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Modeling of Quench Protection Concepts for Canted-Cosine-Theta Type High-Field Magnets

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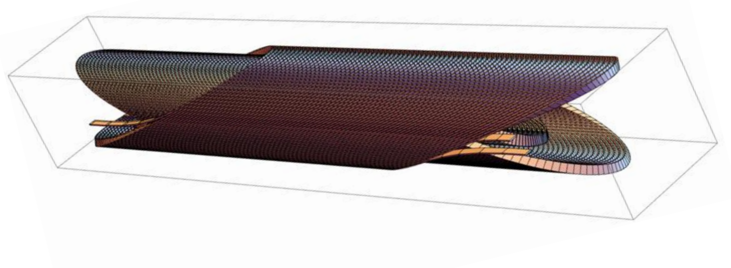
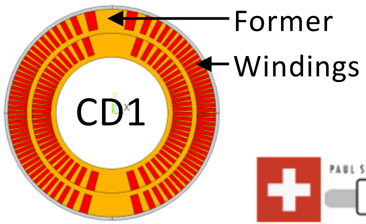
Outline

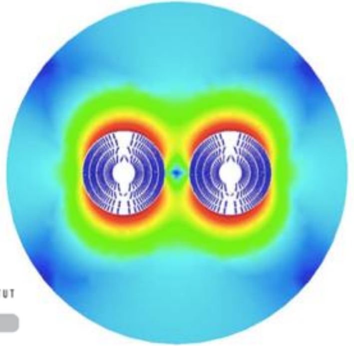
- Introduction
- Quench protection simulations of 2-layer CCT-type magnets
  - Study of energy extraction
  - CLIQ unit behavior
- Conclusion

Introduction

- **Future Circular Collider:** 16 T dipole magnets required
- **Canted-Cosine-Theta:** a possible candidate for FCC
  - Former: mechanical stability ✓, quench propagation ✗



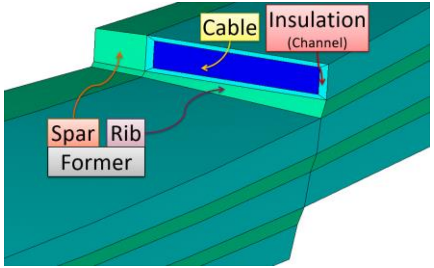




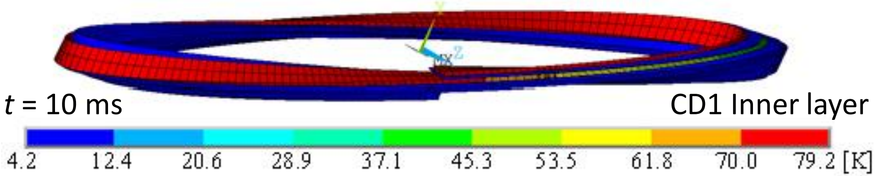
- Quench protection criteria: T_{max} = 350 K, V_{GND} = 1 kV
- Energy extraction + coupling-loss induced quench system selected for CD1
- **First-of-a-kind CCT-type magnet protection study** using 2D ANSYS User-Defined Elements (developed by LBNL)

PSI Superconducting Magnet Lab (Status 2019)

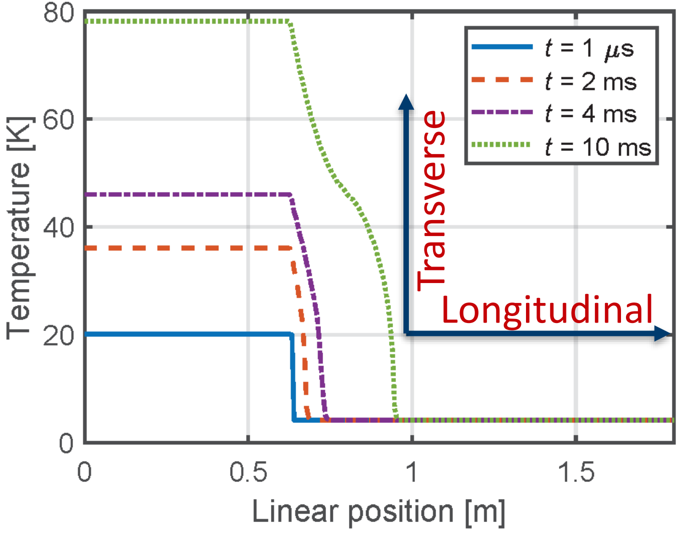
Quench Propagation Simulation



- **3-turn helical model:** I_{ss} = 20 kA, B = 11 T, T_{op} = 4.2 K
- **Initial conditions:** I = 18 kA, T = 20 K for 1st turn and $T = T_{op}$ for the rest

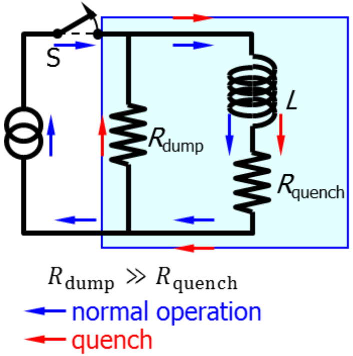


Cable center temp. along the coil



- Fast longitudinal propagation, slow turn-to-turn (and layer-to-layer) propagation due to former
- $T_{cable}(t,x) \rightarrow R_{quench}(t) \rightarrow V_{quench}(t) \xrightarrow{V_{thres}} \Delta t_{thres}$

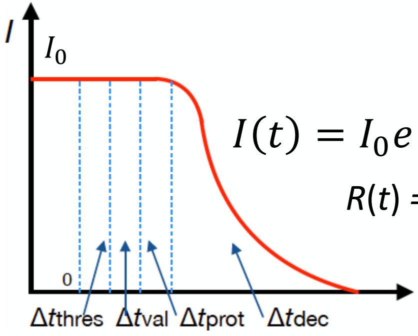
Study of Energy Extraction



Courtesy of L. Bottura

- R_{dump} in series with magnet: R_{dump} = 40 mΩ, V_{GND} = 800 V
- **Voltage detection:** $t_{\text{d}} = \Delta t_{\text{thres}} + \Delta t_{\text{val}} + \Delta t_{\text{switch}}$
- V_{thres} = 500 mV → $\Delta t_{\text{val}} = 0$; Δt_{switch} = 5 ms
- MIITs links a current-decay function to a peak temperature for a given cable type under adiabatic conditions.

$$\text{MIITs} = 10^{-6}\int_0^{\infty} I^2(t)\mathrm{d}t = 10^{-6} v A^2 \int_{T_0}^{T_{\max}} \frac{\overline{c_{\text{v}}(T)}}{\rho_{\text{Cu}}(T)}\mathrm{d}T = F(T_{\max})$$



$$I(t) = I_0 e^{-t\frac{R(t)}{L(I)}}$$

$R(t) = R_{\text{dump}}$

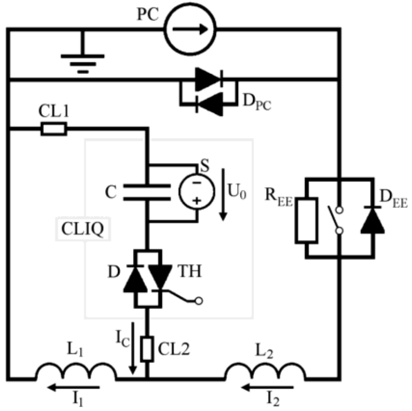
Estimation of $T_{\max}$ after a quench

I [kA]	Δt_{thres} [ms]	t_{d} [ms]	T_{cable} [K]
18	6.3	11.3	332
15	13.7	18.7	250
12	27	32	167

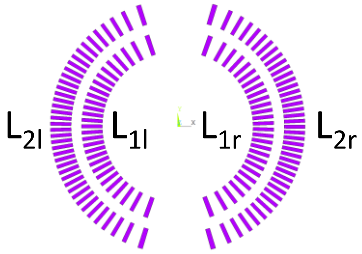
< 350 K
CD1 safe
With EE

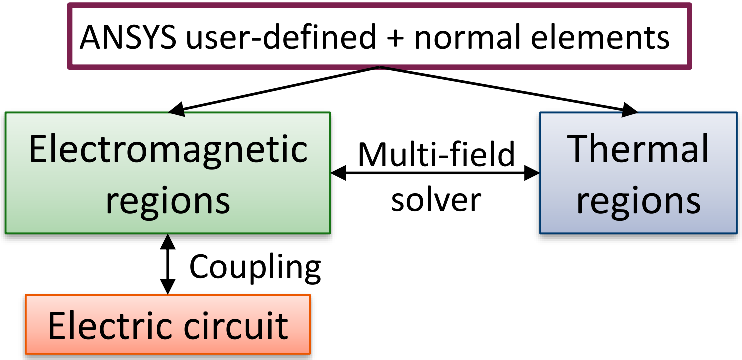
CLIQ Simulation using UDEs

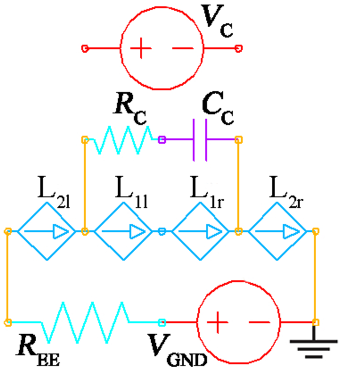
- **Coupling-loss induced quench:** inter-filament coupling losses → heat generated directly in SC → a fast quench
- **Goal:** electromagnetic and electrothermal behavior of CD1 full model based on a 2D cross section model
- **Thermal UDE:** multi-dependence material properties
- **Electromagnetic UDE:** sub-strand IFCLs



Courtesy of E. Ravaioli





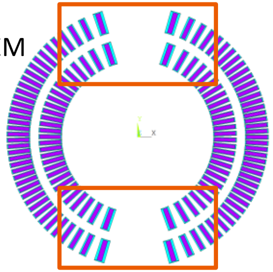


Simplified CD1 circuit with EE and CLIQ in ANSYS

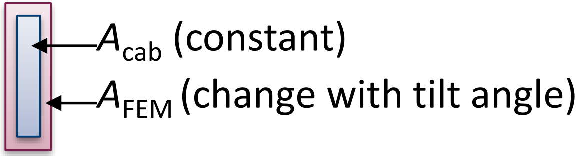
Modifications of UDEs for CCT-type Magnets

- Add CD1 critical current density J_c fit functions

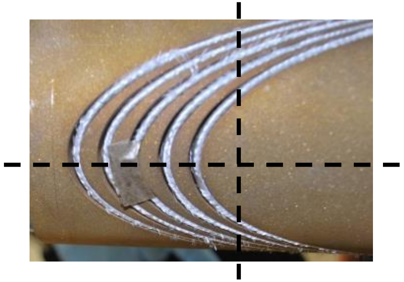
Large A_{FEM}



- Define a tilt factor as $f_{tilt} = A_{cab}/A_{FEM}$, applied in all turns
  → Same J_c
  → Dilute material properties



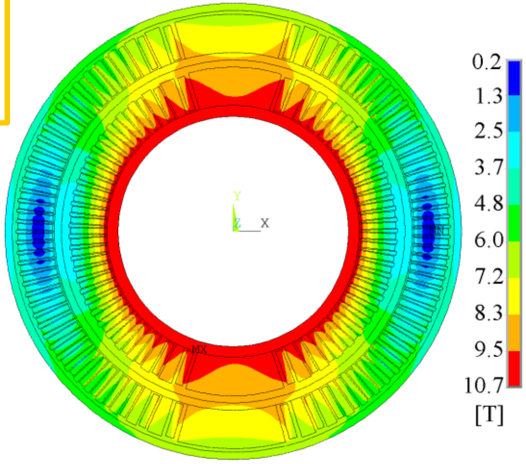
- Adjust cable length of each half-turn
  → Right values of resistance (also *I*, *V*)



Simulation Results

I = 18 kA
T_{init} = 4.2 K

Init. *B* field



CLIQ:
V_C = 400 V
R_C = 25 mΩ
C_C = 10 mF

Constant ρ(4.2 K) for former + shell as a conservative estimate.

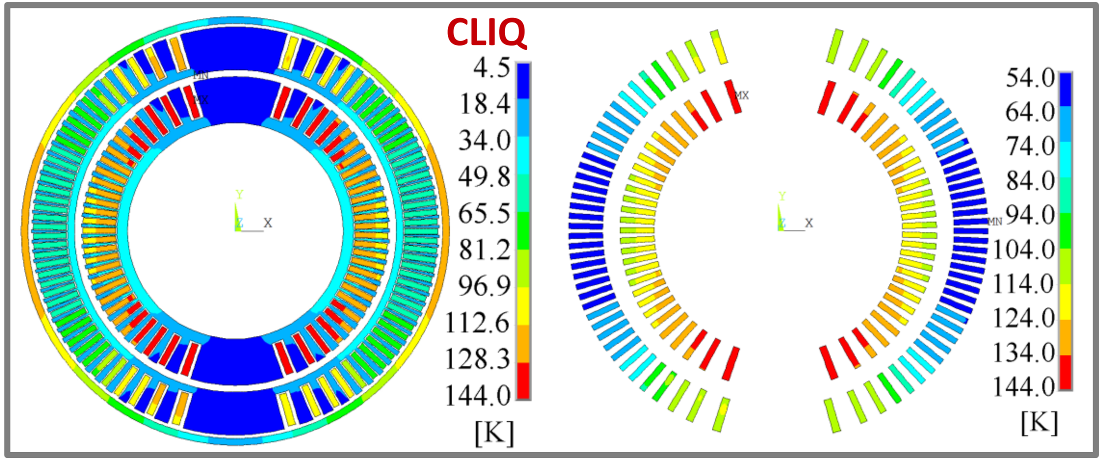
		CLIQ		CLIQ+EE	
I [kA]	B [T]	T_{cable} [K]	T_{coil} [K]	T_{cable} [K]	T_{coil} [K]
18	10.7	144.0	144.0	68.5	129.6
12	7.3	123.8	123.8	38.5	89.0
6	3.7	10	21.3	14.5	55.2

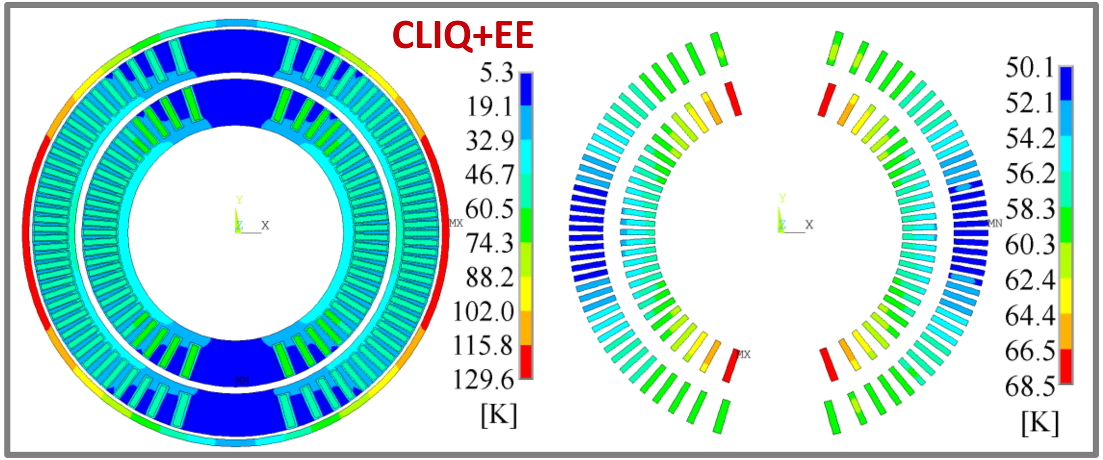
Study of protection system from 4.2 K, temp. rise during detection not included.

***T* at 50 ms**

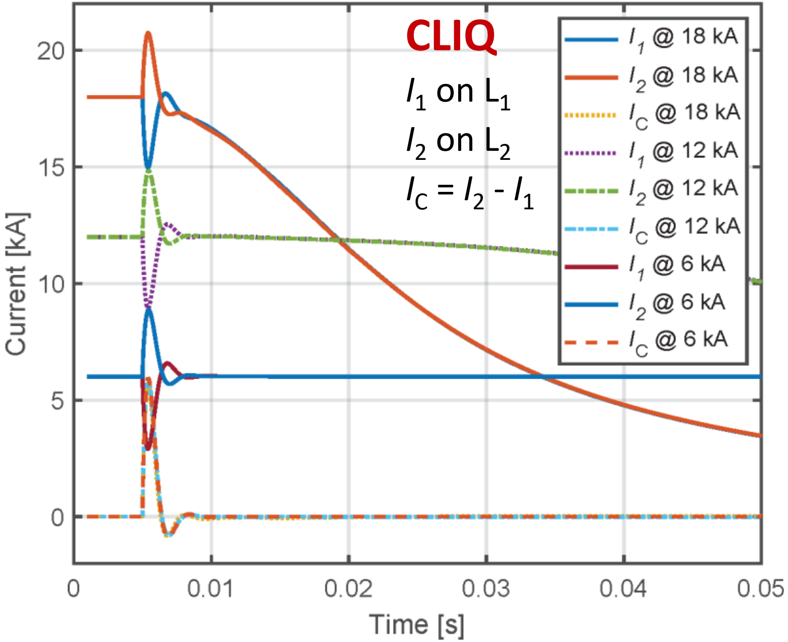
Bare cable, former, Al protective shell

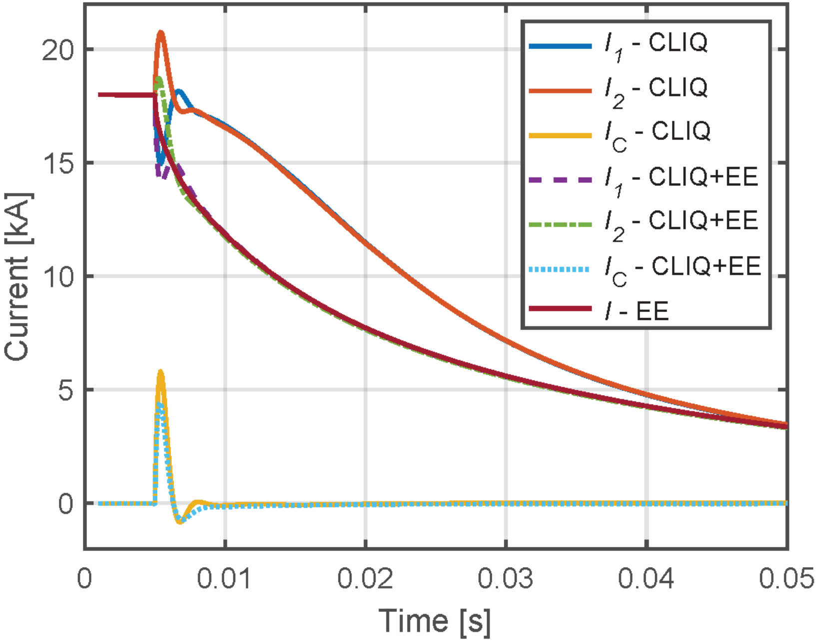
Bare cable





Current Profiles in Stranded Elements





CLIQ works in CCT-type magnet.

→ CLIQ efficiency and EE delay times are to be studied for CD1 test.

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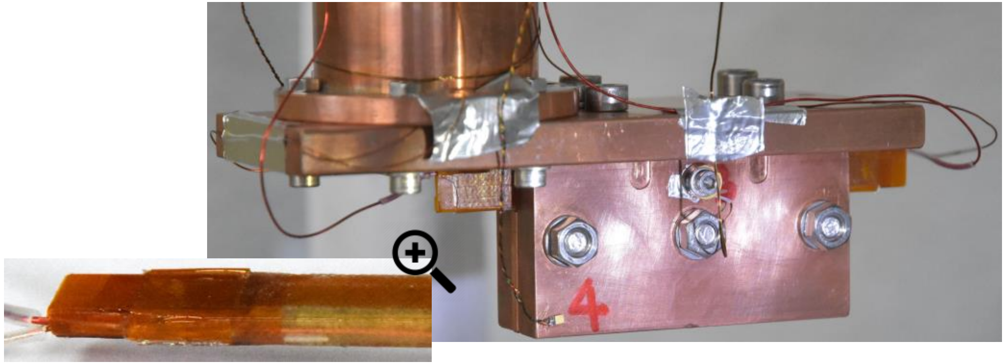
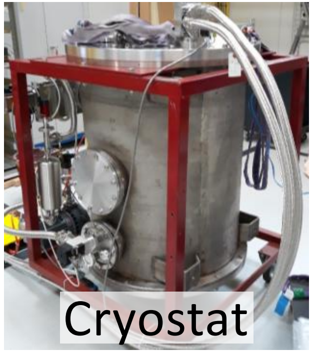
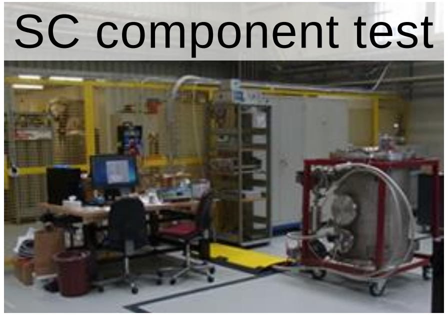
Conclusion

- Quench protection studies of a two-layer CD1 magnet presented
  - CD1 protectable with EE, $T_{peak} < 350$ K
  - Coupled simulations using CLIQ in CCT geometries
  - Simulation results will be compared to CD1 experimental data to validate generic quench simulation models
- CD1 expected to be finished and shipped to LBNL for test in Nov. 2019
- Underway subscale experiments at PSI on current detection



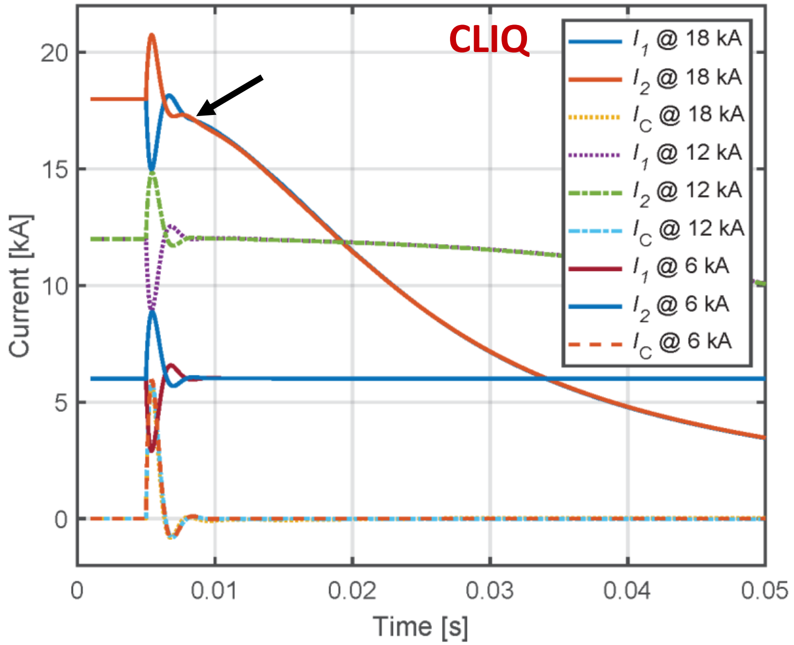




Backup

CLIQ Discharge, After 2 Oscillations

I **= 18 kA**
T_{init} **= 4.2 K**



***T* at 8 ms**

Bare cable, former, Al protective shell