STEAM framework
for simulations of transients in superconducting magnet circuits

Emmanuele Ravaioli and Mariusz Wozniak

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

TE-MPE-PE section meeting 08 June 2022

https://espace.cern.ch/steam

STEAM

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 **S**imulation of **T**ransient **E**ffects in **A**ccelerator **M**agnets

Challenges / Opportunities:

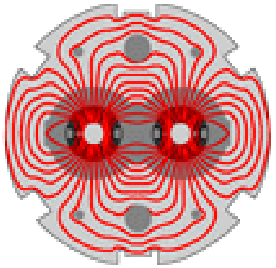
Multi-domain – need to include thermal, magnetic and electrical domains

Multi-physics – need to couple above domains and between models

Multi-rate – need to include fast effects in long time scale models

Multi-scale – need to account for local effects in large models

STEAM is used daily for several flagship projects at CERN:



LHC

HiLumi HL-LHC PROJECT

FCC hh ee he

HFM High Field Magnets

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

STEAM users

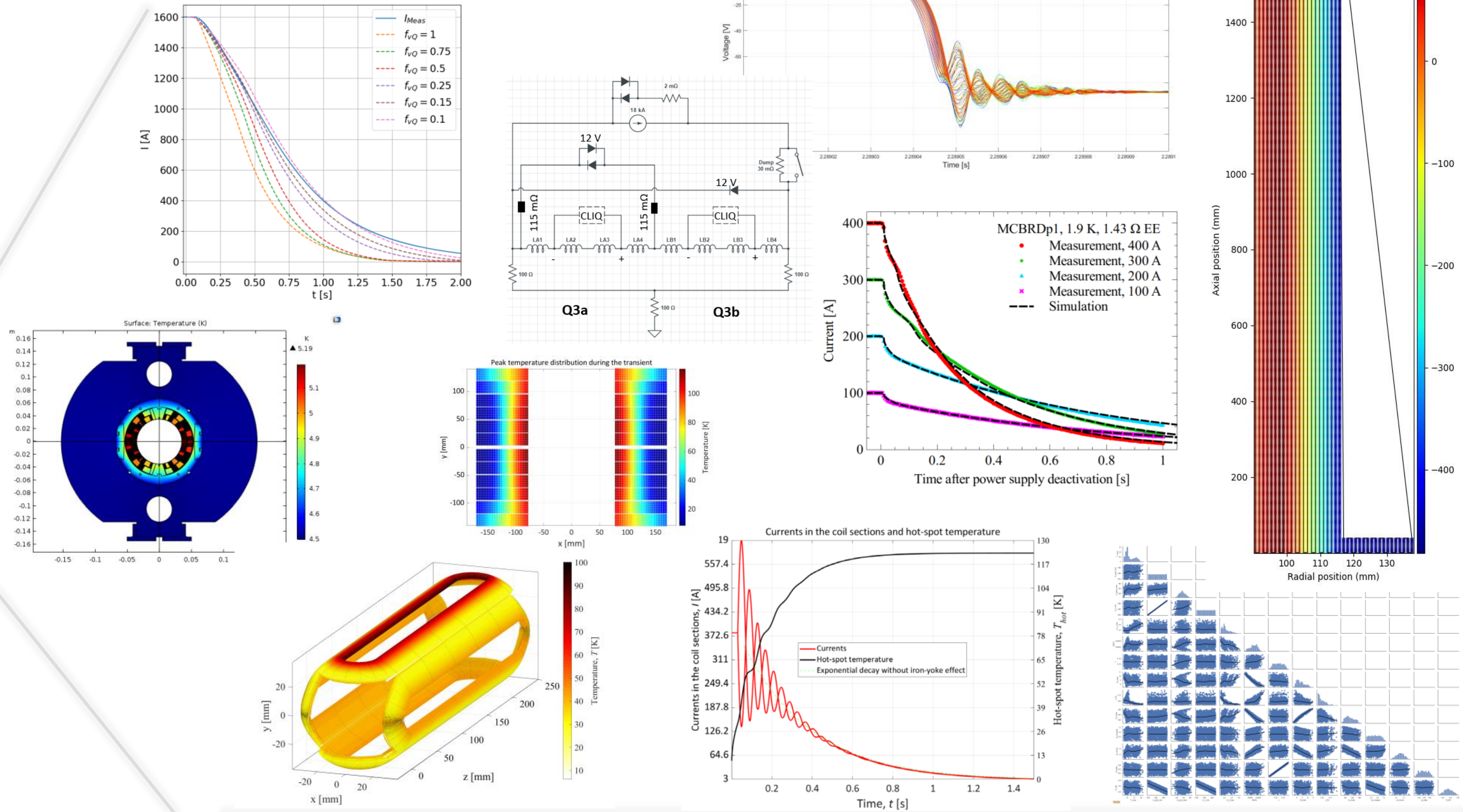
→ We support users in various labs and universities across the world [most revolve around HL-LHC projects]
→ However, most STEAM models/applications are CERN-based as the main driver is CERN circuit simulations

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

Scope of STEAM framework

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

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

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

DIFFERENT CONDUCTOR TYPES
- ✓ Nb-Ti
- ✓ Nb_3Sn
- ✓ Bi-2212
- ✓ YBCO

DIFFERENT LEVEL OF DETAIL
- ✓ Circuit → Magnet → Cable → Wire → Filament

→ We develop, validate, and use different simulation tools for solving different problems

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

ELECTRICAL CIRCUITS

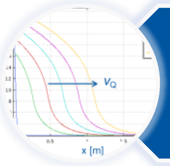
- ✓ Electrodynamics
- ✓ Non-linear components (Diodes, thyristors)
- ✓ Empirical model of magnet eddy-currents
- ✓ Parasitic capacitance to ground
- ✓ Cold Diode heating effect
- ✓ Busbar self-inductance
- ~ Power converter control
- ~ Dependence of inductance on current
- x Heating effect in EE resistor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

MAGNETS

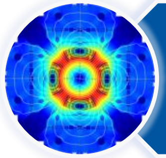
- ✓ Non-linear material properties
- ✓ Quench development and ohmic loss
- ✓ 1D, 2D and 3D thermal diffusion
- ✓ Inter-filament coupling loss
- ✓ Inter-strand coupling loss
- ✓ Iron-yoke saturation effect on self-inductance
- ✓ Cooling to thermal sink (collars, bore, wedges)
- ~ Persistent-currents loss
- ~ Eddy currents in metal elements
- ~ Accurate helium cooling
- x 3D magnetic field
- x Hysteresis in iron yoke
- x Mechanics
- 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. Nope, we can't simulate everything :-/

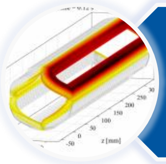
STEAM tools - 2021



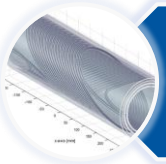
BBQ



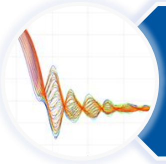
SIGMA



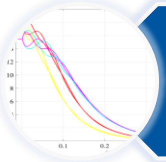
LEDET



PROTECCT



SING



COSIM

Conductor

Magnet

Circuit

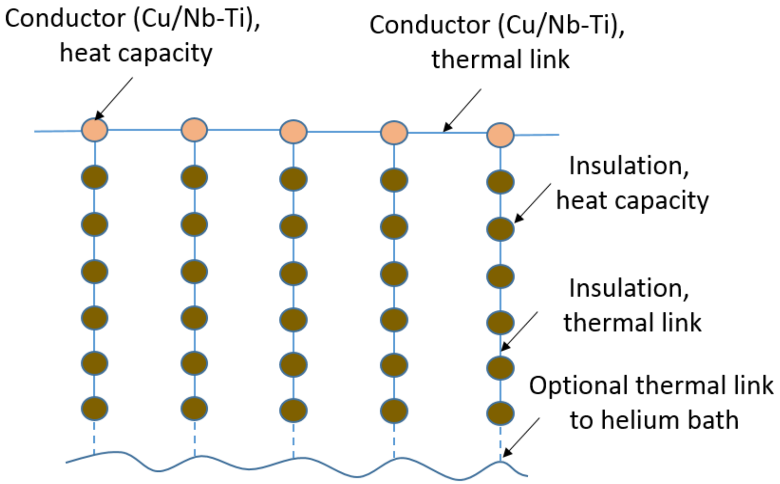
STEAM tools - 2022

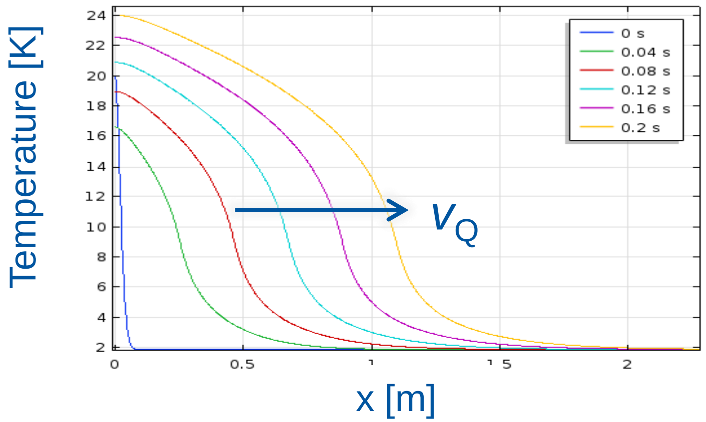
BBQ(Comsol) → PyBBQ BBQ(GetDP)	Conductor
FiQuS	Magnet
SIGMA	Magnet
LEDET	Magnet
PROTECCT	Magnet
SING → PySING	Circuit
COSIM	Circuit

BBQ (BusBar Quench)

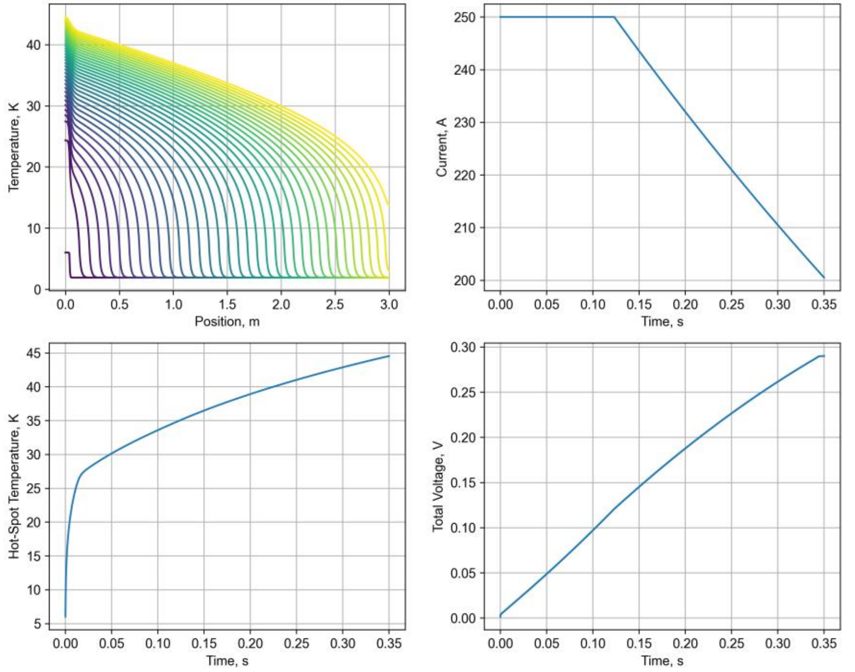
Comsol (FE) based BBQ tool drawbacks (mainly commercial licence and lack of input file) are being addressed.

- Finite difference BBQ coded in python (PyBBQ) is being developed
- Finite difference LEDET can be used for BBQ simulation
- Finite element tool based on GetDP is planned to be developed



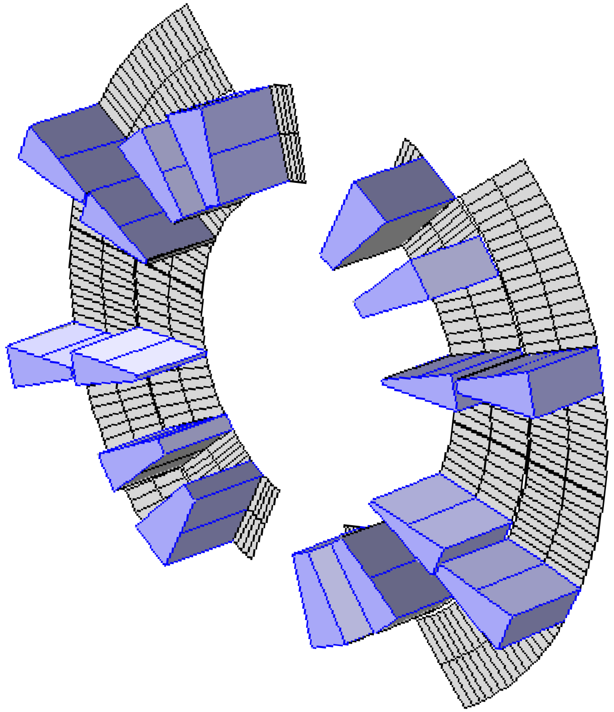


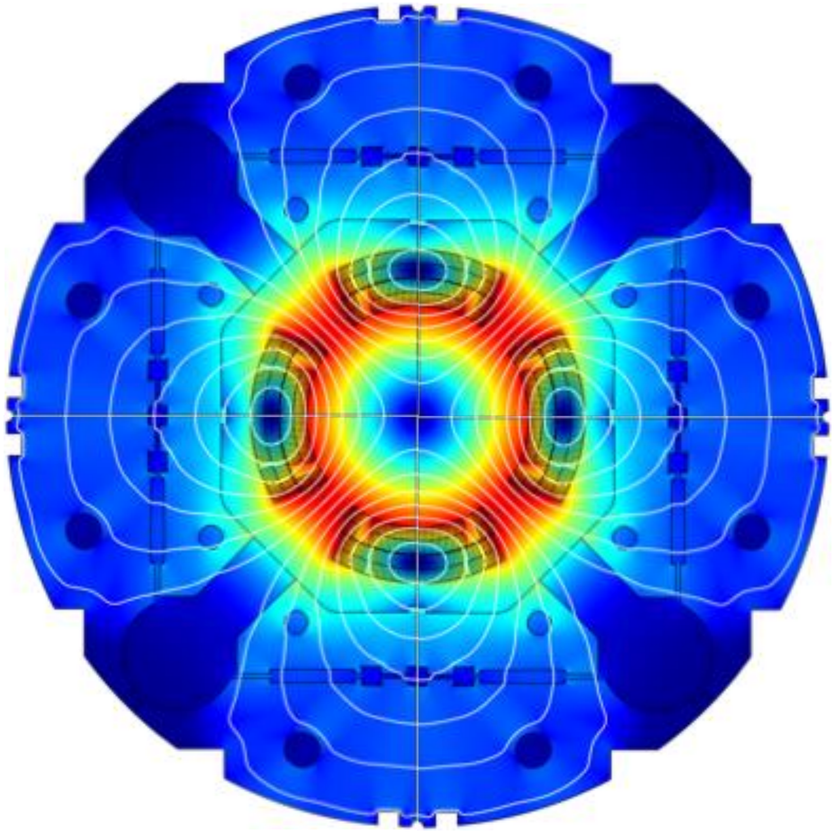
Temperature-development along length of conductor

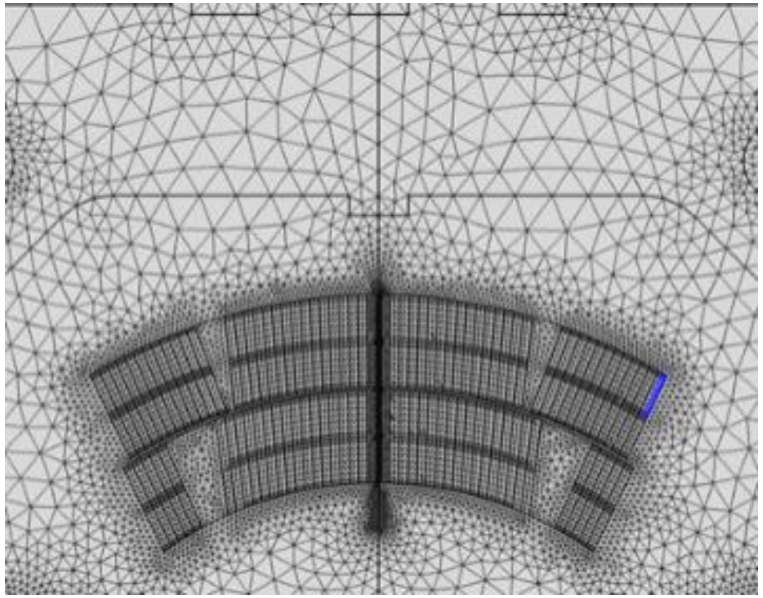


→ To simulate 1D+1D quench propagation in superconducting busbars
→ New development: PyBBQ (Python program, finite difference solver)
→ Future development: BBQ based on GetDP

SIGMA (STEAM Integrated Generator of Magnets for Accelerators)





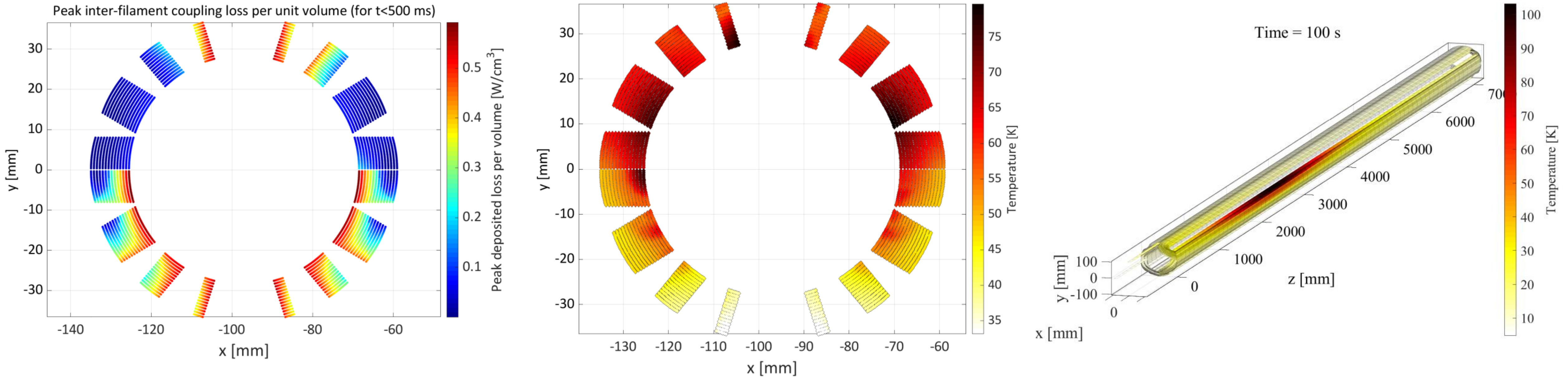


→ To simulate electro-magnetic and thermal transients in superconducting magnets in a 2D geometry using a finite-elements (FE) model

Java

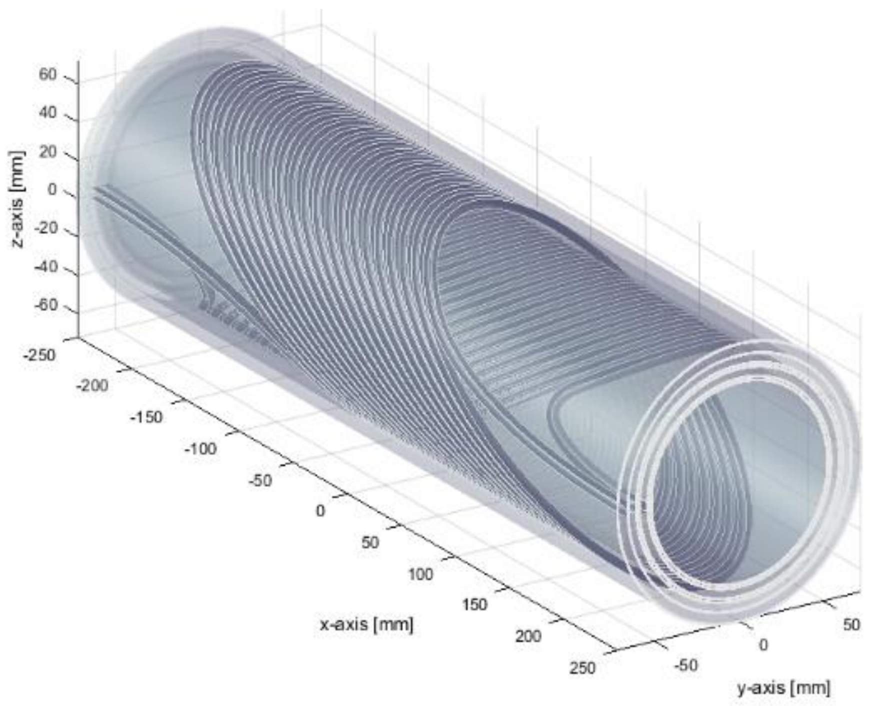
COMSOL MULTIPHYSICS®

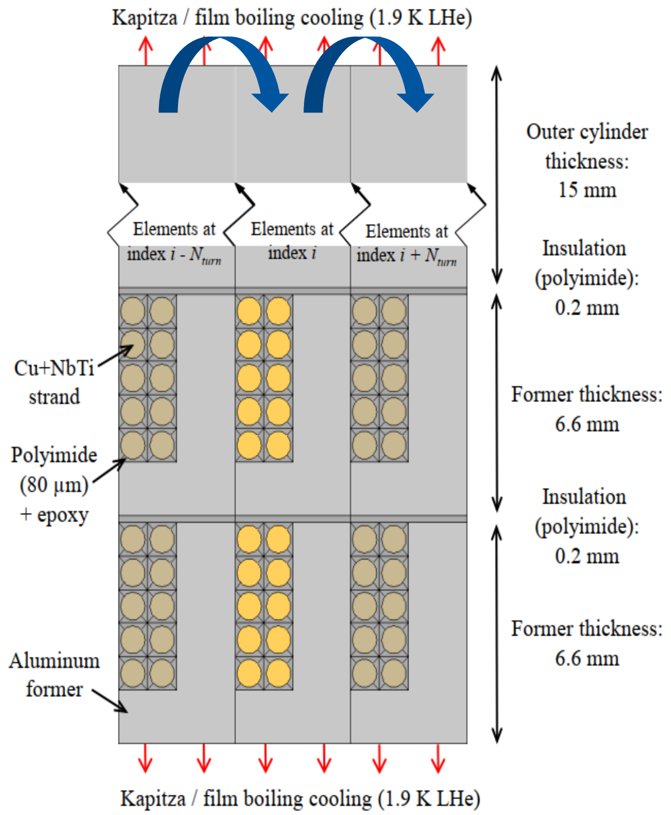
LEDET (Lumped-Element Dynamic Electro-Thermal)

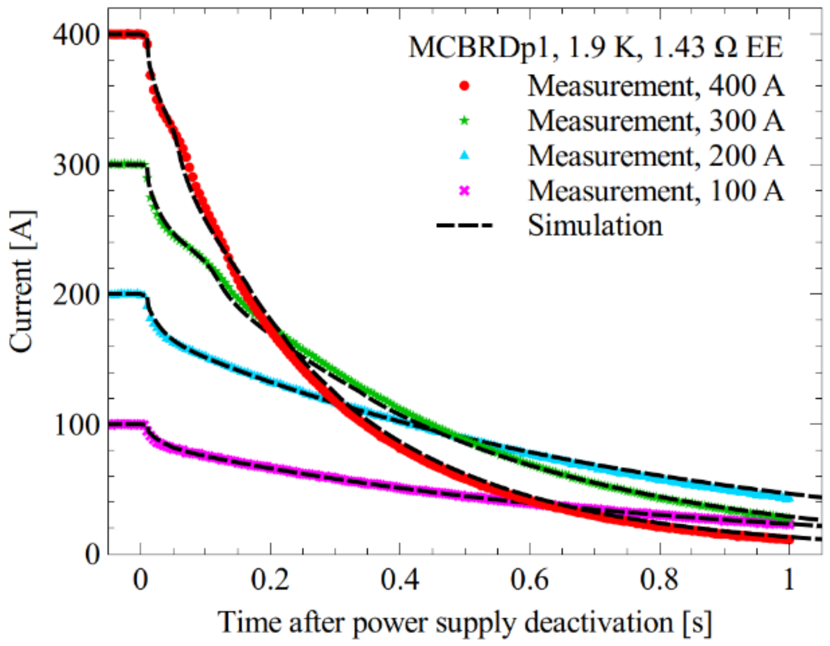


→ To simulate electro-magnetic and thermal transients in superconducting magnets in 2D and 3D geometry using finite-differences method

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

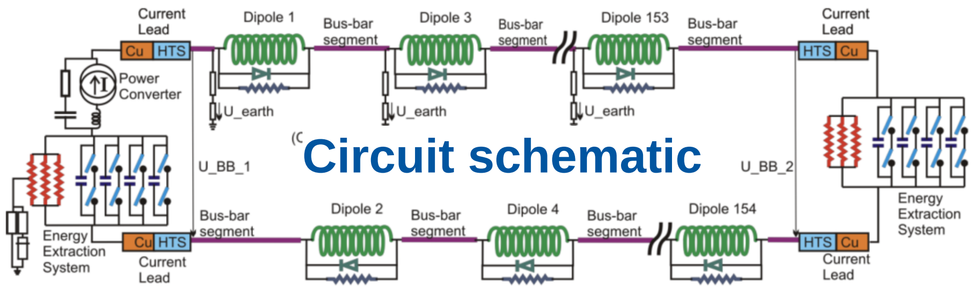


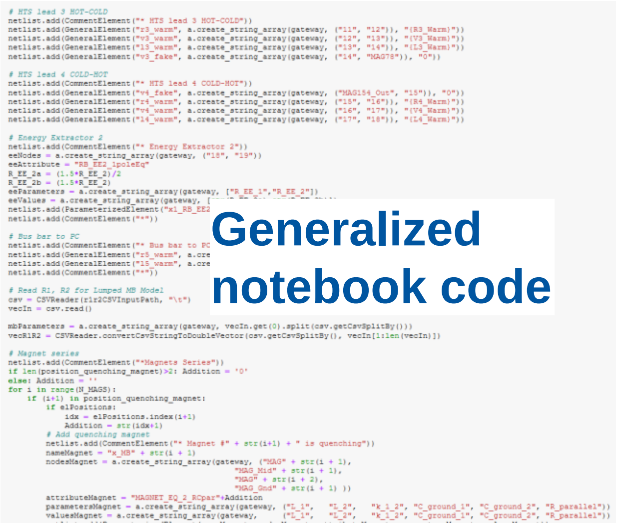


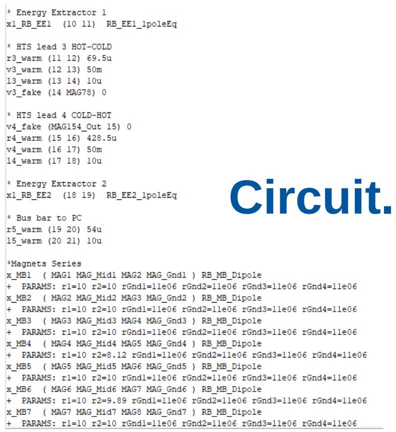


→ To simulate electro-magnetic and thermal transients in canted-cosine-theta (CCT) using finite-differences method

SING (STEAM Integrated Network Generator)







→ To automatically generate PSPICE and LTSPICE circuit models relying on shared sub-components

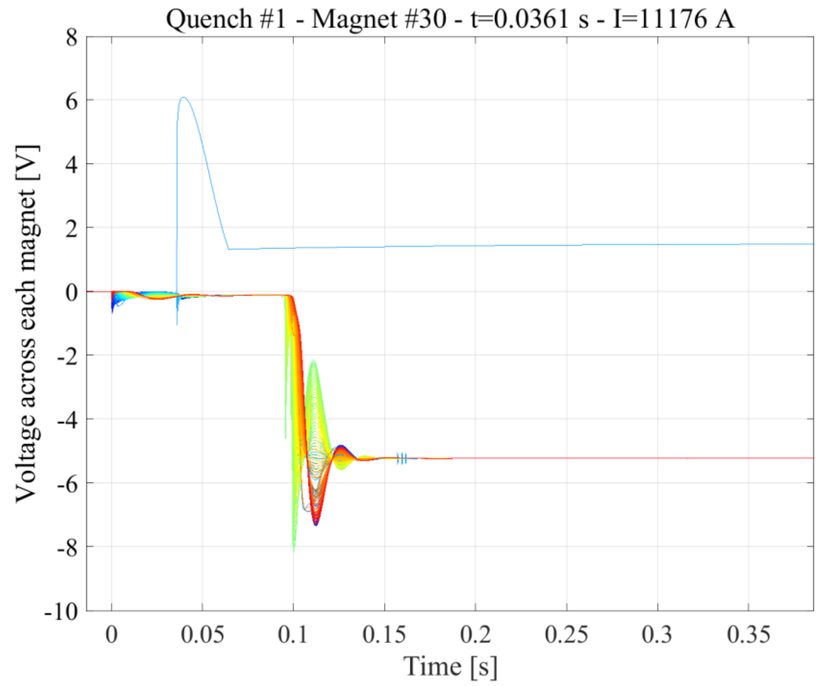
→ In 2022 it was completely re-written in Python (ParserPSPICE):

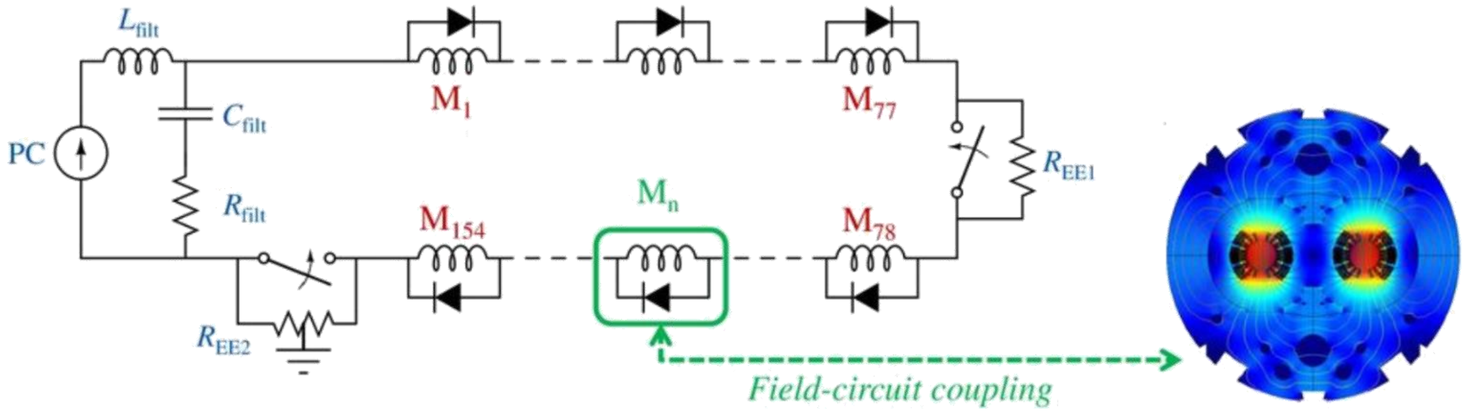
+ less Java code to maintain

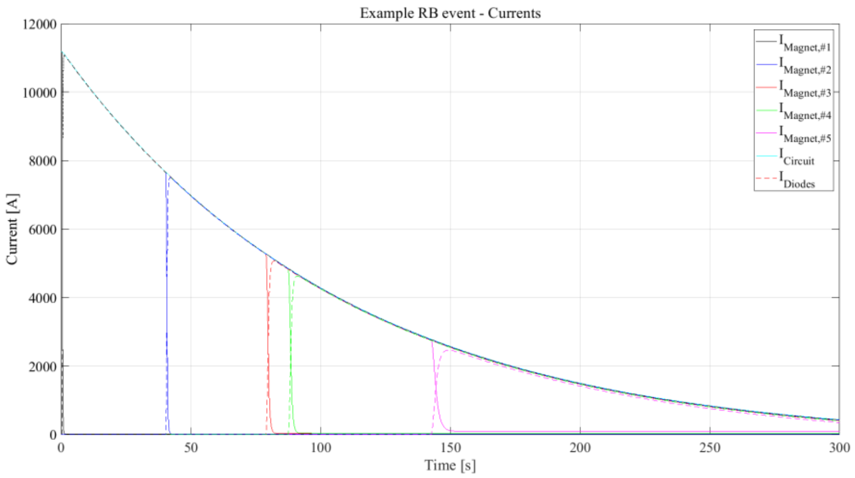
+ inputs are yaml based (as the rest of the framework)

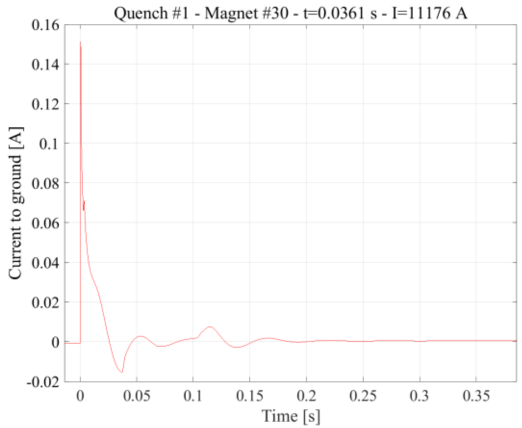
+ automatic writing of yaml circuit file from existing .cir netlist file

COSIM (Co-operative Simulation)





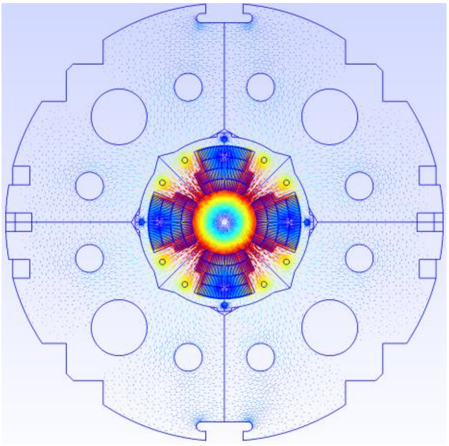




→ To run co-operative simulations of models developed in different programs (and possibly by different people)

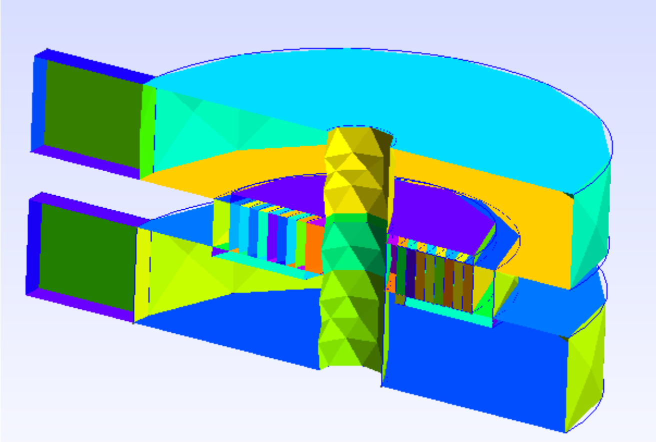
Finite Elements Quench Simulator (FiQuS)

2D Example for quadrupole MQXA



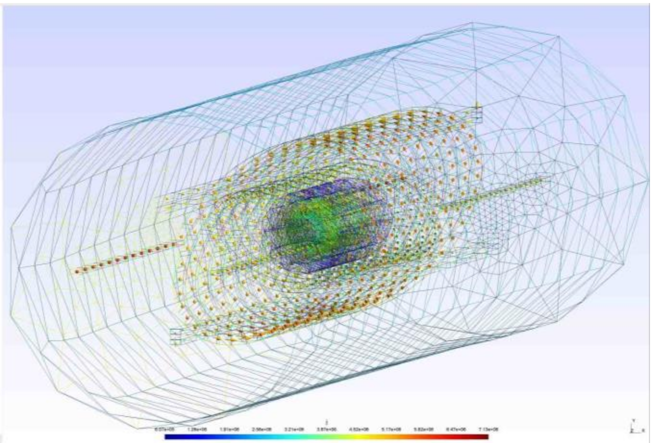
- B and M calculation for LEDET
- Stand-alone quench simulations
- Thermal transient and steady state sim.

3D Example of a NI HTS coil

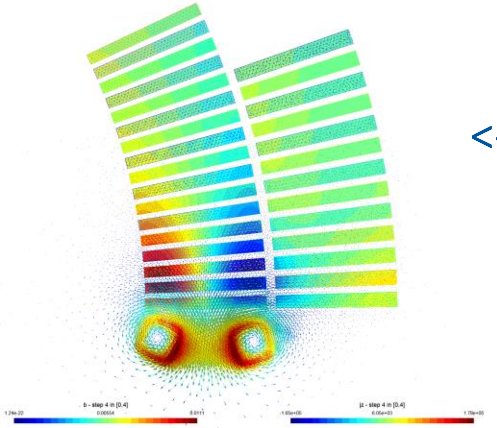


- HTS coils ramp up and down simulations
- HTS coils quench simulations
- Coils with insulation, no-insulation, partial- insulation.

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

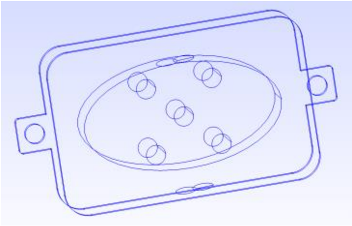


<- 2D coupled Th-EM for E-CLIQ

- Induced currents in all metal parts.
- Joule heating due to induced currents.
- IFCC and ISCC to be introduced.

GMSH for E-CLIQ

- Gmsh used to create 3d models of small demonstrator formers that can be 3d printed.



Gmsh

GetDP

python™

YAML

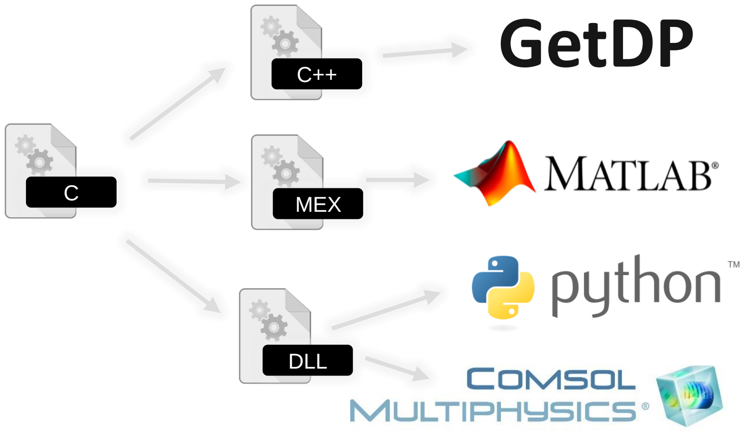
Library of Material Properties

Material Properties

KAPTON	Property	C	MatLab	Inputs	Range(★)	Units	Reference
1 (★★)	Thermal conductivity	CFUN_kKapton	• kKapton • kKapton_mat	T in K (scalar / array)	• [1,500K] • Curve fit error: 2%	W/(K.m)	[1], p. 20
2	Specific heat	CFUN_CvKapton	• cpKapton_nist • cpKapton_nist_mat	T in K (scalar / array)	• [4,300K] • Curve fit error: 3%	J/(Km3)	[1], p. 20

G10	Property	C	MatLab	Inputs	Range	Units	Reference
3	Thermal conductivity	CFUN_kG10	kG10_mat	T in K (scalar)	• [10,300K] for normal direction • [12,300K] for parralel direction • Curve fit error: 5%	W/(K.m)	[1] p. 23
4	Specific Heat - NIST	CFUN_CvG10	• cpG10_nist • cpG10_nist_mat_old • cpG10_nist_mat	T in K (scalar / array)	• [4,300K] • Curve fit error: 2%	J/(Km3)	[1] p. 24

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



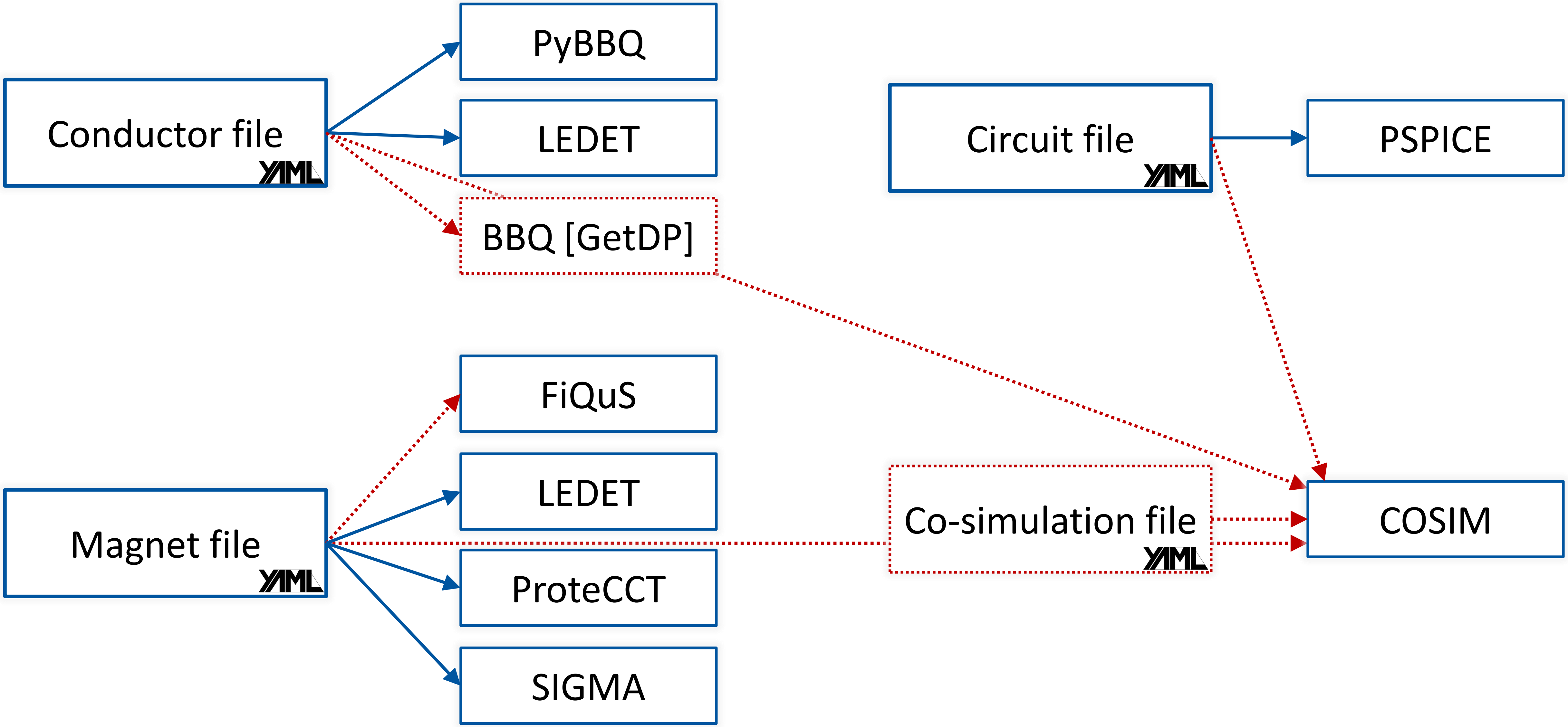
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SitePages/Material%20Properties.aspx
https://gitlab.cern.ch/steam/steam-material-library
https://gitlab.cern.ch/steam/steam-ledet-material-library

→ We share our material property database with users to support a community of users across different labs/universities and to help model cross-checking

STEAM model library: how the models are generated and versioned

Software	2021	2022
BBQ	Manual in COMSOL	Manual in COMSOL
PyBBQ	-	Yaml + Python API
FiQuS	-	Yaml + Python API
SIGMA	Notebook + Java .jar	Notebook + Java .jar
LEDET	Notebook + Python API	Yaml + Python API
ProteCCT	Manual in Excel	Yaml + Python API
SING	Notebook + Java .jar	Yaml + Python API
COSIM	Notebook + Java .jar + Python API	Yaml + Python API (foreseen for the end of 2022)

STEAM model library: Input files [items in red: TO DO]



Why STEAM could be useful to YOU

We can offer help to

→ Obtain reference cases for transients in LHC and HL-LHC circuits (quenches, ELQA high-voltage tests, power-converter switching-off, energy-extraction switch opening, transfer function measurements,…)
→ Understand the behaviour of non-trivial circuits (magnet chains, parallel paths, nested magnets, etc)
→ Assess the impact of proposed changes to circuit hardware or operation modes
→ Study failure scenarios
→ Identify worst-case scenarios for circuit components
→ Attempt to reproduce unexpected events or observations
→ Develop simulations for R&D quench detection and protection techniques
→ Provide boundary conditions for analyses of other systems
→ Obtain material properties in various forms

Examples of what STEAM models were used for in 2021

LHC

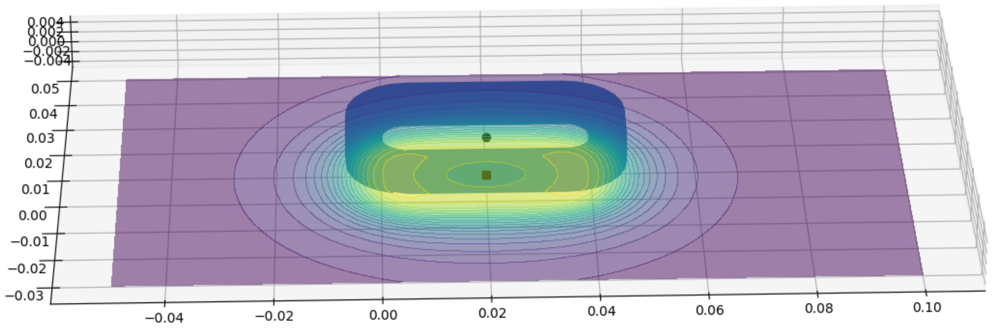
Quench Heaters	→ Assess the consequences of raising MB quench detection thresholds (worst-case analysis) → Analyse quench protection of Q1 magnet in RQX.R1 with non-conform quench heater discharge unit → Calculate the effect of quench-heater field on the beam, including the effects of beam-screen shielding 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

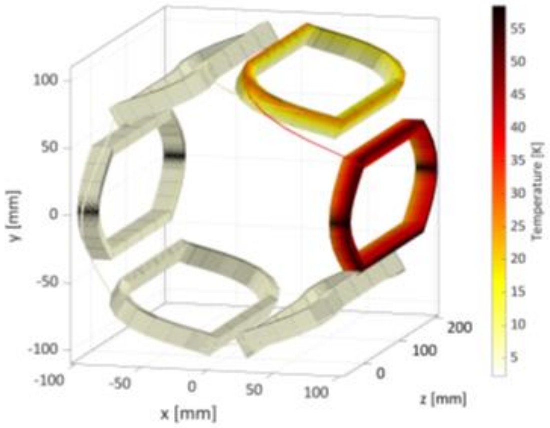
Examples of what STEAM models were used for in 2021

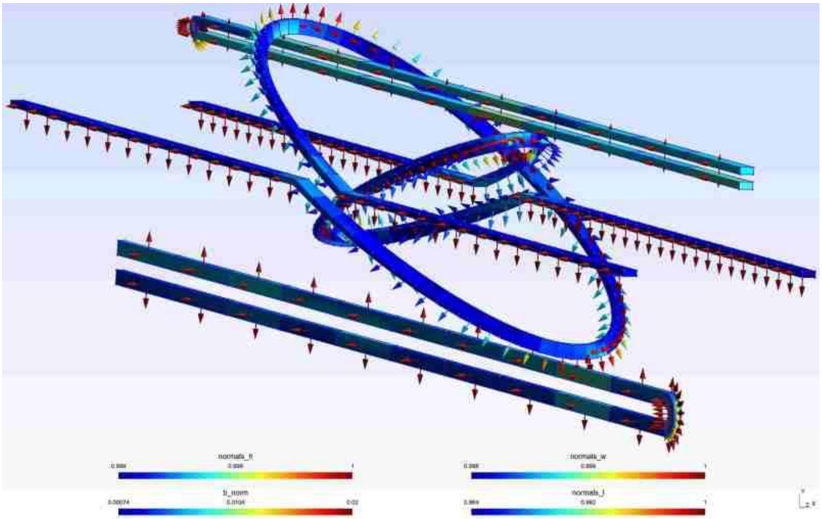
HL-LHC

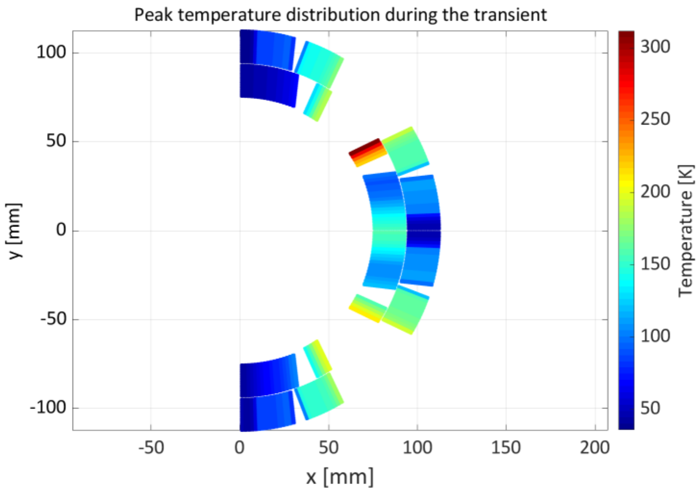
Baseline verification	→ Verification of baseline quench protection for various HL-LHC circuits → Parametric analyses and worst-cases for all circuit components in HL-LHC Inner Triplet circuit → Analyse quench protection of HEL larger solenoids → Uncertainty quantification by automatically performing 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

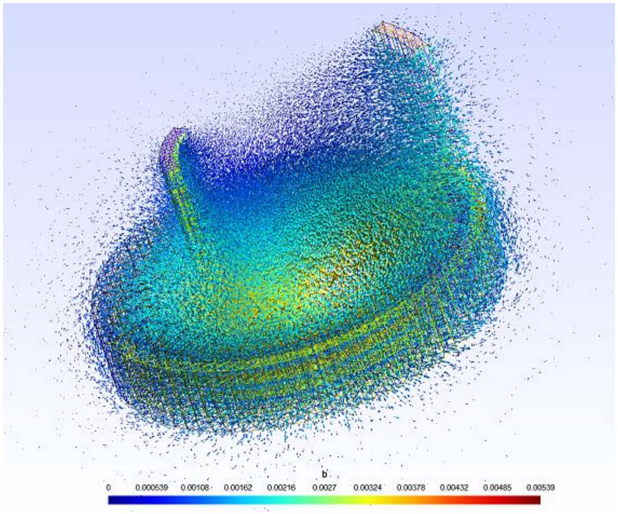
Some highlights from 2022

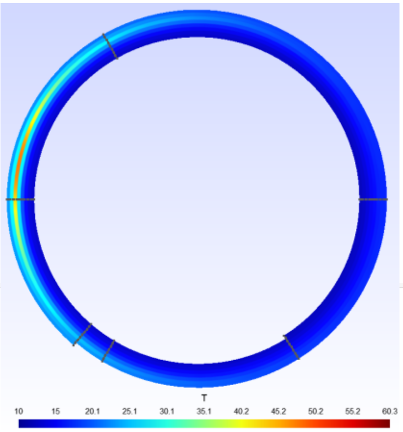


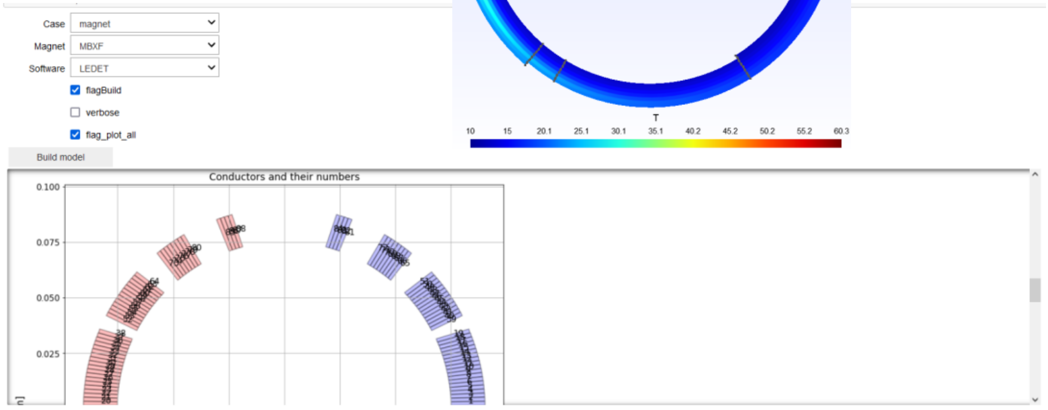








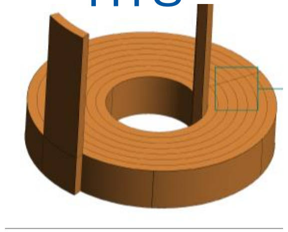




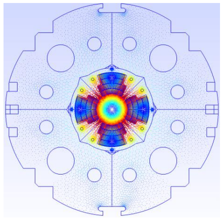
Some topics worked on in 2022

… as a list of abstracts accepted for ASC2022

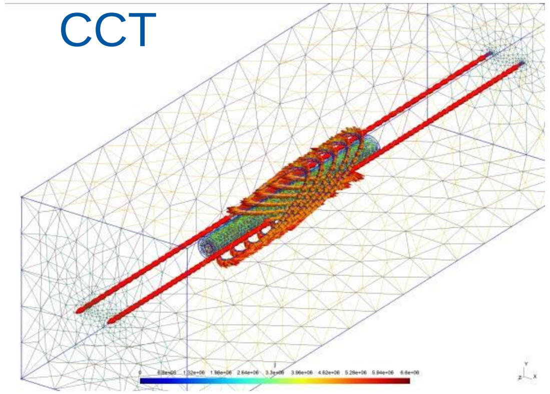
HTS



LHC

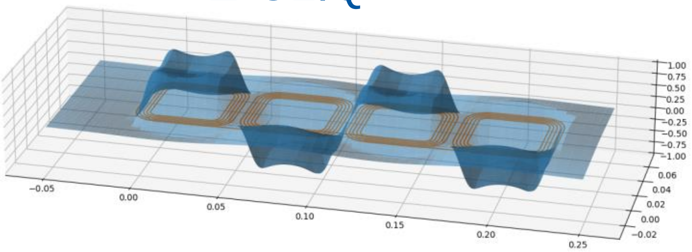


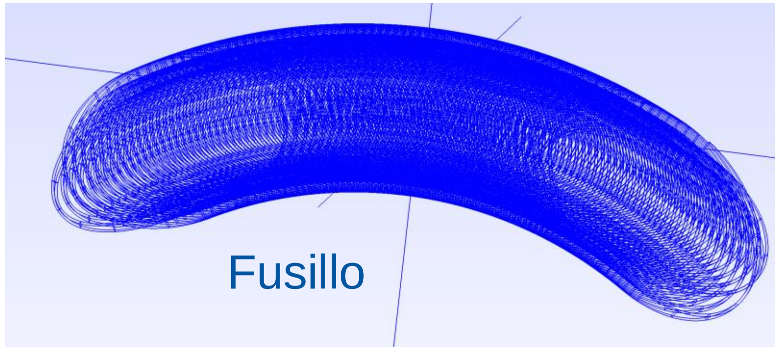
CCT



- **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"

E-CLIQ





Main takeaways – What is the STEAM team doing?

- ✓ We develop and use STEAM software tools to simulate transients in superconducting magnets and circuits
- ✓ We maintain and provide a set of tools that have different strengths and limitations
- ✓ We continuously improve our tools to address the expanding needs of the superconducting community
- ✓ We ensure that STEAM can be used every day for several CERN flagship projects (LHC, HL-LHC, FCC)
- ✓ We offer the simulation tools and material library in order to build a community [*aka gather up superconductivity geeks*] and to facilitate model cross-checking
- ✓ We aim at making the model generation and running processes as easy and intuitive as possible so that newcomers and external users can learn quickly
- ✓ We try to include as much relevant physics as it is practical... but nope, we can't simulate everything :-/
- ✓ We can offer help in simulating powering transients, quenches, ELQA high-voltage tests, power-converter switching-off, energy-extraction switch opening, transfer function measurements, R&D quench protection systems… and we like exotic transients

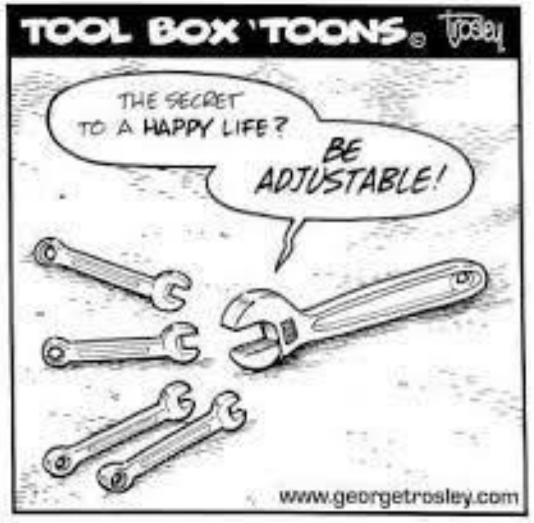
Don't hesitate to contact the STEAM team: *the first coffee is on us!* → steam-team@cern.ch

The future of STEAM

The following slides are copied from 2021 STEAM Workshop

We'll go through them now and discuss the 2022 progress

What this session is about?



- We would like this session to be very interactive
- Please let us know your thoughts on each topic that we present

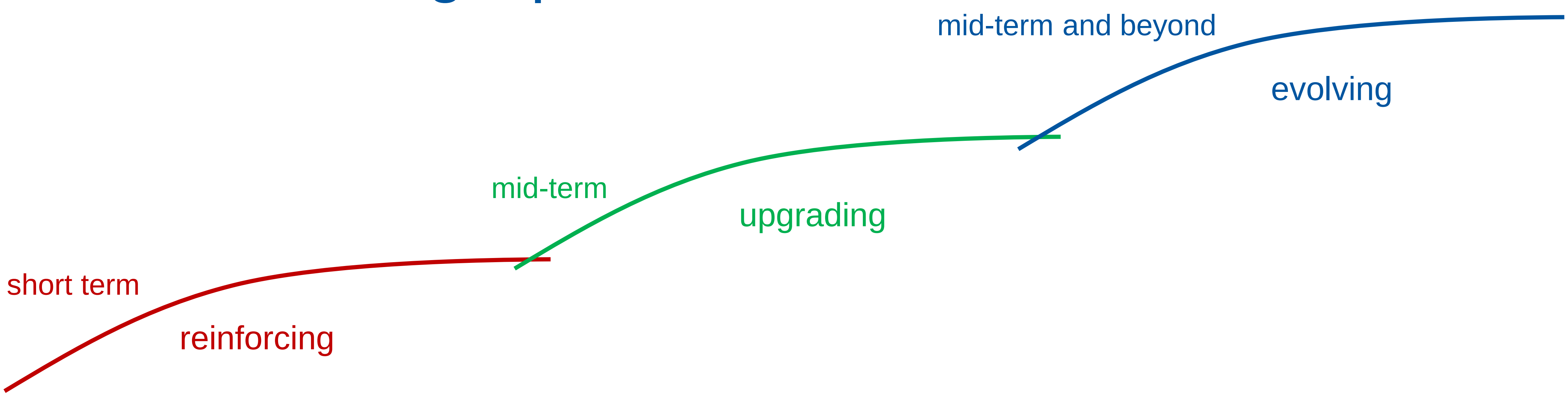
For each slide we would like to know:

- What are your thoughts?
- Would you use this feature / benefit from development?
- Could we do it a different way?
- Do you have experience in this topic you could share?
- Do you know a colleague who would be interested or could help?

These are abbreviated on each slide as a reminder

Thoughts?
Benefits for you?
Different way?
Your experience?
Contact person?

STEAM strategic priorities



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.

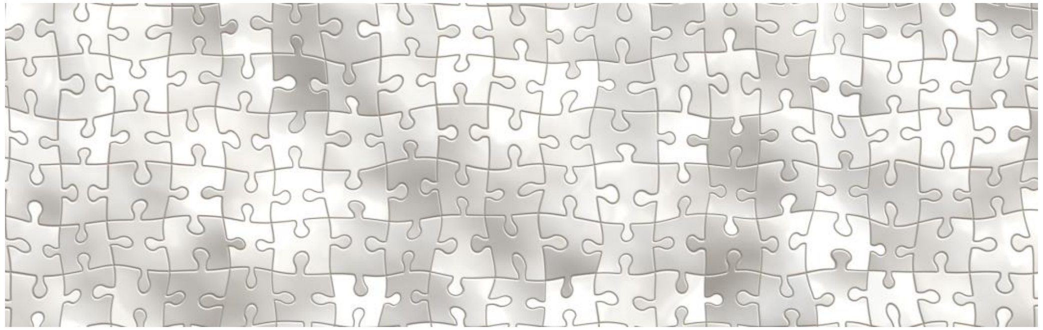
Values

continuity, readiness, simplicity, recognition, completeness, maintainability

Vision

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

STEAM strategic priorities



short term

reinforcing

Increase reliance on the same input files for generating models across the STEAM framework

Broaden capability to simulate all LHC and HL-LHC superconducting magnet circuits

Improve capability for scripted model validation

Increase number of codes covered with software testing

Continue to maintain and version control our models

Keep simulation tools and circuit/magnet models ready to analyze transients occurring in LHC/HL-LHC

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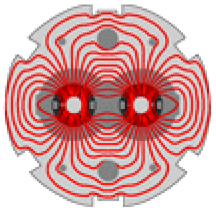
Benefits for you?
Different way?
Your experience?
Contact person?

STEAM strategic priorities

short term

reinforcing



LHC

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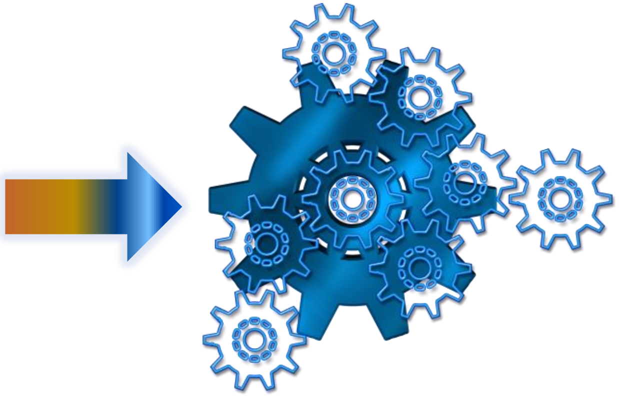
short term

reinforcing



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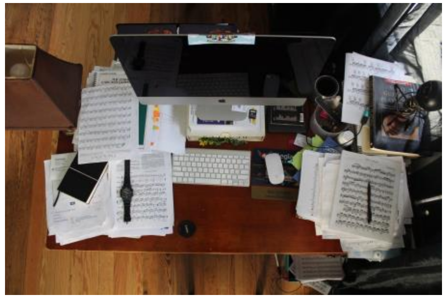

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STEAM strategic priorities

mid-term

upgrading

Review and improve High Performance Computing* capabilities

Decrease dependency on commercial software

Further streamline validation of models with measurements

Improve scripting capabilities for model building, solving and postprocessing

Improve capabilities and provide examples for interfacing with advanced parametric analyses **

Thoughts?
Benefits for you?
Different way?
Your experience?
Contact person?

*Both shared and distributed memory clusters, with focus on machines available at CERN
** and design exploration, model calibration, risk analysis, and uncertainty quantification

STEAM strategic priorities

COMSOL MULTIPHYSICS · Excel · PSpice · ONELAB, GetDP, Gmsh · YAML · LTspice

mid-term

upgrading

What are your thoughts on GetDP replacing Comsol ?
What do you think of free FE solvers ?
Would you recommend other FE tools ?

Review and improve HPC* (High Performance Computing) capabilities

Decrease dependency on commercial software

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STEAM strategic priorities

TDMS

mid-term

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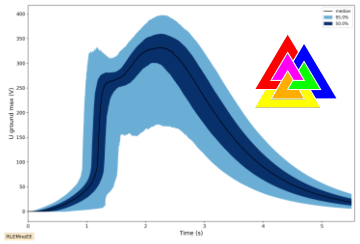
STEAM strategic priorities



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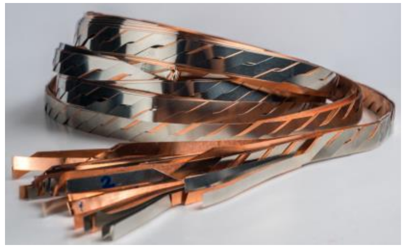
STEAM strategic priorities

mid-term and
beyond

evolving



Adapt tools to the needs of new magnets,
in particular High Field Magnet (HFM) programme at CERN

For the above, include all physics relevant for quench protection and powering transients

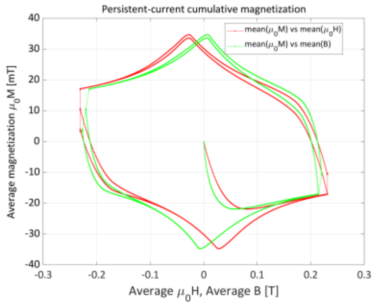
Review and consider improving capabilities to interface with structural analysis software, with a consideration of quench in magnets with brittle superconductors

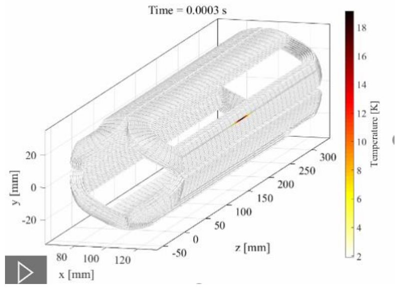
Thoughts?
Benefits for you?
Different way?
Your experience?
Contact person?

STEAM strategic priorities

mid-term and beyond

evolving





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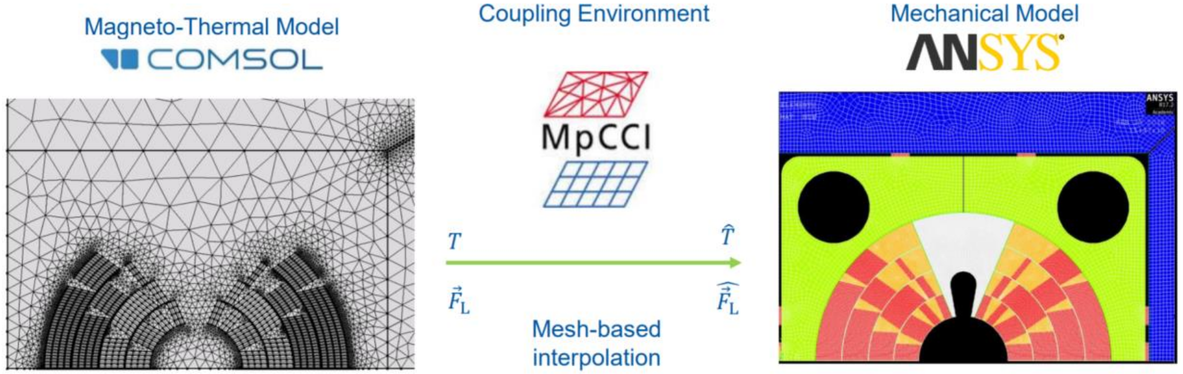
STEAM strategic priorities

mid-term and beyond

evolving



or free FE tool

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* Some previous work: https://indico.cern.ch/event/712782/contributions/2928119/attachments/1616581/2569496/MechanicalStressDuringQuench.pdf

Discussion time !!!

What are we missing in our strategic priorities?
Features, tools (inc. FE), magnets, languages, materials?

What stops you from using STEAM tools?

Are any long-term topics more urgent than we think?

Anything else related to STEAM we should know?

Annex

STEAM Circuit Library structure

INPUT: **Circuit + Magnet info**

- LHC Design Report
- ROXIE magnetic models*
- LHC magnet diagrams
- Experimentally deduced values of unknown parameters

Python-based SWAN notebooks

Python steam-nb-api

PSPICE electrical element library

OUTPUT: **STEAM models**

- **PSPICE** electrical models of circuits in the time domain
- **STEAM-LEDET** electro-magnetic and thermal models of magnets
- **STEAM-SIGMA** FEM magnet models
- **STEAM-COSIM** models [coupled PSPICE circuit model + LEDET magnet model]
- **PSPICE** magnet/circuit models in the frequency domain

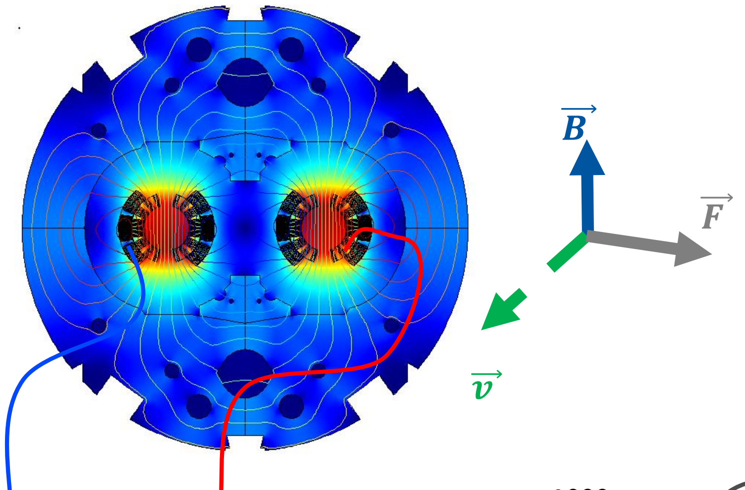
Model validation with existing experimental data plus additional ad-hoc experiments

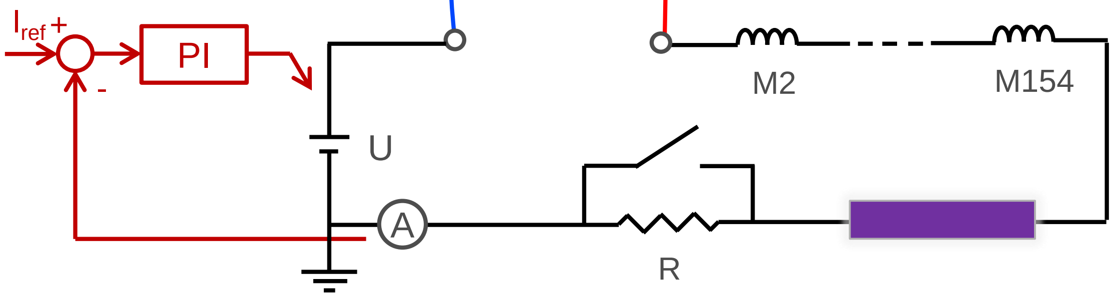
*We don't develop ROXIE models, we only use them. ROXIE LHC magnet repository: https://roxie-lhc-magnets.web.cern.ch/roxie-LHC-magnets/

Superconducting Accelerator Circuits – *Numerical Challenges*

Controller Model

- ✓ Differential-algebraic equations
- ✓ **Fixed frequency of operation**
- ✓ 10-100 elements
- ✓ Non-linear behaviour





Busbar Model

- ✓ Partial differential equations
- ✓ **Varying time constants**
- ✓ **Adaptive mesh refinement**
- ✓ ~1k elements
- ✓ Non-linear behaviour

Field/network model of a magnet

- ✓ Partial differential equations
- ✓ **Varying time constants**
  ~10us (quench) - ~10ms (losses)
- ✓ **Varying geometric scales**
  ~10 um (filaments) - ~10 m (magnet)
- ✓ ~10 k degrees of freedom
- ✓ Highly non-linear material properties and equations

Network model of a circuit

- ✓ Differential-algebraic equations
- ✓ **Varying time constants**
  ~1 ms (switch) - ~10 min (circuit discharge)
- ✓ **Varying geometric scales**
  ~10 cm (diode) - ~10 km (circuit)
- ✓ ~10 k elements
- ✓ Non-linear behaviour

Multi-Domain, Multi-Physics, Multi-Rate and Multi-Scale Simulation

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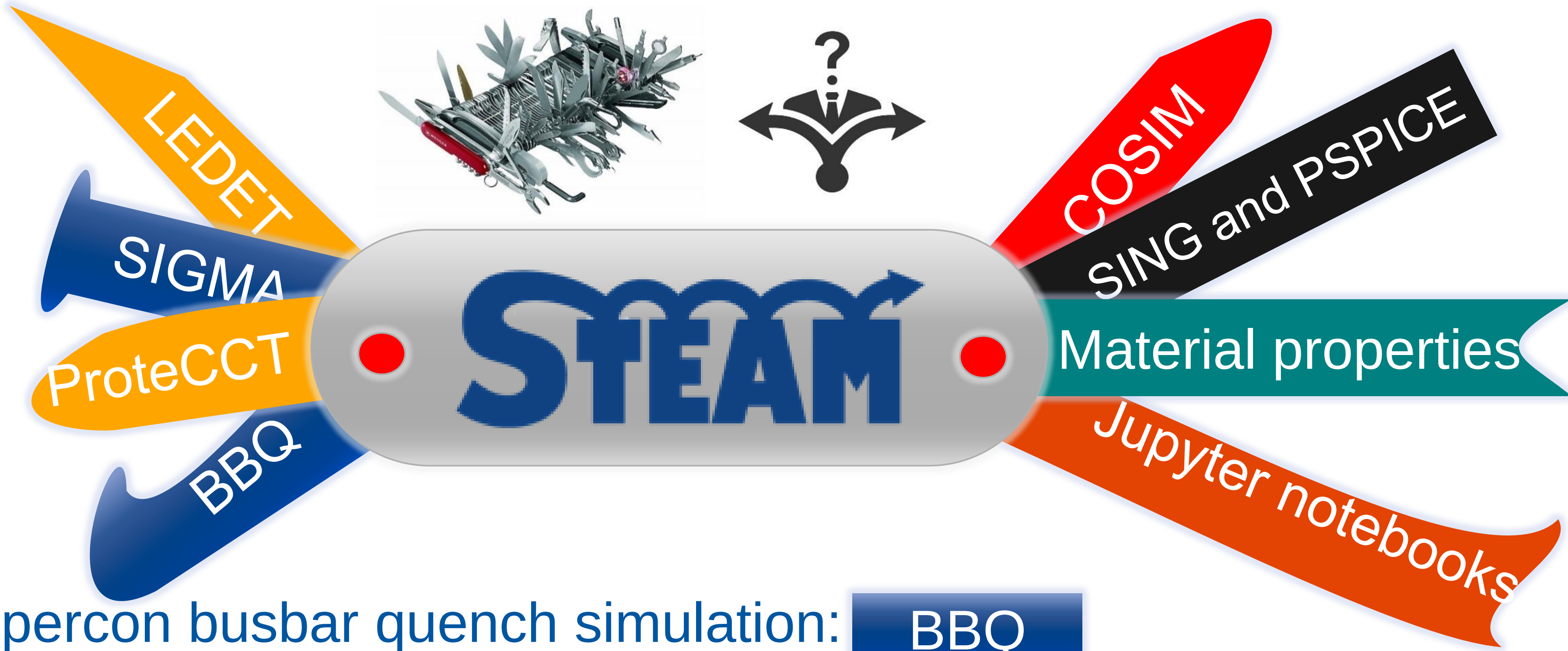
STEAM tools application (over) simplification



- Supercon busbar quench simulation: BBQ
- Supercon magnet / circuit quench simulation: LEDET and / or SIGMA
- Unless, it is a CCT magnet, in that case: ProteCCT
- If it is a more complex circuit, benefit from above and / or: SING and PSPICE
- If any of above need to be used in 'one' simulation, use: COSIM
- In most cases, it is best to start with: Jupyter notebooks
- And most tools have behind exact (or equivalent) : Material properties

STEAM has more tools, but only ones covered in the hands-on sessions are shown

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STEAM tools, solvers, languages, input files

Package	Recommended model generation/editing	Software needed for input generation/editing	Physics engine / logic	Files and software needed for final solve
BBQ	Manual edit of Comsol model	- Comsol Multiphysics	Provided in Comsol model	- Comsol model - Material properties - COMSOL Multiphysics
COSIM	Jupyter notebook with Java and Python API	- Jupyter kernel - Python - Java Runtime Environment	Coded in compiled COSIM.exe file	- COSIM.exe - json files - Models to couple - Java Runtime Environnent
LEDET	- Jupyter notebook with Python API - Roxie or PySoleno or Comsol model for field map and inductance matrix calc.	- Jupyter kernel - Python - Excel - ROXIE/PySoleno*/COMSOL	Coded in compiled LEDET.exe file	- Excel file - LEDET.exe - Field map files - MATLAB Runtime
ProteCCT	- Manual edit of Excel file - Comsol model for field and ind. calc.	- Excel - Comsol Multiphysics	Coded in compiled ProteCCT.exe file	- Excel file - ProteCCT.exe - MATLAB Runtime
SIGMA	Jupyter notebook with Java and Python API	- Jupyter kernel - Python - Java Runtime Environment	Generated and saved in Comsol model by SIGMA.jar	- Comsol model - Material properties - COMSOL Multiphysics
SING and PSPICE	Jupyter notebook with Java API	- Jupyter kernel - Java Runtime Environment	PSPICE circuit solver	- Circuit definition netlist - STEAM PSPICE component library (.cir, .stl) - Cadence Pspice

License fee for file / software: Paid / Free / Free at CERN, Paid outside

* https://gitlab.com/mawoznia/PySoleno

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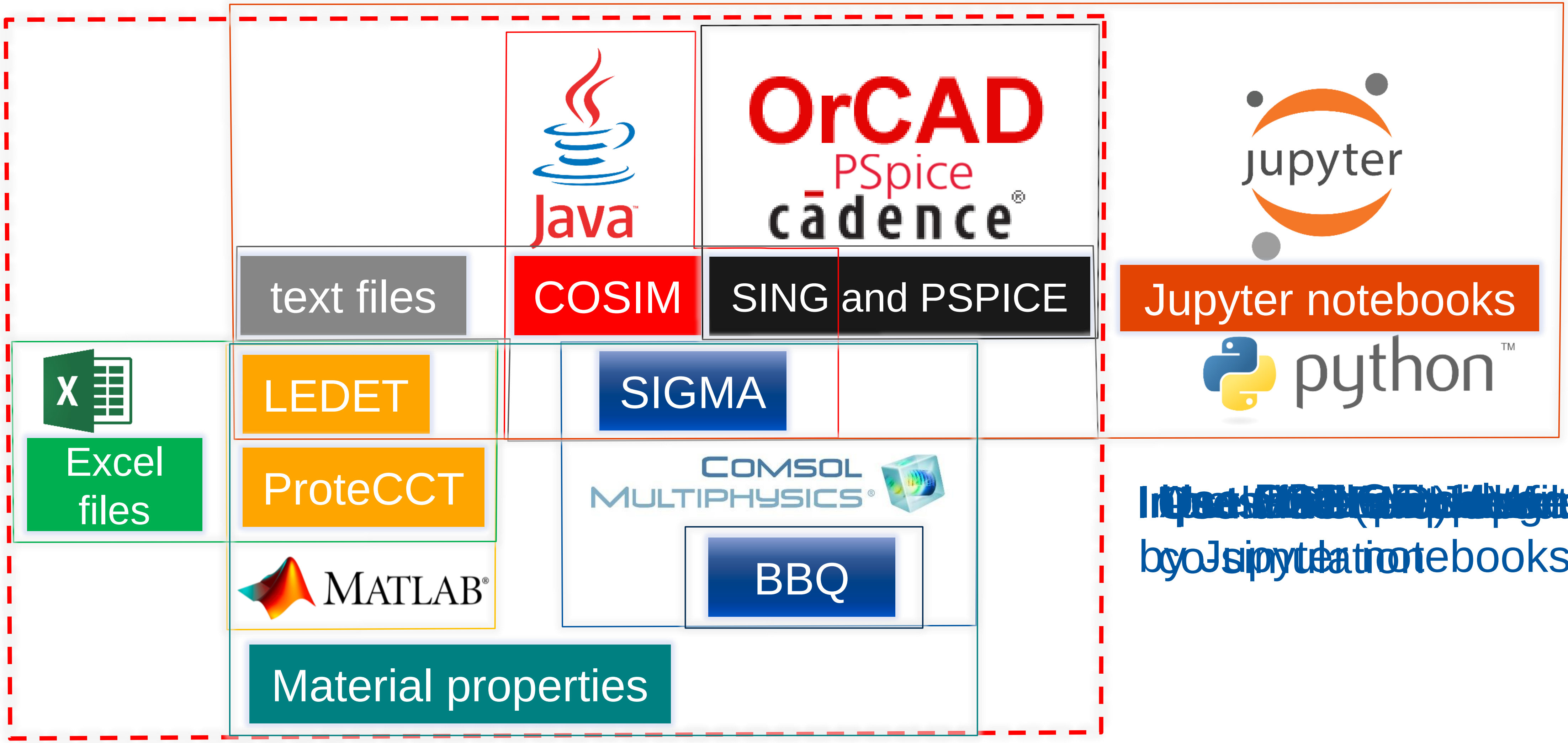
STEAM has more tools, but only ones covered in the hands-on sessions are shown

STEAM tools, solvers, languages, input files



STEAM has more tools, but only ones covered in the hands-on sessions are shown

50

STEAM components

TASKS	CIRCUIT MODELS	FINITE-ELEMENT MAGNET MODELS	FINITE-DIFFERENCE MAGNET MODELS	FREQUENCY-DOMAIN MODELS
In-house model development	+	+	+	+
In-house physics solver			+	
In-house numerical solver				
Automated model generation	+	+	+	+
Versioned library of models	+	+	+	+
Library of sub-components	+	+	+	+

In-house model development: We develop circuit and magnet models that include physical phenomena and assumptions tailored to our applications

In-house physics solver: For finite-difference models, we write the code to solve the physical problem in-house

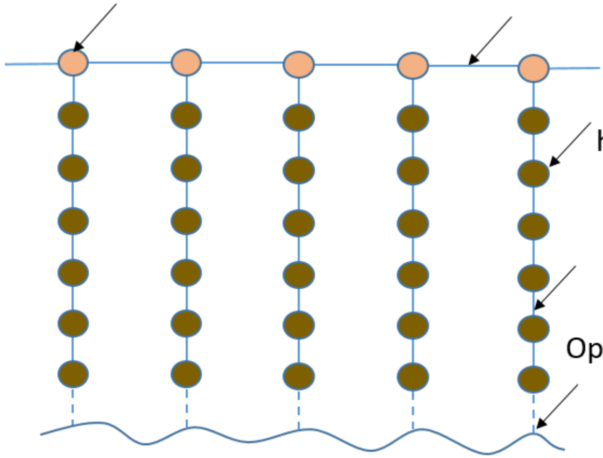
In-house numerical solver: We rely on available low-level solvers: PSPICE for circuits, COMSOL for finite-element models, Matlab for finite-difference models.

Automated model generation: Models can be generated automatically using Java or Python API's

Versioned library of models: Models are routinely versioned on Gitlab

Library of sub-components: We share circuit sub-components and material properties to facilitate model cross-checking

BBQ (BusBar Quench)



- FEM-based Comsol simulation model for superconducting busbars.
- Calculations of:
  - Quench propagation velocity
  - Development of voltage after quench origination for quench detection calc.
  - Hotspot temperature as a function of quench integral (adiabatic and with heat exchange)
- Ability to simulate circuits with known discharge characteristics (time constant)
- Compatible with STEAM co-simulation framework

More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SitePages/BBQ.aspx
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

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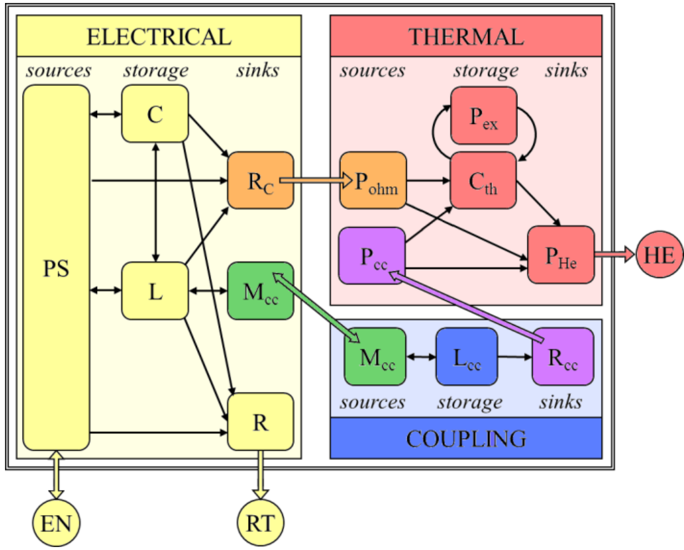
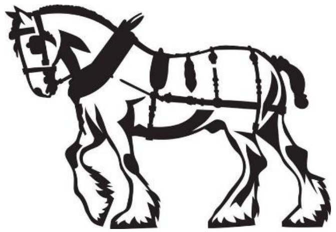
LEDET (**L**umped-**E**lement **D**ynamic **E**lectro-**T**hermal)

Tool to simulate electro-magnetic and thermal transients in superconducting magnets

- 2D, 2D+1D, 3D magnet model + simplified circuit
- Field maps and inductance dependence on iron yoke saturation calculated externally (ROXIE, COMSOL, PySoleno)
- Inter-filament and inter-strand coupling currents
- Turn-to-turn heat exchange, simplified helium cooling
- Energy-extraction, quench heaters, CLIQ transients
- Can be used in co-simulation, benefiting from COSIM
- Computationally efficient, stand-alone exe, so LEDET is fast!
- Some new features, as covered in Emmanuele’s talk
- Currently LEDET is a workhorse of our quench simulations





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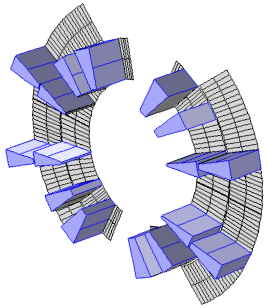
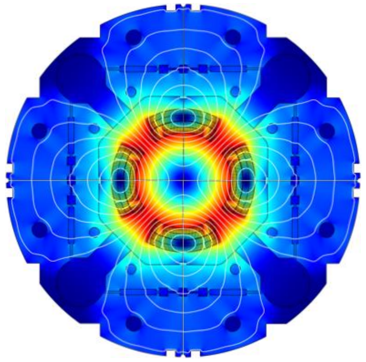
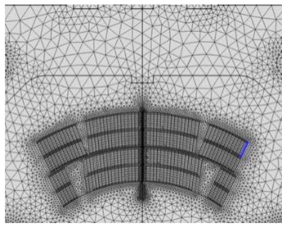
SIGMA (**S**TEAM **I**ntegrated **G**enerator of **M**agnets for **A**ccelerators)

- Automatic COMSOL model generation via Jupyter notebook
- COMSOL models generated with SIGMA implement strongly coupled magnetoquasistatic, thermal and network equations
- These equations (physics engine) are visible and editable in the model and could be expanded to suit user needs (double-edged sword)
- Models provide an interface for co-simulation in a current- and voltage-driven modes, benefiting from COSIM
- The iron yoke and copper wedges could be easily included
- This is fully fledged FE model, expansion and addition of physics and features is virtually limitless (within COMSOL capabilities)
- Material properties library files can be changed in the model, it is possible to use your own (like HTS or high-Cp materials)

More:
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Magnet / Circuit quench simulation

Why have both?

1) **Increased confidence in quench simulation results** (mitigate risk of error in simulations). This is especially important for novel magnets / conductors / circuits configurations when it is more difficult to know what to expect.
2) On detail level, they have different capabilities, limitations, setup and computational effort, like:
   a) Finite differences vs finite elements
   b) Simplifying assumptions, strengths and weaknesses
   c) Hardcoded vs. user editable equations / logic
   d) Ways to deal with iron and conducting structures
   e) Efficiency, solvers, input and output (matrix vs mesh)
   f) Extendibility and flexibility for extension

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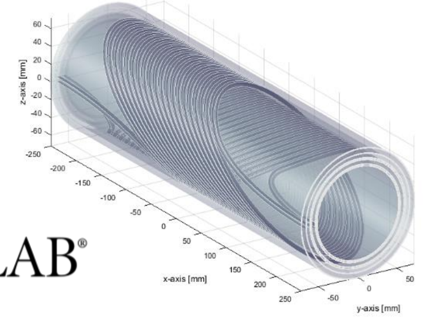
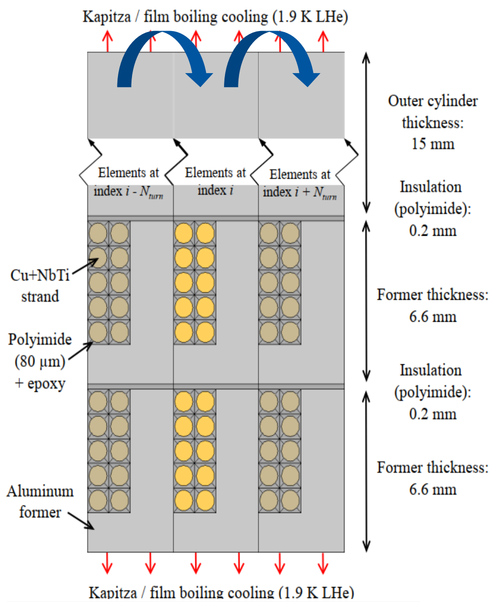
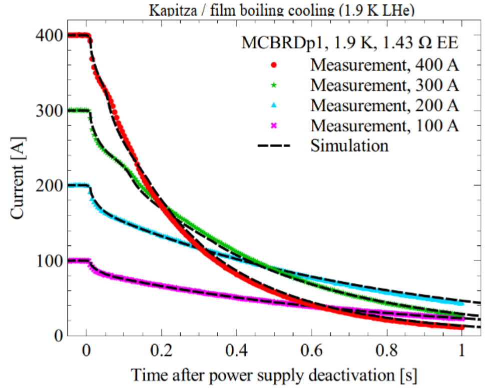
ProteCCT (Protection of Canted-Cosine-Theta) type magnets



Simulation tool for evaluating quench of CCT-type magnets

- Accounts for quench-back from conductive formers
- User-interface: Input and output to / from Excel
- Relies on accompanying COMSOL model for field and inductance calculation when geometry is changed
- High degree of consistency between simulations and experimental observations (for MCBRD magnet)
- Two fixed global correction parameters *fLoopFactor* and *addedHeCpFrac* for all cases
- Computationally efficient, standalone executable, ProteCCT is fast!





More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SitePages/ProteCCT.aspx
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

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SING (**S**TEAM **I**ntegrated **N**etwork **G**enerator) & **PSPICE** (**P**ersonal **S**imulation **P**rogram with **I**ntegrated **C**ircuit **E**mphasis)

Tools for automated generation of complex circuits + circuit solver

- Semi-automatic generation of netlists, useful for large circuits
- Circuit components can be added in programmatic and iterative way, effectively allowing ('for') loops for circuit generation
- Models could be generated more quickly and with fewer bugs and less expert knowledge needed
- Can be used for turns in magnet or magnets in circuit
- Models can be used for frequency domain and transient analysis, like quench and/or short circuits

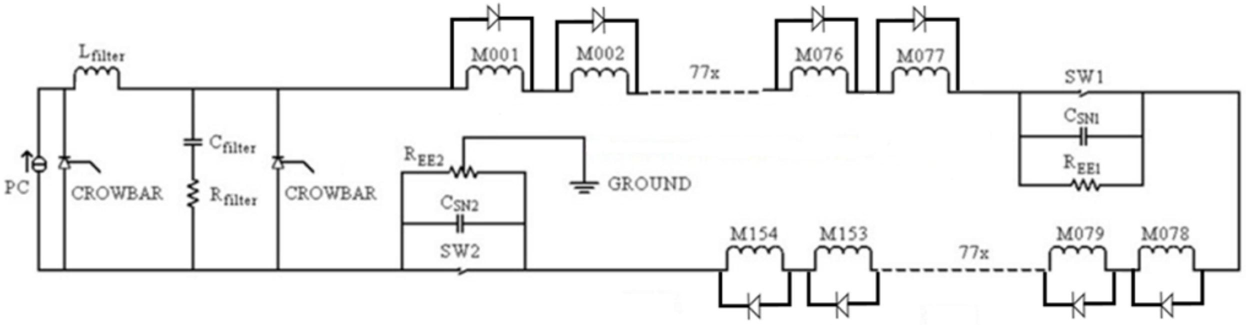
```
.subckt RB_PC_Full  1_pIn   1_pOut

v1_bbIn_PH (1_pIn 100) 0

x_GndLo     (100)                RB_PC_BbGND
x_filterRC  (102 101 103 100)    RB_PC_RCFilter
x_PS1       (101 102)            RB_PC_PS
x_PS2       (101 102)            RB_PC_PS
x_GndHi     (103)                RB_PC_BbGND

v2_bbOut_PH (1_pOut 103) 0

.ends
```



More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SING/
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

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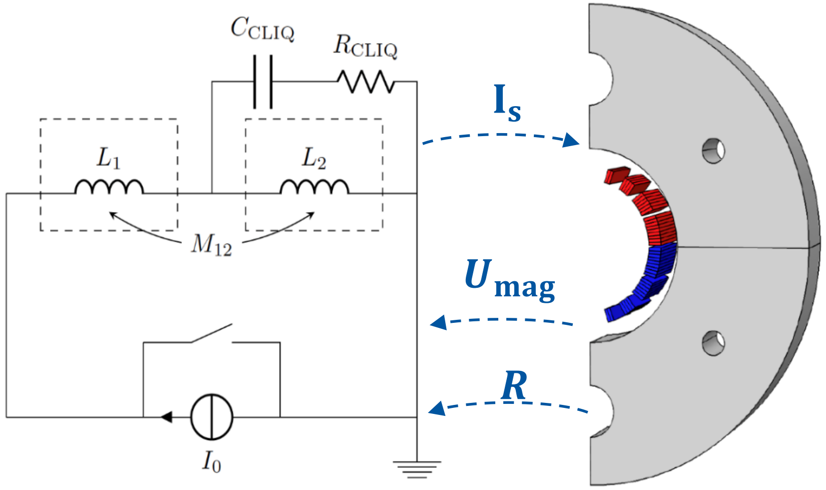
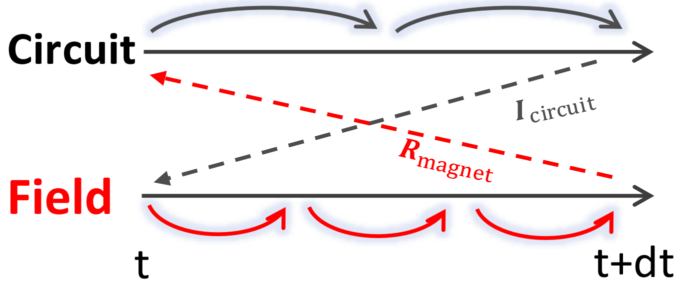
COSIM (Cooperative Simulation)

Tool to couple different software simulating interdependent phenomena occurring in various domains, with different time-scales.

- Most commonly: field model is solved with Lumped Element (LEDET) and/or Finite Element (COMSOL) tool and circuit model is solved with circuit solver (PSPICE)
- Iteration of field and circuit models until consistent solution (convergence of results) is reached
- Relies on data exchange of Input and Output (IO) ports in tools compatible with COSIM (all covered so far)
- Capable of hierarchical co-simulation allows for switching of models and coupling schemes
- Simulations provide consistent results with measurements for several complex cases



Waveform relaxation (Gauss-Seidel Method) coupling :



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Library of Material Properties

C

- Material properties functions coded in:
  - C (compiled files also available)
  - MATLAB
- Properties: c_p, k, ρ, J_c (not: E, σ_y , ν)
- Functions are used by STEAM tools, very useful for cross-checking results
- These materials properties used in many quench models give consistent results with measurements
- We welcome contributions of material properties we do not cover. These need to haver reference

Material Properties

KAPTON	Property	C	MatLab	Inputs	Range(★)	Units	Reference
1 (★★)	Thermal conductivity	CFUN_kKapton	• kKapton • kKapton_mat	T in K (scalar / array)	• [1,500K] • Curve fit error: 2%	W/(K.m)	[1], p. 20
2	Specific heat	CFUN_CvKapton	• cpKapton_nist • cpKapton_nist_mat	T in K (scalar / array)	• [4,300K] • Curve fit error: 3%	J/(Km3)	[1], p. 20

G10	Property	C	MatLab	Inputs	Range	Units	Reference
3	Thermal conductivity	CFUN_kG10	kG10_mat	T in K (scalar)	• [10,300K] for normal direction • [12,300K] for parralel direction • Curve fit error: 5%	W/(K.m)	[1] p. 23
4	Specific Heat - NIST	CFUN_CvG10	• cpG10_nist • cpG10_nist_mat_old • cpG10_nist_mat	T in K (scalar / array)	• [4,300K] • Curve fit error: 2%	J/(Km3)	[1] p. 24

More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SitePages/Material%20Properties.aspx
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/
https://gitlab.cern.ch/steam/steam-material-library
https://gitlab.cern.ch/steam/steam-ledet-material-library

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