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16 T dipole magnet quench protection

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with the EuroCirCol WP5 members

and support from the STEAM team at CERN TE-MPE-PE

FCC week 2019, Brussels, 27th June 2019

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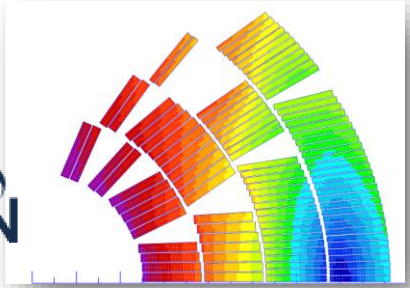
*Canted cosθ analyzed at PSI

EuroCirCol 16 T dipole designs*

INFN



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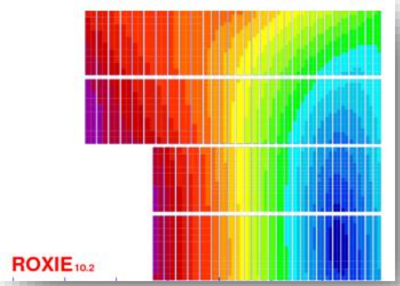

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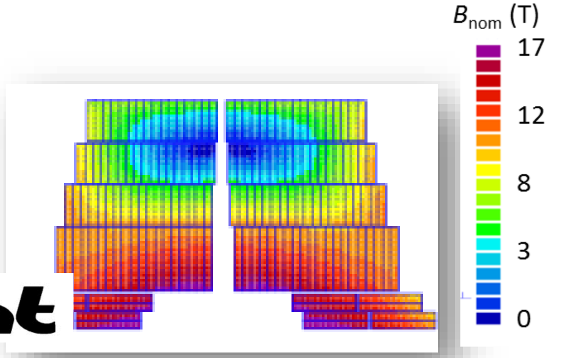

Magnet, version	**Cosθ, 22b_38_v1**		**Block, V2ari204**		**Common coil, vh12_2ac6**	
Inom (A)	11390		10111		16400	
Ld,nom (mH/m)	2 x 19.8		2 x 24.8		21.1	
Cable	**HF-cable**	**LF-cable**	**HF-cable**	**LF-cable**	**HF-cable**	**LF-cable**
Cable *w* x *t* (bare) (mm)	13.2 x 1.95	14.0 x 1.265	12.6 x 2.0	12.6 x 1.27	19.2 x 2.2	12.0 x 2.2
Number of strands	22	38	21	34	30	18
Strand diam. (mm)	1.1	0.7	1.1	0.7	1.2	1.2
Cu/SC	0.82	2.1	0.8	2.0	1.0	2.5

Cable ins. : 0.15 mm, RRR = 100, filament twist = 14 mm, strand twist= 15°

Jc with Bordini fit: T_{c0} = 16 K, B_{c20} = 29.38 T, α = 0.96, C_0 = 267845 A/mm^{2}T

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Outline

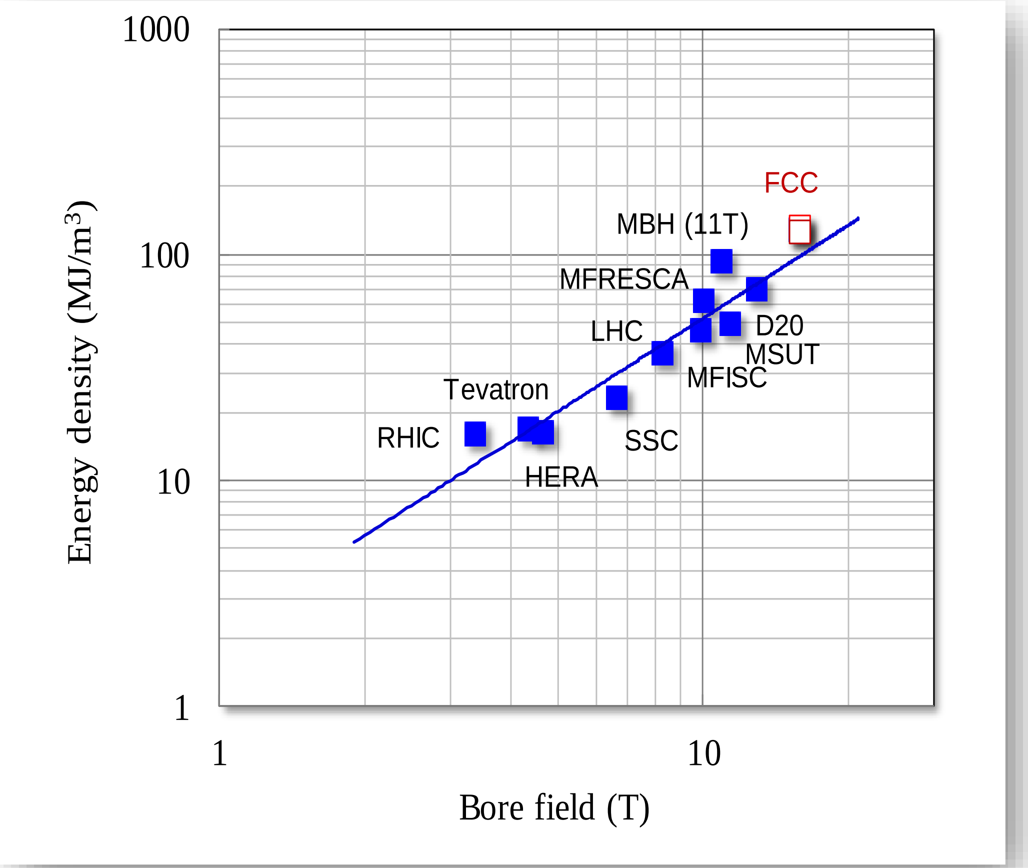
1. Ensuring magnet protectability

2. Simulation tools

3. Conceptual quench protection schemes:
   - CLIQ - Coupling Loss Indusced Quench
   - QH - Quench heaters

4. Simulated temperatures and voltages after quench
   - Comparison of CLIQ and QH

5. Conclusions



Stored energy density in dipoles vs. peak field, by courtecy of L. Bottura and D. Schoerling

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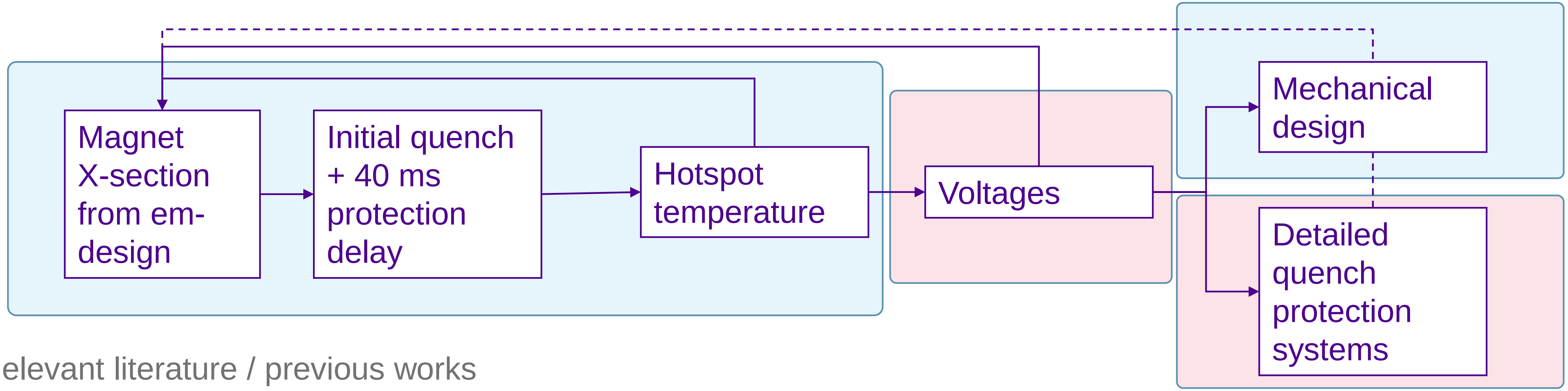
Related publications withing this project

T. Salmi et al, Phys. Rev. Accel. Beams 20, 032401
T. Salmi and D. Schoerling,, *IEEE TAS*, 29(4), 2019, 4900116.

1. Ensuring magnet *protectability*

- Protetability with a real quench protection system (CLIQ or QH)
- Safe limit of temperature and voltages: **350 K**, **2.5 kV** in circuit, **1.2 kV** in single magnet
- **A simplified quench analysis for fast-feedback – The EuroCirCol protectability criterion**
  - Assume a protection system quenches the entire magnet 40 ms after initial quench
  - **20 ms det + 20 ms QH/CLIQ**
  - At 105% of Inom



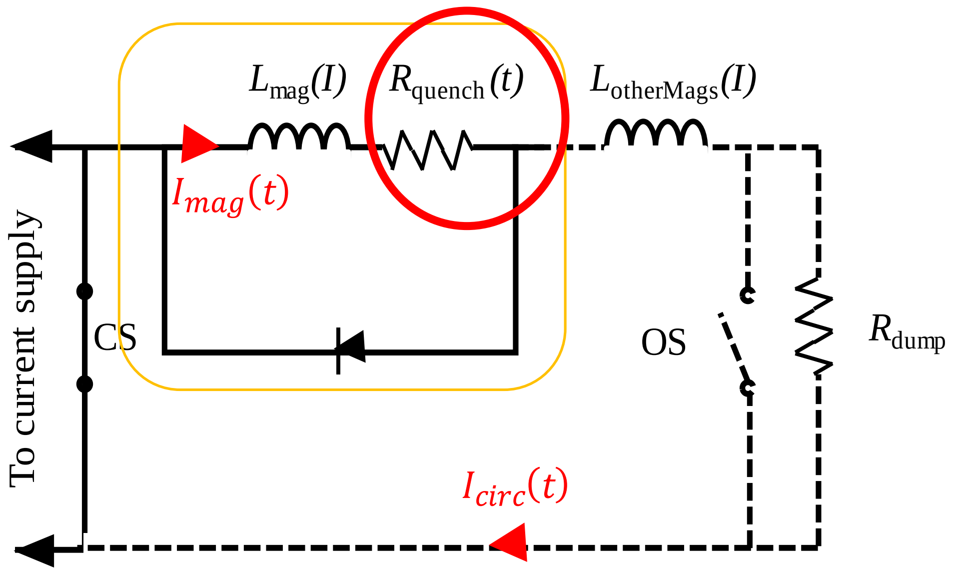
Relevant literature / previous works

E. Todesco, Proc. WAMSDO 2013
G. Amborsio, Proc. WAMSDO 2013

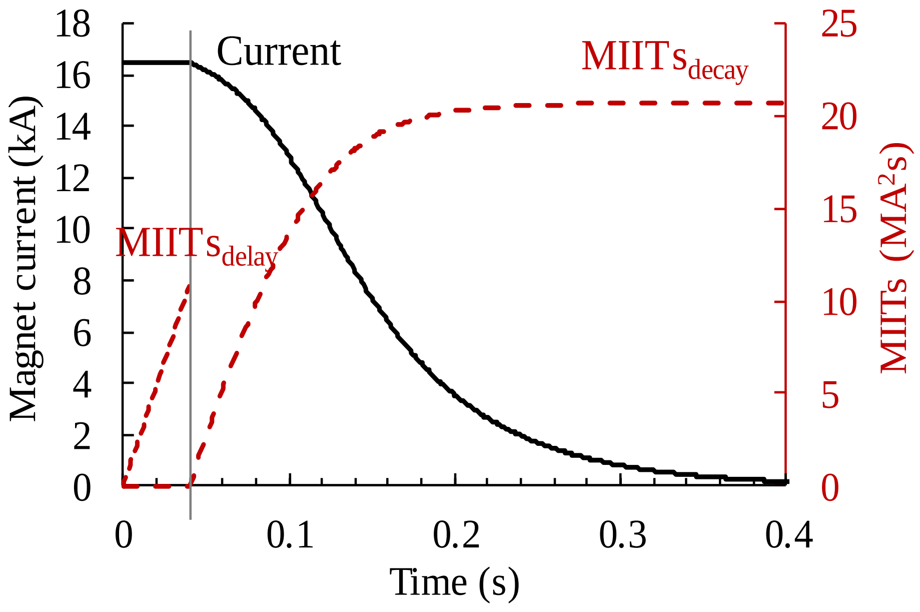
2. Simulation tools

What did we simulate?

- Inital quench and 20 ms detection time with constant current (incl. validation time etc.)
- Coil heating and evolution of normal zones after protection activation (IFCC of CLIQ, or heat from heaters)
- Coil temperature and resistance increase current decay
- Post-process for voltage distribution



Magnet powering circuit in accelerator



Analysis of MIITs separately before and after quench detection

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More details and references in appendix!

How did we simulate?

- Initial analysis with 40 ms uniform quench delay:
  - 0 D thermal

Coodi

QP spreadsheet

T. Salmi et al., PRAB 20, 032401
T. Salmi et al., *IEEE TAS*, 26(4), 2016

- CLIQ design
  - Analytical equations for IFCC
  - Thermal diffusion between turns

COMSOL

LEDET

PSPICE

ANSYS

STEAM

STEAM: Website: https://espace.cern.ch/steam
L. Bortot, et al., IEEE TAS,28(3), 2018.
E. Ravaioli, et al., Cryogenics, 2016.
L. Bortot et al., IEEE TAS, 27(4), 2017.
I. C. Garcia et alIEEE J. on Multiscale and Multiphysics Comp. Techn., 2017.

- QH design
  - 2D heat transfer model for heater delay
  - Adiabatic thermal based on heater delays and given NZPVs

CoHDA

T. Salmi et al, *IEEE TAS*, 24(4), 2014.

Coodi

- Internal voltages with a circuit model

- Profit from tools already used in magnet design for magnetic field, inductance and mechanical modeling

ROXIE

ANSYS

To be presented at MT26, 2019

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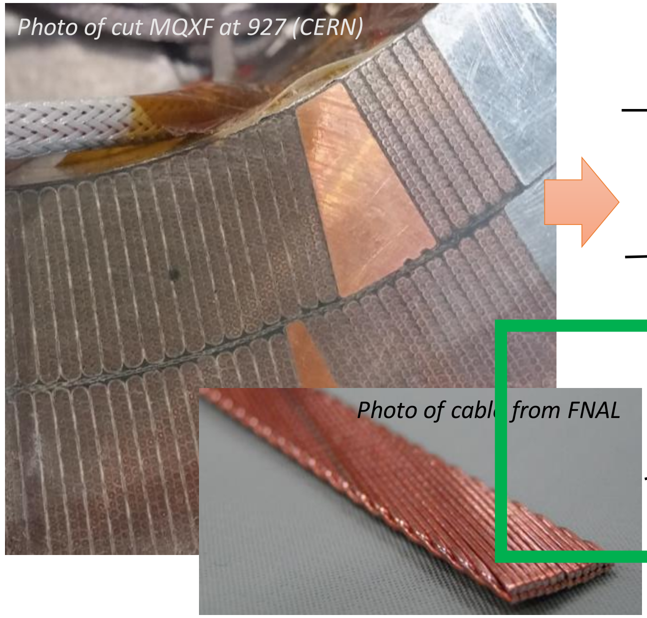
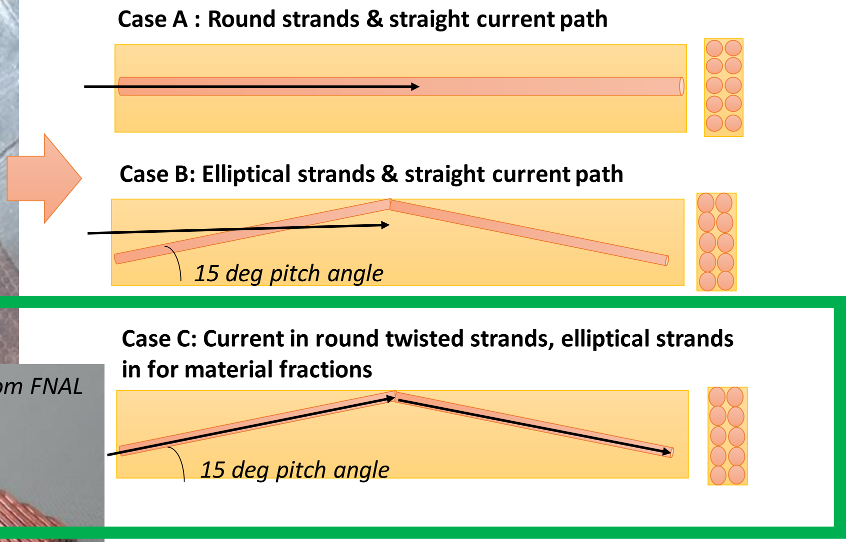
Model validation

- LEDET and CoHDA previously validated with HL-LHC model magnets
- Coodi validated during the time of project
  - Helped to adjust cable simulation method
- Validations mainly are comparison of current decays

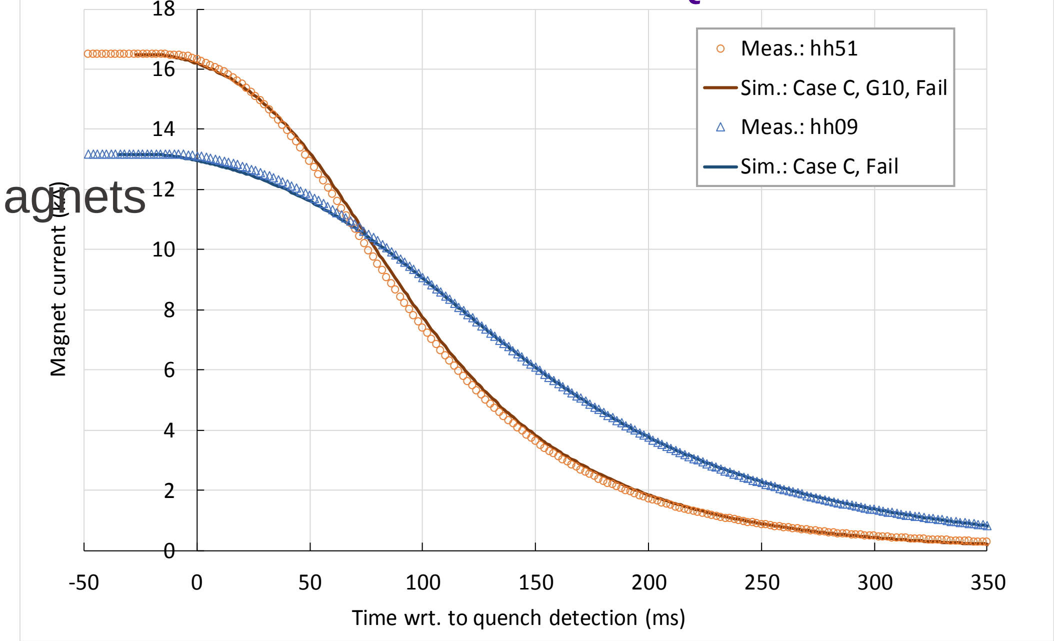
Three different cases on cable modeling assumptions.



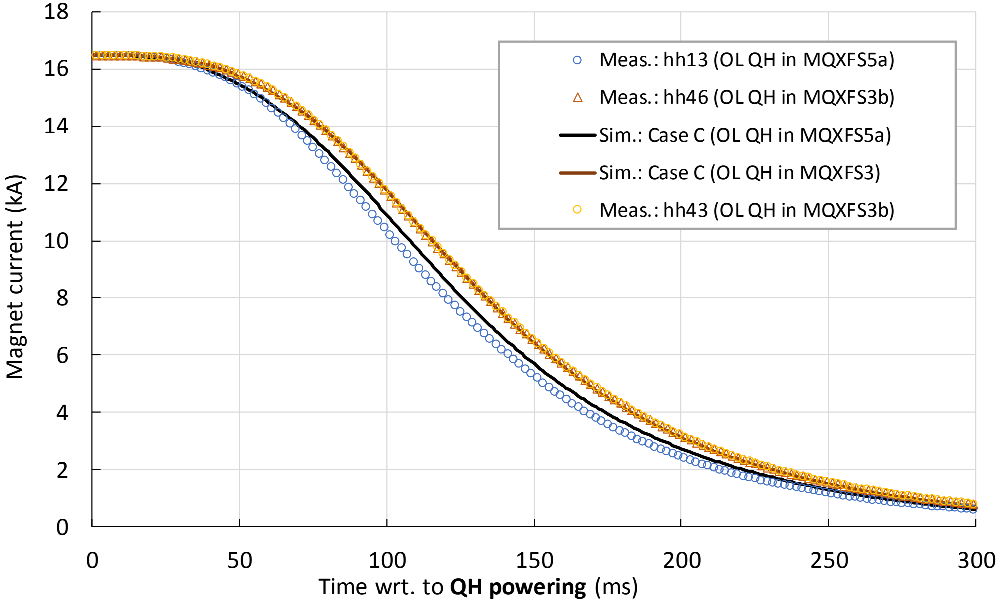


Best match with experimental data

Fire OL+IL heaters in MQXFS3a



Fire OL heaters in MQXFS3b and MQXFS5a



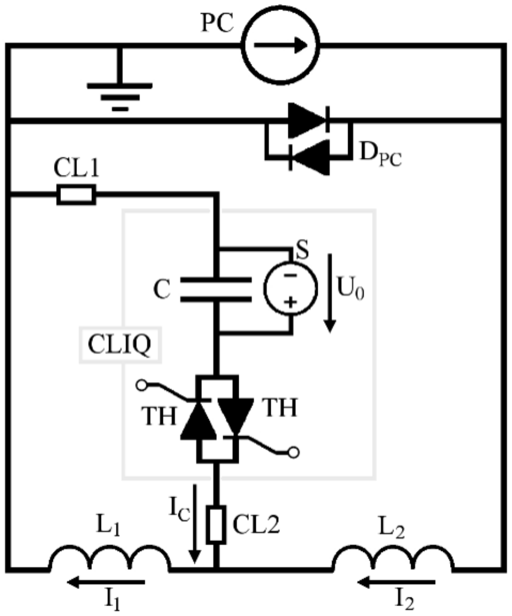
3. Conceptual quench protection schemes

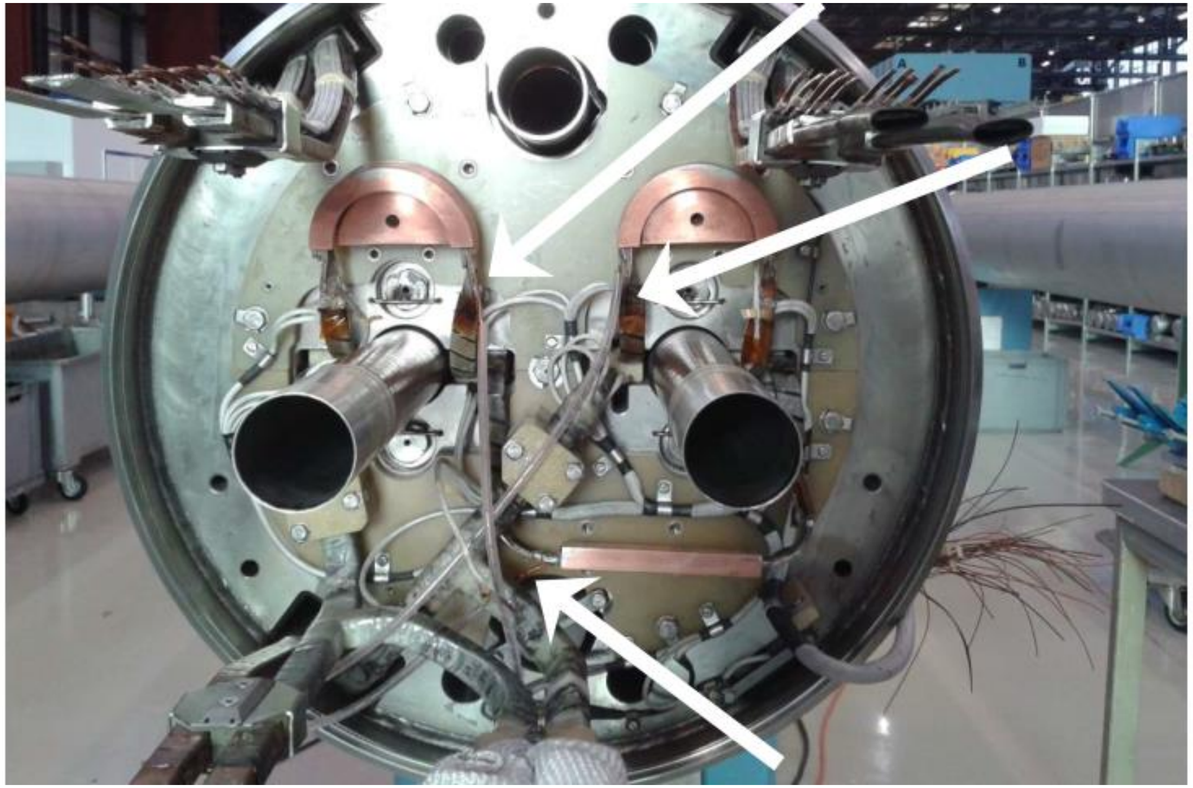
CLIQ – Coupling-Loss Induced Quench

- Discharge capacitor bank across part of the winding

⇨ Oscillations of transport current

⇨ Coupling losses in strands ⇨ Quench





CLIQ leads in the 15 m long LHC main dipole (Aug 2015), Photo by courtesy of E. Ravaioli

E. Raviaoili, PhD Thesis

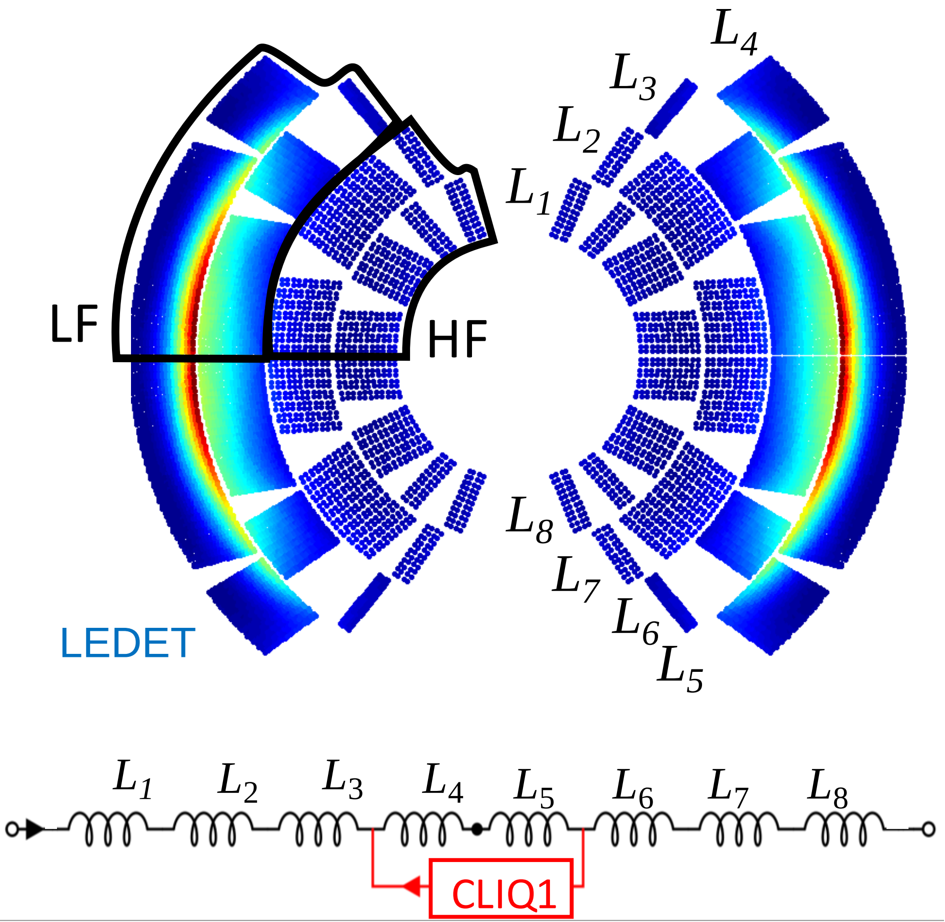
New technology with advantages:

- Connections external to the magnet → Accessible

Design of CLIQ-based protection: Cosθ

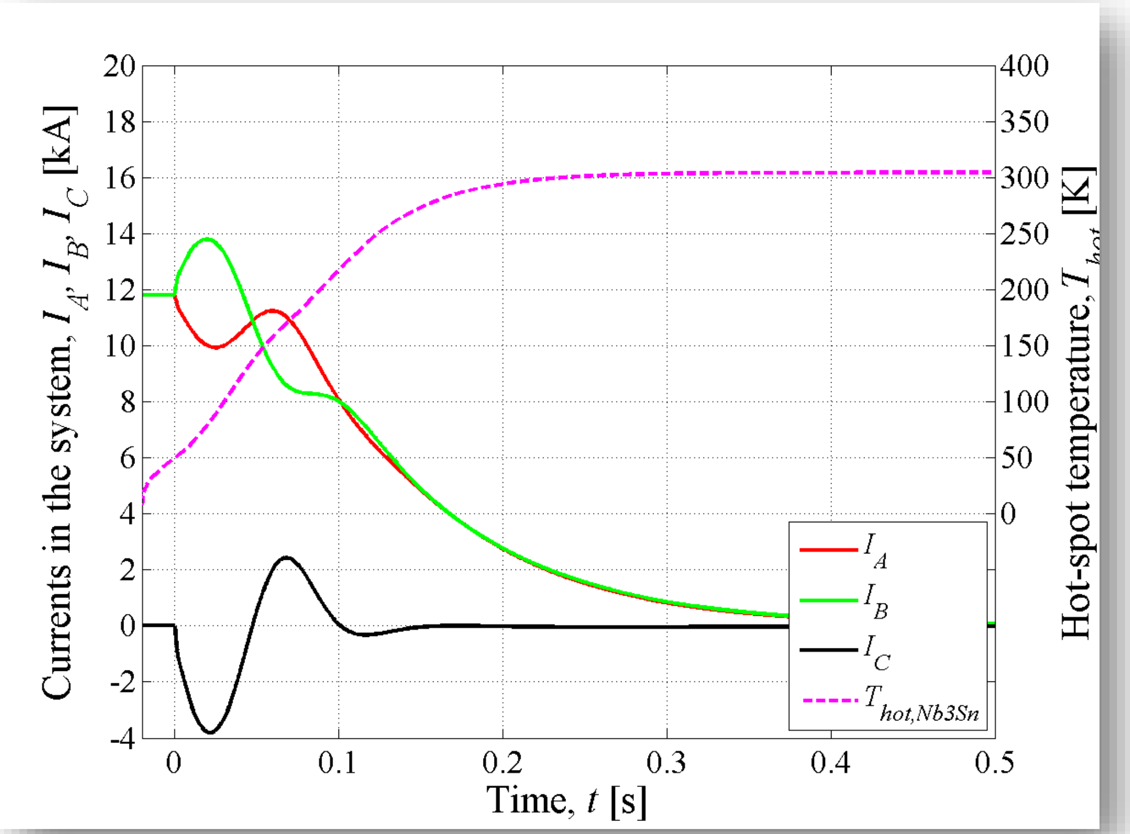
M. Prioli et al., "The CLIQ quench protection system applied to the 16 T FCC-hh dipole magnets", *IEEE TAS (under review)*
T. Salmi et al., *IEEE TAS*, 29(5), 2019, 4700905.
T. Salmi et al., *IEEE TAS*, 27(4), 2017, 4702305.
J. Zhao et al., Physica C: Supercond. and Applic., 550, 2018, 27.

Connection of CLIQ units and the charging voltage and capacitance



V_0=1.25 kV, C=50 mF

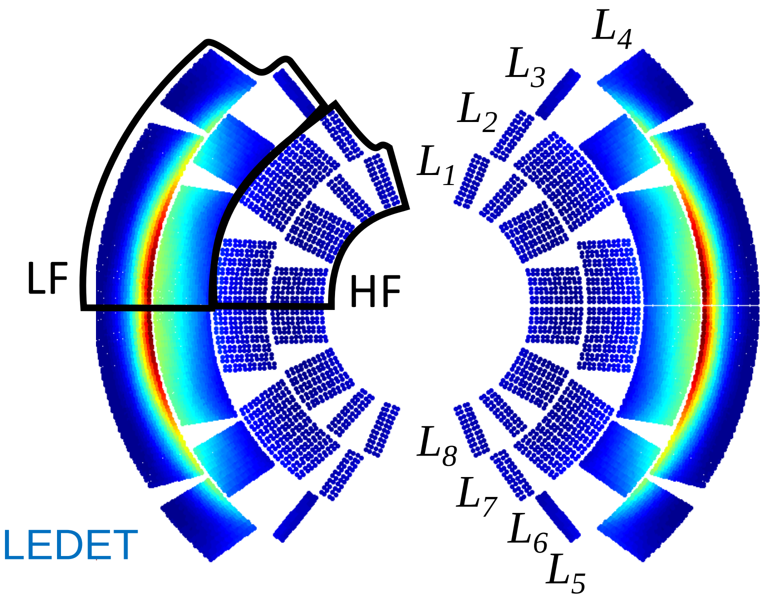
Resulting current oscillations

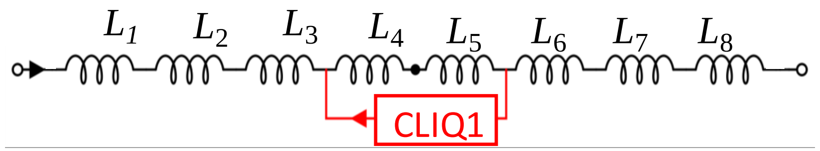


(Example case at 105% Inom)

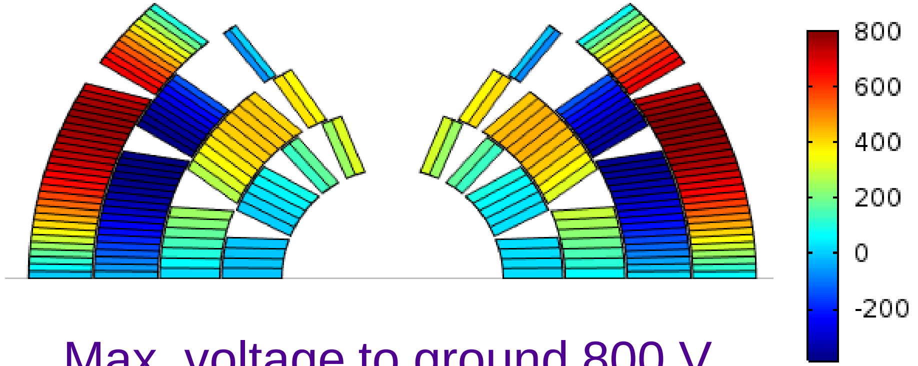
COMSOL simulation at nominal current by M. Prioli

Design of CLIQ-based protection: Cosθ



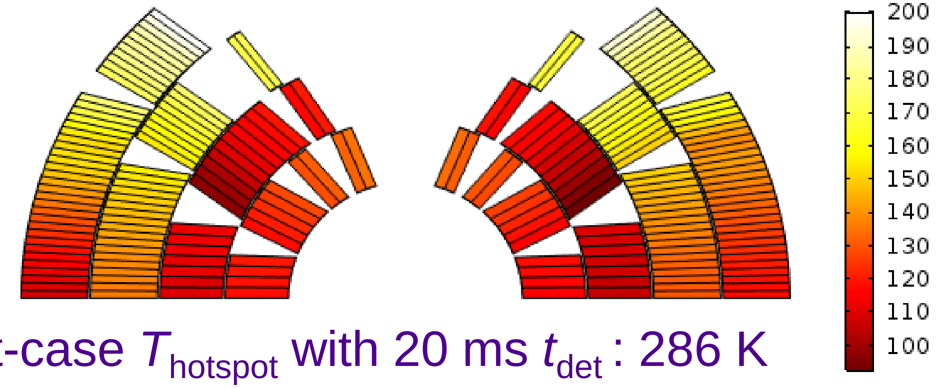


Voltage distribution 120 ms after CLIQ activation



Max. voltage to ground 800 V

Final temperature distribution after CLIQ activation



Worst-case $T_{hotspot}$ with 20 ms t_{det} : 286 K

Mechanical stress after quench and protection in part of the circuit, see:

M. Prioli et al., "The CLIQ quench protection system applied to the 16 T FCC-hh dipole magnets", *IEEE TAS (under review)*
M. Prioli et al., " Conceptual design of the FCC-hh dipole circuits with integrated CLIQ protection system", *IEEE TAS (accepted for pubclication)*

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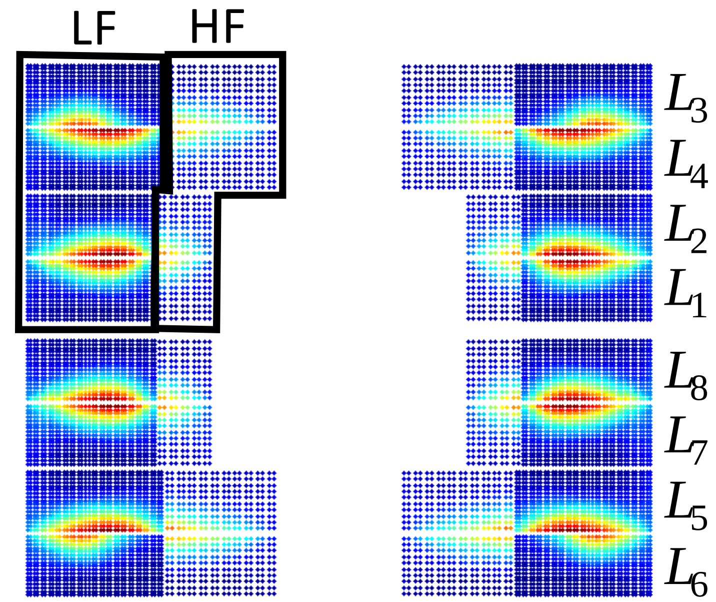
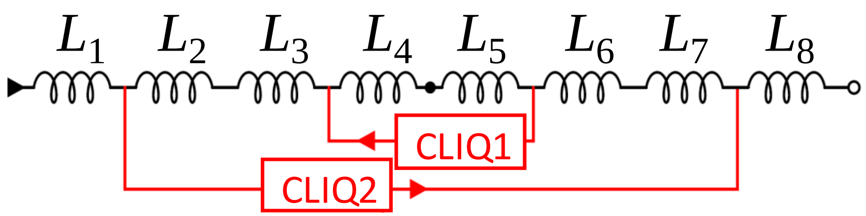
Block



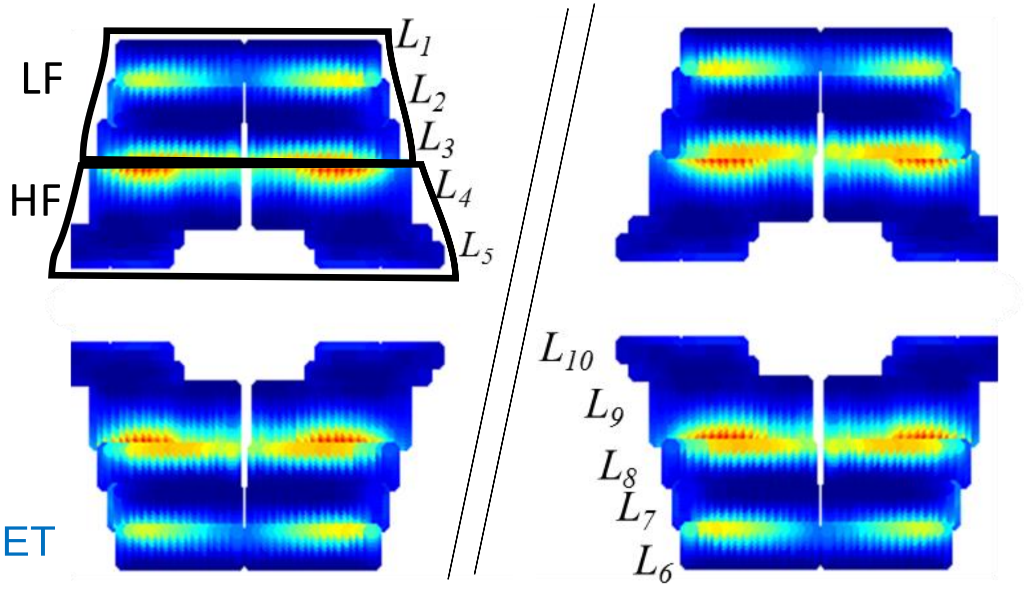


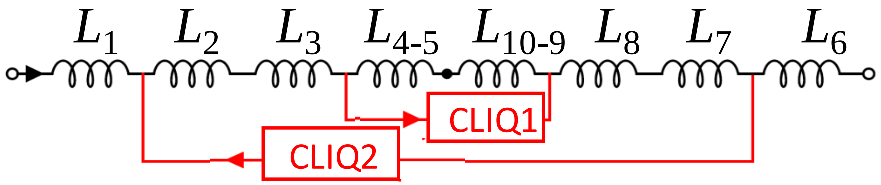
CLIQ1: V_0=0.6 kV, C=50 mF
CLIQ2: V_0=1.2 kV, C=50 mF

COMSOL simulation by M. Prioli:

Hot-spot temperature 286 K
Max. voltage to ground 0.7 kV

Common-coil





CLIQ1,2: V_0=0.9 kV, C=80 mF

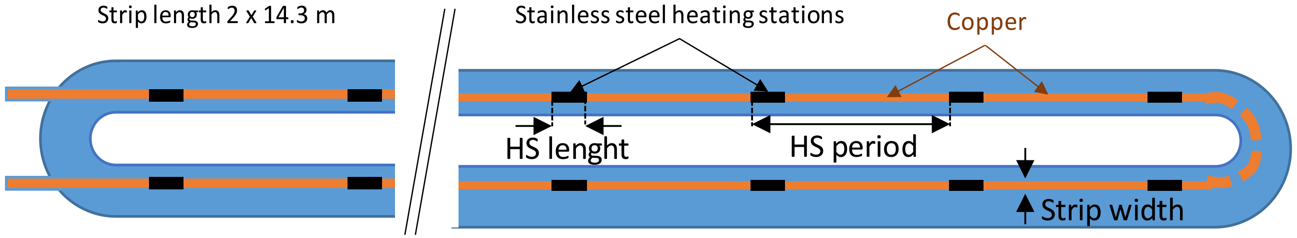
Hot-spot temperature 284 K
Max. voltage to ground 1.1 kV

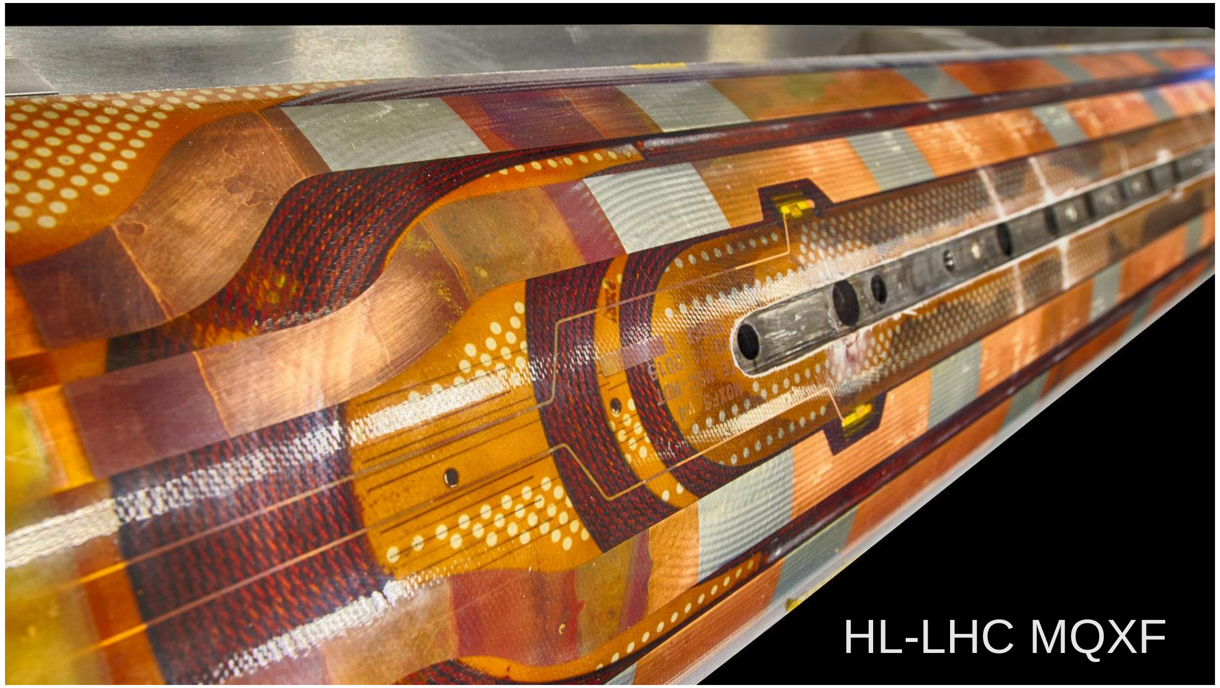
STEAM

QH – Quench heaters

- Similar technology than in LHC and HL-LHC:
  - 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): **1.2 kV and 10 mF** (LHC: 900 V and 7 mF)
  - 1 Ω for wires etc. / circuit

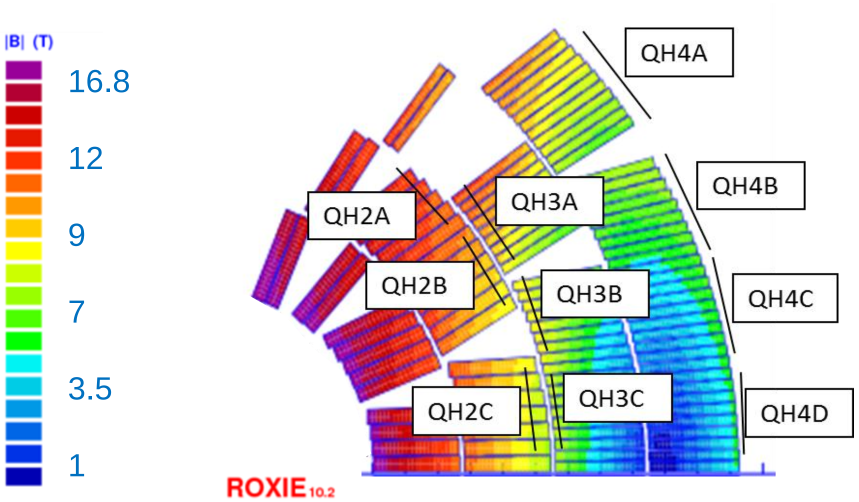


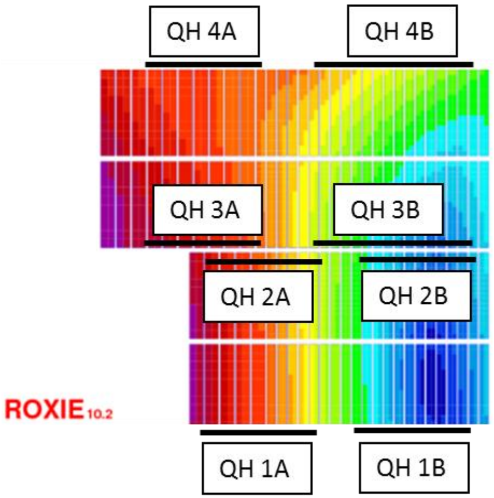


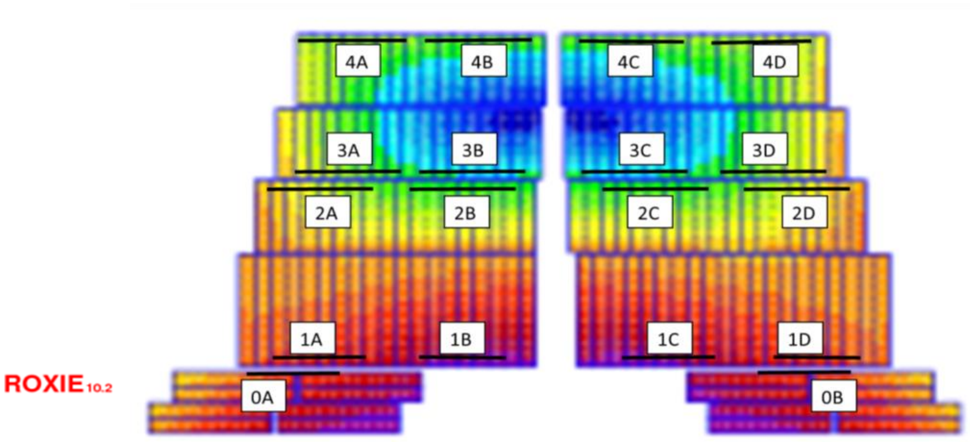
F. Rodriquez-Mateos and F. Sonneman, ”Quench heater studies for the LHC magnets”, Proc. of PAC, 2001.
H. Felice et al., ”Instrumentation and Quench Protection for LARP Nb3Sn Magnets”, *IEEE TAS,* 19(3), 2009.[3]P. Ferracin et al, ”Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi LHC ”, *IEEE TAS,* 26(4), 2016.

T. Salmi et al., *IEEE TAS*, 29(5), 2019, 4700905.
T. Salmi et al., *IEEE TAS*, 27(4), 2017, 4702305.

Locations of heater strips







Strip geometry and powering

	Cosθ		Block				Common-coil	
	QH2-3	QH4	QH1-2 HF	QH1-2 LF	QH3-4 HF	QH3-4 LF	QH0-1	QH2-4
w_{strips} (cm)	1	1.3	1.9	1.8	2.1	2.4	1.5	1.75
HS/per. (cm)	4 / 18	6 / 30	5/22	6/30	5/35	6/30	4/19	6/31
$P_{QH,t=0}$ (W/cm^2)	100	150	100	130	100	110	90	140
τ_{RC} (ms)	40	50	40	40	20	30	30	40

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4. Simulated peak temperatures and voltages

Opearation at nominal current

	$T_{Hotspot}$ (K) with 20 ms detection time		V_{gnd} (V)		$N_{Units/magnet}$	
	CLIQ	QH	CLIQ	QH	CLIQ	QH
Cosθ	286	322	800	870	2	14
Block	281	321	730	870	4	13
C-c	284	330	1100	1040	2	15

- Magnets can be protected with both systems
- 40±5 K lower temperature with CLIQ
- Voltages quite similar
- Simpler system with CLIQ

CLIQ was selected as a baseline, heaters a back-up option

Conclusion

- Quench protection integrated in the magnet em-design to ensure protectable magnets
  - 40 ms/350 K criteria
- Several simulation tools developed for the fast-feedback during initial design, and for the detailed protection designs
- **Protection with CLIQ feasible for all magnet options**
  - Max temperatures below 300 K at nominal current
  - Internal voltages below 1200 V
- Protection with heaters is considered a back-up option
- Experiments with the demo magnets needed to validate the simulation results and adjust designs
- Success is thanks to successful collaboration and communication between the magnet design teams in INFN, CEA and CIEMAT and quench protection teams at TAU and CERN, and project coordination → A winning team!

Thank you!

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Appendix

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Simulation tools and assumptions 1/2

Common assumptions in all simulations:

- Adiab. Hotspot temperature
- Current decay simulated in 2-D, discretized at turn level
- Material properties based on NIST libraries
- Material properties based on cable average magnetic field
- Tcs for quench computed based on the cable peak field
- Hotspot computed for the worst case cable
- 20 ms detection delay

- **”40 ms delay”**:
  - Coodi: Adiabatic model for current decay, temperature, and voltage computation (no heat diffusion between turns)
    - Quench time and propagation for each turn is an input
    - No AC (interfilament coupling loss)
    - Current follows the strand path after quench

- T. Salmi et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider”, Phys. Rev. Accel. Beams 20, 032401
- T. Salmi et al., ”The Impact of Protection Heater Delays Distribution on the Hotspot Temperature in a High-Field Accelerator Magnet”, *IEEE TAS*, 26(4), 2016.

Simulation tools and assumptions 2/2

- **CLIQ studies**:
  - LEDET: Lumped element model for interfilament coupling loss after CLIQ activation
    - Current decay, temperature and voltage evolution
    - Co-simulation used to couple with PSPICE for asymmetric multi-CLIQ simulations
  - COMSOL: FEM for electrothermal behaviour after CLIQ discharge
  - Heat diffusion between turns accounted

- E. Ravaioli, PhD Thesis
- E. Ravaioli, B. Auchmann, M. Maciejewski, H. ten Kate, and A. Verweij, “Lumped-element dynamic electro-thermal model of a superconducting magnet,” Cryogenics, 2016.
- L. Bortot et al., “A consistent simulation of electrothermal transients in accelerator circuits,” IEEE TAS, 27(4), 2017.
- I. C. Garcia et al., “Optimized field/circuit coupling for the simulation of quenches in superconducting magnets,” IEEE Journal on Multiscale and Multiphysics Computational Techniques, 2017.
- STEAM: Simulation of Transient Effects in Accelerator Magnets. Website: https://espace.cern.ch/steam/, Accessed on Sep 28, 2018)
- L. Bortot, et al., “STEAM: A Hierarchical Cosimulation Framework for Superconducting Accelerator Magnet Circuits, IEEE Trans. Appl. Supercond., 28 3, 4900706, 2018.

- **Heater based protection**:
  - CoHDA: 2-D heat diffusion model for heater delays
    - Accounts for the heater station length
    - Quench when cable maximum temperature reaches Tcs

- T. Salmi et al., "A Novel Computer Code for Modeling Quench Protection Heaters in High-Field Nb_3Sn Accelerator Magnets", *IEEE TAS*, 24(4), 2014.
- T. Salmi et al., “Analysis of uncertainties in protection heater delay time measurements and simulations in Nb_3Sn high-field accelerator magnets” *IEEE TAS*, 25(4), 2015.

  - Coodi: Current decay when heater delay and quench propagation velocity are input for each turn
    - Quench propagation: 18 m/s btw heating stations, 11 ms btw turns, 20 ms btw layers at nominal current