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First global fluid simulations of plasma turbulence in a stellarator with an island divertor

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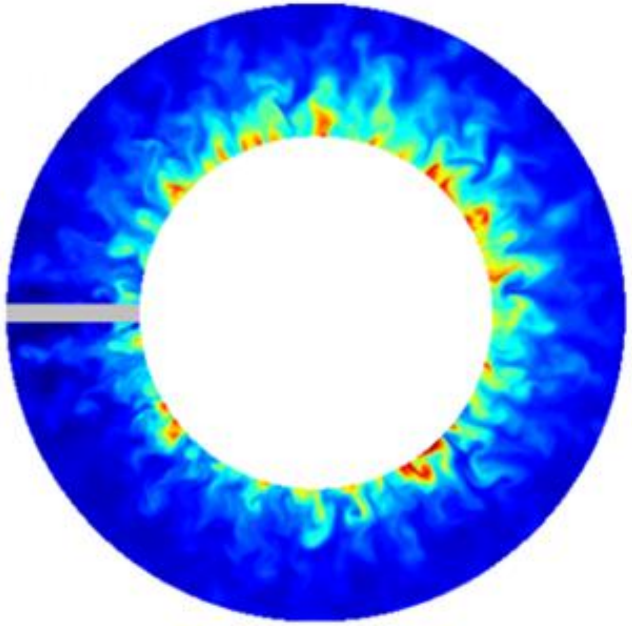
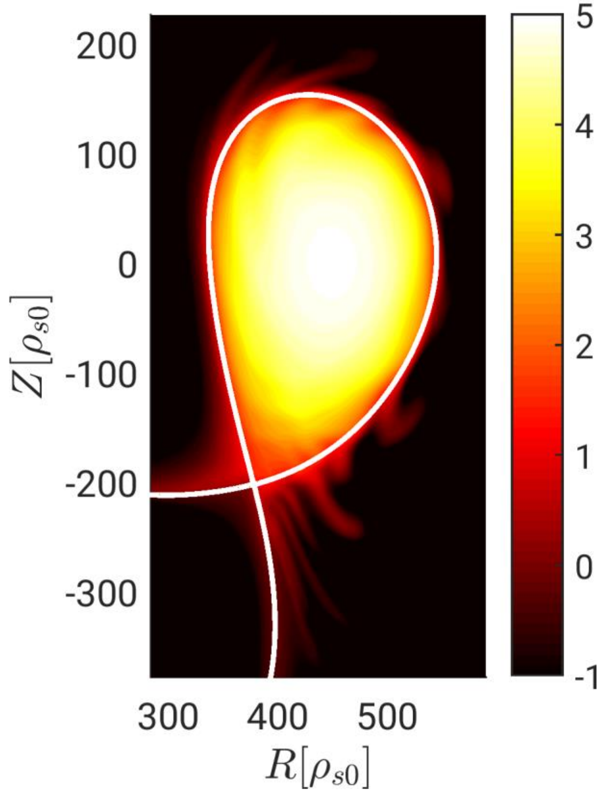
Introduction

- Stellarators are becoming a viable alternative to tokamaks
- So far, no global fluid simulations of stellarators that take into account the boundary
- Plasma boundary determines the heat flux on plasma-facing materials
- In the boundary: collisionality may be high and turbulence time-scales much longer than ω_{ci}^{-1}
  - fluid drift-reduced Braginskii equations [Zeiler, IPP 5/88 1999]
- GBS is a two-fluid, global, flux-driven turbulence code that solves the drift-reduced Braginskii equations

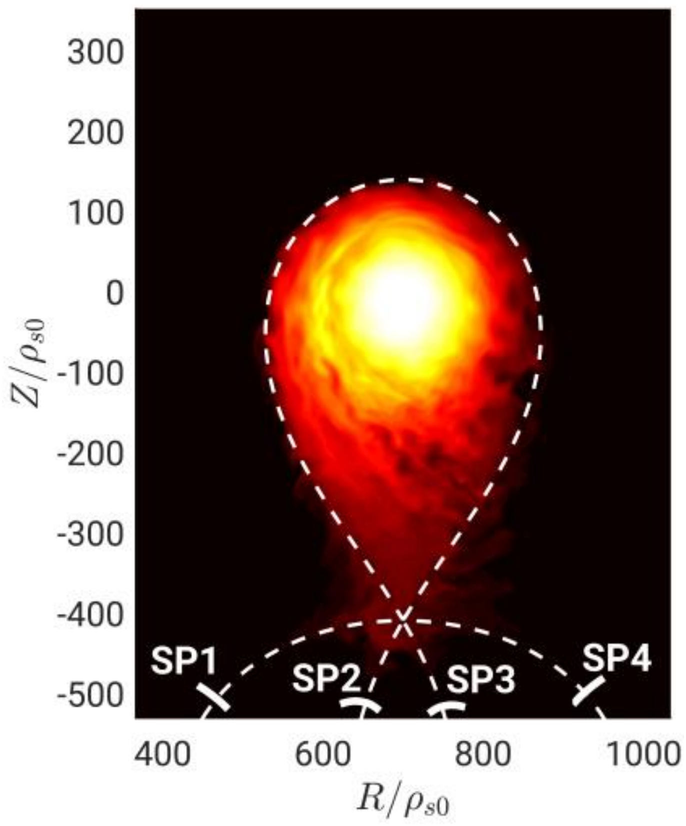
GBS has been used to simulate the edge of tokamaks



Ricci and Rogers, PoP 2013

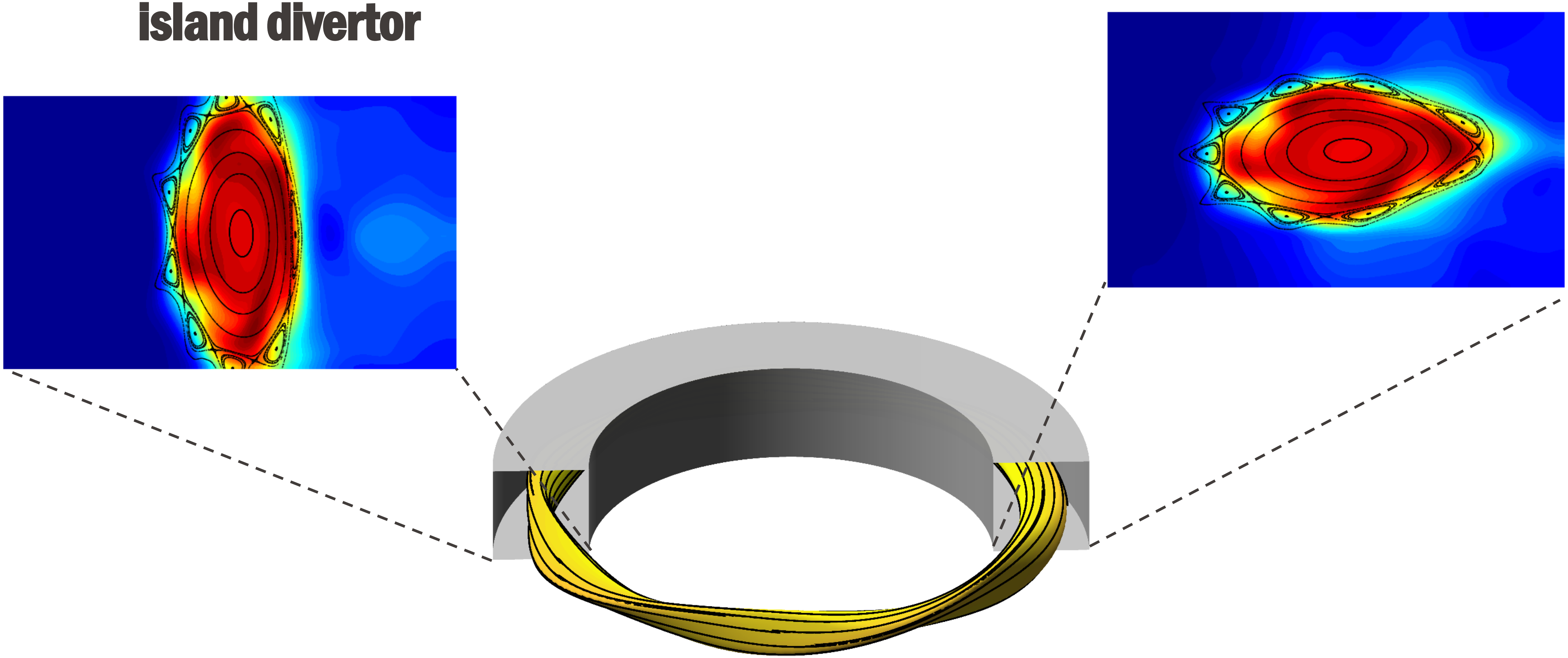


Giacomin et al., submitted to JCP



Giacomin et al., NF 2020

This talk:
Global GBS simulations in a stellarator with an island divertor



- No separation between equilibrium and fluctuating quantities

This talk:
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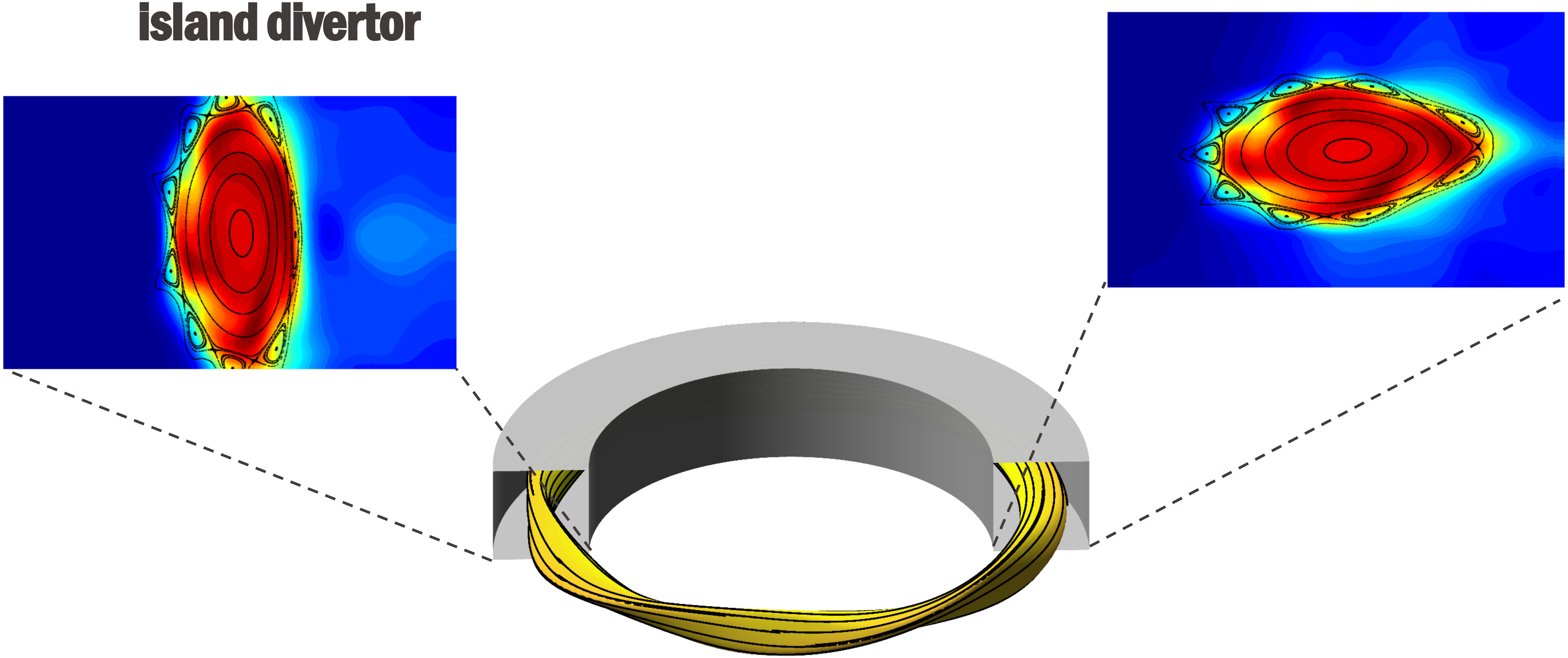


- Density and temperature sources generate the gradients that drive turbulence

GBS solves the drift-reduced Braginskii equations

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

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

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

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

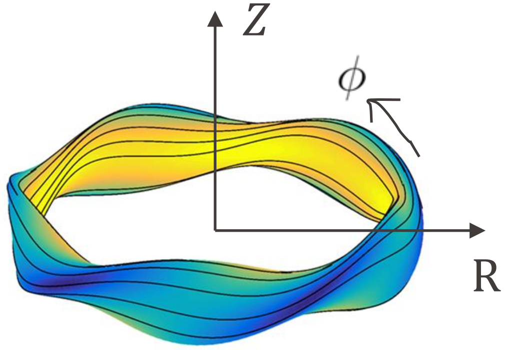
What stellarator vacuum field do we use in the simulation?

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

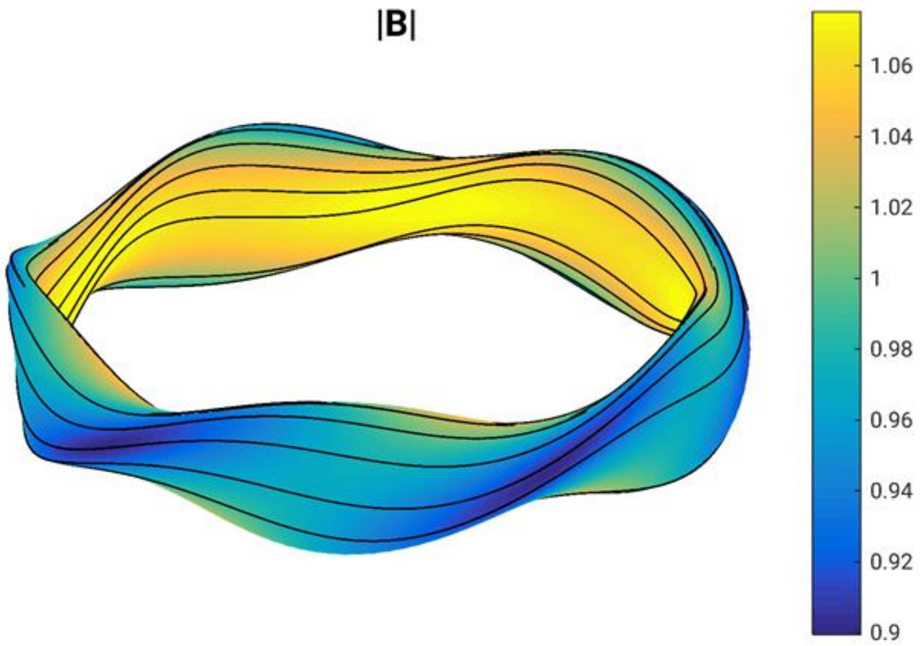
$$\nabla \cdot \mathbf{B} = 0 \rightarrow \nabla^2 V = 0$$

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

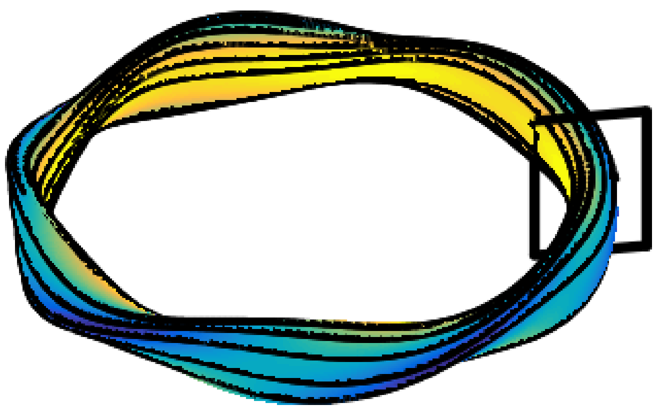
$$V(R, \phi, Z) = \phi + \sum_{m,l} V_{m,l}(R, \phi, Z)$$

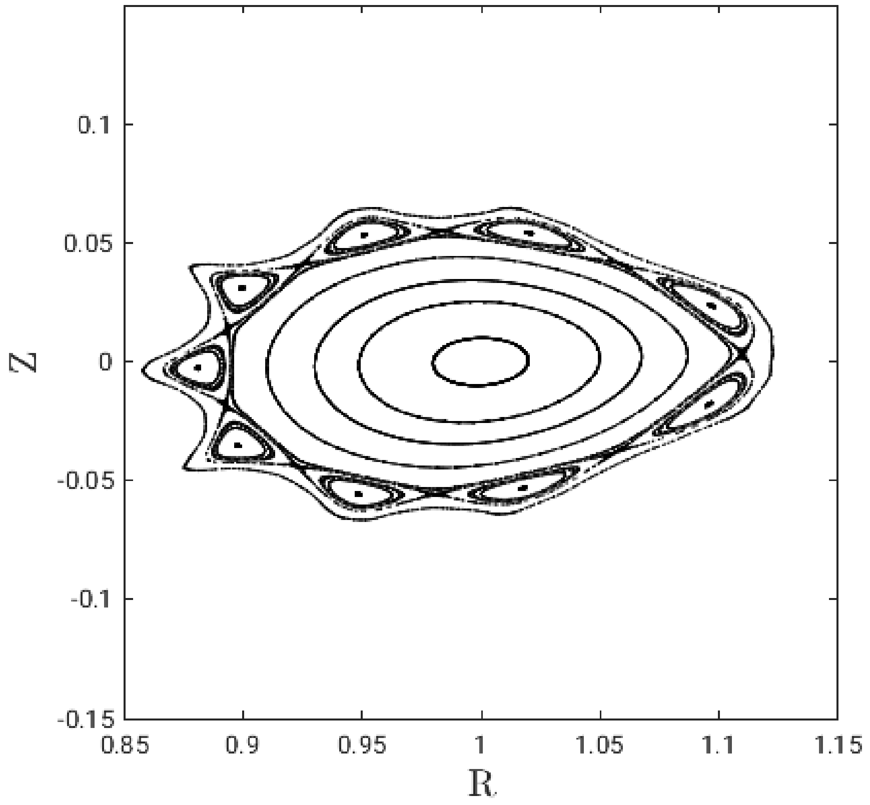


5-field period stellarator



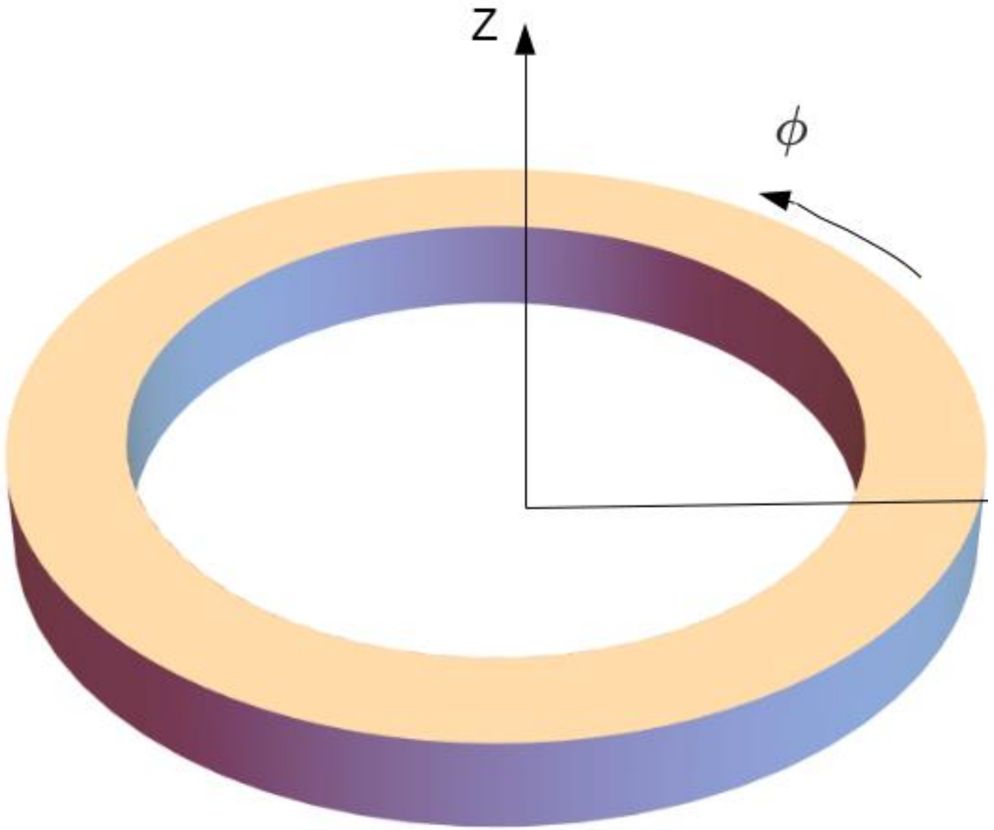
5-field period stellarator with a 5/9 chain of islands

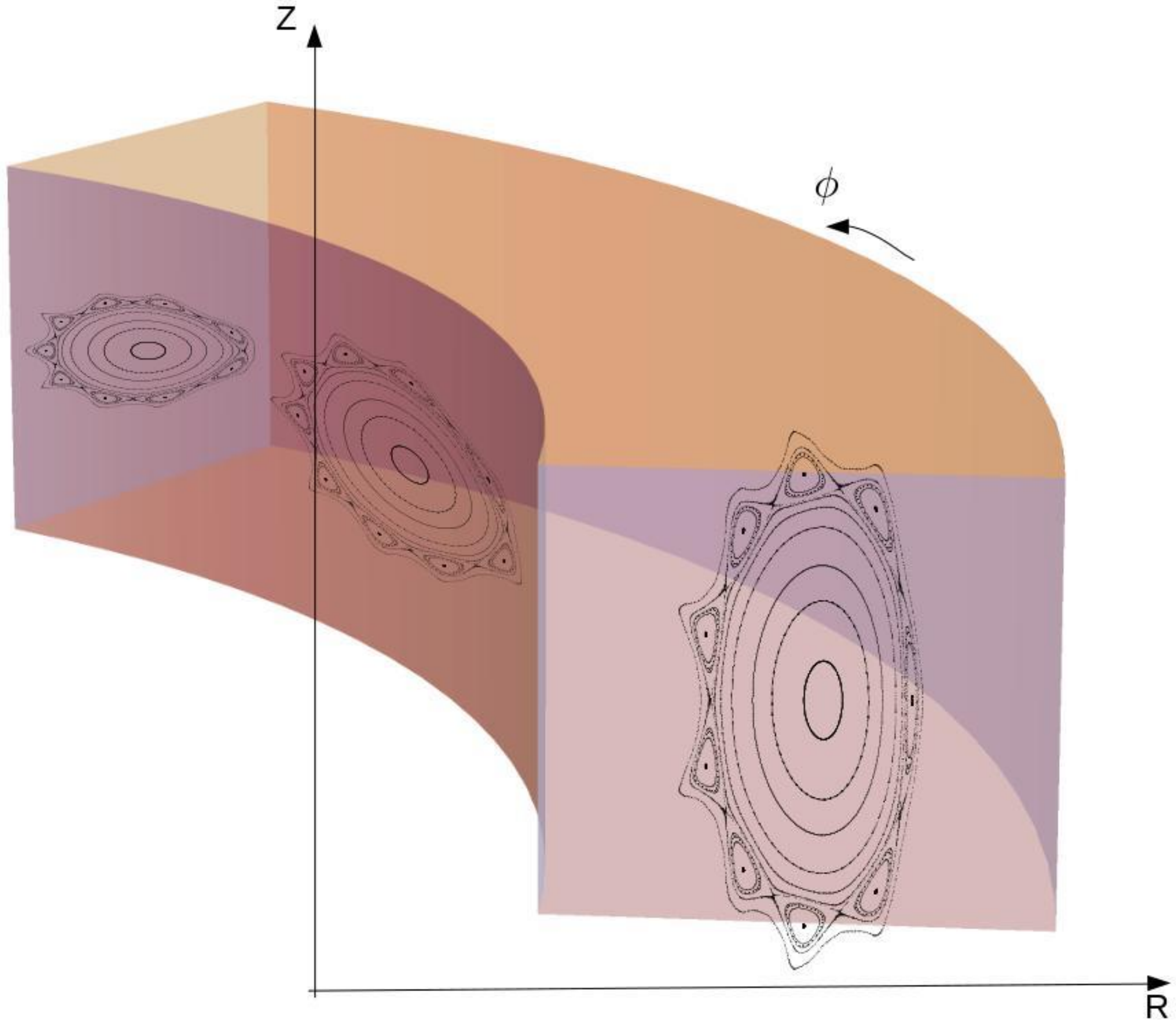




- All rotational transform from rotation of the ellipses

GBS domain boundary intersects divertor islands





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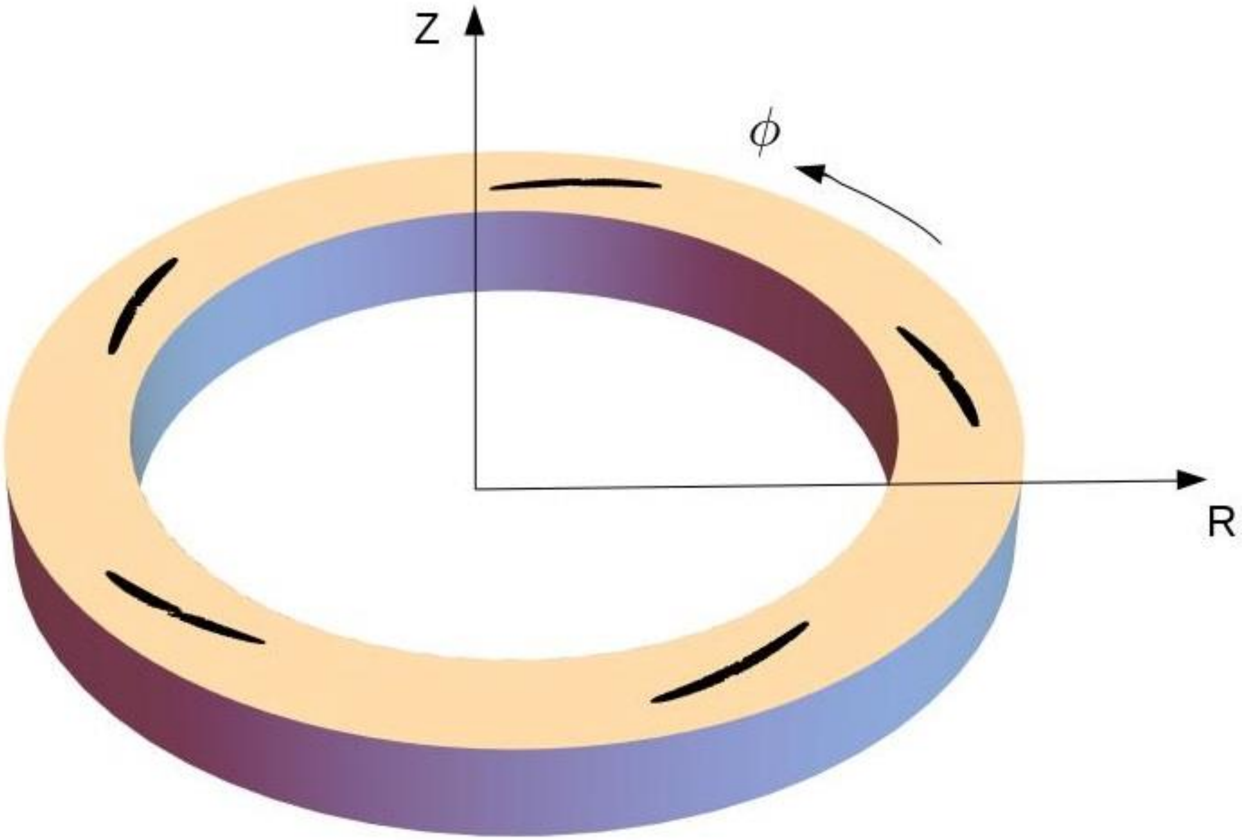
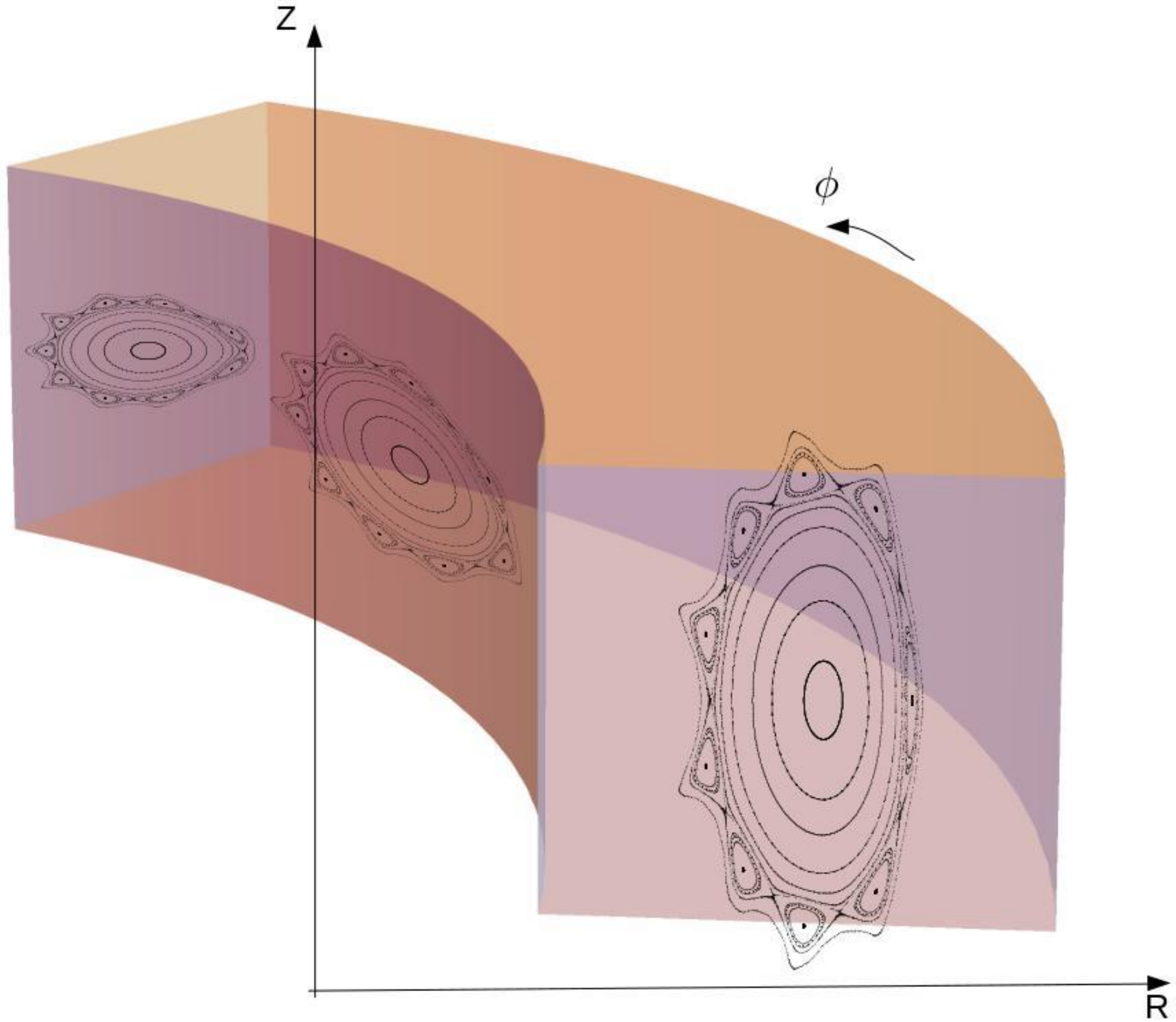
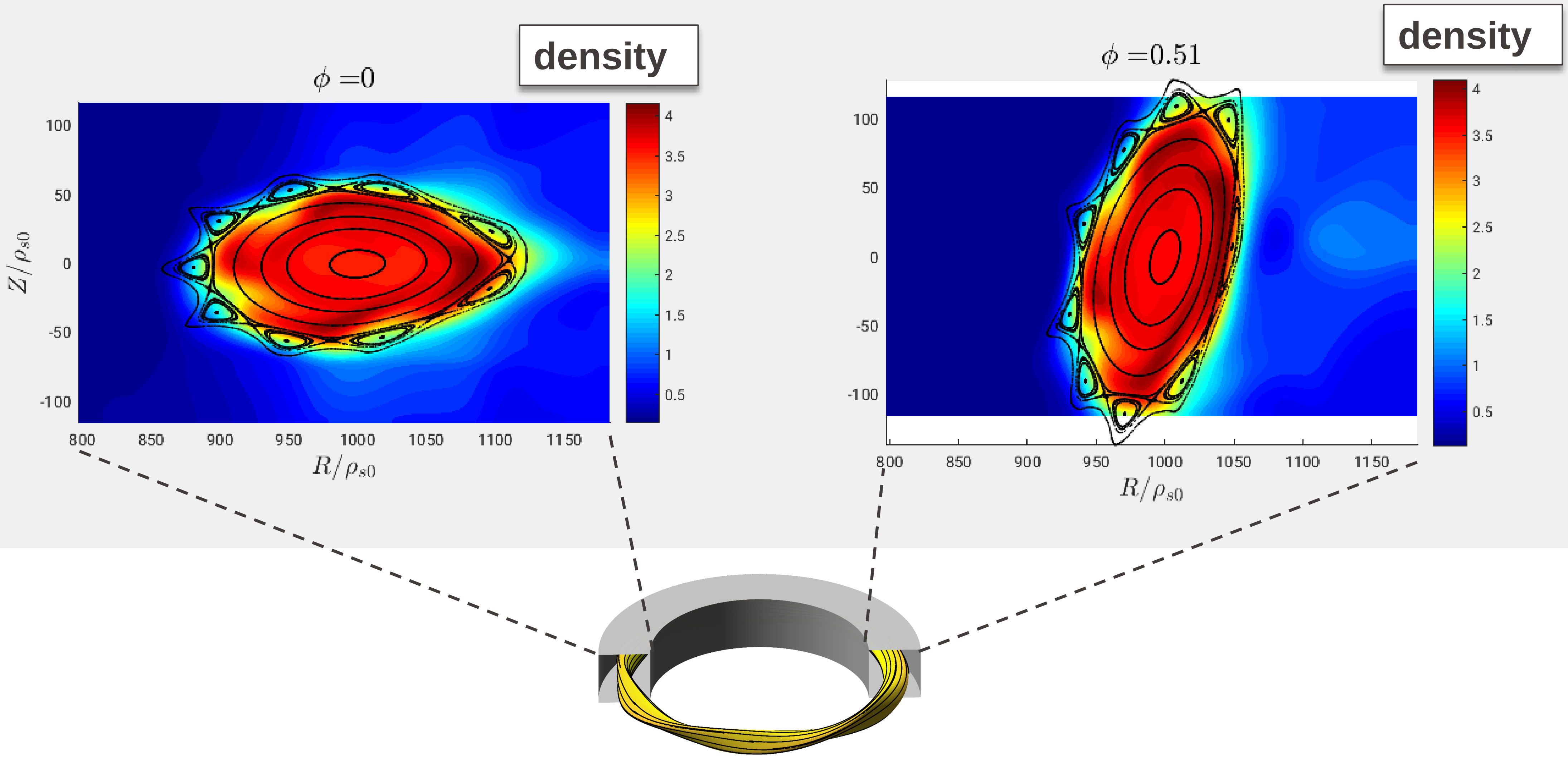




Steady-state of simulation dominated by coherent mode



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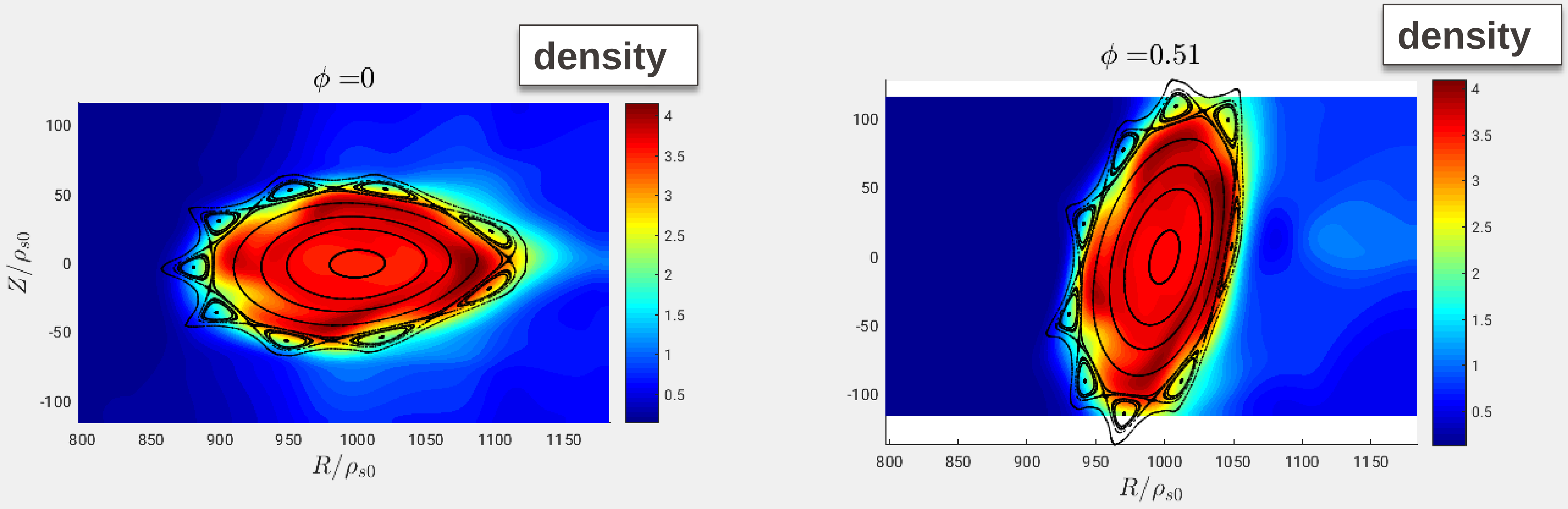
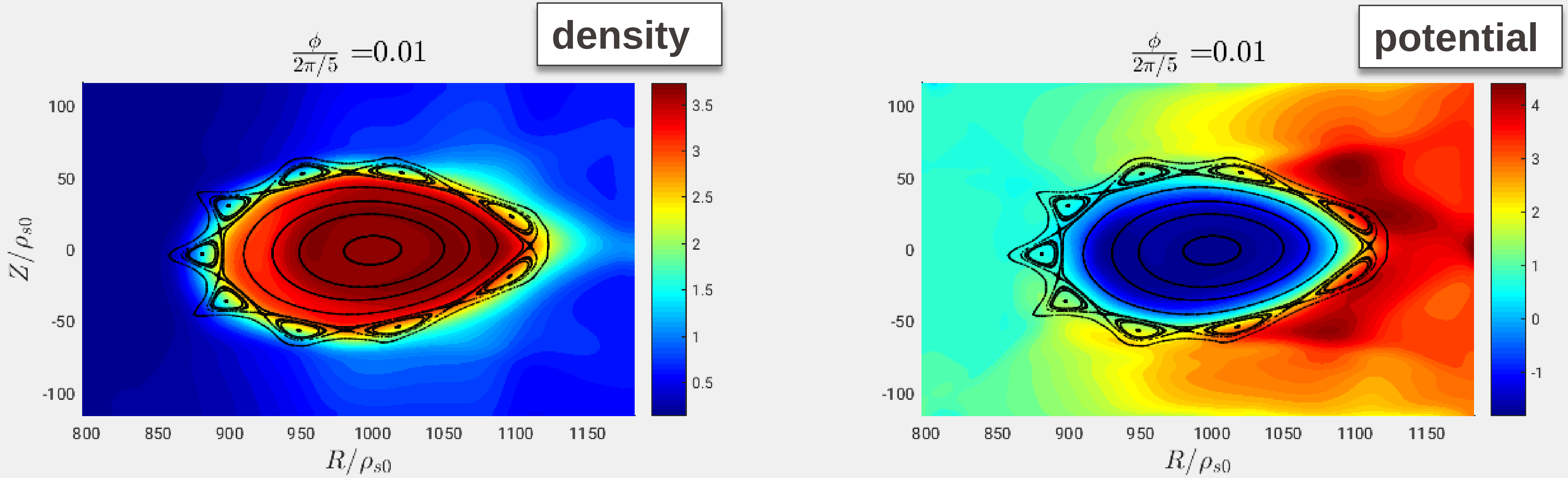
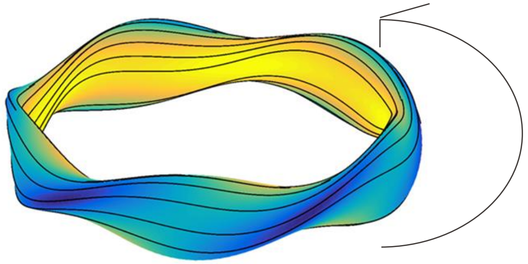


- An m=4 mode that dominates the global dynamics is present in the steady-state
- Mode rotates with ~ ion diamagnetic frequency
- No broad-band turbulence
- Radial transport due to $< \tilde{\Gamma}_{\mathrm{ExB}} >_t = < \tilde{n}\tilde{V}_{\mathrm{ExB}} >_t$ balances source

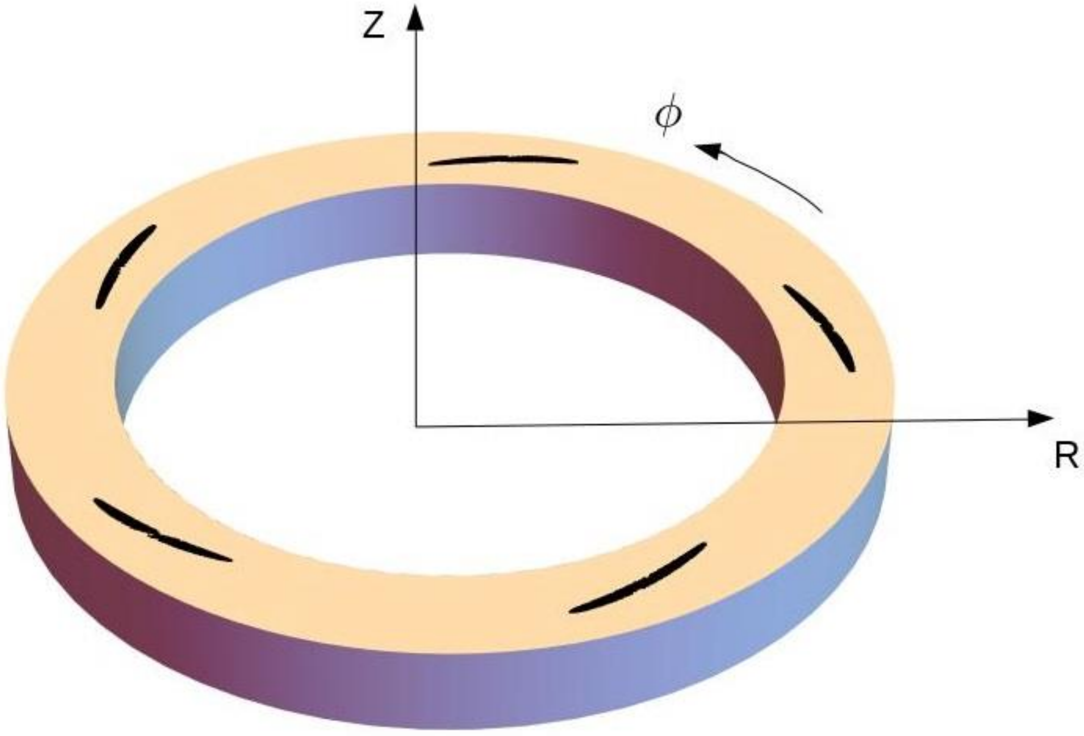
Equilibrium profiles

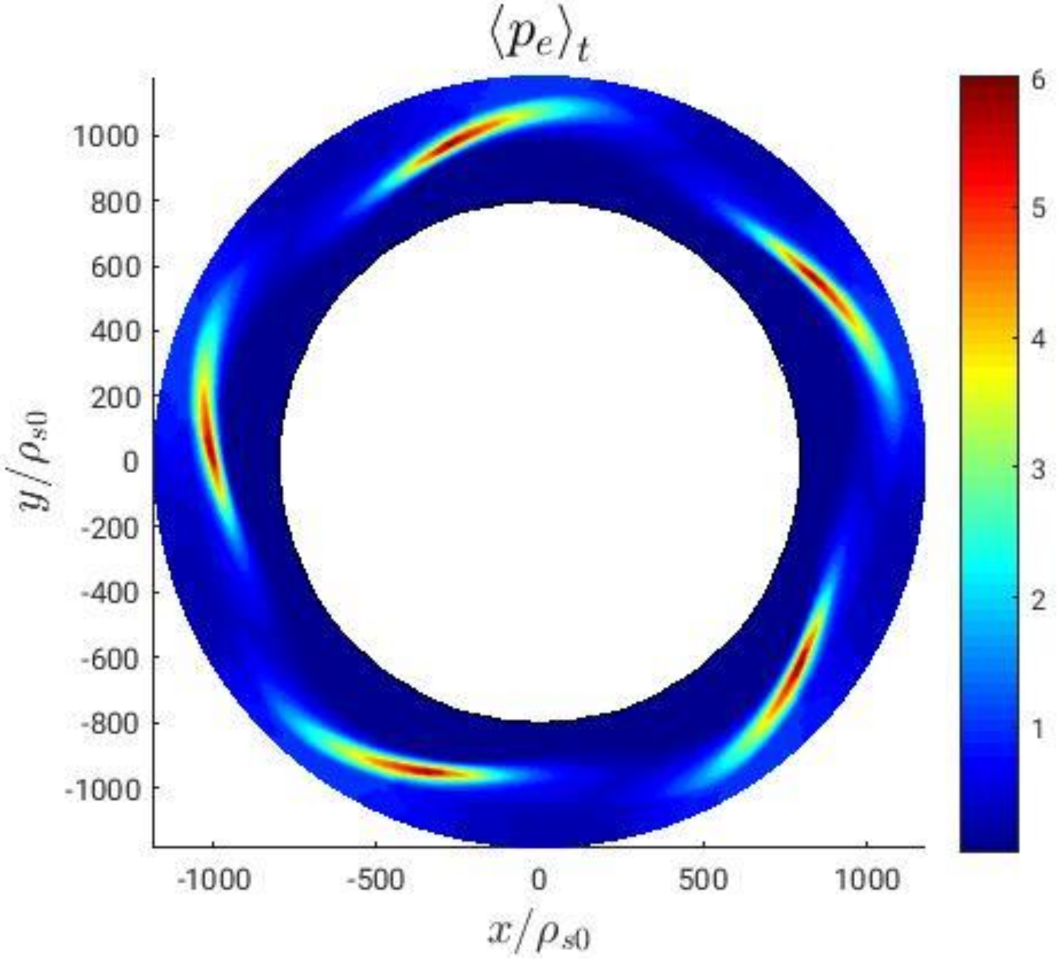




Effectiveness of the island divertor

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





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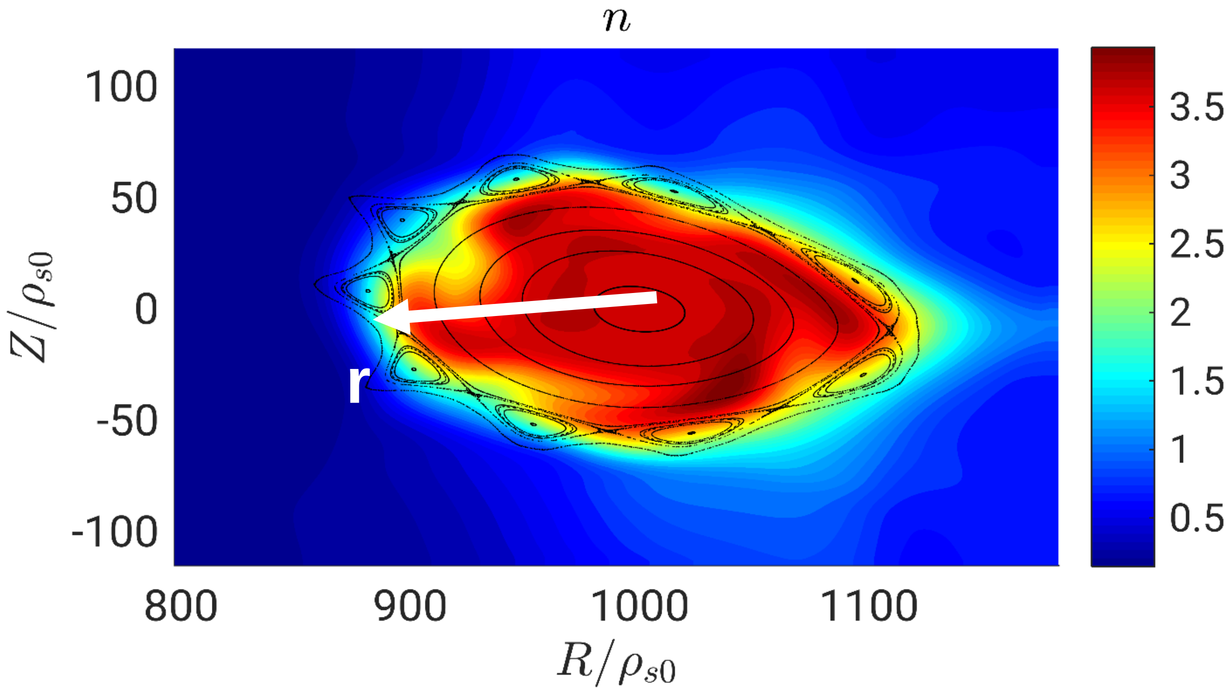
Non-local linear theory predicts the observed m=4 mode

- Linearize GBS equations by assuming quantities vary as:

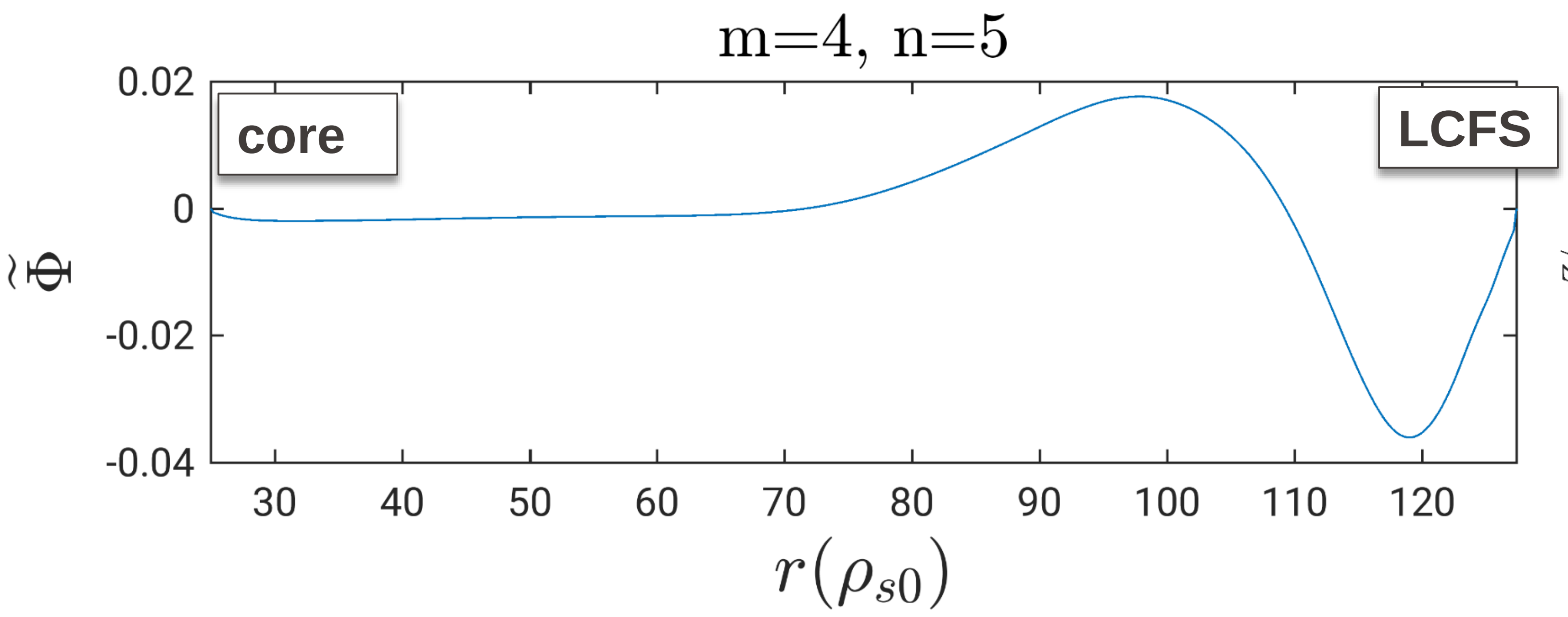
$$n = n_0(r) + \tilde{n}(r)e^{j(m\theta+n\phi)}e^{\gamma t}$$

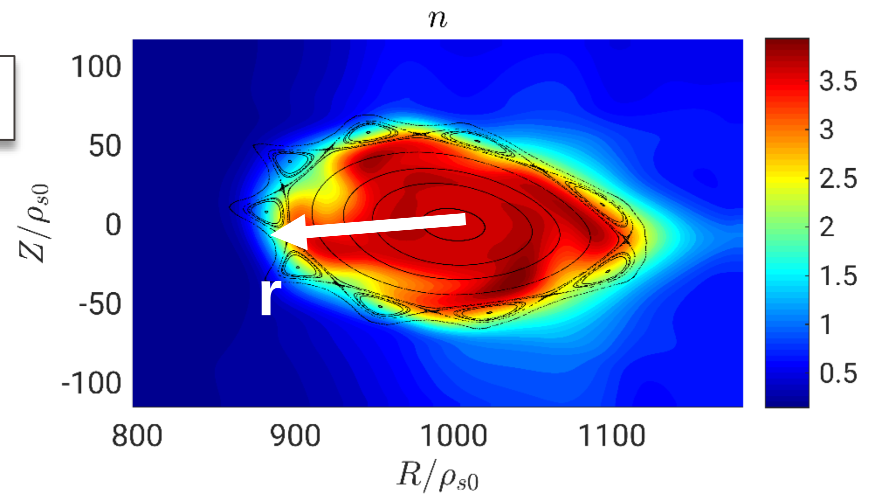
$m = 4$

$n = 5$



Non-local linear theory predicts the observed m=4 mode





Is the linear mode able to transport?

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

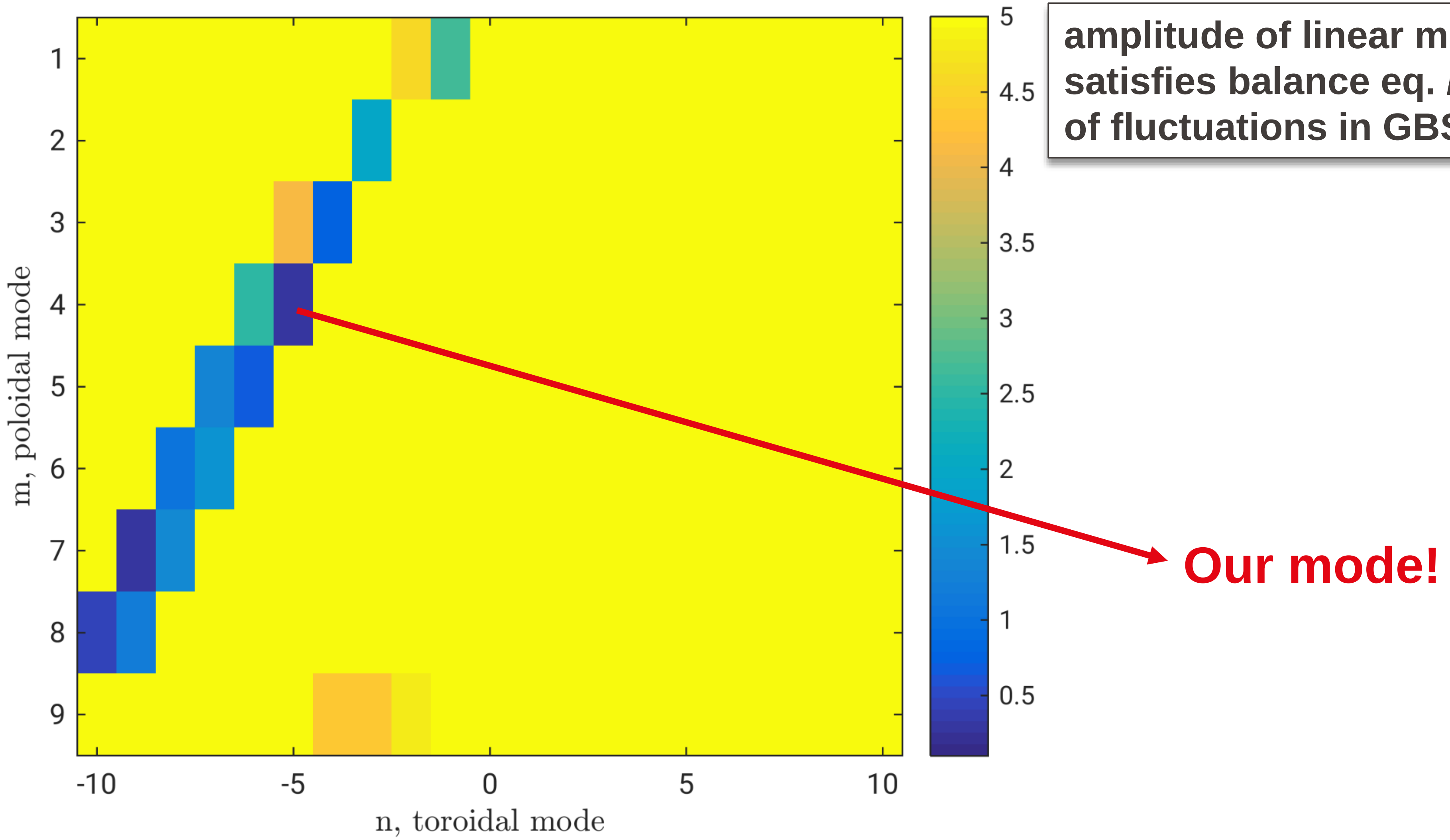
$$|\tilde{n}| \rightarrow n_0|\widetilde{n}|$$

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

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

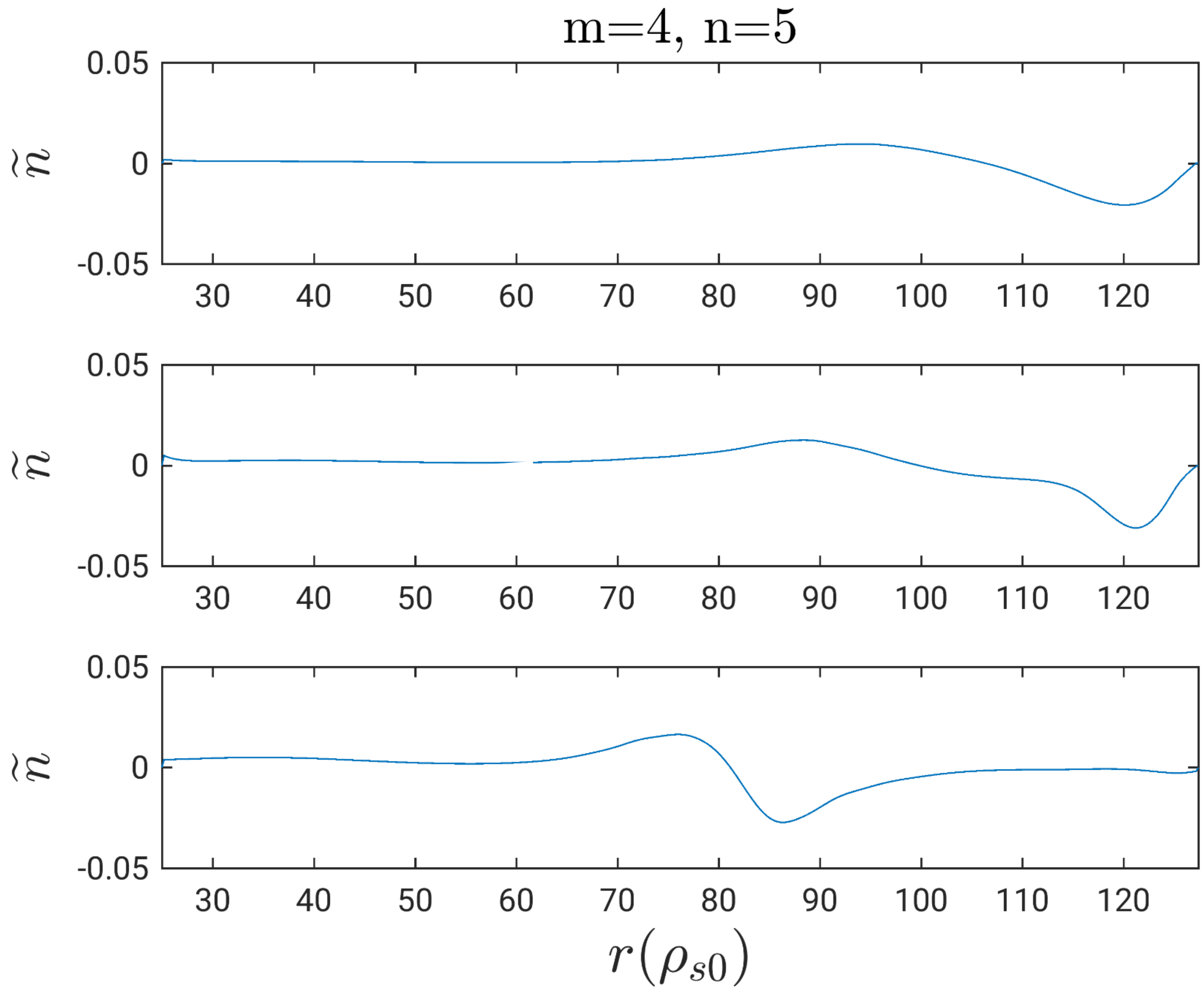
- Solve for $n_0 \sim \Phi_0$ and obtain the perturbation's amplitude needed to balance the source

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

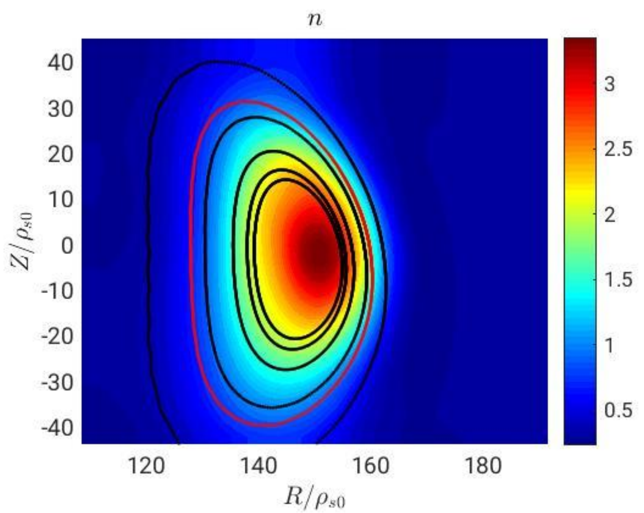
($\nabla_{\parallel} p_e = 0$ in $V_{\parallel e}$ eq.)

No ballooning drive

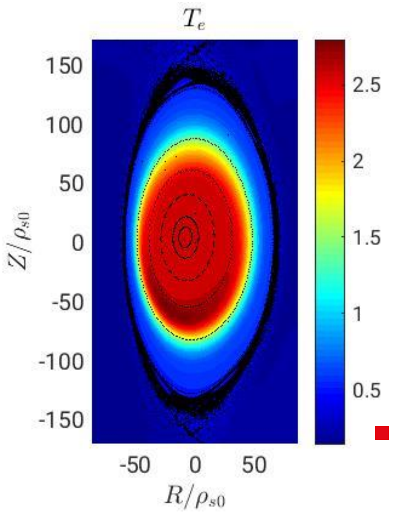
(curvature(p)=0 in vorticity eq.)

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 simulation**
- Linear theory points to **ballooning mode**
- Is this coherent mode a property of the configuration used?



- TJ-K stellarator



- LHD-like stellarator