Non-linear MHD-Simulations of ELMs in ASDEX Upgrade

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Motivation

Edge Localized Modes (ELMs)

- Occur in high-confinement plasmas (H-mode)
- Simplest model: Peeling-Ballooning
- Remove impurities from plasma
- Produce large heat loads at wall and divertor-structures – critical for ITER

Simulations can improve physics understanding

- Linear: Stability-limits
e.g., Helena, . . .
- Non-linear: Filaments, heat-fluxes, mitigation
e.g., Jorek, Nimrod, Bout++, . . .
- Validate against existing machines
- Later predictive simulations
1 JOREK

2 ELM Simulations

3 Comparison to Experiment

4 Summary and Outlook
JOREK
Overview

• 3D non-linear MHD code for divertor tokamaks
• Originally developed by Guido Huysmans at CEA Cadarache
• Toroidal Fourier-decomposition
• 2D Bezier finite elements (3rd order Bernstein polynomials + C1-continuity)
• Fully implicit time-stepping (GMRES solver)
  • Physics-based preconditioner (Direct solver)
  • Comparably large time-steps
  • Large memory consumption
  • Limited scalability (MPI + OpenMP parallelized)
  • Future improvements?

• Standard model: Reduced MHD with toroidal corrections
  • Separate model: Some two-fluid extensions
  • Separate model: Neutrals
  • Full MHD in development
Reduced MHD Equations

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

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

\[ \rho \frac{\partial T}{\partial t} = -\rho v \cdot \nabla T - (\gamma - 1)p \nabla \cdot v + \nabla \cdot (K_\perp \nabla_\perp T + K_\parallel \nabla_\parallel T) + S_T \]

\[ e_\phi \cdot \nabla \times \left\{ \rho \frac{\partial v}{\partial t} = -\rho (v \cdot \nabla) v - \nabla p + j \times B + \mu \Delta v \right\} \]

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

\[ j_\phi = R^2 \nabla \cdot (R^{-2} \nabla \Psi) \]

\[ \omega = \nabla^2_{pol} u \]

\[ B = \frac{F_0}{R} e_\phi + \frac{1}{R} \nabla \Psi \times e_\phi \]

\[ v = -R \nabla u \times e_\phi + v_\parallel B \]

\[ p = \rho T \]

Ideal wall + Bohm boundary conditions
Typical code run

- Initial grid (Grids shown with reduced resolutions)
- Grad-Shafranov equation
- Flux aligned grid (No X-point, single-null, double-null)
- Grad-Shafranov equation
- Equilibrium refinement (Build-up of equilibrium flows)
- Time-integration
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Previous JOREK-Simulations (Selected examples)

- Pellet-triggering of ELMs (G. Huysmans)
- Influence of equilibrium flows on ELMs (S. Pamela)
- Disruptions (C. Reux)

This Talk

- Realistic ASDEX Upgrade geometry
- Early ELM phase
- Focus on high toroidal resolution
  - Describe mode-coupling realistically
  - But: Resistivity and viscosity unrealistically large
• Taken from AUG #23221@4.7s
• Only largest modes shown for clarity
• $n = 10$ most unstable (Uncertainties!)
• $n = 1$ gets large non-linearly
• Fourier-decomposition in straight-fieldline coordinates
• $n = 1$ and $n = 10$ shown
Radial perturbation positions differ
Mode-coupling causes localization of ballooning-filaments
ELM Simulations

Ballooning Structure

- Mode-coupling causes localization of ballooning-filaments
ELM Simulations
Poloidal Flux Perturbation

Periodicity 8 ($n = 0, 8, 16$)

- Magnetic field perturbation also localized due to mode-coupling
ELM Simulations

Poloidal Flux Perturbation

Periodicity 4 ($n = 0, 4, 8, 12, 16$)

- Magnetic field perturbation also localized due to mode-coupling
Periodicity 2 ($n = 0, 2, 4, \ldots, 16$)

- Magnetic field perturbation also localized due to mode-coupling
Periodicity 1 ($n = 0, 1, 2, \ldots, 16$)

- Magnetic field perturbation also localized due to mode-coupling
Magnetic perturbation at outboard midplane

Perturbation amplitude strongly varies toroidally
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Comparison to Experiment
Is our instability ELM-like?

- Compare to type-I ELMs in ASDEX Upgrade
- Dominant toroidal mode-number:
  - Simulations: $10 - 14$ (uncertainties!)
  - Mid-plane manipulator, visible-light imaging: $\approx 15$
    
  - ECE-Imaging: $18 \pm 4$
    
    J.E.Boom et.al., Nucl.Fusion, 51, 103039 (2011)

- Poloidal width of filaments (midplane):
  - Simulations: $10 - 12$ cm
  - Measurements: $5 - 10$ cm
    

- Radial velocity of filaments (midplane):
  - Simulations: Accelerate to $3$ km/s
  - Measurements: Typically $1$ km/s with $20\%$ faster than $2$ km/s
    
• “Solitary magnetic perturbation” at ELM onset [R.P. Wenninger et al, Nucl Fusion, submitted]
• Broad distribution of “solitariness”
• Direct comparison to be done
1 JOREK

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Summary

- Simulations of early ELM-phase
- High toroidal resolution
- Good agreement with type-I ELMs in ASDEX Upgrade
  - Toroidal mode-numbers
  - Poloidal filament-widths
  - Radial velocity
- Localization observed at high toroidal resolution
  - Compatible with solitary magnetic perturbations

⇒ ELM-like ✓ Now for a closer look...
Outlook

- **Continue ELM investigations** (with I. Krebs)
  - Full ELM-crash
  - Further comparisons to experiments (with R. Wenninger, J. Boom, ...)
  - Influence of sheared toroidal flow (with W.-C. Müller, see his talk)
  - Identify different ELM-types
  - Try ELM cycle

- **Resistive wall extension → RWMs, VDEs, ...**
  (with P. Merkel, G. Huysmans, E. Nardon, I. Chapman)

- **Try disruption simulations** (with G. Pautasso)
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