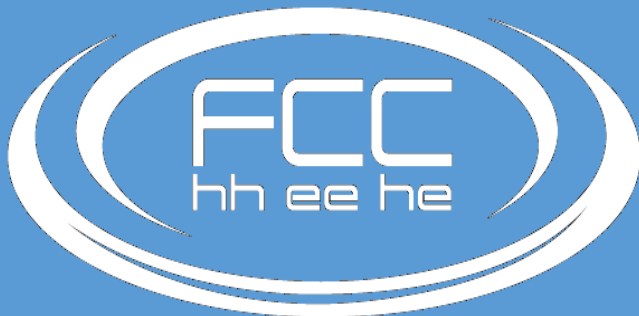


Protection of FCC 16 T dipoles

Tiina Salmi (TUT), Marco Prioli (CERN), Emmanuele Ravaioli (LBNL),
Antti Stenvall (TUT), Bernhard Auchmann (CERN), Arjan Verweij (CERN), Janne Ruuskanen (TUT),
together with all the EuroCirCol WP5 members

FCC week 2017, Berlin

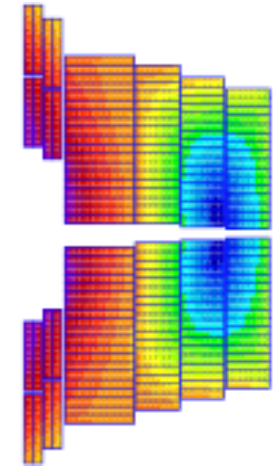
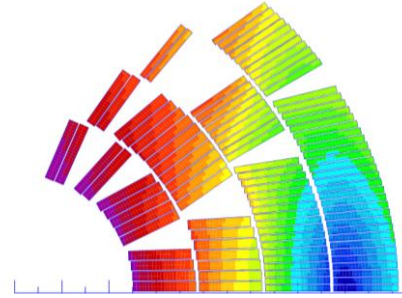
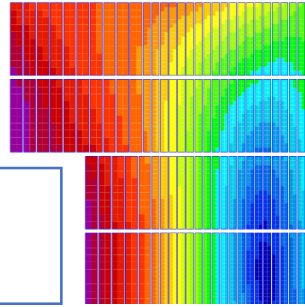


Outline

- 16 T dipole design options in EuroCirCol WP5
- Integration of quench protection into the magnet design
- Protection with quench heaters
- Protection with CLIQ (Block)
- Protection with and CLIQ+heaters (Block)
- Conclusions

Magnet designs

All 14.3 long
Cos θ and Block 1-ap. versions



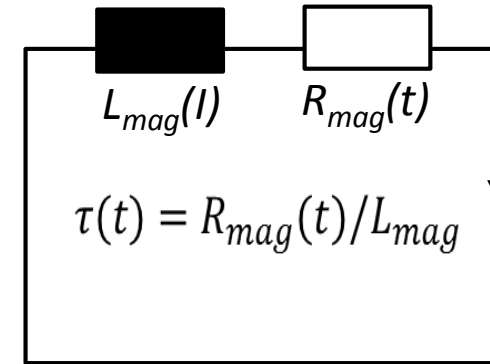
Magnet	Block, V20ar		Cos θ , 22b-37-optd7f8		CommonCoil, vh12_2ac6	
Inom / 105% Inom (A)	11470 / 12040		11240 / 11800		16400 / 17220	
Ld,nom (mH/m)	17.57		18.4		21.1 (2-ap.)	
Cable	HF-cable	LF-cable	HF-cable	LF-cable	HF-cable	LF-cable
Cable w x t (bare) (mm)	13.05 x 2.1	13.05 x 1.25	13.2 x 1.950	13.65 x 1.264	19.2 x 2.2	12.0 x 2.2
Number of strands	21	35	22	37	30	18
Strand diam. (mm)	1.155	0.705	1.1	0.7	1.2	1.2
Cu/SC	0.8	2.3	0.8	2.3	1.0	2.5
Cable ins. (mm)	0.15					
RRR	100					
Fil. twist (mm)	14					
Jc-fit	From B. Bordini with $T_{c0} = 16$ K, $B_{c20} = 29.38$ T, $\alpha = 0.96$, $C_0 = 267845$ A/mm ² T					

Quench protection integrated in magnet design

- After a quench, the magnet must absorb its stored energy

1. Quench detection
2. Switch off magnet current and activate quench protection (QP) system
 - Quenching magnet by-passed with a diode

→ The QP system (heaters or CLIQ) quench the entire magnet → Rapid current discharge



- EuroCirCol WP5: Requirement for quench protection set as a design criterion

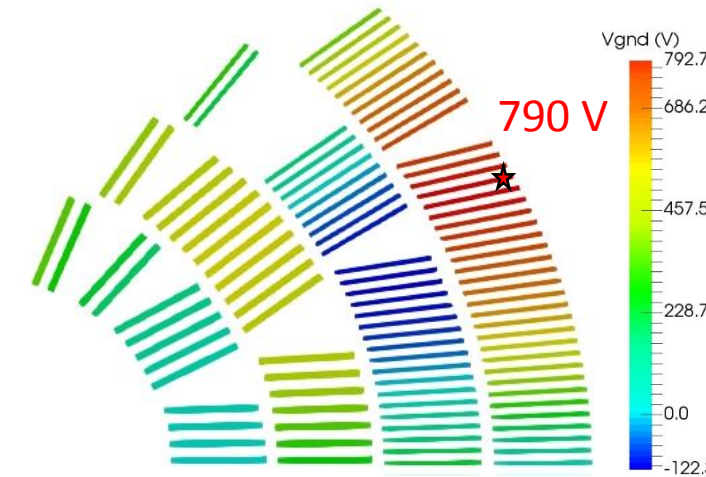
- If quench at 105% of I_{nom} , temperatures must be < 350 K and voltages < 1200 V
 - Assuming 20 ms detection time, and QP system quenching the entire coil in 20 ms
- Fast-feedback quench simulation tools for magnet design adjustments

- Significant impact on conductor quantity and technology:

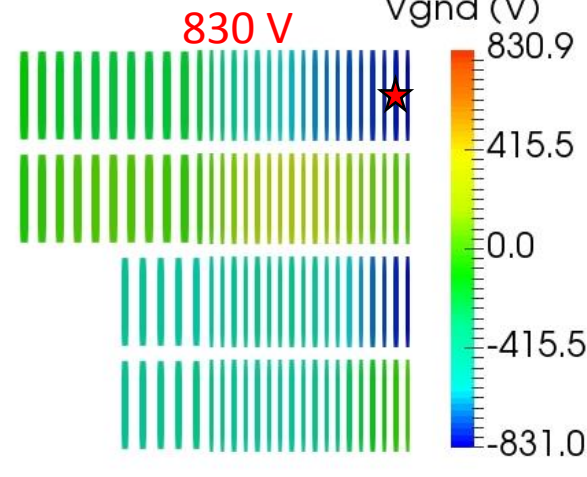
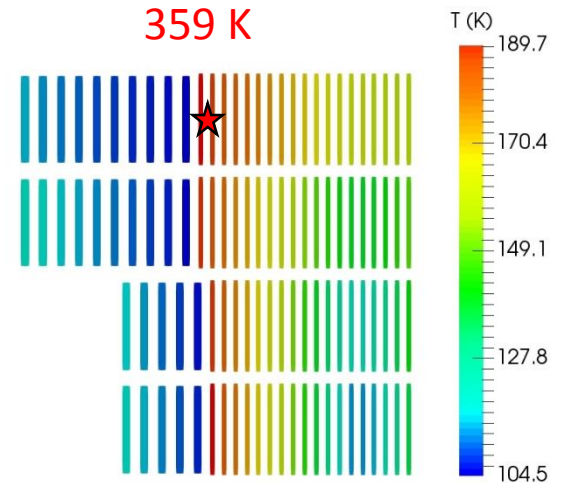
- **Prot. delay and T_{max} → Minimum copper in cable → Coil size**
- **V_{max} → Maximum inductance / minimum current → Cable size / number of turns**

Temperature and voltage after the 20+20=40 ms delay

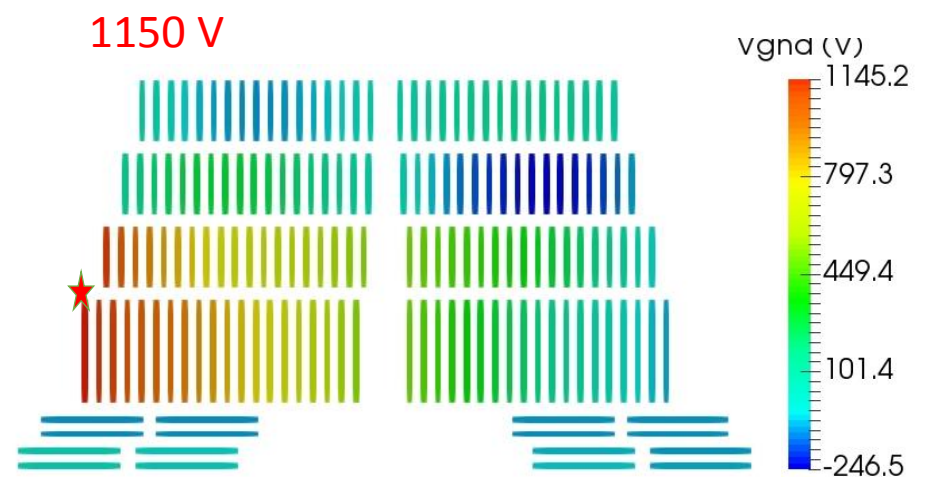
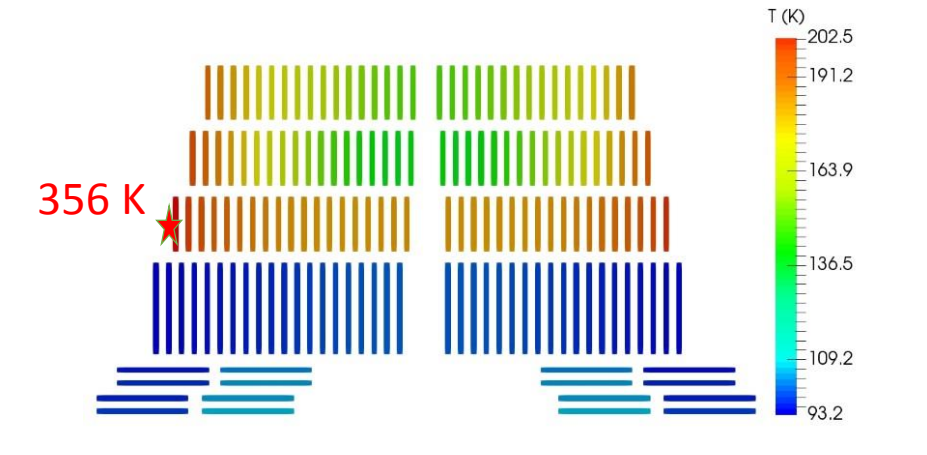
- Assuming that every coil-turn quenches 40 ms after initial quench
- Adiabatic computation with *Coodi* (*Computation of current decay based on known protection delays*)



Cosθ: 22b-37-optd7f8



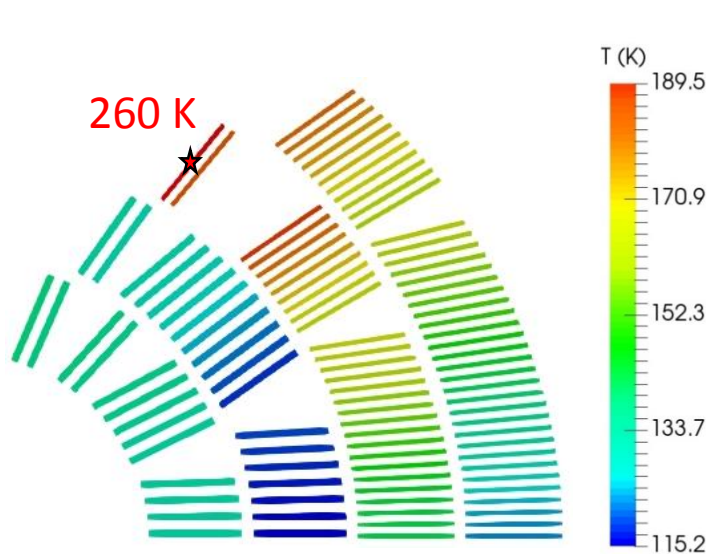
Block: V20ar



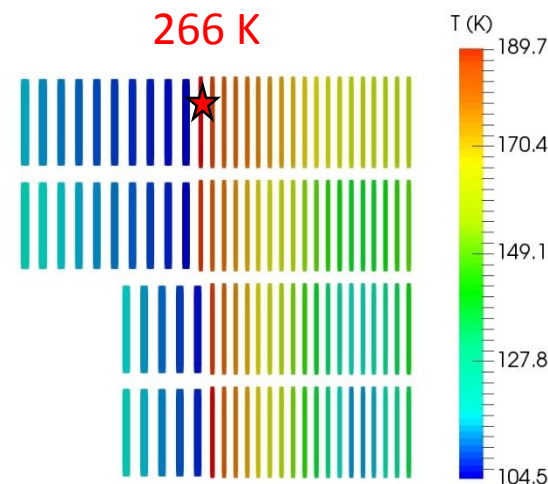
Common-coil: Vh12_2ac6

Temperature and voltage after a 20 + 0 ms delay

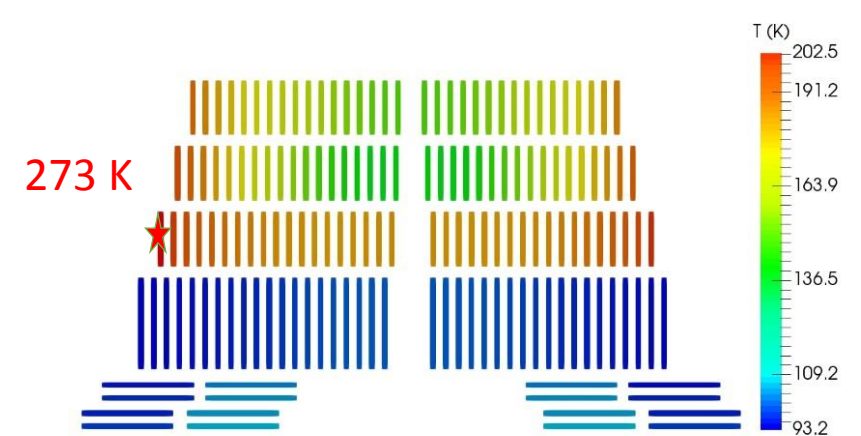
- Lower limit to temperatures that can be obtained with real protection system



Cosθ: 22b-37-optd7f8



Block: V20ar



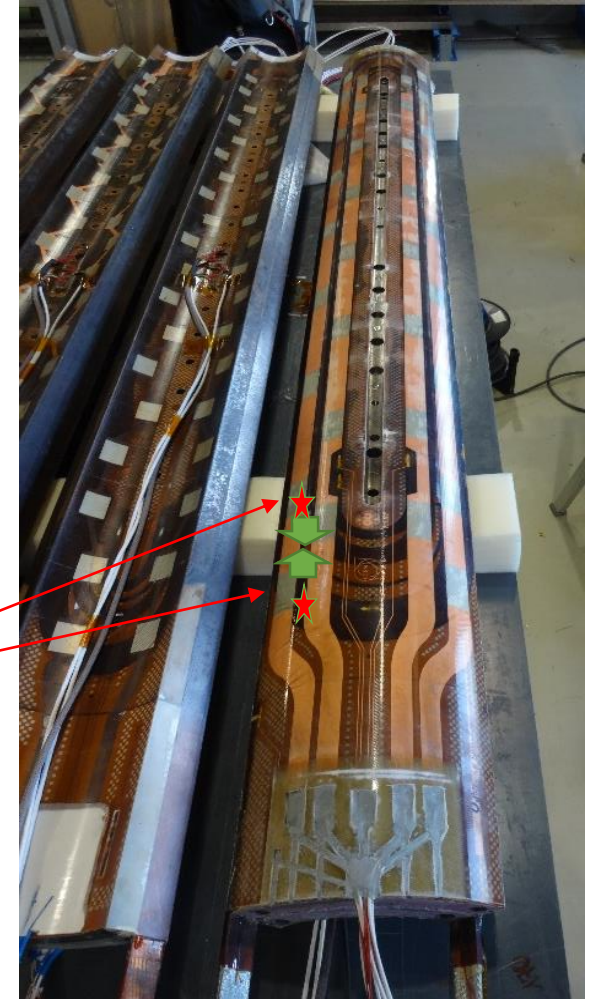
Common-coil: Vh12_2ac6

Design of quench heaters

- Heater technology similar than in LHC and HL-LHC:
 - Cu-plated stainless steel strips:
 - SS thickness 25 μm , Cu thickness 10 μm
 - Insulation to coil: 75 μm polyimide
- Powering with capacitor bank discharge:
 - 1000 V and 10 mF (LHC: 900 V and 7 mF)
- Analysis at 105% of I_{nom}
- The heaters must protect also at low current (1000 A)

Heat focused on
high-resistance
heating stations

Natural quench
propagation between
the heating stations



Heaters on HL-LHC
quadrupole MQXFS03

Simulation software and assumptions

CoHDA

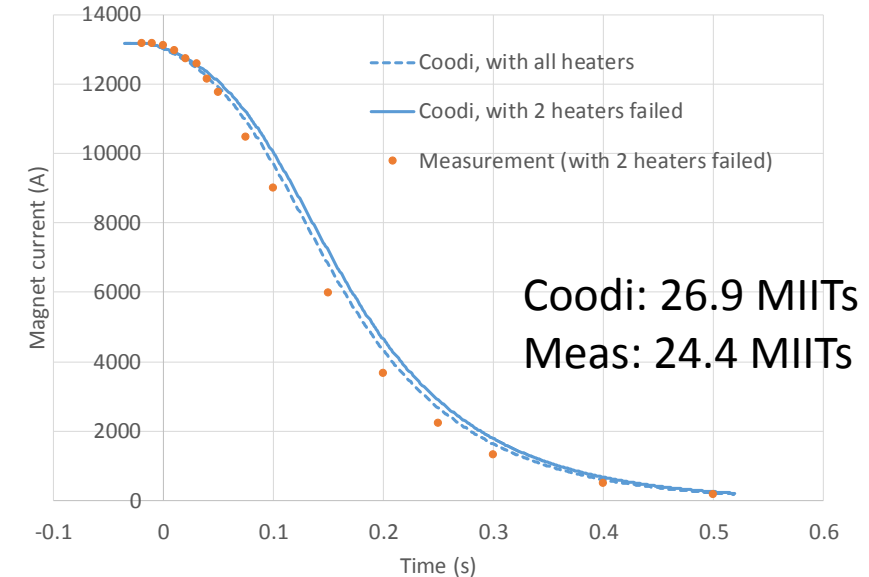
- Calculation of heater delay
- 2-D model for one coil turn, longitudinally
- Heat generation in heater and diffusion to cable

Coodi

- Calculation of coil temperatures and voltages during quench
- Adiabatic
- Inputs:
 - Magnetic field (from ROXIE)
 - Turn mutual inductances
 - Heater delays (from Cohda)
 - Detection time (20 ms at 105% Inom)
 - Quench propagation (20 m/s longit., and 10 ms turn-to-turn at at 105%)
- (Quench propag. and det. time scaled $\propto I_{mag}^2$)

Benchmark

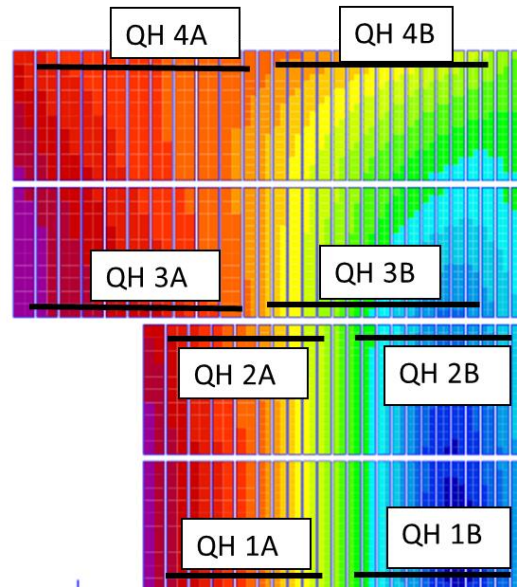
- Simulation of MQXFS03 current decay:
→ Conservative w.r.t. experiment



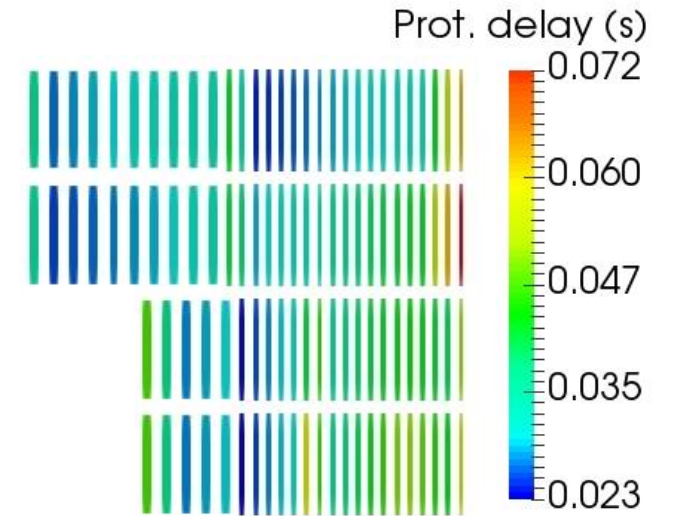
Thanks to S. Izquierdo Bermudez and H. Bajas for exp. data

Quench protection with heaters: Block

Location of heater strips:



Simulated delays in every turn:
(heater delay + 20 ms det. delay):



Heater geometry and powering circuits:

Circuit	QH Strips	Strip width (cm)	HS / period (cm)	$P_{QH}(0)$ (W/cm ²)	τ_{RC} (ms)
HFU#1	1A	1.6	5 / 25	120	80
HFU#2	2A	1.6	5 / 25	120	80
HFU#3	1B	1.6	7 / 40	150	72
HFU#4	2B	1.6	7 / 40	150	72
HFU#5	(3A) (3B)	2.3	7 / 40	95	30
HFU#6	(4A) (4B)	2.3	7 / 40	95	30

Each strip is 14.3 m and always connected in series with identical strip

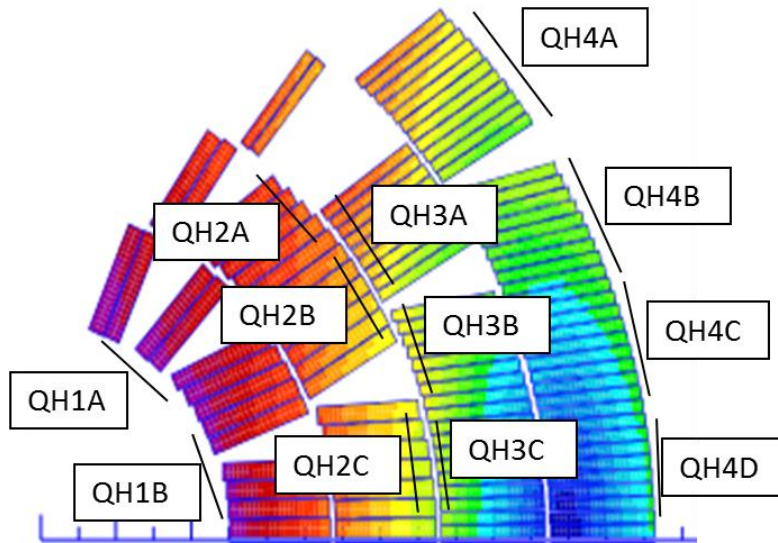
In heater power is assumed strip resistance + 1 Ohm margin for wires, etc.

Result of quench simulation:

$$T_{\max} = 350 \text{ K}, V_{\text{gnd}} = 960 \text{ V}$$

Quench protection with heaters: Cos θ

Location of heater strips:

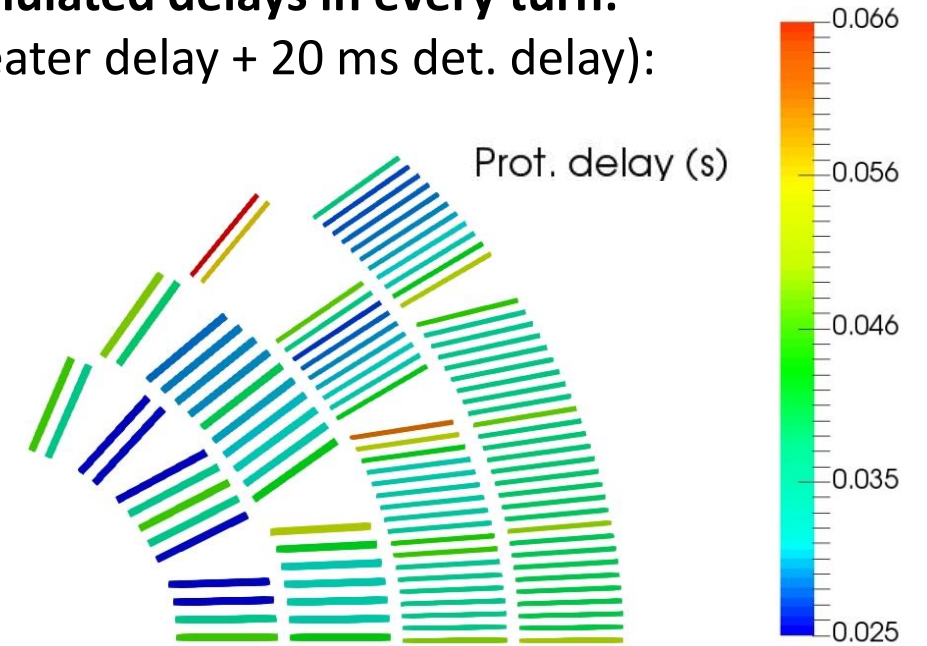


Heater geometry and powering circuits:

Circuit	QH Strips	Strip width (cm)	HS / period (cm)	$P_{QH}(0)$ (W/cm ²)	τ_{RC} (ms)
HFU#1	1B 1A 2A 2B	1.0	3 / 15	85	38
HFU#2	2C 3A 3B 3C	1.0	7 / 35	85	38
HFU#3	4A 4B	1.4	7 / 40	123	45
HFU#4	4C 4D	1.4	7 / 40	123	45

Each strip is 14.3 m and always connected in series with identical strip
 In heater power is assumed strip resistance + 1 Ohm margin for wires, etc.

Simulated delays in every turn:
 (heater delay + 20 ms det. delay):

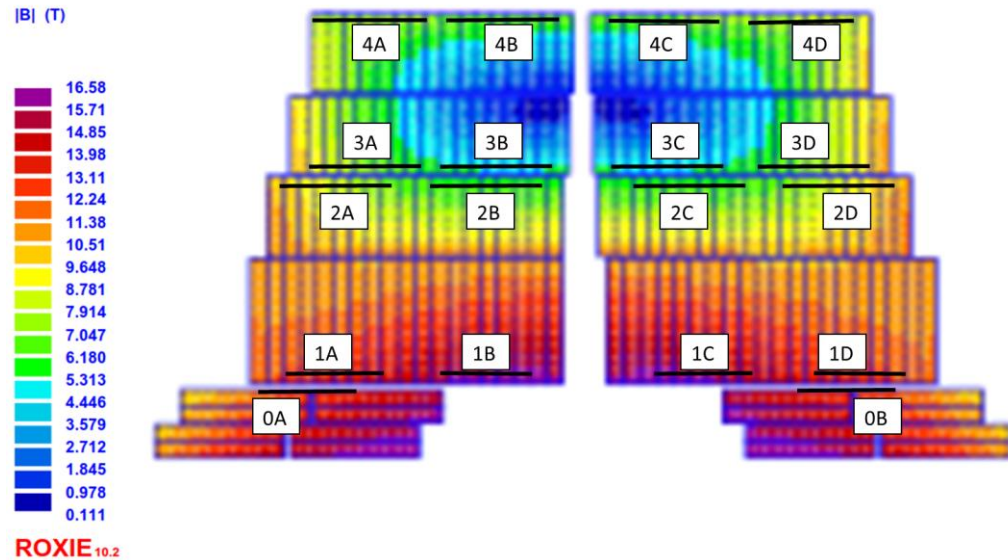


Result of quench simulation:

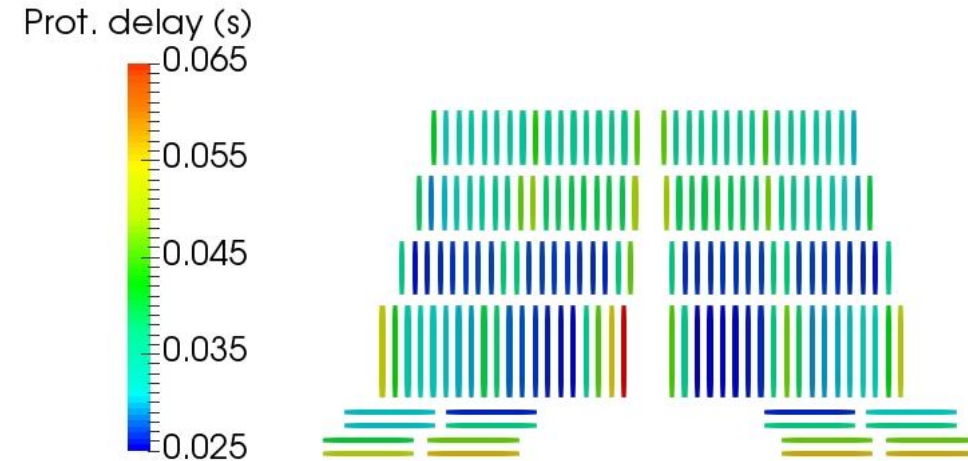
$$T_{\max} = 340 \text{ K}, V_{\text{gnd}} = 1010 \text{ V}$$

Quench protection with heaters: Common coil

Location of heater strips:



Simulated delays in every turn: (heater delay + 20 ms det. delay):



Heater geometry and powering circuits:

Circuit	QH Strips	Strip width (cm)	HS / period (cm)	$P_{QH}(0)$ (W/cm ²)	τ_{RC} (ms)
HFU#1	4A 4B	1.75	6 / 40	138	34
HFU#2	4C 4D	1.75	6 / 40	138	34
HFU#3	3A 3B	1.75	6 / 40	138	34
HFU#4	3C 3D	1.75	6 / 40	138	34
HFU#5	2A 2B	1.75	6 / 40	138	34
HFU#6	2C 2D	1.75	6 / 40	138	34
HFU#7	1A 1B 1C 1D	1.4	4 / 25	87	26
HFU#8	0A 0B 0A _{C2} 0B _{C2}	1.5	4 / 25	87	26

Result of quench simulation:

$$T_{\max} = 350 \text{ K}, V_{\text{gnd}} = 1170 \text{ V}$$

Comparison of magnets with heater based protection

	Block	Cos θ	Common-coil
Hotspot temperature (K) (limit 350 K)	353	341	350
Voltage to ground (V) (limit 1200 V)	960	1010	1170
Energy of QH system (kJ) / 1 aperture	60	40	35

- All heaters quench also at 1000 A
- At I_{nom} hotspot temperature and voltage are smaller by ~15-25 K, and ~100 V
- Work in progress: Further optimizations are possible

Some sensitivity analyses for the Cos θ heater design

Heater design:

- Increase heater polyimide insulation from 0.075 mm to 0.1 mm
→ $T_{\max} +14$ K, $V_{\max} +90$ V
- Remove inner layer heater (layer-to-layer propag. ~ 20 ms):
→ $T_{\max} +8$ K, $V_{\max} -110$ V

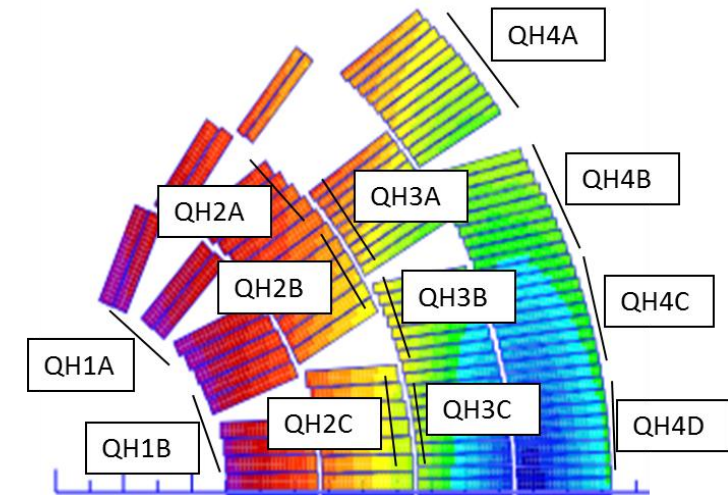
Material parameters and model assumptions:

- Heater delays uncertainty (cable average field instead of peak)
- Material properties (MATPRO instead of NIST)
- Propagation velocities (reduction of 50%)
→ $T_{\max} + < 20$ K, $V_{\max} + < 300$ V

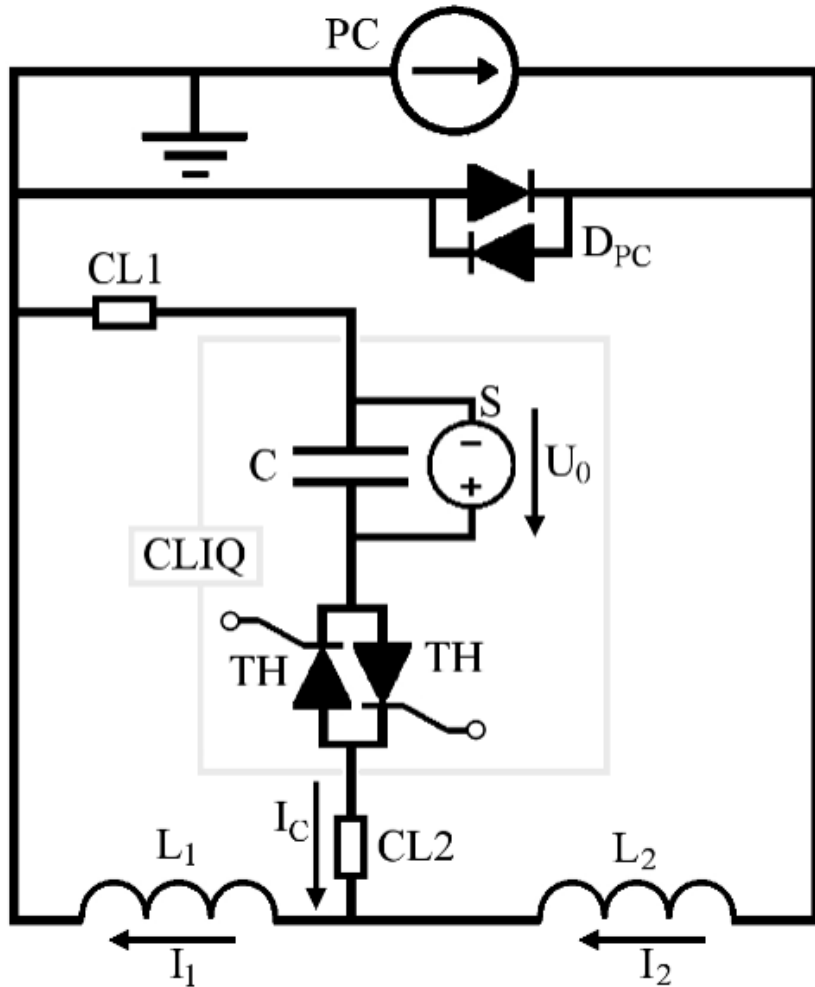
→ **The design is relatively stable**

→ 20 K could be a reasonable margin in later analysis and failure scenarios

Reference at 105 % I_{nom} :
 $T_{\max} = 340$ K, $V_{\max} = 1010$ V



Protection with CLIQ – Coupling-Loss Induced Quench



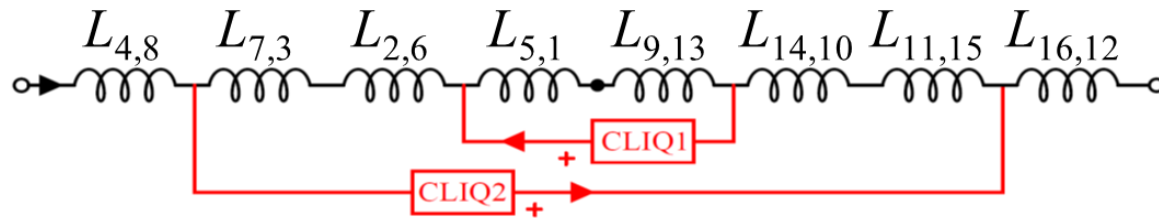
- CLIQ is a new technology for the protection of superconducting magnets. The core component is the capacitor bank that generates:

- An alternated transport current in the magnet
- A variable magnetic field in the coils
- High inter-filament and inter-strand coupling losses
- Heat on the superconductor
- Quick spread of the normal zone after a quench

Protection of the Block with CLIQ

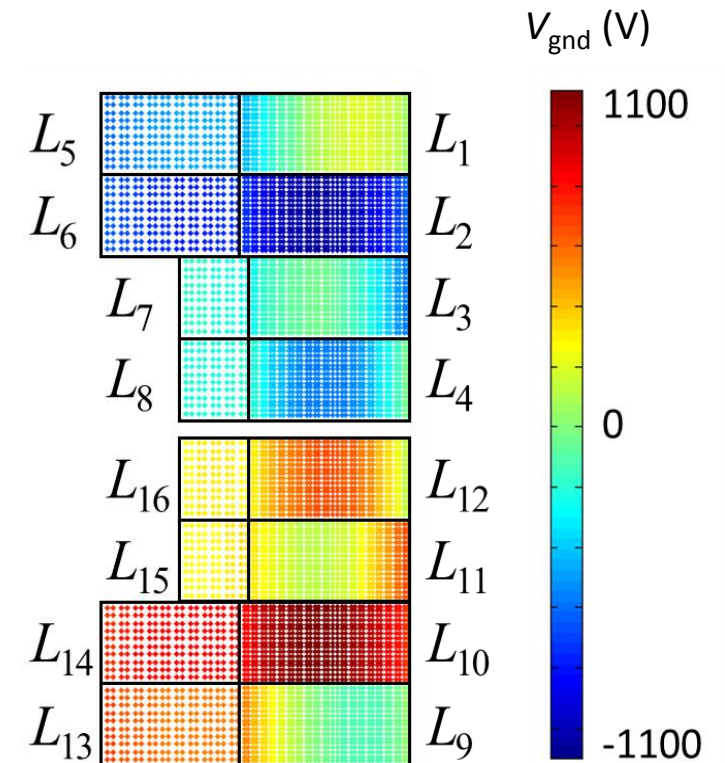
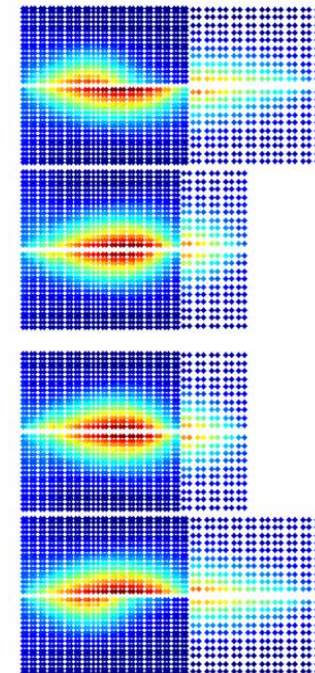
- Very promising results with a Multi-CLIQ system (2 x 1200 V/20 mF)

Details in the poster by M. Prioli



Quench simulation with LEDET¹+PSPICE²

$$T_{\max} = 300 \text{ K}, V_{\text{gnd}} = 1100 \text{ V}$$

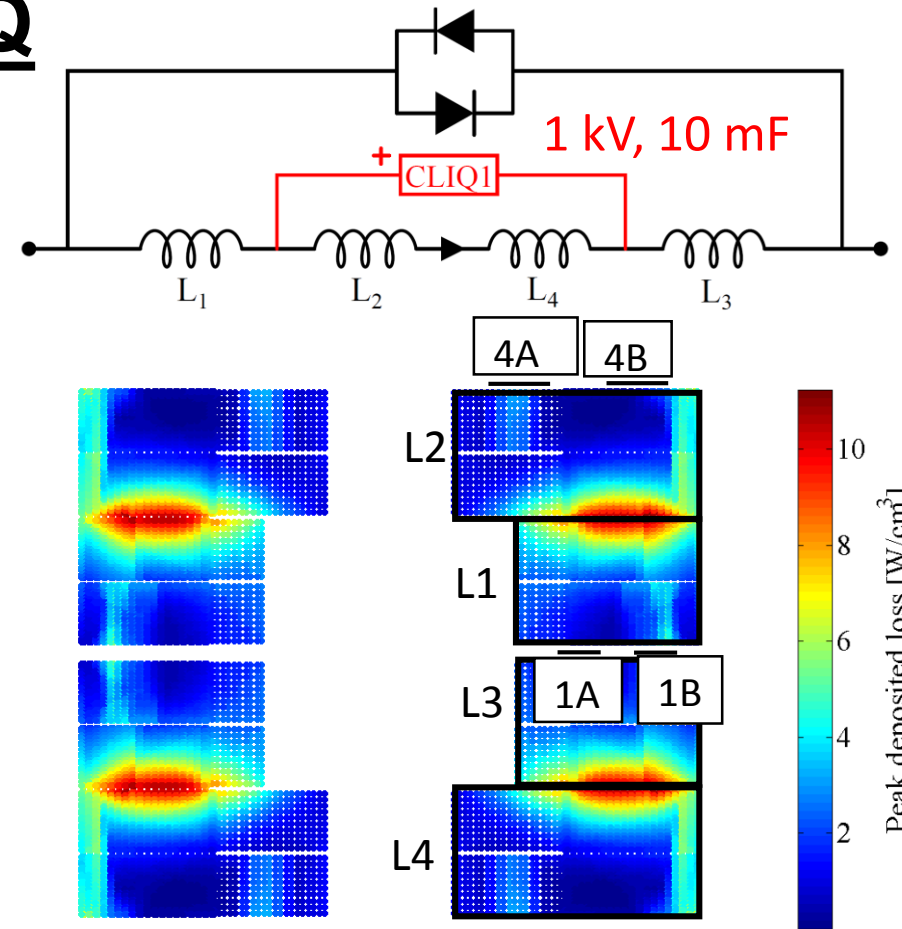


¹E. Ravaioli, *Cryogenics*, 2016.

²I. Cortes Garcia et al., *submitted to IEEE JMMCT*, 2017

Protection with heaters and CLIQ

- CLIQ for fast quenching at high current,
 - QH for voltage control and protection at low current
- **Advantages** when applied to Block:
 1. Allows using a smaller CLIQ unit
 2. No interlayer leads for CLIQ
 3. Heaters only on outer surfaces
 4. Less total energy in the QP-system



Circuit	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm ²)	τ_{RC} (ms)
HFU#1	(1A+4A) (1A+4A)	1A: 1.6,	1A: 5/25	1A: 130	38
		4A: 2.3	4A: 7/40	4A: 63	
HFU#2	(1B+4B) (1B+4B)	1B: 1.6,	7/40	1B: 150	36
		4B: 2.3		4B: 71	

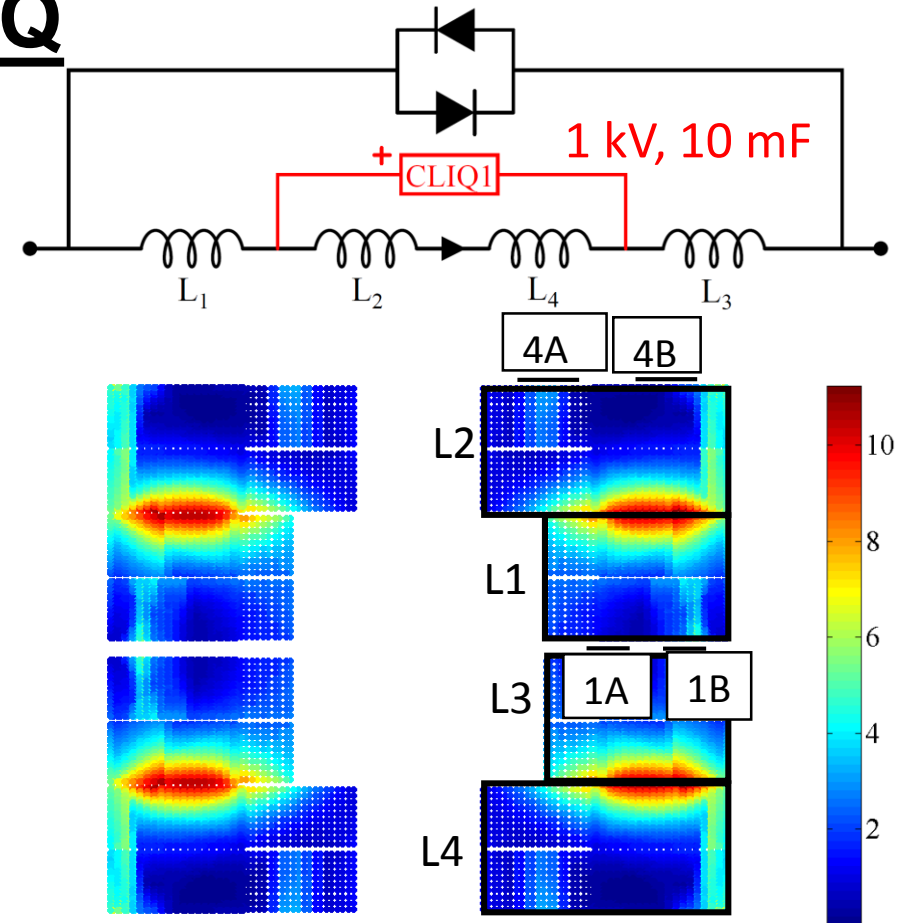
Protection with heaters and CLIQ

Simulation with CoHDA and LEDET

$$T_{\max} = 340 \text{ K}, V_{\text{gnd}} = 1190 \text{ V}$$

A check: Assume that CLIQ decreases the heater delays by 20% and increases longitudinal propagation velocity by 20%:

$$T_{\max} = 340 \text{ K and } V_{\text{gnd}} = 1160 \text{ V}$$



Circuit	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{\text{QH}}(0)$ (W/cm ²)	τ_{RC} (ms)
HFU#1	(1A+4A) (1A+4A)	1A: 1.6,	1A: 5/25	1A: 130	38
		4A: 2.3	4A: 7/40	4A: 63	
HFU#2	(1B+4B) (1B+4B)	1B: 1.6,	7/40	1B: 150	36
		4B: 2.3		4B: 71	

Comparison of different methods applied to Block

	QH only	CLIQ only	CLIQ + QH
Hotspot temperature (K) (limit 350 K)	353	300	343
Voltage to ground (V) (limit 1200 V)	960	1100	1200
Energy of QH system (kJ) / 1 aperture	60 (HFU)	29 (CLIQ)	5 (CLIQ) + 20 (HFU)

- **Work in progress:** Further optimization obtainable for all methods
- Highly efficient CLIQ:
 - Increases the safety margin in protection,
OR can be used to reduce the requirement for copper in the magnet design

Conclusions

- **Quench protection integrated in the 16 T dipole magnets design from beginning**

- At 105% of I_{nom} assumed protection efficiency 40 ms, and required $T_{max} < 350$ K, $V_{max} < 1200$ V



- **Two protection systems available:**

- Quench heaters: T_{max} 340 – 350 K and V_{max} 1000 – 1200 V
- CLIQ: T_{max} 300 K (demonstrated for Block)
- Quench heaters + CLIQ: Reduction of QP system energy (demonstrated for Block)



- **Road map to further optimization of quench protection *and magnet design*:**

1. Analyze CLIQ and CLIQ+QH for all magnets (incl. sensitivity analysis)
2. Update the protection efficiency vs. type of magnet and protection
3. Software calibration with experimental data → Quantify the needed margin
4. Iterate magnet design based on the updated protection efficiency and margin on T_{max}

→ Possible reduction in magnet size

- In parallel: Analyze thermal stresses and protection integration with the circuit design



Posters about quench protection in EuroCirCol WP5

M. Prioli et al.: Voltage reduction, analysis of circuits

J. Zhao et al.: Mechanical analysis during a quench

Strategies to reduce the voltage to ground in the FCC main dipole circuits

M. Prioli¹, T. Salmi², B. Auchmann^{1,3}, L. Bortot¹, M. Maciejewski¹, M. Mentink¹, E. Ravaioli⁴, A. Stenvall² and A. Verweij¹

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² Tampere University of Technology, Finland
³ Paul Scherrer Institute, Villigen, Switzerland
⁴ Lawrence Berkeley National Laboratory, USA

Abstract and goal of the poster

Within the FCC project, the EuroCirCol Work Package 5 is dedicated to the study of the high-field, high-current superconducting dipole magnets. The target performance of these magnets, together with the unprecedented size of the accelerator, poses a number of challenges as, among others, machine integration and protection. As for the LHC, dipole magnets have to be powered in long strings, leading to large stored energy in the circuits. In case of a quench or equipment failure, a safe extraction of the circuit energy in a short amount of time is very challenging, especially due to the development of high voltages to ground. The voltage to ground in the coils of a magnet is composed by two contributions: the voltage drop over the string, from the grounding point to the magnet input, and the coils' internal voltage distribution. Both contributions result from the imbalance of resistive and inductive voltage during the current discharge.

In this poster, we discuss dedicated strategies to reduce the voltage to ground in circuits of superconducting magnets and the simulation tools developed for the analysis. The adopted protection is the Coupling-Induced Quench (CIQ) system and its behavior is modelled by means of the LEDET and Pspice co-simulation. This technique allows one to simulate the electrical transients at the circuit level together with magneto-thermal transients occurring at the magnet level during a quench, using dedicated solvers. The FCC block-coil superconducting dipole magnet is considered in a case study.

The problem

- Circuit point of view: voltage to ground decreased by limiting the number of magnet powered in series in a string. Small circuits with one Energy Extractor (EE).

N. of circuits per 4m PS: 4, $I_{nom} [kA]$: 1.0
 Total n. of circuits: 20, $I_{nom} [kA]$: 2.3
 Magnets per circuit: 54, $I_{nom} [kA]$: 170
 Inductance per coil: 30, $L_{tot} [mH]$: 20
 Stored energy per coil: 2, $E_{st} [J]$: 280

• Magnet point of view: one CLIQ unit per magnet aperture (FCC week 2016) → insufficient protection during quench.
 20 nL, 1.2 kV CLIQ unit → 145 K hot-spot temperature close to the 150 K limit
 → peak voltage to ground above the 1 kV threshold

• More sophisticated configurations need to be studied.

Strategy 1: multi-CLIQ

- Additional CLIQ units: this requires CLIQ leads connected inside the double pancake coils.

→ Hot-spot temperature: 300 K
 • Effective protection for all current levels.

Strategy 2: internal diodes

- Internal diodes to equalize the voltage in selected turns.

→ Hot-spot temperature: 280 K

Strategy 3: different circuits for low-field and high-field coils

- High-field (HF) coils powered with a separate circuit: CLIQ is applied to low-field coils only.

→ Hot-spot temperature: 300 K

Simulation tools

The voltage to ground during quench depends on the specific magnet design, the adopted protection systems and the circuit. Two simulation layers can be identified:

- Magneto-thermal model of the quenching magnet
- Circuit model

Complex multi-physics, multi-scale, multi-rate problem → co-simulation as a solution

- Dedicated models: Circuit → netlist in Cadence Pspice; Magnet → LEDET [1, 2].
- Waveform relaxation, Gauss-Seidel scheme to exchange information [3].
- Series execution of the two models until convergence.
- The co-simulation of LEDET and Pspice allows one to study advanced protection system configurations and their effect on the circuit.

Validation of tools

For the simple CLIQ configuration with one unit per aperture, that can be also simulated using LEDET only (monolithic simulation), the LEDET and Pspice co-simulation was validated.

Further studies

- Optimization of the aforementioned strategies.
- Analysis of the CLIQ compatibility in the FCC main dipole circuit.
- Redundancy studies and failure scenarios, as proposed in [4] for HL-LHC project.

Conclusions

- Co-simulation has proven to be an effective approach for the study of the CLIQ protection system from the circuit and magnet point of view.
- Co-simulation of LEDET and Pspice was validated against LEDET monolithic simulation.
- The multi-CLIQ strategy is a promising option for the quench protection of the FCC block-coil dipole.

References

[1] E. Ravaioli et al., "Lumped-element dynamic electro-thermal model of a superconducting magnet," *Cryogenics*, 2016.
 [2] E. Ravaioli, "CLIQ," Ph.D. dissertation, ETH Zurich, 2015.
 [3] I. Cortes Garcia et al., "Optimized Field-Circuit Coupling for the Simulation of Quenches in Superconducting Magnets, submitted to IEEE *AMTC*, 2017," arXiv:1702.00958.
 [4] E. Ravaioli, "Quench protection studies for the high-momentum LHC inner triplet circuit," internal report, EDMS 1760496 v1.0.

Mechanical behavior of a 16 T FCC dipole magnet during a quench

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Abstract

Future accelerator magnets are pushed to their limits in terms of magnetic field and also from the quench protection point of view. This forces the magnet designers to re-think the quench modelling. One issue that has not so far been largely explored is the mechanical behaviour of the superconducting coils during a quench. This can cause limitations to the design of high field accelerator magnets. This paper focuses on mechanical behavior in the event of a quench of a Nb₃Sn 16 T dipole magnet currently developed in the framework of the EuroCirCol project in view of the Future Circular Collider conceptual design study. The thermo-mechanical analysis is performed through finite element modeling. The analysis takes into account the Lorentz force and the thermal stress due to the non-uniform temperature distribution in the winding during a quench.

Mechanical model and validation

The 2D mechanical analysis includes the following steps:
 (i) Key insertion process. (ii) Cool down. (iii) Excitation. (iv) Quench process

Boundary conditions:
 • The horizontal and vertical assembly interference are 750 μm and 50 μm, respectively
 • Two different types of contacts between the magnet components exist: *glued* and *slid*.
 • The friction coefficient of the sliding contact was 0.2.

	Horizontal stress (MPa)		Von Mises stress (MPa)	
	COMSOL	ANSYS	COMSOL	ANSYS
Key insertion	-141	-135	126	121
Cool-down	-210	-216	200	196
Excitation @ 105% of the nominal current	-202	-195	185	176

Introduction

During the first stages of the EuroCirCol magnet design, it was assumed that the protection system was able to spread the normal zone to the entire winding within 40 ms. In order to ensure the magnet protectability, it was set as a design criterion that the hotspot temperature must remain below 350 K. It is assumed that eventually mechanical failure will be the reason for degradation after a high temperature quench (either through epoxy break or the mechanical failure of Nb₃Sn material). The EuroCirCol 16 T magnet design options are particularly prone to high temperature differences during a quench because for economic reasons they are very compact and employ a graded design. Larger cable in high-field region to ensure enough superconductor, and smaller cable in low-field area. This results in unequal copper cross-section areas for the cables and consequently different heat generation. Because of the grading within a coil layer, the maximum temperature difference between two cables during a quench can be particularly large, around 100 K.

Parameter	Value
Nominal current	11470 A
Bore dipole field	16 T
Peak field in conductor	16.74 T
Operating temperature	4.9 K
Sub-plane shunt thickness	1.75 mm
Laminar margin (L.P.M.)	14.01%
Discretized inductance at nominal current	18.000 H
Stored energy at nominal current	1.2 MJ/m
Cable diameter of dipole	335 mm
Number of turns (L.P. cable per coil)	218/100/100/50
Number of turns (L.P. cable per coil)	10 ³ /10 ³ /10 ³ /74
Maximum Fx/Fy Lorentz force	10390 kN/m/5200 kN/m

Fig. 1. (a) Magnet cross-section within its iron yoke (b) block coil cross-section made of two different Nb₃Sn cables and consisting of two double pancakes.

Results

Quench process and temperature distribution

Stress distribution at different time

Stress and strain variation during a quench

Conclusions

- It is possible to analyze the mechanical behaviour of the FCC magnet using Comsol
- The Lorentz force and the thermal stress was considered during a quench.
- The peak stress behaviour is similar without and with the hotspot occurring in the upper coil.
- The stress distribution is similar to the cool down process
- The dynamic loading response during a quench requires further analysis.