Status of readiness for the CDR

Task	Cosθ	Block	Common coil
"40 ms analysis"	Done	Done	Done
CLIQ design, 2-ap	Done	Done/ to be updated	Done / to be updated
QH design	Done	Done	Done
Mechanical model during quench (protection with CLIQ), 2-ap	Done	Done	Needed for CDR?
CLIQ design, failure analysis, redundancy	Ongoing	Not for CDR	Not for CDR
QH design, failure analysis	Done….	Not for CDR	Not for CDR

- We are writing a final report summarizing these studies (~30 pages, writing ongoing)
- This presentation: Show the FCC week protection talk draft and focus on the updates about CLIQ and heater designs

16 T dipole magnet quench protection

Draft of the slides for FCC-week 2018

Tiina Salmi and Marco Prioli

Acknowledgement:
E. Ravaioli, A. Stenvall,
A. Verweij, …. Etc!!!

35th EuroCirCol coordination meeting ,14th March 2018

Outline for FCC week presentation

1. Introduction, the steps in the quench protection design

2. Protection schemes with CLIQ (baseline)
   - Cosθ, Block, Common-coil
   - Redundancy

>>50% credit to Marco

3. Protection schemes with quench heaters (back-up option)
   - Cosθ, Block, Common-coil

4. Summary

Other work about quench protection:
M. Prioli talks "Mechanical analysis during quench" and "Circuit layout and protection"

1. Quick recap of accelerator magnet quench protection

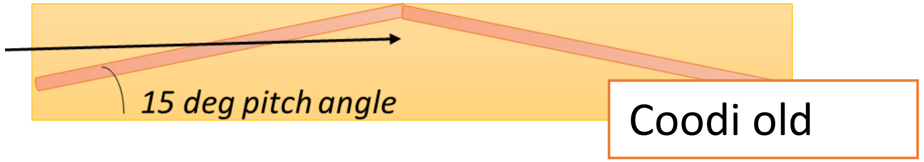
1. The steps in the quench protection design

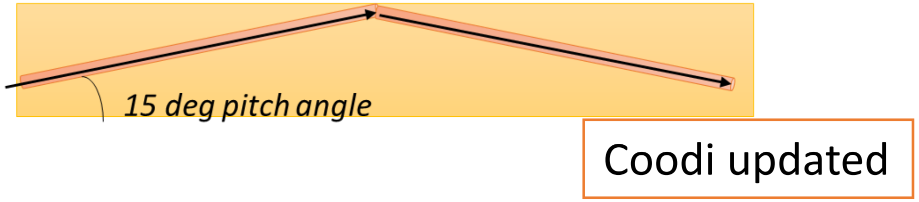
1. Results after 40 ms uniform quench delay

	Cosθ	Block	Common coil
T_{max} (K)	346	343	373
MIITs	19.1	15.0	41.4
V_{gnd} (V)	980	930	1040

Simulation with Coodi

Reminder: More conservative than the initial simulation/design approach

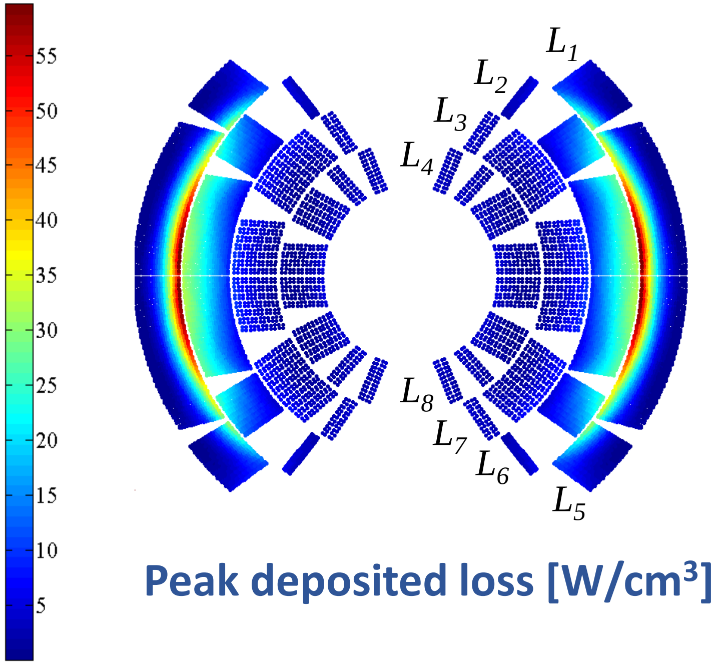




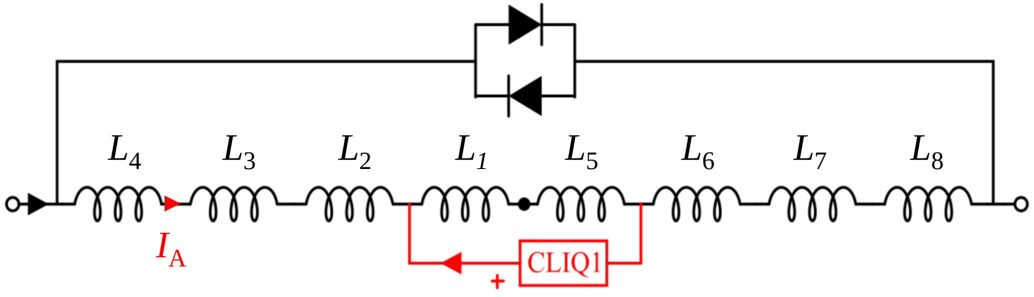
Cosθ and block within specification.

Common coil has higher temperature, but we will show that the protection is feasible using CLIQ.

2. Protection schemes with CLIQ: Cosθ

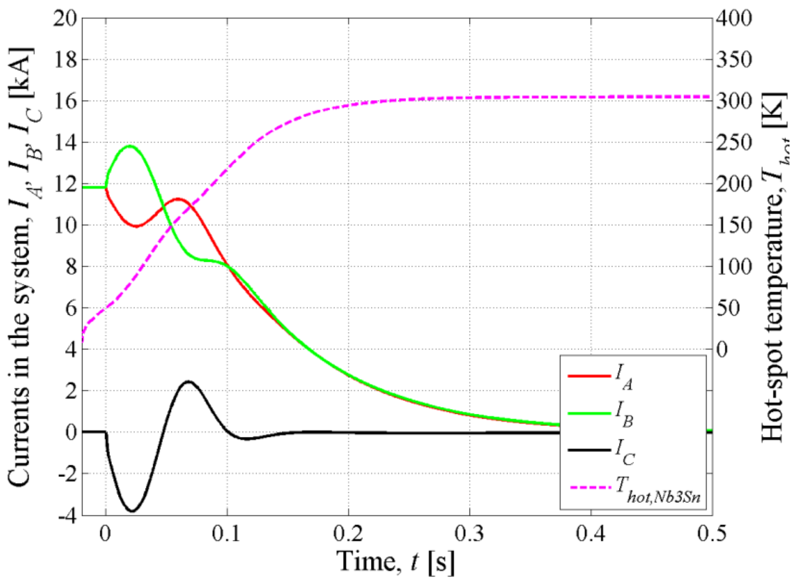


Peak deposited loss [W/cm^3]



1 CLIQ unit / aperture, charged to 1250 V, C = 50 mF

Quench simulation results



T_{max} = 304 K, V_{gnd} = 950 V

Simulation with LEDET, 1 aperture

T_{max} = 308 K, V_{gnd} = 900 V

Simulation with COMSOL, 2 apertures

(details in Marco's presentation)

Sensitivity analysis: Impact of filament twist, RRR and $f_{\rho,eff}$

nominal

Fil. Twist (mm)	RRR HF/LF	MIITs	Tmax (K)	Vmax (V)
14	100/100	18.0	**304**	**950**
10	100/100		**305**	**940**
20	100/100	18.3	**311**	**940**
14	150/150		**312**	**1000**
10	150/150		**312**	**1000**
20	150/150	18.8	**313**	**1010**
14	200/200		**315**	**1000**
10	200/200		**320**	**1000**
20	200/200		**320**	**1010**
14	50/50	16.5	**292**	**950**
10	50/50	16.8	**304**	**950**
20	50/50	16.4	**291**	**1000**
14	50/200	18.8	**306**	**1150**
14	200/50	16.7	**298**	**1170**

Fil. Twist (mm)	RRR HF/LF	Frho_eff	Tmax (K)	Vmax (V)
14	100/100	1	**304**	**950**
14	100/100	0.5	**305**	**970**
14	100/100	2	**311**	**930**

$f_{\rho,eff}$ **= effective matrix transverse resistivity** seen by the interfilament coupling loss.

In cosθ with the proposed CLIQ configuration, the impact of these parameters **is less than 20 K and 300 V.**

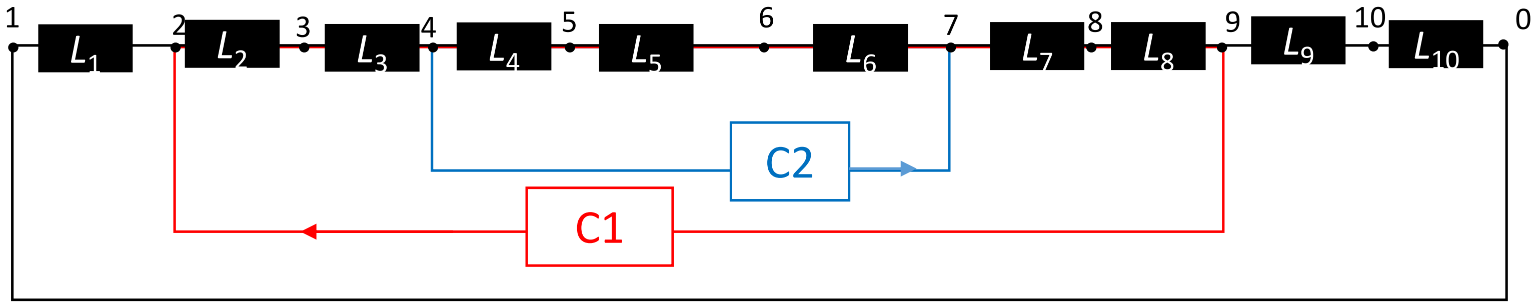
Simulation with LEDET, 1 aperture

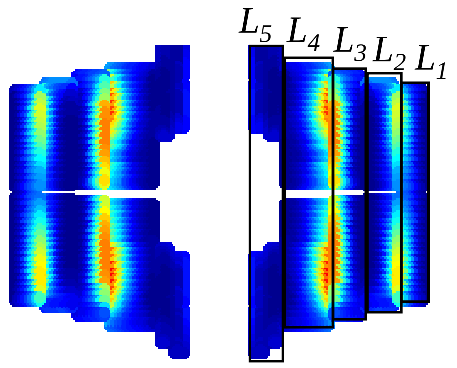
2. Protection schemes with CLIQ: Block

Magnet version and CLIQ configuration updated,
today shown in Marco’s presentation

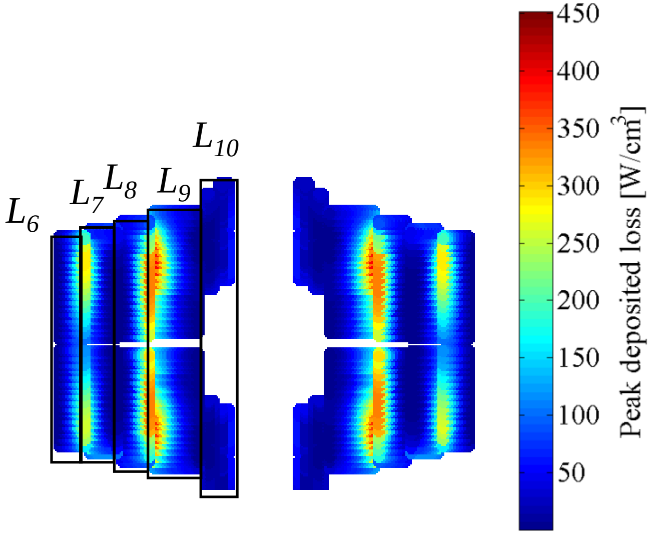
2. Protection schemes with CLIQ: Common-coil

2 CLIQ units: 900 V, C = 80 mF





Peak deposited loss [W/cm³]

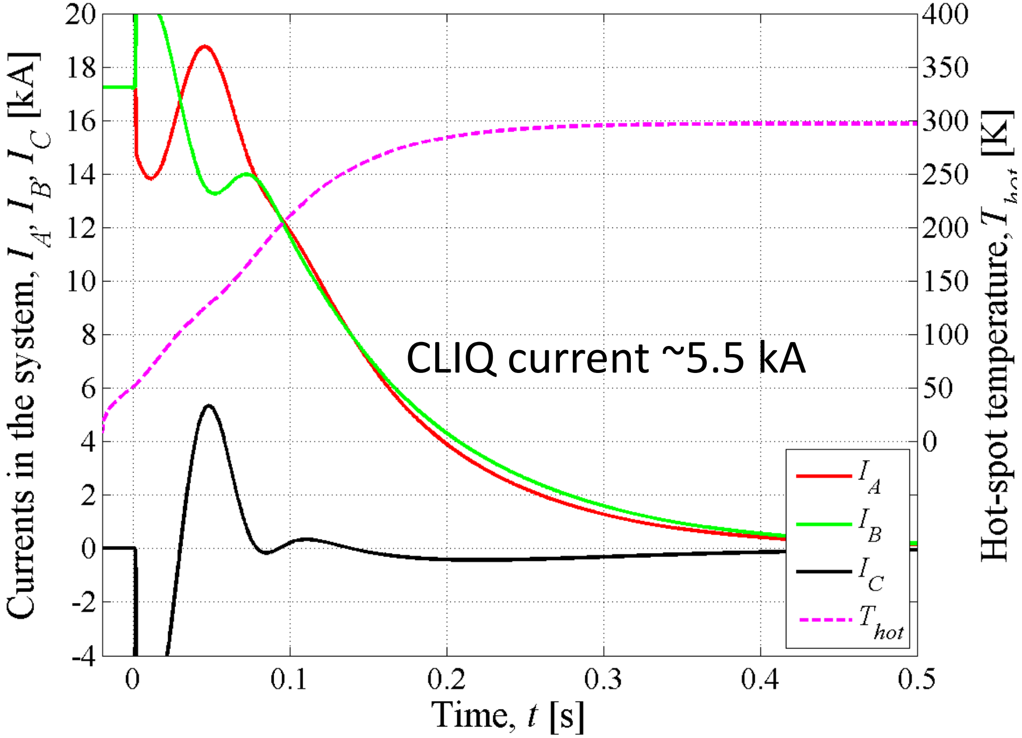


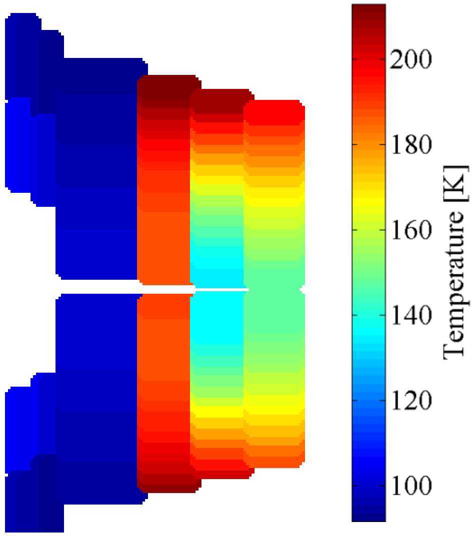
At 105% I_{nom} : T_{max} =300 K, V_{max} =1300 V

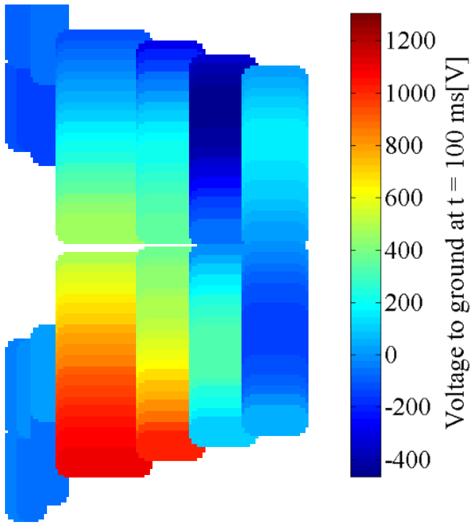
Simulation with LEDET

- Further optimization possible
- Low current protection requires high CLIQ power
- Consider quench heaters for low current protection and reduce CLIQ power?

Resulting currents, temperatures and voltages


CLIQ current ~5.5 kA





Simulation with LEDET

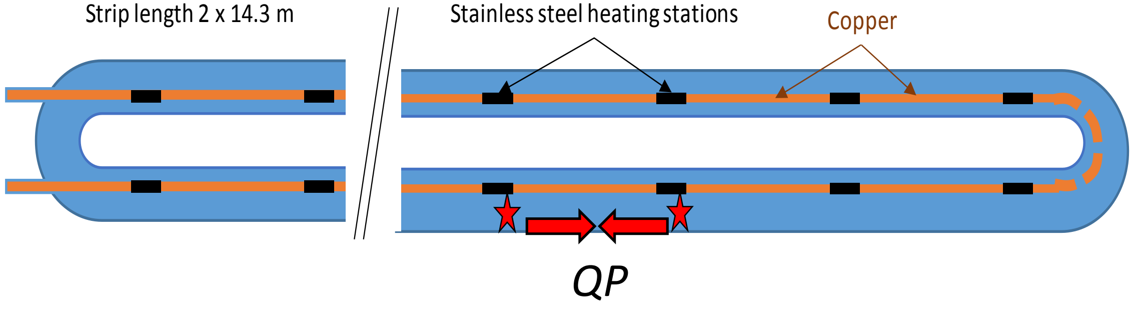
- ✓ Consistent with STEAM PSPICE-LEDET co-simulation.

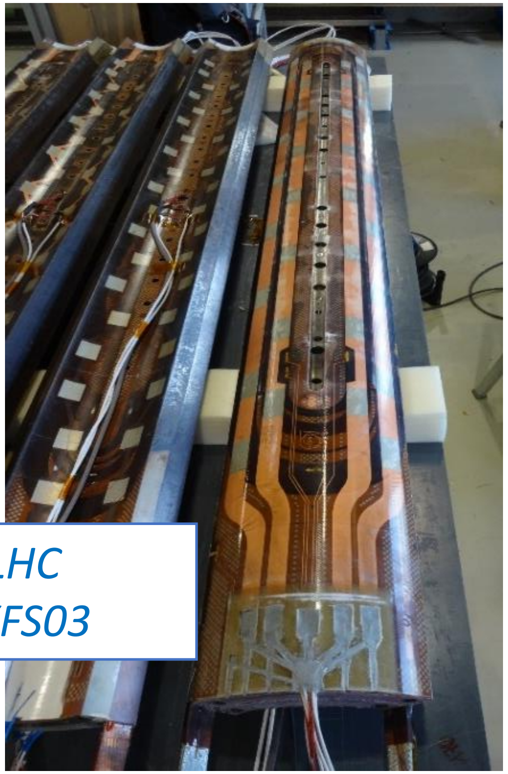
3. Protection schemes with heaters: Heater technology

- Similar technology than in LHC[1] and HL-LHC[2,3]:
  - Cu-plated stainless steel strips:
    - SS thickn. 25 µm, Cu thickn. 10 µm
  - **Insulation to coil: 75 µm polyimide**

- Powering with capacitor bank discharge:
  - Heater Firing Unit (HFU): **1200 V and 10 mF (LHC: 900 V and 7 mF)**
  - 1 Ω for wires etc. / circuit

- Design goal: *T* and *V* within limitations at 105% and minimize number of HFU's





Heaters on HL-LHC quadrupole MQXFS03

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[1] F. Rodriquez-Mateos and F. Sonneman, "Quench heater studies for the LHC magnets", Proc. of PAC, 2001.

[2] H. Felice et al., "Instrumentation and Quench Protection for LARP Nb3Sn Magnets", *IEEE TAS,* 19(3), 2009.

[3] P. Ferracin et al, "Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi LHC", *IEEE TAS,* 26(4), 2016.

3. Protection schemes with heaters: Cosθ

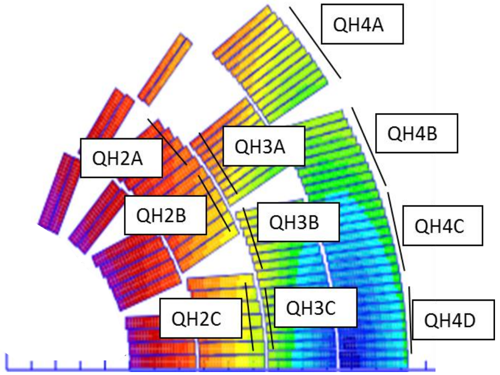
- Heaters cover 62% of turns
  - Under each heater, ~20% coverage by heating stations

- 14 HFU's / 2-ap. magnet (100 kJ)
- Heater peak power 100-150 W/cm^2, time constant 40-50 ms

- **<u>At 105% Inom</u>**: Heater delays: 7-20 ms
  - 20 m/s quench propag. Btw heating stations
  - 10 ms quench propag. Btw turns
  - 20 ms quenhc propag from second to first layer
  - 20 ms quench detection and validation
  - → **Average quench delay 43 ms**

- **<u>Hotspot temperature 350 K</u>**
  - **<u>Peak voltage to ground 1130 V</u>**
  - Between turns 90 V
  - Between layers 1100 V

Locations of heater strips (No inner layer heaters!)



Heater strip geometries and powering

HFU	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH,0}$ (W/cm^2)	τ_{RC} (ms)
#1	$2A_{c1} \Vert 2B_{c1} \Vert 2A_{c2} \Vert 2B_{c2}$	1.0	4/18	100	40
#2	$2C_{c1} \Vert 3A_{c1} \Vert 3B_{c1} \Vert 3C_{c1}$	1.0	4/18	100	40
#3	$4A_{c1} \Vert 4B_{c1}$	1.3	6/30	150	50
#4	$4C_{c1} \Vert 4D_{c1}$	1.3	6/30	150	50
#5	$2C_{c2} \Vert 3A_{c2} \Vert 3B_{c2} \Vert 3C_{c2}$	1.0	4/18	100	40
#6	$4A_{c2} \Vert 4B_{c2}$	1.3	6/30	150	50
#7	$4C_{c2} \Vert 4D_{c2}$	1.3	6/30	150	50

3. Protection schemes with heaters: Block

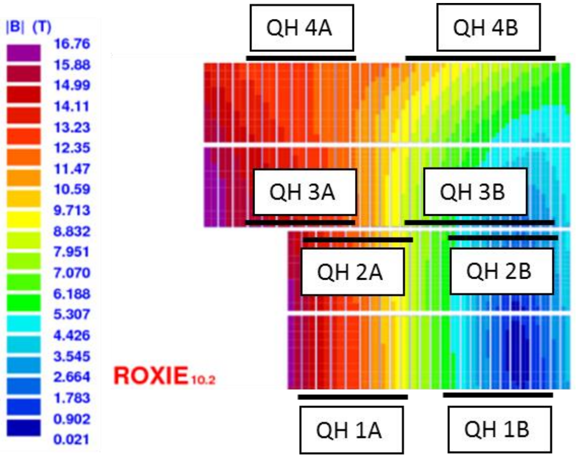
- Heaters cover 77% of turns
  - Under each heater, 14-23% coverage by heating stations

- 13 HFU's / 2-ap. magnet (94 kJ)
- Heater peak power 100-130 W/cm^2, time constant 20-40 ms

- **At 105% Inom**: Heater delays: 6-40 ms
  - 20 m/s quench propag. Btw heating stations
  - 10 ms quench propag. Btw turns
  - 20 ms quench detection and validation
  - → **Average quench delay 45 ms**

- **Hotspot temperature 350 K**
  - **Peak voltage to ground 1000 V**
  - Between turns 100 V
  - Between layers 1340 V

Locations of heater strips



Heater strip geometries and powering

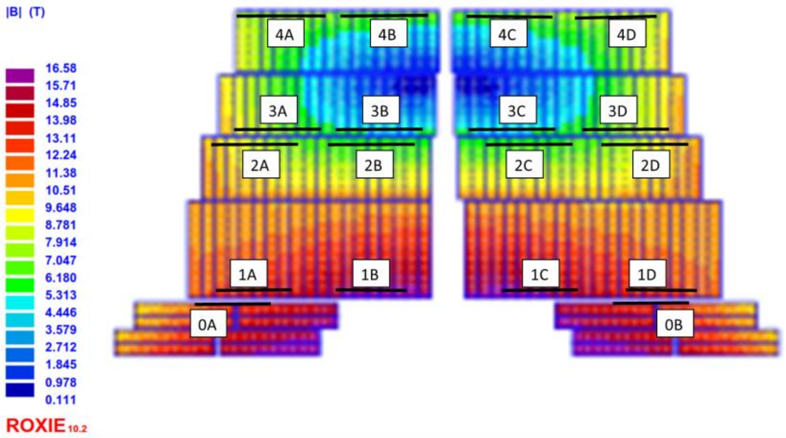
HFU	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
#1	$1A_{c1}\vert\vert 2A_{c1}$	1.9	5/22	100	40
#2	$1B_{c1}\vert\vert 2A_{c1}$	1.8	6/30	130	40
#3	$(3A_{c1}+4A_{c1}+3A_{c2}+4A_{c2})\vert\vert$ $(3A_{c1}+4A_{c1}+3A_{c2}+4A_{c2})^{Ap2}$	2.1	5/35	100	20
#4	$3B_{c1}\vert\vert 4B_{c1}$	2.4	6/30	110	30
#5	$1A_{c1}\vert\vert 2A_{c1}$	1.9	5/22	100	40
#6	$1B_{c1}\vert\vert 2A_{c1}$	1.8	6/30	130	40
#7	$3B_{c1}\vert\vert 4B_{c1}$	2.4	6/30	110	30

3. Protection schemes with heaters: Common-coil

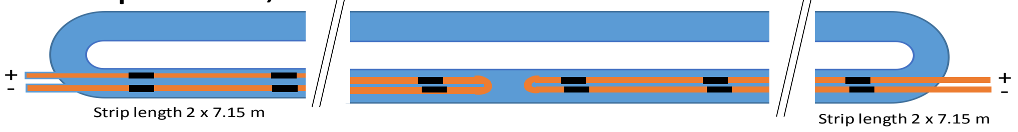
- Heaters cover 70% of turns
    - Under each heater, 19-39% coverage by heating stations

- 23 HFU's / 2-ap. magnet (166 kJ)
- Heater peak power 90-143 W/cm^2, time constant 30-40 ms

- **At 105% Inom**: Heater delays: 5-19 ms
    - 20 m/s quench propag. Btw heating stations
    - 10 ms quench propag. Btw turns
    - 20 ms quench detection and validation
    - → **Average quench delay 39 ms**
- **Hotspot temperature 351 K**
    - **Peak voltage to ground 1200 V**
    - Between turns 90 V
    - Between layers 1150 V
- A remark: The amount of HFU's can be reduced to 15, then hotspot temperature is 358 K



Strips 3A-D, 4A-D



Heater strip geometries and powering

HFU	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
#1	$0A_{c1} \Vert 0B_{c1} \Vert 0A_{c2} \Vert 0B_{c2}$	1.5	4/ 19	90	30
#2	$1A_{c1} \Vert 1B_{c1} \Vert 1C_{c1} \Vert 1D_{c1}$	1.5	4/ 19	90	30
#3	$2A_{c1} \Vert 2B_{c1}$	1.75	6/31	140	40
#4	$2A_{c1} \Vert 2B_{c1}$	1.75	6/31	140	40
#5	$3A_{c1,R}+3B_{c1,R} \Vert 3A^*_{c1,R} + 3B^*_{c1,R}$	1.75	6/16	143	40
#6	$3C_{c1,R}+3B_{c1,R} \Vert 3C^*_{c1,R} + 3D^*_{c1,R}$	1.75	6/16	143	40
#7	$4A_{c1,R}+4B_{c1,R} \Vert 4A^*_{c1,R} + 4B^*_{c1,R}$	1.75	6/16	143	40
#8	$4C_{c1,R}+4B_{c1,R} \Vert 4C^*_{c1,R} + 4D^*_{c1,R}$	1.75	6/16	143	40
#9	$3A_{c1,L}+3B_{c1,L} \Vert 3A^*_{c1,L} + 3B^*_{c1,L}$	1.75	6/16	143	40
#10	$3C_{c1,L}+3B_{c1,L} \Vert 3C^*_{c1,L} + 3D^*_{c1,L}$	1.75	6/16	143	40
#11	$4A_{c1,L}+4B_{c1,L} \Vert 4A^*_{c1,L} + 4B^*_{c1,L}$	1.75	6/16	143	40
#12	$4C_{c1,L}+4B_{c1,L} \Vert 4C^*_{c1,L} + 4D^*_{c1,L}$	1.75	6/16	143	40

Summary

- Magnets were designed to comply with the “40 ms/350 K “ protectability criteria
- Continuous feedback loop between quench protection studies and magnet designs

- **Protection with CLIQ seems feasible for all magnet options**
  - **Max temperatures around 300 K (105% Inom)**
  - **Internal voltages around 1000 V**
  - Redundancy…

- Protection with heaters is considered a back-up option
  - Temperatures and voltages near the limits
  - Difficult to obtain redundancy

→ Used methodology for protection design seems successful and the developed tools useful

- For CDR: Almost all the studies are ready, writing of the report is well underway