HFM
High Field Magnets

Introduction to the activities of WP4.5 at CERN

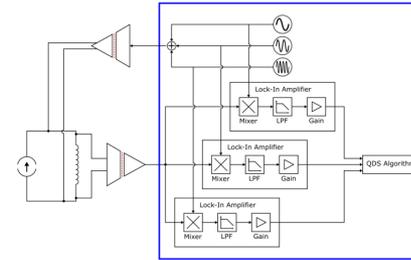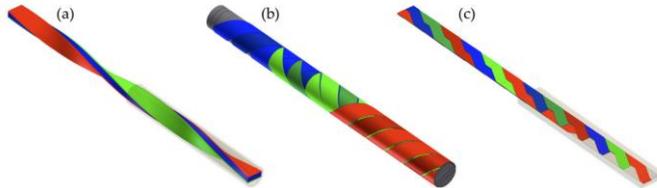Quench detection, protection and diagnostic methods for HFM
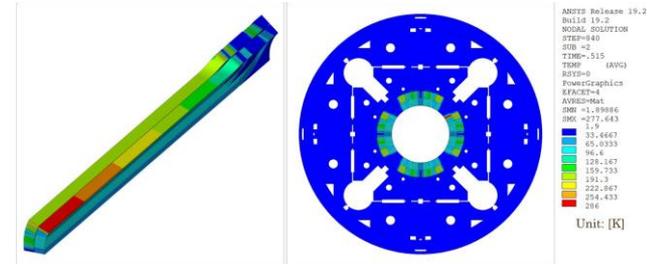
Mariusz Wozniak

18.04.2023

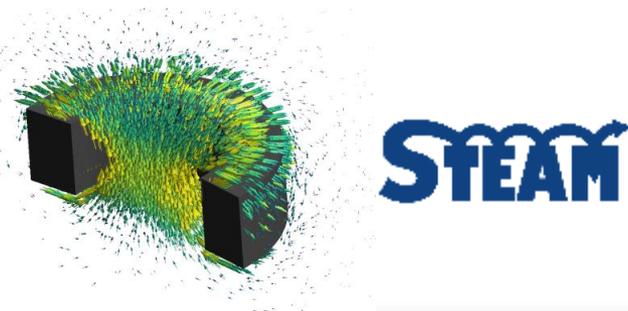# Scope of the WP4.5

1) Quench Detection Technology Development

2) Conductors for Protection

3) Protection Limits Development

4) Protection Technology Development

5) Models and Simulation Tools Development

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Complete list of defined activities

Task/Deliverable	Description
WP4.5-T1	**Quench Detection Technology Development**
WP4.5-T1-D1	Optimization of HTS conductor for quench d.
WP4.5-T1-D2	Advanced signal processing and filtering for d.
WP4.5-T1-D3	Temperature based detection methods
WP4.5-T1-D4	Novel quench detection methods
WP4.5-T1-D5	Impedance based detection methods
WP4.5-T2	**Conductors for protection**
WP4.5-T2-D1	Architecture and specification - Nb3Sn
WP4.5-T2-D2	Architecture and specification - HTS
WP4.5-T3	**Protection Limits Development**
WP4.5-T3-D1	Definition of key measures
WP4.5-T3-D2	Establishing target values
WP4.5-T3-D3	Simulations for the new measures

Task/Deliverable	Description
WP4.5-T4	**Protection Technology Development**
WP4.5-T4-D1	Studies of powering schemes
WP4.5-T4-D2	Local E-CLIQ development
WP4.5-T4-D3	Secondary E-CLIQ development
WP4.5-T4-D4	Development of advanced shunts for HTS
WP4.5-T4-D5	Concepts for protection of HTS coils
WP4.5-T4-D6	Non-linear EE development
WP4.5-T4-D7	Magnetic coupling for EE
WP4.5-T4-D8	Energy recuperation methods
WP4.5-T5	**Models and Simulations Tools Development**
WP4.5-T5-D1	HFM protection studies (requests from RDs)
WP1.1-T5-D2	Accelerator availability studies
WP1.1-T5-D3	Properties of diversified conductors
WP1.1-T5-D4	Conductors in protection
WP1.1-T5-D5	E-CLIQ tools development
WP1.1-T5-D6	HTS quench tools development
WP1.1-T5-D7	Advanced EE tools development
WP1.1-T5-D8	Coupled structural and quench tools
WP1.1-T5-D9	Transient thermal tools
WP1.1-T5-D10	Parametrized quench tools
WP1.1-T5-D11	New materials in quench simulations
WP1.1-T5-D12	Hybrid magnets quench tools
WP1.1-T5-D13	CCT magnet quench tools

The following slides will cover the most recent results on selected activities

If you are interested in not covered activity please contact me for discussion or ask questions at the end.

Note: some activities are not resourced or scheduled for later

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Impedance Measurement for Continuous Condition Monitoring (including quench detection)
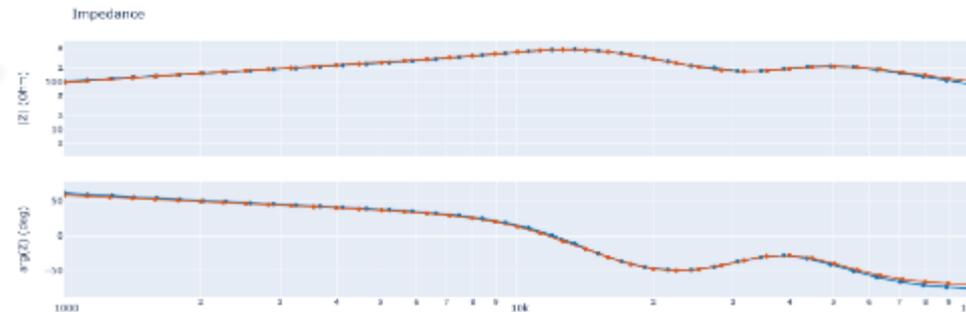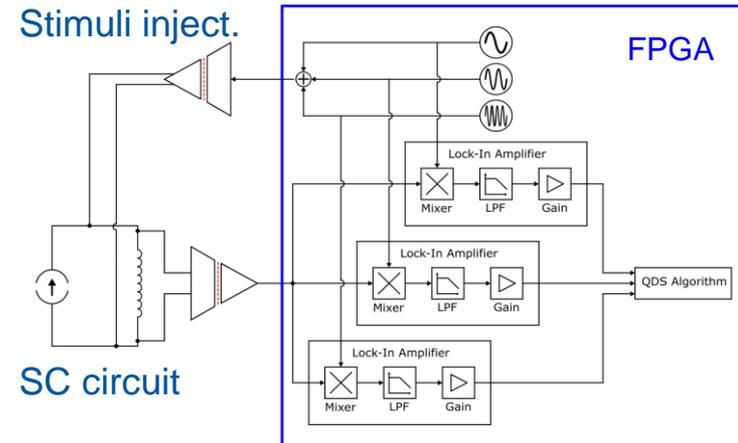
Current Status:

- Built hardware required to inject and measure the response of stimuli signals, like:
  - DAC (inject) & ADC (measure) cards
  - FPGA to supervise the cards and relay the collected samples
- Quantified performance when measuring LTS magnets in non-powered state

Upcoming Tasks:

- Quantify the performance when measuring HTS magnet (non-powered)
- Quantify the performance when powering magnets for LTS and HTS
- Evaluate the systems operational impact on auxiliary systems.

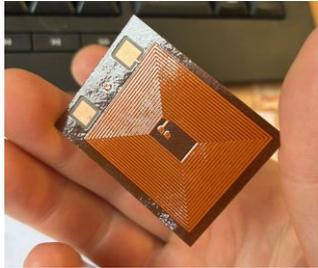Conceptual illustration of how future quench detection may be implemented.

Stimuli inject.

FPGA

SC circuit

Impedance of warm D2 magnet, all coils in series.
Orange – ELQA team with 'commercial hardware',
Blue - Newly Developed hardware, tot. aquisition time 1.2s

Courtesy of Magnus Christensen and SM18 colleagues

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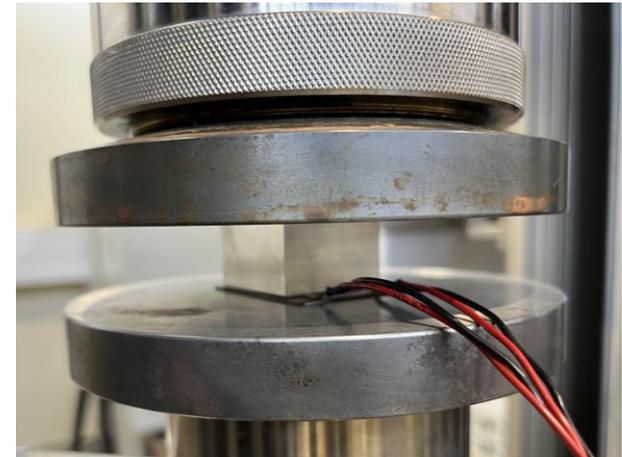
E-CLIQ: External Coil Coupled Loss Induced Quench
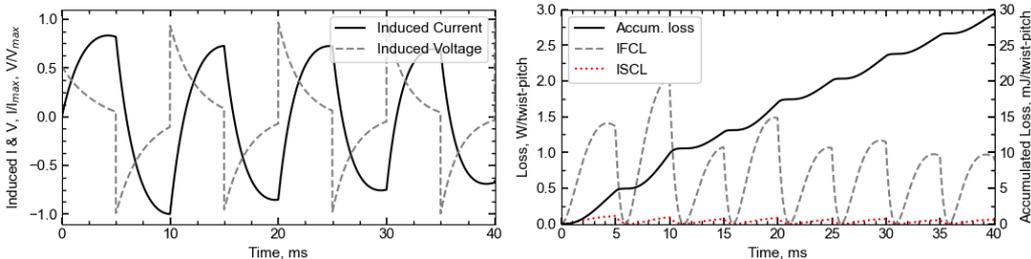

A set of very compact copper coils strategically positioned close to the primary coils, similar to resistive quench heaters, see Mulder et al. 2023

PCB E-CLIQ in development for **integration with an SMC**

- Optimized for use with low-current amplifier

- Able to generate local dB/dt of > 100 T/s

- Compact envelope, width of a Nb_3Sn cable

The design is experimentally verified to withstand mechanical loads of over 200 MPa ✓

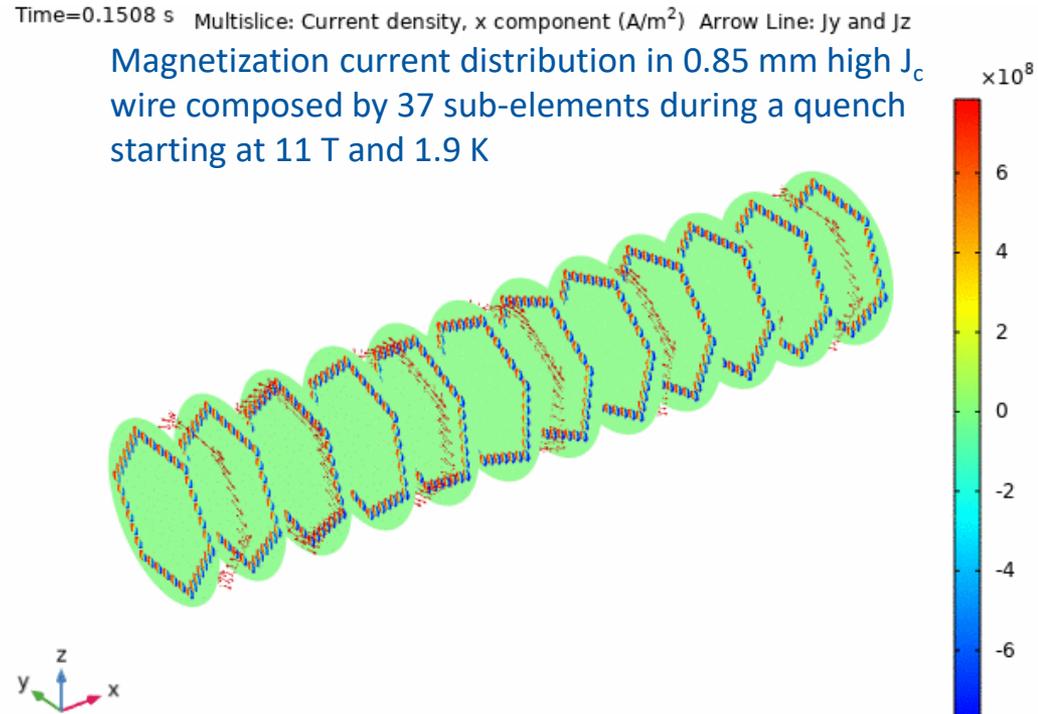Thanks to I. Santillana and A. Terricabras (EN/MME) for effort during the mechanical tests

Modeling tools further matured

Courtesy of Tim Mulder

WP4.5-T4-D2
WP4.5-T5-D5

Dynamic effects in composite superconductors

- Developed a 3 D thermo-electromagnetic FEM (Comsol) model to simulate dynamic effects in twisted composite superconductors
  - Presently built for high-J_c Nb$_3$Sn wires composed by up to 108 sub-elements, the model can be adapted to other superconductors

- Next Steps:
  - Validation vs simple cases having an analytical solution and vs existing representative experimental results
  - Simulate relevant cases to estimate losses and time constants during magnet quenches
  - Derive, from the numerical solutions, semi-analytical formulas that can be implemented in other STEAM codes to estimate the losses in superconducting magnets
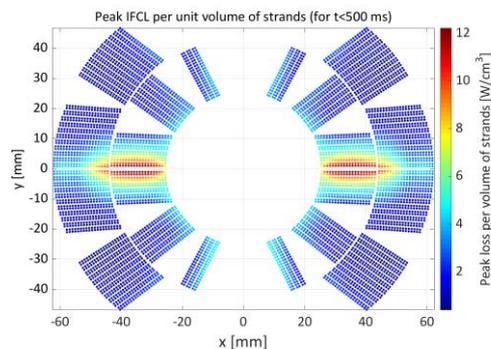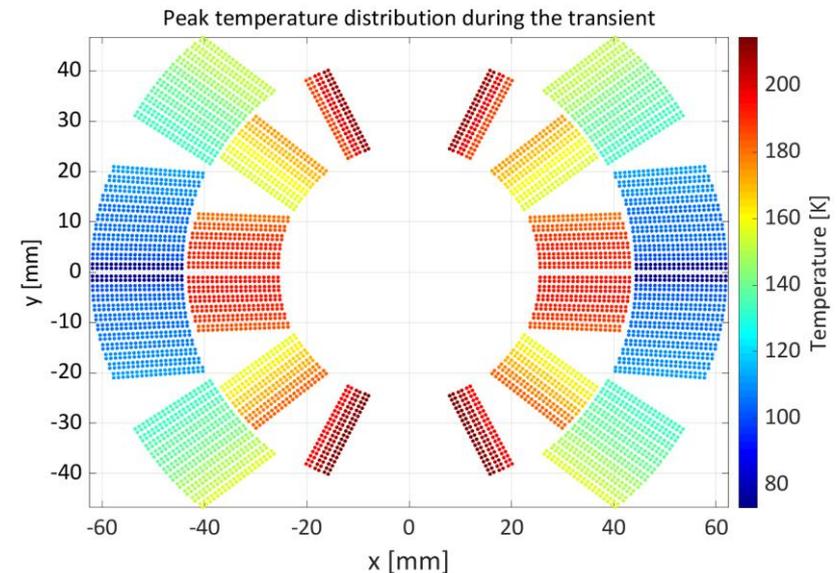
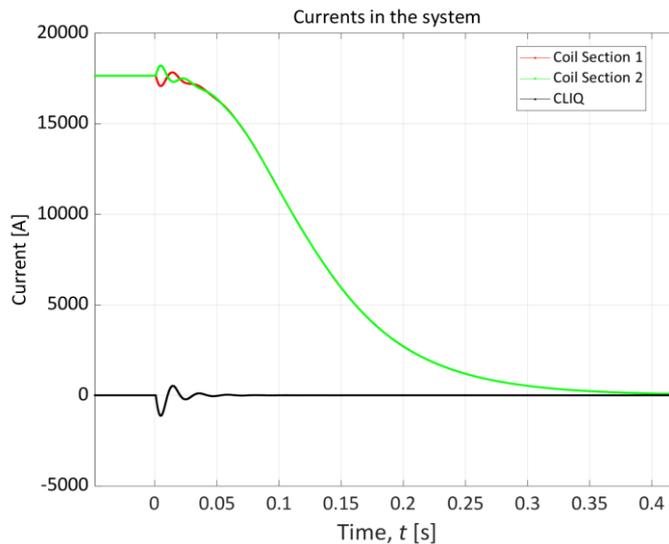Time=0.1508 s   Multislice: Current density, x component (A/m^2) Arrow Line: Jy and Jz

Magnetization current distribution in 0.85 mm high J_c wire composed by 37 sub-elements during a quench starting at 11 T and 1.9 K

Courtesy of Bernardo Bordini

HFM Protection Studies
12T robust dipole - initial concepts

Currents in the system

Peak temperature distribution during the transient

Peak IFCL per unit volume of strands (for t<500 ms)

Results from:
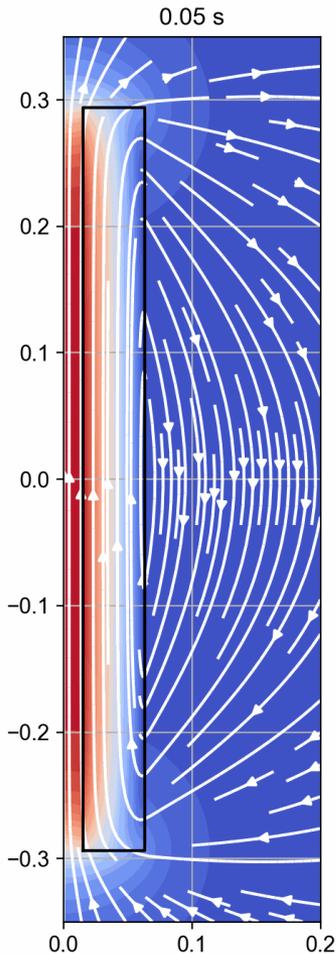https://gitlab.cern.ch/steam/analyses/m12t_r
Tag: 2024.4.0
Case 3 for QH+CLIQ for magnet:
modelData_robust_12T_50_mm_MQXF_cable_5_blocks_V2

Work request from HFM WP3.1. Collaboration with: Diego Perini, Lucio Fiscarelli. With thanks to Emmanuele Ravaioli.
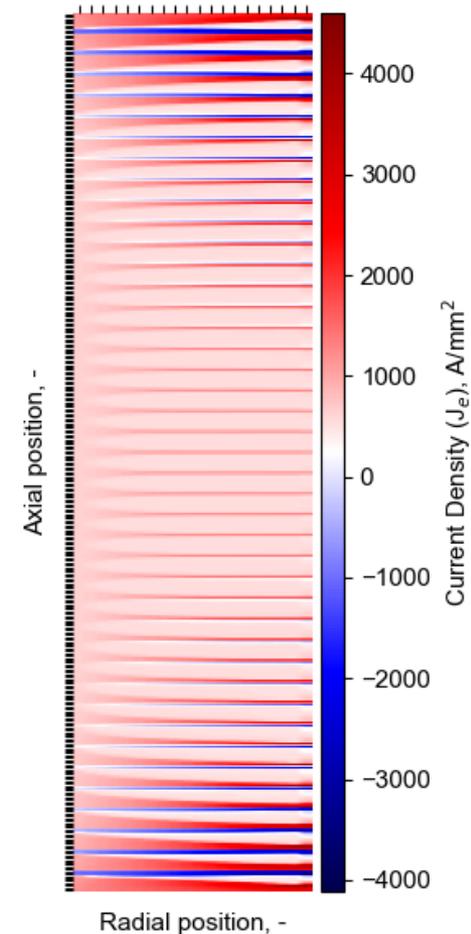
HTS Quench tools development Selected Finite Difference results

0.05 s

- NICQS : No-Insulation HTS Coil Quench Simulator
- Modeling tools are in development to describe the thermo-electromagnetic behavior of NI/Controlled-Resistance HTS coils

- New: persistent currents within the tapes.
  - Required for mechanical evaluation.
  - Magnetization and its loss during operation.
- New: Eddy currents in structural elements.
  - Important for quench protection studies.
  - AC-loss generated during operation.
- Fast, example:
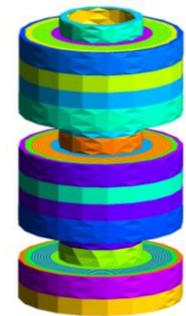 40 T cooling solenoid: 42 pancake coils, 600 turns each -> simulation time of a few minutes to an hour*.

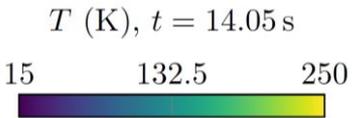* Depending on the scenario and solver settings.

Courtesy of Tim Mulder

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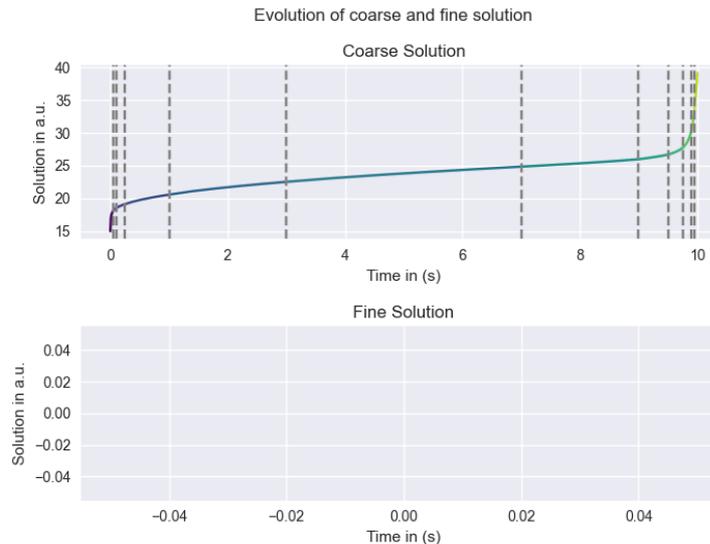# HTS Quench tools development Selected FE results

FiQuS : Finite Element Quench Simulator

Dedicated tools for Quench Sim.: A. Vitrano et al.

Numerical approaches for more efficient or faster solutions:

- Thermal Thin Shell Approx. E. Schnaubelt et al.

- EM (H – φ) Thin Shell Approx. E. Schnaubelt et al.

- Automated geometry, mesh and solution stages

- Concurrent in time and/or space solving (HPC) (w.i.p.)

Mesh of 3D HTS stack of double pancakes

Corse and fine solutions for parareal algorithm

Thermal sol. for multiple pancakes

Courtesy of S. Atalay and E. Schnaubelt

Coupled structural and quench tools

Two-way coupling successfully implemented between ANSYS-LEDET models:
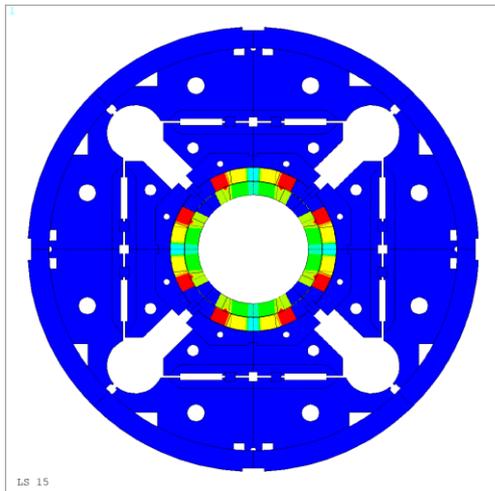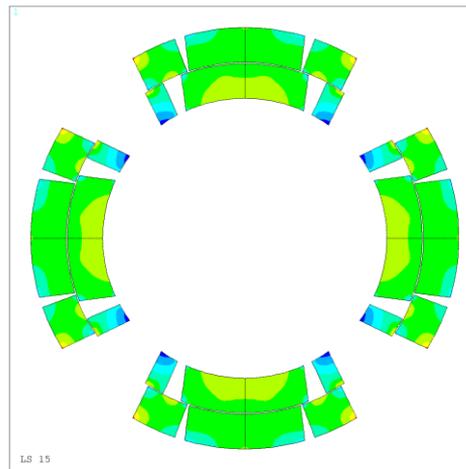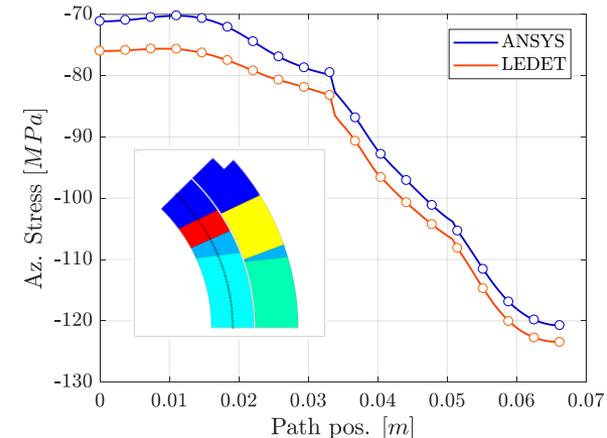
(i)   ANSYS APDL provides the element centroids to LEDET.

(ii)   LEDET solves the transient and transfers back to ANSYS the temperature and e.m. forces across the magnet.

(iii) ANSYS solves the transient mechanics problem as a series of static steps (quasi-static approximation).

Temperature distribution during a Quench Integral test (OL Heater discharge, t = 1 s)
Winding pole is assumed to stay at 1.9 K

Resulting azimuthal stress in the coils. (t = 1 s)

Results comparison (IL path) between this new approach and a full ANSYS model*.
[J. Ferradas, "Mechanical behavior of a Nb_3Sn accelerator magnet during a quench", PhD Thesis)
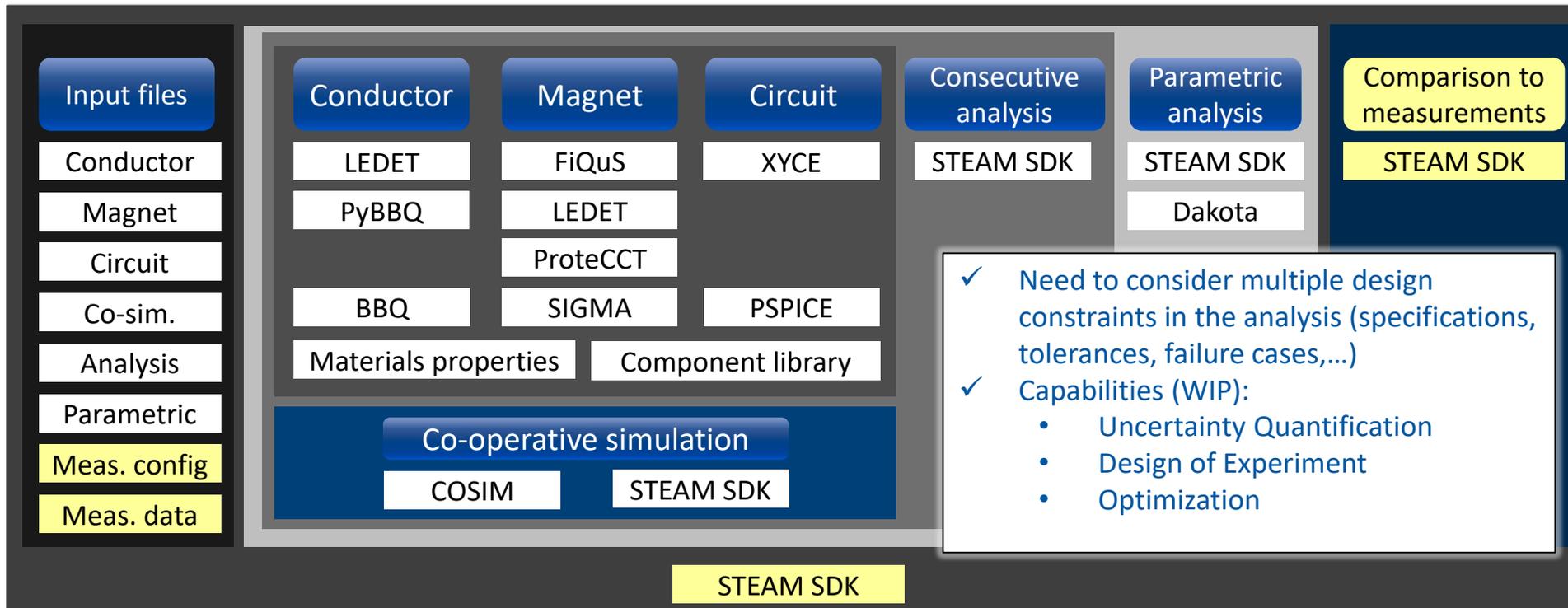
* Largest discrepancy (5 MPa) due to the different pole temperature. Small mismatch in the coil windings due to a larger temperature from LEDET (more accurate coupling losses).

Slide courtesy of J. Ferradas Troitino & E. Ravaioli

Parametrized quench tools

STEAM FRAMEWORK

Input files	Conductor	Magnet	Circuit	Consecutive analysis	Parametric analysis	Comparison to measurements
Conductor	LEDET	FiQuS	XYCE	STEAM SDK	STEAM SDK	STEAM SDK
Magnet	PyBBQ	LEDET			Dakota	
Circuit		ProteCCT				
Co-sim.	BBQ	SIGMA	PSPICE			
Analysis	Materials properties		Component library			
Parametric						
Meas. config						
Meas. data						

Co-operative simulation

COSIM   STEAM SDK

STEAM SDK

- ✓ Need to consider multiple design constraints in the analysis (specifications, tolerances, failure cases,…)
- ✓ Capabilities (WIP):
  - Uncertainty Quantification
  - Design of Experiment
  - Optimization

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

https://espace.cern.ch/steam
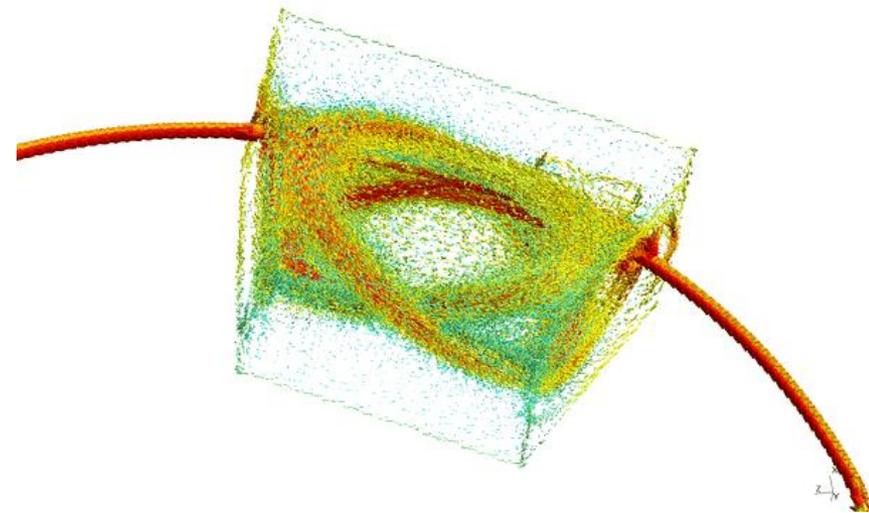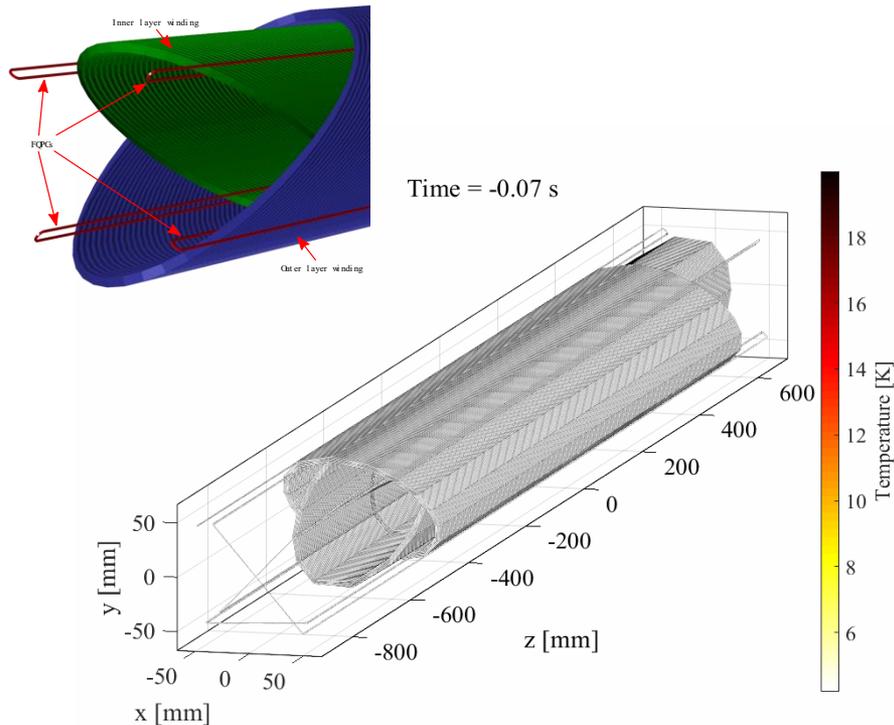https://indico.cern.ch/event/1161448/

Slide courtesy of E. Ravaioli & M. Wozniak

CCT magnet quench tools

- Work to simulate quench in 3D in CCT magnets
- Coupling between FiQuS (FE) and LEDET (FD)
- Exchange of temperatures due to eddy currents (WIP)

Initial simulation of eddy currents in the formers and outer shell of Fusillo magnet (w.i.p.)

Concept of Fast Quench Propagation Conductors for CCT magnets, M. Wozniak et al.

Slide courtesy of E. Ravaioli & M. Wozniak
Collaboration with and support of the Fusillo team at CERN

Conclusions

- Activities scope and structure are defined

- Many interesting R&D topics are identified

- Very good progress on resourced tasks

- Many tasks are not initiated due to a lack of manpower for WP4.5 or collaborating WPs.

- Further refinements and adjustments of activities are expected and required

- Clarification of budget and priorities is required

- Clarification of collaboration in and outside CERN

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