Quench protection methods and simulations for HTS magnets

Focus on high-field accelerator-type multpole/solenoid magnets for future FCC-hh or muon collider

Arjan Verweij, CERN Machine Protection and Electrical Integrity Group

Many slides are based on the work of:
Bernardo Bordini, Julien Dular, Tim Mulder, Emmanuele Ravaioli, Davide Rinaldoni, Erik Schnaubelt, Leon Teichrob, Mariusz Wozniak

CCA 2025

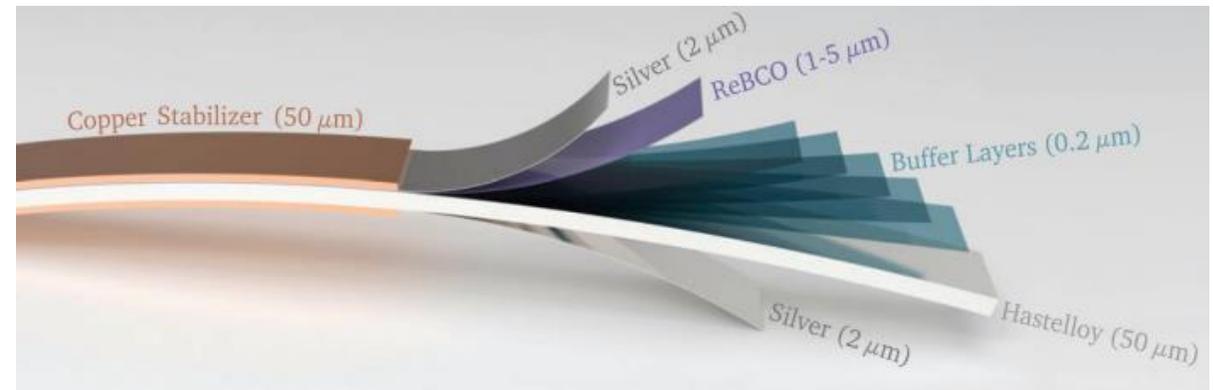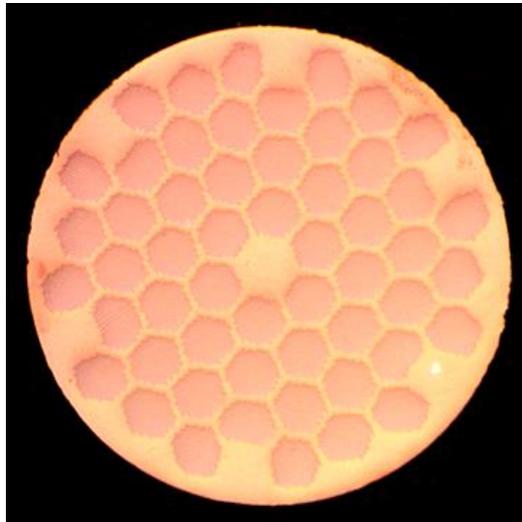International Workshop on Coated Conductors for Applications

CERN | March 11-13, 2025

Intro: LTS versus HTS

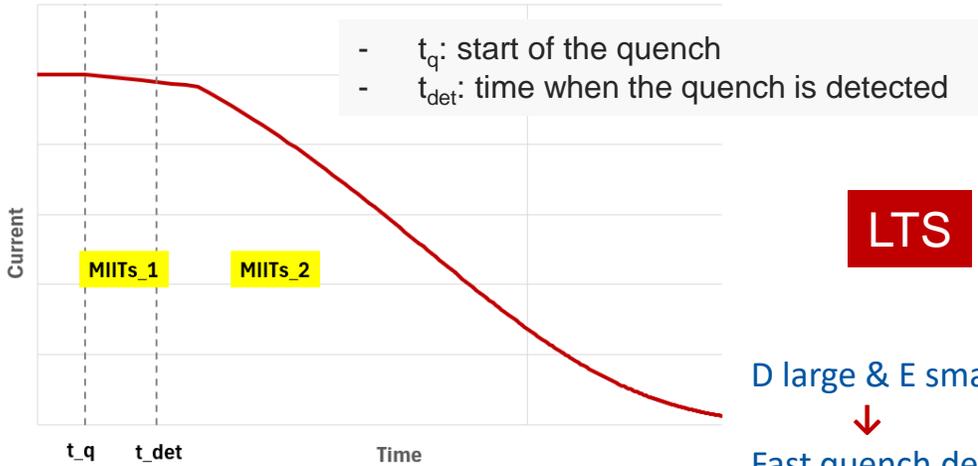|	Cu at 4 K, 8 T	Cu at 30 K, 20 T	Hastelloy at 30 K
ρ [Ohm m] *	5.7e-10	12.5e-10	1.23e-6
k [W/K/m] *	170	600	5.5
C_V [J/K/m^3]	800	270'000	163'000
D=k/C_V [m^2/s]	**0.21**	**0.0022**	**0.000034**
Enthalpy	**~1 mJ/cm^3** (from 1.9 to 4 K)	**~1.5 J/cm^3** (from 20 to 30 K)	**~1 J/cm^3** (from 20 to 30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

Assuming:
- RRR_{Cu}=100,
- Magn. res.=0.5e-10*B,
- $k_{Cu}=L0*T/\rho_{Cu}$

Intro: Quench integral

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

- t_q: start of the quench
- t_{det}: time when the quench is detected

LTS

D large & E small
↓
Fast quench detection
↓
MITTs$_1$ small
↓
available MIITs$_2$ large
↓
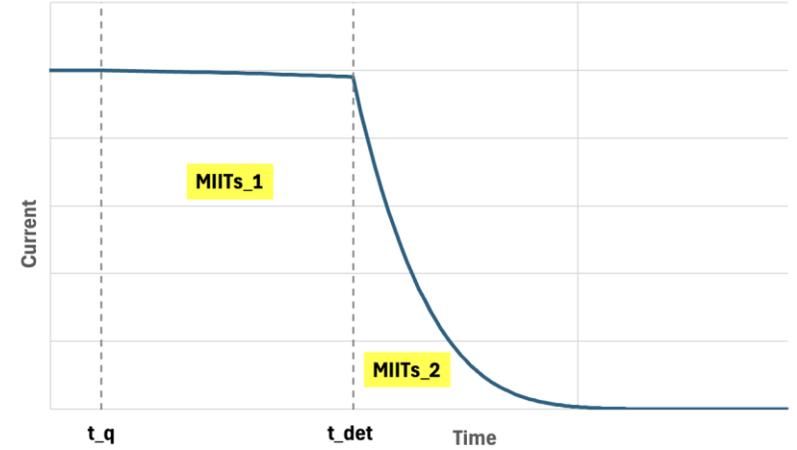'easy' to obtain by adding R in the circuit (EE) or in the magnet (QH/CLIQ)

ReBCO

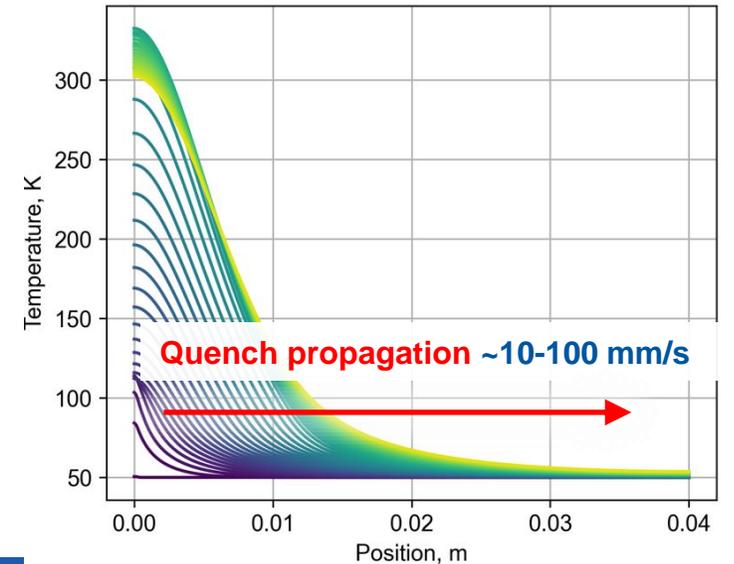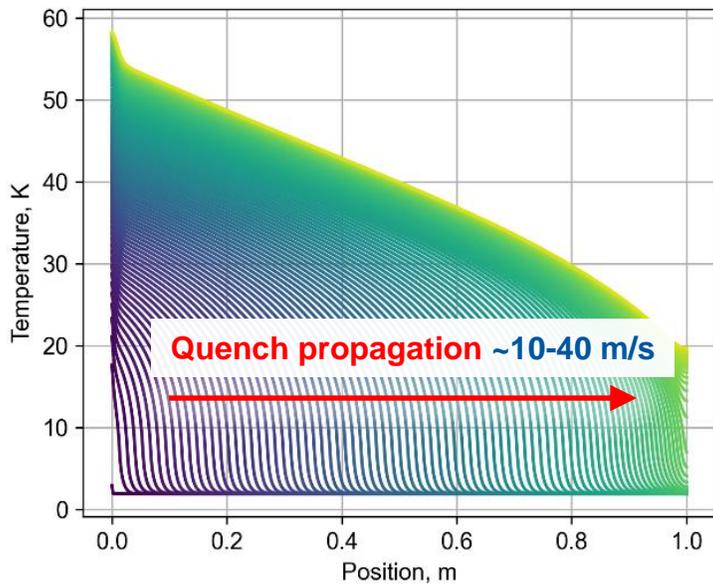D small & E large
↓
Slow quench detection
↓
MITTs$_1$ large
↓
available MIITs$_2$ small
↓
very difficult to obtain high R in the magnet (QH/CLIQ)

Quench propagation ~10-40 m/s

Temp. distribution at t=t$_{det}$

Quench propagation ~10-100 mm/s

Courtesy: T. Mulder

- ➢ Can we detect a quench faster?

- ➢ Can we stick to good old Energy Extraction (EE) and quench heaters (QH)?

- ➢ 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?

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

Good thermal-electro-magnetic (t-e-m) models, preferably coupled to mechanical / structural models, are an absolute must to assess these questions.

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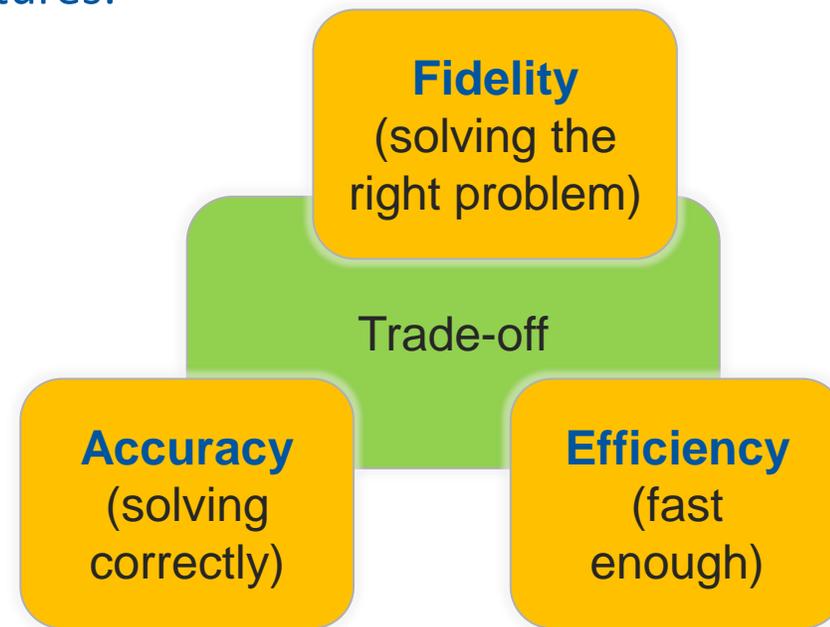
For ReBCO coils we could set multiple thresholds in parallel, e.g. 100 mV/10 ms & 10 mV/1 s & 1 mV/10 s, to be also sensitive to slow voltage onsets (precursors of the real start of a quench).

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
- ....

Fidelity
(solving the right problem)

Trade-off

Accuracy
(solving correctly)

Efficiency
(fast enough)

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.

t-e-m modeling

LTS

ReBCO

- Fast thermal propagation $\Rightarrow t_{det}$ small $\Rightarrow$ **1D+2D** usually sufficient

- Large thermal diffusivity $\Rightarrow$ **homogenisation** over strand (cable) cross-section $\Rightarrow$ **large mesh**

- **Magnetisation** can usually be disregarded due to small filament size

- Lots and lots of quench data are available to validate the models.

- **3D simulations** are often required.

- The highly anisotropic behaviour of the tape and small thermal diffusivity make homogenisation difficult $\Rightarrow$ often **requiring fine mesh**.

- **Screening currents cannot be neglected** due to the large filament size.

- Coupling to **mechanical models often required**.

- Not much experimental data exist to validate the models.

FE can often be replaced by a **fast lumped element** approach.

Nowadays models are well established and produce correct 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.

Adaptive time stepping, adaptive meshing, reduced-order modelling, parallelization in space and/or time, and High-Performance Computing are ways to speed up simulations.

The STEAM framework

The CERN TE-MPE group has started the **STEAM (Simulation of Transient Effect in Accelerator Magnets)** framework in 2016. The goal is to have a dedicated set of tools to analyse transients in LTS and HTS magnets and circuits, with possibility of co-simulation.

Features:

- All types of AC behaviour (coupling currents, magnetisation, eddy currents, quench, quench-back, …)

- Various types of magnet geometries (CosTheta, CCT, block, common coil, racetrack, solenoid, pancake, …)

- Various types of conductors (LTS, HTS, strands, cables, tapes, …)

- Various types of protection devices (quench heaters, EE, CLIQ, e-CLIQ, s-CLIQ, ESC, cap. discharge, …)

- Other circuit components (power converter, bypass diode, …)

- Failure & worst-case scenarios

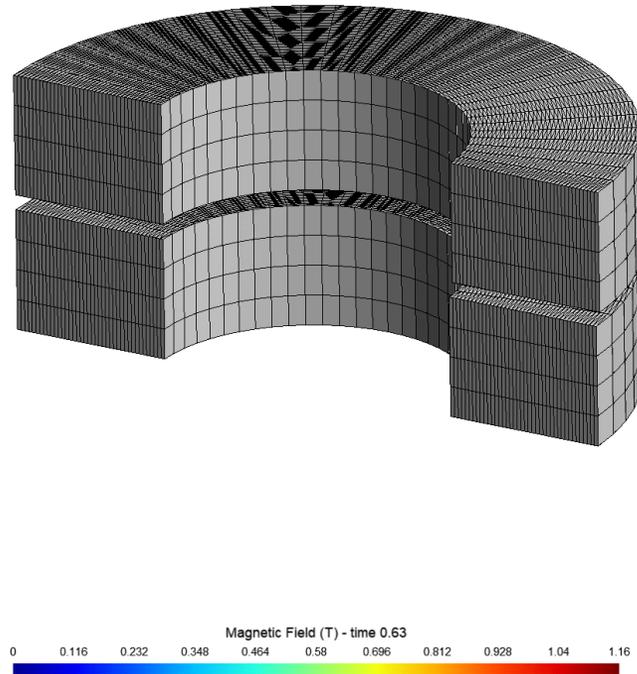- Parametric analysis & optimisation of protection efficiency

https://steam.docs.cern.ch

Arjan Verweij, CCA, 13/3/2025

The STEAM framework

pyBBQ	1D	FD	Python	LTS, HTS	thermal-e-m	Conductor
LEDET	2D / 3D	FD	Matlab	LTS, (HTS)	thermal-e-m	Solenoid, racetrack
ProteCCT	3D	FD	Python	LTS, (HTS)	thermal-e-m	Canted Cosine Theta
FiQuS	2D, 3D	FE	Python, Gmsh, GetDP	LTS, HTS	thermal-e-m	Solenoid, racetrack&CCT in progress
NICQS	2D axisymm.	FD	Python	NI HTS	thermal-e-m	Solenoid
HETS	3D	FD	Python	HTS	thermal-e-m	Solenoid, racetrack
H-FoSTER	3D FE +(1D FE+2D FD)		Comsol-based	HTS	e-m (thermal on-going)	Solenoid

+ commercial software (Spice, PSIM, Ansys), + input from Roxie (magnet design), + implementation of a material database, + SIGMA (Java-based tool to construct 3D accelerator magnet models using Comsol®)

➢ ReBCO based coils can be simulated with 4 tools (**FiQuS, NICQS, HETS, H-FoSTER**), each with their own strong points. For the moment, these 4 tools simulate coils wound from a single tape. Extension to multi-tape cables will come soon.

➢ Cross-checking among the tools will provide insight in the validity of assumptions, homogenisation, simplifications, etc.
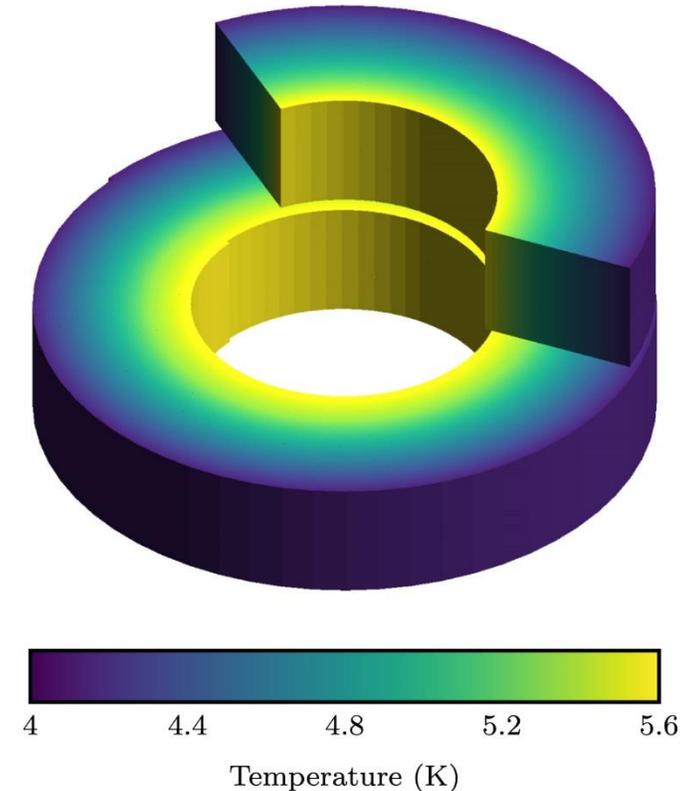
FiQuS: Finite Element Quench Simulation

ramp-up of double pancake [1]

Screening currents after power supply shutdown [1]

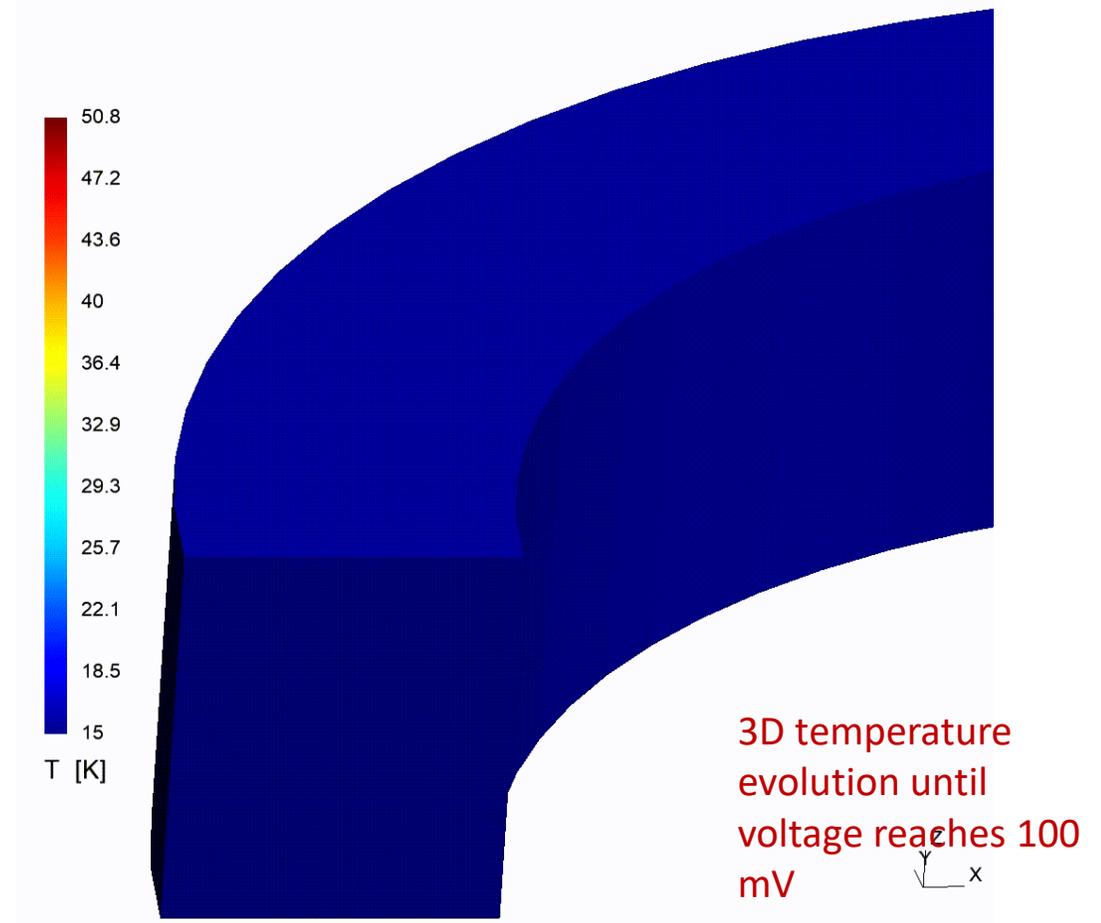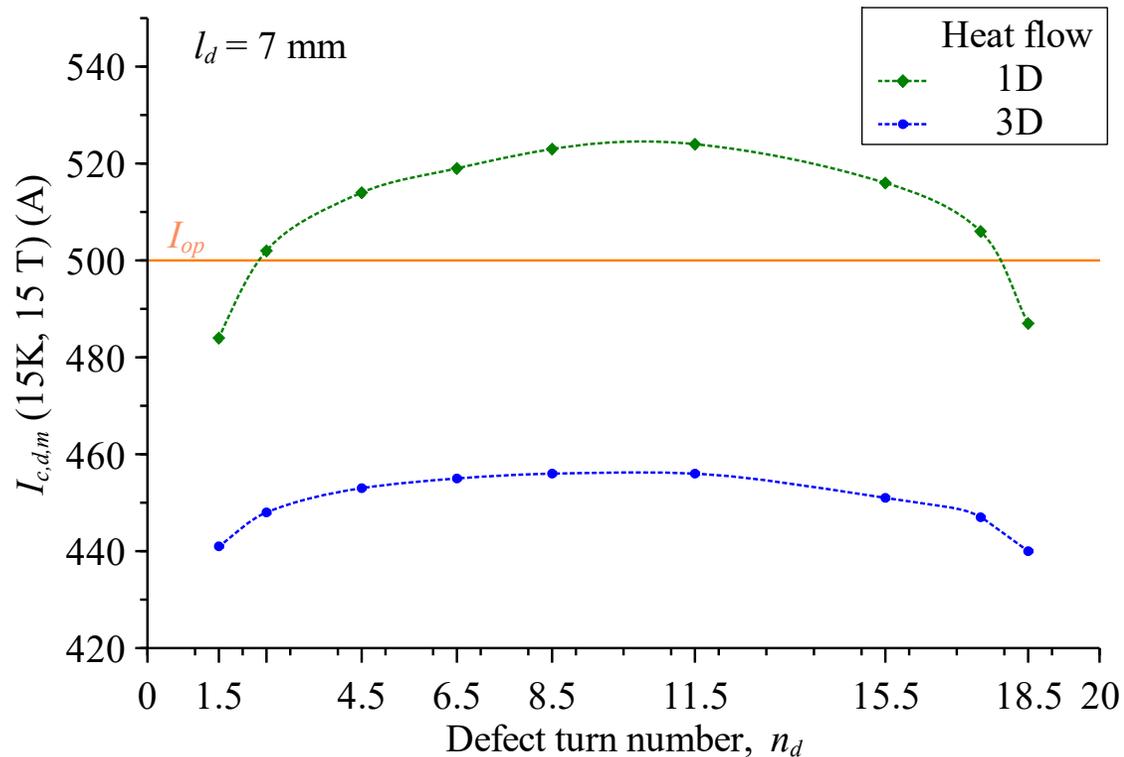Temperature at peak current with cooling via the terminals [2]

[1]: S. Atalay et al., "An open-source 3D FE quench simulation tool for no-insulation HTS pancake coils," Superconductor Science and Technology, vol. 37, no. 6. IOP Publishing, p. 065005, May 08, 2024. doi: 10.1088/1361-6668/ad3f83.

[2]: E. Schnaubelt et al., "Magneto-Thermal Thin Shell Approximation for 3D Finite Element Analysis of No-Insulation Coils," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3. Institute of Electrical and Electronics Engineers (IEEE), pp. 1–6, May 2024. doi: 10.1109/tasc.2023.3340648.

FiQuS: Stable operation of a REBCO coil with local defects

Analysis to see which local defect (with reduced critical current of $I_{C,d,m}$) can be accepted to run a ReBCO coil in a stable way.

Note the large difference between the 1D and 3D approach due to thermal diffusion between turns.
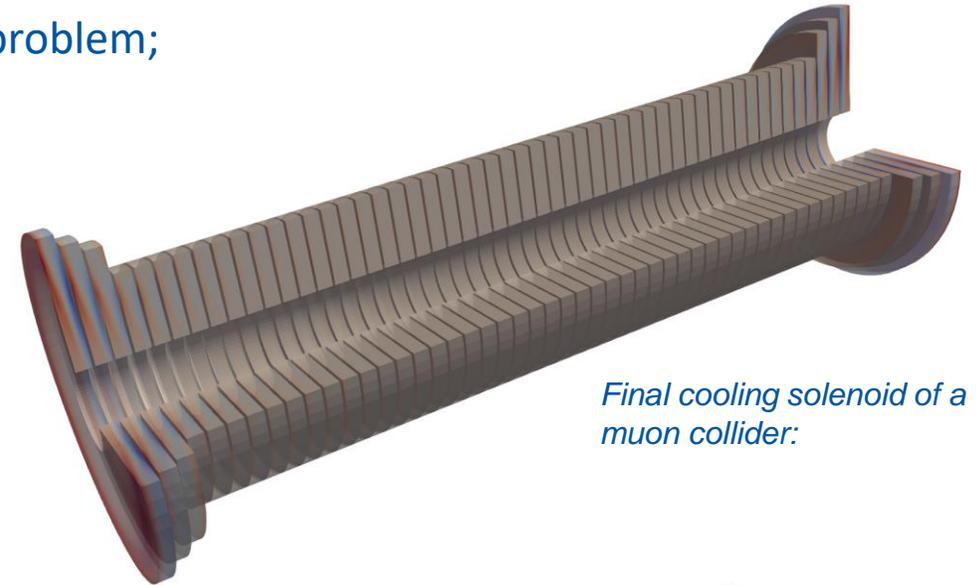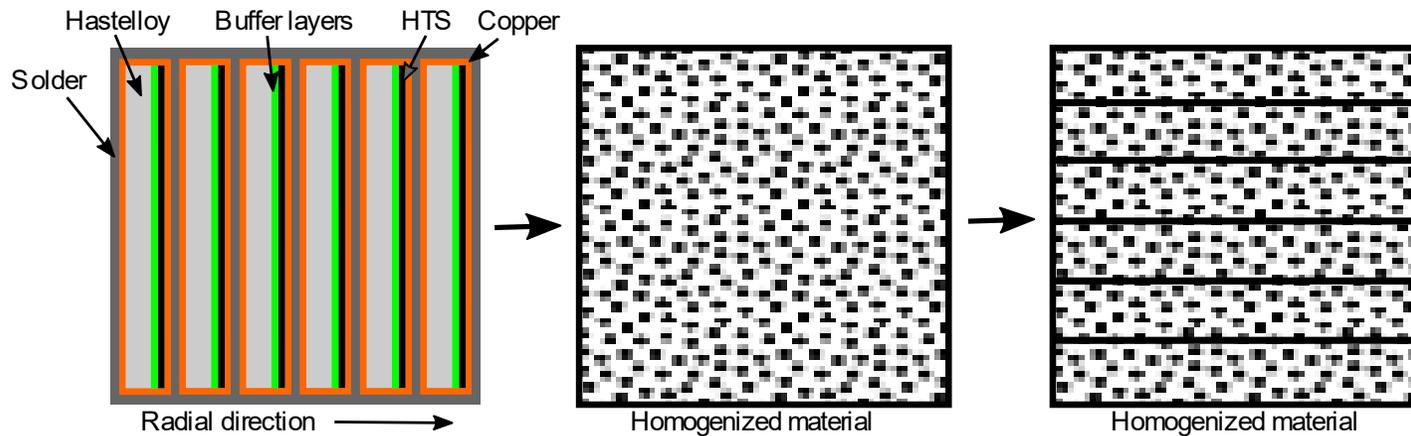

3D temperature evolution until voltage reaches 100 mV

M. Wozniak, et al., IEEE TAS,
https://doi.org/10.1109/TASC.2025.3532246

NICQS: No-Insulation Coil Quench Simulator

- Nodal network model using an ODE solver to solve an axisymmetric FD problem;
- Potential to be fast due to 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.
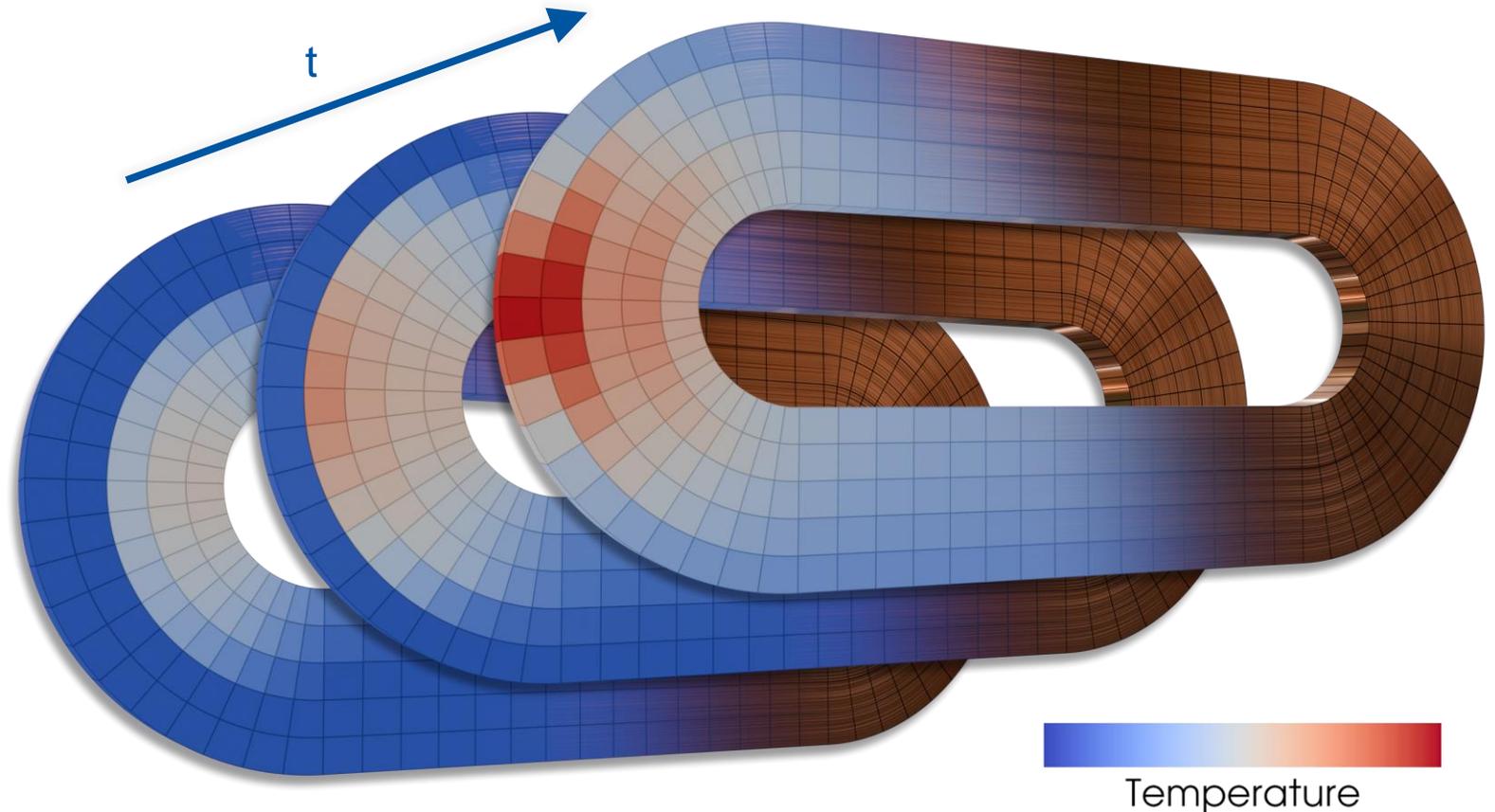

Final cooling solenoid of a muon collider:

Hastelloy   Buffer layers   HTS   Copper

Solder

Radial direction →

Homogenized material   Homogenized material
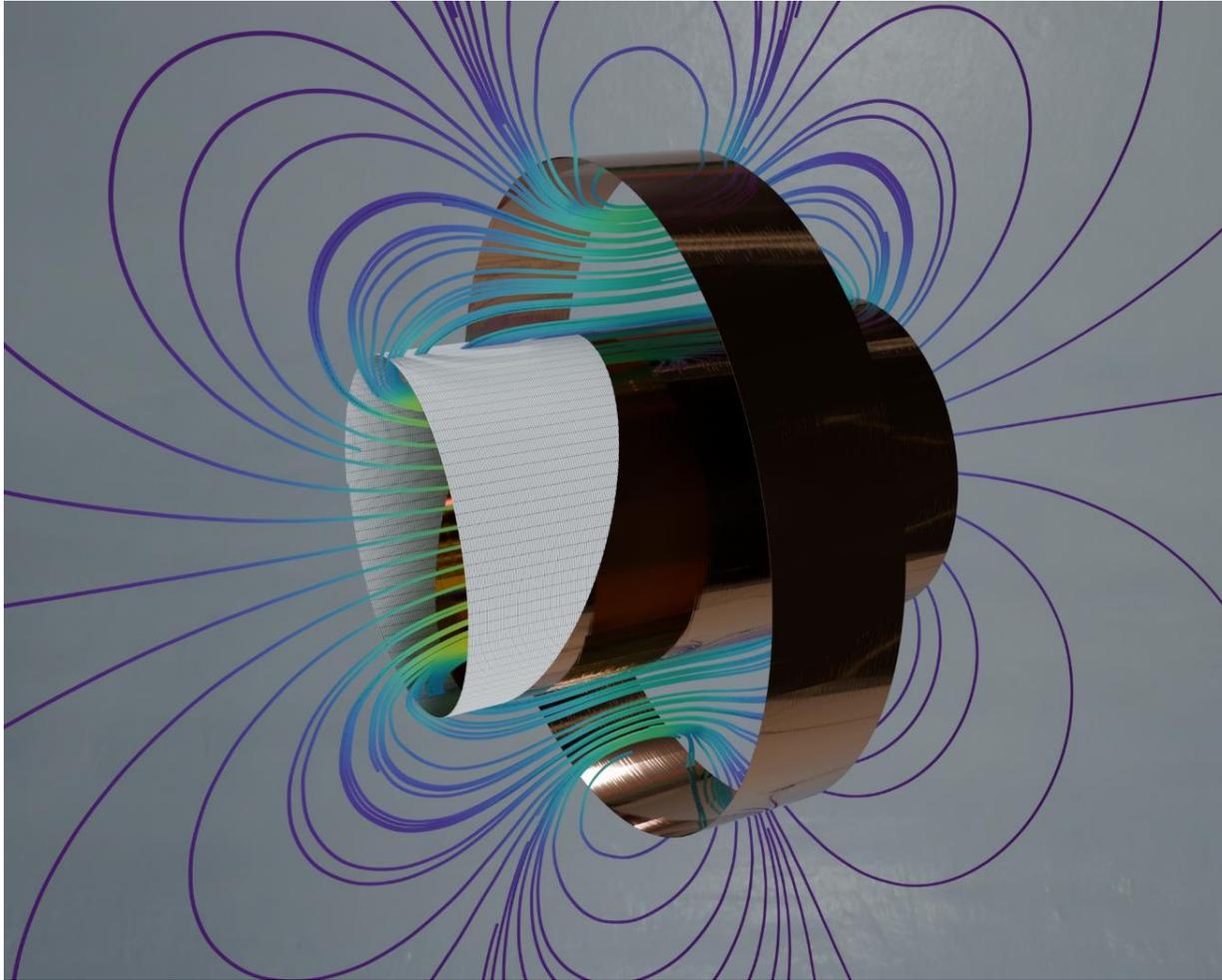
6D cooling chain of a muon collider:

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.
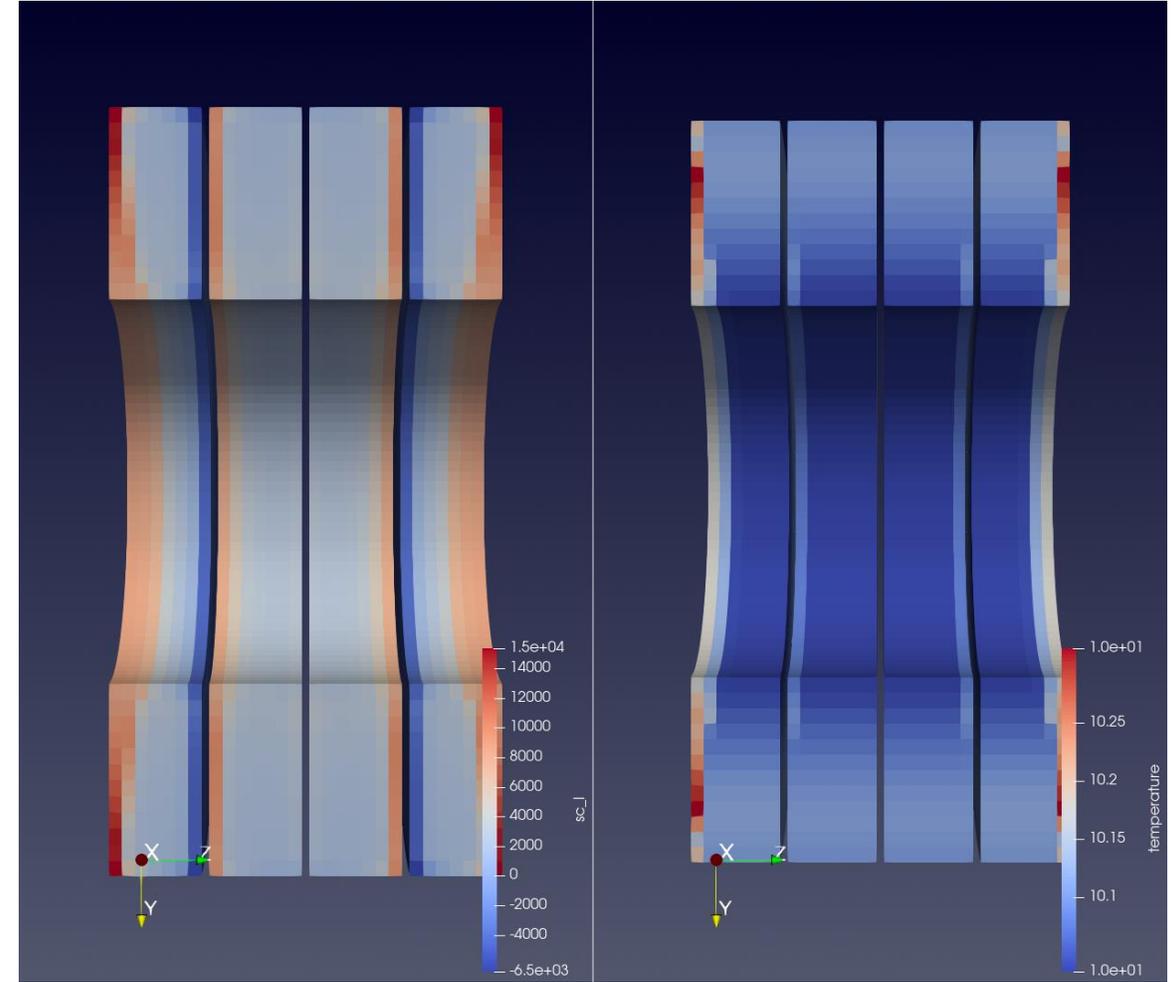

Temperature

Courtesy L. Teichrob

HETS

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

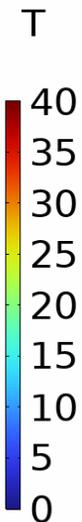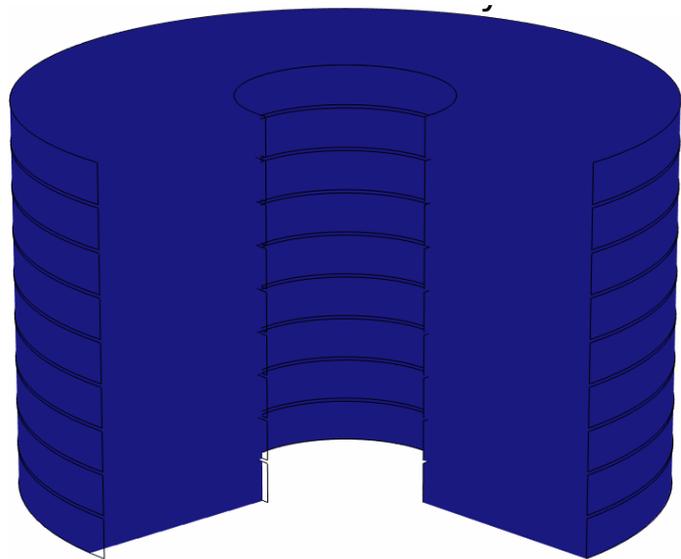Screening currents in an HTS pancake stack

H-FoSTER: Hybrid Formulation for the Simulation of Thermo-Electrodynamics in ReBCO magnets
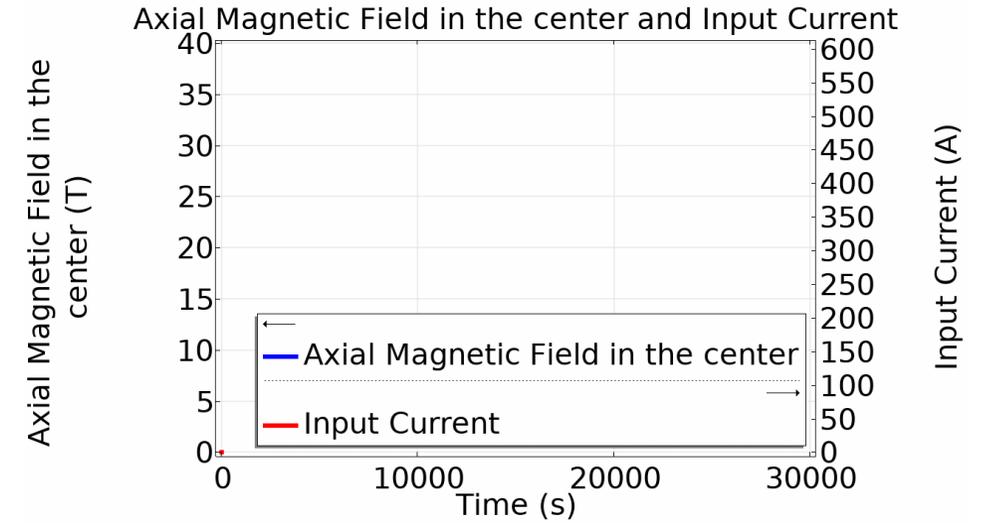
Courtesy D. Rinaldoni and B. Bordini

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

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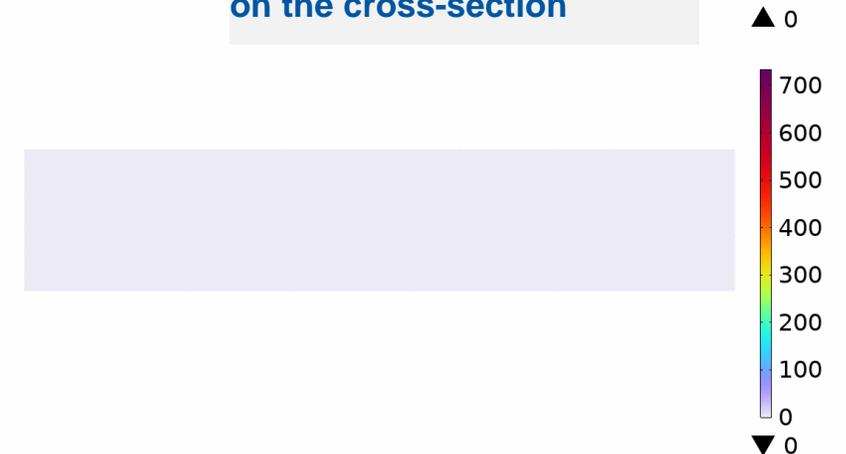- Turn-to-turn contact resistance 10 μΩ cm^2
- 2 mm of air between coils

See also poster
D. Rinaldoni on Wed

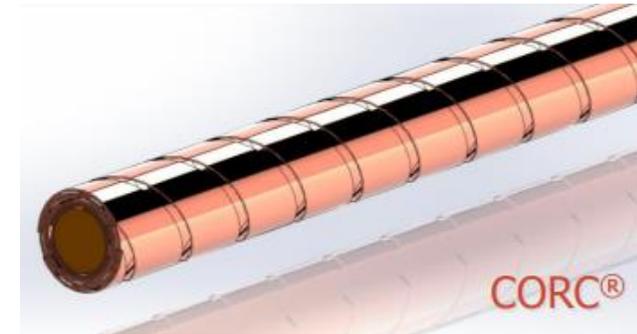Axial Magnetic Field in the center and Input Current

Time=0 s

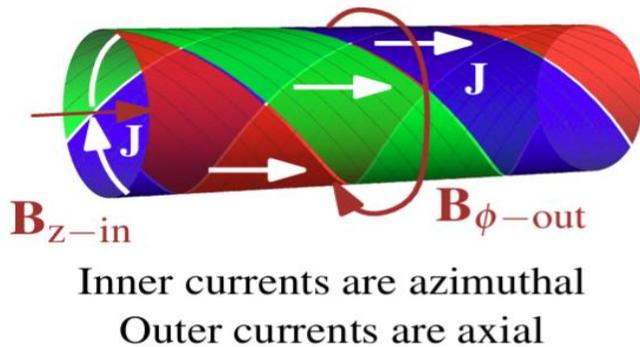**Current Density distribution on the cross-section**
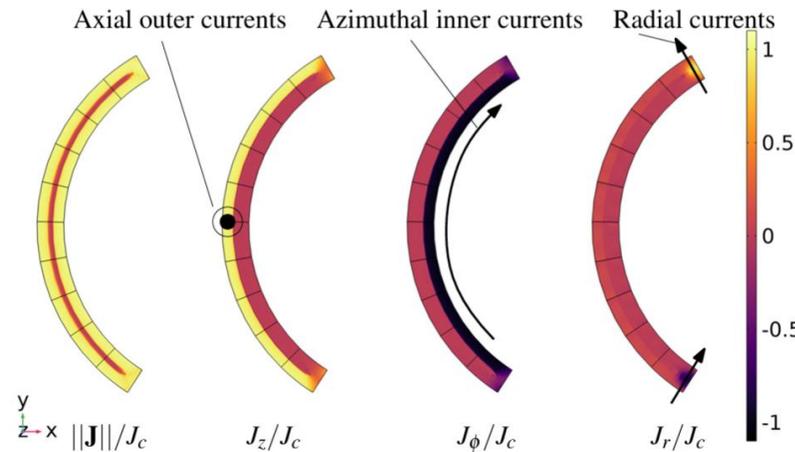
Reduced Order Modelling of CORC® Cables

- 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.
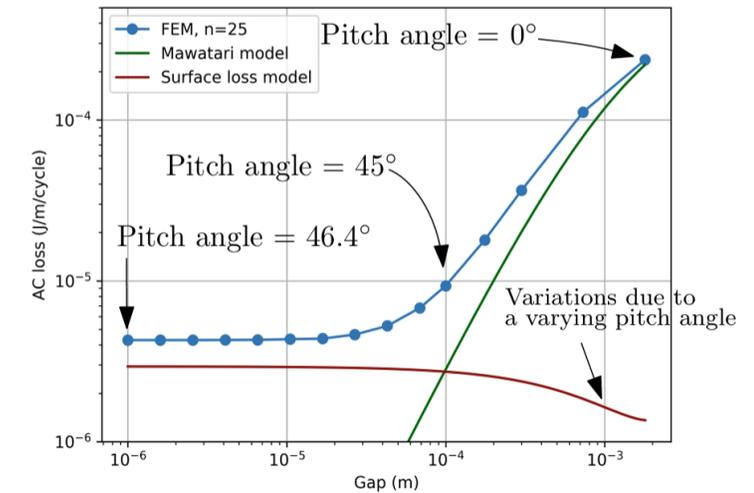

Single-layer geometry

B_{z-in} $B_{\phi-out}$

**Inner currents are azimuthal
Outer currents are axial**

Current density (expanded thickness)

Axial outer currents   Azimuthal inner currents   Radial currents

$||\mathbf{J}||/J_c$ J_z/J_c J_ϕ/J_c J_r/J_c

Influence of the gap on AC loss

- FEM, n=25
- Mawatari model
- Surface loss model

Pitch angle = 0°
Pitch angle = 45°
Pitch angle = 46.4°
Variations due to a varying pitch angle

AC loss (J/m/cycle)
Gap (m)

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

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

Next steps: multi-layer cable, coupling currents.

Protection concepts for ReBCO magnets

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

The next slides show possible concepts for two applications that are of interest to CERN for possible future accelerators:

1. Muon Collider 40 T Solenoid design

2. 20 T ReBCO dipole magnets for FCC-hh

Protection feasibility and methods for other applications can vary a lot since they strongly depend on the tape, conductor, magnet size, field, etc.
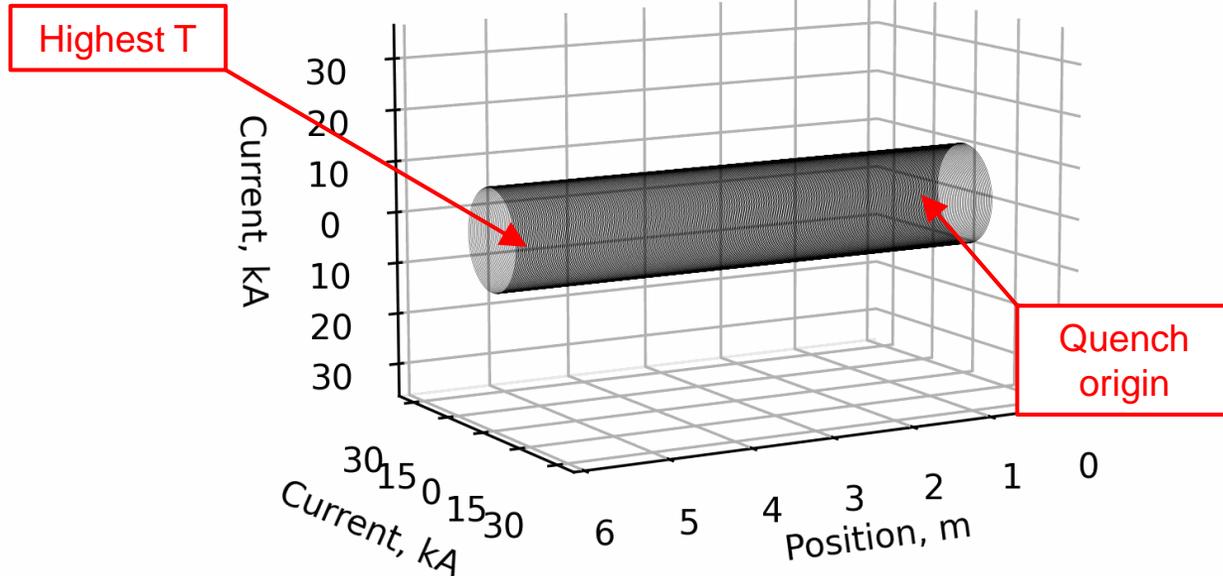
Protection concepts for 40 T muon collider solenoid

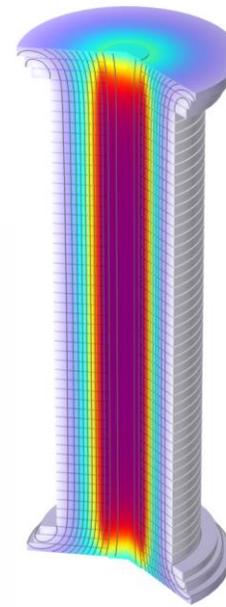Stack of 46+6 NI pancake coils, 0.5 m long, 50 mm bore, designed to operate at 4.5 K.
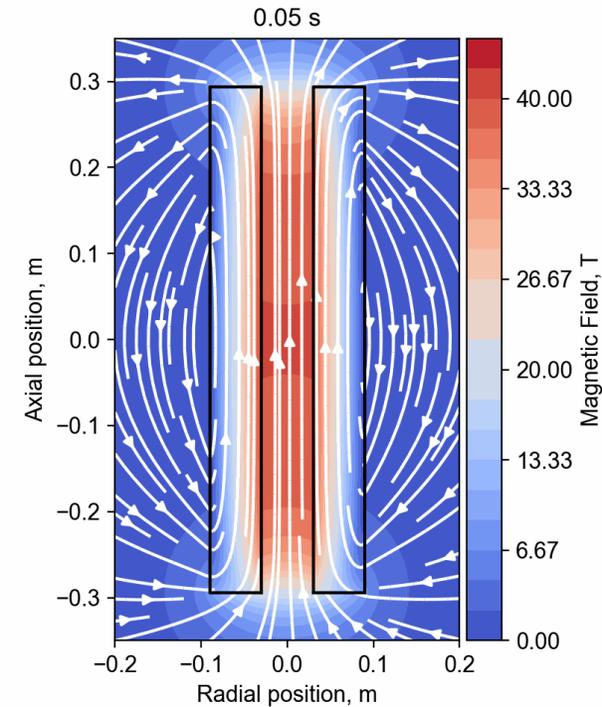
Turn-to-turn resistance control in a range suitable for operation, balancing protection, mechanics, ramp time and field stability.

t = 0.06 s

0.05 s

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.
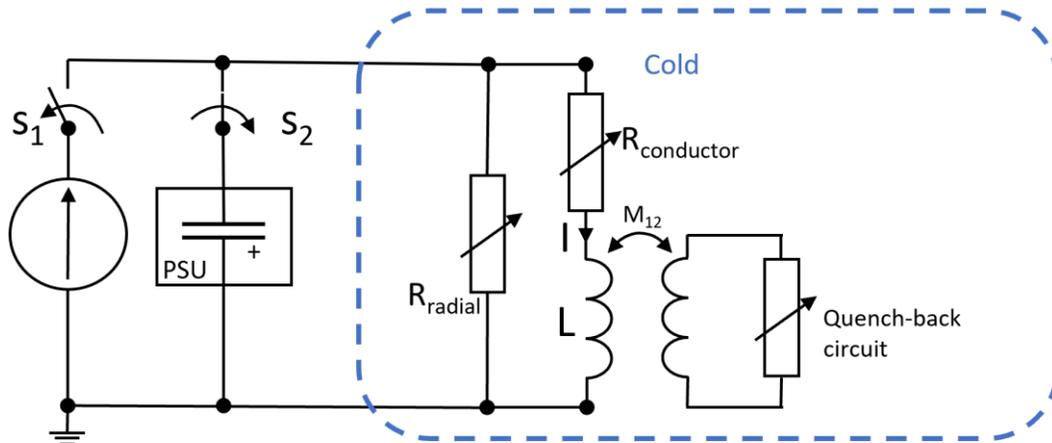
- Mutual coupling between the pancakes results in fast quench propagation along the stack (quench in one coil causes current transfer to adjacent coil ⇒ quench in adjacent coil, and so on)

- 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.
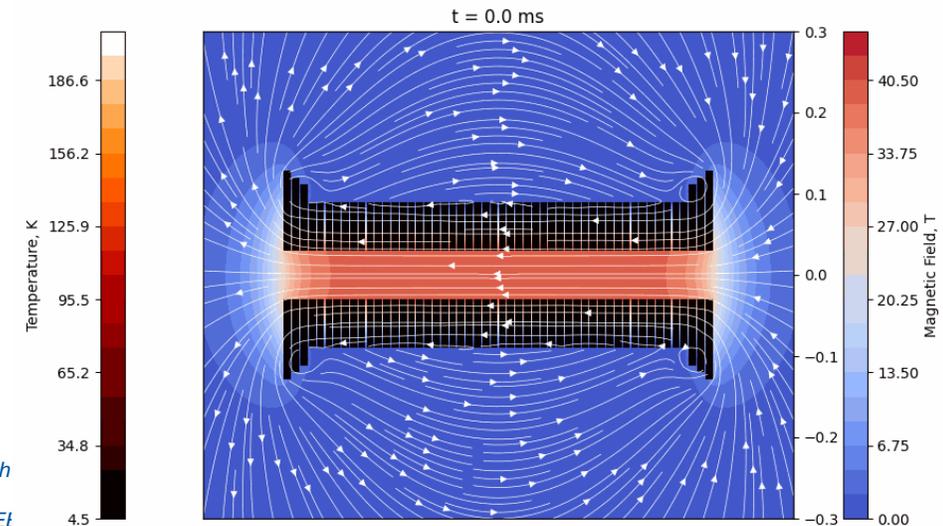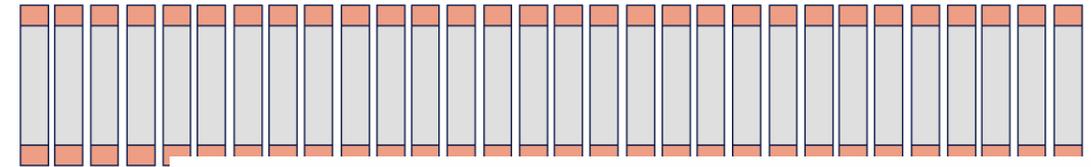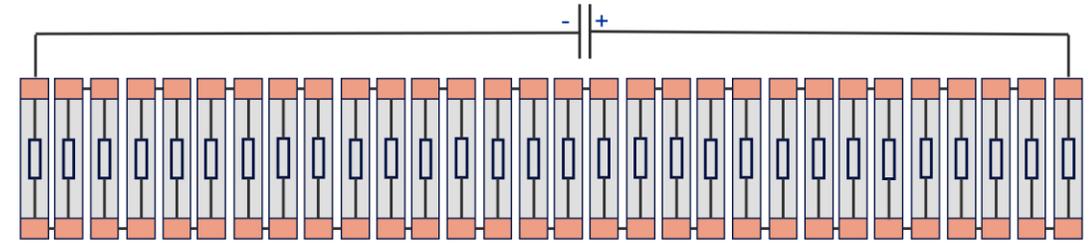
Capacitor Discharge [1]

- Injects a large current pulse upon quench detection by opening an external breaker;
- 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 has to be tuned to correct range
- current connections have to withstand a current of a few kA for several milliseconds.

[1]T. Mulder, M. Wozniak, A. Verweij, Quench Protection of Stacks of No-Insulation HTS Pancake Coils by Capacitor Discharge, IEEE Trans. Appl. SC, Vol 34, Nr 5, 2024.

Arjan Verweij, CCA, 13/3/2025

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

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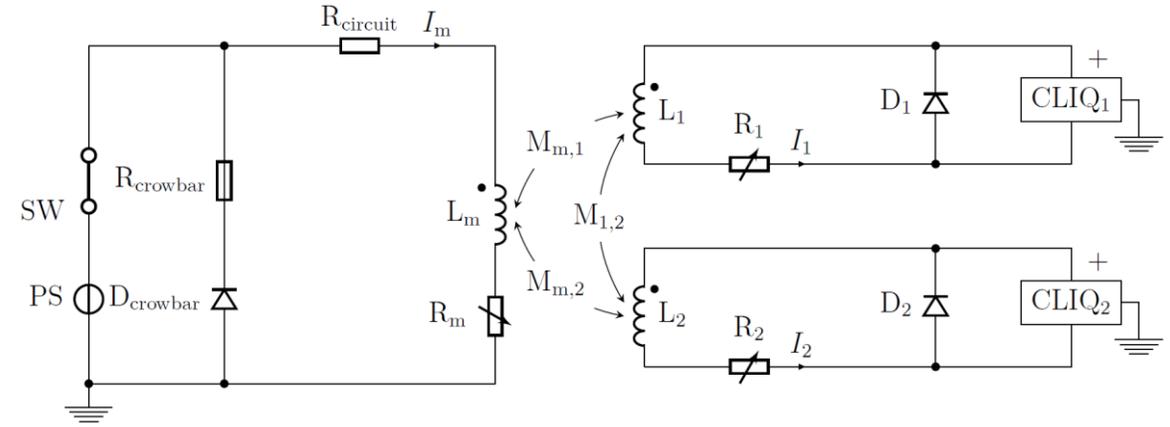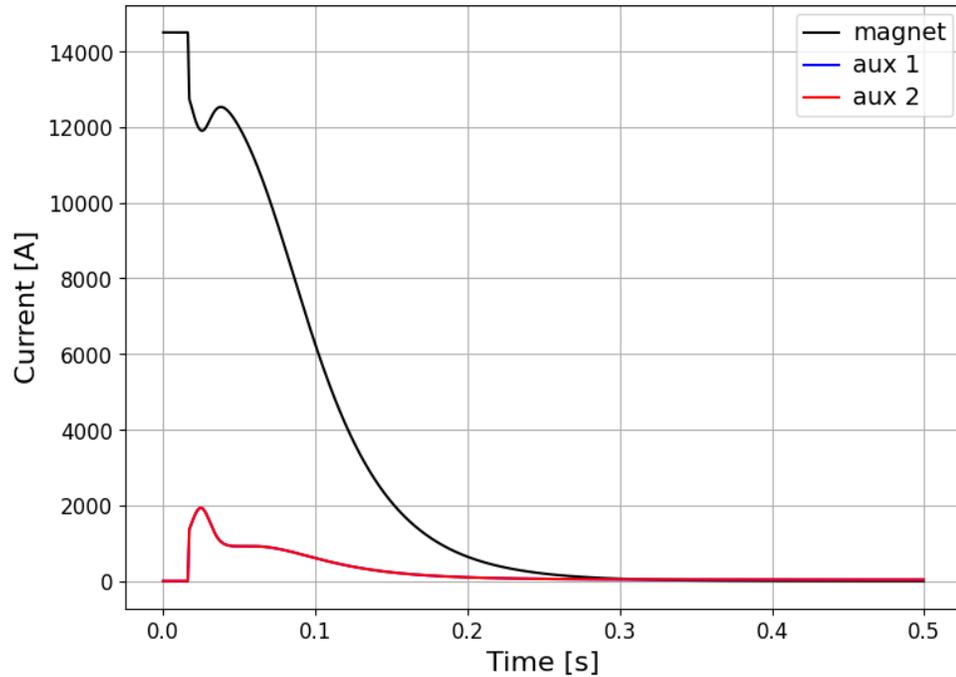
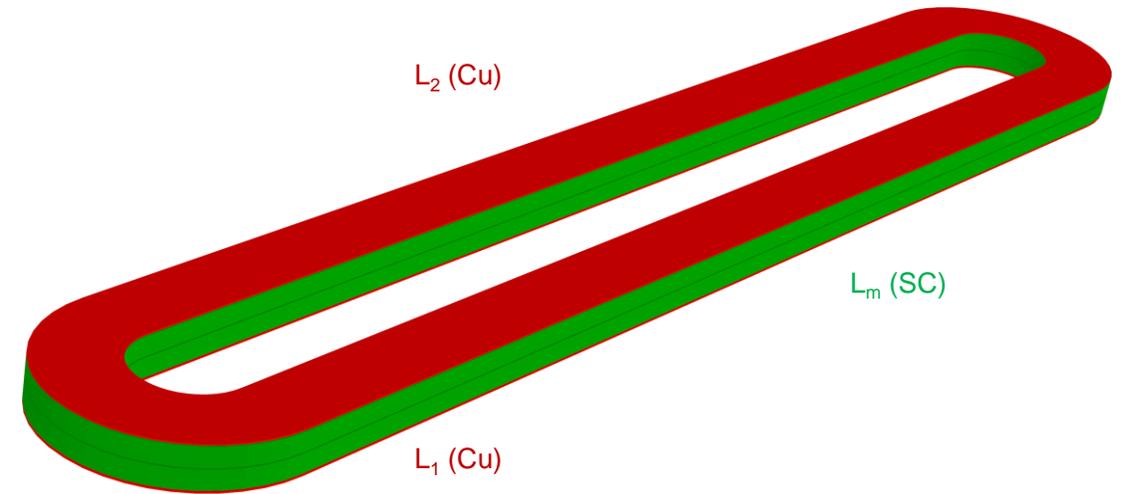A CORC-type cable could be envisaged for easier winding, but lower J_{eng}.

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.

ESC: Energy Shift with Coupling

✓ Quench through magnetization and coupling loss, generated by dB/dt pulse in auxiliary coils.

✓ Electrically insulated from the magnet

✓ Able to extract part of the magnet energy

✓ Good protection redundancy

More details: https://iopscience.iop.org/article/10.1088/1361-6668/ada833

L_2 (Cu)

L_m (SC)

L_1 (Cu)

Courtesy E. Ravaioli

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

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

Conclusion

➢ ReBCO based coils are intrinsically 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 NI coils should be considered which could possibly be designed to be self-protecting.

➢ Operation of the 7000 SC magnets in the LHC has shown that LTS magnets can run quench-free for many years at currents of 10-20% below their training current. ReBCO coils should be much more stable, especially when wound from a **stable multi-tape cable** (1st key objective). This opens the way to run without protection, of course only if all quench causes can be mitigated.

➢ Validated 3D thermal-electromagnetic and structural simulation models of ReBCO tapes, multi-tape cables, and entire magnets are essential for coil design and ramp/quench/protection studies.