Nonlinear Modelling of ELMs and Resistive Walls

Matthias Hölzl

ASDEX Upgrade

Acknowledgements

- **IPP Garching**: I. Krebs, A. Lessig, P. Merkel, M. Dunne, R. Wenninger, E. Franck, E. Strumberger, E. Sonnendrücker, S. Günter, K. Lackner, ASDEX Upgrade Team
- **ITER**: G. Huysmans
- **CEA Cadarache**: E. Nardon, F. Orain, M. Bécoulet
- **CCFE**: I. Chapman, R. McAdams
- **IFERC-CSC**: Helios Supercomputer

▷ **Nonlinear MHD in X-point tokamak geometry**

▷ Originally developed at CEA Cadarache G. Huysmans and O. Czarny. *Nucl Fusion*, 47, 659 (2007)

▷ Well established community CEA, IPP Garching, ITER, CCFE, Nice, DIFFER, ...

▷ **Edge Localized Modes** in

- ASDEX Upgrade M. Hölzl, S. Günter, et al. *Phys Plasmas*, 19, 082505 (2012b)
- MAST S. J. P. Pamela, G. T. A. Huysmans, et al. *PPCF*, 55, 095001 (2013)
- JET S. J. P. Pamela, G. T. A. Huysmans, et al. *PPCF*, 53, 054014 (2011)
- ITER G. Huysmans and A. Loarte. *J Nucl Mater*, 438, s57 (2013)

▷ **Resonant Magnetic Perturbations** F. Orain, M. Becoulet, et al. *Phys Plasmas* (submitted)

▷ **Pellet ELM Triggering** G. Huysmans, S. Pamela, et al. *23rd IAEA*, THS/7-1 (2010)

▷ **Tearing Modes** J. Pratt and E. Westerhof. 54th APS (2012)

▷ **Disruptions** (Thermal quench) C. Reux, G. Huysmans, J. Bucalossi, and M. Bécoulet. 38th EPS (2011)

Reduced MHD

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

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

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

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

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H. R. Strauss. *PhysFluids*, 19, 134 (1976)   **B. Després and R. Sart. *ESAIM, Math Model Numer Anal*, 46, 1081 (2012)**

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

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Variables: Ψ, ρ, T, u, $v_{||}$, j, ω

H. R. Strauss. *PhysFluids*, 19, 134 (1976)   **B. Després and R. Sart. *ESAIM, Math Model Numer Anal*, 46, 1081 (2012)**

Numerics

- Toroidal Fourier decomposition
- 2D Bezier finite elements (C^1, isogeometric)
- Fully implicit time evolution
- Iterative GMRES solver
- Physics-based preconditioning (Pastix solver)
- Hybrid parallelization (MPI + OpenMP within compute nodes)

- Reduced MHD (previous slide)
- Two-fluid extensions (T_i and T_e, diamagnetic drift)
- Neutrals model (Thermal quench)
- Full MHD (development)

- Ideal wall + Bohm boundary conditions

Work on Numerics

- Porting to Intel Xeon Phi

  T. Feher (HLST), G. Latu, M. Hölzl, M. Rampp, S. Pamela (ongoing work)

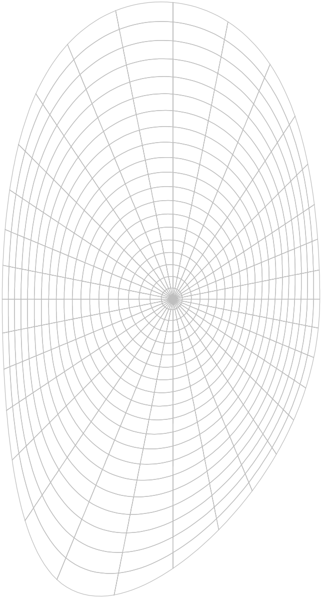
- Toroidal finite elements
- Stabilizing terms

  B. Nkonga, et.al. (ongoing work)

- Verification models
- Nonlinear time integrator (Newton iterations, hyperviscosity)
- Stability of advanced models
- Decoupling of grid and solver (Generalization for arbitrary NURBS)
- Matrix free solver with multi-grid preconditioner (long term)

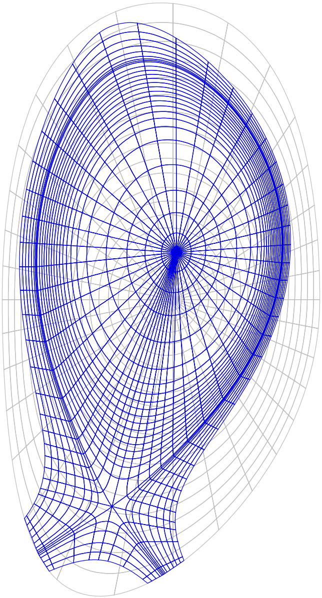
  E. Franck, A. Ratnani, E. Sonnendrücker, M. Hölzl, et.al. (ongoing work)

Typical Simulation



- Initial grid
  (Grids shown with reduced resolution)
- Equilibrium from input profiles
  (F_0, Ψ_{bnd}, profiles for T, ρ, FF')
- Flux aligned X-point grid (meshing)
- Time integration
- Postprocessing

Typical Simulation



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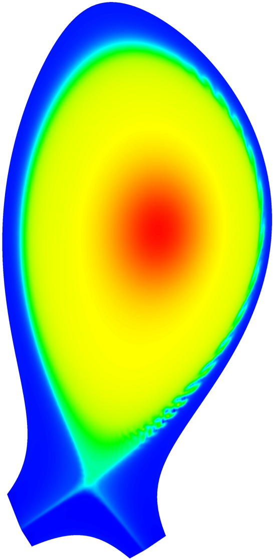

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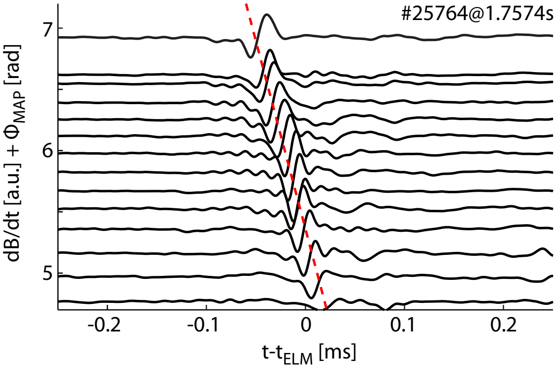
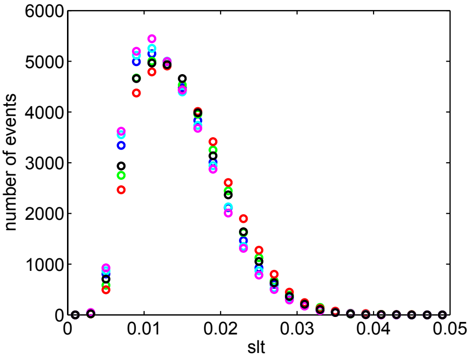
“Solitary” Structures



- Solitary Magnetic Perturbations in ASDEX Upgrade
- Both, expanded and solitary ELMs observed

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

"Solitary" Structures



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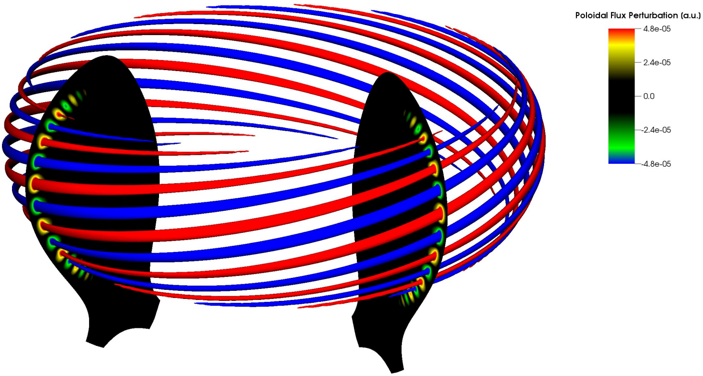
Poloidal Flux Perturbation



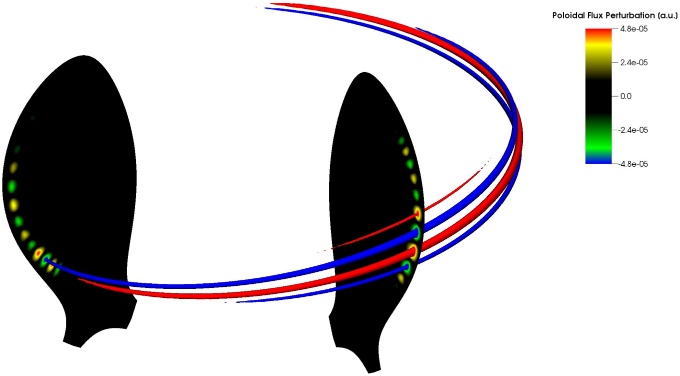
▷ $n = 0, 8$: Uniform perturbation at low-field side

M. Hölzl, S. Günter, and ASDEX Upgrade Team. *38th EPS*, P2.078 (2011)

M. Hölzl, S. Günter, et al. *39th EPS*, P1.048 (2012a)

M. Hölzl, S. Günter, et al. *Phys Plasmas*, 19, 082505 (2012b)

Poloidal Flux Perturbation



- ▷ $n = 0, 1, 2, 3, 4, \ldots, 16$: Poloidal and toroidal localization

$\Rightarrow$ **Similar to Solitary Magnetic Perturbations**

M. Hölzl, S. Günter, and ASDEX Upgrade Team. *38th EPS*, P2.078 (2011)

M. Hölzl, S. Günter, et al. *39th EPS*, P1.048 (2012a)

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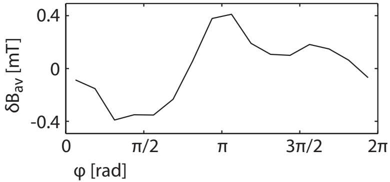
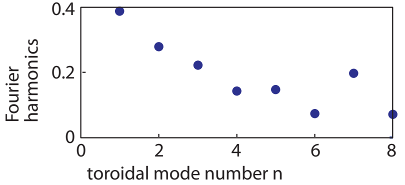
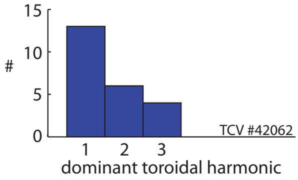
Low-n Structure





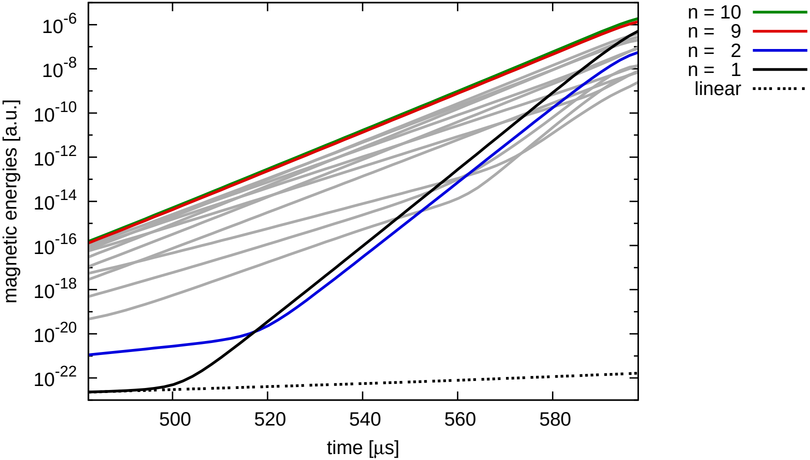
Example for ELM signature with ***strong low-n component***



Dominant magnetic components in a TCV discharge (23 ELMs)

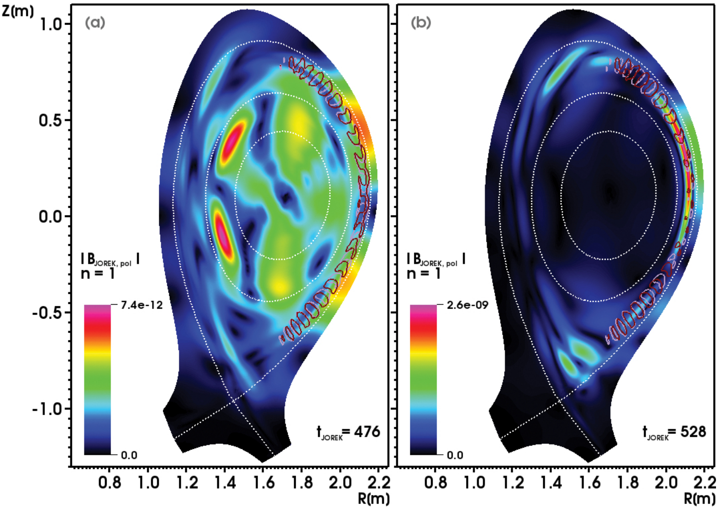
R. P. Wenninger, H. Reimerdes, O. Sauter, and H. Zohm. Nucl Fusion, 53, 113004 (2013)

Nonlinear Drive



- Nonlinear drive of low-n harmonics

$n = 1$ mode structure



- Linear and non-linear modes have entirely different spatial structures

Simple Model

- **Quadratic terms lead to three-wave interaction**
- Assuming mode rigidity and fixed background:

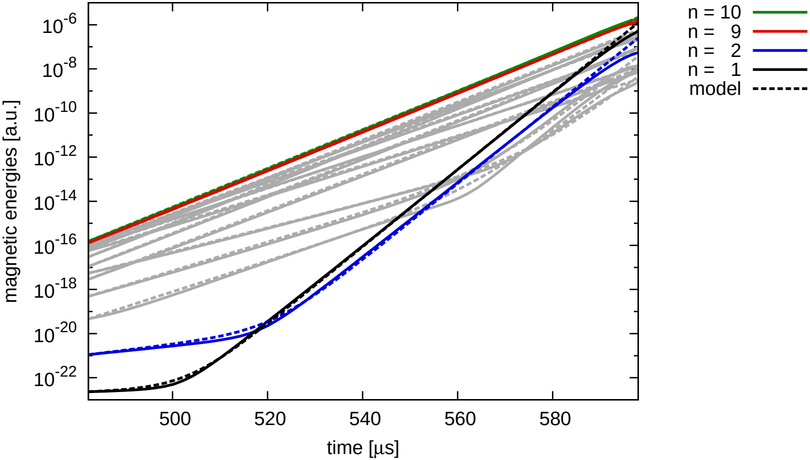
$$\dot{A}_1 = \overbrace{\gamma_1\ A_1}^{\text{linear}} + \overbrace{\gamma_{2,-1}\ A_2\ A_1 + \gamma_{3,-2}\ A_3\ A_2 + \gamma_{4,-3}\ A_4\ A_3 + \ldots}^{\text{nonlinear interaction}}$$

$$\dot{A}_2 = \gamma_2\ A_2 + \gamma_{1,1} A_1\ A_1 + \gamma_{3,-1} A_3\ A_1 + \gamma_{4,-2}\ A_4\ A_2 + \ldots$$

$$\ldots$$

- Linear growth rates from JOREK
- Energy conservation of nonlinear terms
- Remaining free parameters by minimizing quadratic differences
  (Iteration: Solve system of differential equations as initial value problem)

Nonlinear Drive



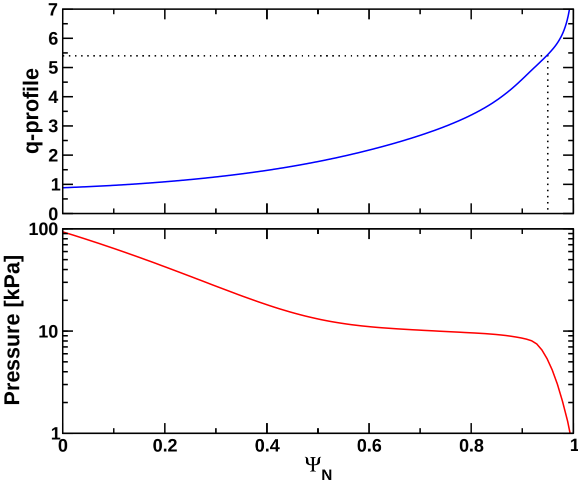
- **Explains low-n features in experimental observations**
- Saturation (of course) not reproduced

I. Krebs, M. Hölzl, K. Lackner, and S. Günter. *Phys Plasmas*, 20, 082506 (2013)

I. Krebs, M. Hölzl, et al. 55th APS (to be presented)

Equilibrium

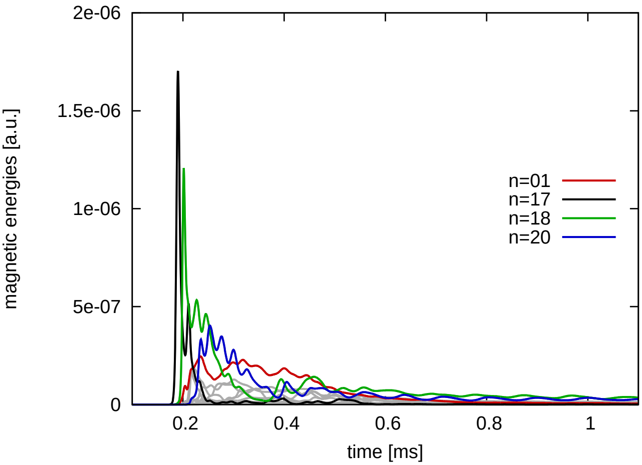
▷ ASDEX Upgrade discharge #29342@4.25s CLISTE reconstruction by Mike Dunne



$T_{e,0} + T_{i,0} \approx 9\mathrm{keV}$

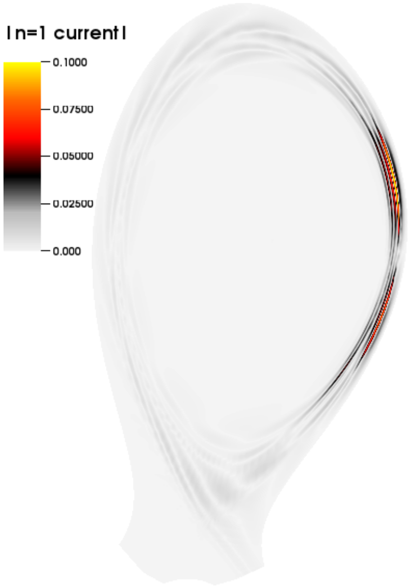
$n_{e,0} \approx 7 \cdot 10^{19} \mathrm{m}^{-3}$

Full Crash Simulation



- Harmonics 0...22 included
- Resistivity in ASDEX Upgrade: $\sim 5 \cdot 10^{-7} \Omega\mathrm{m}$ at axis
- Resistivity in simulation: $5 \cdot 10^{-6} \Omega\mathrm{m}$ (computational reasons)

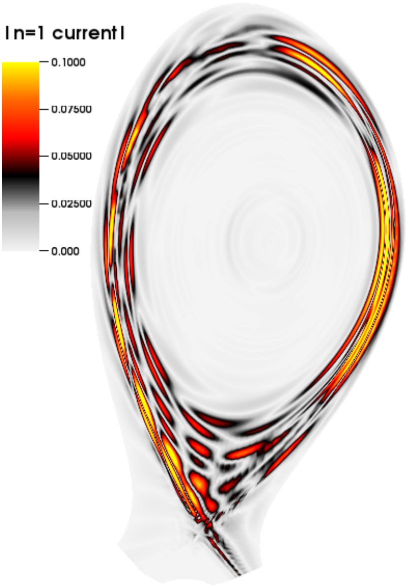
n=1 Structure



- $n = 1$ current perturbation
- Varying spatial structure

$\Rightarrow$ Different three-wave interactions

n=1 Structure



- ▷ $n = 1$ current perturbation
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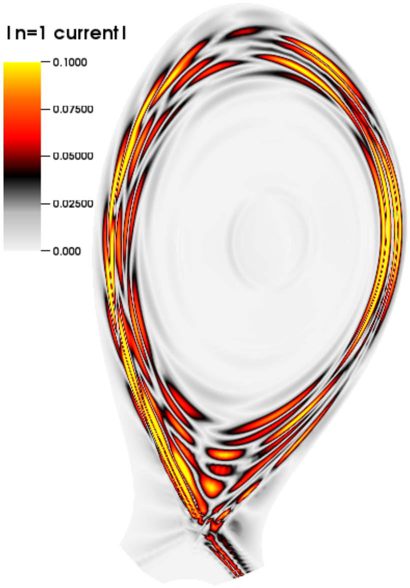
⇒ Different three-wave interactions

n=1 Structure



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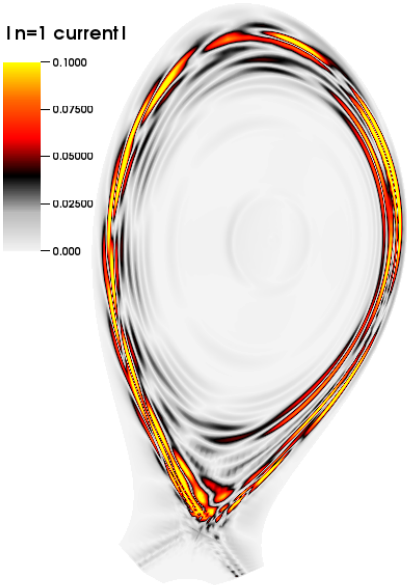

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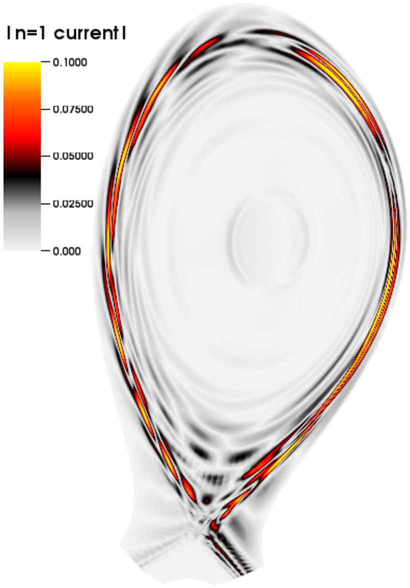

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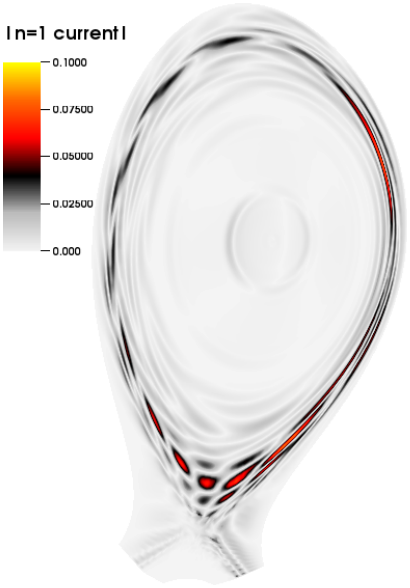

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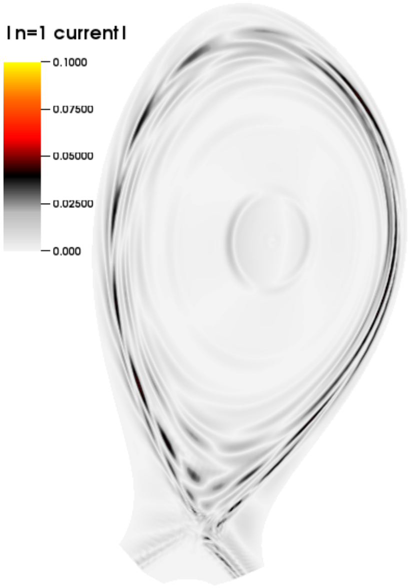

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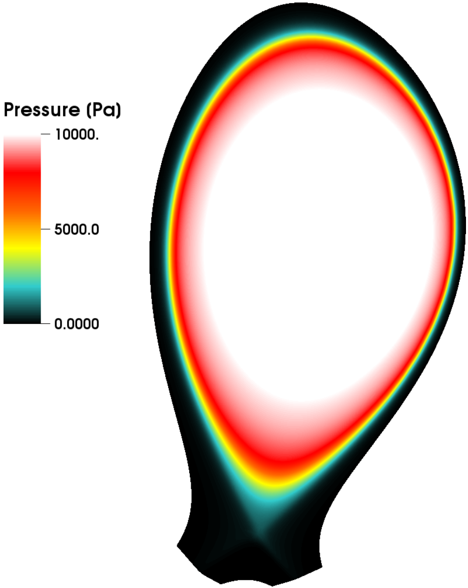
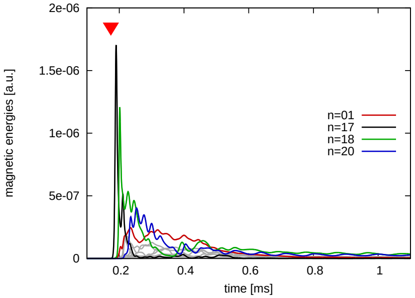
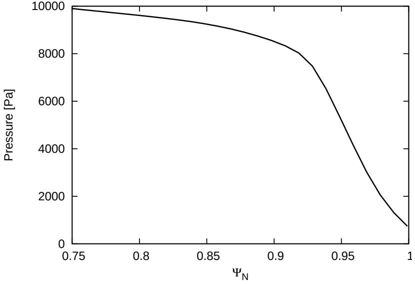
- ▷ Varying spatial structure
- ⇒ Different three-wave interactions

Energy Time-Trace







A. Lessig and M. Hölzl (unpublished)

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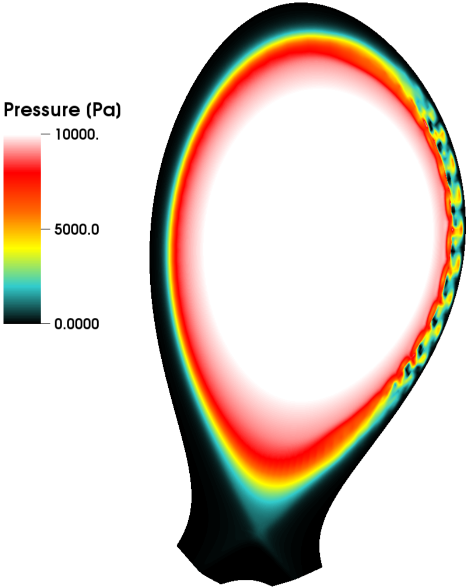

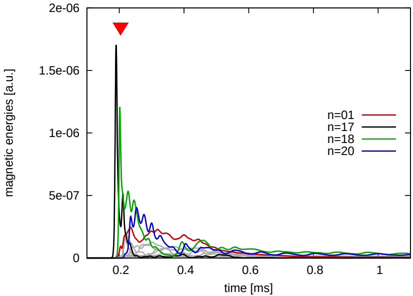

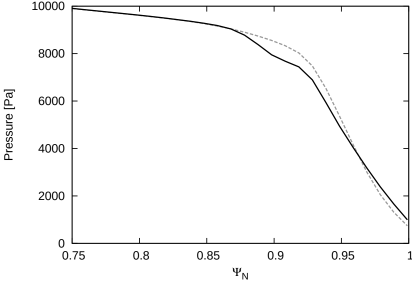

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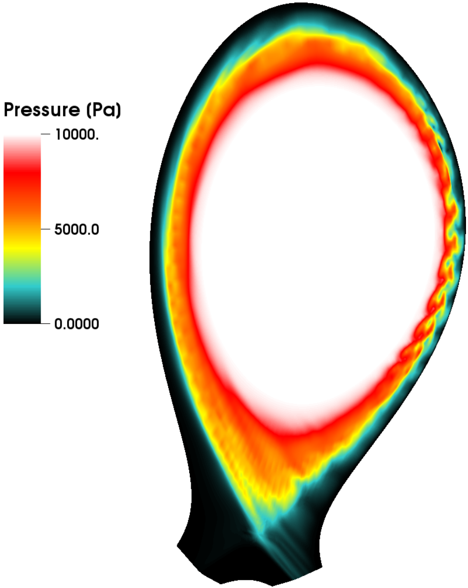

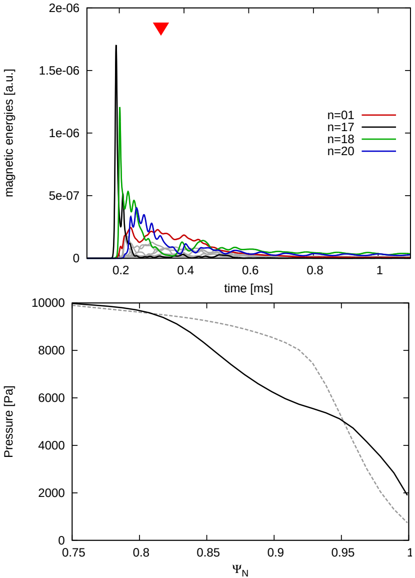

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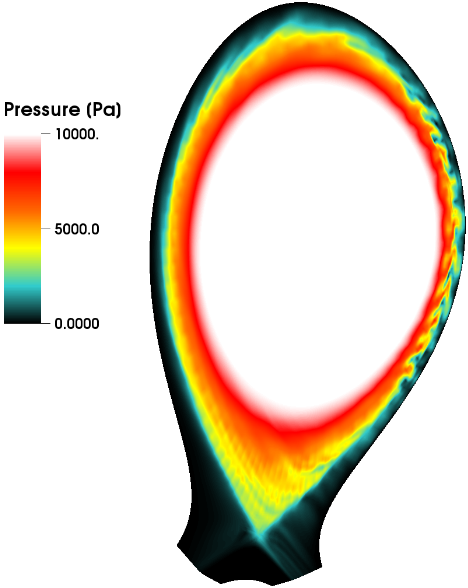

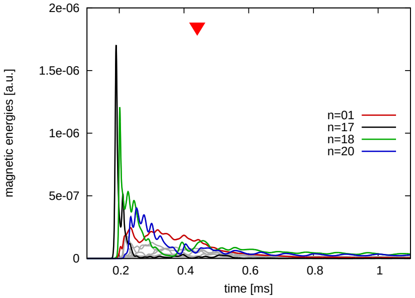

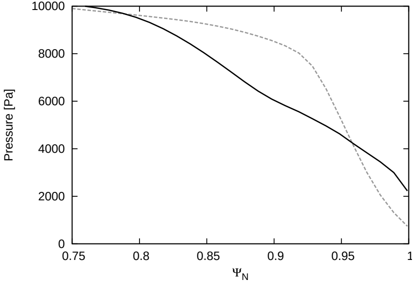

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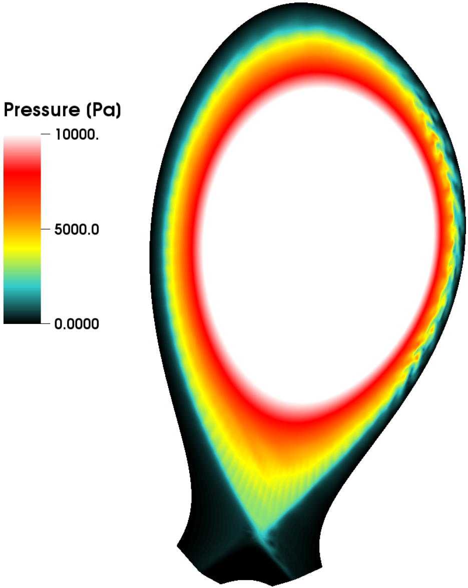
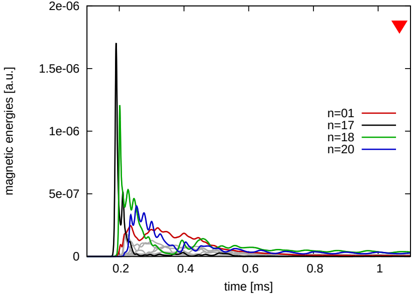
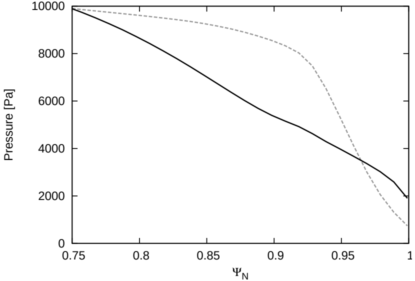
ELMs   Energy Time-Trace







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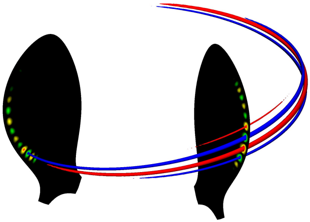
ELMs

Summary

- ▷ “Solitary” structures
- ▷ Nonlinear drive of low-n harmonics
- ▷ Full ELM crash



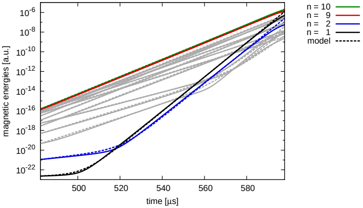
Outlook

- ▷ Two-Fluid
- ▷ ELM types
- ▷ Compare to experiments **(with ASDEX Upgrade Team)**
- ▷ Interaction with RMPs **(with F. Orain and M. Bécoulet)**

ELMs

Summary

- ▷ “Solitary” structures
- ▷ Nonlinear drive of low-n harmonics
- ▷ Full ELM crash



Outlook

- ▷ Two-Fluid
- ▷ ELM types
- ▷ Compare to experiments **(with ASDEX Upgrade Team)**
- ▷ Interaction with RMPs **(with F. Orain and M. Bécoulet)**

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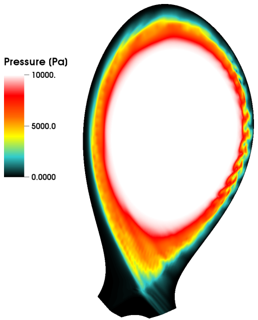

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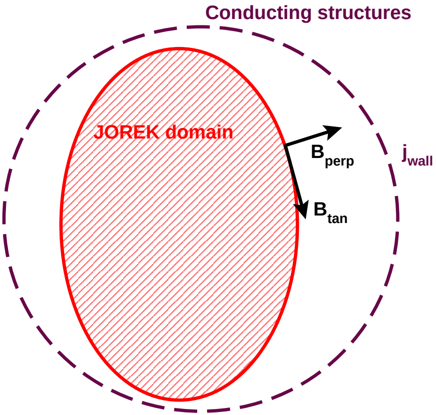
Resistive Wall STARWALL

- Solves vacuum field equations outside JOREK domain

P. Merkel and M. Sempf. *21st IAEA*, TH/P3-8 (2006) P. Merkel, E. Strumberger, et al. (to be published)

- Response matrices:

$$B_{perp} \text{ and } j_{wall} \rightarrow B_{tan}$$
$$\partial_t B_{perp} \text{ and } j_{wall} \rightarrow \partial_t j_{wall}$$



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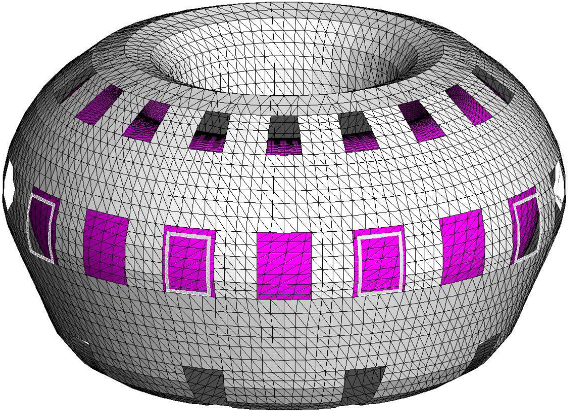


Resistive Wall Coupling

- Current definition equation $j = \Delta^* \Psi$:

$$\int dV \, \frac{j_i^*}{R^2} \, j + \int dV \, \frac{1}{R^2} \, \nabla j_i^* \cdot \nabla \Psi - \oint dA \, \frac{j_i^*}{R} \, \underbrace{(\nabla \Psi \cdot \hat{\mathbf{n}}/R)}_{\equiv B_{\mathrm{tan}}} = 0$$

- Tangential field:

$$B_{\mathrm{tan}} = \sum_i b_i \left(\sum_j \hat{M}_{i,j}^{ee} \, \Psi_j + \sum_k \hat{M}_{i,k}^{ey} \, Y_k \right)$$

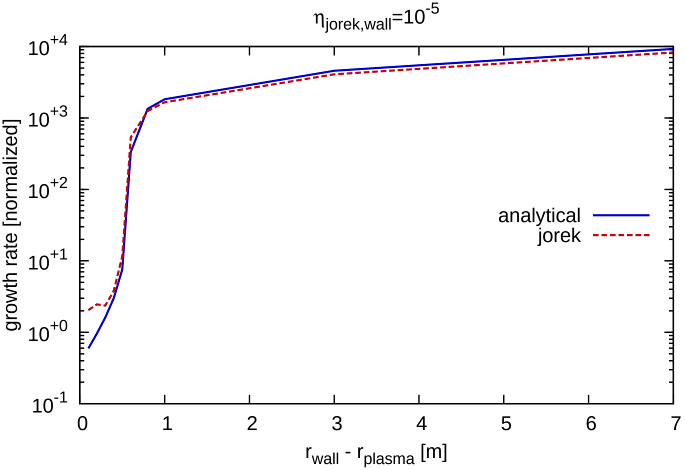
- Wall current evolution:

$$\dot{Y}_k = -\frac{\eta_w}{d_w} \, \hat{M}_{k,k}^{yy} \, Y_k - \sum_j \hat{M}_{k,j}^{ye} \, \dot{\Psi}_j$$

- Natural boundary condition
- Conserves fully implicit time-evolution

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

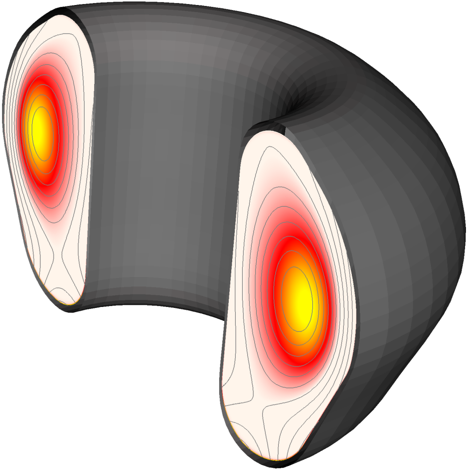
RWM-Benchmark



- Analytical RWM test case **Y. Liu, R. Albanese, et al. *Phys Plasmas*, 15, 072516 (2008)**
- Discrepancy at small $r_{wall} - r_{plasma}$ presumably caused by resolution

R. McAdams, I. Chapman, et al. 55th APS (to be presented)

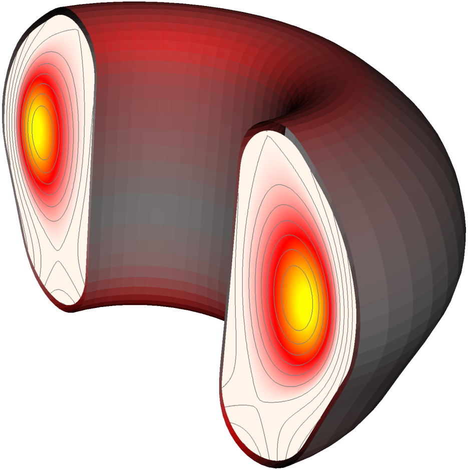
Resistive Wall   VDE-Benchmark



- ITER-like X-point case with closed wall
- Benchmarked versus CEDRES++ code

M. Hölzl and E. Nardon (unpublished)

Resistive Wall VDE-Benchmark



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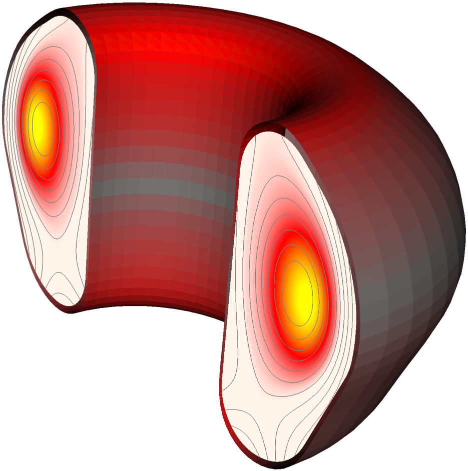

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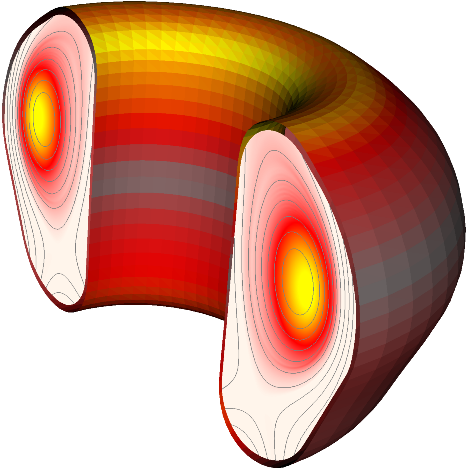

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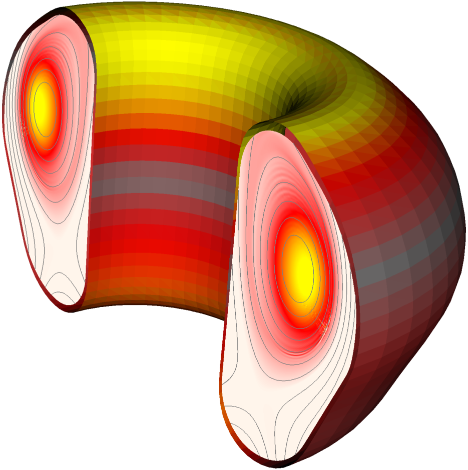

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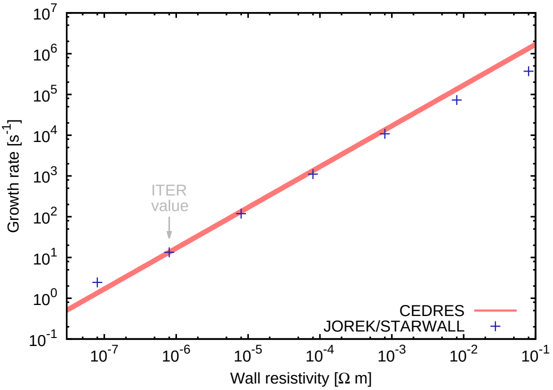

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Resistive Wall

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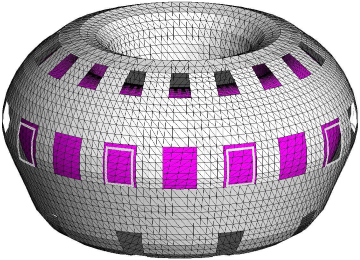
- ▷ Coupling via natural boundary condition conserving full implicitness
- ▷ Resistive Wall Modes
- ▷ Vertical Displacement Event



Outlook

- ▷ Halo currents **(with C. Atanasiu)**
- ▷ Full disruptions (long term)

(with E. Nardon, A. Fil, G. Pautasso, G. Huysmans)

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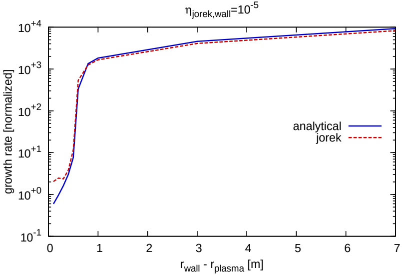

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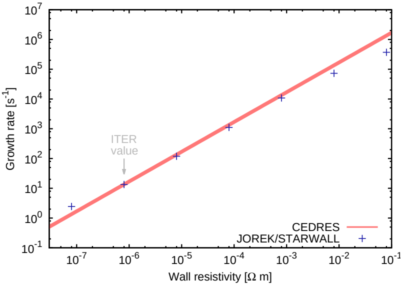

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Conclusions

- **JOREK: Versatile nonlinear MHD code**
  - Well established community
  - ELMs, Pellets, RMPs, Tearing Modes, (Disruptions), . . .

- **Edge Localized Modes**
  - “Solitary” structures
  - Low-n features
  - Full crash
  - → Two-fluid effects
  - → ELM types
  - → RMPs

- **Resistive Walls**
  - Implementation
  - RWMs
  - VDEs
  - → Halo current model for disruptions (longer term)

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