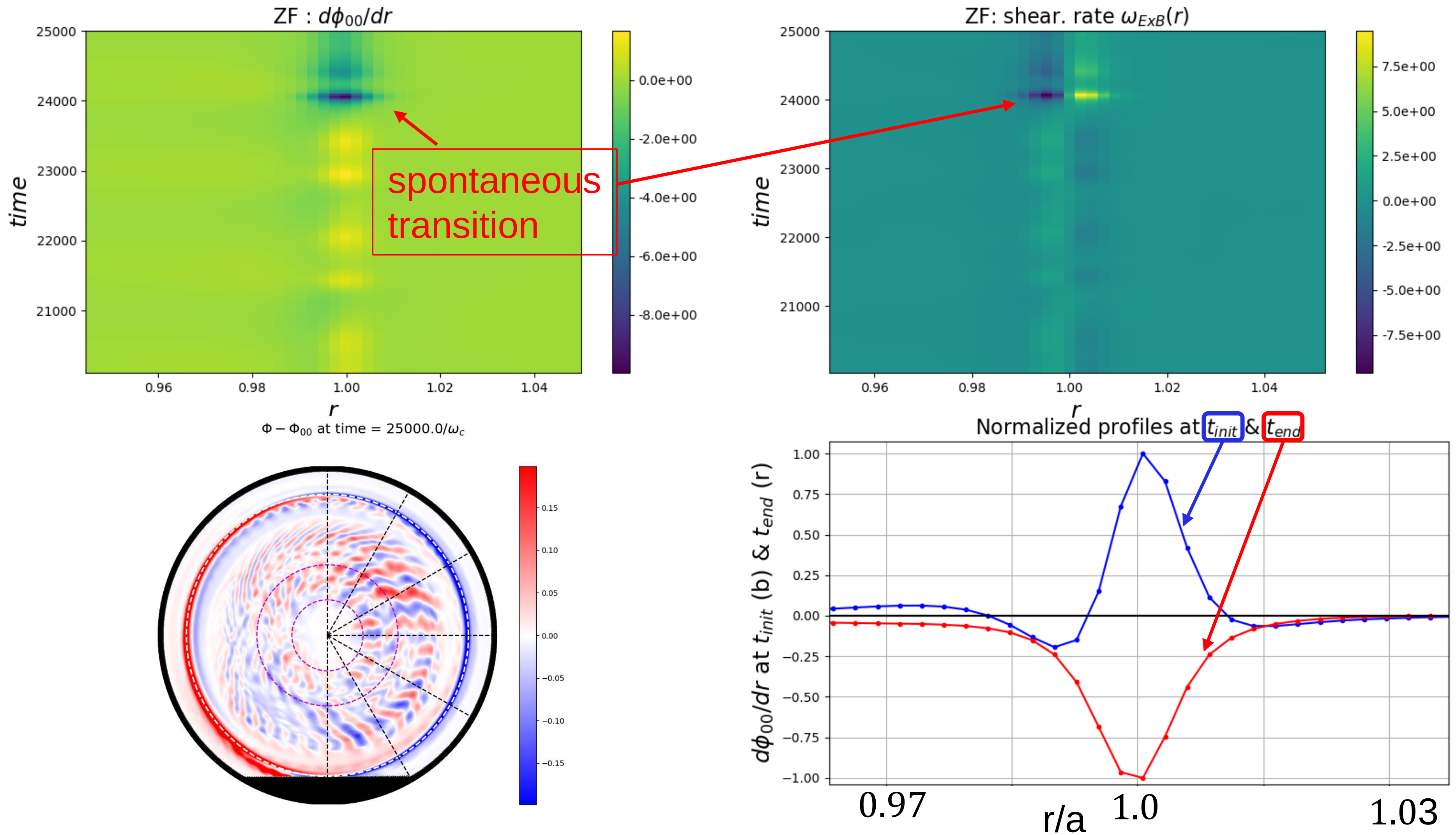
$$\phi^{LIM} = \phi^{\mathrm{TKE}} + \left[1-\mathcal{M}^{SOL}(r)\right]\left[-\phi^{\mathrm{TKE}}_{(m_\star=0,n=0)} + \phi^{\mathrm{FKE}}_{(m_\star=0,n=0)}\right]$$

ELECTRIC POTENTIAL WITH DIFFERENT LIMITER POSITIONS



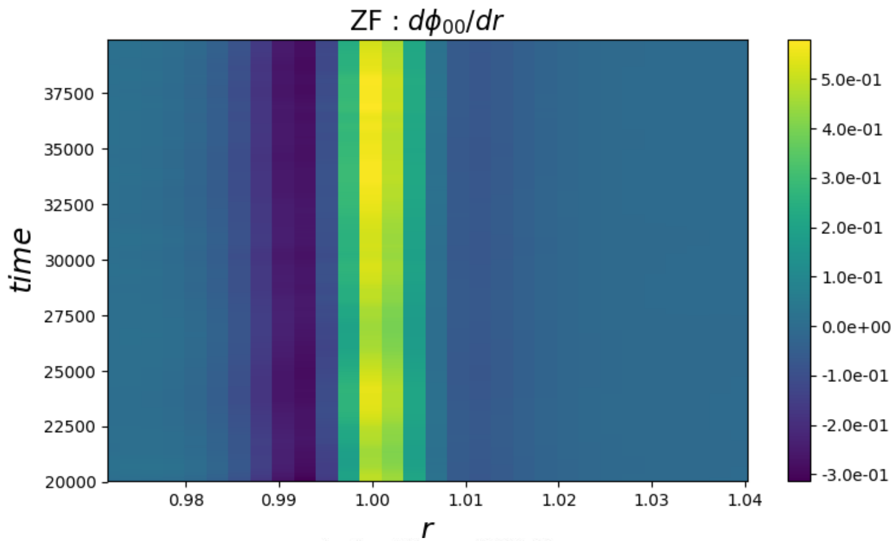
- Small impact of the limiter position in the deep core
- Large impact of limiter position on the poloidal asymmetry of the potential.

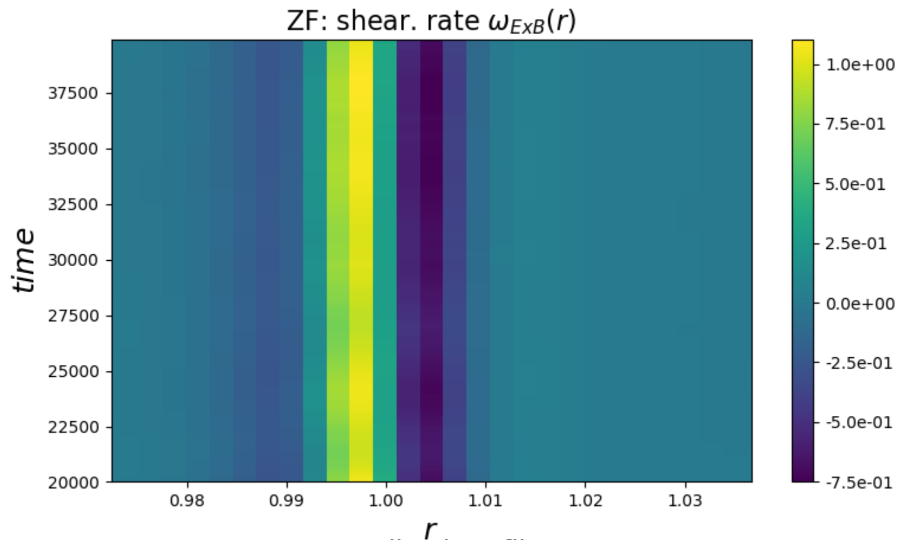
RADIAL ELECTRIC FIELD AT THE EDGE: LIMITER BOTTOM

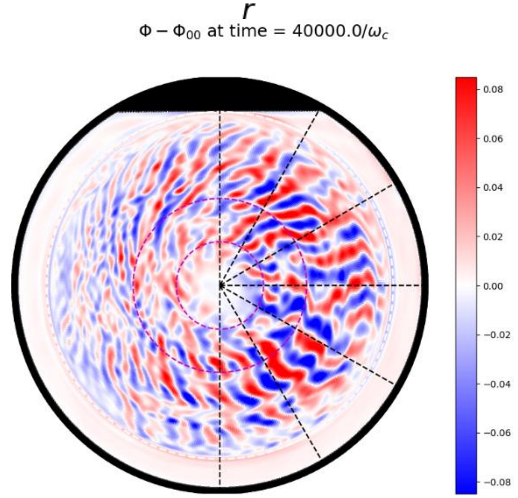


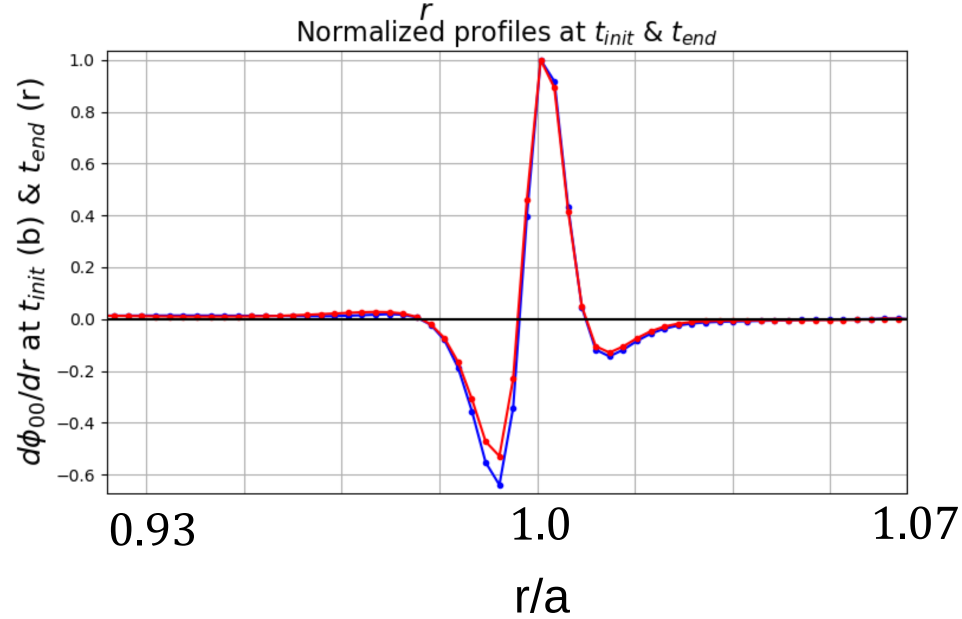
- Spontaneous transition of the edge Er well. Qualitative agreement with experiments.
- Origin of the transition : physics or numerical?

RADIAL ELECTRIC FIELD AT THE EDGE: LIMITER TOP



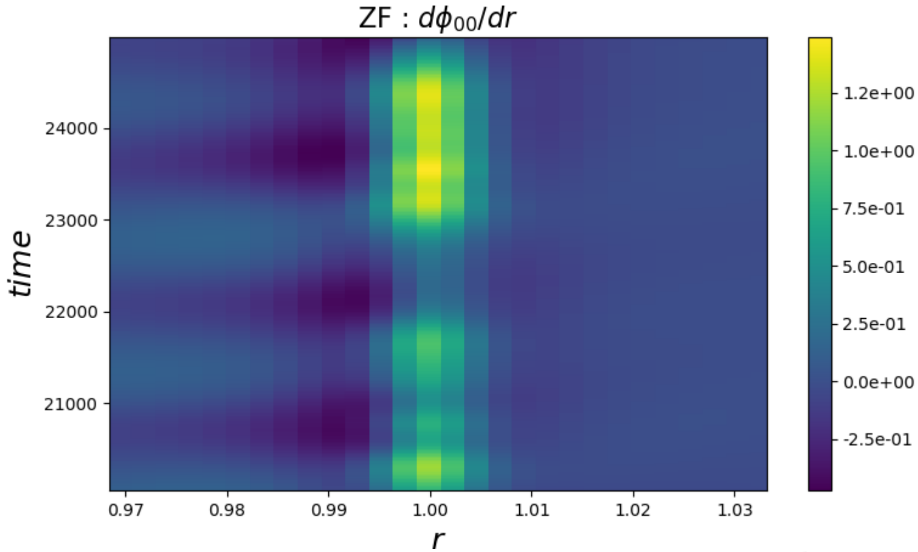


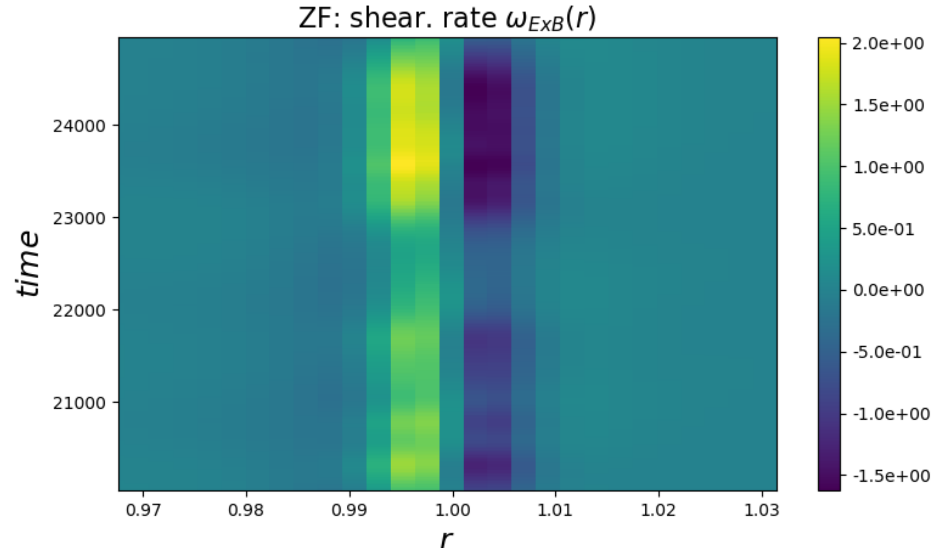


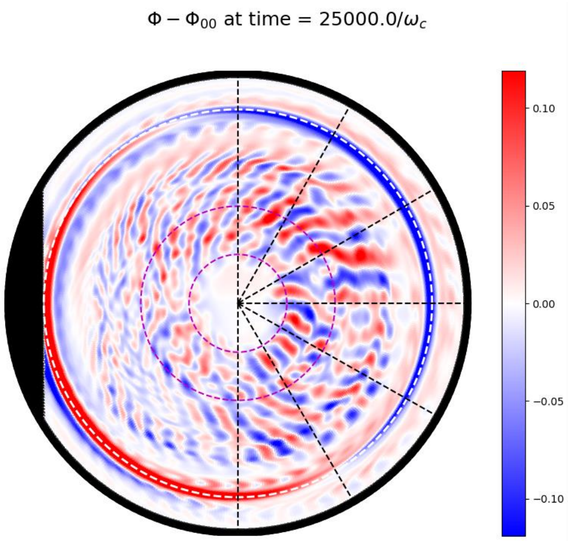


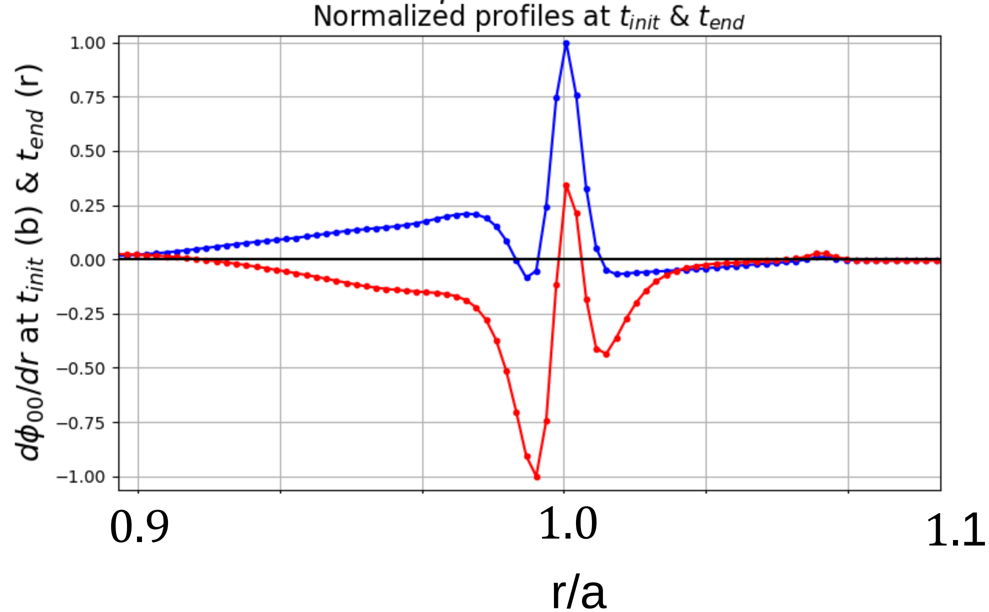
- No large Er well
- No transition

RADIAL ELECTRIC FIELD AT THE EDGE: LIMITER IN





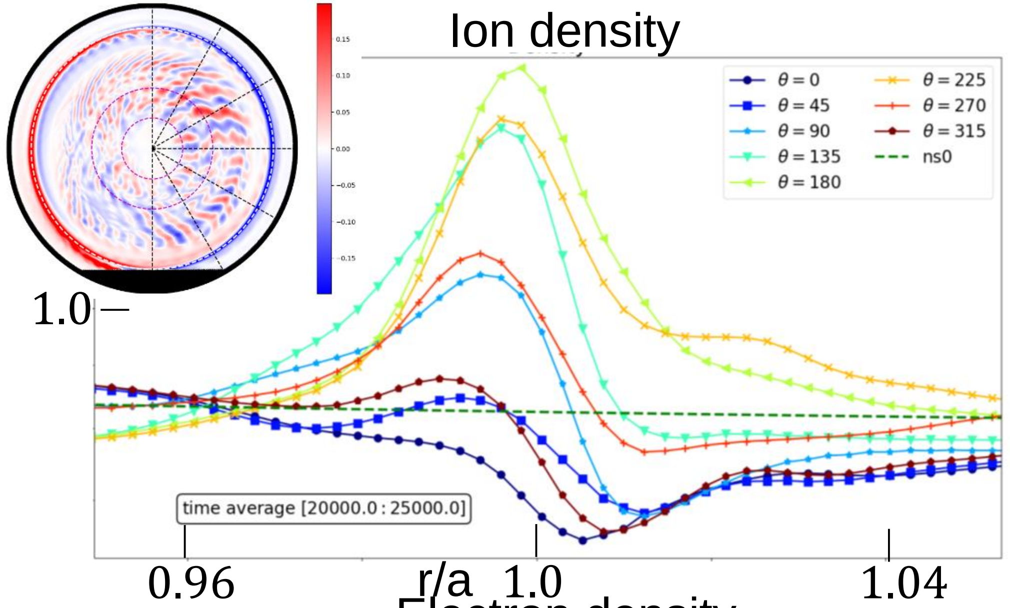




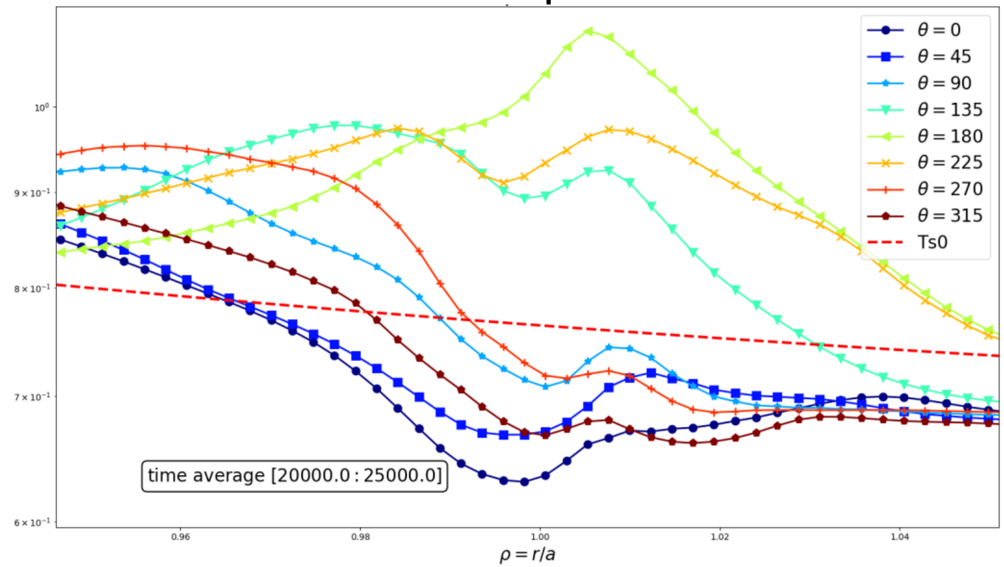
- Fluctuations of the radial electric field

GENERATION OF LARGE POLOIDAL ASYMMETRIES: LIMITER BOTTOM

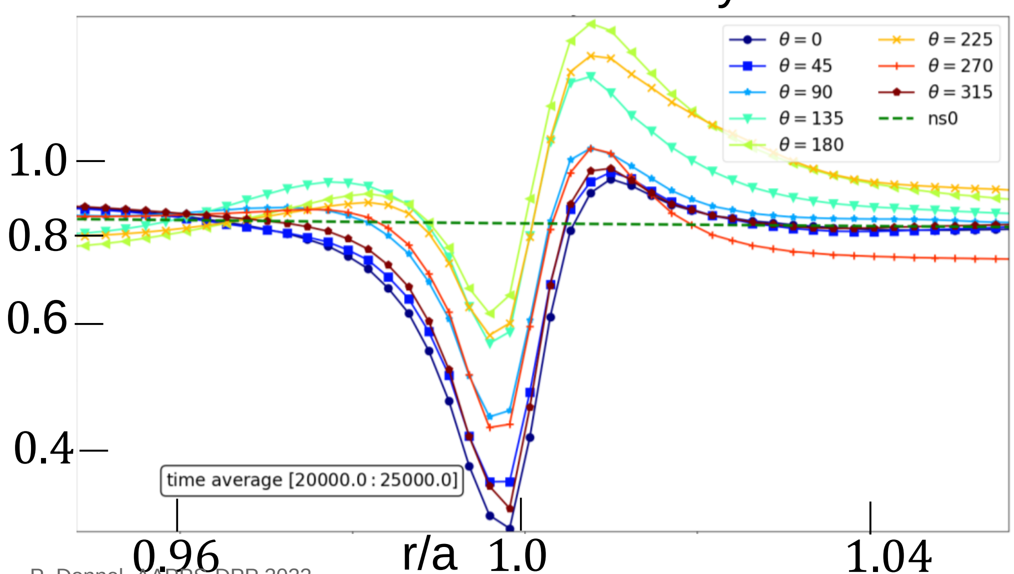
Ion density



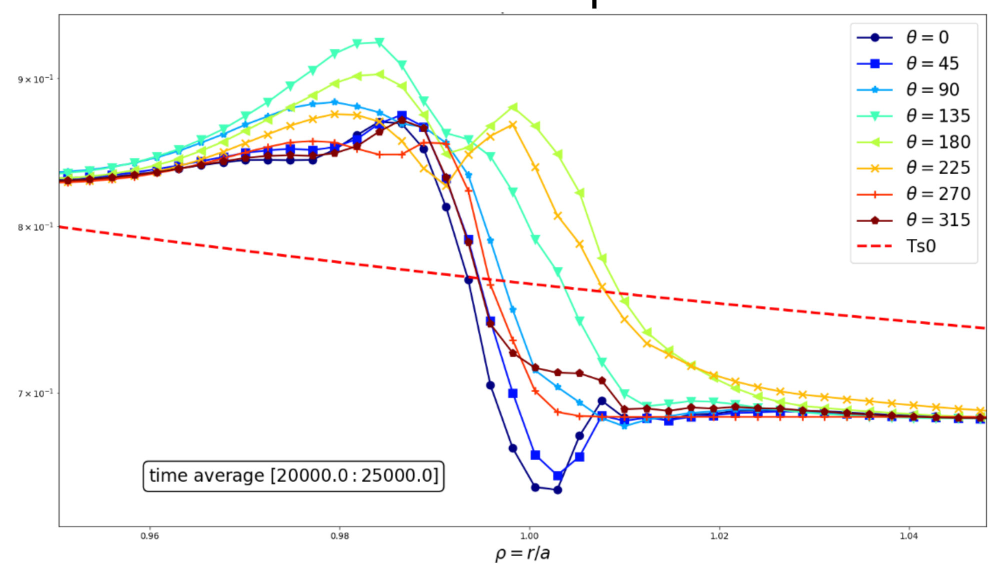
Ion temperature



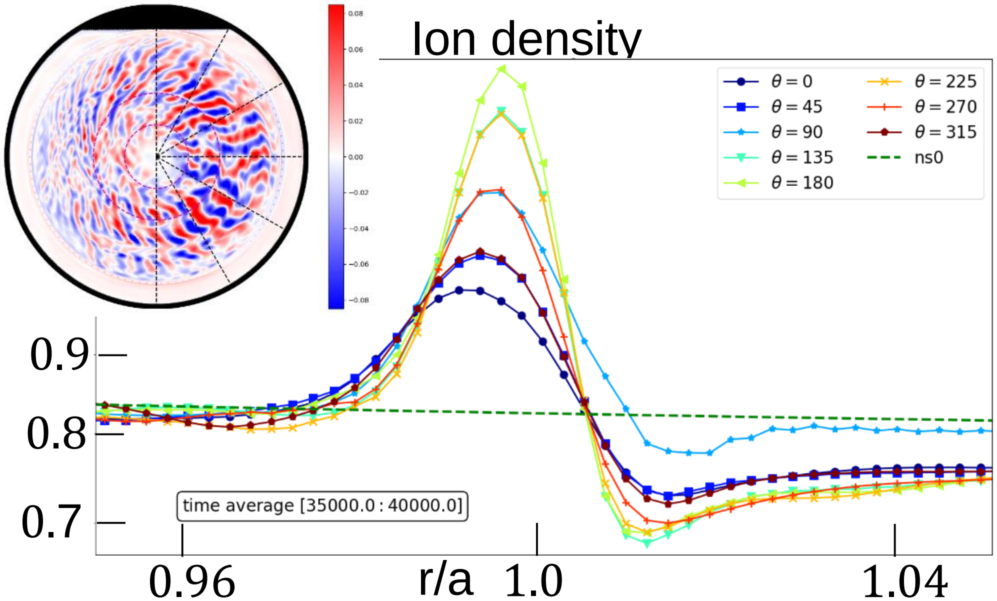
Electron density



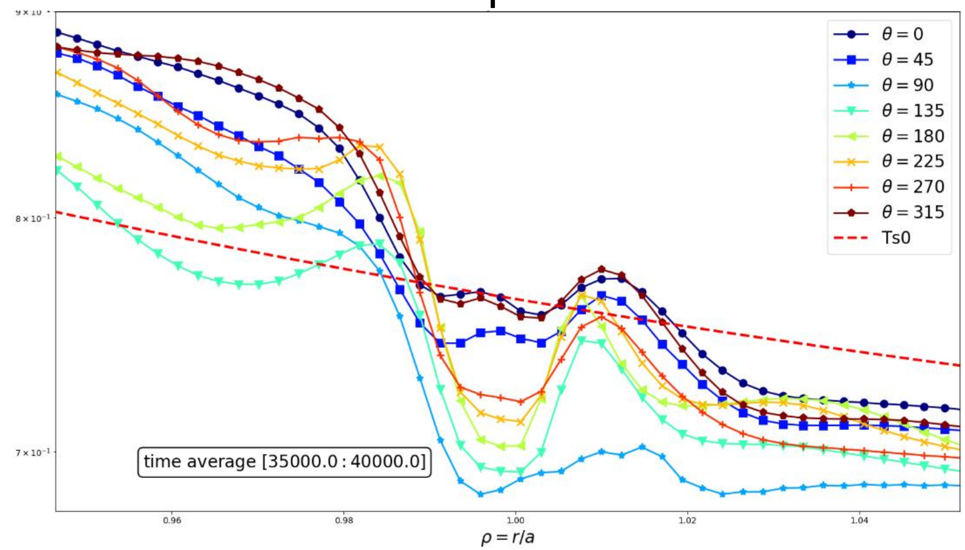
Electron temperature



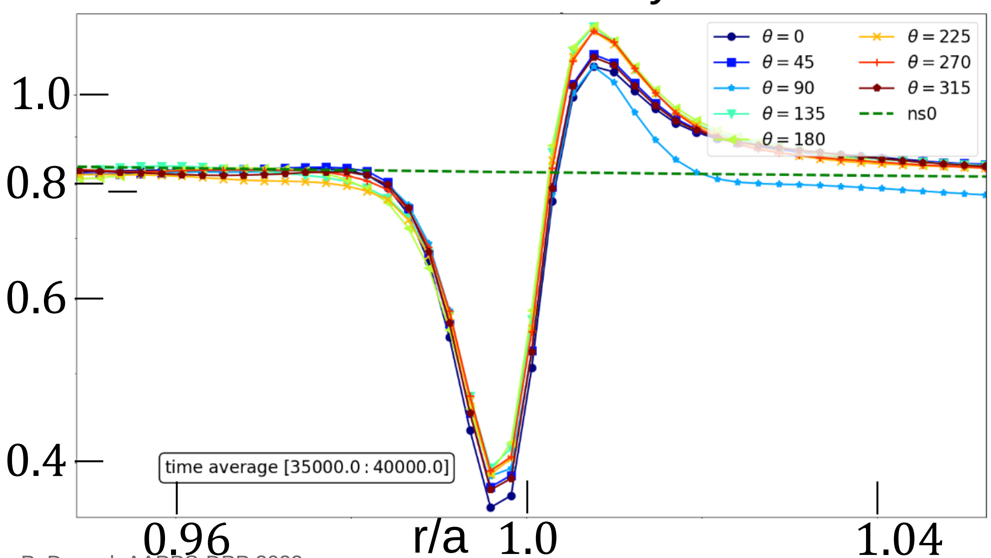
GENERATION OF LARGE POLOIDAL ASYMMETRIES: LIMITER TOP



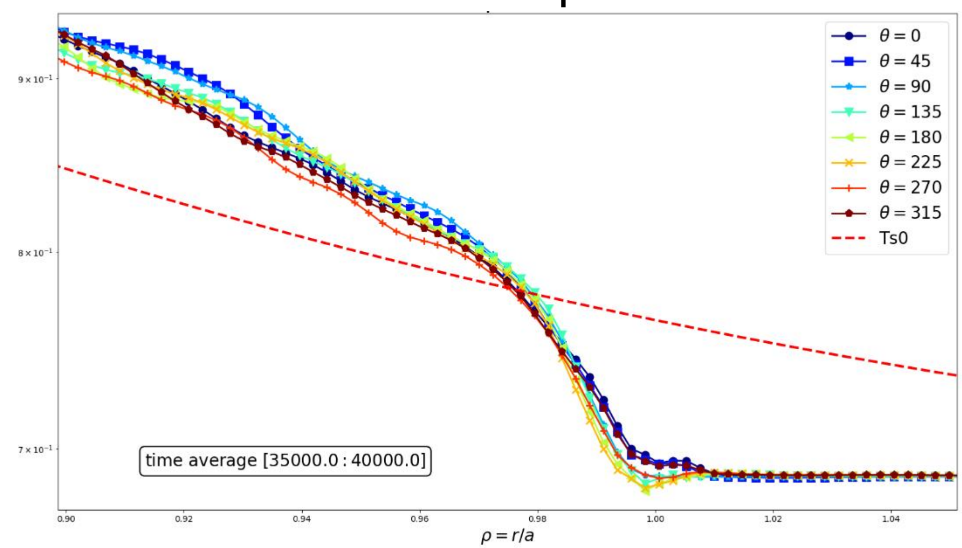
Ion temperature



Electron density



Electron temperature



NECCESITY TO INCLUDE POLOIDAL AND TEMPORAL EVOLUTION OF THE DENSITY IN THE QUASI-NEUTRALITY

Polarisation term

$$\boxed{\mathcal{L}}\phi_{m,n} + \boxed{\bar{\alpha}_{p0}}\frac{\boxed{n_{e_0}}}{Z_0^2 T_e}\left(\phi_{m,n} - \left(1 - \mathcal{M}^{SOL}\right)\langle\, \phi_{m,n}\,\rangle_{\mathrm{FS}}\right) = \rho_{m,n}^{TKE,LIM} \qquad \forall (m,n) \neq (n=0, m_\star = 0)$$

with

$$\rho_{m,n}^{TKE,LIM} = \rho_{m,n}^{TKE} + \boxed{\bar{\alpha}_{p0}}\frac{\boxed{n_{e_0}}}{Z_0^2 T_e}\left[\Lambda\left(\mathcal{M}^{SOL} - \mathcal{M}^{mat}\right)\left(T_e - T_e^{b.c.}\right) + \left(\mathcal{M}^{mat} - \mathcal{M}^{wall}\right)\phi^{bias}\right]$$

Polarisation term

$$\mathcal{L} \;=\; -\sum_i A_i \nabla_\perp \cdot \left(\frac{\boxed{n_{i_0}(r)}}{B_0^2}\nabla_\perp\right)$$

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

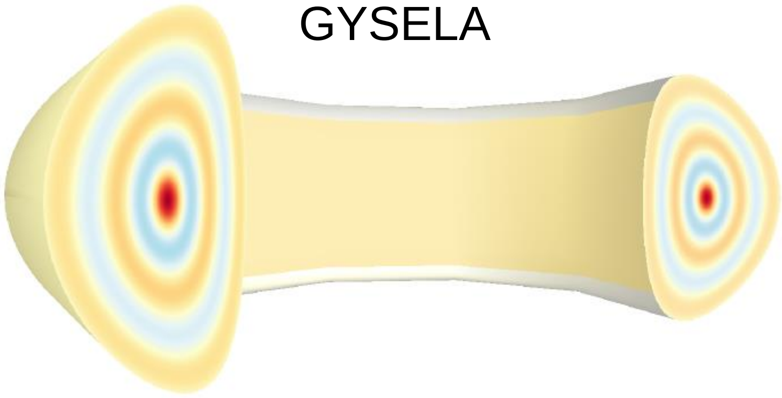
A NEW SPLINE BASED SOLVER (SELALIB)

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

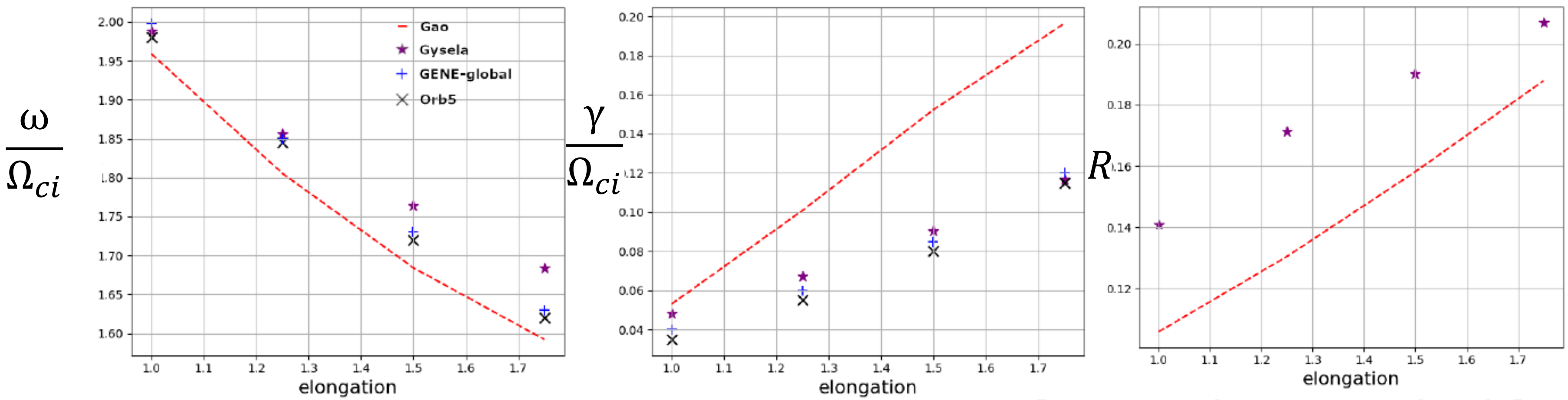
- Finite element-like approach to solve the equation in weak form using a gradient conjugate method.
- For the moment, α and β are functions of flux surfaces and do not evolve in time
- Time evolution of the coefficients is easy
- α and β as 2D functions require more work
- This solver already allows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

GYSELA WITH GENERALISED GEOMETRY

- 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



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



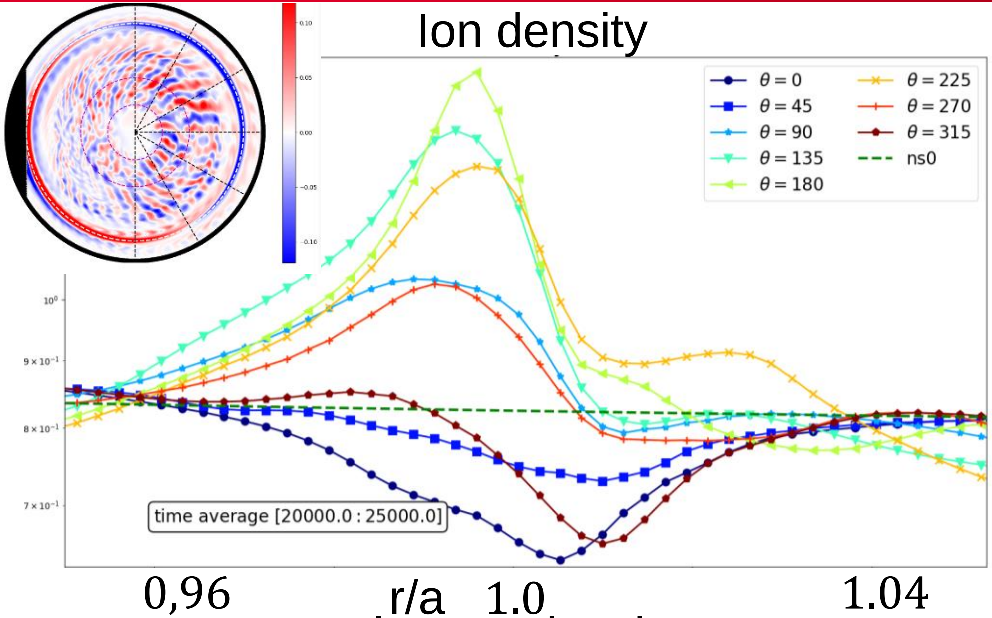
[B. Legouix, master thesis]

CONCLUSION

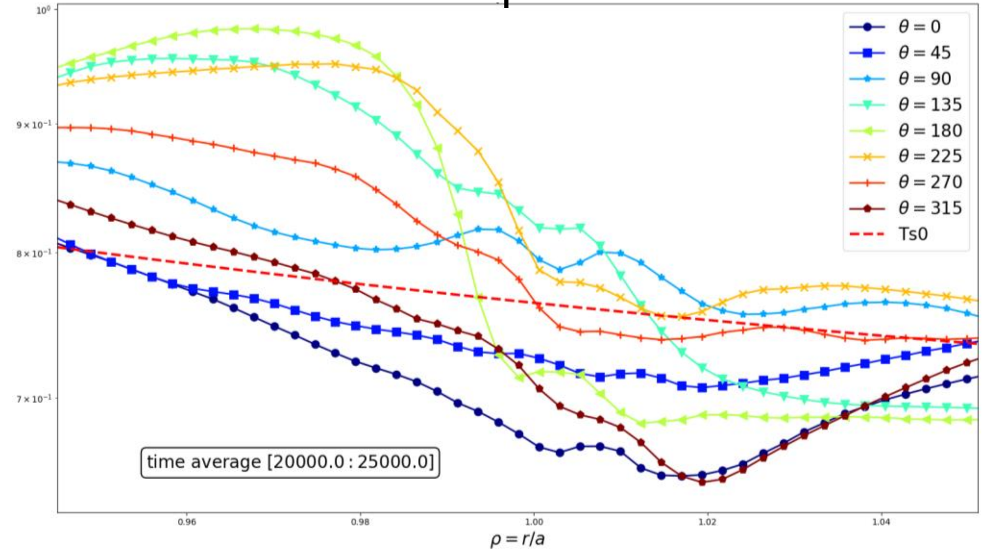
- A limiter model compatible with the hybrid electron model has been developed and implemented in both GYSELA and ORB5 (not shown)
- A large impact of the position of the limiter is found on the level of poloidal asymmetry and the amplitude of the radial electric field
- The evolution of the density 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?

GENERATION OF LARGE POLOIDAL ASYMMETRIES: LIMITER IN

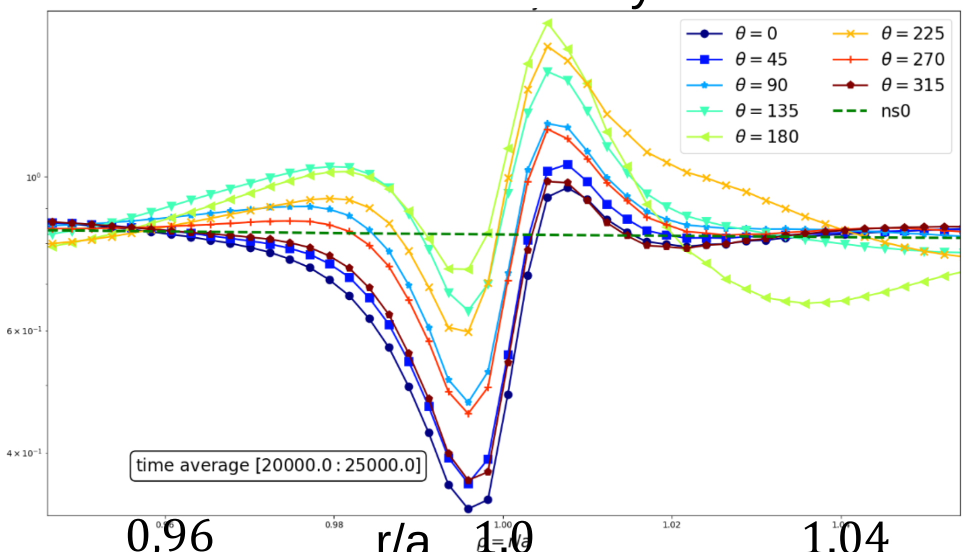
Ion density



Ion temperature



Electron density



Electron temperature