JOREK-STARWALL Developments

M. Hoelzl, C. Atanasiu, S. Mochalskyy, G. Huijsmans, R. Hatzky,
K. Lackner, L. Zakharov, E. Strumberger, F. Orain, J. Artola Such

1 Overview

2 Development Projects

3 Summary & Outlook

1. Overview
2. Development Projects
3. Summary & Outlook

Overview

- Ideal Wall boundary conditions not sufficient to describe Mode Locking, RWMs, VDEs, Halo Currents, . . .

- JOREK-STARWALL: Interaction of the plasma and 3D conducting structures – discretized by thin triangles

  P. Merkel and E. Strumberger. *arXiv*, 1508.04911 (2015); M. Hölzl, P. Merkel, G. Huysmans, E. Nardon, et al. *JPCS*, 401, 012010 (2012)

- RWMs **R. McAdams, I. Chapman, M. Hoelzl, G. Huijsmans, et al. *PPCF* (submitted)**
- VDEs **M. Hoelzl, G. Huijsmans, P. Merkel, C. Atanasiu, et al. *JPCS*, 561, 012011 (2014)**
- Disruptions **A. Fil, E. Nardon, M. Hoelzl, G. Huijsmans, et al. *PoP*, 22, 062509 (2015)**
- QH-Mode **F. Liu, G. Huijsmans, A. Loarte, A. Garofalo, et al. *NF*, 55, 113002 (2015)**

- RMP amplification **F. Orain, M. Hoelzl, et al**
- Vertical kick ELM triggering **J. Artola Such, G.T.A. Huijsmans, M. Hoelzl, et al**
- Halo currents during disruptions **J. Artola Such, G.T.A. Huijsmans, M. Hoelzl, C. Atanasiu, et al**

1. Overview
2. Development Projects
3. Summary & Outlook

Projects

- **Axisymmetric Walls in JOREK** → 6/2016
  – Benchmark Testbed for Halo Current Developments

  M. Hoelzl, et al

- **Consistent Coil Model within JOREK-STARWALL** → 2016
  – Vertical Kicks, Vertical Feedback, RMP Amplification

  J. Artola Such, F. Orain, M. Hoelzl, G. Huijsmans et al

- **Model Extension to Halo currents** → 2017
  – Non-axisymmetric Forces during Disruptions

  C. Atanasiu, M. Hoelzl, K. Lackner, L. Zakharov, G.T.A. Huijsmans, et al

- **MPI Parallelization of JOREK-STARWALL** → 2017
  – Higher Grid Resolution and more Wall Triangles

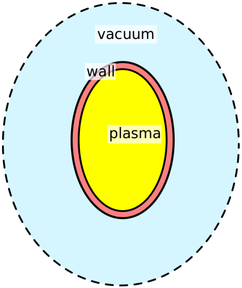
  S. Mochalskyy, M. Hoelzl, R. Hatzky

1. Overview

2. Development Projects
   - Axisymmetric Walls in JOREK
   - Consistent Coil Model with JOREK-STARWALL
   - Model Extension to Halo Currents
   - MPI Parallelization of JOREK-STARWALL

3. Summary & Outlook

Axisym. Walls



- Plasma Region (like now)
- Wall Region (inside JOREK)
- Vacuum Region (either inside JOREK or using STARWALL)

The same equation is solved for the poloidal flux as inside the plasma region, but with fluid velocities set to zero. Starting from

$$\begin{aligned}
\partial_t \mathbf{B} &= -\nabla \times \mathbf{E} \\
\mathbf{E} &= \underbrace{\mathbf{v} \times \mathbf{B}}_{\equiv 0} + \eta_w \mathbf{j} \\
\mathbf{j} &= \nabla \times \mathbf{B} \\
\mathbf{B} &= \frac{F_0}{R}\hat{e}_\phi + \frac{1}{R}\nabla\Psi \times \hat{e}_\phi ,
\end{aligned}$$

where η denotes the wall resistivity, and neglecting $\partial_{\phi\,\phi}\Psi$ we obtain the definition equation for the current and the time evolution equation for the poloidal flux:

$$\begin{aligned}
\partial_t \Psi &= \eta_w j \\
j &= \Delta^* \Psi
\end{aligned}$$

We assume Halo currents to be electrostatic. Thus, we solve $\nabla \cdot \mathbf{j} = 0$ with $\mathbf{j} = \sigma \cdot \nabla u$, where u is the electric potential and $\sigma = \eta^{-1}$ the electrical conductivity. So the equation to be solved is

$$\nabla \cdot (\sigma \, \nabla u) = 0$$

or in weak form

$$\int_\Omega \nabla \cdot (\sigma \, \nabla u) \, v^* \, dV = -\int_\Omega \sigma \, \nabla u \cdot \nabla v^* \, dV + \int_{\partial\Omega} \sigma \nabla u \cdot \hat{n} \, v^* \, dS = 0$$

Here, v^* denotes the test function. The boundary integral vanishes at the wall-vacuum interface, but *not* at the plasma-wall interface.

- Assumptions (at plasma-wall boundary):

$$\begin{aligned} \mathbf{j}_{||} &\approx \mathbf{j}_{\text{tor}} \\ |\nabla p\cdot\hat{e}_\phi| &\ll |\nabla p| \\ B_{\text{pol}} &\ll B_{\text{tor}} \\ \mathbf{j}_{\text{pol}}\times\mathbf{B}\approx\nabla p \quad &\Rightarrow \quad \mathbf{j}_{\text{pol}}\approx\frac{\mathbf{B}\times\nabla p}{B^2} \end{aligned}$$

- Poloidal current into the wall:

$$\mathbf{j}_{\text{pol}}\cdot\hat{n}\approx\frac{\nabla p\cdot(\hat{n}\times\mathbf{B}_{\text{tor}})}{B_{\text{tor}}^2}$$

- Parallel current into the wall:

$$\mathbf{j}_{||}\cdot\hat{n}\approx\frac{j_{\text{tor}}}{B}\,\mathbf{B}\cdot\hat{n}\approx\frac{j_{\text{tor}}}{B_{\text{tor}}}\,\mathbf{B}_{\text{pol}}\cdot\hat{n}$$

Plasma-Wall Boundary

$$
\begin{aligned}
\Psi_p &= \Psi_w \\
\mathbf{j}_p \cdot \hat{n} &= \mathbf{j}_w \cdot \hat{n} \\
u_p &= u_w
\end{aligned}
$$

Wall-Vacuum Boundary

$$
\begin{aligned}
\Psi_w &= \Psi_v \\
\mathbf{j}_w \cdot \hat{n} &= 0 \\
u_w &= 0
\end{aligned}
$$

- Variables inside the wall are Ψ, u, and j (other variables zero).
- E.g., the electric potential u is not C^1 continuous across the plasma-wall boundary. Thus, the wall needs to be a separate grid domain, i.e., the nodes at the plasma-wall interface must be duplicated and boundary conditions need to be implemented to connect the two domains.
- For the vacuum region it is possible to use STARWALL or implement an additional coarse grid region (solve simply $\Delta^*\Psi = 0$).

1. Overview
2. Development Projects
    - Axisymmetric Walls in JOREK
    - Consistent Coil Model with JOREK-STARWALL
    - Model Extension to Halo Currents
    - MPI Parallelization of JOREK-STARWALL
3. Summary & Outlook

Projects Coils

- Coils can be discretized by thin triangles just like the conducting wall
- This is largely prepared inside STARWALL already
- Coupling needs to be extended slightly (hopefully ready 6/2016)

1. Overview

2. Development Projects
    - Axisymmetric Walls in JOREK
    - Consistent Coil Model with JOREK-STARWALL
    - Model Extension to Halo Currents
    - MPI Parallelization of JOREK-STARWALL

3. Summary & Outlook

Projects Halo

- Surface current in STARWALL:

  $$\mathbf{j} = \nabla I \times \hat{n} \quad \text{– \textbf{\textit{divergence free!}}}$$

- Additional component required for Halo currents:

  $$\mathbf{j} = \nabla I \times \hat{n} + \sigma d \nabla \Phi$$

L. Zakharov, C. Atanasiu, K. Lackner, M. Hoelzl, and E. Strumberger. *JPlasmaPhys*, 81, 515810610 (2015)

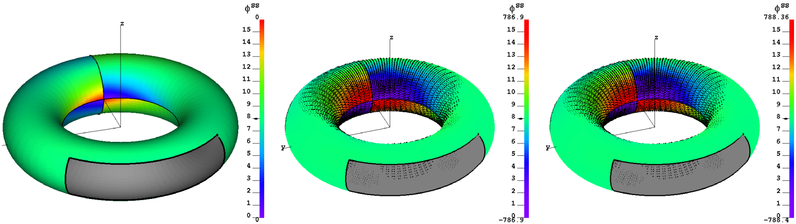
- The divergence of the surface current $\nabla \cdot \mathbf{j} = \nabla \cdot (\sigma d \nabla \Phi)$ is the source/sink of the surface currents, i.e., the currents flowing from the plasma into the wall (or from the wall into the plasma).

- The Halo current model has been implemented (into a separate code for the moment) using the STARWALL discretization of the wall (thin triangles).

C. Atanasiu et al

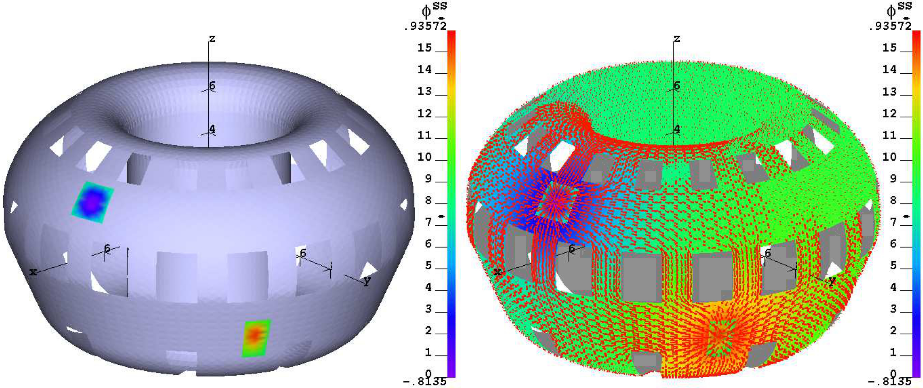
- It calculates a “response matrix” allowing to directly calculate the current distribution for a given source/sink distribution:

  $$\Phi_\alpha = \sum_\beta \hat{M}_{\alpha,\beta} \, (j_{\text{plasma}} \cdot \hat{n})_\beta$$



- ▹ Source/sink distribution; Numerical solution; Analytical solution
- ▹ Convergence:
  - 32x32 triangles: Error 0.015
  - 64x64 triangles: Error 0.003
  - 128x128 triangles: Error 0.001
- ▹ Numerically "cheap" compared to STARWALL – no far-distance interaction of all triangles with all triangles, i.e., sparse versus dense matrix problem

Example for ITER Wall



- Solution for prescribed source/sink distribution
- Non-uniform conductivity already working
- “Branching” structures should be possible soon
- Now we need to think about the coupling...

1. Overview

2. Development Projects
   - Axisymmetric Walls in JOREK
   - Consistent Coil Model with JOREK-STARWALL
   - Model Extension to Halo Currents
   - MPI Parallelization of JOREK-STARWALL

3. Summary & Outlook

▷ STARWALL:

- Only parts OpenMP parallelized

▷ JOREK:

- Coupling terms OpenMP parallelized
- Complete response matrices stored on each MPI task

⇒ Accessible problem size limited by memory consumption and execution time

▷ Required:

- MPI Parallelization of STARWALL → **this presentation**
- Parallelization of coupling terms and matrix storage in JOREK → **2017**

▷ Aim:

- “Production run” $\equiv$ 200k triangles for plasma and 500k triangles for wall
- Run STARWALL on Helios with < 100 compute nodes for < 24 hours

- Typical run possible so far is a factor 5-10 smaller than production size and uses 60 GB of memory and 24 hours of execution time.

- Production size run would require about 6 TB of memory and something of the order six months execution time…

- Largest matrices:
  - `dima` – ***Temporary matrix with non-local access pattern (2 TB)!***
  - `a_ww` – Largest response matrix (500 GB)

- Memory consumption of library calls comparable to response matrices

- Most time consuming: Lapack routine `dsygv` used for similarity transformation, but many other places important as well

- Large temporary matrices:
  - Replaced temporary matrices by scalars
  - Execution time for matrix construction ×2
  - Maximum memory consumption : 2

- Parallelize the whole code:
  - Replaced all Lapack calls by ScaLapack calls
  - This required a parallelization of all matrix construction routines as well

- Optimization and parallelization almost finished

- Successfully benchmarked against serial code

- Test run a few days ago (70% of aimed production size run):
  Execution time 7 hours on 64 Helios compute nodes

- Within the next weeks:
  - Output STARWALL response matrices
  - Document the implementation
  - Commit to repository

- Until 2017:
  - Distribution of matrices over compute nodes in JOREK
  - Parallelization of coupling terms
  - Parallel I/O

1 Overview

2 Development Projects

3 Summary & Outlook

Summary

- Implementation of axisymmetric wall for test purposes hopefully soon
- Implementation of consistent coils for RMP Amplification, Vertical Kicks, and Vertical Feedback hopefully soon
- Halo current model derived, implemented, and validated in separate code; Coupling will be started soon and should be ready 2017
- Parallelization of STARWALL implemented and validated; Parallelization of coupling terms in JOREK should be ready 2017

References

A. Fil, E. Nardon, M. Hoelzl, G. Huijsmans, et al. *PoP*, 22, 062509 (2015).

M. Hoelzl, G. Huijsmans, P. Merkel, C. Atanasiu, et al. *JPCS*, 561, 012011 (2014).

M. Hölzl, P. Merkel, G. Huysmans, E. Nardon, et al. *JPCS*, 401, 012010 (2012).

F. Liu, G. Huijsmans, A. Loarte, A. Garofalo, et al. *NF*, 55, 113002 (2015).

R. McAdams, I. Chapman, M. Hoelzl, G. Huijsmans, et al. *PPCF* (submitted).

P. Merkel and E. Strumberger. *arXiv*, 1508.04911 (2015).

L. Zakharov, C. Atanasiu, K. Lackner, M. Hoelzl, and E. Strumberger. *JPlasmaPhys*, 81, 515810610 (2015).