IPP

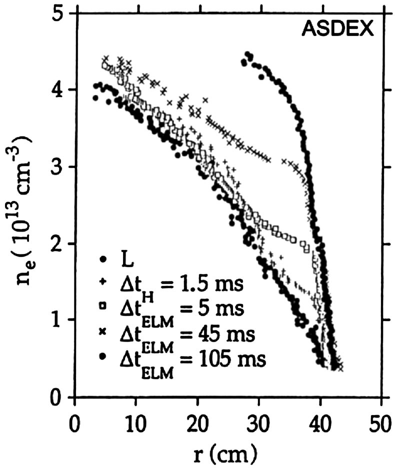
ASDEX Upgrade

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

Matthias Hölzl, Isabel Krebs, Karl Lackner, Sibylle Günter

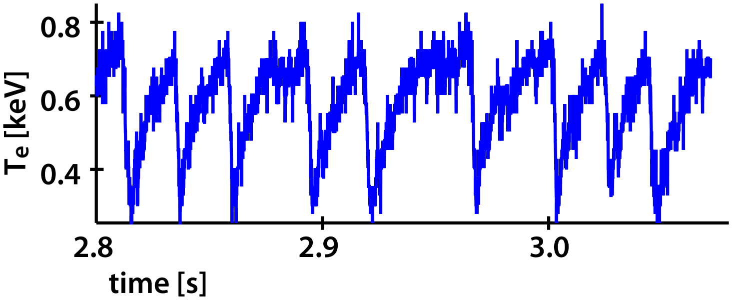
H-Mode

- High Confinement Mode first observed in ASDEX [F. Wagner, et al. *PRL*, 49, 1408 (1982)]
- Sudden rise of edge gradients and confinement time
- Extremely beneficial for fusion



Formation of density pedestal during L-H transition *[M. E. Manso. PPCF, 35, B141 (1993)]*

Introduction ELMs

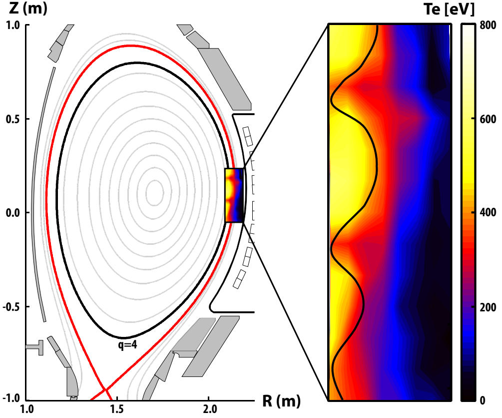


- Edge Localized Modes (ELMs) appear in H-Mode
- Periodic collapse of pedestal
- Up to 10% of stored energy lost
- Critical for ITER → mitigation

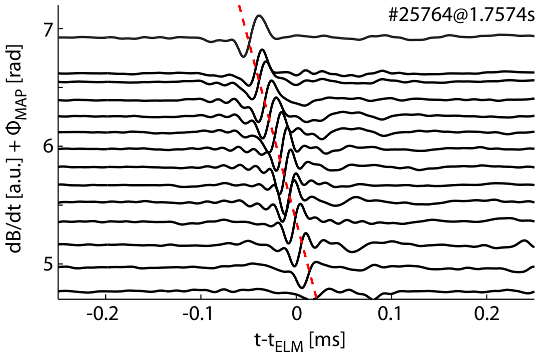
ELMs (2)

Electron temperature at ELM onset in ASDEX Upgrade: Dominant toroidal Fourier harmonic $n \approx 11$

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



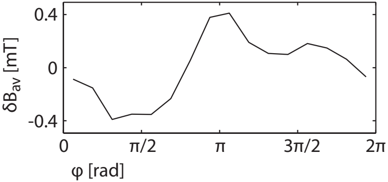
- ASDEX Upgrade: Expanded and localized ELMs observed

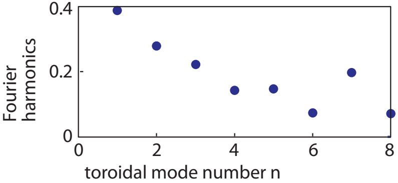


Signature of a Solitary Magnetic Perturbation in ASDEX Upgrade

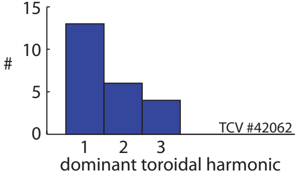
[R. P. Wenninger, et al. Nucl.Fusion, 42, 114025 (2012)]

Low-n Harmonics



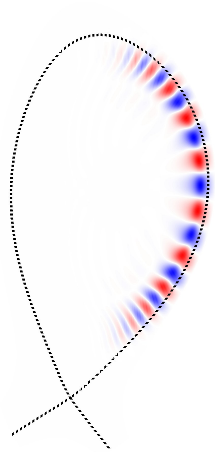


Example for ELM signature with strong low-n component



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

[R. P. Wenninger, et al. to be published (2013)]



Poloidal flux perturbation caused by a ballooning instability (linear MHD calculation)

Non-linear simulations

- Low mode numbers
- Localization
- ELM sizes
- Mitigation

. . .

Model JOREK

- Originally developed at CEA Cadarache

  [G. Huysmans and O. Czarny. *Nucl.Fusion*, 47, 659 (2007); O. Czarny and G. Huysmans. *J.Comput.Phys*, 227, 7423 (2008)]
- Non-linear reduced MHD in toroidal geometry (next slide)
- Full MHD in development

- Toroidal Fourier decomposition
- Bezier finite elements
- Fully implicit time evolution

- Selected results:
  - Pellet ELM triggering [G. Huysmans, et al. *23rd IAEA*, THS/7-1 (2010)]
  - ELMs in JET [S. J. P. Pamela, et al. *PPCF*, 53, 054014 (2011)]
  - RMP field penetration [M. Becoulet, et al. *24th IAEA*, TH/2-1 (2012)]

Reduced MHD Equations

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

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

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

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

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

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

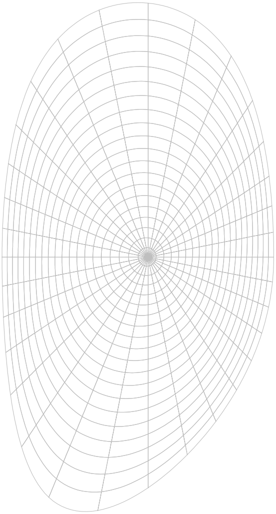
$$\omega \equiv -\omega_\phi = \nabla^2_{pol}\, u$$

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 $\mathbf{v} \equiv -R \nabla u \times \mathbf{e}_\phi + v_{||} \mathbf{B}$

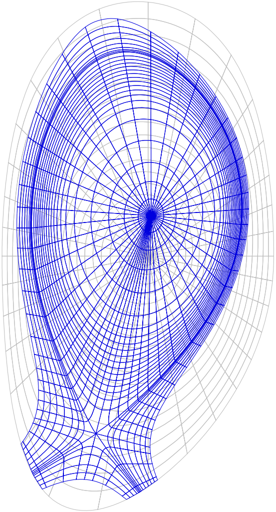
[H. R. Strauss. *Phys.Fluids*, 19, 134 (1976)]

Typical code run



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

Typical code run



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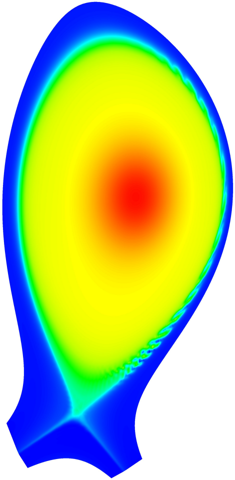

- Initial grid (Grids shown with reduced resolution)
- Flux aligned grid including X-point(s)
- Radial and poloidal grid meshing
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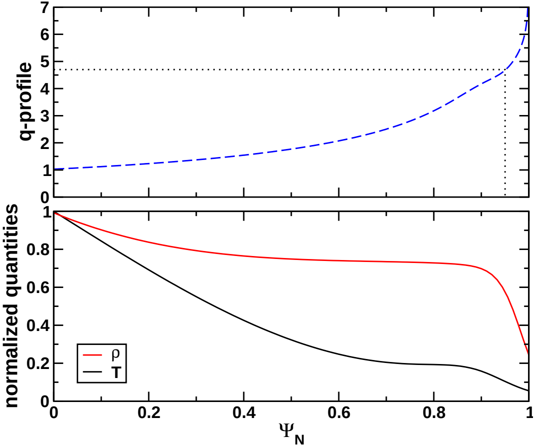
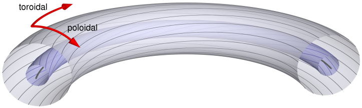
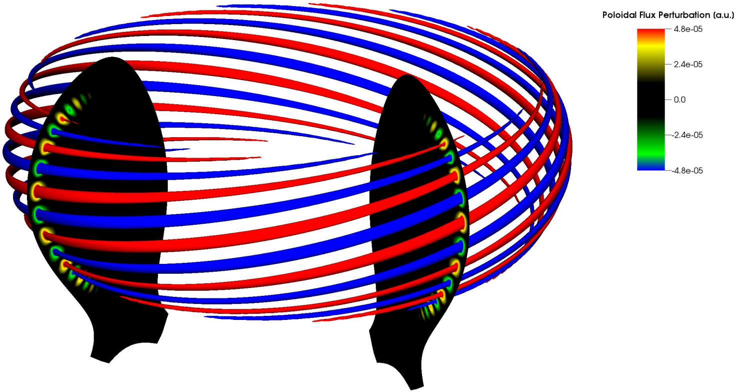
- ELMs in typical ASDEX Upgrade H-mode equilibrium
- Many toroidal harmonics
- Resistivity too large by factor 10 due to numerical constraints (improving)





$$q = \frac{\text{toroidal turns}}{\text{poloidal turns}}$$

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)]

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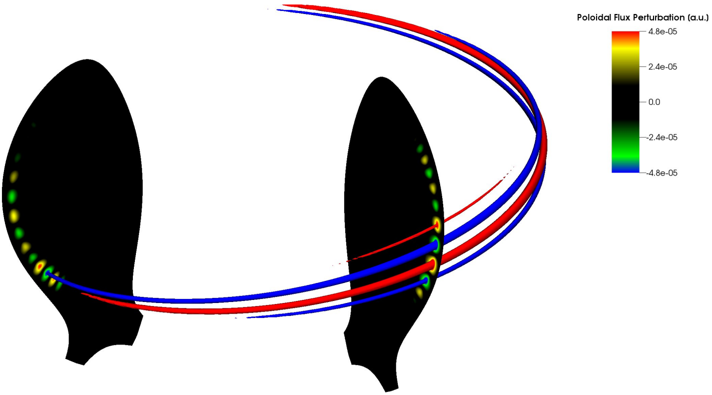


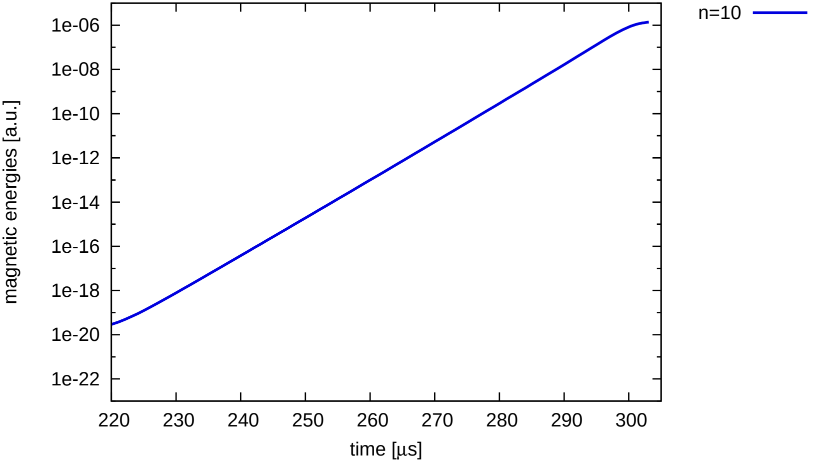
$n = 0, 1, 2, 3, 4, \ldots, 16$

- ▷ 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 Energy Timetraces



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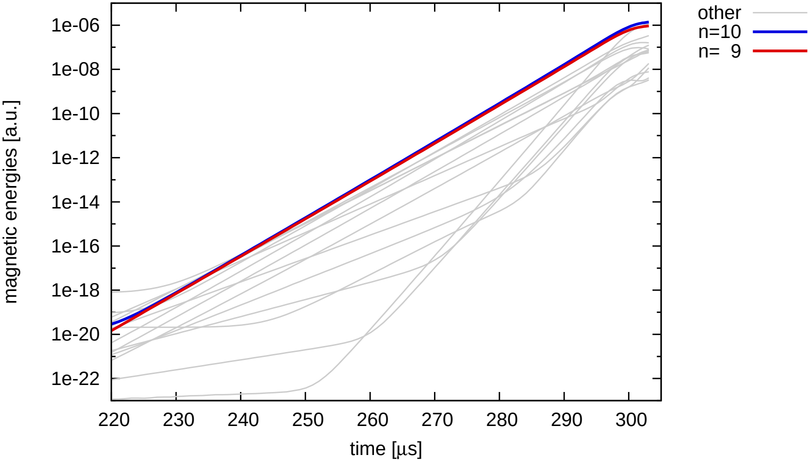
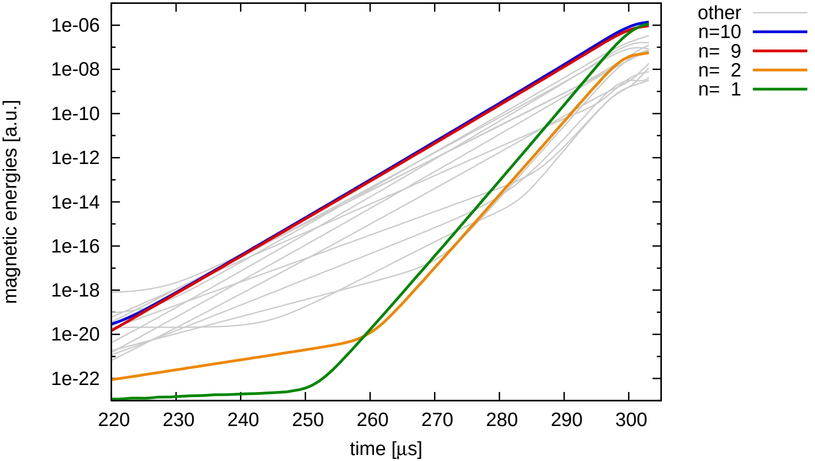


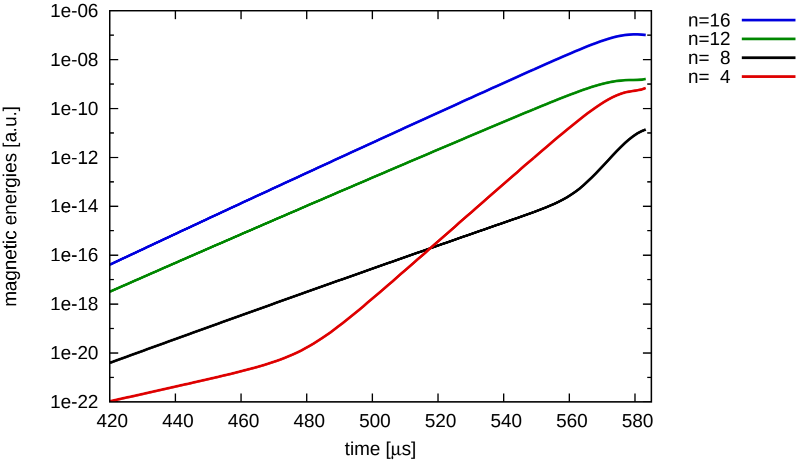
- Simulation including $n = 0, 1, \ldots, 15, 16$
- $n = 9$ and 10 are linearly most unstable

Results Energy Timetraces



- Simulation including $n = 0, 1, \ldots, 15, 16$
- $n = 9$ and 10 are linearly most unstable
- low-n modes driven non-linearly to large amplitudes
- Can we understand this with a simple model?

Mode Interaction Model



- Simplified case with $n = 0, 4, 8, 12, 16$
- Quadratic terms lead to mode coupling $(n_1, n_2) \leftrightarrow n_1 \pm n_2$
- For instance: $(16, 12) \leftrightarrow 4$

Mode Interaction Model (2)

- Model assuming mode rigidity and fixed background:

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

[I. Krebs, et al. to be published (2013)]

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

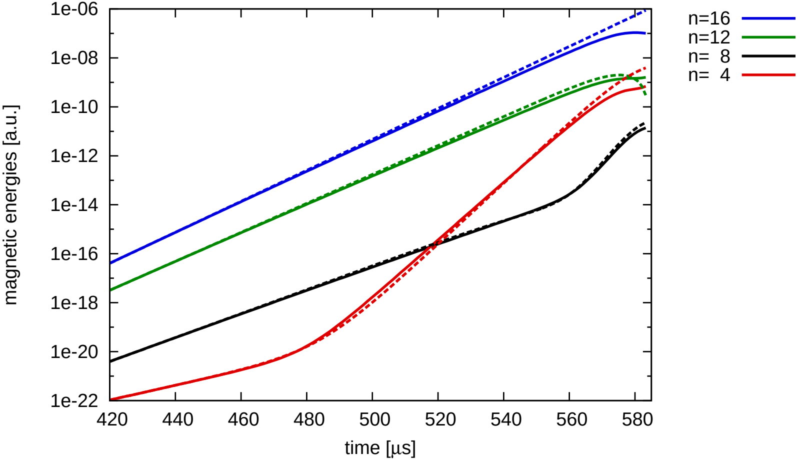
$$\dot{A}_{12} = \gamma_{12}\ A_{12} + \gamma_{4,8}\ A_4\ A_8 + \gamma_{16,-4}\ A_{16}\ A_4$$

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

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

[I. Krebs, et al. to be published (2013)]

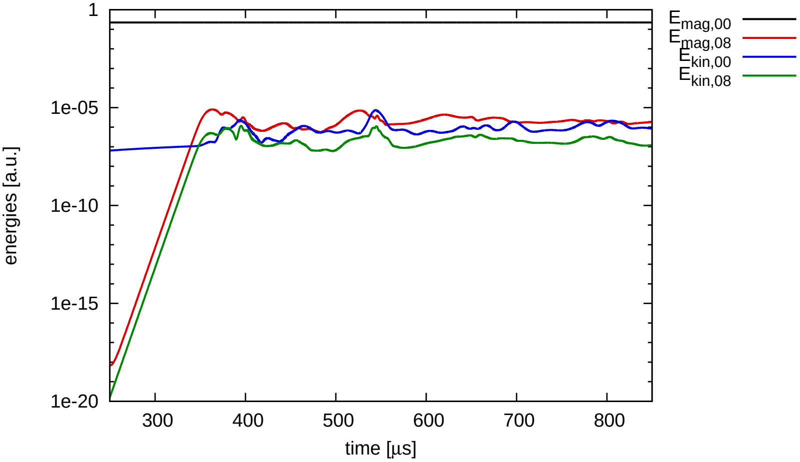
Mode Interaction Model (2)



- ▷ Non-linear drive recovered
- ▷ Saturation not recovered (of course)
- ▷ Explains low-n features in experimental observations

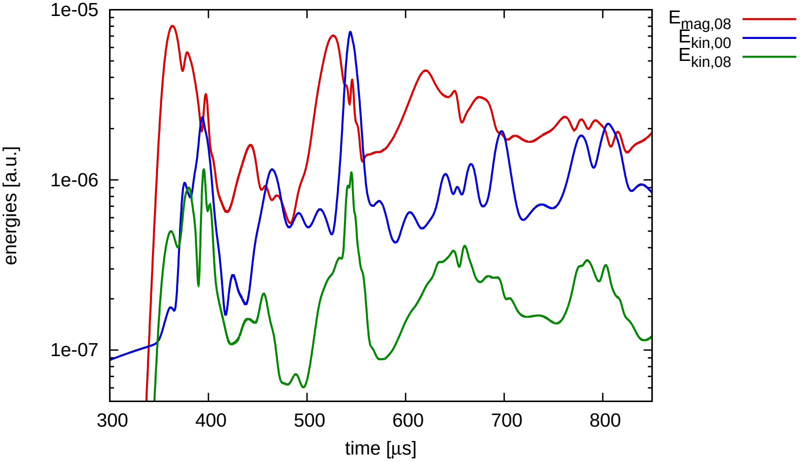
→ Poster: Isabel Krebs, P19.15 (Thursday)

Non-linear phase



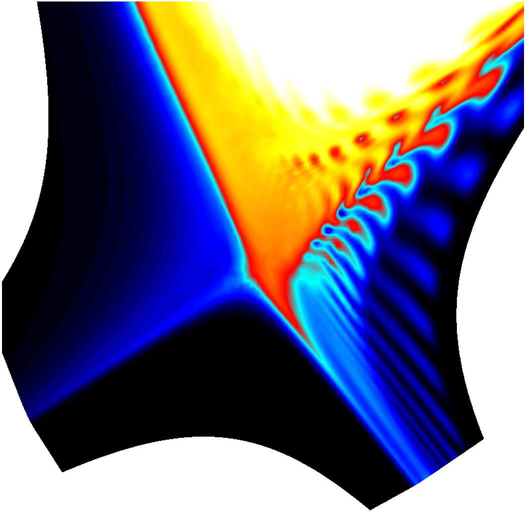
Energy time traces during the fully non-linear phase.

Non-linear phase



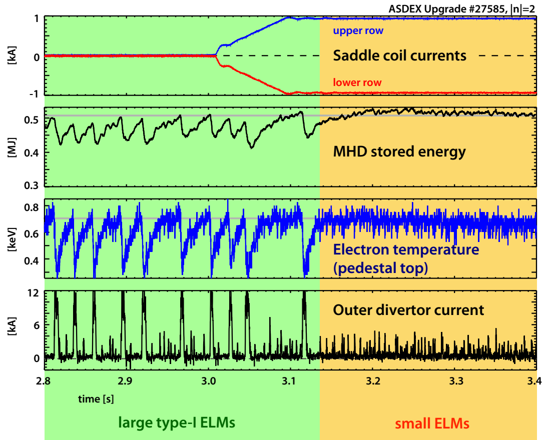
Energy time traces during the fully non-linear phase.

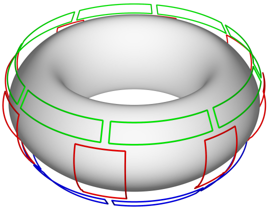
Filament Formation



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

ELM Mitigation





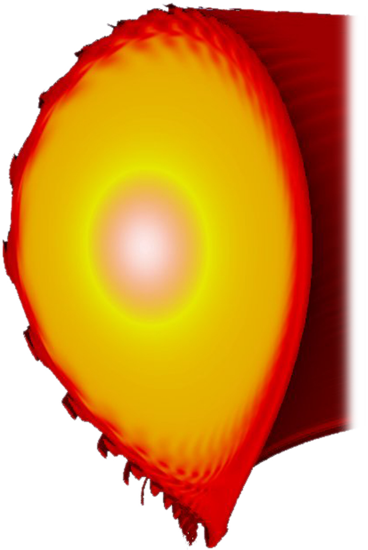
16 perturbation coils are currently installed in ASDEX Upgrade

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

- ELM mitigation with magnetic perturbations
- Important option for ITER

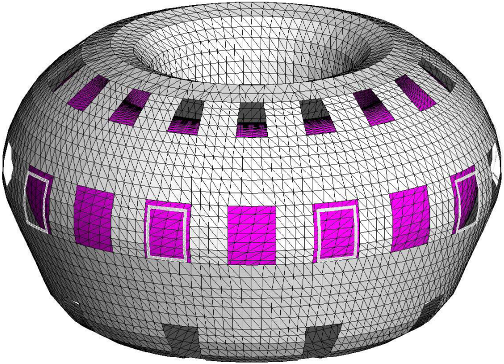
→ Simulate penetration and interaction with ELMs (with M. Becoulet and F. Orain)

Continue Investigations



- ▷ Heat flux pattern
- ▷ Full ELM crash
- ▷ ELM types
- ▷ Two fluid
- ▷ Rotation
- ▷ ...

Resistive Walls



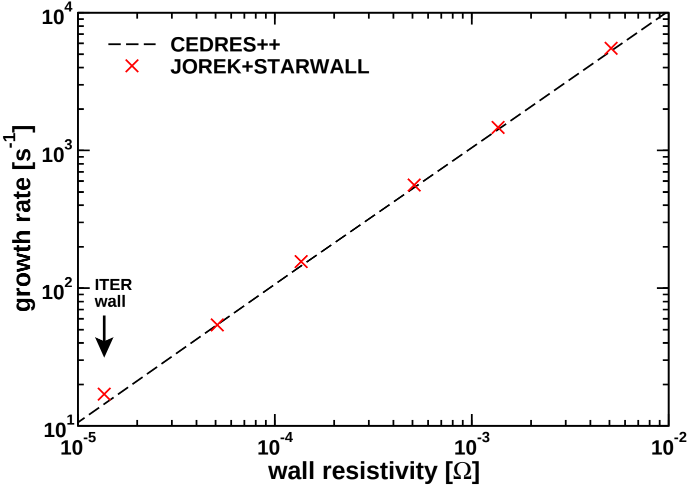
Discretization of first ITER wall in the STARWALL code which describes vacuum region and wall currents

[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
- Coupling via natural boundary condition [M. Hölzl, et al. *JPCS*, 401, 012010 (2012a)]

Resistive Walls (2)



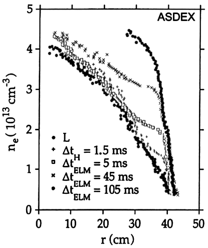
- Vertical Displacement Event in ITER-like limiter plasma
- Good agreement with CEDRES++ code
- Next Steps: X-point cases, 3D wall

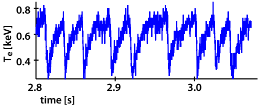
Summary

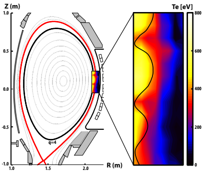
- ▷ Edge Localized Modes in H-Mode plasmas
- ▷ Mitigation important for ITER

- ▷ Non-linear simulations in realistic geometry
- ▷ **Localization**
- ▷ **Low-n features**
- ▷ **Filament formation**

- → ELM mitigation with magnetic perturbations
- → ELM types, heat flux patterns, . . .
- → Resistive Walls







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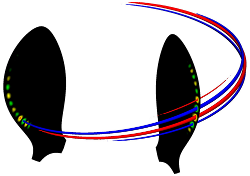

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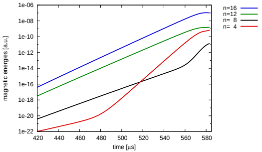
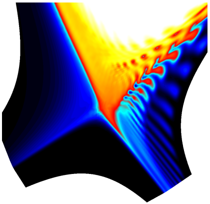


→ ELM mitigation with magnetic perturbations
→ ELM types, heat flux patterns, . . .
→ Resistive Walls



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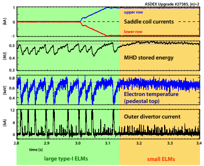

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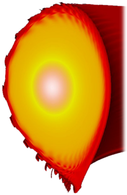

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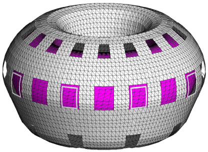

References

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F. Wagner, et al. *PRL*, 49, 1408 (1982).

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

R. P. Wenninger, et al. to be published (2013).

Slides and Publications

http://me.steindaube.de

Co-Authors

I. Krebs, K. Lackner, S. Günter

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G. Huysmans, E. Strumberger, P. Merkel,
R. Wenninger