Non-linear Simulations of ELMs, RMPs, and ELM-RMP Interaction

M. Hoelzl, F. Orain, A. Lessig, M. Becoulet

1. JOREK
2. Selected Results
   - ELMs
   - RMPs
   - Interaction
3. Summary + Outlook

JOREK

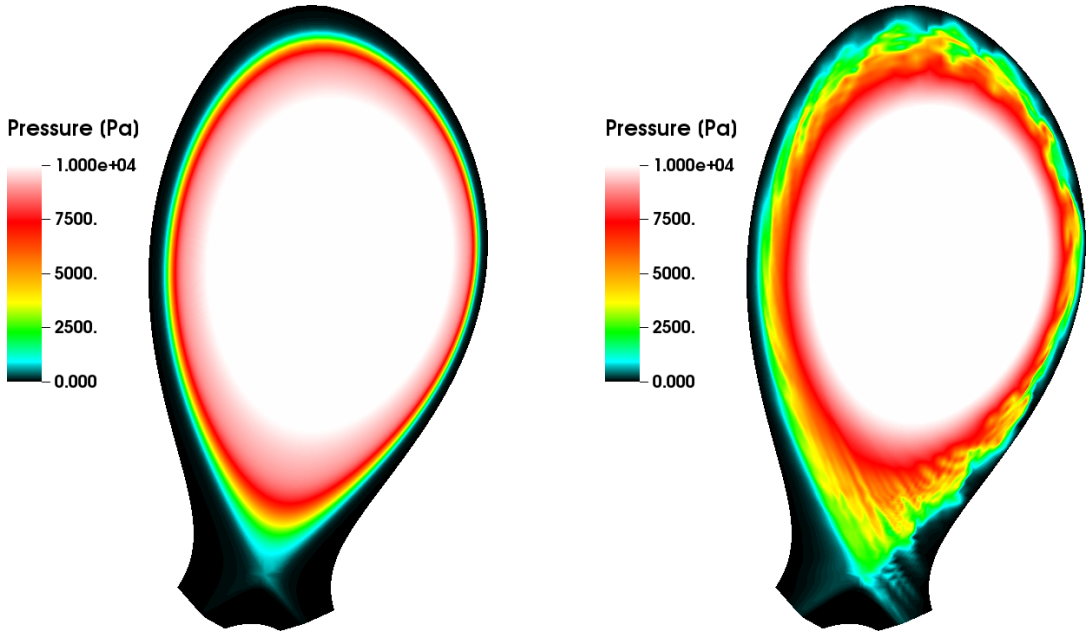
- **Non-linear MHD in realistic tokamak X-point geometry**

- Bezier finite elements + toroidal Fourier decomposition
- Fully implicit time integration
- Hybrid MPI + OpenMP parallelization
- Supercomputers like HELIOS and HYDRA

- Originally developed by Guido Huysmans G. Huysmans and O. Czarny. *NF*, 47, 659 (2007)
- Further developed by CEA, IPP, ITER, CCFE, ...

- ER 2014 (PI M. Becoulet): ELM Physics
- ER 2015–2017 (PI M. Hoelzl): ELM and Disruption Physics, Numerics

JOREK

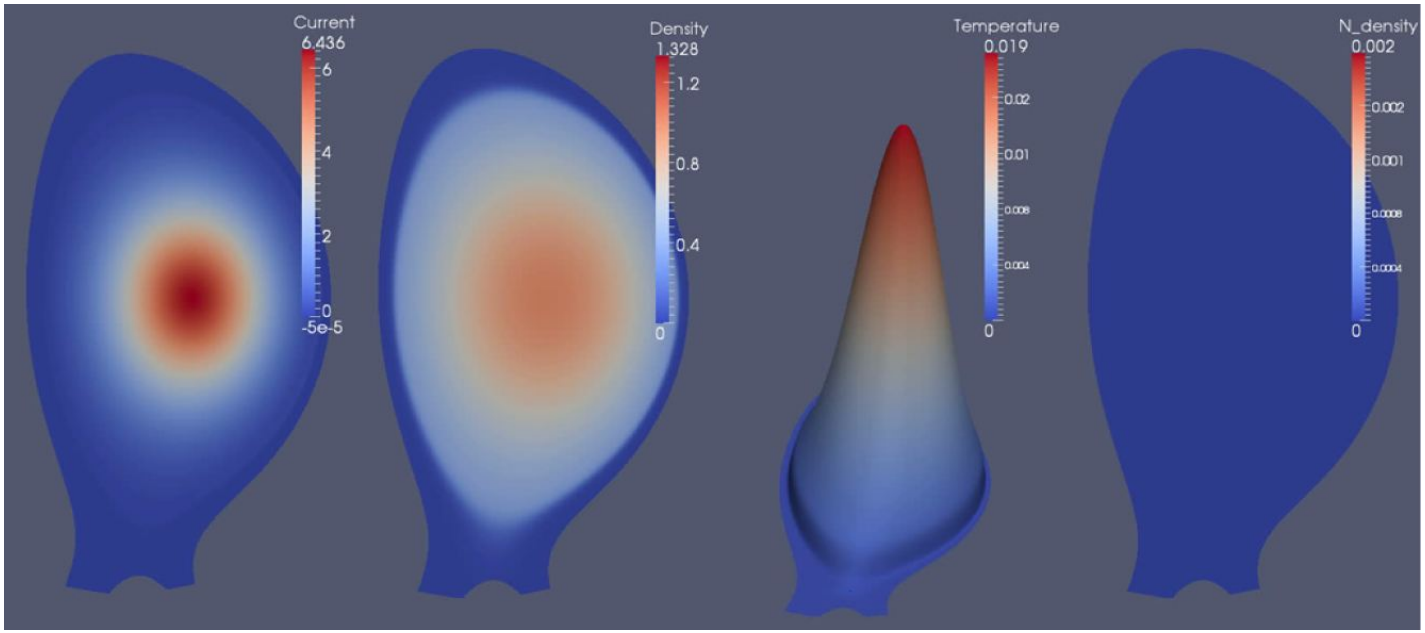


A. Lessig and M. Hölzl (unpublished)

- Reduced MHD with diamagnetic, neoclassical and toroidal rotation
  - → **ELMs, Pellets, RMPs**
- Extensions for neutrals and resistive walls
  - → **Deuterium MGI, Disruptions, (Impurity MGI), (Runaways)**
  - → **QH-Mode, VDEs, RWMs, (Halo Currents)**
- Full MHD model

- Typically increased resistivity due to computational limitations

JOREK



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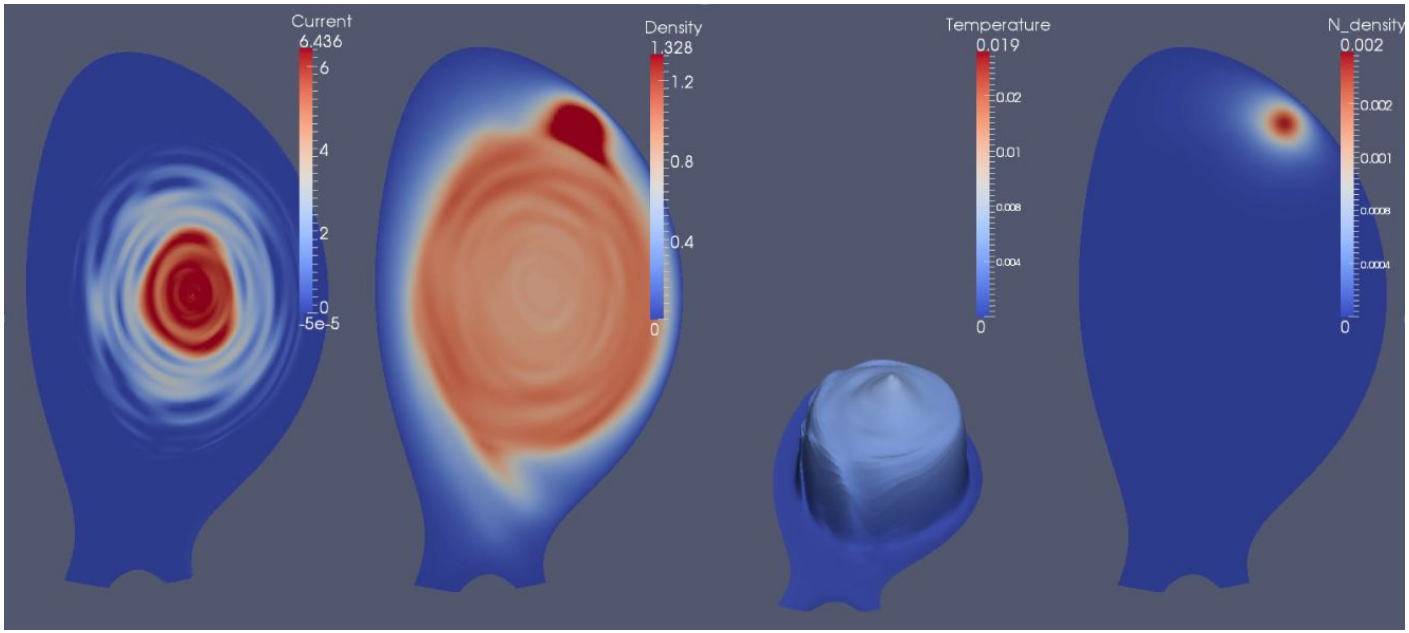

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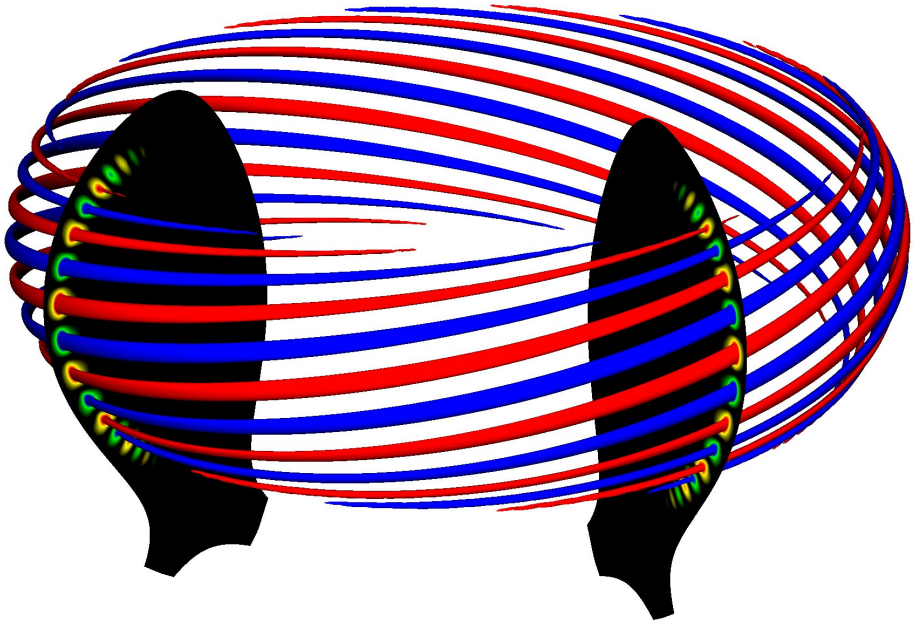
Localized ELMs

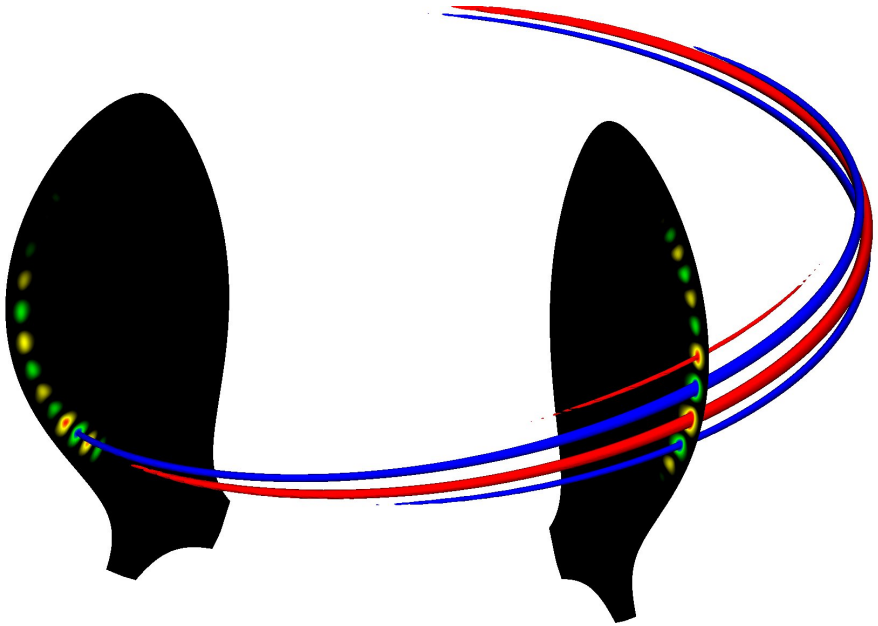


M. Hölzl, S. Günter, et al. *PoP*, 19, 082505 (2012)

- Poloidally and toroidally localized ELMs
- Similar to Solitary Magnetic Perturbations

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

Localized ELMs



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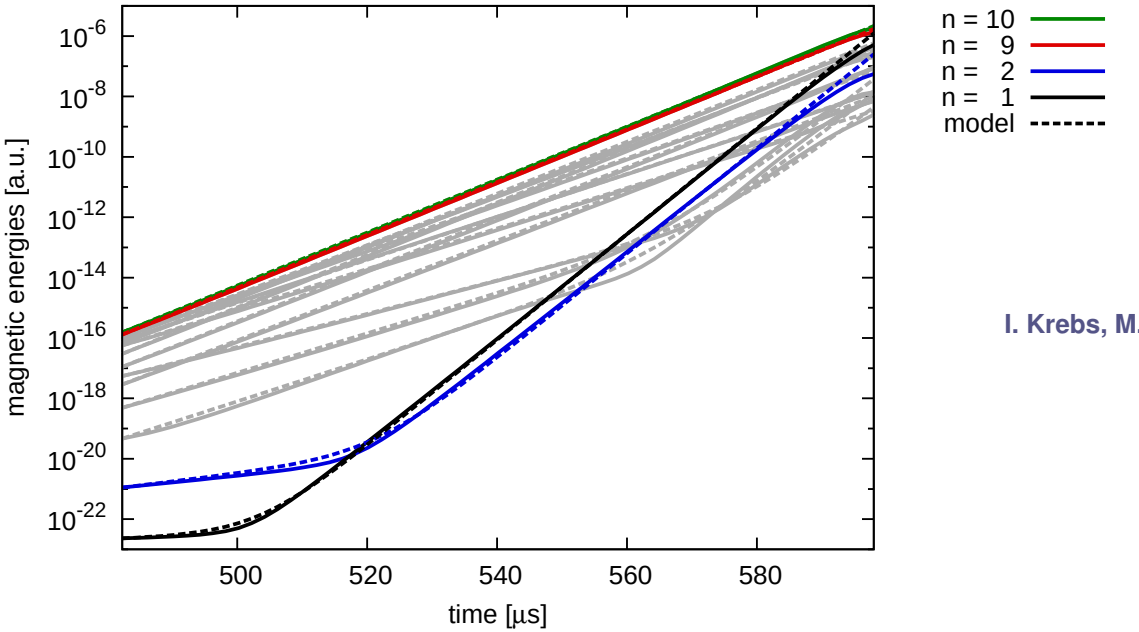
Selected Results Mode Coupling



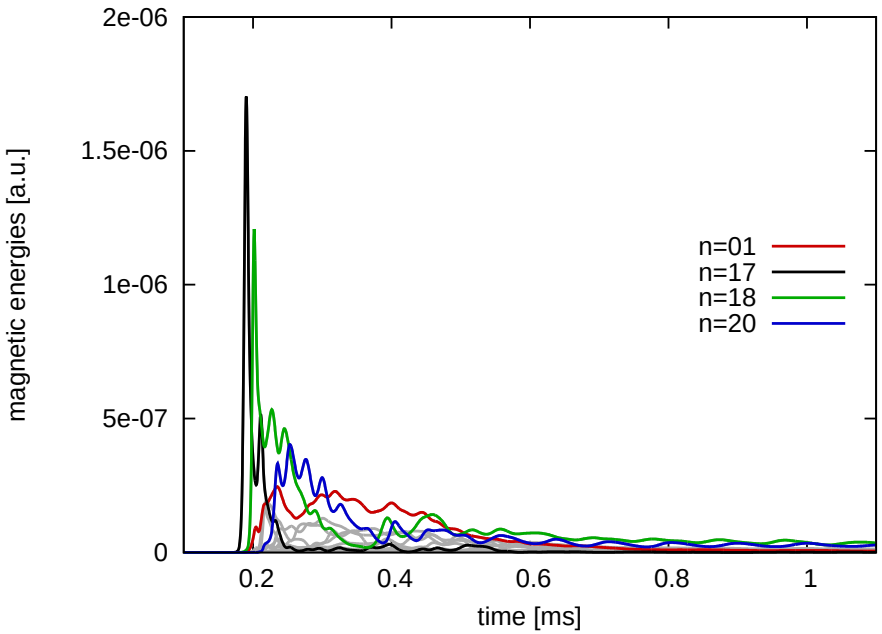
I. Krebs, M. Hölzl, K. Lackner, and S. Günter. *PoP*, 20, 082506 (2013)

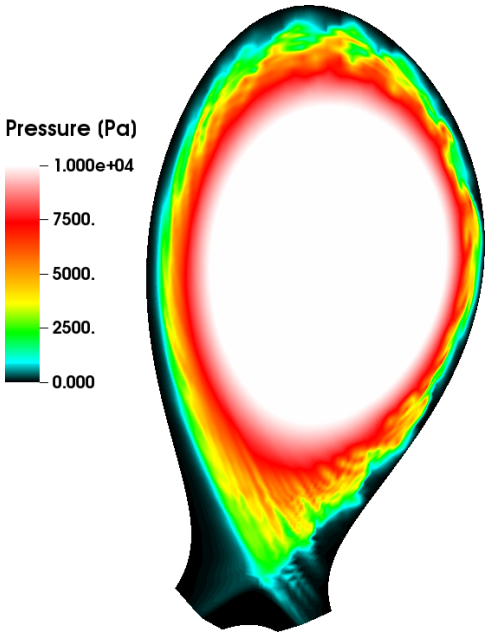
- Non-linear mode coupling: n_1 and n_2 drive $n_1 \pm n_2$
- Low-n harmonics driven to large amplitudes
- Broadening of the spectrum

- Similar to low-n observations on TCV

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

Selected Results — Full Crash



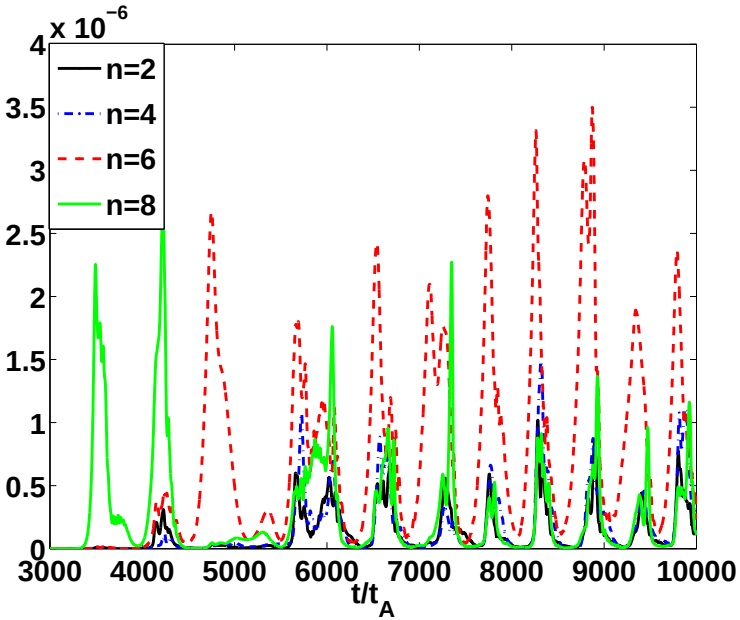


A. Lessig and M. Hölzl (unpublished)

- Based on AUG equilibrium
- Toroidal modes n=0...22
- High/medium-n most unstable, low-n driven
- Crash followed by ballooning turbulence which prevents pedestal build-up

- Diamagnetic drift required (also for RMPs)

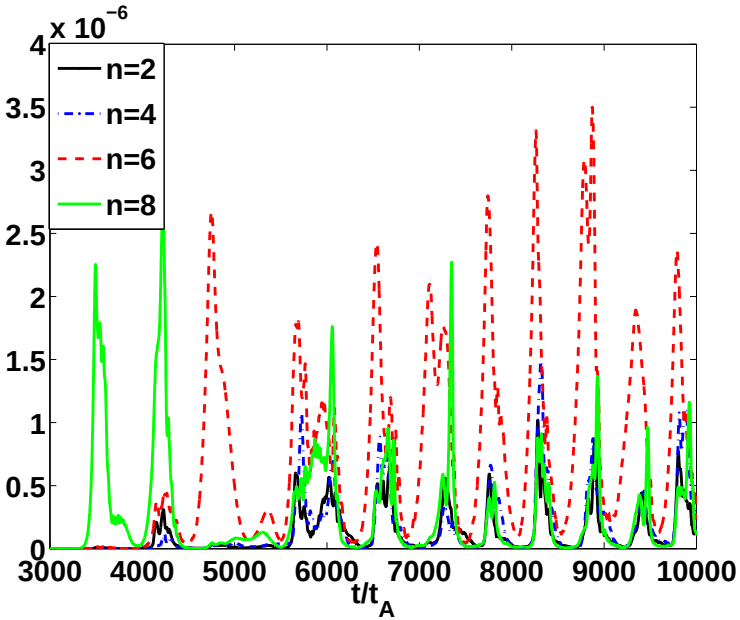
Selected Results ELM Cycle



F. Orain, M. Becoulet, et al. *PPCF* (accepted)

- Based on JET equilibrium
- Toroidal modes n=0,2,4,6,8
- Diamagnetic drift
- Periodic crashes

Selected Results ELM Cycle



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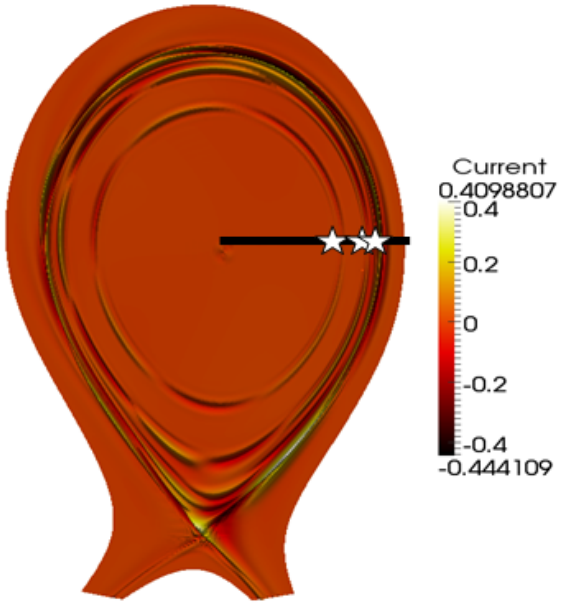
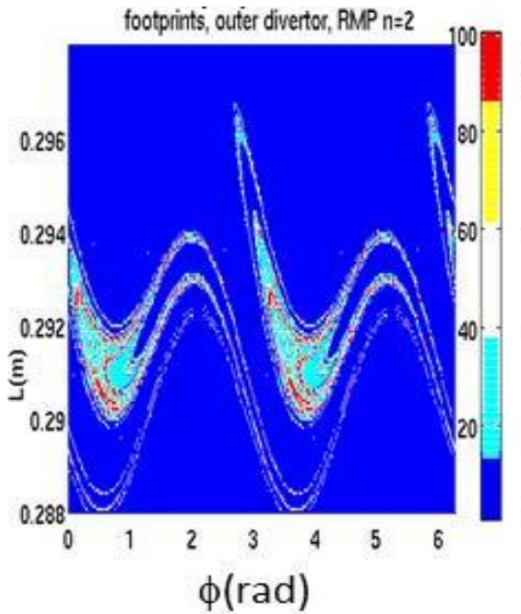
- Numerically complicated: $\propto \tau_{IC}/\rho$
- Progress with ASDEX Upgrade cases

Selected Results

Penetration

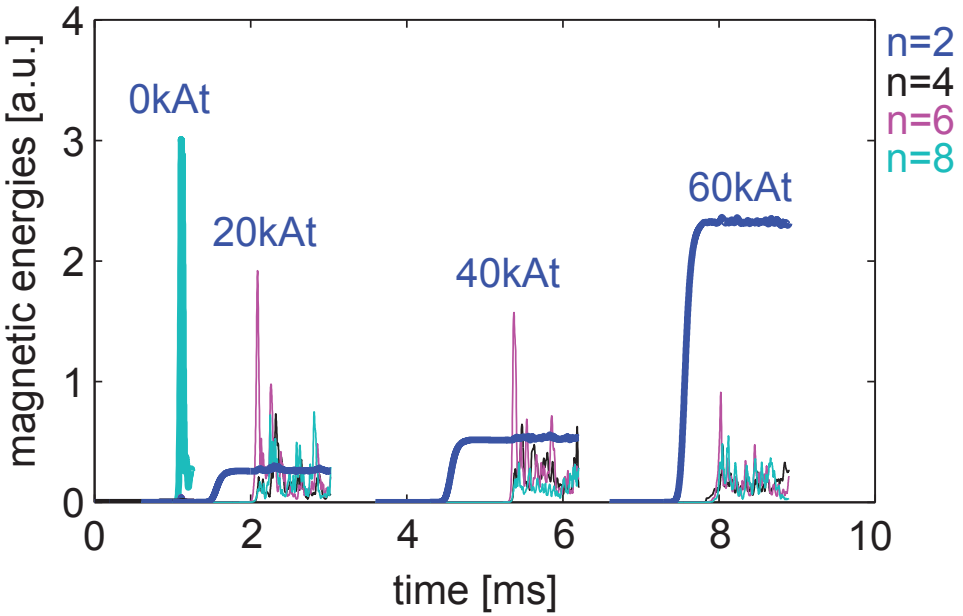




F. Orain, M. Becoulet, et al. *SFP Juelich* (2013)

- Based on JET equilibrium (pure n=2 field; fixed at boundary)
- Penetration: n=2 driven to large amplitude by external field
- Islands, edge ergodization, rotation braking, separatrix deformation
- Strike point splitting

Selected Results ELM-RMP Interaction



M. Bécoulet, F. Orain, et al. *PRL*, 113, 115001 (2014)

- Based on JET equilibrium (pure n=2 field)
- Mitigation like behaviour observed
- Strongly reduced heat loads

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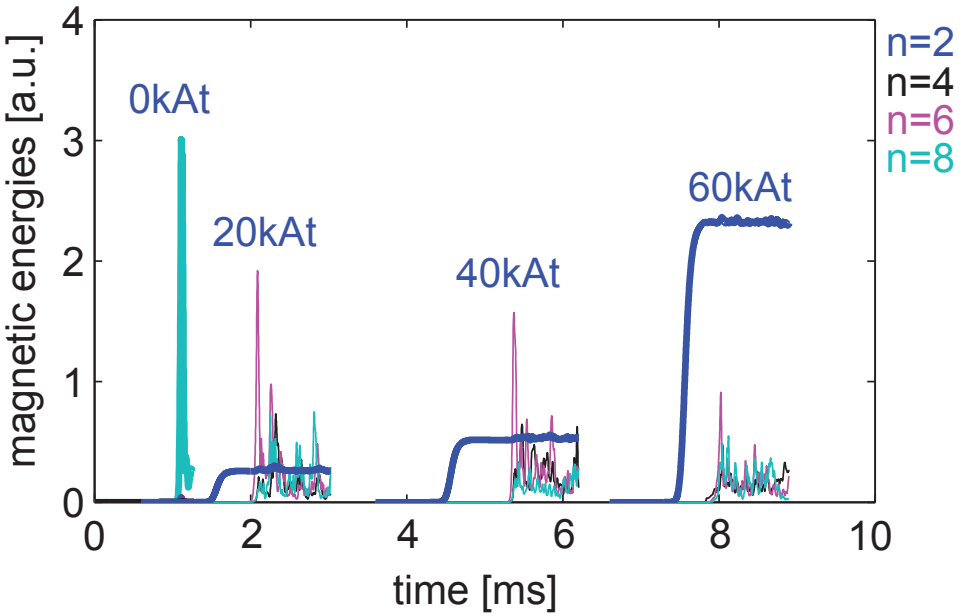

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- Not caused by reduced pressure gradient or 3D deformation
- Caused by non-linear mode coupling

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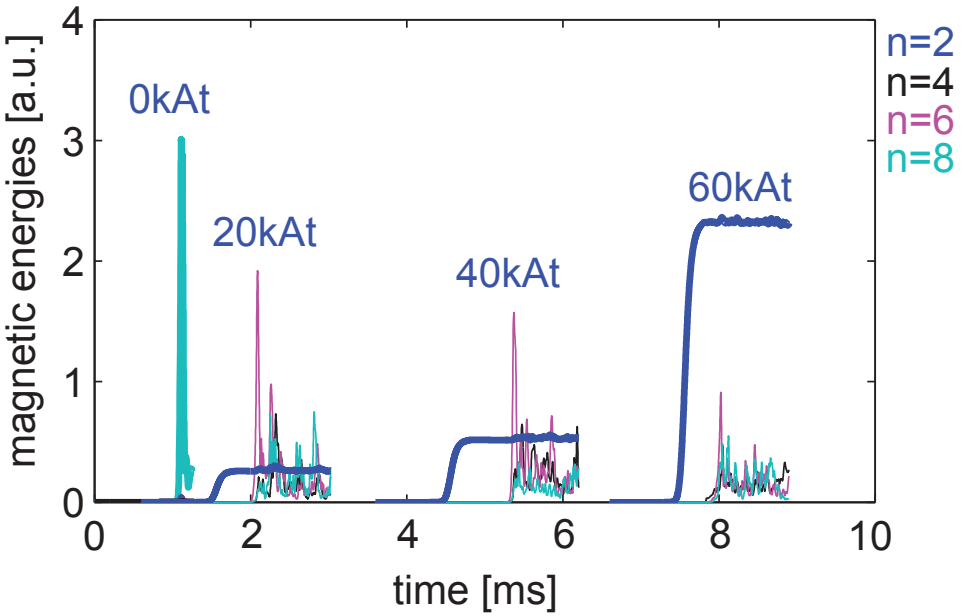

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- **Open:** Resistivity dependence, quantitative analysis in comparison with experiment, mitigation/suppression conditions, consistent amplification model, pump-out mechanism

Summary + Outlook

- JOREK: Non-linear MHD in realistic X-point geometry
- Increased resistivity due to computational costs
- ELM and disruption physics

- Poloidally/toroidally localized ELMs
- Low-n features due to non-linear mode coupling
- Full crash simulation for ASDEX Upgrade
- ELM cycle with diamagnetic drift
- RMP penetration
- ELM mitigation due to non-linear mode coupling

- Significant work ahead: Physics and numerics – ER 2015-2017

Summary + Outlook

- Comparison to experiment with ASDEX Upgrade Team and linear theory with E. Strumberger

- ELMs A. Lessig, M. Hoelzl, F. Orain
  - → ELM size and types
  - → Filaments
  - → Footprints
  - → Time scales
  - → Mode numbers
  - → Pedestal profile evolution

- RMPs and ELM-RMP interaction F. Orain, M. Hoelzl
  - → Deformation of flux surfaces/separatrix
  - → Influence on rotation, electric field
  - → Footprints and lobes
  - → Mitigation suppression conditions
  - → Kink/island response
  - → Field amplification
  - → Pump-out mechanism

References

M. Bécoulet, F. Orain, et al. *PRL*, 113, 115001 (2014).

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