TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTIONS FROM DARMSTADT TO NEXT GENERATION MAGNET FIELD SIMULATION TOOLS

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07.05.2025

MAGNET SIMULATION TOOLS

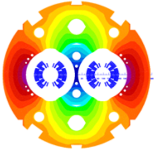
Commercial software

Opera Simulation Software

Ansys

COMSOL

STEAM framework



ROXIE

SIGMA (STEAM-COMSOL)

FiQuS

MAGNET SIMULATION

Components

- Magnetodynamic Maxwell equations
- Spatial discretisation (finite element method, integral methods)
- Static, in time or frequency domain
- Material models (e.g. fits for superconducting materials)
- Field-circuit couplings (external circuitry)
- Multiphysics couplings (thermodynamics, fluid dynamics, structural dynamics)
- Extraction of surrogate models
- Parameter studies, uncertainty quantification, optimisation

Challenges

- Large models, small time scales
- Complicated material behaviour (e.g. HTS)
- Multiphysics, variabilities
- Design cycles, simulation data management, knowledge management

Opportunities

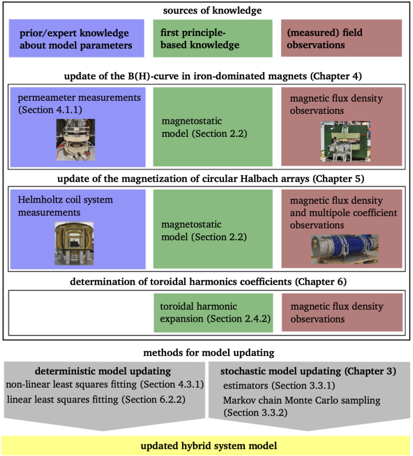
- Improved hardware (limited!)
- Improved algorithms
- Freeware software platforms
- Data-augmented models
- Multi-fidelity simulation

DIGITAL TWINS OF ACCELERATOR MAGNETS

- **Increase measurement precision using simulations**: M. Liebsch et al. used a boundary element model to project noisy and possibly faulty raw measurement data such that it fulfills Maxwell's equations
- **Update a simulation model using data**: L. Fleig et al. improved a finite element model based on old design specifications and nominal material data by new measurements and solving the Bayesian inverse problems, i.e., realizes the idea of **digital twin**.

[1] I.G. Ion, M. Liebsch, A. Simona, D. Loukrezis, C. Petrone, S. Russenschuck, H. De Gersem, and S. Schöps. *Local field reconstruction from rotating coil measurements in particle accelerator magnets*. Nucl. Instrum. Meth. A, 2021.

[2] L. Fleig, M. Liebsch, S. Russenschuck, and S. Schöps. *Combination of measurement data and domain knowledge for simulation of Halbach arrays with Bayesian inference*. IEEE Trans. Magn., 2023



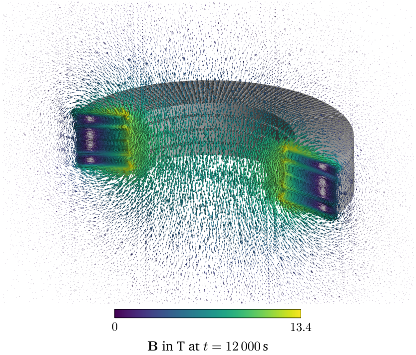
QUENCH PROTECTION

Investigate **quench (protection)** based on simulation.

- L. Bortot et al. developed a 2D quench simulator based on COMSOL and a coupling environment (STEAM) to simulate the surrounding circuit, control logic etc.
- E. Schnaubelt et al. replaced COMSOL workflow by a new 2D/3D open-source implementation (FIQUS) with thin shell models for tapes, contact resistance etc. It handles simulations of LTS, HTS and in particular NI coils.

[1] L. Bortot, B. Auchmann, I. Cortes Garcia, A. M. F. Navarro, M. Maciejewski, M. Mentink, M. Prioli, E. Ravaioli, S. Schöps, and A, Verweij. STEAM: a hierarchical co-simulation framework for superconducting accelerator magnet circuits. IEEE Trans. Appl. Super., 2018.

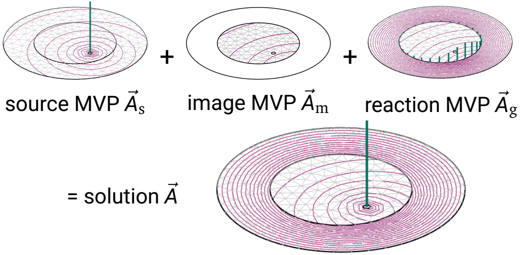
[2] E. Schnaubelt, S. Atalay, M. Wozniak, J. Dular, C. Geuzaine, N. Marsic, B. Vanderheyden, A. Verweij, and S. Schöps. Magneto-thermal thin shell approximation for 3d finite element analysis of no-insulation coils. IEEE Trans. Appl. Super., 2024.

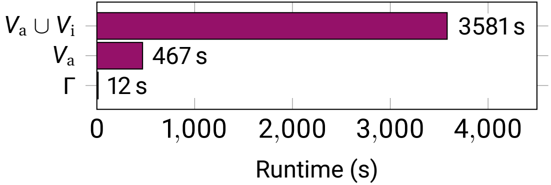


NI Pancake with 5.3 M DoF (4 x 250 turns).

NUMERICAL METHODS FOR HTS TAPES

Updated RMVP formulation

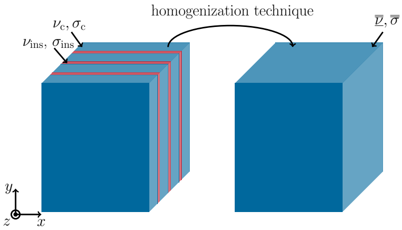


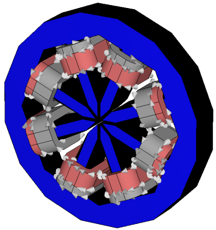


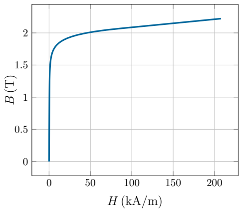
[1] L.A.M. D'Angelo, D. Moll, A. Vitrano, N. Marsic, E. Schnaubelt, M. Wozniak, H. De Gersem, B. Auchmann, Efficient reduced magnetic vector potential formulation for the magnetic field simulation of accelerator magnets. IEEE Trans. Magn. 60(3), 2024, doi: 10.1109/TMAG.2024.3352113.

ORBIT CORRECTOR MAGNETS (DESY)

Homogenized harmonic balance FEM





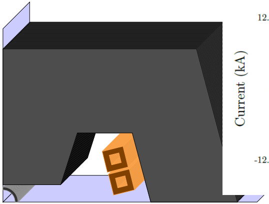


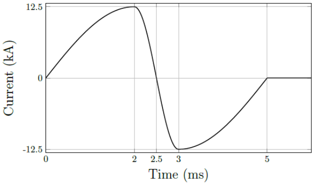
[1] J.M. Christmann, L.A.M. D'Angelo, H. De Gersem, A. Aloev, S.H. Mirza, S. Pfeiffer, H. Schlarb, M. Thede, Findings of simulation studies for the fast corrector magnets of PETRA IV. IPAC 2024, Nashville, Tennessee, USA, TUPR53, May 2024, doi: 10.18429/JACoW-IPAC2024-TUPR53.

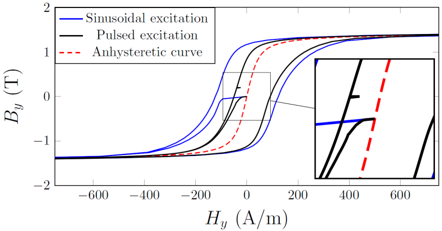
[2] J.M. Christmann, L.A.M. D'Angelo, H. De Gersem, S. Pfeiffer, S.H. Mirza, M. Thede, A. Aloev, H. Schlarb, Homogenized harmonic balance finite element method for nonlinear eddy current simulations of fast correct magnets. ArXiv 2503.19657, 2025, doi: 10.48550/arXiv.2503.19657.

FAST-RAMPED MUON COLLIDER MAGNET

Dynamic energy-based hysteresis model







[1] D. Moll, J.M. Christmann, L.A.M. D'Angelo, H. De Gersem, F. Boattini, L. Bottura, M. Breschi, Marco, Transient finite-element simulations of fast-ramping muon-collider magnets. IPAC 2024, Nashville, Tennessee, USA, TUPR54, May 2024, doi: 10.18429/JACoW-IPAC2024-TUPR54.

[2] E. Diehl, M. von Tresckow, L. Scholtissek, D. Loukrezis, N. Marsic, W.F.O. Müller, H. De Gersem, Quadrupole magnet design based on genetic multi-objective optimization, Electr. Eng. 106(2) 1179–1189, 2023, doi: 10.1007/s00202-023-02132-7.

CONCLUSIONS

- Progress in superconducting and normal-conducting magnet technology requires progress in magnet simulation (tools and algorithms)
- New algorithms exist and show promising results