https://espace.cern.ch/steam

STEAM Framework

2nd STEAM Workshop, 11th – 15th October 2021

Mariusz Wozniak

on behalf of the STEAM team

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My slides are based on various slides from the 1st STEAM Workshop from 2019

STEAM

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.

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
Simulation of Transient Effects in Accelerator Magnets

Challenges / Opportunities:

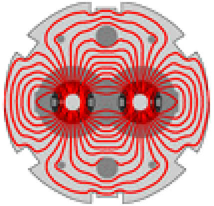
Multi-domain – need to include thermal, magnetic and electrical domains

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 was used for several flagship projects at CERN:



LHC

HiLumi HL-LHC PROJECT

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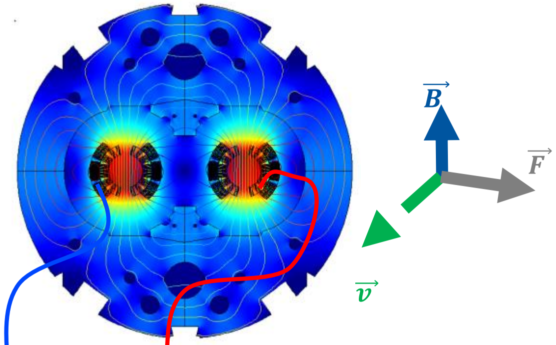
CERN | STEAM

Superconducting Accelerator Circuits – *Numerical Challenges*

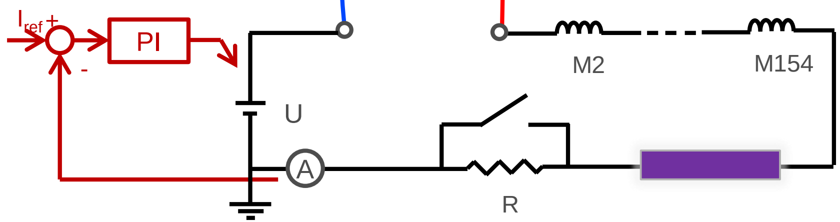


Field/network model of a magnet

- ✓ 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

Controller Model

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



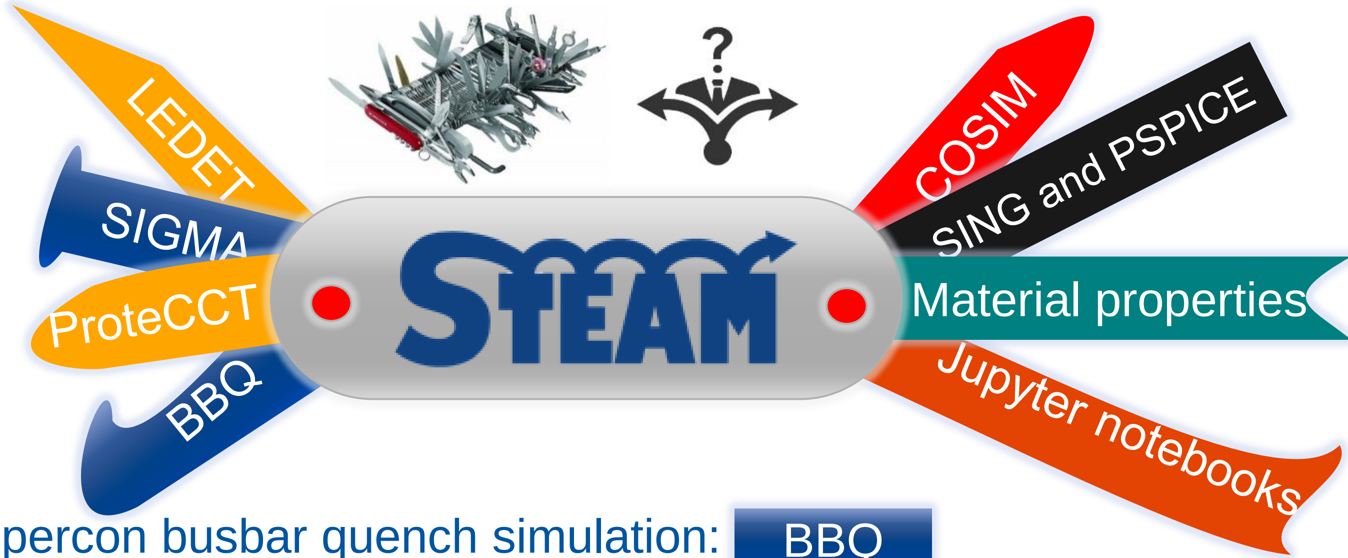
Network model of a circuit

- ✓ 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

Busbar Model

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

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

STEAM tools, solvers, languages, input files

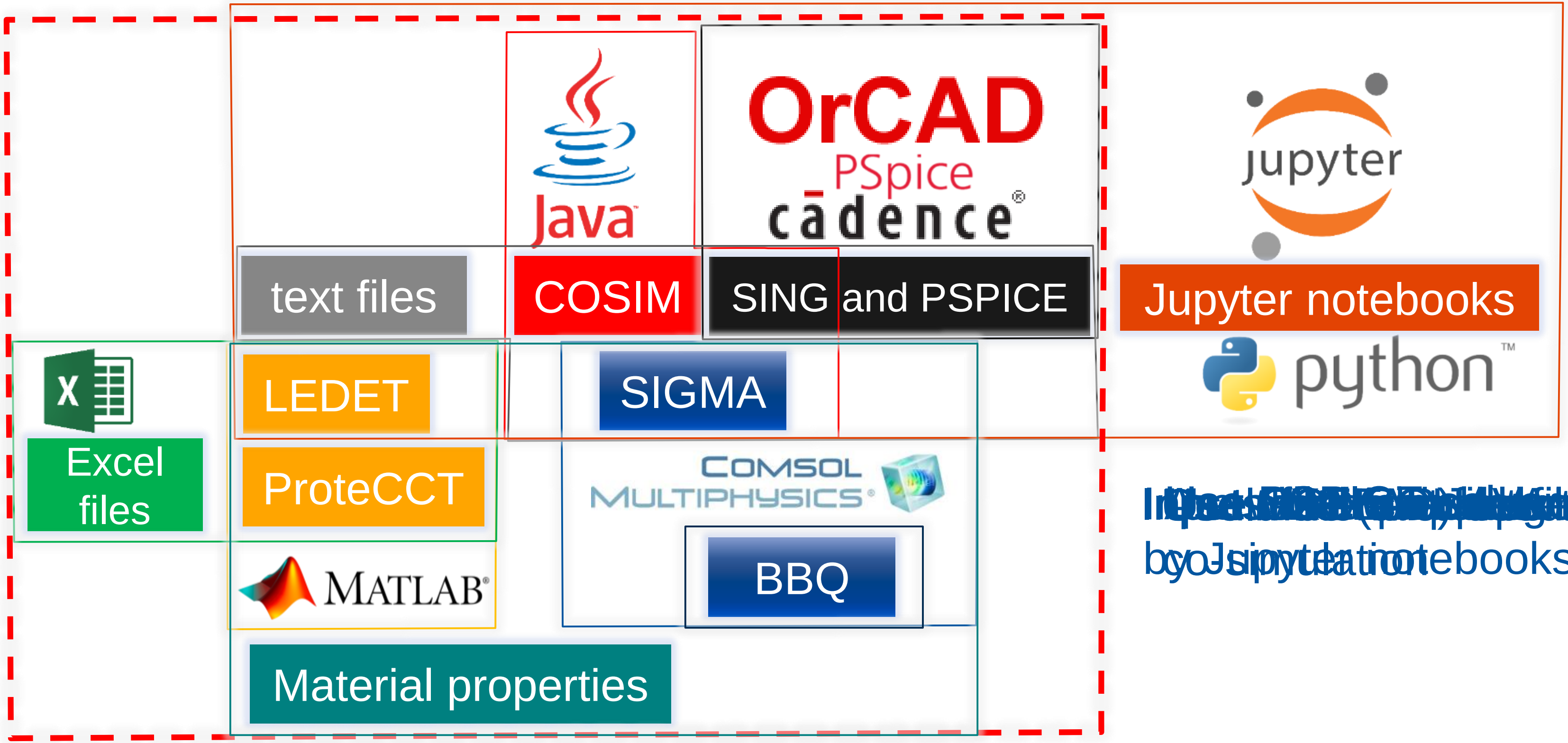
Package	Recommended model generation/editing	Software needed for input generation/editing	Physics engine / logic	Files and software needed for final solve
BBQ	Manual edit of Comsol model	- Comsol Multiphysics	Provided in Comsol model	- Comsol model - Material properties - COMSOL Multiphysics
COSIM	Jupyter 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

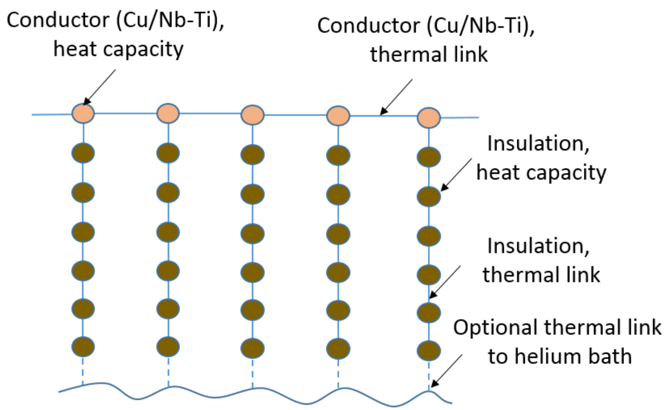
STEAM has more tools, but only ones covered in the hands-on sessions are shown

STEAM tools, solvers, languages, input files



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

BBQ (BusBar Quench)



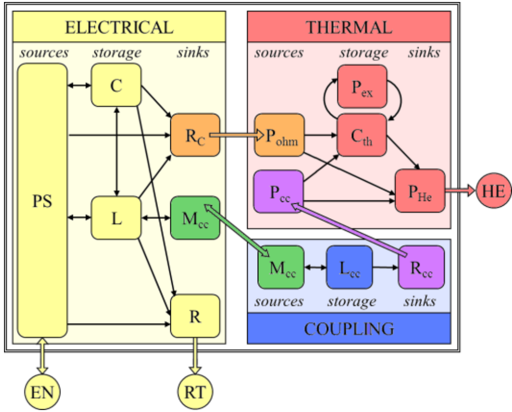
- FEM-based Comsol simulation model for superconducting busbars.
- Calculations of:
  - Quench propagation velocity
  - Development of voltage after quench origination for quench detection calc.
  - Hotspot temperature as a function of quench integral (adiabatic and with heat exchange)
- Ability to simulate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

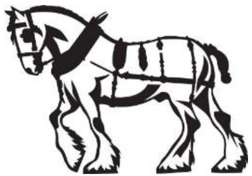
More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SitePages/BBQ.aspx
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

LEDET (Lumped-Element Dynamic Electro-Thermal)

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

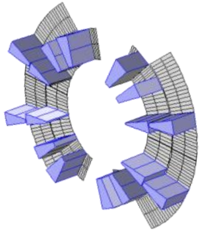
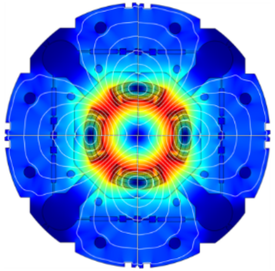
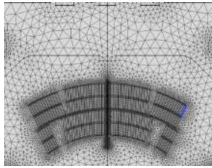




More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SitePages/BBQ.aspx
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

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)

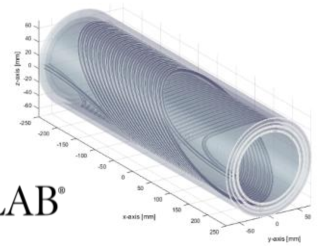
More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SIGMA/
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

Magnet / Circuit quench simulation

Why have both?

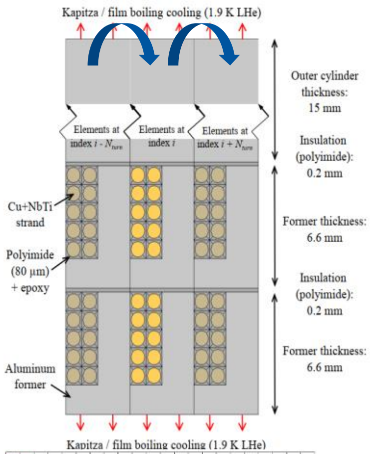
1) **Increased confidence in quench simulation results** (mitigate risk of error in simulations). This is especially important for novel magnets / conductors / circuits configurations when it is more difficult to know what to expect.
2) On detail level, they have different capabilities, limitations, 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

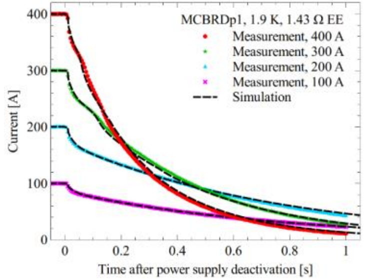
ProteCCT (Protection of Canted-Cosine-Theta) type magnets



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/

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

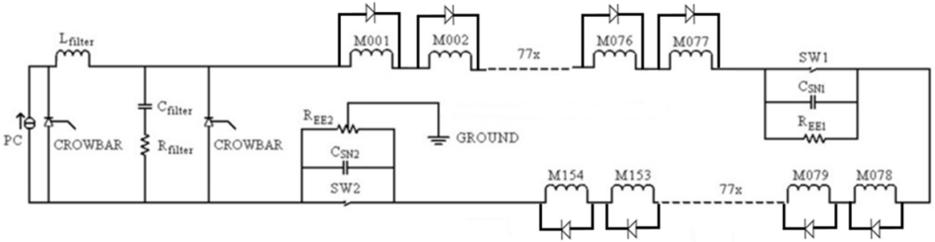
```
.subckt RB_PC_Full  1_pIn   1_pOut

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
```

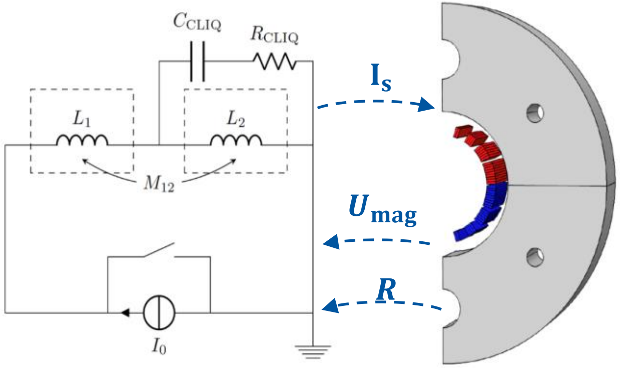


More:
STEAM website: https://espace.cern.ch/steam/_layouts/15/start.aspx#/SING/
1st STEAM workshop (2019): https://indico.cern.ch/event/808547/timetable/

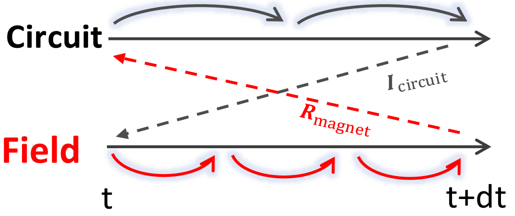
COSIM (Cooperative Simulation)

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 :



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 parrallel 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

- Questions related to the STEAM framework?
- Please keep questions on individual tool for the hands-on sessions
- New developments covered in the next talk
- Future direction and discussion on Friday