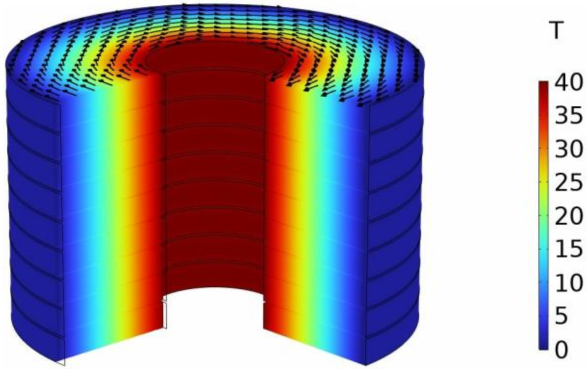
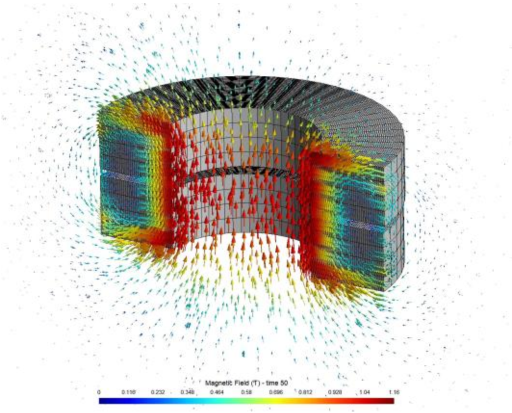
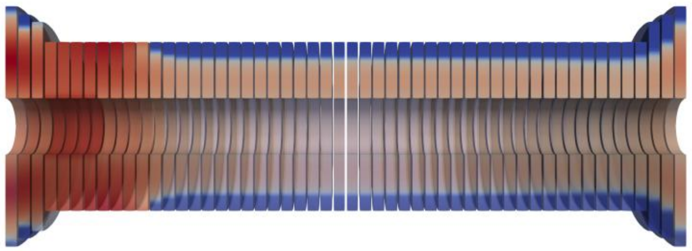






Protection concepts and simulation tools for REBCO magnets

Focus on high-field accelerator-type multipole/solenoid magnets

Erik Schnaubelt, Arjan Verweij

CERN, TE-MPE

With many inputs and slides from:

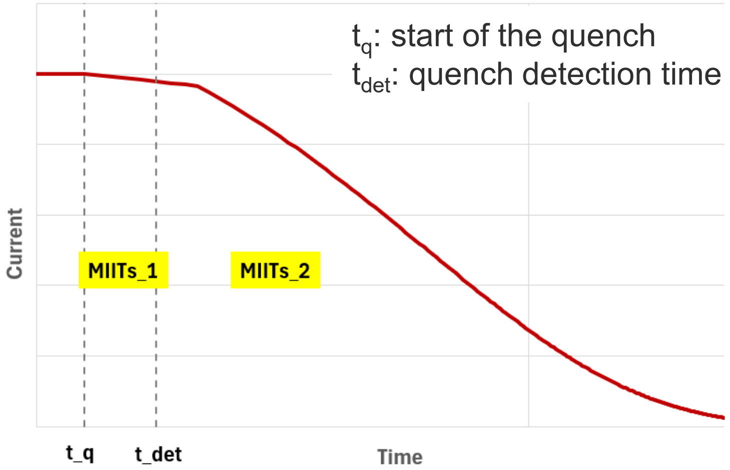
Bernardo Bordini, Julien Dular, Alexander Glock, Daniel Mayr, Tim Mulder, Emmanuele Ravaioli, Davide Rinaldoni, Leon Teichröb, Benoît Vanderheyden, Wybren Walinga, Mariusz Wozniak

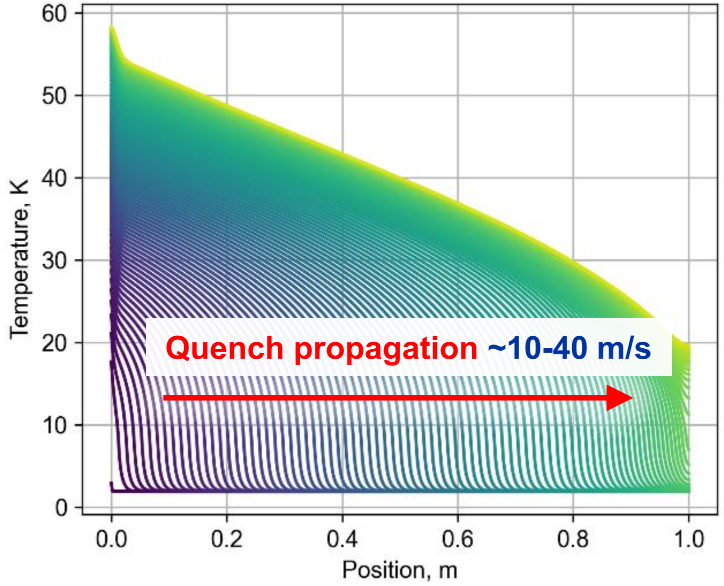
Thu-Mo-Spec1-05

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025.
Presentation given at MT29, Boston, MA, USA, July 2025.

Introduction: Quench Integral

$$\int_0^{\infty} J^2(t)dt = \int_{T_{op}}^{T_{max}} c_V(T)/\rho(T)dT = F(T_{max})$$





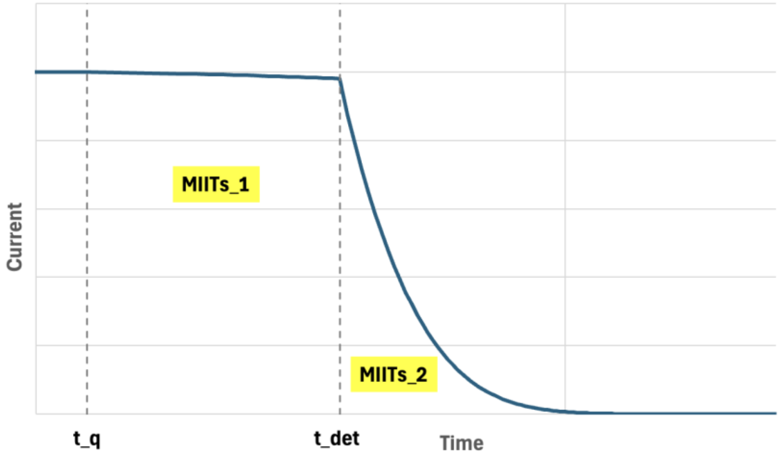
LTS

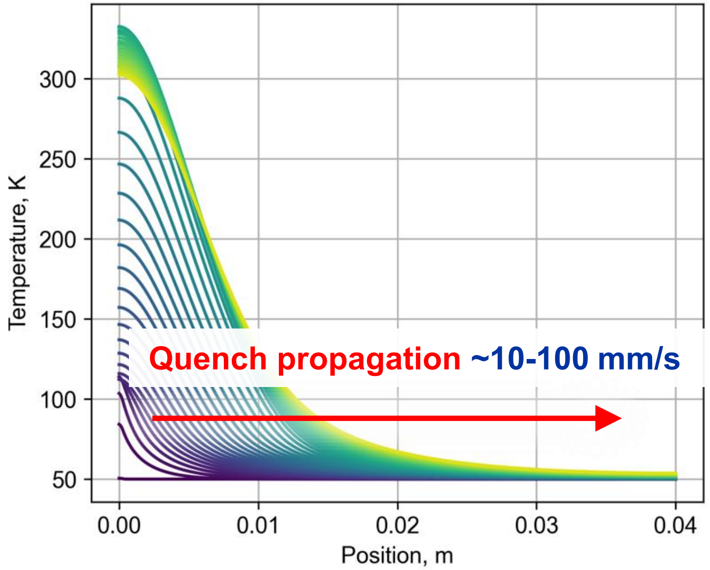
Diffusivity large & enthalpy margin small
↓
Fast quench detection
↓
MITTs_1 small
↓
available MIITs_2 large
↓
'easy' to obtain sufficiently large R in the circuit (EE) or magnet (QH/CLIQ)

ReBCO

Diffusivity small & enthalpy margin large
↓
Slow quench detection
↓
MITTs_1 large
↓
available MIITs_2 small
↓
large R in the circuit is needed, difficult to obtain high R in the magnet (QH/CLIQ)

Courtesy T. Mulder





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Presentation given at MT29, Boston, MA, USA, July 2025.

Important Questions

- Would **energy extraction** (EE) and **quench heaters** (QH) **suffice**?
- Are there **more appropriate 'non-classical' ways** to quench a large volume of the coil?
- Can **no-insulation** coils be a **solution**, at least for (quasi) DC applications?
- And many more (detection, self-protected, ...)

Protection constraints strongly affect the cost/size/feasibility/complexity of a magnet.

How to appropriately model quenches in ReBCO-based applications?

Modeling: LTS vs. ReBCO

LTS

- Fast normal zone propagation velocity → low detection time → **2D + 1D sufficiently accurate**
- Small Nb-Ti filament size → **magnetization can be usually neglected** with reasonably accuracy
- Experimental **quench data vastly available**

General approaches (e.g., FE, VI) can be replaced by **fast custom-made lumped element models**.

Nowadays models are well established and produce accurate results, **if the input data are well-known**.

STEAM-LEDET is the workhorse at CERN for quench analysis of the LHC and HL-LHC magnets.

ReBCO

- Slow normal zone propagation velocity → normal zones local → **3D simulations favorable**
- Wide ReBCO layer → **screening currents cannot be neglected**
- Experimental **quench data sparse**
- Mechanical coupling, thin layers, J_c degradation, contact resistances, …

Due to 3D models, **simulations become expensive**.

Advanced simulation techniques (e.g., reduced order models) **are required** for practical computation times.

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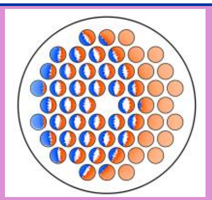
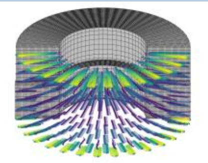
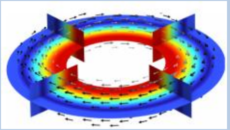
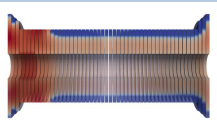
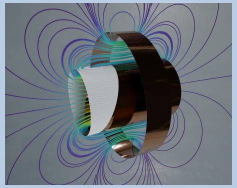
The STEAM Framework

									
Level	**General**	**Bus Bar**	**Conductor**	**Magnet**					
Acronym	**SMaLi**	**PyBBQ**	**FiQuS**		**H-FoSTER**	**NICQS**	**HETS**	**SIGMA**	**LEDET**
Method	Material fcts.	FD	FE Gmsh/GetDP		FE COMSOL®	PEEC (lumped)	PEEC (lumped)	FE COMSOL®	Finite difference
Languages / Interface	C, C++, .dll MATLAB, Python	Python	Python, C++		COMSOL® GUI	Python	Python, Julia	Python, COMSOL®	MATLAB (run time .exe)
Conductor	LTS & HTS	LTS & HTS	LTS	LTS & HTS	HTS	HTS	HTS	LTS/HTS	LTS
Type (Dims)	All models	Bus Bar (1D)	Twisted strands (2D)	Pancake (3D) Block, Cosine Theta (2D)	Pancake (3D FE + 1D FE + 2D FD)	Pancake (2D axisymmetric)	Pancake (3D)	Cosine Theta, Block (2D)	Solenoid, Block, Cosine Theta, Common (2D)
Link	cern.ch/smali	cern.ch/bbq	cern.ch/fiqus		Thesis	cern.ch/nicqs	cern.ch/hets	cern.ch/pysigma	cern.ch/ledet

+ external software (XYCE, Spice, Dakota, Ansys), + input from Roxie (magnet design), + co-simulation and parametric analysis capability

- ReBCO-based coils can be simulated with 4 tools (**FiQuS, H-FoSTER, NICQS, HETS**).
- **Cross-checking among the tools** provides insight in the validity of assumptions, homogenization, simplifications, etc.

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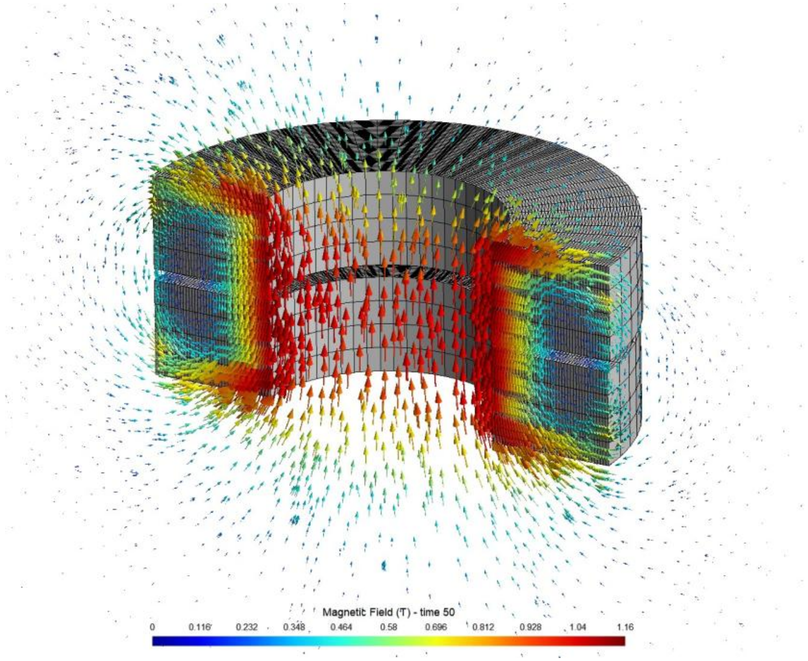
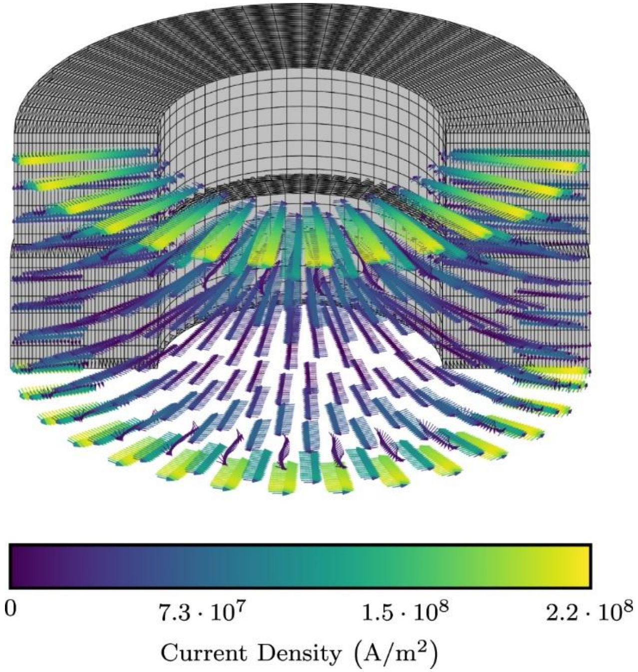
FiQuS: Finite Element Quench Simulator

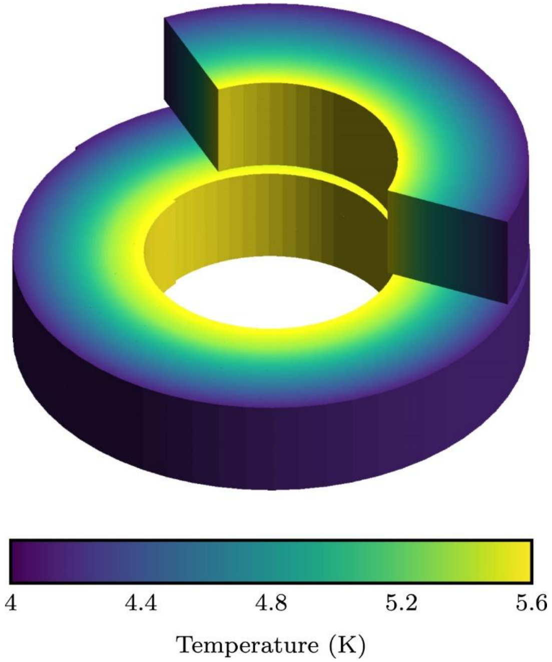
- **3D magneto-thermal FE simulation** of (stacks of) pancake coils using conductor homogenization, thin shell approximation, parallel methods, and non-uniform J_c distributions
- **Free and open-source** software, enabling parallel simulations **without license cost**



Ramp-up of double pancake [1]



Screening currents after power supply shutdown [1]

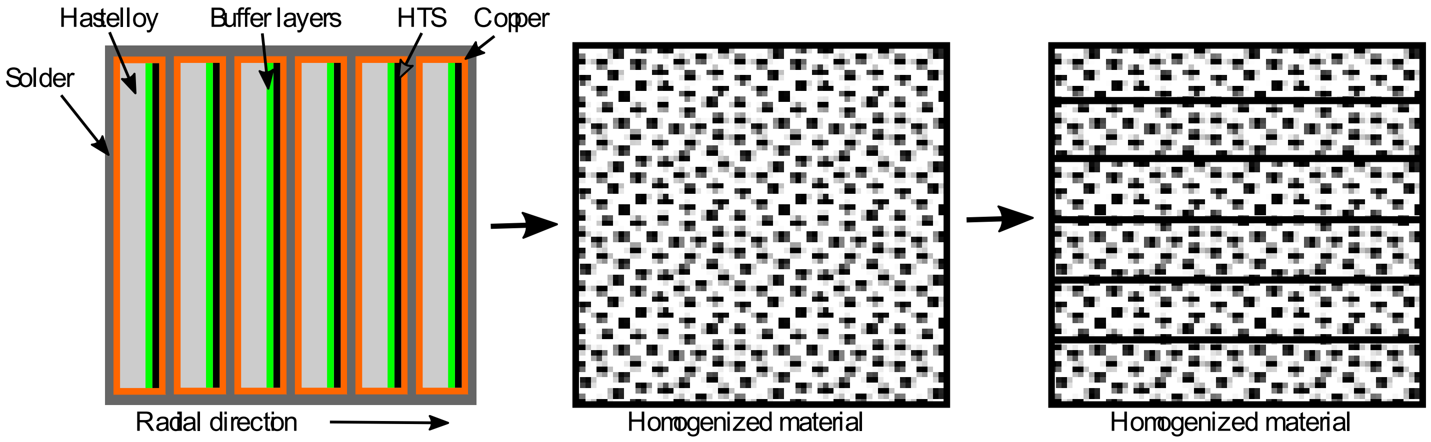


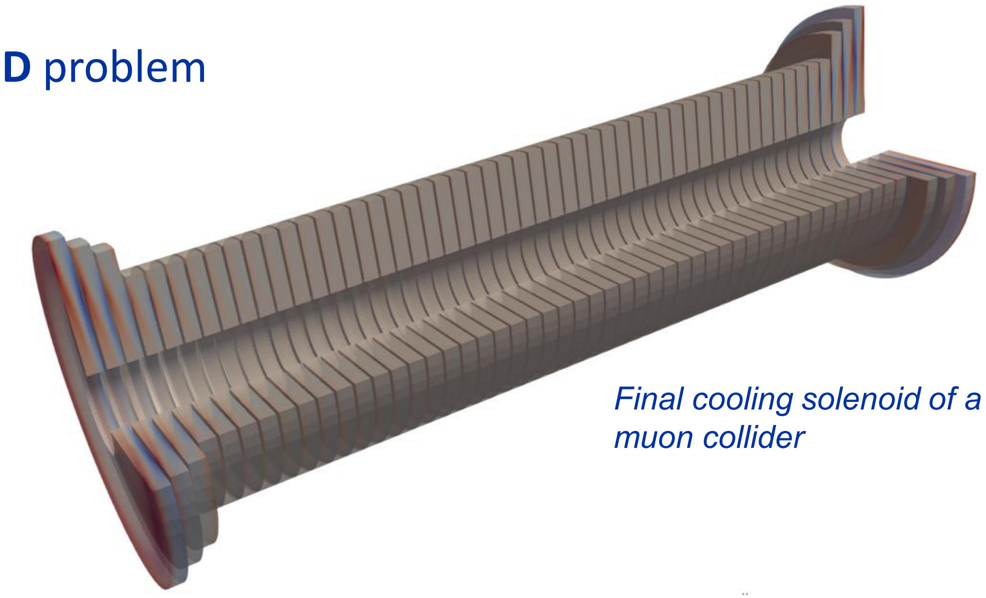
Temperature at peak current with cooling via terminals [2]

[1]: S. Atalay et al., SUST 2024, DOI: 10.1088/1361-6668/ad3f83, [2]: E. Schnaubelt et al., IEEE TAS 2023, DOI: 10.1109/tasc.2023.3340648

NICQS: No-Insulation Coil Quench Simulator

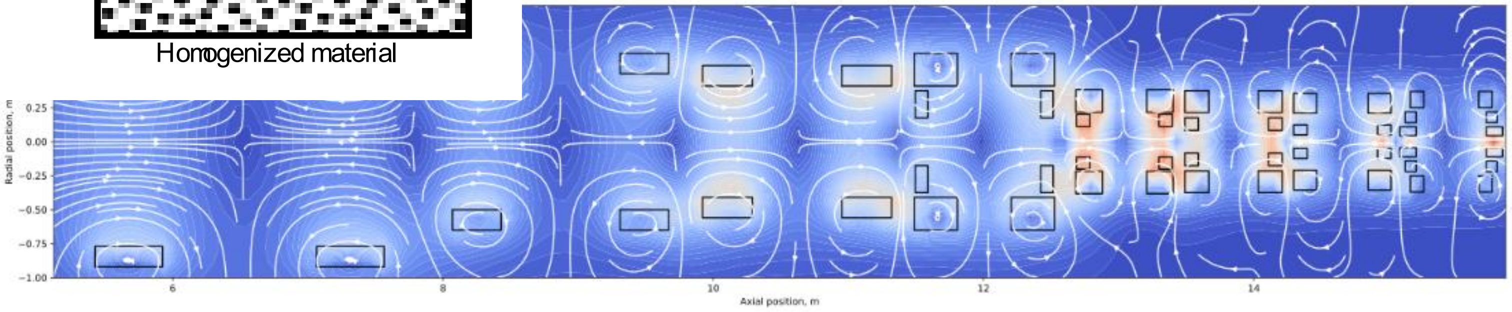
- Nodal network model using an ODE solver to solve a **2D axisymmetric FD** problem
- Smart homogenization of the tapes
- Can solve magnets with > 10000 turns
- Screening currents and eddy currents included
- Ramp optimization (important due to turn-to-turn resistance)
- Various quench protection concepts included
- Calculation of Lorentz forces to evaluate conductor stress





Final cooling solenoid of a muon collider

6D cooling chain of a muon collider:



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Presentation given at MT29, Boston, MA, USA, July 2025.

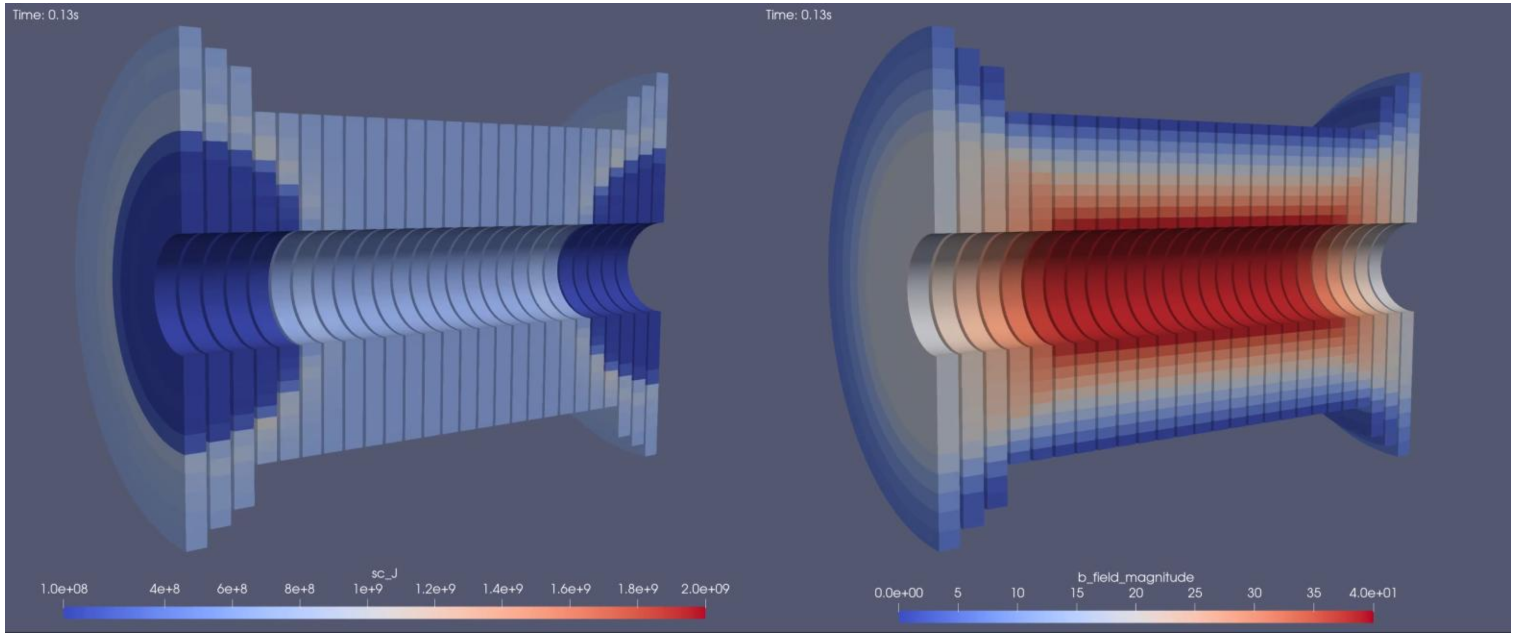
Courtesy L. Teichröb
W. Walinga

HETS: Homogenized Electrothermal Transients of Superconductors

- **Builds upon the ideas of NICQS**, extending it to 3D
- Model of **full-size 3D coils**, with **smart homogenization** technique
- **Circuit model** for electrical part and **FD** for thermal part
- Some features: screening currents, curved elements, user-defined quench protection, arbitrary circuits

Quench of a 40T final cooling solenoid of a muon collider

Current density | Magnetic field



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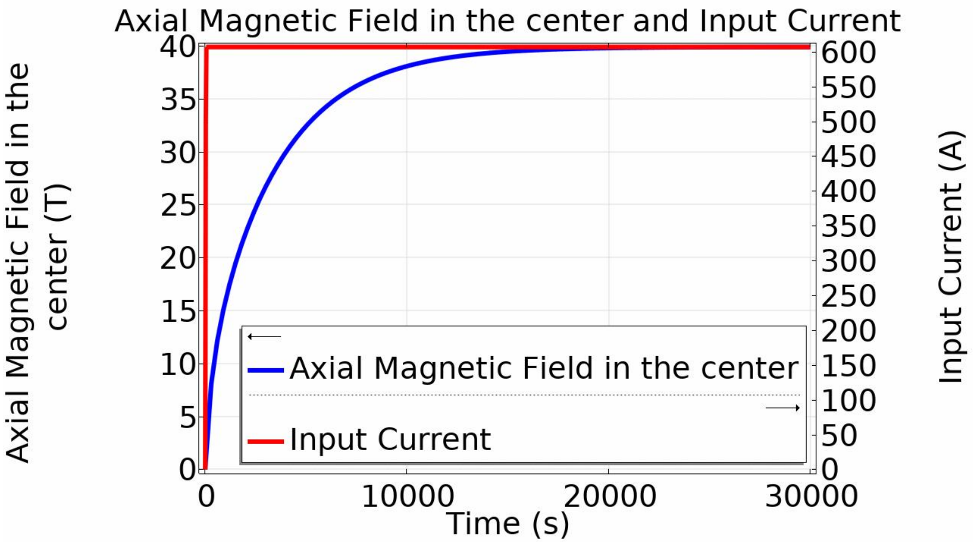
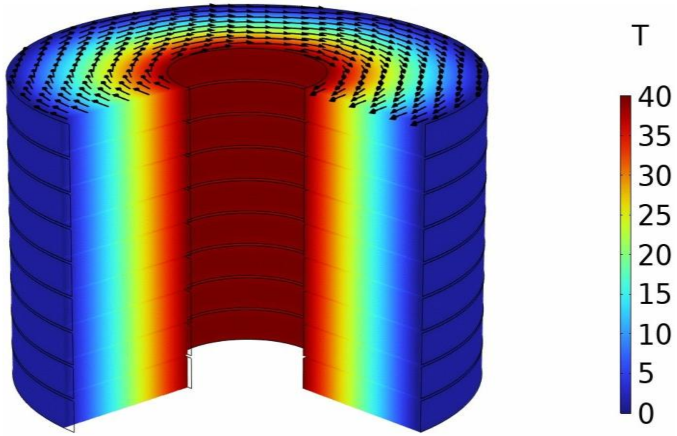
H-FoSTER: Hybrid Formulation for the Simulation of Thermo-Electrodynamics in ReBCO magnets

New **hybrid formulation** that couples a **3D FE magnetic module** with a **1D FE + 2D FD electric module**, implemented in **COMSOL Multiphysics**

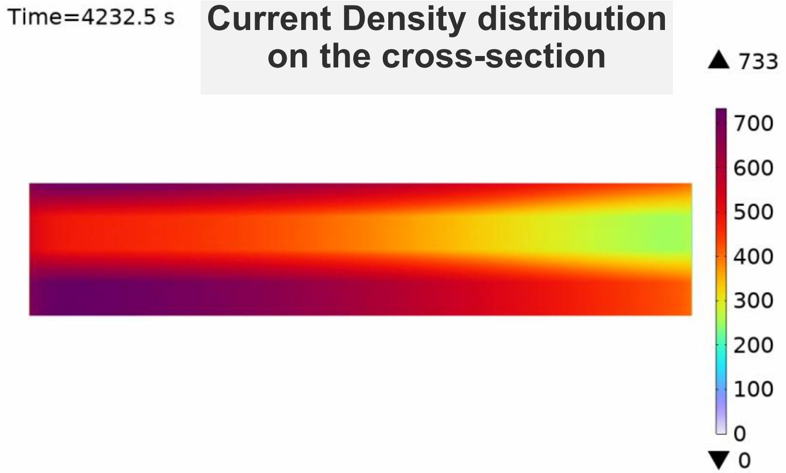
Example of application: 3D electro-magnetic simulation of ramp up/down of the **Muon Collider 40 T Solenoid**

- Infinite number of identical 3D pancakes ➔ to simulate the modular part of the magnet
- Coil winding thickness 6 cm
- 750 layers of ReBCO tape (12 mm x 80 µm)
- Turn-to-turn contact resistance 10 µΩ cm^2
- 2 mm of air between coils





Courtesy D. Rinaldoni and B. Bordini



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Protection Concepts for ReBCO Magnets

Protection strongly affects the cost/size/feasibility/complexity of a magnet.

- **Protection feasibility and methods vary a lot between different magnets**
- **Next slides will discuss three examples:**
  1. Capacitor discharge for protection of stacks of NI HTS pancake coils
  2. Energy shift with coupling
  3. Stability of ReBCO coils with local J_c degradation
- **Many others skipped**
  - Quench heaters, energy extraction, coupled loss induced quench (CLIQ), external coil CLIQ (e-CLIQ), ...
  - **Multi-tape cables to improve stability**, robustness against local defects and quench voltages
  - **No-protection concept** (run without protection exploiting high enthalpy margin)

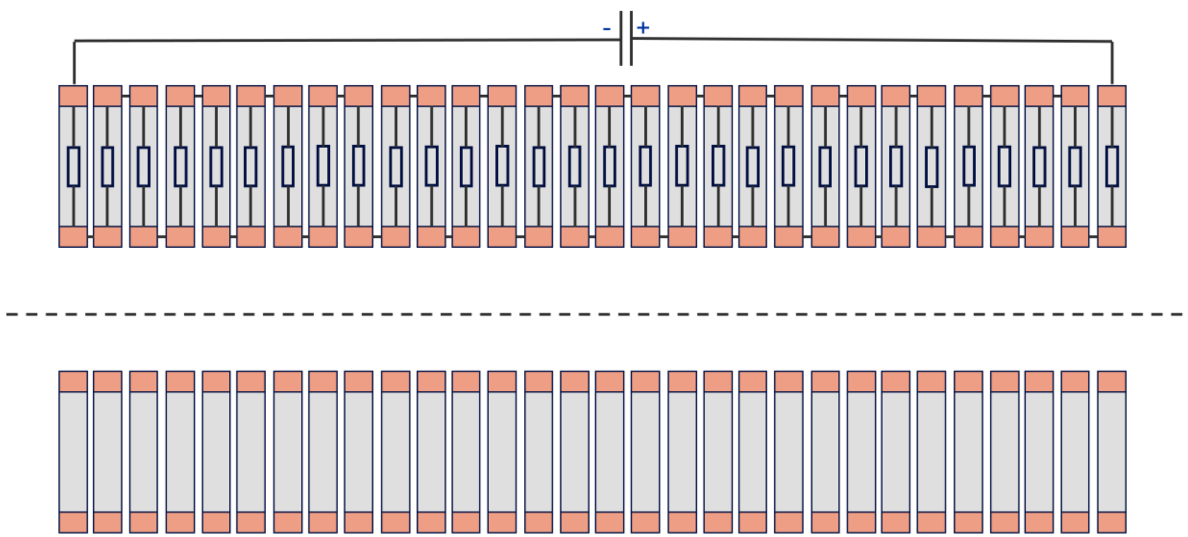
More: presentation "Aspects of quench detection and protection for HTS" by T. Mulder

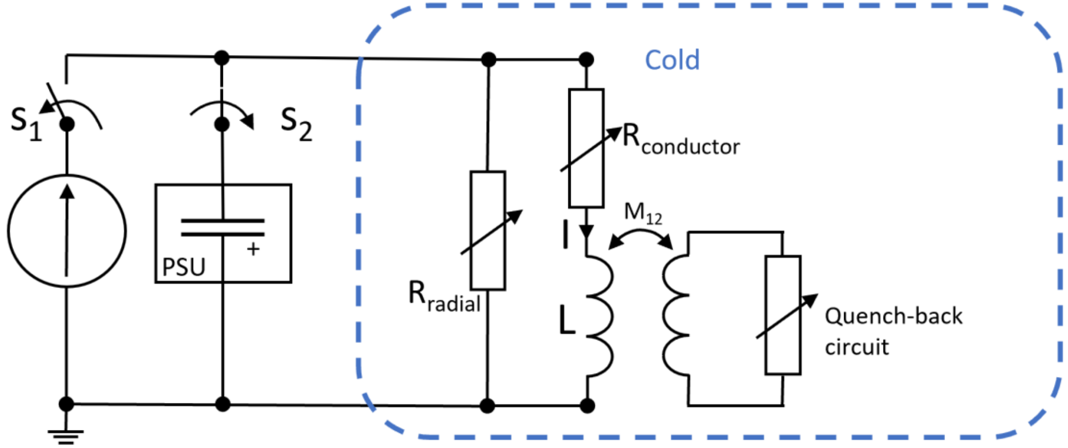
CD: Capacitor Discharge

- **Injects a large current pulse** upon quench detection by discharging capacitor into an NI coil-based magnet
- Generates **heat in the turn-to-turn resistance** (alternative to quench heaters)
- Can **transition the full magnet to the normal state** within ms

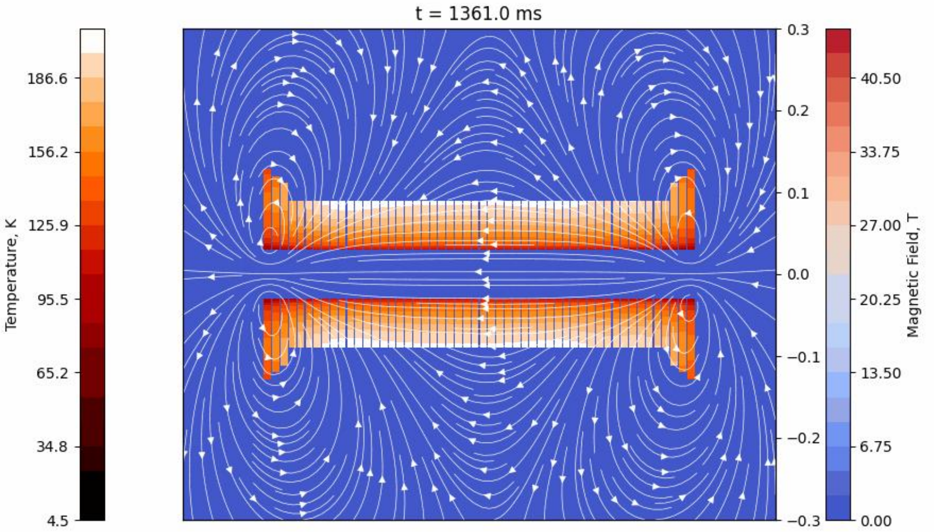
Requirements:

- **Turn-to-turn resistance** of the pancake coils **must be tuned** to correct range
- **Current connections must withstand a current of a few kA** for several milliseconds





T. Mulder et al., IEEE TAS 2024, DOI: 10.1109/TASC.2024.3362755

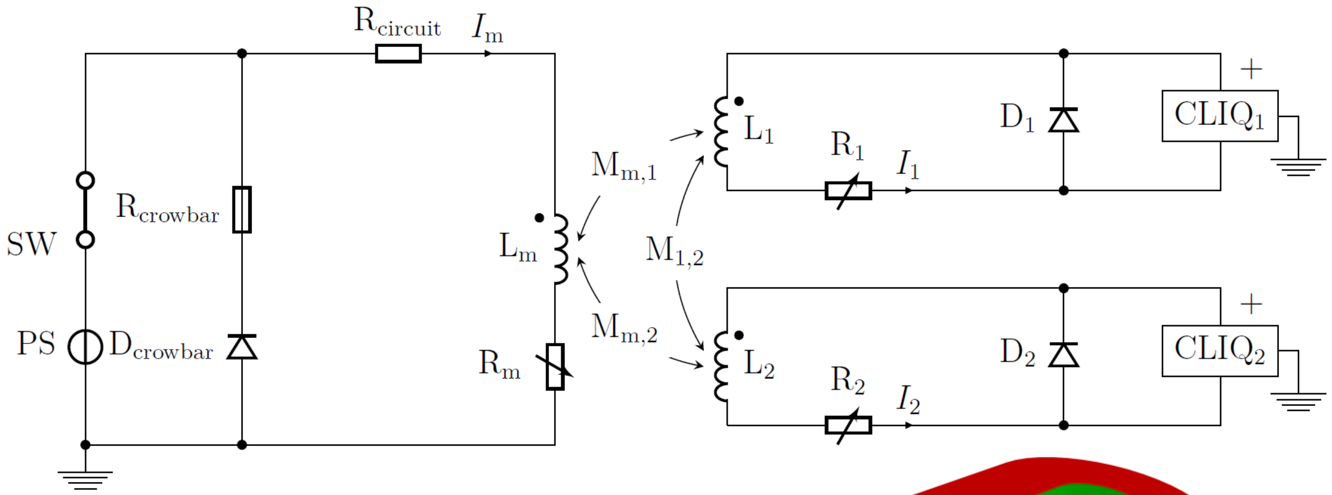


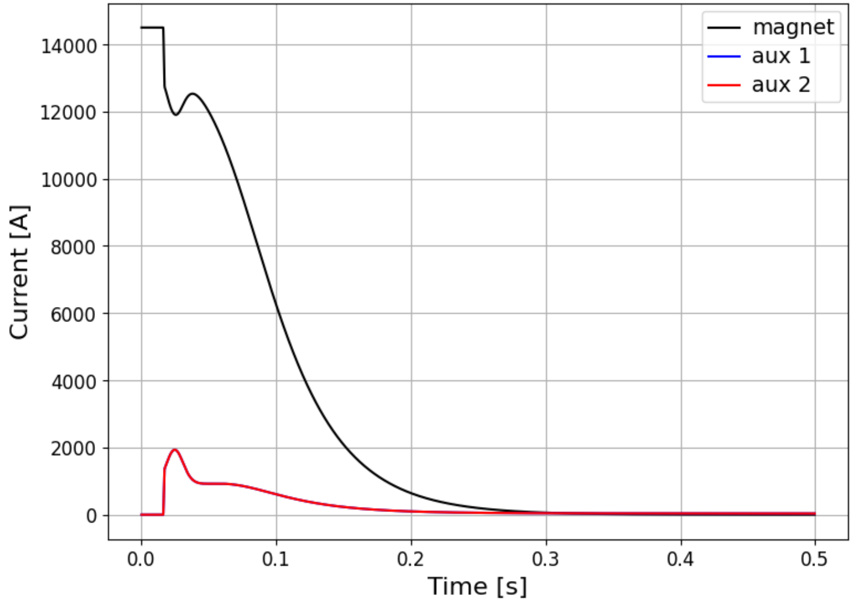
Rather homogeneous simulated temperature distribution after using the CD technique on a final cooling solenoid of a muon collider.

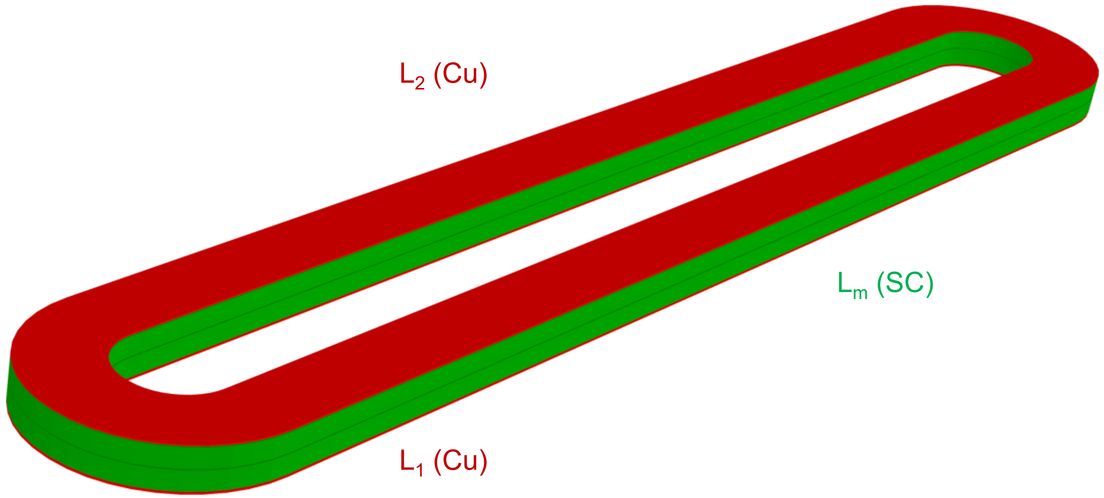
ESC: Energy Shift with Coupling

E. Ravaioli et al., SUST 2025, DOI: 10.1088/1361-6668/ada833

- **Quench through magnetization and coupling loss**, generated by dB/dt pulse in auxiliary coils
- Electrically **insulated** from the magnet
- **Extracts** part of the **magnet energy**
- Good protection **redundancy**







See Fri-Mo-Or6-01 on Friday for first test on common-coil magnet!

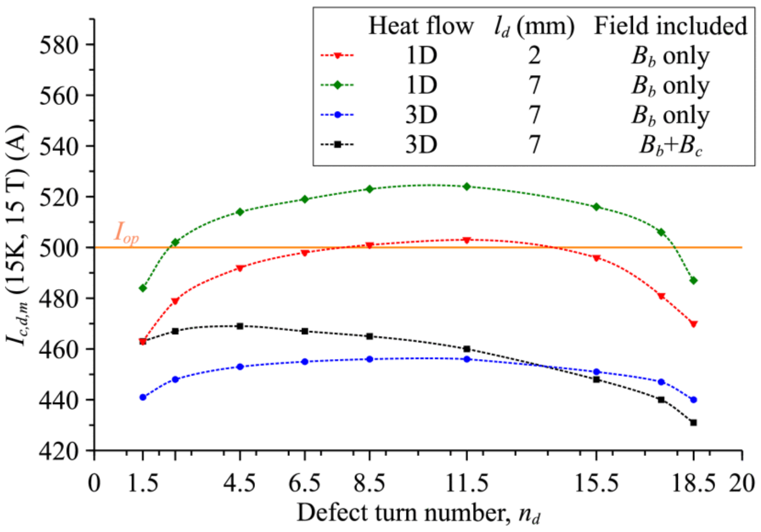
More details in this dedicated presentation by E. Ravaioli

Stability of ReBCO Coil with Local Defects

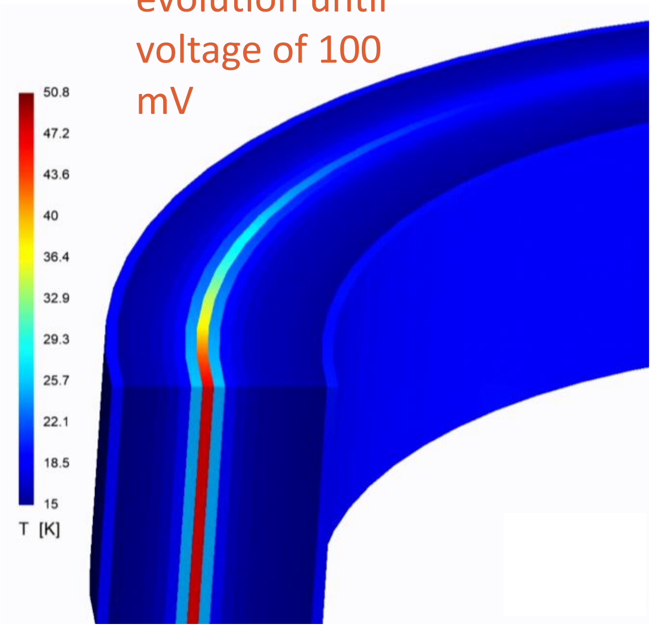
Can ReBCO coils with **local I_c defect** still be operated in a stable way?

Insulated coil

What minimum critical current density $I_{c,d,m}$ can be tolerated?



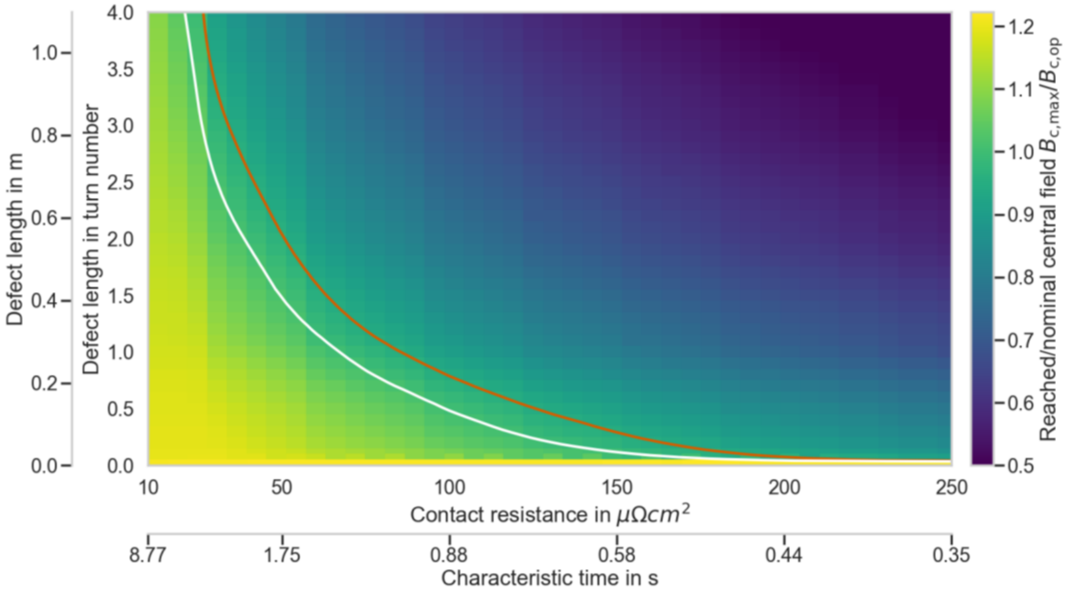
3D temperature evolution until voltage of 100 mV



M. Wozniak, et al., IEEE TAS 2025, DOI: 10.1109/TASC.2025.3532246

No-Insulation coil

Given a contact resistance, what defect length still allows to reach nominal field?



Analysis for NI coils: Thu-Mo-Po.04-07 this morning

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Conclusion

- **ReBCO-based coils are difficult to protect** due to small thermal diffusivity and large enthalpy margin.
- In addition to 'classical' quench heaters and EE, we have developed **several new promising protection concepts** (CLIQ, eCLIQ, ESC, CD) in recent years, which we plan to test on HTS coils in the coming year(s).
- For (quasi) **DC applications**, the use of (possibly self-protecting) **NI coils should be considered**.
- **Development of stable multi-tape cables** is key to fulfill voltage and stability controls (unless following no-protection concept). The option to run without protection should be considered.
- **Validated 3D thermal-electromagnetic and structural simulation models** are essential for coil design and ramp/quench/protection studies.
- A proper quench protection analysis of an HTS coil is a **multi-disciplinary team effort**.
- **We are always interested to join forces** with other groups to validate our software tools against their measured HTS coils and to provide insights into the transient effects.

Many thanks! Questions? **erik.schnaubelt@cern.ch**

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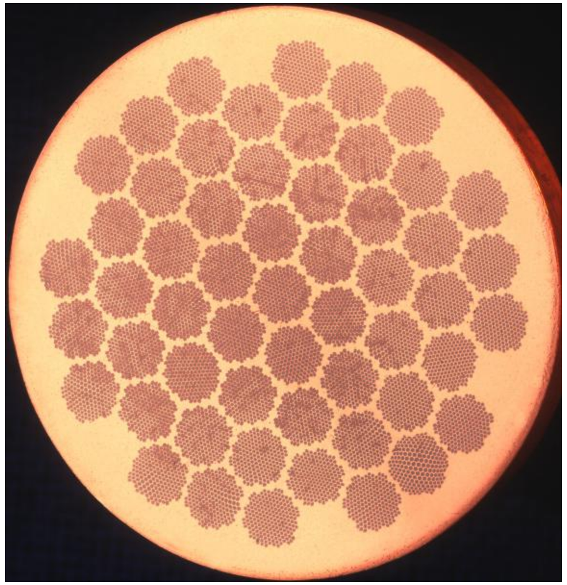
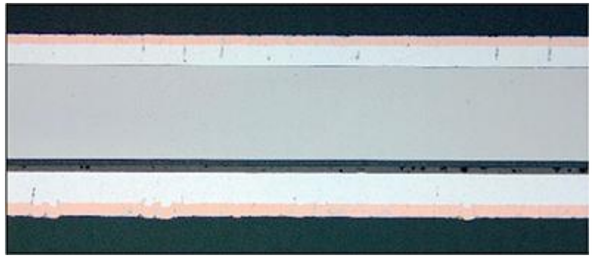
Introduction: LTS vs. ReBCO Enthalpy/Diffusivity

	Cu at 4 K, 8 T	Cu at 30 K, 20 T	Hastelloy at 30 K
ρ [Ohm m] *	$5.7 \cdot 10^{-10}$	$12.5 \cdot 10^{-10}$	$1.23 \cdot 10^{-6}$
k [W/K/m] *	170	600	5.5
C_V [J/K/m^3]	800	270’000	163’000
D=k/C_V [m^2/s]	**0.21**	**0.0022**	**0.000034**
Enthalpy per unit vol.	**~1 mJ/cm^3 (from 1.9 to 4 K)**	**~1.5 J/cm^3 (from 20 to 30 K)**	**~1 J/cm^3 (from 20 to 30 K)**

*Assuming:
- RRR_{Cu} = 100
- Magnetoresistivity = $0.5 \cdot 10^{-10} B$
- Wiedemann-Franz law

$$k_{cu} = \frac{LT}{\rho_{cu}}$$





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Can we detect a quench faster?

In the LHC main dipoles we typically use a quench detection threshold of 100 mV with an evaluation time of 10 ms, comparing the voltage of the two halves of the magnet (hence removing inductive component).

We can do maybe a factor 2 better but this rally requires that the two halves of the magnet have a very similar frequency transfer function.

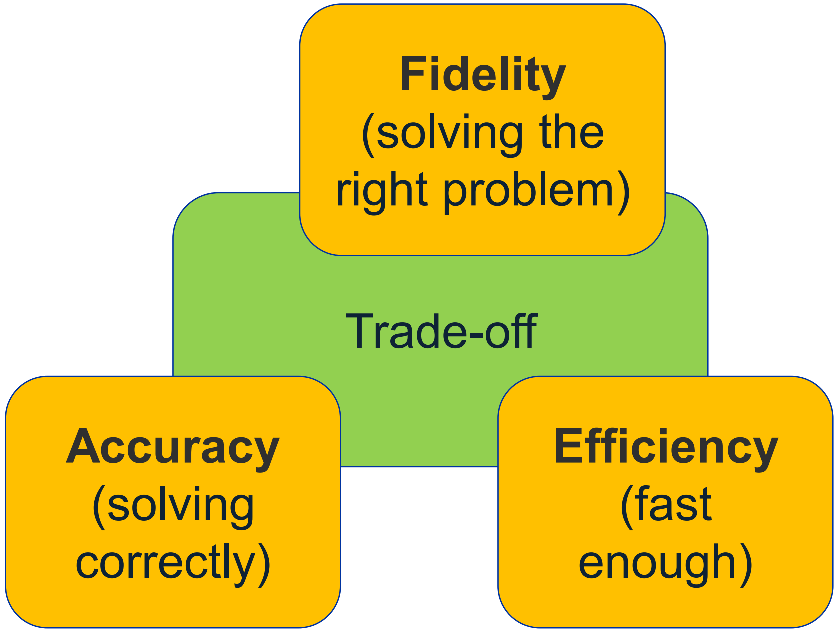
For ReBCO coils we could set multiple thresholds in parallel, e.g. 100 mV/10 ms & 10 mV/1 s & 1 mV/10 s, to be also sensitive to slow voltage onsets (precursors of the real start of a quench).

Additional detection methods could be added, e.g. based on temp. sensors, optical fibers, field probes, especially for NI coils, for which detection based on ΔV is not obvious (due the strongly varying differential inductance).

Modeling

A model should be 3D and preferably include the following features:

- Transport current distribution (along the tape, turn-to-turn)
- Magnetisation / Screening currents
- Coupling currents / ac Losses
- Thermal diffusion / Cooling
- Forces, bonding etc
- Anisotropy and thin layers
- Material properties & manufacturing tolerances & local defects
- Parametric analysis
- Hybrid coils
- ....



FE can do all this but will quickly result in extremely high computational cost, since quenches are strongly non-linear, multi-scale, multi-physics events.

Protection concepts for 20 T ReBCO dipole magnets for FCC-hh

- Accurate relation between current and field, also during ramping, requires **insulated** turns.
- Voltage and stability constraints require the use of **multi-tape cables**.
- Current distribution, field uniformity, AC loss and stability aspects favourize **transposed** cables.
- Cost aspects require **high J_{eng}**.
- Windability apects favourize **bendable/flexible** cables.

These requirements tend towards high-current (striated) Roebel-type cable, and a 'Common-coil', 'Block-coil' or CCT design.

A CORC-type cable could be envisaged for easier winding, but lower J_{eng}.

Protection:
- Stand-alone magnets: EE possibly combined with magnetically coupled dump coils is a good option.
- Series connected magnets: ESC protection (see next slide) is a promising option, along with bypass diodes.

‘No-Protection’ concept for 20 T ReBCO dipole magnets for FCC-hh

- Can we detect a quench faster?
- Can we stick to good old Energy Extraction (EE) and Quench Heaters?
- Are there non-classical ways to quench a large volume of the coil?
- Can No-Insulation coils be a solution, at least for (quasi) DC applications?
- Do we need to protect a ReBCO coil at all?

Avoid quenches:

- **Training quenches**: No significant training expected due to large enthalpy margin and thermal-electro stabilised multi-tape cable. Recipe: Test well below I_C (e.g. at $0.7I_C$), then install, and operate even lower (e.g. $0.6I_C$).
- **Beam-induced quenches**: Experience from the LHC shows that we can dump the beam well before the beam losses reach 10 mJ/cm^3 level. With the 100x larger enthalpy margin of ReBCO we should be fine.
- **Quenches due to lack of cooling**: Use temperature sensors, sufficient heat reserve. Experience from the LHC (LHe, 1.9 K) shows no quenches since 2010.
- **Quenches due to spurious quench triggers or spurious QH firings**: Obviously impossible for ‘NoProtection’ concept.

For redundancy, monitor voltage and ramp down if larger than threshold.

Mitigate consequences in the very unlikely event of a quench:

- Avoid quench propagation to neighbouring magnets → quench stoppers, cryogenic separation.
- Enable fast exchange of a magnet → spare magnet available, fast thermal cycle
- Avoid collateral damage → no arcing, no damage to beam tube, …

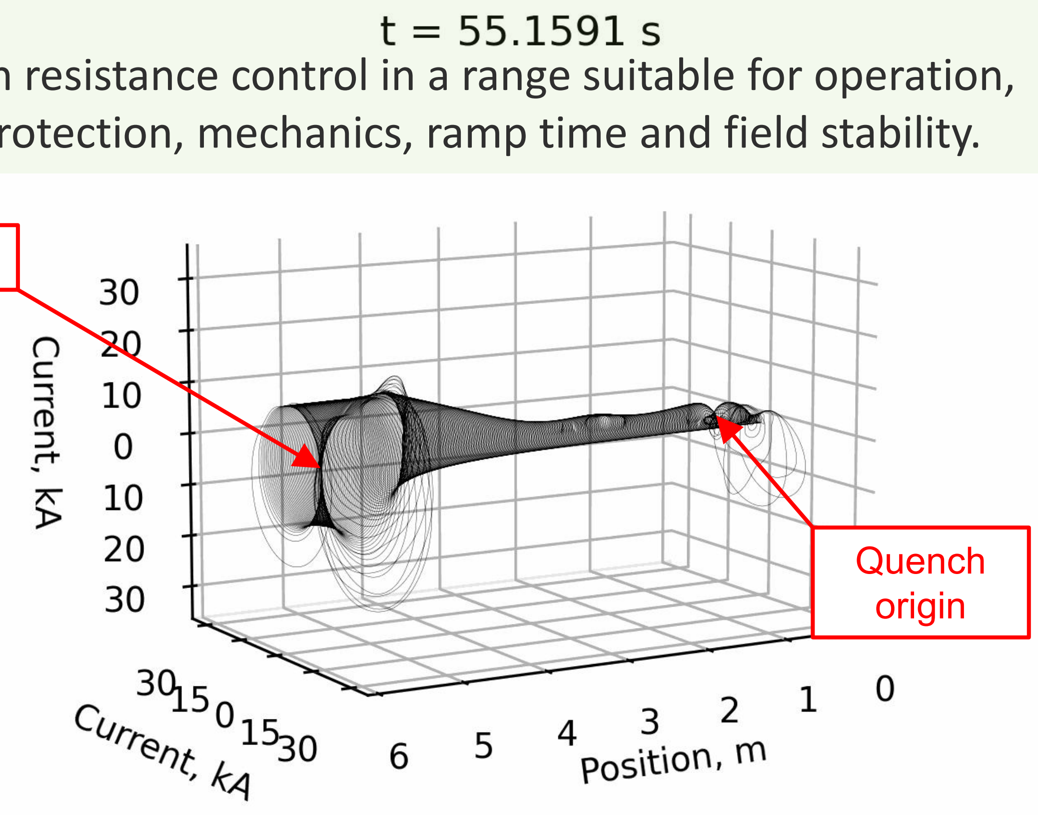
Definitely promising

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at MT29, Boston, MA, USA, July 2025.

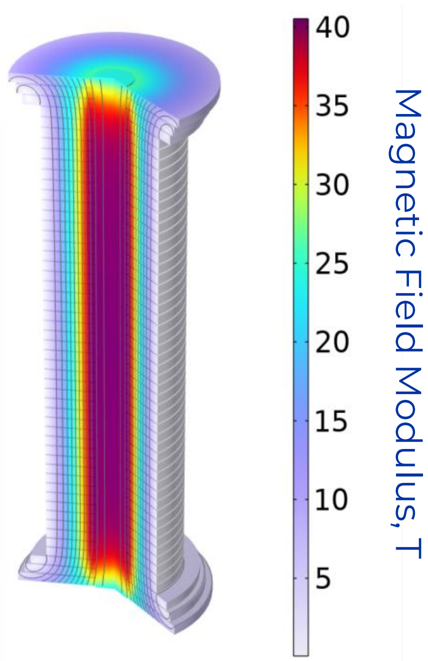
Protection concepts for 40 T muon collider solenoid

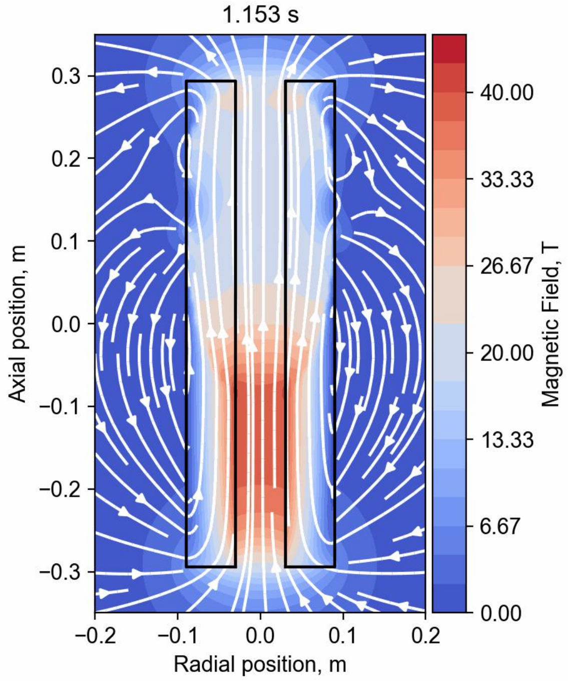
Stack of 46+6 NI pancake coils, 0.5 m long, 50 mm bore, designed to operate at 4.5 K.

Turn-to-turn resistance control in a range suitable for operation, balancing protection, mechanics, ramp time and field stability.



Example of inductive quench propagation for a thin-walled solenoid: E_{stored}=14.3 MJ, length=6 m, diameter=4 m.





Self protection relying on inductive quench propagation could be effective, especially at higher current levels.

- Mutual coupling between the pancakes results in fast quench propagation along the stack
- Possible issues: increased local forces and hot spot, especially in the last pancake to quench. The ***'Capacitor Discharge'*** is a promising concept to avoid this.

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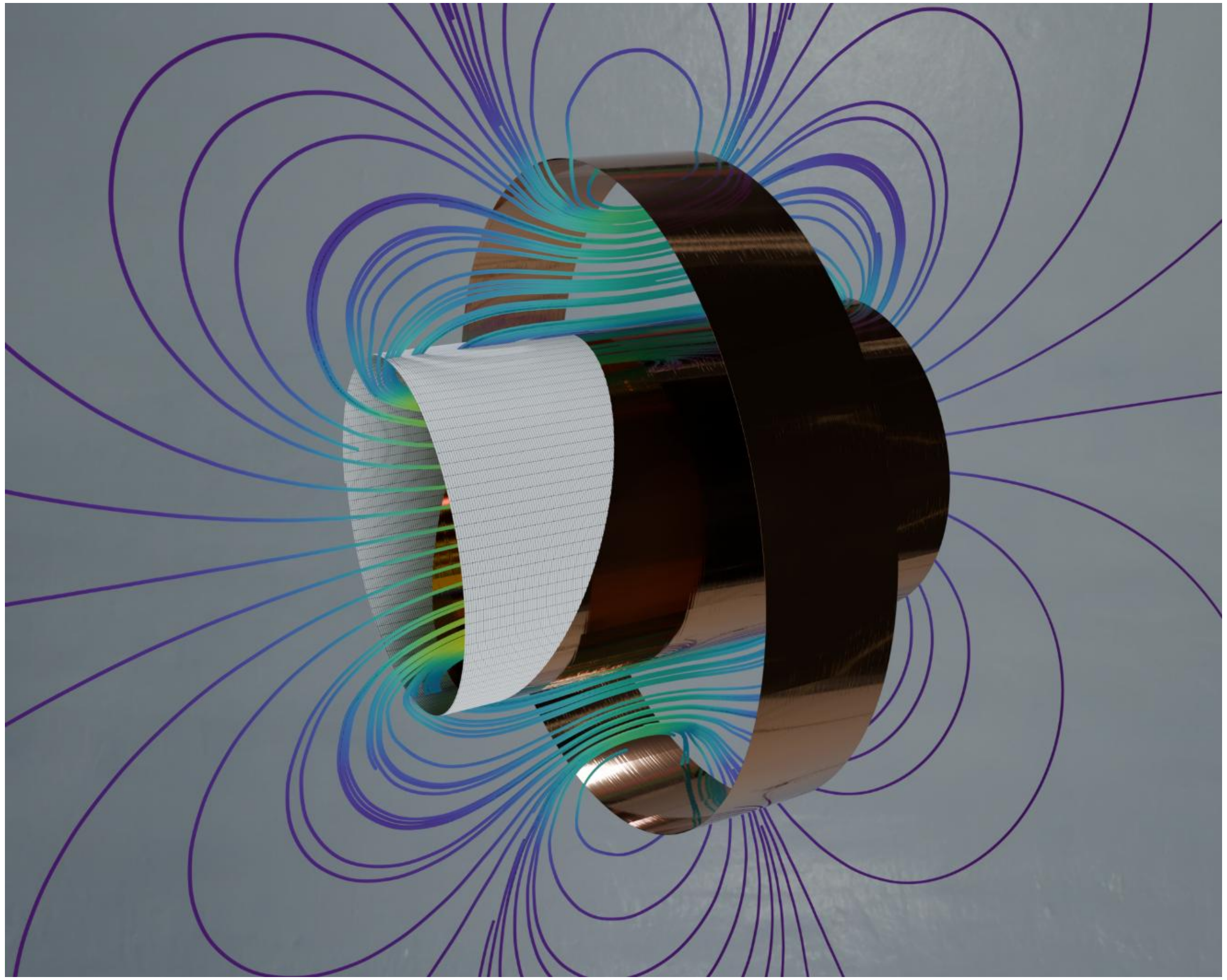
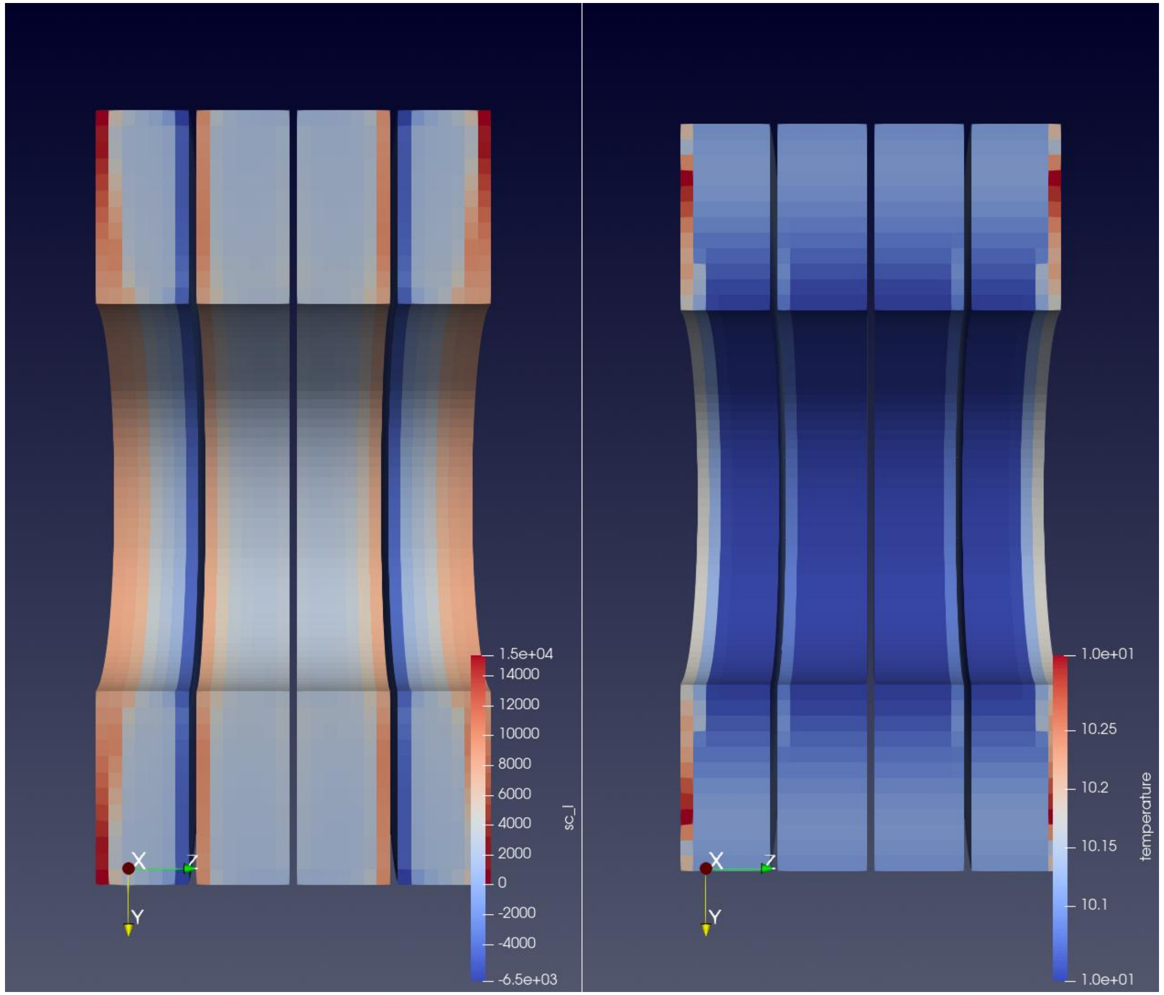
HETS

Courtesy L. Teichröb

AMS-100 Solenoid (l=6 m, d=4 m, about 100 km of tape)



Screening currents in an HTS pancake stack

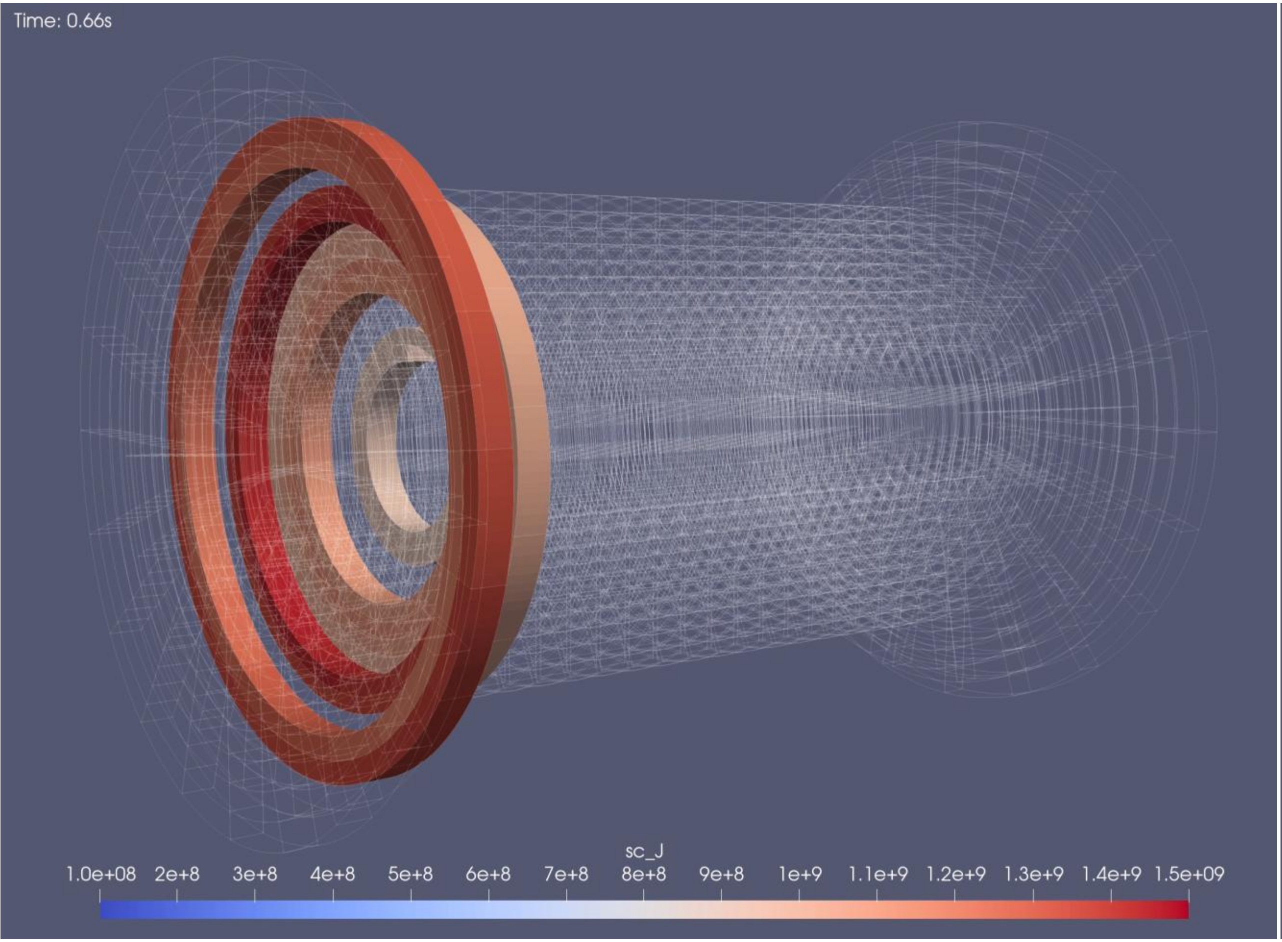


HETS

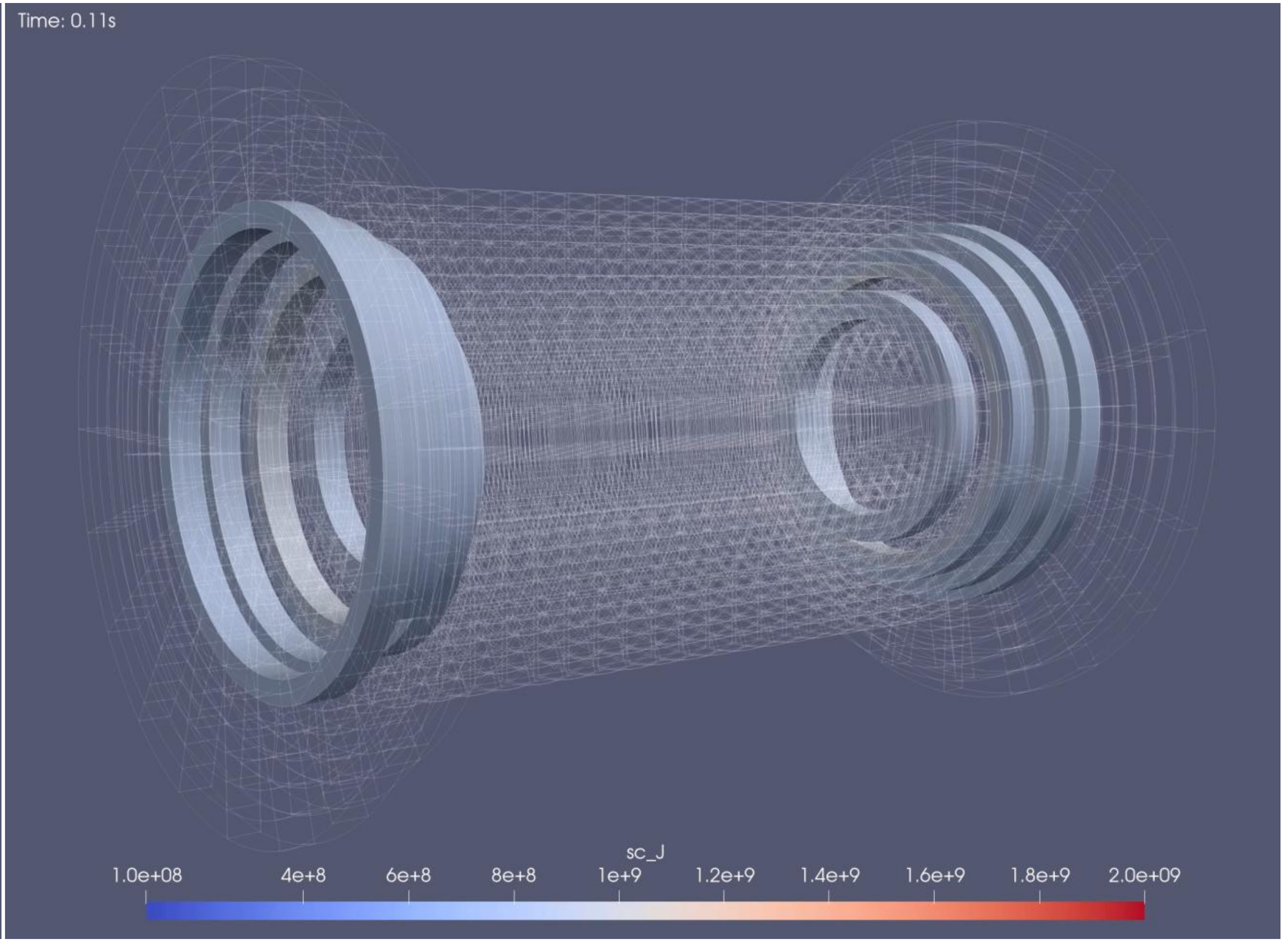
Courtesy W. Walinga

Quench of a 40T final cooling solenoid of a muon collider

No QP – Peak current density propagation



QP – Peak current density propagation

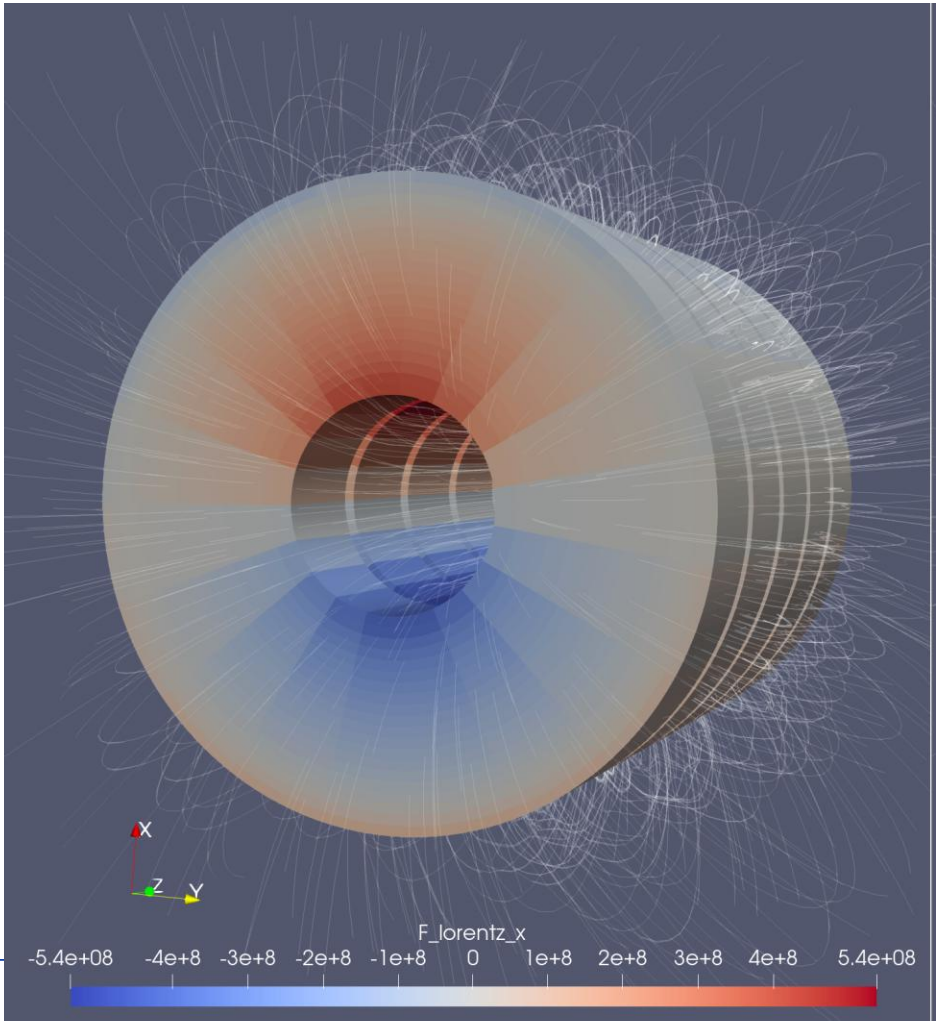


HETS

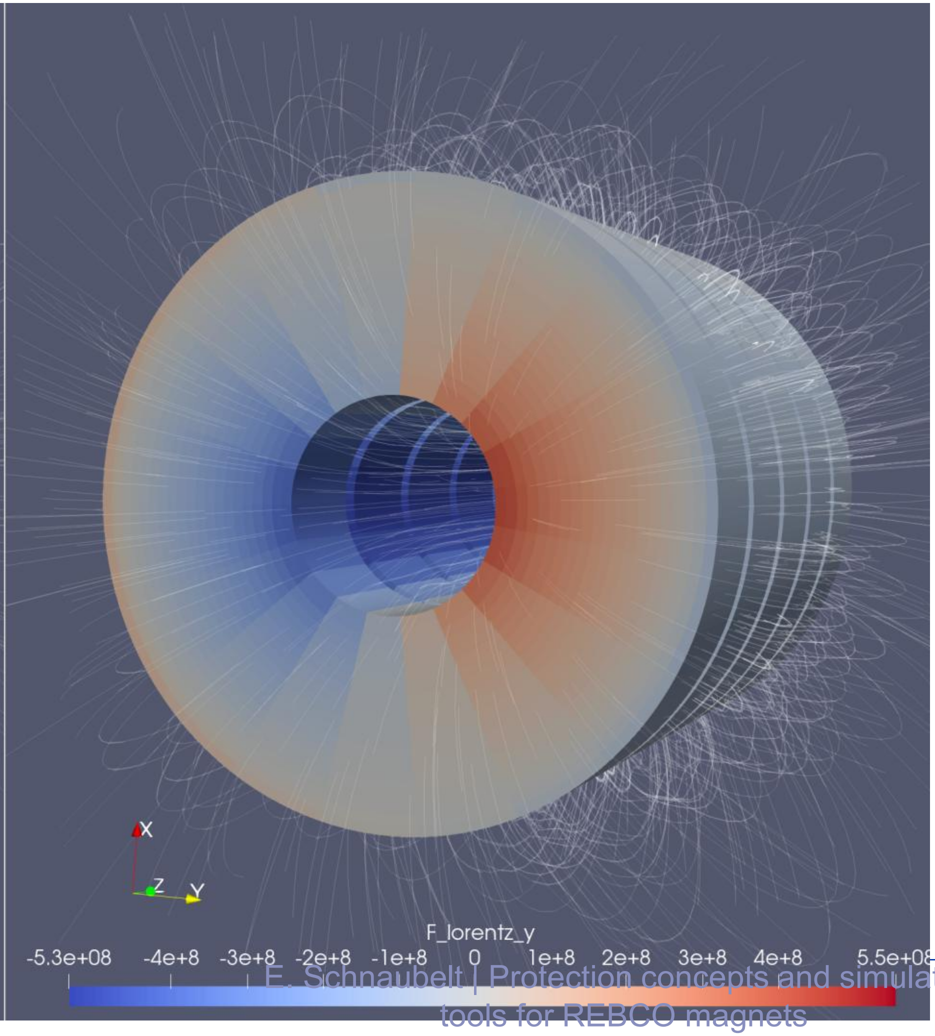
Courtesy W. Walinga

Lorentz forces working on a pancake stack coil

Lorentz forces in the x-direction

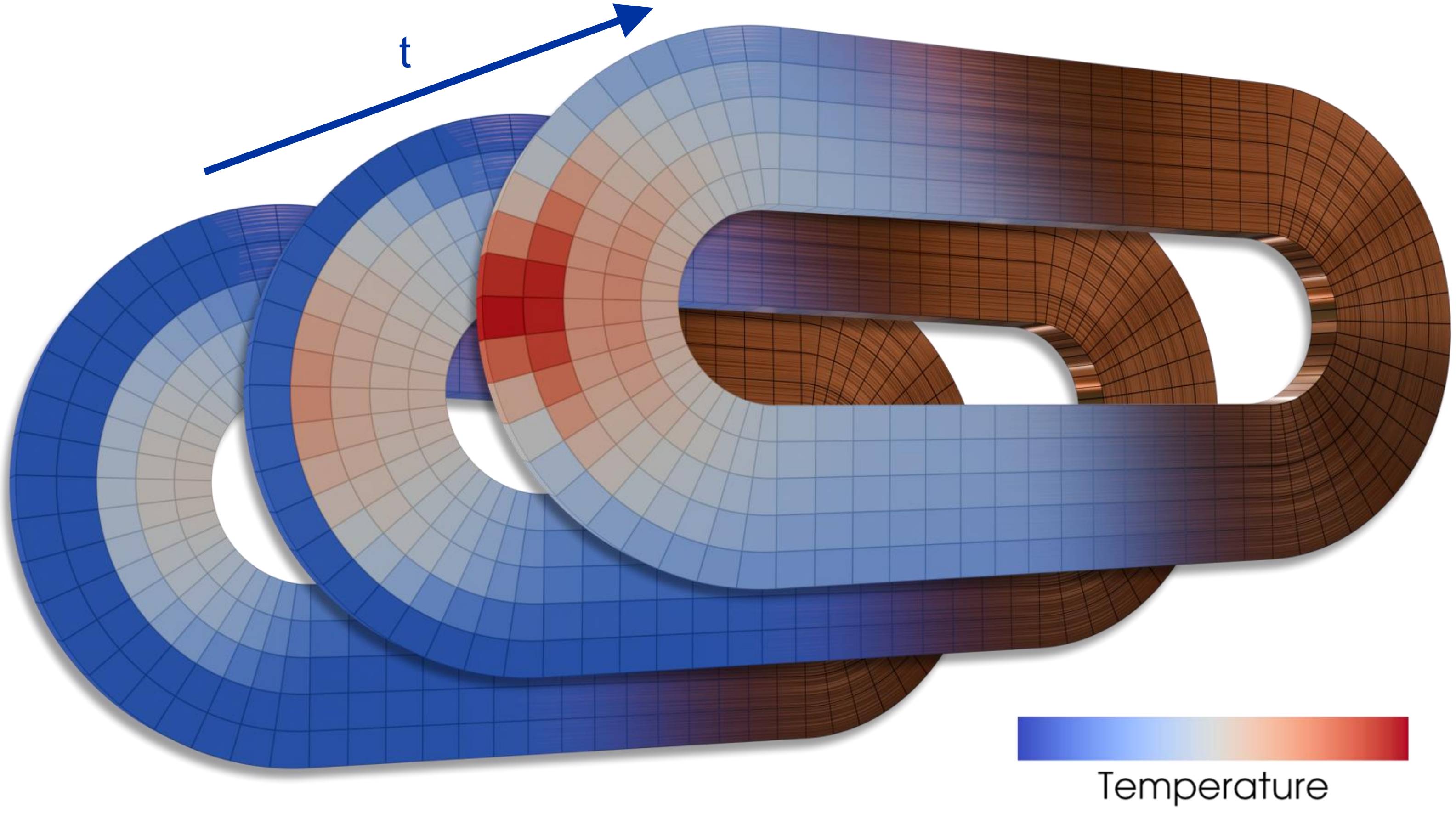


Lorentz forces in the y-direction



HETS: Homogenised Electrothermal Transients of Superconductors

- Builds further upon the ideas of NICQS, extending it to 3D.
- Model of full-size 3D coils, with smart homogenization technique.
- Circuit model for electrical part and finite differences for thermal part.
- Some features: Screening currents, curved elements, user-defined quench protection, arbitrary circuits.



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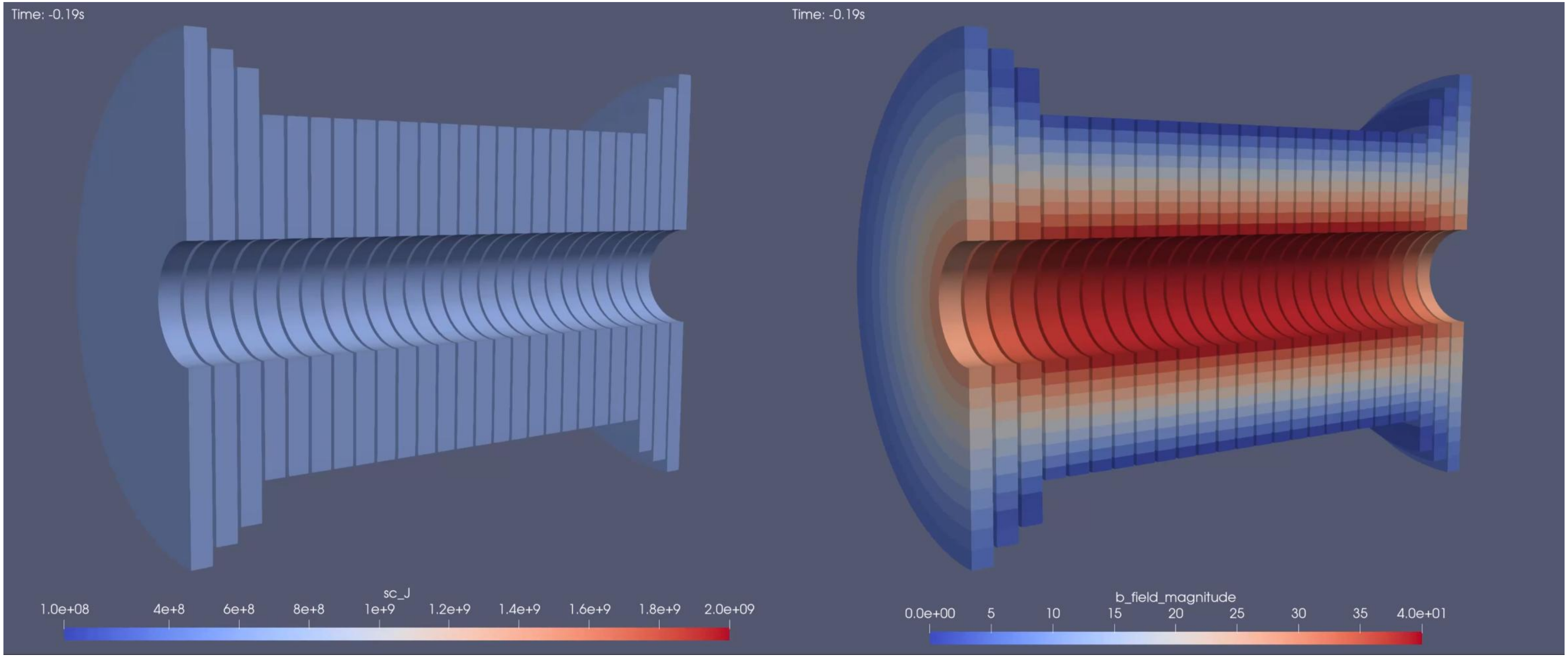
Courtesy W. Walinga

HETS
Quench of a 40T final cooling solenoid of a muon collider

Current density | Magnetic field



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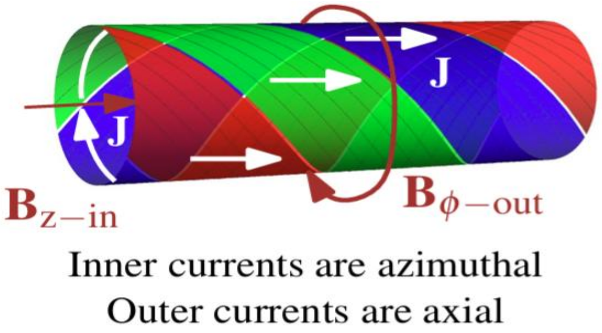
Reduced Order Modelling of CORC® Cables

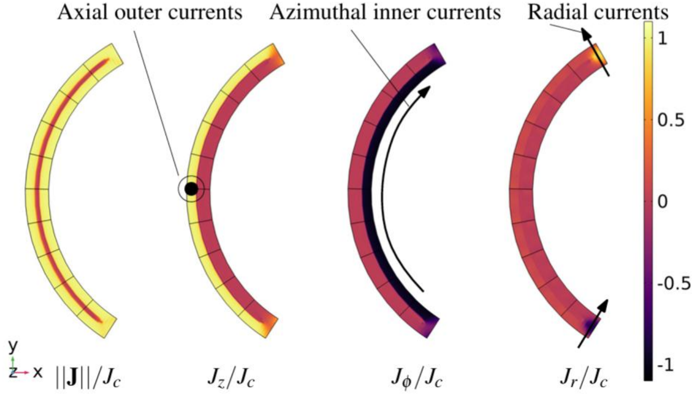
Courtesy
B. Vanderheyden,
J. Dular, M.
Wozniak, F. Grilli

- Analysis of single-layer Conductor on Round Core cables with **helicoidal transformation.**
- Reduced dimension from **3D to 2D**.
- **Non-trivial current flow** over REBCO tape thickness due to the twist → effect on AC loss.

Single-layer geometry

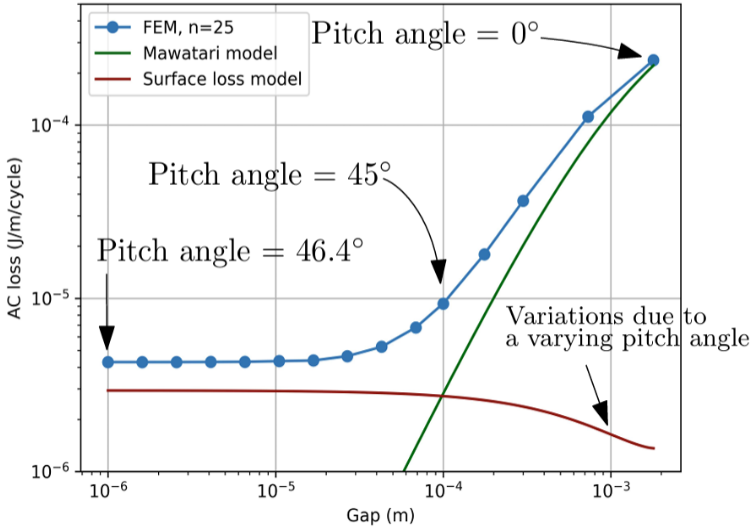


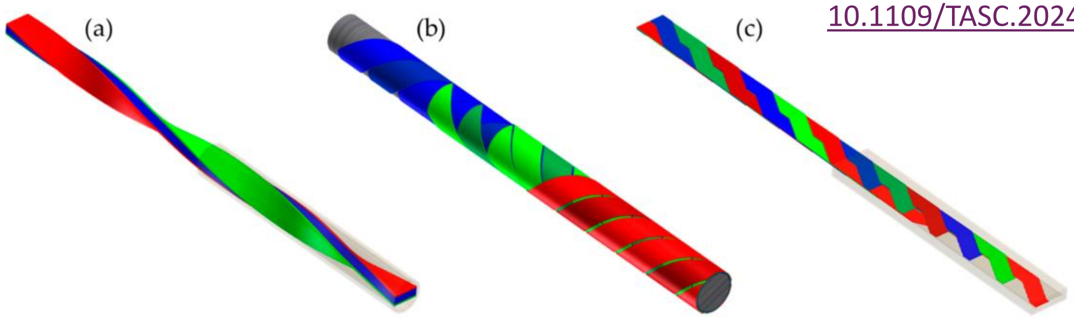
Current density (expanded thickness)



Picture: S. Elschner, et al., IEEE TAS 2024, DOI: 10.1109/TASC.2024.3356435

Influence of the gap on AC loss





Picture: L. Rossi, et al., Instruments 2021, DOI: 10.3390/instruments5010008

Next step: Development of reduced order and homogenized models for twisted stacks (a), CORC® (b), and Roebel cables (c).

J. Dular, et al., IEEE TAS, DOI: 10.1109/TASC.2024.3416524

The STEAM Framework

cern.ch/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.

TRANSIENTS

- ✓ Energy extraction and quench-back

CIRCUIT TYPES

- ✓ Stand-alone magnets

No single tool can do it all. Therefore, we have many tools connected by the framework.

- ✓ Bi-2212
- ✓ YBCO

MAGNET TYPES

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

LEVEL OF DETAIL

- ✓ Circuit → Magnet → Cable → Wire → Filament

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