Quench Protection of Very Large, 50 GJ Class and High-temperature Superconductor Based Detector Magnets

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Content
- 8 T, 50 GJ detector magnet using CORC-CICC conductor
- Minimum Quench Energy (MQE) and Thermal runaway
- Classical quench protection, heaters, Quench Back, Extraction
- Novel Approach: Rapid Quench Transformation Concept
- Conclusion
Motivation

Development of Conductor-On-Round-Core (CORC) Cable-In-Conduit- Conductors (CICC)

- CORC-CICC: Excellent superconducting properties, no high temperature reactions needed, AC loss reduction through striation, solder-coating and copper stabilizer for stability, good mechanical properties, excellent stability at elevated temperatures (i.e. no training)

- Rapid enhancement in CORC performance in recent years, latest record: 340 A/mm² at 17 T, 4.2 K (Ten Kate et al., 3PoBD_2)

- Development of first six-around-one Cable-In-Conduit conductor, 45 kA at 10 T, 4.2 K, currently being finalized (Mulder et al., 3PoBD_0)

- Development of tapering solution for low-resistivity homogeneous current distribution at joint terminals (Mulder et al., 3OrAB_06)

- But what about Quench Detection and Protection at elevated temperatures?

→ Perform a preliminary analysis of quench behaviour in a large detector magnet operating at 40 K
Conceptual design of an 8 T, 50 GJ HTS-based superconducting magnet

- Operates at 40 K, for the purpose of investigating quench behaviour at elevated temperature. Excellent stability due to 500x enthalpy margin, ≈10x lower cooling cost than at 4.5 K
- 1 mm fiber glass-epoxy insulation between turns, 2 mm to support cylinder
- Layer-wound (CMS-like) geometry, with grading to minimize the required amount of HTS tape
- Primary and secondary (RQT) circuit, electrically insulated except for electrical connection at approximately half of the total cable length (i.e. between 6th and 7th layer)
- RQT conductor (Al-2%Ni, RRR=170, Yield strength ≈160 MPa) in secondary circuit provides mechanical support for conductor in primary circuit, in addition to assisting protection.
50 kA CORC-CIC Conductor assumed

- Graded Conductor-on-Round-Core (CORC) Cable-in-Conduit Conductor (CICC) operating at 90% of $I_c$ at 40 K in each layer.

- Assumption #1: decent electrical and thermal conductance within cable (solder-coated ReBCO tapes, minimal amount of layers).

- Assumption #2 (worst case): Poor thermal conductance (1 mm of epoxy) and no electrical conductance to jacket.

- Assumption #3: normal state behaviour of cable dominated by copper (RRR=150), 85% of cross-section.
ReBCO: Superconducting until \( \approx 80 \) K \( \rightarrow \) CORC-CICC is superconducting even at temperatures well exceeding current sharing temperature.

Conductor grading (each layer operating at 90\% of \( I_c \)): temperature dependent normalized \( I_c \) of each layer approximately overlaps, in spite of different applied fields
- 2.5 K temperature margin
- 500x enthalpy margin compared to 4.5 K, due to non-linear heat capacity.

Critical current approximately inversely proportional to magnetic field, in the 40-60 K range.

Temperature and field dependent \( I_c \) after Xu et al., Phys. Rev. B. 86 (2012)
Thermal simulations: Minimum Quench Energy (MQE)

- MQE calculations: Locally (200 mm cable section) elevated temperature \( \rightarrow \) Determine occurrence of thermal runaway.

- Considers local temperature dependent superconducting properties.

- Result: thermal runaway occurs when \( T_{\text{initial}} > 50 \pm 1 \) K, equivalent MQE = 2.1 \( \pm \) 0.3 kJ.

- Validation: consistent MQE (within error margin) for 50 mm cable section, thus implying point-source-like behaviour.
Thermal simulations: locally degraded $J_c$ -> thermal runaway

- Thermal runaway due to locally degraded $I_c$: local (200 mm section) degradation in $I_c$ to 85% of nominal $I_c$ (operating current at 90% of nominal $I_c$).
- Heating $\rightarrow$ Initial slow rise, accelerating with increasing temperature.
- $T_{\text{hotspot}}$ increases over time: 60 $\rightarrow$ 100 K: $\approx$20 s, 60 $\rightarrow$ 400K: $\approx$100s
- Very slow quench propagation velocity: $\approx$20 mm/s
Problem #1. Quench Detection

Very sensitive quench detection needed

- Monitoring for resistive voltage complicated due to presence of inductive noise
- Typical detector magnet threshold level: 1000 mV (such as CMS [1])
  - But, at 1000 mV, $T_{\text{hotspot}}$ already at room temperature
  - < 20 mV to limit $T_{\text{hotspot}}$ to just below 60 K --> 50x reduction in inductive noise needed
- How to reduce inductive noise?
  - Co-wound voltage taps?

Problem #2. quench mitigation

- Very slow quench propagation velocity: \( \approx 20 \text{ mm/s} \) --> Entire coil winding needs to be heated to induce a normal zone throughout the coil winding
- Need \( T >> T_{sh} \), for instance 60 K --> Enthalpy between 40 and 60 K: 10 GJ for entire coil winding
- Thermal runaway duration: 60 K --> 100 K: \( \approx 20 \text{ s} \). Must raise \( T \) to 60 K in about 20 s --> 500 MW!
  - Quench heaters: not feasible high power needed (several times total power consumption of CERN)
  - Quench back: Dissipation whenever there is \( dI/dt \), so 500 MW of dissipation at 1000 V extraction means 2.5 MW of cooling power required at 70 V (regular ramping).
  --> Quench heaters and quench back are not feasible.
- Extraction with dump resistor
  - Feasible, but high voltage (>20 kV) required for \( T_{\text{hotspot}} < 100 \text{ K} \) (challenging conductor insulation)
Novel quench protection: Rapid Quench Transformation (RQT)

Rapid Quench Transformation (RQT): solves two problems at once:

1. Used with a geometry with high magnetic coupling factor (here: 99.91%)
2. No current transfer to secondary RQT coil while ramping due to blocking diodes
3. Solution for problem #1: co-wound coil (functions as a co-wound voltage tap):
   - More than 100x reduction in inductive noise for low-threshold quench detection
   - Experimental demonstration [2]: 80x more inductive noise suppression with co-wound coil compared to balanced coil approach
   --> 20 mV threshold is feasible, so quench detection at $T_{\text{hotspot}}$ just below 60 K.
4. Solution for problem #2: After Quench Detection $\rightarrow$ Transform your way out of trouble (variation of an old concept, [3,4])

Rapid Quench Transformation: quench mitigation (1)

Rapid Quench Transformation:
--> transform your way out of trouble.

• After quench detection:
  - Fast dump breaker opens → Current transfer to RQT circuit
  - Transfer speed determined by magnetic coupling factor $k$
    
    $k = 99.91% \rightarrow \frac{1}{1-k^2} = 560x$ faster than RL-time
    
    --\>$50%$ current transfer to RQT circuit in about $4$ s

• Peak extraction voltage: $1500$ V (just resistor), or $1000$ V ($60$F supercapacitor array parallel to main dump resistor).
Rapid Quench Transformation: quench mitigation (2)

- Before quench detection:
  - Hot-spot heating until 20 mV detection threshold is reached (at $T_{\text{hotspot}}$ just below 60 K)
- Quench detection: current transformation into RQT circuit
  - Hot spot heating is dramatically reduced, due to reduced current: 10x reduction after couple of seconds, and then continues to drop
  - RQT circuit homogeneously heats up the entire cold mass
- After current extraction:
  - Almost 80% of stored energy extracted, 20% dissipated in RQT coil
  - Peak temperature just above 60 K and maximum temperature gradient < 20 K
Variations of the RQT concept

- Multiple RQT circuits per primary circuit
- Further reduction in inductive noise
- Faster current transformation
- Reduced layer-to-layer voltage
- Stable current distribution between RQT circuits due to negative feedback loop.

- All energy dissipated in cold mass
- Superconducting switch provides $\frac{dI}{dt}$
- Most energy may be dissipated in RQT coil.

- All energy dissipated in cold mass
- Allows for individual homogeneous quench of a magnet in a string of magnets.
Preliminary study of the quench behaviour of a very large 50 GJ detector magnet using ReBCO-based CORC-CICC technology at 40 K

- Excellent stability in worst case scenario assumptions: MQE in the kJ range
- Very low quench propagation velocity: \( \approx 20 \text{ mm/s} \)
- Thermal runaway time: \( 60 \text{ K} \rightarrow 100 \text{ K} \) in \( \approx 20 \text{ s} \)
  - Not feasible to protect the magnet with Quench Heaters / Quench Back
  - Feasible is high-voltage extraction (>20 kV), but challenging for insulation.

Novel Concept: Rapid Quench Transformation (RQT)

- Possible alternative for “classical” quench protection solutions
- Co-wound geometry mitigates inductive noise (similar to co-wound voltage tap), thus enabling low-threshold quench detection
- No transformation during regular ramping, due to blocking diodes
- Very rapid current transformation after quench detection by opening a single breaker, followed by gradual extraction
- Concept may be applied for high extraction (as illustrated here) or complete dissipation in cold mass, and is compatible with bypass diodes for individual homogeneous quenching of a magnet in a string of superconducting magnets.