Quench Protection of CCT-type High-field Magnets for Accelerators

PAUL SCHERRER INSTITUT PSI · CERN · BERKELEY LAB

J. Gao (PSI), B. Auchmann (CERN/PSI), L. Brouwer (LBNL), S. Caspi (LBNL), J. Mazet (CERN), G. Montenero (PSI), S. Sanfilippo (PSI)

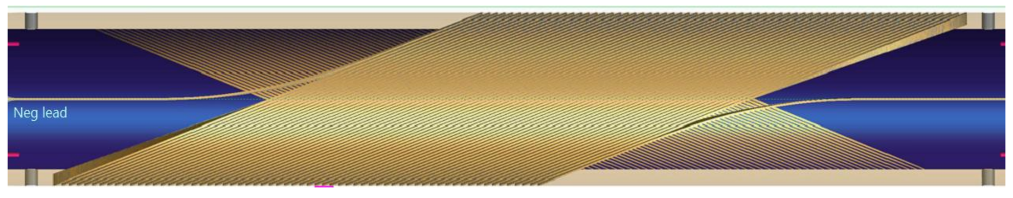
Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Abstract

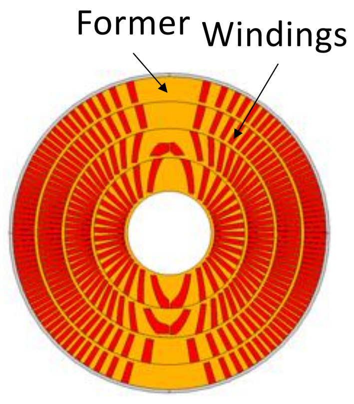
The Canted-Cosine-Theta (CCT) type magnet has been proposed for Future Circular Collider (FCC) design. Its unique geometry lowers the coil stress intrinsically. Nevertheless, the former itself is also a barrier for heat to quickly propagate in case of a quench. To succeed in the magnet design and construction, further investigation is required on its electrothermal behavior. The potential detection & protection concepts are studied in both aspects of multiphysics simulations and experiments. The results will allow us to validate the conceptual design and feasibility of the construction of a fast and efficient quench protection system of CCT-type magnets for accelerators.

Context

- CCT: Nested & tilted solenoids oppositely canted; Production of a pure vertical field
- Windings placed within formers intercepting Lorentz forces on each turn to prevent stress accumulation



Two-layer CCT (L. Brouwer)

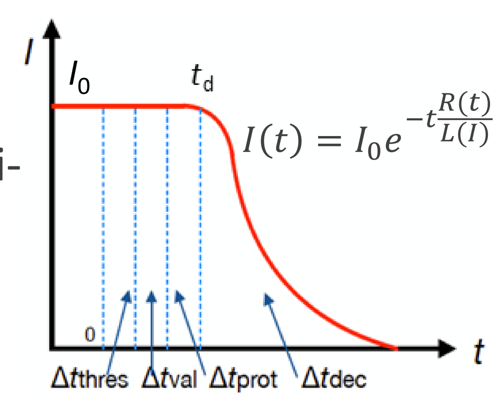


FCC Four-layer CCT

- PSI CCT program with CERN & LBNL to optimize FCC design in performance, protection and cost reduction
- At PSI, construction of two-layer canted dipole model magnets CD1 and CD2
- Studies on two-layer model magnets to prove four-layer magnet technologies, especially searching for ways to significantly reduce overall quench detection time, and these studies may also benefit other magnet designs

Quench

- Transition from superconducting to normal-conducting state: R_{quench} ↗ Joule heating in Cu, causing T ↗ in normal zone
- Protection: Dissipate magnetic energy as heat or quench entire coil to limit T_{peak} and avoid damage
- Different phases in a quench:
  - I constant, heat propagation:
    - 1a. Detection Δt_{thres}
    - 1b. Validation Δt_{val}
  - I decreases, energy dissipation by Joule heating:
    - 2a. Protection Δt_{prot}
    - 2b. Discharge Δt_{dec}



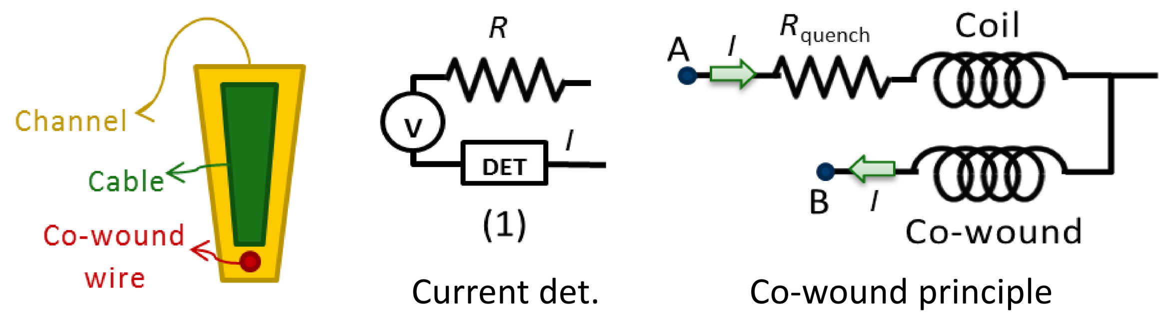
- Time scale in millisecond! Magnet design efficiency: less protection time = less Cu fraction in SC strand = smaller coil

Simulation Methods

- Main tool: ANSYS Mechanical APDL - miss features like multi-dependency material properties and cable-eddy currents
- Objectives: Electromagnetic-thermal coupled quench simulation in a hierarchical approach and use of thermal and electrodynamic elements (User-Defined Elements) developed by LBNL

Detection Concepts

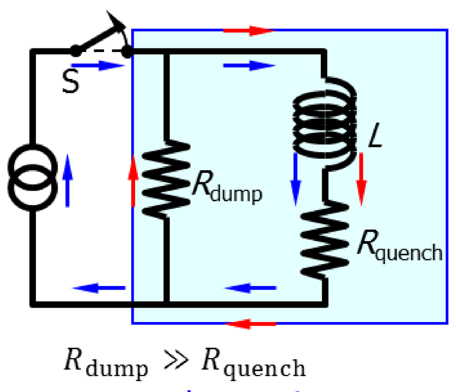
- Voltage detection using co-wound Cu wires: $V_{meas} = V_q$; low-risk but Δt_{val} obligatory
- Current detection using co-wound Nb_3Sn wires: expect to eliminate Δt_{val}; can be studied in detail
- Optical detection using co-wound optical fibers: temperature and strain data from analysis of spectral shift (Rayleigh backscattering spectra); high-risk but shorter delay time; collaboration with NCSU



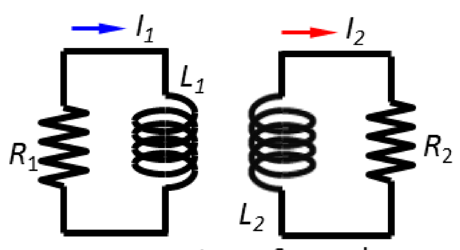
Current det. Co-wound principle

Protection Concepts

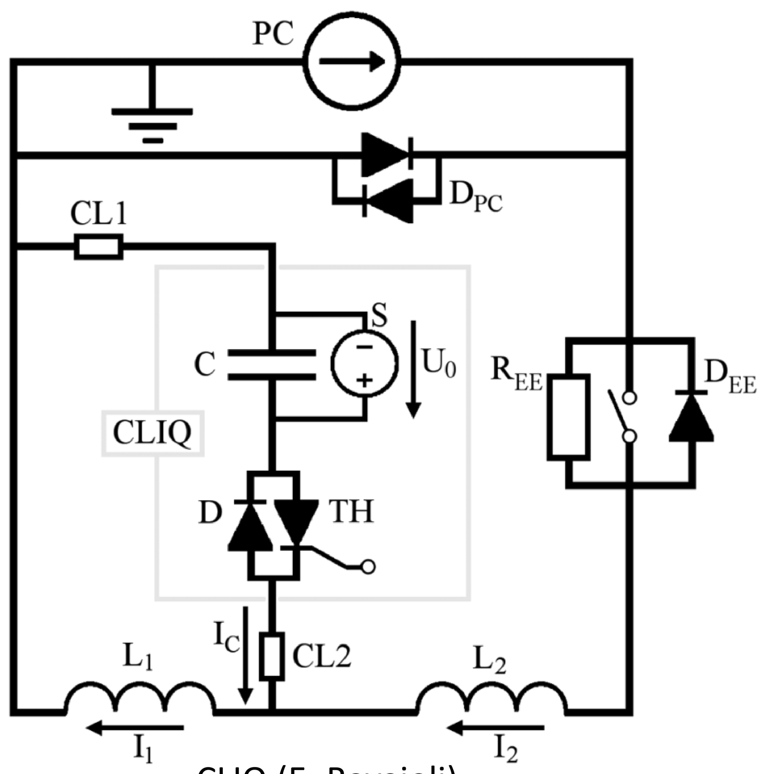
- Energy extraction: suitable for a single-magnet system
- Coupling-Loss Induced Quench (CLIQ): I oscillations → coupling losses → quench; most promising method
- Inductive protection using co-wound Cu tapes: quench process enhancement



Energy extraction (L. Bottura)



Inductive protection



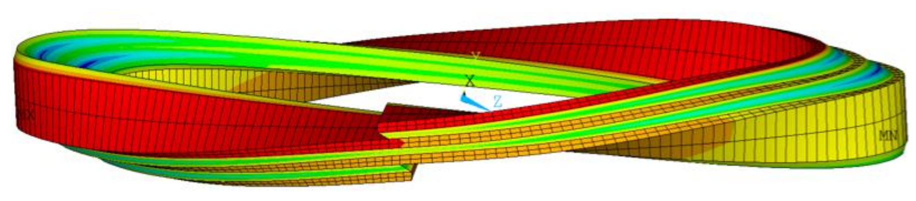
CLIQ (E. Ravaioli)

Protection of a two-layer model CD1 with energy extraction

- CD1: I_{ss} = 18 kA, B = 11 T, T_{op} = 4.2 K
- Voltage detection: $t_d = \Delta t_{thres} + \Delta t_{val} + \Delta t_{switch}$
- Energy extraction: $R_{dump} = 55.6\ \text{m}\Omega$ ($U_{max} = 1$ kV)

- MIITs gives time budget t_d for a given superconductor and a given current decay: If $T_{max} < 350$ K → MIITs < 10 → Upper-limit Δt_{thres}^{ref}
- No Δt_{val} if a high U_{thres} used (500 mV)
- Assume $\Delta t_{switch} = 5$ ms → Upper-limit t_d

- For a same U_{thres}, quench simulation gives Δt_{thres}^{ANSYS}
- Slow turn-to-turn and layer-to-layer propagation

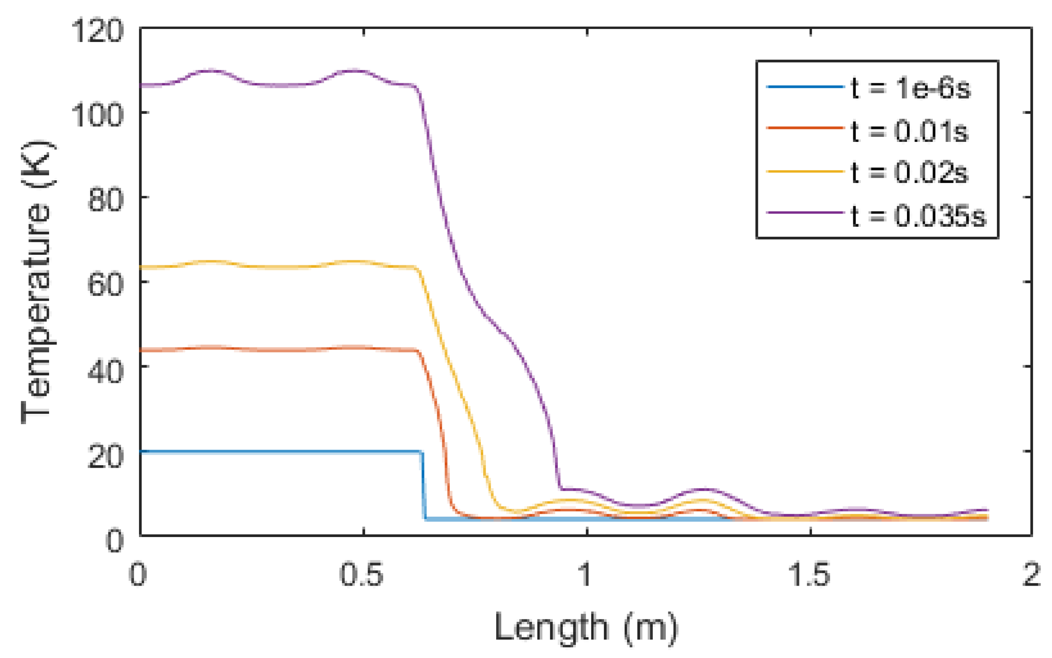


3-turn Helical model at I = 12 kA, B = 7.3 T
Initial conditions: T = 20 K for 1st turn (T_{cs} = 9.8 K) and $T = T_{op}$ for others
Better observation of quench propagation at a low operation level (t longer)

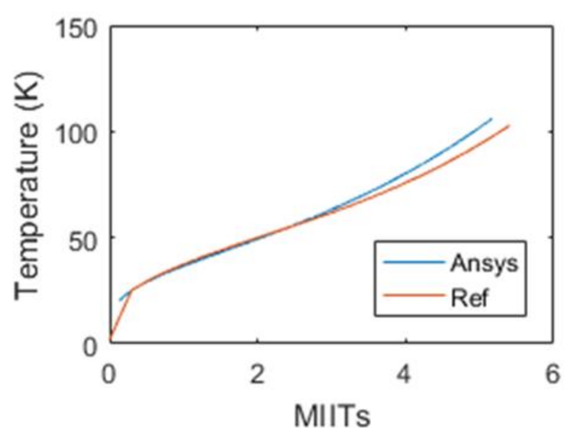
I [kA]	B [T]	Δt_{thres}^{ref} [ms]	Δt_{thres}^{ANSYS} [ms]	MIITs [MA²S]	T_{max} [K]
18	11	23.5	3.8	7.6	199
15.5	9.5	33.5	12	7.5	193
12	7.3	59	26.9	6.8	145

MIITs: Total MIITs in a quench, including the current decay
T_{max}: Max temperature estimated by MIITs after a quench

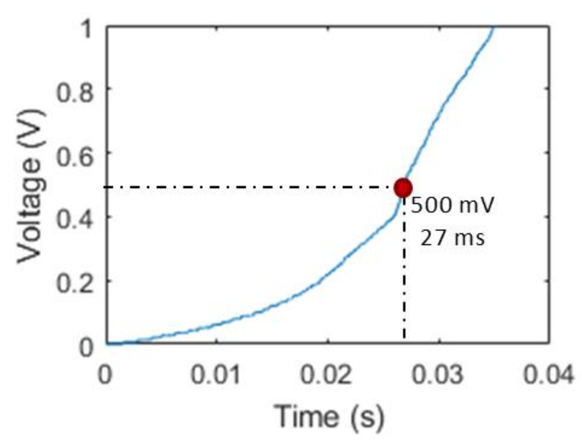
Temperature profiles along the coil at different times



Comparison of MIITs and temperature coherence



Evolution of detectable voltage with time



Conclusion

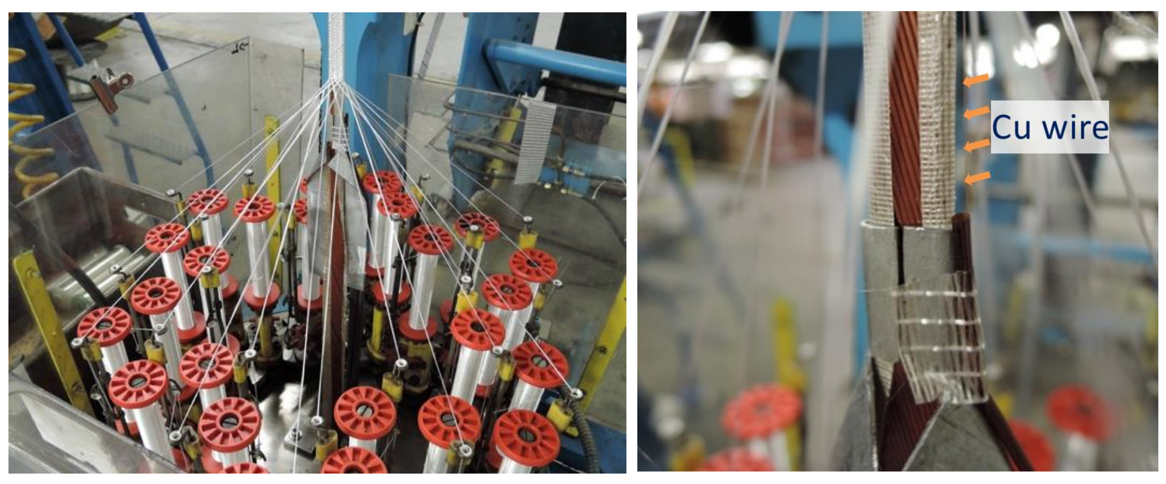
- Good time margin and temperature margin
- CD1 protectable magnet with energy extraction; Test-bed for other detection & protection methods

Future Directions

- Study different protection concepts, especially CLIQ, via simulations in two-/four-layer magnets
- Implement, test and validate the system in two-layer model magnets

Experimentation

	CD1	CD2
Detection	Co-wound Cu wire + optical fiber	Co-wound Nb_3Sn wire + optical fiber
Protection	Energy extraction + CLIQ	Energy extraction + CLIQ, possibly with co-wound Cu tapes
Diagnostics	Spot heaters + acoustic emission sensors	



Insulation braiding with thin co-wound Cu wire

Acknowledgements

I would like to thank F. Scurti (NCSU) for his expert advice and help so far with the optical wire in the project.

References

1) Auchmann, B., et al. Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC. *IEEE Transactions on Applied Superconductivity, 28*(3), 1-5, 2018.
2) Bottura, L. Superconductors. Presentation, November 2012.
3) Brouwer, L. *Canted-Cosine-Theta Superconducting Accelerator Magnets for High Energy Physics and Ion Beam Cancer Therapy.* PhD thesis, University of California, Berkeley, 2015.
4) Marchevsky, M. Protection of superconducting magnet circuits. Lecture notes of U.S. Particle Accelerator School, 2017.