STEAM

Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

Emmanuele Ravaioli and Mariusz Wozniak

on behalf of the STEAM team:
Lennard Bender, Bernardo Bordini, Vijay Chakravarty, Marvin Janitschke, Johanna Lidholm, Tim Mulder, Emmanuele Ravaioli, Erik Schnaubelt, Lena Anna Sommer, Arjan Verweij, Andrea Vitrano, Mariusz Wozniak
with thanks to all the past STEAM members

29th September 2022

https://espace.cern.ch/steam

OUR VISION

Achieve specialized, trusted, consistent, repeatable and sustainable software tools and models for rapid **S**imulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits.

Scope of STEAM framework

TRANSIENTS

- ✓ Energy extraction and quench-back
- ✓ Quench heater induced quench
- ✓ CLIQ induced quench
- ✓ Powering
- ✓ Short circuit
- ✓ Electrical arc
- ✓ Frequency transfer measurement
- ✓ No-Insulation coils

MAGNET TYPES

- ✓ Cos-theta, Block-coil, Common coil
- ✓ Canted Cos-Theta (CCT)
- ✓ Solenoid, pancake coils

CIRCUIT TYPES

- ✓ Stand-alone magnets
- ✓ Nested circuits
- ✓ Series-connected magnets
- ✓ …many combinations of those

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.

STEAM FRAMEWORK

STEAM framework

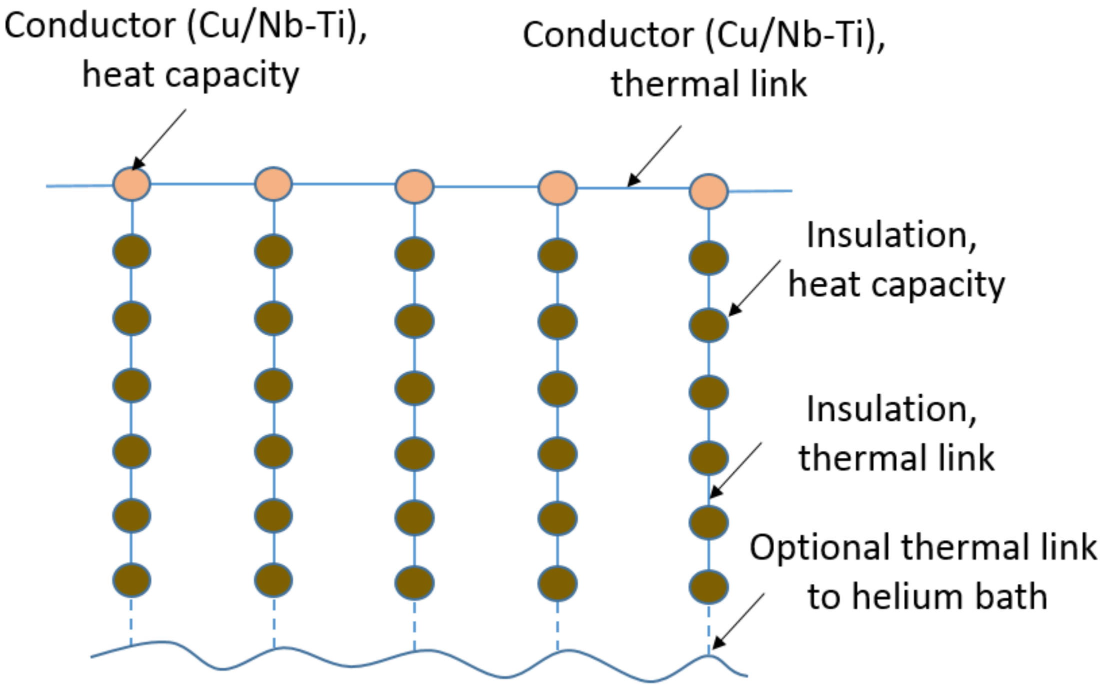
Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE*
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE**

CHALLENGES

- ✓ Need of trusted simulation tools
- ✓ Validation process is time consuming
- ✓ Impractical to implement all magnet geometries and physics in one tool

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

BBQ (BusBar Quench)

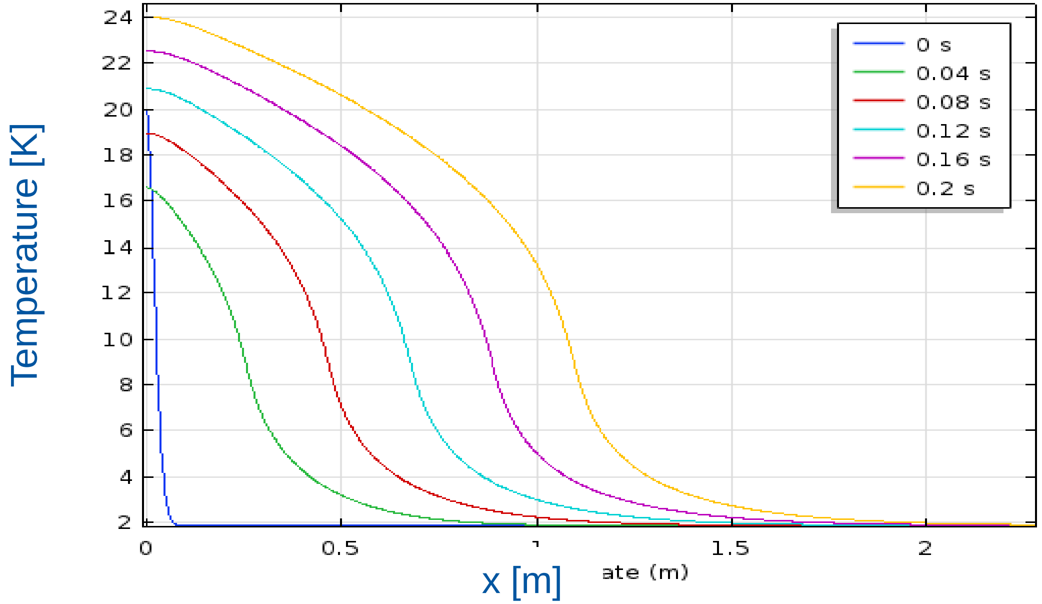

Conductor (Cu/Nb-Ti), heat capacity

Conductor (Cu/Nb-Ti), thermal link

Insulation, heat capacity

Insulation, thermal link

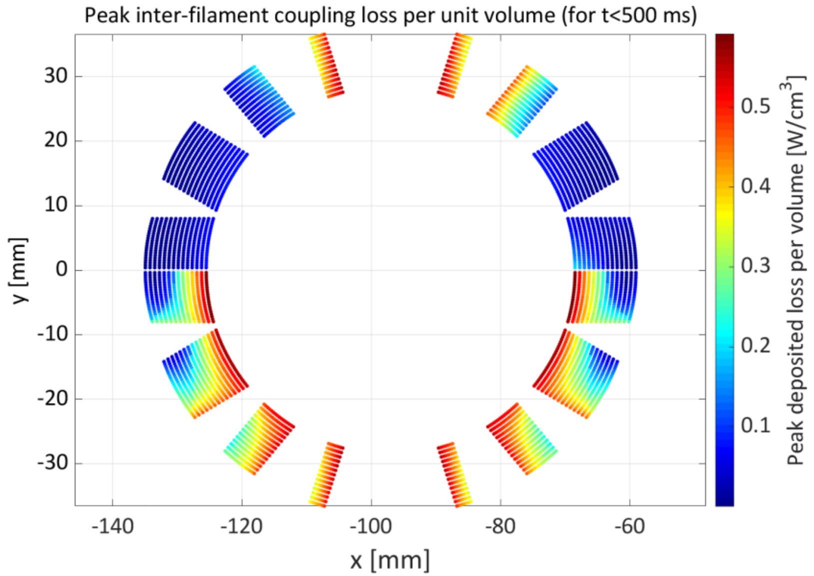
Optional thermal link to helium bath

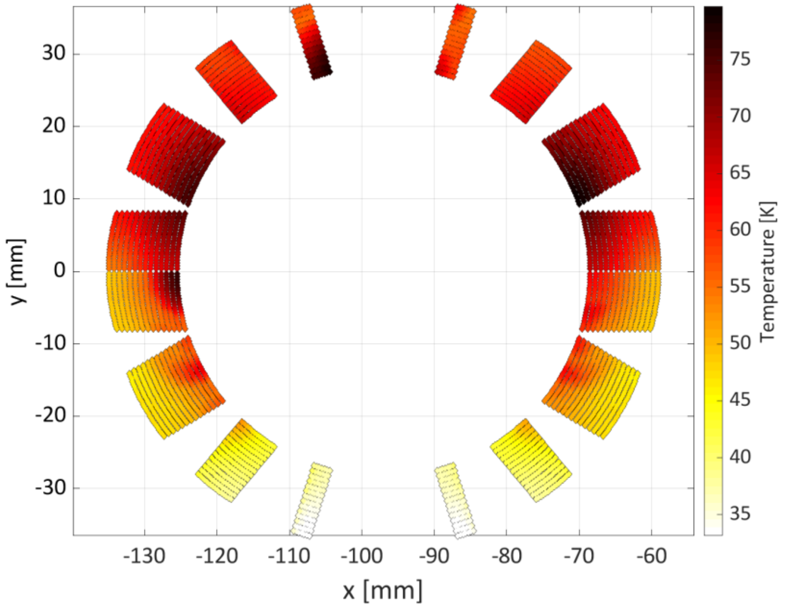


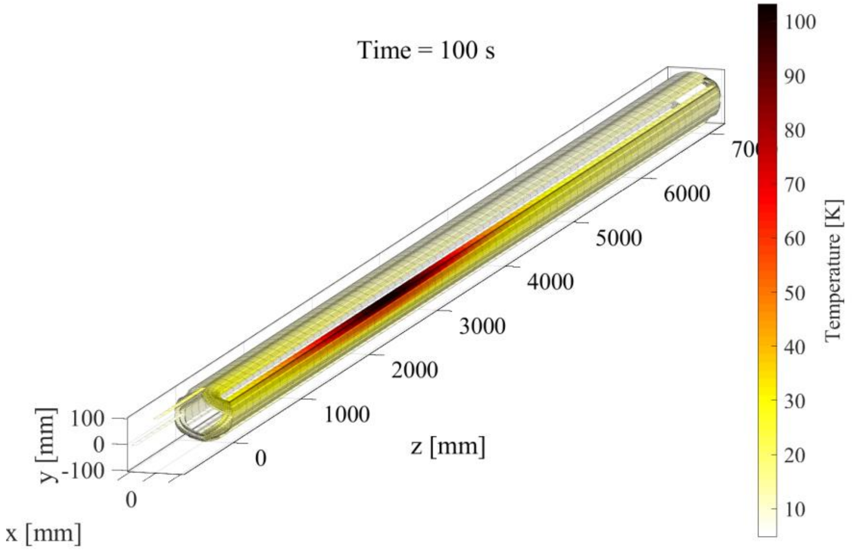
Temperature-development along the conductor

→ 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)

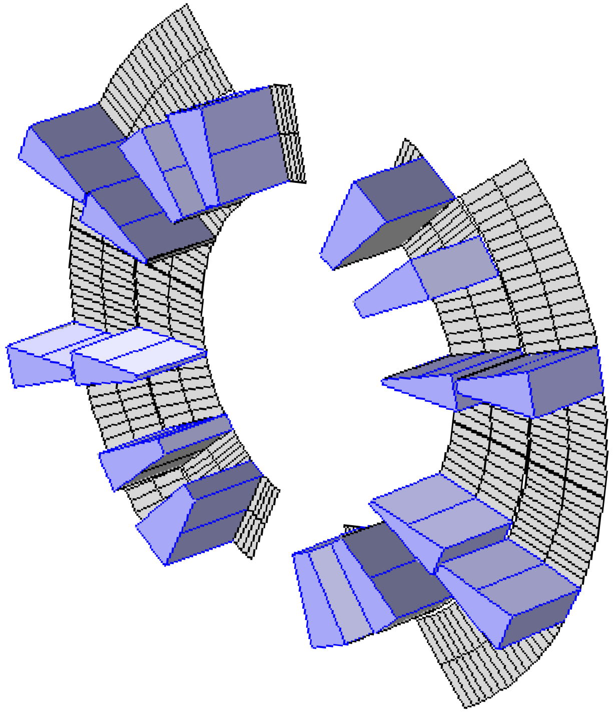


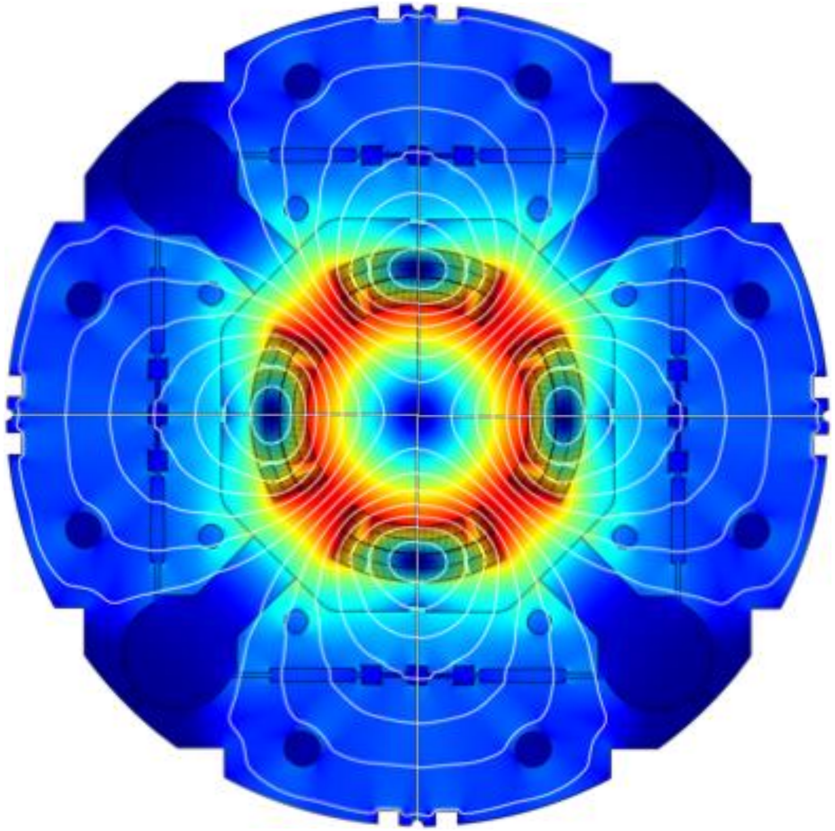


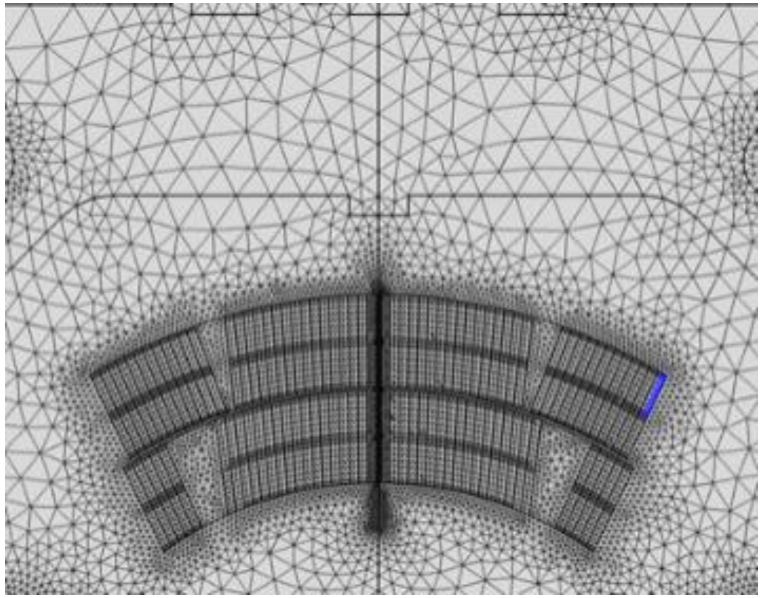


→ Simulate electro-magnetic and thermal transients in superconducting magnets in 2D and 3D geometry using the finite-differences method

SIGMA (STEAM Integrated Generator of Magnets for Accelerators)



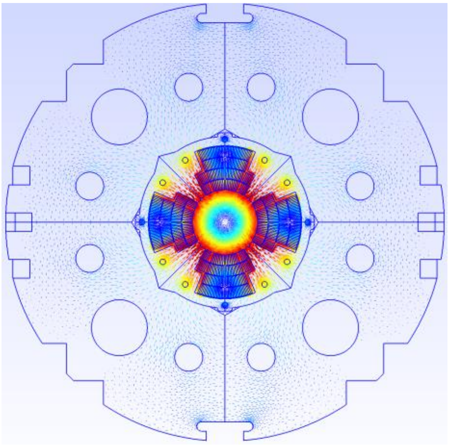




→ Simulate electro-magnetic and thermal transients in superconducting magnets in a 2D geometry using a COMSOL finite-elements (FE) model

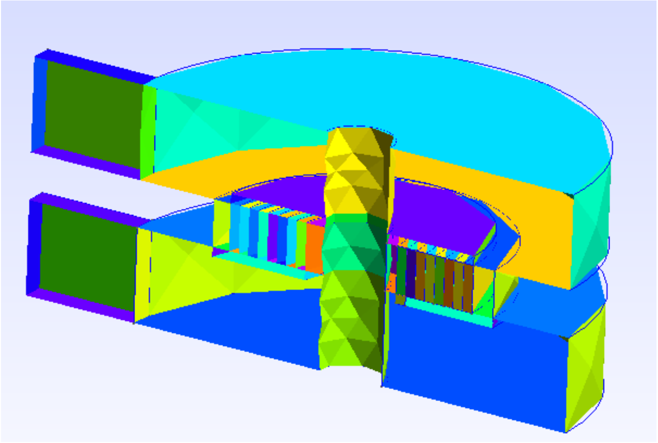
Finite Elements Quench Simulator (FiQuS)

2D Example for quadrupole MQXA



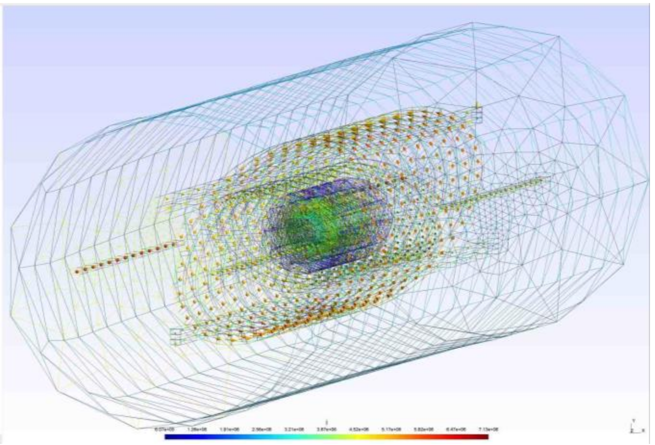
- B and M calculation for LEDET
- Stand-alone quench simulations
- Thermal transient and steady state sim.

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.

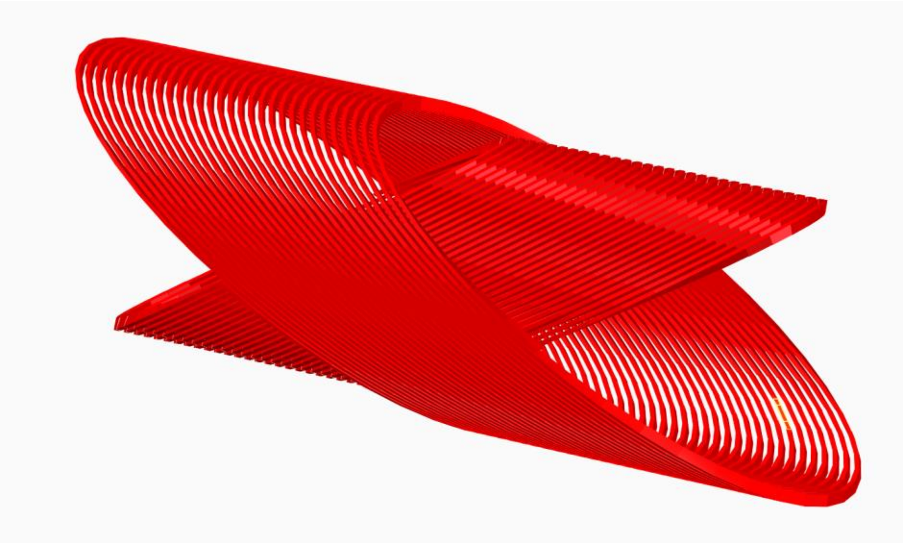
3D Example of a CCT magnet

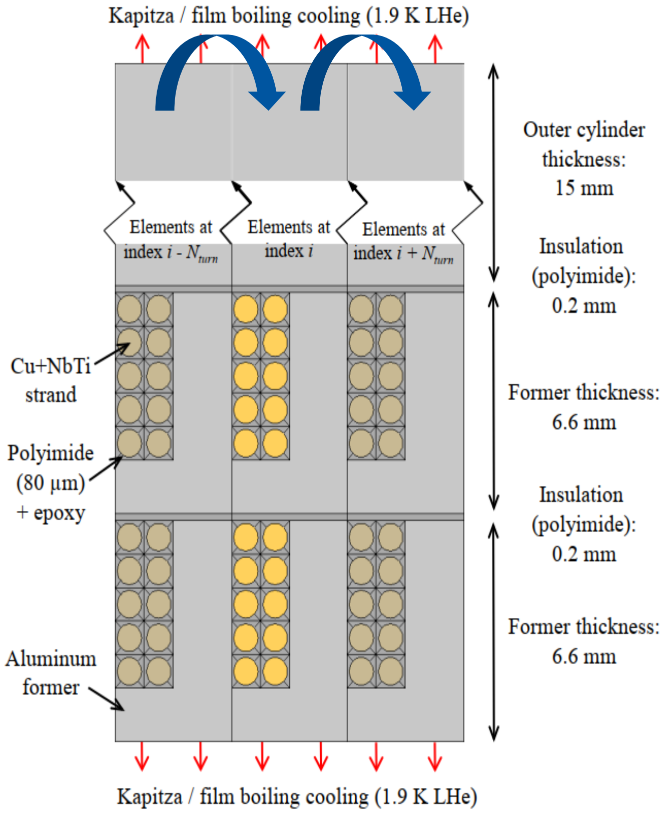


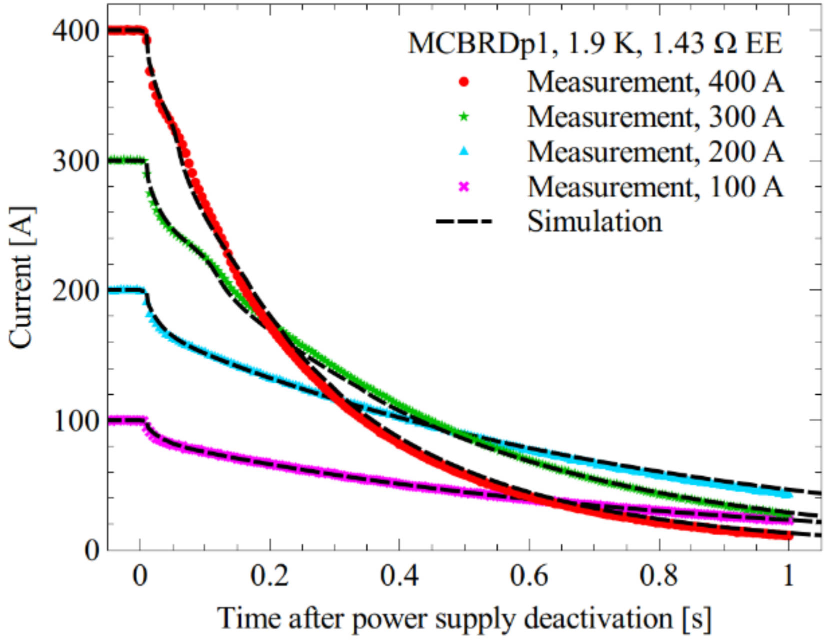
- B and M calculation for LEDET
- Eddy currents in the formers
- Temperature of the formers
- No plans for a stand alone quench simulation

→ 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

STEAM framework

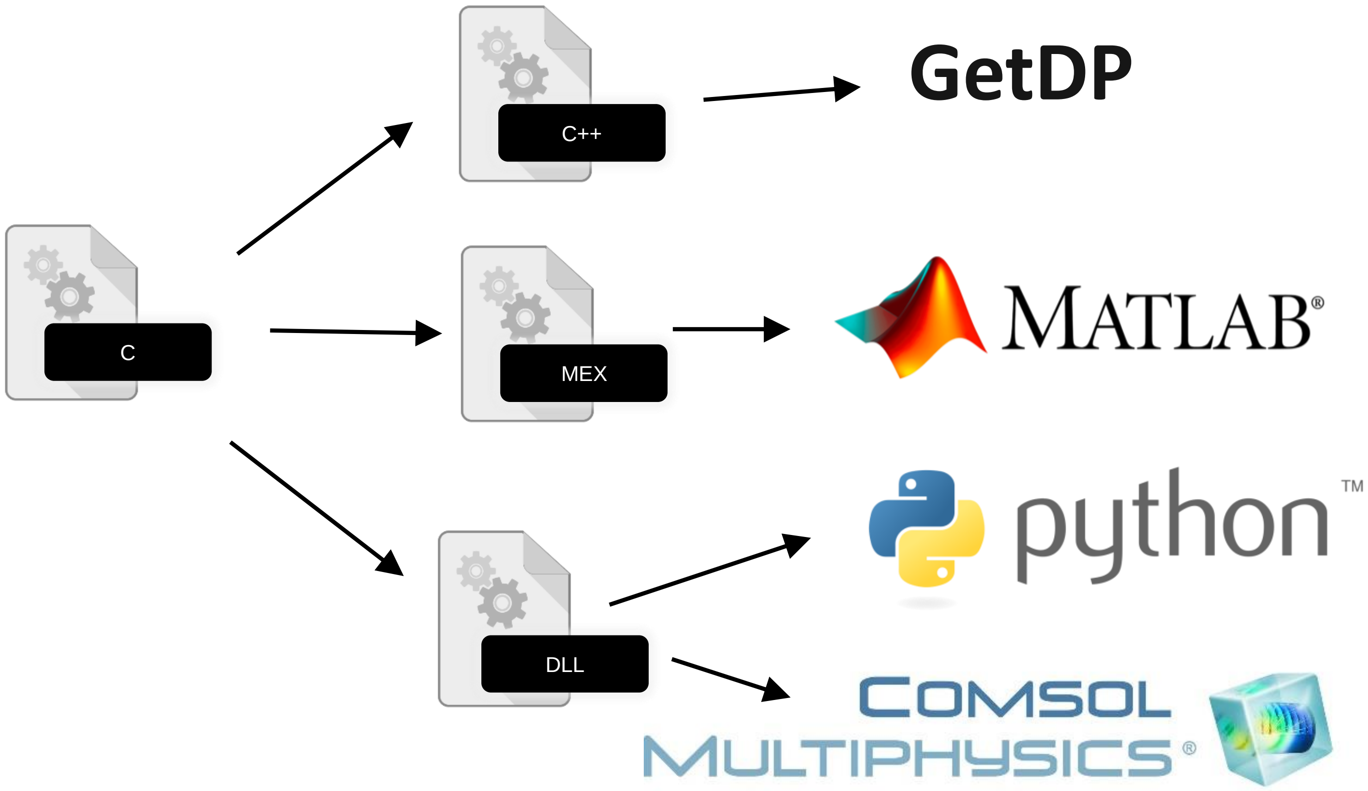
Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE

Materials properties

CHALLENGES

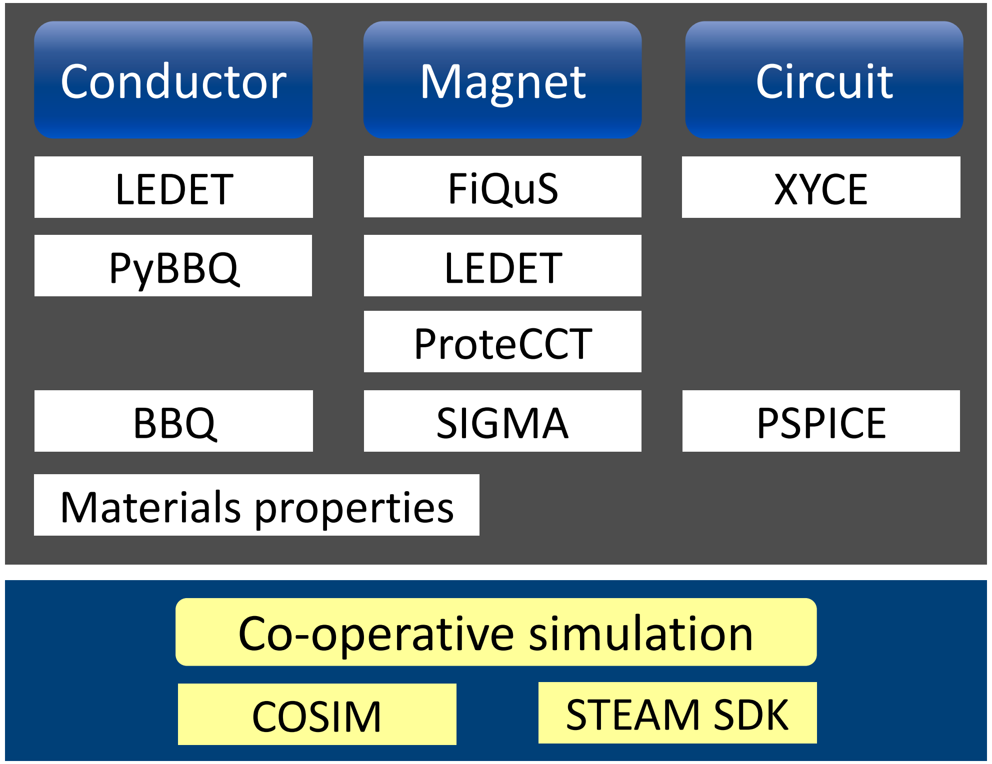
- ✓ Maintain consistency across simulation tools
- ✓ Use the same material properties in different tools

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).

STEAM framework



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

Materials properties

Co-operative simulation

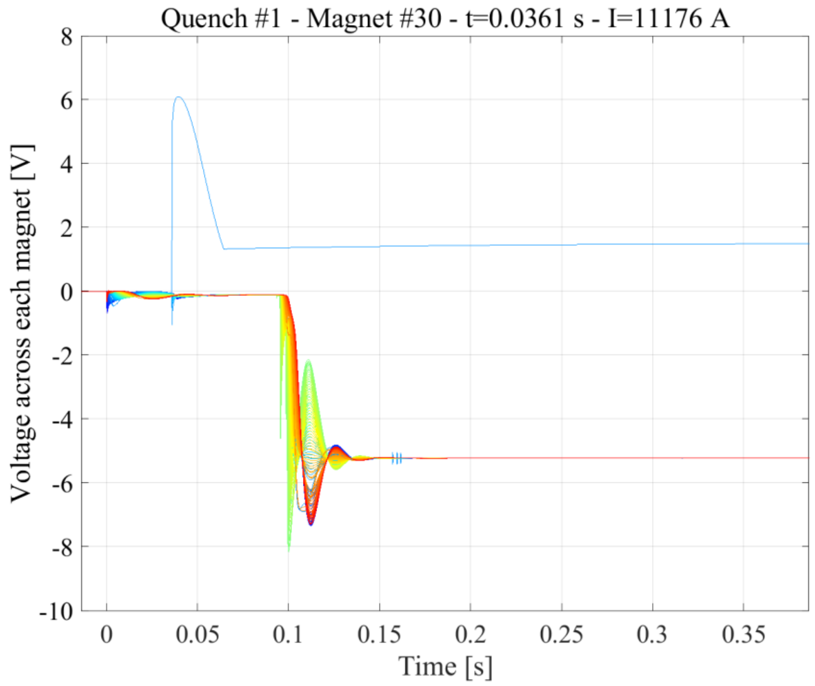
COSIM

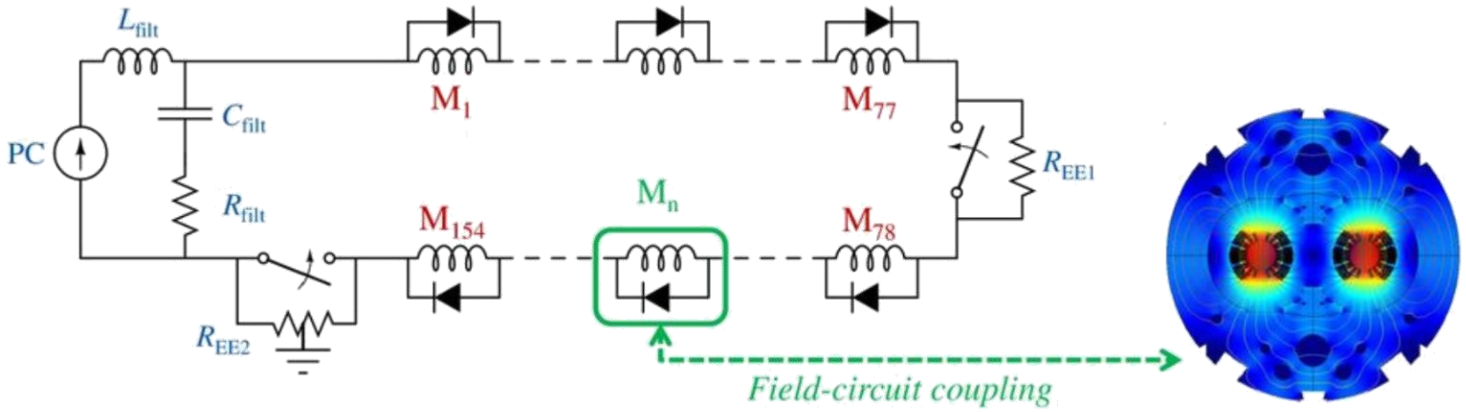
STEAM SDK

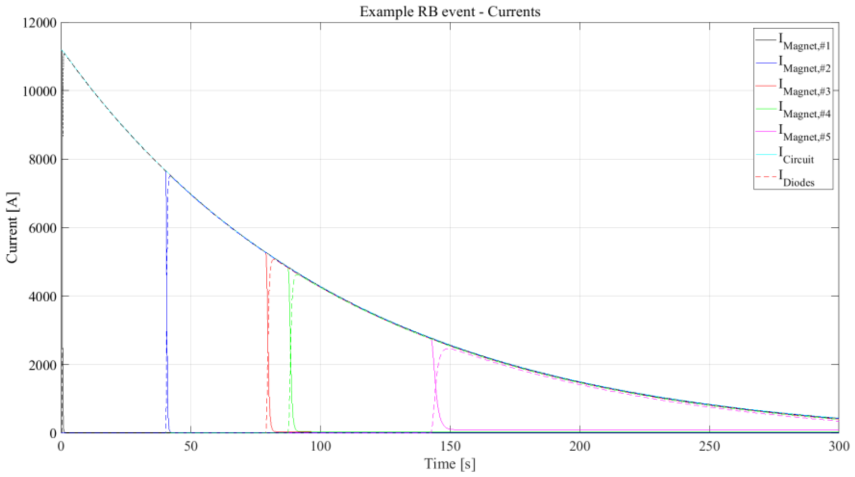
CHALLENGES

- ✓ Bridging functionalities of different simulation tools (impractical to implement all features in one tool)

COSIM (Co-operative Simulation)



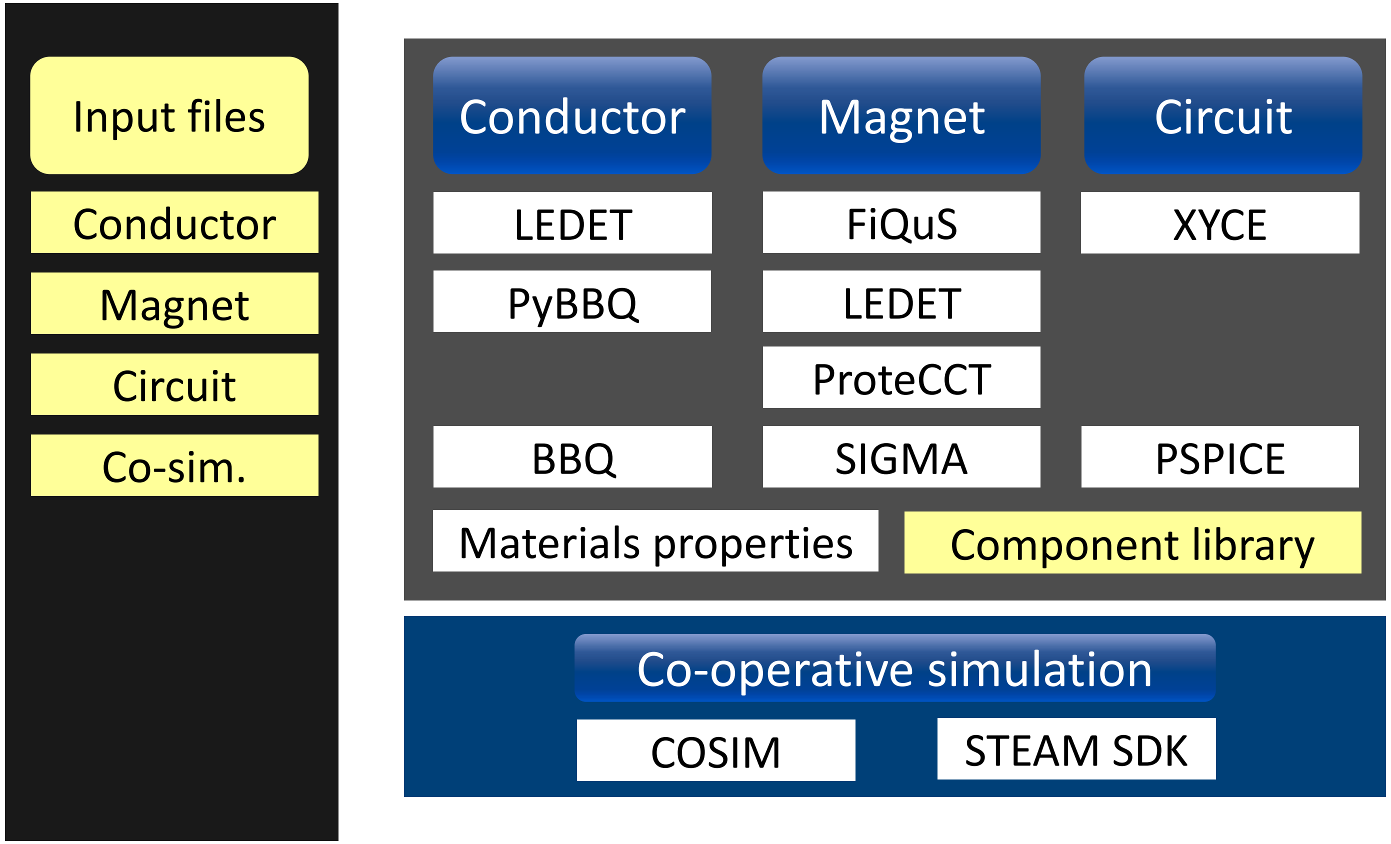




→ To run co-operative simulations of models developed in different software

→ Main use case is to couple magnet models to circuit models

STEAM framework



Input files
- Conductor
- Magnet
- Circuit
- Co-sim.

Conductor
- LEDET
- PyBBQ
- BBQ

Magnet
- FiQuS
- LEDET
- ProteCCT
- SIGMA

Circuit
- XYCE
- PSPICE

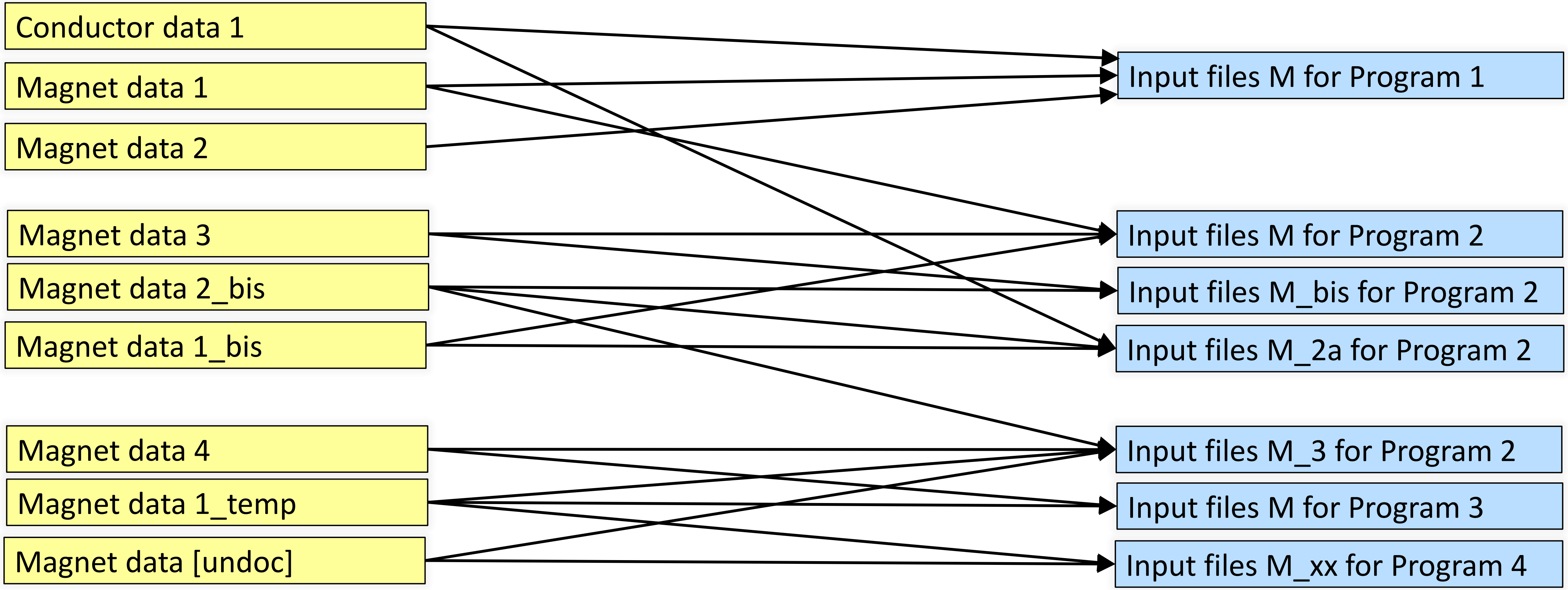
Materials properties

Component library

Co-operative simulation
- COSIM
- STEAM SDK

CHALLENGES
- ✓ Deal with multiple scattered inputs
- ✓ Duplication of the same inputs in multiple files
- ✓ Maintain a library of validated reference models, but remain flexible to deal with exceptions

What we should avoid



Conductor data 1

Magnet data 1

Magnet data 2

Magnet data 3

Magnet data 2_bis

Magnet data 1_bis

Magnet data 4

Magnet data 1_temp

Magnet data [undoc]

Input files M for Program 1

Input files M for Program 2

Input files M_bis for Program 2

Input files M_2a for Program 2

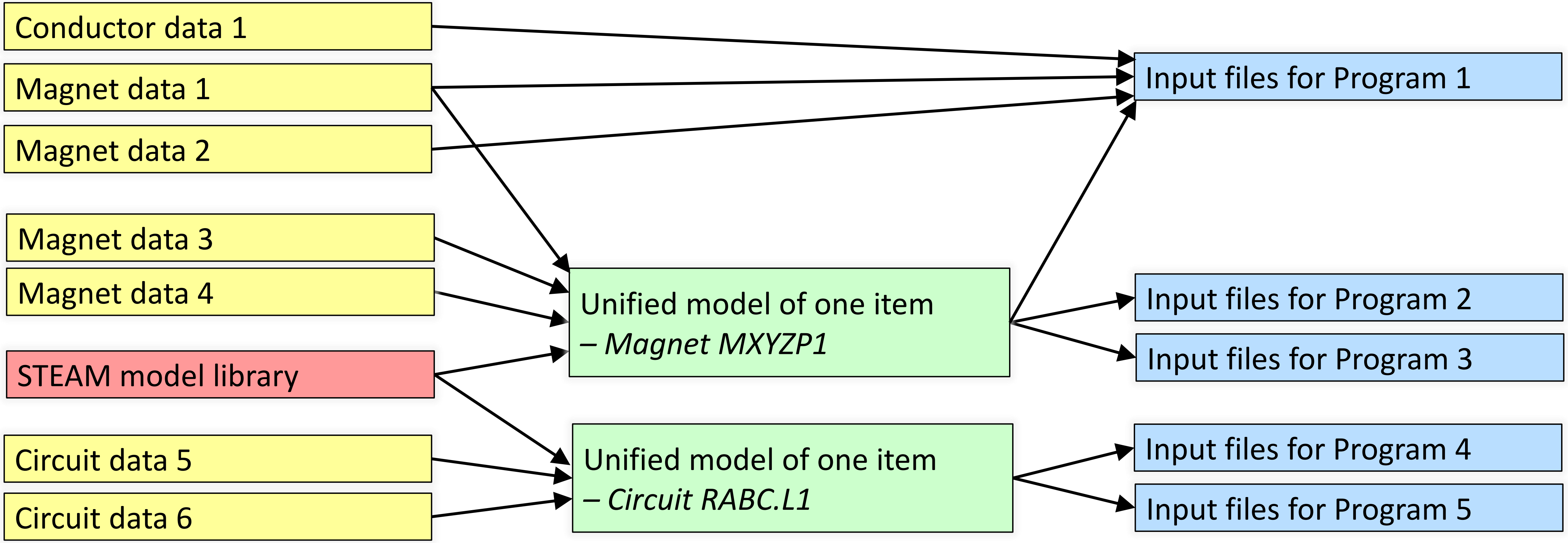
Input files M_3 for Program 2

Input files M for Program 3

Input files M_xx for Program 4

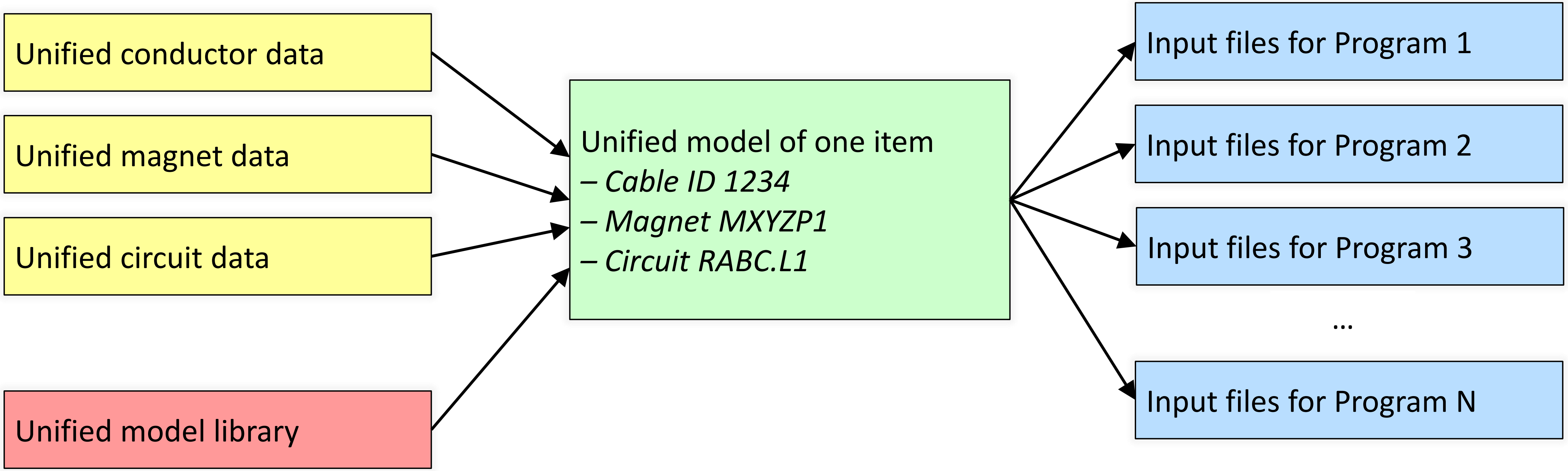
→ Information on the same element (for ex: magnet) is defined in multiple places, which might be inconsistent
→ Models are likely generated with different, often undocumented assumptions and features
→ Documenting what was done is challenging, and the analysis is likely not reproducible even in the near future

What we have



→ Model library of unified models allows generating models for different programs from the same input
→ Model library and the code to generate and run the models are versioned on Gitlab
→ Conductor, magnet, circuit information is collected manually from different sources (a weak link)

What we dream of



Unified conductor data

Unified magnet data

Unified circuit data

Unified model library

Unified model of one item
– *Cable ID 1234*
– *Magnet MXYZP1*
– *Circuit RABC.L1*

Input files for Program 1

Input files for Program 2

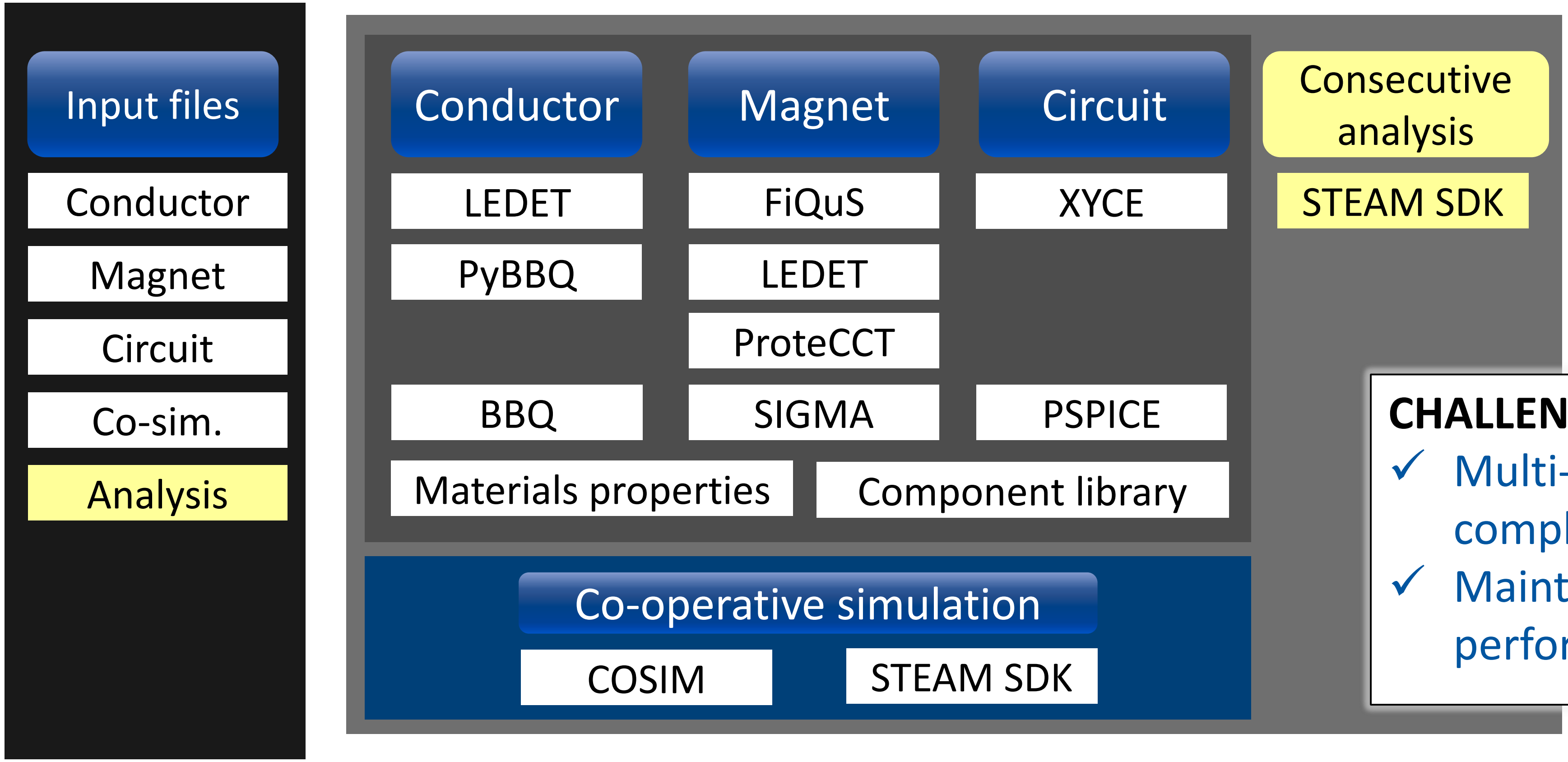
Input files for Program 3

…

Input files for Program N

→ All items are handled with the same code during model generation and run
→ This structure can grow naturally by handling more items and more programs
→ Whenever any project contributor adds a feature (for ex: new software, new input source,…), all contributors immediately benefit from it (better inputs, more capabilities, more precise boundary conditions, more accurate predictions,…)

STEAM framework



Input files

Conductor

Magnet

Circuit

Co-sim.

Analysis

Conductor

LEDET

PyBBQ

BBQ

Magnet

FiQuS

LEDET

ProteCCT

SIGMA

Circuit

XYCE

PSPICE

Materials properties

Component library

Consecutive analysis

STEAM SDK

Co-operative simulation

COSIM

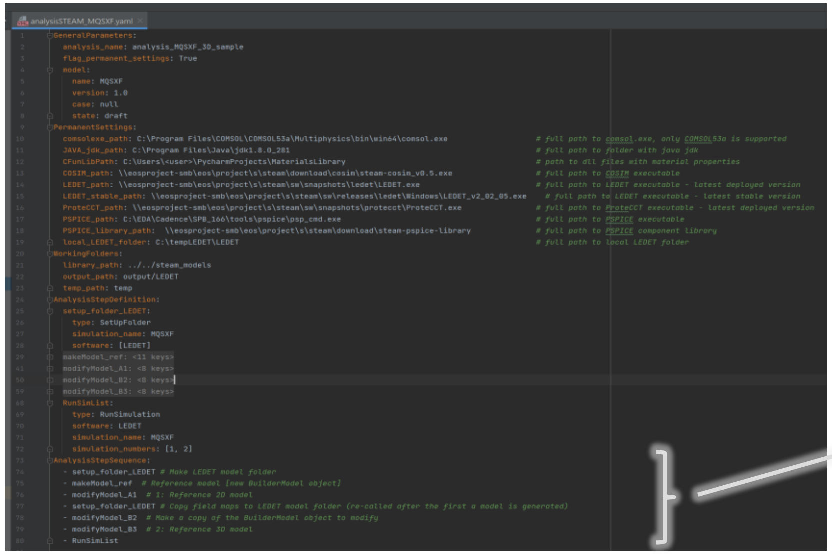
STEAM SDK

CHALLENGES

- ✓ Multi-step, multi-tool workflows are complicated
- ✓ Maintain long-term reproducibility of performed analyses

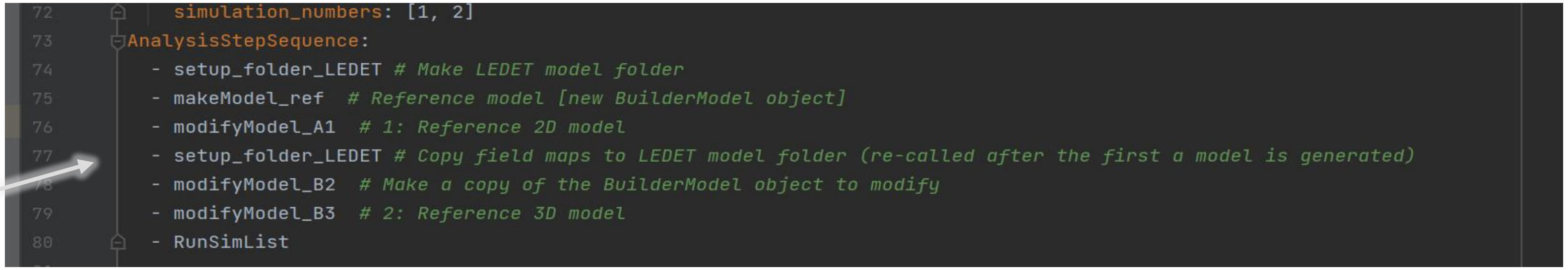
Consecutive Analysis

Setup folder → Load reference model → Change something in the model and give it a new number → Change something else in the model and give it another number → Run both simulations



analysisSTEAM_MQSXF.yaml

```
GeneralParameters:
  analysis_name: analysis_MQSXF_3D_sample
  flag_permanent_settings: True
  model:
    name: MQSXF
    version: 1.0
    case: null
    state: draft
PermanentSettings:
  comsolexe_path: C:\Program Files\COMSOL\COMSOL53a\Multiphysics\bin\win64\comsol.exe           # full path to comsol.exe, only COMSOL53a is supported
  JAVA_jdk_path: C:\Program Files\Java\jdk1.8.0_281                                             # full path to folder with java jdk
  CFunLibPath: C:\Users\<user>\PycharmProjects\MaterialsLibrary                                 # path to dll files with material properties
  COSIM_path: \\eosproject-smb\eos\project\s\steam\download\cosim\steam-cosim_v0.5.exe          # full path to COSIM executable
  LEDET_path: \\eosproject-smb\eos\project\s\steam\sw\snapshots\ledet\LEDET.exe                 # full path to LEDET executable - latest deployed version
  LEDET_stable_path: \\eosproject-smb\eos\project\s\steam\sw\releases\ledet\Windows\LEDET_v2_02_05.exe   # full path to LEDET executable - latest stable version
  ProteCCT_path: \\eosproject-smb\eos\project\s\steam\sw\snapshots\protecct\ProteCCT.exe        # full path to ProteCCT executable - latest deployed version
  PSPICE_path: C:\EDA\Cadence\SPB_166\tools\pspice\psp_cmd.exe                                  # full path to PSPICE executable
  PSPICE_library_path:  \\eosproject-smb\eos\project\s\steam\download\steam-pspice-library      # full path to PSPICE component library
  local_LEDET_folder: C:\tempLEDET\LEDET                                                        # full path to local LEDET folder
WorkingFolders:
  library_path: ../../steam_models
  output_path: output/LEDET
  temp_path: temp
AnalysisStepDefinition:
  setup_folder_LEDET:
    type: SetUpFolder
    simulation_name: MQSXF
    software: [LEDET]
  makeModel_ref: <11 keys>
  modifyModel_A1: <8 keys>
  modifyModel_B2: <8 keys>
  modifyModel_B3: <8 keys>
  RunSimList:
    type: RunSimulation
    software: LEDET
    simulation_name: MQSXF
    simulation_numbers: [1, 2]
AnalysisStepSequence:
  - setup_folder_LEDET # Make LEDET model folder
  - makeModel_ref  # Reference model [new BuilderModel object]
  - modifyModel_A1  # 1: Reference 2D model
  - setup_folder_LEDET # Copy field maps to LEDET model folder (re-called after the first a model is generated)
  - modifyModel_B2  # Make a copy of the BuilderModel object to modify
  - modifyModel_B3  # 2: Reference 3D model
  - RunSimList
```



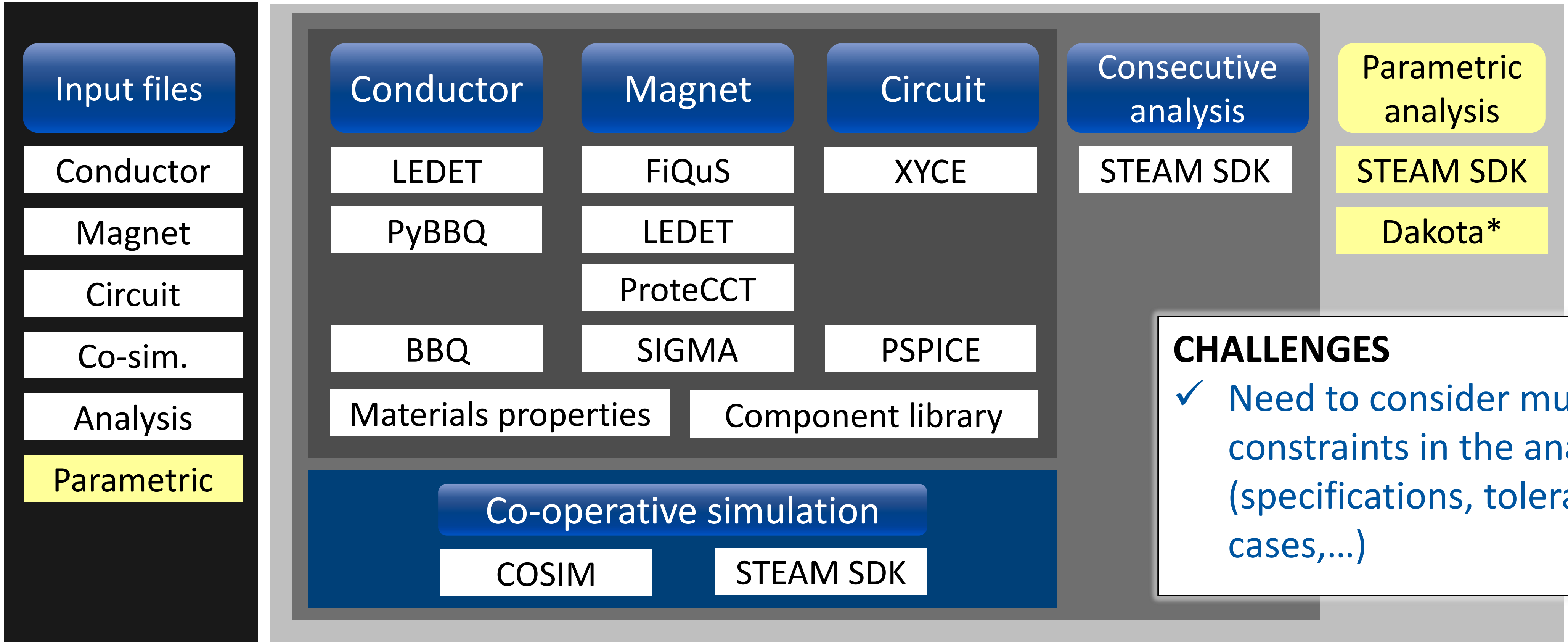
```
    simulation_numbers: [1, 2]
AnalysisStepSequence:
  - setup_folder_LEDET # Make LEDET model folder
  - makeModel_ref  # Reference model [new BuilderModel object]
  - modifyModel_A1  # 1: Reference 2D model
  - setup_folder_LEDET # Copy field maps to LEDET model folder (re-called after the first a model is generated)
  - modifyModel_B2  # Make a copy of the BuilderModel object to modify
  - modifyModel_B3  # 2: Reference 3D model
  - RunSimList
```

→ Programmatically setup folders, change model parameters, and run models
→ Achieved with a dedicated yaml file per analysis to allow to keep history of what was done
→ Records which software versions have been used for analysis
→ Greatly simplifies model setup and allows for changes to the reference models

Fun challenge

Full analysis without ever opening a model input file

STEAM framework



Input files
- Conductor
- Magnet
- Circuit
- Co-sim.
- Analysis
- Parametric

Conductor
- LEDET
- PyBBQ
- BBQ

Magnet
- FiQuS
- LEDET
- ProteCCT
- SIGMA

Circuit
- XYCE
- PSPICE

Materials properties

Component library

Consecutive analysis
- STEAM SDK

Parametric analysis
- STEAM SDK
- Dakota*

Co-operative simulation
- COSIM
- STEAM SDK

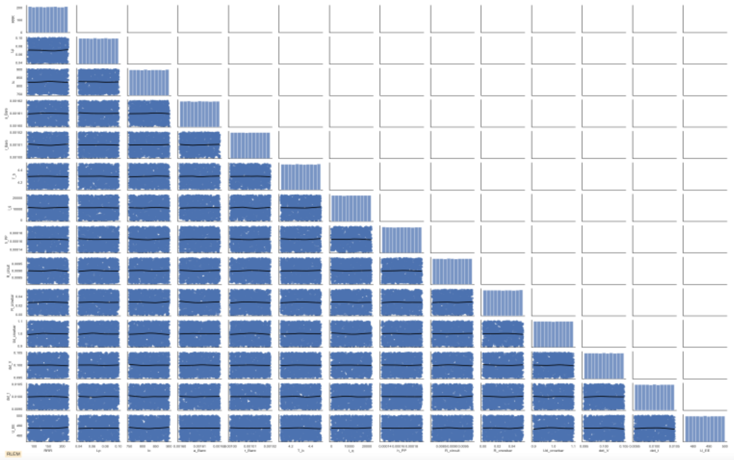
CHALLENGES

✓ Need to consider multiple design constraints in the analysis (specifications, tolerances, failure cases,…)

*Free tool from Sandia Labs.

Parametric analysis

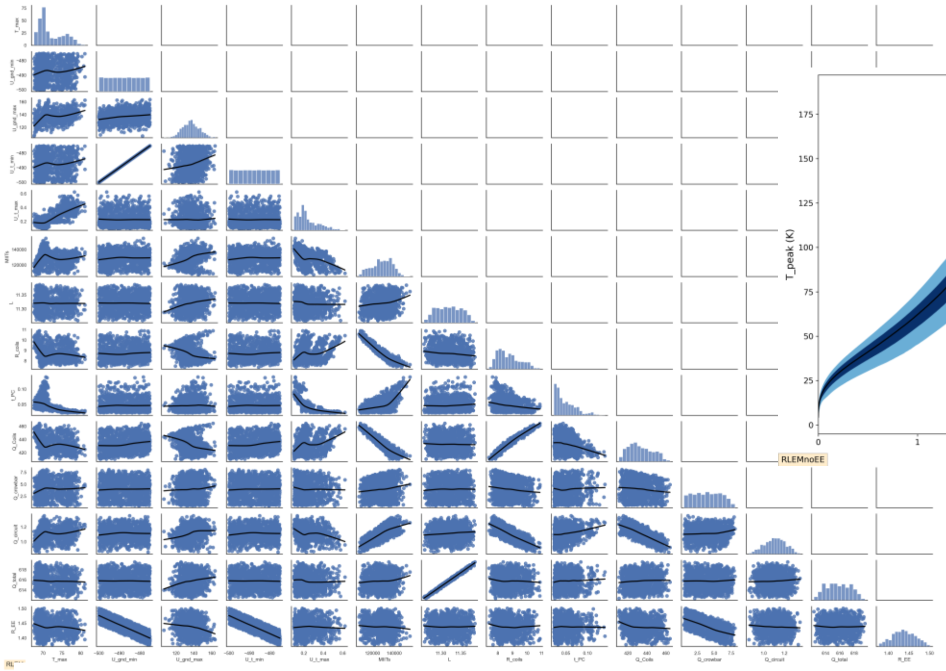
Part	#	Variable name	Nominal	Absolute range		% range		Unit	Circuit
Wire	1	RRR	100	80	220	-20%	120%	-	All
	2	Twist pitch length	50	40	100	-20%	100%	mm	All
	3	Ic @ 4T, 4.2K	750	750	900	0%	20%	A	All
	4	Bare height	1.61	1.60	1.62	-0.6%	0.6%	mm	All
	5	Bare width	1.01	1.00	1.02	-1.0%	1.0%	mm	All
Magnet	6	Bath temperature	4.2	4.10	4.50	-2.4%	7.1%	K	All
	7	Quench ini. turn	1	first turn	last turn	0.0%	100.0%	-	All
	8	Pre-Preg thickness	150	135	195	-10%	30%	um	All
Circuit	9	R warm circuit	90	81	99	-10%	10%	mΩ	600A
			54	48.6	59.4	-10%	10%	mΩ	120A
	10	R crowbar	50	0*	55	-100%	10%	mΩ	600A
			80	0*	88	-100%	10%	mΩ	120A
	11	Ud crowbar	1	0.9	1.1	-10%	10%	V	All
	12	EE voltage	500	475	500	-5%	0%	V	EE
			0	0	0	-5%	0%	V	noEE
Detection	13	Detection threshold	100	95	105	-5%	5%	mV	All
	14	Discrimination time	10	9.5	10.5	-5%	5%	ms	All

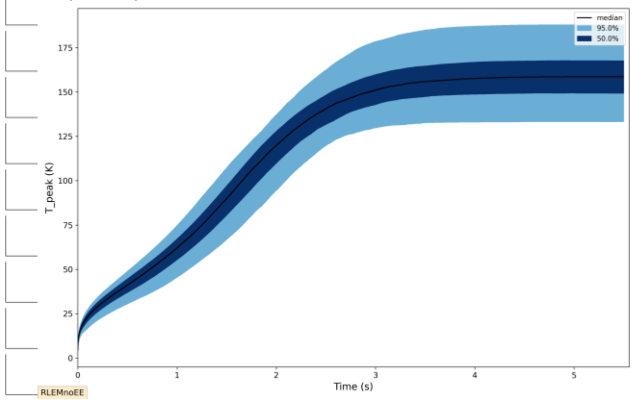


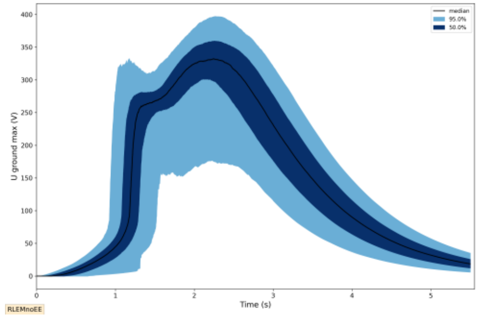
Example of Uncertainty Quantification

DAKOTA
Explore and predict with confidence

Sandia National Laboratories







Other capabilities:

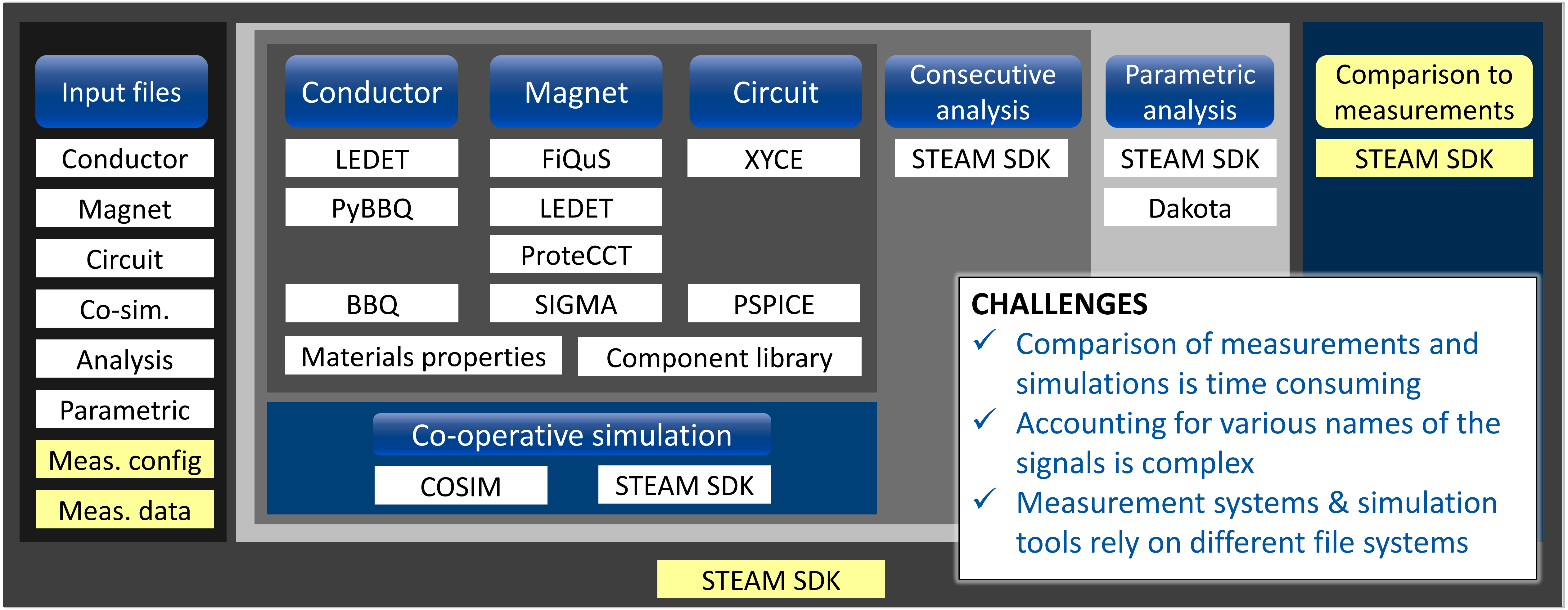
- Parametric studies
- Design of Experiment
- Optimization

→ Benefits from text-based input files for models, virtually any input can be changed

→ Works ‘on top’ of consecutive analysis files, so complicated sequence of steps is possible (WIP)

→ Works with cooperative-simulations, so multitool parametric setups are possible (WIP)

STEAM framework

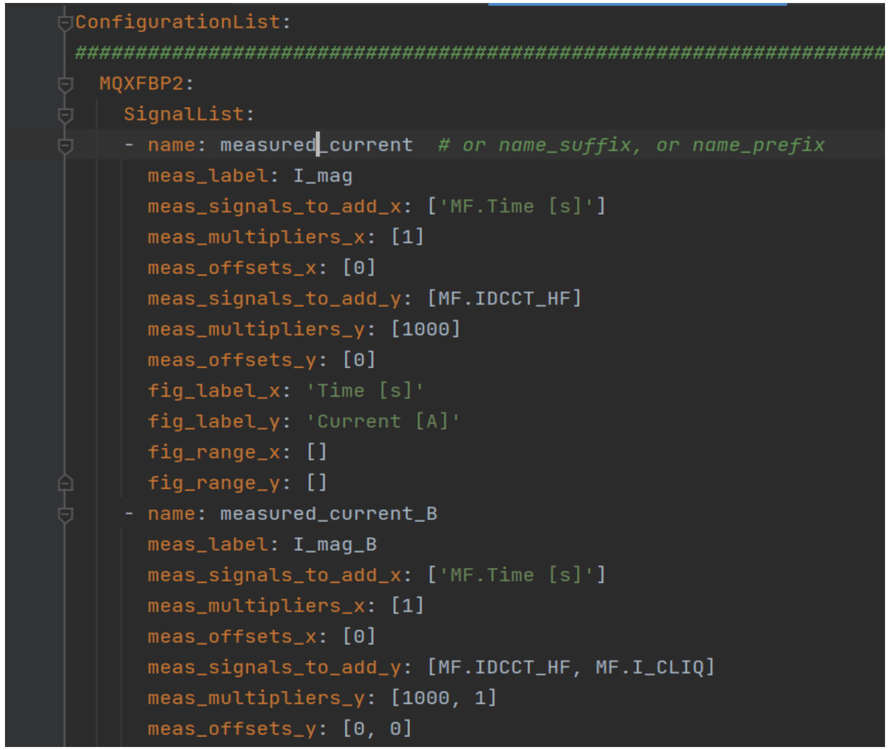


CHALLENGES

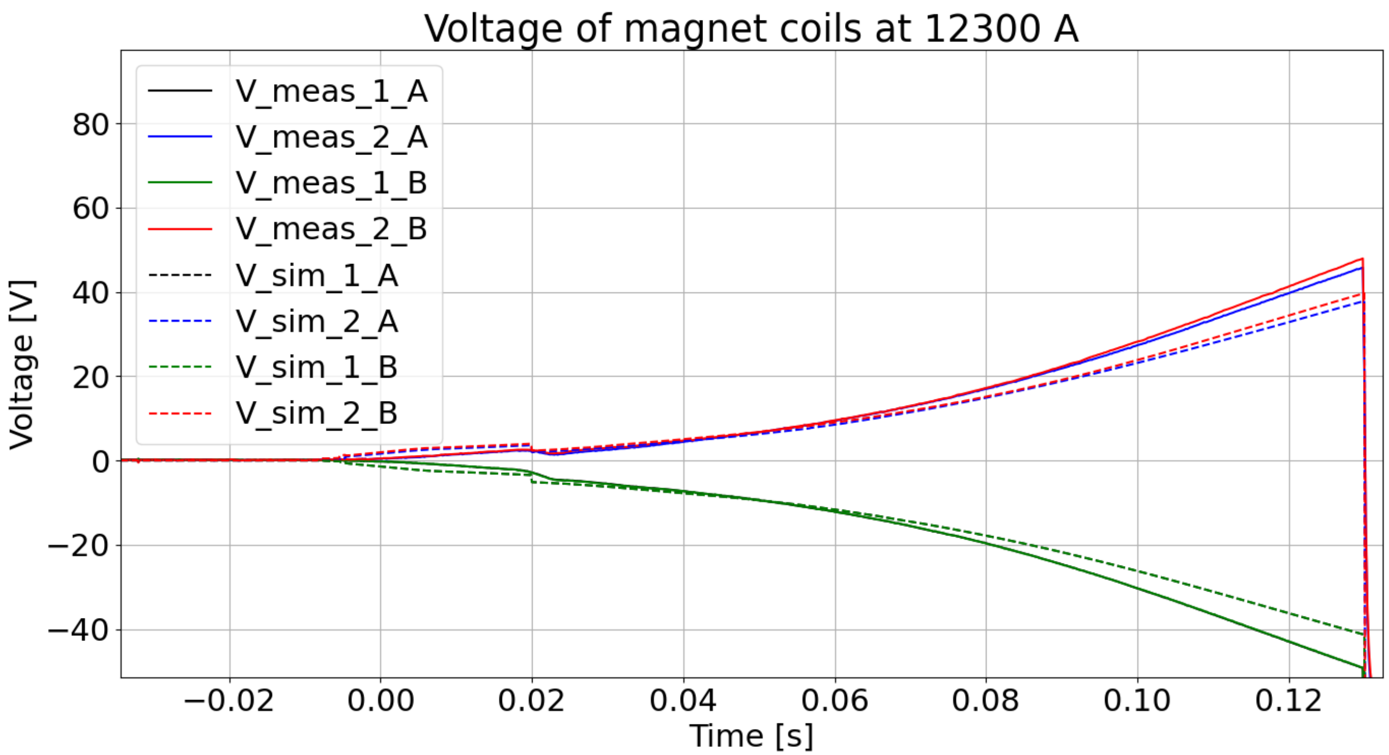
- ✓ Comparison of measurements and simulations is time consuming
- ✓ Accounting for various names of the signals is complex
- ✓ Measurement systems & simulation tools rely on different file systems

some functionality is under active development

Measurements and simulations comparison



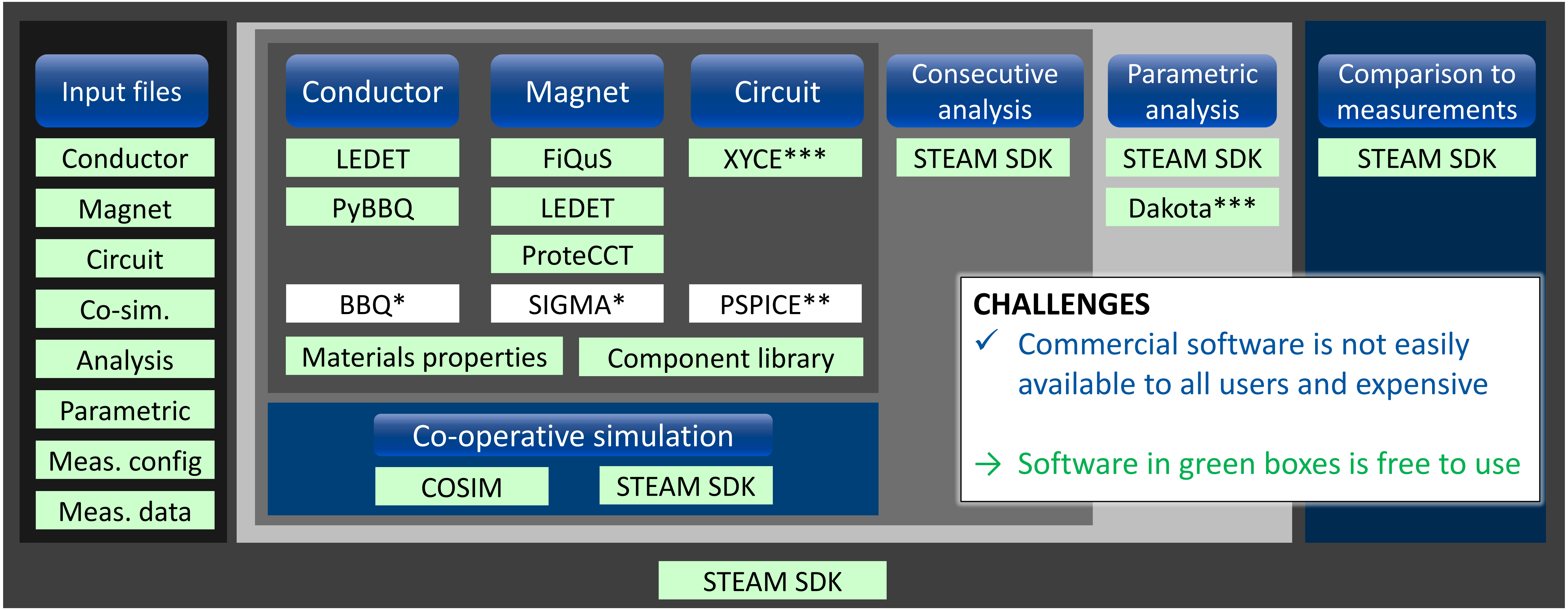
```
ConfigurationList:
###################################################################
  MQXFBP2:
    SignalList:
    - name: measured_current  # or name_suffix, or name_prefix
      meas_label: I_mag
      meas_signals_to_add_x: ['MF.Time [s]']
      meas_multipliers_x: [1]
      meas_offsets_x: [0]
      meas_signals_to_add_y: [MF.IDCCT_HF]
      meas_multipliers_y: [1000]
      meas_offsets_y: [0]
      fig_label_x: 'Time [s]'
      fig_label_y: 'Current [A]'
      fig_range_x: []
      fig_range_y: []
    - name: measured_current_B
      meas_label: I_mag_B
      meas_signals_to_add_x: ['MF.Time [s]']
      meas_multipliers_x: [1]
      meas_offsets_x: [0]
      meas_signals_to_add_y: [MF.IDCCT_HF, MF.I_CLIQ]
      meas_multipliers_y: [1000, 1]
      meas_offsets_y: [0, 0]
```



→ Allow defining equivalent signals in measurements and simulation files
→ Particularly useful to define "templates" for similar analyses (for ex: series magnets)
→ Simple operations like adding v-taps signal for a total signal are supported
→ Flexible setup able to cope with exceptions (for ex: missing v-tap during a campaign)

Measurement data: F. Mangiarotti
Analysis: L. Bender, TECH

STEAM framework



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

Conductor
- LEDET
- PyBBQ
- BBQ*

Magnet
- FiQuS
- LEDET
- ProteCCT
- SIGMA*

Circuit
- XYCE***
- PSPICE**

Materials properties

Component library

Co-operative simulation
- COSIM
- STEAM SDK

Consecutive analysis
- STEAM SDK

Parametric analysis
- STEAM SDK
- Dakota***

Comparison to measurements
- STEAM SDK

STEAM SDK

CHALLENGES

✓ Commercial software is not easily available to all users and expensive

→ Software in green boxes is free to use

some functionality is under active development

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

STEAM LIBRARY

STEAM superconducting magnet circuit library

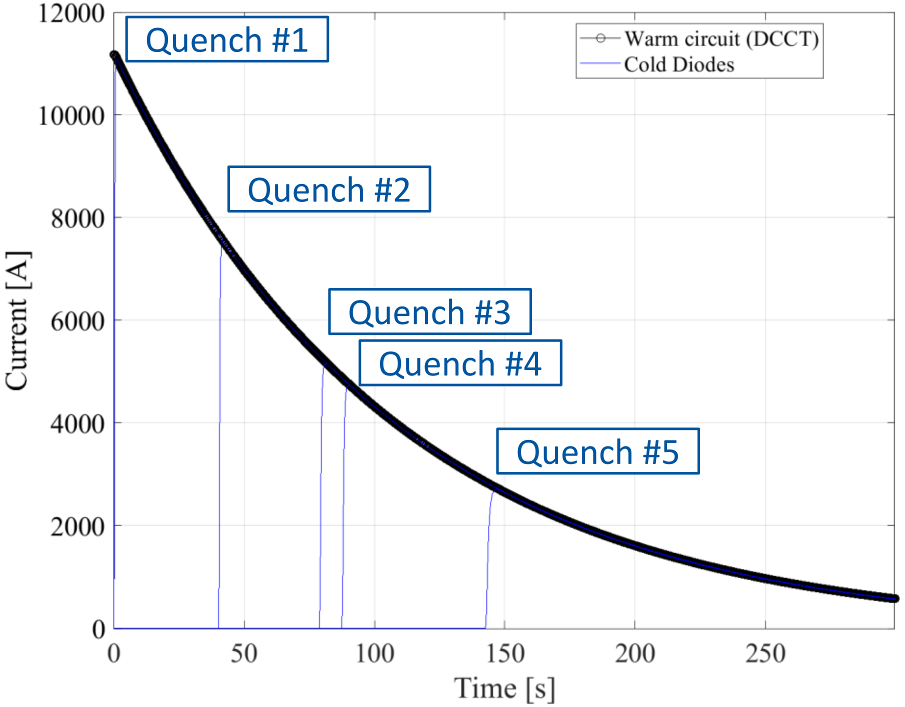
Magnet type	Self-protected (3D)	EE + quench-back	QH	CLIQ	Co-simulation	Short-circuit	NI
Multipole	√	√	√	√	√	√	
Solenoid	√	√			√		
CCT	√	√			w.i.p.		
Curved CCT	w.i.p.	w.i.p.			w.i.p.		
Pancakes	w.i.p.						w.i.p.

- ✓ ~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

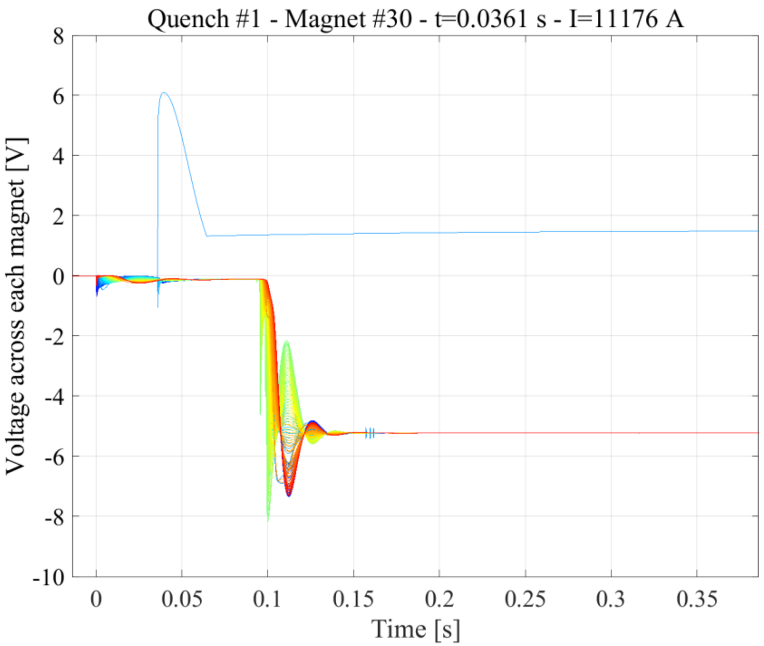
LHC TRANSIENTS

Example of simulated quenches and FPA in an RB circuit

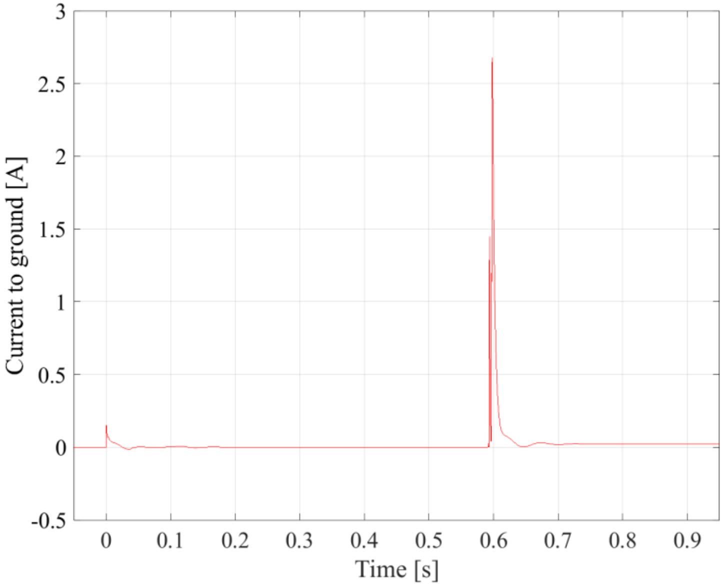
Circuit and and magnet currents



Voltages across the magnets



Earth current

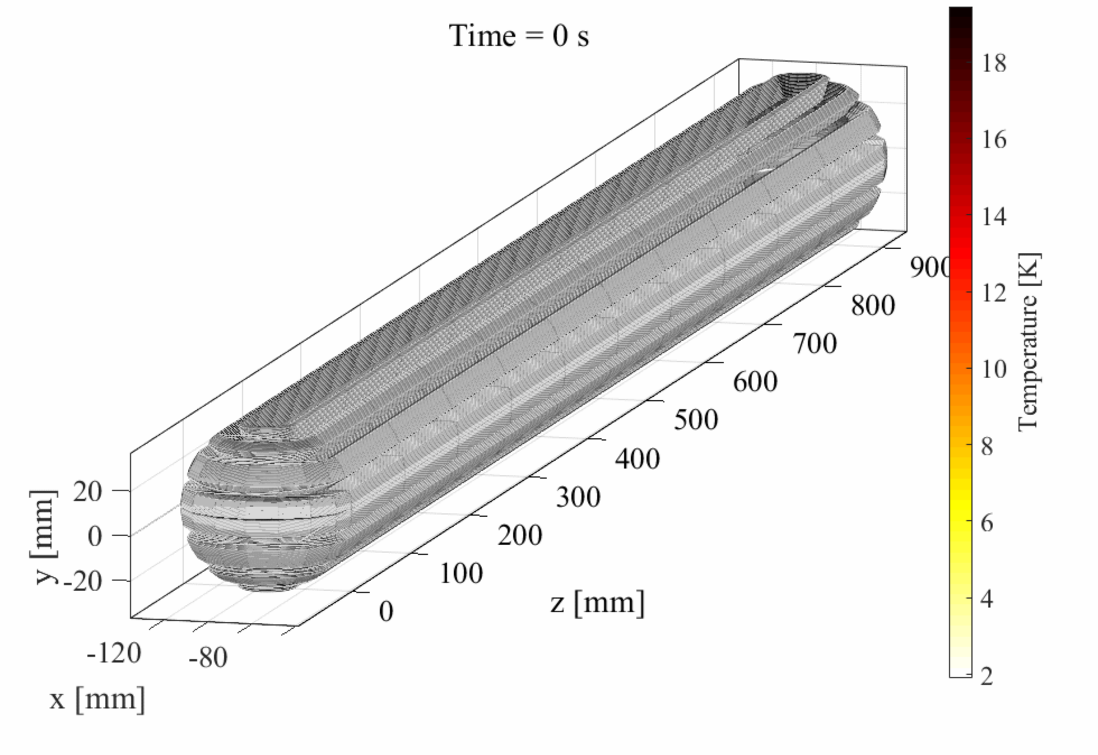


✓ Simulations of specific fast power abort (FPA) events in RB circuits are generated automatically based on the information provided by the LHC-SIGMON notebooks

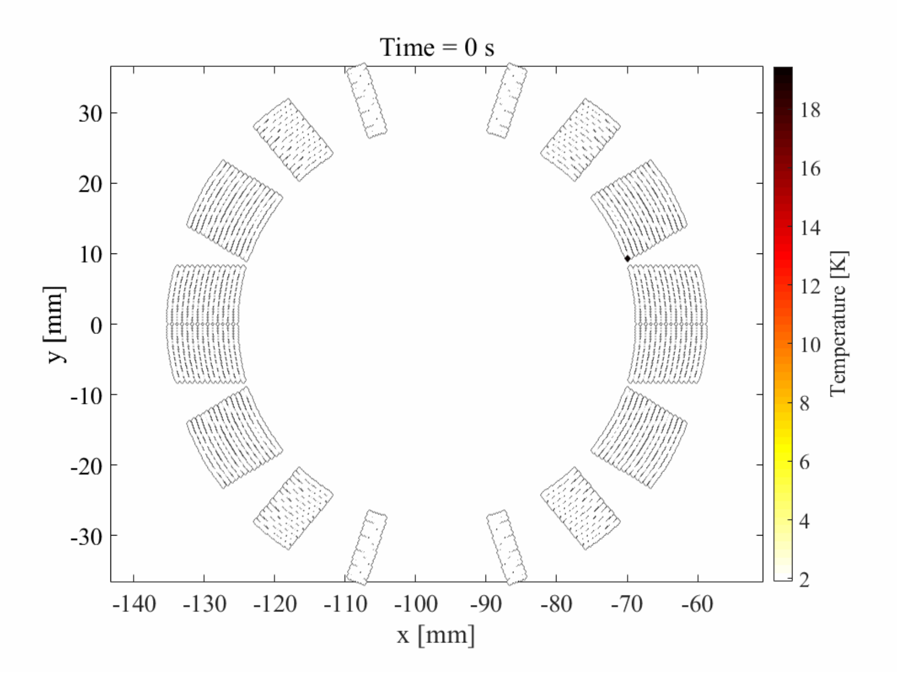
M. Janitschke, TECH

Example of simulated quench in a 120 A magnet

Temperature evolution in the coil turns



Temperature evolution in coil cross-section



- ✓ 3D model of a self-protecting magnet coil during a quench discharge
- ✓ Coupling loss is included in the simulation as well
- ✓ Simulation time <1 h

Example of simulated quench and FPA in a 600 A undulator circuit -1

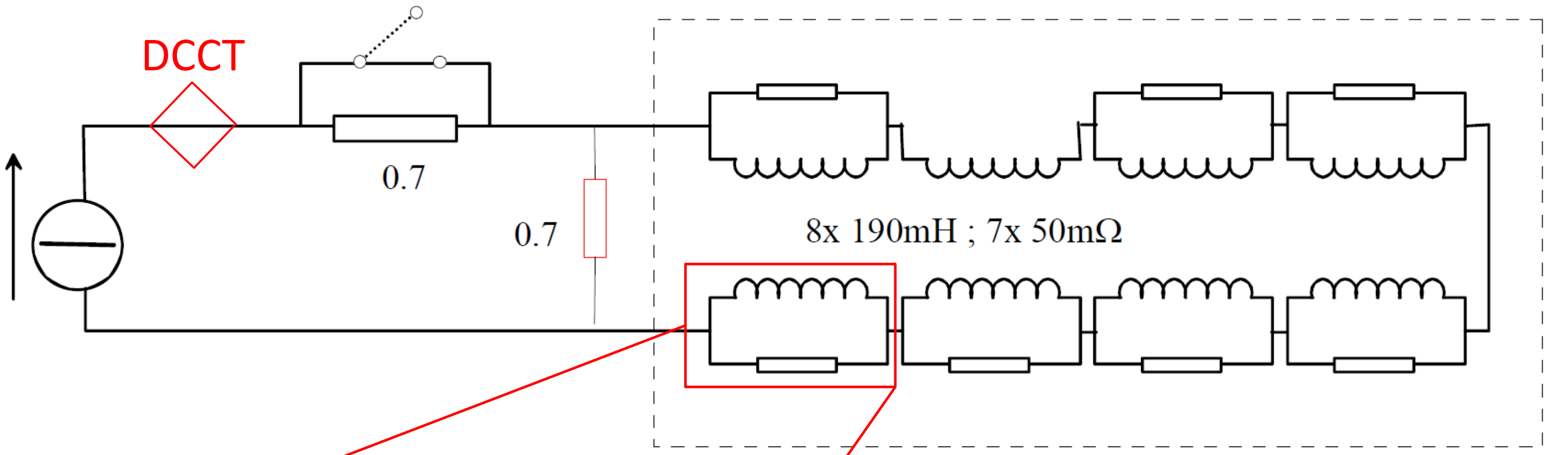
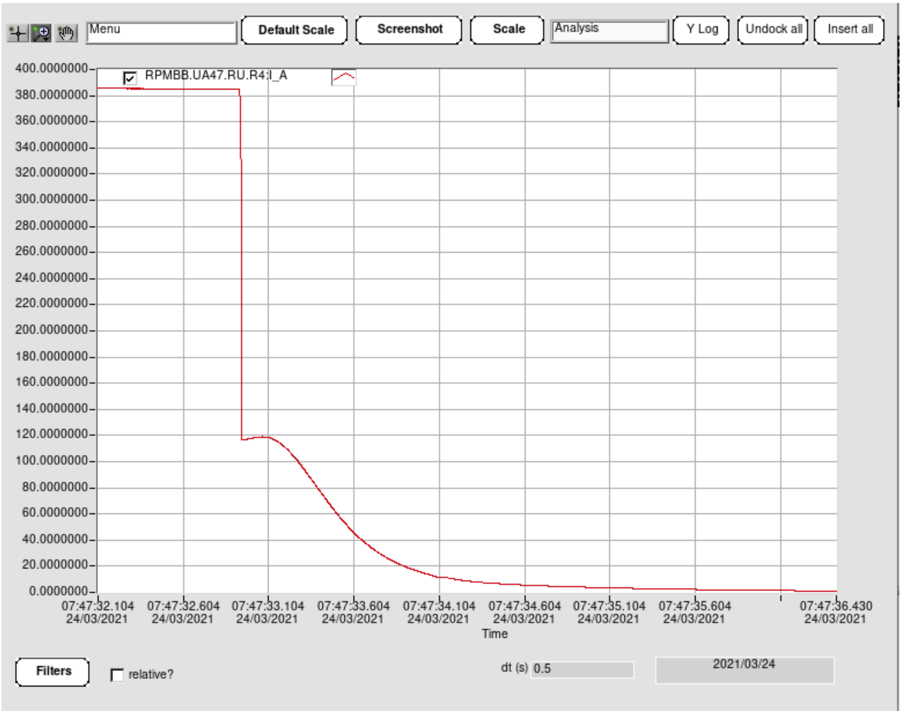
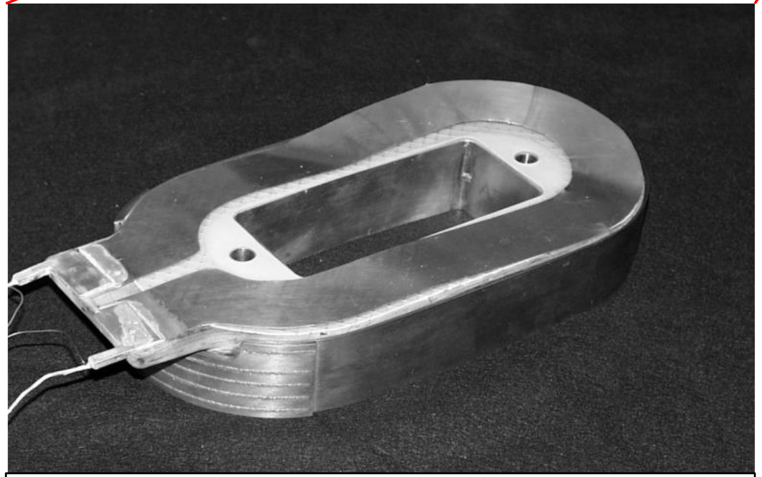


Figure 4: MU-L4 Simplified circuit layout modified



Circuit current measured by the DCCT



From LHC Project Report 894

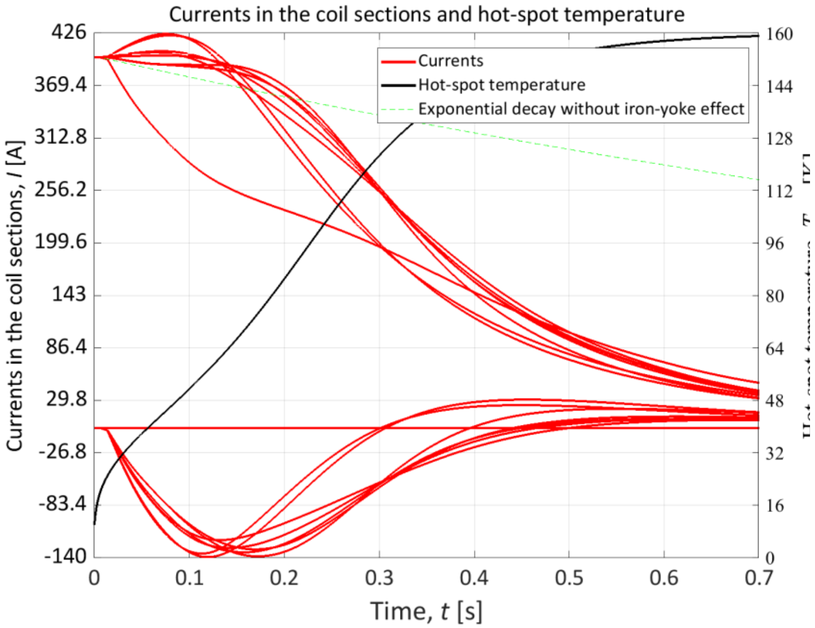
- ✓ Very difficult to understand, let alone analyze, such a difficult transient with the available measurements
- ✓ Note that the parallel resistors also act as quench heaters

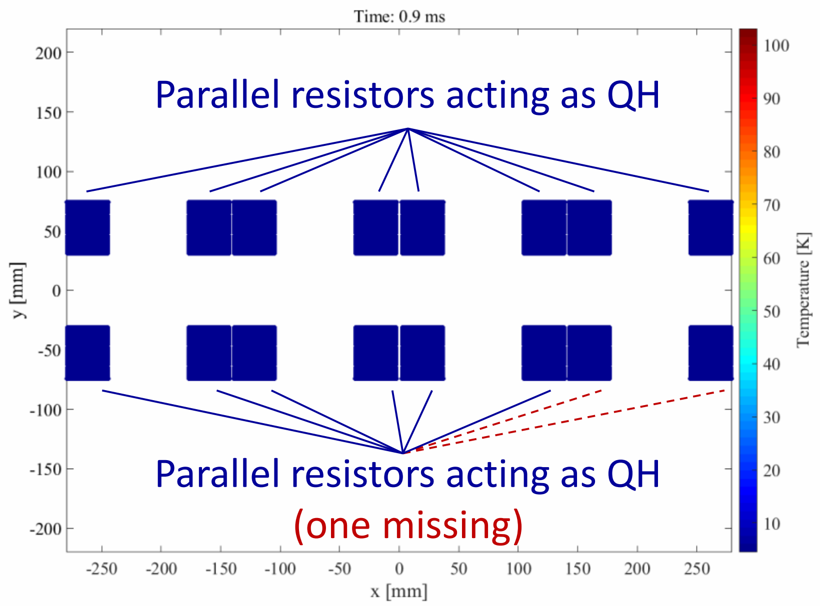
Example of simulated quench and FPA in a 600 A undulator circuit -2

Currents of 8 coils
and 7 parallel resistors

Evolution of the temperature
in the coil turns

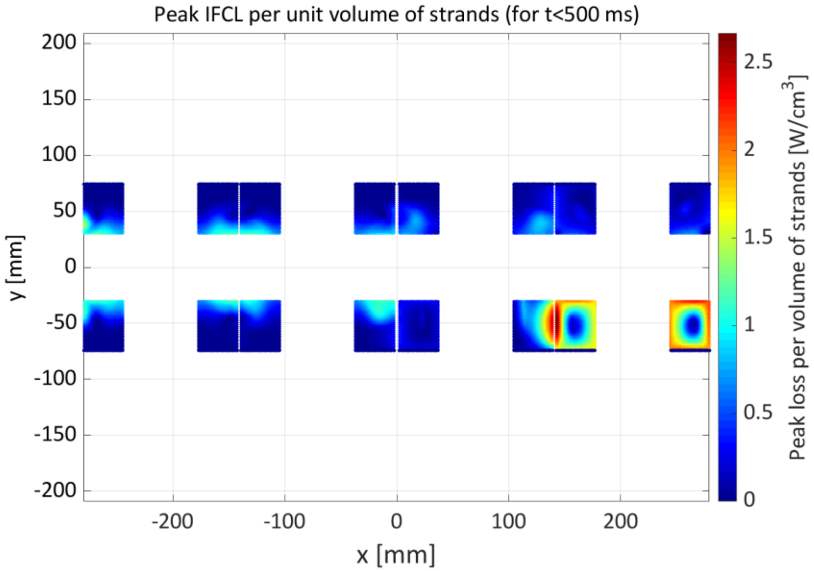
Peak power deposition
due to coupling loss





Parallel resistors acting as QH

Parallel resistors acting as QH
(one missing)



- ✓ To simulate this transient, the software must include quench development, thermal diffusion from the resistors to the turns and among turns, longitudinal quench propagation, mutual coupling between coils and parallel resistors, coupling loss,…

In the not-so-distant future…

Circuit data

Magnet data

Conductor data

Unified model

Measurement data

LHC event data

`awesome_function_1(circuit_name, LHC_event_name)`

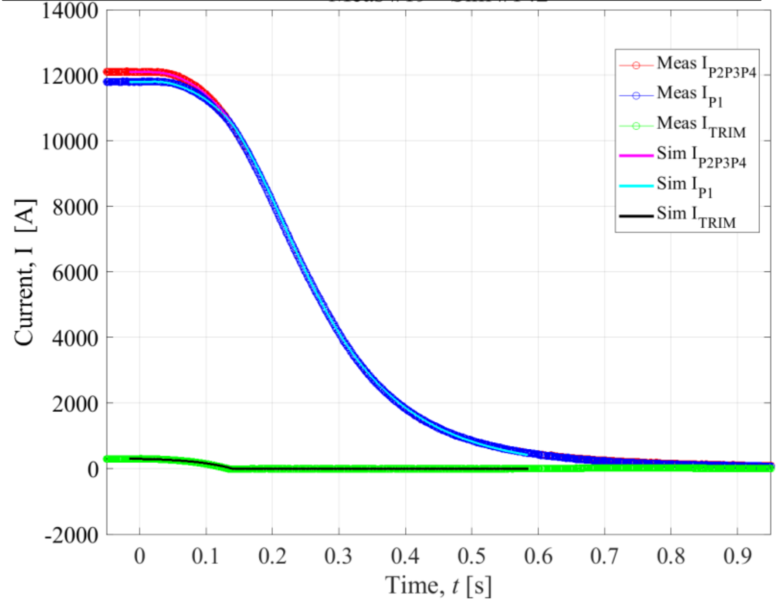
Simulation of the selected event

Comparison to measurements

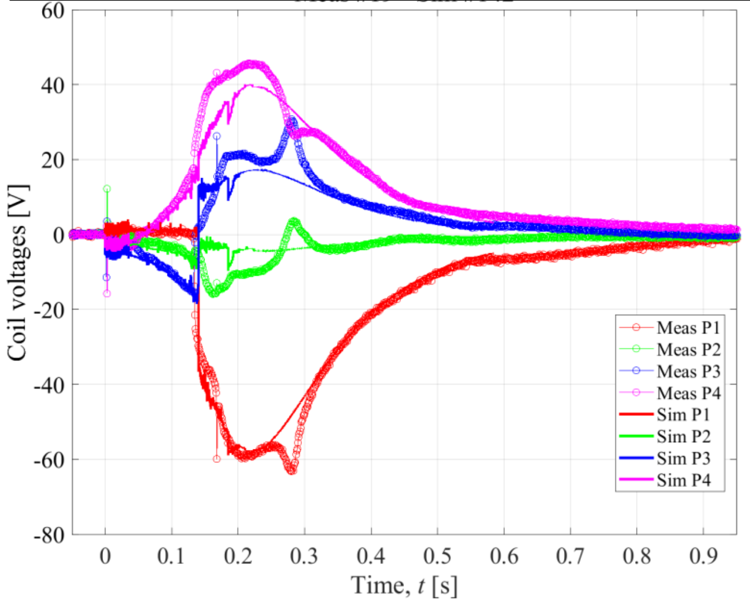
HL-LHC TRANSIENTS

MQXFBP2 trimmed powering tests -1

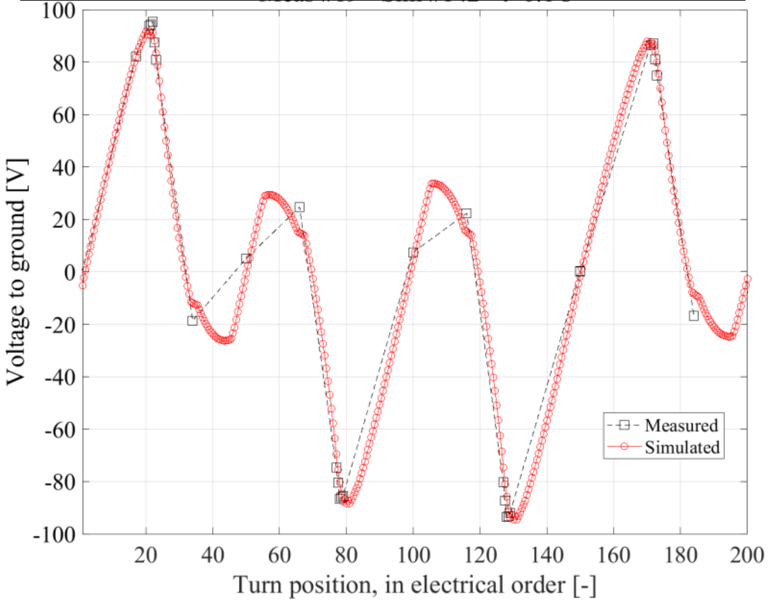
Currents in the circuit



Voltages across the four coils



Voltages to ground at t=150 ms

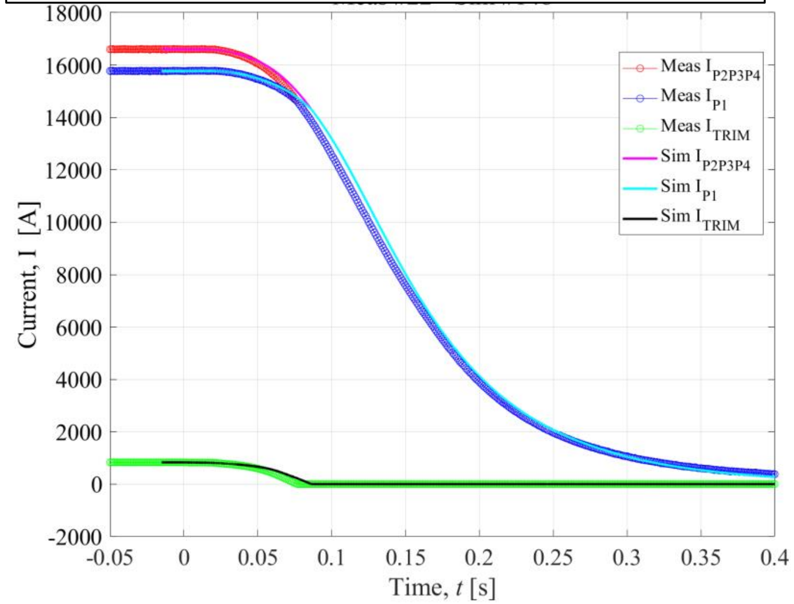


- ✓ Co-simulation between MQXF magnet model [LEDET] and electrical circuit [PSPICE]
- ✓ Good agreement achieved between simulations and measurements

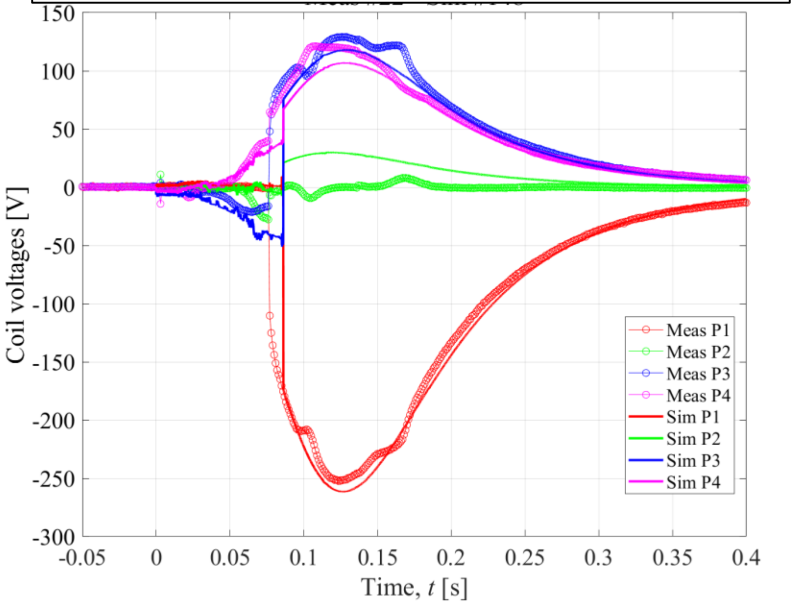
Measurements data: F. Mangiarotti

MQXFBP2 trimmed powering tests -2

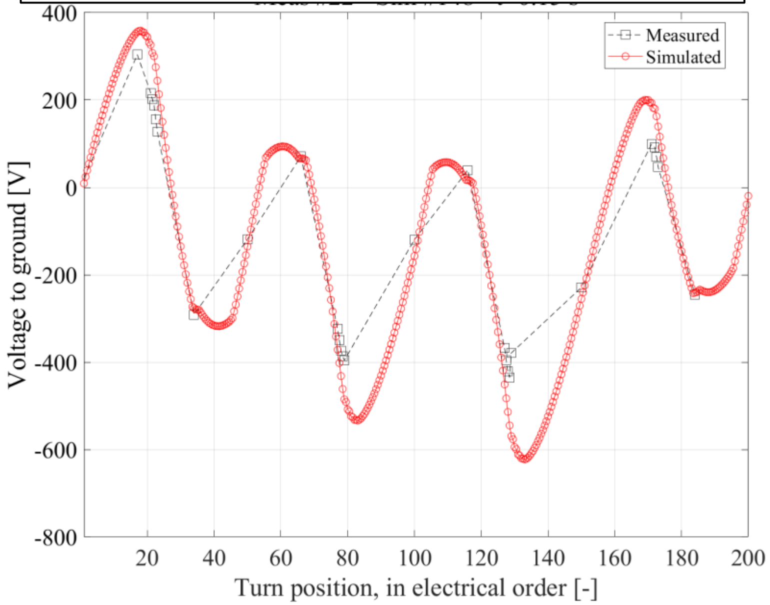
Currents in the circuit



Voltages across the four coils



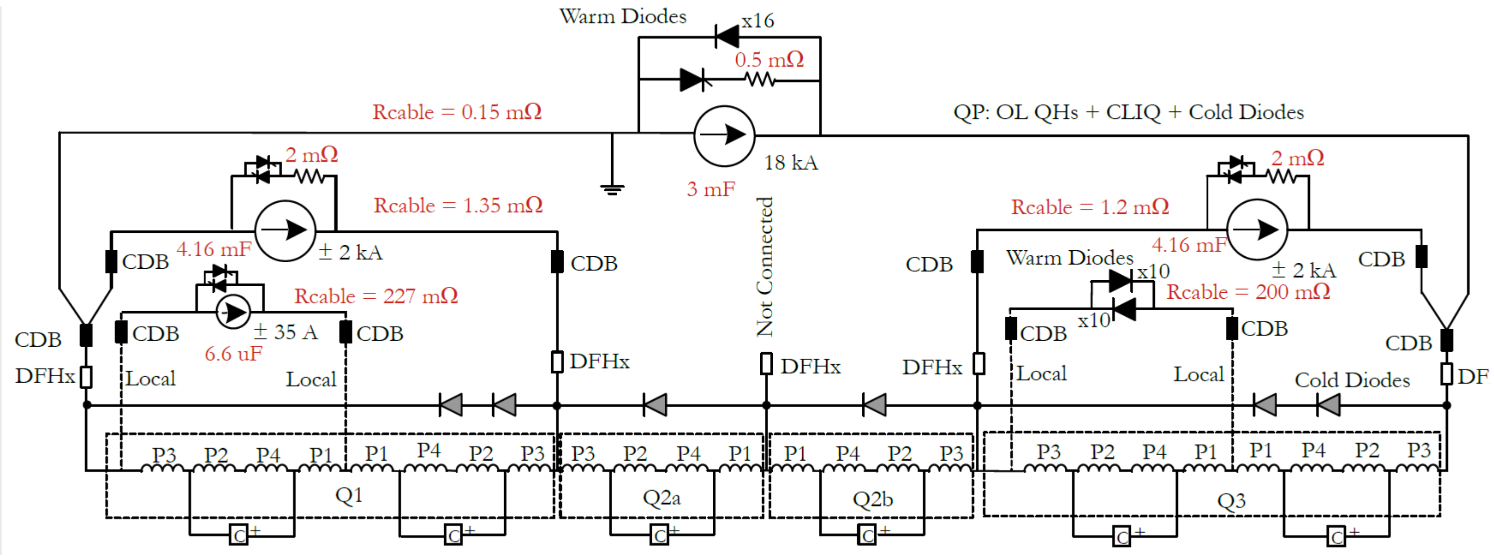
Voltages to ground at t=150 ms



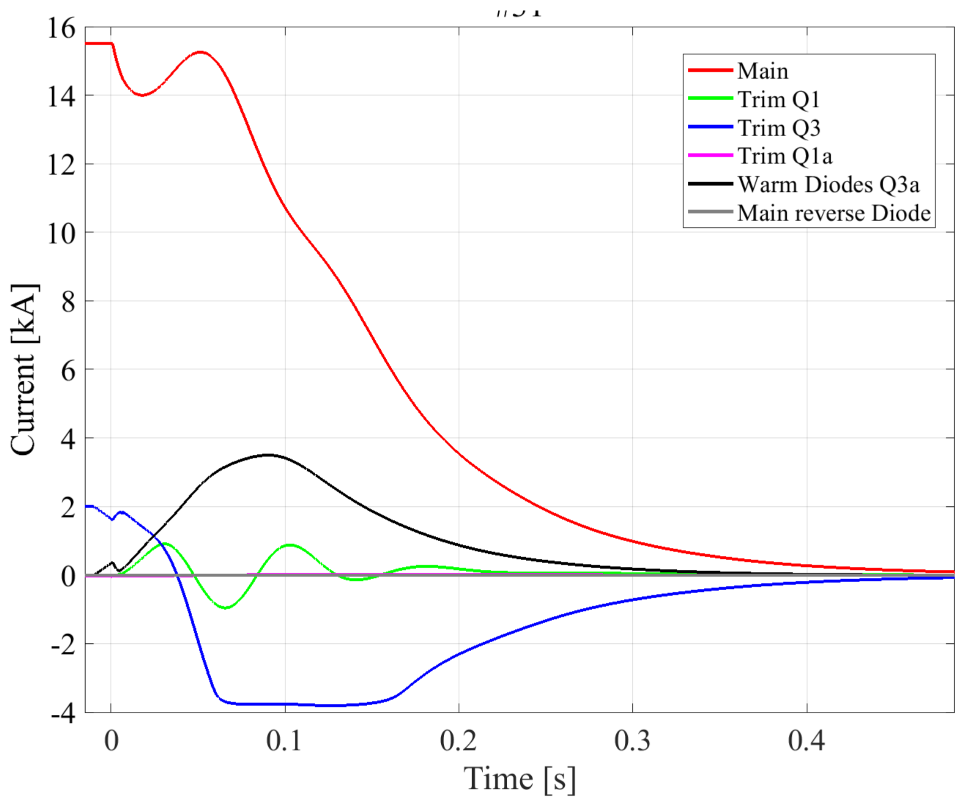
- ✓ Good prediction capability demonstrated (after non-uniform RRR in the wire was modeled, see next slide)
- ✓ Simulations allow assessing the peak voltages to ground when voltage taps are unavailable or too coarse

Measurements data: F. Mangiarotti

HL-LHC Inner Triplet circuit simulations

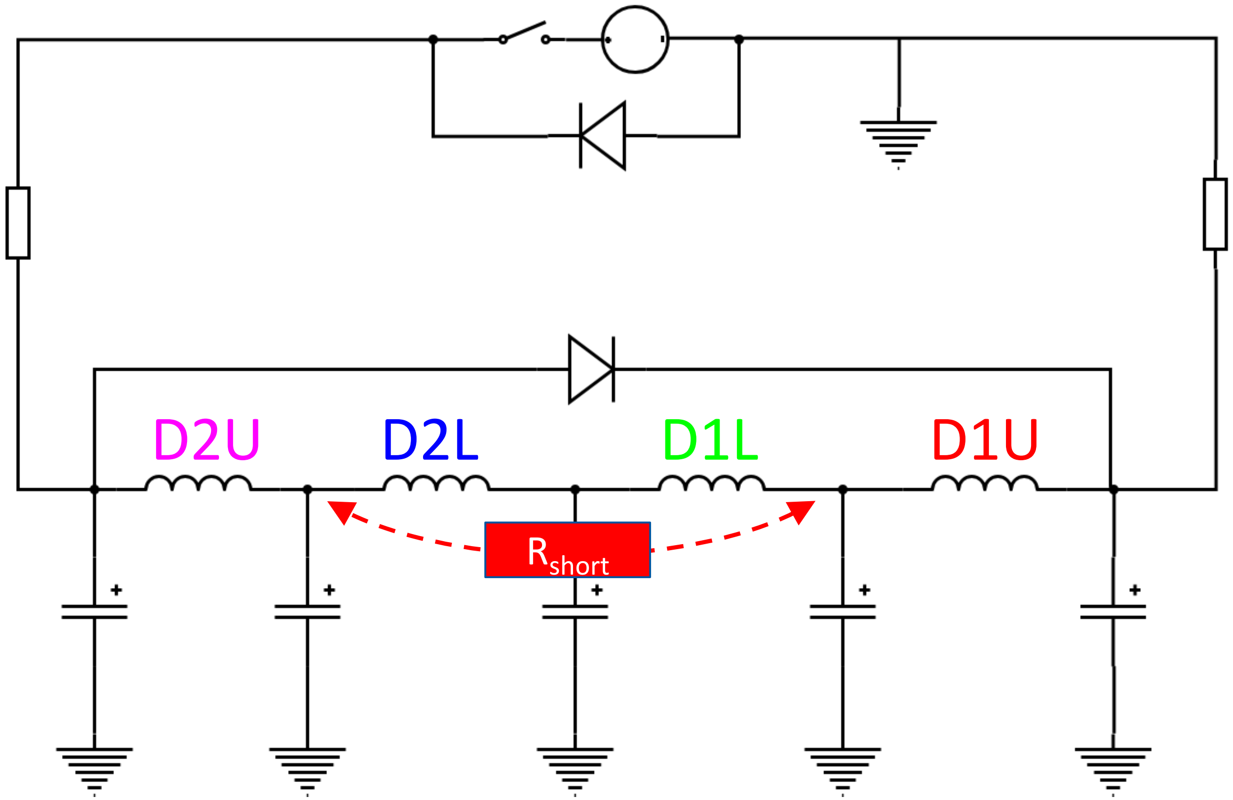


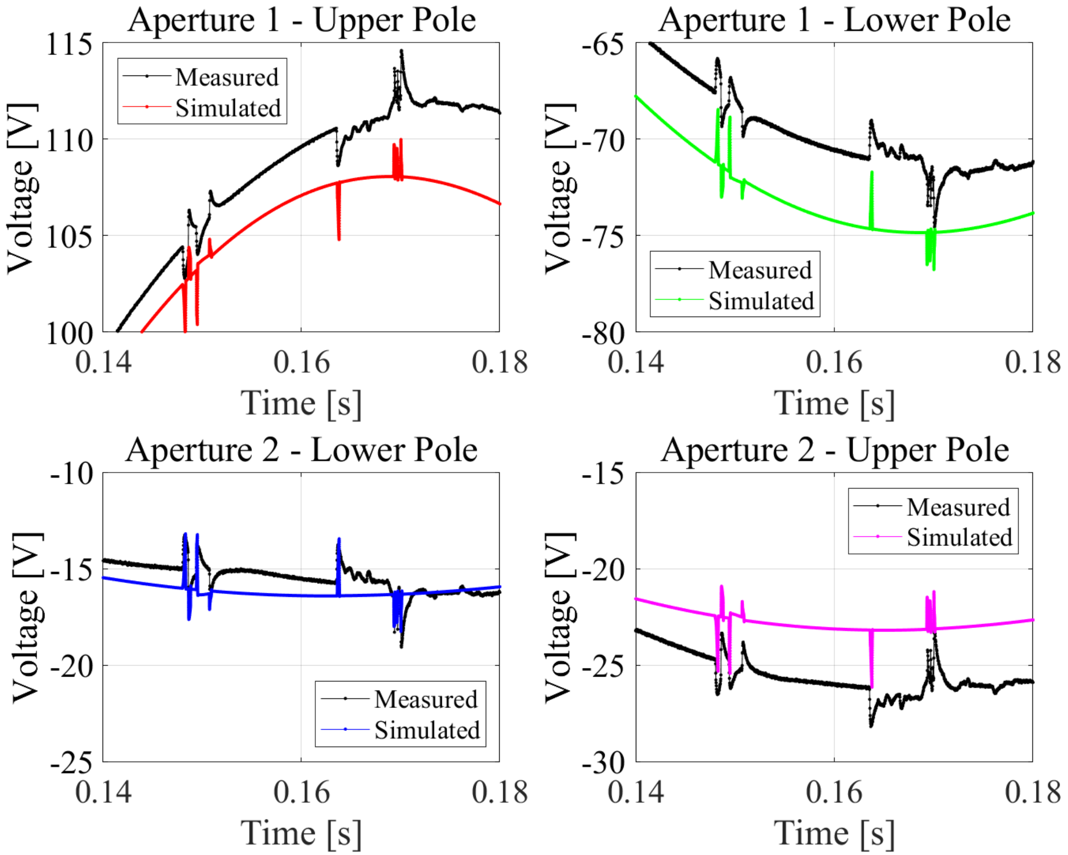
Courtesy of S. Yammine



- ✓ Failure analysis to identify the worst-case scenario for each circuit component (crowbars and current leads of the main and trim power converters, warm and cold Diodes, …) and allow their dimensioning
- ✓ Analysis performed by combining one PSPICE circuit with 6 LEDET magnet models in a co-simulation

Simulations of an intermittent short-circuit in an 11 T dipole magnet





- ✓ Analysis performed with a combination of LEDET and PSPICE magnet models
- ✓ Experimental observations qualitatively reproduced with the developed model
  [Note: The analysis remains inconclusive: no clear evidence of a short-circuit]

Measurements data: G. Willering

In the not-so-distant future…

Circuit data

Magnet data

Conductor data

Unified model

Measurement data

Test campaign plan

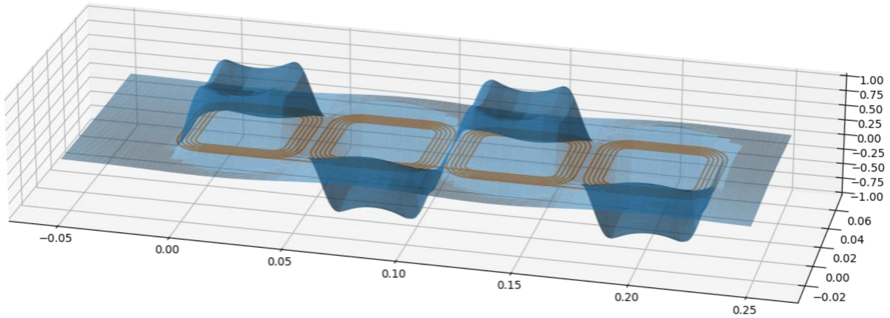
awesome_function_2(magnet_name, test_campaign_name, test_name)

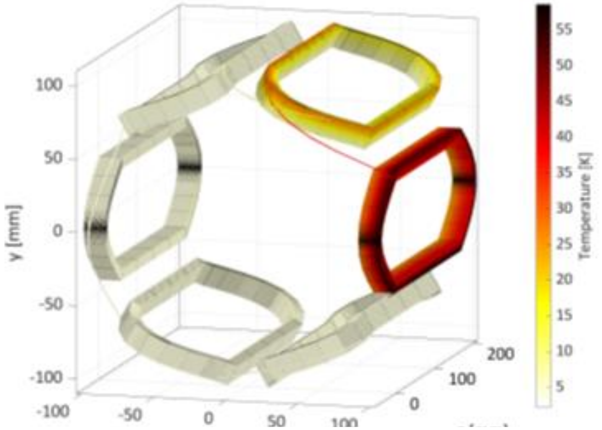
Simulation of the selected test

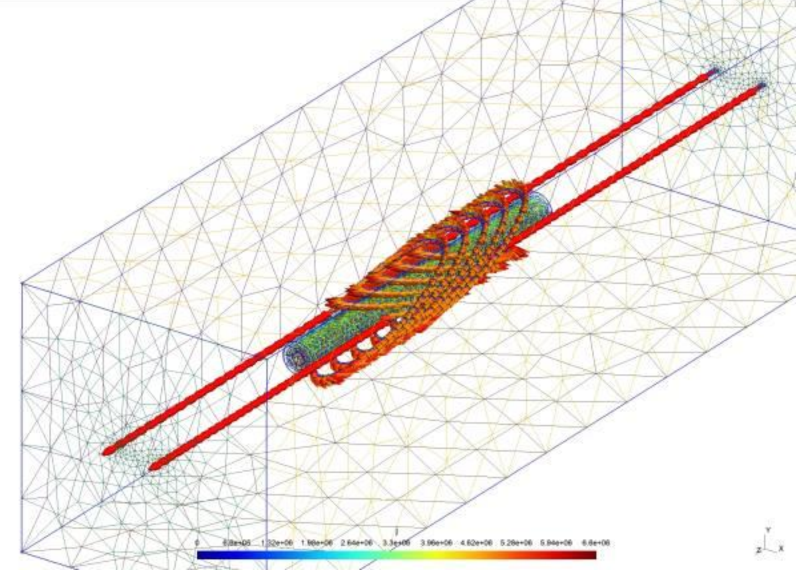
Comparison to measurements

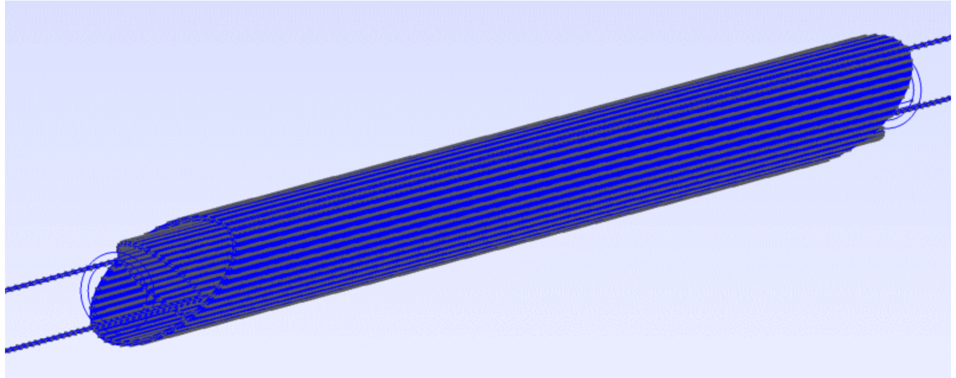
SOME HIGHLIGHTS FROM 2022

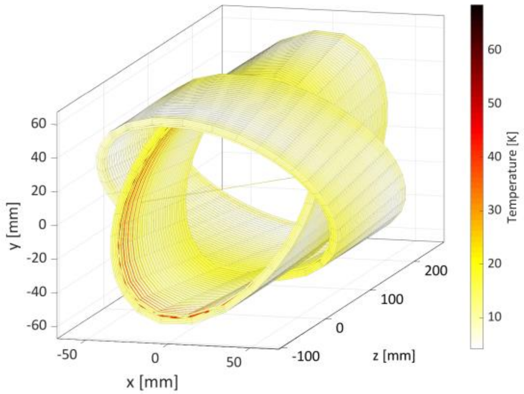
Some highlights from 2022

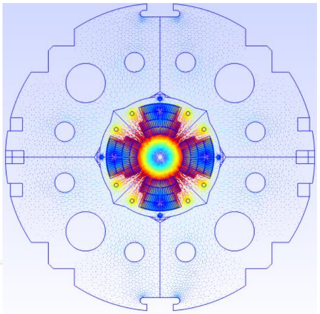


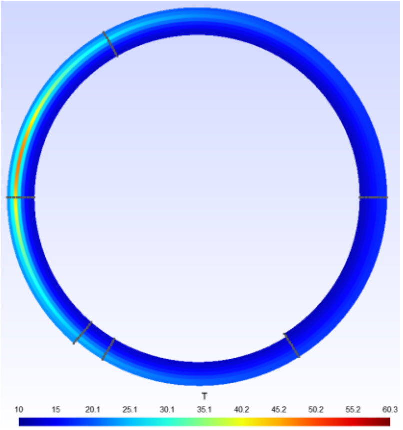


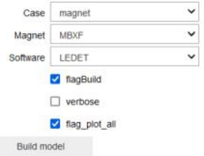


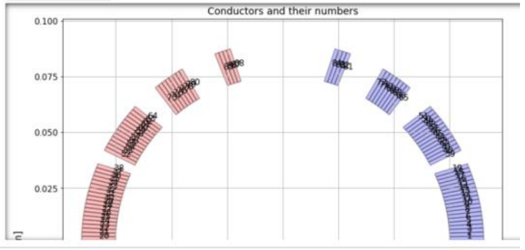


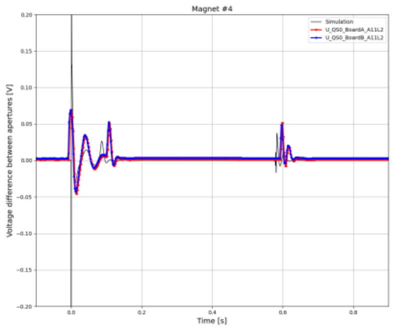


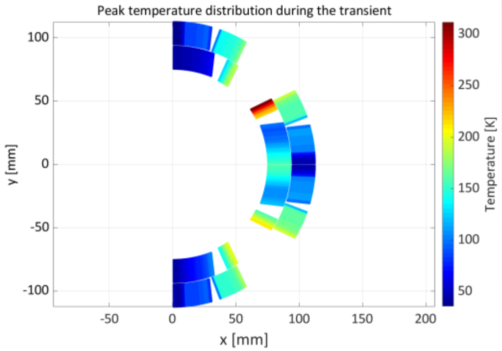


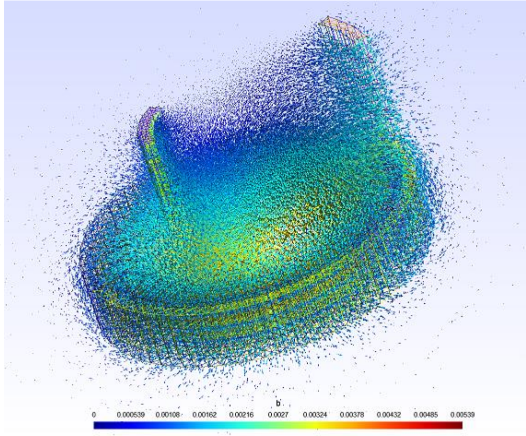


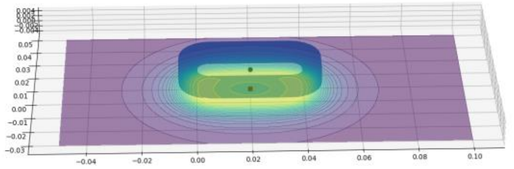

Case magnet
Magnet MBXF
Software LEDET
☑ flagBuild
☐ verbose
☑ flag_plot_all











WHY STEAM
COULD BE USEFUL FOR YOU

STEAM relevance to YOU

Provide

→ reference cases for transients in LHC and HL-LHC magnets and circuits (quenches, power-converter switching-off, energy-extraction switch opening, frequency transfer measurements, ELQA high-voltage tests, suspected failures…)

→ boundary conditions for analyses of other systems

→ material properties in various forms for transient simulations

STEAM relevance to YOU

Study

→ impact on protection of proposed changes to circuit hardware or operation modes

→ failure scenarios

→ worst-case scenarios for circuit components

→ with simulations many various R&D quench detection and protection techniques

STEAM relevance to YOU

Help

→ to understand the behaviour of non-trivial circuits (magnet chains, parallel paths, nested magnets, etc)

→ to reproduce unexpected events or observations

→ to benchmark simulation tools, especially when new features are developed

→ to integrate between measurements and STEAM framework and other tools at all levels

THANK YOU

Don’t hesitate to contact the STEAM team:

the first coffee is on us!

→ steam-team@cern.ch

Useful links

STEAM website	http://cern.ch/steam
STEAM Workshop	https://indico.cern.ch/event/1060073/
STEAM meetings	https://indico.cern.ch/category/11772/
Section publications	https://twiki.cern.ch/twiki/bin/view/TEMPEPE/SectionPapers
Section technical notes	https://twiki.cern.ch/twiki/bin/viewauth/TEMPEPE/SectionVariousContributions
Section talks	https://twiki.cern.ch/twiki/bin/view/TEMPEPE/SectionTalks

ANNEX

What drives the development?

Vision

Achieve specialized, trusted, consistent, repeatable and sustainable software tools and models for rapid **S**imulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits.

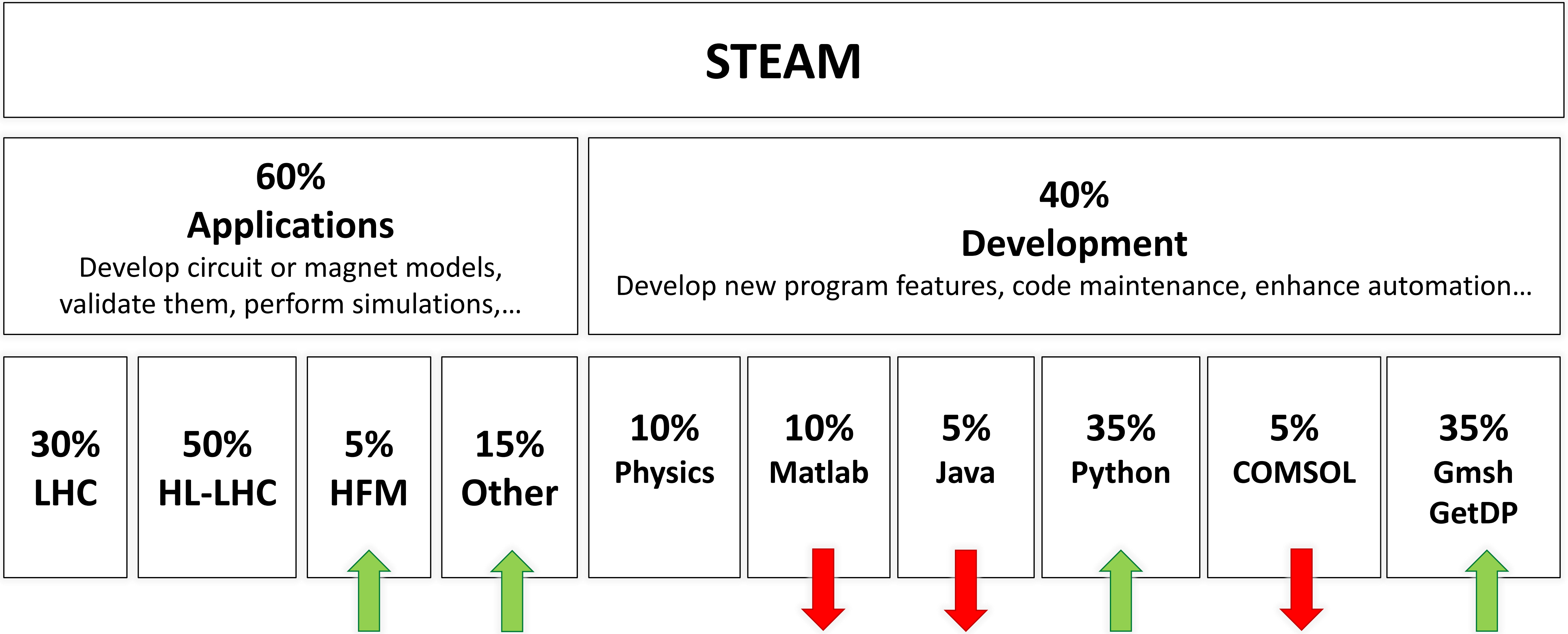
Mission

Develop capability and know-how for simulation with an appropriate utilization of established and modern technology. Engage community in framework adaptation and validation by sharing well documented tools and models. Support tools that are part of STEAM and welcome integration with externally developed code.

Values

continuity, readiness, simplicity, recognition, completeness, maintainability

STEAM project in the last few years and future trends



STEAM

60%
Applications
Develop circuit or magnet models, validate them, perform simulations,…

40%
Development
Develop new program features, code maintenance, enhance automation…

30%
LHC

50%
HL-LHC

5%
HFM

15%
Other

10%
Physics

10%
Matlab

5%
Java

35%
Python

5%
COMSOL

35%
Gmsh
GetDP

Note: All figures are only meant to give a rough estimation

Which physics is included in the STEAM models – and which isn't

ELECTRICAL CIRCUITS

- ✓ Electrodynamics
- ✓ Non-linear components (Diodes, thyristors)
- ✓ Empirical model of magnet eddy-currents
- ✓ Parasitic capacitance to ground
- ✓ Cold Diode heating effect
- ✓ Busbar self-inductance
- ~ Power converter control
- ~ Dependence of inductance on current
- x Heating effect in EE resistor
- x Mutual coupling between busbars of different circuits
- x …

MAGNETS

- ✓ Non-linear material properties
- ✓ Quench development and ohmic loss
- ✓ 1D, 2D and 3D thermal diffusion
- ✓ Inter-filament coupling loss
- ✓ Inter-strand coupling loss
- ✓ Iron-yoke saturation effect on self-inductance
- ✓ Cooling to thermal sink (collars, bore, wedges)
- ✓ 3D magnetic field
- ~ Persistent-currents loss
- ~ Mechanics
- ~ Eddy currents in metal elements
- ~ Accurate helium cooling
- x Hysteresis in iron yoke
- x …

Main takeaways: 1. Transients in superconducting circuits are complex. 2. We try to include as much relevant physics as it is practical in each tool, but each includes simplifications. 3. We can't simulate everything (yet ;))

Key points on software development

1. Separate input files (data) and software (code)

2. The above is versioned in separate repositories on CERN GitLab
3. Input files are text based – a must for version control of models
4. Code repositories have good test coverage. We use CI with CERN Gitlab

5. Single Source of Truth (SSOT) for model inputs – common input file - YAML
6. SSOT for material properties – write it once for all the tools and repackage

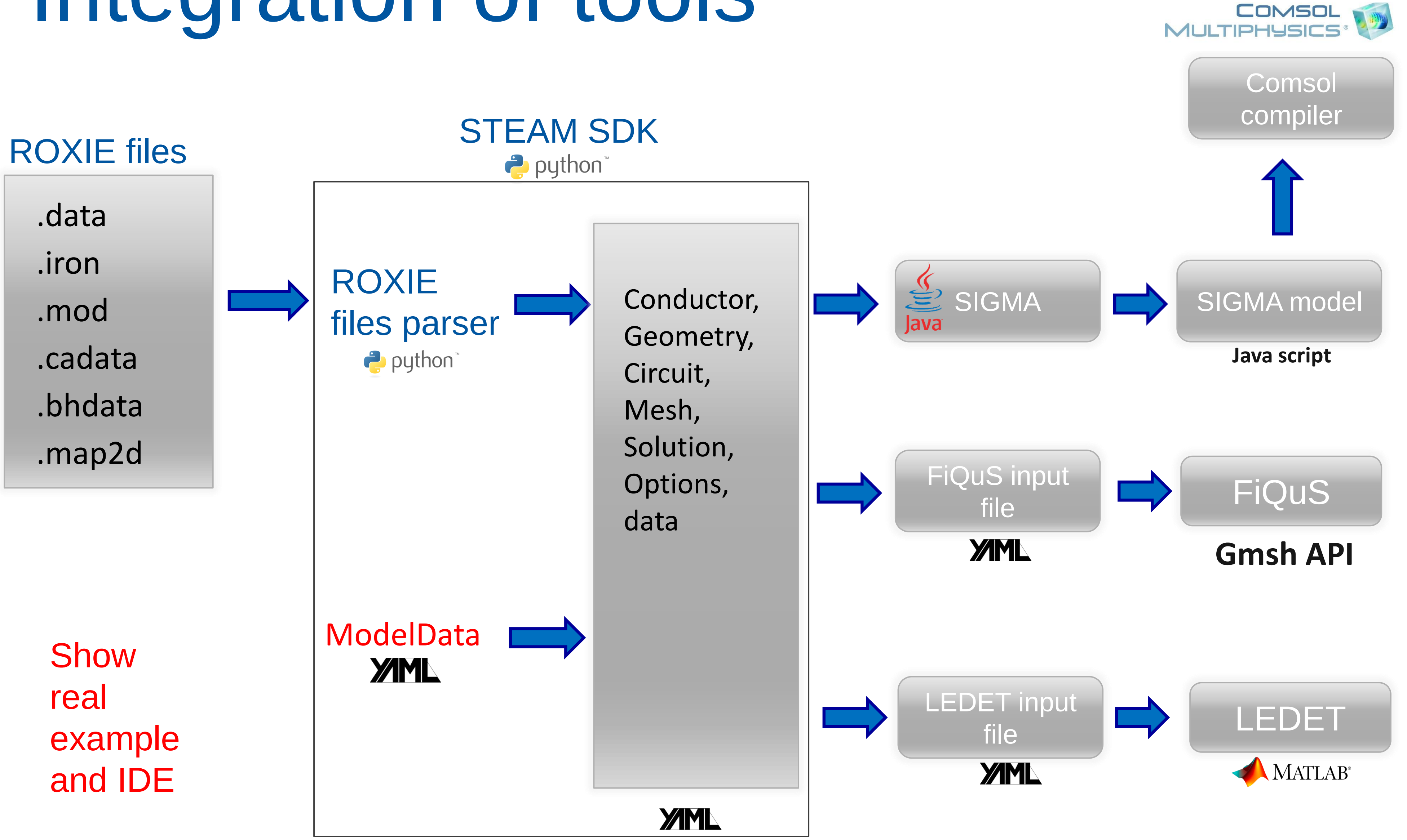
7. Due to point 1., we aim to keep to minimum the use of Jupyter notebooks
8. However, we are compatible as a user friendly GUI / “frontend”, although with limited functionality

9. We maintain tools in a few languages, but aim to maximize python use

10. We use commercial tools, but long term aim to only use free software

Gmsh
GetDP

Integration of tools



ROXIE files

- .data
- .iron
- .mod
- .cadata
- .bhdata
- .map2d

STEAM SDK

python

ROXIE files parser

python

Conductor, Geometry, Circuit, Mesh, Solution, Options, data

YAML

ModelData

YAML

SIGMA

Java

SIGMA model

Java script

COMSOL MULTIPHYSICS

Comsol compiler

FiQuS input file

YAML

FiQuS

Gmsh API

LEDET input file

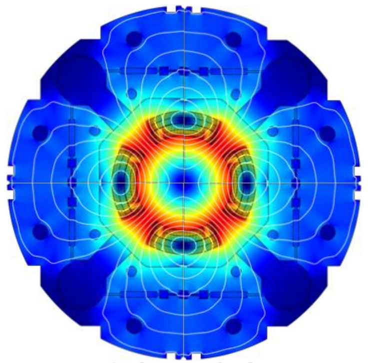
YAML

LEDET

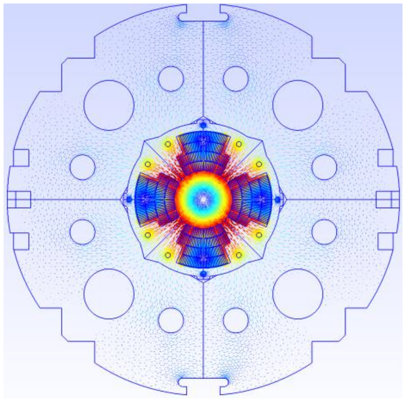
MATLAB

Show real example and IDE

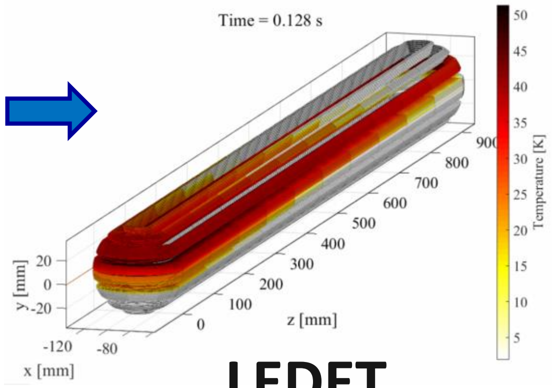
Quench model



COMSOL



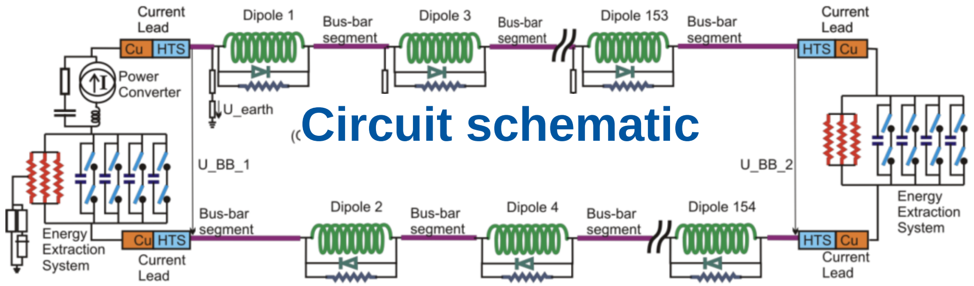
FiQuS (GetDP)



LEDET

and more…

SING (STEAM Integrated Network Generator)



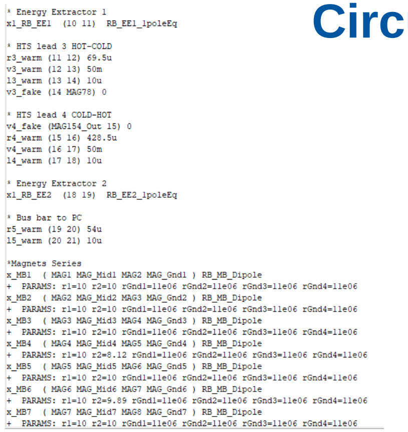
Circuit schematic

YAML file with circuit information

ParserPSPICE

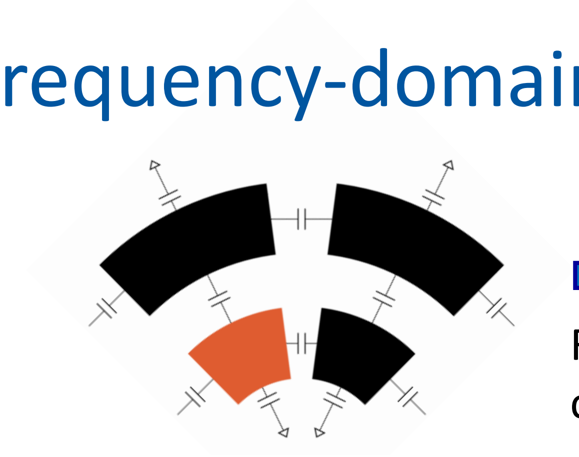
(SING)

Circuit.cir file

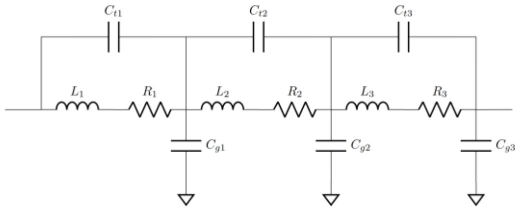


```
* Energy Extractor 1
x1_RB_EE1  (10 11)  RB_EE1_1poleEq

* HTS lead 3 HOT-COLD
r3_warm (11 12) 69.5u
v3_warm (12 13) 50m
l3_warm (13 14) 10u
v3_fake (14 MAG78) 0

* HTS lead 4 COLD-HOT
v4_fake (MAG154_Out 15) 0
r4_warm (15 16) 428.5u
v4_warm (16 17) 50m
l4_warm (17 18) 10u

* Energy Extractor 2
x1_RB_EE2  (18 19)  RB_EE2_1poleEq

* Bus bar to PC
r5_warm (19 20) 54u
l5_warm (20 21) 10u

*Magnets Series
x_MB1  ( MAG1 MAG_Mid1 MAG2 MAG_Gnd1 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=10 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
x_MB2  ( MAG2 MAG_Mid2 MAG3 MAG_Gnd2 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=10 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
x_MB3  ( MAG3 MAG_Mid3 MAG4 MAG_Gnd3 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=10 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
x_MB4  ( MAG4 MAG_Mid4 MAG5 MAG_Gnd4 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=8.12 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
x_MB5  ( MAG5 MAG_Mid5 MAG6 MAG_Gnd5 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=10 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
x_MB6  ( MAG6 MAG_Mid6 MAG7 MAG_Gnd6 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=9.89 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
x_MB7  ( MAG7 MAG_Mid7 MAG8 MAG_Gnd7 ) RB_MB_Dipole
+  PARAMS: r1=10 r2=10 rGnd1=1le06 rGnd2=1le06 rGnd3=1le06 rGnd4=1le06
```

Frequency-domain model generator

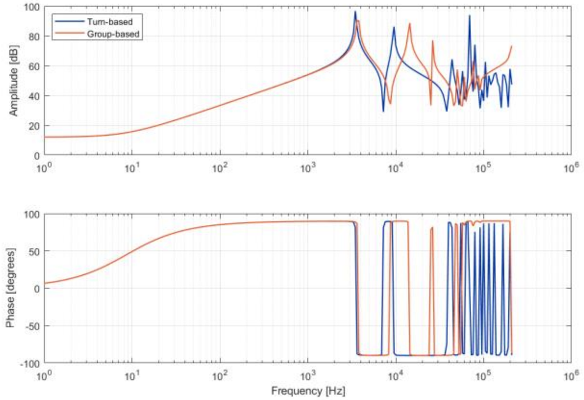


R, L, C calculation



PSPICE frequency model

Solve



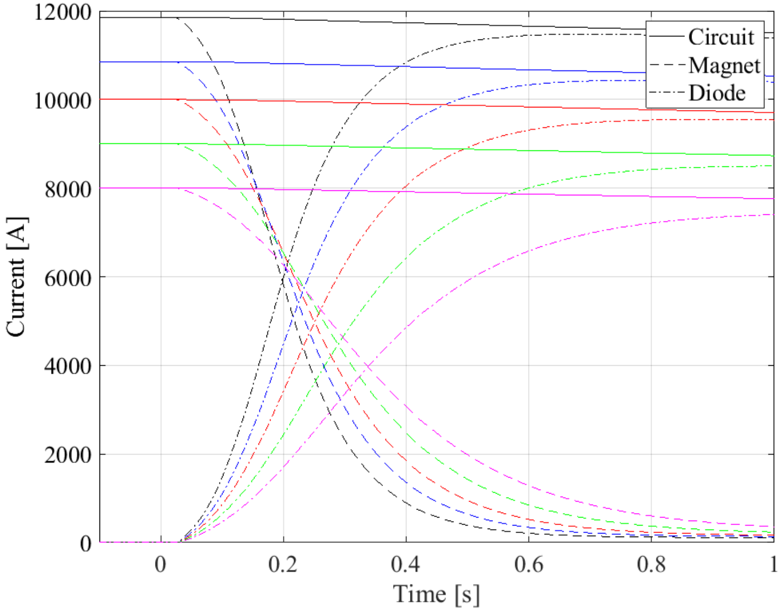
Magnet or circuit impedance vs frequency

→ SING is used to automatically generate PSPICE and LTSPICE circuit models relying on shared sub-components. The tool was re-written in Python (ParserPSPICE) in 2022.

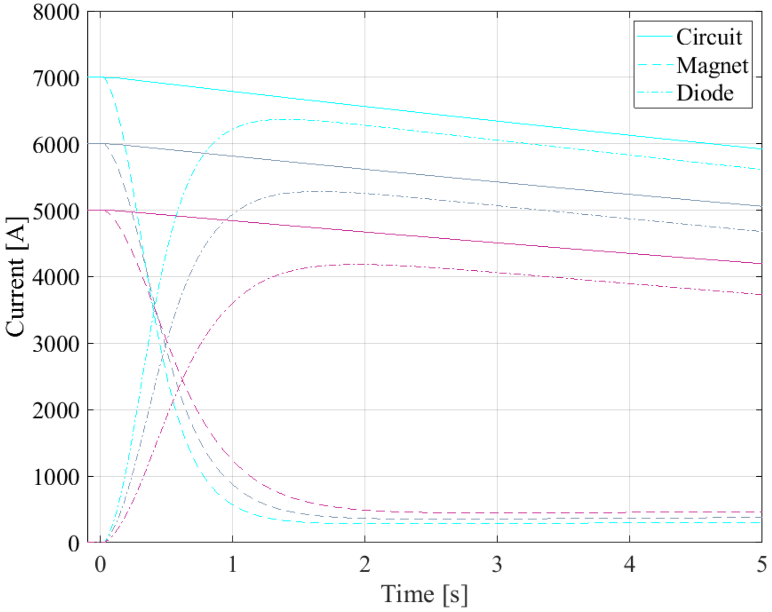
→ Automatic generation of frequency-domain model of a magnet in resistive or superconducting state starting from STEAM input files.

Example of simulated quench and FPA in an RQ circuit

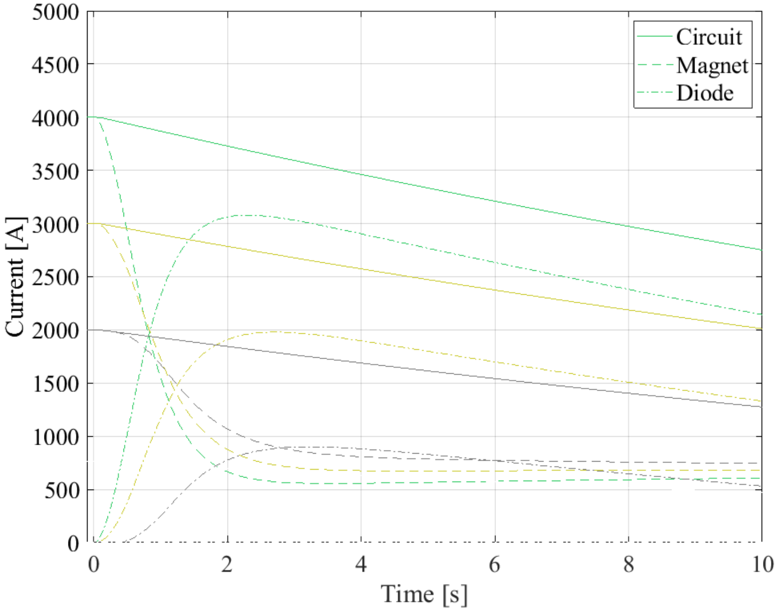
Fast power aborts at 8-12 kA



Fast power aborts at 5-7 kA



Fast power aborts at 2-4 kA

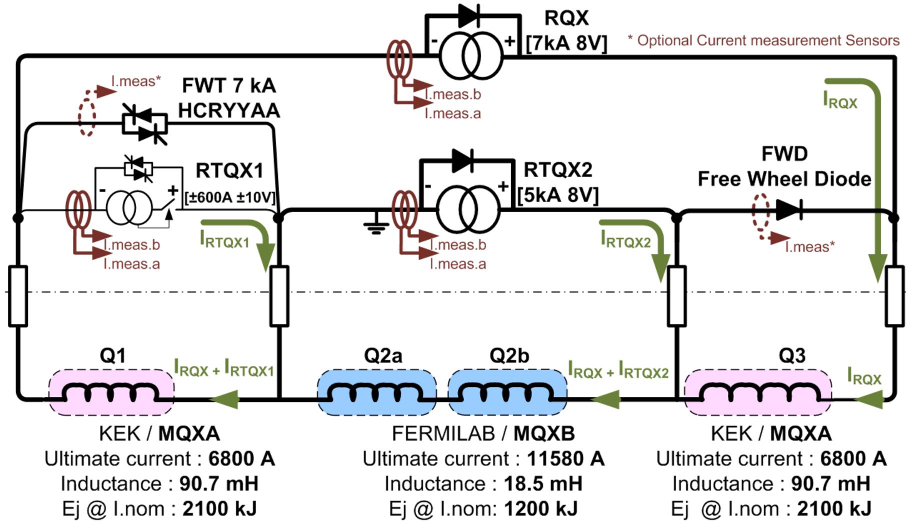


- ✓ Reference FPA curves simulated for different current levels
- ✓ Currents through the magnets and cold Diodes are not measured and can be assessed only by simulations

D. Pracht and M. Janitschke, TECH

Example of simulated quench and FPA in an Inner Triplet circuit

Circuit schematic

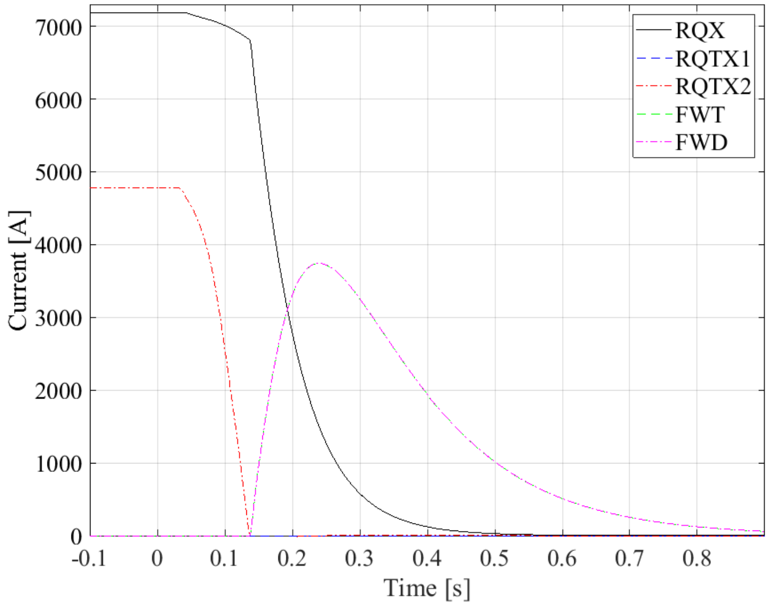


KEK / **MQXA**
Ultimate current : **6800 A**
Inductance : **90.7 mH**
Ej @ I.nom : **2100 kJ**

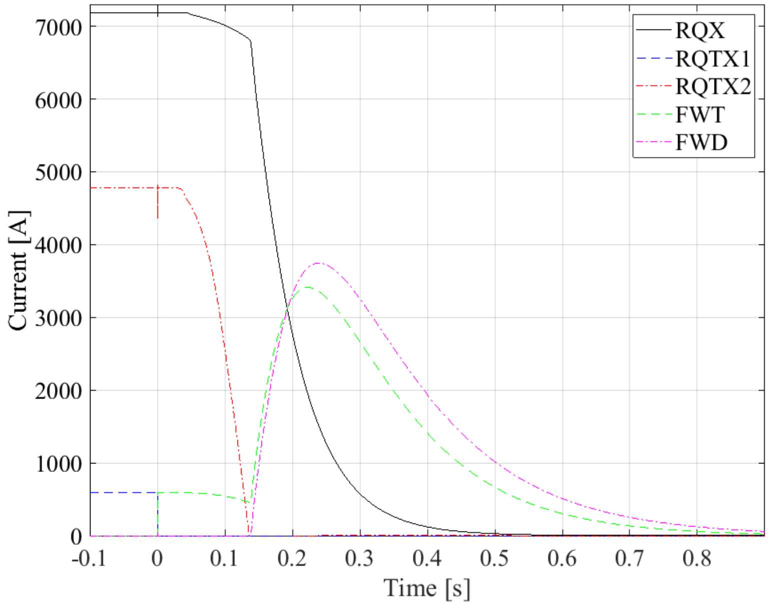
FERMILAB / **MQXB**
Ultimate current : **11580 A**
Inductance : **18.5 mH**
Ej @ I.nom: **1200 kJ**

KEK / **MQXA**
Ultimate current : **6800 A**
Inductance : **90.7 mH**
Ej @ I.nom : **2100 kJ**

FPA without trim current



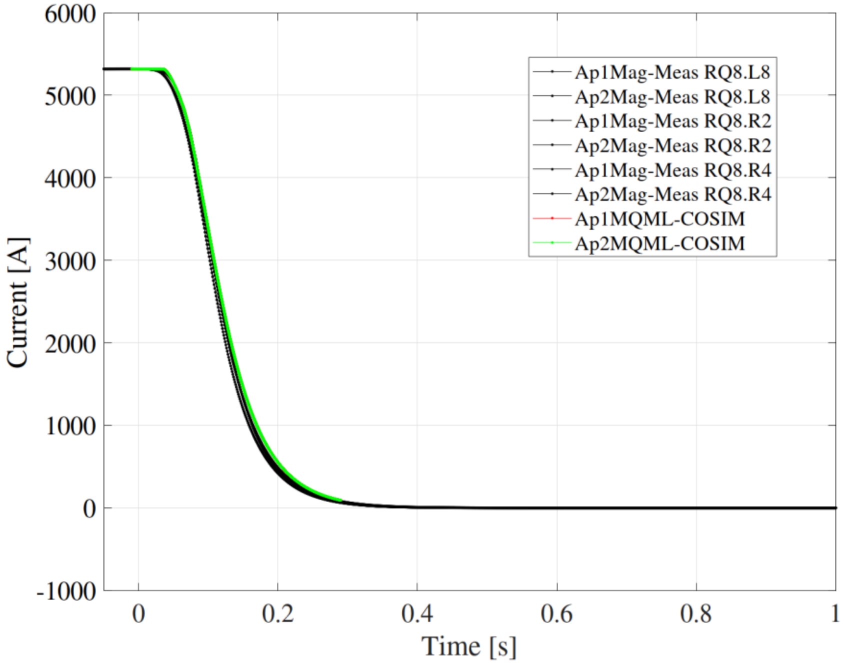
FPA with trim current



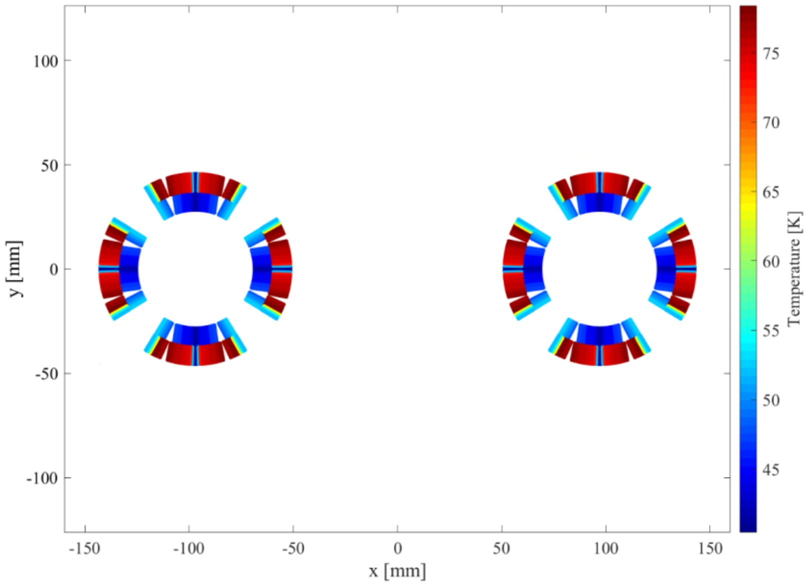
- ✓ Reference FPA curves simulated for different initial currents in the nested power converters
- ✓ Currents through the magnets and free-wheel Diodes and thyristors are not measured and can be assessed only by simulations

Example of simulated quench and FPA in an IPQ circuit

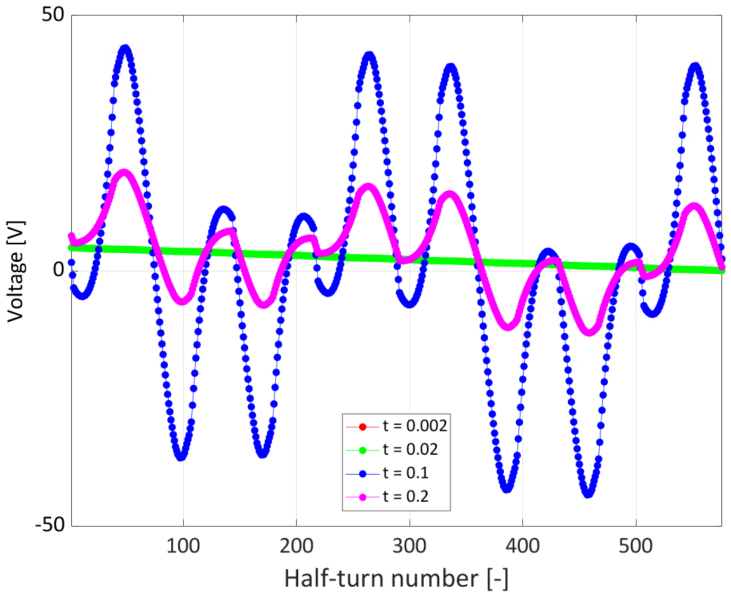
Magnet current



Temperature in the coil turns



Voltage to ground distribution

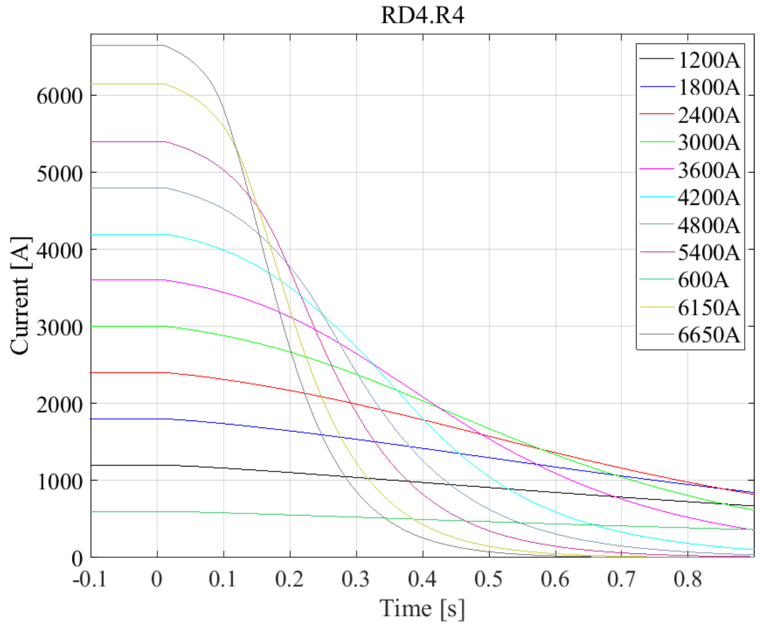


- ✓ Simulations can bring additional information regarding the magnet behavior. In this example, we see the temperature distribution at the end of the discharge (note the hotter turns in contact with QH) and the voltage to ground distribution at different times (note the periodic pattern due to magnet symmetry).

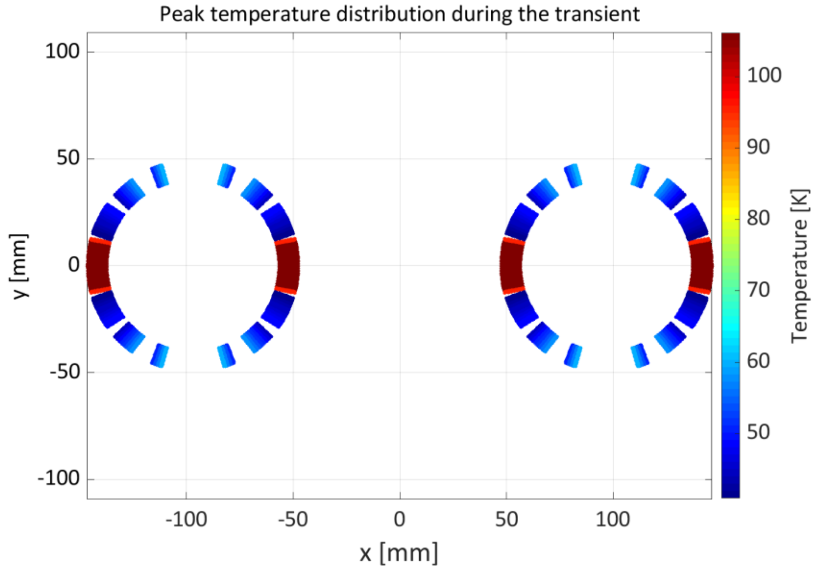
F. Murgia, TECH

Example of simulated quench and FPA in an IPD circuit

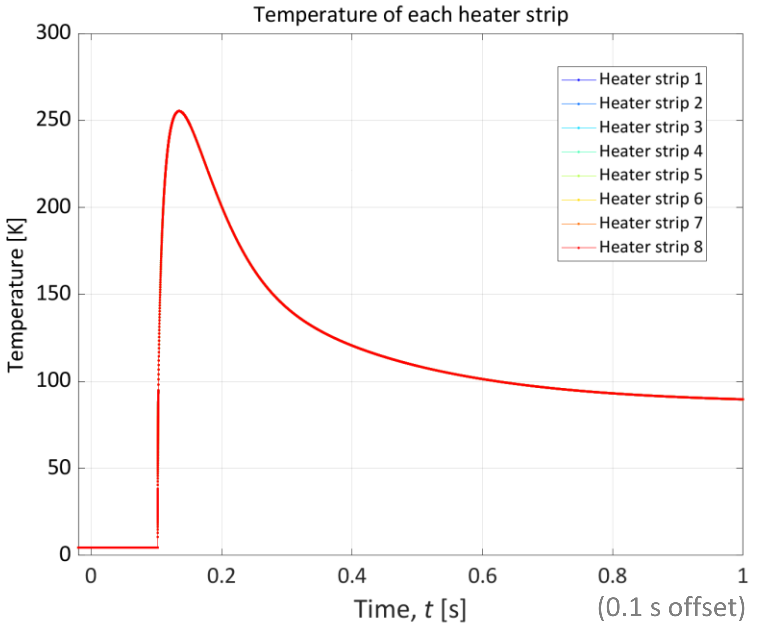
Magnet current



Temperature in the coil turns



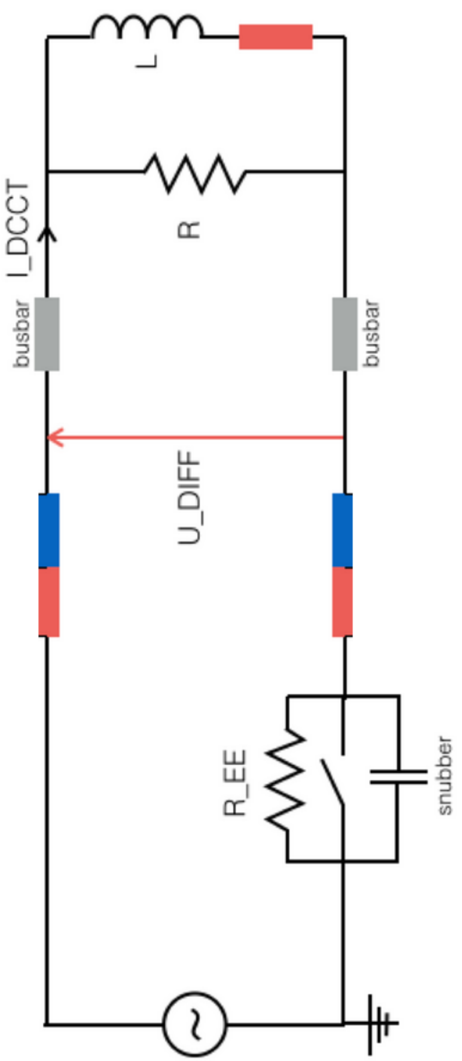
Temperature of the QH strips



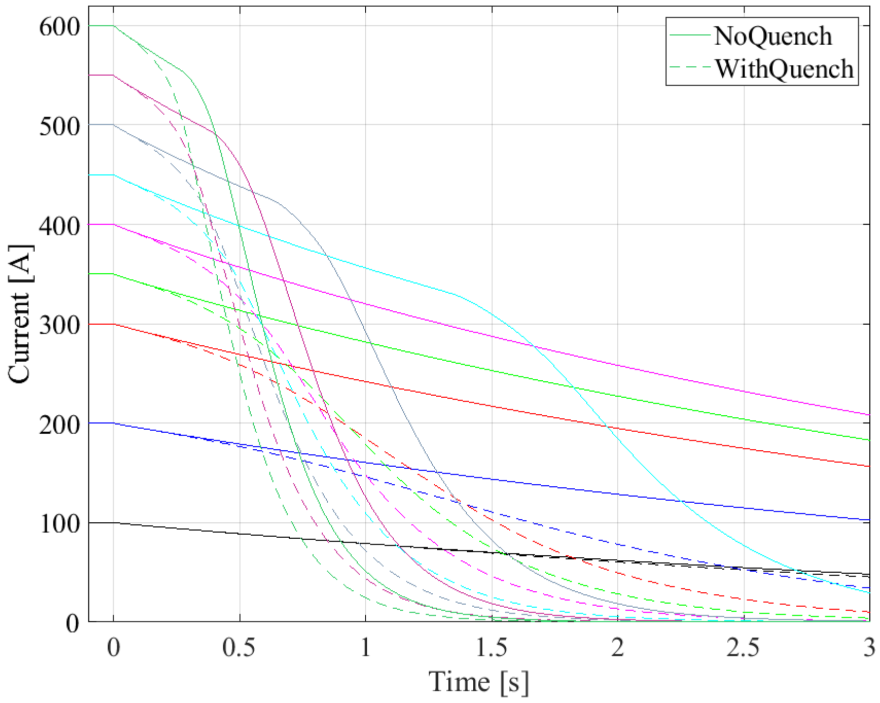
✓ Simulations can bring additional information regarding the magnet behavior. In this example, we see the temperature distribution at the end of the discharge (note the hotter turns in contact with QH) and the temperature of the QH strip (note that they get hotter than the coil).

M. Janitschke, TECH

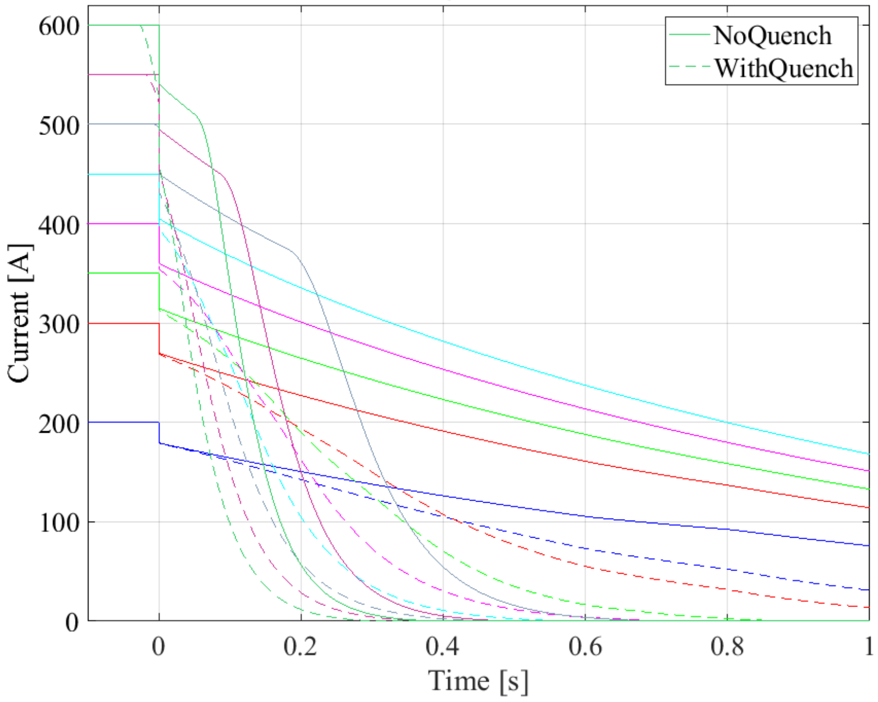
Example of simulated quench and FPA in 600 A circuits



Discharges without Energy Extraction



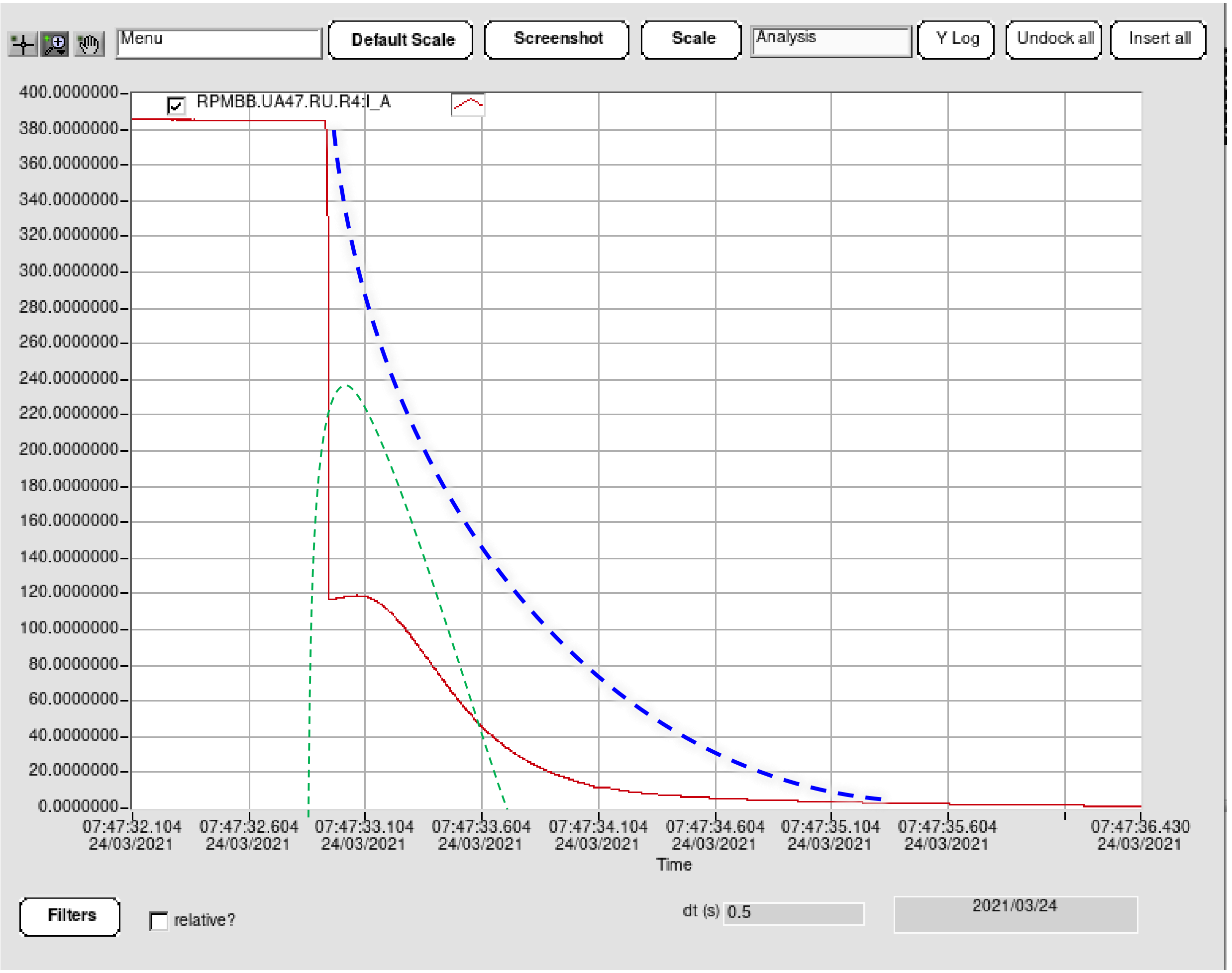
Discharges with Energy Extraction



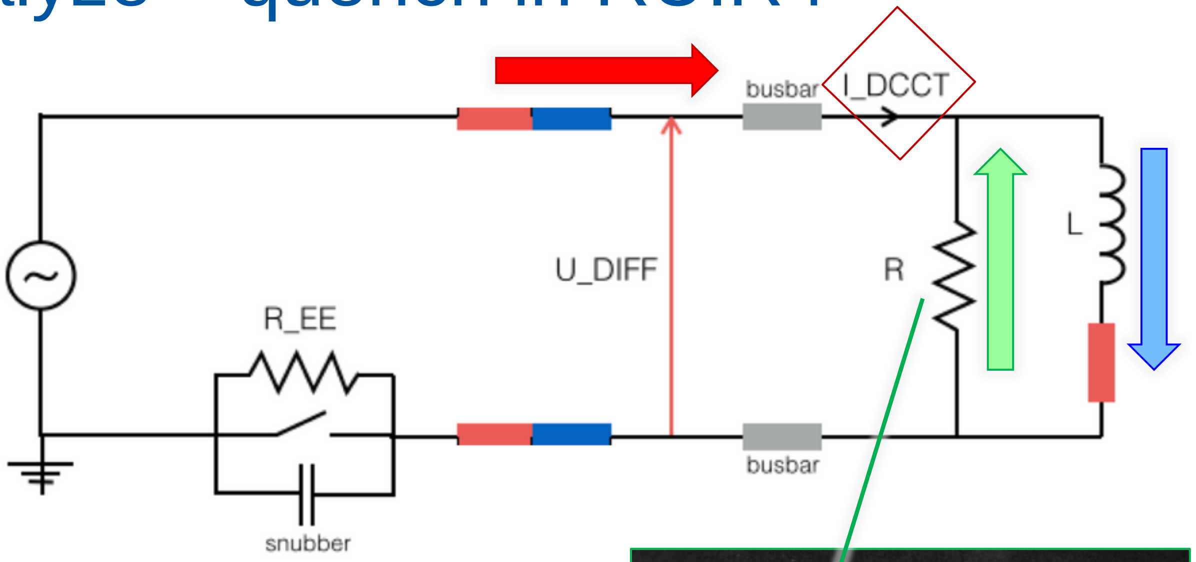
- ✓ Reference FPA curves simulated for all circuit types at different current levels
- ✓ Simulations provide a useful reference to analyze FPA events and understand unusual events
- ✓ Currents through magnets and parallel resistors (if present) are not measured

M. Janitschke, TECH

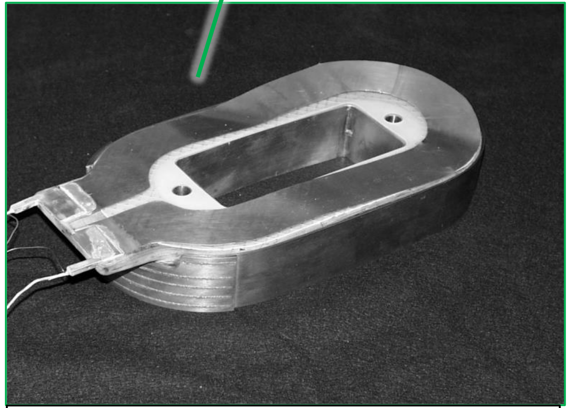
Example of unusual transient to analyze – quench in RU.R4



Circuit current drops suddenly...?
Then bounces back up...?

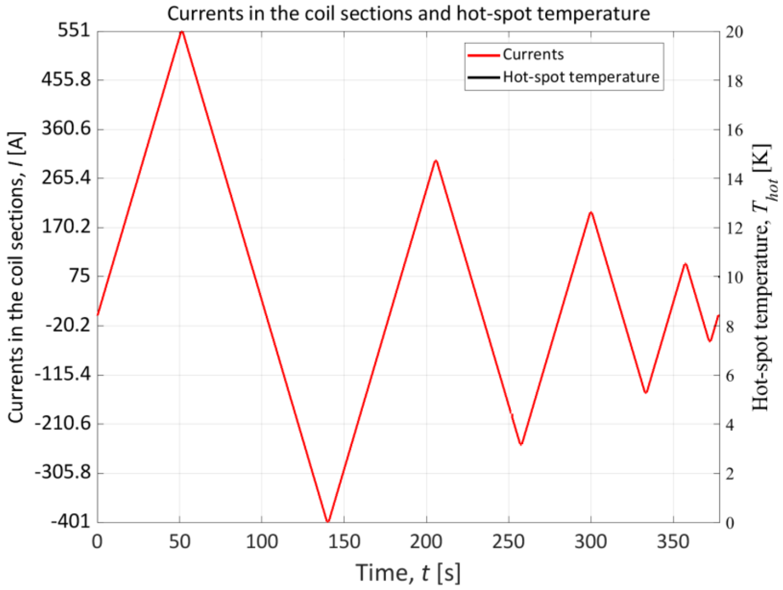


Hint: Parallel resistor is also a quench heater and heats up pretty quickly…



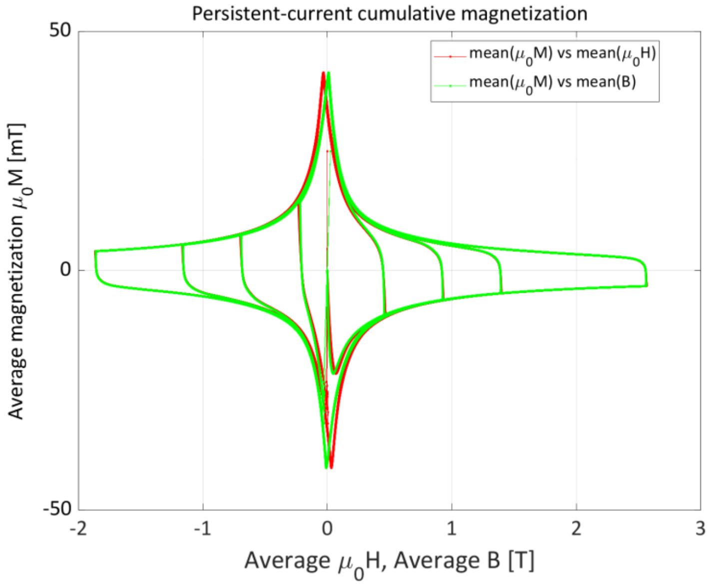
from LHC Project Report 894

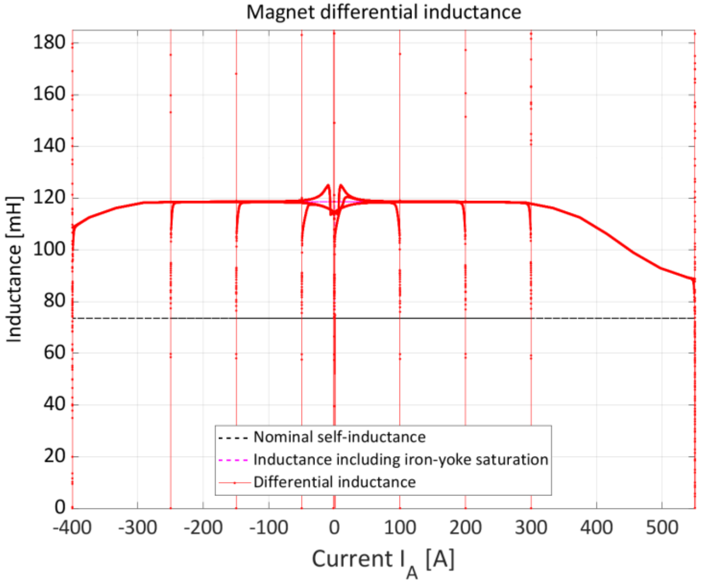
Simulated electrical, magnetic, thermal model of persistent currents



Current versus time

Average magnetization versus average field

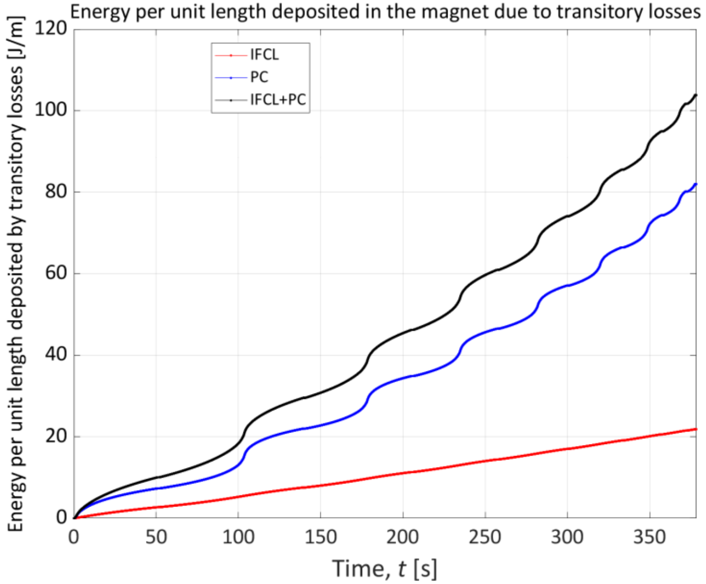




Differential inductance versus current

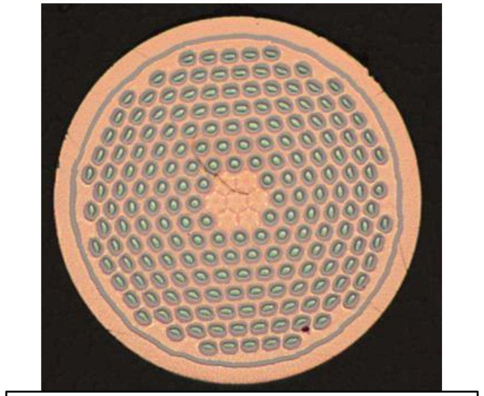
Hysteresis and IFCL loss versus time

- ✓ Included: average magnetization in each strand, hysteresis loss, effect of persistent currents on the magnet differential inductance



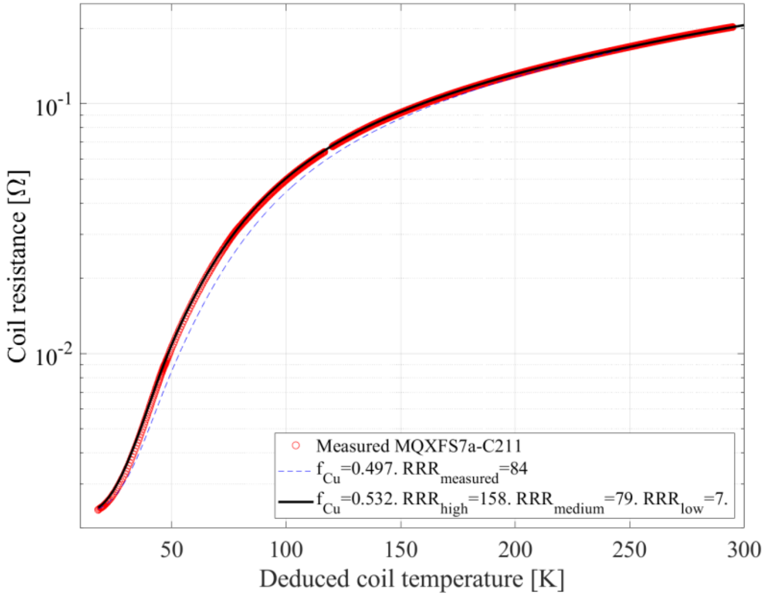
Effect of non-uniform RRR within the Nb_3Sn/Cu wire

Wire cross-section

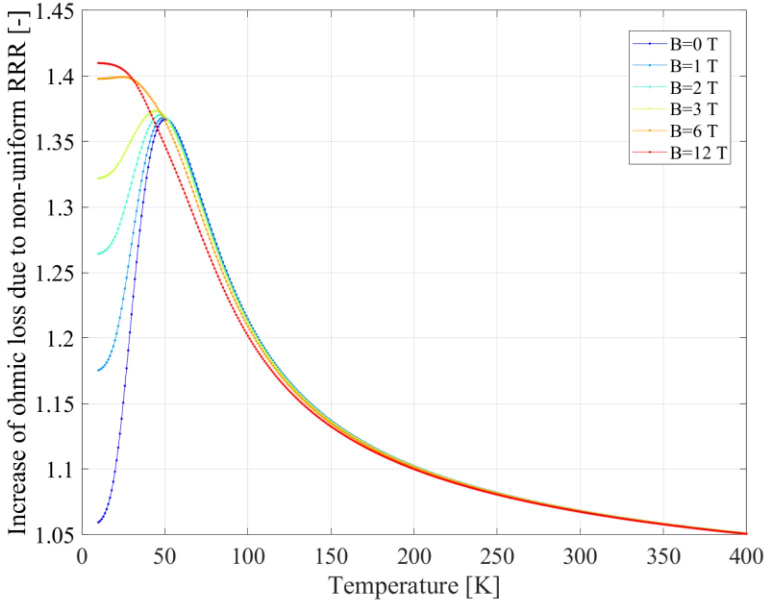


Courtesy of B. Bordini

Coil resistance during warm-up



Extra ohmic heating due to wire Cu RRR non-uniformity



- ✓ During MQXFS7b model magnet test, resistive voltage much higher than expected was observed in one coil
- ✓ The observed transients were reproduced by including in the LEDET software the option to model the wire thermal evolution assuming three Cu regions with different RRR: high RRR (~160) Cu outside the barrier, medium RRR (~80) Cu inside the barrier in the core, low RRR (<10) Cu inside the barrier between filaments.

Thanks to B. Bordini, F. Mangiarotti, G. Willering

STEAM applications

LHC

- → Versioned library of validated models of all magnets and all circuits
- → Scripts to rapidly reproduce specific events (different initial current, quench location and time, energy-extraction timing, etc) in specific circuits (different warm resistance, energy-extraction resistance, etc)
- → Assist in understanding and reproducing unexpected transients during operation

HL-LHC

- → Versioned library of validated models of all magnets and all circuits (ready for the String test)
- → Parametric studies, failure analyses, and worst-case identification (hot-spot temperature, voltages to ground)
- → Assist in understanding and reproducing unexpected transients during testing

HFM and external collaborations

- → Develop quench protection models for new/less explored magnet concepts (CCT, curved CCT, …)
- → Develop capability to model new quench protection systems (Secondary-CLIQ, external-CLIQ, …)
- → Integrate HTS and non-insulated (NI) coils into the STEAM framework

Examples of what STEAM models were used for in 2021

LHC

Quench Heaters

→ Assess the consequences of raising MB quench detection thresholds (worst-case analysis)
→ Analyse quench protection of Q1 magnet in RQX.R1 with non-conform quench heater discharge unit
→ Calculate the effect of quench-heater field on the beam, including the effects of beam-screen shielding and inter-filament coupling currents in the magnet coil
→ Simulate quench-heater protection of MQY magnet at T=1.9 K

Short circuits

→ Simulate an internal short-circuit in an MB magnet (in RB, main dipole circuit)
→ Analyse earth current in RB circuits during quenches and FPA
→ Simulate powering transients of an MCBY magnet with an internal short-circuit

Frequency domain

→ Reproduce the measured frequency-domain impedance of MB magnets measured in the tunnel, including the effect of neighbouring magnets

SC effects

→ Assess when quench-back is expected in 600 A circuits
→ Simulate the effects of persistent-currents on the powering transients in LHC circuits

Examples of what STEAM models were used for in 2021

HL-LHC

Baseline verification

- → Verification of baseline quench protection for various HL-LHC circuits
- → Parametric analyses and worst-cases for all circuit components in HL-LHC Inner Triplet circuit
- → Analyse quench protection of HEL larger solenoids
- → Uncertainty quantification by automatically performing hundreds of parametric simulations
- → Simulate of the effects of additional insulation layers between quench heaters and coil
- → Propose MQXF coil electrical order that minimizes the expected peak voltage to ground

Validation and Predictions

- → Systematic measurement/simulation comparison during events in various test campaigns SM18
- → Simulation of transients in CCT-type magnet, and validation with MCBRD prototype magnet data
- → Simulate proposed MQXF special trimmed powering tests
- → Explain the observed extra ohmic loss in coils made of conductor with non-uniform RRR
- → Estimate the effect of QH discharge on voltages across coils and quench-antenna coils

Frequency domain

- → Frequency transfer function analysis of one MQXF coil

STEAM superconducting circuit library

Circuit family	Number of circuit types	Number of circuits	Circuit protection
Main dipole	1	8	QH + By-pass Diode + EE
Main quadrupole	1	16	QH + By-pass Diode + EE
Inner triplets	1	8	QH
Individually powered dipoles	3	16	QH
Individually powered quadrupoles	7	78	QH
600A - with EE	11	200	EE
600A - without EE	10	192	Self-protecting
600A undulators	1	2	EE + Parallel resistors acting as QH
80A-120A circuits	10	300	Self-protecting
60A circuits	2	752	Self-protecting
Total	**47**	**1572**	

EE = Energy-extraction system. QH = Quench Heaters

- ✓All LHC circuit types are modelled in the Circuit Library, with the exception of the inner triplet nested correctors.
- ✓Models of individual circuits can be generated on demand (small differences in warm resistance, EE, etc).
- ✓Models of HL-LHC magnet circuits are being prepared following the same approach.

Some practical examples to continue and enhance cooperation between STEAM and CERN magnet lifetime

Design

→ Failure cases considered when designing a magnet
→ Worst-case scenarios used to define electrical design criteria
→ Integrating new quench protection systems into the design at early stage
→ Assessment of new quench protection concepts

Manufacturing

→ Information on wires, cables, coils, magnets, circuits is linked to models
→ Influence of coil electrical order on peak voltages to ground assessed
→ Frequency transfer measurements at different stages

Testing

→ Automatic simulation of each proposed test plan
→ Systematic validation of the simulation results
→ Proposed non-standard tests can be evaluated
→ Unexpected transients can be analyzed and reproduced

Operation

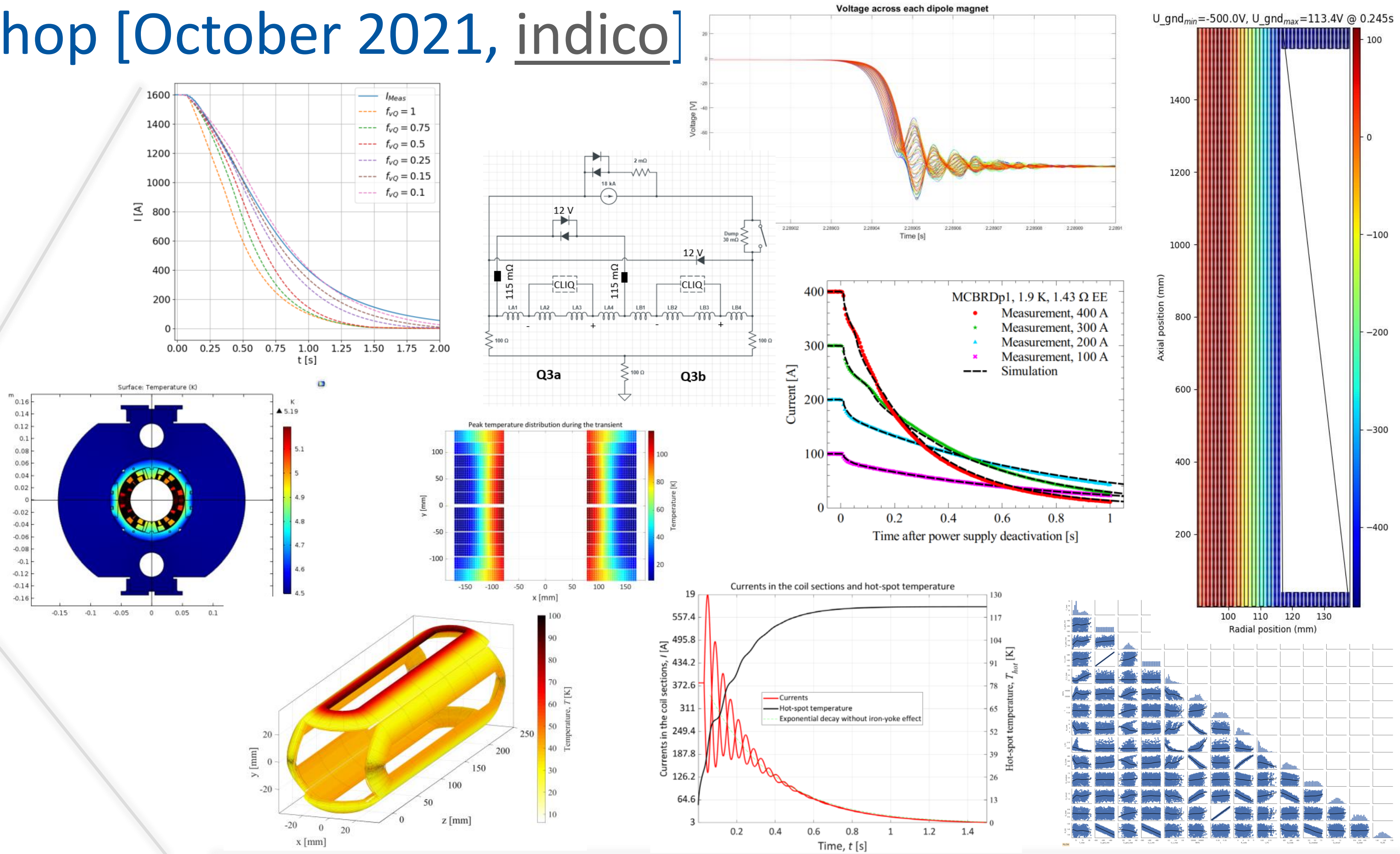
→ The same model that has been validated is used to understand and reproduce unexpected events
→ All conductor, magnet, circuit models can be linked in consistent co-simulations
→ Effect of hardware (EE, power supply crowbars,…) or operation changes (quench detection thresholds, EE timing,…) can be evaluated

2nd STEAM workshop [October 2021, indico]

UPDATES ON STEAM DEVELOPMENT

PRESENTATIONS FROM STEAM USERS

HANDS-ON SESSIONS ON ALL THE TOOLS



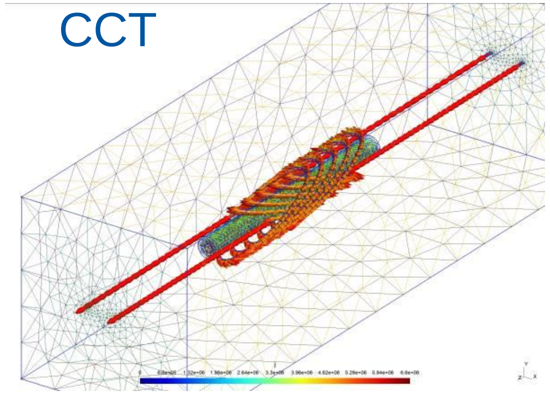
Figures from the presentations at the workshop by D. Davis, D. Delkov, V. Ferrentino, M. Janitschke, V. Marinozzi, M. Mentink, X. Sarasola, O. Tranum Arnegaard, M. Wozniak

Some topics worked on in 2022

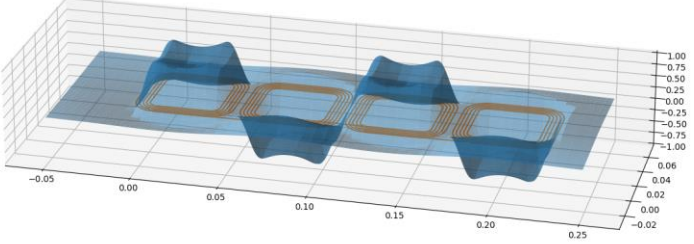
… as a list of abstracts accepted for ASC2022

- **M. Wozniak**, **E. Ravaioli**, **A. Verweij**, "Co-Simulation of Quench Behaviour of HL-LHC Dipole Canted Cos-Theta Orbit Corrector Prototypes"
- **A. Vitrano**, **M. Wozniak**, **E. Schnaubelt**, **T. Mulder**, **E. Ravaioli**, **A. Verweij**, "An open-source finite element quench simulation tool for superconducting magnets"
- **T. Mulder**, **E. Schnaubelt**, **M. Wozniak**, **E. Ravaioli** and **A. Verweij**, "External Coil Coupled Loss Induced Quench (E-CLIQ) System for Protection of LTS Magnets"
- **E. Ravaioli**, **A. Verweij**, **M. Wozniak**, "Analysis of an internal electrical short in an LHC orbit-corrector magnet with a 3D multiphysics simulation"
- **E. Schnaubelt**, **M. Wozniak**, S. Schöps, "Quench Simulation of No-Insulation HTS Coils With 3D FEM Using a Thin Shell Approximation"
- B. Caiffi, **L. Bender**, A. Bersani, S. Farinon, A. Foussat, F. Levi, F. Mangiarotti, D.Novelli, A. Pampaloni, **E. Ravaioli**, E. Todesco, G. Willering, "Protection Scheme Effectiveness Study for the Hi Luminosity LHC MBRD magnet"
- S. Yammine,..., **E. Ravaioli**,..., et al., "Experimental Program of the HL-LHC Inner Triplet String Test at CERN"

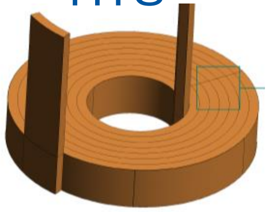
CCT



E-CLIQ



HTS



LHC