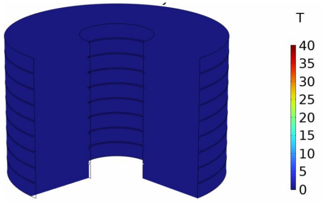
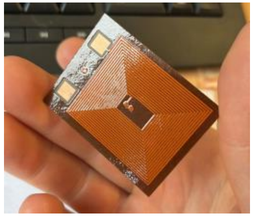
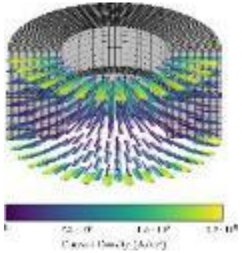
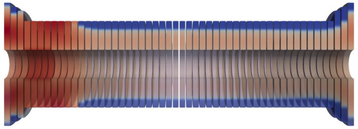
HFM

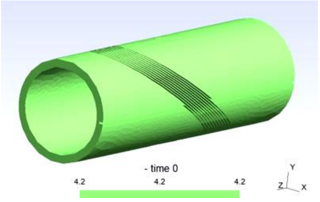
High Field Magnets











Quench detection, protection and diagnostic methods for Nb_3Sn and HTS high-field magnets

HFM WP4.5, WPL: Mariusz Wozniak

Arjan Verweij

TE-HFM day, 19th Sept 2024

Related presentations
HFM annual meeting 2023
https://indico.cern.ch/event/1302031
- STEAM – E. Ravaioli & M. Wozniak
- WP4.5 – M. Wozniak

Quench protection in a few words

Detect fast & Discharge fast (i.e. add resistance in the circuit, τ=L/R) in order to keep the MIIts (Integral of I^2dt) sufficiently low.

LTS magnets:

- Small stand-alone/series magnets: voltage detection + EE/R_{par} (if needed)
- Large magnets: voltage detection + quench heaters/CLIQ
- Large magnets in series-connection: add EE + bypass diodes

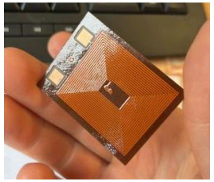
HTS magnets:

- Fast quench detection is problematic (due to very slow quench propagation)
- Small coils: EE usually possible
- Large coils: hard to achieve fast current reduction (as it is difficult to quench a large part of the coil due to high enthalpy margin)
- Non/Metal-Insulation (N/M-I) coils might offer a solution, but ramp losses and field errors could pose problems

Outline

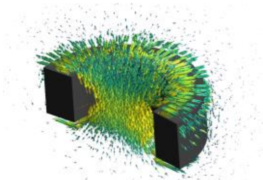
Detection Technology

- Quench Detection Through Electrical Stimuli



Protection Technology

- CLIQ (Coupling Loss Induced Quench) Optimization
- 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



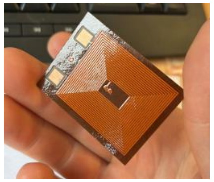
Transient **Simulations**

- STEAM & Material Library
- 12T Quench Protection studies using LEDET
- Reduced order modelling
- Transients in LTS and HTS using FiQuS
- High Performance Computing and Protectability studies
- 3D electrodynamics on the MuonColl 40 T solenoid
- No Insulation Coils Quench Simulator - NICQS
- 3D CCT Quench Co-simulations

Outline

Detection Technology

- Quench Detection Through Electrical Stimuli



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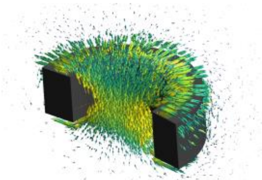

STEAM

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Quench Detection through electrical stimuli

Courtesy of Magnus Christensen

Concept:

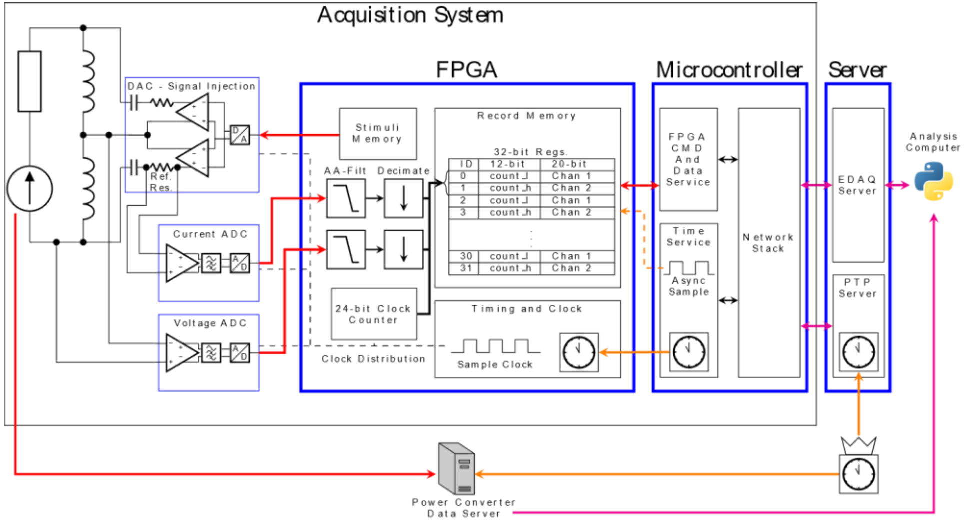
- Based on magnet's response to electrical stimuli signal.
- Use low voltage stimuli and differential probing to minimize impact on peripheral equipment.
- Inject multi-sine stimuli to measure the impedance at multiple frequencies concurrently.
- Continuous impedance measurement of operational magnets is possible.

Status:

- Hardware and software development completed.
    - publication to be submitted very soon.
- First (unpowered) HTS coils at PSI measured.
- MQXFS magnet measured during powering.

Next steps:

- MQXFS with (heater induced) quench, with f<1 kHz, and with ramp rates up to few 100 A/s.
- Measure HTS coil at CERN.
- Apply this method on other (LTS or HTS) magnets during powering/quench.

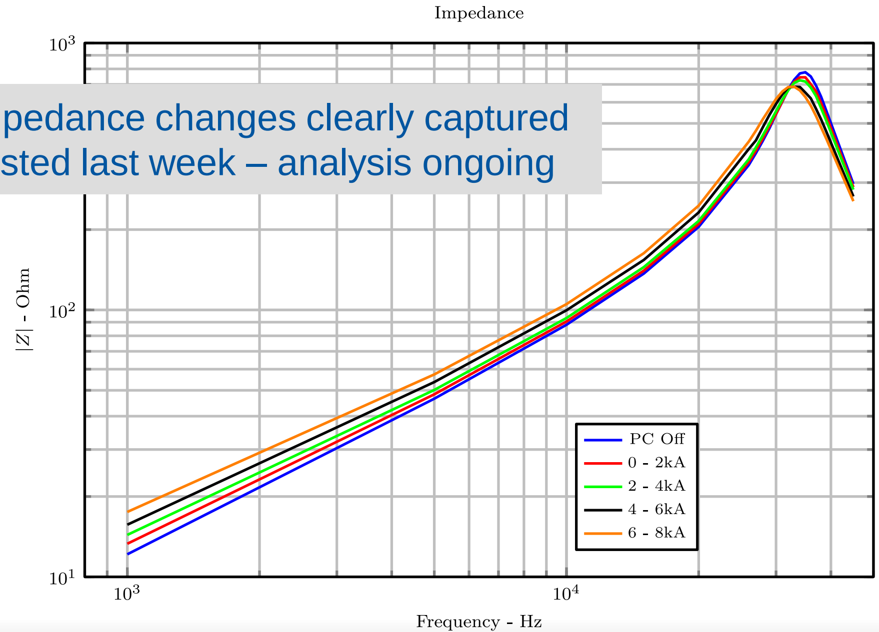


ID	12-bit	20-bit
0	count_l	Chan 1
1	count_h	Chan 2
2	count_l	Chan 1
3	count_h	Chan 2
⋮		
30	count_l	Chan 1
31	count_h	Chan 2

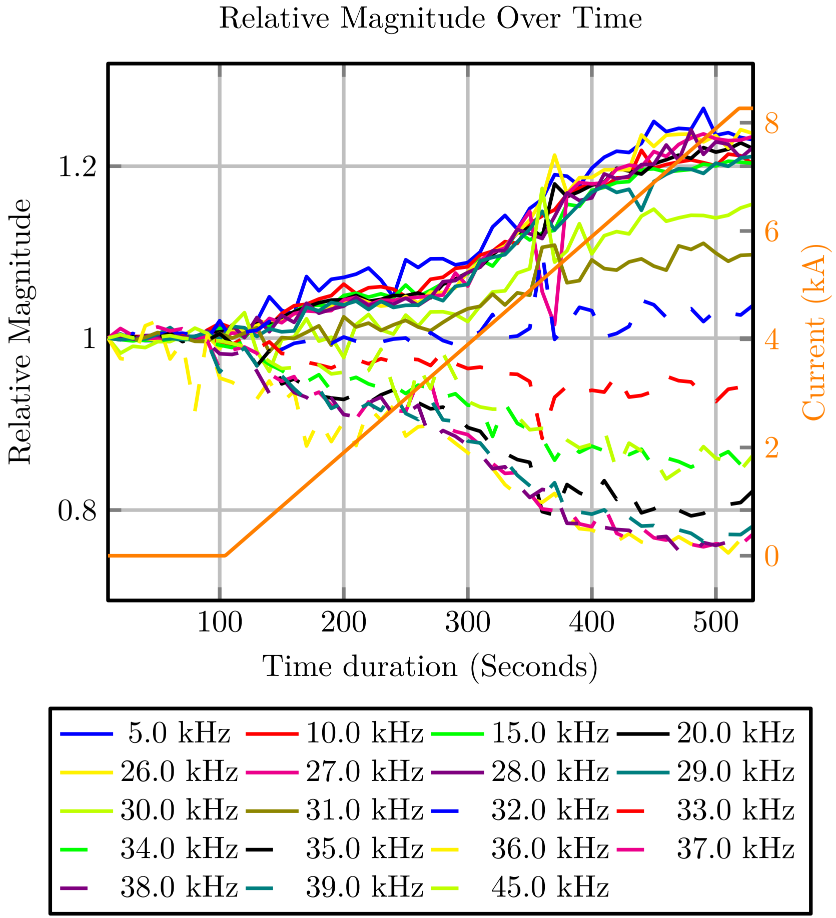
Quench Detection through electrical stimuli on a powered MQXFS magnet

Courtesy of Magnus Christensen
Ackn. SM-18

- Impedance measurement of MQXFS7J magnet @1.9 K during current ramping to 8.2 kA
- Stimuli composed of 20 frequencies from 1 to 45 kHz
- Stimuli amplitude less than 20 mV



Impedance changes clearly captured
Tested last week – analysis ongoing



Outline

Detection Technology

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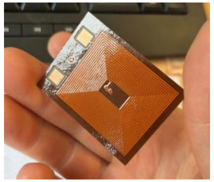

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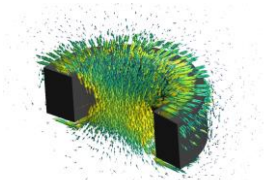

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CLIQ – Coupling Loss Induced Quench system

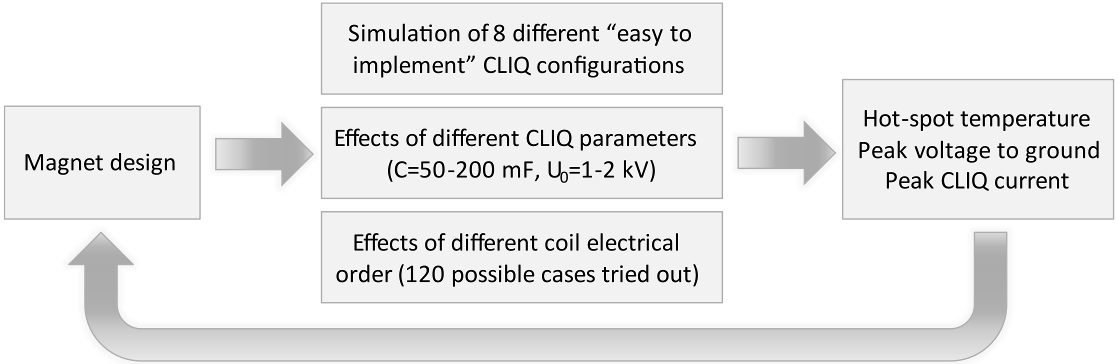
Courtesy of Emmanuele Ravaioli

After many validations on various magnets and implementation in the Hilumi triplets, CLIQ is now a well-established protection method.

Ongoing and next steps:

For any future magnet circuit, CLIQ has be optimized to target optimum protection, i.e. low T_{hot}, low voltages, small-sized leads, high redundancy, ...

As an example: optimization recently done in collaboration with PSI and WP 3.14 for the 14 T SMACC magnet using the STEAM-LEDET tool.



Magnet design

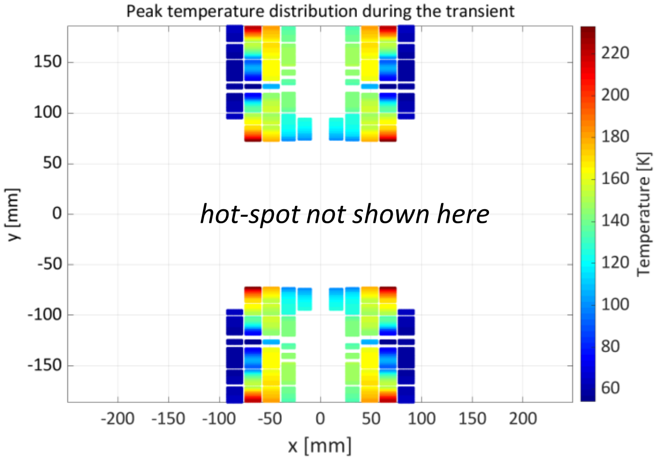
Simulation of 8 different "easy to implement" CLIQ configurations

Effects of different CLIQ parameters (C=50-200 mF, U_0=1-2 kV)

Effects of different coil electrical order (120 possible cases tried out)

Hot-spot temperature
Peak voltage to ground
Peak CLIQ current

STEAM LEDET



Magnet designed by D.M. Araujo (PSI)

E-CLIQ: External Coupling Loss Induced Quench system

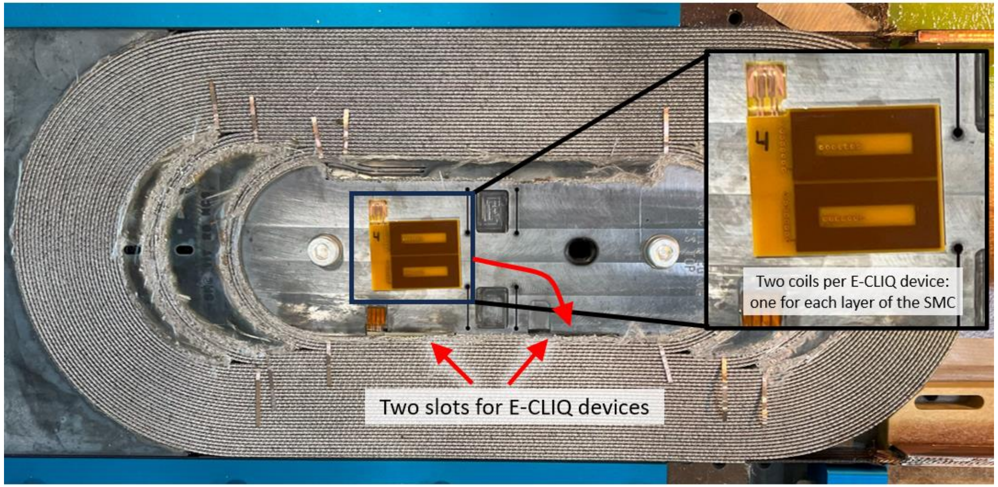
Courtesy of Tim Mulder

Ackn. to Cryolab and WP4.6

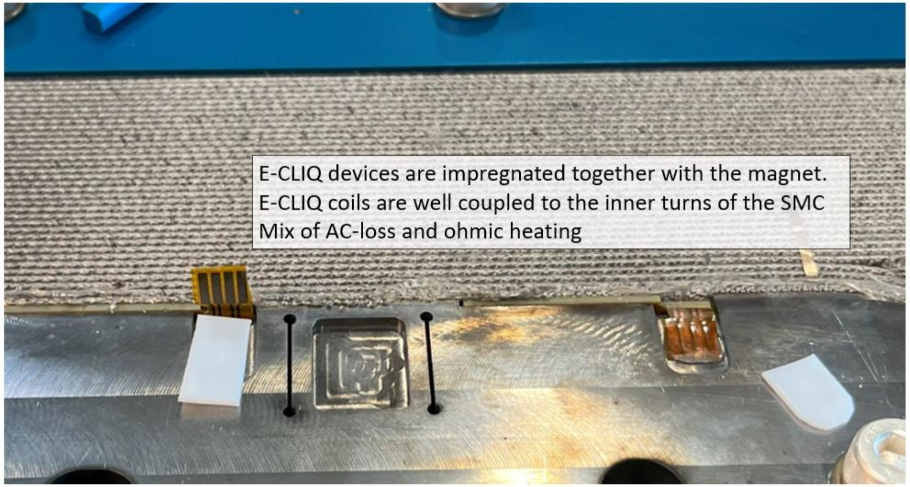
- E-CLIQ generates a large local dB/dt and thus AC loss, quickly increasing the temperature of the SC. E-CLIQ, in principle, also acts as a resistive quench heater.
- 116 measurements performed on Ruth. Cable in the CryoLab using various E-CLIQ frequencies, amplitudes, duration, and external magnetic field values.

Next steps:

- Application and testing of E-CLIQ in an SMC magnet: Coil winding, reaction, E-CLIQ implementation and instrumentation ongoing. Testing foreseen for end 2024.
- Possible application for HTS coils.


Two coils per E-CLIQ device: one for each layer of the SMC

Two slots for E-CLIQ devices


E-CLIQ devices are impregnated together with the magnet.
E-CLIQ coils are well coupled to the inner turns of the SMC
Mix of AC-loss and ohmic heating

S-CLIQ – Secondary Coupling Loss Induced Quench system

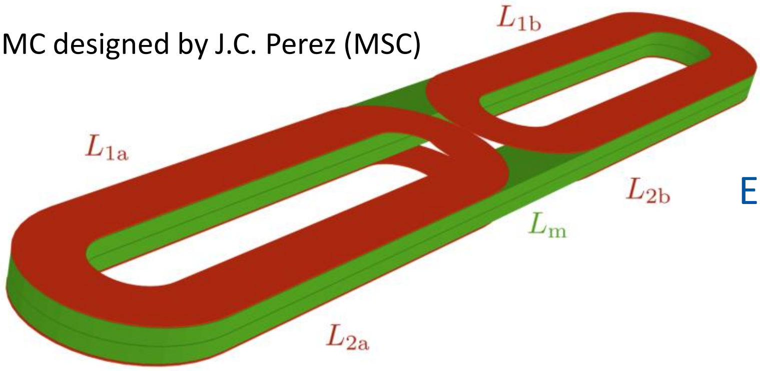
Courtesy of Emmanuele Ravaioli

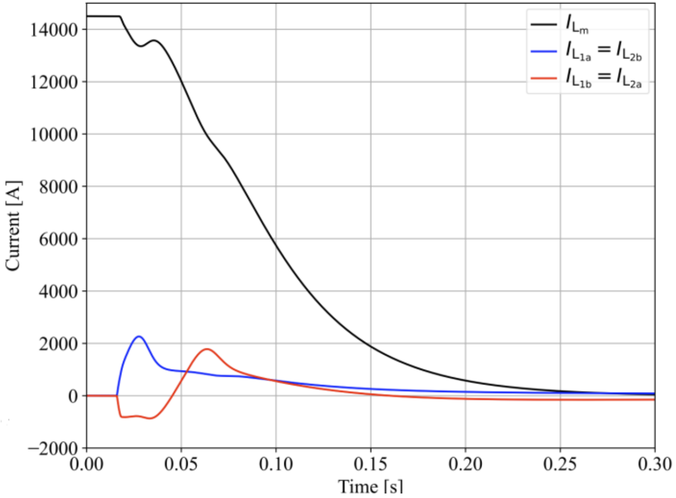
- ✓ As fast as CLIQ or faster in terms of quenching the magnet
- ✓ Able to extract part of the magnet energy
- ✓ Electrically insulated from the magnet
- ✓ Good protection redundancy

Next steps:

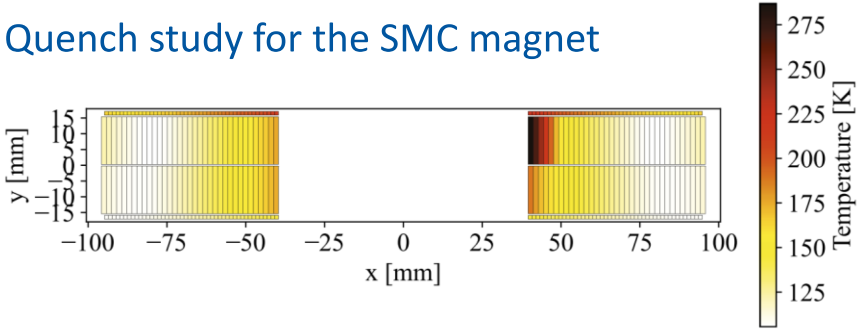
On hold, awaiting results from ESC (next slide)

SMC designed by J.C. Perez (MSC)





Example: Quench study for the SMC magnet



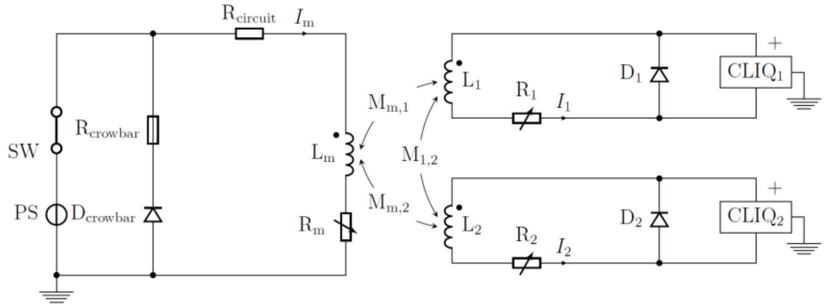
More details: https://doi.org/10.1109/TASC.2023.3336272

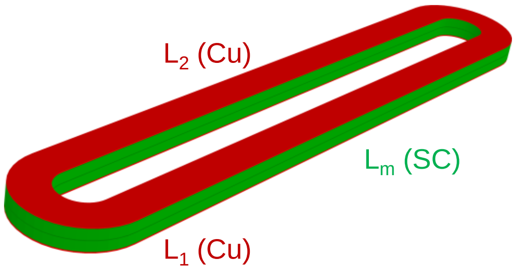
ESC – Energy Shift with Coupling

Courtesy of Emmanuele Ravaioli

Same advantages as S-CLIQ and on top also lower Ohmic loss due to sudden initial current decrease (hence lower MIIts and lower Thot)

More details:
https://indico.cern.ch/event/1321217/
https://indico.cern.ch/event/1347179/





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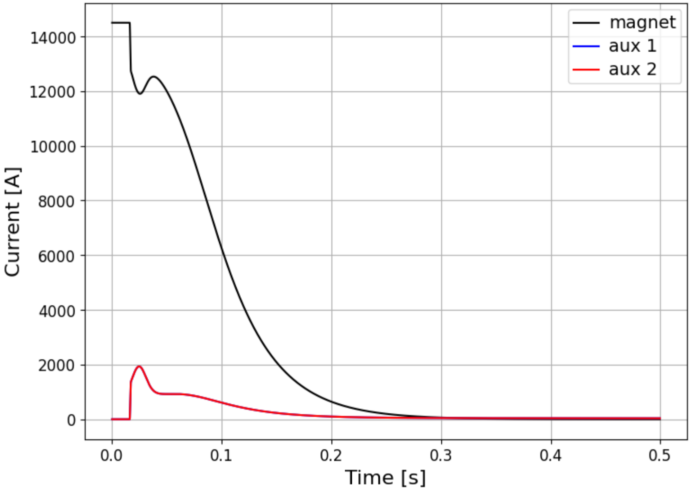


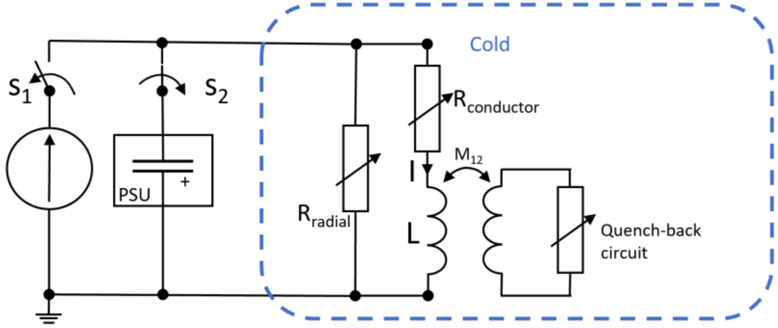
Next steps:

- ESC coil design finalized with contribution from MSC-MDT, MSC-NCM, MPE-PE colleagues
- Tests foreseen in Q3-2024 in SM18
- Add ESC in PSI subscale
- Study ESC on several 12 T magnet designs
- Study mechanics for adding ESC coils

Capacitive Discharge: New method for protection of a stack of NI HTS pancakes

Courtesy of Tim Mulder

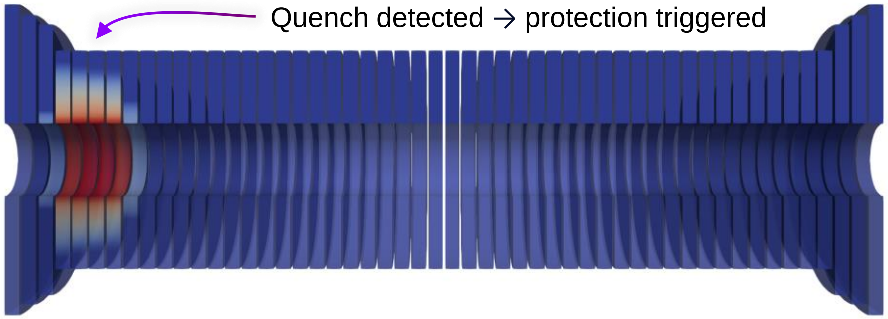
- use turn-to-turn resistance as an internal quench heater
- fast: potential to quench turns within ms
- potential to reduce energy redistribution between pancakes and therefore reduce radial peak force density during quench
- flexible/redundant: discharge to all or some pancakes

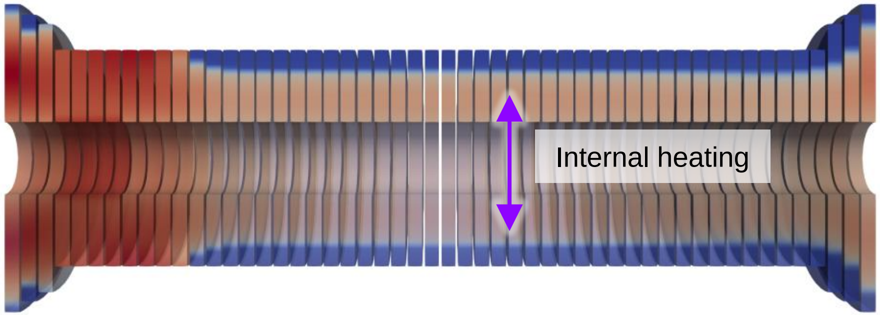


T. Mulder, M. Wozniak, A. Verweij, Quench Protection of Stacks of No-Insulation HTS Pancake Coils by Capacitor Discharge, IEEE Trans. Appl. Supercond., Vol 34, Nr 5, 2024.
https://doi.org/10.1109/TASC.2024.3362755

Next steps:

Awaiting validation on one or more NI HTS coils





Energy extraction (EE) with energy recuperation

Courtesy of Bozhidar Panev

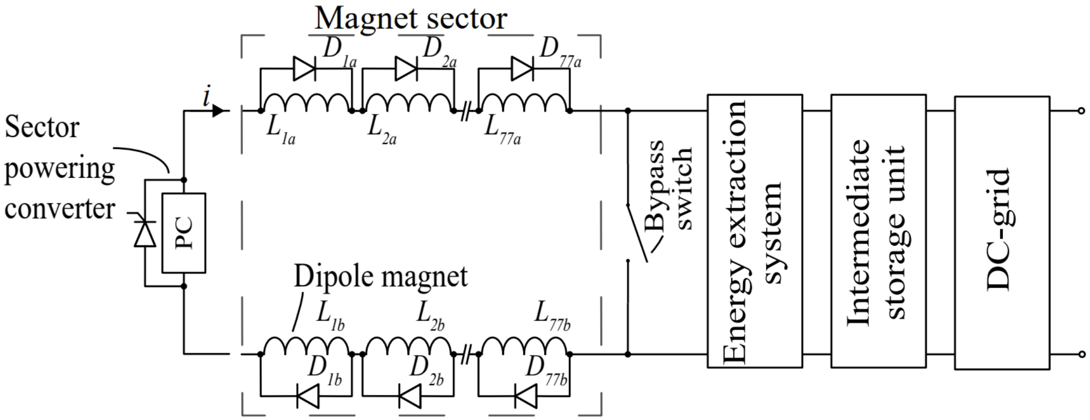
In view of future larger accelerators, involving huge amount of stored magnetic energy in the SC circuits, energy recuperation is certainly interesting.

Principle

1) In case of quench or trip, the magnetic stored energy from the SC circuit is saved in the storage unit (battery/capacitor)
2) The energy from the storage unit is injected in the network grid or used as a DC source

Next steps:

- Study profitability & reliability
- Select intermediate storage and technology
- Design and manufacture a mock-up



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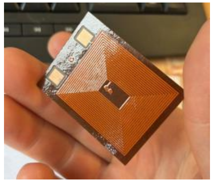

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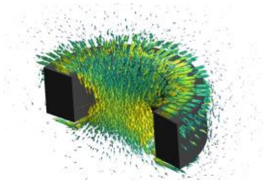

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The STEAM framework

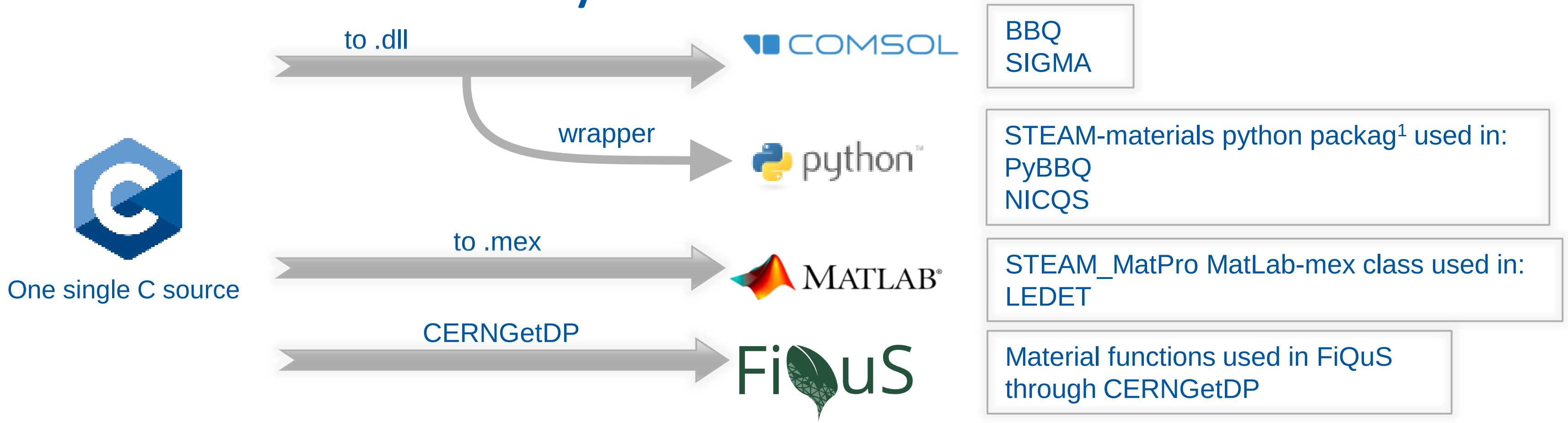
Collection of tools, with possibility of co-simulation, for the analysis of transient (and steady-state) behaviour of superconducting magnets and circuits.

- Tools: (py)BBQ, LEDET, ProteCCT, FiQuS, COSIM, NICQS, SIGMA, Comsol and SPice models
- Electro-magnetic-thermal simulations. Co-simulation with mechanical models (ANSYS) possible.
- Development and maintenance by MPE-PE, also in collaboration with other institutes
- All types of AC behaviour (coupling currents, magnetisation, eddy currents, quench, quench-back, …)
- All types of magnet geometries (CosTheta, curved-CCT, block, common coil, racetrack, solenoid, pancake, …)
- All types of conductors (LTS, HTS, strands, cables, tapes, …)
- Various types of protection devices (quench heaters, EE, CLIQ, e-CLIQ, s-CLIQ, ESC, cap. discharge, …)

Including:

- Other circuit components (power converter, bypass diode, EE unit, …)
- Failure scenarios
- Parametric analysis & optimisation of protection efficiency

STEAM-material-library



BBQ
SIGMA

STEAM-materials python packag[1] used in:
PyBBQ
NICQS

STEAM_MatPro MatLab-mex class used in:
LEDET

Material functions used in FiQuS through CERNGetDP

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

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

Supported Materials

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

Properties

Volumetric heat capacity

Thermal conductivity

Resistivity

Jc: Critical Current density (LTS & HTS)

Next steps:

- Adding more materials
- Adding additional properties

Courtesy of Georgia Zachou

Example of 12T Quench Protection studies

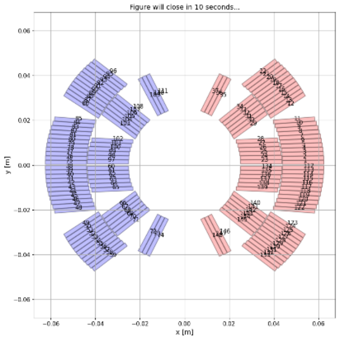
Courtesy of Emmanuele Ravaioli

Magnet designs: courtesy of Lucio Fiscarelli

Parametric study of protection efficiency of 3 magnet designs, with 3 ways of heater application, and various combinations of heaters and CLIQ.

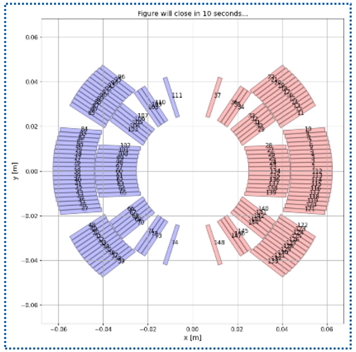
More information: https://edms.cern.ch/document/2908421/1

50 mm, 5 blocks

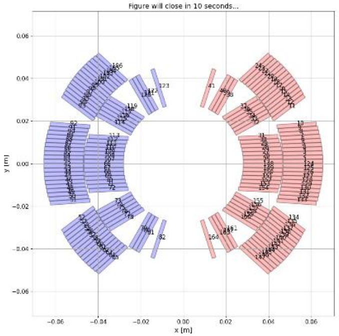


Heaters application	Glued			Miniswap			Impregnated		
Magnet design	50mm 5b	50mm 6b	56mm 6b	50mm 5b	50mm 6b	56mm 6b	50mm 5b	50mm 6b	56mm 6b
Protection case	Maximum adiabatic hot spot temperature (K)								
outer QH only	354	360	350	327	332	323	304	308	301
inner QH only	311	313	307	296	299	293	284	286	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

50 mm, 6 blocks



56 mm, 6 blocks



STEAM LEDET

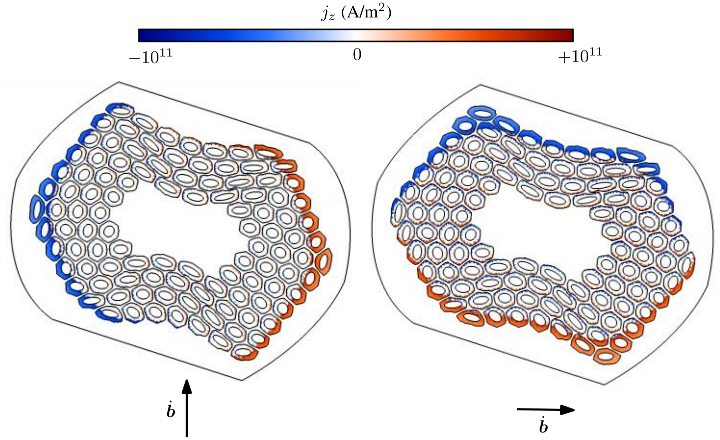
Reduced Order Modelling of SC Magnets

Courtesy of Julien Dular, Fredrik Magnus

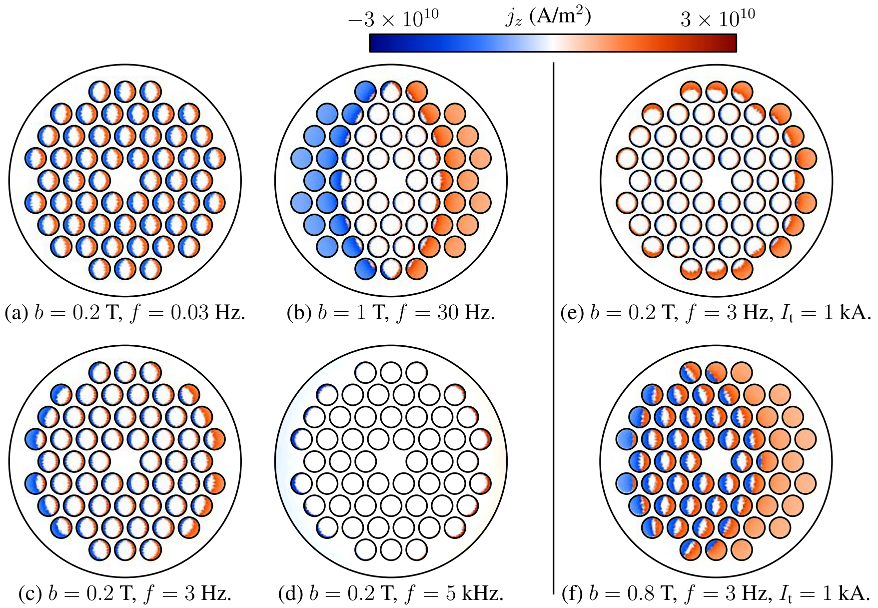
Aim: correct simulation of SC effects at μm scale for entire 3D magnets with acceptable computing cost/time.

Phase 1 – Coupled Axial and Transverse currents (**CATI**) method:

- Applied on multifilamentary SC strand and cable models in transient conditions.
- **2D finite element** model: fast and accurate.
- Relies on **periodicity**, not **symmetry**, and hence applies to **deformed** geometries.
- Perfect agreement with reference 3D model



Deformed strand geometry, courtesy of B. Clavijo, J. Baumann, S. Hopkins (MSC-LSC)



(a) $b = 0.2$ T, $f = 0.03$ Hz. (b) $b = 1$ T, $f = 30$ Hz. (e) $b = 0.2$ T, $f = 3$ Hz, $I_t = 1$ kA.

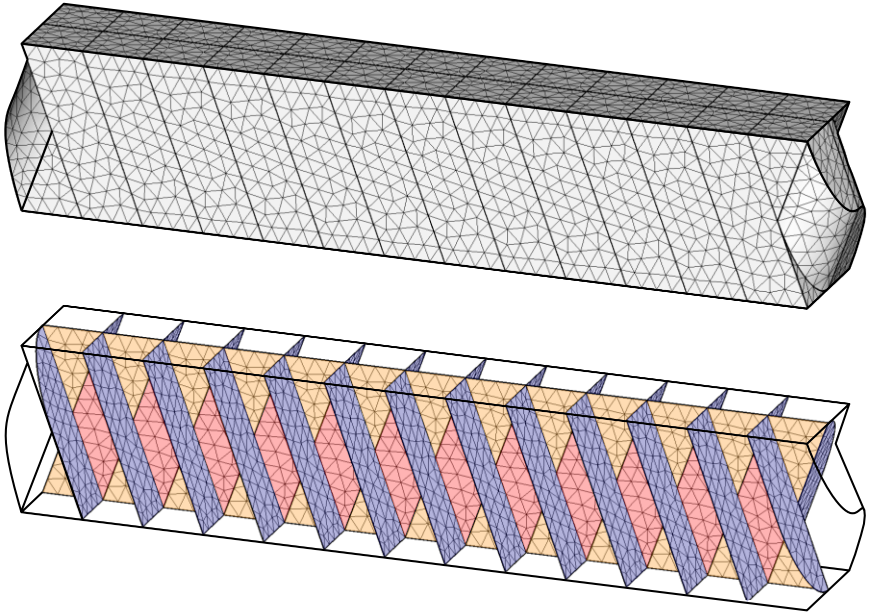
(c) $b = 0.2$ T, $f = 3$ Hz. (d) $b = 0.2$ T, $f = 5$ kHz. (f) $b = 0.8$ T, $f = 3$ Hz, $I_t = 1$ kA.

Reduced Order Modelling of SC Magnets

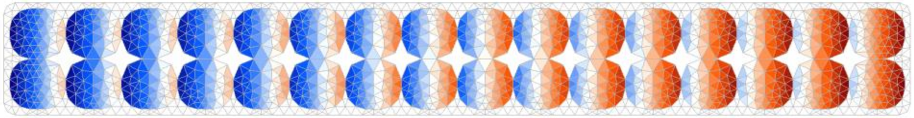
Courtesy of Julien Dular, Fredrik Magnus

Phase 1 – Application of CATI for a Rutherford cable

3D reference model



2D CATI model

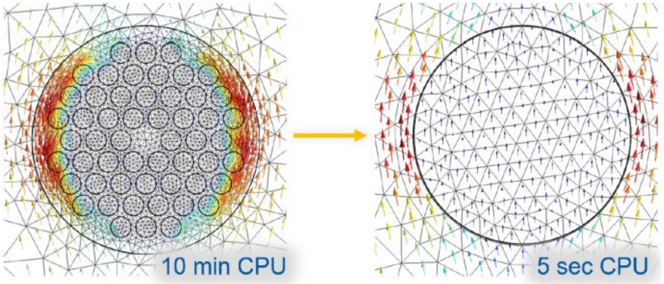


Next steps:

- Extract impedance from transport current excitations, and its coupling with external field.
- Other cable types
- Automate process
- Define homogenized impedance

Reduced Order Modelling of SC Magnets

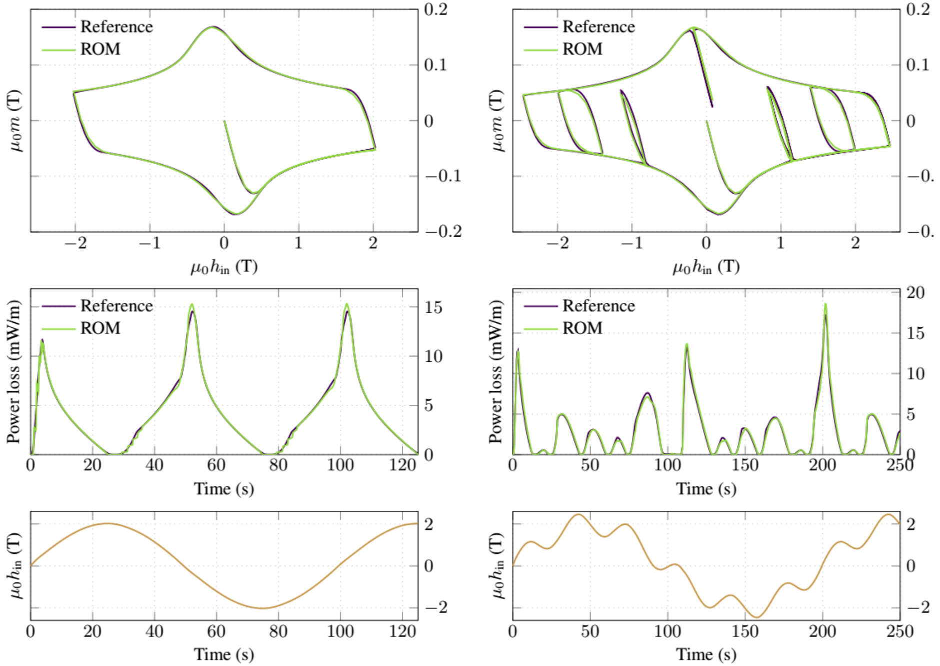
Courtesy of Julien Dular, Fredrik Magnus



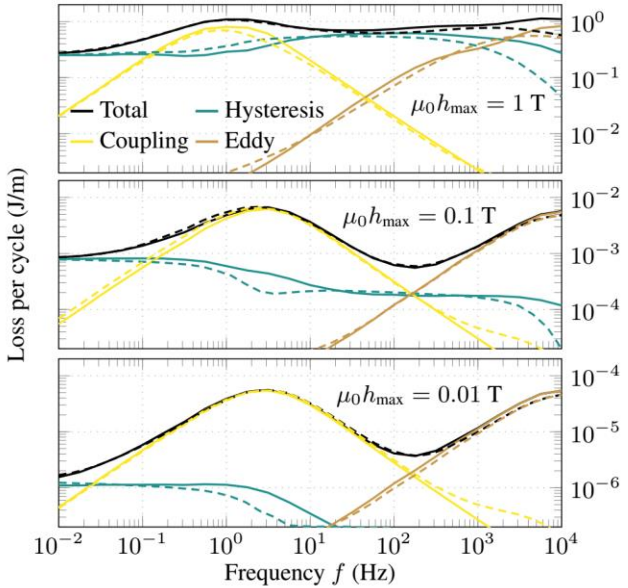
Phase 2 – Reduced Order Hysteretic Magnetization (**ROHM**)

- Describes **AC loss** and **magnetization** of a strand or cable subject to external field.
- Inspired by **ferromagnetic** hysteresis models, and extended for eddy and coupling currents.

Rate-independent case



Rate-dependent case



FiQuS: Transients in LTS Multipole Magnets

Courtesy of Erik Schnaubelt
Ackn. Andrea Vitrano

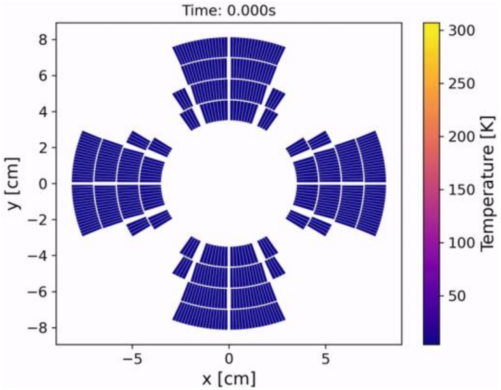
Coupling of 2D finite element (FE) magnetostatic and transient thermal simulations

- Fully automated computation of geometry, mesh, and solution from ROXIE and text-based versioned input files

Thin shell approximations (TSA) [1] to model thermal gradients across insulation layers accurately and efficiently

- Enables correct modelling of Quench Heaters (computationally prohibitive for classical FE)

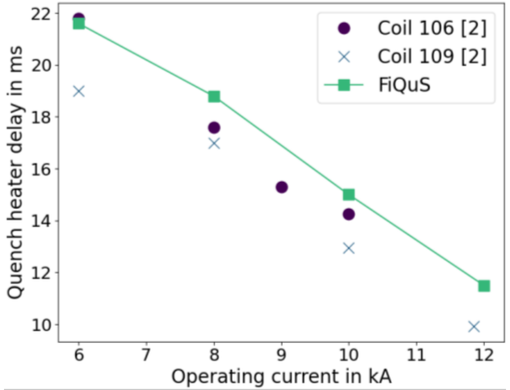
[1] E. Schnaubelt et al., Supercond. Sci. Technol. (2023), DOI 10.1088/1361-6668/acbeea



Hot spot during quench (using TSA).
~ 40 times faster than FE reference
Rel. error compared to FE reference: 1%

Next steps:

- Finalize SUST paper (almost ready)
- Extend multipole model by homogenization techniques to incorporate accurate AC loss
- Implement active quench detection and protection circuits for QH, EE, CLIQ, and ESC
- Validate this extended model against experimental data



QH delay vs. measurements for MBH
[S. Izquierdo Bermudez et al., IEEE TAS (2016), DOI 10.1109/TASC.2016.2536653]

FiQuS: Transients in HTS Pancake Coils

Courtesy of Erik Schnaubelt
Ackn. Sina Atalay

Previously: 3D FE magnetodynamic-thermal transient simulation of NI pancake coils

- Screening currents and magnetization included by construction

E. Schnaubelt et al., IEEE TAS (2024), DOI 10.1109/TASC.2023.3340648
S. Atalay et al., Supercond. Sci. Technol. (2024), DOI 10.1088/1361-6668/ad3f83

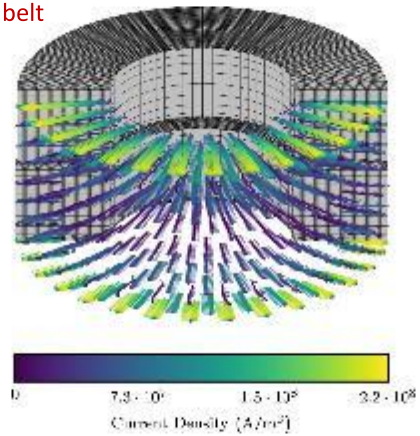
Latest: detection and protection studies of (insulated) pancake coils

- Two ways to induce local normal zone
  1. Variation/degradation of J_c along length of the HTS conductor
  2. Induced local hot spots by heater power deposition
- Study on the protectability due to thermal conductivity between turns, assuming quench detection with voltage bridge

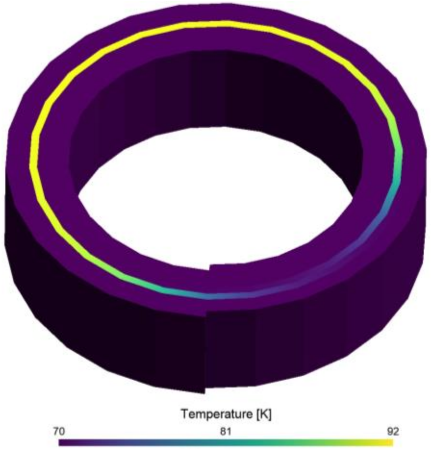
M. Wozniak et al., ASC’24 proceedings (to be submitted), 1LPo1I-02.

Next steps:

- Uncertainty quantification study for quench detection and protection of insulated pancake coils using Sandia Labs’ Dakota
- Validate NI model further against experimental data



Screening currents after current shut-off in a stack of two pancakes



Heater induced hot spot in a small insulated pancake coil

FiQuS: High-Performance Computing (HPC)

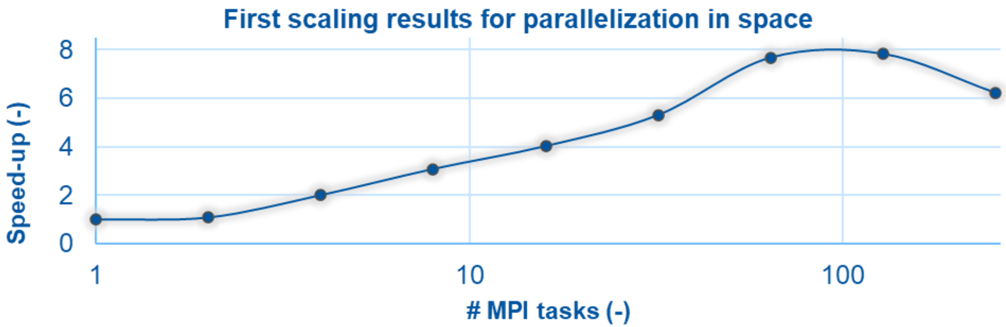
Courtesy of Erik Schnaubelt

FiQuS runs on high-throughput and HPC clusters thanks to containerization (Docker/Singularity)

- Algorithms are missing that use the full potential of massive number of available CPUs

Parallelization in space is very promising and already yield a speed-up of around 8

- Still far away from (ideal) linear scaling with number of parallel tasks → dedicated research at CERN



Parallelization in time only yields a speed-up around 2, even after specific extension to classical algorithm [1]

- More intricate methods promise to perform better but require more fundamental numerical research [2]
  → dedicated algorithm research should be carried out outside of CERN

New algorithms must be useable by non-experts in a (quasi-)black-box fashion

[1] E. Schnaubelt et al., SCEE’24 proceedings (accepted after review), DOI 10.48550/arXiv.2404.13333
[2] T. Baumann et al., submitted to Springer Numerical Algorithms, DOI 10.48550/arXiv.2403.13454

Protectability studies of HTS coils

Courtesy of Mariusz Wozniak

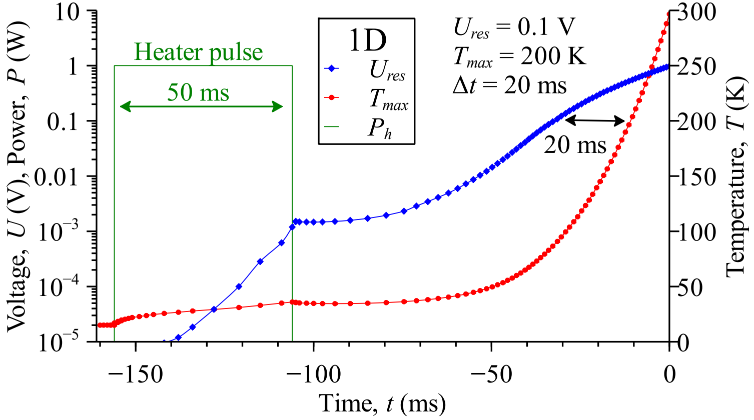
STEAM FiQuS

Quench detection in HTS coils is an issue due to slow longitudinal propagation.
In classical 1 D simulations this often results in late detection ⇒ insufficient time to extract the current ⇒ burn-through.

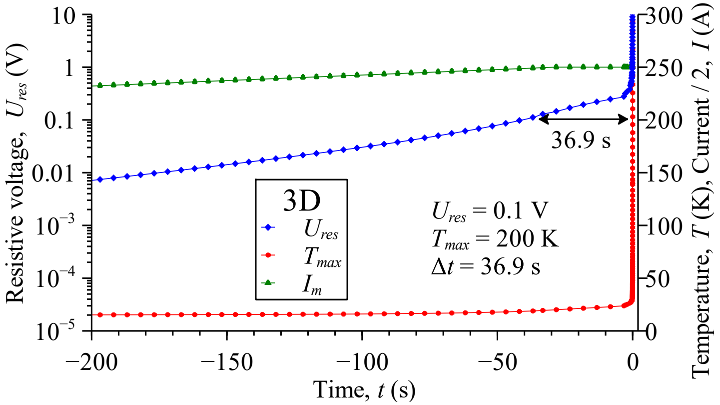
However, due to turn-to-turn heat diffusion and large enthalpy margin (especially when operating at higher temperature) real coils might be more stable and easier protectable.

Studies are performed in 3D using FiQuS for external and internal heat dissipation to better understand the protectability of HTS coils.

Also, the stability of coils due to local defects in the tape (i.e. local I_C reduction) is assessed.



Quench detection voltage and thermal runaway look very different for 1D case with heater (above) and 3D heat diffusion with I_c defect (below)



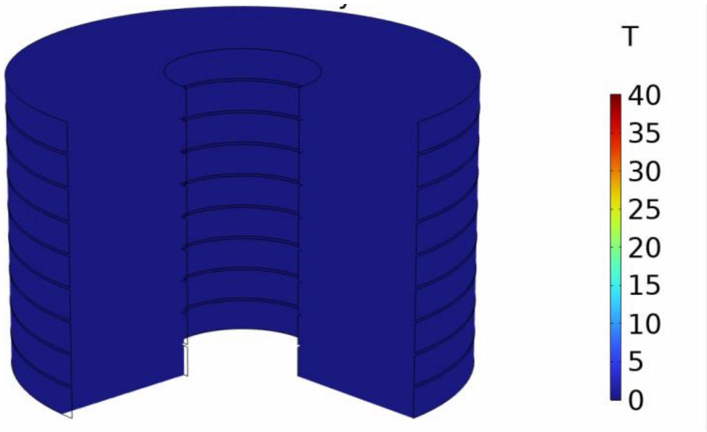
3D electrodynamic models of NI coils – The MC 40 T Solenoid

Courtesy of Bernardo Bordini, Davide Rinaldoni

Collaboration with WP2.6

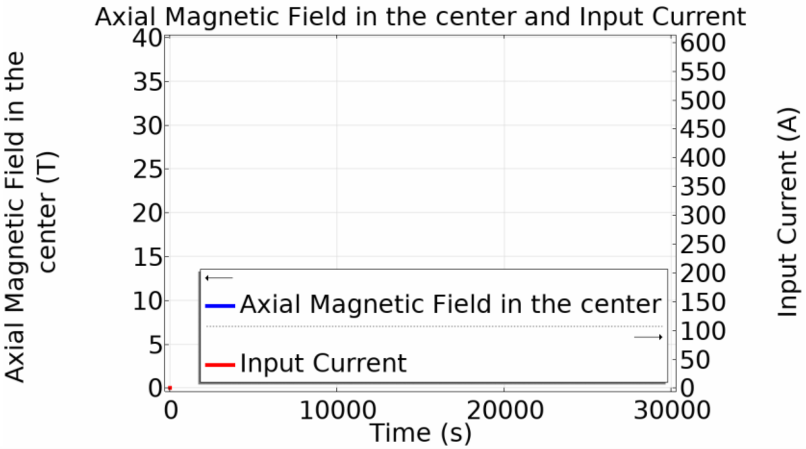
Comsol model based on new mathematical formulation developed in MPE-PE.

Very fast: only one-hour on a standard PC !!!



Model set-up:

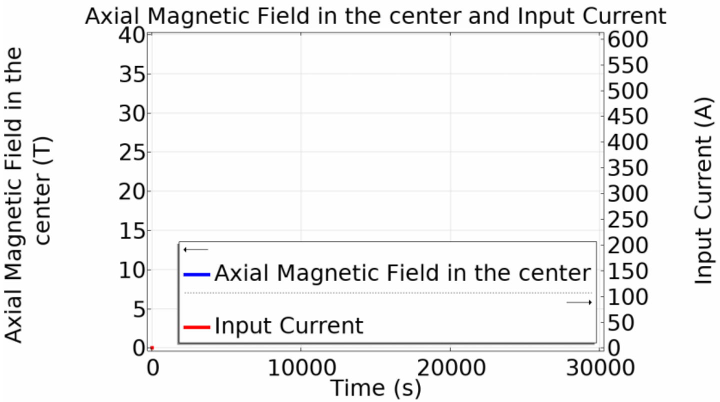
- Infinite number of identical 3D pancakes
- Coil winding thickness 6 cm
- 750 layers of conductor (each layer simulated)
- Conductor: 12 mm x 80 µm tape
- Turn-to-turn contact resistance: 10 µΩ cm^2
- 2 mm of air between coils

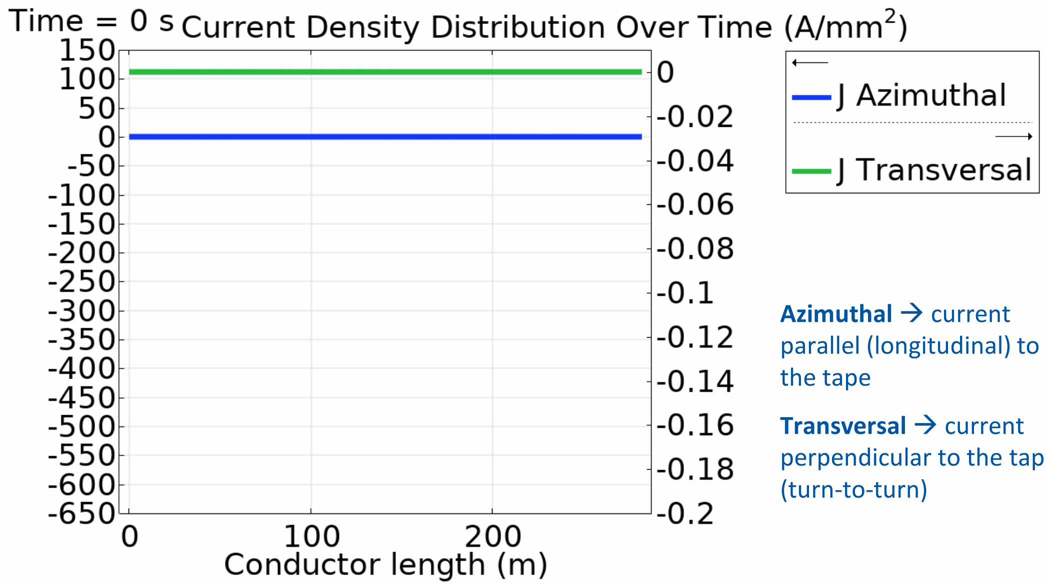


3D electrodynamic models of NI coils – The MC 40 T Solenoid

Courtesy of Bernardo Bordini, Davide Rinaldoni
Collaboration with WP2.6

Evolution of the current distribution during ramp-up





Azimuthal → current parallel (longitudinal) to the tape

Transversal → current perpendicular to the tape (turn-to-turn)

Next steps:

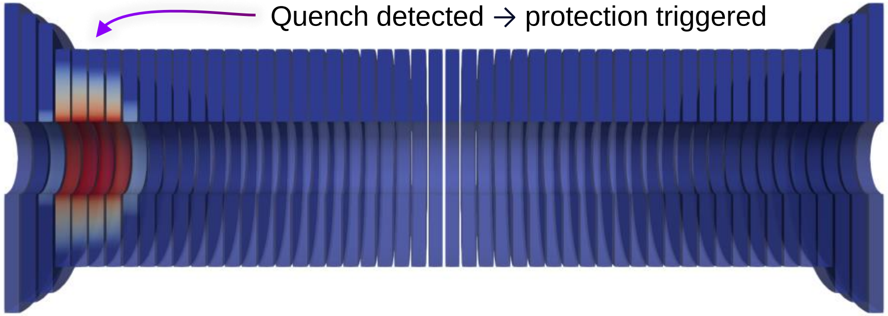
- Add and validate joints and all types of AC effects
- Study effect of turn-to-turn resistance on protectability
- Cross-check results with NICQS and FiQuS
- Validate results on real HTS coils

No-Insulation Coils Quench Simulator (NICQS)

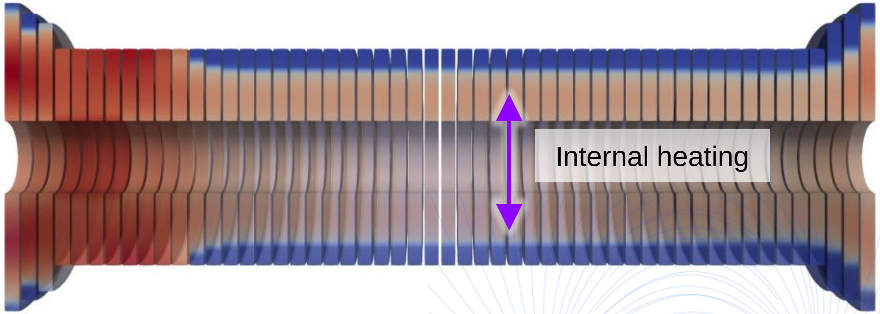
Courtesy of Tim Mulder

Features:

- Smart homogenization of the tapes to allow fast modeling of HTS NI magnets with >>10000 turns.
- Quench behaviour, screening currents and other magnetization effects.
- Evaluation of the thermal stability during ramp and optimization of ramp schemes to limit the ramp-loss.
- Investigation of efficiency of quench heaters and/or capacitive discharge.
- Calculation of Lorentz forces to evaluate conductor stress (using other specialized software tools).
- Use of GPU to boost computational speed.



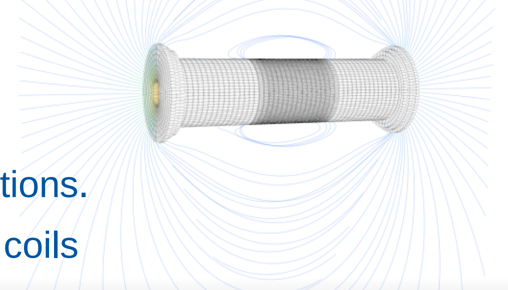
Quench detected → protection triggered



Internal heating

Next steps:

- 3D coil geometries for insulated and non-insulated HTS magnets.
- 3D solenoids, 3D racetrack coils, geometry combinations, rotations and translations.
- Cross-check with FiQuS and Comsol models, and validate results on real HTS coils

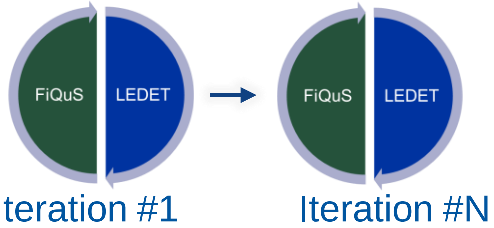


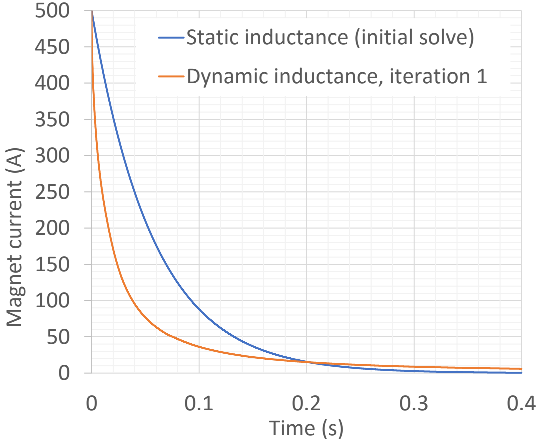
CCT magnets quench simulation in 3D

Courtesy of Mariusz Wozniak

Co-simulation approach used

FiQuS magnetostatic → LEDET fixed L and T

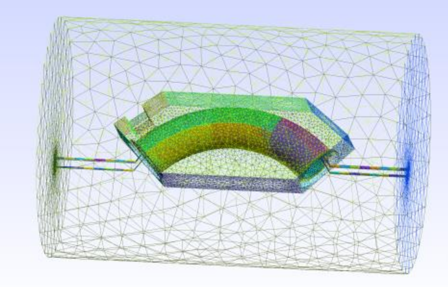




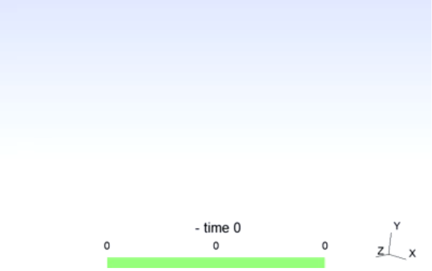
More details:
https://doi.org/10.1109/TASC.2023.3338142
https://doi.org/10.1109/TASC.2024.3355358

STEAM LEDET FiQuS

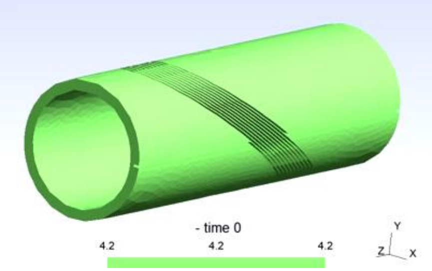
Magnet designs by **A. Haziot** and the Fusillo team



Eddy currents formers



Temperature of former



Next steps:

- Preparation of Fusillo demonstrator model
- Adjustments to improve mesh quality
- Quench simulation of Fusillo demo by Sep 2024

Final comments WP4.5 - **LTS**

- **Detection**: good old V-bridge
- **Protection**: e-CLIQ, s-CLIQ and ESC could offer improved efficiency and reliability, but also impact the mechanical design; now ready to be tested on magnets.
- **Modeling**: LEDET is the work horse for most protection studies; FE quickly progressing and a must for certain magnets, especially if 2D is not sufficiently accurate. Homogenisation important for FE to simulate in 3D with affordable computing time. Tests on magnets are always needed to further validate the models.

Final comments WP4.5 - **HTS**

- **Detection** through electrical stimuli is very promising. First tests on a powered and quenching magnet expected soon.
- **Protection**: Capacitive discharge promising method for N/M-I coils. Awaiting tests. Protectability studies ongoing for insulated and N/M-I coils.
- **Modeling**: Thin-layer anisotropic tapes pose serious challenges. We are STEAM-ing ahead in 3 directions (Comsol, FiQuS, and NICQS). Cross-checking of the models is ongoing. More physics to be implemented. Reducing the computing cost for (3D) simulations of (large) HTS coils is assessed by means of homogenisation, adaptive time stepping/meshing, HPC, parallelization in space/time, multicore etc.

We really need HTS coils (of any shape, size) to demonstrate our new detection and protection concepts, and validate our models.

HTS magnet technology is still in its infancy as compared to LTS but has a huge potential.
The R&D gap might be bridged in the next 10 years if CERN is prepared to commit significant resources, also taking advantage of synergies between different programmes/projects.