Modelling Activities in TE-MPE-PE:
FE Models, Transients in SC Magnets, and Quench Protection

Julien Dular, on behalf of the TE-MPE-PE section members

CERN, Switzerland

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Contents

Contents

Quench of Superconducting Magnets

- **Quench: Loss of superconductivity leading to a thermal runaway.**
  - Violent process: high voltage, temperature, thermal and mechanical stress.
  - Dissipation of stored magnetic energy in the coolant (rapid boil-off).
- **Complex phenomenon:**
  - Multi-physics, -rate, and -scale problem.
  - Highly nonlinear process.
  - Local phenomenon → need for 3D models or clever 2D reduced order models.
- **Accurate and robust modelling tools are essential for magnet protection.**

- **Stored energy in each main dipole circuit of the LHC:**

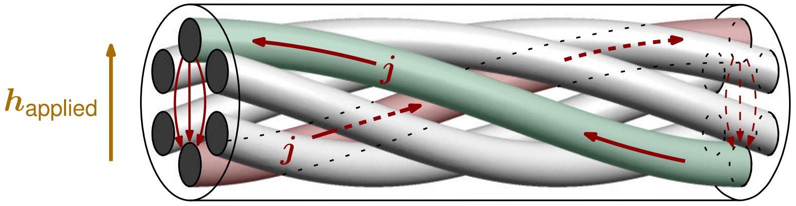
~ 1 GJ = 250 kg of TNT.

Quench in coil due to interturn short

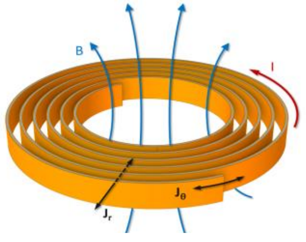
Ph. Lebrun, et al., “Report of the task force on the incident of 19th September 2008 at the LHC” . Technical report, CERN (2009), https://cds.cern.ch/record/1168025.

Modelling Challenges

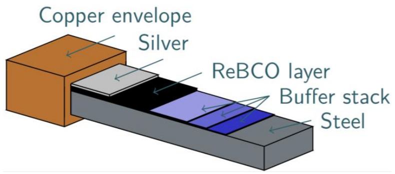
- Magnets are **multi-scale** structures.
- The **macroscopic** response depends on currents at **small scales**, which must be resolved **accurately**:
  - **Interfilament** coupling in LTS strands.
  - **Interstrand** coupling in LTS cables.
  - Current sharing in **multilayer** HTS tapes.
  - **Intertape** coupling in HTS coils.



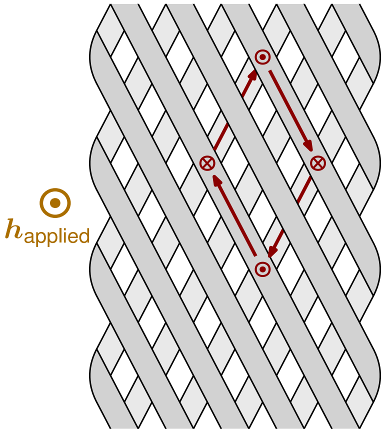
Interfilament coupling currents



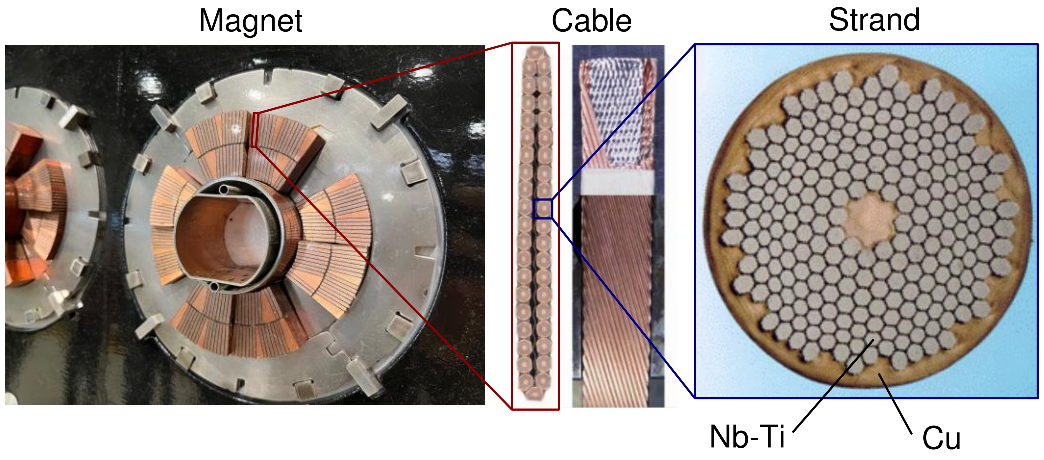
Intertape coupling currents [G. Vernassa]



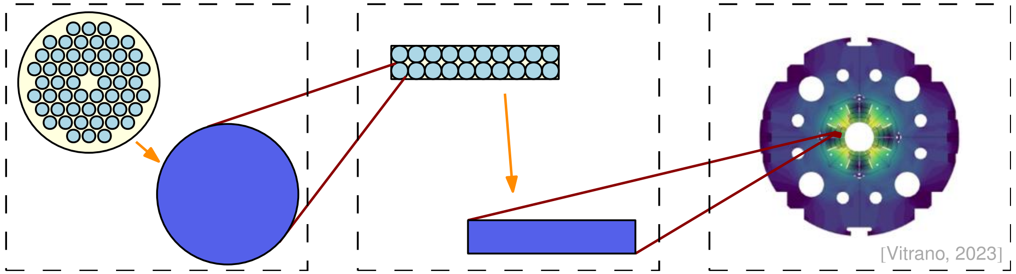
Multilayer HTS tapes [E. Schnaubelt]



Interstrand coupling currents



- Detailed magnet models are too **computationally expensive**.
- Need for efficient and reliable techniques:
  - Homogenization, reduced order modelling, parallelization, thin-shell approximations…



[Vitrano, 2023]

Simulation of Transient Effects in Accelerator superconducting Magnet circuits - STEAM

TRANSIENTS

- ✓ Energy extraction and quench-back
- ✓ Quench heater induced quench
- ✓ Fast current discharges (CLIQ)
- ✓ Electro-Magneto-Thermal(-Mechanical)
- ✓ Sensitivity studies
- ✓ Fault analysis
- ✓ Short circuit
- ✓ Electrical arc
- ✓ Frequency transfer measurement

MAGNET TYPES

- ✓ Cos-theta, Block-coil, Common coil
- ✓ Canted Cos-Theta (CCT), Curved CCT
- ✓ Solenoid, Pancake coils (Insulated, No-, Metallic-)

CIRCUIT TYPES

- ✓ Stand-alone magnets
- ✓ Nested circuits
- ✓ Series-connected magnets
- ✓ … for LHC, HiLumi, and future projects

CONDUCTOR TYPES

- ✓ Nb-Ti
- ✓ Nb_3Sn
- ✓ Bi-2212
- ✓ YBCO

LEVEL OF DETAIL

- ✓ Circuit → Magnet → Cable → Wire → Filament

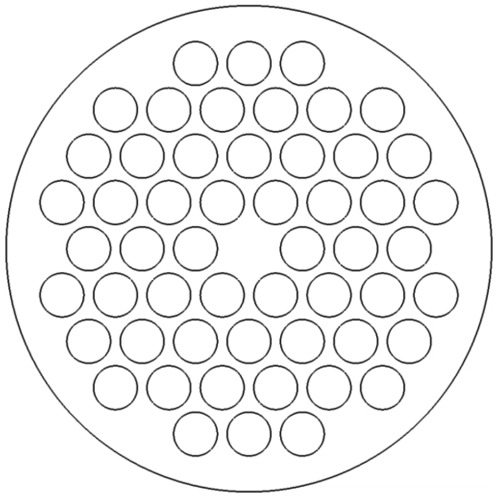
No single tool can do it all. Therefore, we have many tools connected by the framework.

Courtesy of Mariusz Wozniak, Emmanuele Ravaioli

Contents

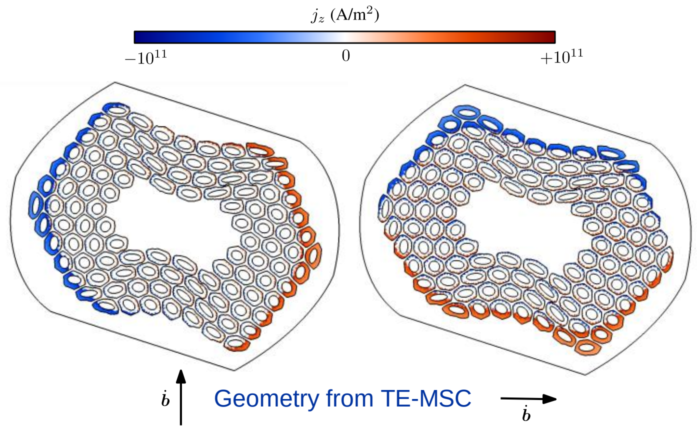
LTS Conductors – 2D FE Models

- **Phase 1 – Detailed 2D-based models**:
  - Transients in superconducting strands and Rutherford cables.
  - Coupled Axial and Transverse currents (**CATI**) method, 2D Finite Element (FE)

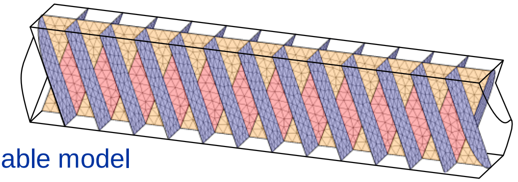


Multifilamentary strand

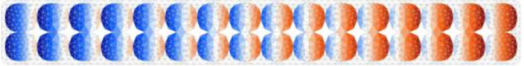
J. Dular et al. 2024 DOI: 10.1088/1361-6668/ad650d



Geometry from TE-MSC



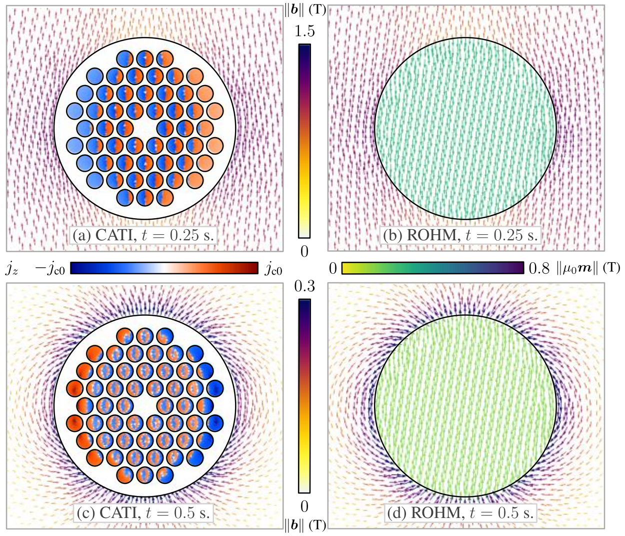
Rutherford cable model

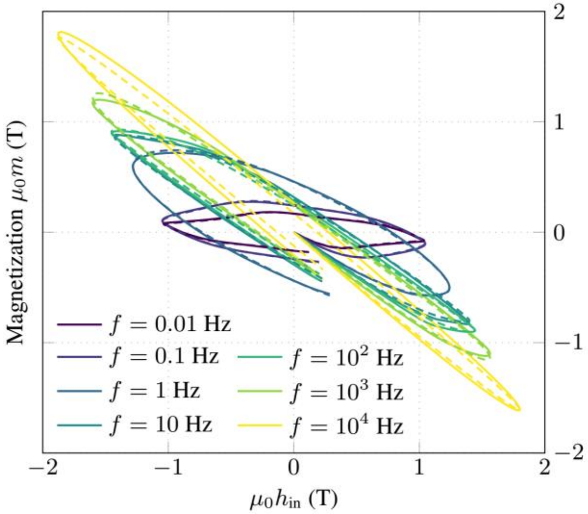


J. Dular et al. 2024
https://arxiv.org/abs/2411.13347

- **Phase 2 – Homogenized model:**
  - Reduced Order **Hysteretic** Magnetization (**ROHM**) model:
    - Describes **AC loss** and **magnetization**.
    - Includes **rate-dependent** effects.

J. Dular et al. 2024
https://arxiv.org/abs/2409.13653





Next steps:

- Transport current effect, HTS Conductors.

Courtesy of Fredrik Magnus, Alexander Glock and Mariusz Wozniak

LTS Magnet – 2D FE Model

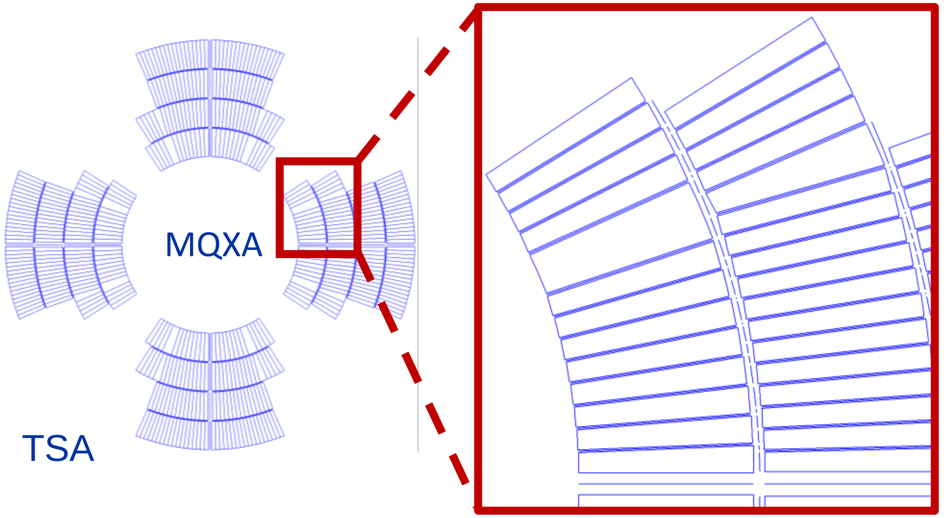
Coupled 2D FE magnetostatic and transient thermal models of LTS multipole magnets:

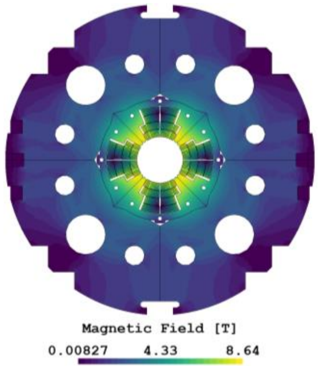
- Automated computation of geometry, mesh, and solution from ROXIE and text-based versioned files.

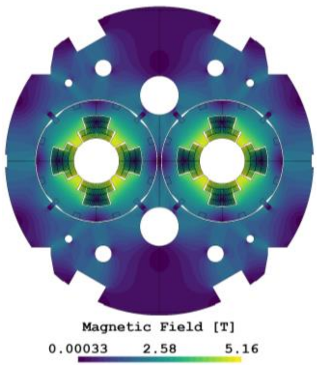
Thin shell approximations (TSA) to model thermal gradients across insulation layers:

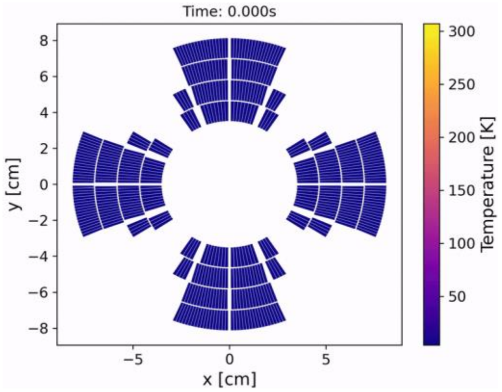
- Enables correct modelling of Quench Heaters (computationally prohibitive for classical FE).

E. Schnaubelt et al., SUST 2023, DOI 10.1088/1361-6668/acbeea









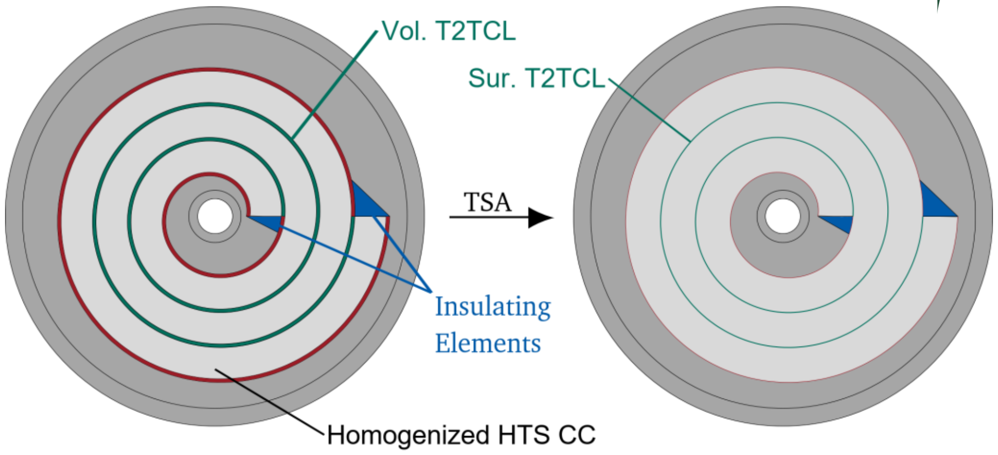
Next steps:

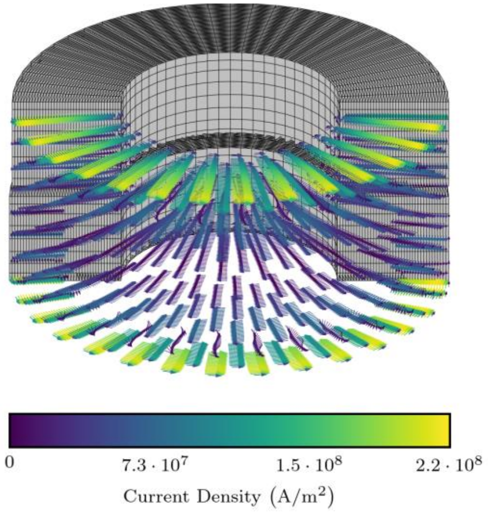
- Incorporate ROHM method for accurate AC loss modelling.
- Implement active quench detection and protection circuits for QH, EE, CLIQ, and ESC.
- Validate this model against experimental data.

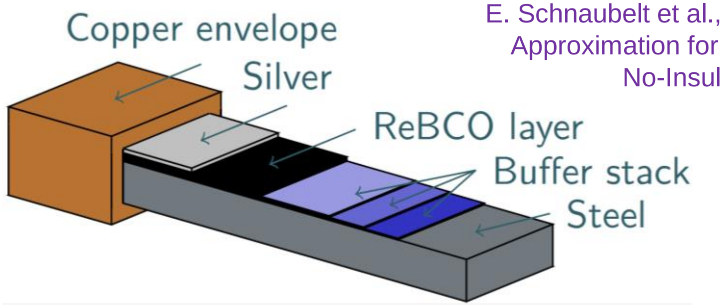
Courtesy of Erik Schnaubelt, Andrea Vitrano and Mariusz Wozniak

No Insulation HTS Coil – 3D FE Model

- **3D magneto-thermal** model in FiQuS/GetDP.
- **Homogenization** of the HTS coated conductor (CC):
  - Power law with angle dependency for HTS.
  - Anisotropic homogenization.
- Thin-Shell Approximation (**TSA**) for the turn-to-turn contact layer (T2TCL): both thermal and magnetic.
- **HPC** and **parallelization** efforts with benefits for all FiQuS models (parallelization in time, MPI with PETSc).

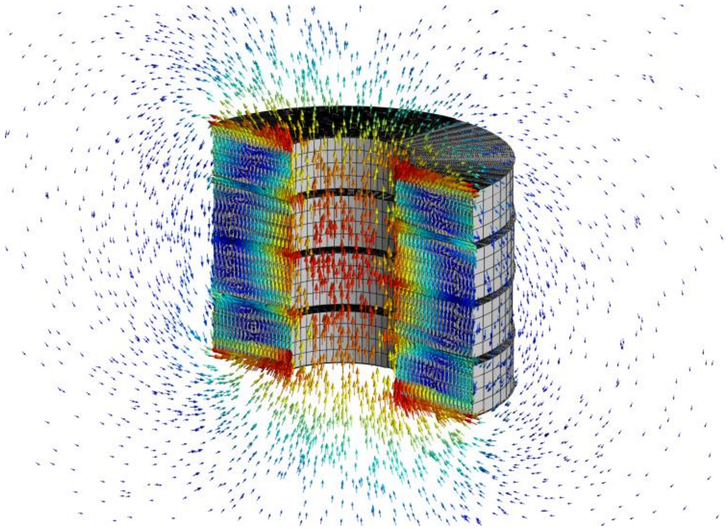






E. Schnaubelt et al., "Magneto-Thermal Thin Shell Approximation for 3D Finite Element Analysis of No-Insulation Coils," IEEE TAS (2024)

E. Schnaubelt et al., "Parallel-in-Time Integration of Transient Phenomena in No-Insulation Superconducting Coils Using Parareal", SCEE'24 proceedings

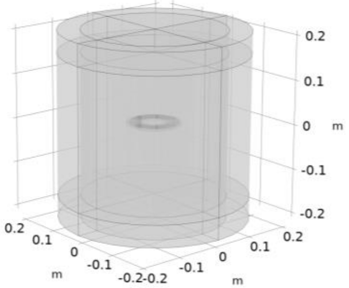


Courtesy of Erik Schnaubelt, Sina Atalay and Mariusz Wozniak

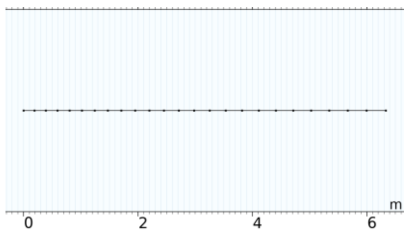
No Insulation HTS Coil – 3D+2D FE Model

COMSOL

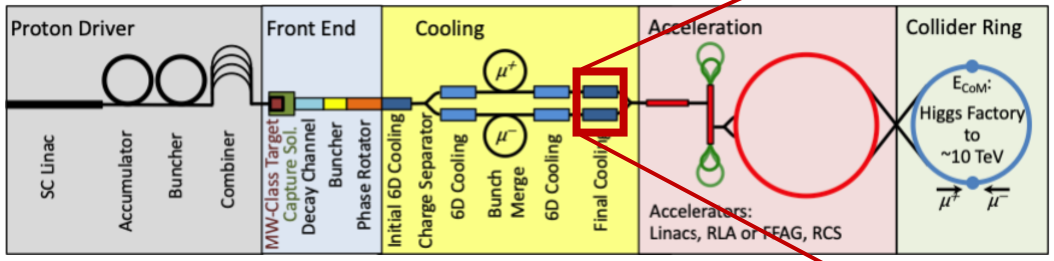
- Modelling of the **40 T Final Cooling Solenoid** of the Muon Collider.
- Iterative scheme: **3D FE** magnetic coupled with **1D+2D FD** electric.



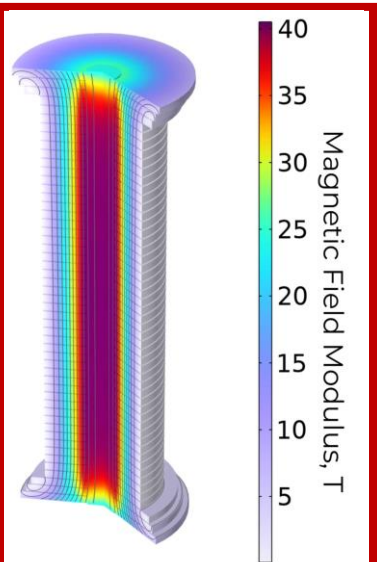
3D: Computes m.v.p. based on current density



1D/2D: Longitudinal, turn-to-turn and screening currents

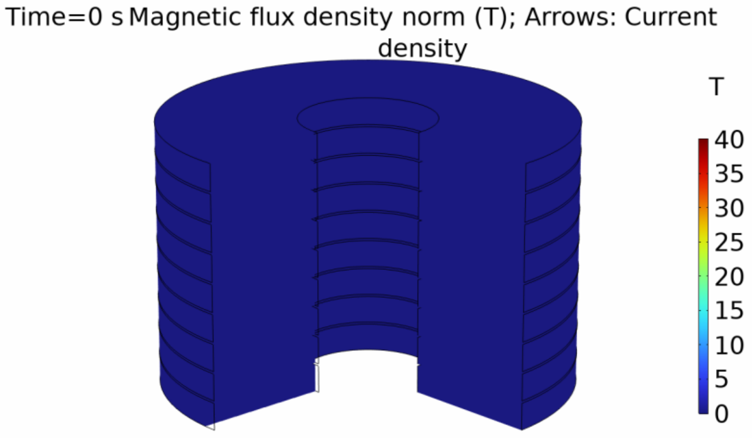


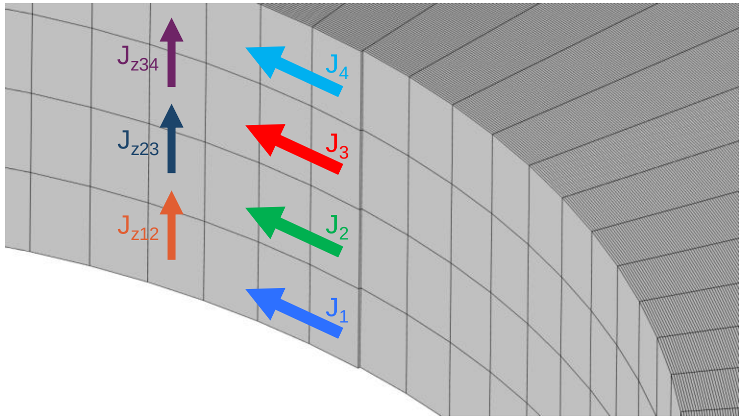
US Muon Accelerator Program



Bordini et al. (2024)

- Model in **Comsol Multiphysics**.
- Work in progress with the T-A homogeneous formulation.

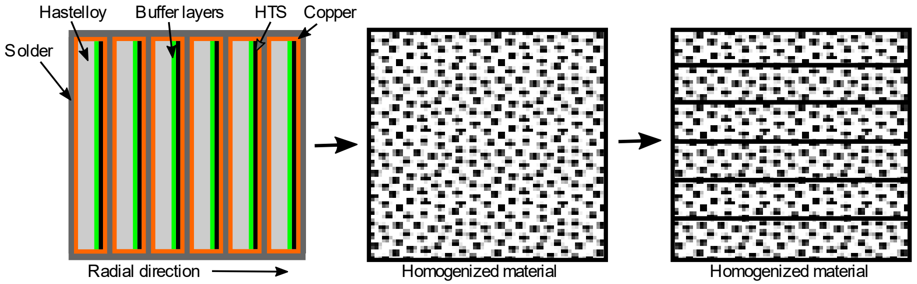


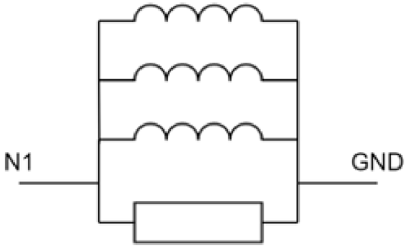


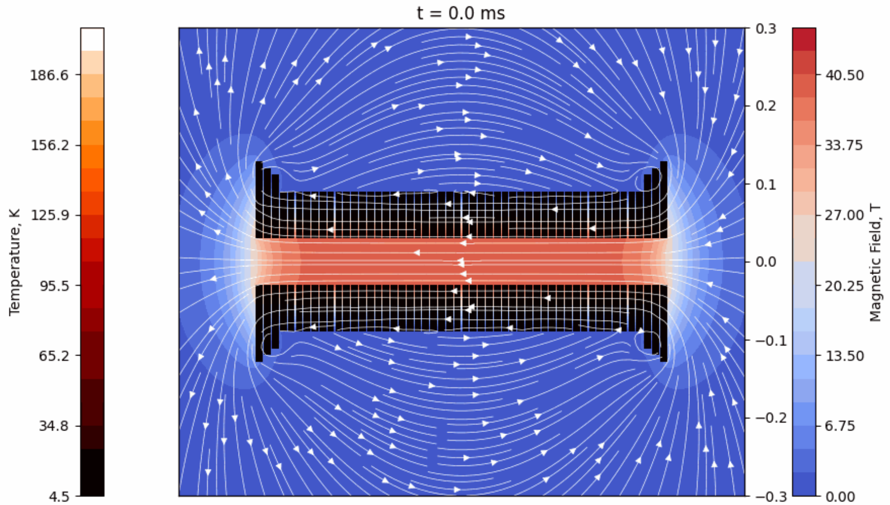
Courtesy of Davide Rinaldoni and Bernardo Bordini

No Insulation HTS Coil – 2D/3D Network Model

- **NICQS**: No Insulation Coil Quench Simulator
  - Network model (PEEC): finite difference solved with ODE solver.
  - Smart homogenization → ideal for solenoids with many turns.



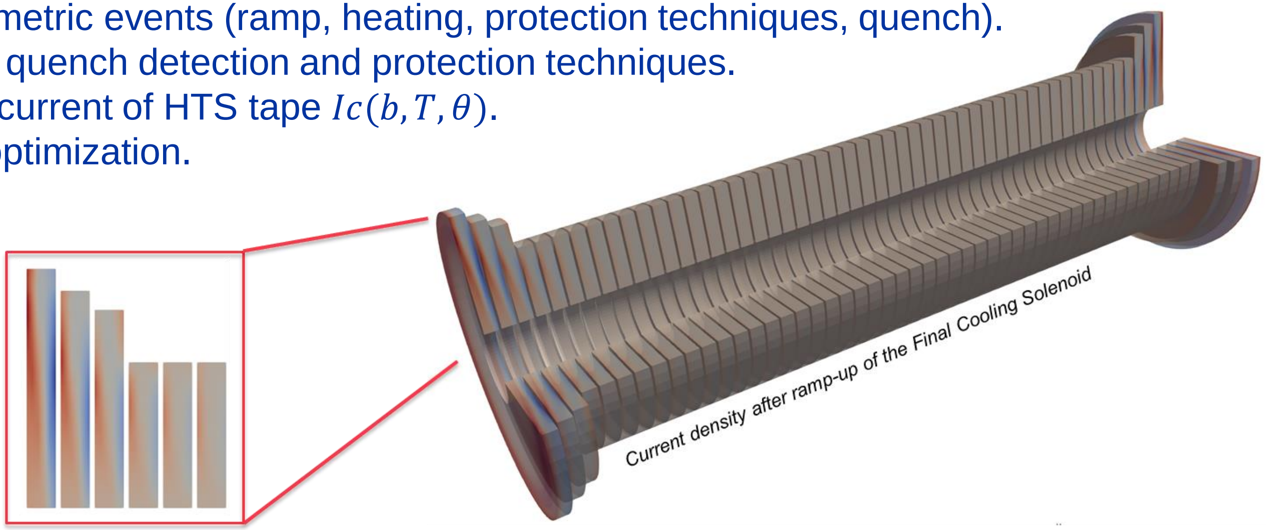




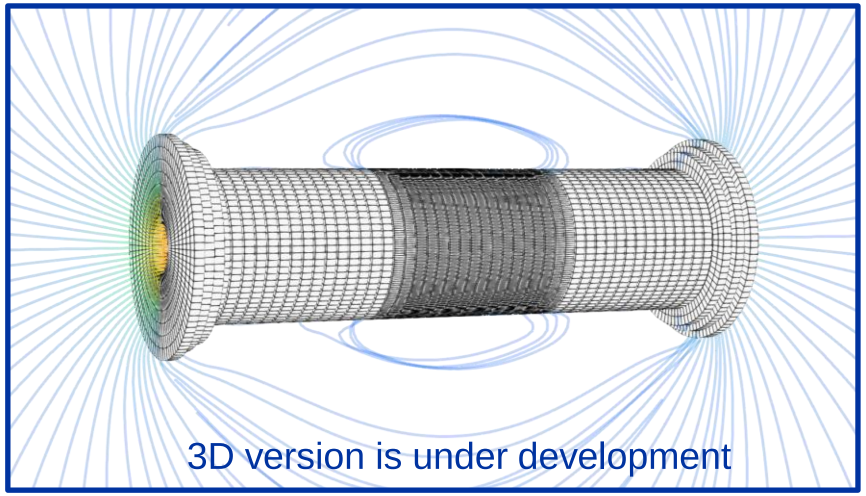
NICQS is being used as one of the design tools for a 40 T final cooling solenoid for a muon collider

Supports:

- Screening currents and eddy currents in coupled cylindrical normal conducting elements.
- Axisymmetric events (ramp, heating, protection techniques, quench).
- Various quench detection and protection techniques.
- Critical current of HTS tape $Ic(b,T,\theta)$.
- Ramp optimization.



Current density after ramp-up of the Final Cooling Solenoid



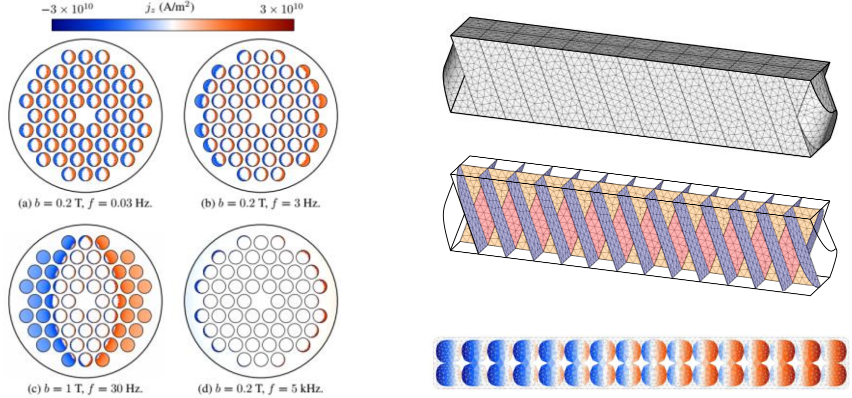
3D version is under development

Courtesy of Tim Mulder and Leon Teichrob

Contents

Finite element Quench Simulator

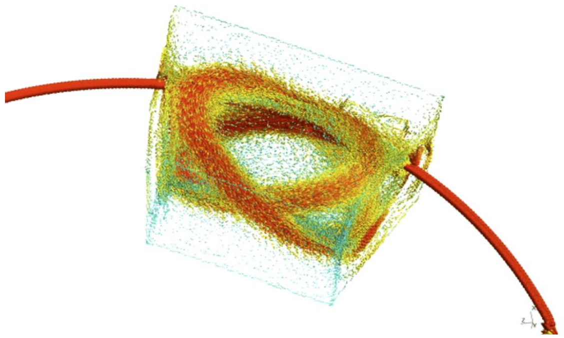
CATI method on strands and cables (2D)



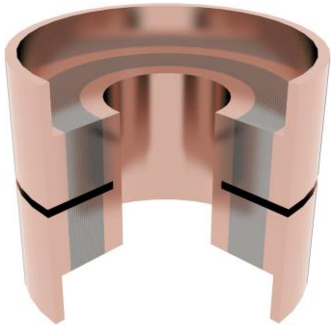
(a) $b = 0.2$ T, $f = 0.03$ Hz. (b) $b = 0.2$ T, $f = 3$ Hz.

(c) $b = 1$ T, $f = 30$ Hz. (d) $b = 0.2$ T, $f = 5$ kHz.

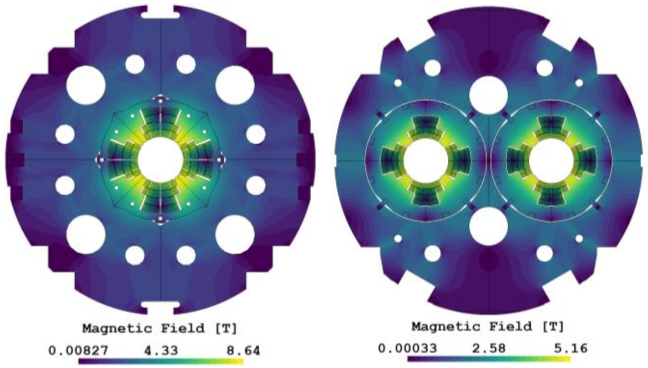
Curved CCT magnet (3D)



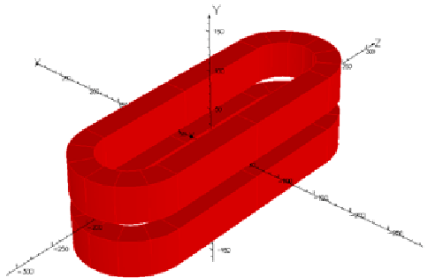
No-insulation HTS coil (3D)



Multipole models (2D)



HTS and LTS Racetrack coils (3D)

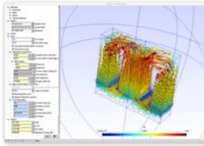


Developed in TE-MPE-PE

In STEAM framework

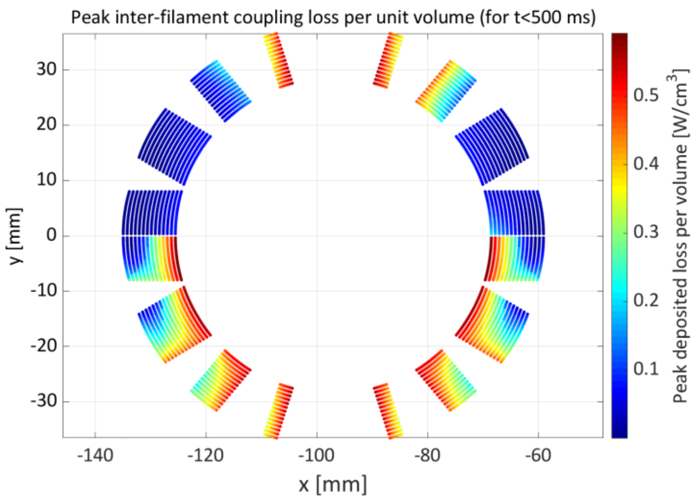
Coded in Python

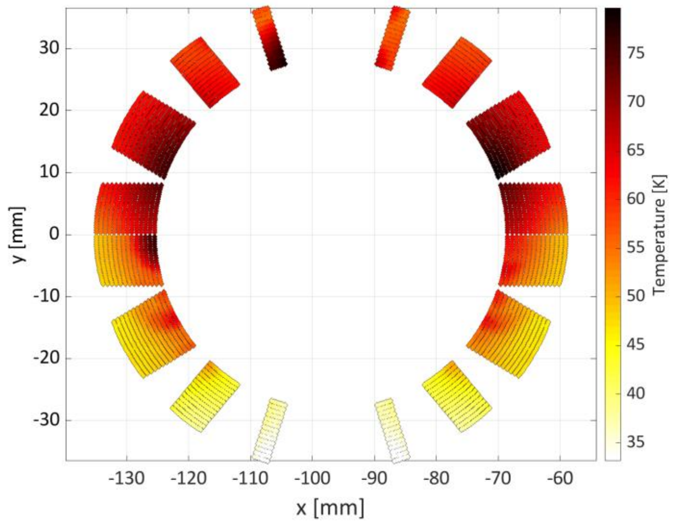
Based on **Gmsh** and **GetDP**

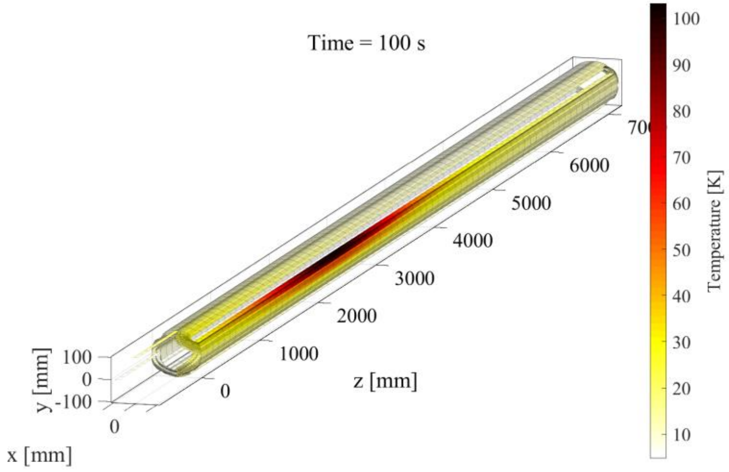


Lumped-Element Dynamic Electro-Thermal - LEDET

- Simulate electro-magnetic and thermal transients in superconducting magnets in **2D and 3D geometry** using the **Finite Difference (FD) method.**


Peak inter-filament coupling loss per unit volume (for t<500 ms)

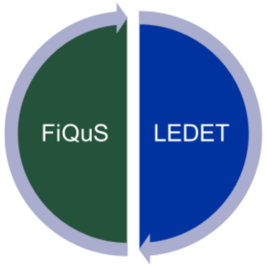


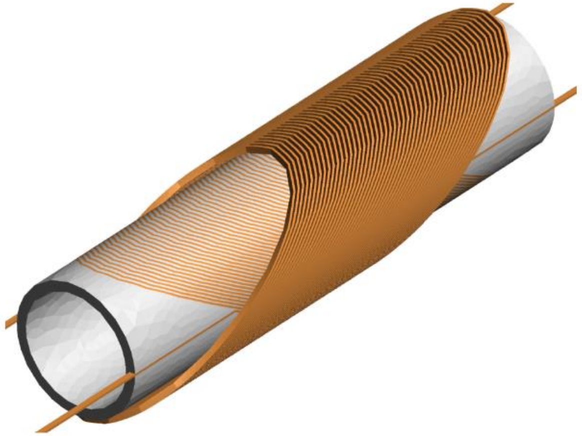


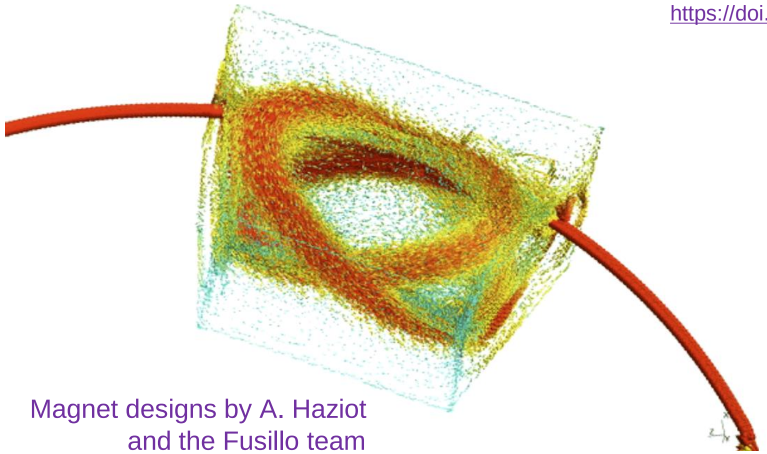
Courtesy of Emmanuele Ravaioli

FiQuS – LEDET Co-Simulation

- Co-simulation for Canted-Cos-Theta (CCT) magnets:
  - **FiQuS: 3D FE magneto-thermal** model with homogenized conductors, for eddy currents in formers and shell.
    - **Thin-shell** insulations between windings, formers and shell for efficient simulations and simplified meshing.
  - **LEDET:** finite difference for currents, loss, and temperature in windings.



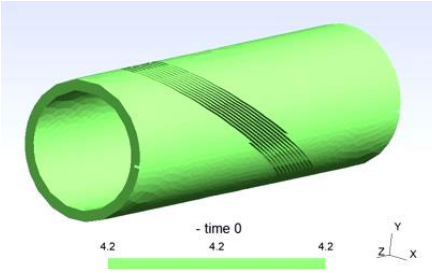


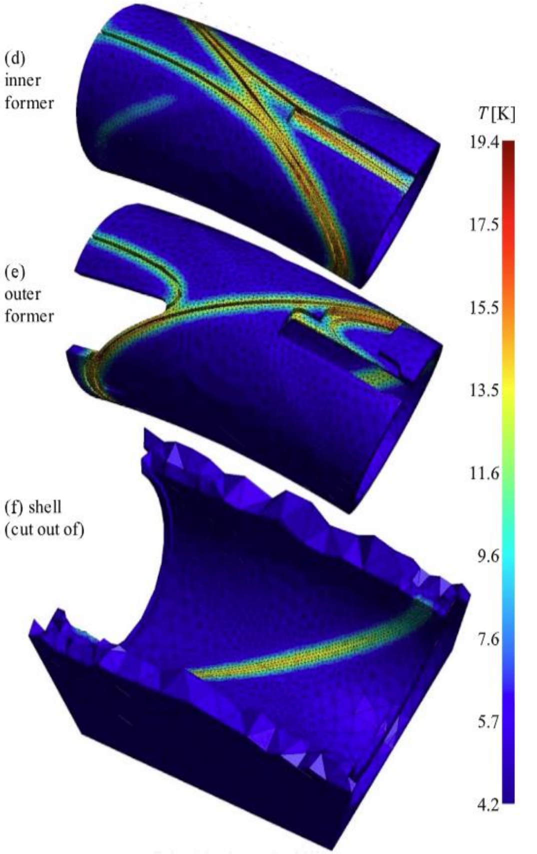


Magnet designs by A. Haziot and the Fusillo team

More details:
https://doi.org/10.1109/TASC.2023.3338142
https://doi.org/10.1109/TASC.2024.3355358

Temperature of former



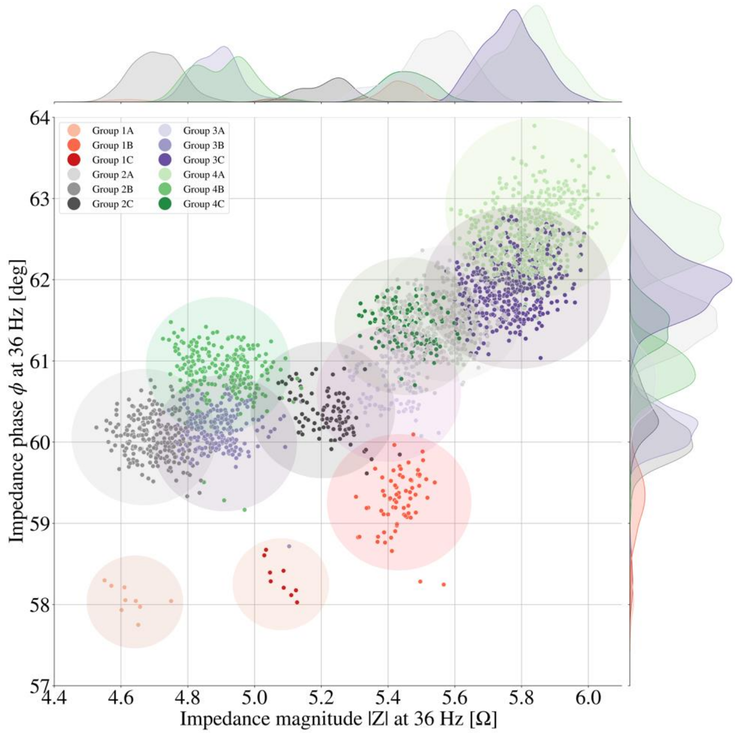


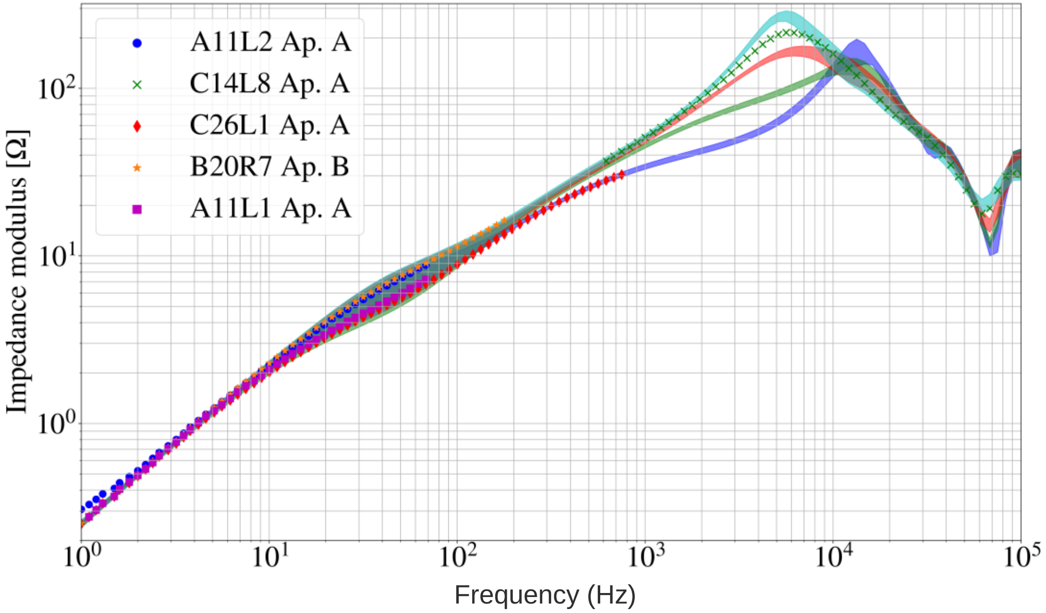
M. Wozniak et al., "Quench Co-Simulation of Canted Cos-Theta Magnets," IEEE TAS (2023)

Courtesy of Mariusz Wozniak, Emmanuele Ravaioli and Erik Schnaubelt

Dipole Magnets Impedance Model

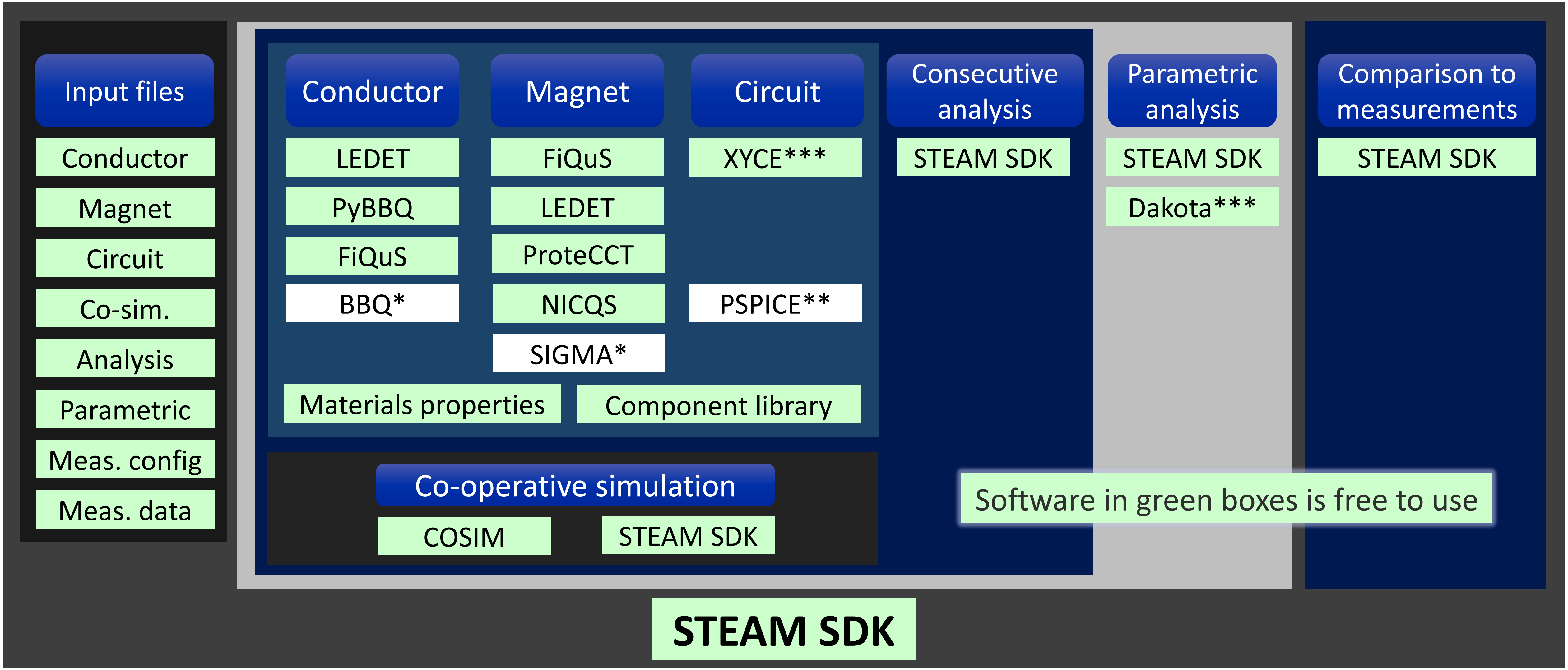
- Transfer Function Measurements (**TFM**) on all **1232 dipole magnets** of the LHC.
- Model to reproduce impedances based on FE, analytical models, and circuit equations.
- Average **error below 5 %** up to 10 kHz.
- Identification of **outlier magnets**.





Courtesy of Marvin Janitschke, Emmanuele Ravaioli and Valentina Reynaud

The STEAM framework



Input files
- Conductor
- Magnet
- Circuit
- Co-sim.
- Analysis
- Parametric
- Meas. config
- Meas. data

Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE***
PyBBQ	LEDET	
FiQuS	ProteCCT	
BBQ*	NICQS	PSPICE**
	SIGMA*	

Materials properties

Component library

Co-operative simulation
- COSIM
- STEAM SDK

Consecutive analysis
- STEAM SDK

Parametric analysis
- STEAM SDK
- Dakota***

Comparison to measurements
- STEAM SDK

Software in green boxes is free to use

STEAM SDK

*COMSOL license needed. **Commercial circuit solver from Cadence Design Systems. ***Free tools from Sandia Labs.

Courtesy of Mariusz Wozniak, Emmanuele Ravaioli

Contents

Summary and Perspectives

- **Superconducting Conductors and Magnets Modelling.**
  - For LTS: efforts for development of **FE** and **FD** models.
  - For HTS: efforts for development in **four directions** (FiQuS, NICQS, LEDET, and Comsol).
  - **Homogenization** and **reduced order modelling** are necessary to obtain affordable computing time.
  - **HPC**, **parallelization** in space/time are a must-have for 3D modelling.

→ Need for **novel methods** and **cutting-edge modelling tools**.

- **Perspectives for collaborations with modelling experts at the University of Liège.**
  - Research on formulations, homogenization techniques, coupling between machine learning techniques and reduced order modelling approaches.
  - Synergies for the use and development of open-source software and modelling tools.
  - Co-simulation with mechanical and/or cryogenic models.

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