WP4.5 - Quench detection, protection and diagnostic methods for Nb_3Sn and HTS high-field magnets - CERN

HFM annual meeting 2023

HFM
High Field Magnets

30 October 2023 to 2 November 2023
CERN

Mariusz Wozniak

1st November 2023

Quench Protection – Goals and increasing complexity

Quench protection: **managing the release of the stored magnetic energy** in a way that prevents/mitigates any potential damage to the magnet, its circuitry, and surrounding components.

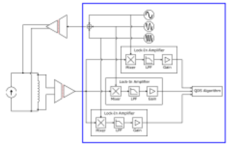
With increasing magnetic field, quench protection becomes more important and more complex:

- **Nb-Ti -> voltages** and **temperature** (in most cases)
- **Nb_3Sn -> voltages**, **temperatures,** and **conductor level stresses**
- **HTS -> voltages**, **temperatures**, **conductor level stress** and often **superconductor level stress** and for **NI coils,** a potential for a **force density redistribution**

Quench protection should be an integral part of the design of a superconducting magnet, affecting the design of the conductor (e.g. Cu/SC ratio, insulation) and coil, the choice of operating current, etc.

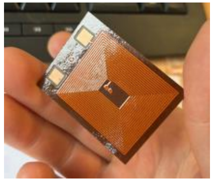
Proper quench protection analysis of high-field magnets requires advanced computer tools, and is a multidisciplinary team effort!

Outline



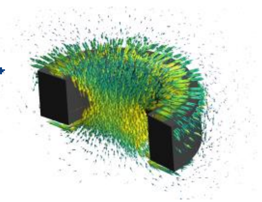
Detection Technology

- Quench Detection Through Electrical Stimuli



Protection Technology

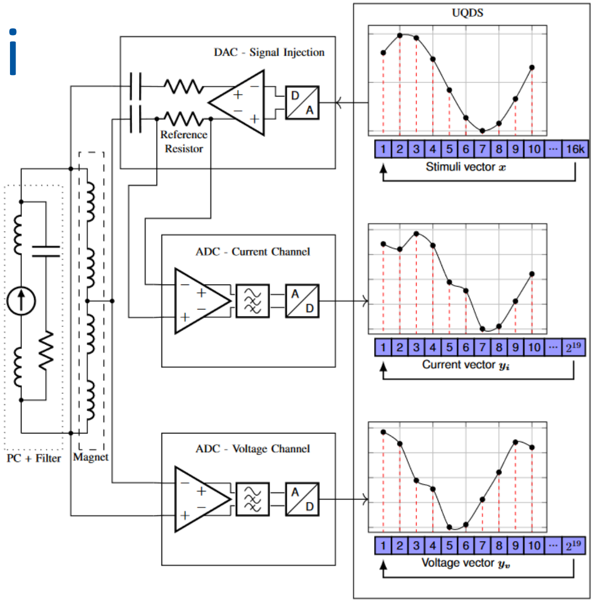
- E-CLIQ (External CLIQ) Development Progress
- S-CLIQ (Secondary CLIQ) Simulations
- ESC (Energy Shift with Coupling) Concept
- CD (Capacitive Discharge) Protection for HTS
- EE (Energy Extraction) with energy recuperation



Transient **Simulations**

- 12T VE Quench Simulation study
- New tool for 2D FE quench simulations
- AC loss LTS – 3D
- AC loss LTS – 2D reduced order
- 3D FE Simulations of HTS pancakes
- 3D FE Simulations - High Performance Computing
- 2D FD Simulations of HTS pancakes stacks
- 3D CCT Quench Co-simulations
- Material properties in Simulations

Quench Detection Through Electrical Stimuli



Concept:

- QD and electrical quality assurance based on magnet's response to electrical stimuli signal.

Current Status:

- Successfully measured impedance of powered superconducting magnet circuit.
- Measured 5 Quenching magnet (SMC).

Upcoming Tasks

- Analyze quench data and look for Quench precursors/indicators.
- Upgrade measurement hardware for better low noise performance.
- Perform more quench measurements – possibly on different magnets.

Quench Detection Through Electrical Stimuli

Key Results:

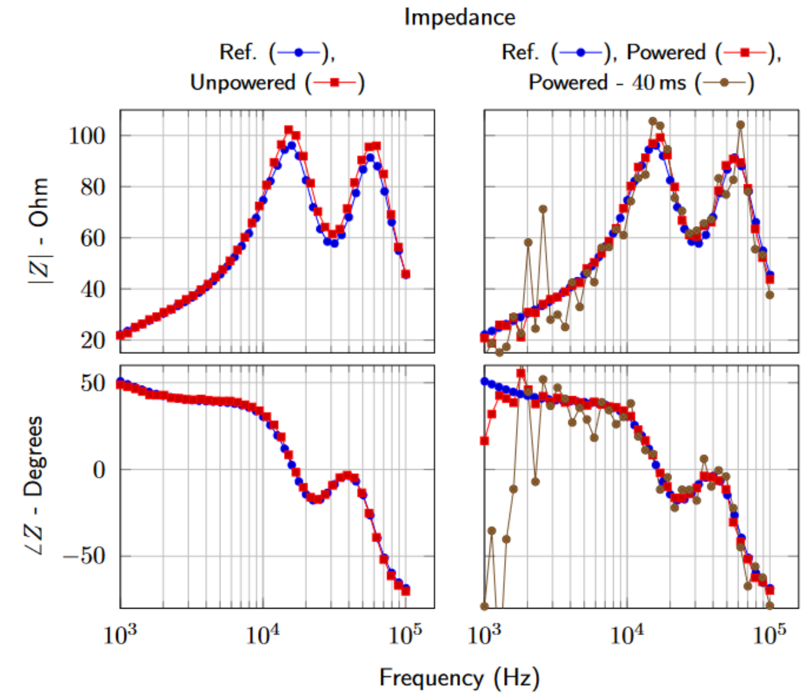
We tested the system on a D2 prototype magnet

- The magnet was measured when unpowered and powered (50 A)
- Impedance estimate based on 1.28 S (2^{19} samples) of data acquisition.
- Results show good correspondence between the powered, unpowered, and reference measurements.
- Impedance estimates based on shorter measurement windows need additional work

Enabling Real-Time Impedance Measurements of Operational Superconducting Circuits of Accelerator Magnets

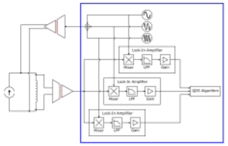
M. B. B. Christensen [1,2], M. J. Bednarek [1], R. Denz [1], P. Koch [2], J. Ludwin [1,3], F. Rodriguez-Mateos [1], T. Podzorny [1], E. Ravaioli [1], J. Steckert [1], A. Verweij [1], M. Wozniak [1], and J. Østergaard [2]

[1] European Organization for Nuclear Research, Geneva, Switzerland
[2] Aalborg University, Aalborg, Denmark
[3] Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland



Publication in proceedings of MT28 under review

Outline



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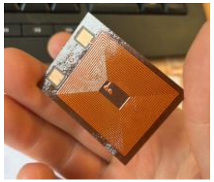

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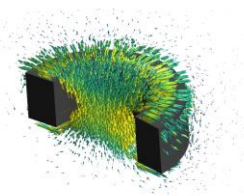
STEAM



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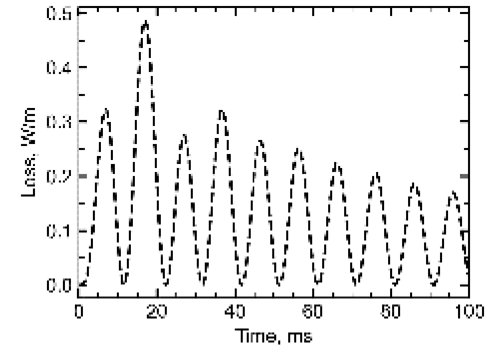
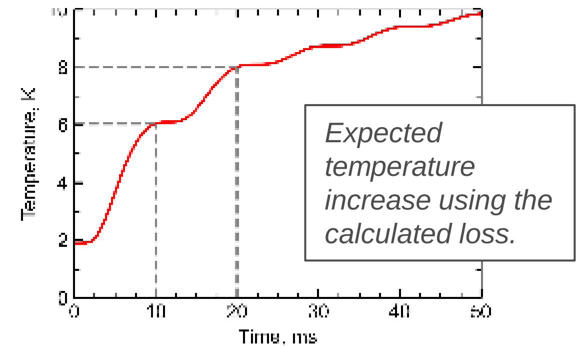
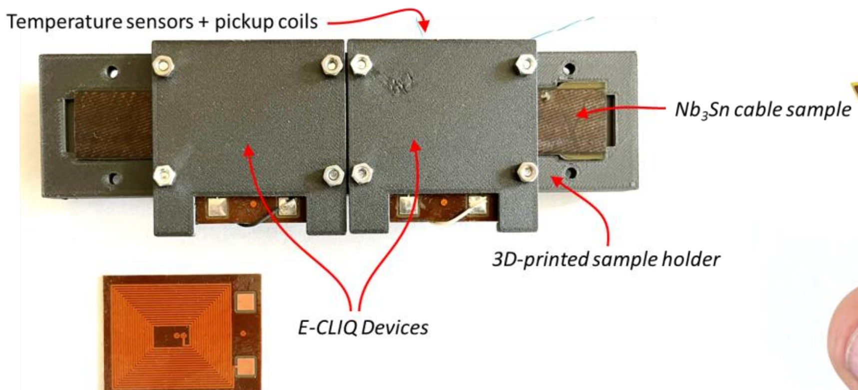
External CLIQ (E-CLIQ)

New developments:

- Further matured modeling tools to design and predict the behavior of the E-CLIQ coils and the expected loss in the conductor.
- E-CLIQ demonstration test on a Nb_3Sn cable sample preparation.
- Test will be performed in GHe in cryolab.
- New E-CLIQ coils designed and produced for test in combination with a SMC. Integration discussions in progress.

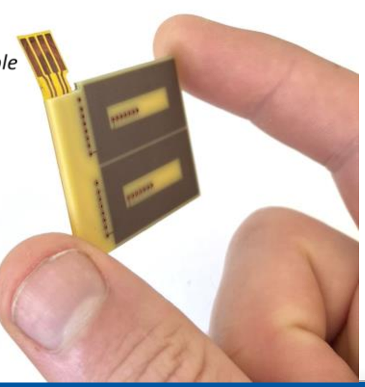


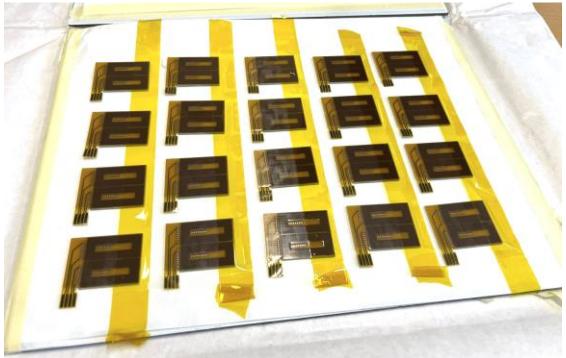




Setup for test in cryolab.

New E-CLIQ coils

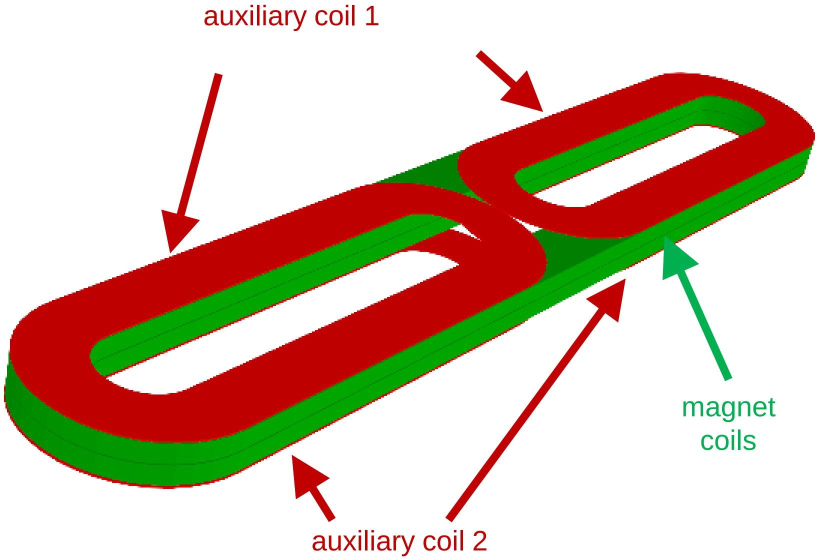


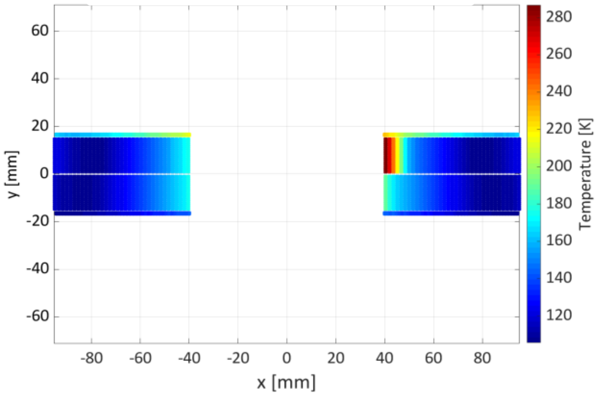


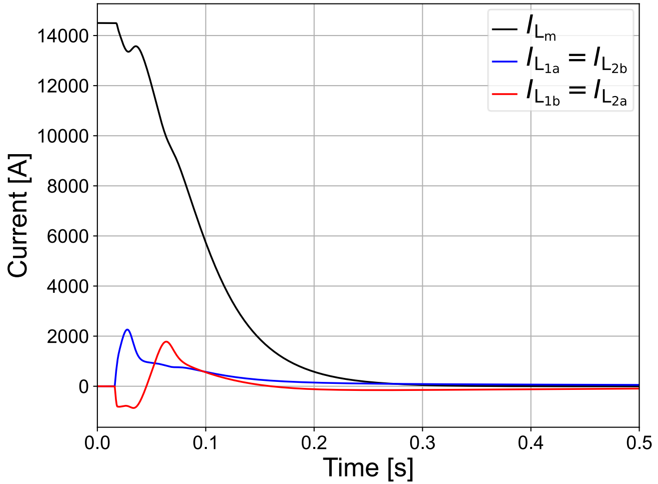
Secondary CLIQ (S-CLIQ)

- ✓ As fast as CLIQ or faster
- ✓ Extracts part of the magnet energy
- ✓ Electrically insulated from coil
- ✓ Easier redundancy

[1] M. Mentink and E. Ravaioli, SuST, 2020



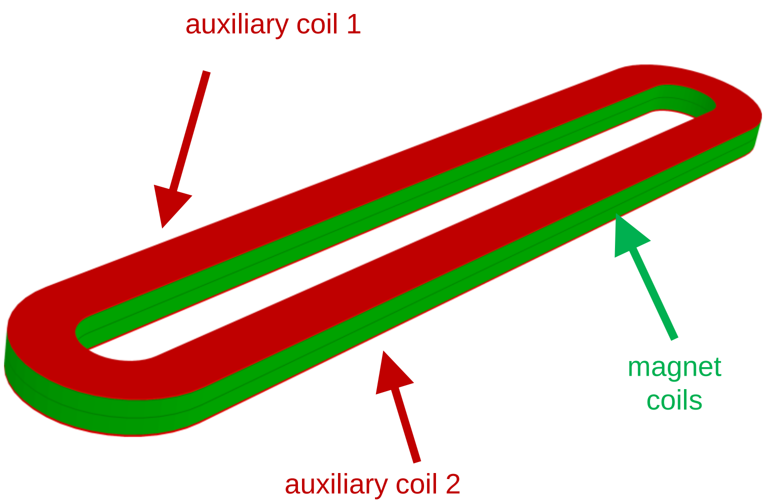


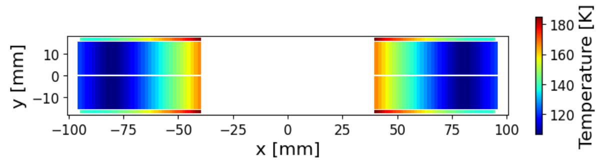


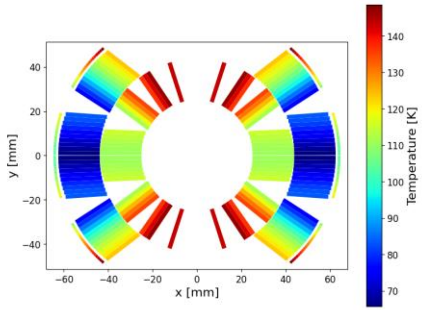
ESC (Energy Shift with Coupling)

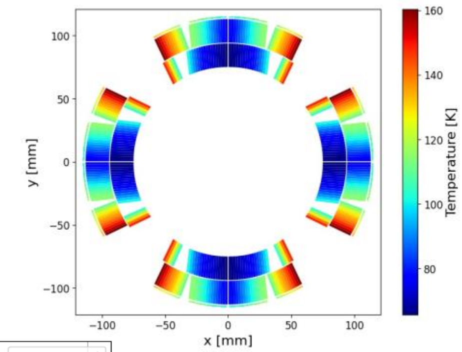
- ✓ As fast as CLIQ or faster
- ✓ Extracts part of the magnet energy
- ✓ Sudden current drop → lower ohmic loss
- ✓ Electrically insulated from coil
- ✓ Easier redundancy

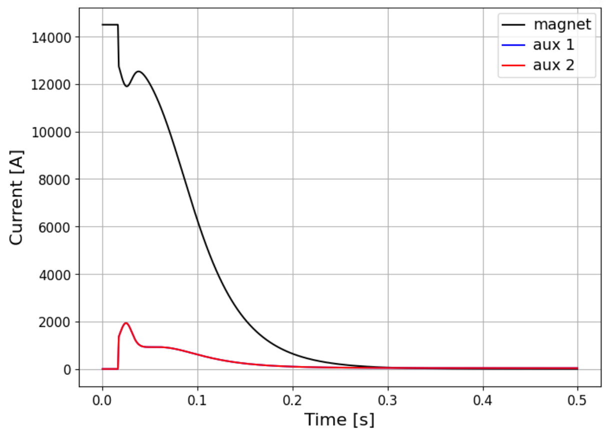
https://indico.cern.ch/event/1321217/









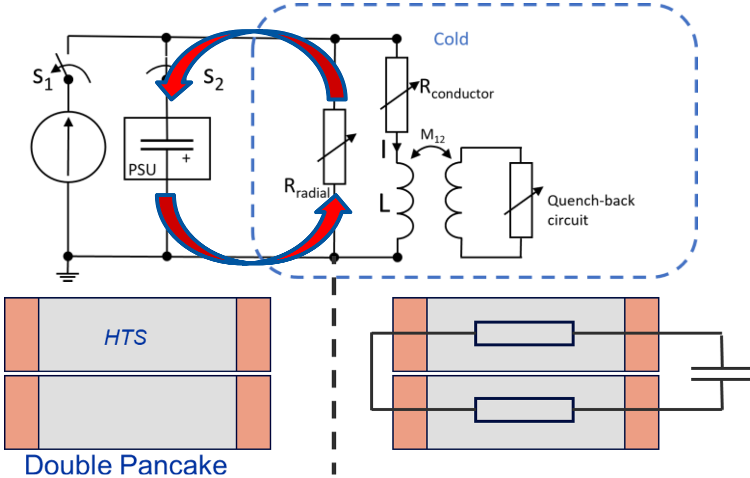


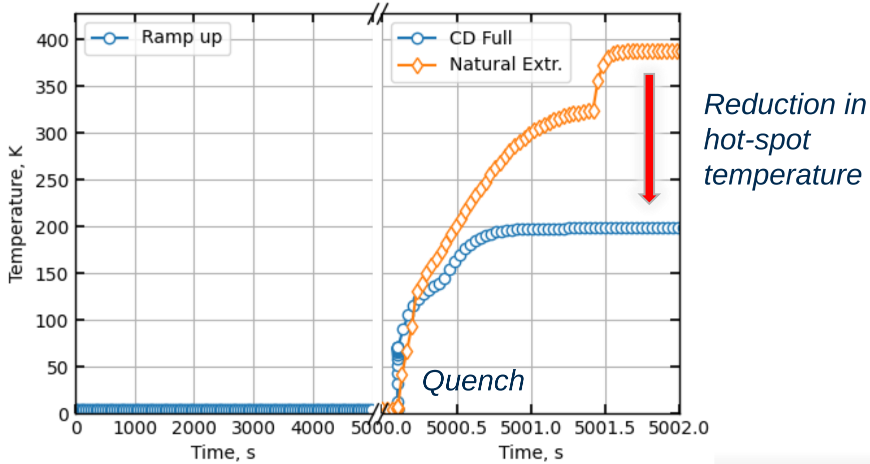
Capacitor Discharge Quench Protection

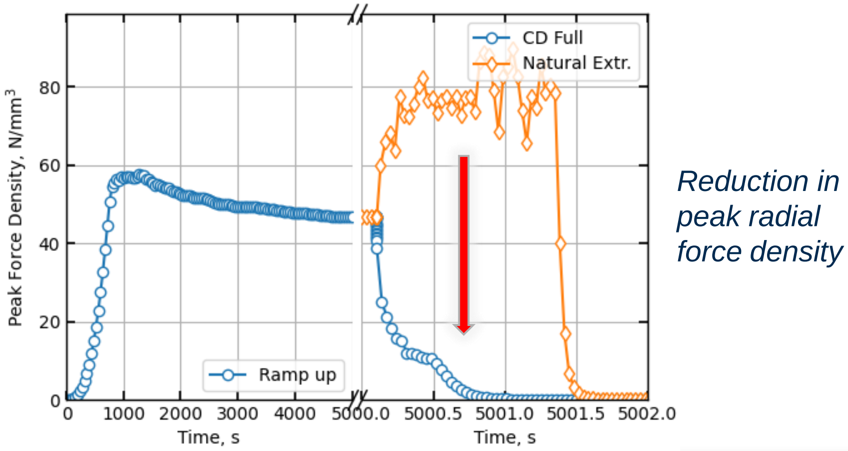
for Stacks of HTS NI Pancake Coils

Quench Protection Concept:

- Upon quench detection, a charged capacitor bank is discharged into the NI coils.
- High current pulse generates heat in the turn-to-turn resistive connections.
- Fast, potentially very effective, no additional internal components required.





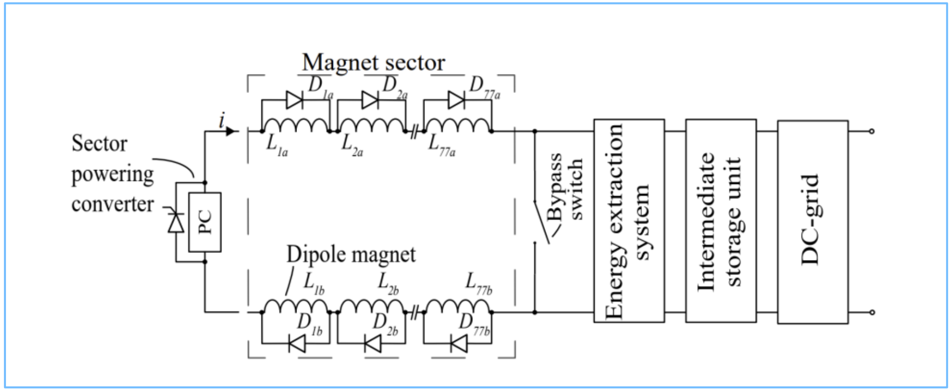


Energy extraction (EE) with energy recuperation

- A new idea from the recent years proposed an implementation of energy recuperation function in energy extraction (EE) systems

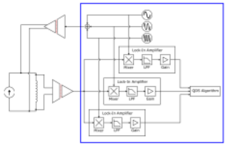
- Principle
  - 1st step: In case of quench or trip, the magnetic stored energy from SC circuit is saved in the storage unit (battery/capacitor) instead of being dumped as thermal losses in a resistor
  - 2nd step: The energy from the storage unit is injected in the network grid or used as a DC source

- A study on the following aspects is foreseen in the coming years:
  - Profitability of such functionality
  - Intermediate storage and technology selection
  - Reliability and circuit protection
  - Design and mock-up manufacturing



- In the light of future and bigger accelerators construction involving huge amount of stored energy, such recuperation function becomes a must.

Outline



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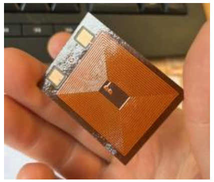

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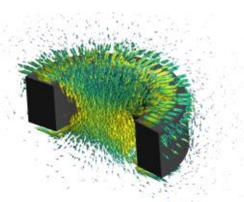

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12T VE Quench Protection studies – initial review

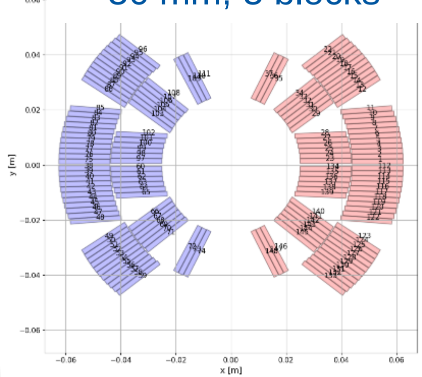
LEDET

Magnet Length	Heaters application	Glued			Miniswap			Impregnated		
	Magnet design	50mm 5b	50mm 6b	56mm 6b	50mm 5b	50mm 6b	56mm 6b	50mm 5b	50mm 6b	56mm 6b
	Protection case	Maximum adiabatic hot spot temperature (K)								
Short 1.7 m	outer QH only	354	360	350	327	332	323	304	308	301
	inner QH only	311	313	307	296	299	293	284	286	281
	outer & Inner QH	276	278	271	260	262	255	245	247	241
	CLIQ only	262	264	263	262	264	263	262	264	263
	inner QH & CLIQ	258	258	255	257	257	254	255	255	252
	outer QH & CLIQ	245	247	243	240	243	239	235	237	234
	o. & i. QH & CLIQ	242	242	238	237	237	233	231	230	226
Long 14.3 m	outer QH only	354	360	350	327	332	323	304	308	301
	inner QH only	311	313	307	296	299	293	284	286	281
	outer & inner QH	276	278	271	260	262	255	245	247	241
	CLIQ only	262	264	263	262	264	263	262	264	263
	inner QH & CLIQ	258	258	255	257	257	254	255	255	252
	outer QH & CLIQ	245	247	243	240	243	239	235	237	234
	o. & i. QH & CLIQ	242	242	238	237	237	233	231	230	226

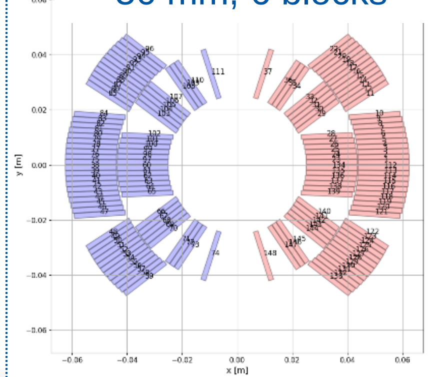
We have parametric quench protection software. Looking at many options is relatively low effort for us.

Thanks for great collaboration to the 12 T **VE magnet** team.

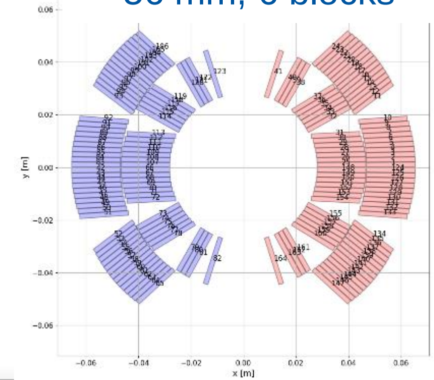
50 mm, 5 blocks



50 mm, 6 blocks



56 mm, 6 blocks



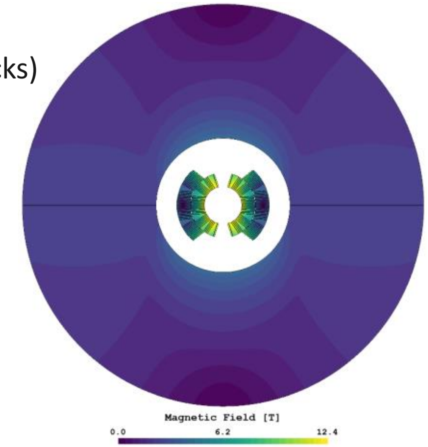
Magnet designs Courtesy of **L. Fiscarelli**

FiQuS Multipole magnets magnetic and thermal simulations

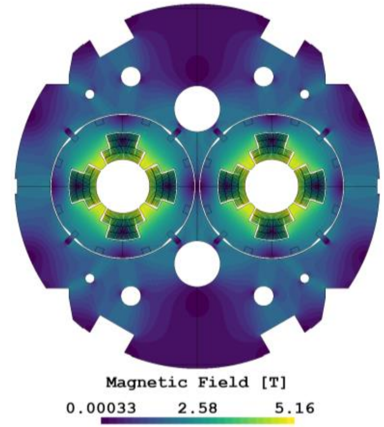
Robust 12 T VE

(MQXF cable with 6 blocks)

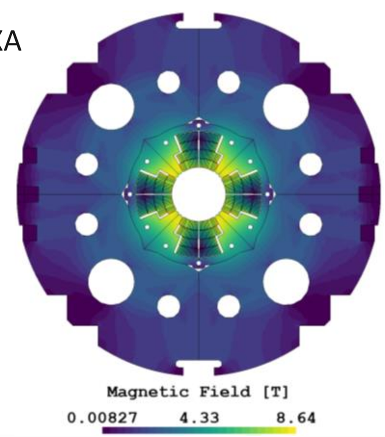
Magnet design
Courtesy of
L. Fiscarelli



MQY

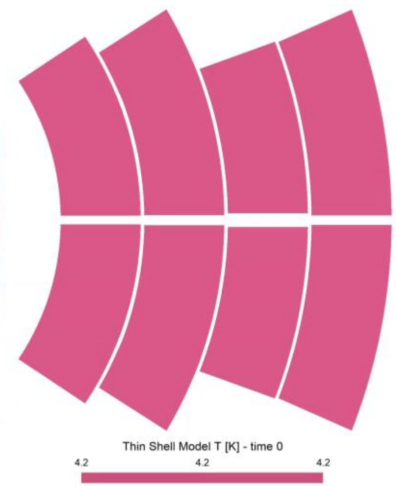


MQXA



77’380 DoFs

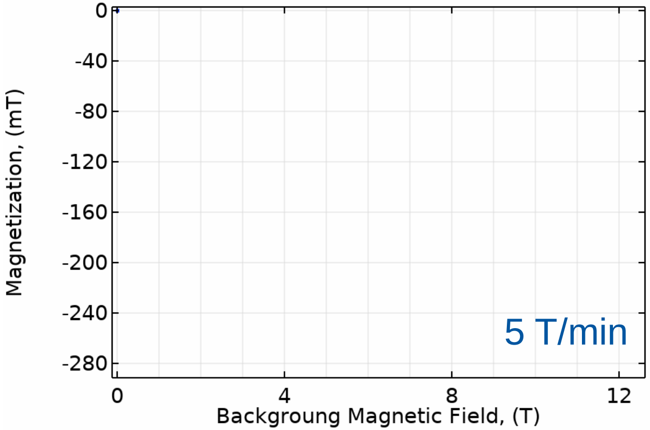
MQXA:
Nb-Ti / Cu cables
Cu wedges
Kapton insulations

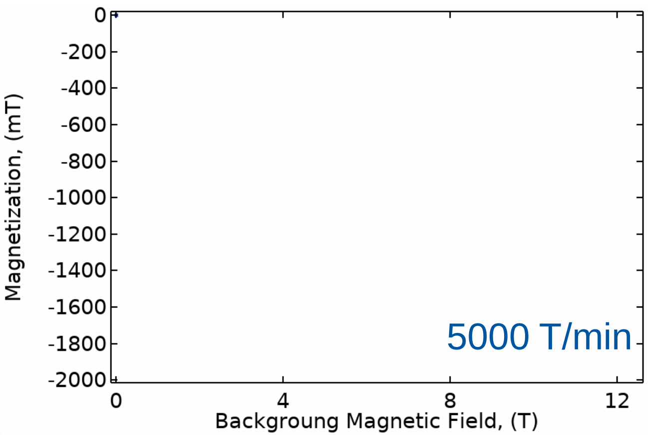


13’143 DoFs

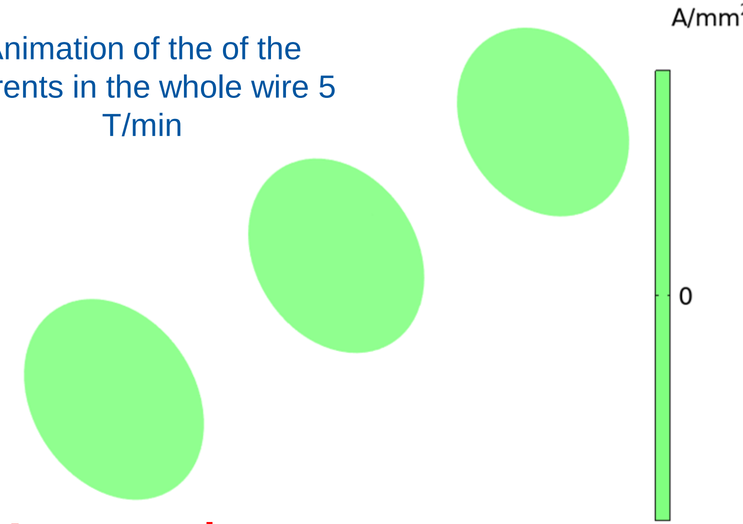
10 times shorter solution time!

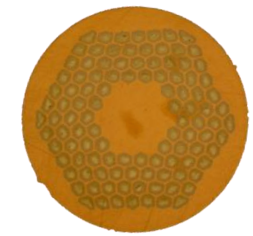
A 3D FEM thermo-electro-magnetic model to simulate twisted composite superconductors in transient regimes



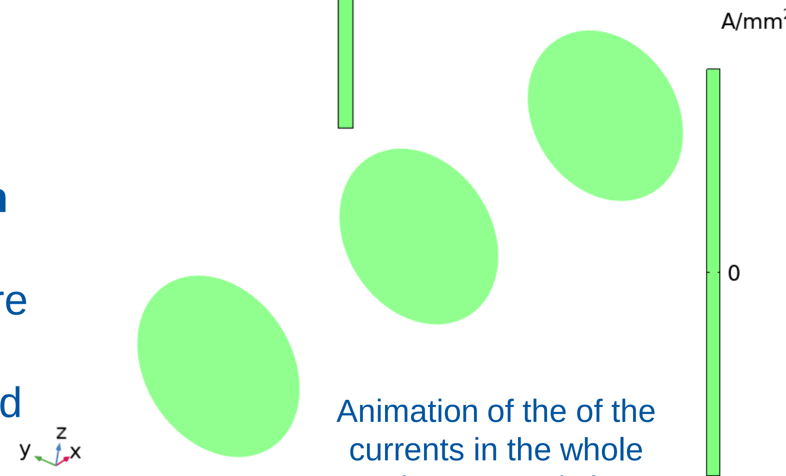


Animation of the of the currents in the whole wire 5 T/min



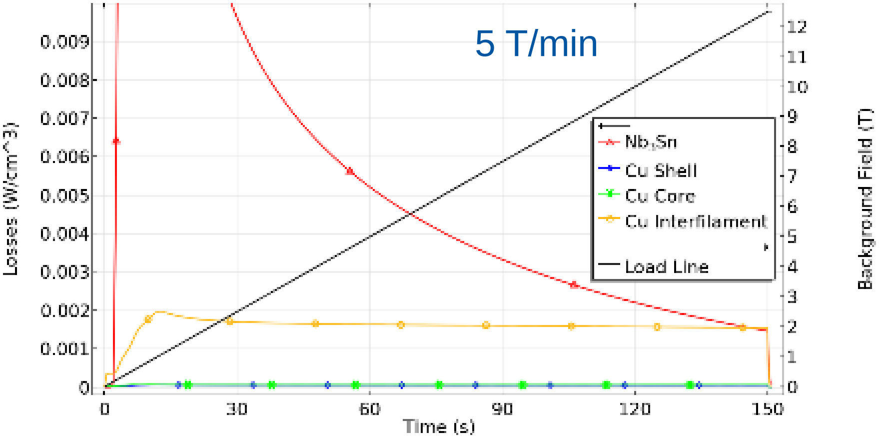


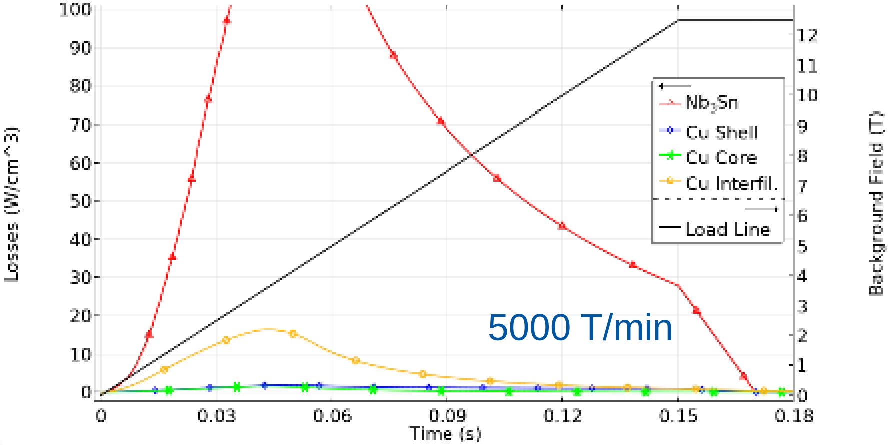
An example:
Current distribution and **Magnetization** in a MQXF Nb_3Sn wire exposed to an increasing background field at 1.9 K



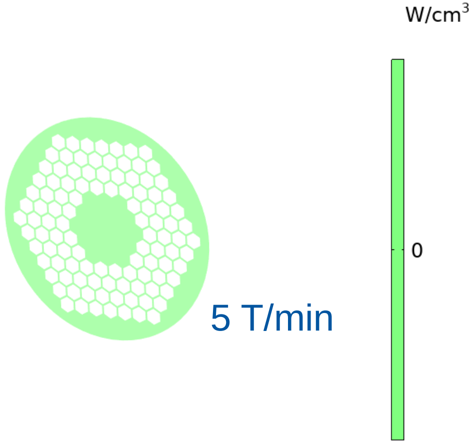
Animation of the of the currents in the whole wire, 5000 T/min

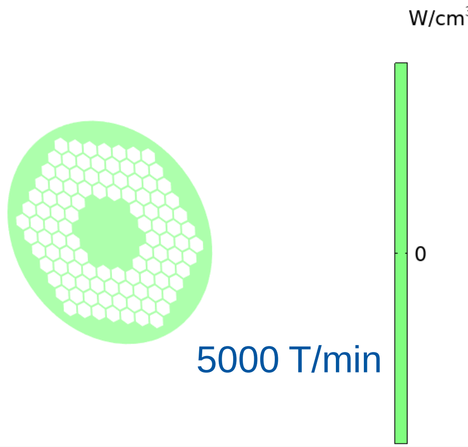
A 3D FEM thermo-electro-magnetic model to simulate twisted composite superconductors in transient regimes





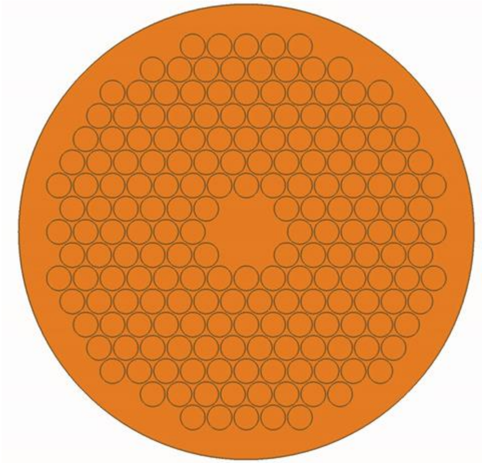
An example: **Copper Current distribution** (animations on the right) and **Overall Losses** (plots on the left) in a MQXF Nb_3Sn wire exposed to an increasing background field at 1.9 K

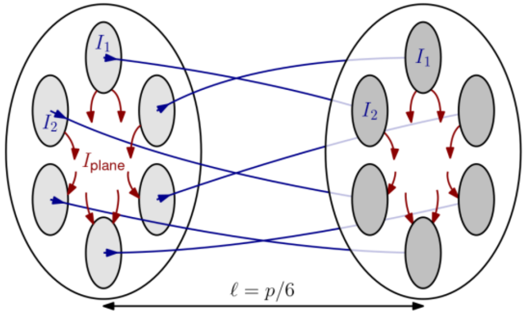




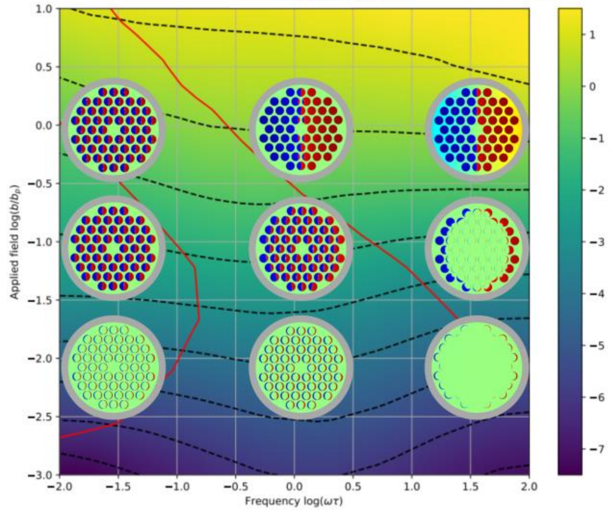
Reduced Order Modelling of Composite Wires and Cables

- **Objective**: describe the response of composite superconductors in view of their homogenization,
  - AC loss, magnetization, inductance.
- We propose a 2D model:
  - One problem with in-plane currents,
  - One problem with out-of-plane currents,
  - Coupling via circuit equations.



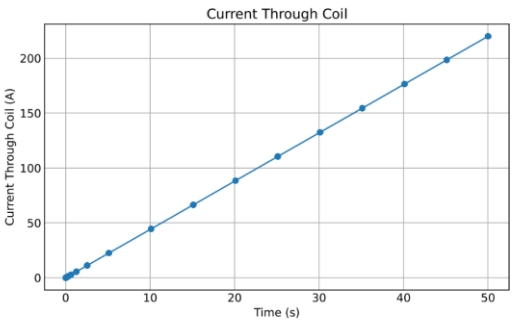


- Example - AC loss w.r.t. field and frequency:

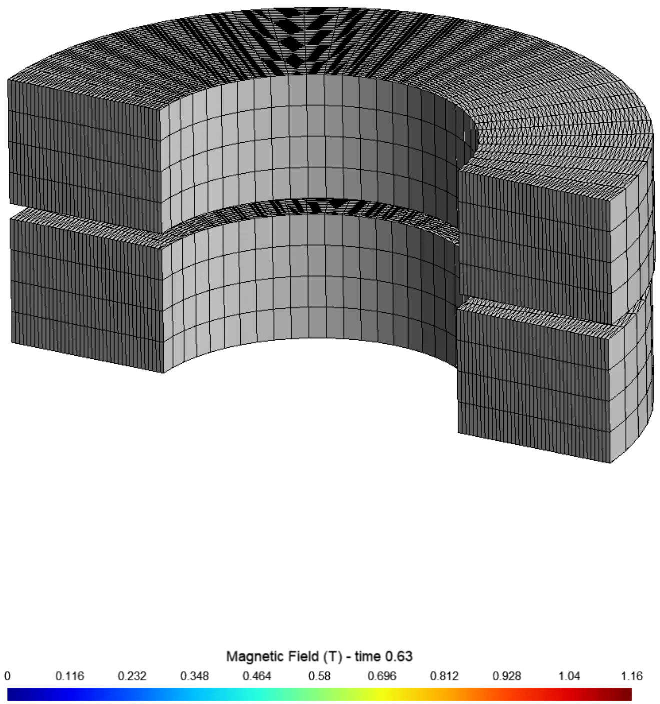


3D FE Simulations of HTS No-Insulation Pancake Coils

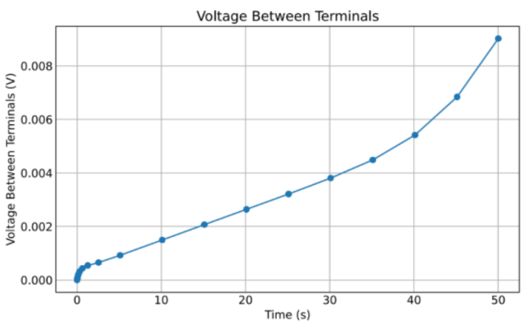
- Coupled 3D magneto-thermal models resolving all turns
  - Using specialized thin shell approximations



40 turns double pancake with linear current ramp



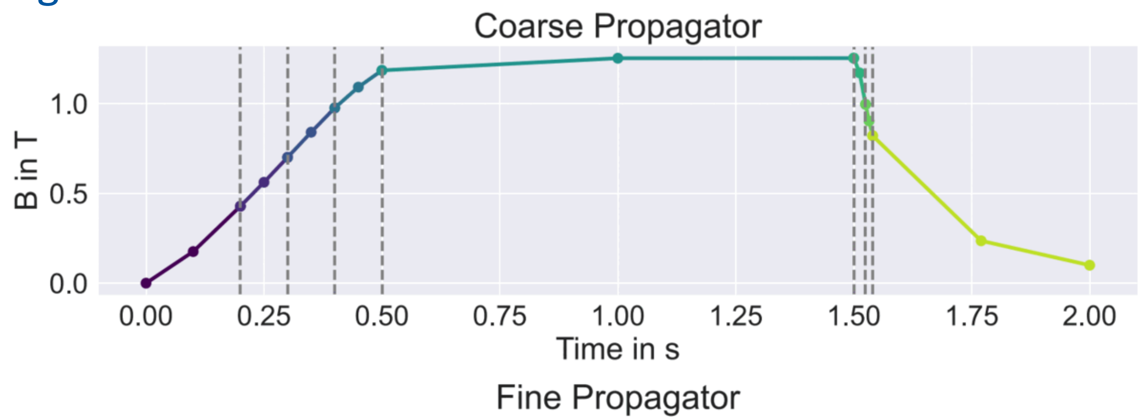
Fully non-linear and anisotropic material relations



E. Schnaubelt et al., "Magneto-Thermal Thin Shell Approximation for 3D Finite Element Analysis of No-Insulation Coils". In: arXiv:2310.03138

HPC Methods for Parallel FE Simulations

- Parallelization in Time
  - Parallelization in Space in progress



Parallel-in-time integration of central field of no-insulation HTS pancake coil

E. Schnaubelt et al., “Parallel-in-Time Integration of Transients in Superconducting Accelerator Magnets”. In: *93rd Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM 2023)*. Dresden, May 30, 2023.

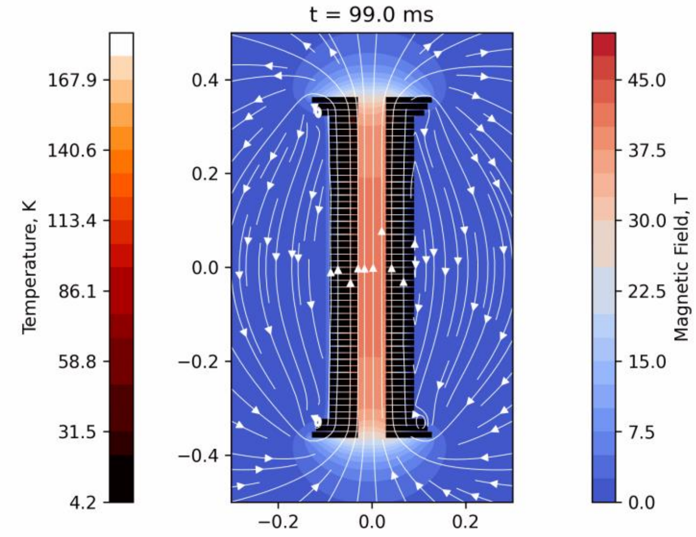
NICQS : No-Insulation HTS Coil Quench Simulator

2D-Simulation of NI-Pancake coils

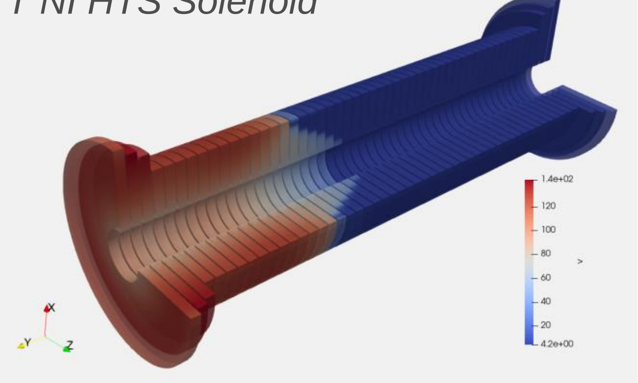
Designed for the thermo-electromagnetic simulation of stacks of NI pancake coils.

New developments:

- Accepts multiple pancake geometries using different conductor layouts on different circuits in one simulation.
- Quench back in surround rings is possible.
- Screening currents and its corresponding AC loss are fully included.
- Force density can be exported for analysis in COMSOL / other software.
- Used to test various quench protection strategies for stacks of NI pancake coils.

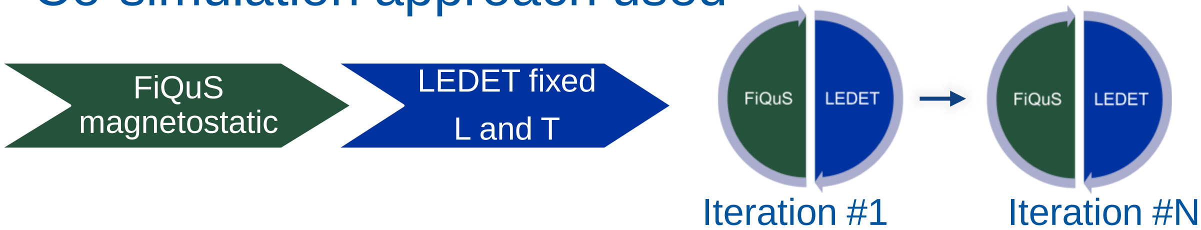


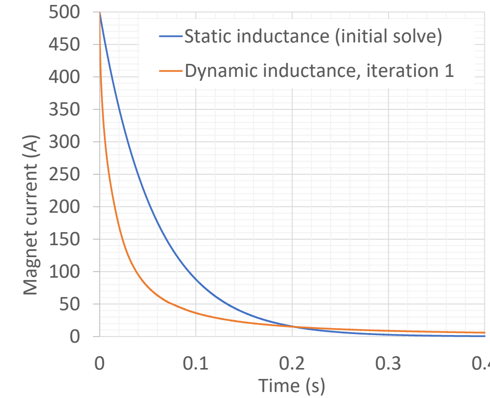
40 T NI HTS Solenoid



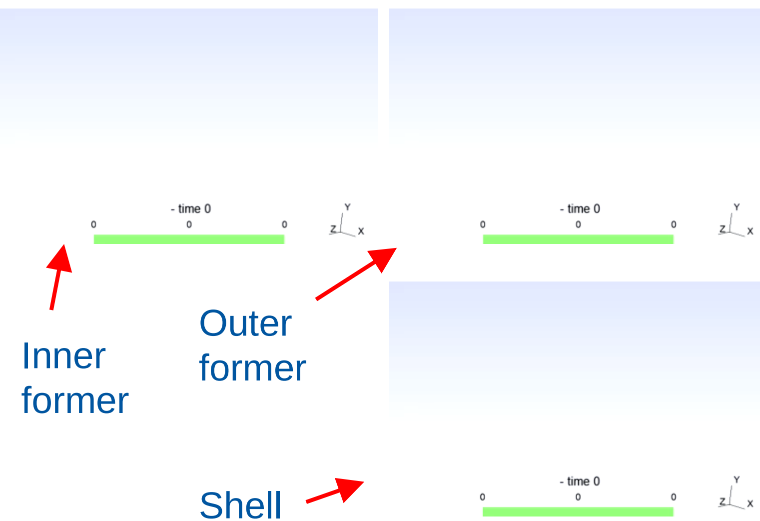
CCT magnets quench simulation in 3D

Co-simulation approach used

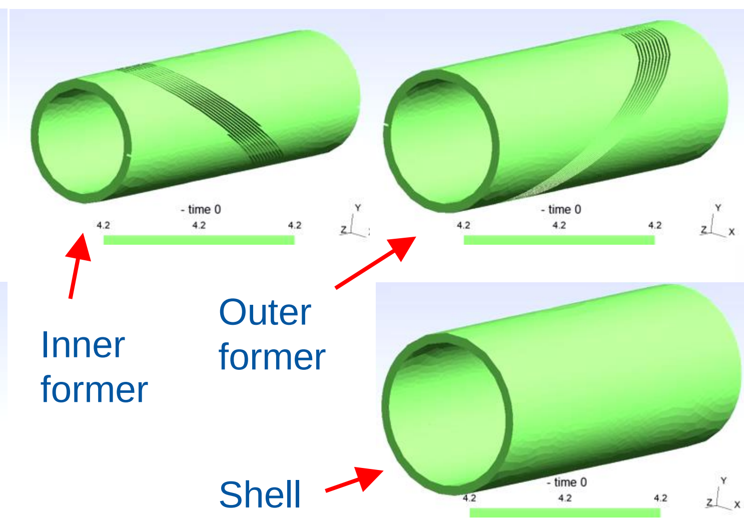




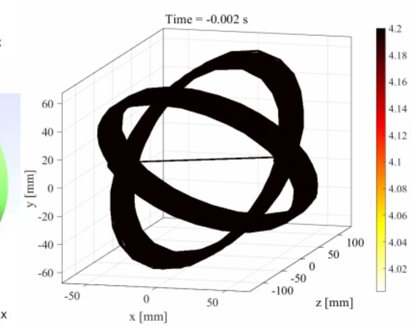
Eddy currents Formers and Shell



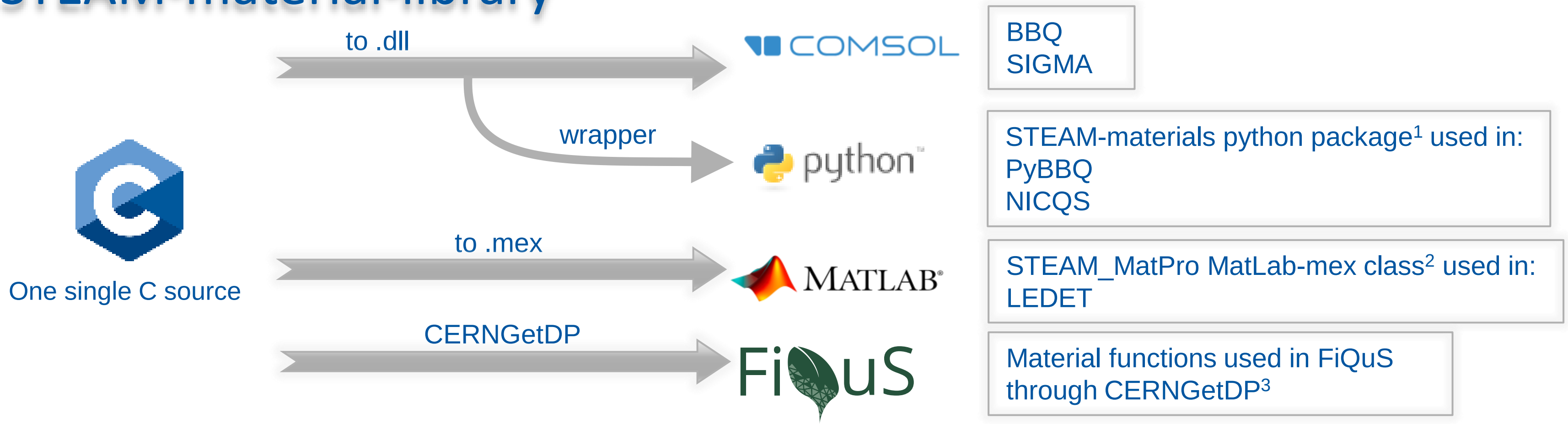
Temperature Formers and Shell



Temperature Windings



STEAM-material-library



- ✓ One single source assures that the material property functions are always the same in all simulation tools.
- ✓ Most common materials for superconducting magnet design are already included.
- ✓ Analytical derivatives of selected material functions available.
- ✓ Properties are available to everybody via the steam git repository.

Supported Materials

Ag	He
AgMg	Iron (BH)
Al	Kapton
BeCu	Nb_3Sn
Brass	NbTi
BSCCO	Steel(Stainless
Cu	Steel)
G10	Stycast
Hastelloy	More to come…

Properties

- Volumetric heat capacity
- thermal conductivity
- Resistivity
- Jc: Critical Current density (LTS & HTS)

https://steam-material-library.docs.cern.ch/

[1]Pypi steam-material-library
[3]STEAM_MatPro MatLab class
[3]CERNGetDP interface

Summary

- WP4.5 focuses on quench protection, and should work together with magnet designers, builders and testers.
- We already have several excellent collaborations in place between WP4.5 and other HFM work packages and other projects, like the Muon collider study.
- We are ready and motivated to join up with more magnet teams/groups by:
  - helping you to choose among the various quench protection technologies
  - providing simulations and assessing the results (advantages and disadvantages)
  - (co-)analysing the protection-related test results, to validate and further improve our models.
- Let's try to work together on an integrated conductor–magnet–quench protection design. How hard can it be?

HFM
High Field Magnets