Non-linear Simulations of MHD Instabilities in Tokamaks Including Eddy Current Effects and Perspectives for the Extension to Halo Currents

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Abstract. The relevance of a resistive wall model is directly evident for Resistive Wall Modes (RWMs) or Vertical Displacement Events (VDEs). However, all large scale plasma instabilities may be influenced by the interaction with currents flowing in conducting vessel structures. Especially eddy currents and halo currents are important. With this in mind, the non-linear MHD code JOREK [1, 2] has been coupled [3] with the resistive wall code STARWALL [4], allowing to include eddy current effects in non-linear MHD simulations. We present benchmarks and first physics applications. The model will be extended to halo currents in the future.

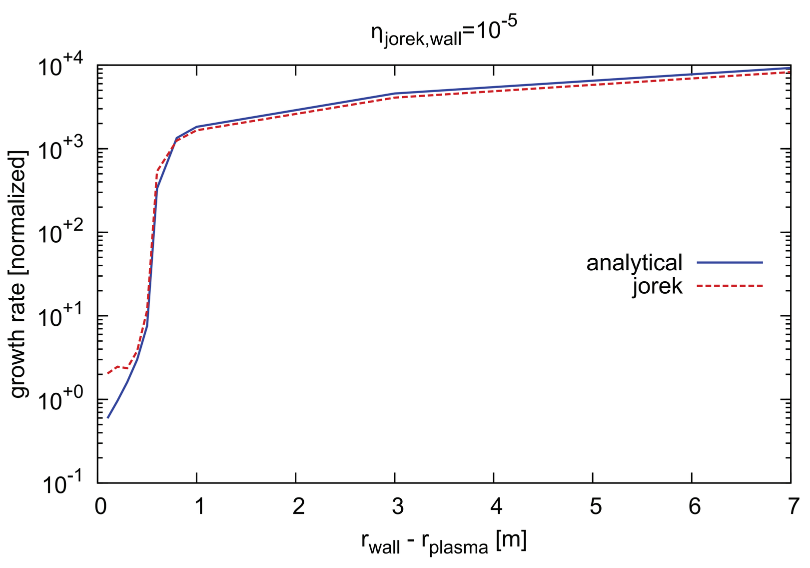
The non-linear MHD code JOREK [1,2] solves reduced MHD equations [5, 6] in realistic toroidal X-point geometry. Two-fluid extensions (diamagnetic drift, two temperatures) and a neutrals model exist. The full MHD model [7] is currently extended by divertor boundary conditions and two-fluid terms.

STARWALL is a resistive wall code [4, 8] capable of linear stability analysis of MHD modes in the presence of 3D resistive walls using the thin-wall approximation (see Poster P-31 by E. Strumberger for CASTOR-STARWALL coupling).

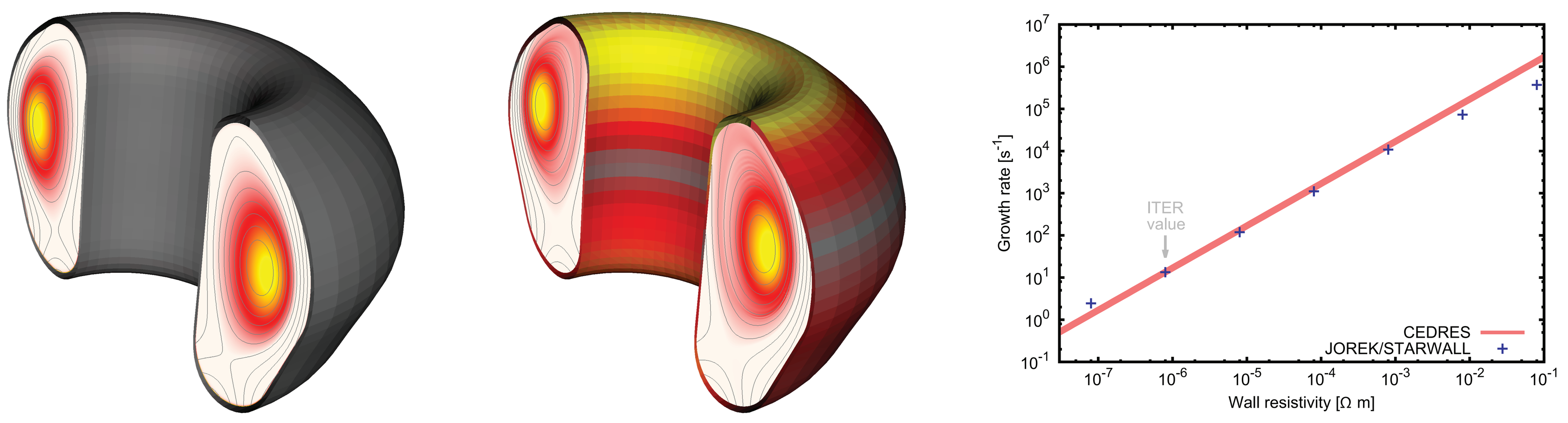
The coupled JOREK-STARWALL codes [3] solve the non-linear MHD equations including 3D resistive wall effects. The boundary of the JOREK computational domain is used as "interface". STARWALL solves the field equations outside the interface by a variational ansatz providing a wall current evolution equation (terms for induction and resistive decay). The tangential magnetic field at the interface calculated by STARWALL for all "unit perturbations" of poloidal flux and wall currents is used in JOREK to compute a natural boundary condition (surface integral in the current definition equation originating from partial integration). The implementation conserves full implicitness.

Extension to Halo Currents
Halo currents arising during a disruption event are a major concern for ITER due to rotating asymmetric forces on vessel structures. The JOREK-STARWALL code, however, currently assumes divergence free wall surface currents limiting it to eddy currents. The formulation will be extended to include halo currents which effectively are current sources or sinks for the wall currents.

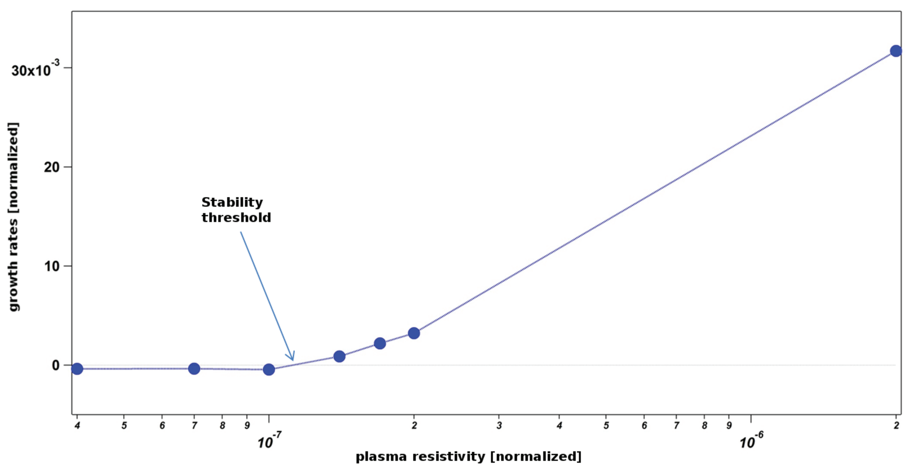
$$j_w = n \times \nabla\phi_w + \nabla\varphi_w$$



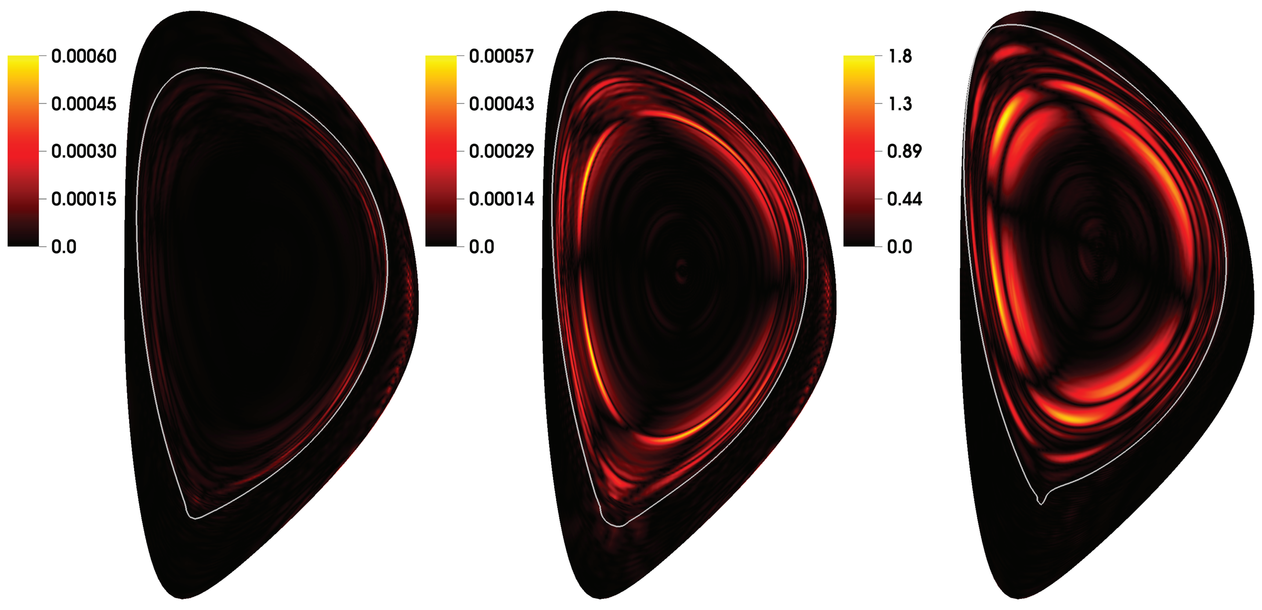
RWM benchmark [9]: Simulations in simplified geometry reproduce analytical predictions very well for different wall distances and resistivities. Cases with extremely small growth rates of the order 1 s^{-1} are hard to resolve.



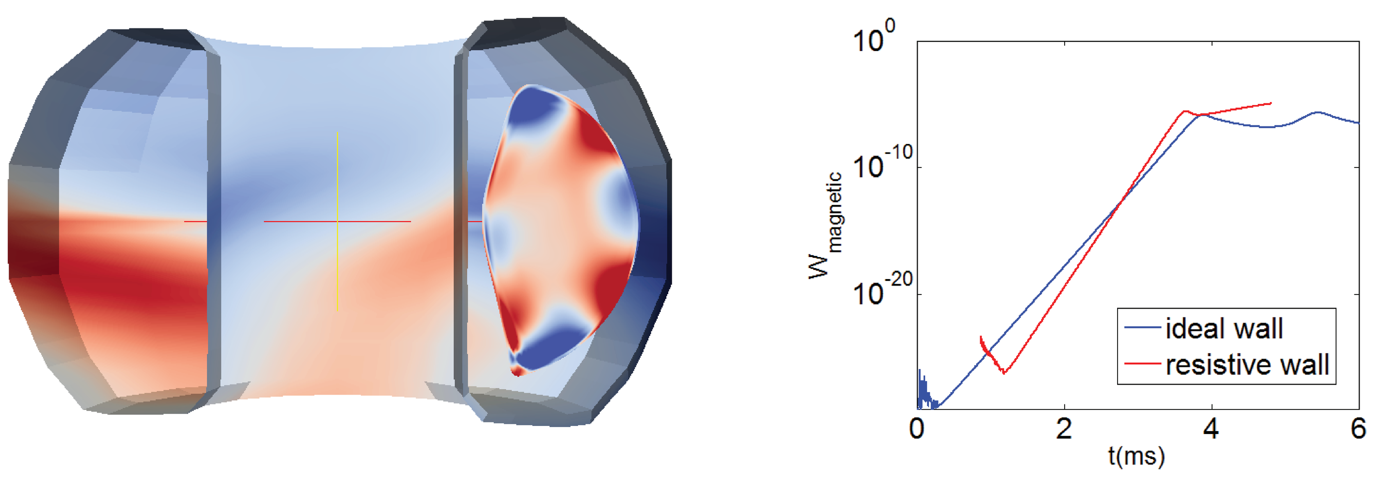
VDE Benchmark [11]: Simulations in ITER-like X-point geometry were carried out and benchmarked successfully versus the CEDRES++ code for different wall resistivities.



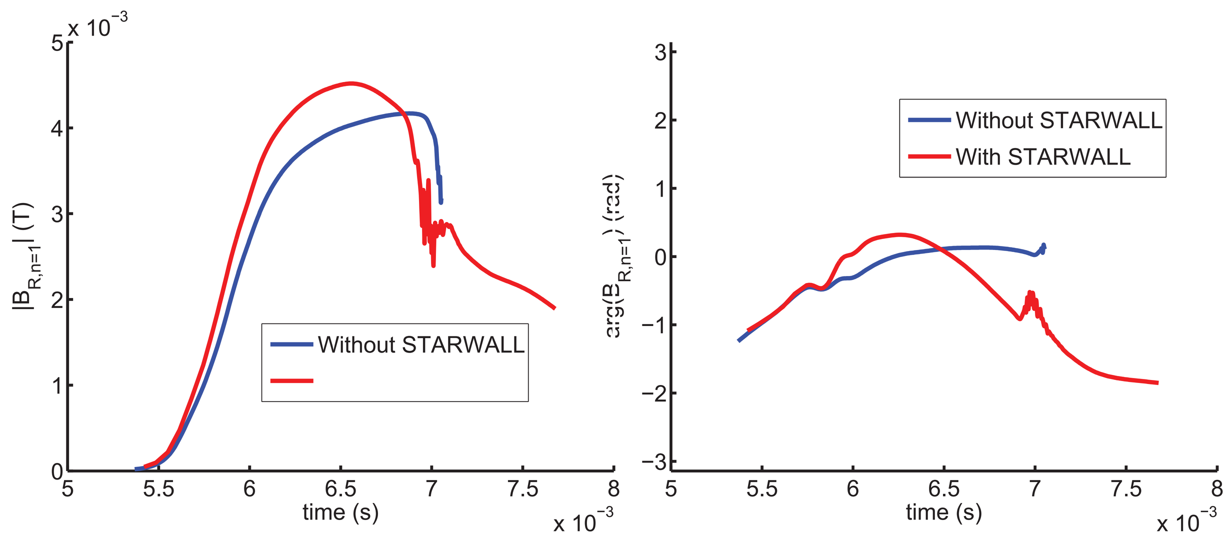
RWM simulations for a realistic ITER X-point case with different plasma wall distances and wall resistivities [10]: Below a certain threshold of the plasma resistivity, the RWM is fully stabilized.



VDEs in ITER [12]: The originally axi-symmetric instability develops an n=1 component (the n=1 component of the current density is plotted).



QH-mode plasma in DIII-D geometry [13]: With JOREK-STARWALL (resistive walls), growth rates and saturation levels are higher compared to ideal wall boundary conditions.



Disruption induced by massive gas injection in JET [14]: Resistive walls influence the time evolution and are important for mode locking, current quench, and VDEs.

Summary. Resistive wall effects play an important role for many large-scale plasma instabilities. JOREK-STARWALL aims at such simulations. Benchmarks against linear codes and analytical theory are presented as well as physics applications to RWMs, VDEs, QH-mode and disruptions. An outlook is given to the extension for halo currents. Together with separate developments, this will allow comprehensive non-linear simulations of disruptions.

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