Global fluid simulations of plasma turbulence in diverted stellarators

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Content of this talk

1. Introduction: plasma boundary and GBS code

2. Simulation of an island divertor stellarator

3. First approach to simulate a stellarator with an ergodic divertor

Introduction

- Plasma **boundary** determines the heat flux on plasma-facing materials

- In tokamaks, the boundary has been addressed **experimentally** and through **simulations**:
  - Broad-band turbulence and blobs

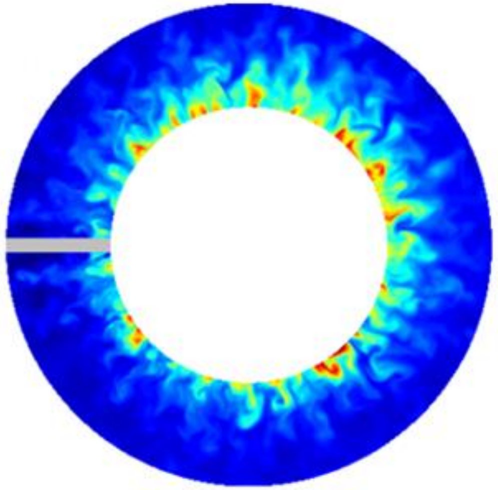
- Recent **W7-X experiments** showed significant differences with respect to tokamaks:
  - Filaments bound to their flux surface [Killer, 2021]

- Stellarator turbulence simulations still in its infancy:
  - Gyrokinetic δf codes (GENE-3D, Stella, XGC-S, …) – study the core
  - Fluid code BOUT++ simulated edge filaments in a rotating ellipse [Shanahan, 2019]

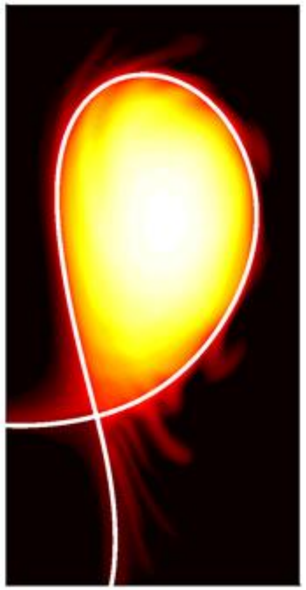
Introduction

- In the boundary: collisionality may be high and turbulence time-scales longer than ω_{ci}^{-1}
  - fluid drift-reduced Braginskii equations [Zeiler, 1999]

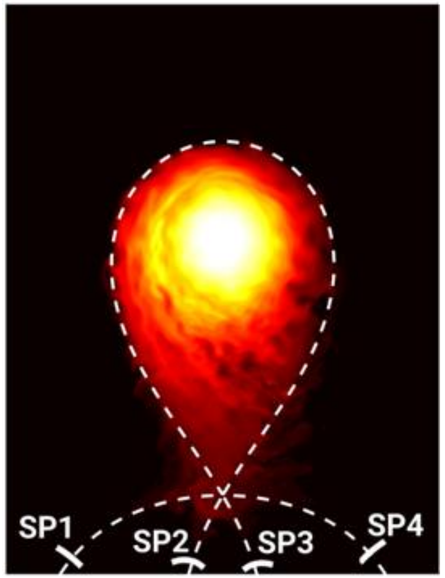
- GBS is a two-fluid, global, flux-driven turbulence code that solves the drift-reduced Braginskii equations



Ricci and Rogers, PoP 2013

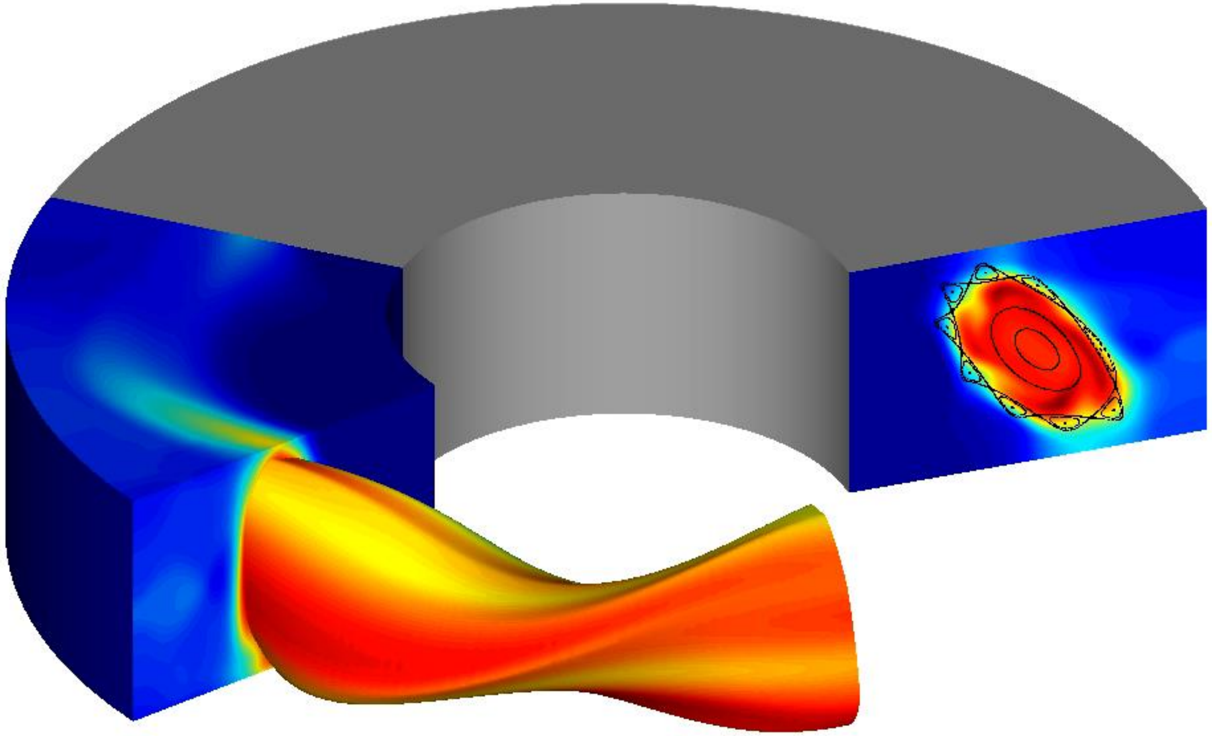


Giacomin et al., submitted to JCP



Giacomin et al., NF 2020

This talk:
Global fluid simulations of diverted stellarators with GBS



- Density and temperature sources generate the gradients that drive turbulence
- No separation between equilibrium and fluctuating quantities

GBS solves the drift-reduced Braginskii equations

- Set of equations for $n, T_e, T_i, V_{\parallel e}, V_{\parallel i}, \omega, \phi$
  - Density (n) equation:

$$\nabla \cdot \mathbf{\Gamma}_{\mathrm{ExB}} = \mathbf{b} \cdot [\nabla\phi \times \nabla n] + 2n\frac{B}{2}\left[\nabla \times \frac{\mathbf{b}}{B}\right] \cdot \nabla\phi$$

$$\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{\Gamma}_{\mathrm{ExB}} + \nabla \cdot \mathbf{\Gamma}_{\mathrm{dia}} + \nabla \cdot \mathbf{\Gamma}_{\parallel e} = \mathcal{S}_n$$

  - Electron and ion temperatures (T_e, T_i) equations: energy conservation
  - Parallel electron and ion velocities ($V_{\parallel e}, V_{\parallel i}$): parallel force balance
  - Electrostatic potential (Φ): obtained from vorticity (quasi-neutrality)

Content of this talk

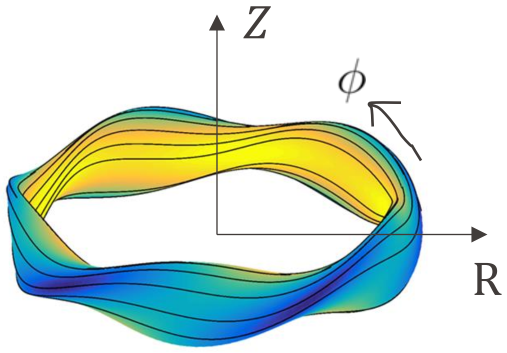
Stellarator with an island divertor

$$\nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = \nabla V$$

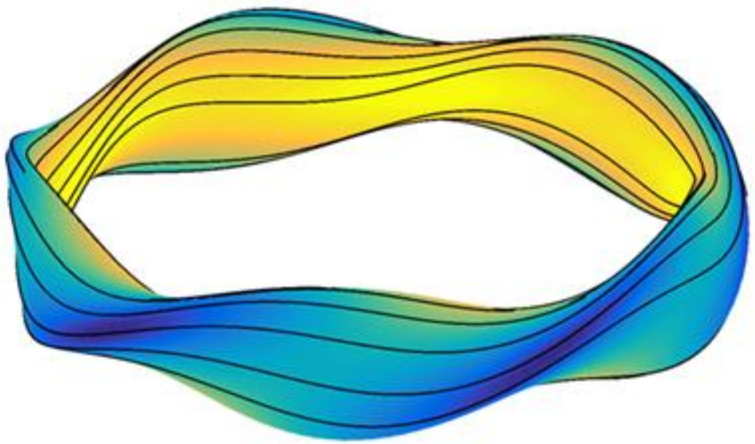
$$\nabla \cdot \mathbf{B} = 0 \rightarrow \nabla^2 V = 0$$

- Dommaschk potentials [Dommaschk, CPC 1986] are a solution of Laplace's equation in a torus:

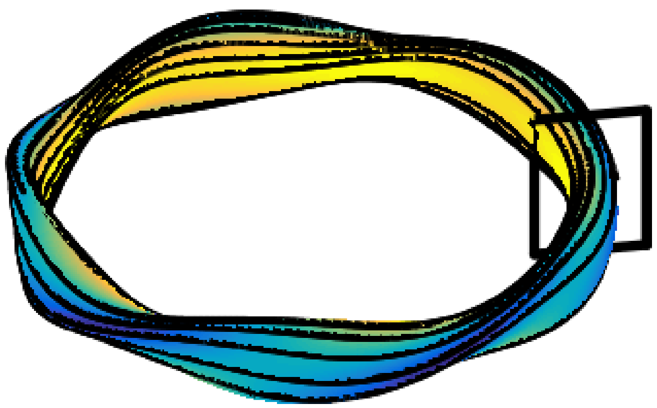
$$V(R, \phi, Z) = \phi + \sum_{m,l} V_{m,l}(R, \phi, Z)$$

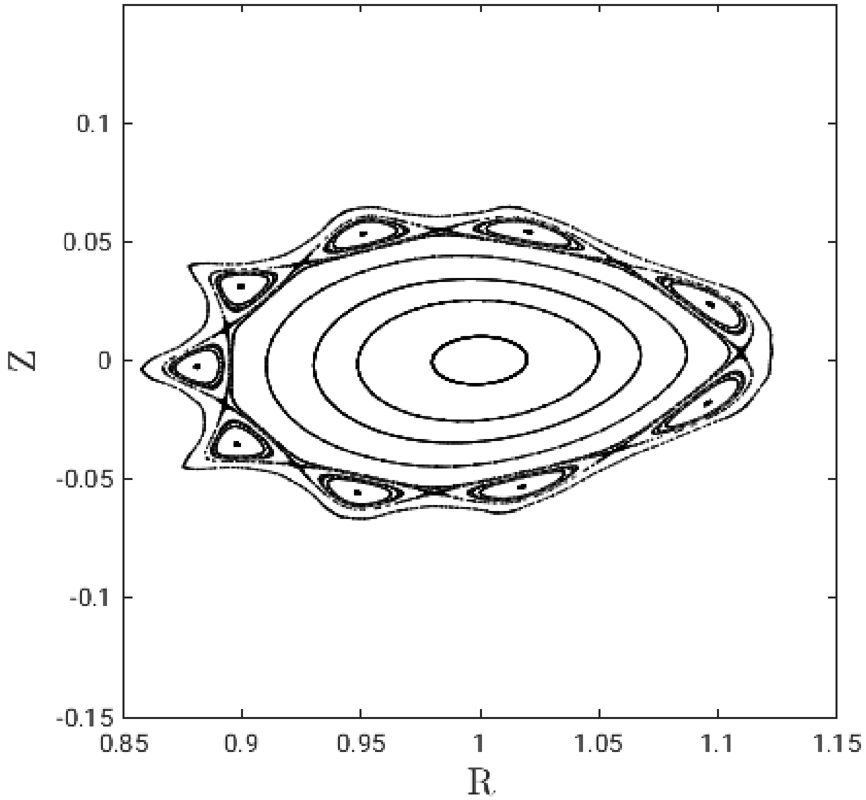


We simulate a 5-field period stellarator…



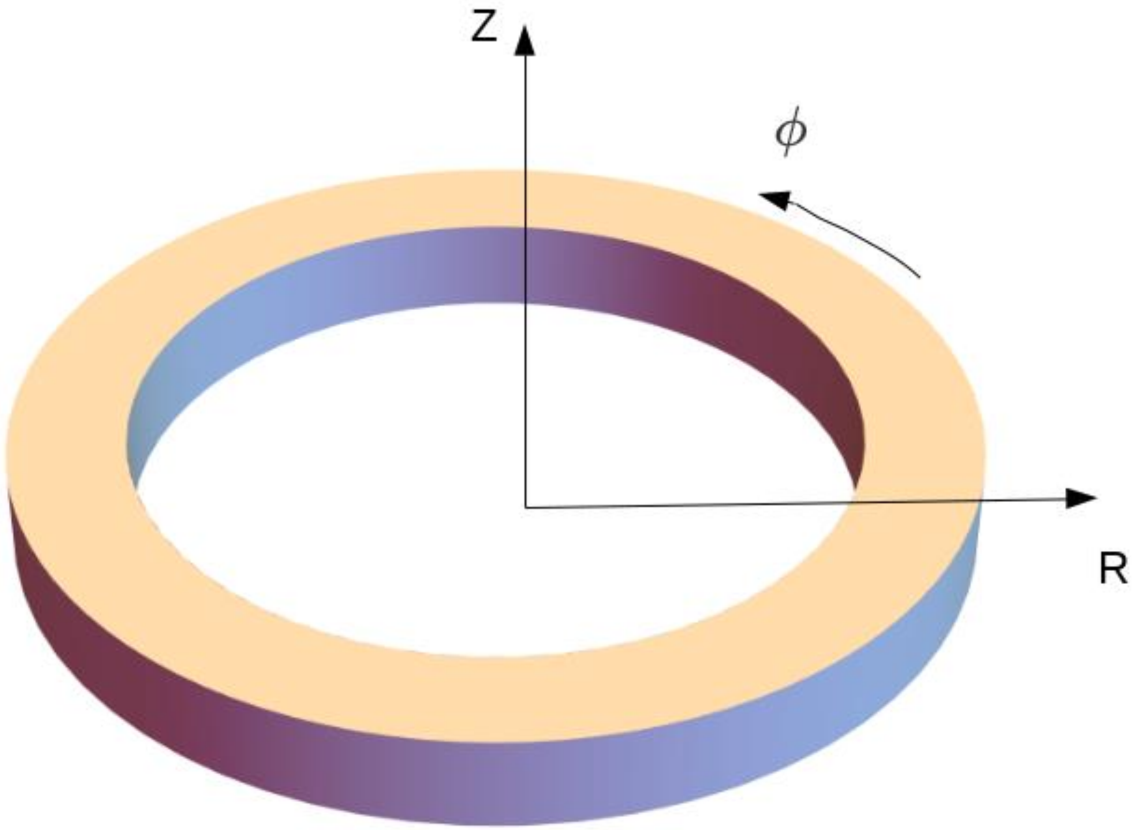
We simulate a 5-field period stellarator... with a 5/9 chain of islands

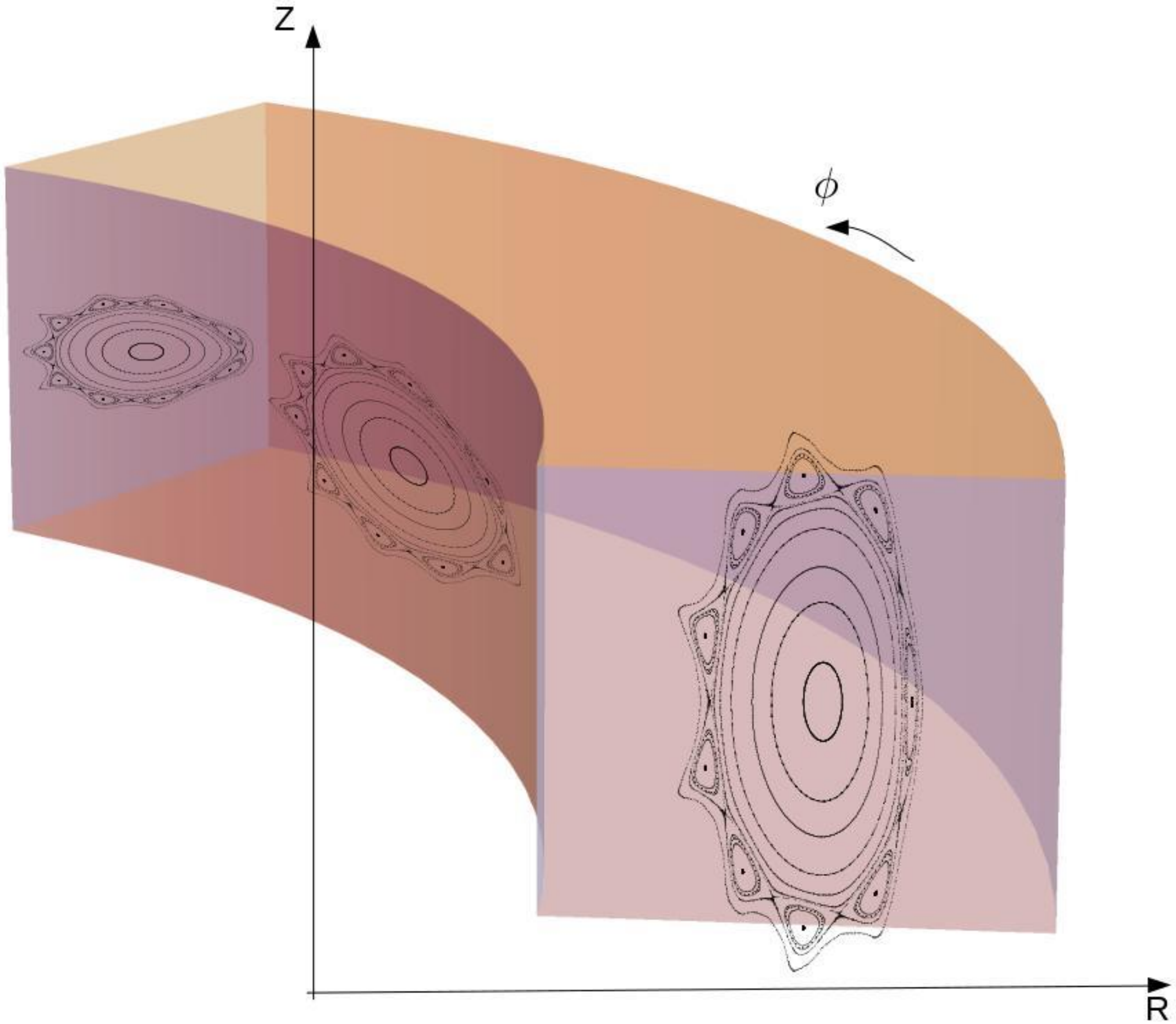




- All rotational transform from rotation of the ellipses

GBS domain boundary intersects divertor islands





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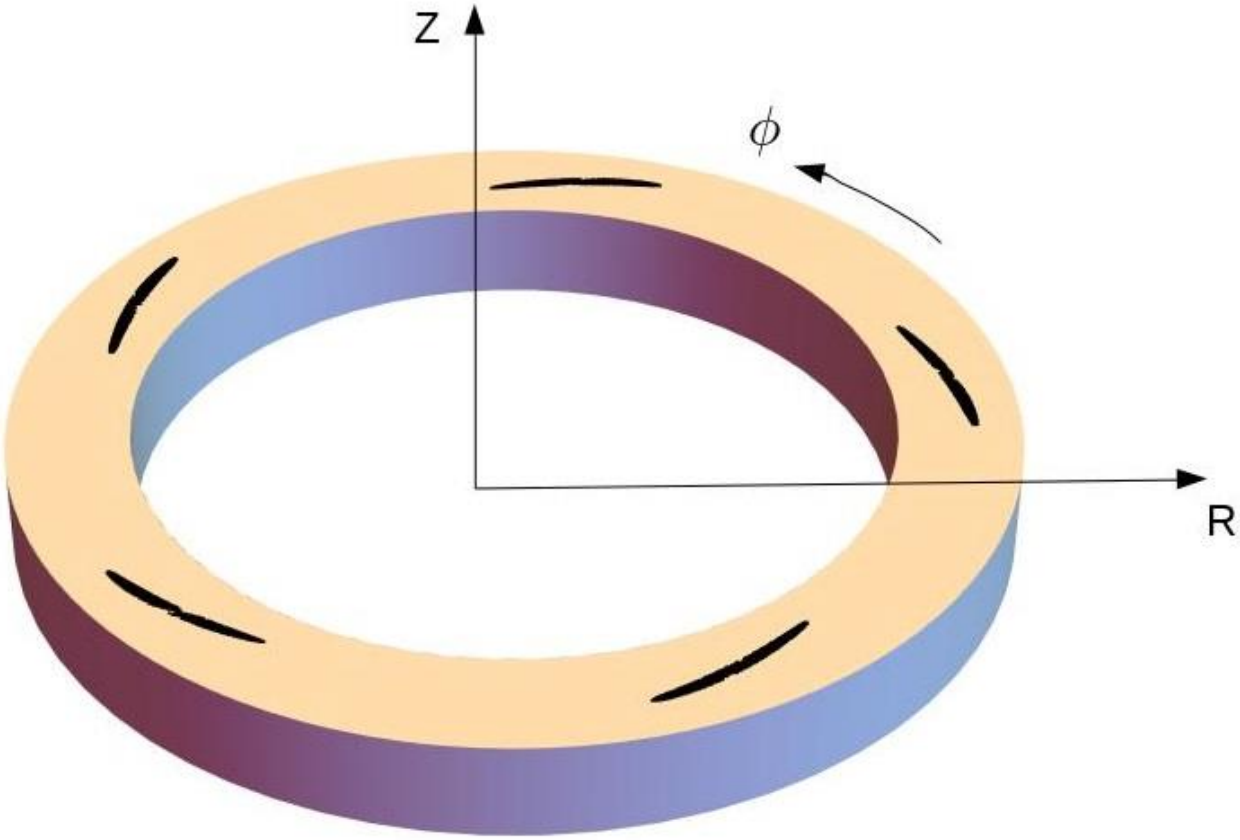
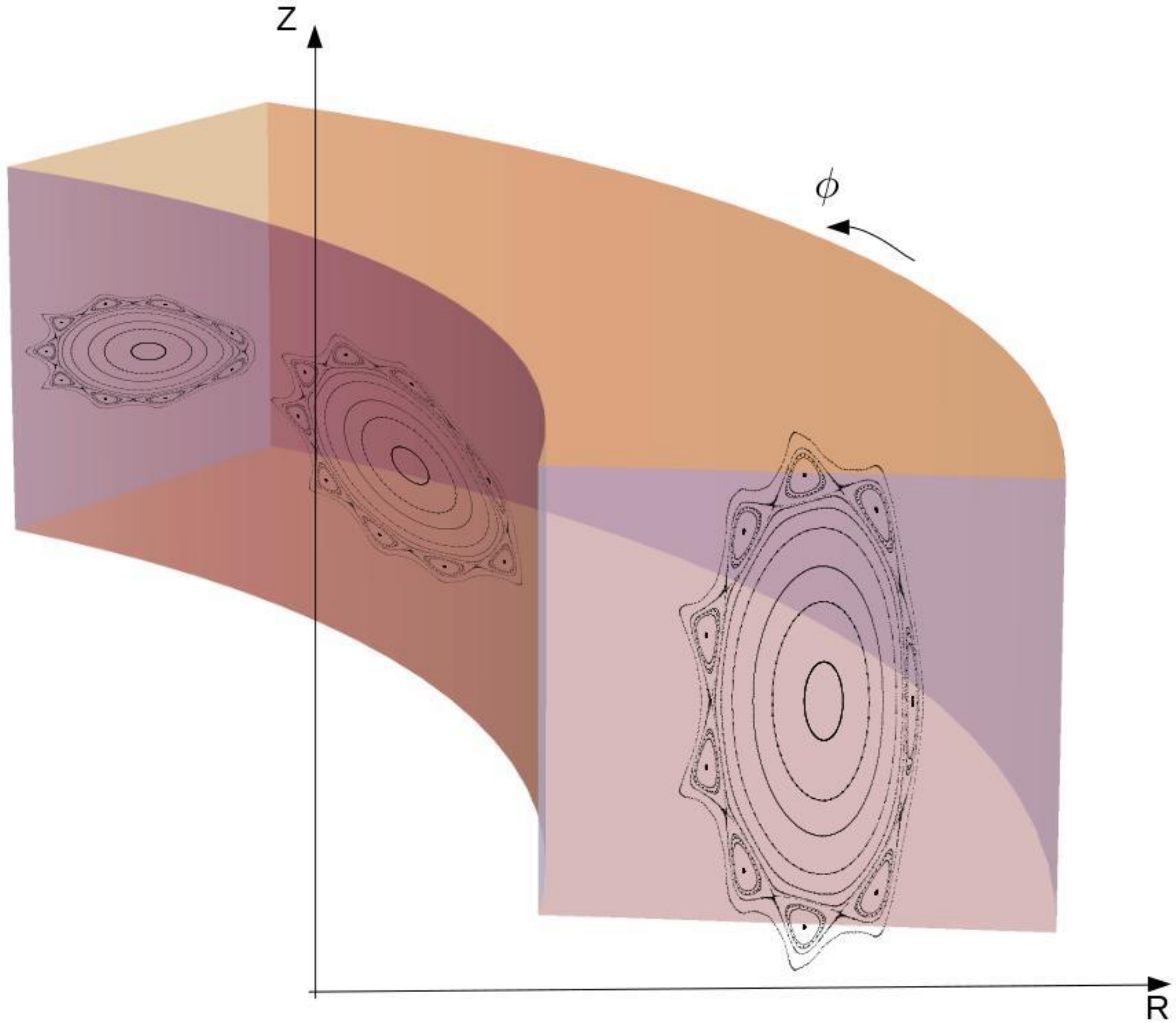
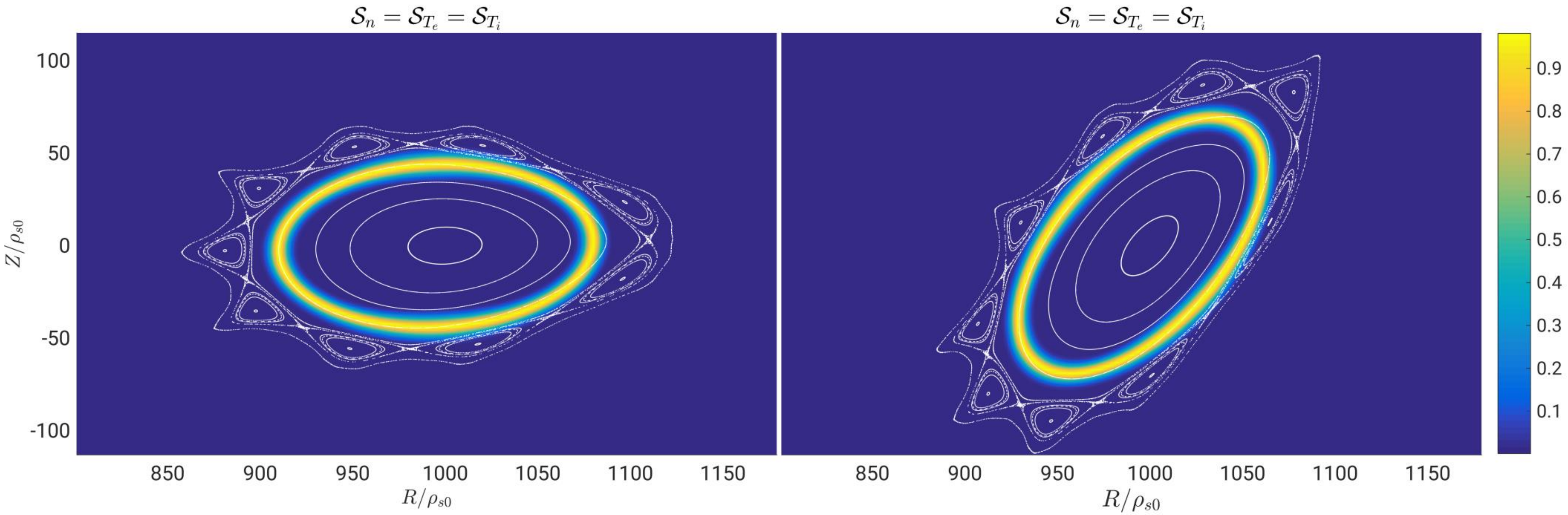


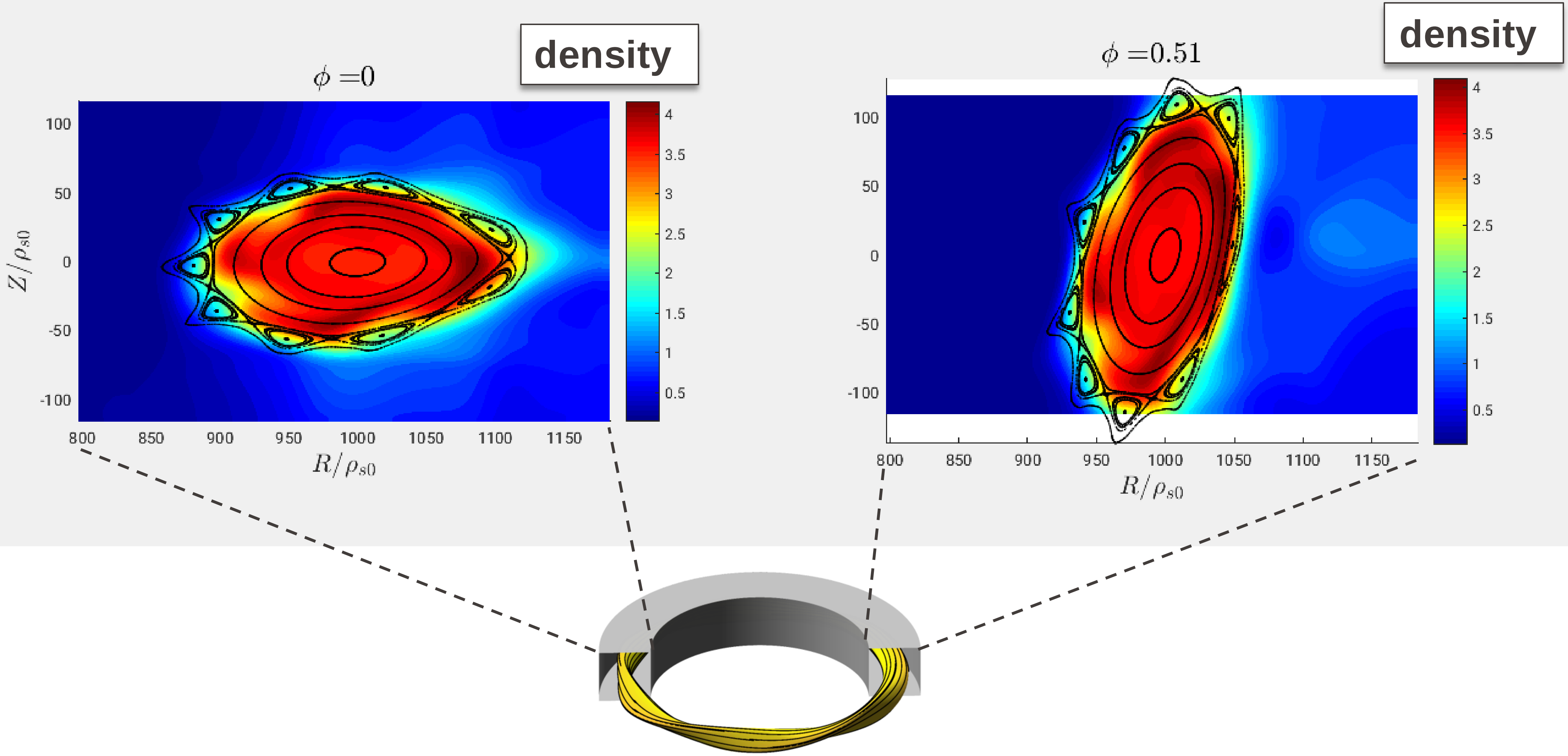


Source for density and temperature localized around a magnetic surface

- Simulation doesn't strongly depend on the sources' profile



Steady-state of simulation dominated by coherent mode



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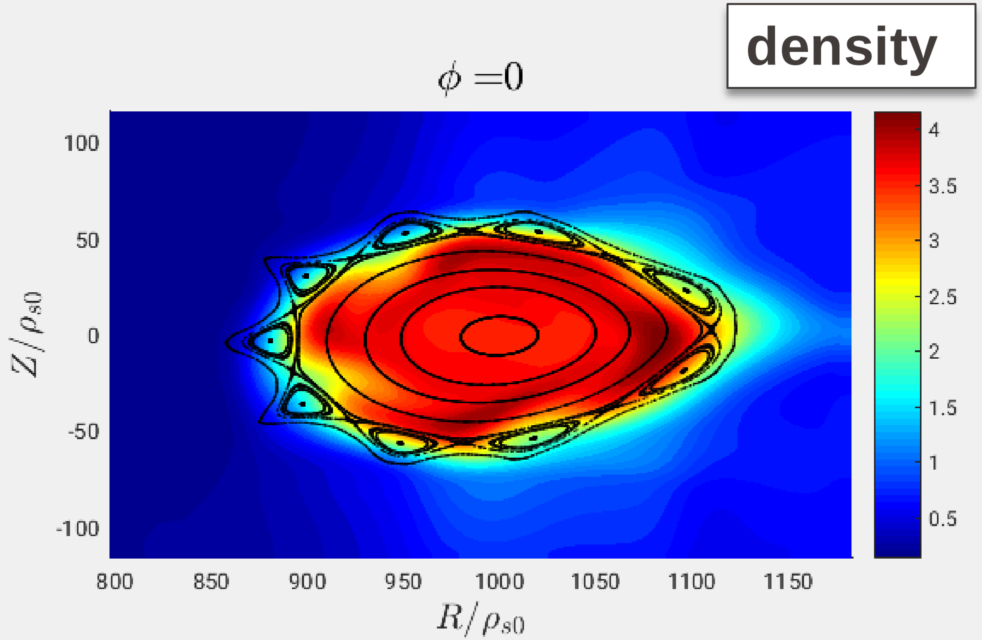
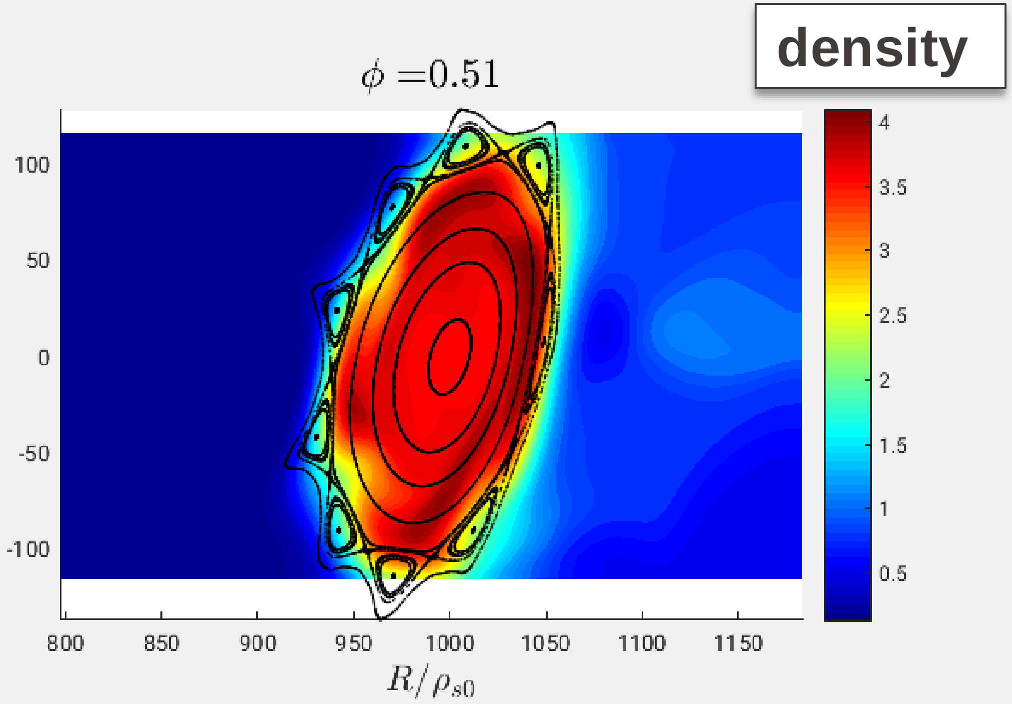
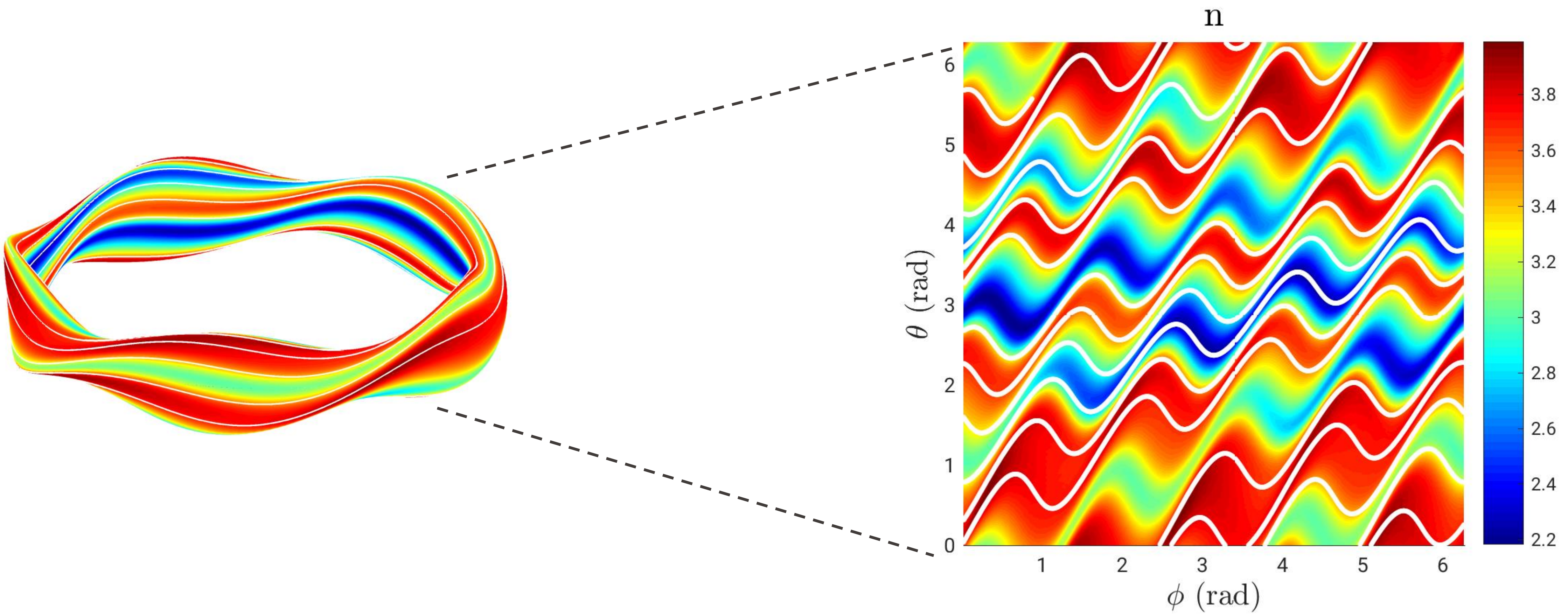


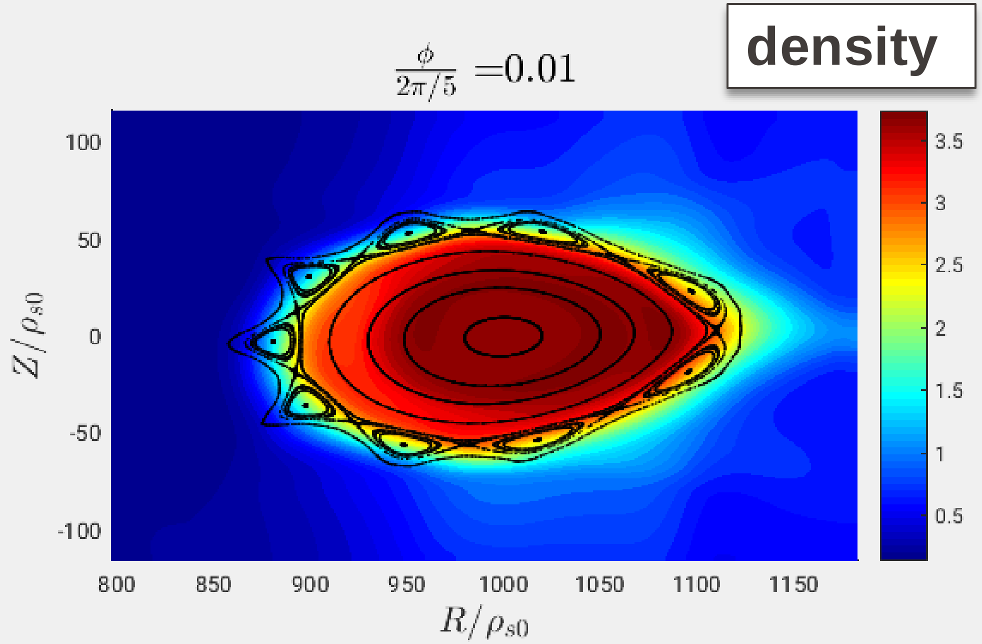


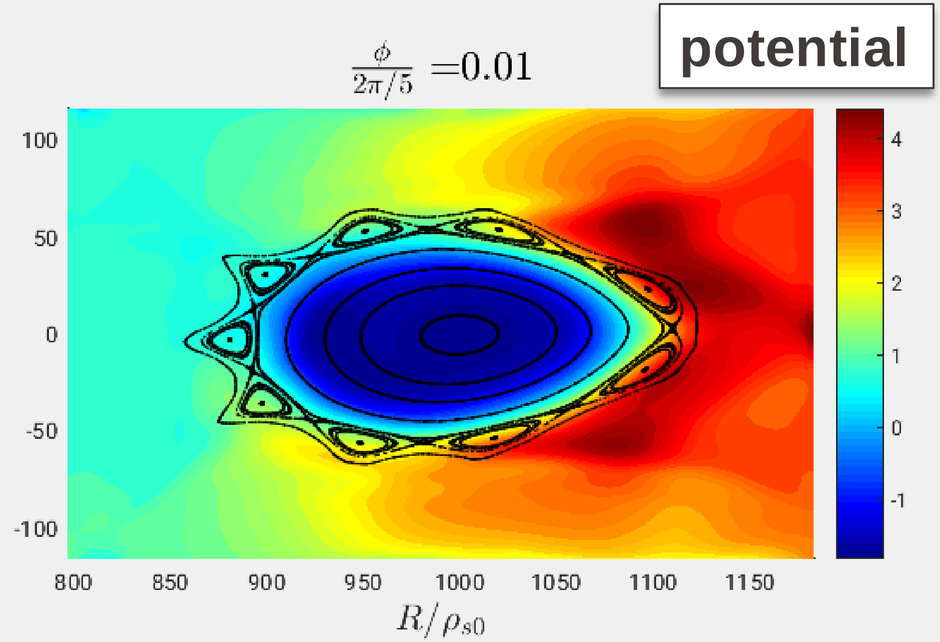
- An m=4 mode dominates the global dynamics
- Mode rotates with ~ ion diamagnetic frequency
- No broad-band turbulence
- Radial turbulent transport due to $<\tilde{\Gamma}_{\text{ExB}}>_t = <\tilde{n}\tilde{V}_{\text{ExB}}>_t$ balances source

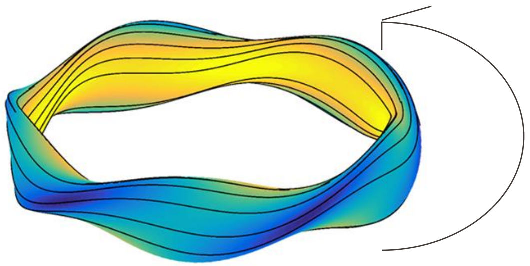
Mode is field-aligned



Equilibrium profiles

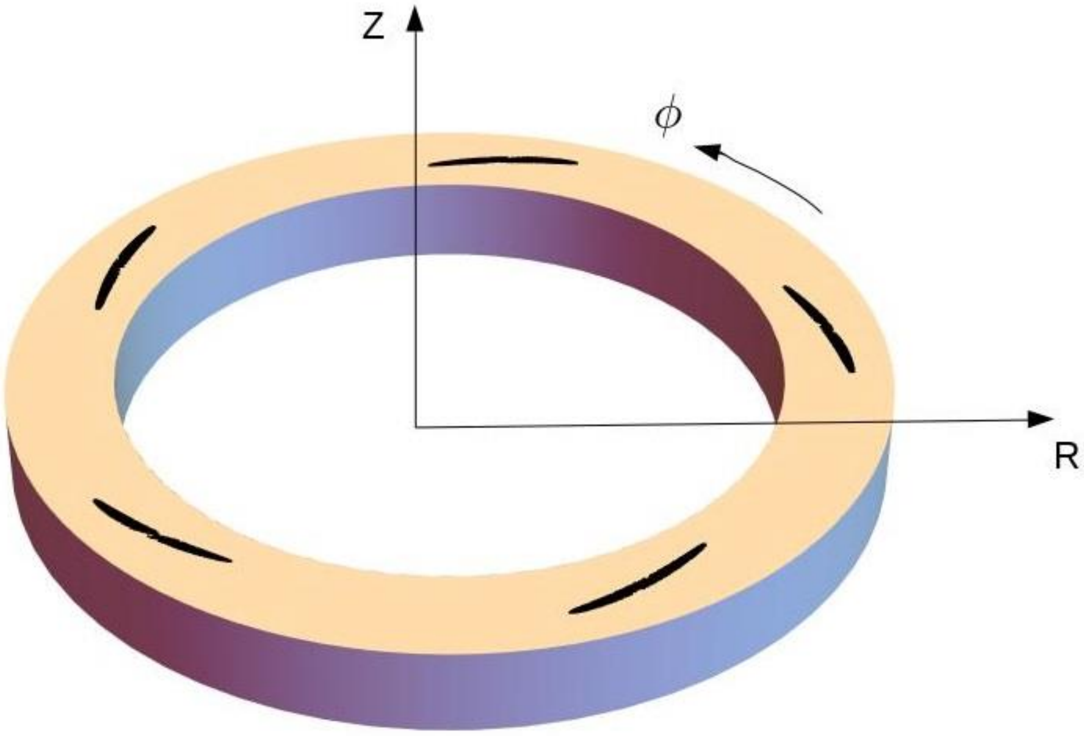


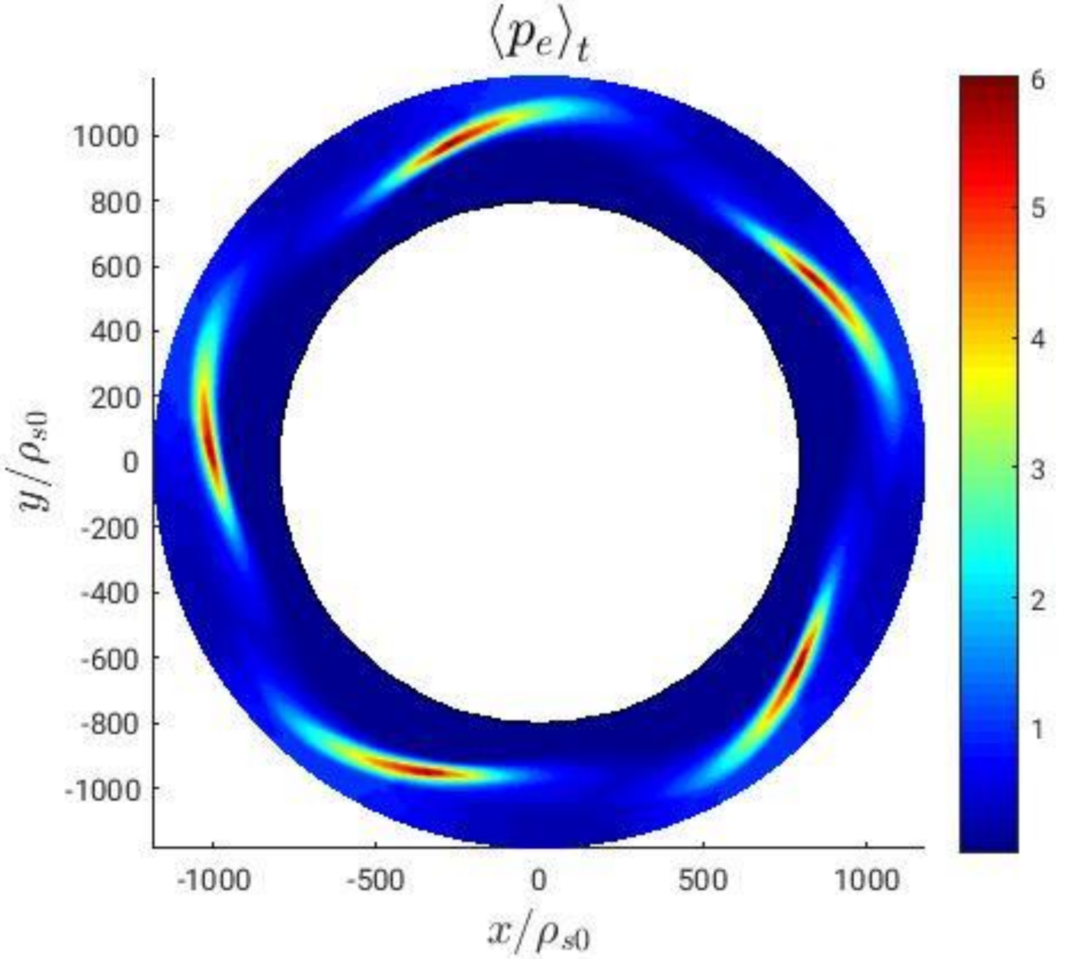




Effectiveness of the island divertor

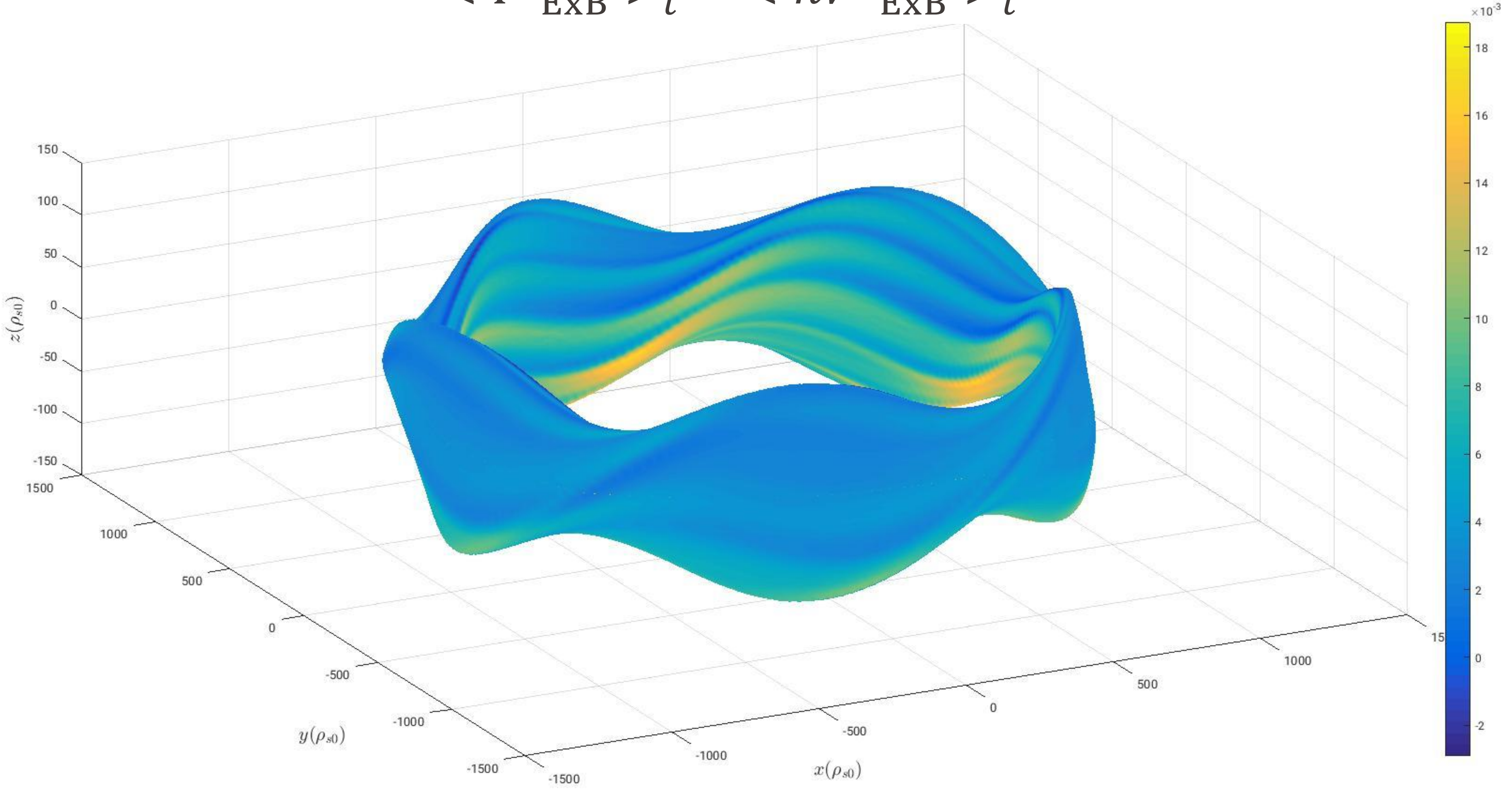
- On the **TOP** of the simulation box, pressure is maximum where field lines strike:





Asymmetry of ExB-flux between HFS/LFS

$$<\widetilde{\Gamma^{r}}_{\mathrm{ExB}}>_t = <\tilde{n}\widetilde{V^{r}}_{\mathrm{ExB}}>_t$$



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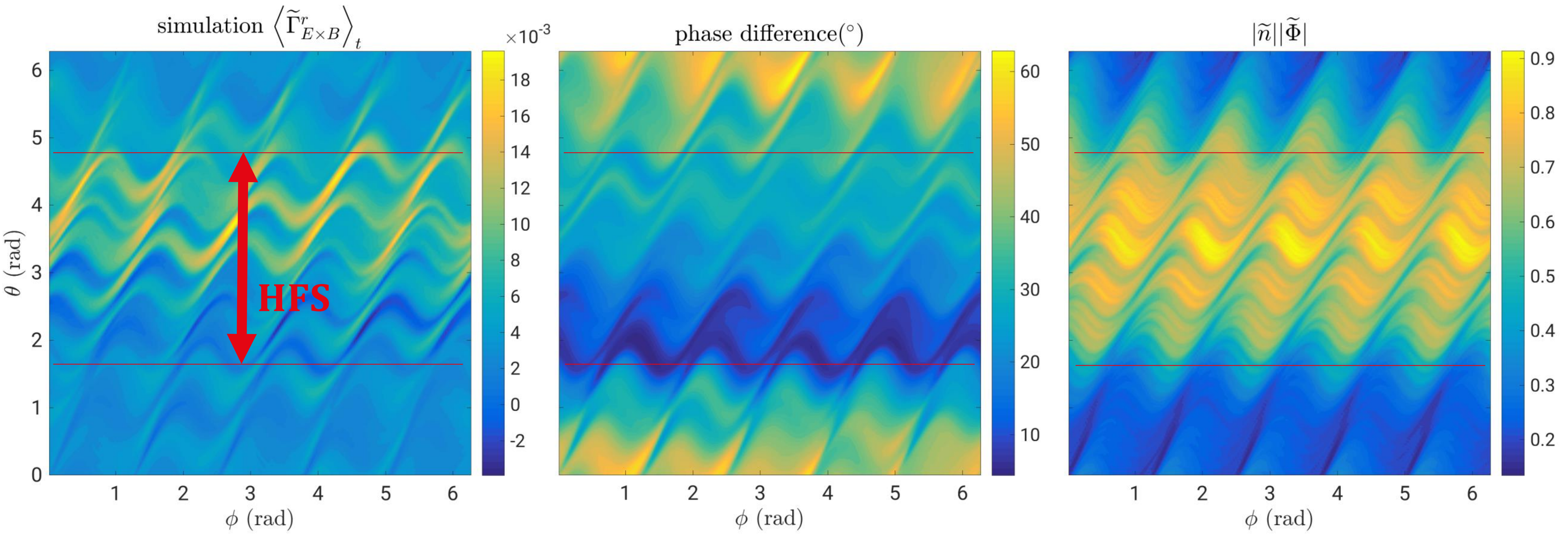


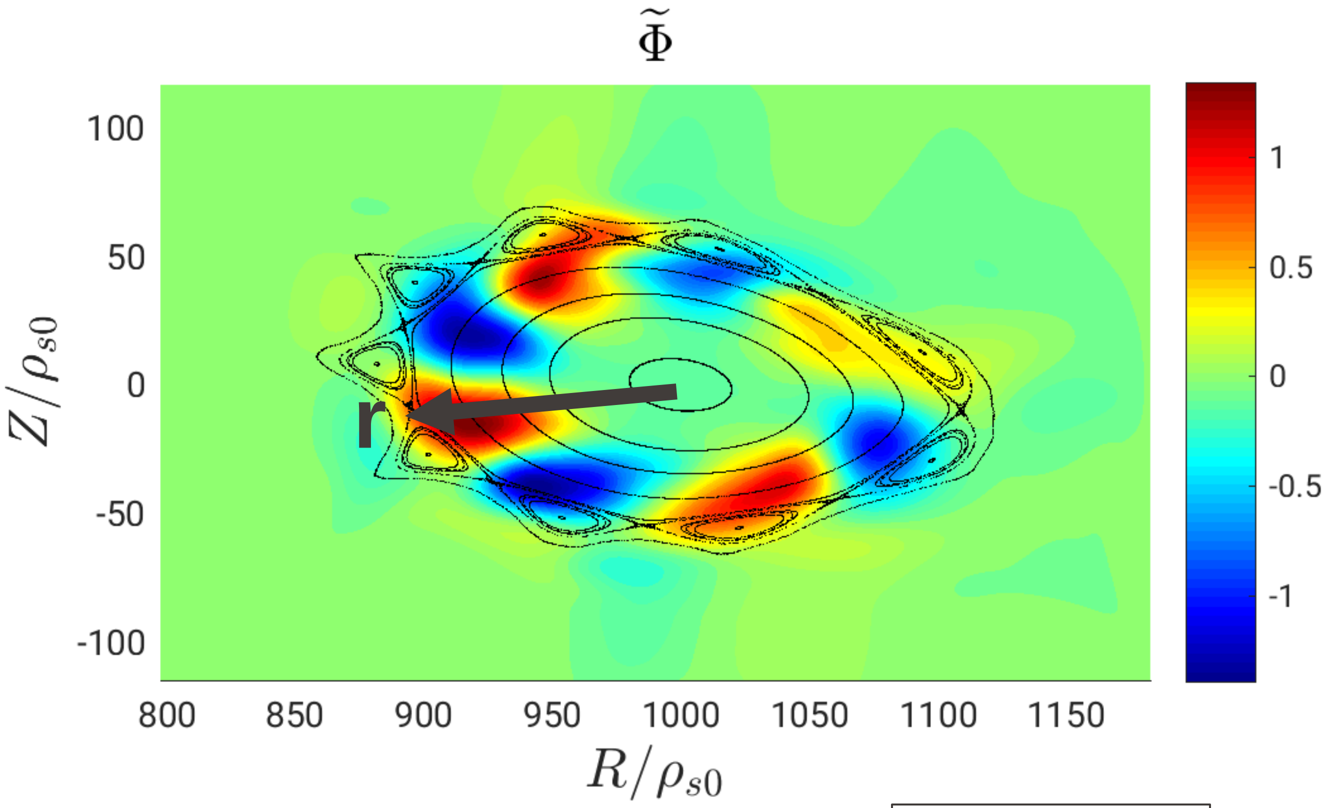
Understand the mode with non-local linear theory

- Linearize GBS equations by assuming quantities vary as:

$$n = n_0(r) + \tilde{n}(r)e^{j(m\theta+n\phi)}e^{\gamma t}$$

$m = 4$

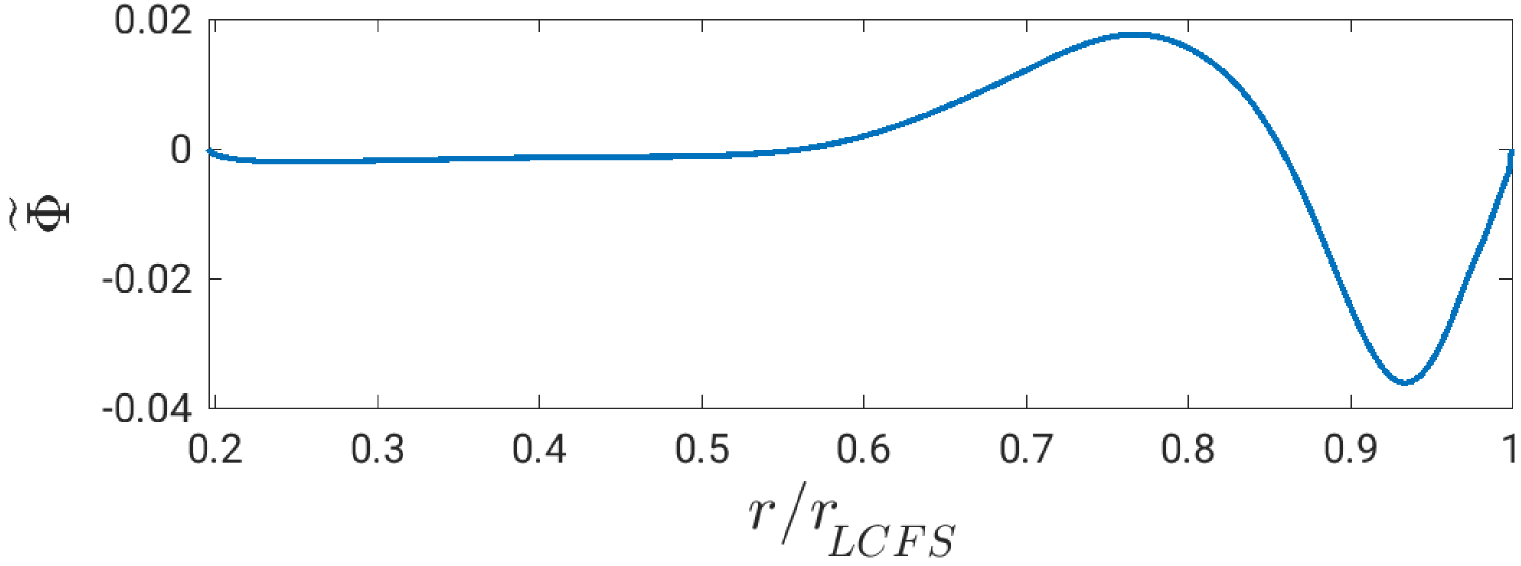
$n = 5$



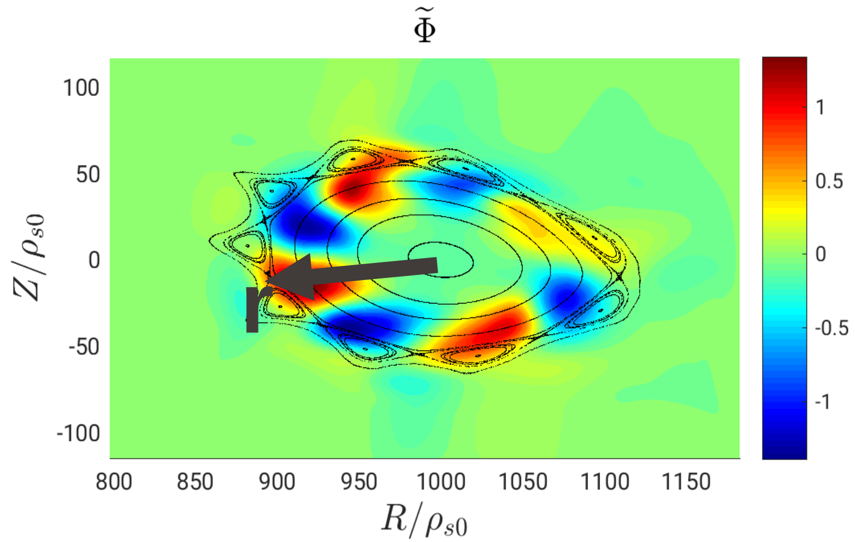
GBS simulation

Linear theory predicts the observed mode

Linear theory



GBS simulation



Is the linear mode able to transport the same Γ_{ExB}?

$$\Gamma_{E\times B} \sim m|\tilde{n}||\tilde{\Phi}|\sin(\varphi_\phi - \varphi_n)$$

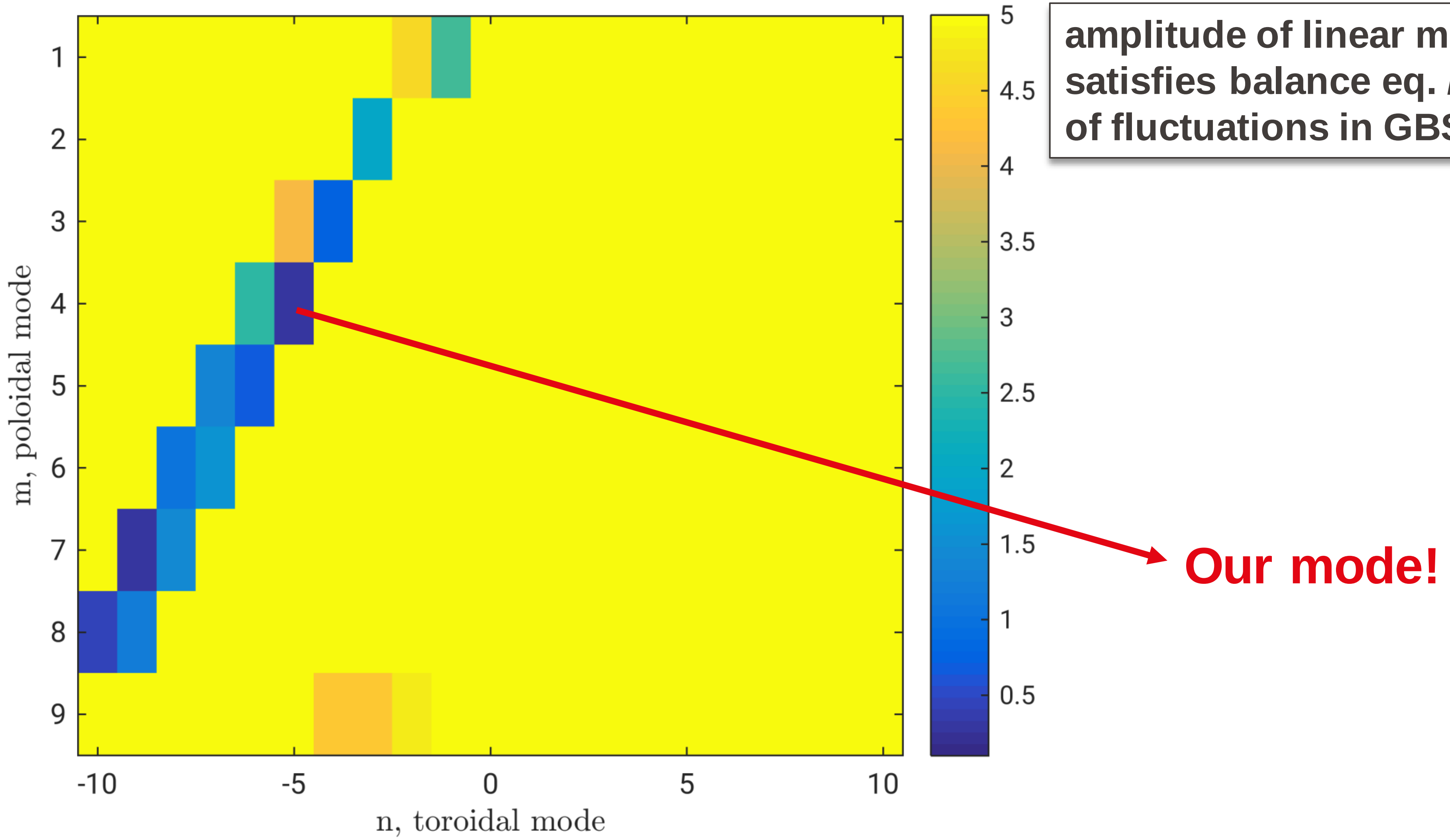
$$|\tilde{n}| \rightarrow n_0|\widetilde{n}|$$

$$|\tilde{\Phi}| \rightarrow \Phi_0|\widetilde{\Phi}|$$

$$< \Gamma_{E\times B} > \int_{\mathrm{LCFS}} dS = \int_{\mathrm{LCFS}} \mathcal{S}_n dV$$

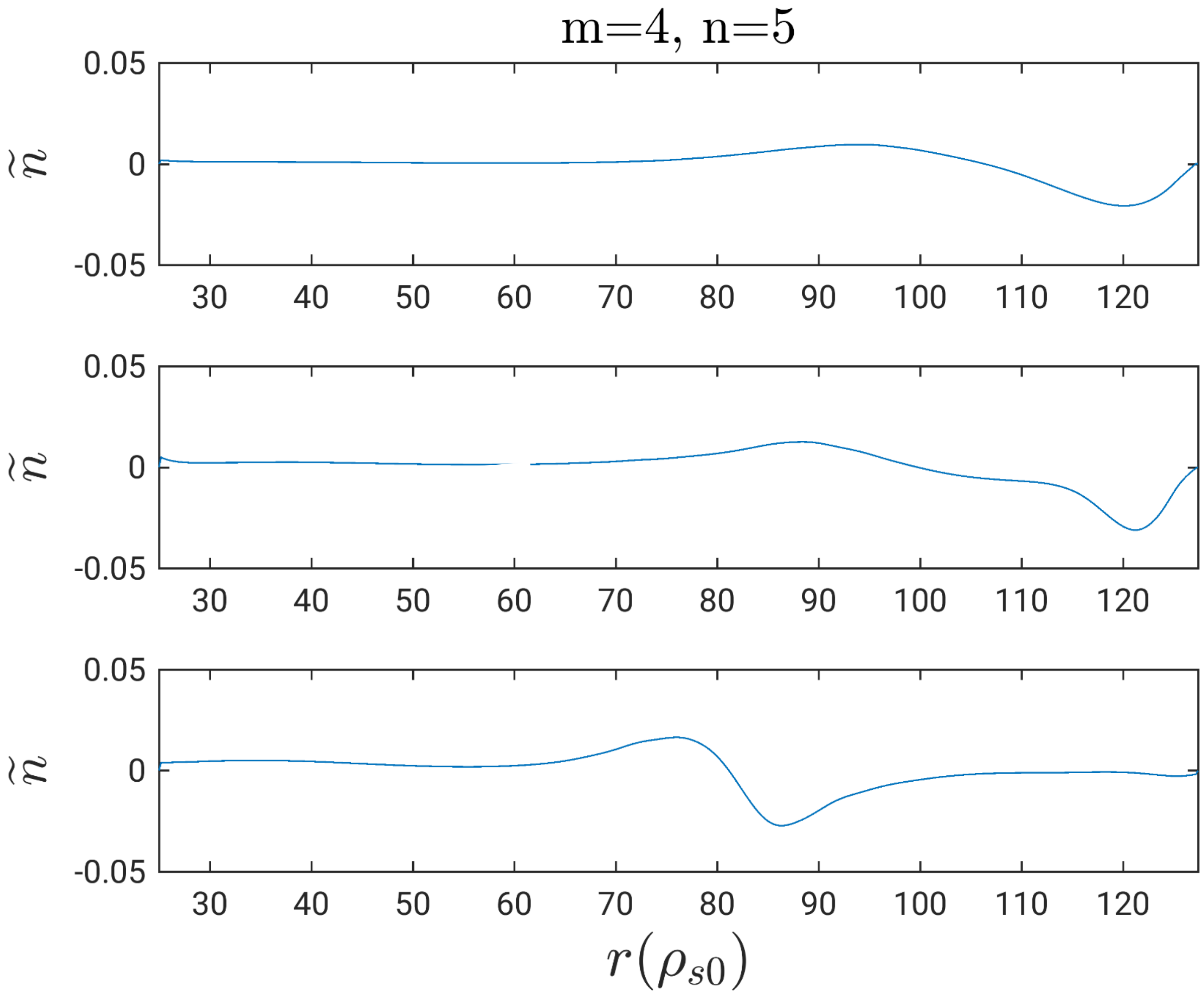
- Solve for $n_0 \sim \Phi_0$ and obtain the perturbation's amplitude needed to balance the source

Linear mode is able to transport the same Γ_{ExB}



amplitude of linear mode s.t. satisfies balance eq. / amplitude of fluctuations in GBS

Nature of the linear mode: balloning



No drift-waves drive

($\nabla_{\parallel} p_e = 0$ in $V_{\parallel e}$ eq.)

No ballooning drive

(curvature(p)=0 in vorticity eq.)

Content of this talk

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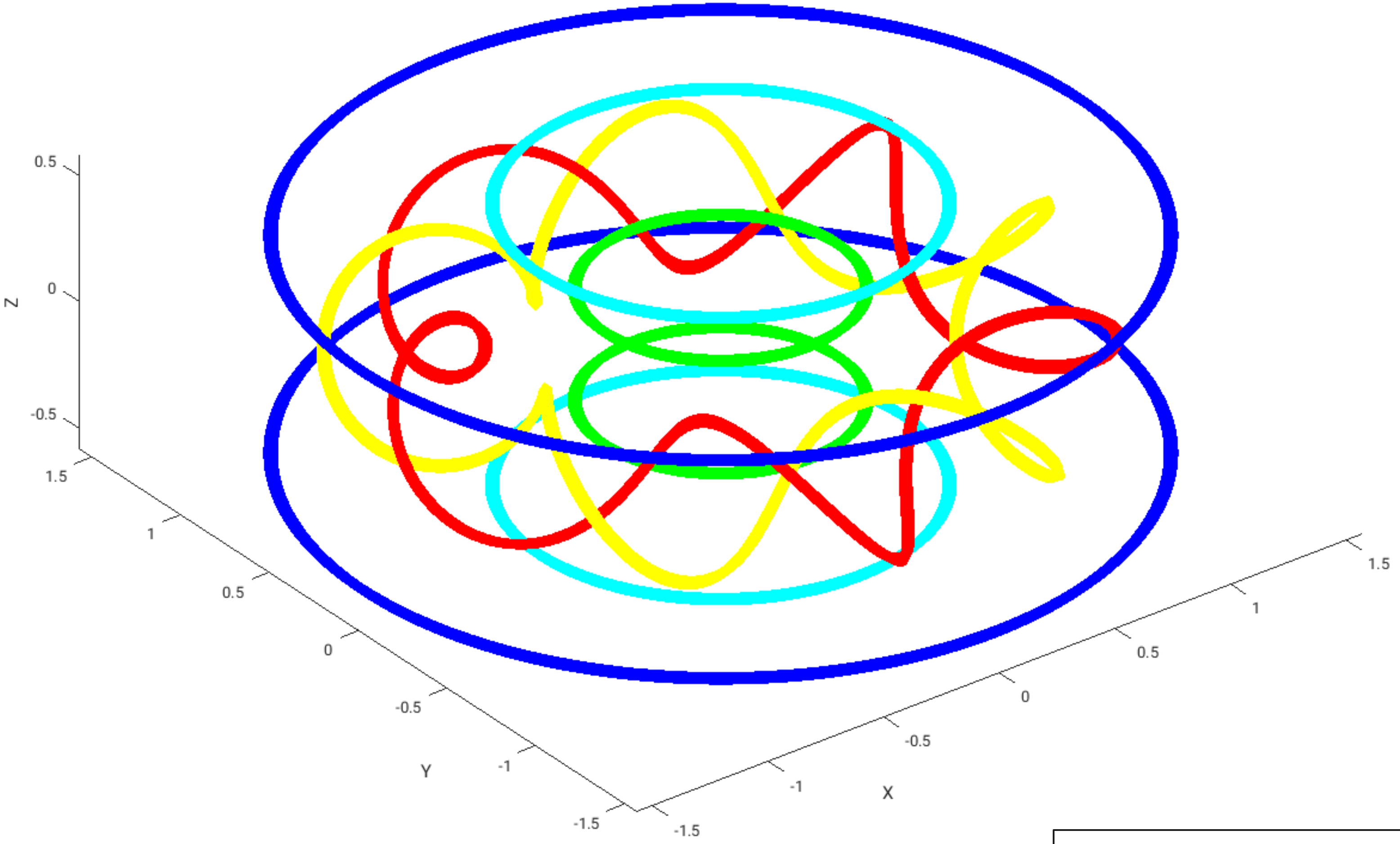
3. **First approach to simulate a stellarator with an ergodic divertor**

Arrangement of the coils

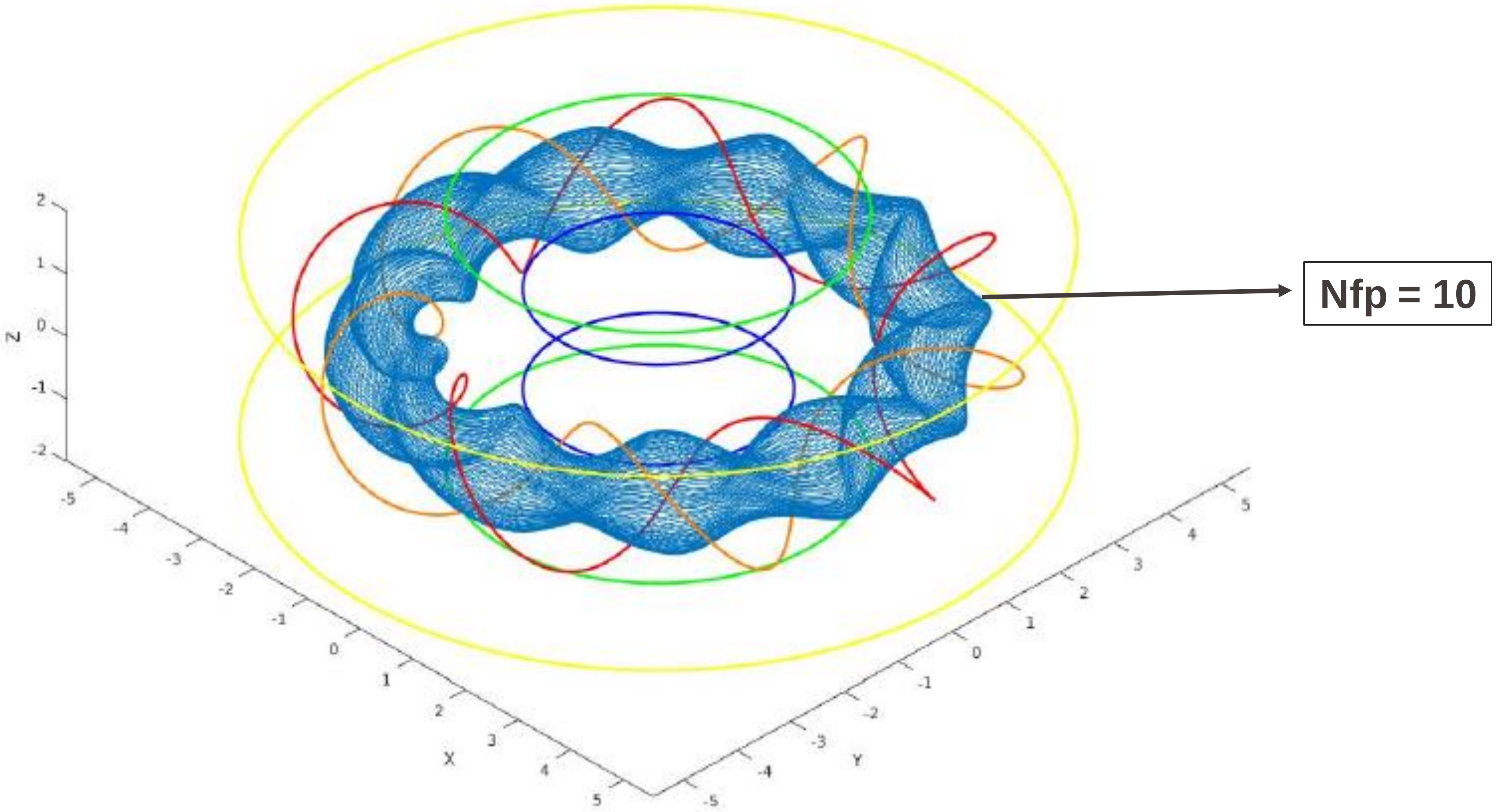


3 pairs of circular coils

2 helical coils with period=5

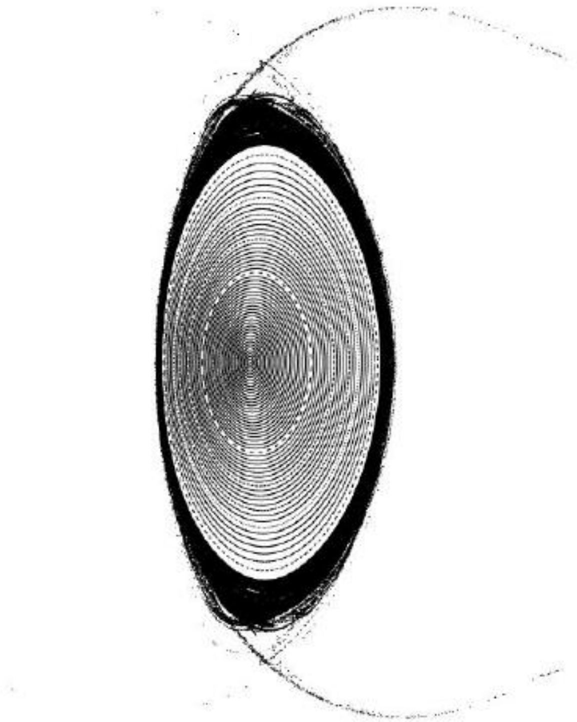
LHD-like scaled down by a factor of ~3.5

Arrangement of the coils

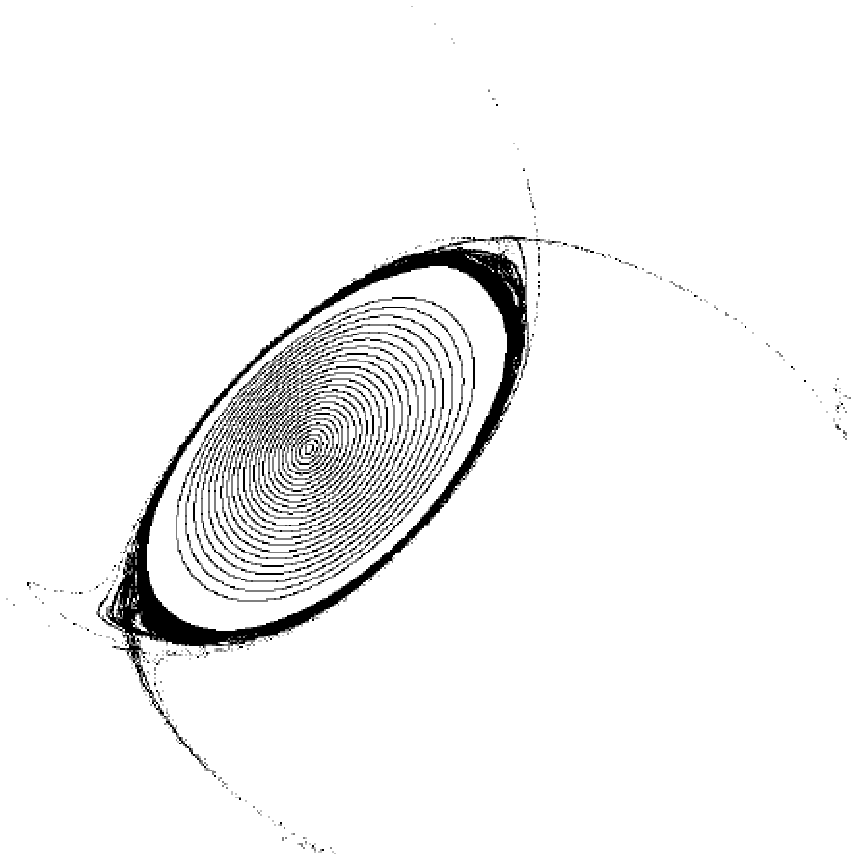


Poincaré plots

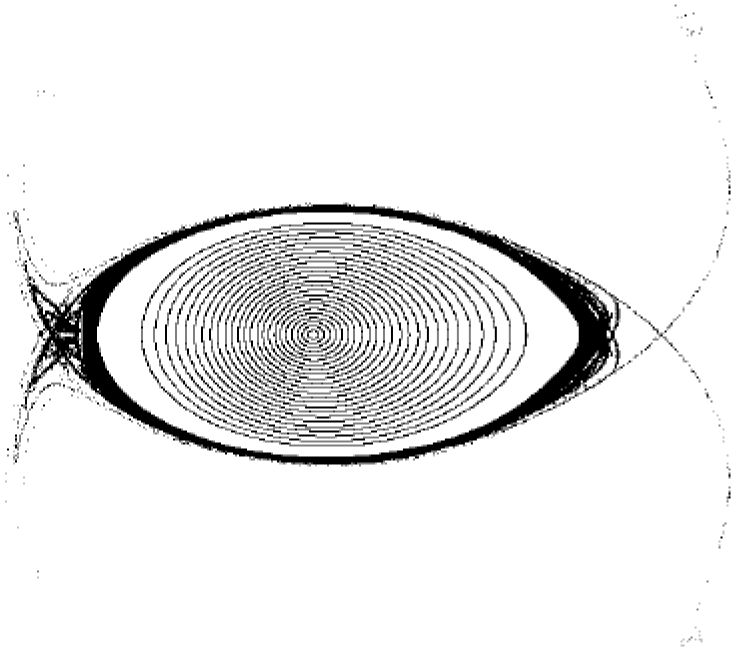
with **MAKEGRID** & **FIELDLINES** from **STELLOPT:**



$\phi = 0$

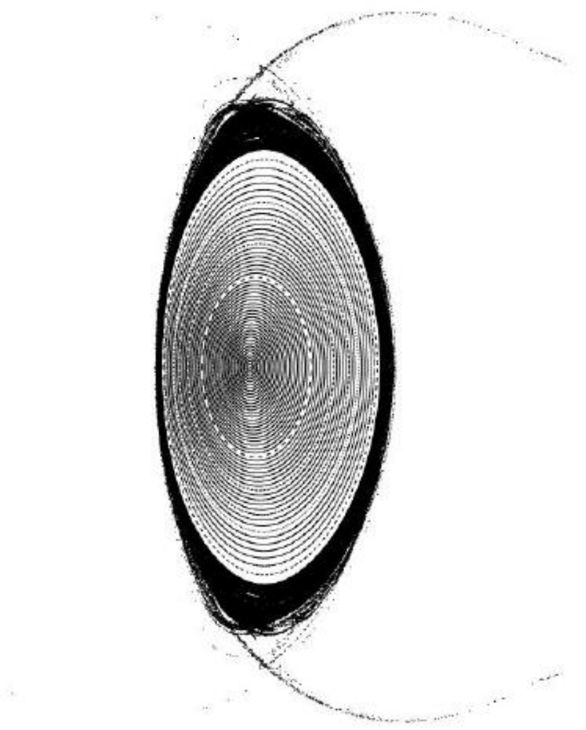


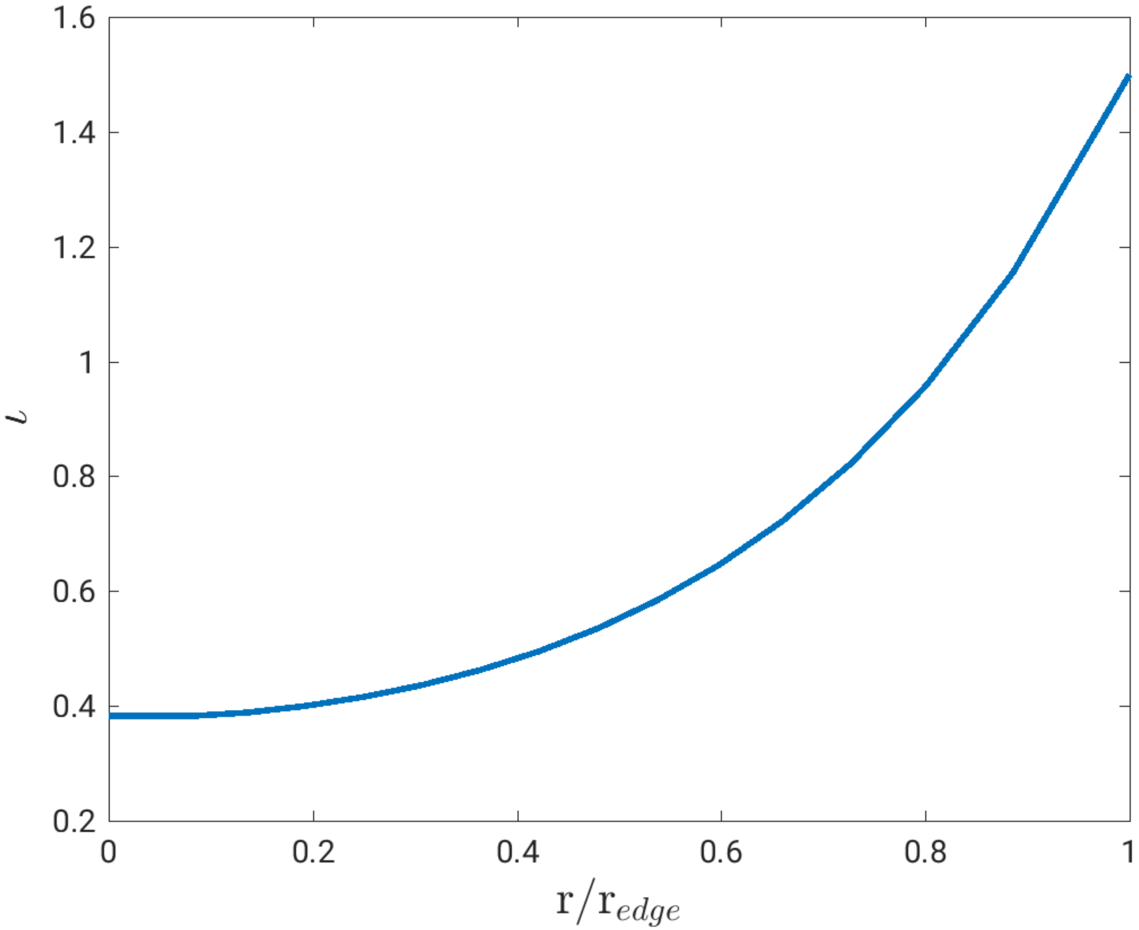
$\phi = 0.25\ \frac{2\pi}{10}$



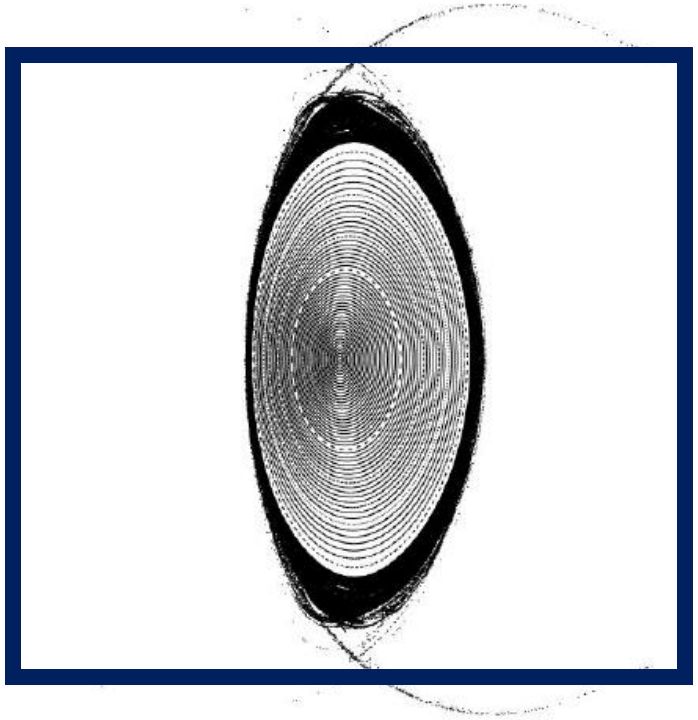
$\phi = 0.5\ \frac{2\pi}{10}$

Rotational transform

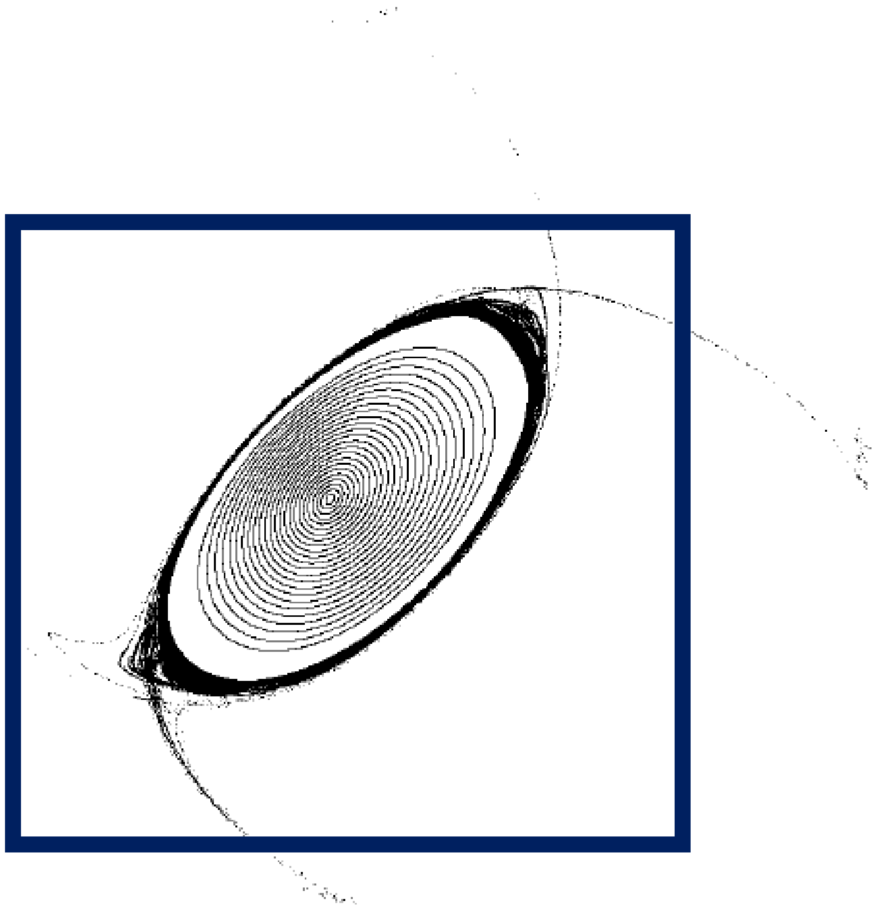




Fixed GBS box is not a good idea



$\phi = 0$



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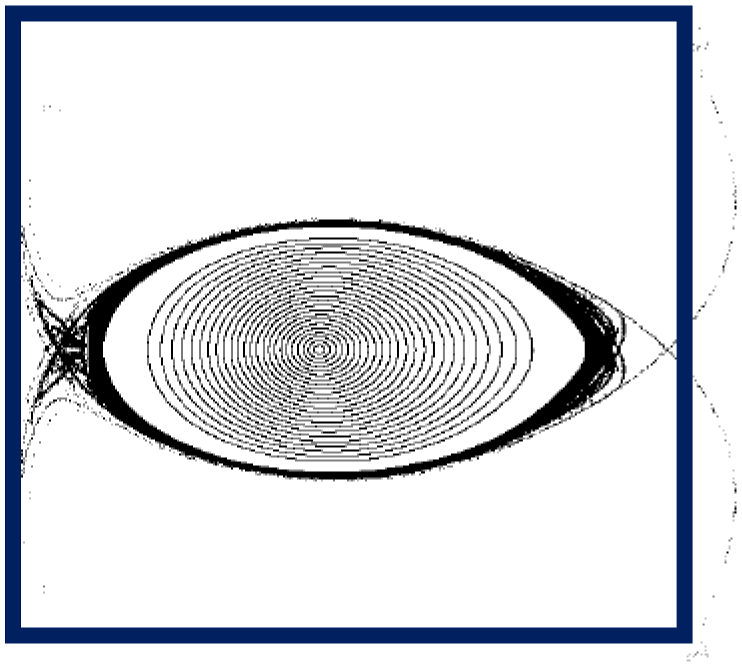
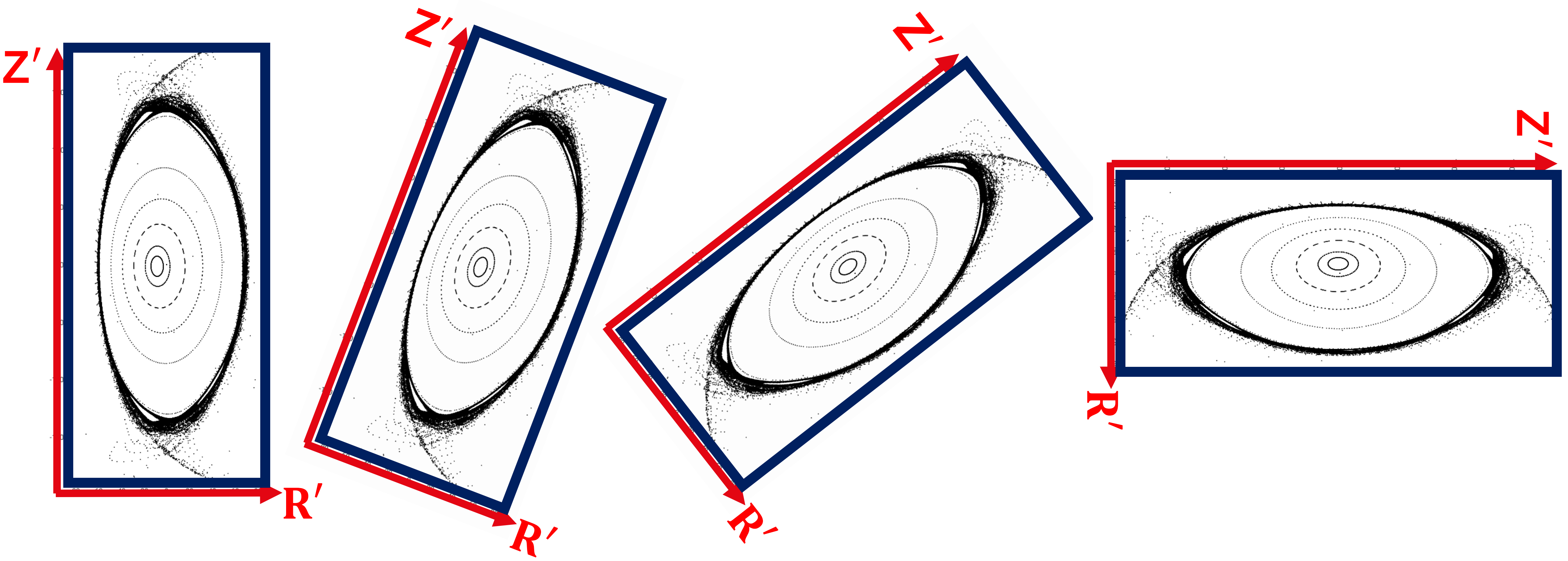
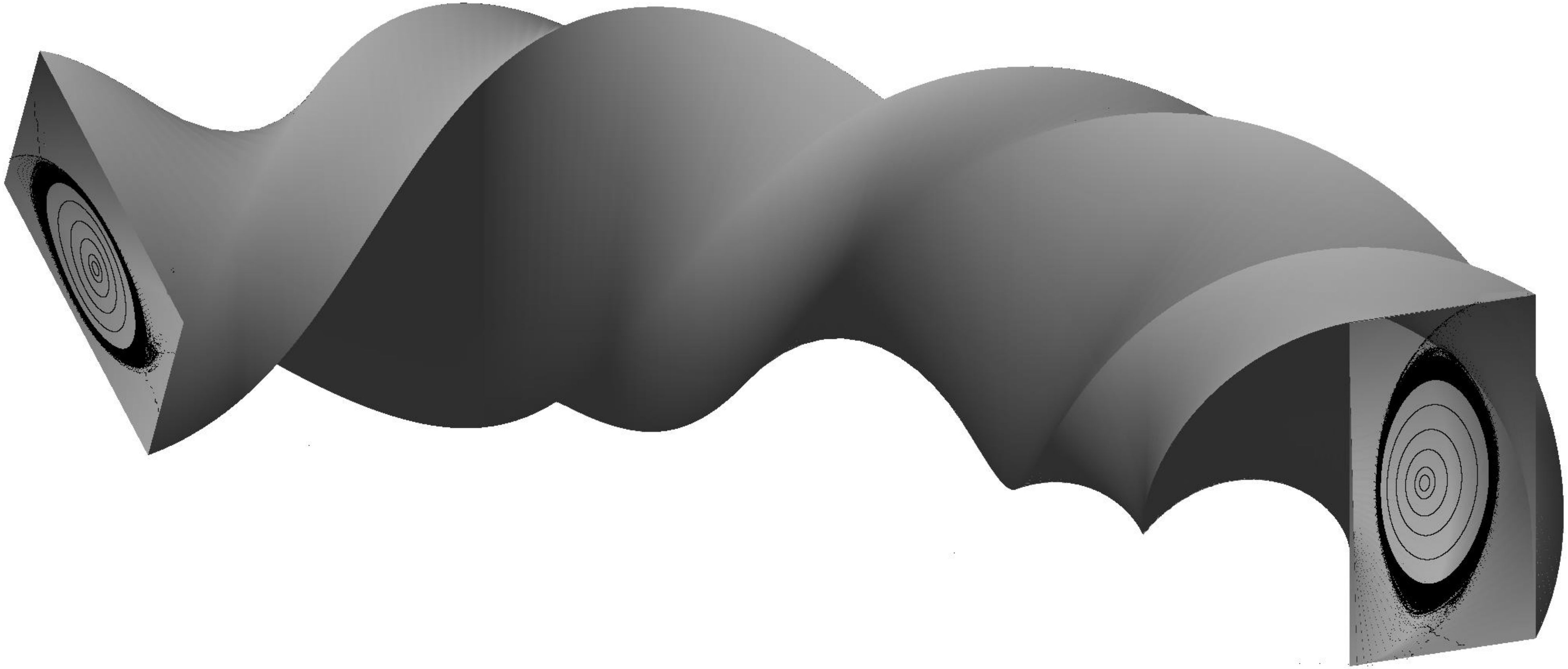


$\phi = 0.5\,\frac{2\pi}{10}$

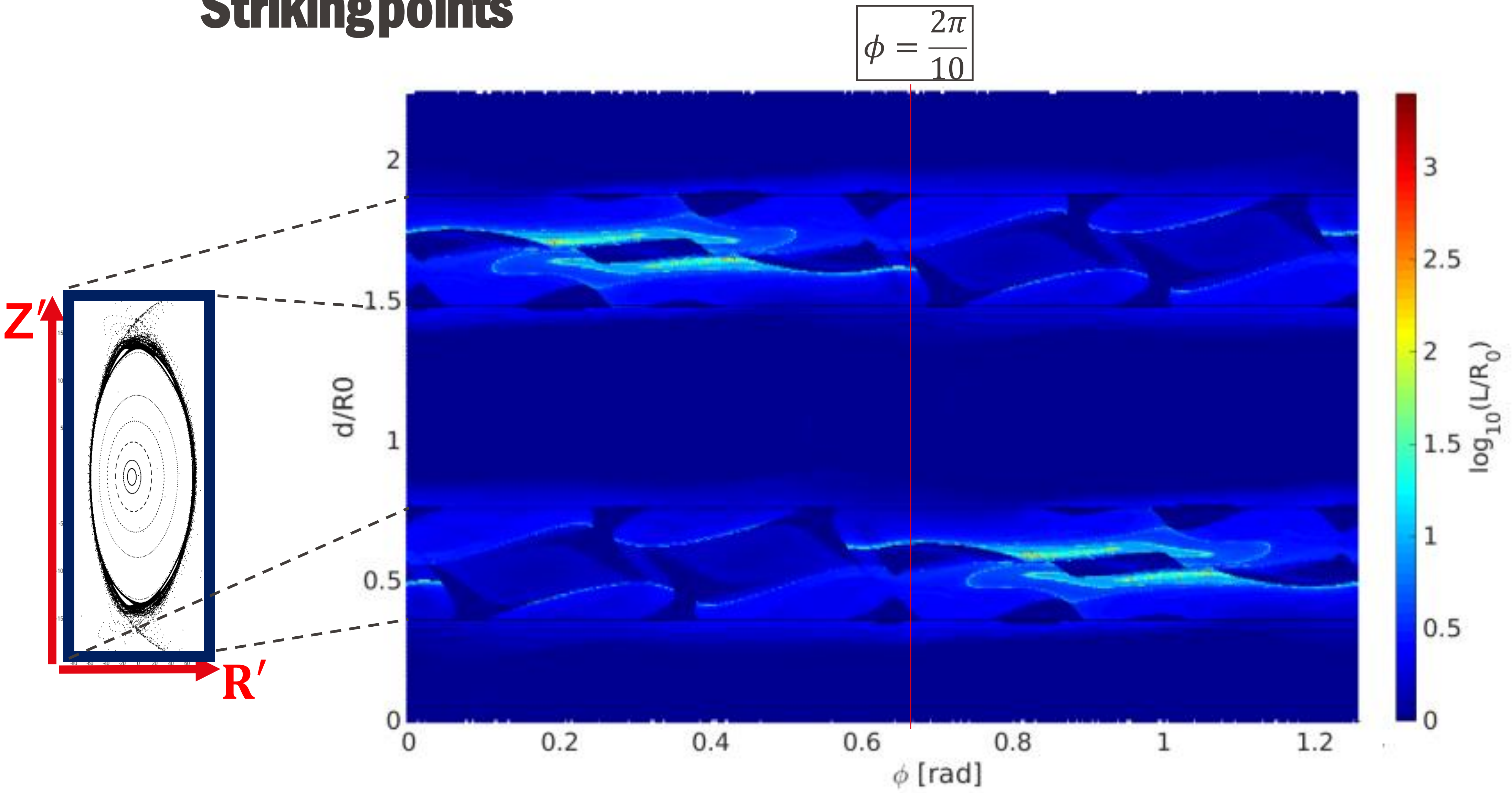
Change of coordinates



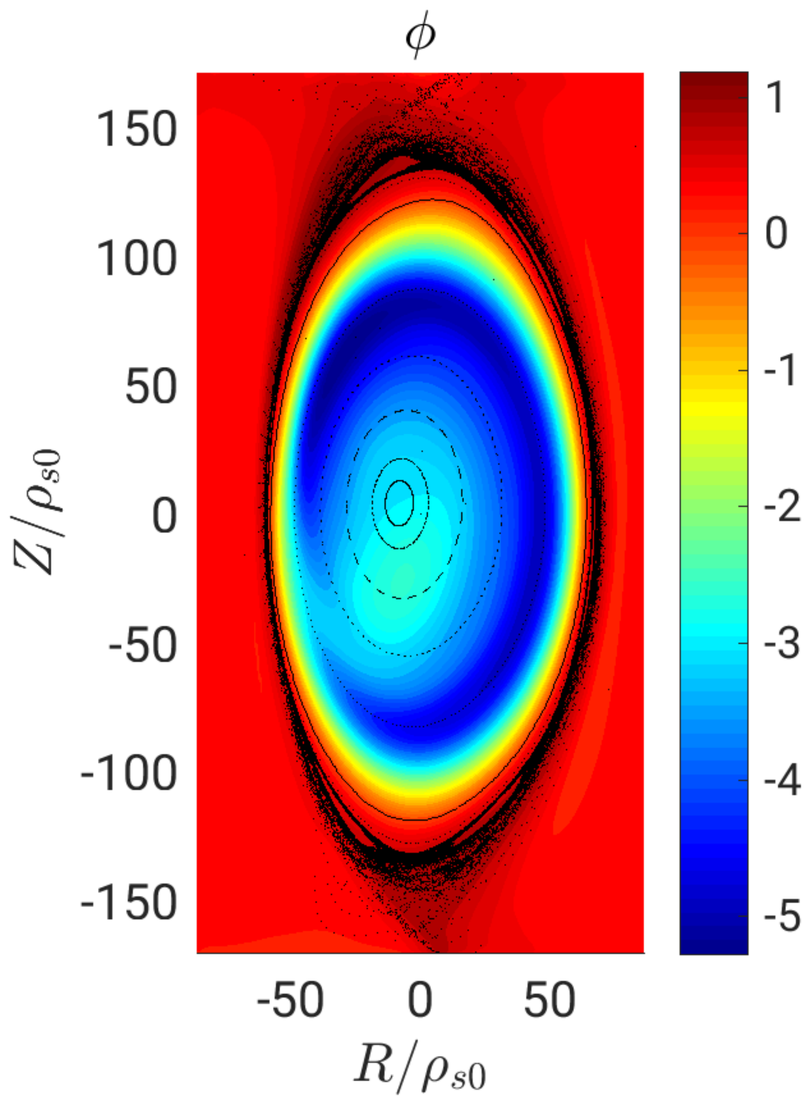
Change of coordinates

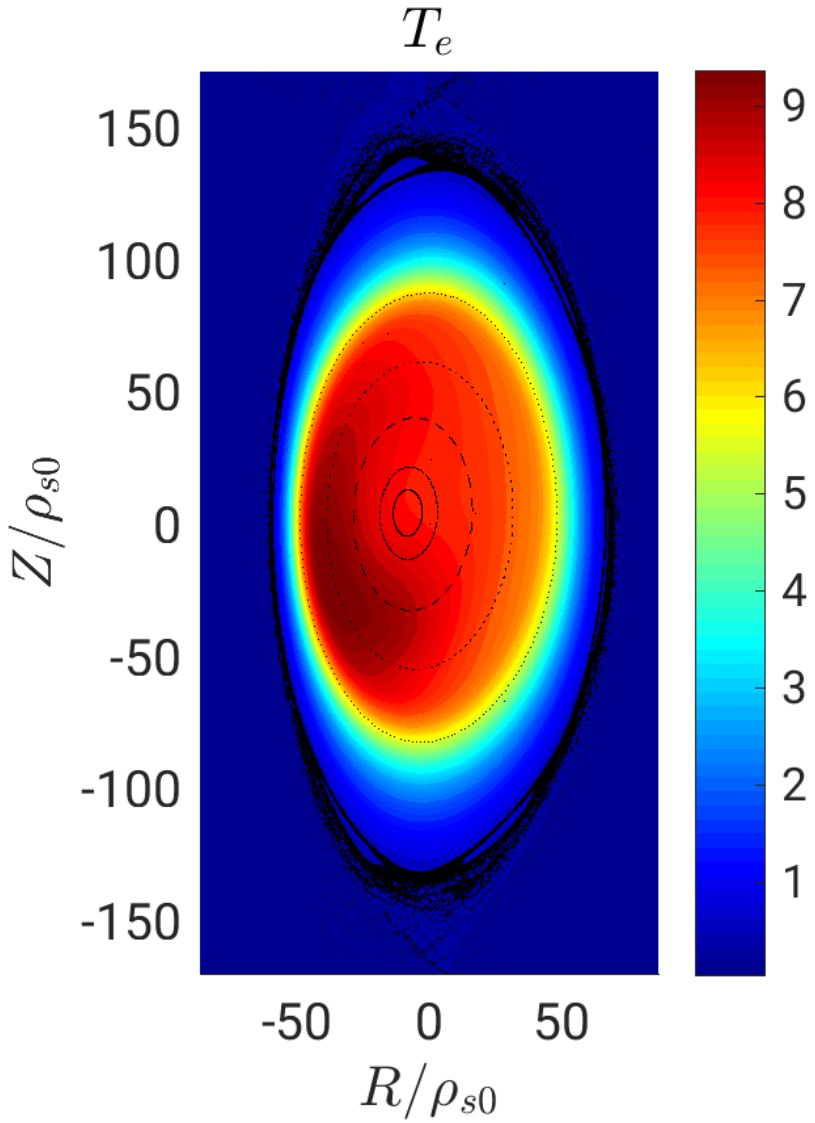


Striking points



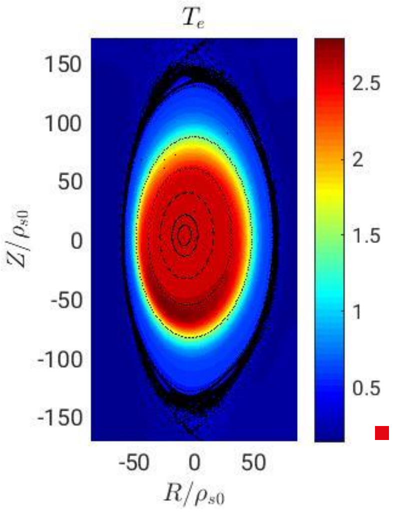
Simulation still in the beginning



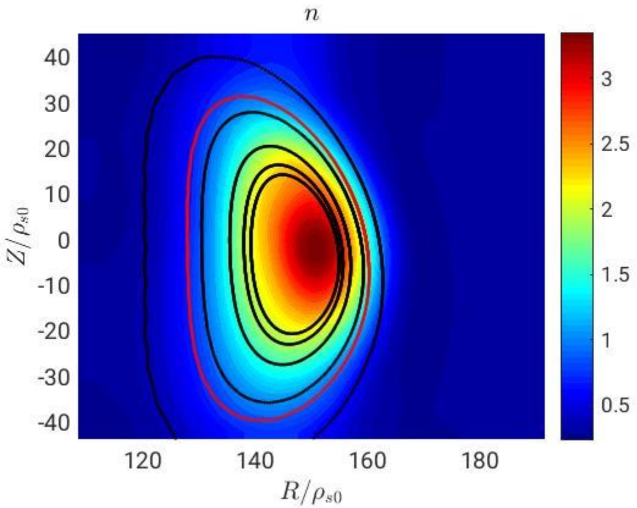


Conclusions & Future Work

- First global fluid simulations of a **stellarator** have been performed with **GBS code**
- Unlike tokamak experiments/simulations, **no broad-band turbulence nor blobs** were observed. Instead, a low **poloidal mode (m=4) dominates transport**
- Linear theory points to **ballooning mode**
- Is this coherent mode a property of the configuration used?



- LHD-like stellarator



- TJ-K stellarator