MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ASDEX Upgrade

Non-linear free boundary MHD simulations of ELM suppression by resonant magnetic perturbations in ASDEX Upgrade plasmas

V Mitterauer

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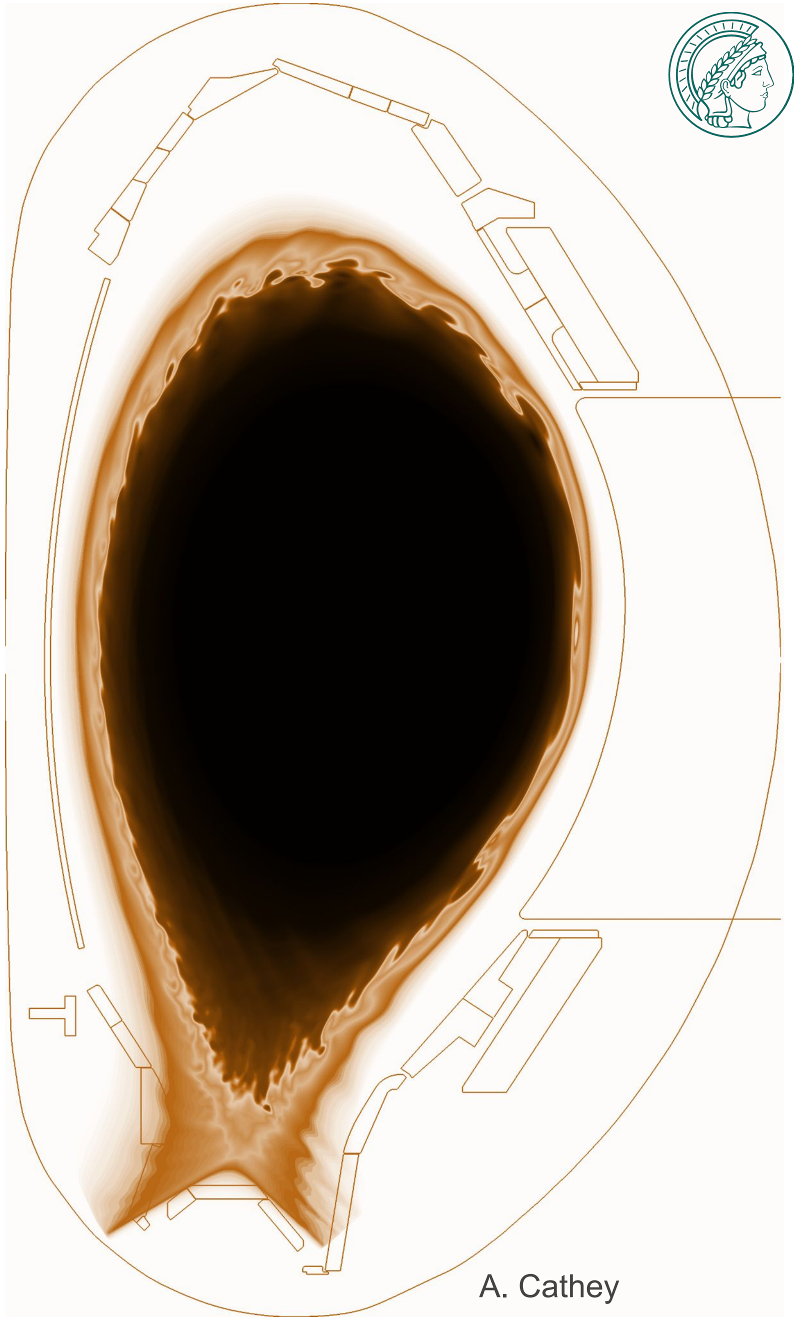
JOREK Team, ASDEX Upgrade Team
& EUROfusion MST1 Team

Motivation

Edge Localized Modes

Periodical expulsions of heat and particles from the boundary of the plasma. Large Type-I ELMs can reduce the lifetime of wall components in future devices



A. Cathey

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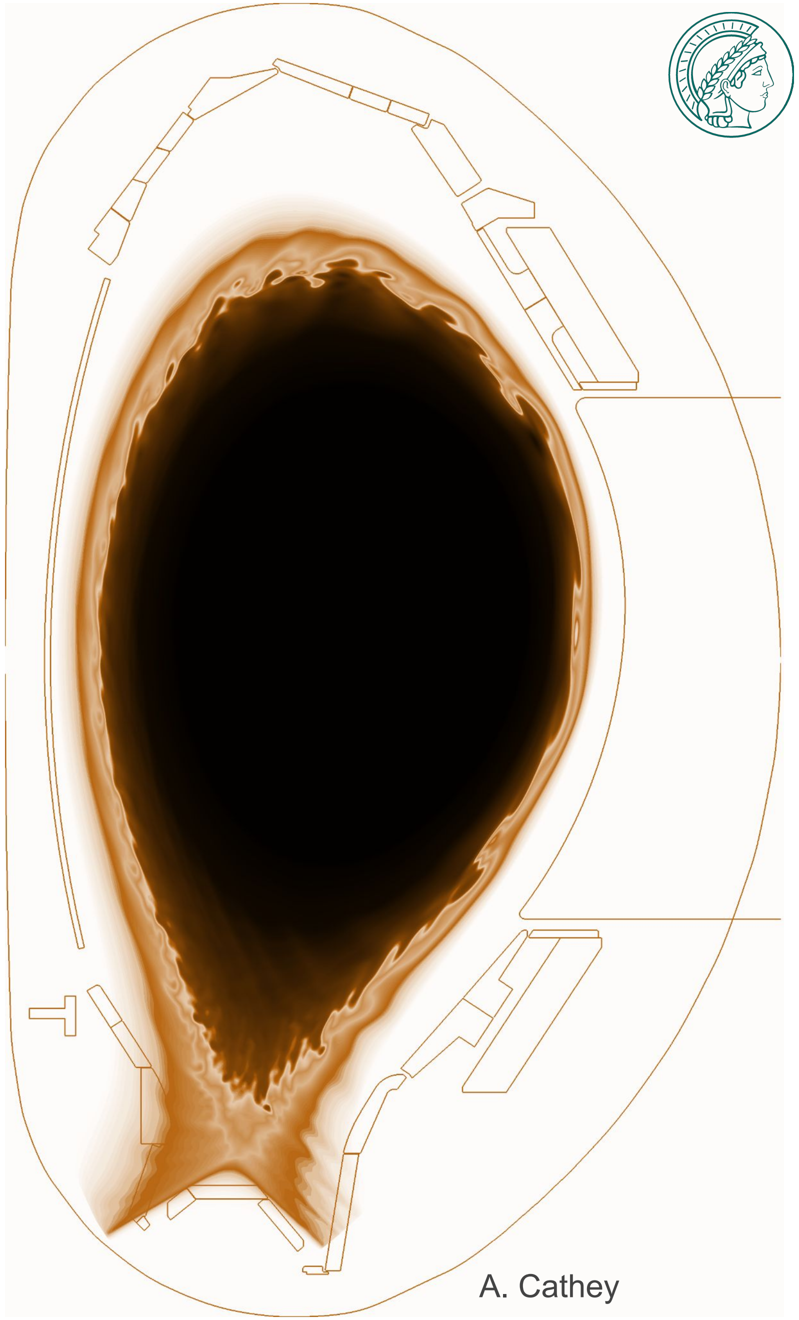
Resonant Magnetic Perturbations

Small 3D perturbations to the axisymmetric field of a tokamak. Planned method of ELM control for ITER



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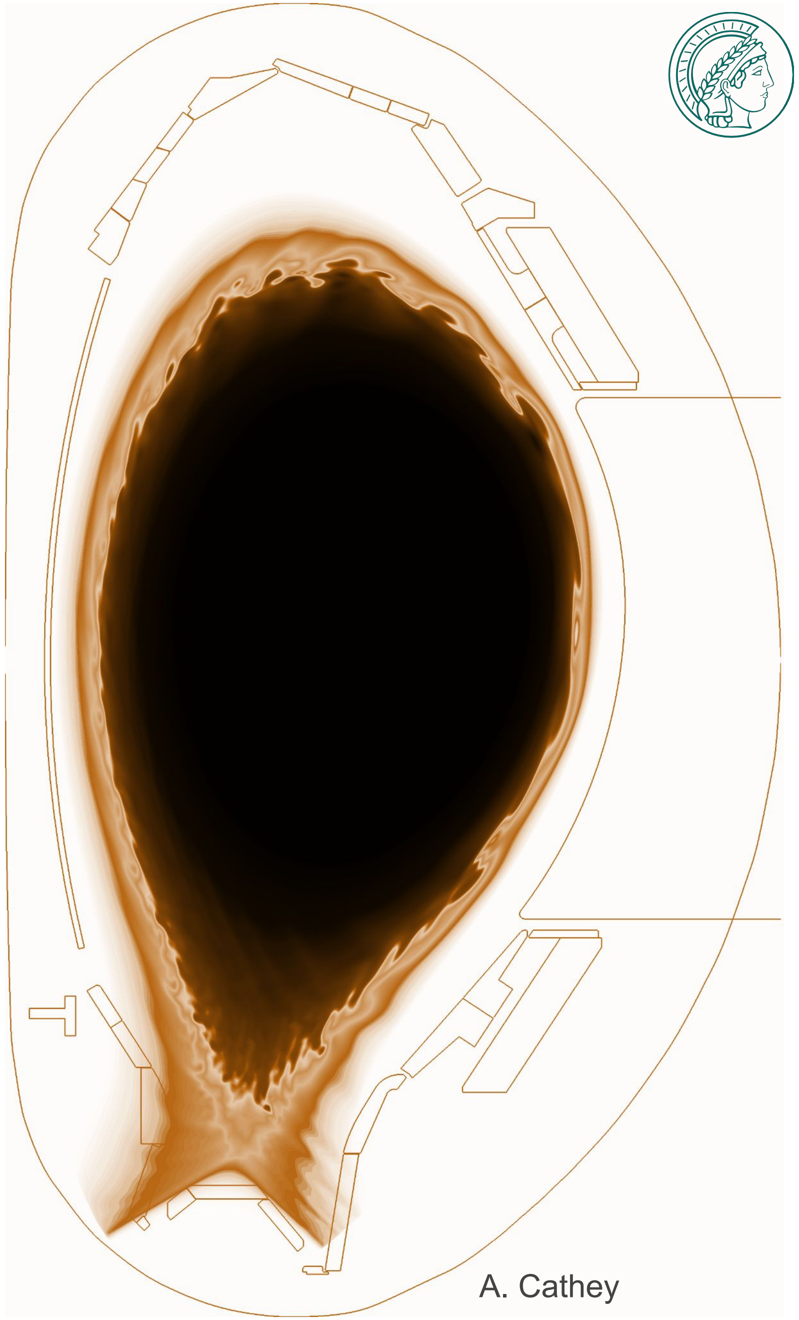
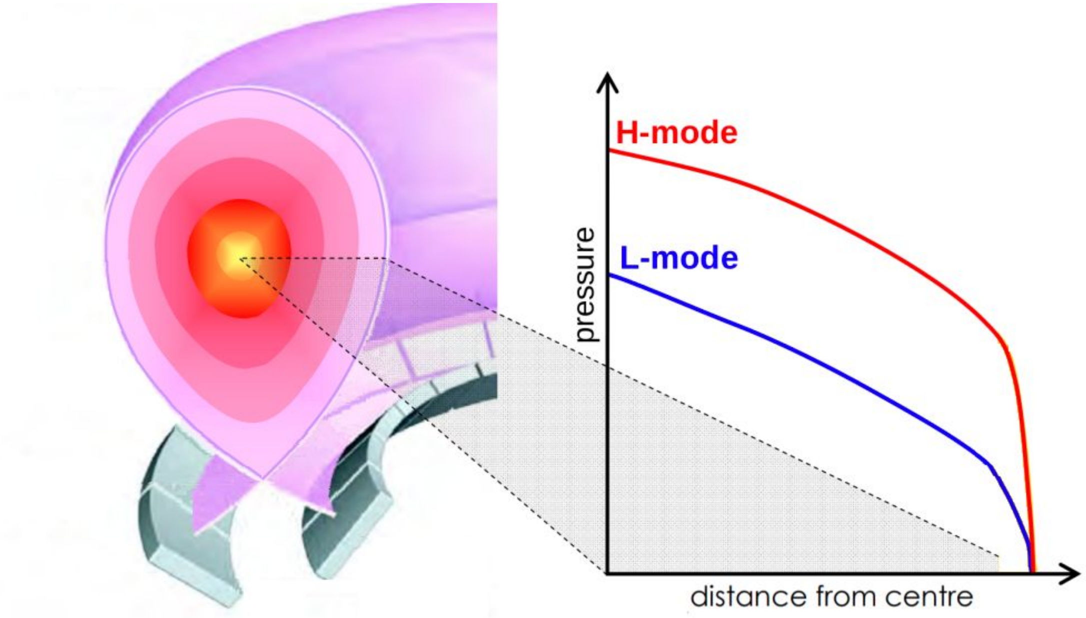
In this talk:

- Introduce basic ELM & RMP physics
- Development of self-consistent boundary conditions for RMP studies with JOREK-STARWALL
- Confirmation of experimental evidence supporting a RMP-ELM suppression theory
- Outlook towards advanced kinetic simulations



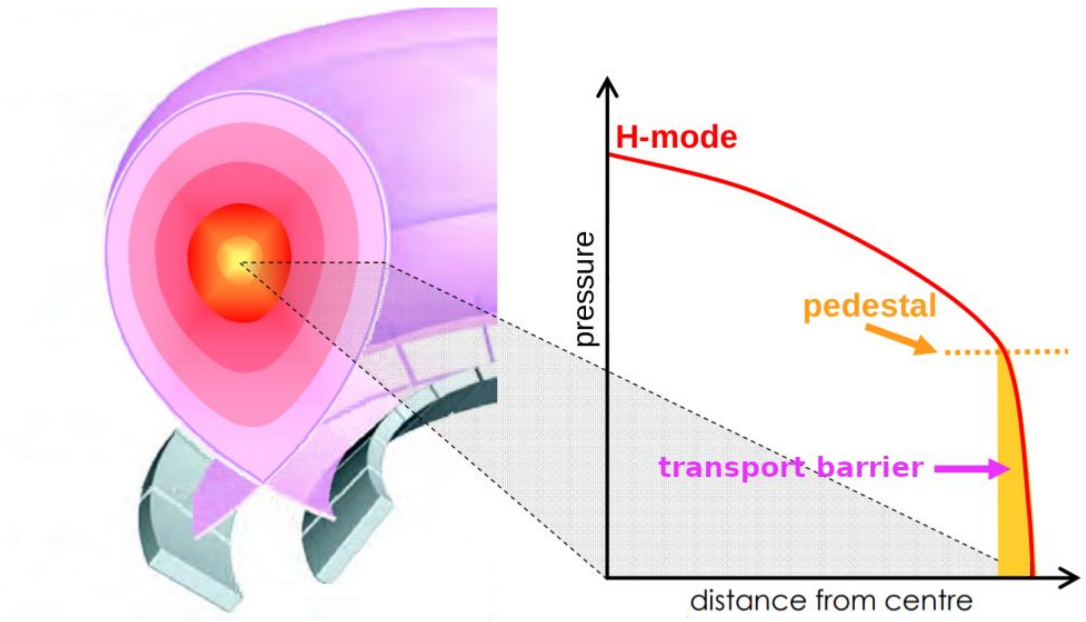
High confinement mode in tokamaks



K. Park 2019 AiP

- H-Mode pressure profile characterized by steep pressure gradient at the edge

High confinement mode in tokamaks



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- Transport is suppressed close to separatrix & leads to build up of pedestal

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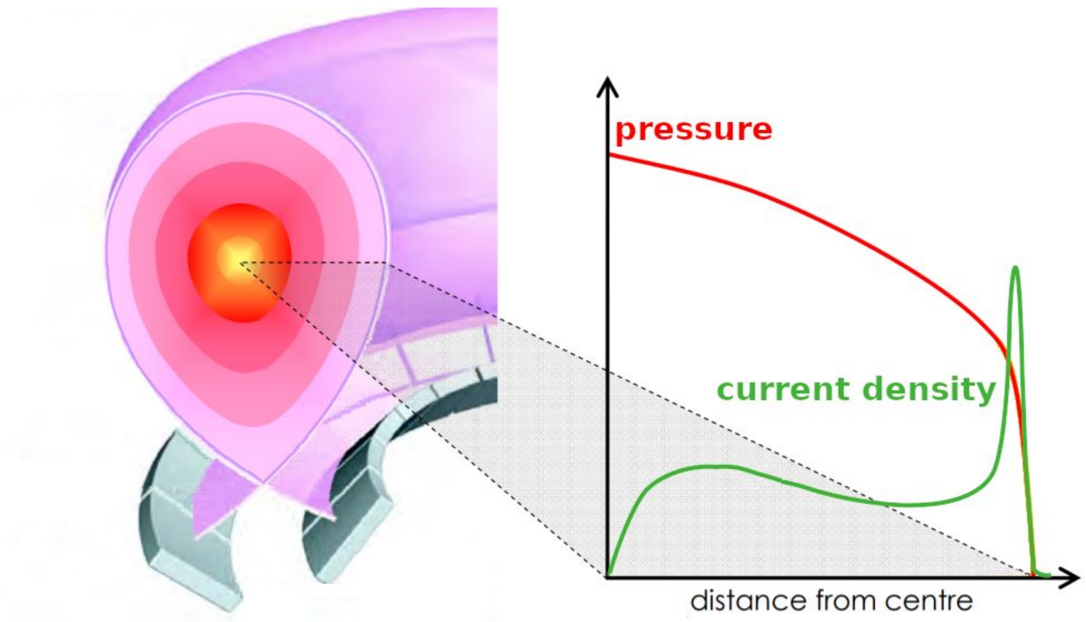

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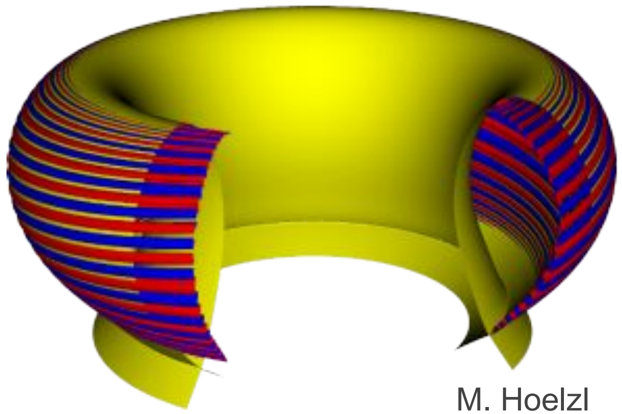
- H-Mode pressure profile characterized by steep pressure gradient at the edge
- Transport is suppressed close to separatrix & leads to build up of pedestal
- High current density follows from steep pressure gradient
- MHD instabilities can be both pressure gradient driven and current density driven

Ideal MHD instabilities in H-Mode pedestal

Ballooning Mode:

- pressure gradient driven
- high toroidal modes
- localized at low field side



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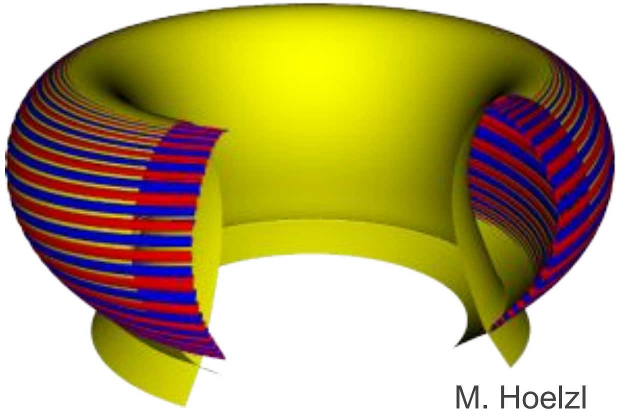

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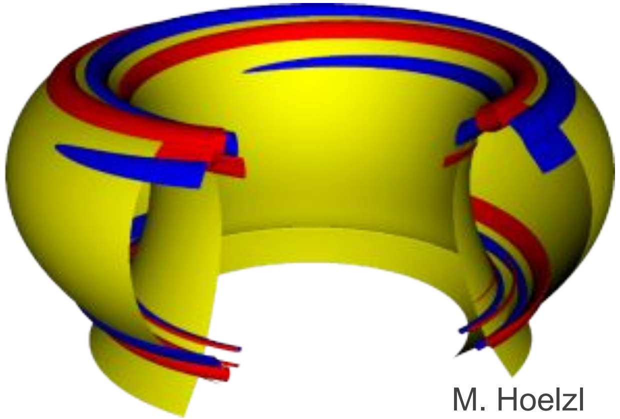
Peeling Mode:

- current density driven
- low toroidal modes



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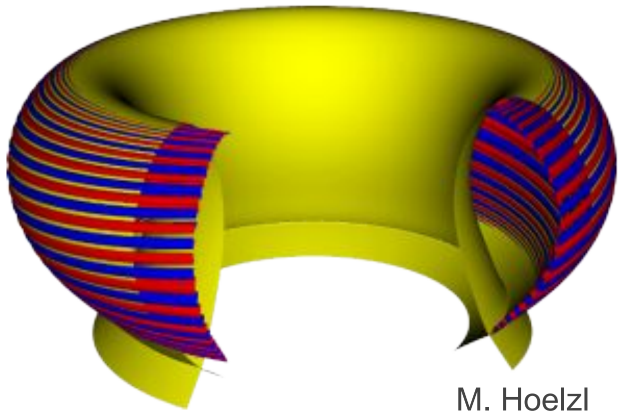

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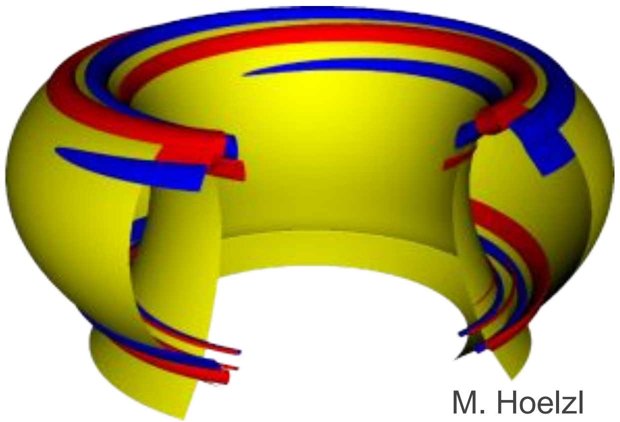

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- Transport is suppressed close to separatrix & leads to build up of pedestal
- High current density follows from steep pressure gradient
- MHD instabilities can be both pressure gradient driven and current density driven
- Peeling and ballooning mode can couple to a coupled peeling-ballooning mode
- ELMs are the non-linear consequence of peeling-ballooning modes

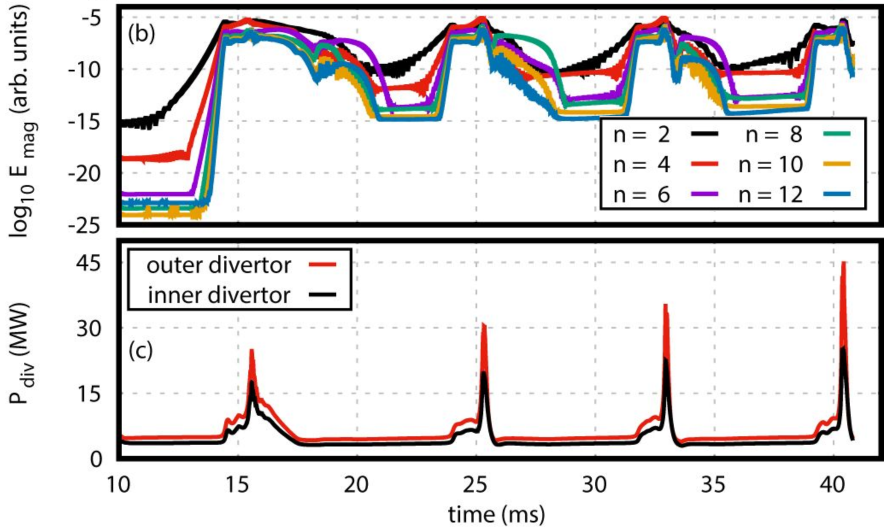
Edge Localized Modes [A. Cathey 2022 NF]

(1) **Precursor Phase:** Destabilization of precursor peeling-ballooning modes due to pressure gradient and current density

(2) **ELM onset:** Reduction in plasma flows - begin of faster-than exponential growth

(3) **ELM crash:** Convective and conductive losses degrade the pedestal gradients

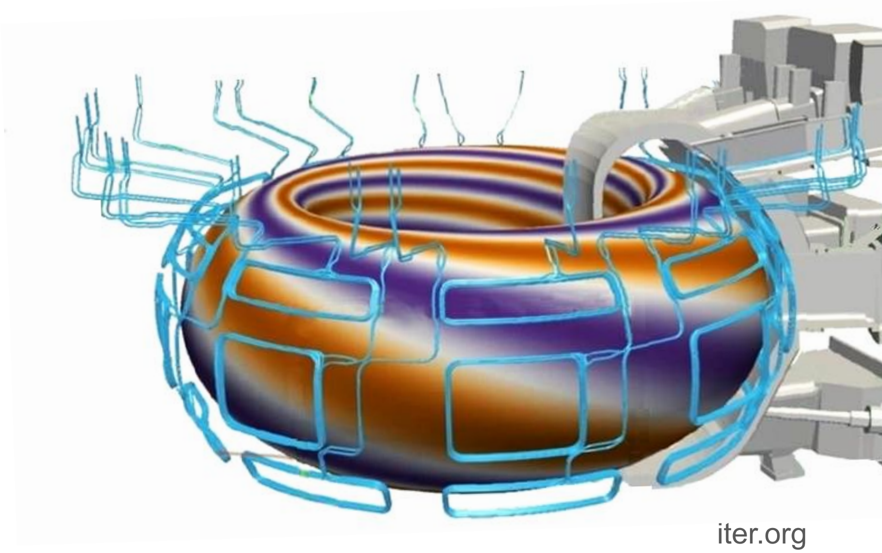
(4) **Recovery:** Pedestal rebuilds



ELM cycles in AUG
by A. Cathey using JOREK
[A. Cathey 2022 NF]

Type-I ELMs not supportable in future machines

- Type-1 ELM eject typically 5-10% of plasma stored energy [Eich T. et al 2017 NME]
- Losses during ELM crash directed towards divertor plates and cause high transient fluxes
- not tolerable for future fusion devices
- **ELM control mechanisms under development**
  - Naturally ELM-free or small ELM Regimes
  - Pellet Injection
  - **Application of Resonant Magnetic Perturbations**
    - **Small helical field applied with external coils**
    - **One dominant toroidal mode n_{RMP} broad poloidal spectrum**



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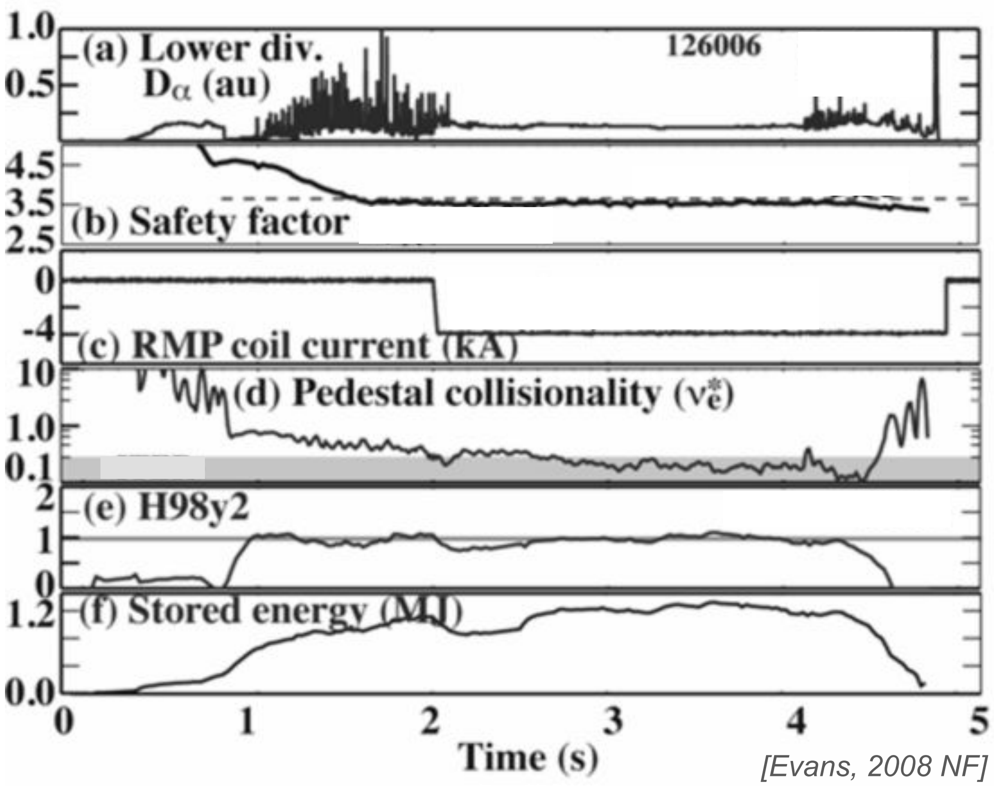
Magnetic perturbations can fully suppress ELMs



[Evans, 2008 NF]

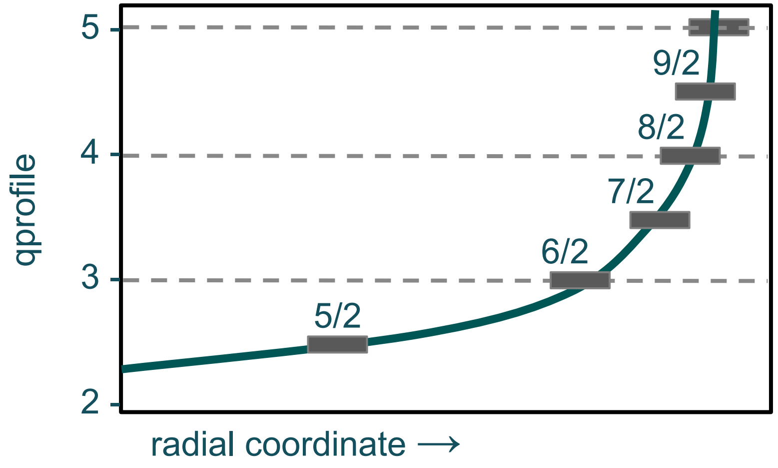
DIIID discharge with RMP-ELM suppression

- D-alpha signal as measure for ELM occurrences
  ⇒ RMP ramp up followed by ELM free phase
- Empirical operational windows have been found
  [W. Suttrop 2018 NF]
  - Plasma edge density below critical threshold
  - q95 within parameter ranges
  - Requirements to plasma shaping and plasma pressure

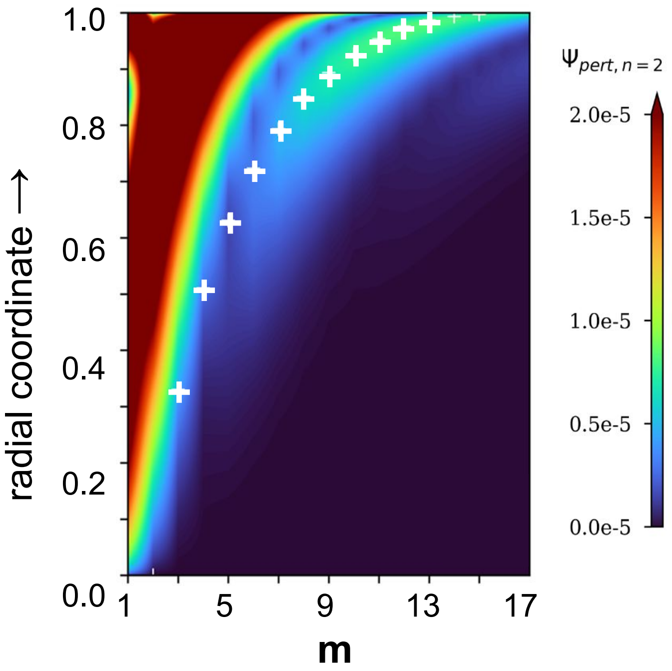
Initial hypothesis: 3D perturbation leads to stochastic edge

- Rational surface: m/n helicity
- **Resonant** surface: m/n_{RMP} helicity

q-profile determines radial location $q=m/n_{RMP}$



Poloidal spectrum of applied n=2 perturbation
(without plasma response)



+ … resonant surfaces

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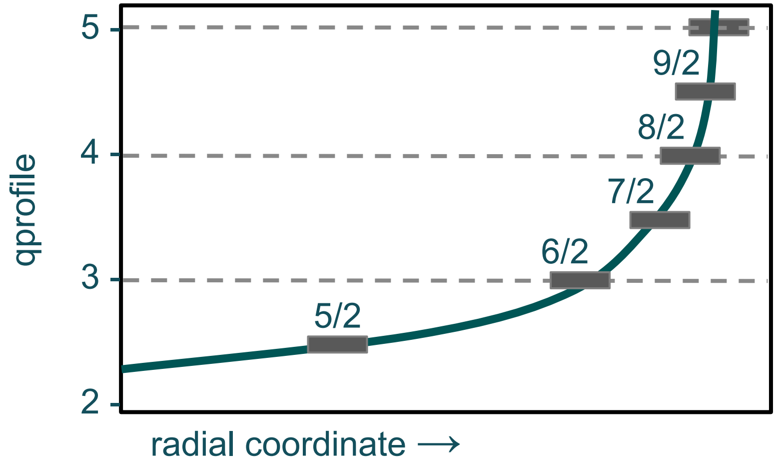

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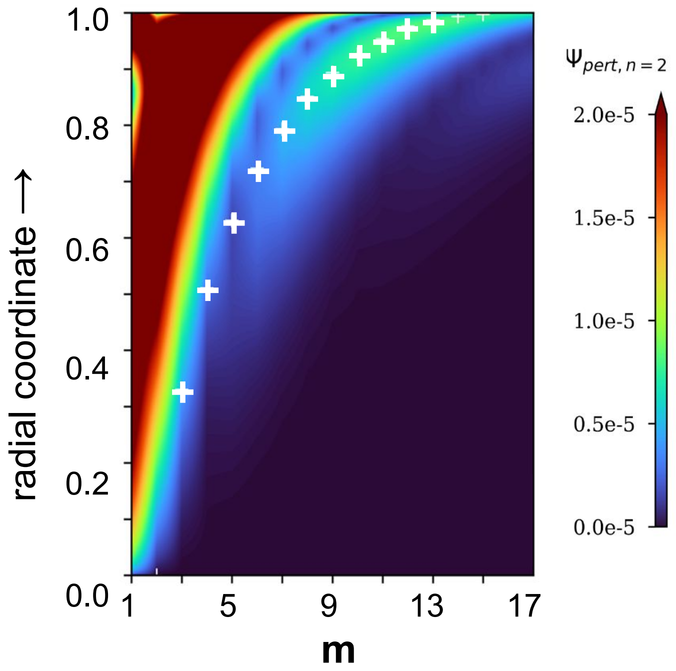

+ … resonant surfaces

m/n_{RMP} component of perturbation non-zero at position of resonant flux surface - magnetic island forms

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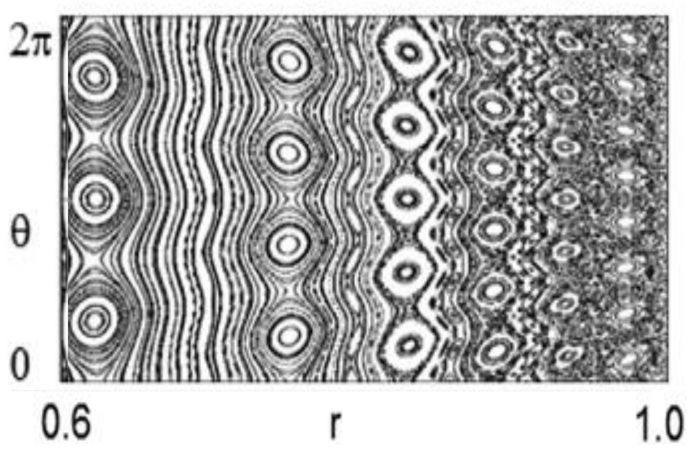


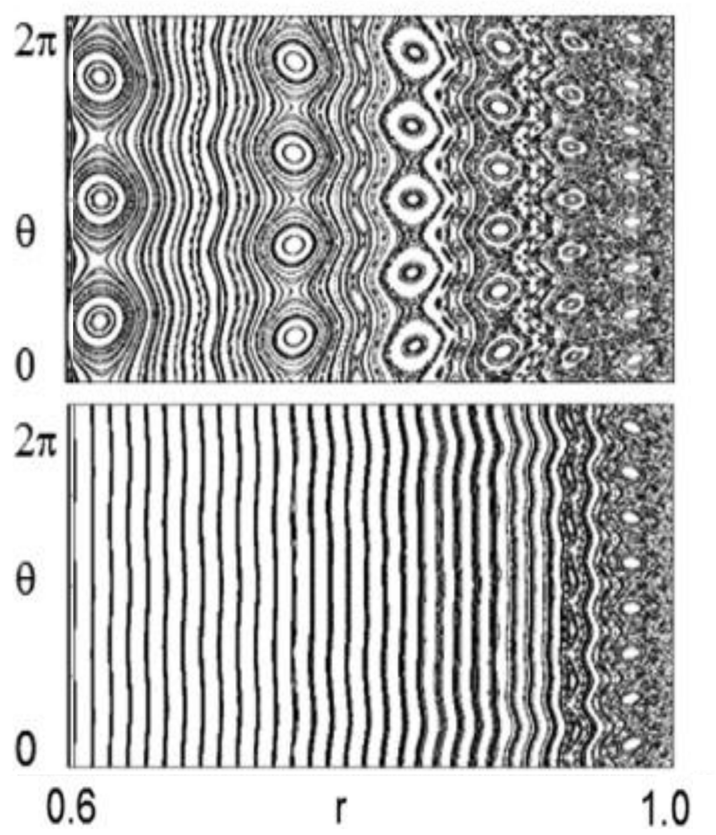
- Islands overlap at the edge and result in stochastic layer
- Fast heat transport along field lines
  ⇒ Reduction of Te in pedestal
  ⇒ stabilization of edge region

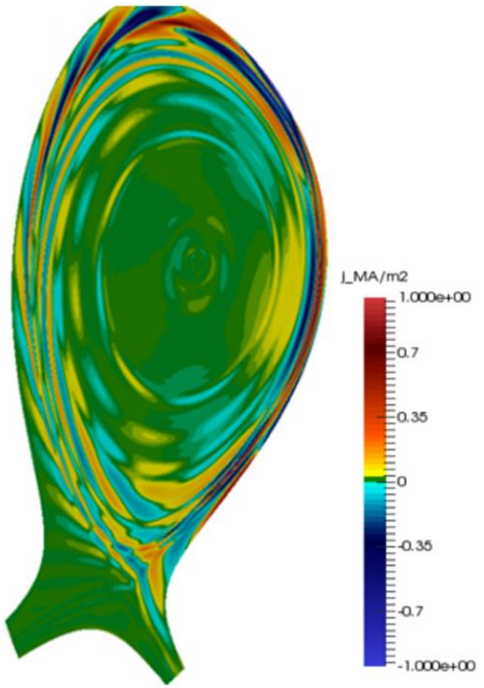
But: Te reduction generally not observed in experiment

[T. Evans Nature 2006]

:
M. Becoulet 2012 NF
F. Orain 2016 NF

Plasma currents alter the total perturbation





- Perturbation induces currents on resonant surfaces ⇒ Local screening of perturbation ⇒ Fewer islands form

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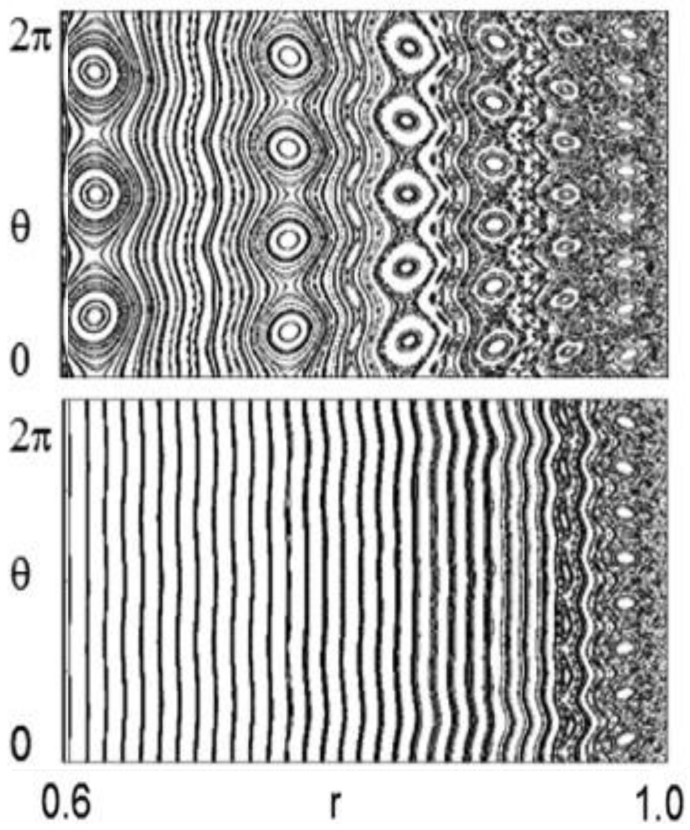

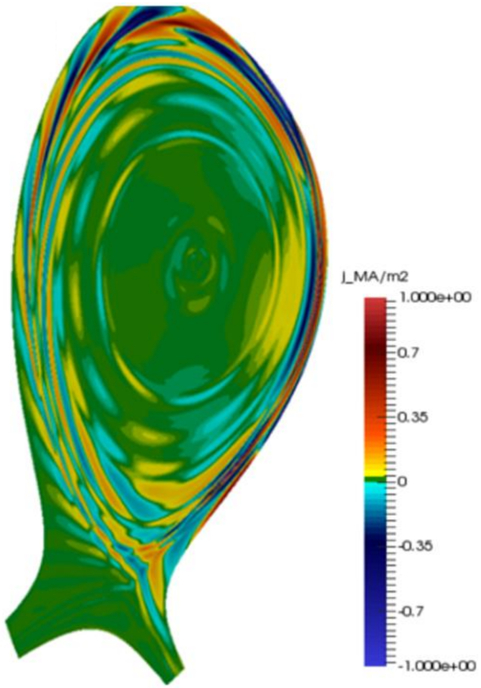

- Perturbation induces currents on resonant surfaces ⇒ Local screening of perturbation ⇒ Fewer islands form
- Screening currents described by Ohm's Law:

$$\eta\vec{\mathbf{j}} = \vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}} \Rightarrow \eta \mathbf{j}_{\parallel}^{\mathbf{m,n}} = \mathbf{E}_{\parallel} + \mathbf{v}_{\perp,\mathbf{e}} \mathbf{b}_{\mathbf{r}}^{\mathbf{m,n}}$$

- Small stochastic edge region remains due to resistivity
- In addition: If diamagnetic and ***E***×***B***-flows cancel locally ($v_{\perp,e}$=0) islands may penetrate on individual resonant surfaces
- Two-fluid model requires $v_{\perp,e}$=0
  Other conditions in kinetic models [Heyn 2014 NF] and experiment [Suttrop 2019 NF, Paz-Soldan 2020 NF]

M. Becoulet 2012 NF
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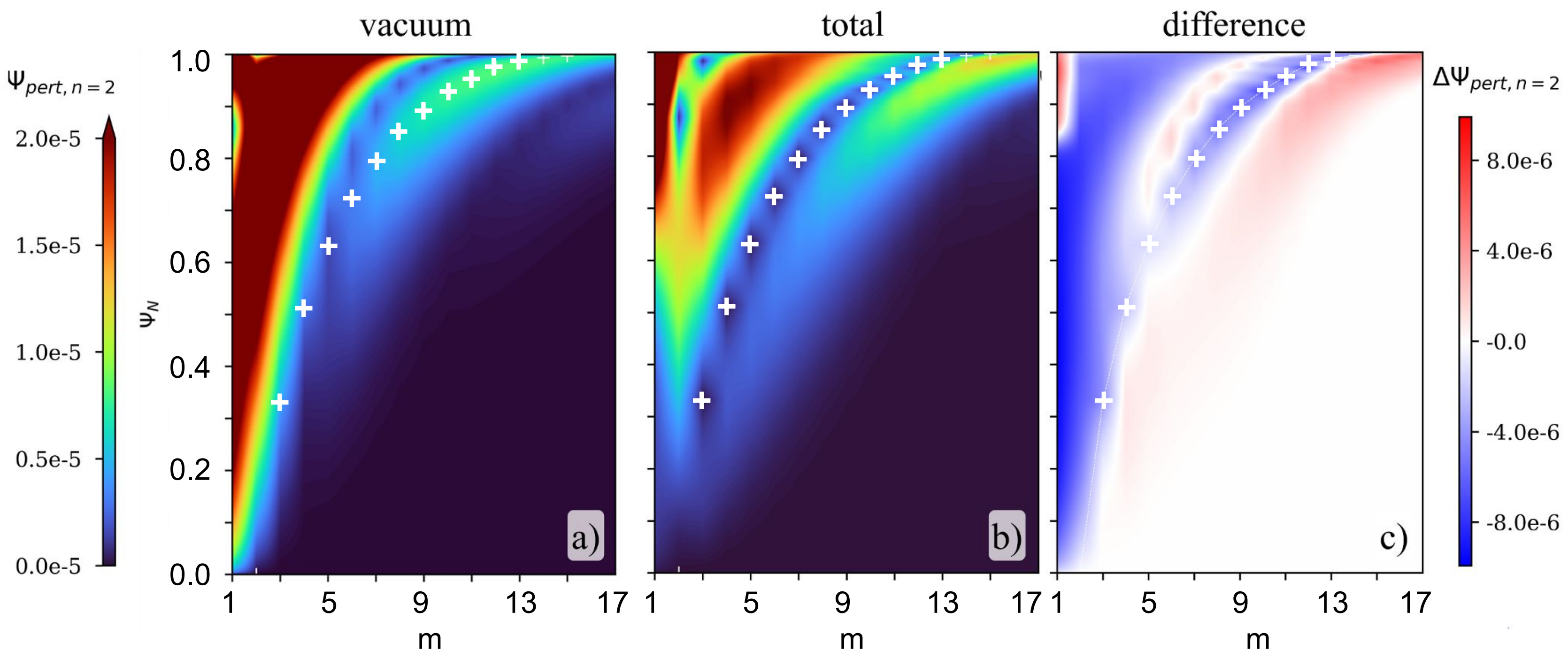
Perturbation screening and kink amplification

Resonant Contributions are screened at the position of the respective resonant surfaces



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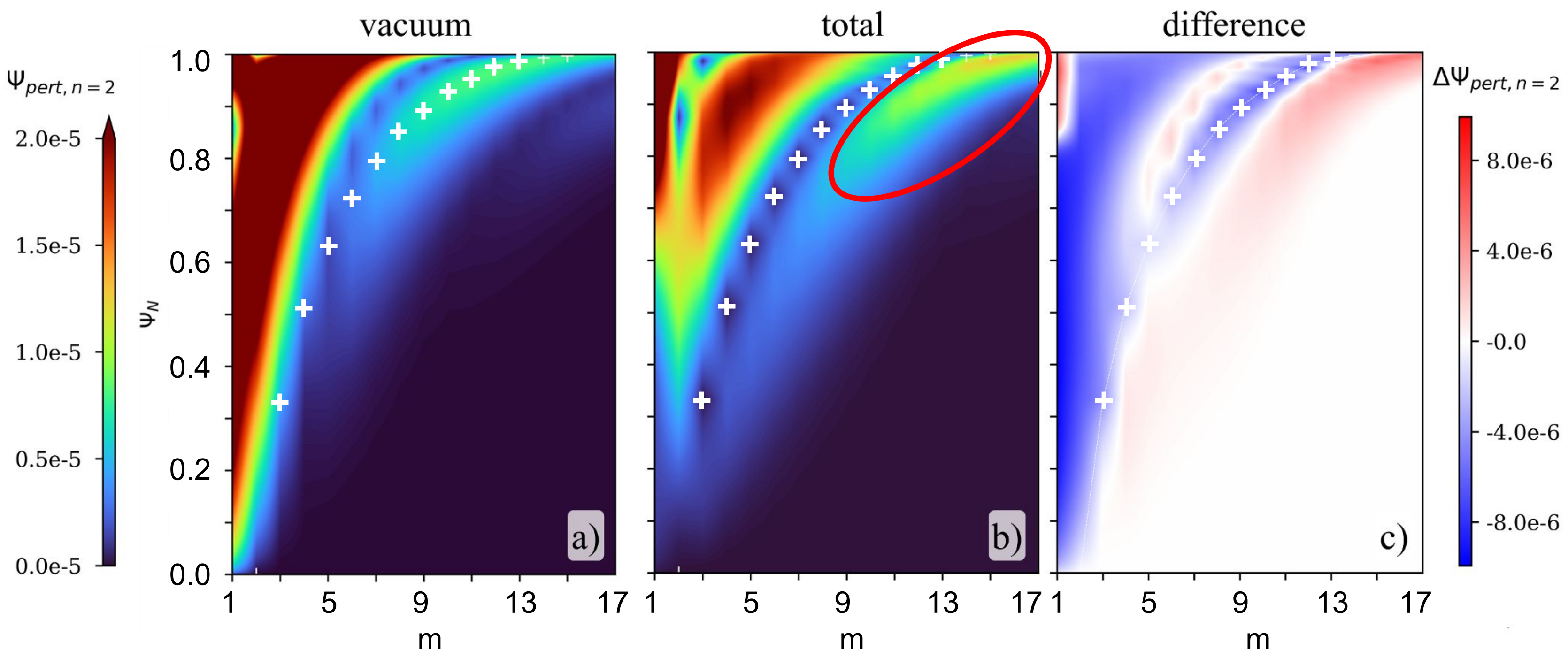
O Amplified **Edge Kink Modes**



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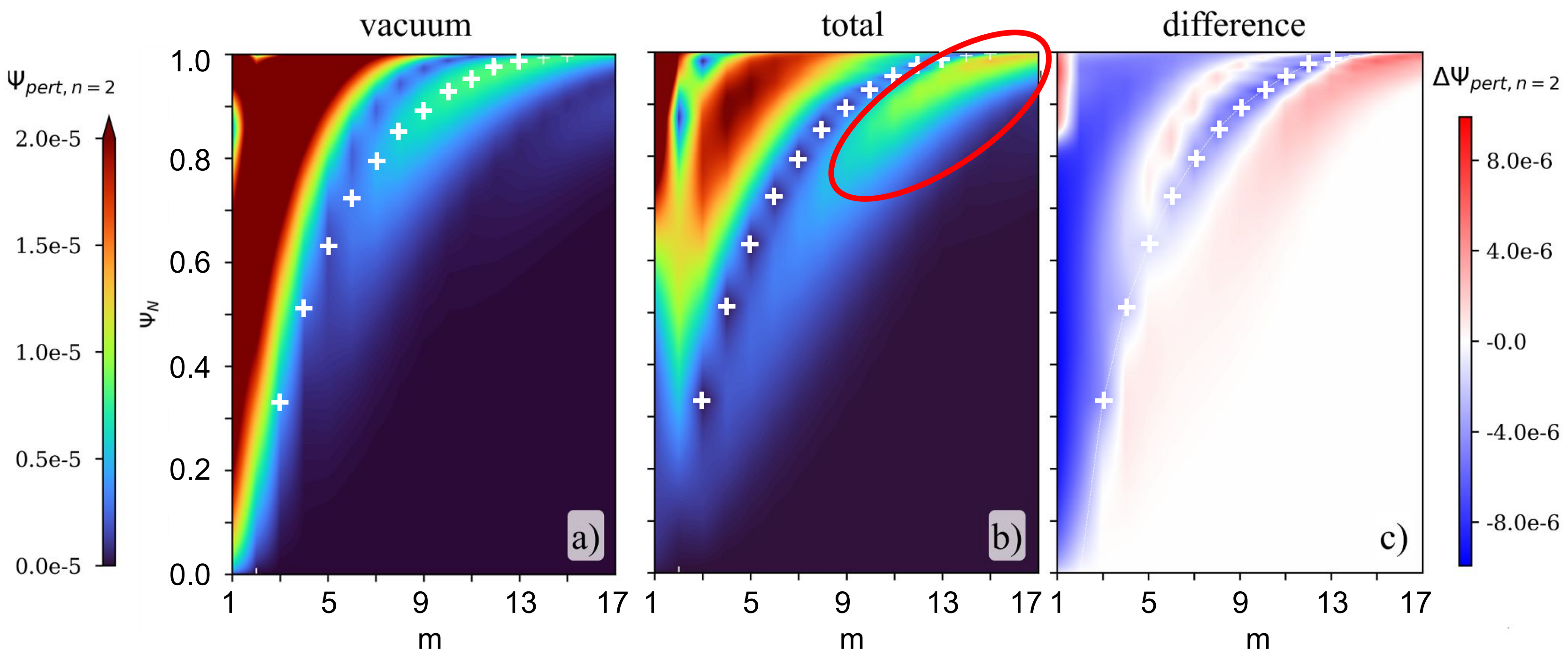
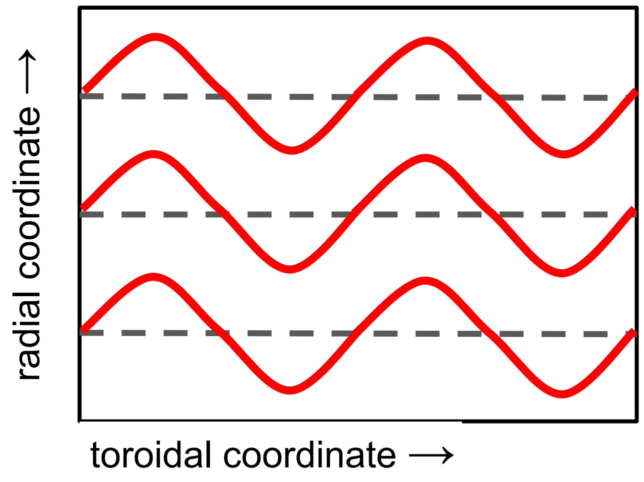
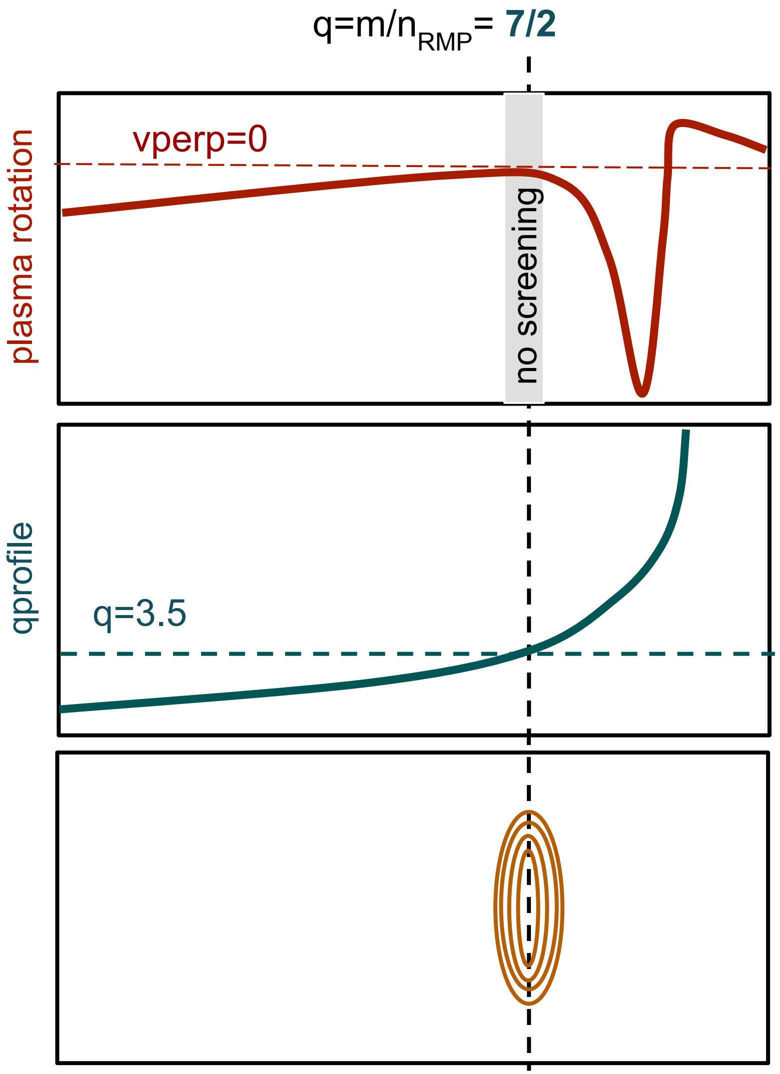


Ideal Kink Modes deform flux surfaces from their equilibrium positions (-----)



Island penetration at pedestal top

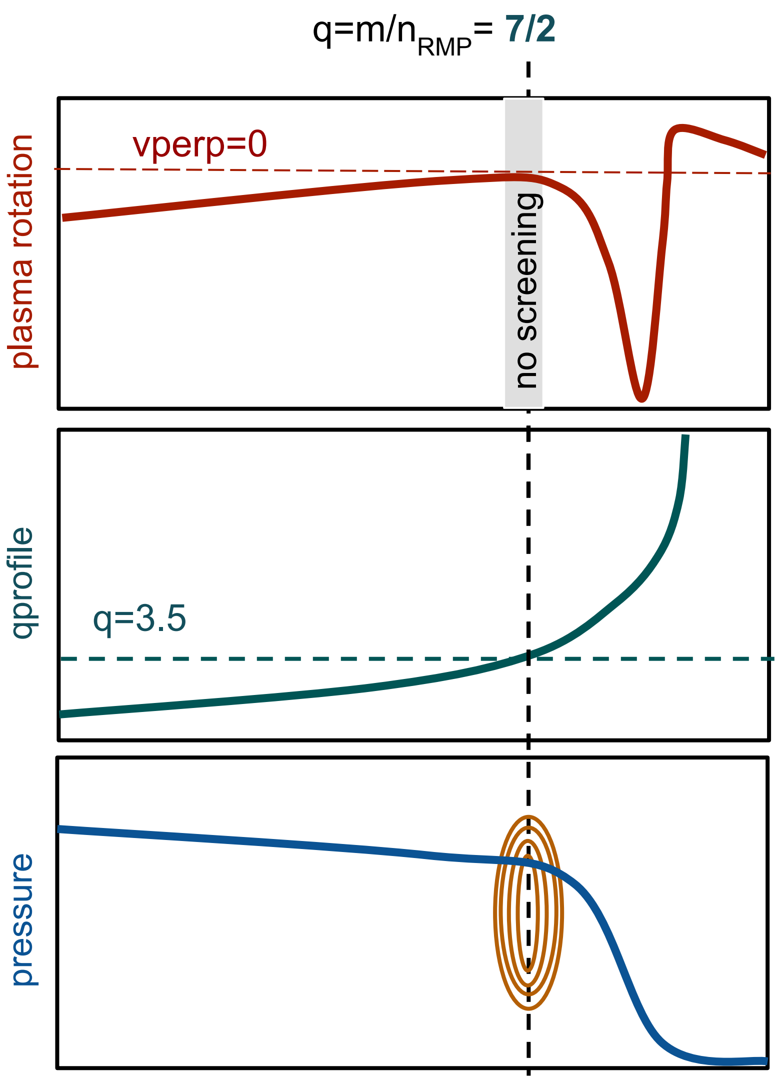


- Plasma rotation (close to) zero locally
  ⇒ Perturbation is not screened

- RMP induced rotation braking on resonant surfaces through
  - jxB currents
  - toroidal mode coupling [F. Orain]

- $v_{\perp,e} \approx 0$ at the position of a resonant surface: magnetic island penetrates and locks to perturbation

Island penetration at pedestal top



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- $v_{\perp,e} \approx 0$ at the position of a resonant surface: magnetic island penetrates and locks to perturbation
- Island at pedestal top generates additional transport to keep the pedestal from widening ⇒ Pedestal remains stable [P Snyder 2012 PoP]
- Supported by experimental findings of q95 windows

Increased particle transport

"Density Pump Out": 3D geometry enhances several particle transport mechanisms:

- Polarization Drift

  Q.M. Hu et al 2020 Nucl. Fusion - TM1

- Neoclassical Toroidal Viscosity

  S.K. Kim et al 2023 Nucl. Fusion - JOREK-PENTRC

- Increased Turbulence

  N. Leuthold et al 2023 Nucl. Fusion - AUG

Increased particle transport

"Density Pump Out": 3D geometry enhances several particle transport mechanisms:

- **Polarization Drift**
  Q.M. Hu et al 2020 Nucl. Fusion - TM1
  - with RMPs, narrow islands in the pedestal region
  - Parallel transport is increased around magnetic islands
- Neoclassical Toroidal Viscosity
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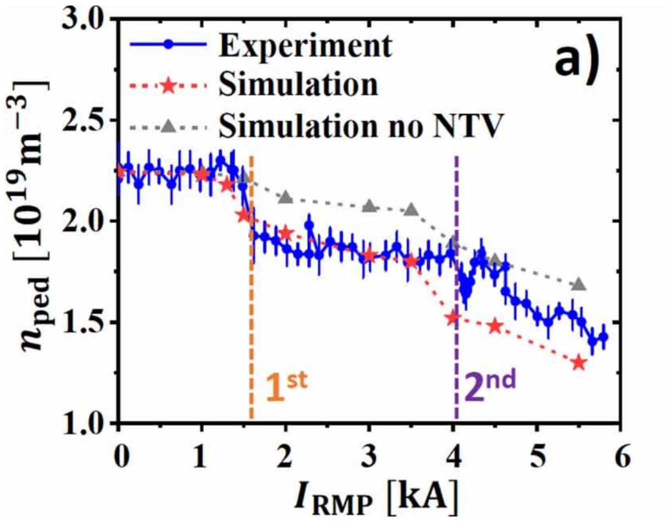
  - non-axisymmetry changes neoclassical transport
  - particle drift across flux surfaces
  - modelling of polarization drift + NTV matches quite well KSTAR pump out

- Increased Turbulence

  N. Leuthold et al 2023 Nucl. Fusion - AUG



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- **Increased Turbulence**
  N. Leuthold et al 2023 Nucl. Fusion - AUG
  - Broadband Turbulence and QCM impact particle transport
  - Toroidally and radially localized structures observed

Increased particle transport

“Density Pump Out”: 3D geometry enhances several particle transport mechanisms:

- Polarization Drift

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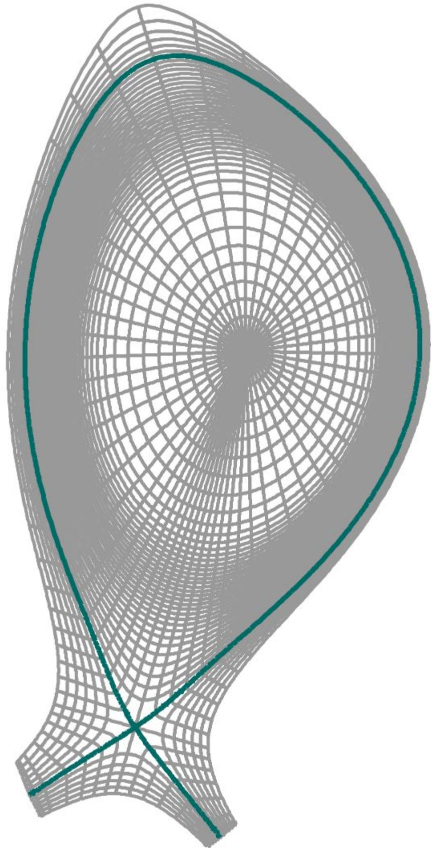
⇒ Particle transport might keep pressure below ELM stability limit

⇒ supported by experimentally observed edge density threshold for ELM suppression [W. Suttrop 2018 NF]

JOREK - 3D non-linear extended MHD code

- Magneto-hydrodynamics (MHD) describes plasma as fluid
- JOREK solves extended full or reduced MHD equations that describe evolution
  - Density
  - Temperature
  - Velocity
  - Current
  - Magnetic Field
  - Electric Field

- 2D finite elements with realistic geometry, toroidal Fourier expansion
- Different MHD-models and extensions available
- Here we use a reduced MHD model inc extensions for
  two fluid effects, bootstrap current and
  free boundary conditions with STARWALL extension

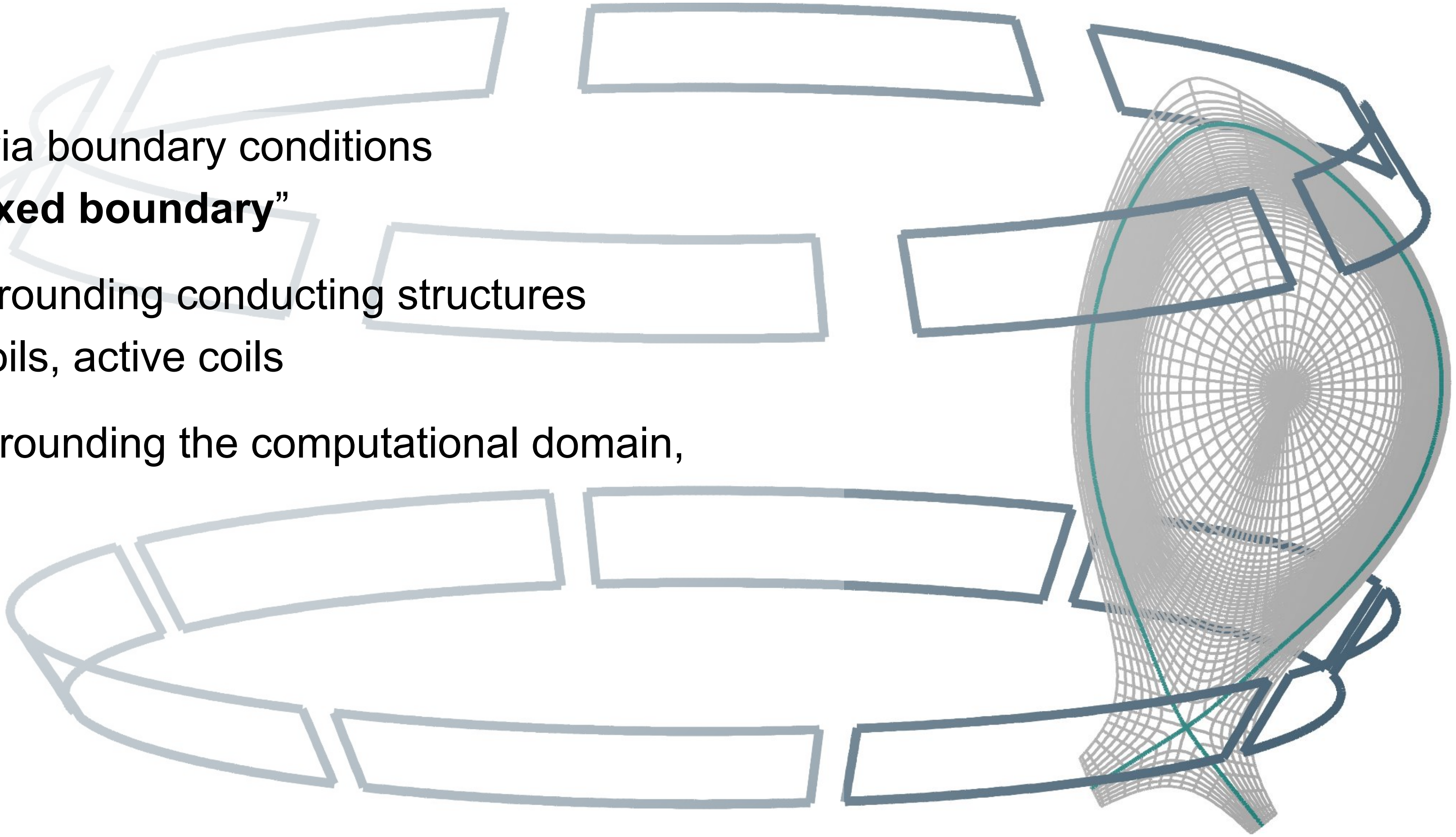


JOREK grid w reduced resolution

Separatrix (green) for orientation

STARWALL

- JOREK-STARWALL coupling via boundary conditions
  “**free boundary**” instead of “**fixed boundary**”
- Provides information about surrounding conducting structures
  e.g. vacuum vessel, passive coils, active coils
- Model of the magnetic field surrounding the computational domain,
  linked by $B_{\perp}$ and $B_{\parallel}$.



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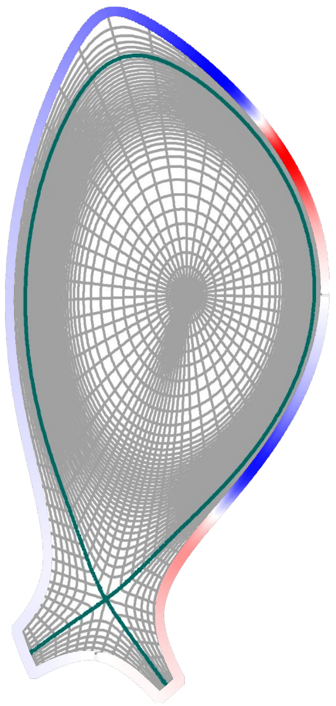
Impact of boundary conditions

Fixed boundary (JOREK)

- Vacuum perturbation is applied directly at the boundary as magnetic flux boundary condition
- Screening / amplification are neglected at boundary
- Perturbation remains fixed in time: plasma response has to converge to vacuum solution at the boundary at all times



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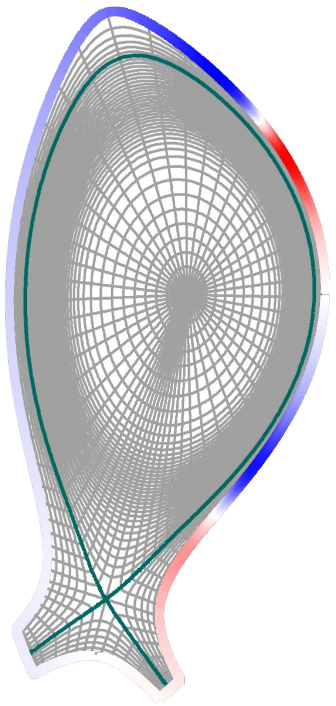
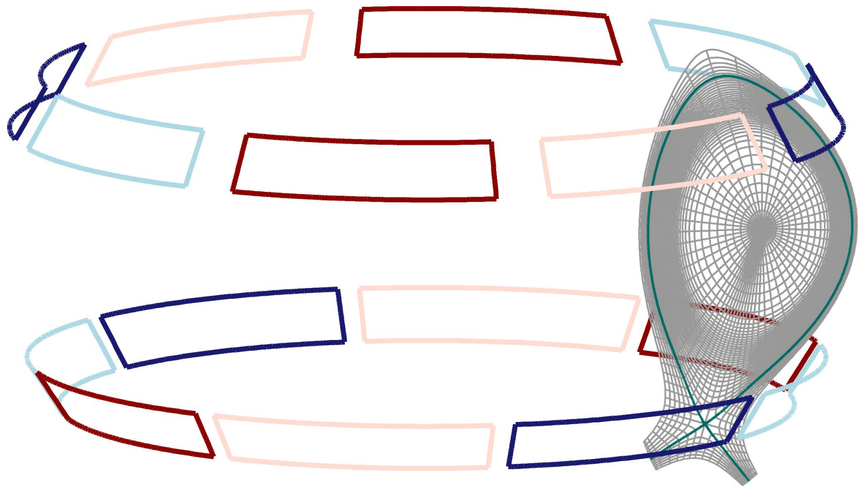


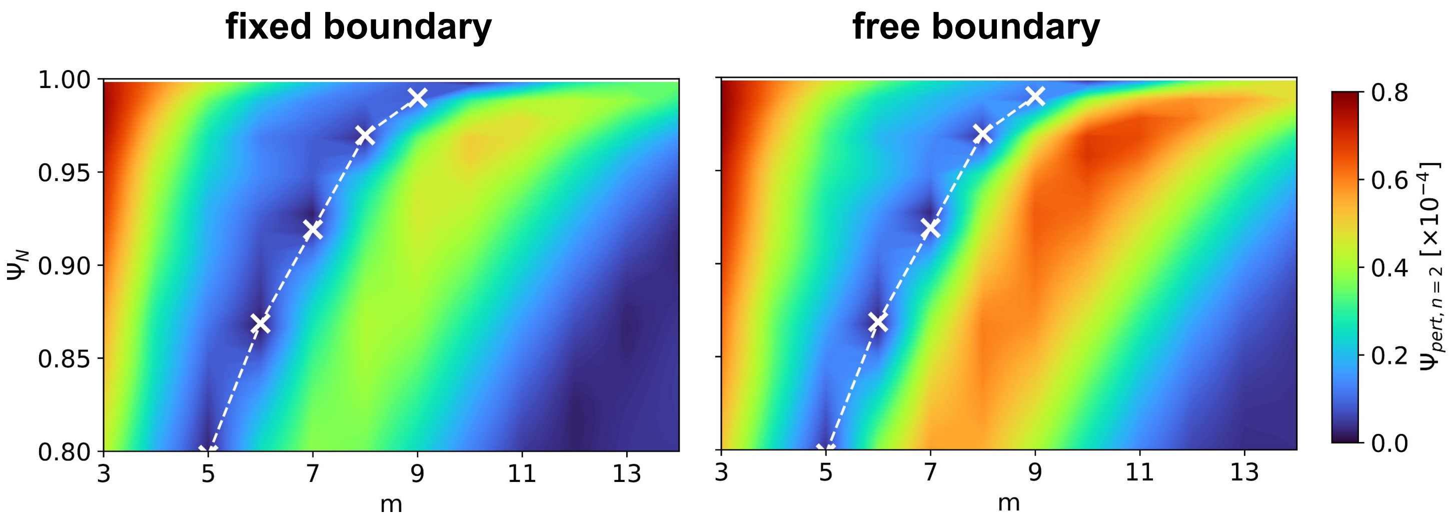
Free boundary (JOREK-STARWALL)

- Perturbation evolves according to coil currents
- Flux fully self consistent, no artificial constraints as in fixed boundary
- Plasma response taken into account in the full computational domain at all times



Impact of boundary conditions [V.Mitterauer et al. 2022]

Poloidal Mode spectrum of n=2 component of magnetic perturbation



- Kink Mode Amplification larger in free boundary simulations
- Fixed boundary artificially damps kink amplification at the edge to converge to vacuum perturbation at the boundary

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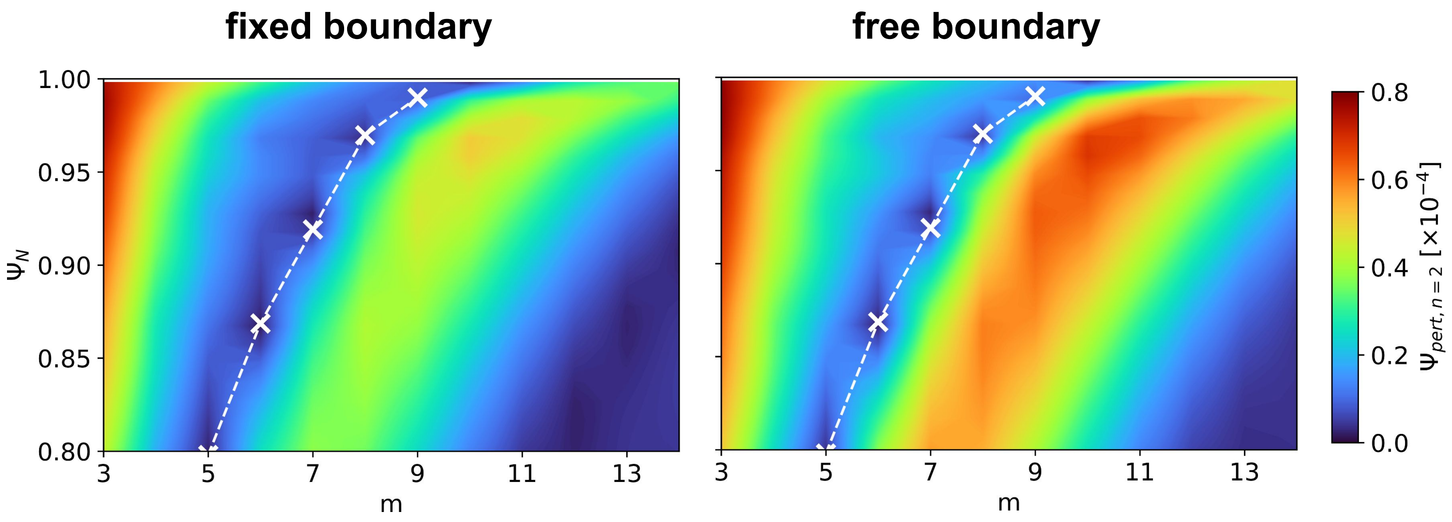

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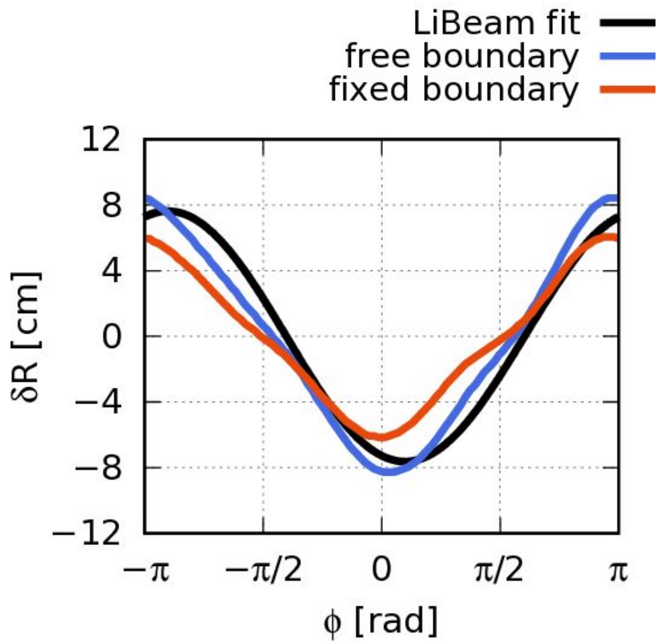
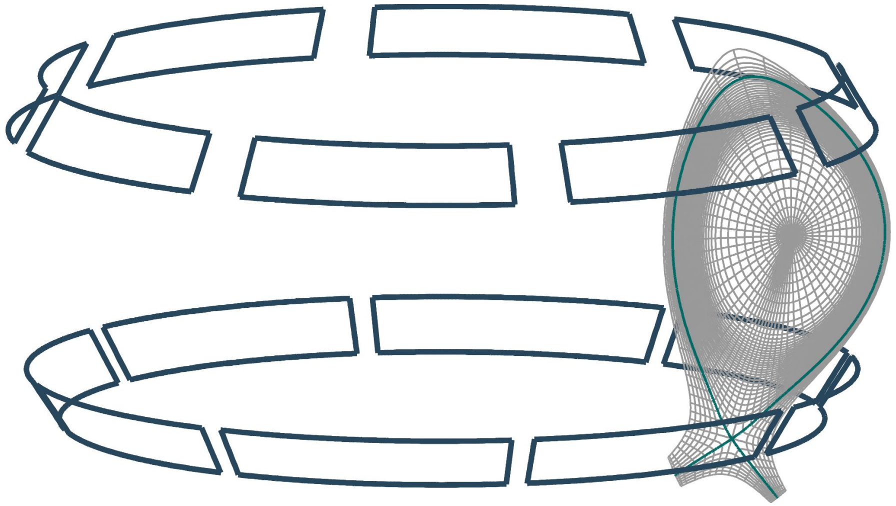
Deformation of separatrix from equilibrium position by RMPs



Free boundary improves match with experimental measurements (LiBeam fit)

Simulation setup

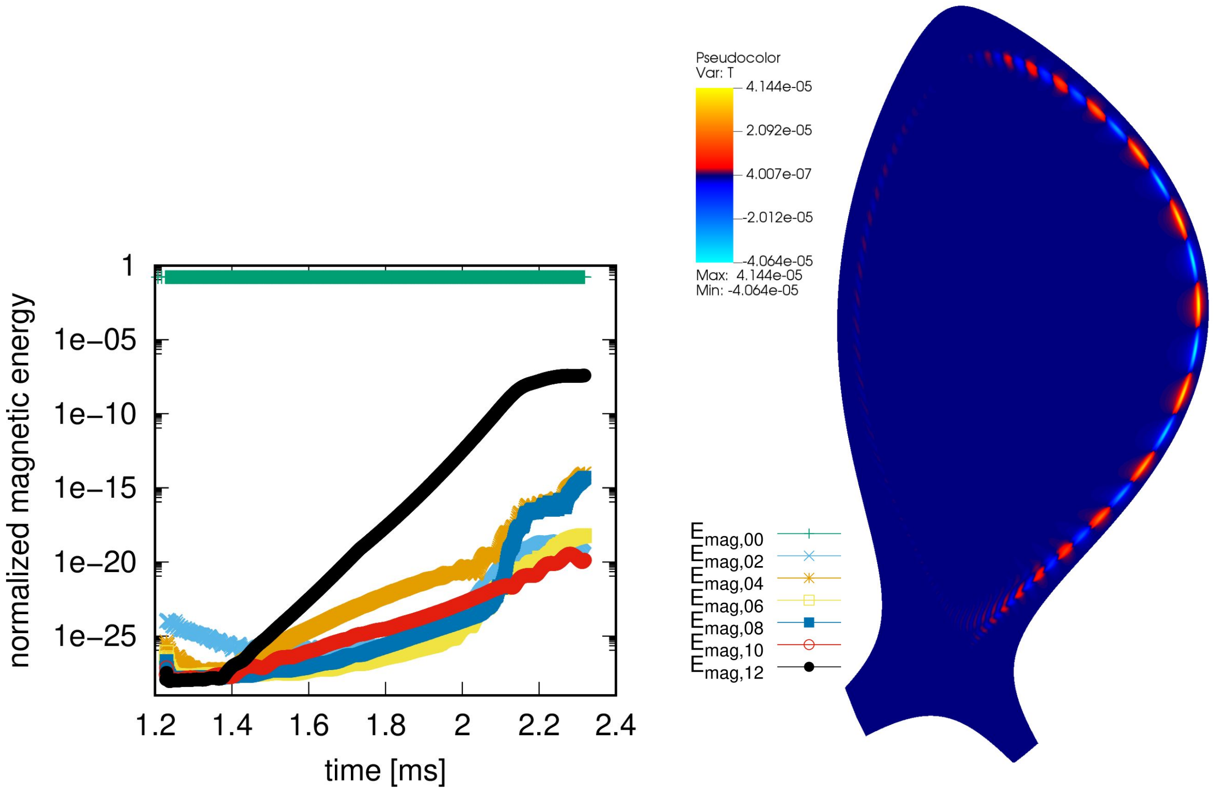
- Building up on previous work done with JOREK
- close to experiment - despite **high demand to computational resources** & **numerical stability**
  - Equilibrium is reconstructed from experimental density and temperature measurements
  - RMP coil current pattern applied according to experiment
  - Spitzer resistivity with neoclassical corrections and $T^{-3/2}$ dependency
  - Realistic viscosity: ~1 m^2/s
  - Realistic flows:
    - Toroidal rotation torque source
    - ExB and electron- and ion-diamagnetic flows self-consistent according to force balance



RMPs stabilize plasma edge

without application of RMPs:

ballooning unstable



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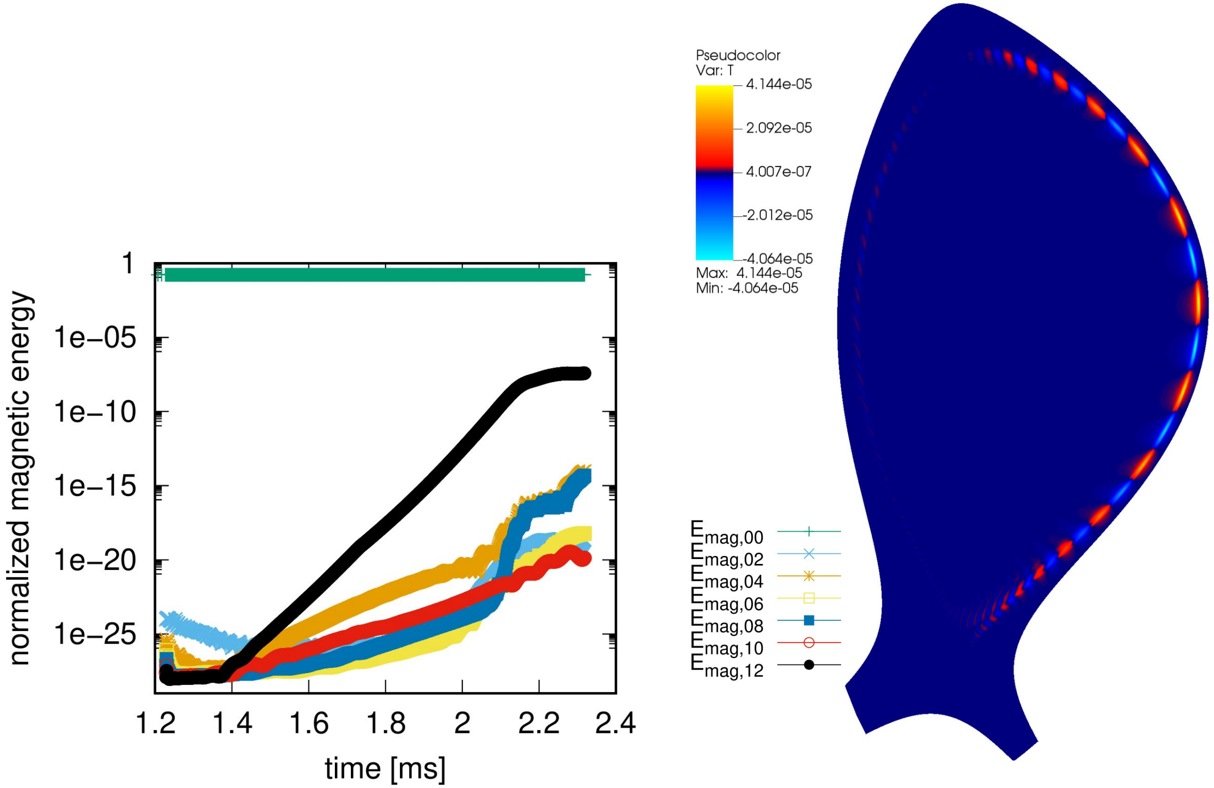
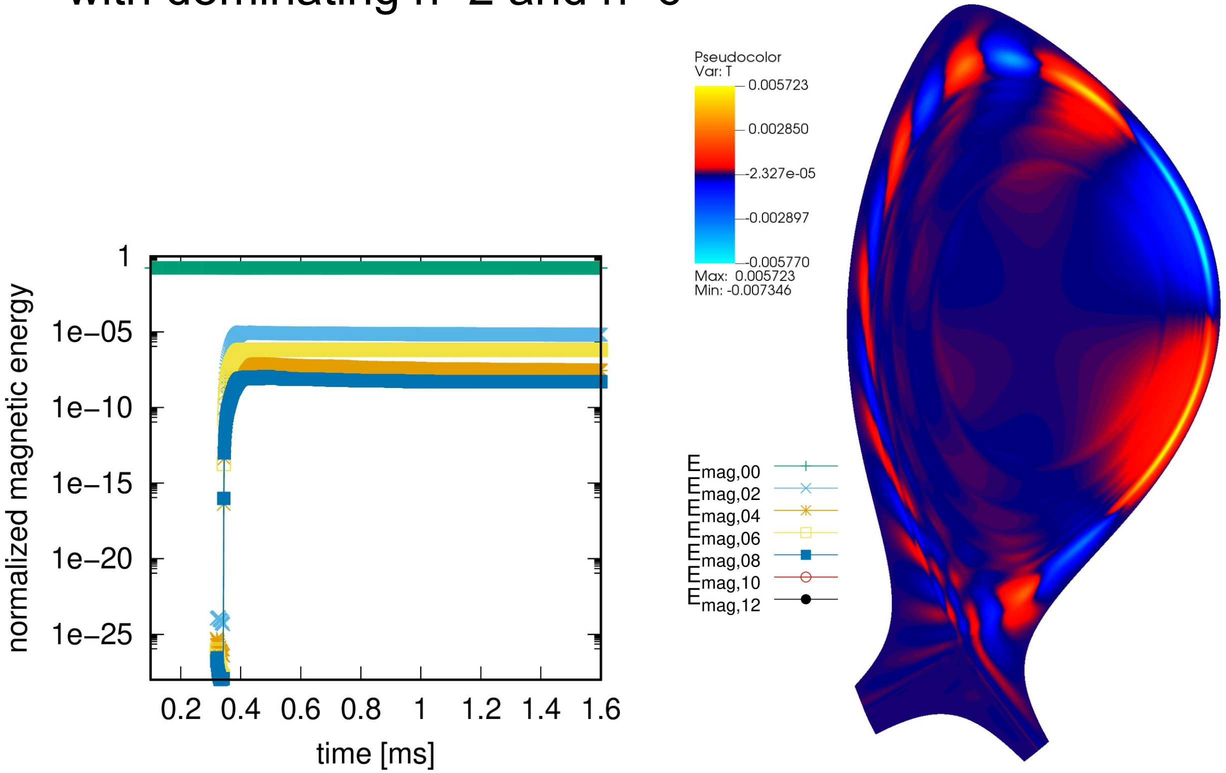


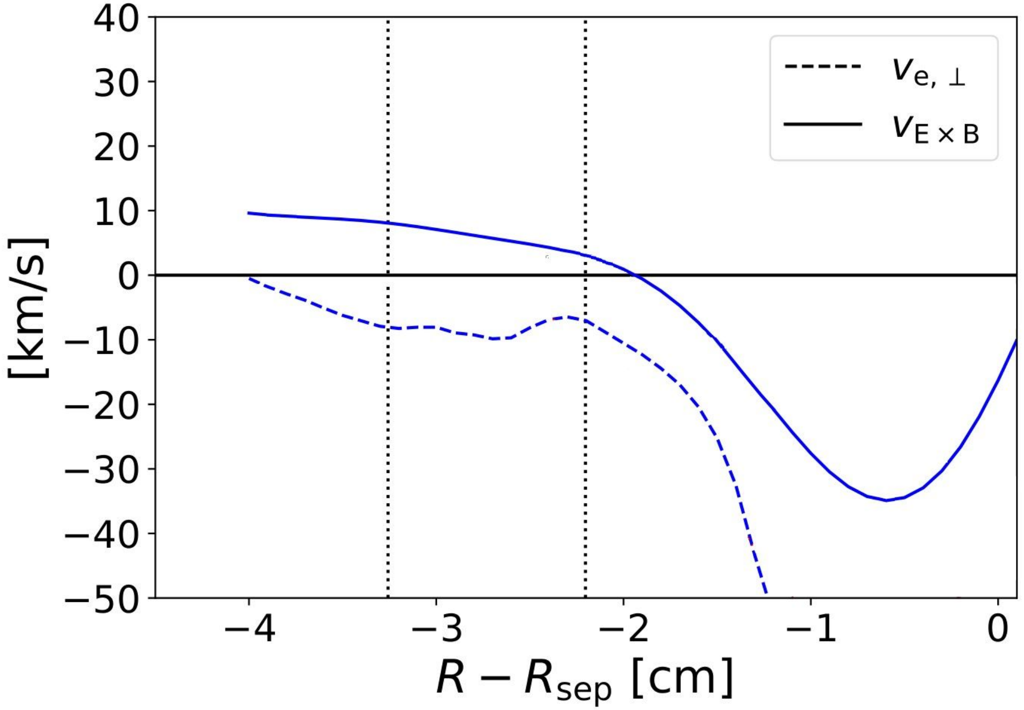
with application of RMPs

Modes saturate after RMP ramp up,
with dominating n=2 and n=6

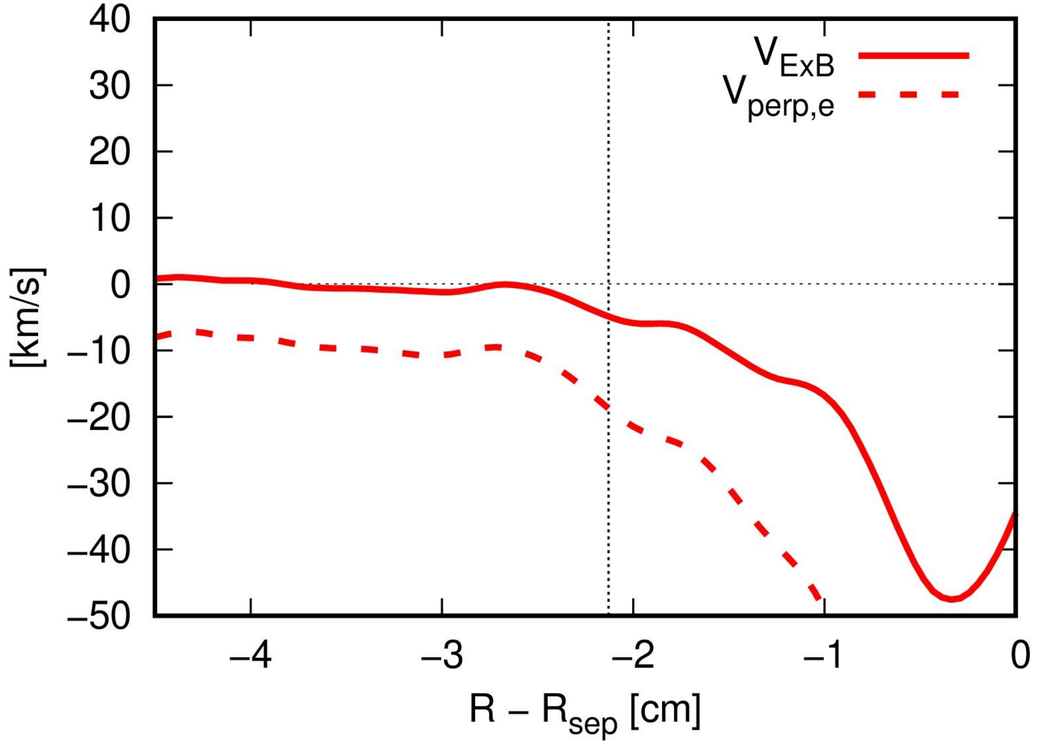


Comparison of plasma flows

Plasma flows in experiment



Plasma flows in JOREK

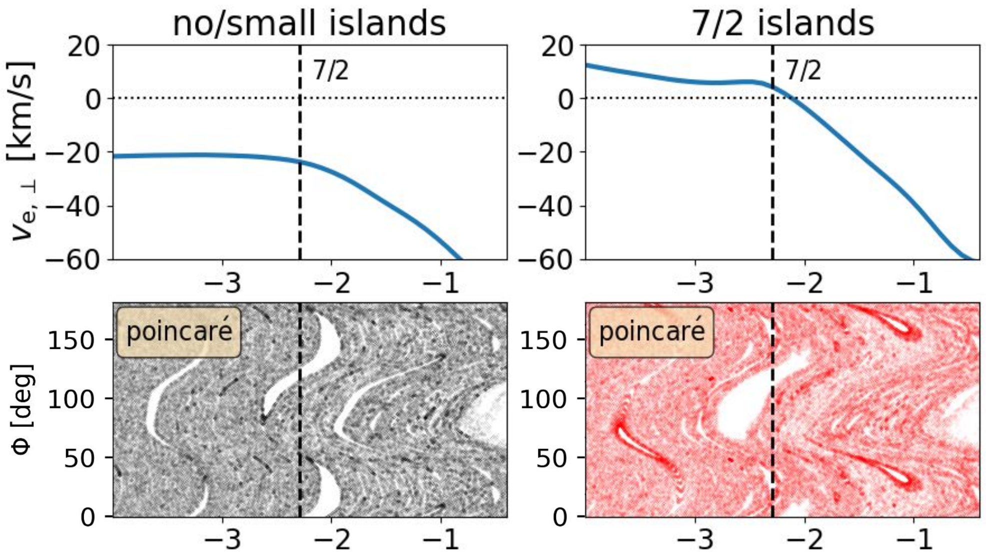


Island penetration and mode locking

- Artificial Rotation Source applied to force zero-crossing of rotation at the 7/2 rational surface

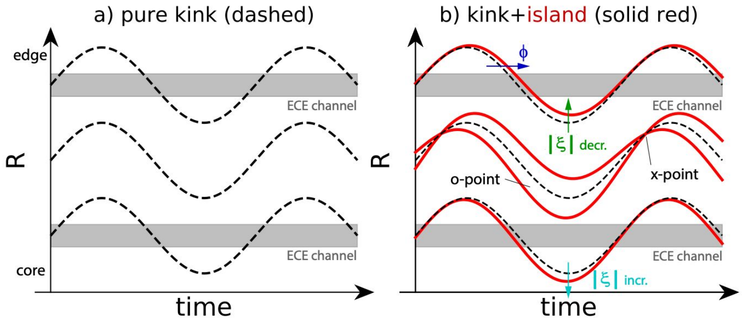
- **Without zero crossing:** small rotating islands

  With zero crossing: Island penetrates, bifurcation to large size and locking to perturbation



Experimental detection of magnetic islands during RMP application

- Island detection difficult in experiment, as the strong kink response dominates over tearing mode
- Detection possible based on change of the **amplitude and phase of the deformation of the flux surfaces** in vicinity of islands [M. Willensdorfer 2023, in review NP]



- Requires high resolution temperature measurements, possible in AUG with ECE diagnostic.

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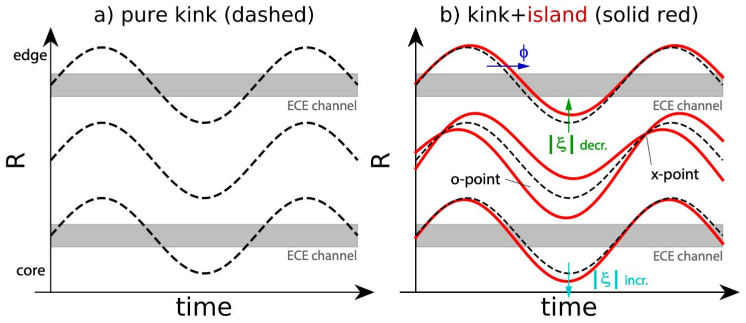

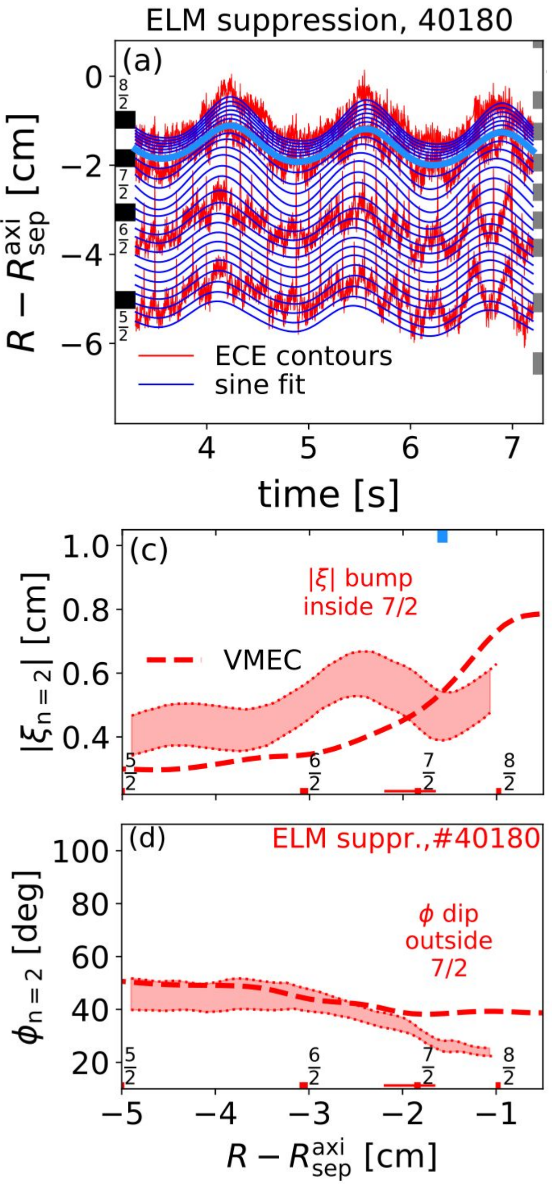

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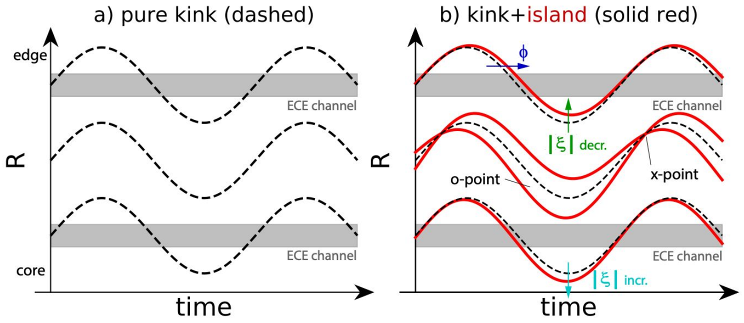

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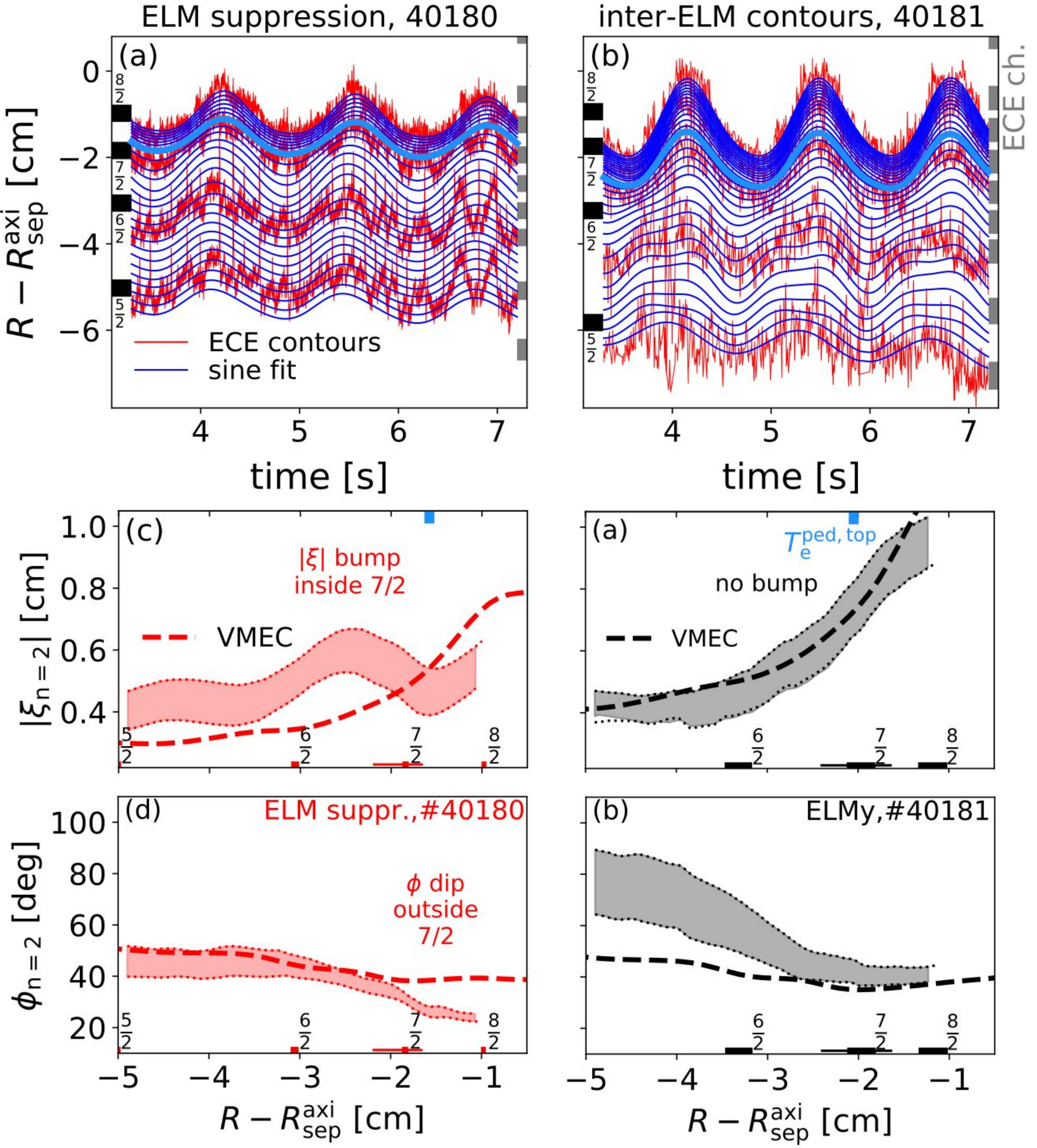
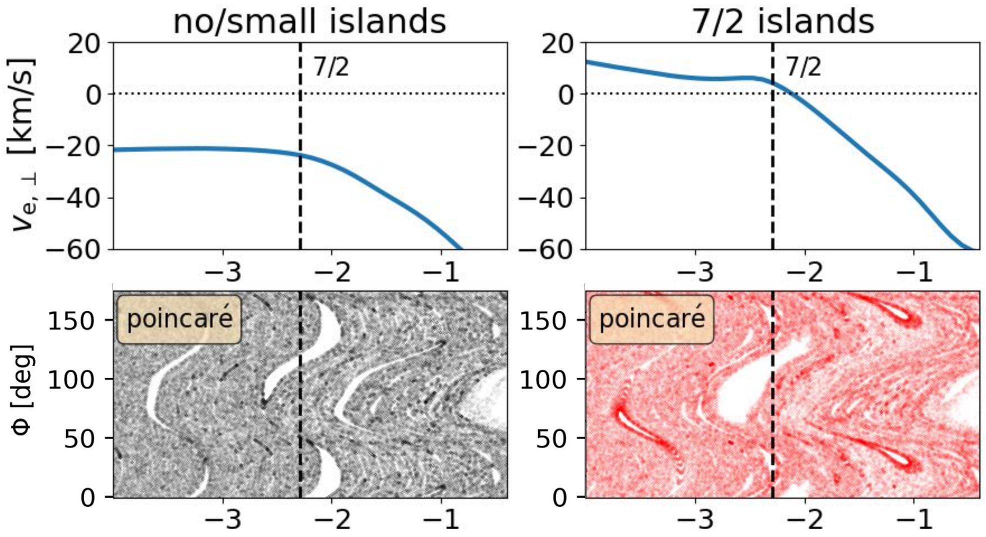


Confirming experimental island observation



- Corrugation Amplitude and Phase obtained with the same diagnostic procedure in JOREK

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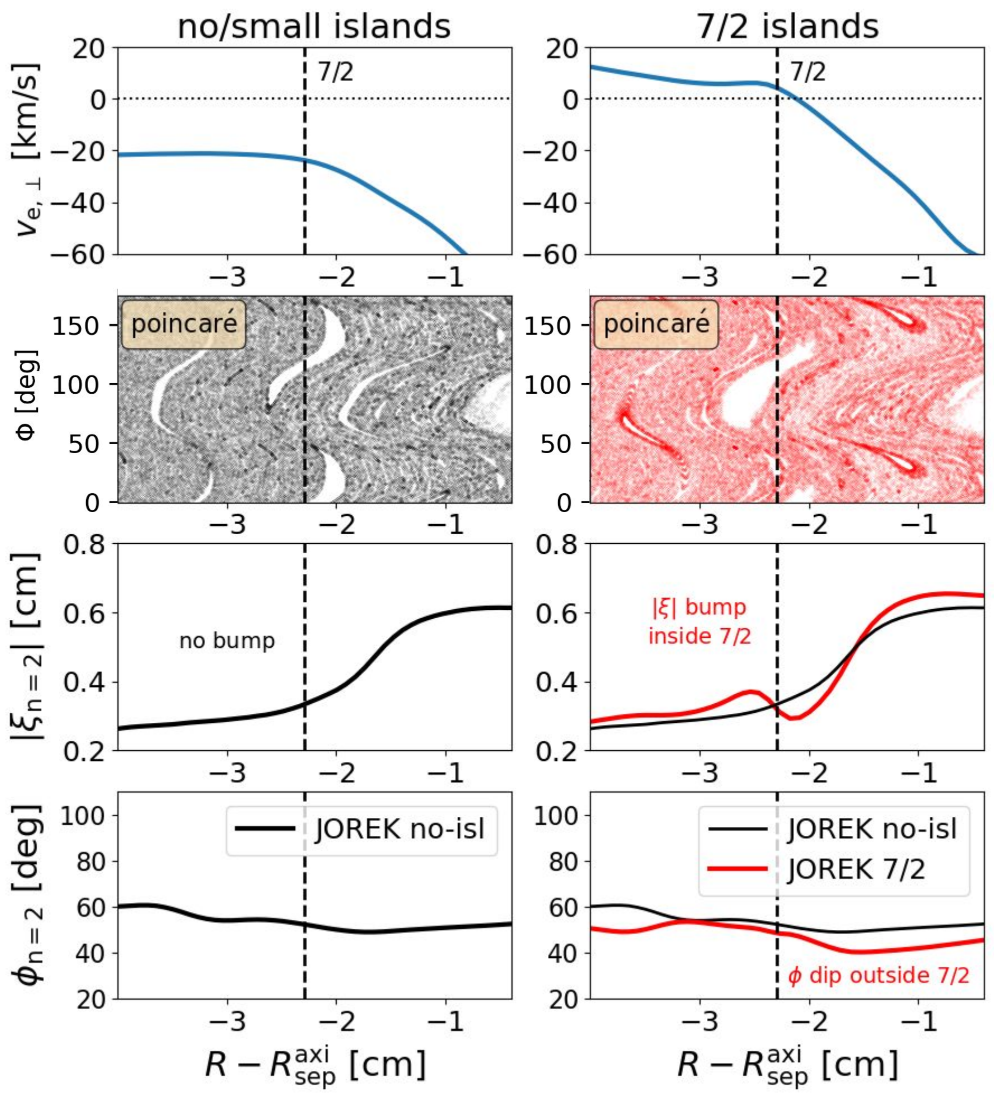

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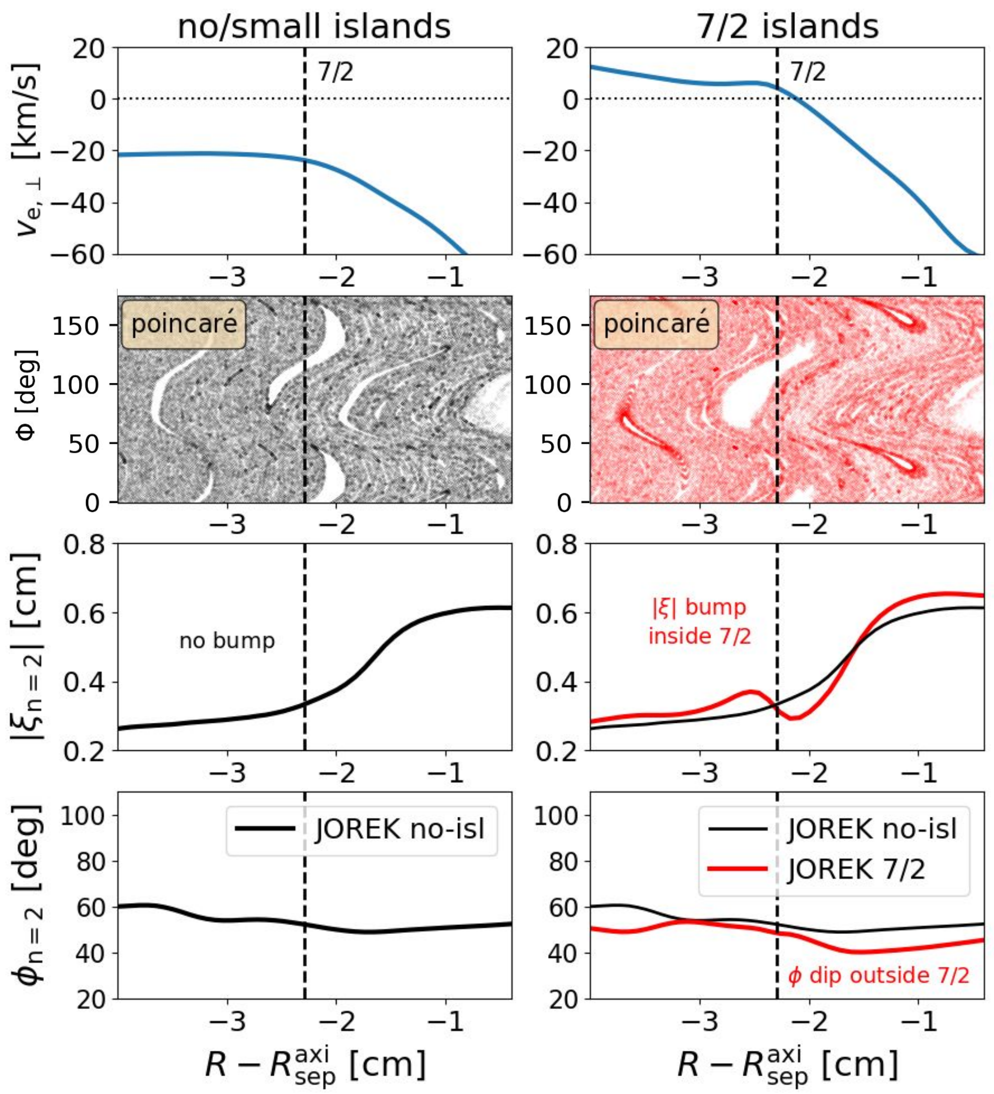
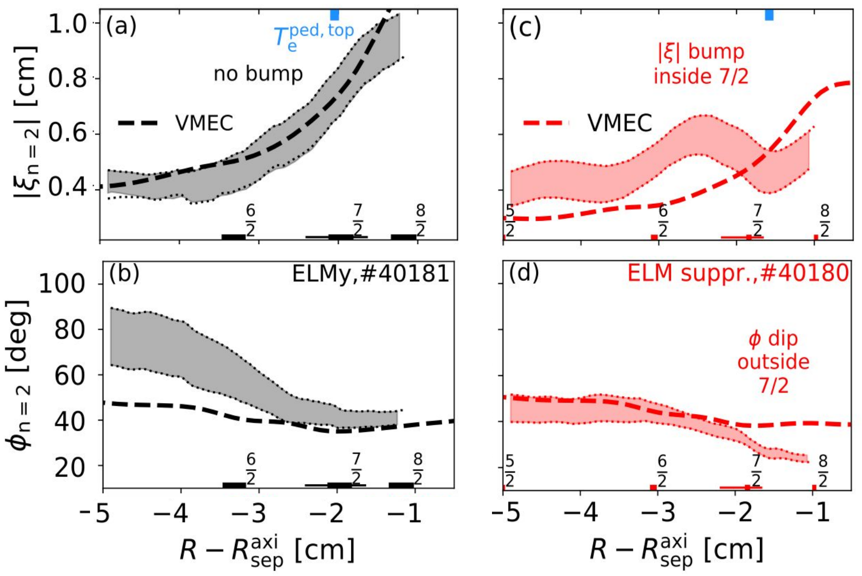
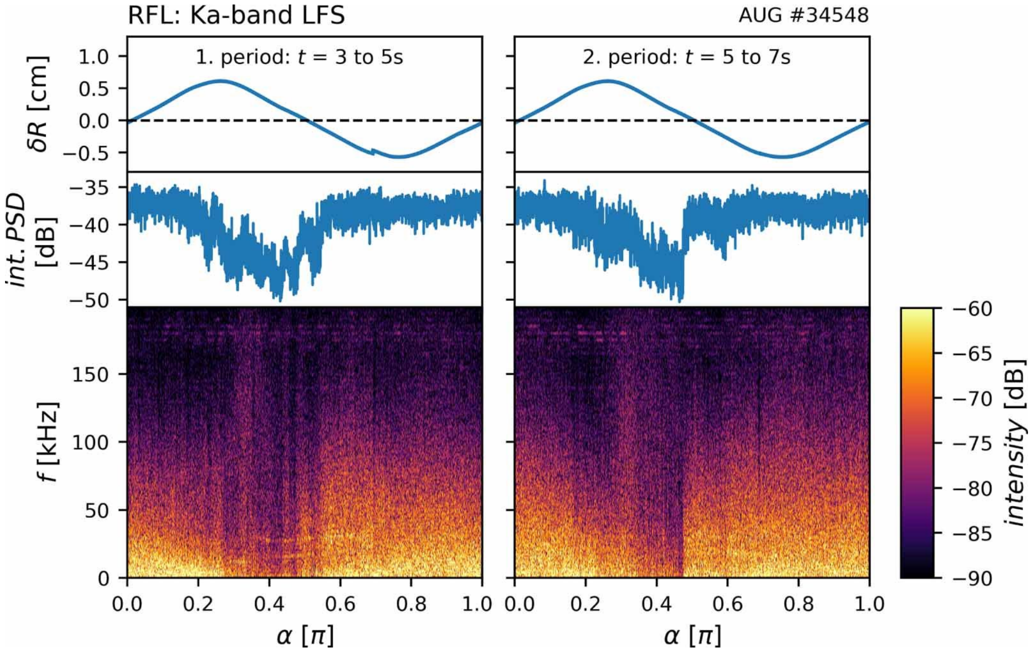


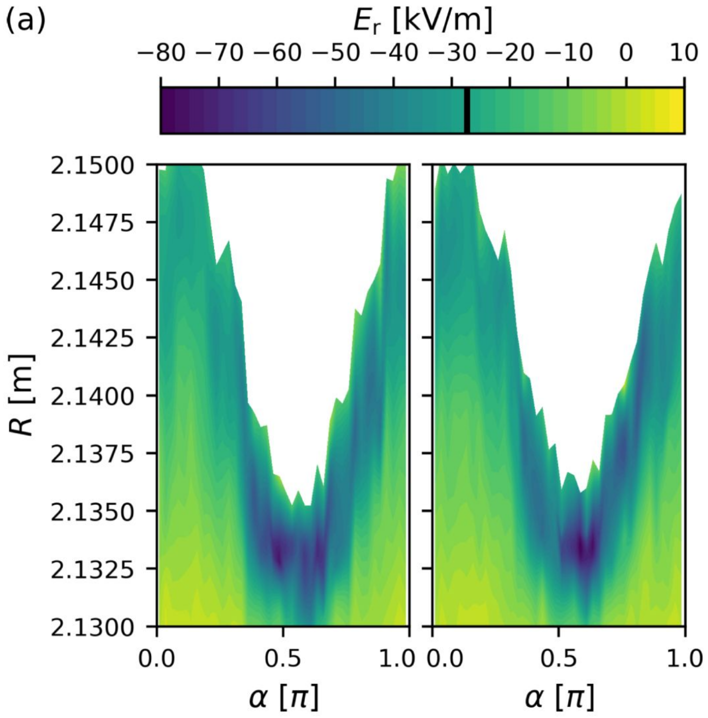
- Corrugation Amplitude and Phase obtained with the same diagnostic procedure in JOREK
- Bump in presence of penetrated island, but none if island is not penetrated
- Confirms experimental observation is associated with presence of island



Increased turbulent transport in AUG-RMP experiments

- Experimentally observed turbulent transport likely to contribute to density pump-out [N. Leuthold 2023, NF]
- Fluctuation disappears in region with highest ExB shear





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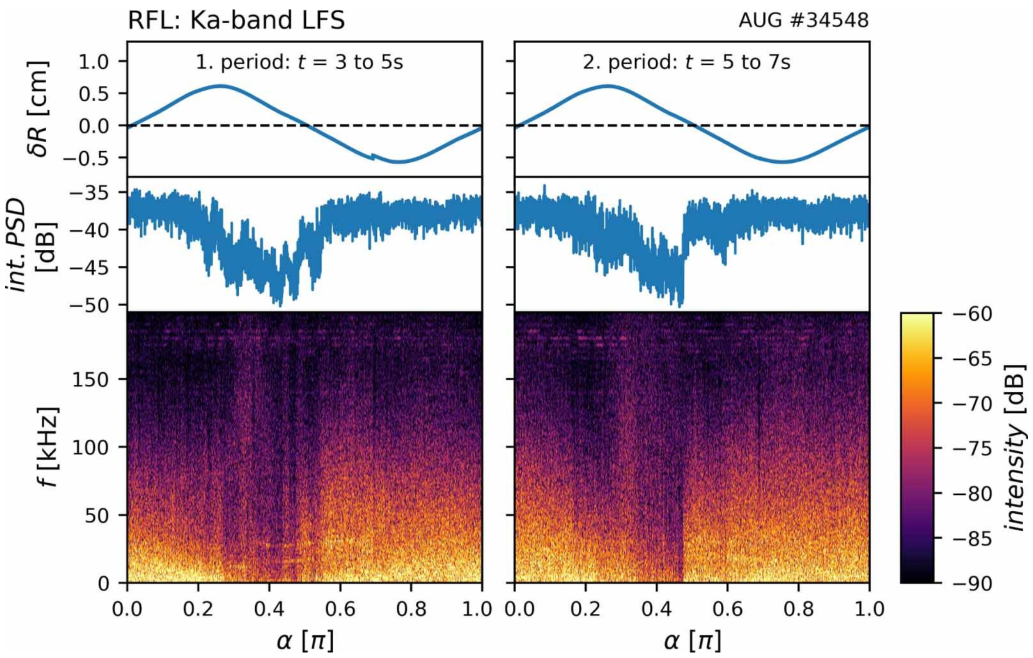
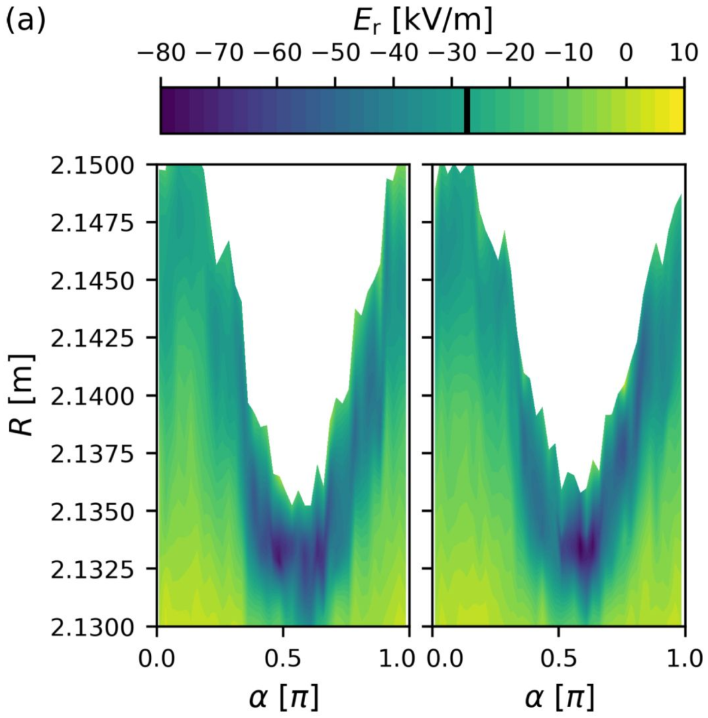
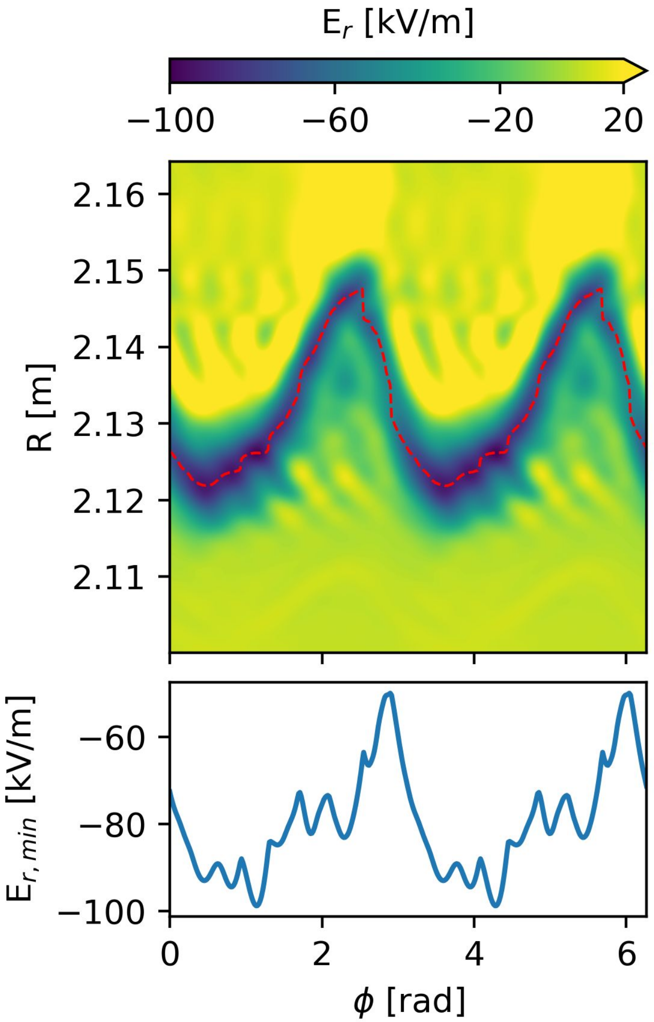
JOREK shows comparable Er variation:

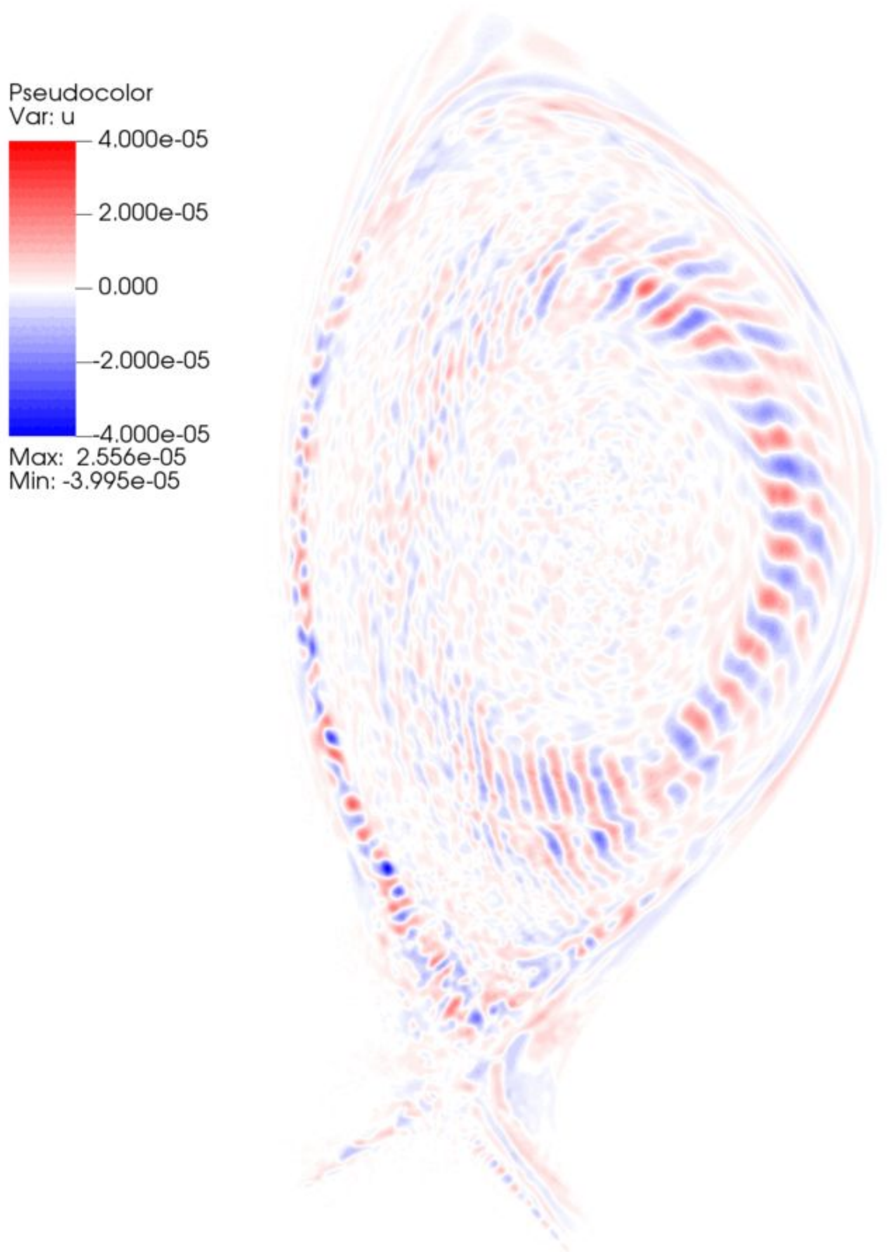






ITG Simulations on RMP fields

- JOREK ITG Simulations building up on work by M. Becoulet
- First results with turbulent structures on AUG-RMP fields
- Adding collision operators to keep corrugated Er well



Summary

- **Type-I Edge Localized Modes** unsupportable in future devices
- **Resonant Magnetic Perturbations** are the planned ELM control mechanism for ITER
- JOREK-STARWALL Simulations of AUG RMPs now with improved boundary conditions
- Found support for experimental evidence of island at pedestal top during ELM suppression
- JOREK ITG Simulations on RMP fields are on the way