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Protection of FCC 16 T dipoles

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together with all the EuroCirCol WP5 members

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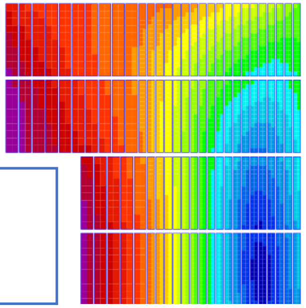
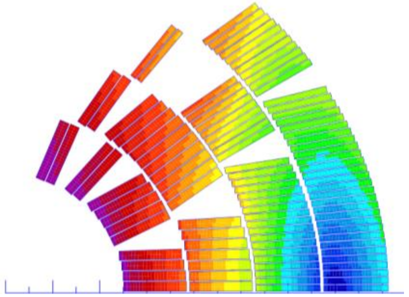
Outline

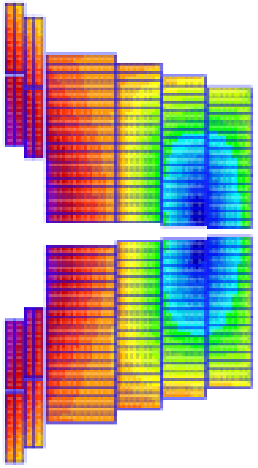
- 16 T dipole design options in EuroCirCol WP5
- Integration of quench protection into the magnet design
- Protection with quench heaters
- Protection with CLIQ (Block)
- Protection with and CLIQ+heaters (Block)
- Conclusions

Magnet designs

All 14.3 long
Cosθ and Block 1-ap. versions

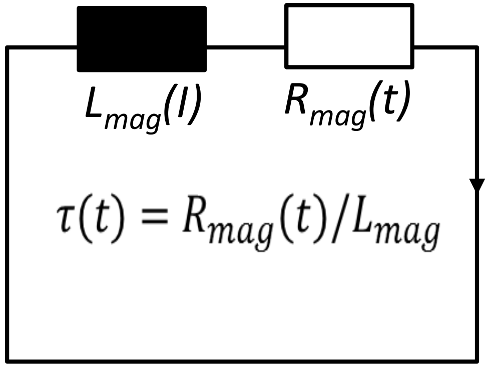






Magnet	Block, V20ar		Cosθ, 22b-37-optd7f8		CommonCoil, vh12_2ac6	
Inom / 105% Inom (A)	11470 / 12040		11240 / 11800		16400 / 17220	
Ld,nom (mH/m)	17.57		18.4		21.1 (2-ap.)	
Cable	**HF-cable**	**LF-cable**	**HF-cable**	**LF-cable**	**HF-cable**	**LF-cable**
Cable *w* x *t* (bare) (mm)	13.05 x 2.1	13.05 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, α = 0.96, C_0 = 267845 A/mm^{2}T					

Quench protection integrated in magnet design



$$\tau(t) = R_{mag}(t)/L_{mag}$$

- **After a quench, the magnet must absorp its stored energy**
  1. Quench detection
  2. Switch off magnet current and activate quench protection (QP) system
     - Quenching magnet by-passed with a diode

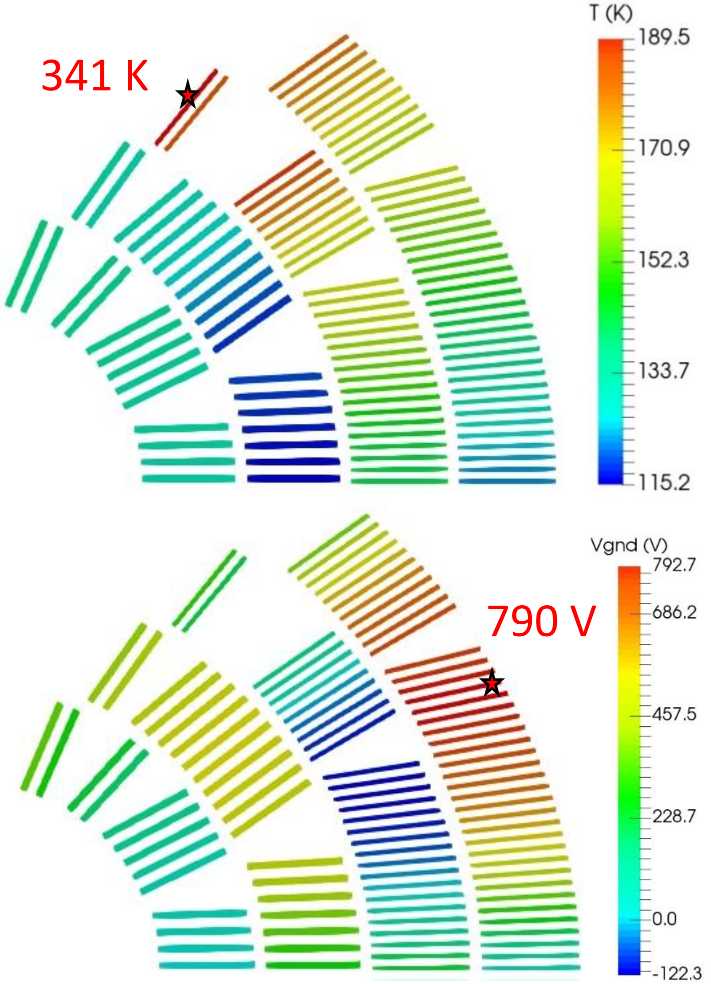
→The QP system (heaters or CLIQ) quench the entire magnet → Rapid current discharge

- **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**

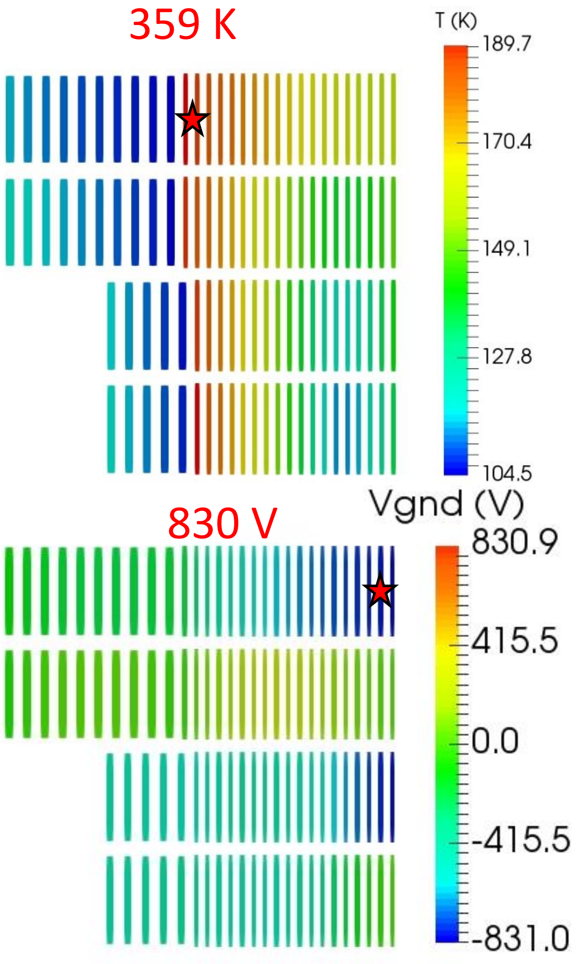
Temperature and voltage after the 20+20=40 ms delay

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


341 K

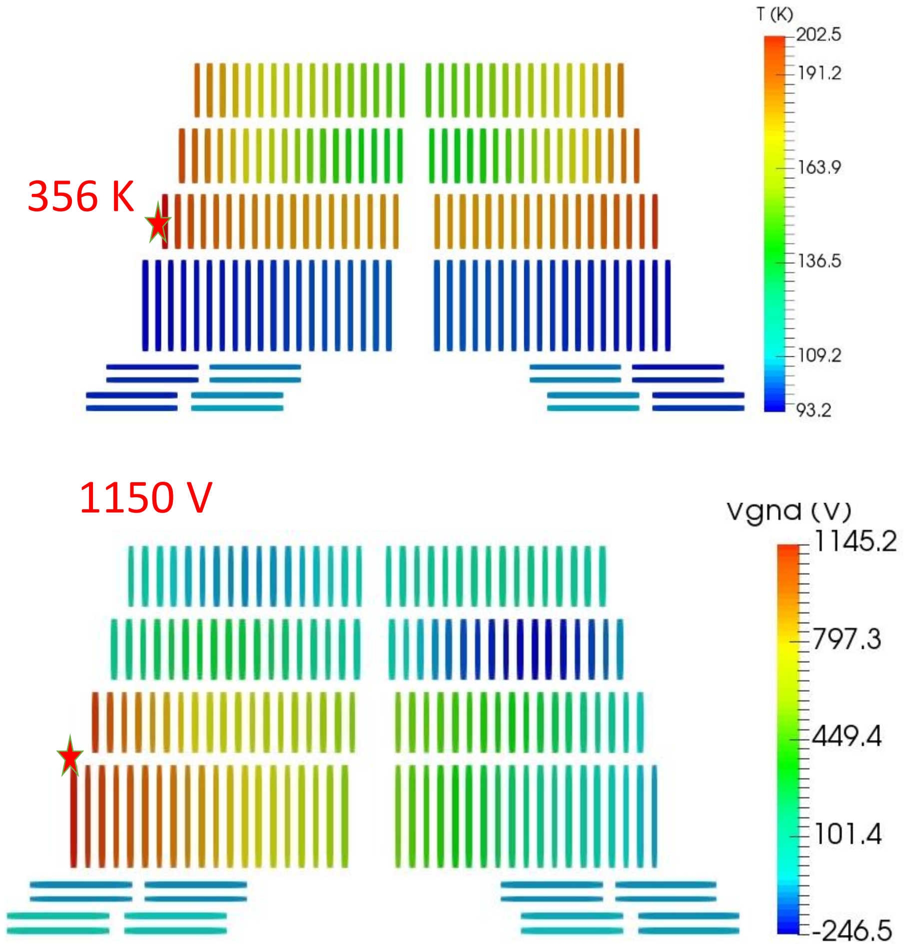
790 V

Cosθ: 22b-37-optd7f8


359 K

830 V

Block: V20ar

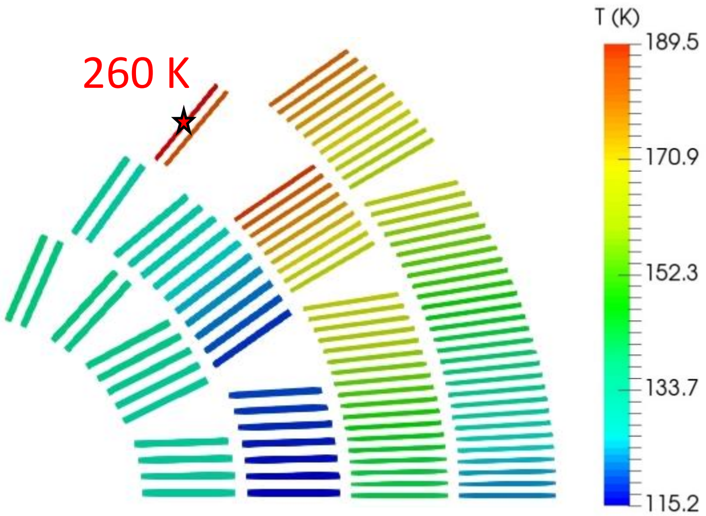

356 K

1150 V

Common-coil: Vh12_2ac6

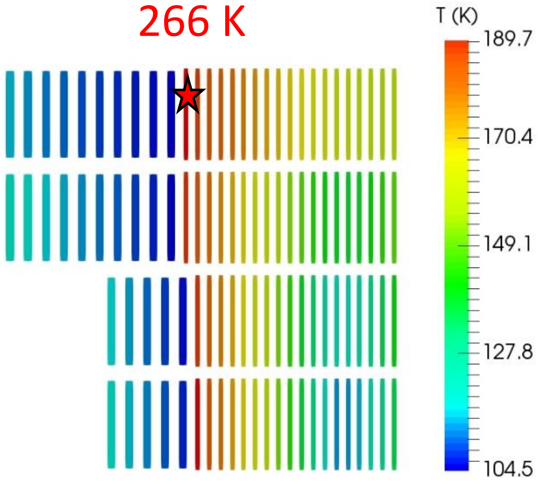
Temperature and voltage after a 20 + 0 ms delay

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



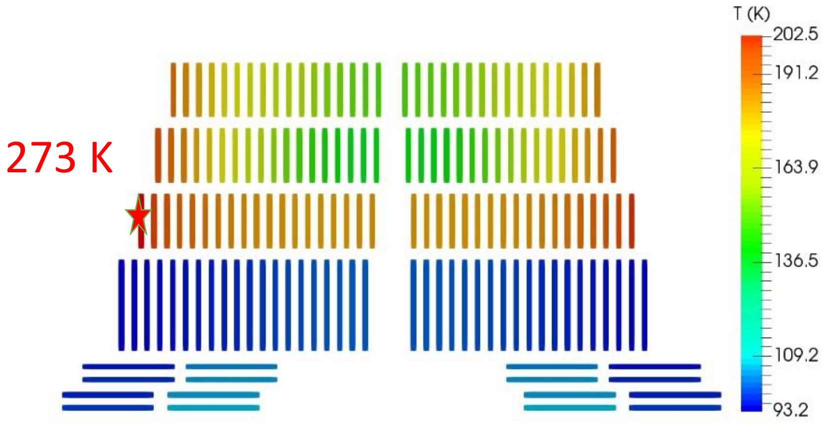
260 K

Cosθ: 22b-37-optd7f8



266 K

Block: V20ar



273 K

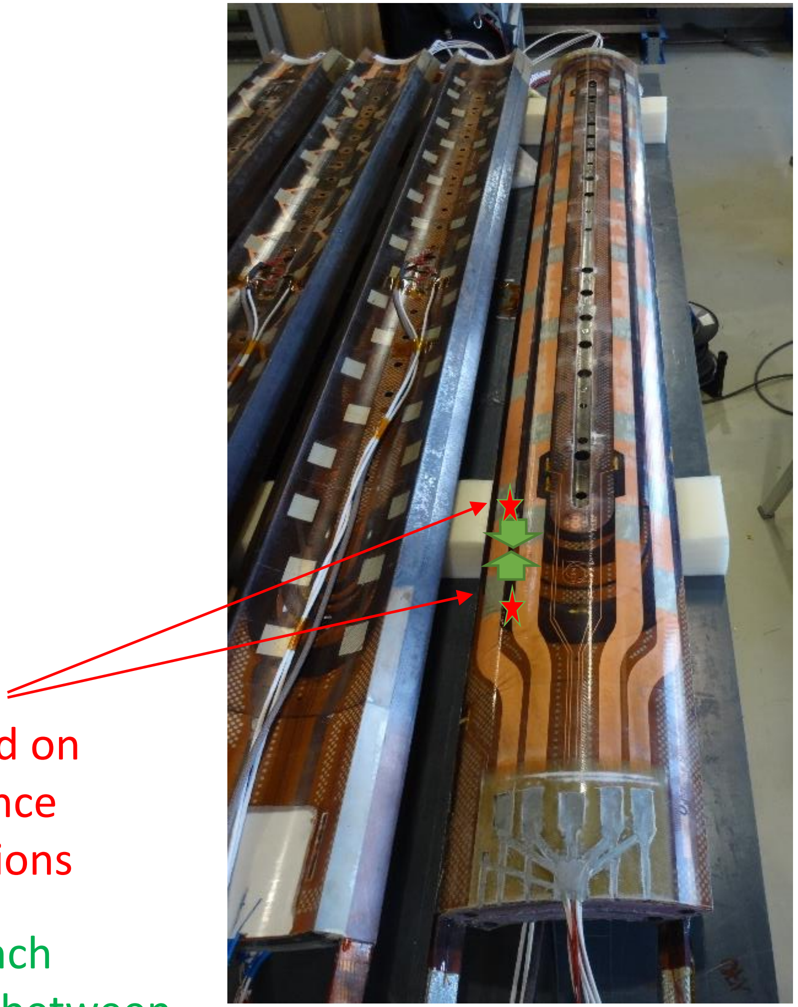
Common-coil: Vh12_2ac6

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)



Heaters on HL-LHC quadrupole MQXFS03

Simulation software and assumptions

CoHDA

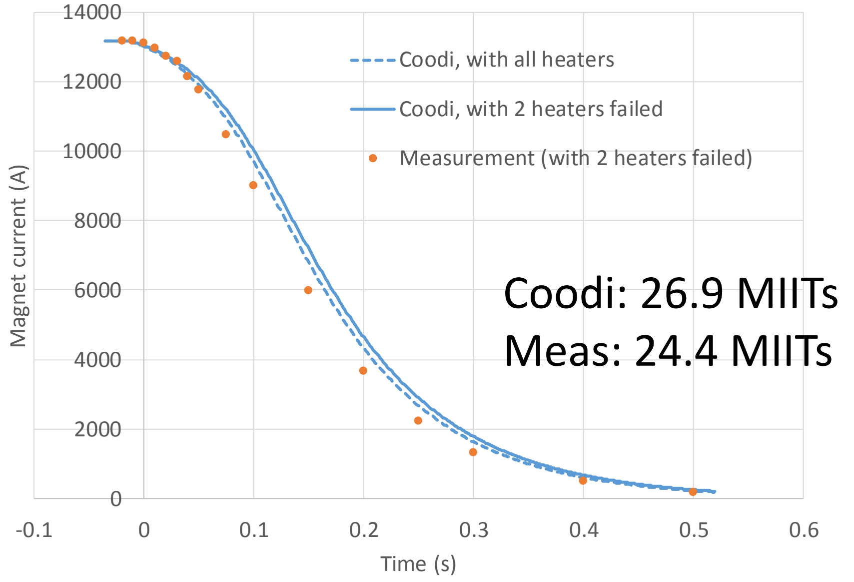
- Calculation of heater delay
- 2-D model for one coil turn, longitudinally
- Heat generation in heater and diffusion to cable

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 ∝ I_{mag}^2)

Benchmark

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

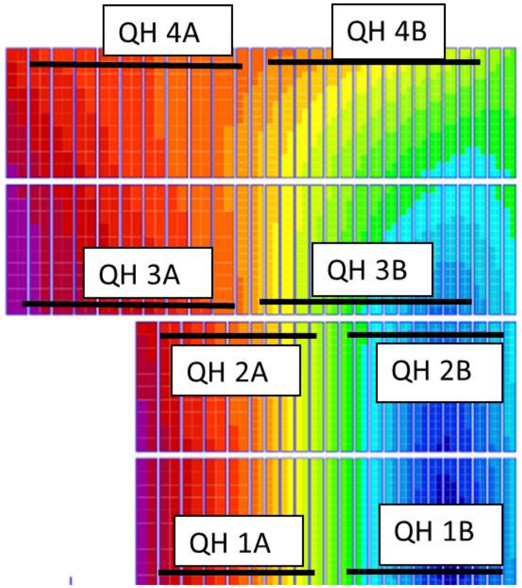


Coodi: 26.9 MIITs
Meas: 24.4 MIITs

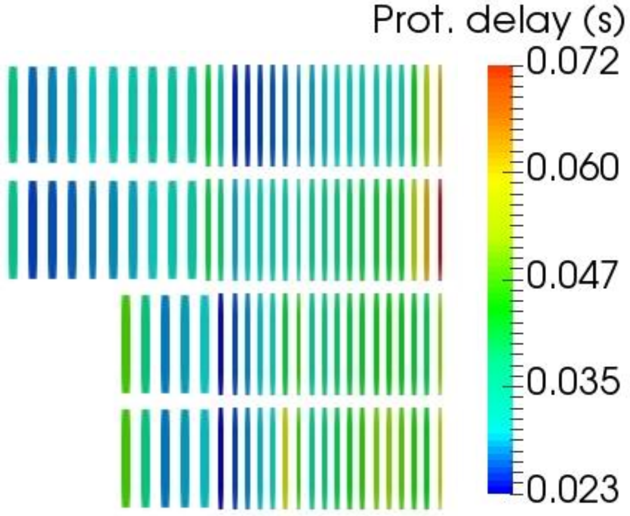
Thanks to S. Izquierdo Bermudez and H. Bajas for exp. data

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

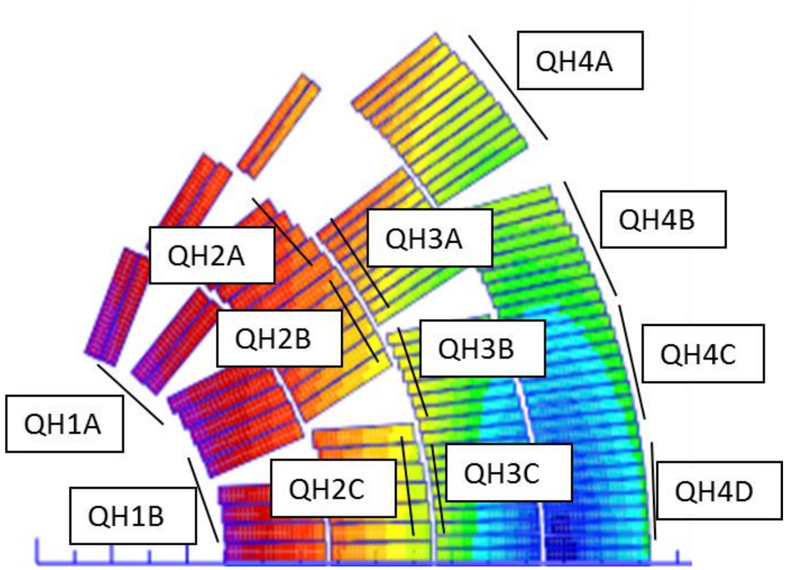
In heater power is assumed strip resistance + 1 Ohm margin for wires, etc.

Result of quench simulation:

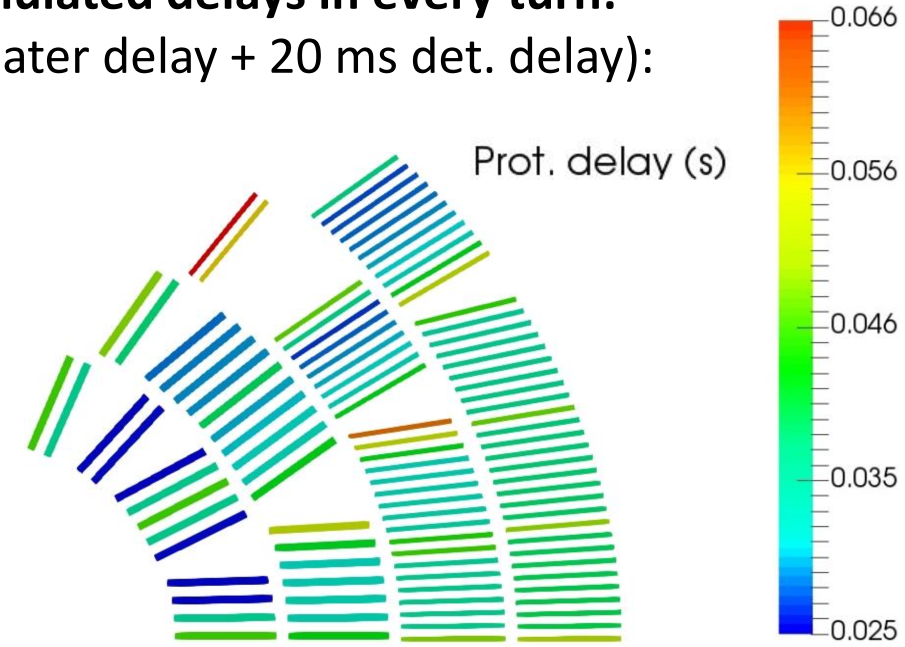
T_{max} = 350 K, V_{gnd} = 960 V

Quench protection with heaters: Cosθ

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	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

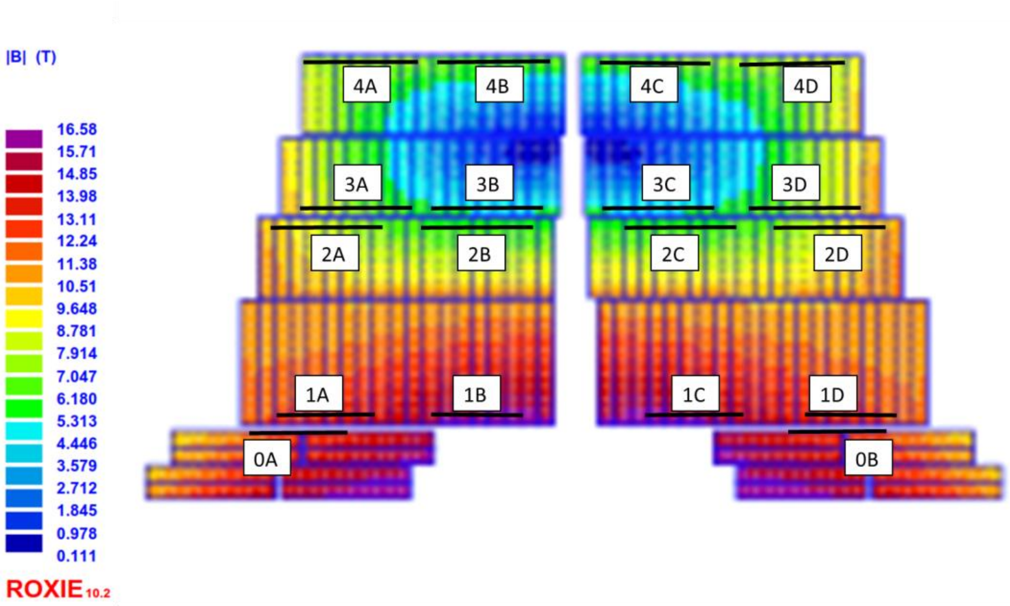
Each strip is 14.3 m and always connected in series with identical strip
In heater power is assumed strip resistance + 1 Ohm margin for wires, etc.

Result of quench simulation:

T_{max} = 340 K, V_{gnd} = 1010 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 K, V_{gnd} = 1170 V

Comparison of magnets with heater based protection

	Block	**Cosθ**	**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 Cosθ heater design

Heater design:

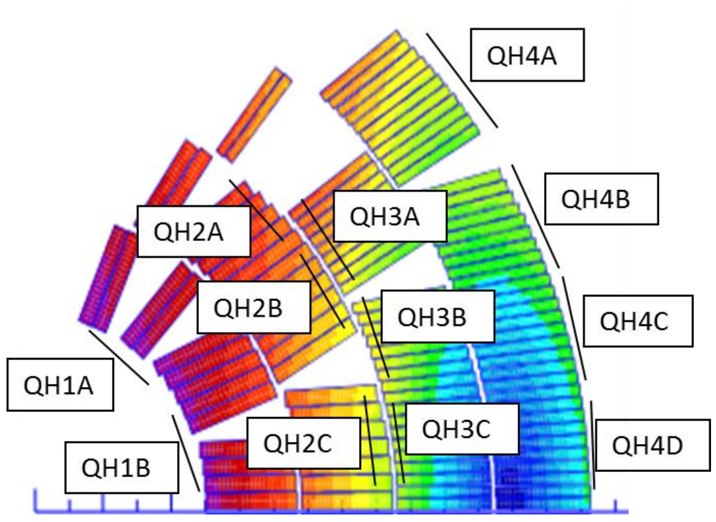
- Increase heater polyimide insulation from 0.075 mm to 0.1 mm

  → 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

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



Material parameters and model assumptions:

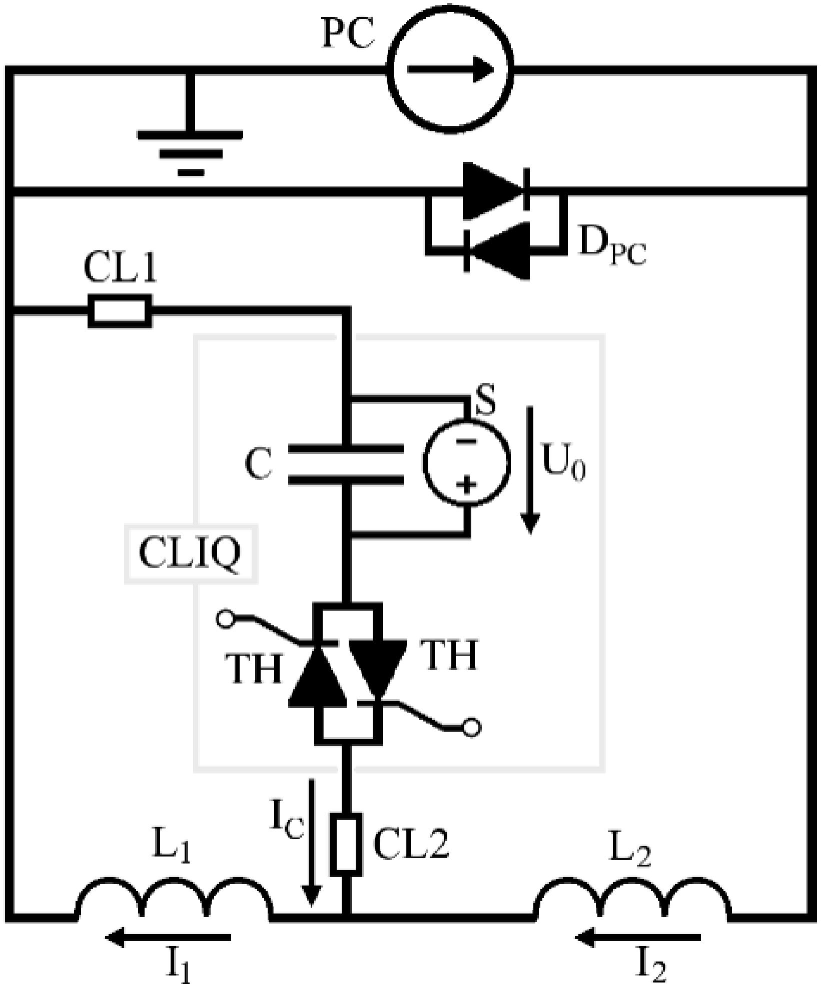
  - Heater delays uncertainty (cable average field instead of peak)
  - Material properties (MATPRO instead of NIST)
  - Propagation velocities (reduction of 50%)

  → 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

Protection with CLIQ – Coupling-Loss Induced Quench

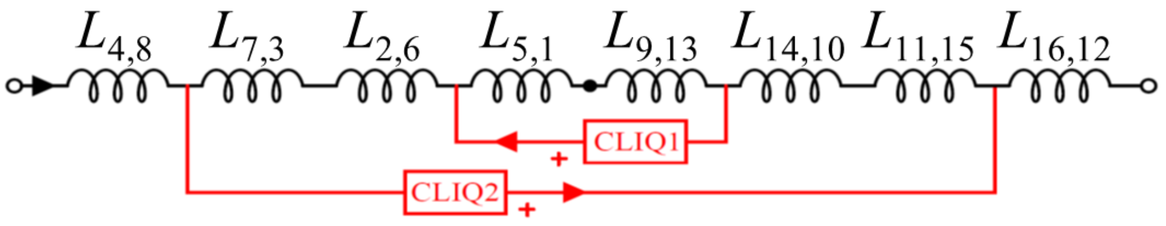


- CLIQ is a new technology for the protection of superconducting magnets. The core component is the capacitor bank that generates:
  - An alternated transport current in the magnet
  - A variable magnetic field in the coils
  - High inter-filament and inter-strand coupling losses
  - Heat on the superconductor
  - Quick spread of the normal zone after a quench

Protection of the Block with CLIQ

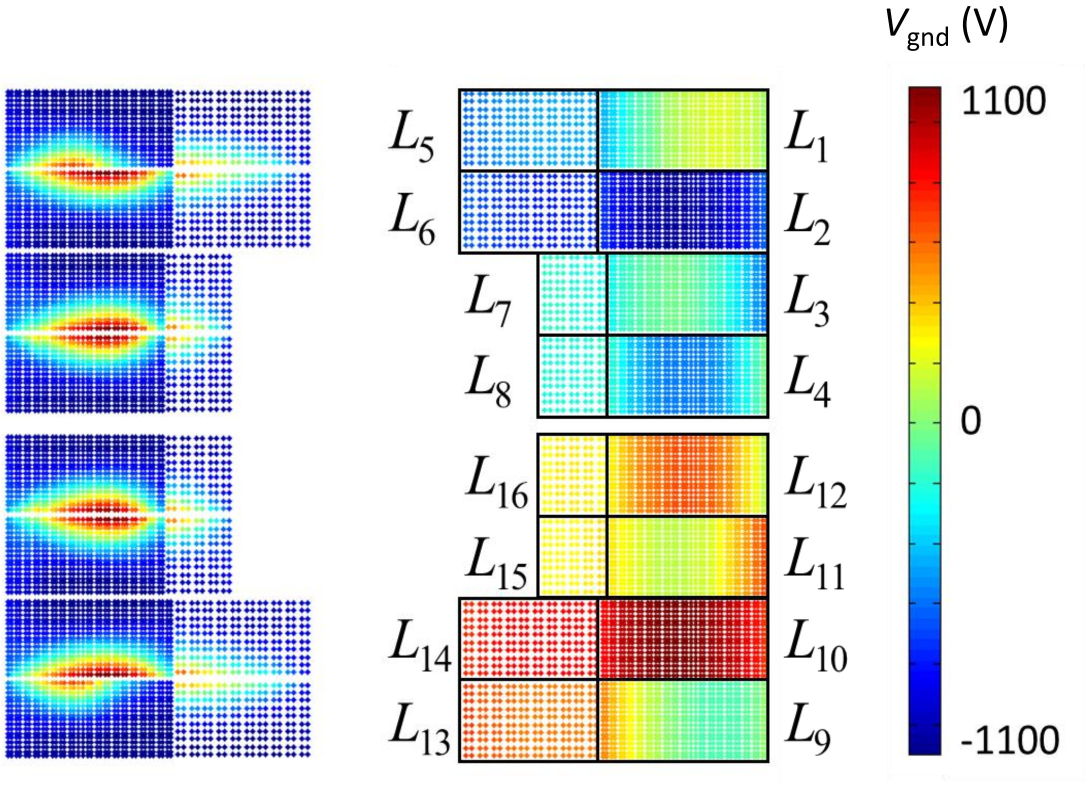
- Very promising results with a Multi-CLIQ system (2 x 1200 V/20 mF)

Details in the poster by M. Prioli



Quench simulation with LEDET[1]+PSPICE[2]

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



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[1] E. Ravaioli, *Cryogenics*, 2016.

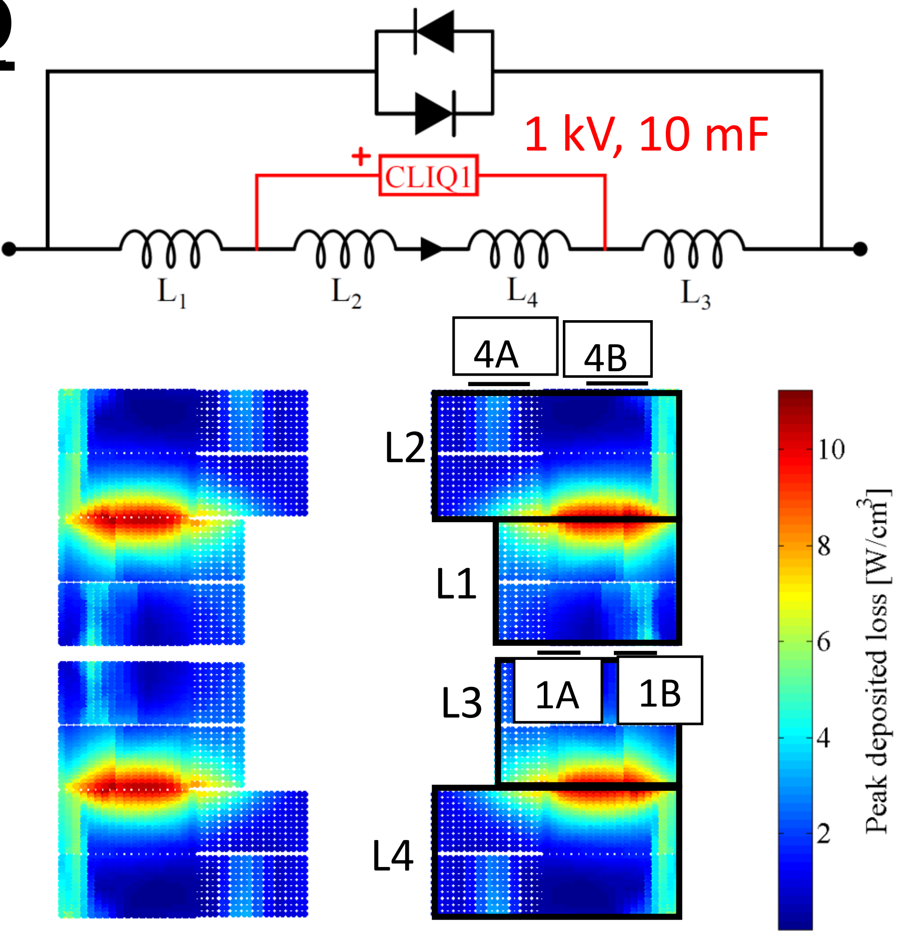
[2] I. Cortes Garcia et al., *submitted to IEEE JMMCT*, 2017

Protection with heaters and CLIQ

- CLIQ for fast quenching at high current,
- QH for voltage control and protection at low current

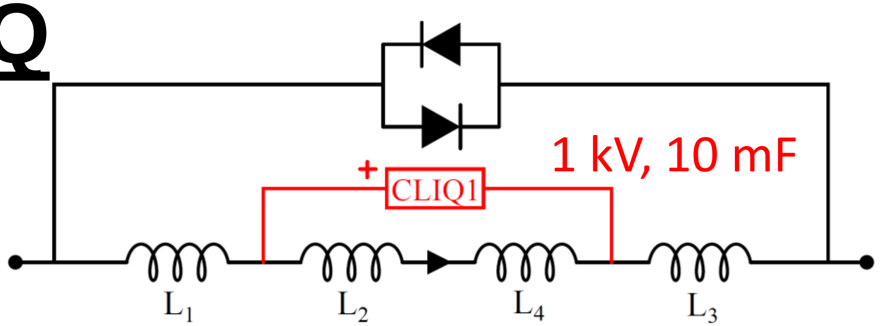
- **Advantages** when applied to Block:

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, 4A: 2.3	1A: 5/25 4A: 7/40	1A: 130 4A: 63	38
HFU#2	(1B+4B) || (1B+4B)	1B: 1.6, 4B: 2.3	7/40	1B: 150 4B: 71	36

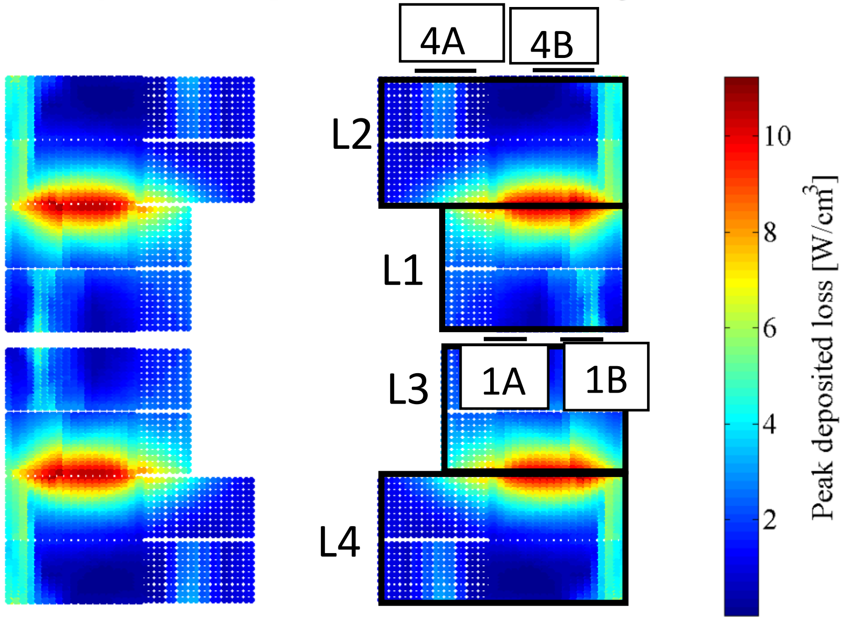
Protection with heaters and CLIQ



Simulation with CoHDA and LEDET

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

A check: Assume that CLIQ decreases the heater delays by 20% and increases longitudinal propagation velocity by 20%: T_{max} = 340 K and V_{gnd} = 1160 V



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, 4A: 2.3	1A: 5/25 4A: 7/40	1A: 130 4A: 63	38
HFU#2	(1B+4B) || (1B+4B)	1B: 1.6, 4B: 2.3	7/40	1B: 150 4B: 71	36

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

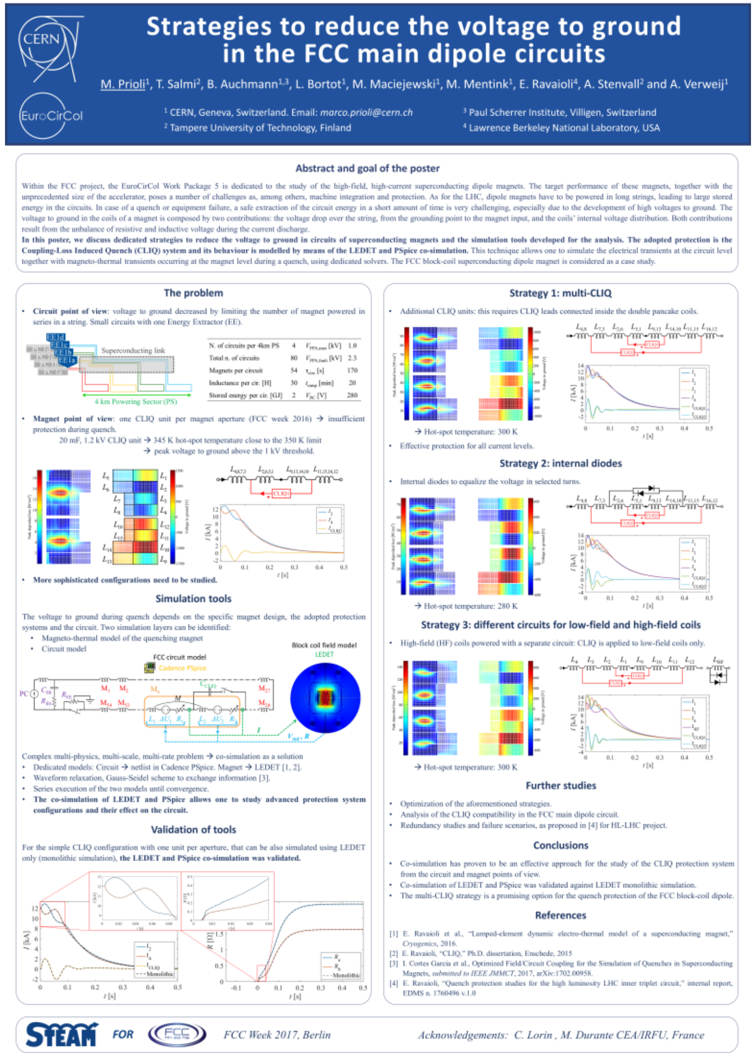
- **Quench protection integrated in the 16 T dipole magnets design from beginning**
  - At 105% of I_{nom} assumed protection efficiency 40 ms, and required $T_{max} < 350$ K, $V_{max} < 1200$ V
- **Two protection systems available:**
  - Quench heaters: T_{max} 340 – 350 K and V_{max} 1000 – 1200 V
  - 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



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

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[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 unbalance 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-Loss Induced Quench (CLIQ) system and its behaviour 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 as 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).

Strategy 1: multi-CLIQ

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

Strategy 2: internal diodes

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

Simulation tools

Validation of tools

Further studies

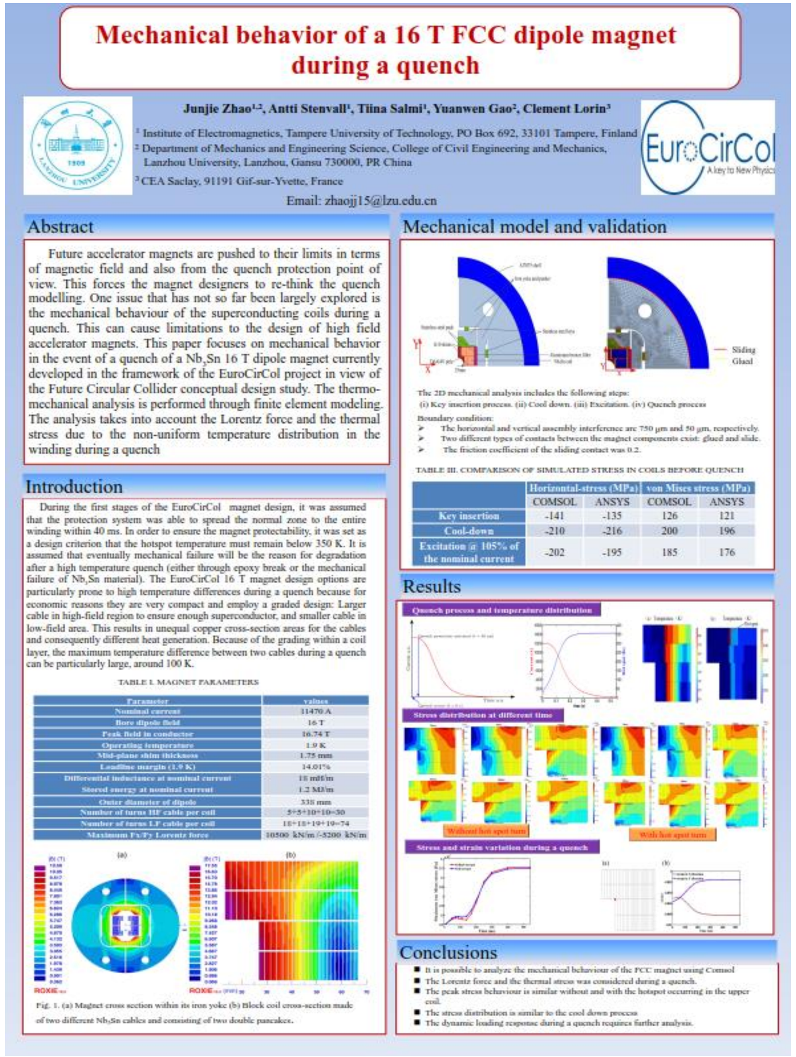
Conclusions

References

FCC Week 2017, Berlin

Acknowledgements: C. Lorin , M. Durante CEA/IRFU, France

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



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 Nb_3Sn 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 condition:
- 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 slide.
- The friction coefficient of the sliding contact was 0.2.

TABLE III. COMPARISON OF SIMULATED STRESS IN COILS BEFORE QUENCH

	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

Results

Conclusions