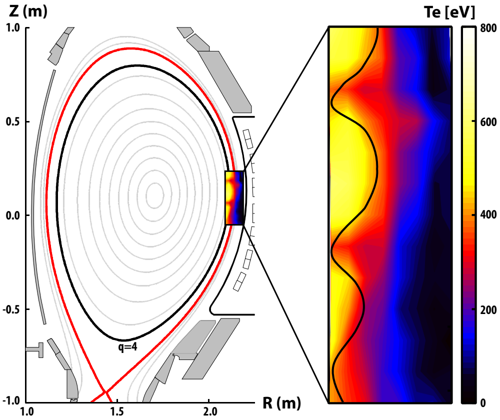
Non-linear Simulations of Edge Localized Modes in ASDEX Upgrade

Matthias Hölzl
(Postdoc at IPP Garching)

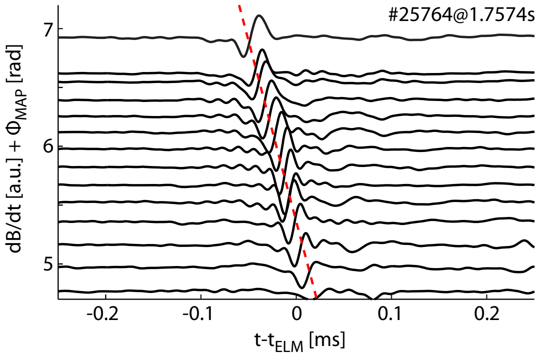
Edge Localized Modes

Electron temperature measured with ECE-Imaging at an ELM onset in ASDEX Upgrade: Dominant toroidal Fourier harmonic $n \approx 11$

[J. E. Boom, et al. 37th EPS, P2.119 (2010)]



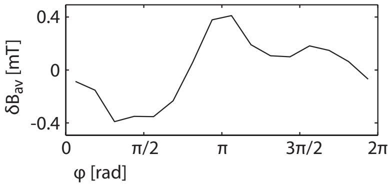
- ASDEX Upgrade: Expanded and localized ELMs observed (distribution)

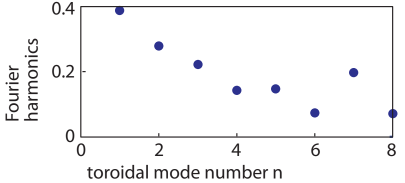


Signature of a Solitary Magnetic Perturbation in ASDEX Upgrade

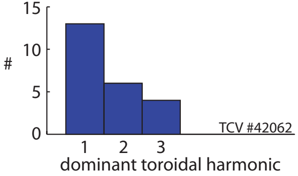
[R. P. Wenninger, et al. Nucl.Fusion, 42, 114025 (2012)]

Low-n Harmonics





Example for ELM signature with strong low-n component



Histogram of dominant components in a TCV discharge (23 ELMs)

[R. P. Wenninger, et al. Nucl.Fusion (to be submitted)]

- Originally developed at CEA Cadarache

  [G. Huysmans and O. Czarny. *Nucl.Fusion*, 47, 659 (2007)]
- Non-linear reduced MHD in toroidal geometry (next slide)
- Two-fluid extensions
- Full MHD in development

- Bezier finite elements + Toroidal Fourier decomposition
- Fully implicit time evolution
- GMRES with physics-based preconditioning

Reduced MHD Equations

$$\frac{\partial \Psi}{\partial t} = \eta j - R\,[u, \Psi] - F_0 \frac{\partial u}{\partial \phi}$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot (D_\perp \nabla_\perp \rho) + S_\rho$$

$$\frac{\partial (\rho T)}{\partial t} = -\mathbf{v} \cdot \nabla(\rho T) - \gamma \rho T \nabla \cdot \mathbf{v} + \nabla \cdot \left(K_\perp \nabla_\perp T + K_{||} \nabla_{||} T \right) + S_T$$

$$\mathbf{e}_\phi \cdot \nabla \times \left\{ \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho(\mathbf{v} \cdot \nabla)\mathbf{v} - \nabla p + \mathbf{j} \times \mathbf{B} + \mu \Delta \mathbf{v} \right\}$$

$$\mathbf{B} \cdot \left\{ \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho(\mathbf{v} \cdot \nabla)\mathbf{v} - \nabla p + \mathbf{j} \times \mathbf{B} + \mu \Delta \mathbf{v} \right\}$$

$$j \equiv -j_\phi = \Delta^* \Psi$$

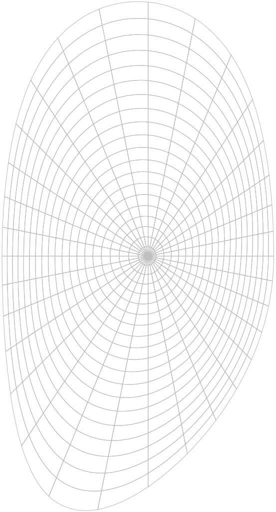
$$\omega \equiv -\omega_\phi = \nabla^2_{pol}\, u$$

Variables: Ψ, u, j, ω, ρ, T, $v_{||}$

Definitions: $\mathbf{B} \equiv \frac{F_0}{R} \mathbf{e}_\phi + \frac{1}{R} \nabla \Psi \times \mathbf{e}_\phi$ and $\mathbf{v} \equiv -R \nabla u \times \mathbf{e}_\phi + v_{||} \mathbf{B}$

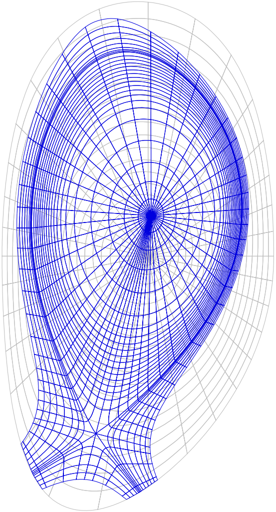
[H. R. Strauss. *Phys.Fluids*, 19, 134 (1976)]

Typical code run



- Initial grid (Grids shown with reduced resolution)
- Flux aligned grid including X-point(s)
- Equilibrium flows
- Time-integration

Typical code run



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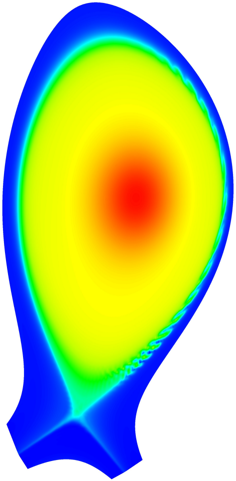
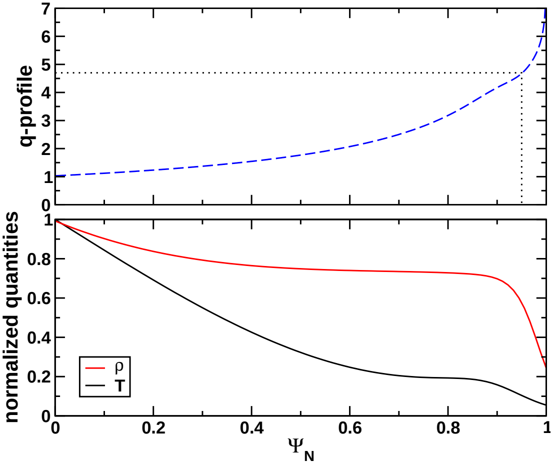
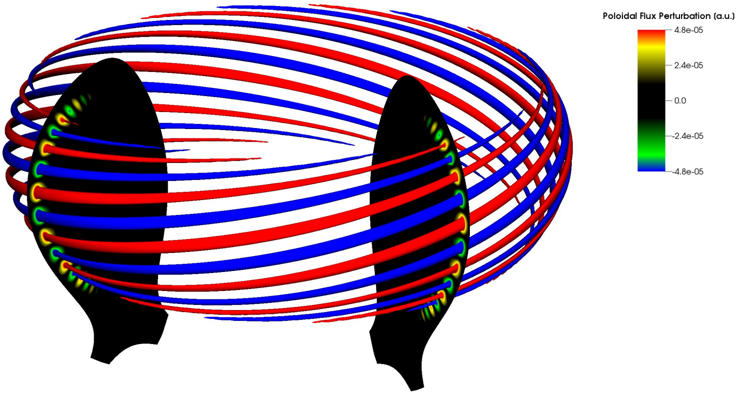


- Initial grid (Grids shown with reduced resolution)
- Flux aligned grid including X-point(s)
- Equilibrium flows
- Time-integration

- ELMs in typical ASDEX Upgrade H-mode equilibrium
- Many toroidal harmonics
- Resistivity too large by factor 10 due to numerical constraints (improving)



Poloidal Flux Perturbation

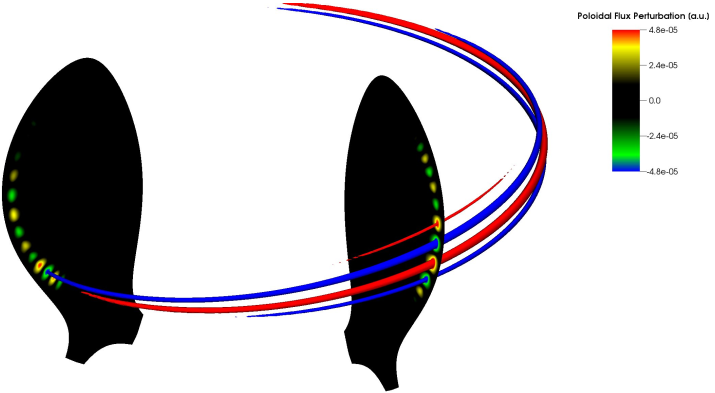


$n = 0, 8, 16$

- Red/blue surfaces correspond to 70 percent of maximum/minimum values

[M. Hölzl, et al. *38th EPS*, P2.078 (2011); M. Hölzl, et al. *Phys.Plasmas*, 19, 082505 (2012b)]

Poloidal Flux Perturbation



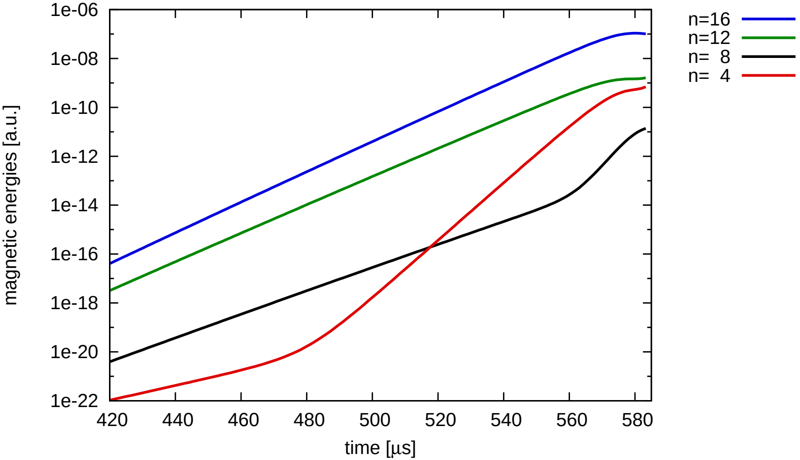
$\mathrm{n} = 0, 1, 2, 3, 4, \ldots, 16$

- ▷ Red/blue surfaces correspond to 70 percent of maximum/minimum values
- ▷ Localized due to several strong harmonics with adjacent n

⇒ **Similar to Solitary Magnetic Perturbations in ASDEX Upgrade**

[M. Hölzl, et al. *38th EPS*, P2.078 (2011); M. Hölzl, et al. *Phys.Plasmas*, 19, 082505 (2012b)]

Results Mode Interaction Model



- ▷ Non-linear drive of low-n modes
- ▷ Start with simplified case including $n = 0, 4, 8, 12, 16$ (periodicity 4)

Mode Interaction Model

- Quadratic terms lead to mode coupling $(n_1, n_2) \leftrightarrow n_1 \pm n_2$
- For instance: $(16, 12) \leftrightarrow 4$
- Model assuming mode rigidity and fixed background:

$$\dot{A}_4 = \overbrace{\gamma_4 \, A_4}^{\text{linear}} + \overbrace{\gamma_{8,-4} \, A_8 \, A_4 + \gamma_{12,-8} \, A_{12} \, A_8 + \gamma_{16,-12} \, A_{16} \, A_{12}}^{\text{non-linear interaction}}$$

$$\dot{A}_8 = \gamma_8 \, A_8 + \gamma_{4,4} A_4 \, A_4 + \gamma_{12,-4} A_{12} \, A_4 + \gamma_{16,-8} \, A_{16} \, A_8$$

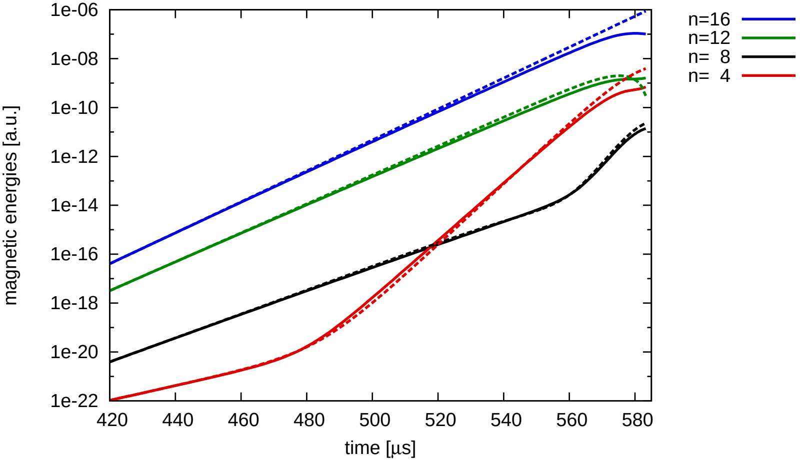
$$\dot{A}_{12} = \gamma_{12} \, A_{12} + \gamma_{4,8} \, A_4 \, A_8 + \gamma_{16,-4} \, A_{16} \, A_4$$

$$\dot{A}_{16} = \gamma_{16} \, A_{16} + \gamma_{8,8} \, A_8 \, A_8 + \gamma_{4,12} \, A_4 \, A_{12}$$

- Linear growth rates from JOREK simulation + Energy conservation
- Determine few free parameters by minimizing quadratic differences

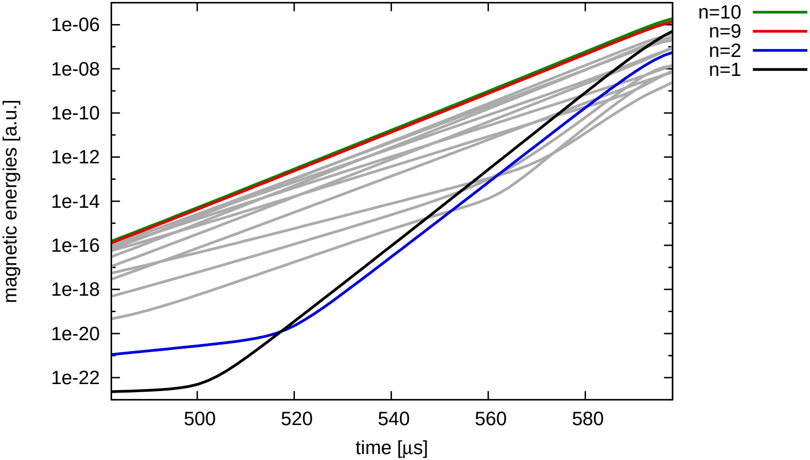
[I. Krebs. Master's thesis, LMU, Munich (2012)]

Results Mode Interaction Model



- ▷ Non-linear drive recovered
- ▷ Saturation not recovered (of course)

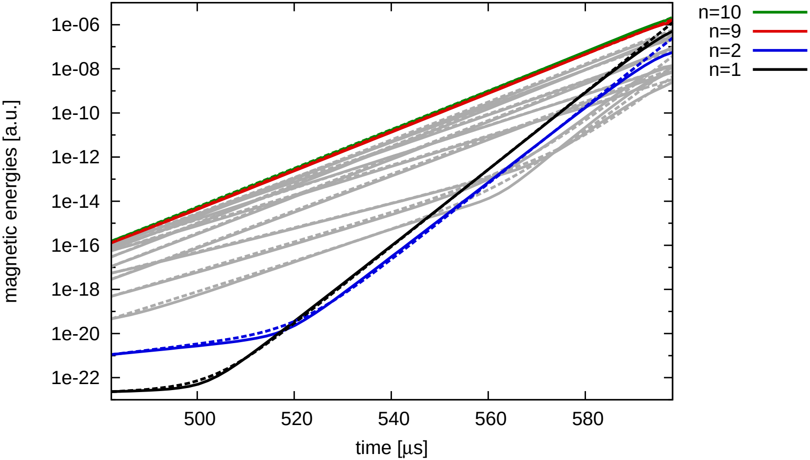
Mode Interaction Model



- Applied to full simulation with $n = 0 \ldots 16$
- **Explains low-n features in experimental observations**

[I. Krebs, et al. *Phys.Plasmas* (to be submitted)]

Mode Interaction Model



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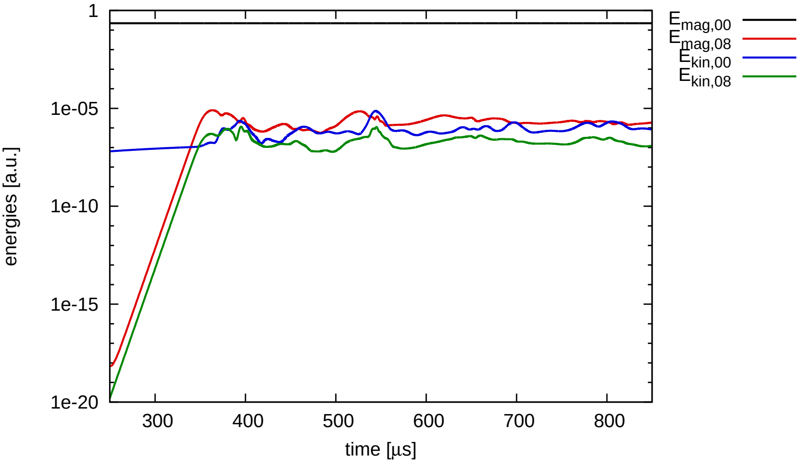
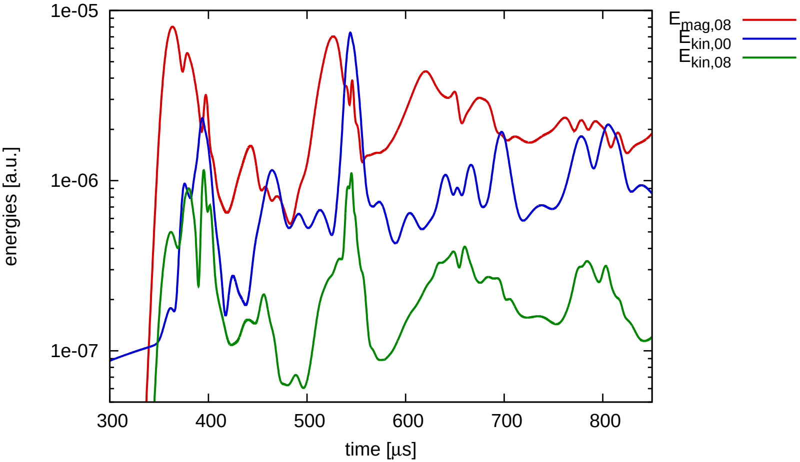
Non-linear phase



- Energy time traces during an ELM crash
- Simulation with $n = 0, 8$
- Several bursts

Non-linear phase



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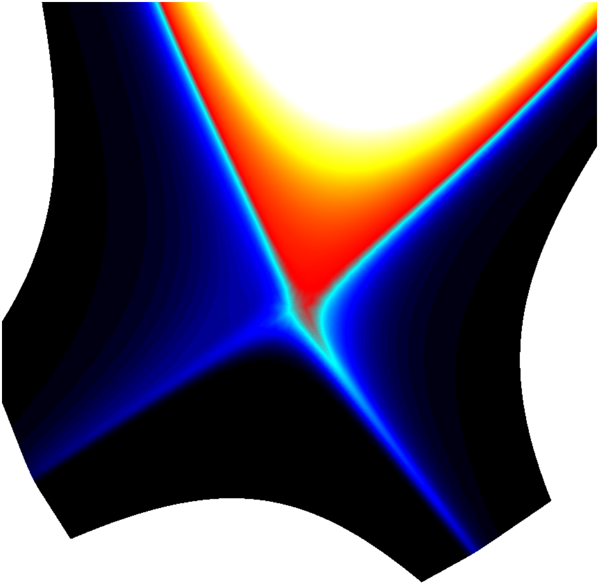
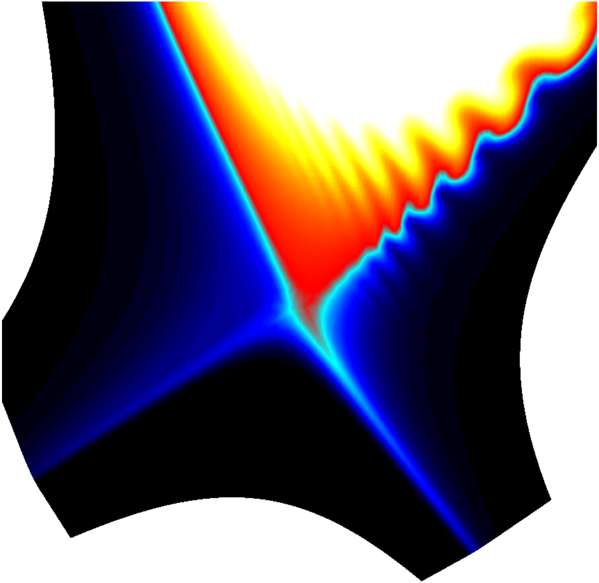
Filament Formation



Detached filaments quickly lose their pressure due to fast parallel heat conduction. Substructures appear in divertor heat flux patterns.

Filament Formation



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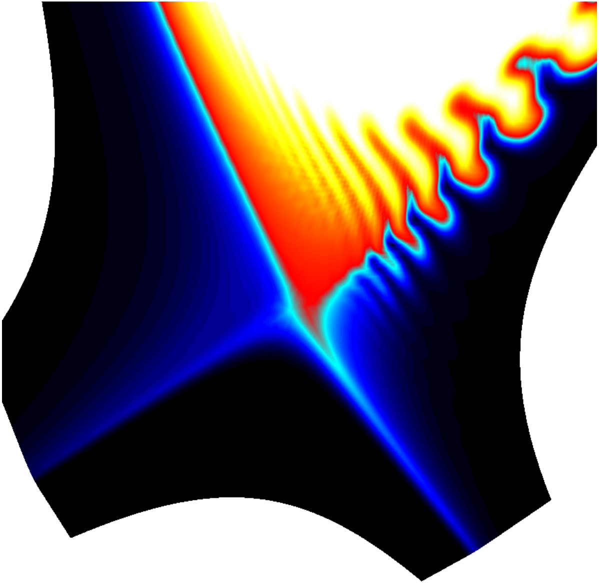

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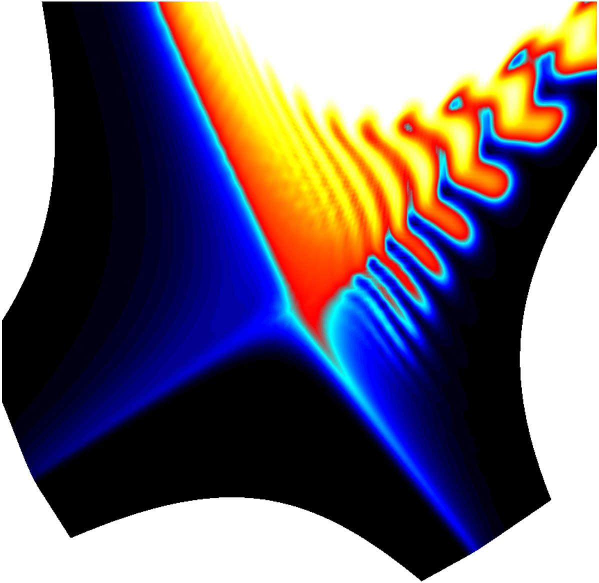

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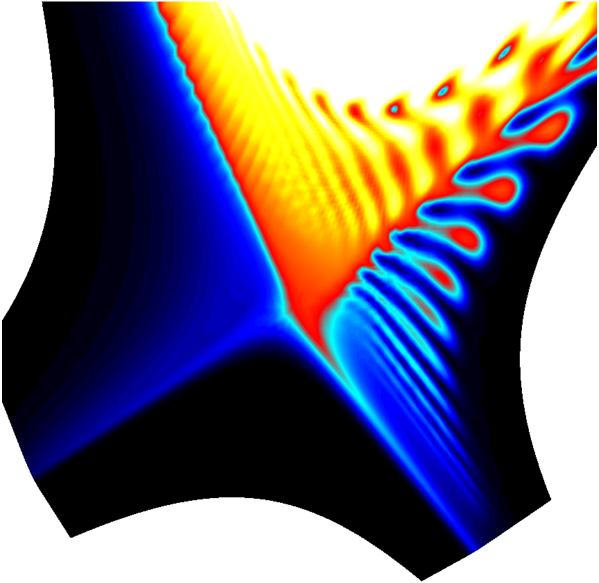

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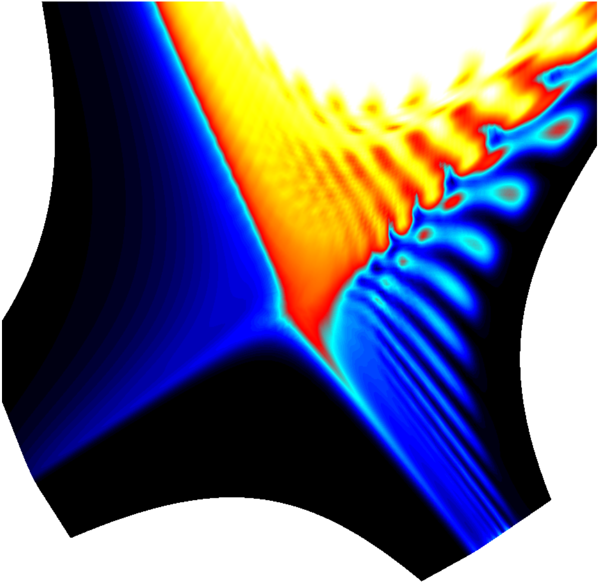

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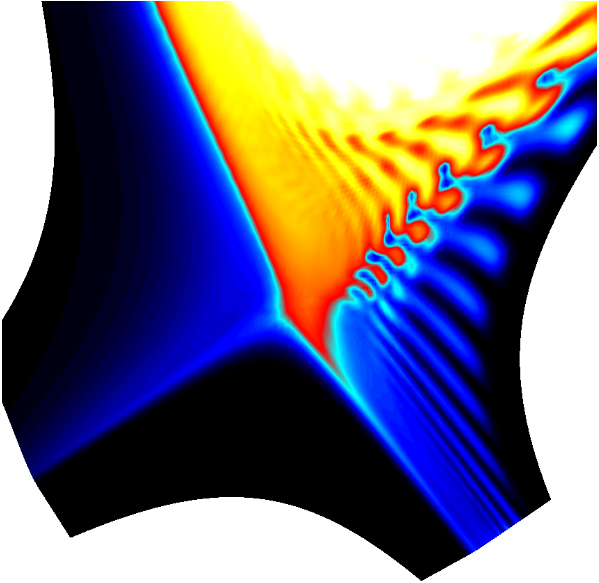

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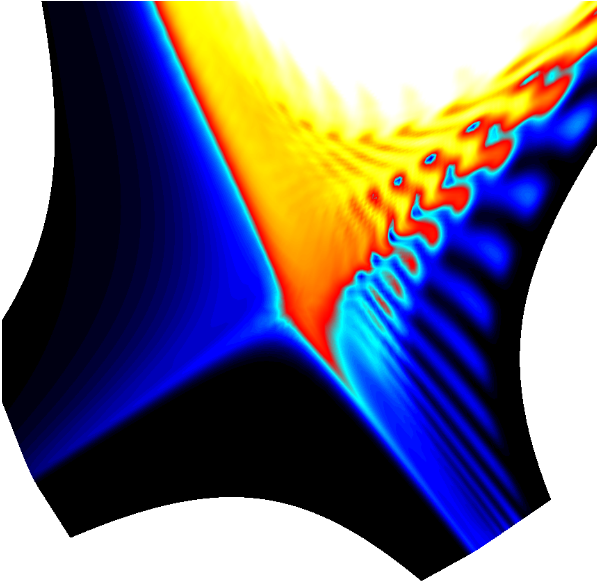

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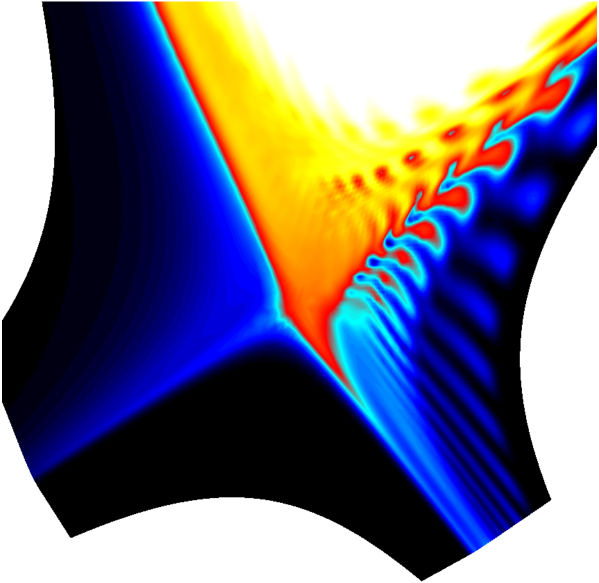

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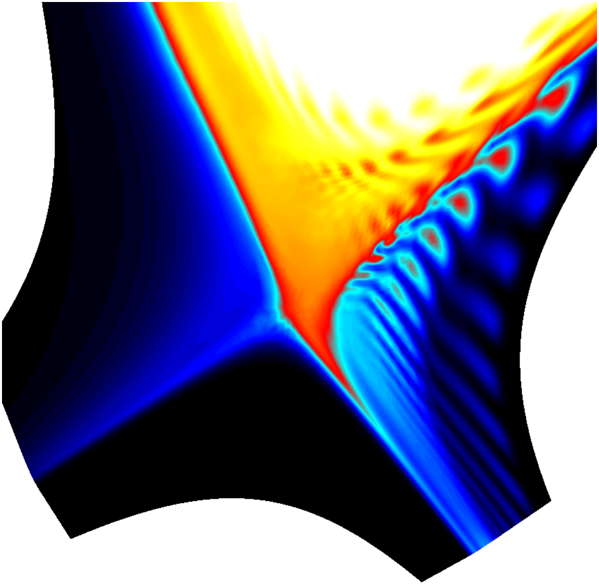

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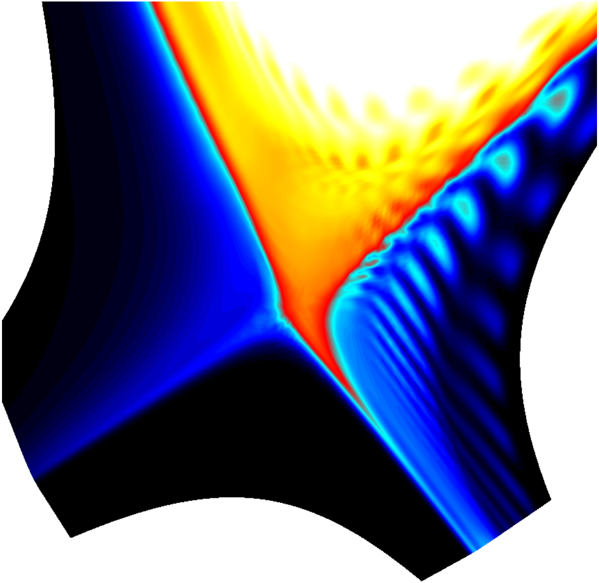

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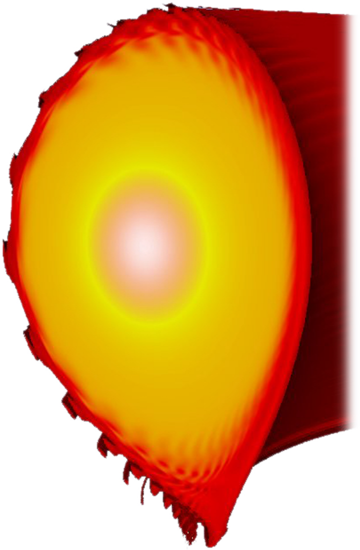
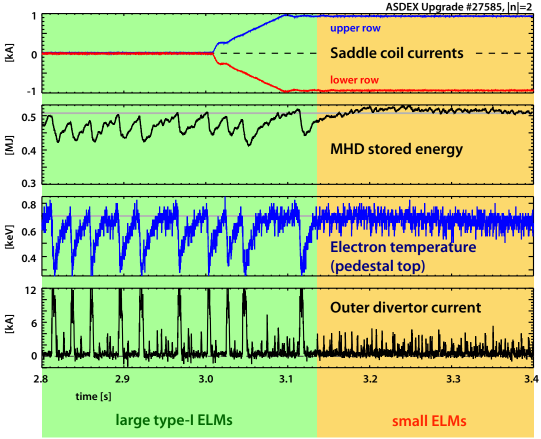
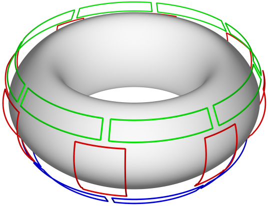
PhD Project



- More quantitative comparisons
- Heat flux patterns
- Full ELM crash
- ELM types
- …

ELM Mitigation



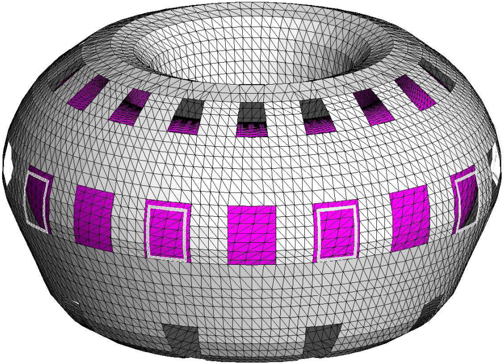


16 perturbation coils are currently installed in ASDEX Upgrade

[W. Suttrop, et al. *24th IAEA*, EX/3-4 (2012)]

- ▷ ELM mitigation with magnetic perturbations
- ▷ Important option for ITER
- → Simulate penetration and interaction with ELMs (with M. Becoulet and F. Orain)

Resistive Walls

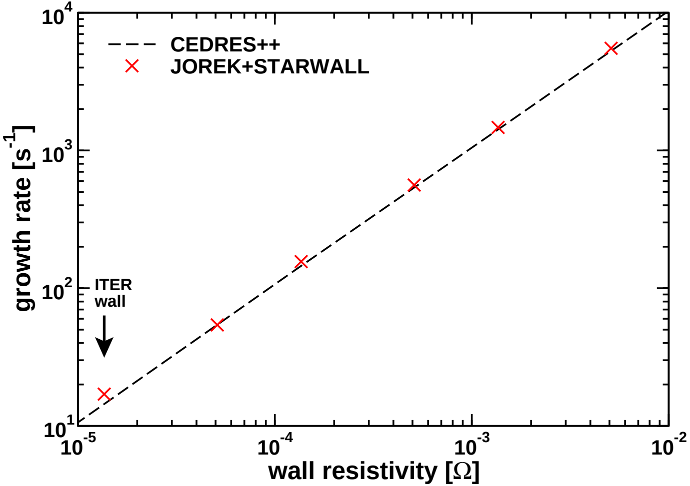


Discretization of first ITER wall in the STARWALL code which describes vacuum region and wall currents

[P. Merkel and M. Sempf. 21st IAEA, TH/P3-8 (2006); E. Strumberger, et al. 38th EPS, P5.082 (2011)]

- Interaction of instabilities with conducting structures (RWMs, VDEs, disruptions, . . .)
- Coupling via natural boundary condition [M. Hölzl, et al. *JPCS*, 401, 012010 (2012a)]

Resistive Walls (2)



- Vertical Displacement Event in ITER-like limiter plasma
- Good agreement with CEDRES++ code
- Next Steps: X-point cases, 3D wall

Summary

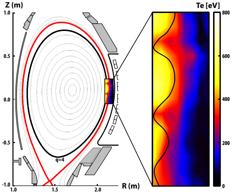
- Non-linear MHD simulations of Edge Localized Modes in ASDEX Upgrade

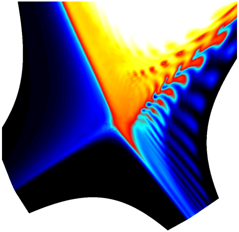
- Experiment and Simulations:
  - **Filament formation**
  - **Localization**
  - **Low-n features**

→ ELM types, heat flux patterns, . . .

→ Magnetic perturbations

→ Resistive walls





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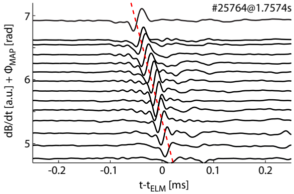

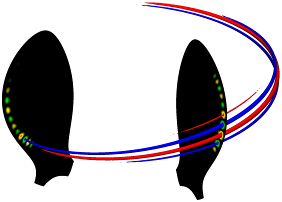

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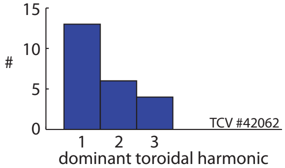

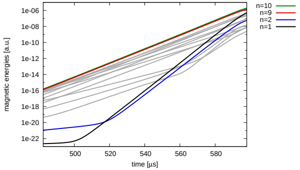

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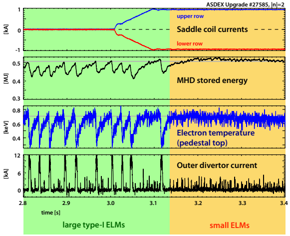

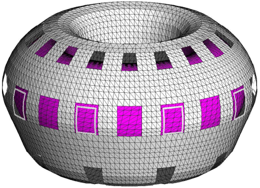

References

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M. Hölzl, et al. *38th EPS*, P2.078 (2011).

M. Hölzl, et al. *JPCS*, 401, 012010 (2012a).

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R. P. Wenninger, et al. *Nucl.Fusion*, 42, 114025 (2012).

R. P. Wenninger, et al. *Nucl.Fusion* (to be submitted).

Slides and Publications

http://me.steindaube.de

Co-Authors

I. Krebs, K. Lackner, S. Günter

Acknowledgements

G. Huysmans, P. Merkel, E. Nardon,
R. Wenninger, E. Strumberger, M. Bécoulet,
F. Orain

$n = 1$ mode structure