Non-linear MHD-Simulations of ELMs in ASDEX Upgrade

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Motivation

Edge Localized Modes (ELMs)

- Occur in high-confinement plasmas (H-mode)
- Simplest model: Peeling-Ballooning
- Remove impurities from plasma
- Produce large heat loads at wall and divertor-structures – critical for ITER

Simulations can improve physics understanding

- Linear: Stability-limits
  e.g., Helena, . . .
- Non-linear: Filaments, heat-fluxes, mitigation
  e.g., Jorek, Nimrod, Bout++, . . .
- Validate against existing machines
- Later predictive simulations

1. JOREK
2. ELM Simulations
3. Comparison to Experiment
4. Summary and Outlook

Overview

- 3D non-linear MHD code for divertor tokamaks
- Originally developed by Guido Huysmans at CEA Cadarache
- Toroidal Fourier-decomposition
- 2D Bezier finite elements (3rd order Bernstein polynomials + C^1-continuity)
- Fully implicit time-stepping (GMRES solver)
  - Physics-based preconditioner (Direct solver)
  - Comparably large time-steps
  - Large memory consumption
  - Limited scalability (MPI + OpenMP parallelized)
  - Future improvements?
- Standard model: Reduced MHD with toroidal corrections
  - Separate model: Some two-fluid extensions
  - Separate model: Neutrals
  - Full MHD in development

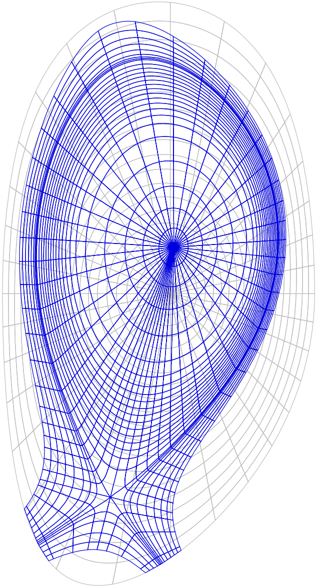
Reduced MHD Equations

$$
\begin{aligned}
\frac{\partial \Psi}{\partial t} &= \eta j - R\,[u,\Psi] - F_0 \frac{\partial u}{\partial \phi} \\
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot (D_\perp \nabla_\perp\, \rho) + S_\rho \\
\rho \frac{\partial T}{\partial t} &= -\rho \mathbf{v} \cdot \nabla T - (\gamma - 1) p \nabla \cdot \mathbf{v} + \nabla \cdot \left(K_\perp \nabla_\perp\, T + K_{||} \nabla_{||} T \right) + S_T \\
\mathbf{e}_\phi \cdot \nabla \times \left\{ \rho \frac{\partial \mathbf{v}}{\partial t} \right. &= \left. -\rho (\mathbf{v} \cdot \nabla) \mathbf{v} - \nabla p + \mathbf{j} \times \mathbf{B} + \mu \Delta \mathbf{v} \right\} \\
\mathbf{B} \cdot \left\{ \rho \frac{\partial \mathbf{v}}{\partial t} \right. &= \left. -\rho (\mathbf{v} \cdot \nabla) \mathbf{v} - \nabla p + \mathbf{j} \times \mathbf{B} + \mu \Delta \mathbf{v} \right\} \\
j_\phi &= R^2 \nabla \cdot (R^{-2} \nabla \Psi) \\
\omega &= \nabla^2_{pol}\, u
\end{aligned}
$$

$\mathbf{B} = \frac{F_0}{R} \mathbf{e}_\phi + \frac{1}{R} \nabla \Psi \times \mathbf{e}_\phi$ $\qquad$ $\mathbf{v} = -R \nabla u \times \mathbf{e}_\phi + v_{||} \mathbf{B}$ $\qquad$ $p = \rho T$

Ideal wall + Bohm boundary conditions

Typical code run



- Initial grid (Grids shown with reduced resolutions)
- Grad-Shafranov equation
- Flux aligned grid (No X-point, single-null, double-null)
- Grad-Shafranov equation
- Equilibrium refinement (Build-up of equilibrium flows)
- Time-integration

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Overview

Previous JOREK-Simulations (Selected examples)

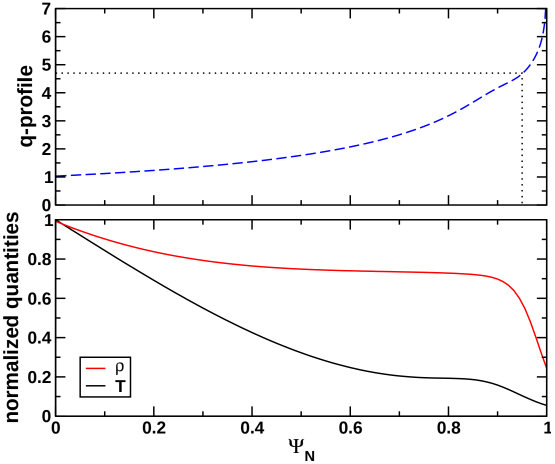
- Pellet-triggering of ELMs (G. Huysmans)
- Influence of equilibrium flows on ELMs (S. Pamela)
- Disruptions (C. Reux)

This Talk

- Realistic ASDEX Upgrade geometry
- Early ELM phase
- Focus on high toroidal resolution
  - Describe mode-coupling realistically
  - But: Resistivity and viscosity unrealistically large

ELM Simulations

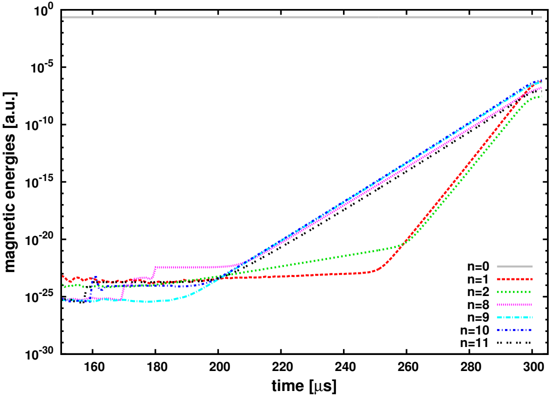
Input Profiles



- Taken from AUG #23221@4.7s

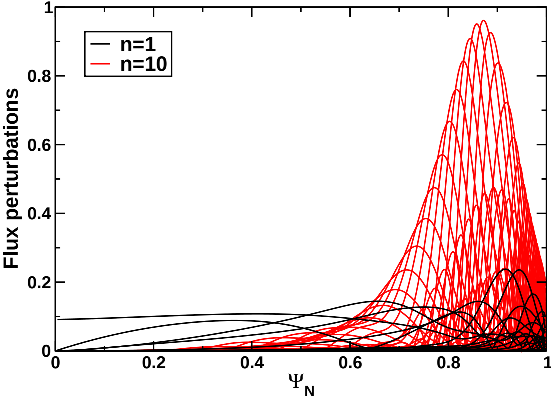
ELM Simulations

Energy Diagnostics



- Only largest modes shown for clarity
- $n = 10$ most unstable (Uncertainties!)
- $n = 1$ gets large non-linearly

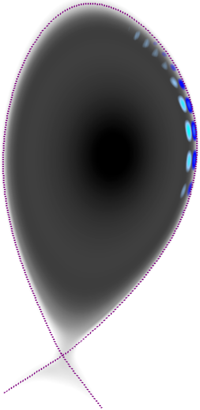
Flux Perturbation Harmonics

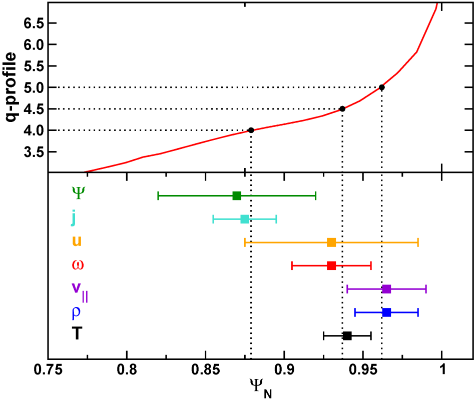


- Fourier-decomposition in straight-fieldline coordinates
- $n = 1$ and $n = 10$ shown

ELM Simulations

Position of Perturbations

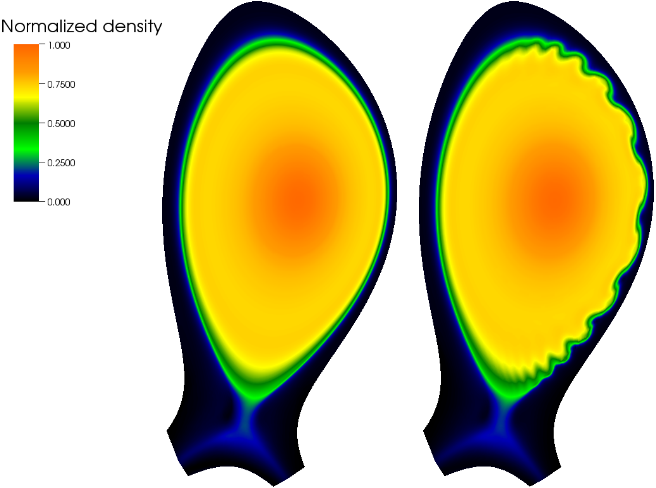




- Radial perturbation positions differ

ELM Simulations

Ballooning Structure

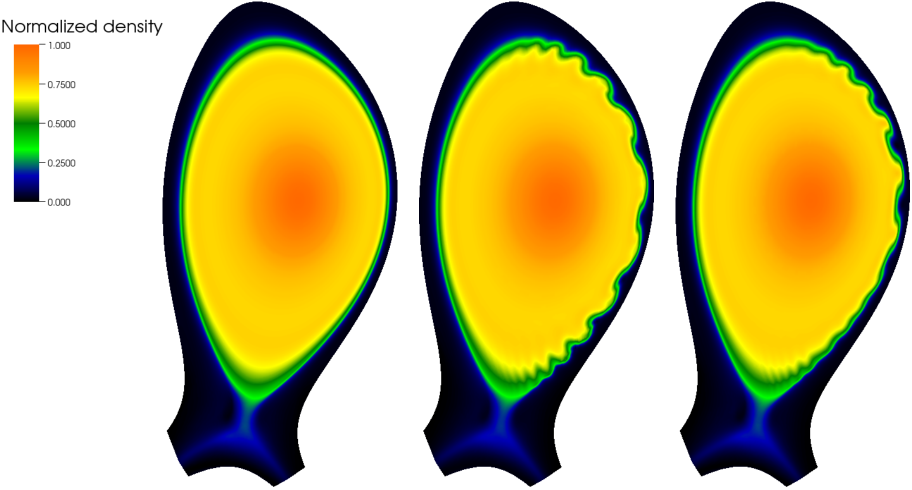


unperturbed $n = 0, 8, 16$

- Mode-coupling causes localization of ballooning-filaments

ELM Simulations

Ballooning Structure

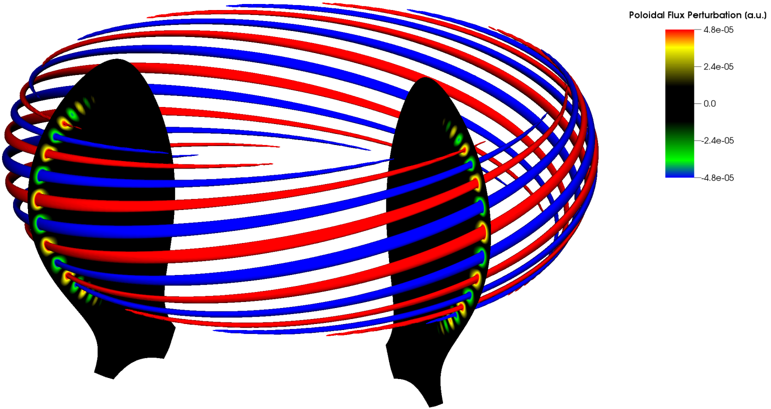


unperturbed $n = 0, 8, 16$ $n = 0, 1, 2, \ldots, 16$

- Mode-coupling causes localization of ballooning-filaments

ELM Simulations

Poloidal Flux Perturbation

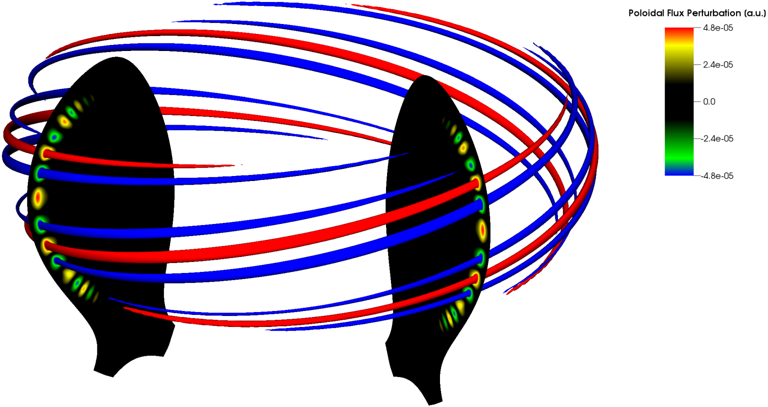


Periodicity 8 ($n = 0, 8, 16$)

- Magnetic field perturbation also localized due to mode-coupling

ELM Simulations

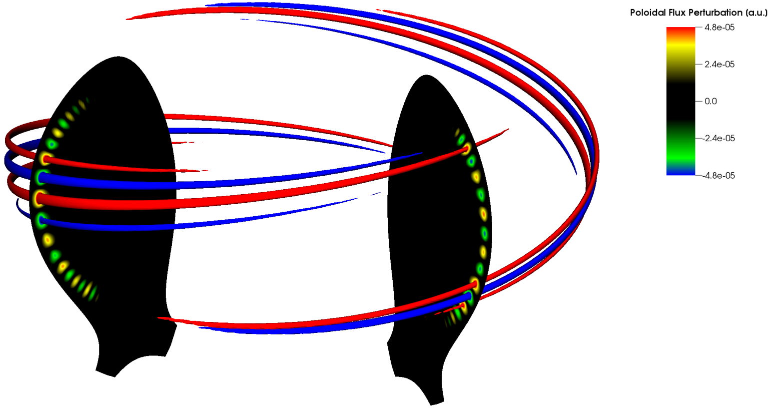
Poloidal Flux Perturbation



Periodicity 4 ($n = 0, 4, 8, 12, 16$)

- Magnetic field perturbation also localized due to mode-coupling

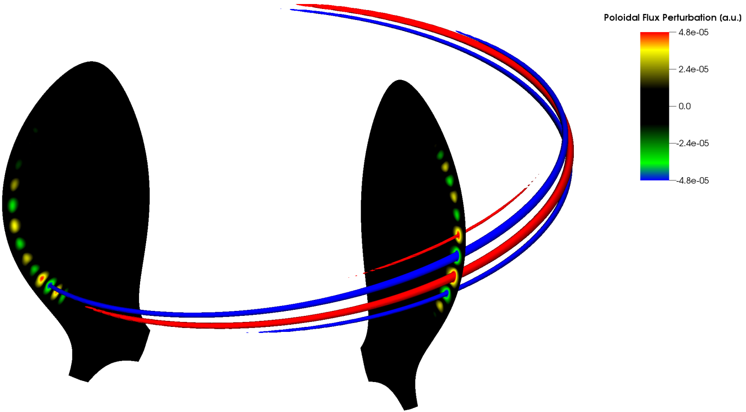
Poloidal Flux Perturbation



Periodicity 2 ($n = 0, 2, 4, \ldots, 16$)

- Magnetic field perturbation also localized due to mode-coupling

Poloidal Flux Perturbation

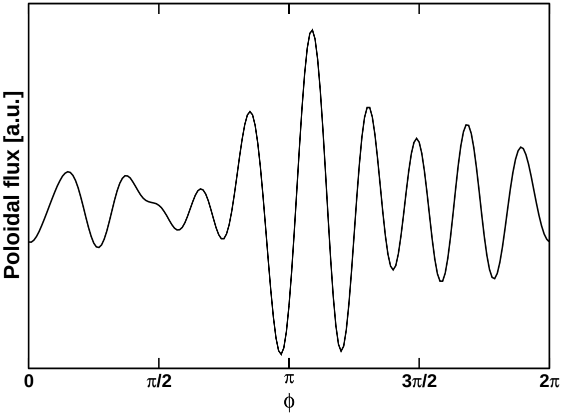


Periodicity 1 ($n = 0, 1, 2, \ldots, 16$)

- Magnetic field perturbation also localized due to mode-coupling

ELM Simulations

Perturbation along toroidal angle



- Magnetic perturbation at outboard midplane
- Perturbation amplitude strongly varies toroidally

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Comparison to Experiment

Is our instability ELM-like?

- Compare to type-I ELMs in ASDEX Upgrade
- Dominant toroidal mode-number:
  - Simulations: $10 - 14$ (uncertainties!)
  - Mid-plane manipulator, visible-light imaging: ≈ 15

    A.Kirk et.al., Plasma Phys.Control.Fusion, 47, 995 (2005)
  - ECE-Imaging: 18 ± 4

    J.E.Boom et.al., Nucl.Fusion, 51, 103039 (2011)
- Poloidal width of filaments (midplane):
  - Simulations: $10 - 12$ cm
  - Measurements: $5 - 10$ cm

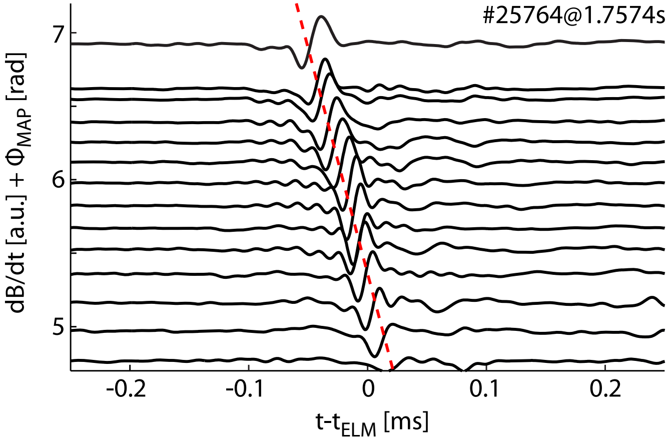
    A.Kirk et.al., Plasma Phys.Control.Fusion, 47, 995 (2005)
- Radial velocity of filaments (midplane):
  - Simulations: Accelerate to 3 km/s
  - Measurements: Typically 1 km/s with 20% faster than 2 km/s

    A.Schmid et.al., Plasma Phys.Control.Fusion, 50, 045007 (2008)

    A.Kirk et.al., Plasma Phys.Control.Fusion, 53, 035003 (2011)

Comparison to Experiment

Localization



- “Solitary magnetic perturbation” at ELM onset [R.P.Wenninger et al, Nucl Fusion, submitted]
- Broad distribution of “solitariness”
- Direct comparison to be done

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Summary

- Simulations of early ELM-phase
- High toroidal resolution
- Good agreement with type-I ELMs in ASDEX Upgrade
  - Toroidal mode-numbers
  - Poloidal filament-widths
  - Radial velocity
- Localization observed at high toroidal resolution
  - Compatible with solitary magnetic perturbations

⇒ ELM-like ✓ Now for a closer look…

Outlook

- Continue ELM investigations (with I. Krebs)
  - Full ELM-crash
  - Further comparisons to experiments (with R. Wenninger, J. Boom,. . .)
  - Influence of sheared toroidal flow (with W.-C. Müller, see his talk)
  - Identify different ELM-types
  - Try ELM cycle
- Resistive wall extension → RWMs, VDEs, . . .

  (with P. Merkel, G. Huysmans, E. Nardon, I. Chapman)
- Try disruption simulations (with G. Pautasso)

Acknowledgements

- Sibylle Günter
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