IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
Invited presentation 3OrAC_02 given at MT24; Seoul, Korea, October 18 to 23, 2015.

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

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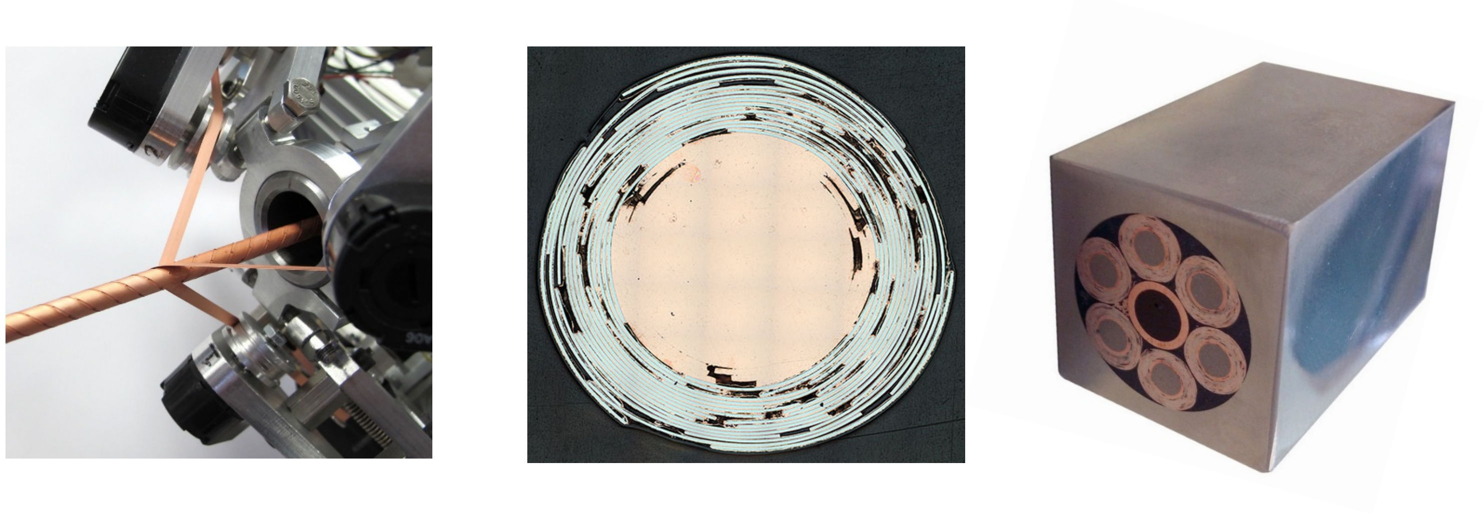
Magnet Technology conference, 10/21/15, Seoul (Korea)

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/mm^2 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

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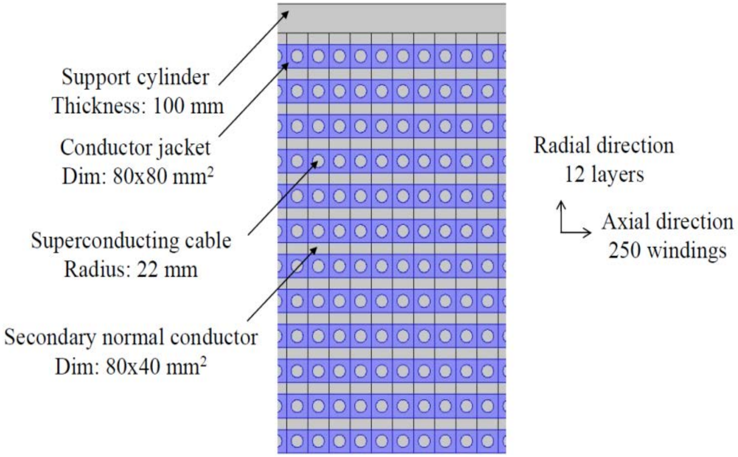
8 T, 50 GJ detector magnet operating at 40 K

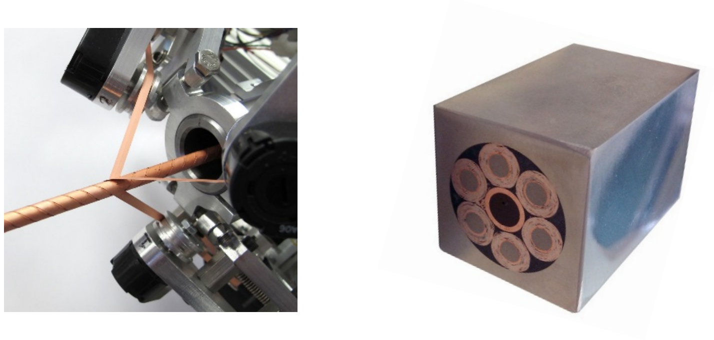


Property	Value	Property	Value
Coil length	20 m	B_{center}	8.0 T
Coil inner radius	5.0 m	$B_{conductor}$	8.5 T
Coil outer radius	6.4 m	Stored energy	50.0 GJ
Number layers	12	Operating current	49 kA
Number turns	250	Self-Inductance primary circuit	41.5 H
Operating temp.	40 K	Coupling coefficient	99.9%

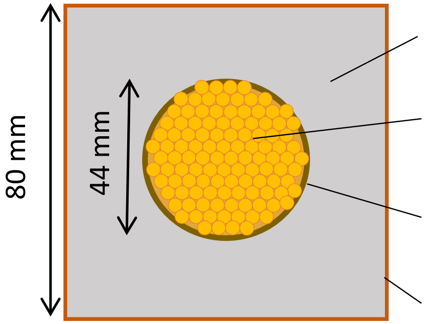
Conceptual design of an 8 T, 50 GJ HTS-based superconducting magnet

- 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



Demonstration conductor: 6-around-1 Conductor-in-Round-Core (CORC) Cable-in-Conduit Conductor (CICC)



Structural reinforcement: Al-alloy

Core: 3-4 mm CORC strands (100+) bundled together in ITER-like fashion

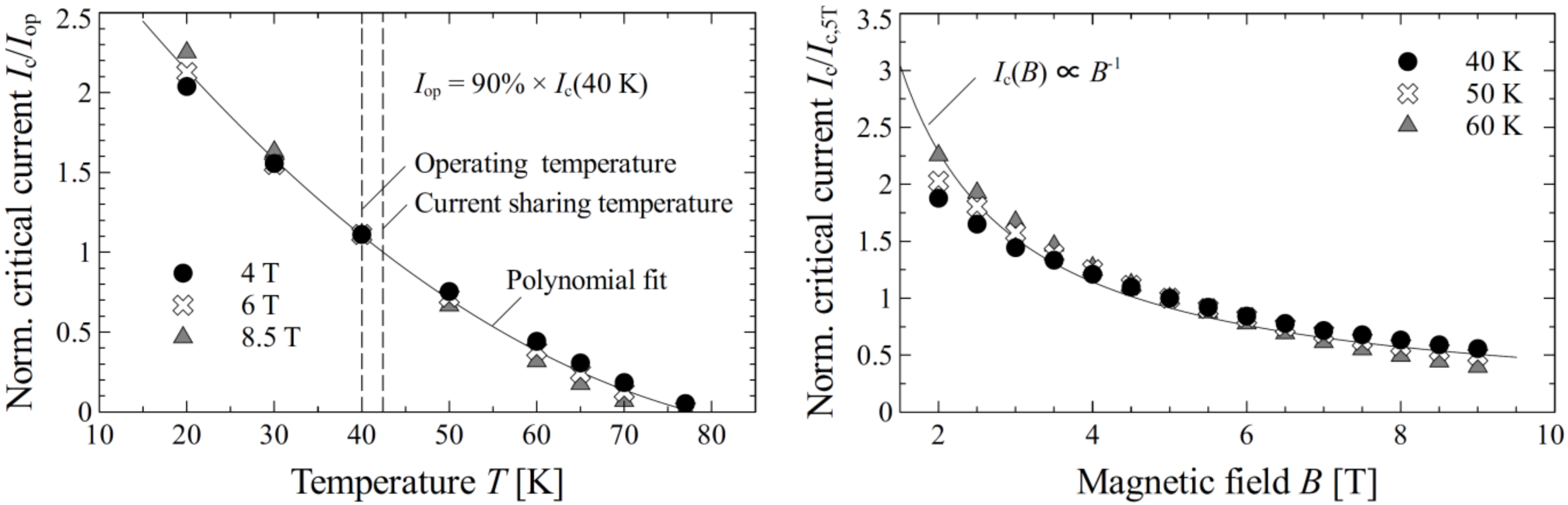
1 mm epoxy between core and jacket (worst case scenario assumption)

Insulation: 1 mm fiber glass-epoxy

Assumed conductor: Conduction-cooled Cable-in-Conduit with relatively poor electrical / thermal contact between cable and jacket

- 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.

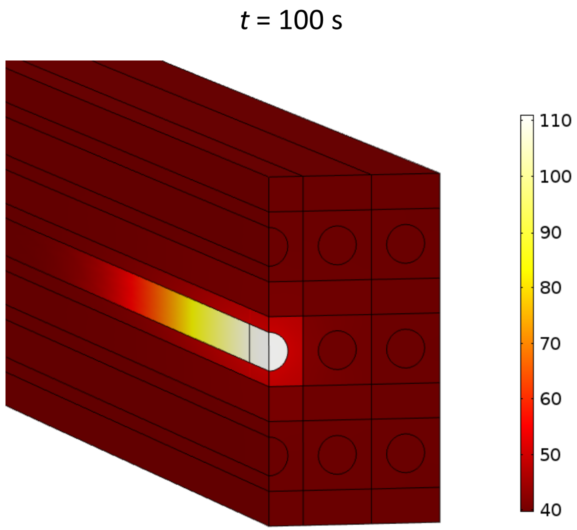
T and B dependence of ReBCO critical current

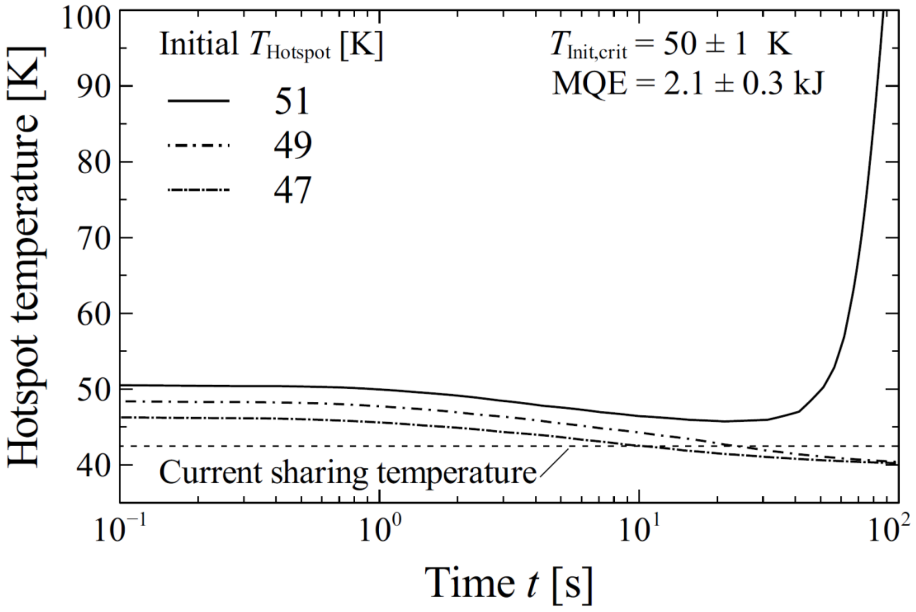


Temperature and field dependent I_c, after Xu et al., Phys. Rev. B. 86 (2012)

- ReBCO: Superconducting until ≈80 K → 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.

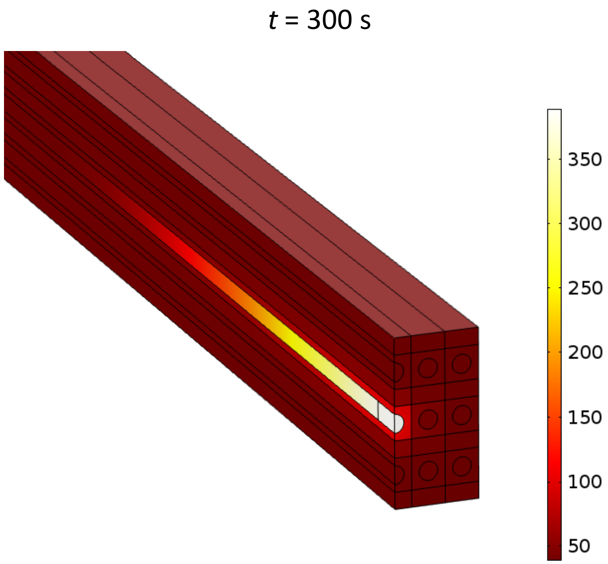
Thermal simulations: Minimum Quench Energy (MQE)

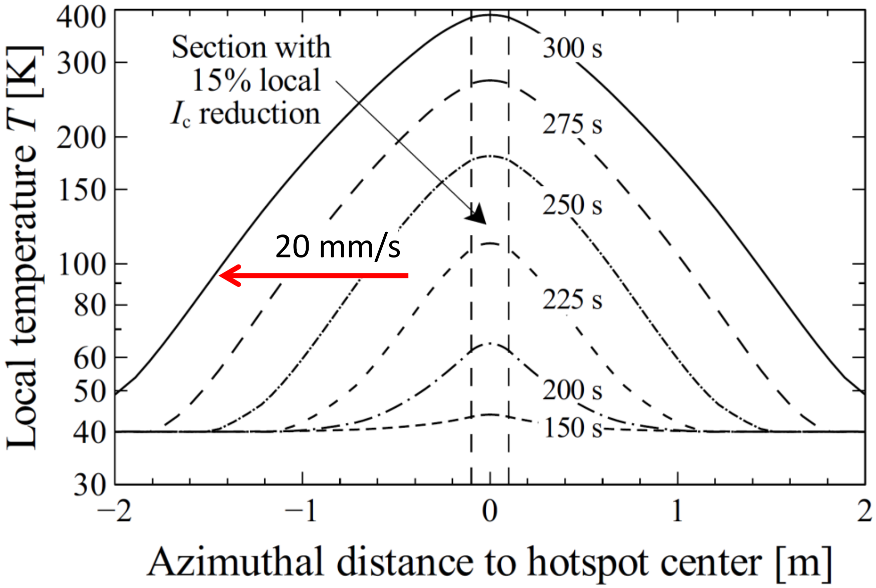




- MQE calculations: Locally (200 mm cable section) elevated temperature → Determine occurrence of thermal runaway.
- Considers local temperature dependent superconducting properties.
- Result: thermal runaway occurs when $T_{\text{initial}} > 50 \pm 1$ K, equivalent MQE = 2.1 ± 0.3 kJ.
- Validation: consistent MQE (within error margin) for 50 mm cable section, thus implying point-source-like behaviour.

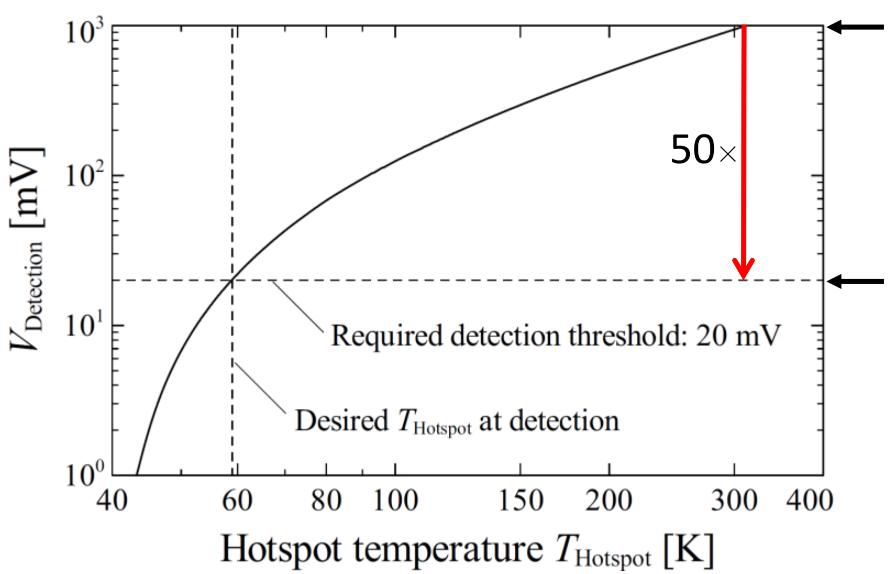
Thermal simulations: locally degraded J_c -> thermal runaway





- 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 → Initial slow rise, accelerating with increasing temperature.
- $T_{hotspot}$ increases over time: 60 → 100 K: ≈20 s, 60 → 400K: ≈100s
- Very slow quench propagation velocity: ≈20 mm/s

Problem #1. Quench Detection



Typical threshold level

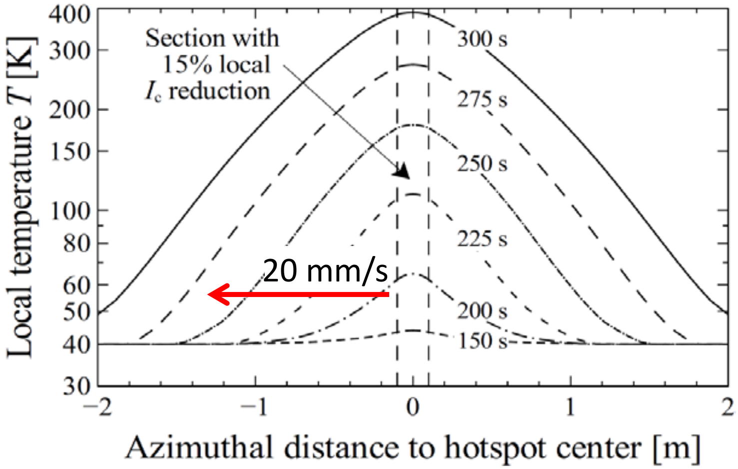
Required threshold level

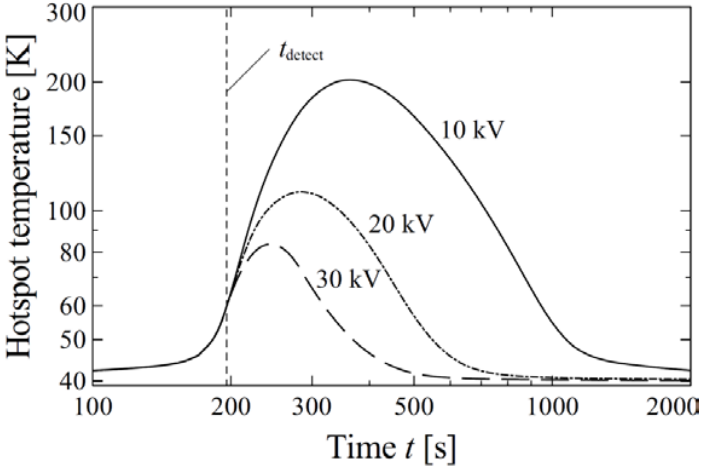
Very sensitive quench detection needed

- 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_{hotspot} already at room temperature
  - < 20 mV to limit T_{hotspot} to just below 60 K --> 50x reduction in inductive noise needed
- How to reduce inductive noise?
  - Co-wound voltage taps?

[1] Fazilleau et al. IEEE Trans. Appl. Supercond. 16 (2006)

Problem #2. quench mitigation

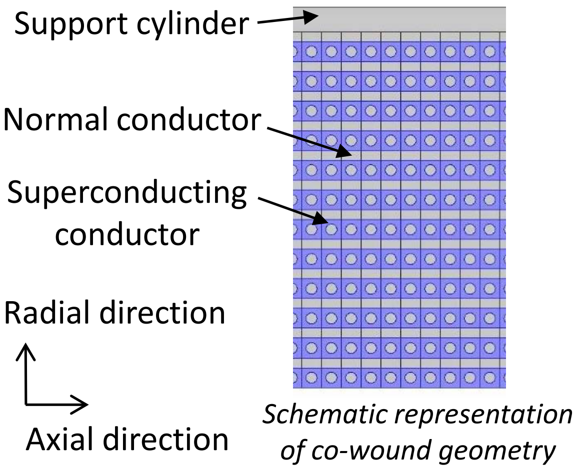




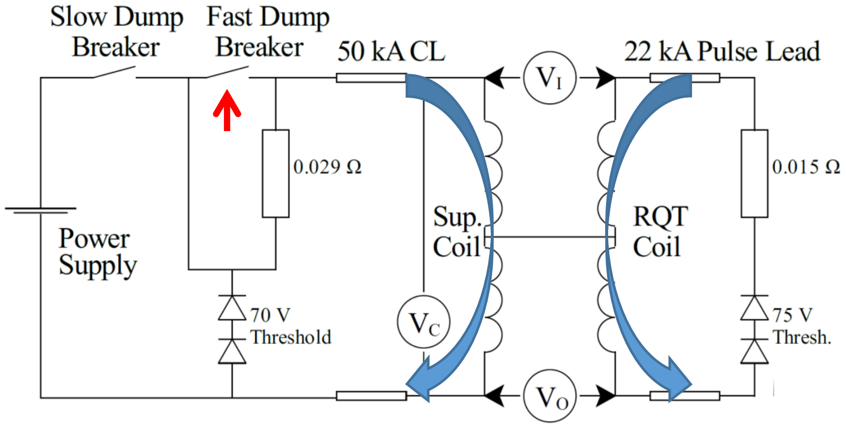
- Very slow quench propagation velocity: ≈20 mm/s --> Entire coil winding needs to be heated to induce a normal zone throughout the coil winding
- Need T >> T_{sh}, for instance 60 K --> Enthalpy between 40 and 60 K: 10 GJ for entire coil winding
- Thermal runaway duration: 60 K --> 100 K: ≈20 s. Must 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 $T_{hotspot}$ < 100 K (challenging conductor insulation)

Novel quench protection: Rapid Quench Transformation (RQT)



Schematic representation of co-wound geometry



Electrical scheme of RQT concept

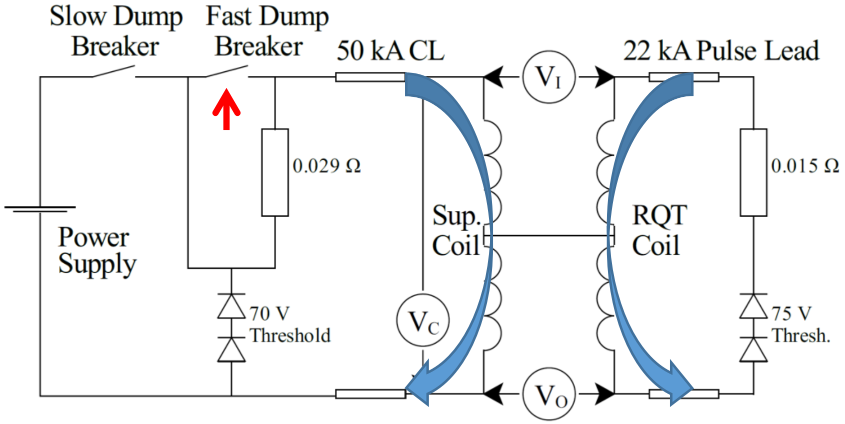
Rapid Quench Transformation (RQT): solves two problems at once:

- Used with a geometry with high magnetic coupling factor (here: 99.91%)
- No current transfer to secondary RQT coil while ramping due to blocking diodes
- 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

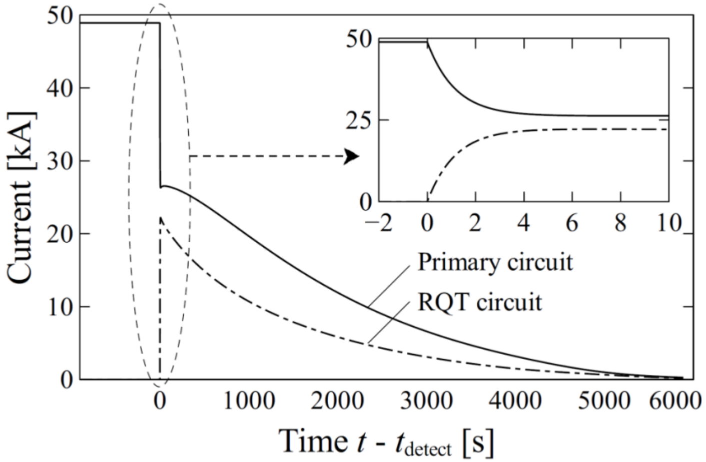
  --> 20 mV threshold is feasible, so quench detection at $T_{hotspot}$ just below 60 K.
- Solution for problem #2: After Quench Detection → Transform your way out of trouble (variation of an old concept, [3,4])

[2] Ariyama et al. Presented at EUCAS conference, Lyon (2015)
[3] Smith, Rev. Sci. Instrum. 34 (1963)
[4] Takahata et al. Int. Stell. Workshop, Toki (2007)

Rapid Quench Transformation: quench mitigation (1)



Electrical scheme of RQT concept



$$\frac{dI_{\mathrm{sup}}}{dt} = \left(\frac{1}{1-k^2}\right)\left(\frac{-V_{\mathrm{sup}}}{L_{\mathrm{sup}}} + \frac{MV_{\mathrm{RQT}}}{L_{\mathrm{RQT}}L_{\mathrm{RQT}}}\right)$$

$$\frac{dI_{\mathrm{RQT}}}{dt} = \left(\frac{1}{1-k^2}\right)\left(\frac{-V_{\mathrm{RQT}}}{L_{\mathrm{RQT}}} + \frac{MV_{\mathrm{sup}}}{L_{\mathrm{RQT}}L_{\mathrm{RQT}}}\right)$$

Rapid Quench Transformation:

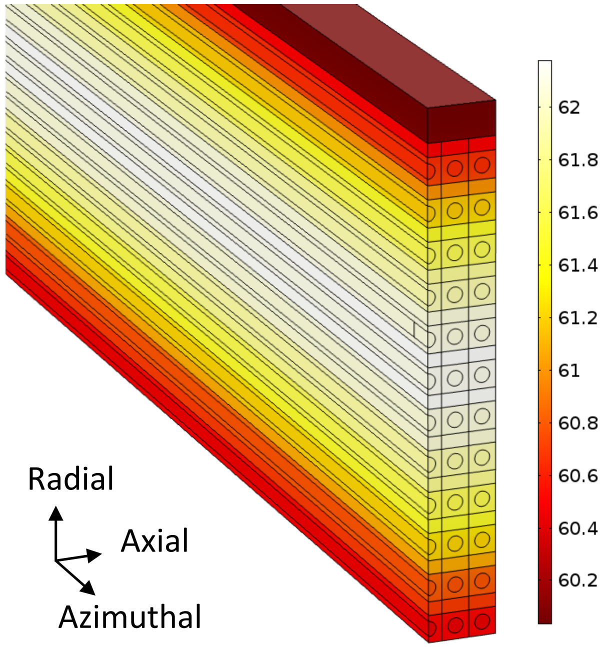
--> transform your way out of trouble.

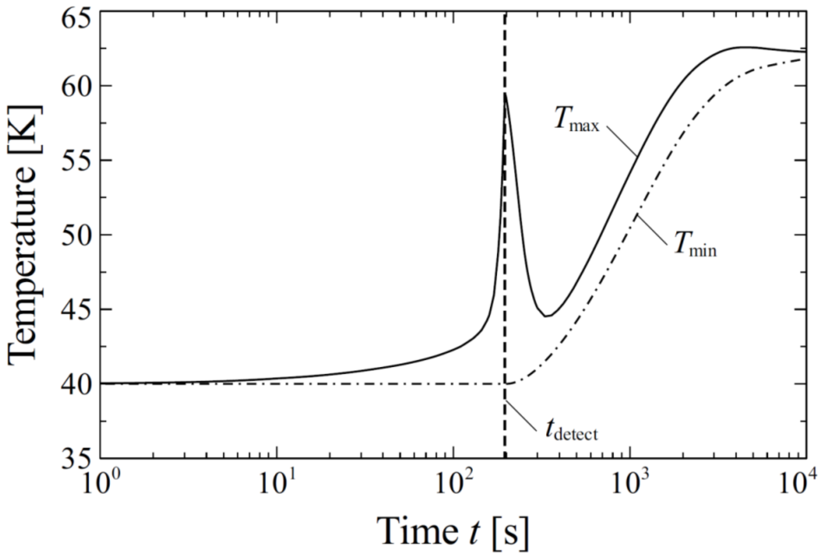
- After quench detection:
  - Fast dump breaker opens → Current transfer to RQT circuit
  - Transfer speed determined by magnetic coupling factor *k*

    k = 99.91% → $1/(1-k^2)$ = 560x faster than RL-time

    --> Just under 50% current transfer to RQT circuit in about 4 s
- Peak extraction voltage: 1500 V (just resistor), or 1000 V (60F supercapacitor array parallel to main dump resistor).

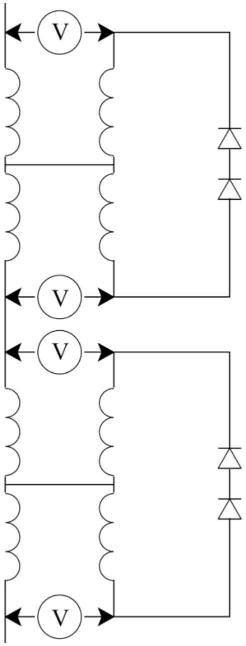
Rapid Quench Transformation: quench mitigation (2)


$t = t_{detect} + 3600$ s

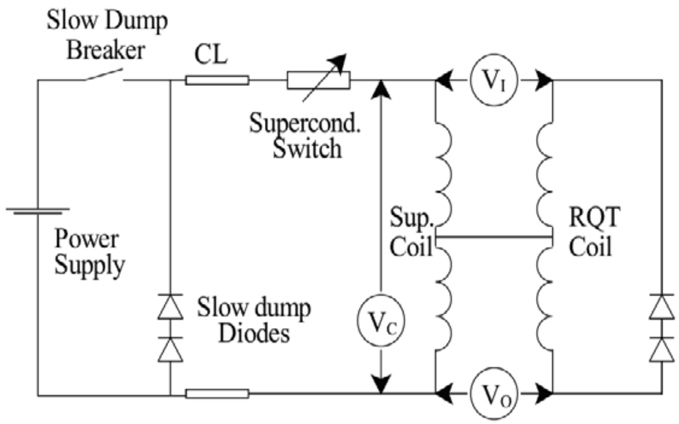


- Before quench detection:
  - Hot-spot heating until 20 mV detection threshold is reached (at $T_{hotspot}$ just below 60 K)
- Quench detection: current transformation into RQT circuit
  - Hot spot heating is dramatically reduced, due to reduced current: 10x reduction after couple of seconds, and then 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

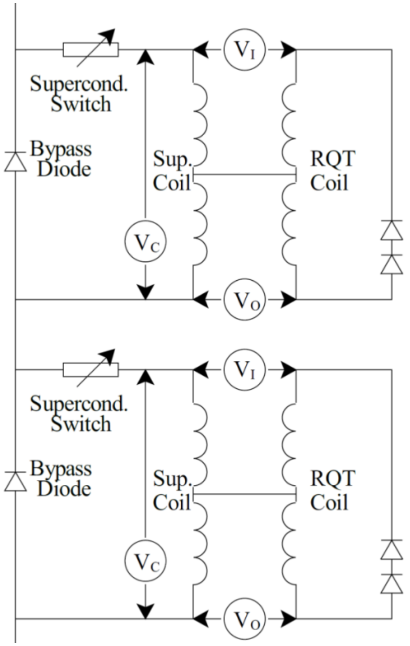
Variations of the RQT concept



- 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 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.

Conclusion

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: ≈ 20 mm/s
- Thermal runaway time: 60 K → 100 K in ≈ 20 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.