Resistive Wall Simulations with JOREK

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• Why?

• How do we couple?

• What is possible already?

• How to include Halo currents?

• What needs to be done technically?
Why?

- Time varying magnetic fields induce **eddy currents** in conducting structures

- Important if distance between resonant surface and wall is significantly smaller than the poloidal wave length

- This is often the case (however, sometimes an ideal wall is sufficient)

JOREK-STARWALL allows to study:

- *Plasma-wall interaction via eddy currents*
- *Instabilities without conducting walls*
Why?

During disruptions/VDEs, currents can flow from the plasma into the walls: **Halo currents**

- Mostly poloidal if axi-symmetric
- Asymmetries observed, especially $n=1$
- Large asymmetric forces
- Rotating (resonances!)
- Important constraints for disruption mitigation
How do we couple?

STARWALL:
- Thin wall approximation, triangles, divergence-free surface currents
- 3D wall with holes
- Greens functions

[P. Merkel, M. Sempf, 21st IAEA FEC (Chengdu, China) TH/P3-8 (2006)]
[P. Merkel, E. Strumberger, to be submitted]

JOREK:
- “Response matrices” calculated by STARWALL (unit perturbations):

\[
B_{tan} = \sum_i b_i \left( \sum_j M_{ij} \Psi_j + \sum_k N_{ik} Y_k \right)
\]

\[
\dot{Y}_k = -\frac{\eta}{d} P_{kk} Y_k - \sum_j Q_{kj} \dot{\Psi}_j
\]

- Boundary integral in current definition equation from partial integration: \(B_{\text{tan}}\) plugged in (natural boundary condition)

[M. Hoelzl, P. Merkel, G.Huijsmans et al., JPCS 401, 012010 (2012)]
What is possible already?

- **Resistive wall modes** – Benchmark in simplified geometry and initial cases for ITER-like plasma
  
What is possible already?

- **Vertical displacement events** (without Halo currents) – Benchmark with CEDRES++ in ITER-like geometry

What is possible already?

- Influence of wall onto MHD modes during **disruption**
  [A. Fil, E. Nardon, M. Hoelzl, et al., unpublished]
What is possible already?

- Influence of wall onto quiescent H-Mode
  [F. Liu, G.T.A. Huijsmans, et al., EPS (2014)]
How to include Halo currents?

A) Directly in JOREK (for first tests and as a benchmark)

- Full MHD model
- Add a grid region for the wall and solve there:
  \[
  \frac{\partial A}{\partial t} = -\eta \nabla \times \nabla \times A
  \]
- Set \( \delta \rho = \delta T = \delta u = 0 \) at the boundary
- Add vacuum region (directly or via response matrices):
  \[
  \nabla \times \nabla \times \delta A = 0
  \]
- Apply to 2D and 3D VDE ITER cases
- Hopefully finished this summer

[M. Hoelzl, K. Lackner, G. Huijsmans]
[ITER project on Halo currents]
How to include Halo currents?

B) In JOREK-STARWALL

Coupling condition: \( \nabla \cdot J_w = J_{JOREK} \cdot \hat{n}_w \)

But currently \( \nabla \cdot J_w = \nabla \cdot (\hat{n}_w \times \nabla \xi) = 0 \) in STARWALL

We have thought of three approaches for extending JOREK-STARWALL to halo currents:

1. New current component: \( J_w = \hat{n}_w \times \nabla \xi + \sigma d \nabla \Phi \)
2. “Halo current paths” between current entry points
3. Independent current potentials \( \xi \) for each triangle

[C. Atanasiu, P. Merkel, M. Hoelzl, K. Lackner, G. Huijsmans, E. Strumberger]
[ITER project on Halo currents]
How to include Halo currents?

We decided to compare approaches 1 (new current component) and 2 (current paths) for a simple test case and decide soon afterwards which approach to implement into STARWALL.

- Torus with a single hole
- Slits at $\theta$ and $\phi = 2\pi$
- Compare current at $\theta = \pi$
How to include Halo currents?

- Qualitatively reasonable
- Test cases probably different *(very recent)*
- Analytical test case considered as well
- Next: Select an approach

[P. Merkel, C. Atanasiu, M. Hoelzl, K. Lackner]
[ITER project on Halo currents]
What needs to be done technically?

Currently: Maximum of ~100,000 wall triangles
- STARWALL on large memory node with runtime ~one week!
- In JOREK, ~half of the memory is taken by response matrices!

Aim: 500,000 wall triangles
- STARWALL run takes ~1 day and costs ~1% of JOREK run
- Response matrices in JOREK <10% of memory

STARWALL currently not parallel (a few parts OpenMP)
- Distribute matrices and use parallel libraries (ScaLAPACK etc.)

Coupling terms in JOREK not parallel (a few parts OpenMP)
- MPI-parallel calculation of boundary integral and matrix storage
Summary

- Why?
  - Plasma-wall interaction via eddy currents
  - Simulations without conducting walls
  - Asymmetric rotating forces caused by Halo currents

- How do we couple?
  - Response matrices calculated by STARWALL (unit perturbations)
  - Natural boundary condition in JOREK

- What is possible already?
  - RWMs
  - VDEs
  - QH-Mode
  - Disruptions

- How to include Halo currents?
  - Axi-symmetric walls directly in JOREK
  - Different approaches currently analyzed for JOREK-STARWALL

- What needs to be done technically?
  - MPI parallelization of STARWALL and the coupling terms in JOREK