Passive and Active Quench Protection for UHF Solenoids (+ Stability)

T. Mulder, B. Bordini, R. Unterrainer, A. Chmielinska,
M. Wozniak, A. Verweij.

Outline

- Overview of a few high field magnets
- Quench mechanism in (NI) UHF solenoids
- Comparison to other magnet geometries
- Active and Passive Protection Methods
- Simulation Results (using the 40 T FCS layout of the Muon Collider)
- Summary

Focus on stacks of NI ReBCO pancake coils

Disclaimer: some statements based on simulation results.

Overview of UHF HTS solenoids

Program / Magnet (year)	Field [T]	R_{in} [mm]	L [H]	Characteristic time τ (s)	Insulation style	Quench protection	Quenched	Damaged / Degraded
SuNAM & MIT — 26 T, 35 mm all-REBCO (2016)	26.4	35	12.79	947 s @ 77 K	**No-insulation** (multi-width NI)	NI self-protection	Yes	No
NHMFL — 32 T all-superconducting user magnet (2017)	32	34	254	-	**Insulated** REBCO co-wound with insulated stainless-steel tape (turn-to-turn insulation via the SS tape)	REBCO quench heaters (battery-powered) and LTS outsert heaters in the design.	Yes	Yes
LNCMI/CEA — NOUGAT MI insert (2019)	32.5	38	0.825	23.06 s @4.2 K	**Metal-as-insulation (MI)**; REBCO co-wound with Durnomag foil	MI self-protection; passive dump/breaker concept discussed for high Rct regimes.	Yes	Yes
MIT-CFS TFMC 20 T SPARC	20		0.14	3.2 h @4.5K	NI	NI self-protection	Yes	Yes
ASIPP 20 T (32 T)	20	8.5	0.266/0.833	?	NI/MI	NI self-protection	Yes	Yes
ASIPP 20 T	27	15	1.57	?	NI	NI self-protection	Yes	No
IEE-CAS / SECUF — 32.35 T all-SC	32.35	35	Not reported	Not reported	**No-insulation** REBCO inserts (two) with LTS outsert	NI self-protection	Not Reported	
MIT/FBML — Cryogen-free 25 T ENI prototype (2022)	25	22.2	1.41	~ 39 min	**Extreme-No-Insulation (ENI)**; solder shunt layers on DP faces	ENI self-protection via solder surface shunts	Not Reported	
IEE-CAS/SECUF — 30 T metal-as-insulated user superconducting magnet (2024)	30	35	14.5	5.3 @4.35 K	**MI** (REBCO tapes co-wound with stainless-steel)	MI self-protection for the insert	Not Reported	
IEE-CAS — Large-bore HTS MI AC/DC magnet (2024) [12]		453	2.62	400 @20 K	**Metal-insulation** (REBCO + **316L SS** tape)	MI self-protection	Not Reported	
IEE-CAS — H835 19.6 T solid-N_2 (2025) [13]	19;6	88	20.3	31 000 @4.5K	**Metal-insulation** (REBCO + **SS304** tapes) with **indium surface shunt**	MI + surface-shunted protection	Not Reported	

Table adapted from T. Nes, HiTaT presentation, 23.10.2025. Some values may not be up to date.

T. Mulder, UHF Solenoids Workshop, CERN, 26.11.2025

Self-protection not Guaranteed

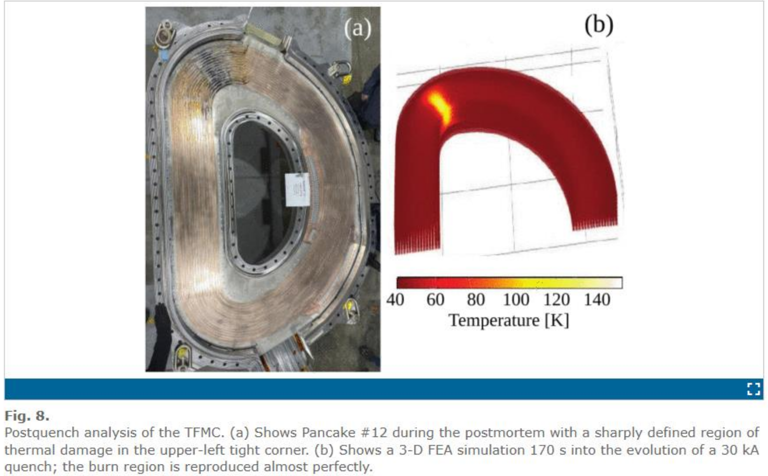
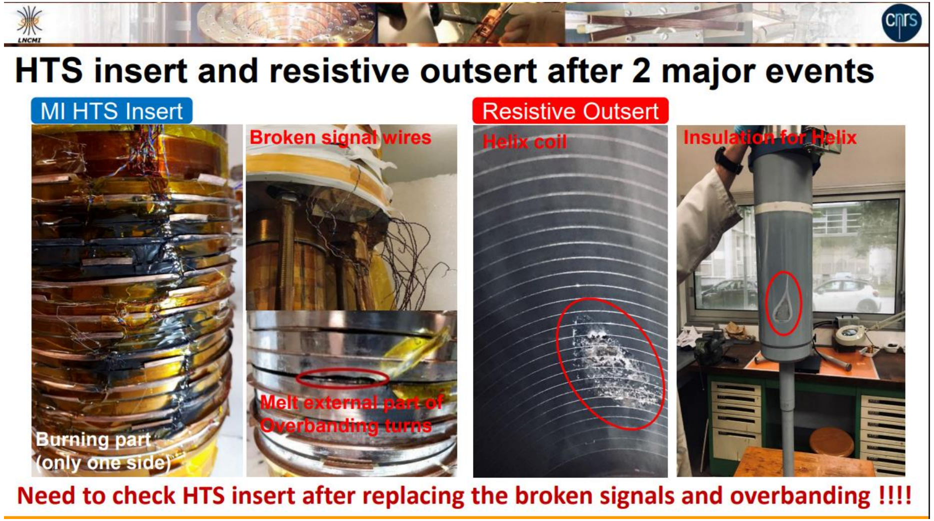


Fig. 8.
Postquench analysis of the TFMC. (a) Shows Pancake #12 during the postmortem with a sharply defined region of thermal damage in the upper-left tight corner. (b) Shows a 3-D FEA simulation 170 s into the evolution of a 30 kA quench; the burn region is reproduced almost perfectly.

Z. S. Hartwig *et al.*, 2024, doi: 10.1109/TASC.2023.3332613



HTS insert and resistive outsert after 2 major events

MI HTS Insert

Broken signal wires

Burning part (only one side)

Melt external part of Overbanding turns

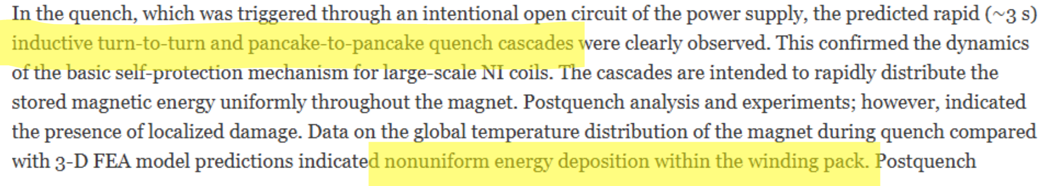
Resistive Outsert

Helix coil

Insulation for Helix

Need to check HTS insert after replacing the broken signals and overbanding !!!!

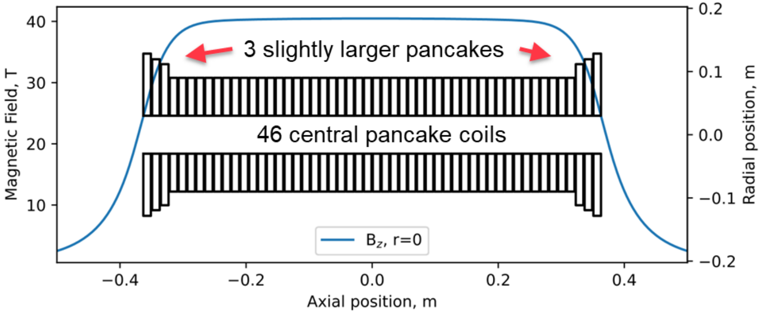
J.B. Song, https://indico.cern.ch/event/1175126/contributions/5024243/



In the quench, which was triggered through an intentional open circuit of the power supply, the predicted rapid (~3 s) inductive turn-to-turn and pancake-to-pancake quench cascades were clearly observed. This confirmed the dynamics of the basic self-protection mechanism for large-scale NI coils. The cascades are intended to rapidly distribute the stored magnetic energy uniformly throughout the magnet. Postquench analysis and experiments; however, indicated the presence of localized damage. Data on the global temperature distribution of the magnet during quench compared with 3-D FEA model predictions indicated nonuniform energy deposition within the winding pack. Postquench

40 T Final Cooling Solenoid

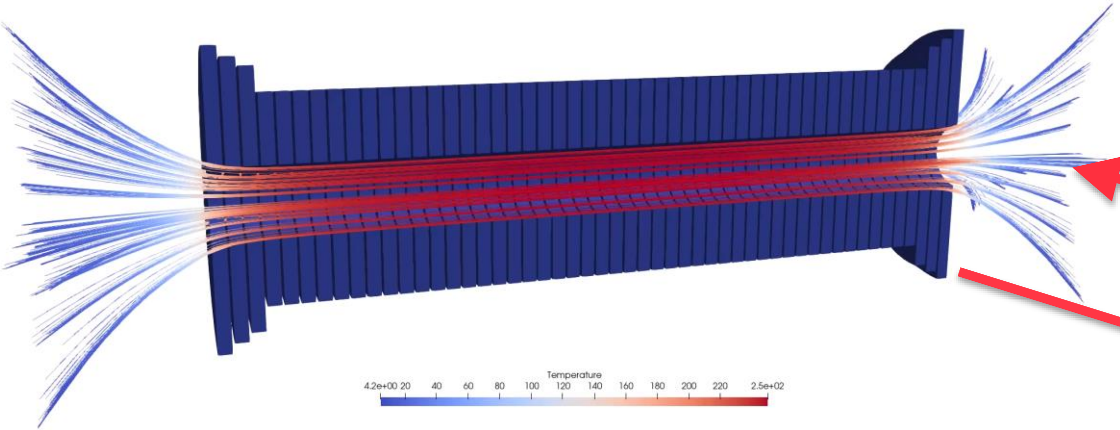
	Single tape	Unit
Number of parallel tapes	1	-
Turns central pancakes	750	-
Turns outer 3 pancakes	1020/1118/1230	-
Inductance	23.3	H
Current	607	A
Current density	632	A/mm^2
Stored Energy (@40T)	4.1	MJ
Mass (HTS tape)	140	kg
Energy Density	29	kJ/kg
Total tape length	16	km
Tape width	12	mm
Tape thickness	75	µm
Number of pancake coils	52	-
Characteristic Time	5 - 45	Minutes
Operating Temperature	4.5	K

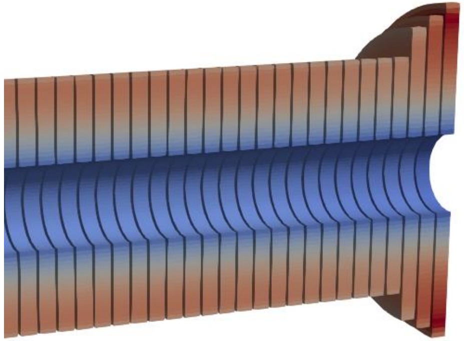


Preliminary design, subject to design change in consolidation with input from cryogenic engineers and beam physicists.

Inductive Quench Propagation

Quench without protection
2D simulation



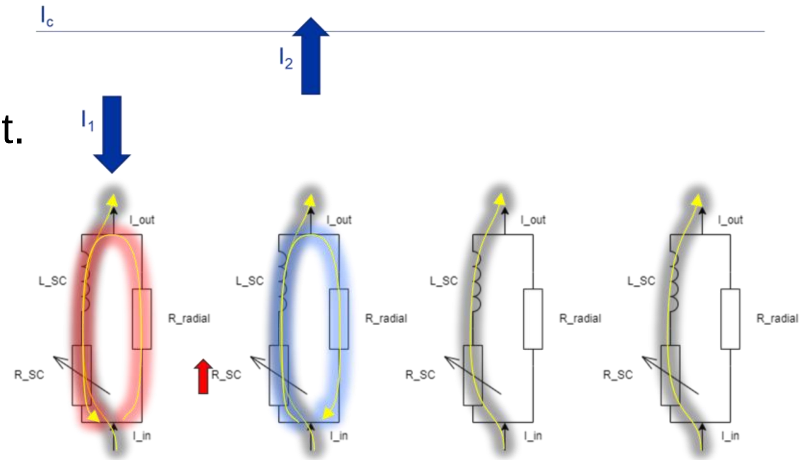


Peak temperatures observed in the coil extremities

✓ Large portion of the magnet in normal state due to inductive quench propagation.
✓ Peak temperatures < 300 K.
Do we even need protection?

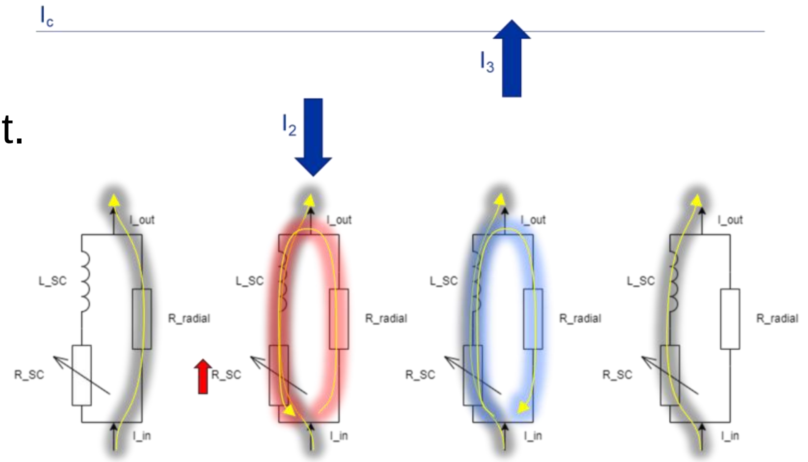
Inductive Quench Propagation

- Observed in simulation, observed in measurement.
- Magnets with large stored energy, stored energy density and a relatively high characteristic time.
- Mechanism relies on magnetic redistribution of the stored energy and can cause fast normal zone propagation throughout the magnet.
- Can be an advantage, or a burden.
- Large induced current → large Lorenz forces.
- A quench is initially a 3D phenomenon → hot spot.
- Magnet shape matters!



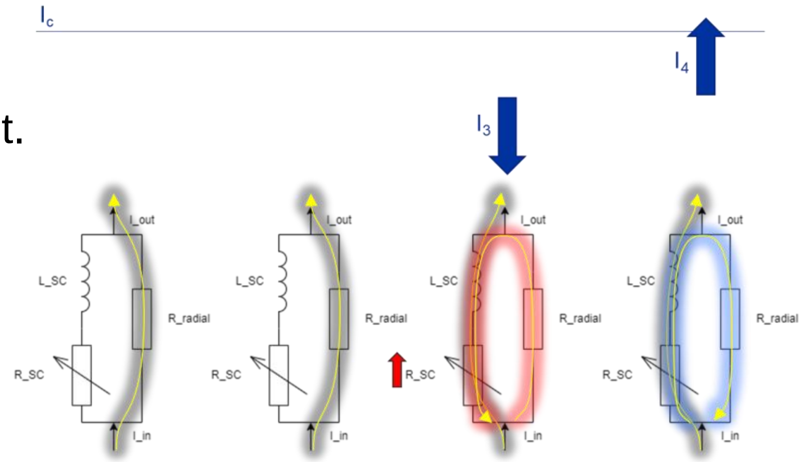
Inductive Quench Propagation

- Observed in simulation, observed in measurement.
- Magnets with large stored energy, stored energy density and a relatively high characteristic time.
- Mechanism relies on magnetic redistribution of the stored energy and can cause fast normal zone propagation throughout the magnet.
- Can be an advantage, or a burden.
- Large induced current → large Lorenz forces.
- A quench is initially a 3D phenomenon → hot spot.
- Magnet shape matters!



Inductive Quench Propagation

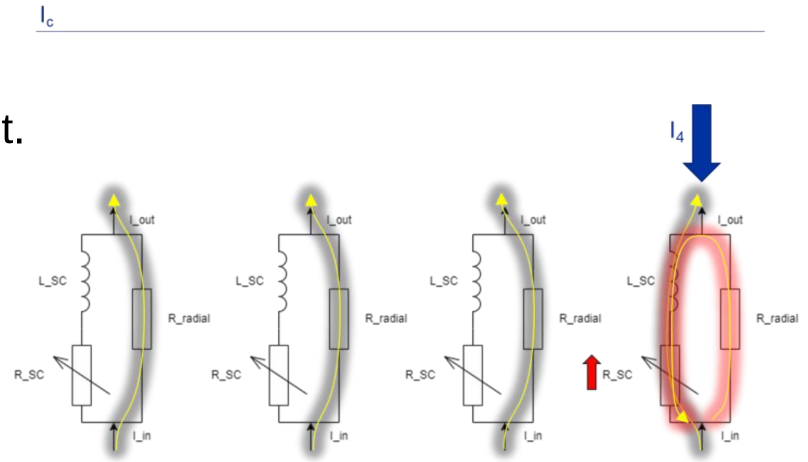
- Observed in simulation, observed in measurement.
- Magnets with large stored energy, stored energy density and a relatively high characteristic time.
- Mechanism relies on magnetic redistribution of the stored energy and can cause fast normal zone propagation throughout the magnet.
- Can be an advantage, or a burden.
- Large induced current → large Lorenz forces.
- A quench is initially a 3D phenomenon → hot spot.
- Magnet shape matters!



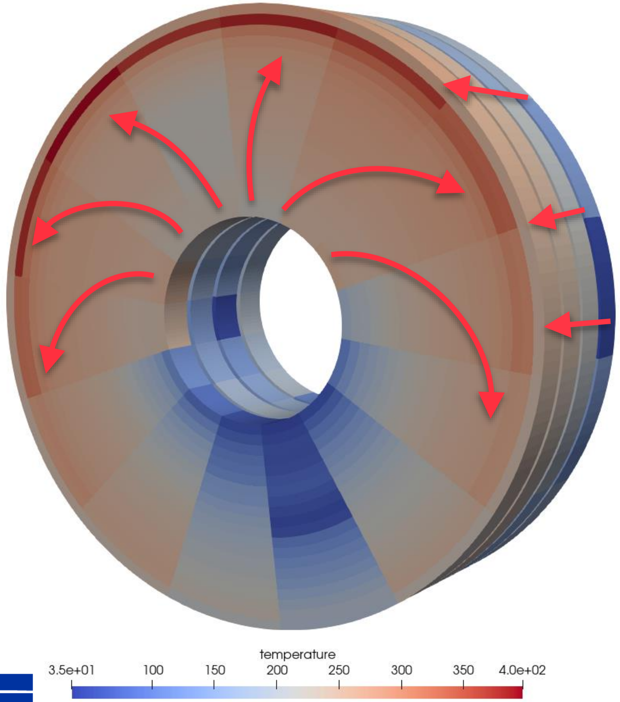
T. Mulder, UHF Solenoids Workshop, CERN, 26.11.2025

Inductive Quench Propagation

- Observed in simulation, observed in measurement.
- Magnets with large stored energy, stored energy density and a relatively high characteristic time.
- Mechanism relies on magnetic redistribution of the stored energy and can cause fast normal zone propagation throughout the magnet.
- Can be an advantage, or a burden.
- Large induced current → large Lorenz forces.
- A quench is initially a 3D phenomenon → hot spot.
- Magnet shape matters!



3D Sim: Short Coil Quench



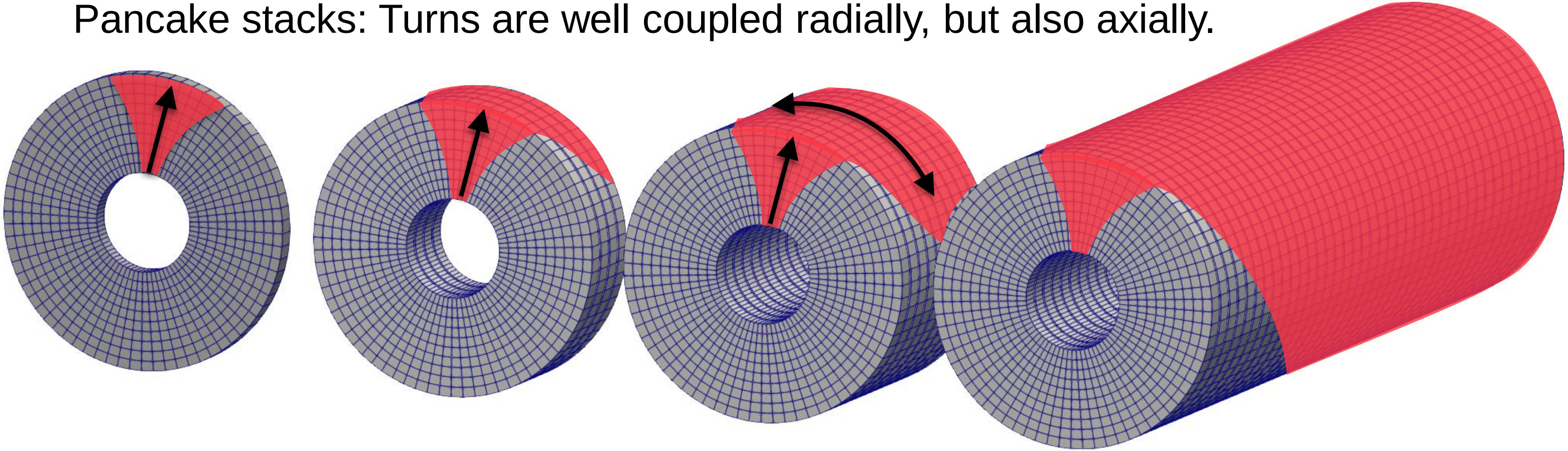
Parameter	Value	Unit
ID/OD	60/180	Mm/mm
Pancakes	4	-
Characteristic Time	500	s
Magnetic Field	24	T
Stored Energy	260	kJ
Energy Density	26.8	kJ/kg

- Radial and axial quench propagation.
- Parts of the coil are still superconducting

T. Mulder, UHF Solenoids Workshop, CERN, 26.11.2025

Quench behavior of long solenoids

Pancake stacks: Turns are well coupled radially, but also axially.



Single pancakes → likely self protected, not enough stored energy to cause damage.
Short stacks of small bore pancakes → energy displaced partially, local hot-spots.
Long stacks → current/energy has length to be displaced.

T. Mulder, UHF Solenoids Workshop, CERN, 26.11.2025

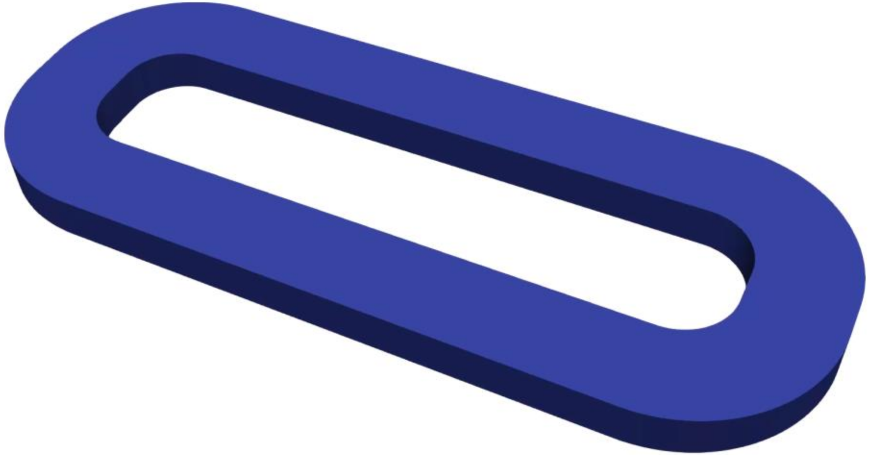
Comparison to NI Racetrack Coils

Racetrack coils:

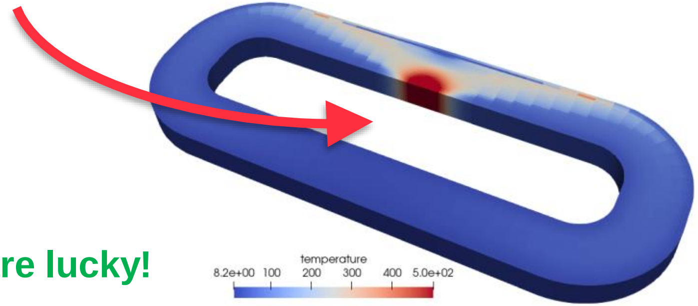
- Large energy per turn results in local hot-spots.
- When the length of a NI racetrack coil is increased:
  - Inductance increases.
  - Interturn resistance decreases.
  - Energy per turn increases.
- D-shaped coils and short stacks of large bore solenoids face similar challenges.

Stacks of compact NI pancake coils:

- When the length of the stack is increased:
  - Inductance increases.
  - Interturn resistance increases.
- Quench protection methods can be scaled more practically.
- Pancakes are inductively well coupled in axial direction. **We are lucky!**

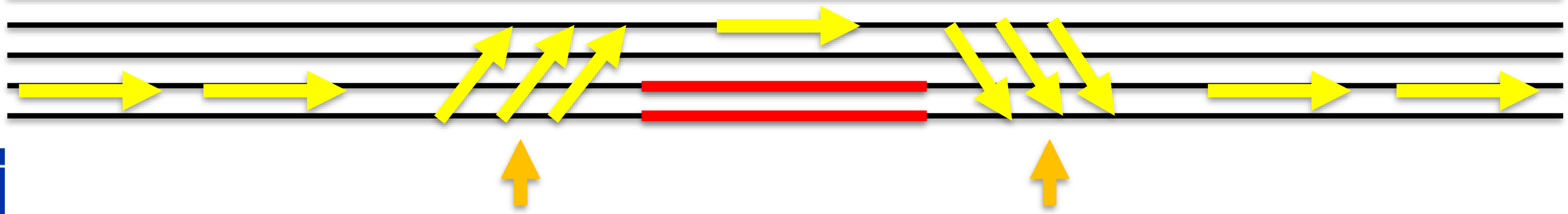


Local hot spot



Resistive Quench Propagation

- NZPV along a single HTS tape is low ~ cm/s
- Inductive effects tend to retain current paths, even during a quench.
- When the interturn resistance is large. Heat dissipation may speed up longitudinal normal zone propagation.
- When the interturn resistance is low → previous inductive quench propagation dominant.
- When the interturn resistance is too high → current cannot be displaced easily, will likely burn in the original quench position.



Heat production in interturn connections

Characteristic Time

- Characteristic time is important for magnet stability, ramp loss and ramp time.
- Characteristic time influences thermal runaway behavior.
- Commonly characteristic time is **not very important** for quench dynamics.

Observed that a quench of a >20 T magnet occurs in less than a 1 s. It does not matter if the characteristic time is 1000 s, 10000 s, or 24 h.

When the characteristic time is much closer to the quench time, resistive effects present.

Interturn resistance (related to the characteristic time) large effect on which protection methods are feasible.

Open Circuit / Energy Extraction

Open circuit forces current to return via the interturn resistive connections of the magnet:

- Stored energy rather evenly dissipated at heat, interturn connections used as quench heater.
- Needs to transition the magnet to normal faster than NZP, high interturn R required.
- Requires the interturn resistance to be relatively large for it to be used as protection.

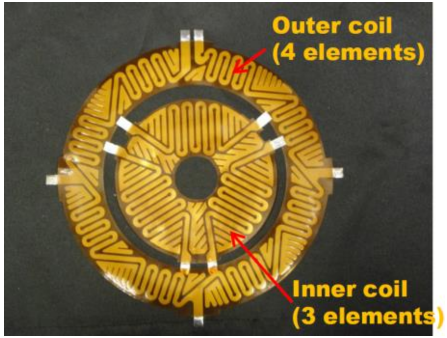
Energy extraction is still valid form of protection, however:

- Extraction resistor equal to the coil’s internal resistance.
- If the extraction resistor is **much lower** → not enough energy dissipated
- If the extraction resistor is **much higher** → majority of the current flows through the magnet’s internal resistance.
- May not have the protection benefits of using the internal resistance as quench heaters.
- For insulated HTS magnets, this is the preferred protection method.

Quench heaters

Insulated HTS magnets

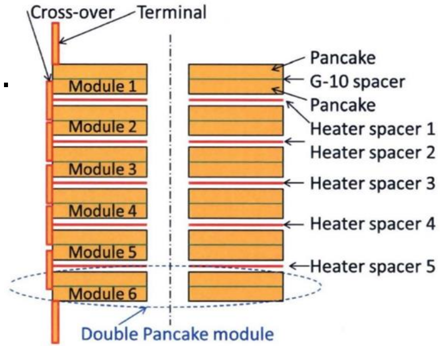
- NZPV is low, in general heaters are not very efficient.
- Heaters only effective when large section heated, large energy requirement.
- Low field region of the coil requires significant energy to transitions to normal state.



HTS quench heater [1]

Non-insulated HTS magnets

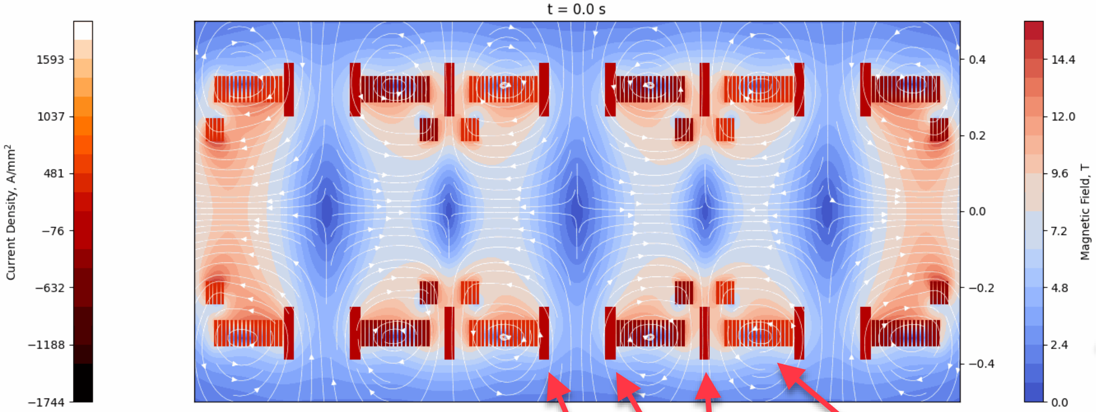
- Used to initiate a hot-spot, followed by inductive quench propagation.
- Magnet can be quenched in most favorable position.
- Potentially ineffective on the initially quenched turns.
- May cause issues due to mechanical stress concentrations & electrical integrity.
- Requires large battery/capacitor bank/an insulated outsert magnet.
- Requires many electrical connections.



[1] A. Gavrilin et al. Comprehensive quench analysis of the NHMFL 32T all-superconducting magnet, CHATS 2015, Bologna, Italy

Quench-Back Cylinders

- Quench-back cylinders accept part of the stored energy / high induced current during fast transients.
- Slow down / prevent inductive quench propagation through a magnet.
- Minor additional dissipation during ramp.
- Ideally made from a low resistivity material → often soft and not ideal for mechanical support.
- Placement not always trivial.



Copper quench-back cylinders
Not optimized

Quench initiation by heaters

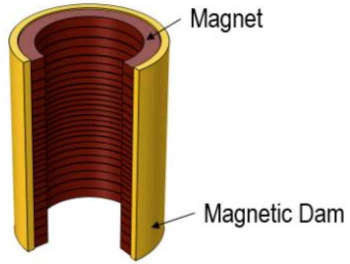


Fig. 5. A to-scale three-quarter section view of the designed “magnetic dam” together with the 7 T all-REBCO magnet. The magnetic dam having a radial build of 6 mm is radially aligned to the magnet.

S. An *et al*, doi: 10.1109/TASC.2020.2972221

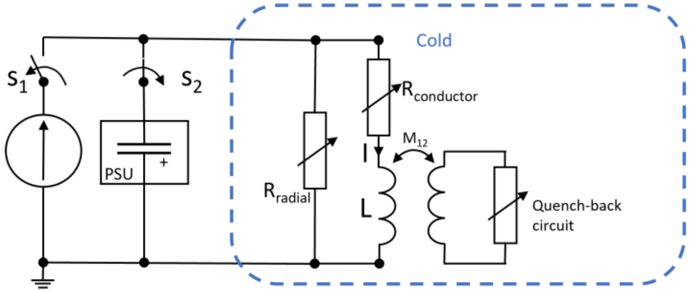
Capacitor Discharge QP

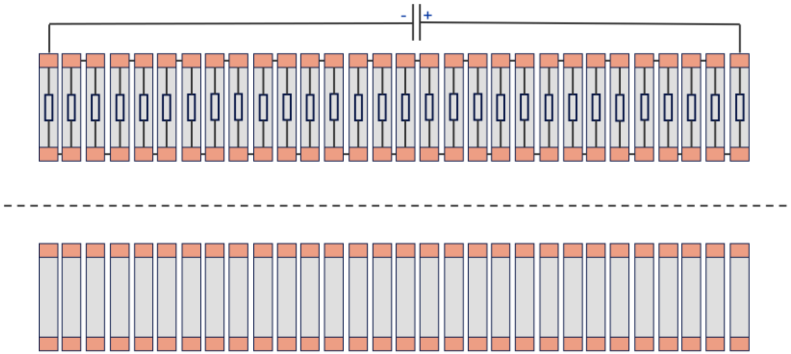
Magnet protection is a serious challenge as:

- The stored energy density of UHF solenoids is commonly large, in the order of 30 kJ/kg.
- NI-coil layout has the risk of large induced currents during a quench, potentially resulting in large Lorentz forces and thus mechanical stress.

Several quench protection solutions are being investigated, such as resistive heaters and a novel quench protection technique using a capacitor discharge[1].

- Capacitor Discharge (CD) offers a robust and elegant quench protection solution, as it can transition the full magnet to normal state within milliseconds without the need of additional electrical infrastructure.
- Combination of opening the breaker and injecting additional current to heat the magnet using its internal turn-to-turn resistance.

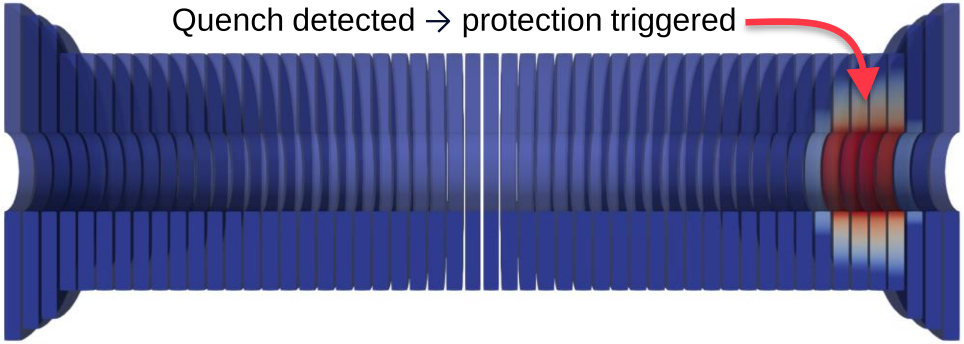




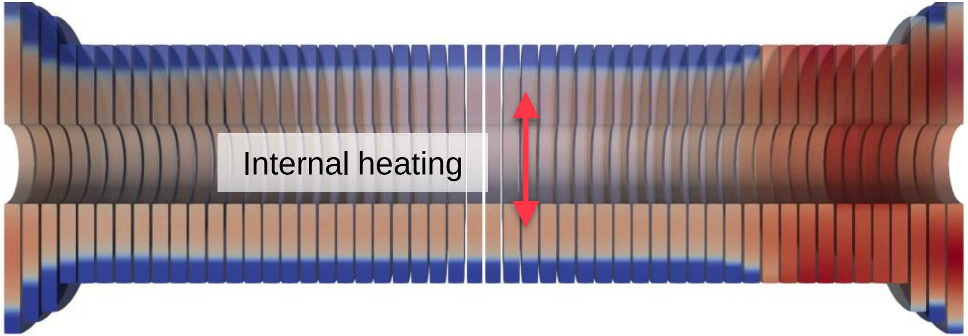
---

[1] *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.*

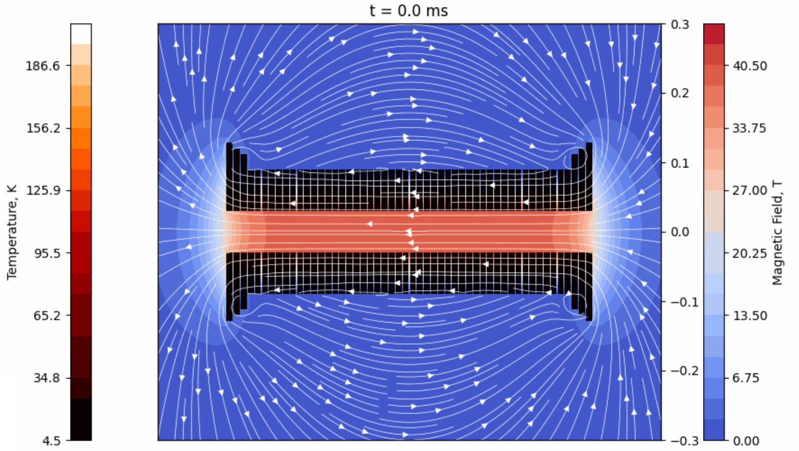
CD Quench Protection

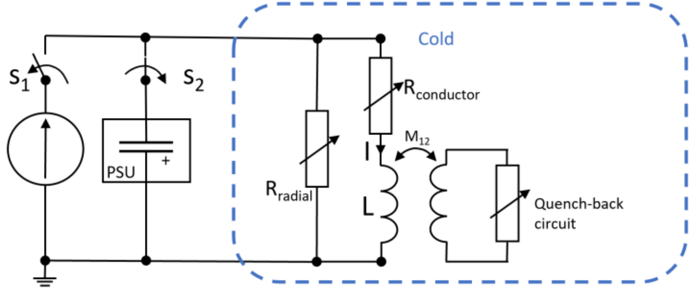


Quench detected → protection triggered

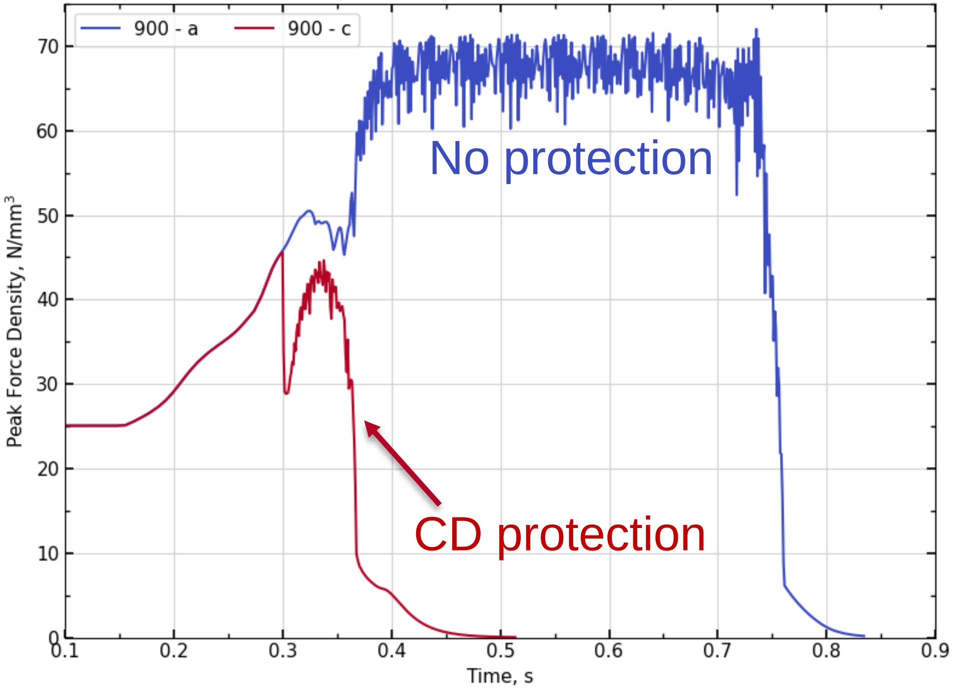


Internal heating



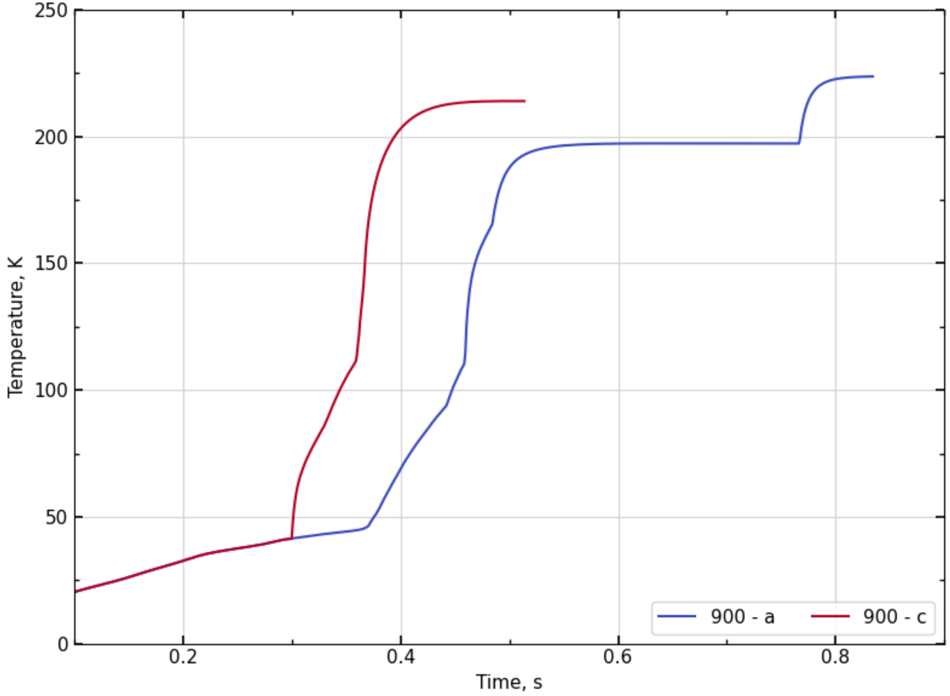


Simulated Reduction in Force Density



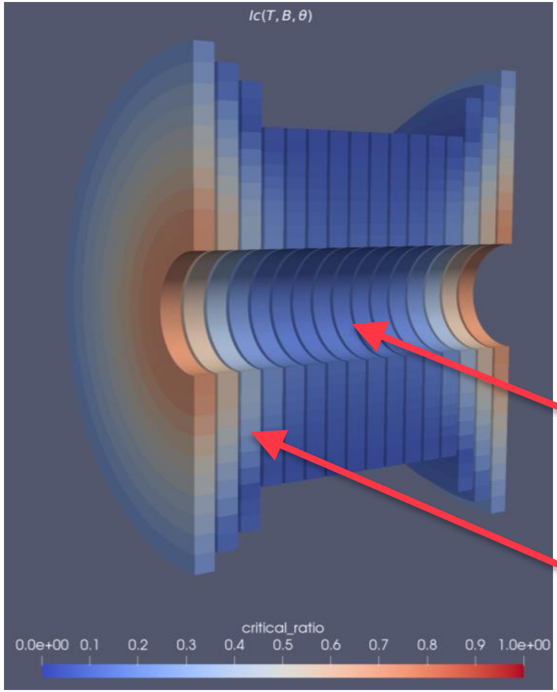
No protection

CD protection



Significant decrease in peak radial force density observed using CD protection vs no protection.

Angle dependency of I_c



Quench protection more challenging due to field-angle dependent critical current.

→ CD quench protection would initiate a NZ in the outer pancakes first, resulting in inductive quench propagation in the inward direction.

→ Coil grading (lower I_c coils in the center) or different characteristic times (higher τ coils in the extremities)

Central turns operate far below critical due to the field angle dependency.

Pancake coils at the extremities have much lower I_c.

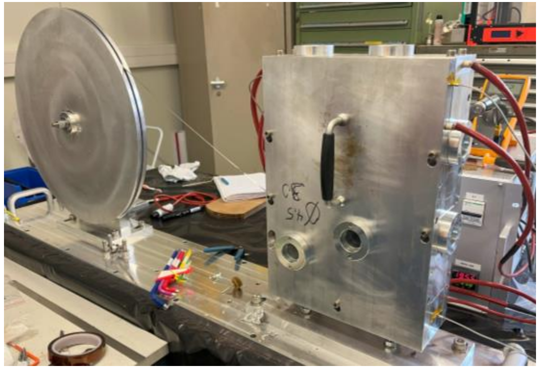
CD Quench Protection Limitation

- R is too large (low characteristic time) → High capacitor bank voltage is required to induce loss within a short timespan.
- R is too large (low characteristic time) → Opening the breaker forces current through the high interturn resistance, potentially sufficient.
- R is too low (high characteristic time) → Potentially extremely high currents are needed, very impractical.
- ρ (Ωm) is too low → Not enough loss per mass of tape. Occurs with large bore solenoids. → Mainly suitable for compact UHF solenoids.

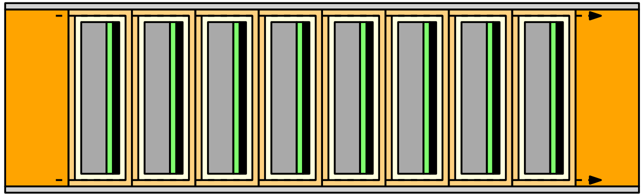
Final Cooling Solenoid of the Muon Collider located in a good resistance to mass ratio range for CD quench protection to work.

Tuning the Radial Resistance

Remove-and-Replace (RaR) method to tune the radial resistance.

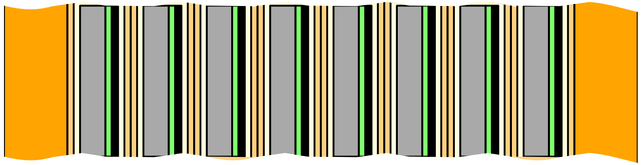


①



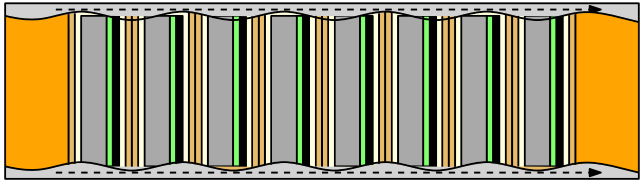
Preparing a fully solder NI coil.

②

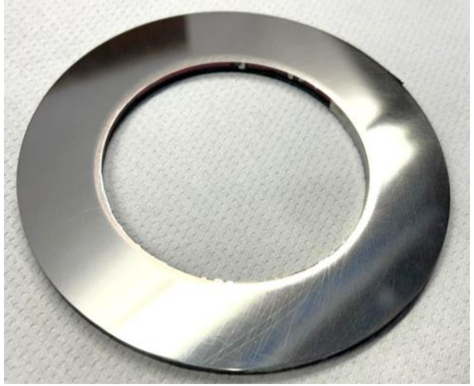


Removing the low resistance radial path: removing the coil's sides.

③



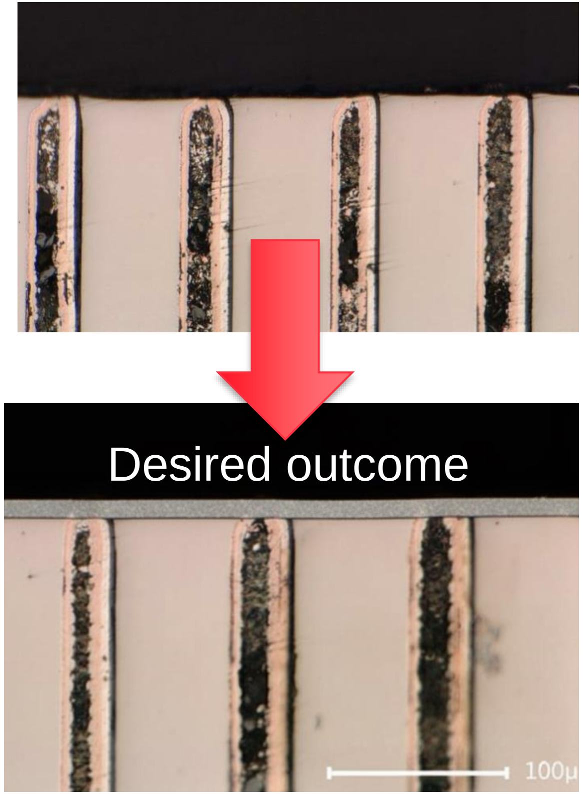
Removing the low resistance radial path: removing the coil's sides.



RaR: Desired Outcome

Metal / Alloy	**Effective Resistivity* @ 10 K (1e-8 Ωm)**	**Char. Time Reduction**
Reference interturn ρ*	2	1
Titanium	9	4.5
Monel (67Ni-30Cu)	110	55
Invar	150	75
Stainless Steel 316	160	80
Inconel 718	320	160
Hastelloy 276C	370	185
Titanium Aluminum	440	220

* Assuming 3 times the bulk resistivity.



Development in progress, if successful:

- ✓ Controlled interturn resistance, for operation and protection.
- ✓ Potentially improved mechanical strength.

No Protection

- No active protection does not automatically mean ‘self-protected’.
- Sufficiently high thermal-electrical stability that no quench occurs. In practice, this means a high magnet characteristic time.
- Or sufficiently low stored energy.
- Requires an abundancy of cooling + cryogenic back-up / buffer.
- Requires a UPS, in case of a power cut
- React on any sign of thermal run-away, or worse, failure of the cryogenic system.
- Coil may be supplemented with quench-back cylinders.
- **Detection is key!**

2015: “*HTS is very stable and requires a lot of energy to quench, no quench protection would be needed.*”

Summary

- Many passive and active quench protection strategies available.
- Strategically placed quench-back elements reduce energy dissipated inside of the magnets and Lorentz forces inside the conductor during a quench.
- Open circuit / energy extraction can be situationally effective, depending on the interturn resistance / circuit layout.
- Heaters are situationally effective, however, add complexity.
- Capacitor Discharge quench protection is on paper very powerful, to be proven and limited to an interturn resistance range for a practically sized capacitor bank.
- No quench and no protection is a valid strategy.
- **No one-size-fits-all solution.**