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
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3 Summary + Outlook
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

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
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
Reduced MHD with diamagnetic, neoclassical and toroidal rotation
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Selected Results

Localized ELMs

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


Selected Results

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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


**Selected Results**

**Full Crash**

![Graph showing magnetic energies and time](image)

**A. Lessig and M. Hölzl (unpublished)**

- Based on AUG equilibrium
- Toroidal modes $n=0 \ldots 22$
- 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

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

F. Orain, M. Becoulet, et al. *PPCF* (accepted)
Based on JET equilibrium
Toroidal modes $n=0, 2, 4, 6, 8$
Diamagnetic drift
Periodic crashes

Numerically complicated: $\propto \frac{\tau_{IC}}{\rho}$
Progress with ASDEX Upgrade cases
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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
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Based on JET equilibrium (pure n=2 field)
Mitigation like behaviour observed
Strongly reduced heat loads
Based on JET equilibrium (pure n=2 field)
Mitigation like behaviour observed
Strongly reduced heat loads
Not caused by reduced pressure gradient or 3D deformation
Caused by non-linear mode coupling
Based on JET equilibrium (pure n=2 field)

- Mitigation like behaviour observed
- Strongly reduced heat loads
- Not caused by reduced pressure gradient or 3D deformation
- Caused by non-linear mode coupling

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


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