16 T DIPOLE QUENCH PROTECTION

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Acknowledgement: E. Ravaioli[2], A. Stenvall[1], A. Verweij[2], and EuroCirCol WP5 magnet designers and the team

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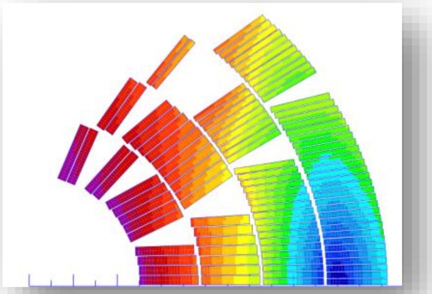
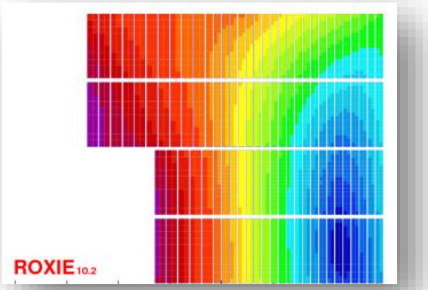
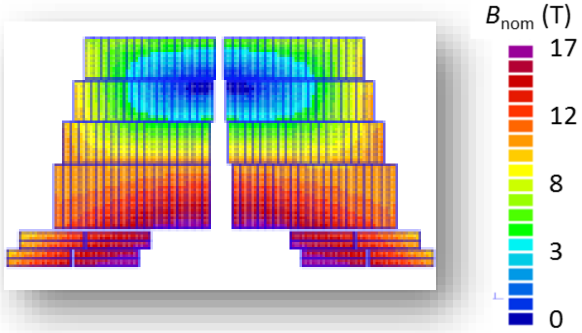
Considered EuroCirCol 16 T dipole designs







Magnet, version	Cosθ, 22b_38_v1		Block, V2ari194		Common coil, vh12_2ac6 (#11)	
Inom (A)	11390		10000		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

Outline

Introduction: Why is quench protection so critical?

1. The steps in the quench protection design

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

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

4. Summary

Appendix: Description of the computational tools and assumptions

See also the talks by M. Prioli “Mechanical analysis during quench” and “Circuit layout and protection”

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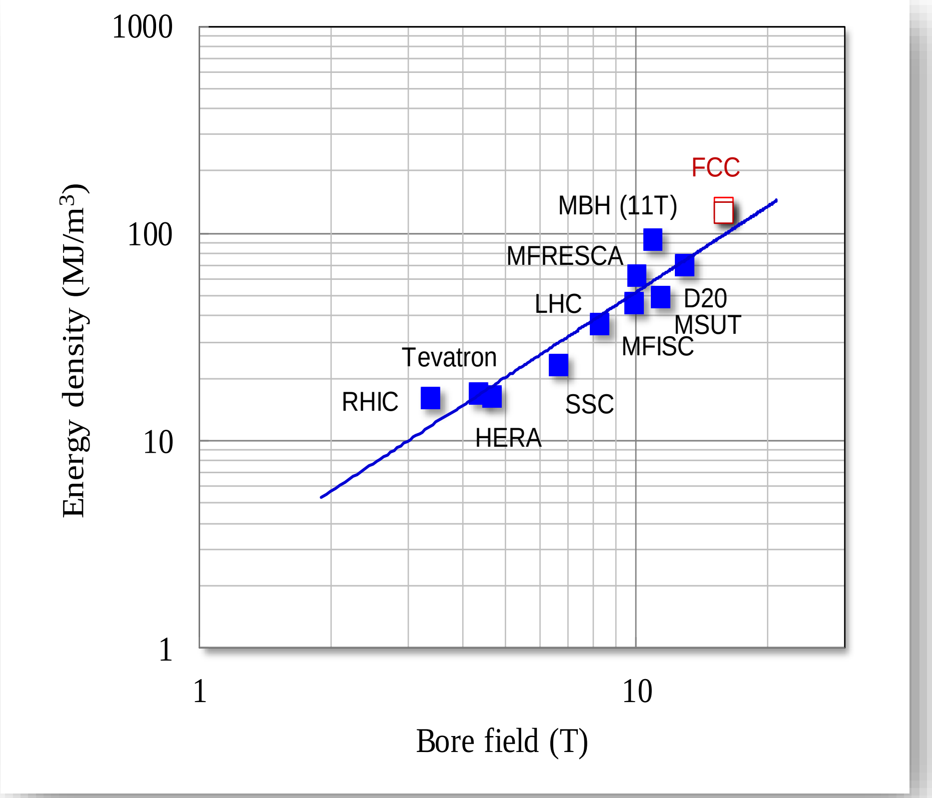
Introduction: Why quench protection is so critical?

- High magnetic field + compact size → High stored energy density
  - 16 T CosT, Block, C-c: ~40 MJ, ~130 MJ/m^3

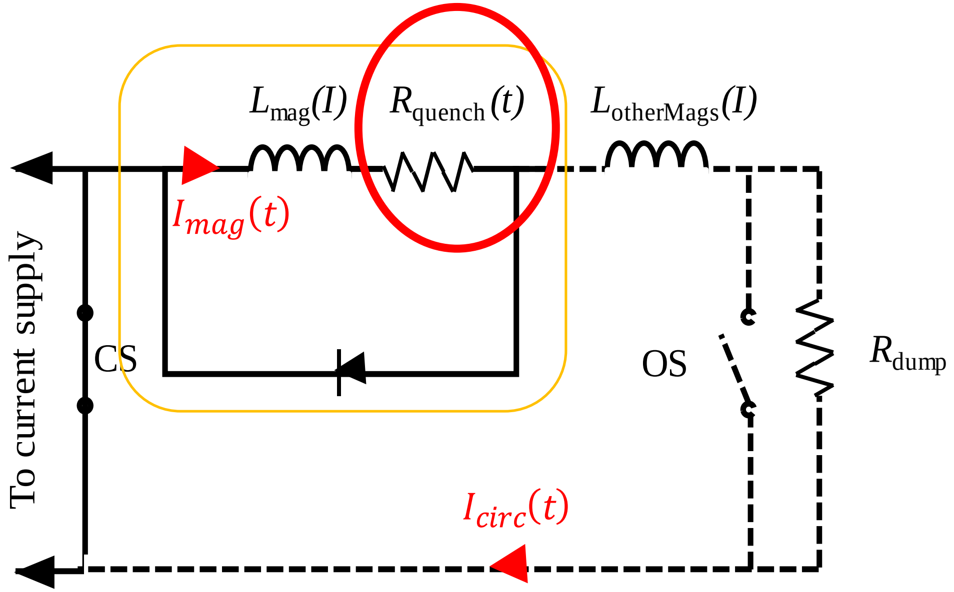
- Quench → Energy needs to be absorbed
  - Joule heating in the quenched cables



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

Introduction: Why quench protection is so critical?

- High magnetic field + compact size → High stored energy density
  - 16 T CosT, Block, C-c: ~40 MJ, ~130 MJ/m^3
- Quench → Energy needs to be absorbed
  - Joule heating in the quenched cables
- Magnet resistance drives the energy discharge
- Need to quench the entire magnet fast !
  - Detection (~20 ms)
  - Heaters/CLIQ (~10-30 ms)



Magnet powering circuit in accelerator

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1. The steps in the quench protection design

STEP 1: Design criteria
Max temperature 350 K and voltage 1200 V

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Max temperature 350 K and voltage 1200 V

STEP 2: Simplified analysis

- Protection efficiency: 20 ms det. + 20 ms heaters
- Tools for quick feedback

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STEP 1: Design criteria

Max temperature 350 K and voltage 1200 V

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- Protection efficiency: 20 ms det. + 20 ms hea
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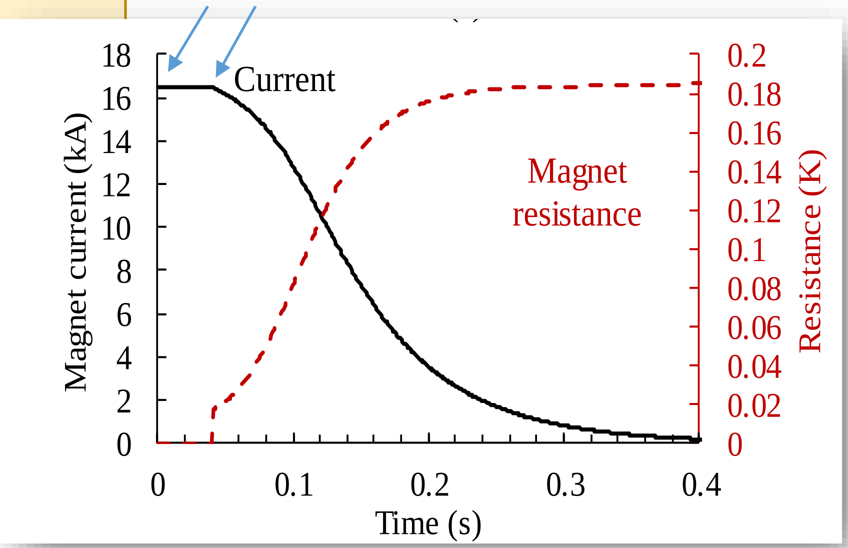

Schematic of magnet current decay after 20+20 ms protection delays

1. The steps in the quench protection design

STEP 1: Design criteria
Max temperature 350 K and voltage 1200 V

STEP 2: Simplified analysis
- Protection efficiency: 20 ms det. + 20 ms heaters
- Tools for quick feedback

STEP 3: Detailed protection schemes
- CLIQ, quench heaters, circuit
- Detection time 20 ms
- Developed tools

TODAY

Magnets can be protected: CLIQ chosen as baseline, heaters a back-up solution

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2. Protection with CLIQ: The principle

CLIQ – Coupling Loss Induced Quench

- Discharge capacitor bank across part of the winding

  ➡ Oscillations of transport current

  ➡ Coupling losses ➡ Quench

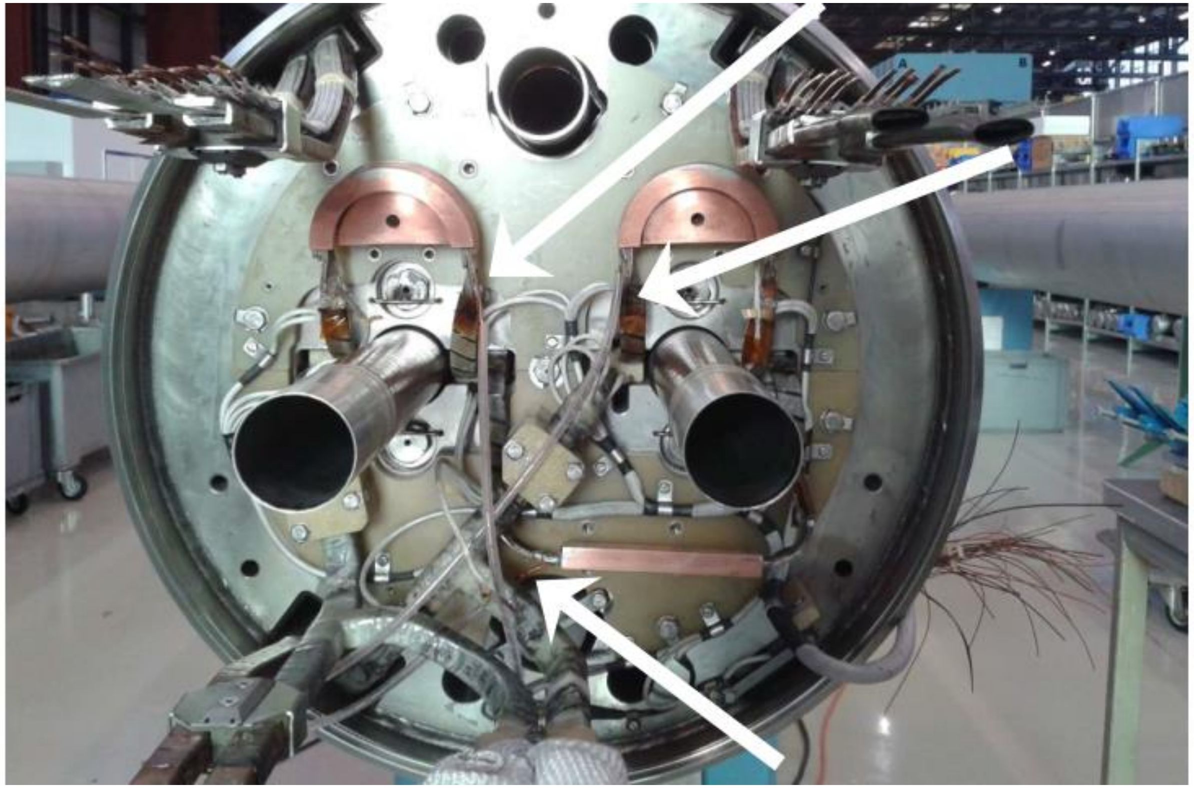
Advantages:

- Heat deposition directly to the strand
- Connection can be made external to the magnet → Accessible for repair etc.

Cautions:

- New technology, HL-LHC will provide first experience in real accelerator

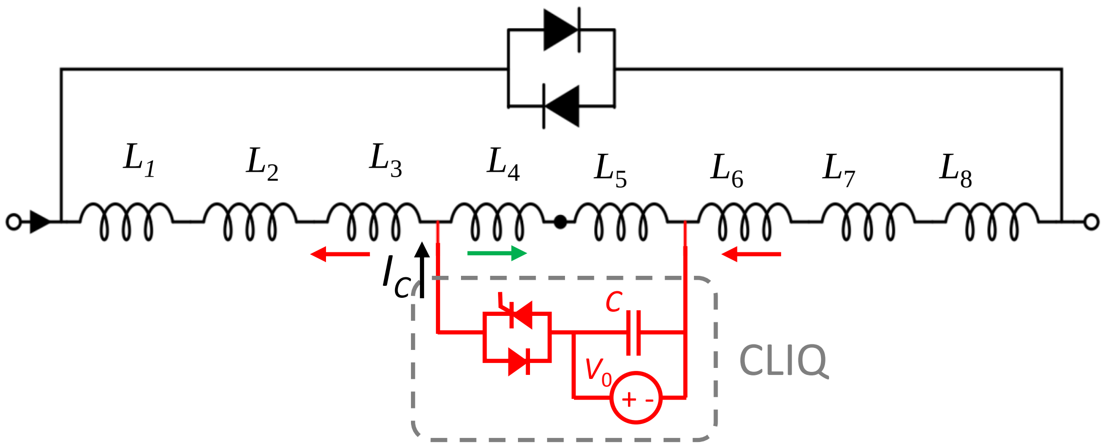
CLIQ leads in the 15 m long LHC main dipole (Aug 2015), Photo by courtecy of E. Ravaioli

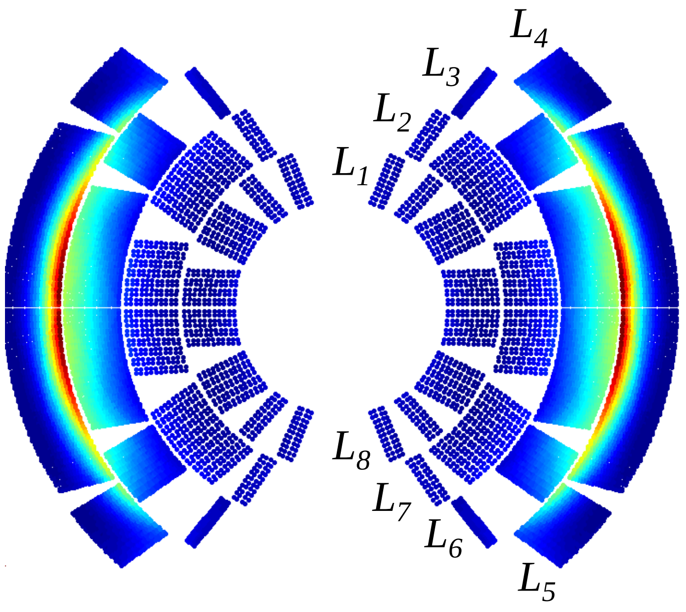


2. Protection with CLIQ: Design considerations

- **Important CLIQ design parameters:**
  - Location of the CLIQ leads
    - Location of losses, voltage accumulation
  - Number of CLIQ units
  - Charging voltage and capacitance of the units

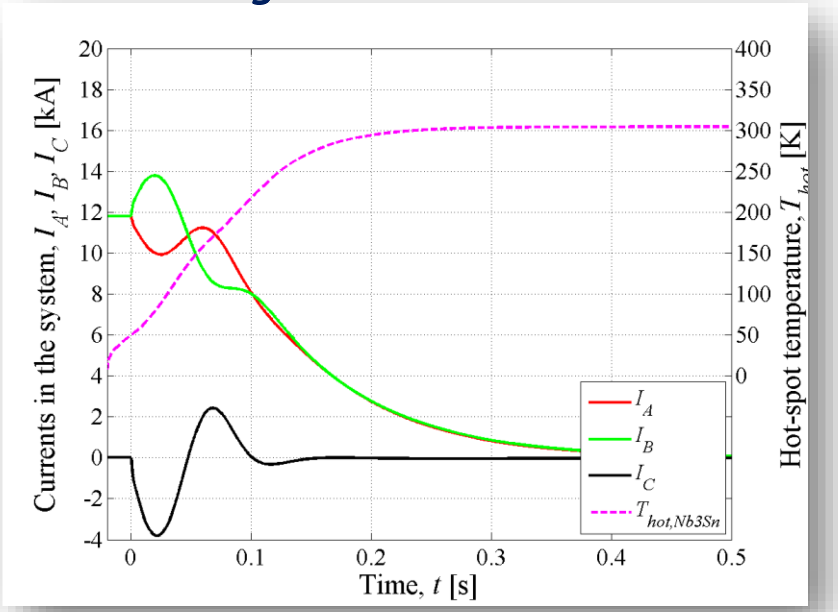
CLIQ connection scheme





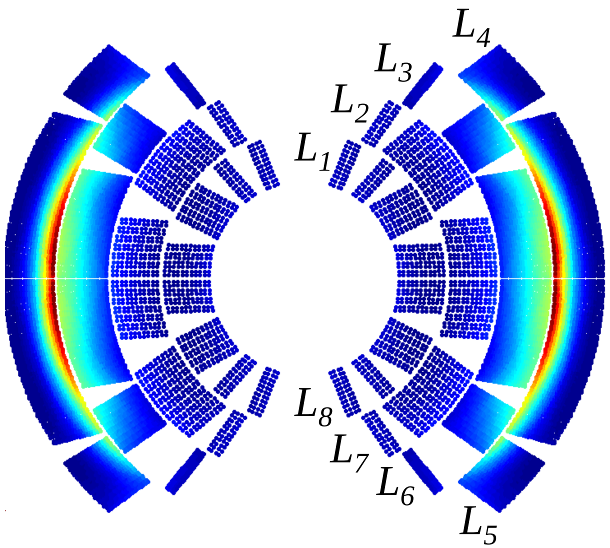
Division of the magnet to electrical parts (8)

Resulting current oscillations

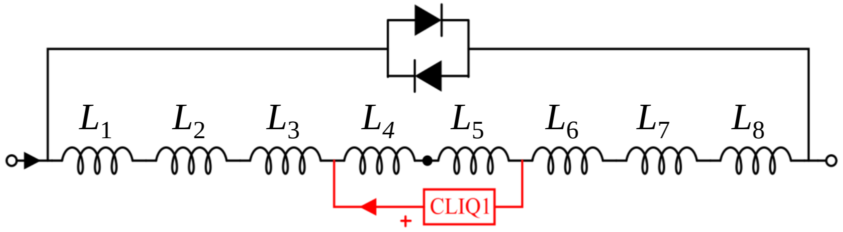


2. Protection with CLIQ: Cosθ

Location of the peak heat deposition in CLIQ-protected 2-aperture magnet

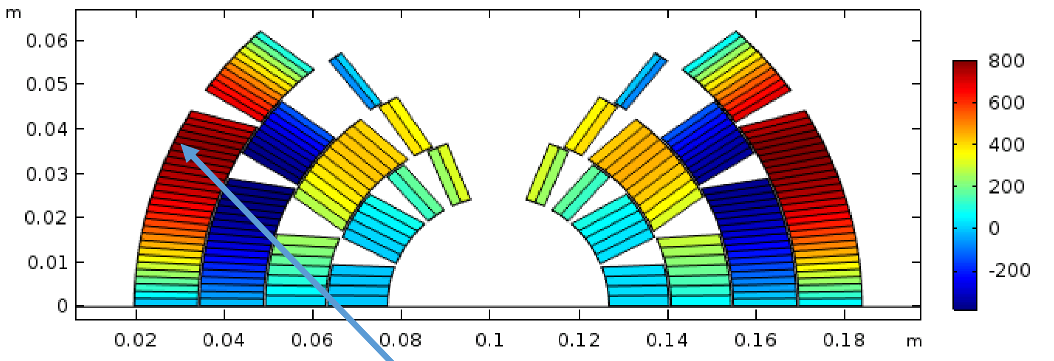


CLIQ configuration



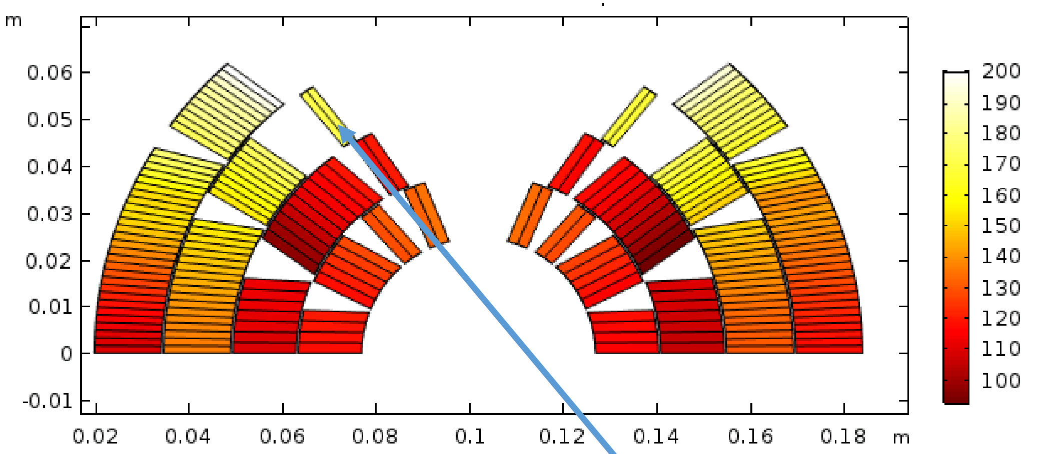
V_0=1.25 kV, C=50 mF

Voltage distribution 120 ms after CLIQ activation



Max. voltage to ground 800 V

Final temperature distribution after CLIQ activation



Hot-spot temperature 286 K

Simulation with STEAM -COMSOL (at I_{nom}) – M. Prioli

2. Protection with CLIQ: Cosθ - Sensitivity analysis and redundancy

Simulated temperature and voltage for varying cable parameters

Ref.

Simulation with LEDET

Fil. Twist (mm)	RRR HF/LF	$f_{\rho,eff}$	Tmax (K)	Vmax (V)
14	100/100	1	304	950
10	100/100	1	305	940
20	100/100	1	311	940
14	150/150	1	312	1000
10	150/150	1	312	1000
20	150/150	1	313	1010
14	200/200	1	315	1000
10	200/200	1	320	1000
20	200/200	1	320	1010
14	50/50	1	292	950
10	50/50	1	304	950
20	50/50	1	291	1000
14	50/200	1	306	1150
14	200/50	1	298	1170

Fil. Twist (mm)	RRR HF/LF	$f_{\rho,eff}$	Tmax (K)	Vmax (V)
14	100/100	0.5	305	970
14	100/100	2	311	930

$f_{\rho,eff}$ = Scaling factor for matrix transverse resistivity for interfil. coupling loss.

This analysis is done at 105% of Inom (1-ap.).

→ Impact of filament twist, RRR and $f_{\rho,eff}$ is < 20 K, 250 V.

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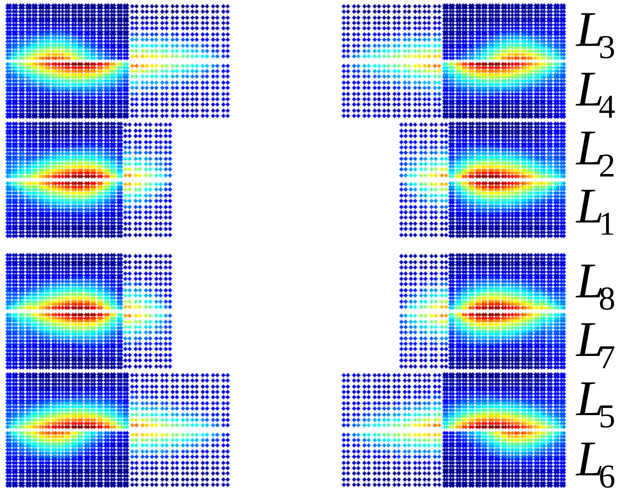
Based on a CLIQ reliability study by A. Fernandez:

Redundancy can be obtained within the CLIQ unit:

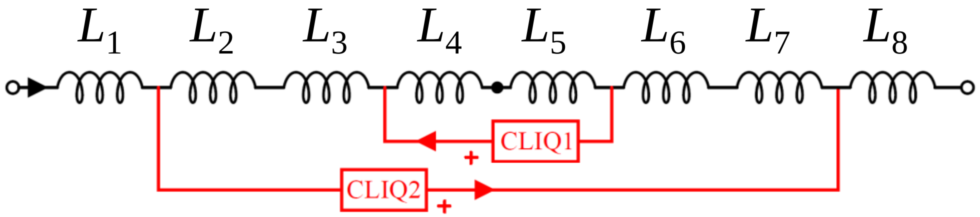
- Components related to triggering fully redundant
- Configuration of several capacitors: Short circuit in one leads only to reduction of energy.

2. Protection with CLIQ: Block

Location of the peak heat deposition in CLIQ-protected 2-aperture magnet

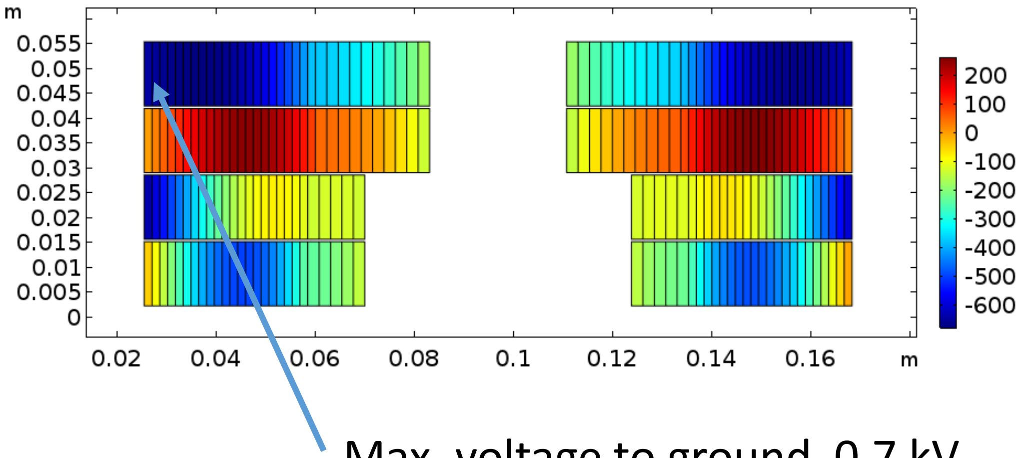


CLIQ configuration



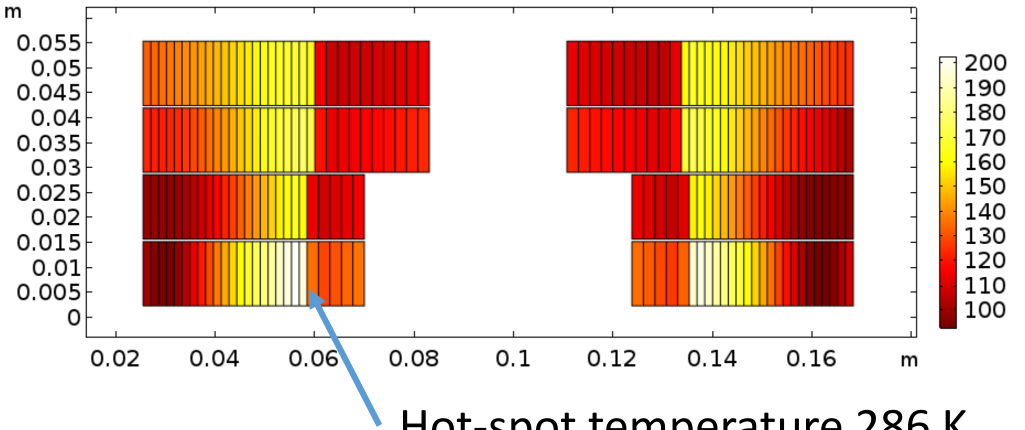
CLIQ1: V_0=0.6 kV, C=50 mF
CLIQ2: V_0=1.2 kV, C=50 mF

Voltage distribution 70 ms after CLIQ activation



Max. voltage to ground 0.7 kV

Final temperature distribution after CLIQ activation

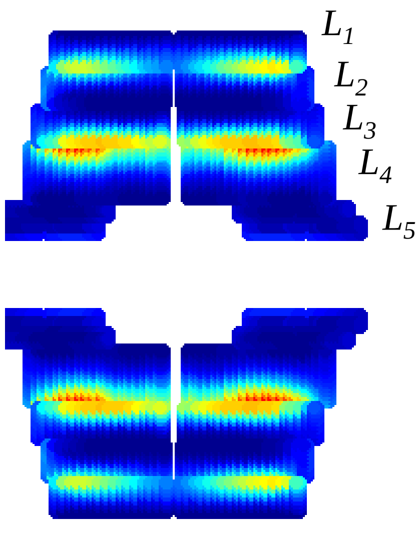


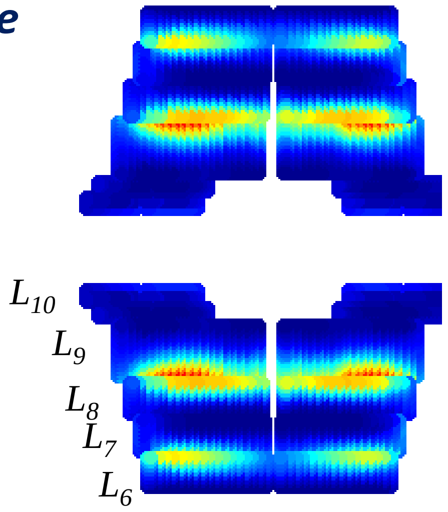
Hot-spot temperature 286 K

Simulation with STEAM-COMSOL (at I_{nom}) – M. Prioli

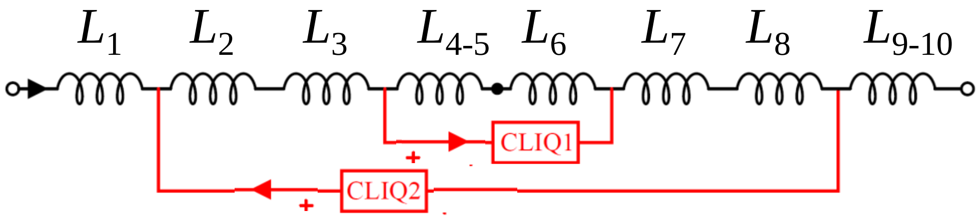
2. Protection with CLIQ: Common-coil

Location of the peak heat deposition in CLIQ-protected 2-aperture magnet



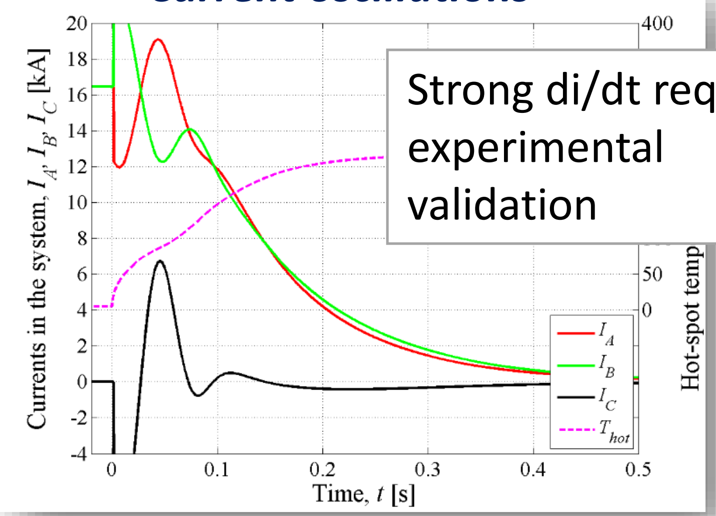


CLIQ configuration



CLIQ1: V_0=0.9 kV, C=80 mF, CLIQ2: V_0=0.9 kV, C=80 mF

Current oscillations

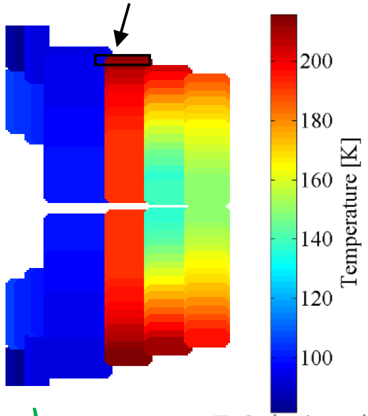


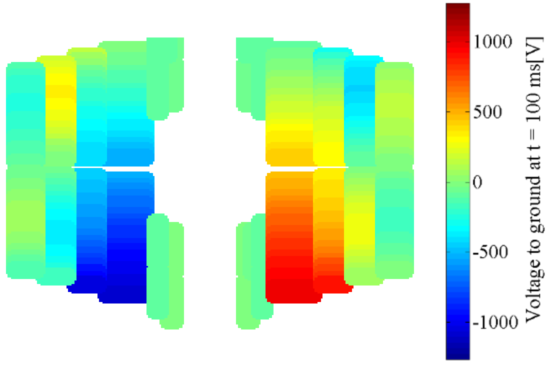
Strong di/dt requires experimental validation

Temperature and voltage distribution

Hot-spot temperature 280 K

Max. voltage to ground 1.35 kV





Simulation with STEAM-LEDET, 2 apertures (at I_{nom})

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   - Cosθ, Block, Common-coil

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

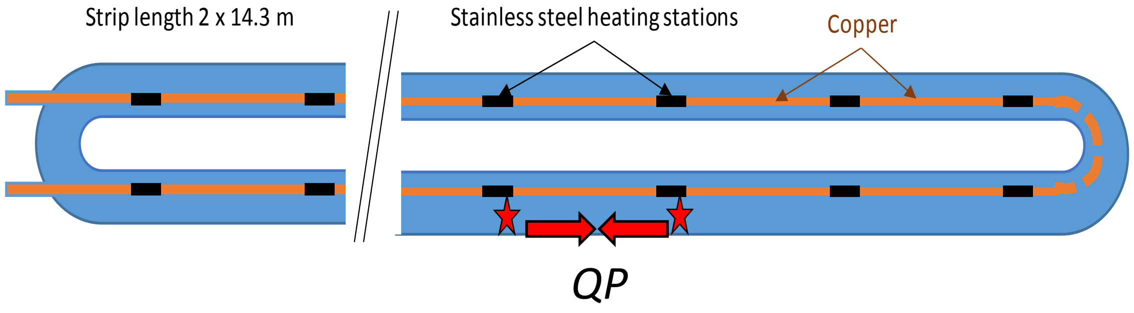
4. Summary

Appendix: Description of the computational tools and assumptions

3. Protection 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

Schematic of heater strip layout



Heaters on HL-LHC quadrupole MQXFS03, Photo: CERN

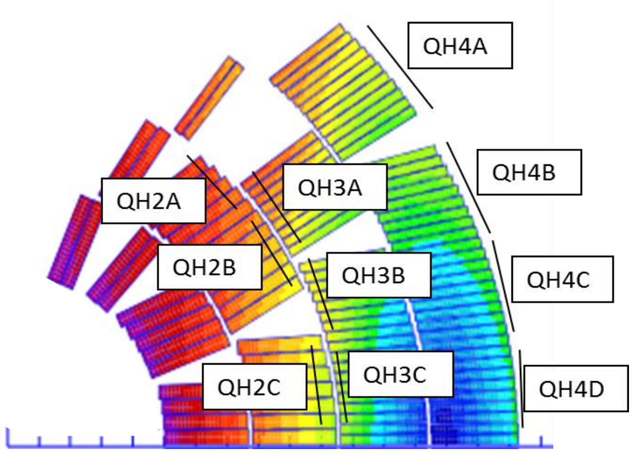
[1]F. Rodriquez-Mateos and F. Sonneman, ”Quench heater studies for the LHC magnets”, Proc. of PAC, 2001.
[2]H. Felice et al., ”Instrumentation and Quench Protection for LARP Nb3Sn Magnets”, *IEEE TAS,* 19(3), 2009.
[3]P. Ferracin et al, ”Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi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

3. Protection with heaters: Cosθ

- Heaters cover 62% of turns
- 14 HFU's / 2-ap. magnet
- **At 100% Inom**: Heater delays: 8-21 ms
- **Hotspot temperature 322 K**
  - **Peak voltage to ground 980 V**
  - Between turns 80 V
  - Between layers 980 V

Simulation with CoHDA+Coodi

Locations of heater strips (No inner layer heaters!)

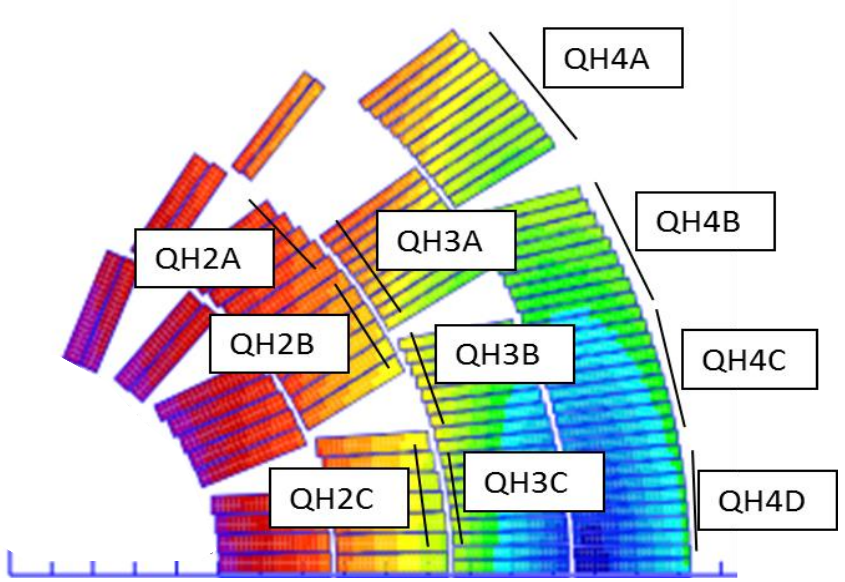


Heater strip geometries and powering

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

3. Protection with heaters: Cosθ -Failure analysis

- 1 strip fails on both sides of the coil, for both apertures
- → Temperature and voltage increases only 5 K & 100 V



No failures: 322 K, 960 V

Simulation of temperature and voltage after strip failure*,**

Failed strip	Tmax (K)	Vmax, gnd (V)
QH2A	325	930
QH2B	324	930
QH2C	324	930
QH3A	327	900
QH3B	325	910
QH3C	324	930
QH4A	330	870
QH4B	326	1130
QH4C	325	1100
Qh4D	324	1070

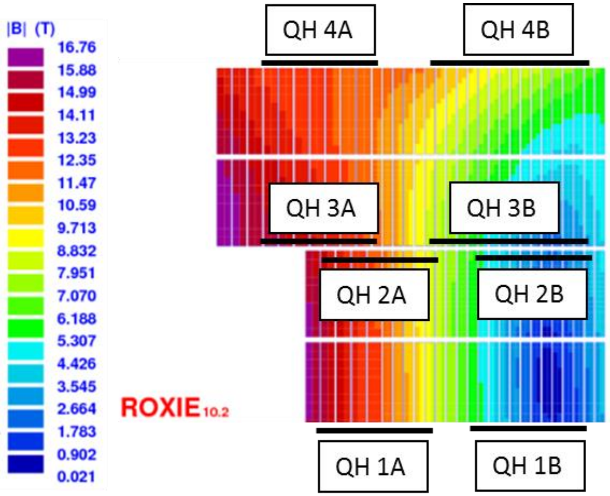
Simulation with CoHDA+Coodi

*Turns under failed strip quench 40 ms after heater activation (layers 2-3) and 50 ms later (layer 4)
**Failures on layer 2 do not affect the quenching time of layer 1

3. Protection with heaters: Block

- Heaters cover 77% of turns
- 13 HFU's / 2-ap. magnet
- **At 100% Inom**: Heater delays: 7-41 ms
- **Hotspot temperature 321 K**
  - **Peak voltage to ground 870 V**
  - Between turns 90 V
  - Between layers 1160 V

Locations of heater strips



Heater strip geometries and powering

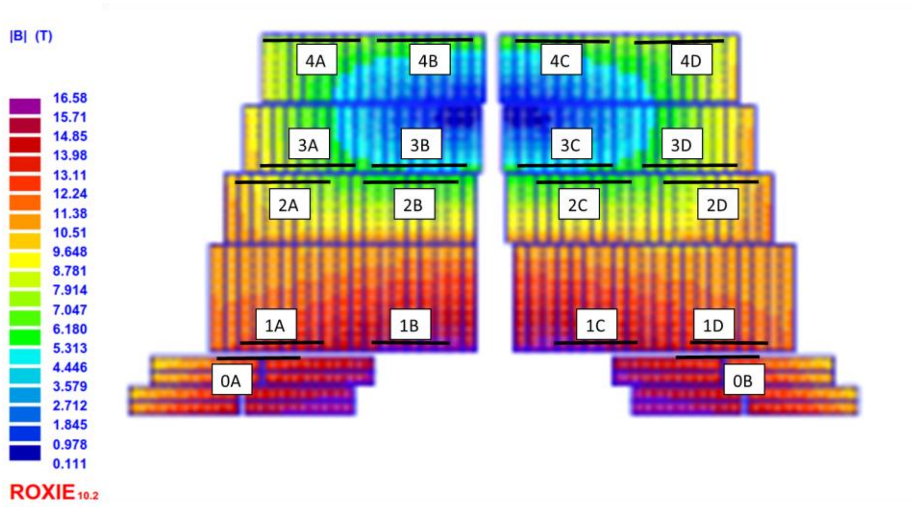
HFU	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
#1	$1A_{c1}$ || $2A_{c1}$	1.9	5/22	100	40
#2	$1B_{c1}$ || $2A_{c1}$	1.8	6/30	130	40
#3	$(3A_{c1} + 4A_{c1} + 3A_{c2} + 4A_{c2})$ || $(3A_{c1} + 4A_{c1} + 3A_{c2} + 4A_{c2})^{Ap2}$	2.1	5/35	100	20
#4	$3B_{c1}$ || $4B_{c1}$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

Simulation with CoHDA+Coodi

3. Protection with heaters: Common-coil

- Heaters cover 70% of turns
- 15 HFU's / 2-ap. magnet
- **At 100% Inom**: Heater delays: 6-20 ms
- **Hotspot temperature 330 K**
  - **Peak voltage to ground 1040 V**
  - Between turns 80 V
  - Between layers 1060 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	$0A_{c1}$ || $0B_{c1}$ || $0A_{c2}$ || $0B_{c2}$	1.5	4/ 19	90	30
#2	$1A_{c1}$ || $1B_{c1}$ || $1C_{c1}$ || $1D_{c1}$	1.5	4/ 19	90	30
#3	$2A_{c1}$ || $2B_{c1}$	1.75	6/31	140	40
#4	$2A_{c1}$ || $2B_{c1}$	1.75	6/31	140	40
#5	$3A_{c1}$ || $3B_{c1}$	1.75	6/31	140	40
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#8	$4C_{c1}$ || $4D_{c1}$	1.75	6/31	140	40

Simulation with CoHDA+Coodi

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Comparison of the methods

	Cosθ		Block		Common-coil	
	CLIQ	**Heaters**	**CLIQ**	**Heaters**	**CLIQ**	**Heaters**
Tmax (K)	286	322	286	321	280	330
Vmax (V)	800	980	700	870	1350	1040
Units/2-ap.	2	14	4	13	2	15
Estored in QPS (kJ)	78	101	90	94	65	108

Comparison of the methods

	Cosθ		Block		Common-coil	
	CLIQ	**Heaters**	**CLIQ**	**Heaters**	**CLIQ**	**Heaters**
Tmax (K)	286	322	286	321	280	330
Vmax (V)	800	980	700	870	1350	1040
Units/2-ap.	2	14	4	13	2	15
Estored in QPS (kJ)	78	101	90	94	65	108

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	Pros	**Cons**	**Pros**	**Cons**
Efficiency	Homog., efficient, loss	Low current prot.	Focused heating	Diffusion delay
Technology	Accessible connection	Leads btw pancake layers, part of magnet circuit	External circuit	Delicate technology
Cost / complexity	Few units needed	Complex units	Simple units	Many units+heaters needed

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Summary

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

- **Protection with CLIQ feasible for all magnet options**
  - Max temperatures below 300 K
  - Internal voltages below 1000 V (except C-c, but work in progress)

- Protection with heaters is considered a back-up option

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

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

Outline

Introduction: Why is quench protection so critical?

1. The steps in the quench protection design

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

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

4. Summary

Appendix: Description of the computational tools and assumptions

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
- 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.

- **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