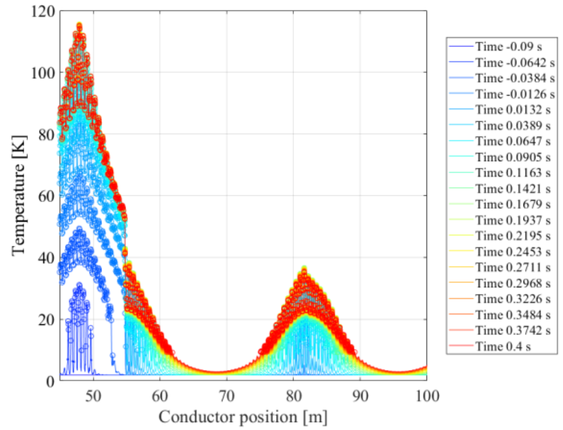
STEAM for HFM

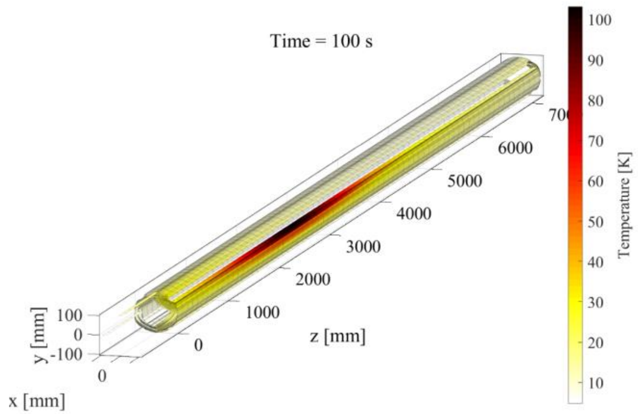
HFM Protection Studies

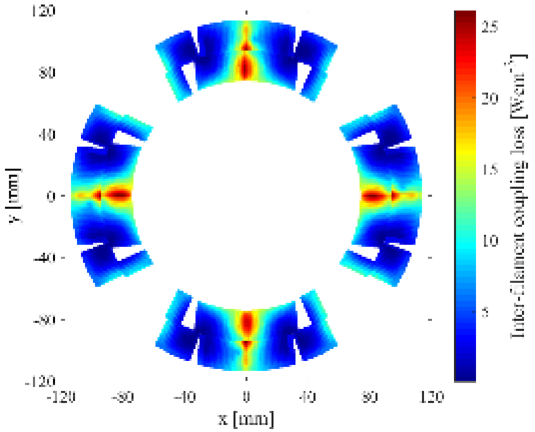
WP4.5-T5-D10

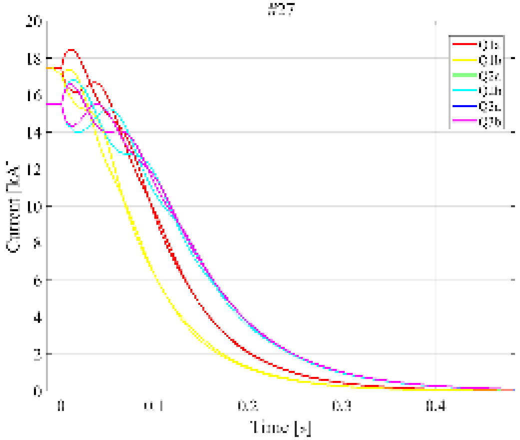
Emmanuele Ravaioli and Mariusz Wozniak, on behalf of the STEAM team

01.11.2023

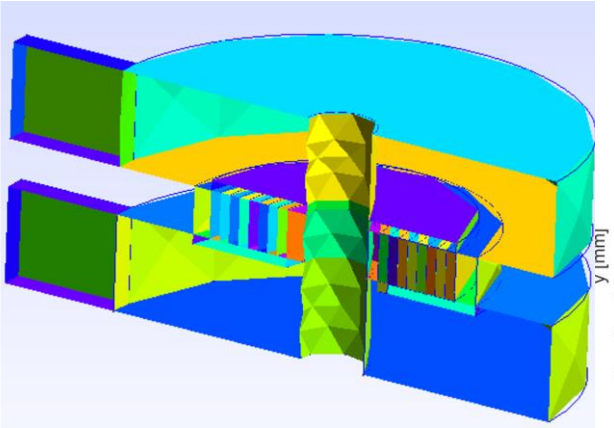


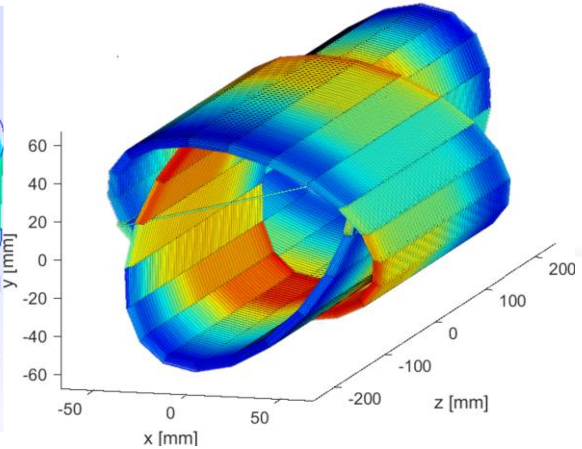


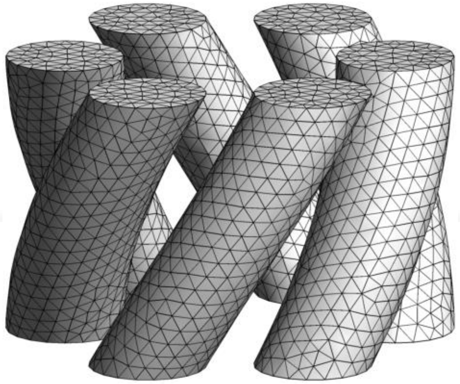


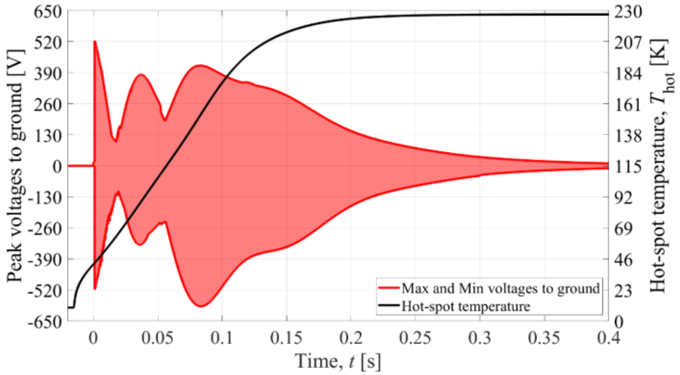


For a general introduction on STEAM:
https://indico.cern.ch/event/1161448/









8 T

- ✓ Nb-Ti
- ✓ Quite some margin in terms of hot-spot temperature, peak voltages to ground, peak stresses
- ✓ Often quenching ~20% of the coil volume is enough to protect the magnet

12 T

- ✓ Nb_3Sn
- ✓ Tighter margin in terms of hot-spot temperature and peak voltages to ground
- ✓ New quench protection method introduced
- ✓ Peak stresses are an issue as Nb_3Sn is quite sensitive to stress/strain

14-16 T

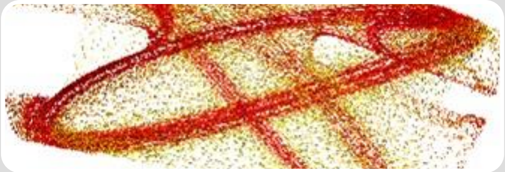
- ✓ Nb_3Sn
- ✓ Even tighter margins
- ✓ Peak stresses are a significant issue and require rethinking the support structure

20+ T

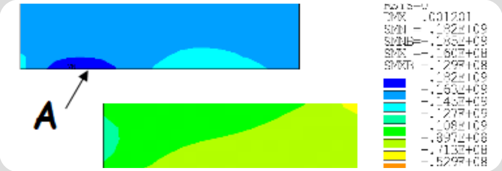
- ✓ HTS
- ✓ New quench protection methods needed
- ✓ Screening currents during transients can cause very high stresses
- ✓ If LTS+HTS, insert/outsert solution is possible
- ✓ Non-insulated coils are under discussion

Requirements for transient simulations in HFM

Trusted, validated simulation tools

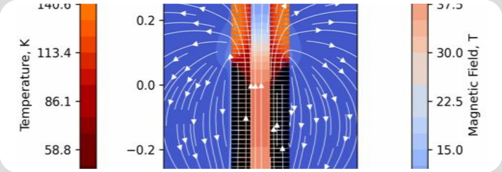


Flexibility to deal with special geometries or scenarios



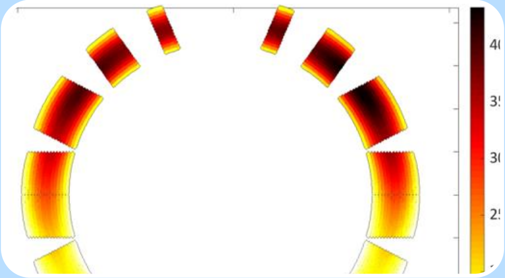
Deeper integration of quench protection in the magnet design

More accurate modeling of transient losses



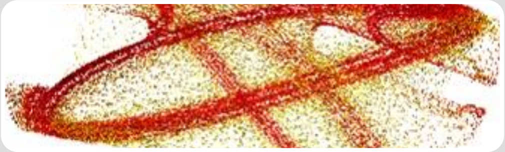
HTS

Requirements for transient simulations in HFM



Trusted, validated simulation tools

✓ Re-use knowledge, material properties, models to increase consistency and efficiency



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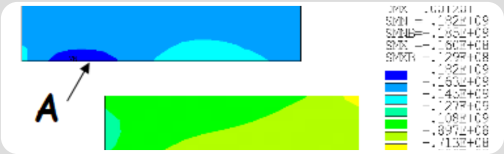

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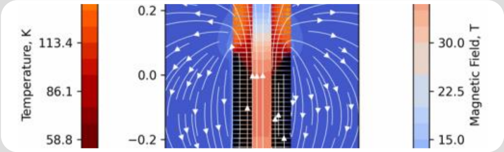

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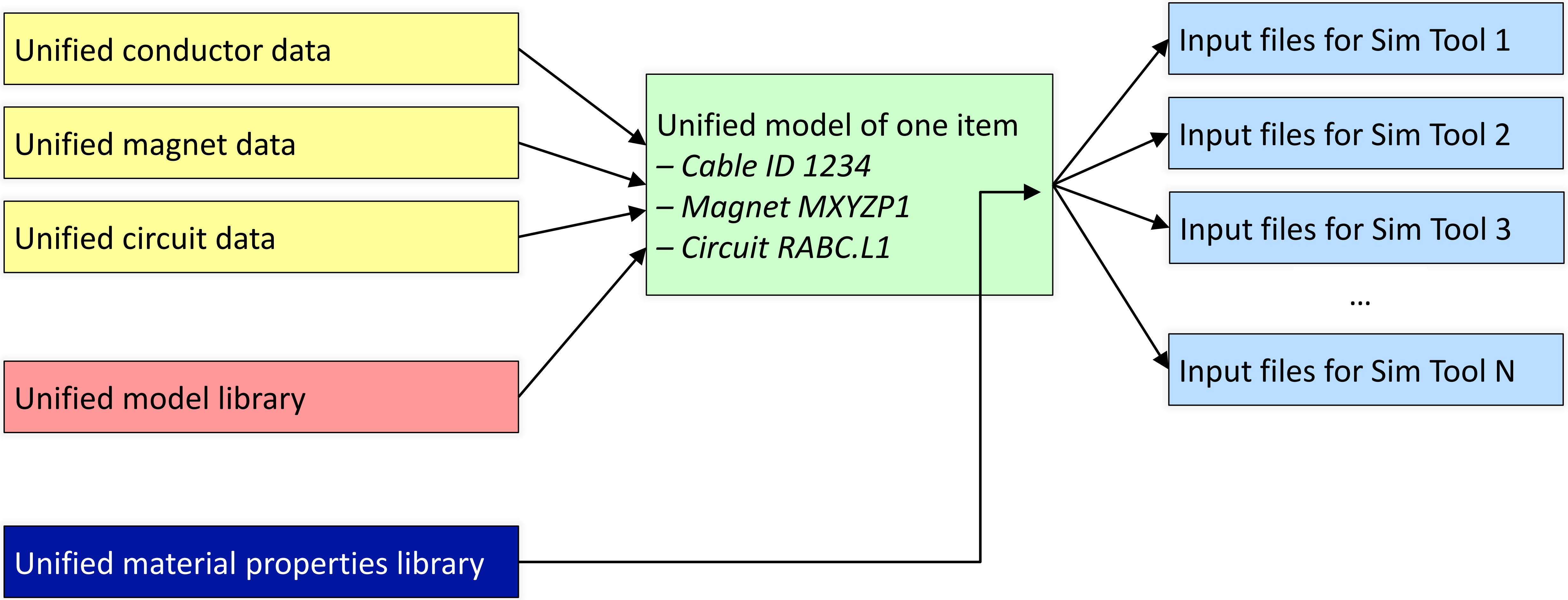
STEAM framework

Libraries

Tools

Analyses

STEAM libraries



STEAM superconducting magnet circuit library

Magnet type	Self-protected (3D)	EE + quench-back	QH	CLIQ	S-CLIQ ESC	Co-simulation	Stresses during quench	NI
Multipole	√	√	√	√	NEW in 2023	√	NEW in 2023	
Solenoid	√	√				√		NEW in 2023
CCT	√	√				NEW in 2023		
Curved CCT	NEW in 2023	NEW in 2023				NEW in 2023		
Pancakes	NEW in 2023							NEW in 2023

- ✓ ~60 magnet models, all validated, including the great majority of LHC and HL-LHC magnets
- ✓ ~50 models of circuit types, all validated, including all LHC circuit types
- ✓ Magnet/circuit models in the frequency domain available as well, but very few are validated

LHC

STEAM tools (software in green is developed by STEAM)

Conductor	Magnet	Circuit
LEDET	FiQuS**	XYCE***
PyBBQ	LEDET	
	ProteCCT	
BBQ*	SIGMA*	PSPICE****
Materials properties		Component library

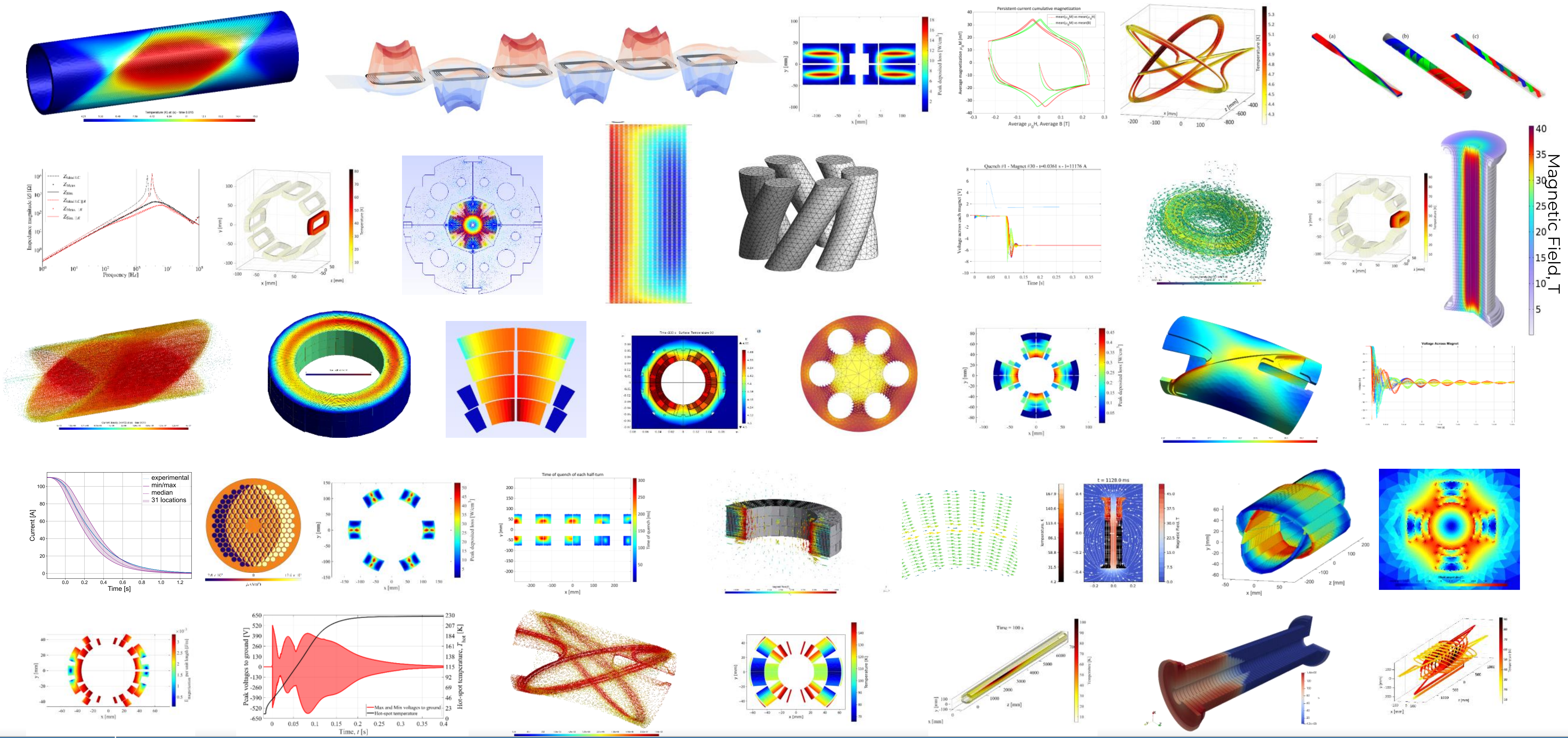
Co-operative simulation

COSIM	STEAM SDK

More STEAM tools are under development, in particular for simulating AC losses and non-insulated coils.

*COMSOL license needed. **Free Gmesh/GetDP needed. ***Free tool from Sandia Labs.
****Commercial circuit solver from Cadence Design Systems.

Examples of STEAM simulations from the last couple of years

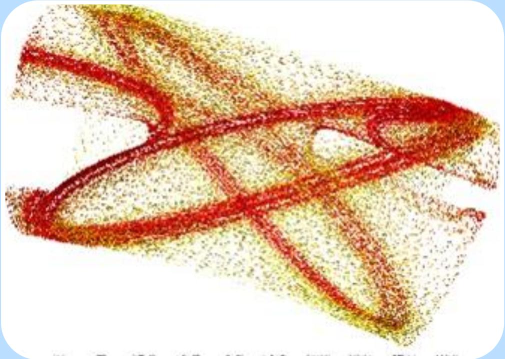


STEAM analyses

- ❑ Take the reference model of magnet X from the STEAM library
- ❑ Take the conductor data for coils X1 and X2
- ❑ Make an input file for software A
- ❑ Run simulation
- ❑ Compare to measurements from file F
- ❑ Sit and relax

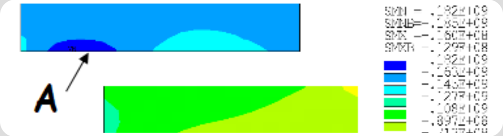
Requirements for transient simulations in HFM

Trusted, validated simulation tools



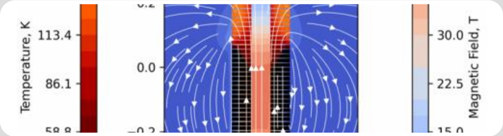
Flexibility to deal with special geometries or scenarios

- ✓ Cooperative simulation to couple models from different domains or geometries
- ✓ “Model any 3D geometry” capability



Deeper integration of quench protection in the magnet design

More accurate modeling of transient losses



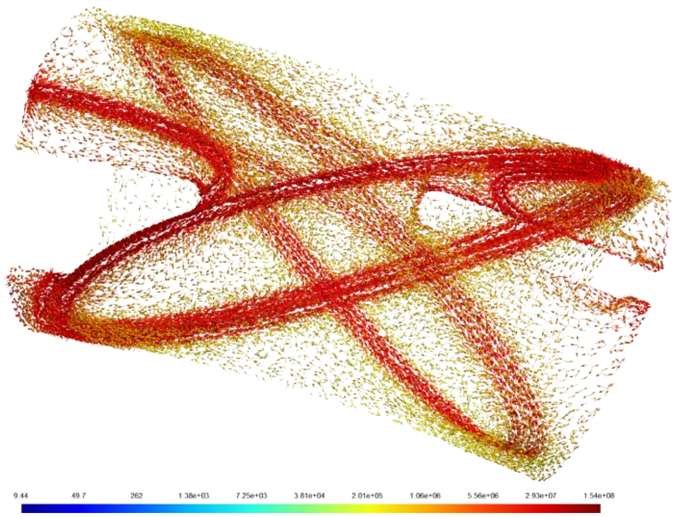
HTS

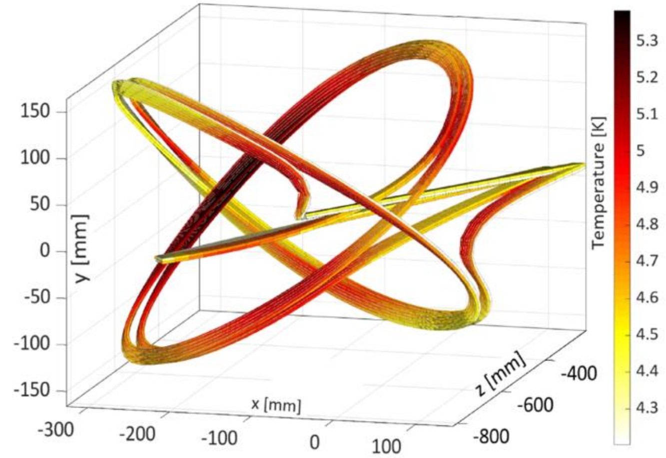
COSIM: Flexibility to deal with special geometries or scenarios

CCT magnet: FiQuS + LEDET

LEDET

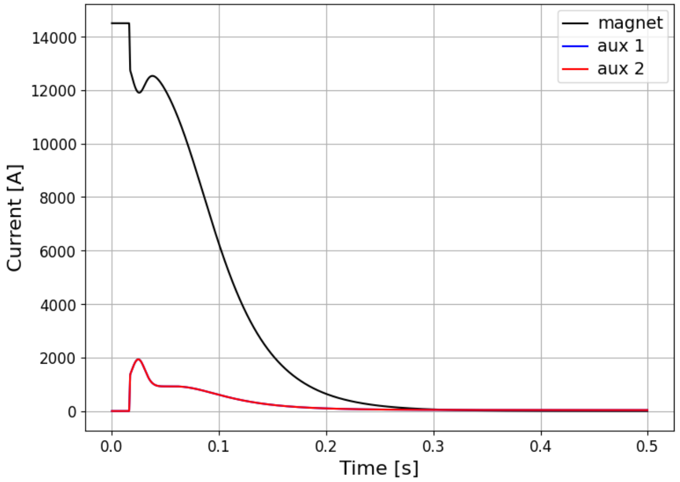
Magnet design courtesy of Fusillo design team at CERN

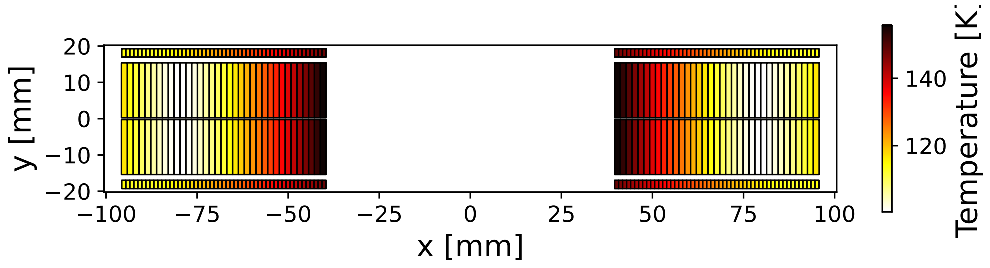




ESC transient: PSPICE + LEDET

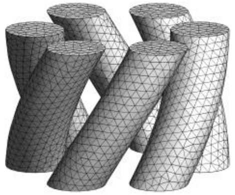
LEDET





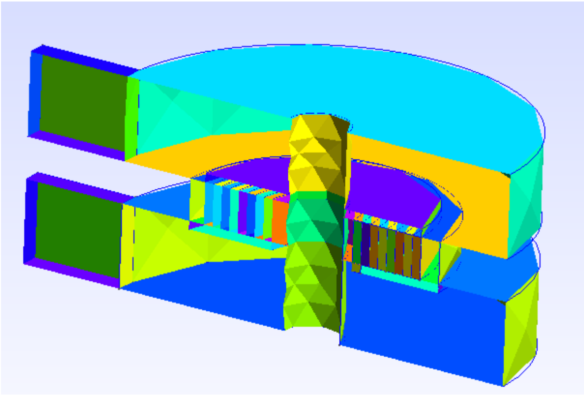
“Model any 3D geometry” capability

The FiQuS (Finite element Quench Simulations) project started in 2022, is based on GetDP open source, and is quickly gaining momentum.
Work is ongoing for strands, tapes, various cables, and various types of magnets.
Depending on the application and geometry, simulations are performed in 1D, 2D or 3D.
Aiming for magnetostatic, transient electromagnetic + thermal.
Including eddy currents in structural components, magnetic coupling, and various quench protection concepts



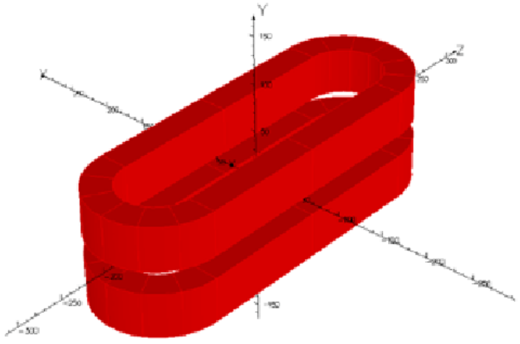
3D HTS pancakes

Single / double pancake
Stacks of double pancakes



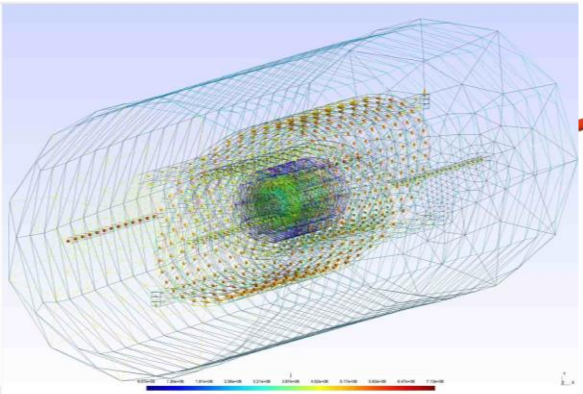
3D Race track magnets

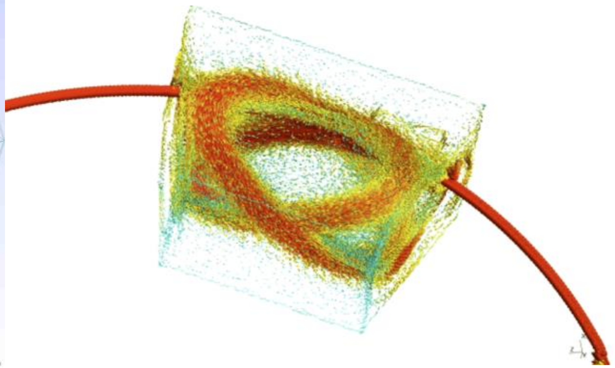
Block cols, racetracks, etc.
Iron yoke, eddy currents



3D CCT magnets

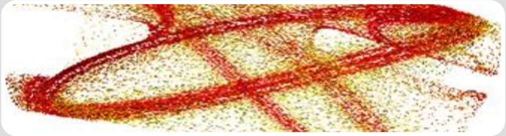
Straight CCT
Curved / combined function CCT
Direct wound magnets





Requirements for transient simulations in HFM

Trusted, validated simulation tools



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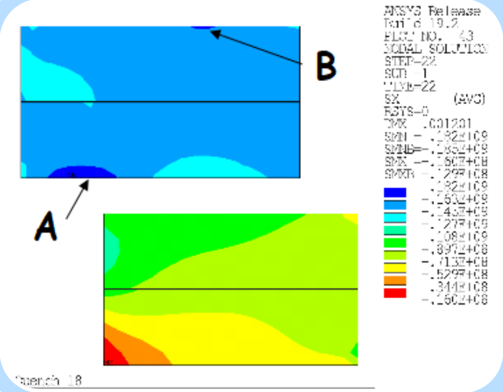
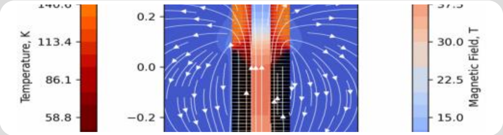


Deeper integration of quench protection in the magnet design

- ✓ Fast but broad parametric studies
- ✓ Consider also the stresses developed during quench transients

More accurate modeling of transient losses

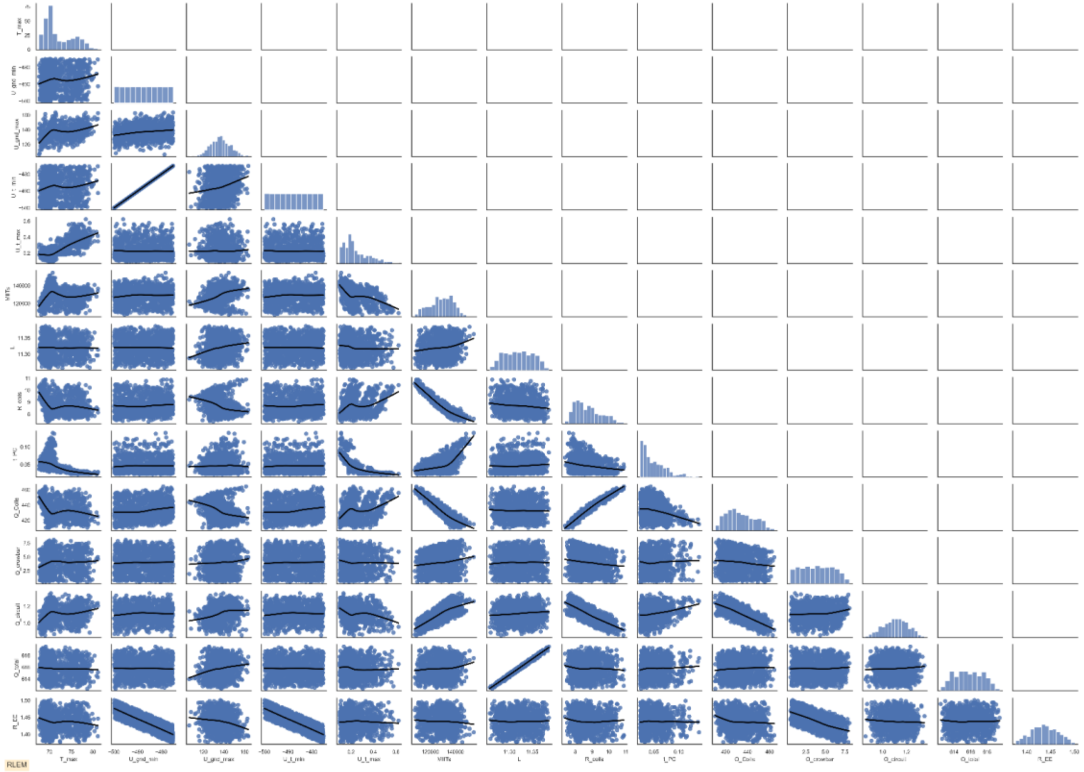


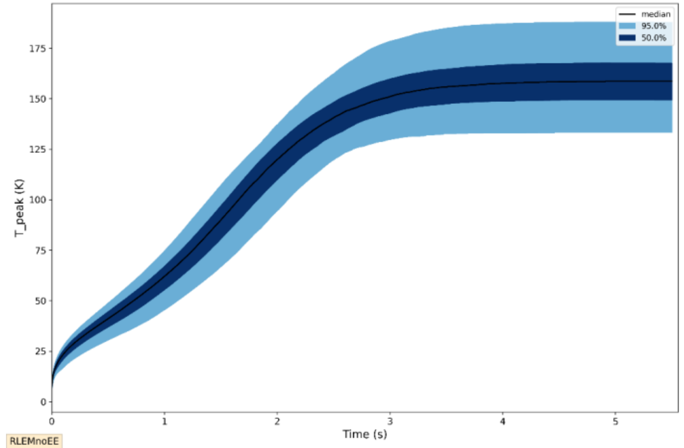
HTS

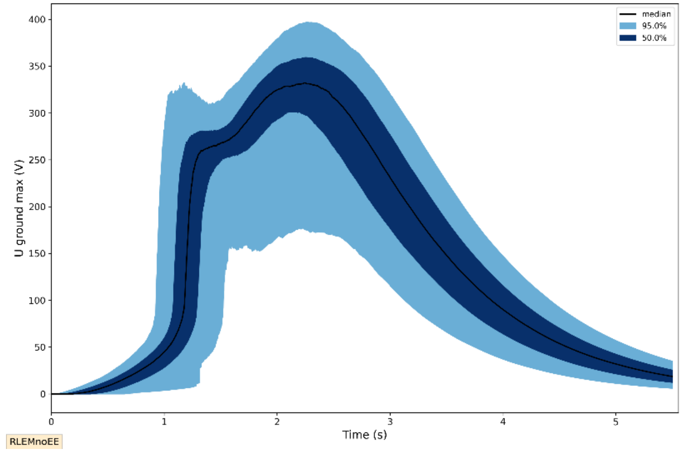
Fast but broad parametric studies

Variation or uncertainty on input parameters

Impact or uncertainty on quench protection results

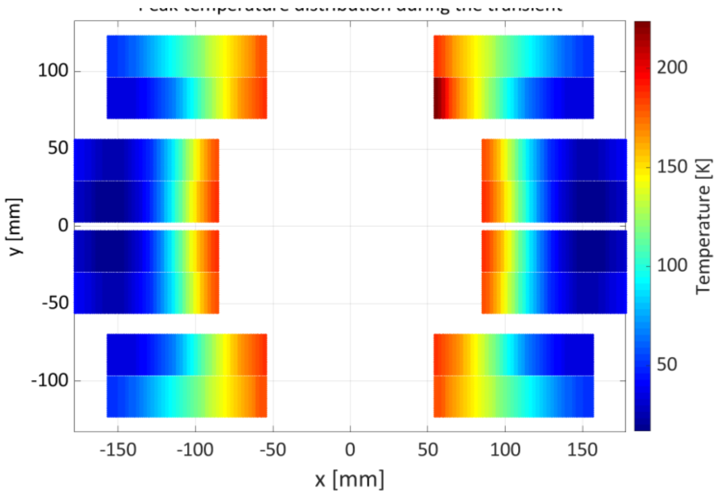




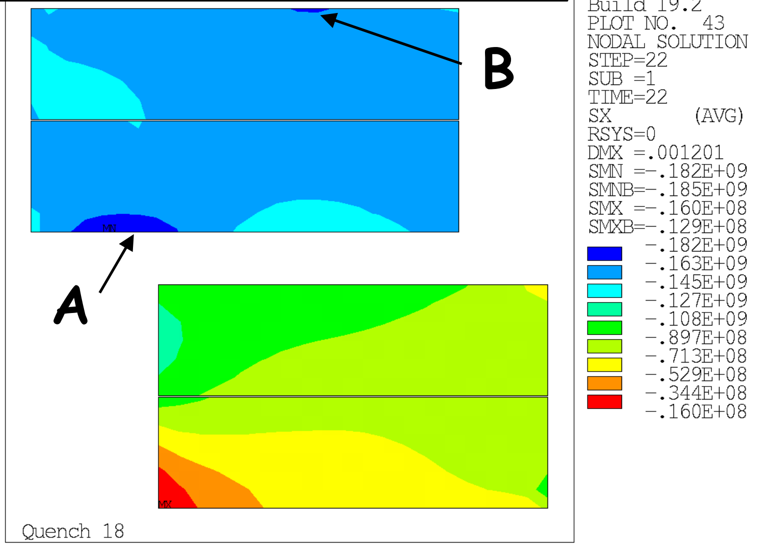


Simulating stresses during a quench transient

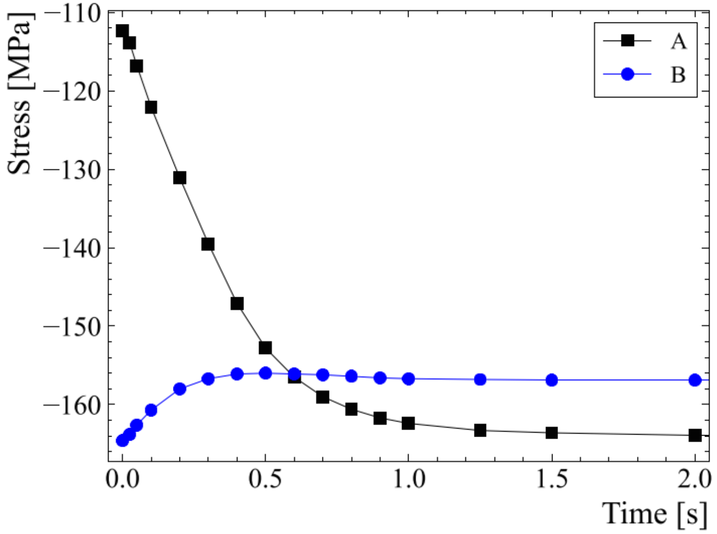
Temperature



Stress



Stresses versus time



STEAM-LEDET

Electrical domain
Magnetic domain
Thermal domain

Temperatures
e.m. forces

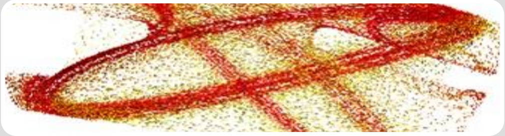
ANSYS

Mechanical domain

This workflow was developed with G. Vallone (LBNL)

Requirements for transient simulations in HFM

Trusted, validated simulation tools



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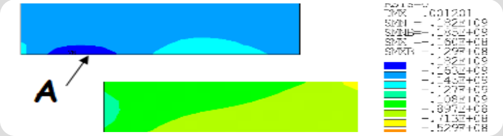
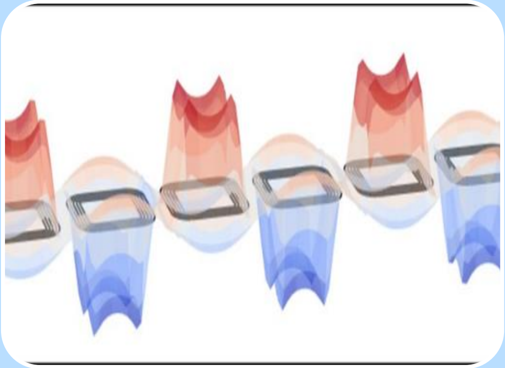
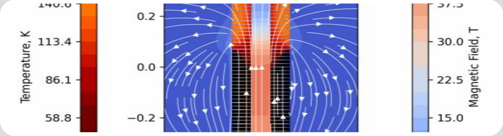


Deeper integration of quench protection in the magnet design



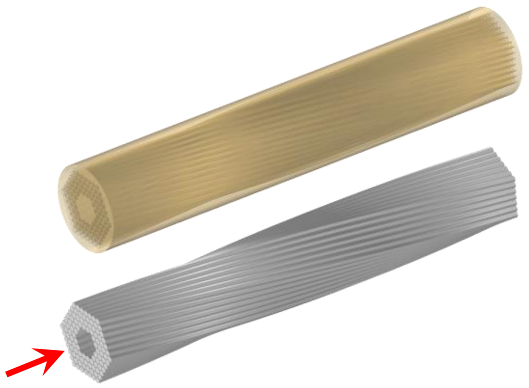
More accurate modeling of transient losses

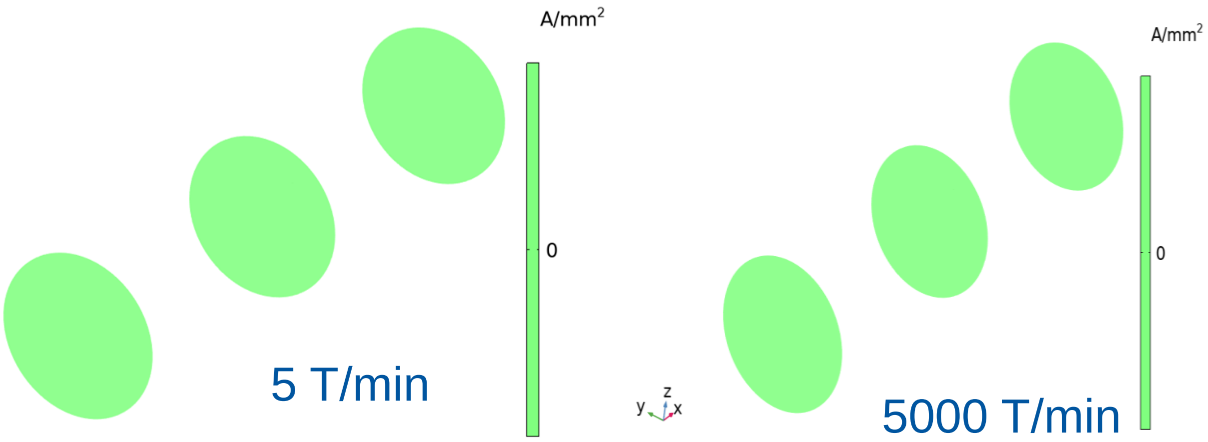
- ✓ Reduce margin of error in simulations
- ✓ Model new quench protection methods based on transient losses

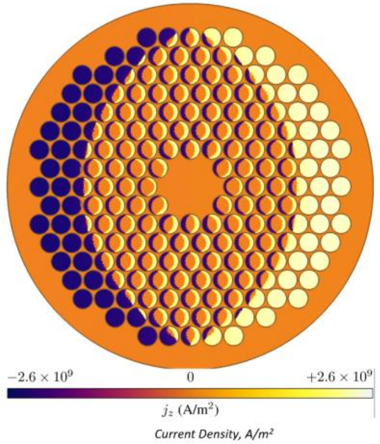


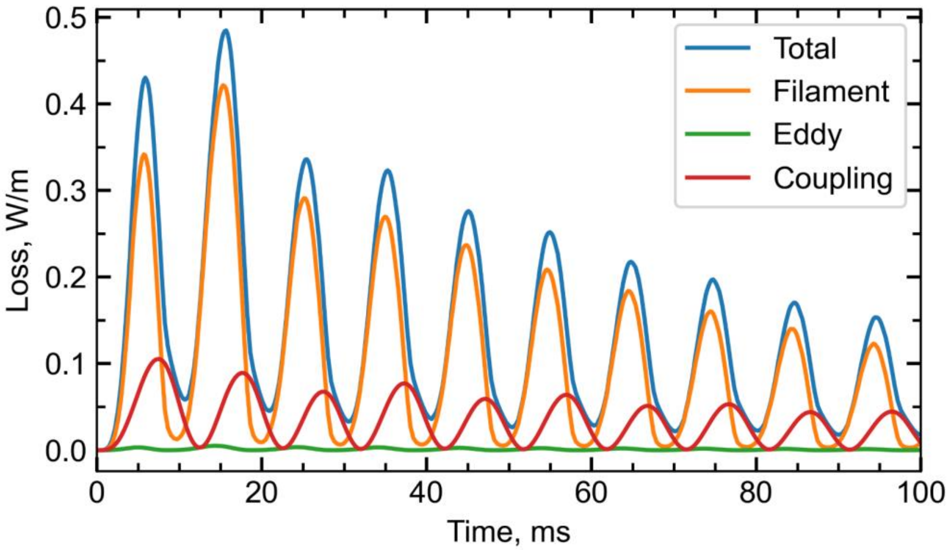
HTS

More accurate modeling of transient losses







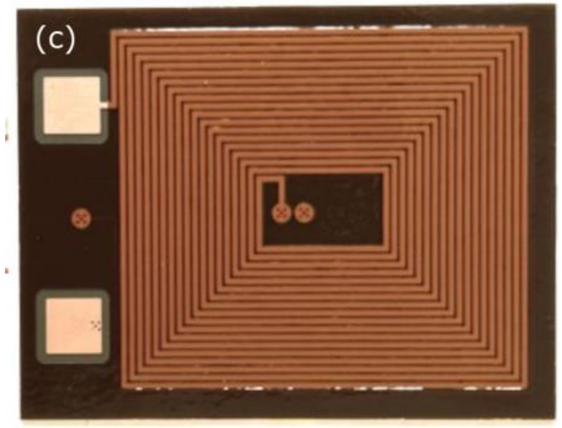


COMSOL 3D FEM thermo-electro-magnetic model to simulate twisted composite superconductors in transient regimes

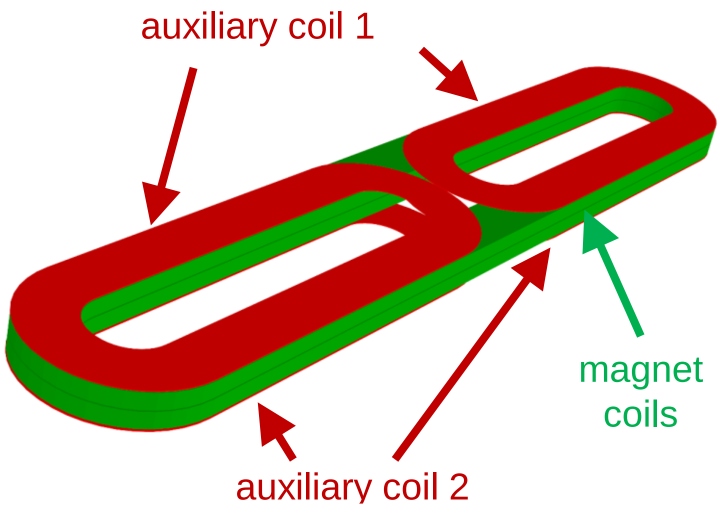
FiQuS / GetDP detailed loss calculation in a multifilament strand

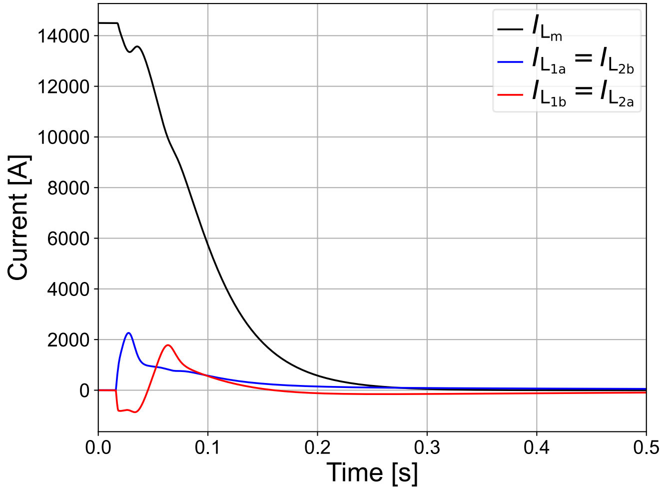
Model new quench protection methods based on transient losses

E-CLIQ

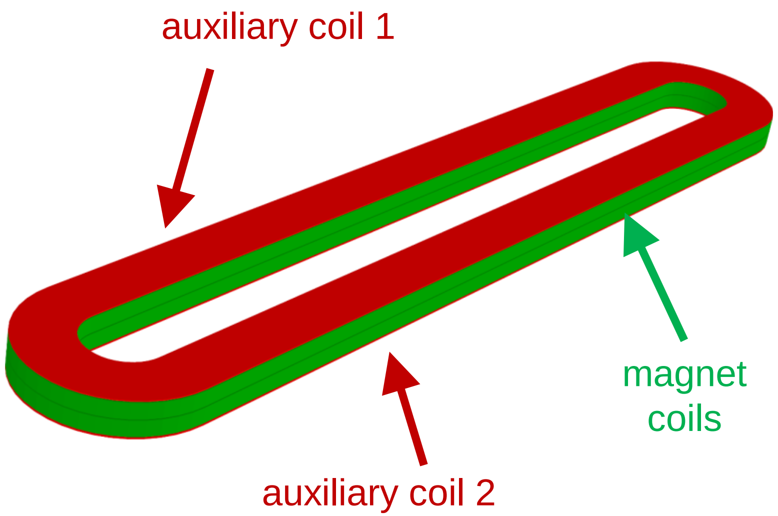


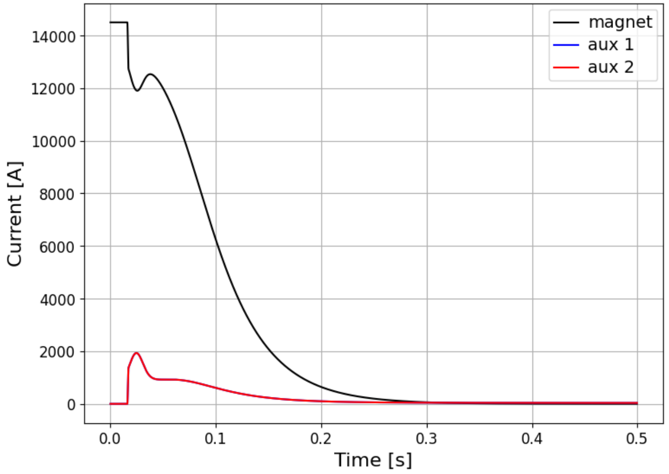
S-CLIQ





ESC

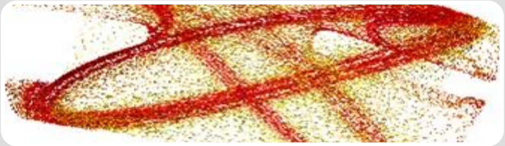




More info on new quench protection methods in Mariusz Wozniak's WP4.5 talk

Requirements for transient simulations in HFM

Trusted, validated simulation tools



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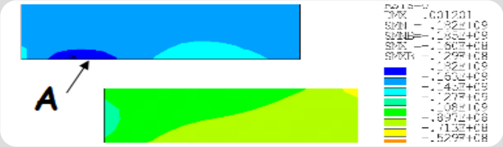

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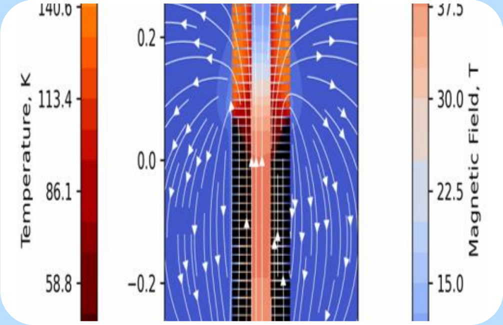
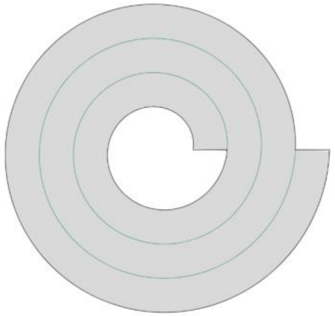


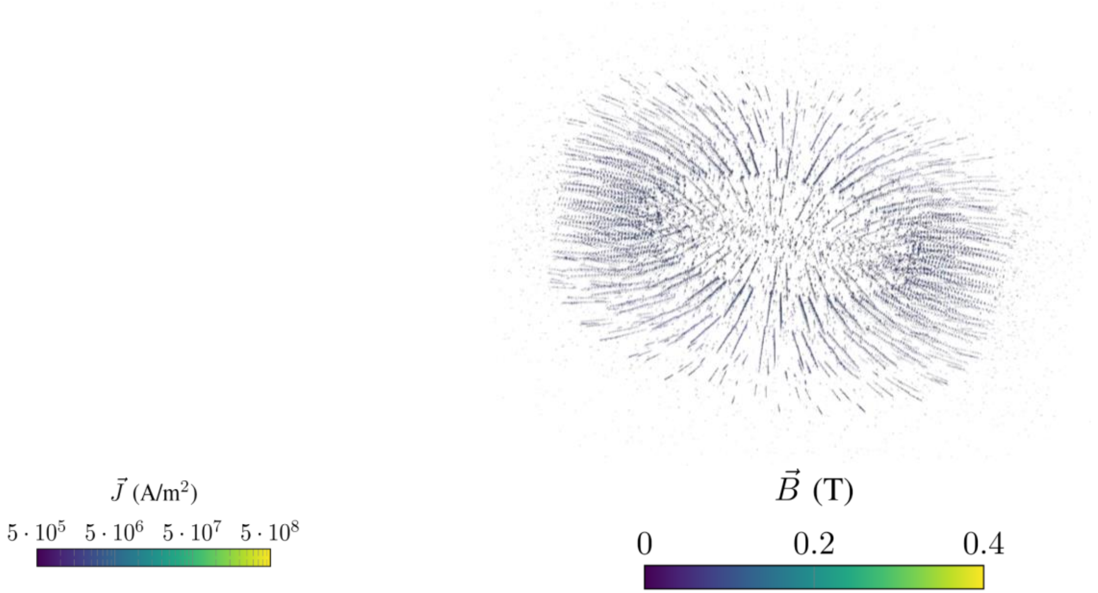
HTS

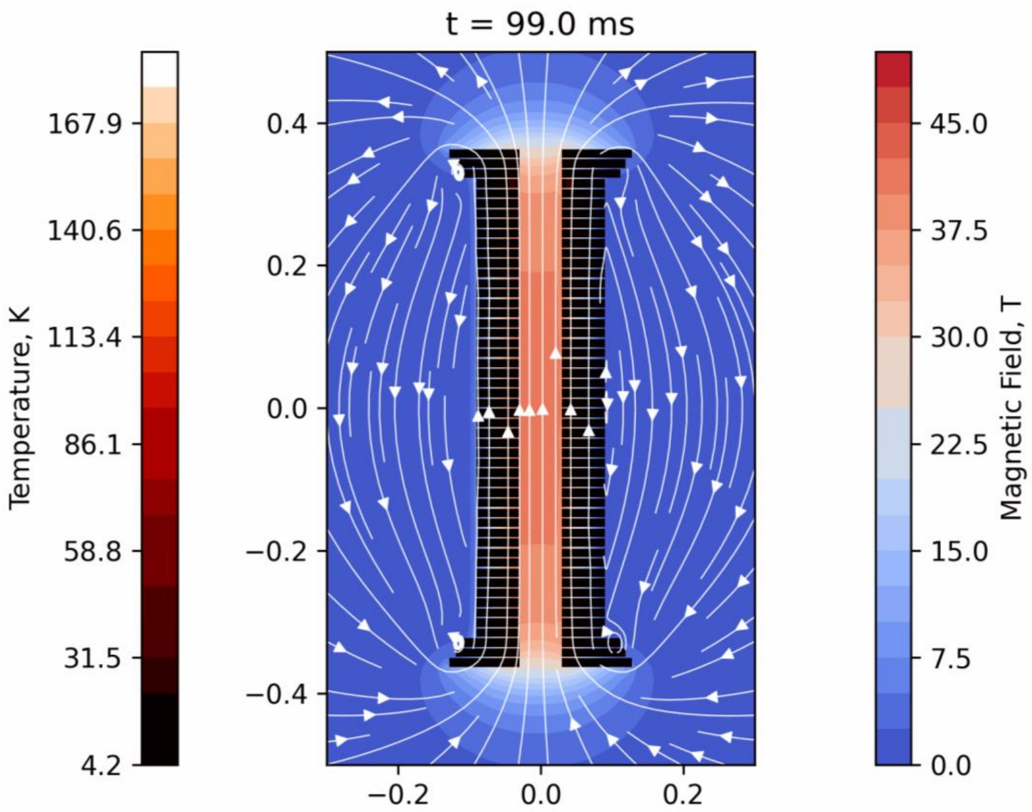
✓New material properties

✓Non-insulated (NI) coils

Non-insulated HTS coils





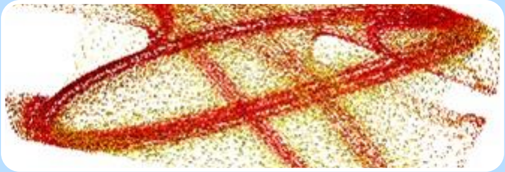


3D Magneto-Thermal FE simulation of a NI HTS coil
Screening current are included.

Quench at 40 T starting from the first 'modular' coil from the top. In the coil the colour represents temperature. In the remaining domain the magnetic field.

STEAM for HFM

Trusted, validated simulation tools



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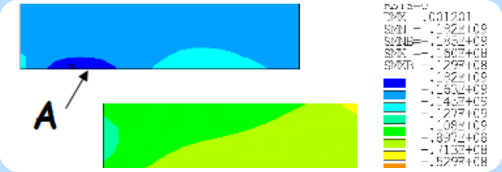

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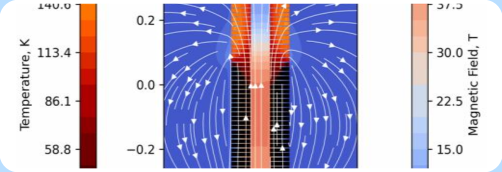


HTS

STEAM

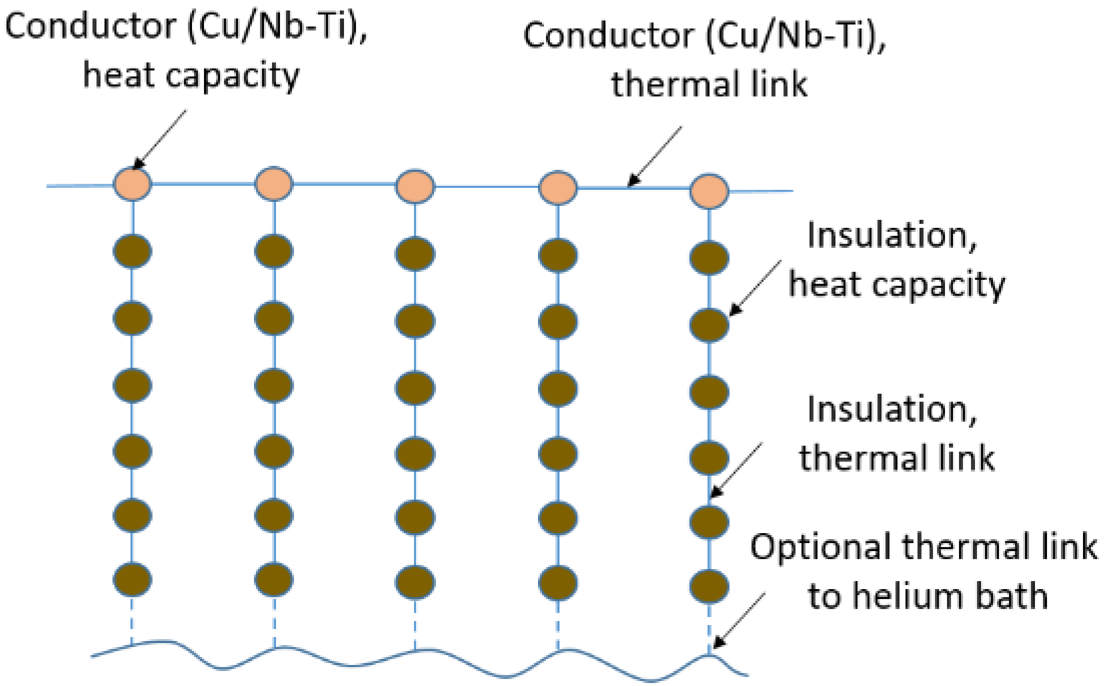
We're here to help

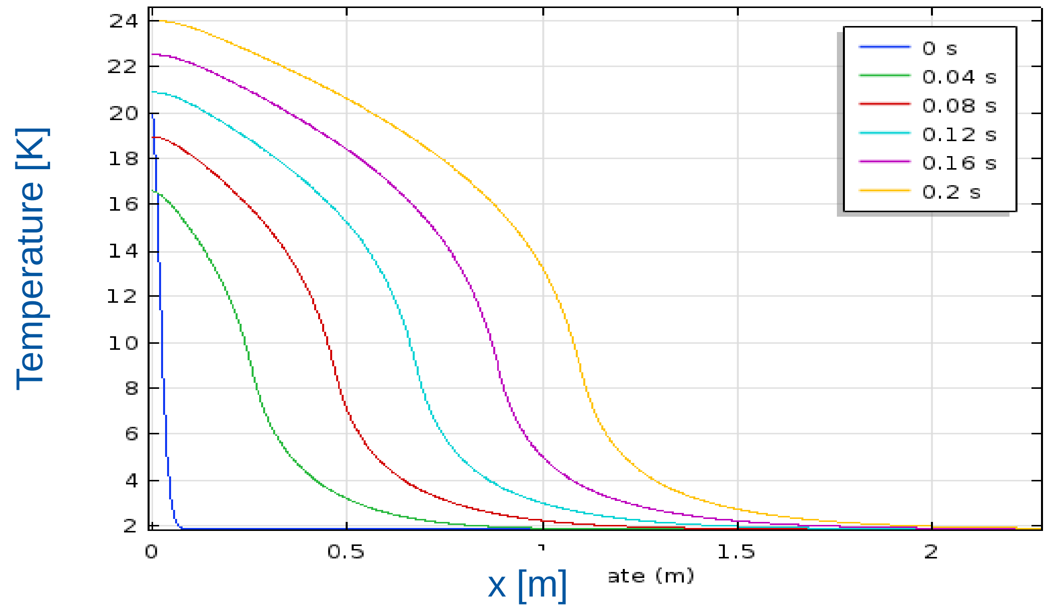
We are ready and motivated to join up with more magnet teams/groups by:

- helping you to choose among the various **quench protection technologies**
- performing **simulations** and assessing the results (advantages and disadvantages)
- (co-)analysing the **protection-related test results** to validate and further improve our models.

Annex

BBQ (BusBar Quench)

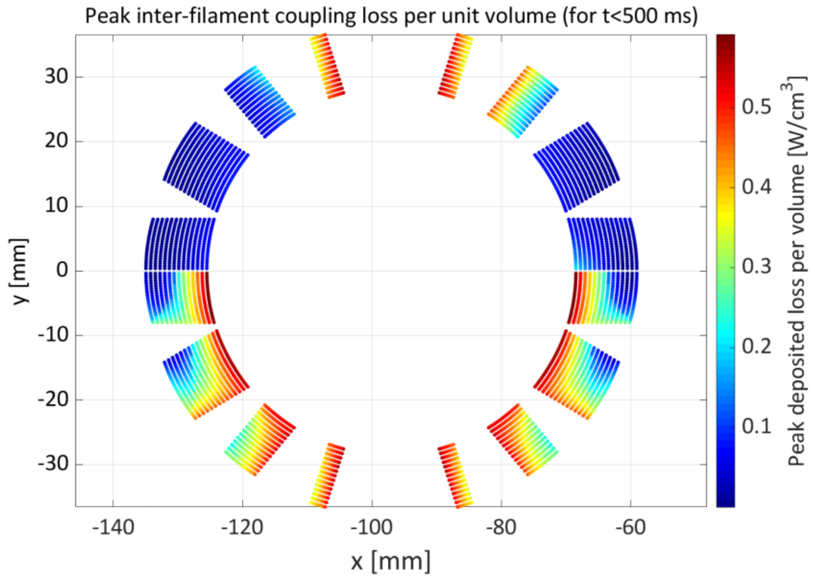


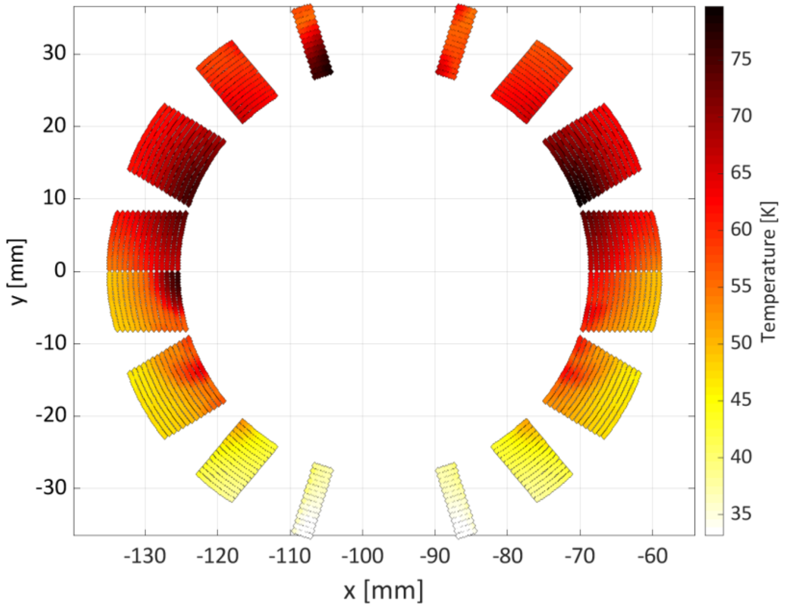


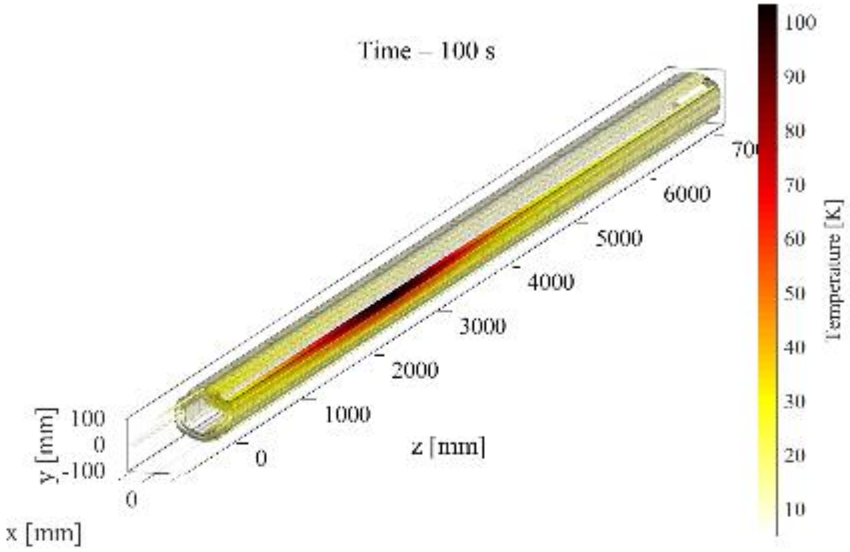
Temperature-development along the conductor

→ Simulate 1D+1D quench propagation in superconducting busbars
→ Legacy: BBQ (COMSOL model, finite elements solver)
→ New development: PyBBQ (Python program, finite difference solver)

LEDET (Lumped-Element Dynamic Electro-Thermal)

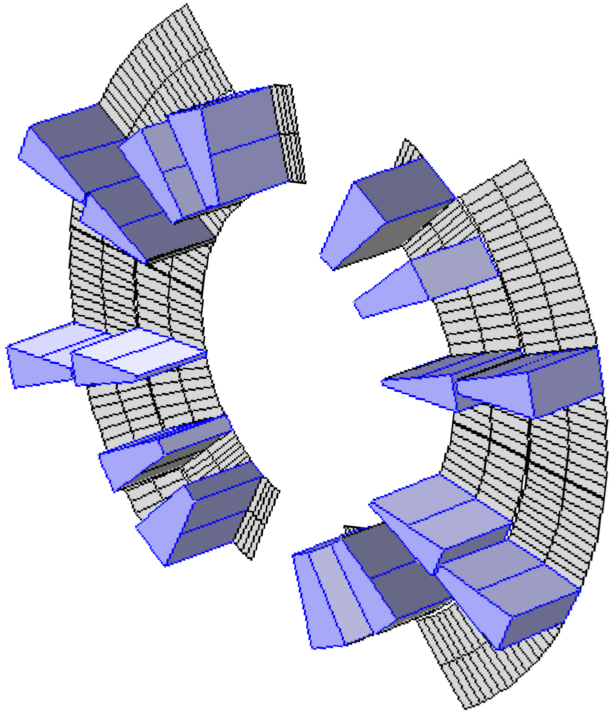


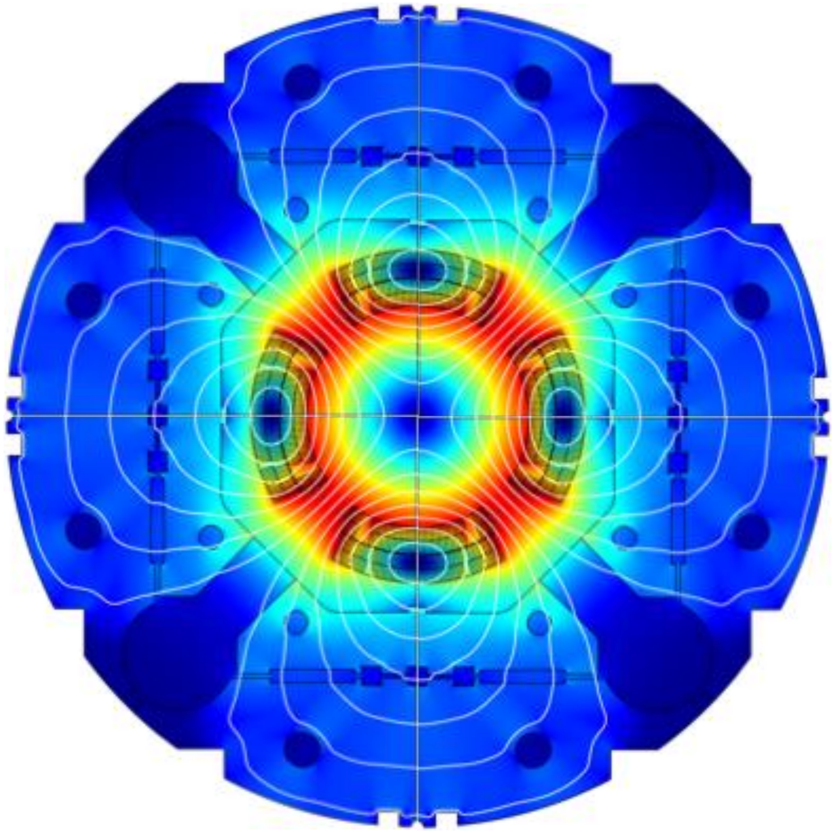


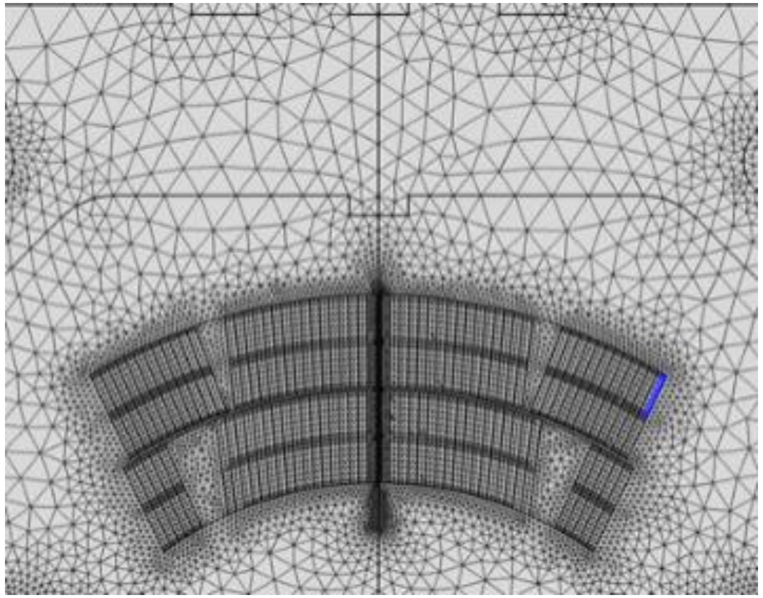


→ Simulate electro-magnetic and thermal transients in superconducting magnets in 2D and 3D geometry using the finite-differences method

SIGMA (STEAM Integrated Generator of Magnets for Accelerators)



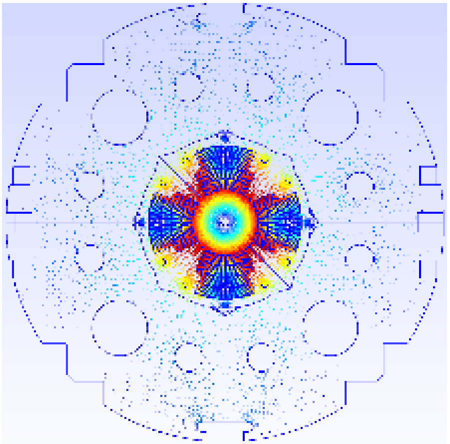




→ Simulate electro-magnetic and thermal transients in superconducting magnets in a 2D geometry using a COMSOL finite-elements (FE) model

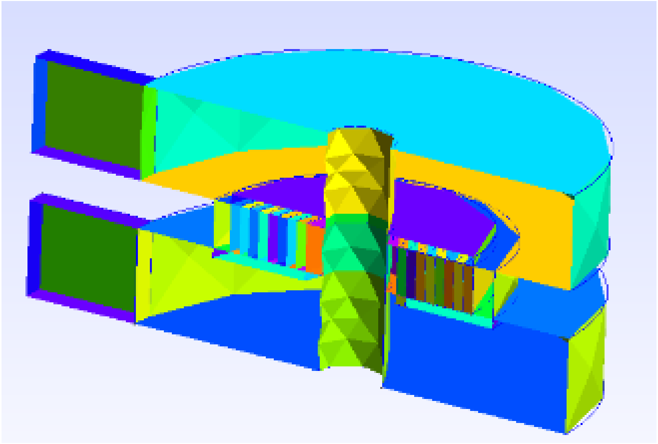
Finite Elements Quench Simulator (FiQuS)

2D Example for quadrupole MQXA



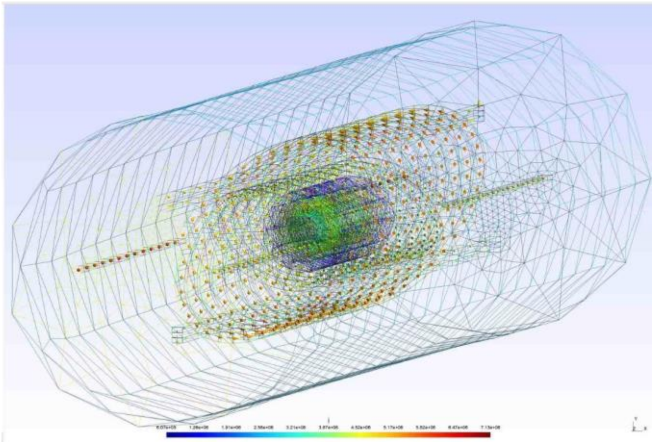
- B and M calculation for LEDET
- Stand-alone quench simulations
- Thermal transient and steady state sim.

3D Example of a NI HTS coil



- HTS coils ramp up and down simulations
- HTS coils quench simulations
- Coils with insulation, no-insulation, partial- insulation.

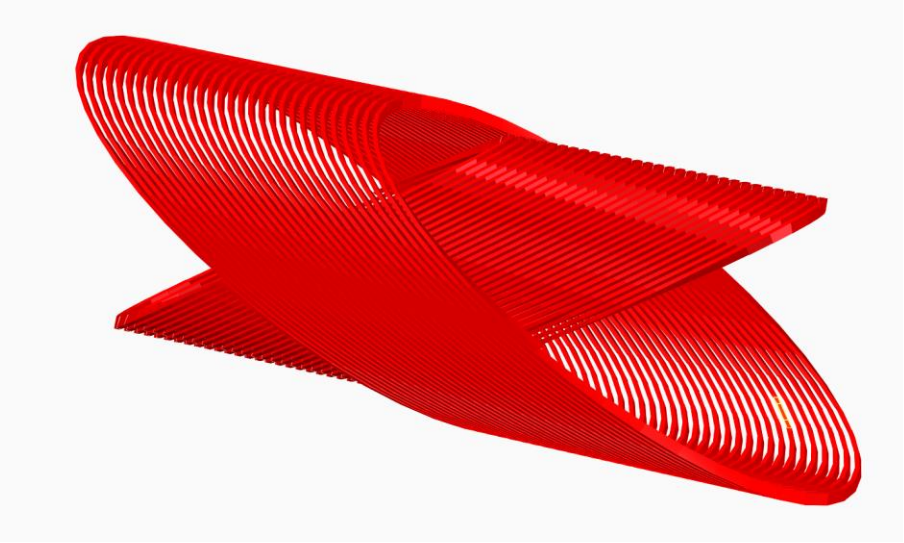
3D Example of a CCT magnet

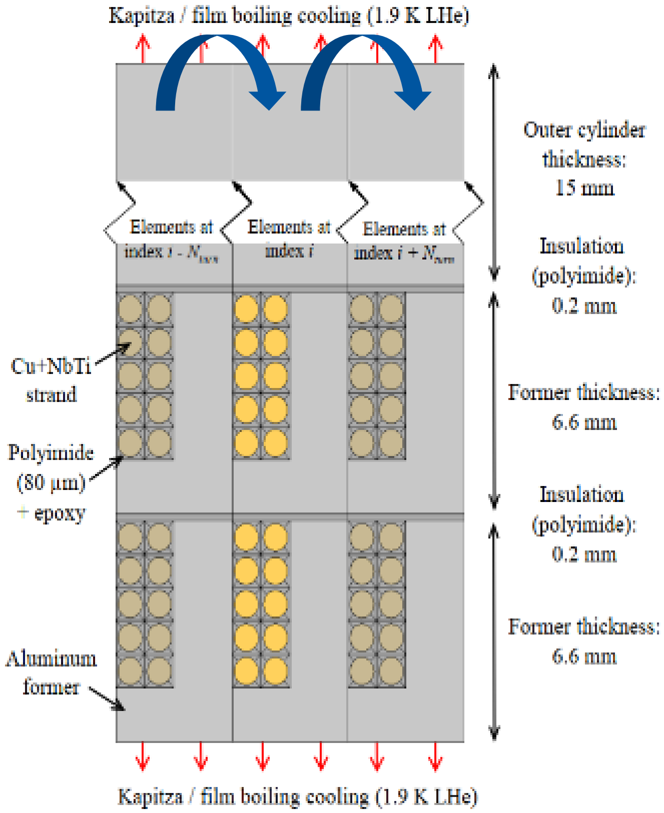


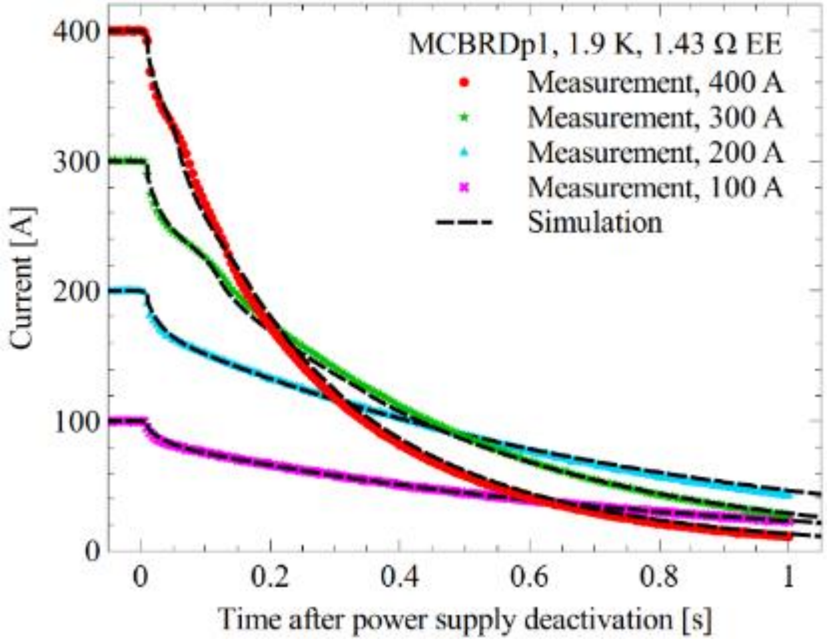
- B and M calculation for LEDET
- Eddy currents in the formers
- Temperature of the formers
- No plans for a stand alone quench simulation

→ FiQuS relies on Gmsh for geometry and meshing and on GetDP for solving and postprocessing.

ProteCCT (Protection of Canted-Cosine-Theta) type magnets

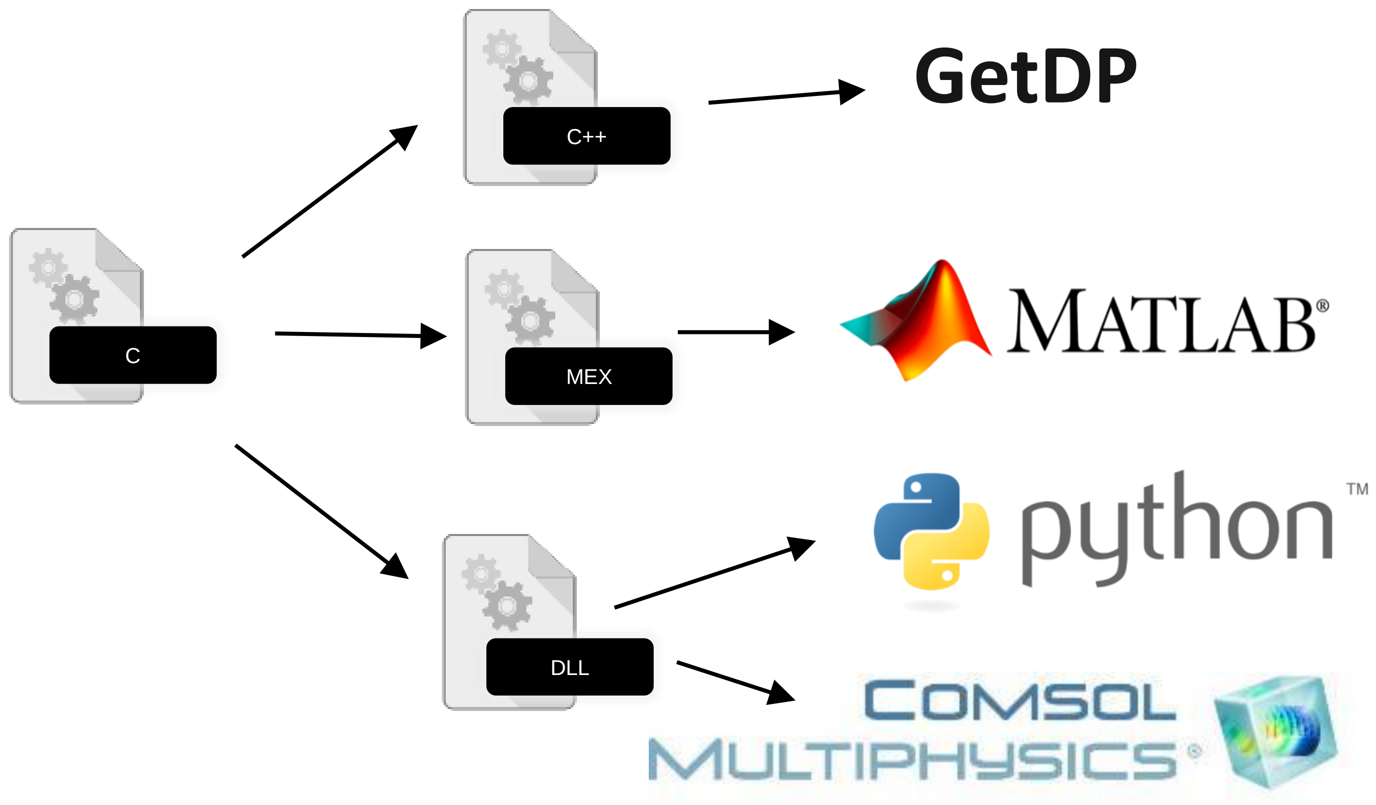






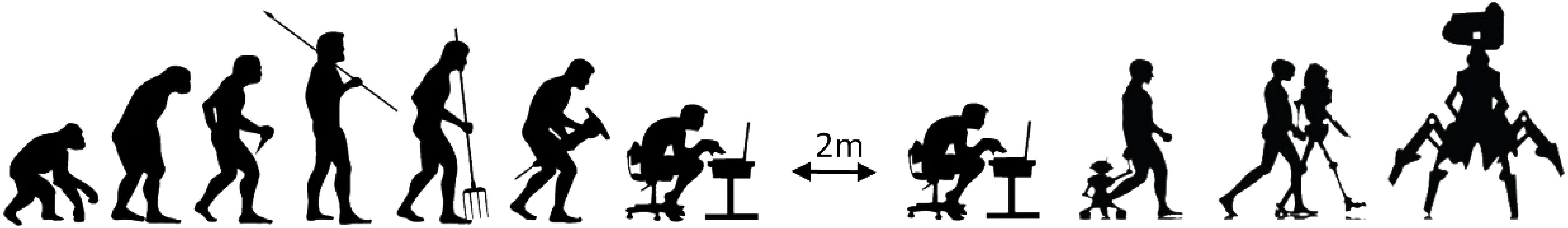
→ Simulate electro-magnetic and thermal transients in canted-cosine-theta (CCT) using finite-differences method

Library of Material Properties



→ Work has been done to allow using the same material properties (coded in C) across tools written in Python, MATLAB and FE solvers (Comsol, GetDP i.e. FiQuS).

Fast but broad parametric studies



SCALE OF AUTOMATION

LEVEL 0	HUMAN MANUALLY GENERATING AND RUNNING A MODEL
LEVEL 1	SOFTWARE GENERATING AND RUNNING MODELS
LEVEL 2	SOFTWARE SETTING UP PARAMETRIC STUDIES
LEVEL 3	SOFTWARE SIMULATING ON THE FLY EVENTS THAT JUST OCCURRED ← **2023**
LEVEL 4	SOFTWARE VALIDATING MODEL ASSUMPTIONS ACROSS MANY EVENTS