Update on the Inner Triplet quench simulations and current in the circuit branches

E. Ravaioli (CERN)

Thanks to:

S. Izquierdo Bermudez, L. De Mallac, F. Mangiarotti, M. Mentink, F. Rodriguez Mateos, A. Verweij, D. Wollmann, S. Yammine (CERN) and many other colleagues for their inputs

21 September 2022

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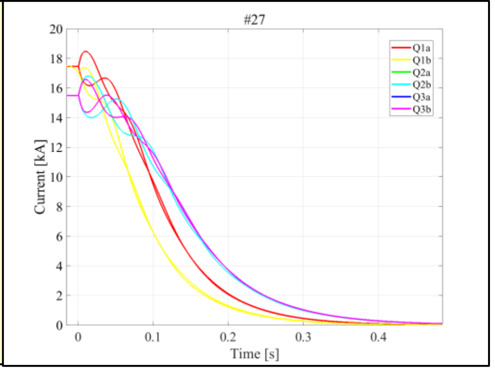
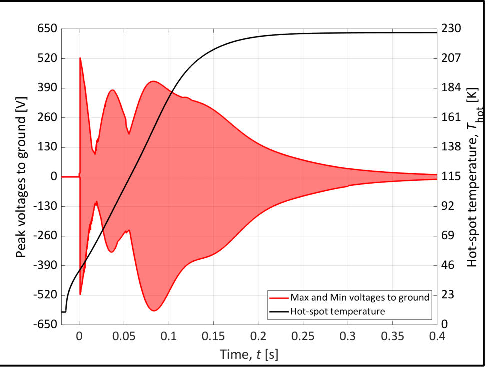
Circuit analysis

- Calculate worst-case peak currents and thermal loads in all circuit branches
- Update figures following last circuit fine tuning



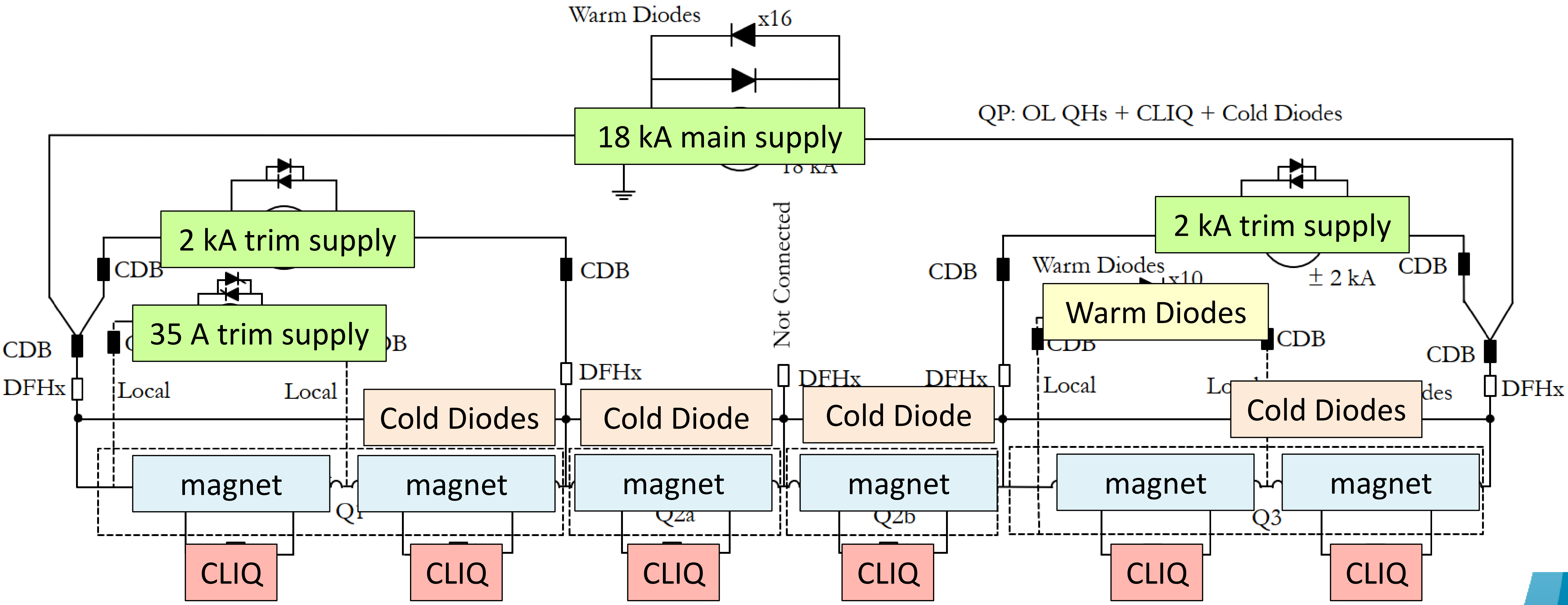
Magnet quench protection analysis

- Demonstrate protection strategy
- Calculate worst-case hot-spot temperature and peak voltage to ground



- The quench protection of the HL-LHC Inner Triplet circuit is adequate in all foreseen operation scenarios, and resilient to all plausible failure scenarios and conductor variations.

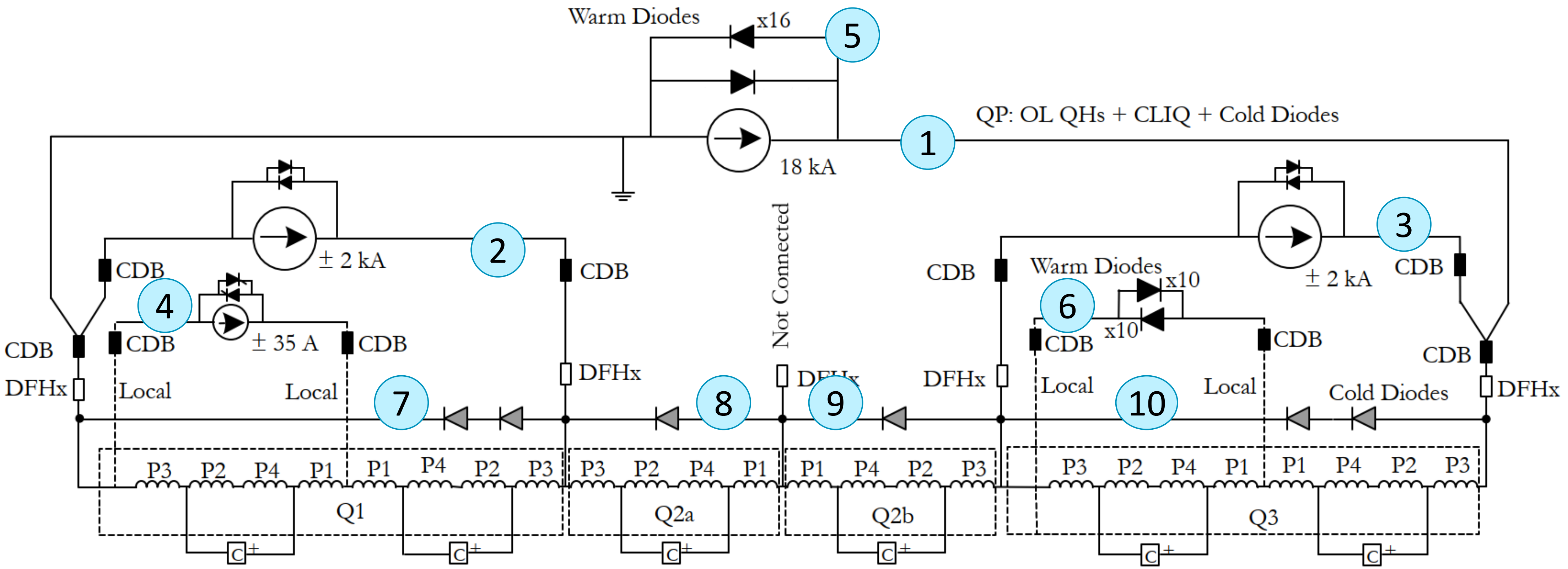
HL-LHC Inner Triplet Circuit



Note: This schematic includes the proposed changes to the crowbars, see MCF meetings #84, 91, 107

Schematic courtesy of S. Yammine

Circuit branches considered in the analysis

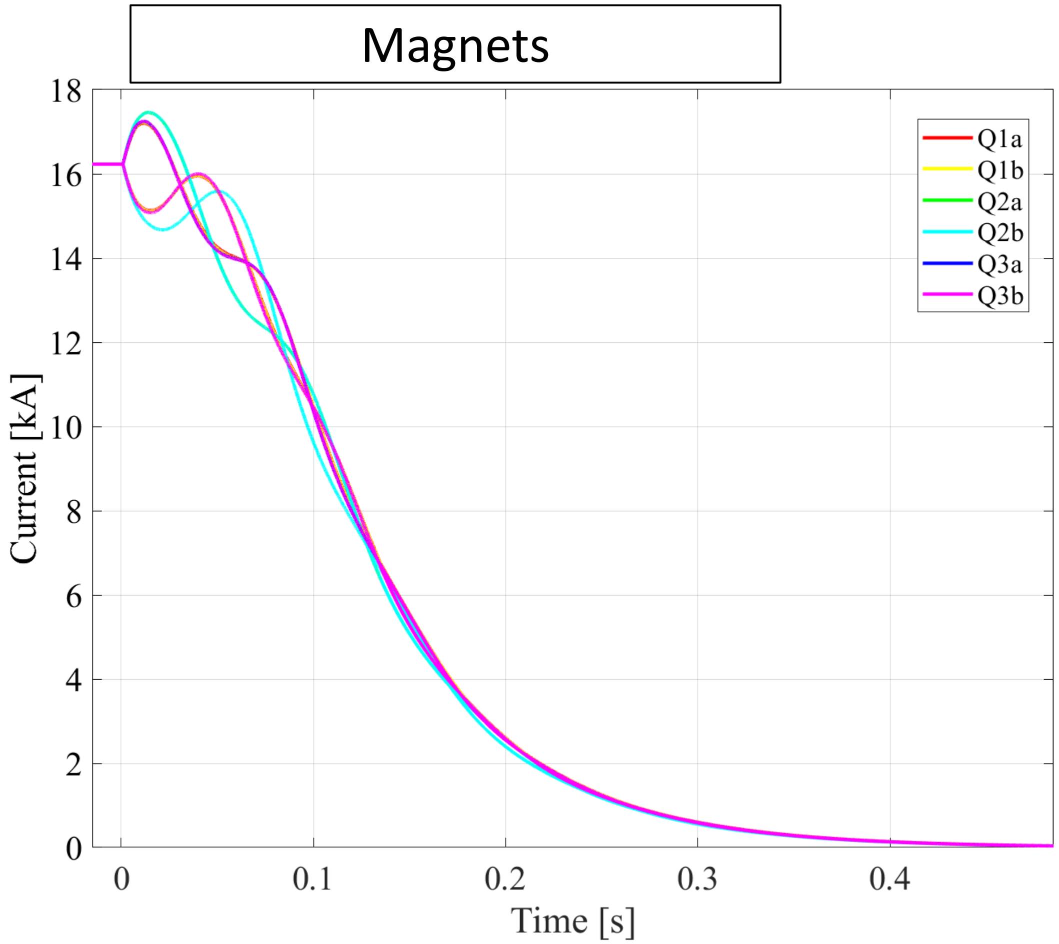


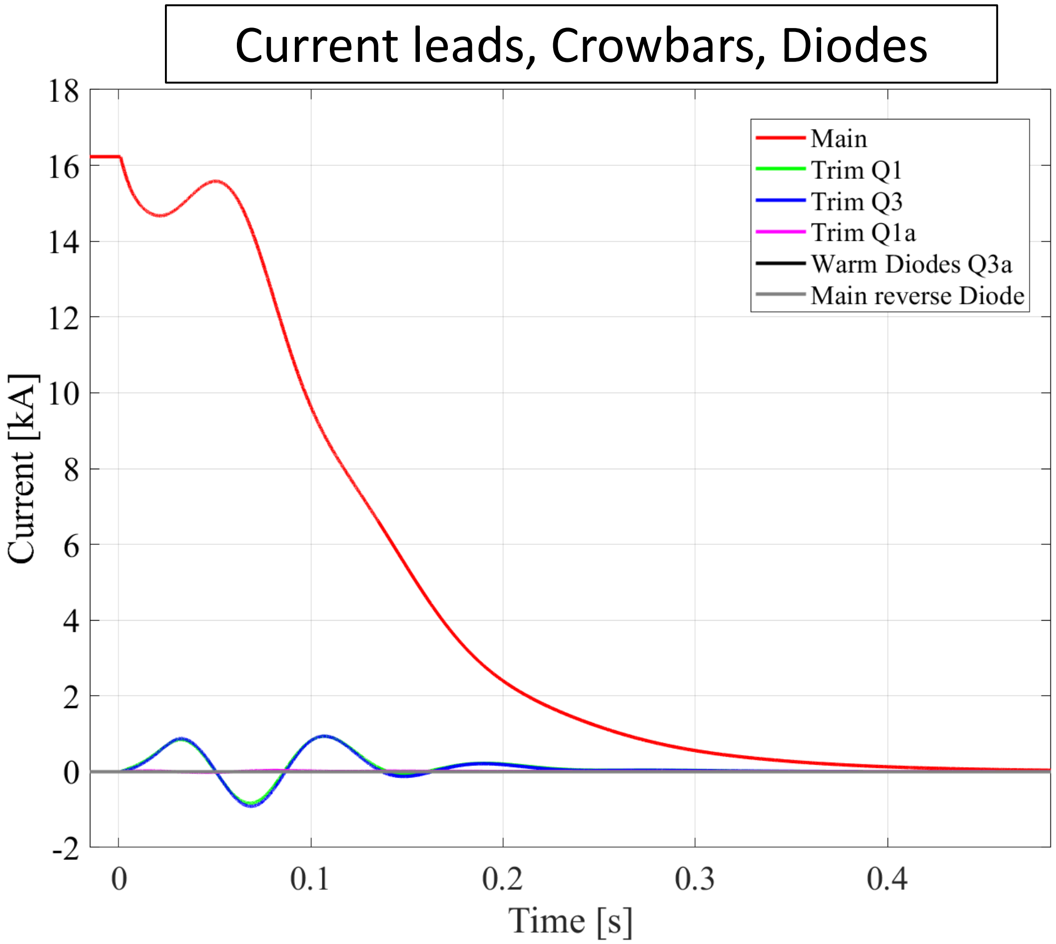
Identify **conservative worst-cases** for these components based on circuit operating cases, failure cases, magnet conductor parameters. For each case, calculate **peak current** and **thermal load**.

1. Main power supply crowbar and leads
2. Q1 trim power supply crowbar and leads
3. Q3 trim power supply crowbar and leads
4. Q1a trim power supply crowbar and leads
5. Main power supply reverse Diodes
6. Q3a Warm Diodes
7. Q1 Cold Diodes
8. Q2a Cold Diodes
9. Q2b Cold Diodes
10. Q3 Cold Diodes

Schematic courtesy of S. Yammine

Reference circuit discharge after a quench





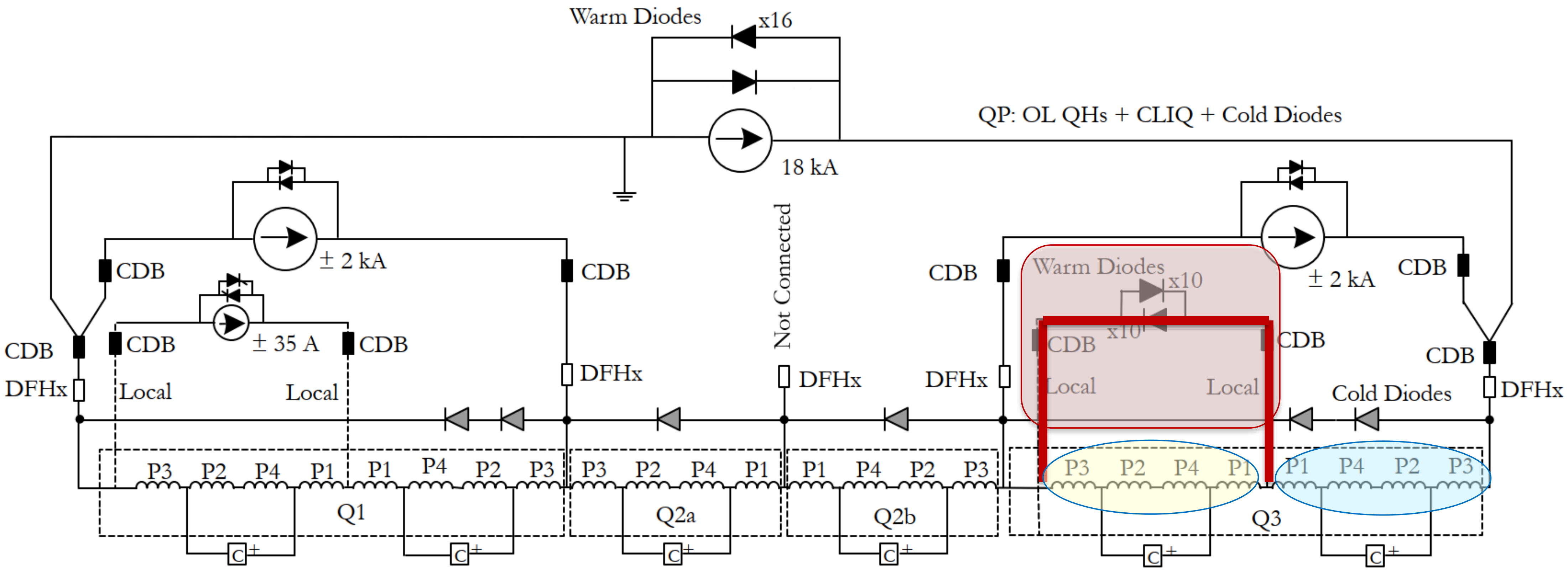
STEAM simulations

Factor considered while identifying the worst-cases

Power supply initial currents	Conductor parameters	Sudden quench of whole magnet	Diode forward voltages	Spurious triggers and failure cases

Very conservative worst-cases

Example: Identify worst-case for Q3a Warm Diode -1

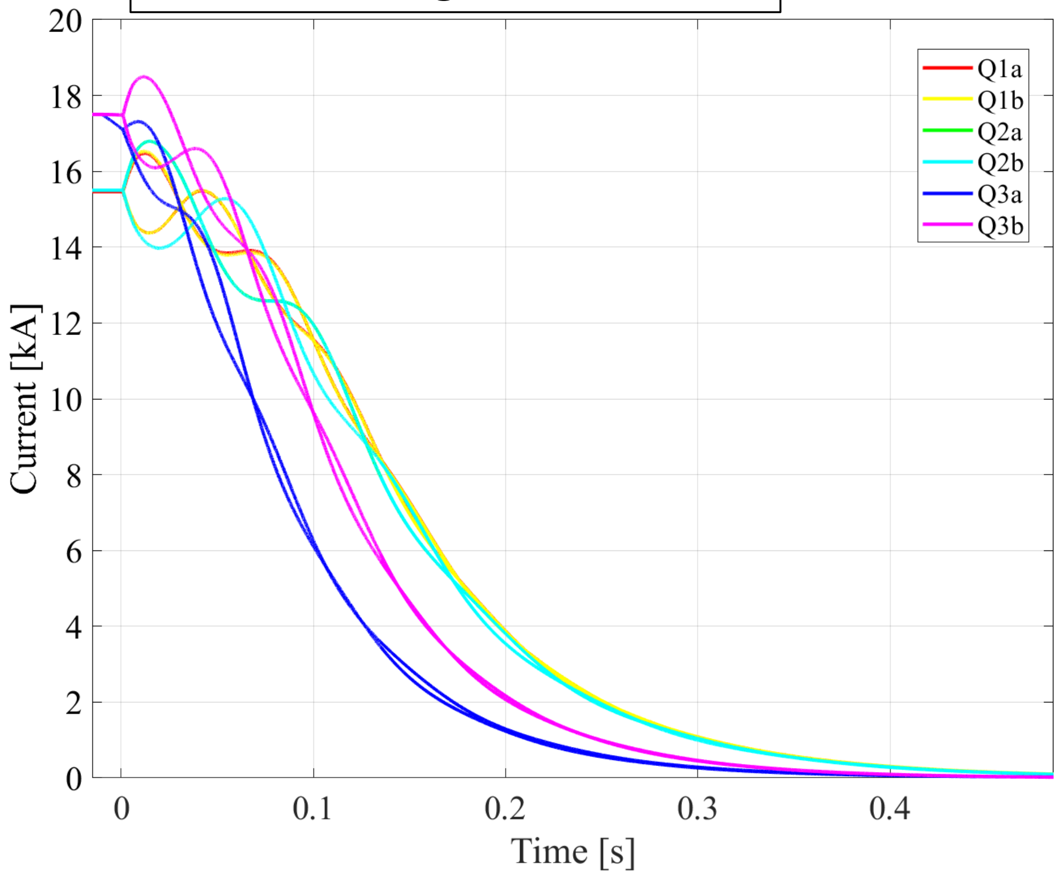


- I_main=15.5 kA, I_trimQ1=0, I_trimQ3=2 kA, I_trimQ1a=-35 A
- All fours Q3a coils suddenly quench [*by choice this is unrealistically conservative*]
- Q3a coils have f_Cu/noCu=1.1 and RRR=100. All other coils have f_Cu/noCu=1.3 and RRR=300

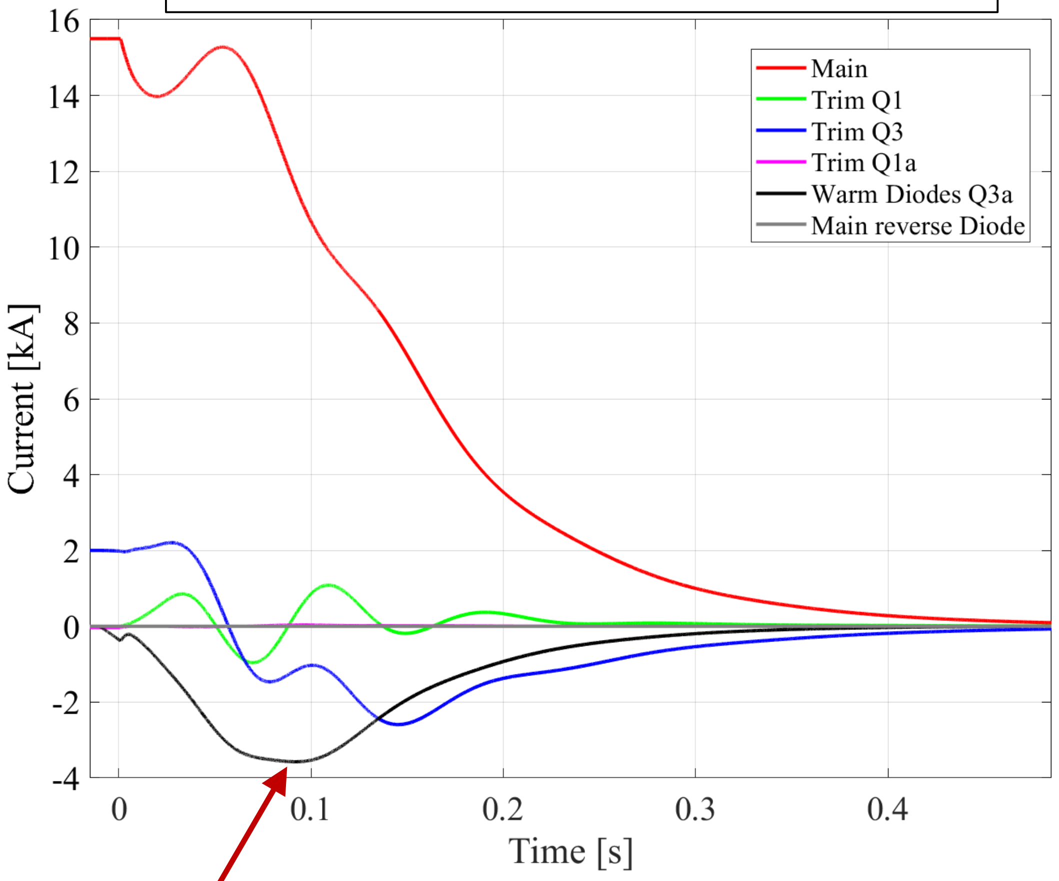
Schematic courtesy of S. Yammine

Example: Identify worst-case for Q3a Warm Diode -2

Magnets



Current leads, Crowbars, Diodes



Peak current ~3.6 kA

STEAM simulations

Max identified peak currents and thermal loads (magnets excluded)

Component	Peak current	Characteristic time
Main power supply crowbar and leads	17.5 kA	~120 ms
Q1/Q3 trim power supply leads	<5.0 kA	~120 ms
Cold Diodes	<5.2 kA	~120 ms
Q1a trim power supply crowbar and leads	<3.7 kA	~100 ms
Q3a Warm Diodes	<3.6 kA	~100 ms
Main power supply reverse Diodes	<1.0 kA	~ 15 ms

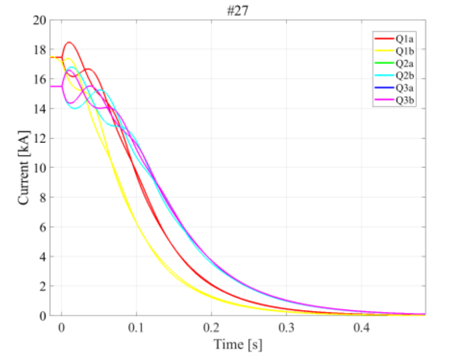
- Values obtained at ultimate current under very conservative assumptions
- Circuit components dimensioned for these requirements without headaches
- The proposed change of crowbar configuration did not increase significantly these figures

STEAM simulations

Update on the Inner Triplet quench simulations and current in the circuit branches

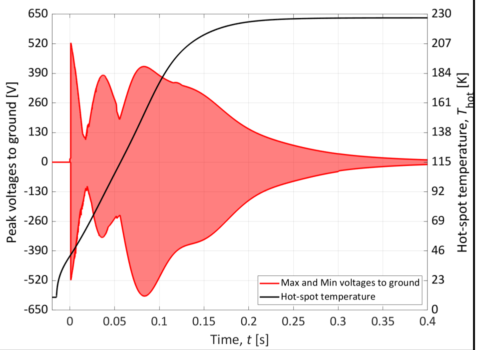
Circuit analysis

- Calculate worst-case peak currents and thermal loads in all circuit branches
- Update figures following last circuit fine tuning



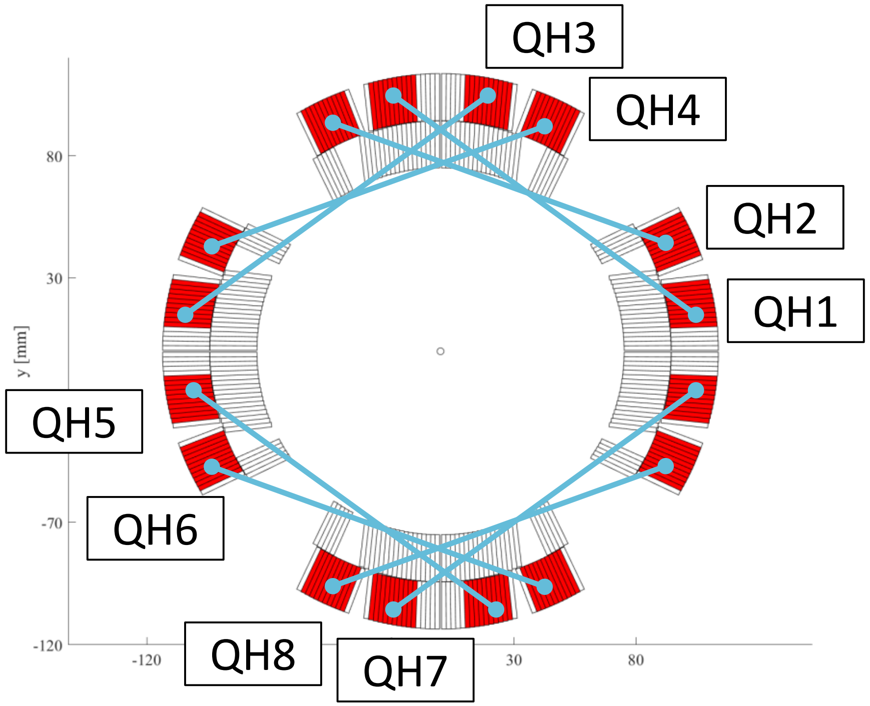
Magnet quench protection analysis

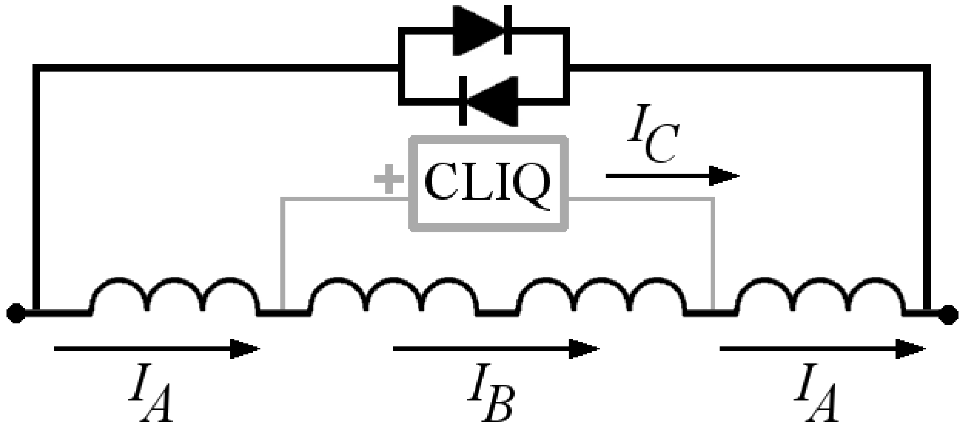
- Demonstrate protection strategy
- Calculate worst-case hot-spot temperature and peak voltage to ground



- The quench protection of the HL-LHC Inner Triplet circuit is adequate in all foreseen operation scenarios, and resilient to all plausible failure scenarios and conductor variations.

MQXF magnet quench protection system





QUENCH HEATERS (QH)	CLIQ (COUPLING-LOSS INDUCED QUENCH)
8x 7.05 mF **QH** units charged to 940 V	1x 40 mF **CLIQ** unit charged to 600 V or to 1000 V for 4.2 m or 7.15 m long MQXF

MQXF quench protection strategy

I [kA] — 1.5 — 2 — 5 — 8 — I_{nom} 16.2 — I_{ult} 17.5

Self-protected ≤2 kA → Demonstrated with 3D simulations

QH effective ≥1.5 kA → Demonstrated with QH minimum energy to quench

CLIQ effective ≥5 kA → Demonstrated with CLIQ-only tests

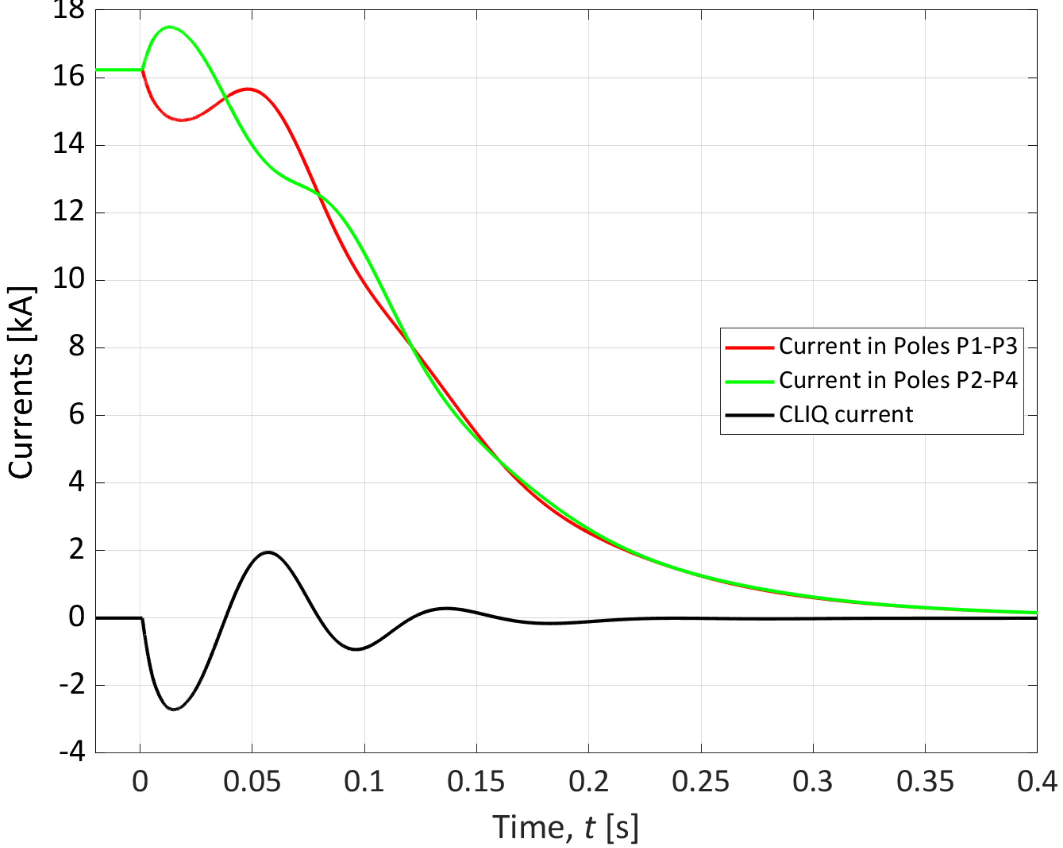
At low to medium current levels, outer-layer quench heaters are fully redundant (4 out of 8 QH circuits are sufficient)
→ Demonstrated with dedicated tests at CERN

MQXF quench protection is most critical at high current.
CLIQ reduces the quench load by ~20% at medium-high current (hot-spot temperature reduced by ~100 K)
→ Demonstrated with dedicated tests at CERN, BNL, FNAL

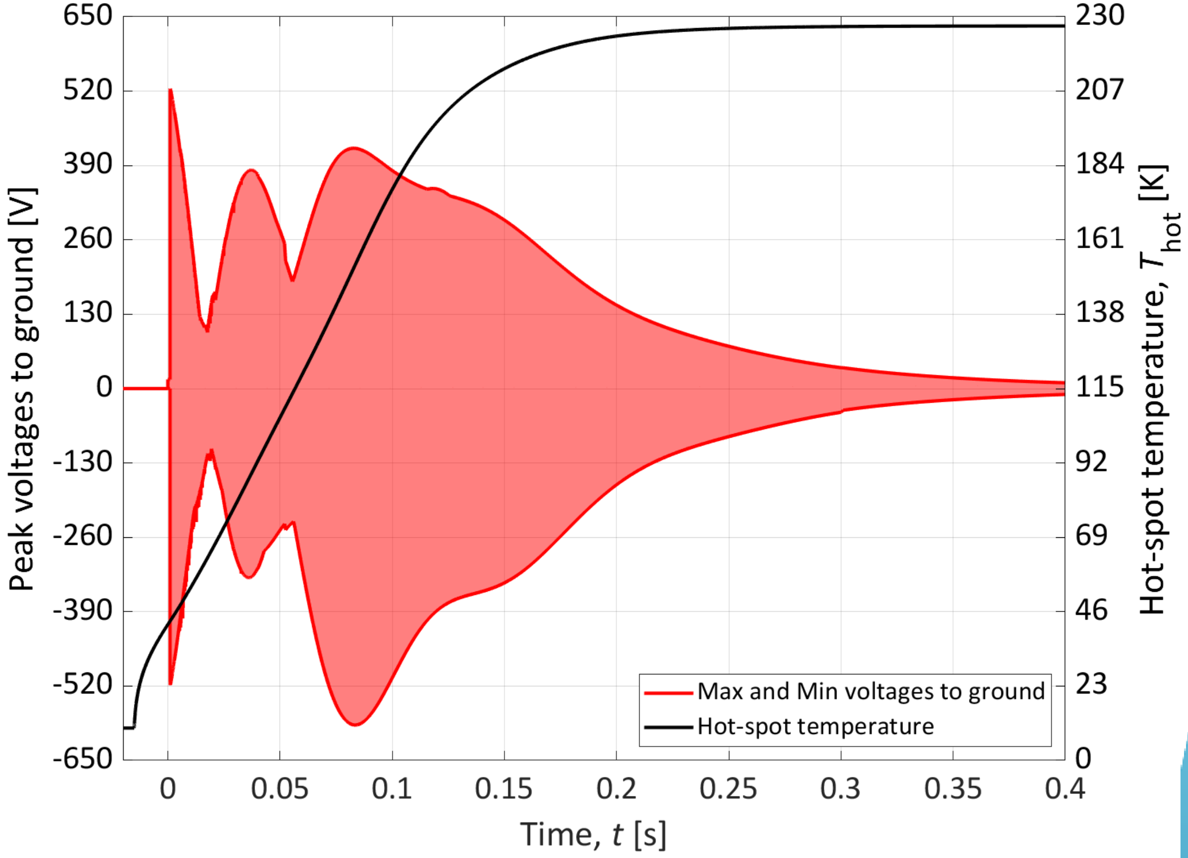
Simulation of quench discharge in the reference case

I [kA] 1.5 2 5 8 16.2 17.5

Currents in the system



Min/Max coil-to-ground voltages, and hot-spot temperature



Reference case: 8 QH units + 1 CLIQ unit per magnet. No failures. Uniform conductor parameters

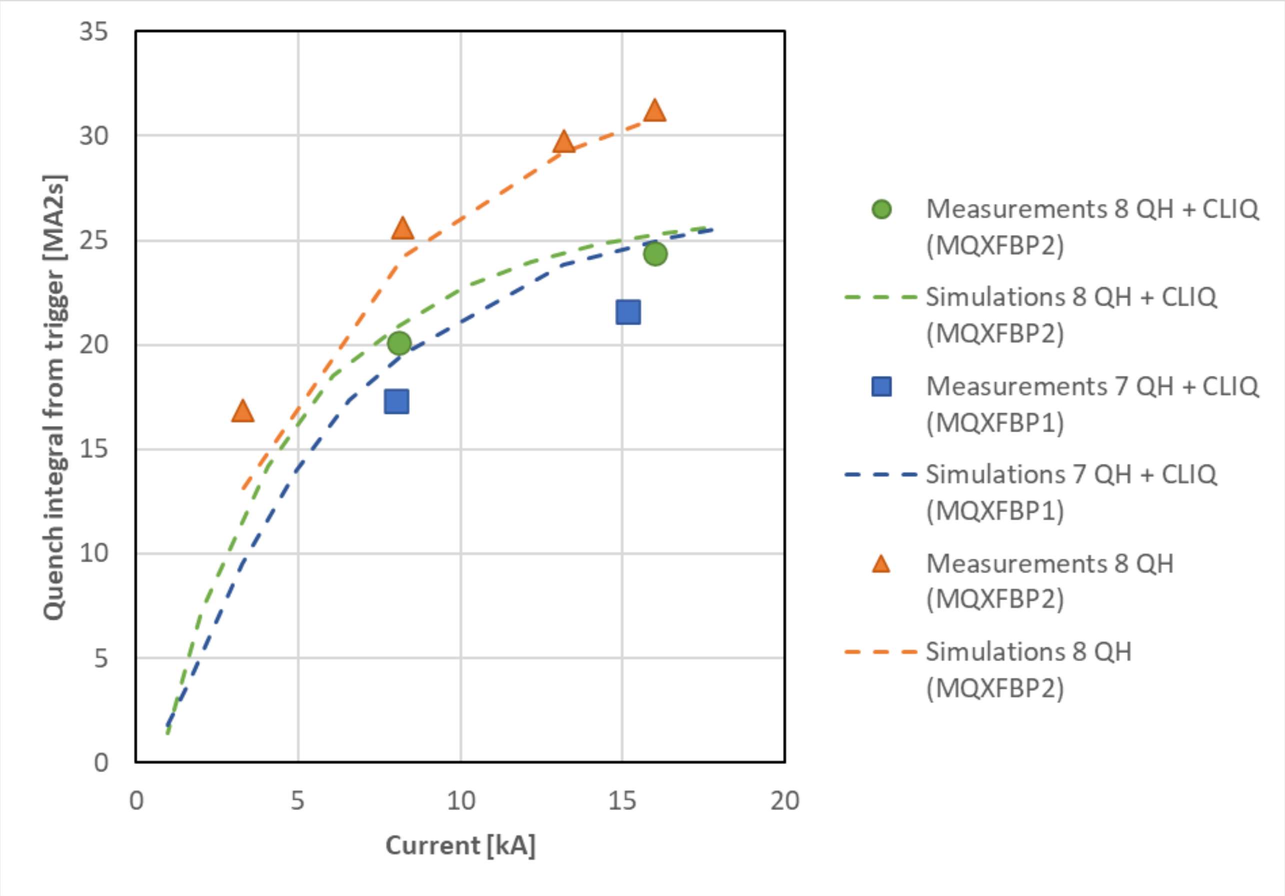
→ Hot-spot temperature ~230 K → Peak voltage to ground ~600 V

STEAM simulations

MQXFB protection

Measured quench integral in good agreement with computations.

- For nominal protection configuration (QH+CLIQ), QI from triggering ≈ 25 MA^2s, with a hot-spot temperature ≈ 250 K
- In MQXFBP2, during the trim current test, the magnet was protected only with quench heaters, reaching a hot-spot temperature of ~330 K without impact on magnet performance
  → validate design choice of allowable T_{hot}



Measurements: F. Mangiarotti. Simulations: E. Ravaioli. Analysis: S. Izquierdo Bermudez

Worst-case analysis

Reference case
- 8 QH units + 1 CLIQ unit per magnet
- Uniform conductor parameters

→ Hot-spot temperature **~230 K**

→ Peak voltage to ground **~600 V**

Worst case
- Two simultaneous units failing
- Non-uniform conductor parameters
- BUT electrical order of the four coils optimized

→ Worst-case temperature of 370-400 K considered **acceptable** for a one-in-a-lifetime event as a double failure

→ Worst-case voltage to ground at nominal current remains **below electrical design criteria** (<670 V)

STEAM simulations

Conclusion

The quench protection of the HL-LHC Inner Triplet circuit has been **successfully demonstrated in all foreseen operation scenarios**, and for various failure scenarios and conductor variations.

- **0-2 kA**: Magnet is self-protected. Demonstrated with conservative 3D quench simulations.
- **1.5-8 kA**: Quench heaters only are fully redundant. Demonstrated with dedicated measurements.
- **5-17.5 kA**: CLIQ + Quench heaters are fully redundant. Demonstrated with dedicated measurements.

→ Results from **MQXFB** test campaigns are in line with **simulations**

Circuit analysis:

→ Peak currents and quench loads **in all circuit components** calculated and judged not critical

Magnet quench protection analysis:

Reference case: 8 QH units + CLIQ unit per magnet, and uniform conductor parameters

→ Hot-spot temperature **~230 K** → Peak voltage to ground **~600 V**

Worst-case: Two failing units and non-uniform conductor parameters

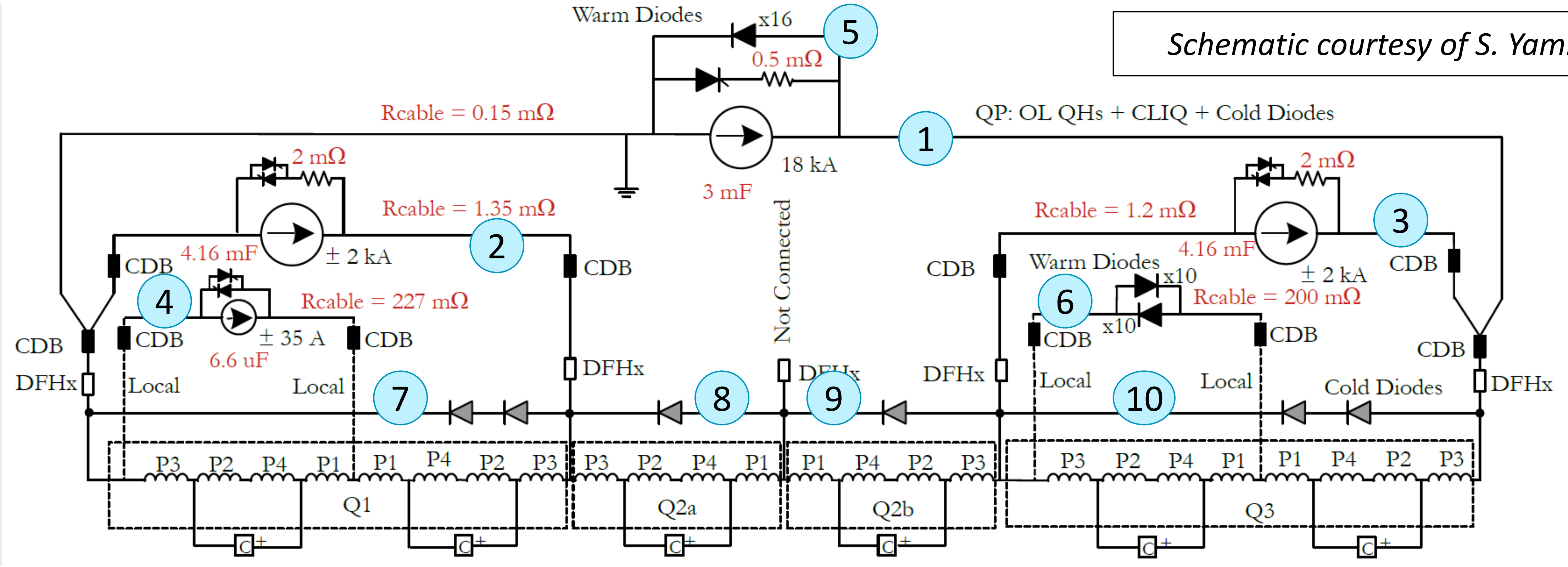
→ Worst-case temperature of 370-400 K considered **acceptable** for a one-in-a-lifetime event as a double failure

→ Worst-case voltage to ground at nominal current remains **below electrical design criteria** (<670 V)

Annex

HL-LHC Inner Triplet Circuit – Current baseline

Schematic courtesy of S. Yammine



Identify **conservative worst-cases** for these components based on circuit operating cases, failure cases, magnet conductor parameters. For each case, calculate **peak current** and **thermal load**.

1. Main power supply crowbar and leads
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7. Q1 Cold Diodes
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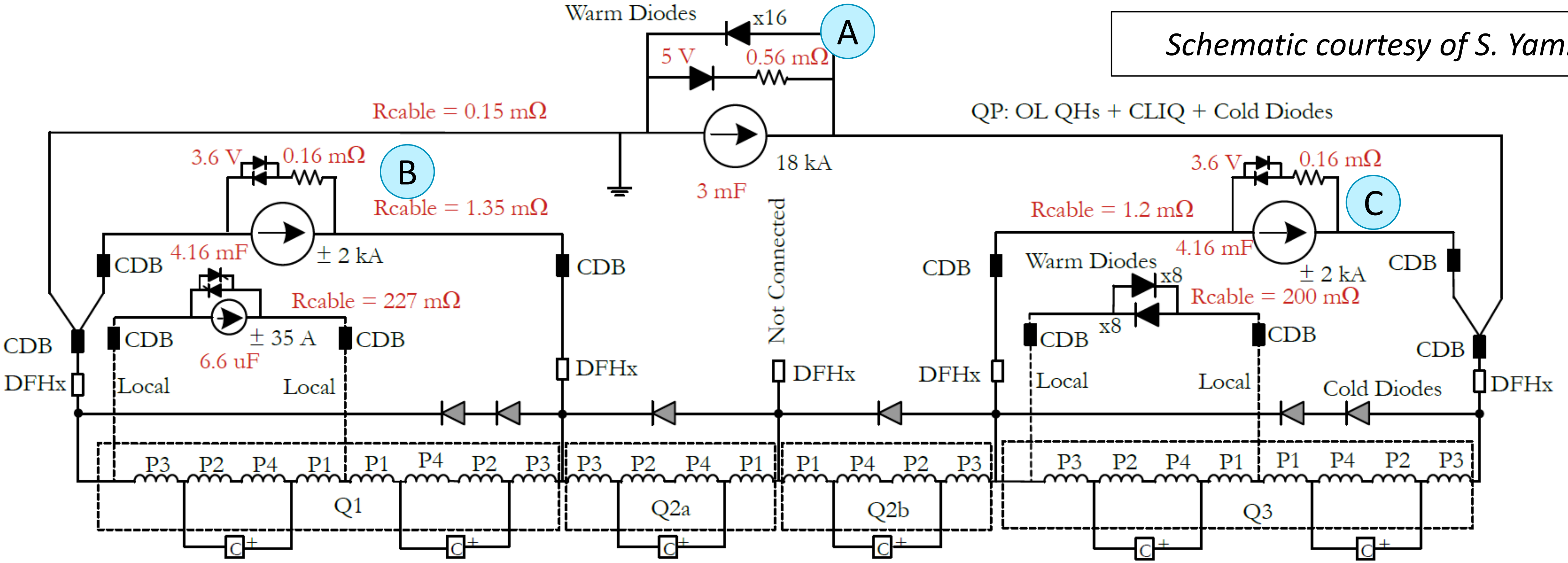
10. Q3 Cold Diodes

HL-LHC Inner Triplet Circuit – Fine tuning

Schematic courtesy of S. Yammine



The alternative configuration includes these main changes:

A. Crowbar of RQX main power converter has Diodes (rather than thyristors)

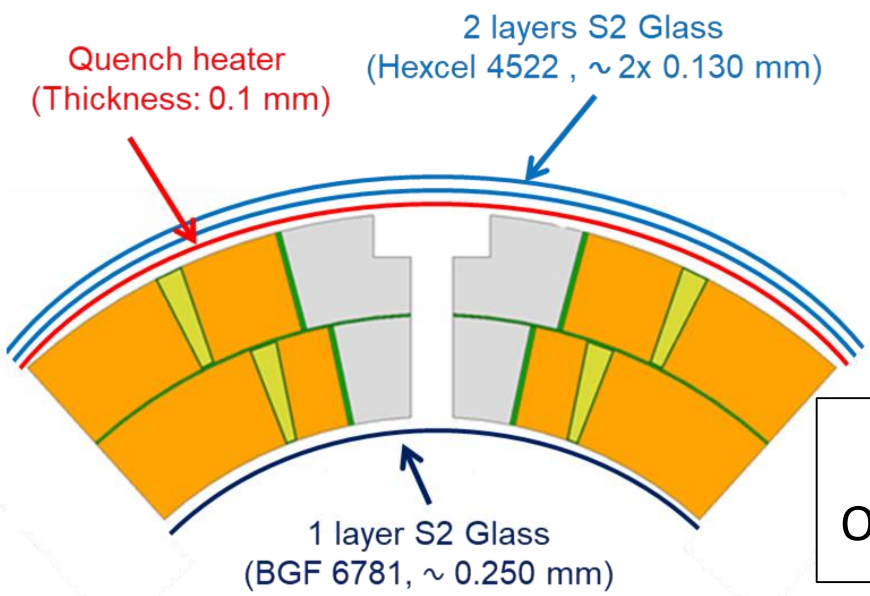
B. Crowbar of RQTX1 trim power converter has Diodes (rather than thyristors)

C. Crowbar of RQTX3 trim power converter has Diodes (rather than thyristors)

Note: Crowbar of RQTXA1 trim power converter is unchanged with respect to the baseline (i.e. it has thyristors)

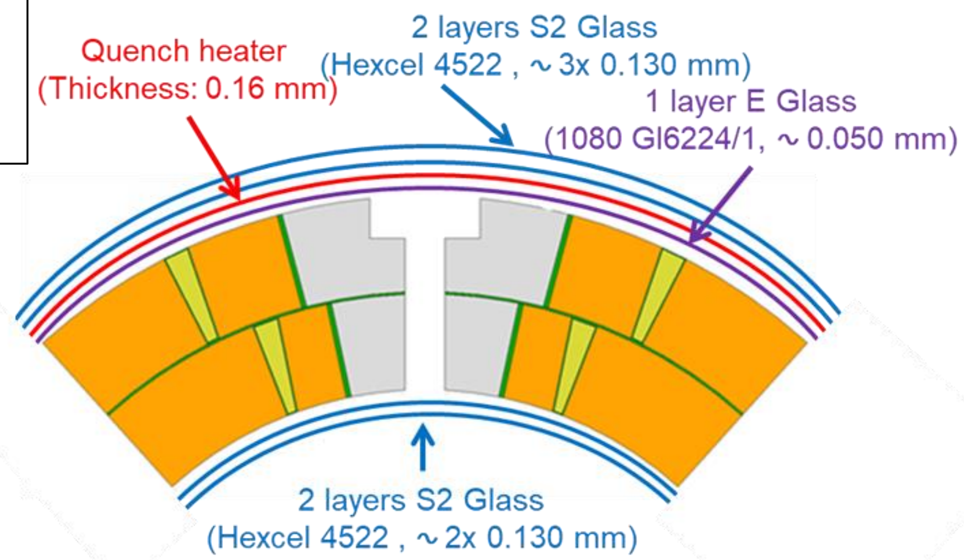
https://indico.cern.ch/event/1039101/
https://indico.cern.ch/event/1083268/
https://indico.cern.ch/event/1191497/

Quench protection **heaters** (QH)



MQXFA
Original design

MQXFB
“mini-swap”



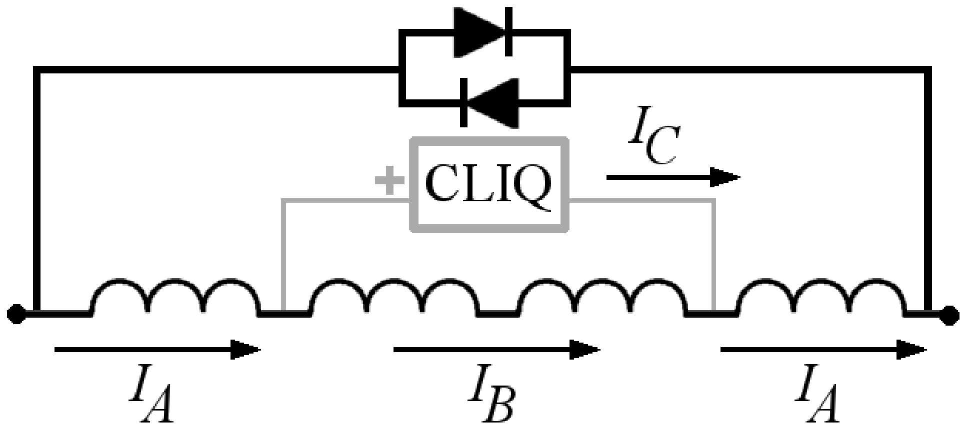
- MQXFB magnets: Added a 0.055 mm layer of E Glass between quench heater and coil (**“mini-swap”**)
  - ✓ Better insulation between heater and coil
  - ✓ Limited impact on quench protection
- MQXFA magnets stay with the previous QH design

8x 7.05 mF **QH** units charged to **940 V**

✓ Spread on QH power supplies parameters decreased: magnet is protected including tolerances

David Carrillo, Edward Nowak
https://indico.cern.ch/event/1079026/contributions/4546310/

CLIQ (Coupling-Loss Induced Quench)



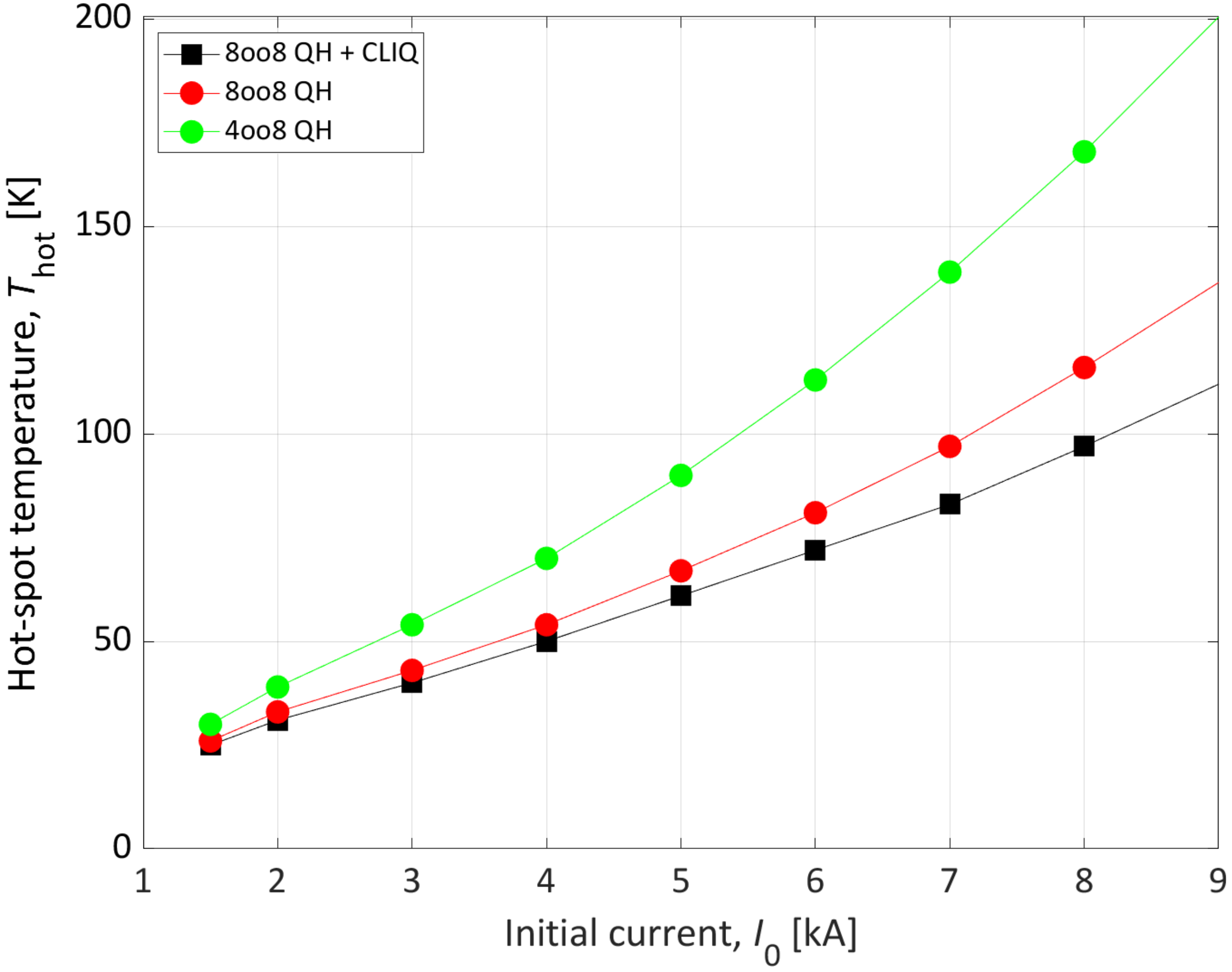
1x 40 mF **CLIQ** unit charged to 600 V or to 1000 V for 4.2 m or 7.15 m long MQXF

- CLIQ lead parameters confirmed for Q1/Q2/Q3
  - ✓ CLIQ lead lengths: 350-420 m (2-ways)
  - ✓ CLIQ total circuit resistance: 26-38 mΩ
  - ✓ CLIQ lead self-inductance: 0.35-0.42 mH
- These parameters do not pose any performance problem

https://indico.cern.ch/event/1079026/contributions/4546310/

David Carrillo, Edward Nowak, Samer Yammine

[1.5-8 kA] Low-medium current: QHs are fully redundant

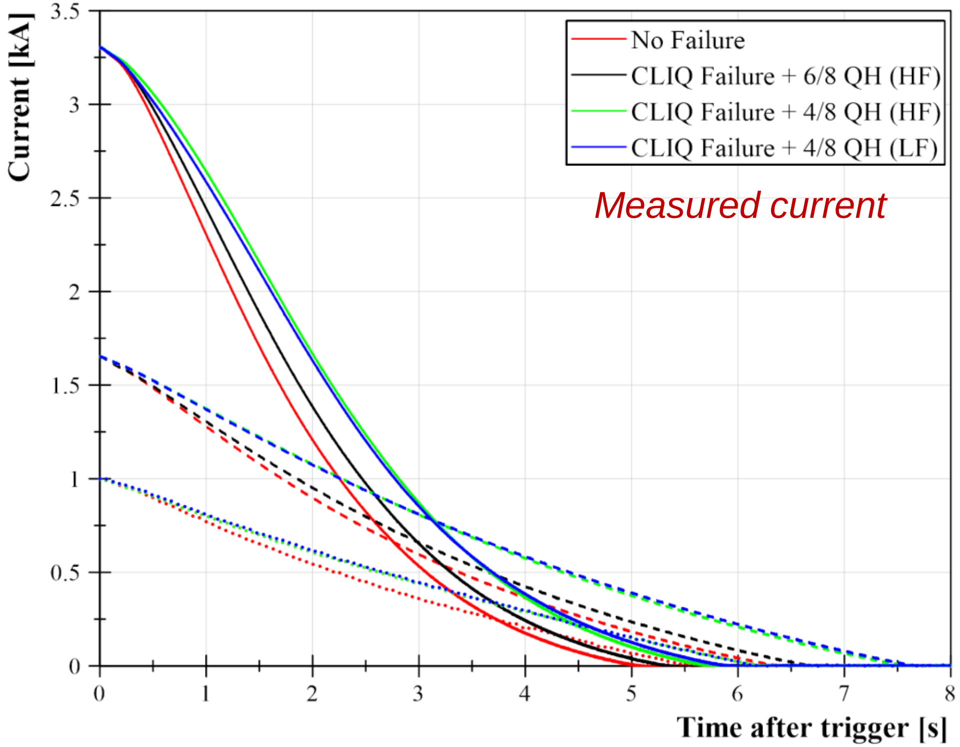


→ At low-medium current, **QH system is fully redundant**

→ Simulations show that half of the QHs are sufficient to maintain the peak temperature **<170 K** at 8 kA

STEAM-LEDET simulations

Redundancy of the quench protection at low current

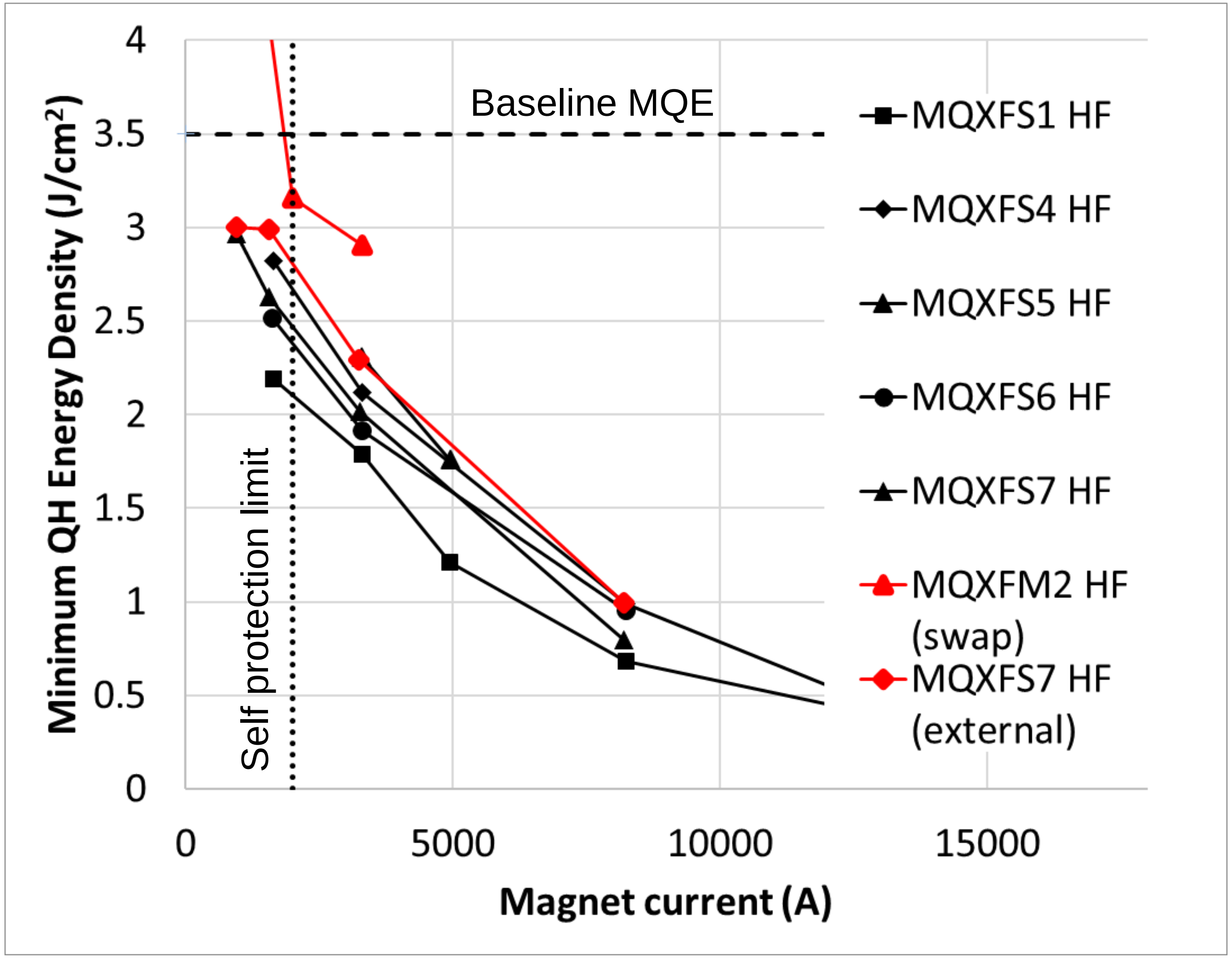


Measured quench integral (MA^2s) from protection triggering					
Case	**CLIQ**	**Low-field QH**	**High-field QH**	**I, kA**	**QI, MA^2s**
No failure	Yes	4oo4	3oo4 [1 strip unavailable]	1	1.54
				1.65	4.26
				3.3	12.36
CLIQ failure + 2 QH failures	No	4oo4	2oo4	1	0.24
				1.65	4.58
				3.3	13.67
CLIQ failure + 4 QH failures	No	0oo4	3oo4 [1 strip unavailable]	1	1.82
				1.65	5.54
				3.3	15.50
	No	4oo4	0oo4	1	1.78
				1.65	5.53
				3.3	15.98

→ Excellent redundancy demonstrated at low current on MQXFS4 short model
→ 4 out of 8 QH circuits (4oo8) assure quench protection at low current.

Franco Mangiarotti, Michal Duda, Salvador Ferradas

Minimum quench-heater energy density to quench



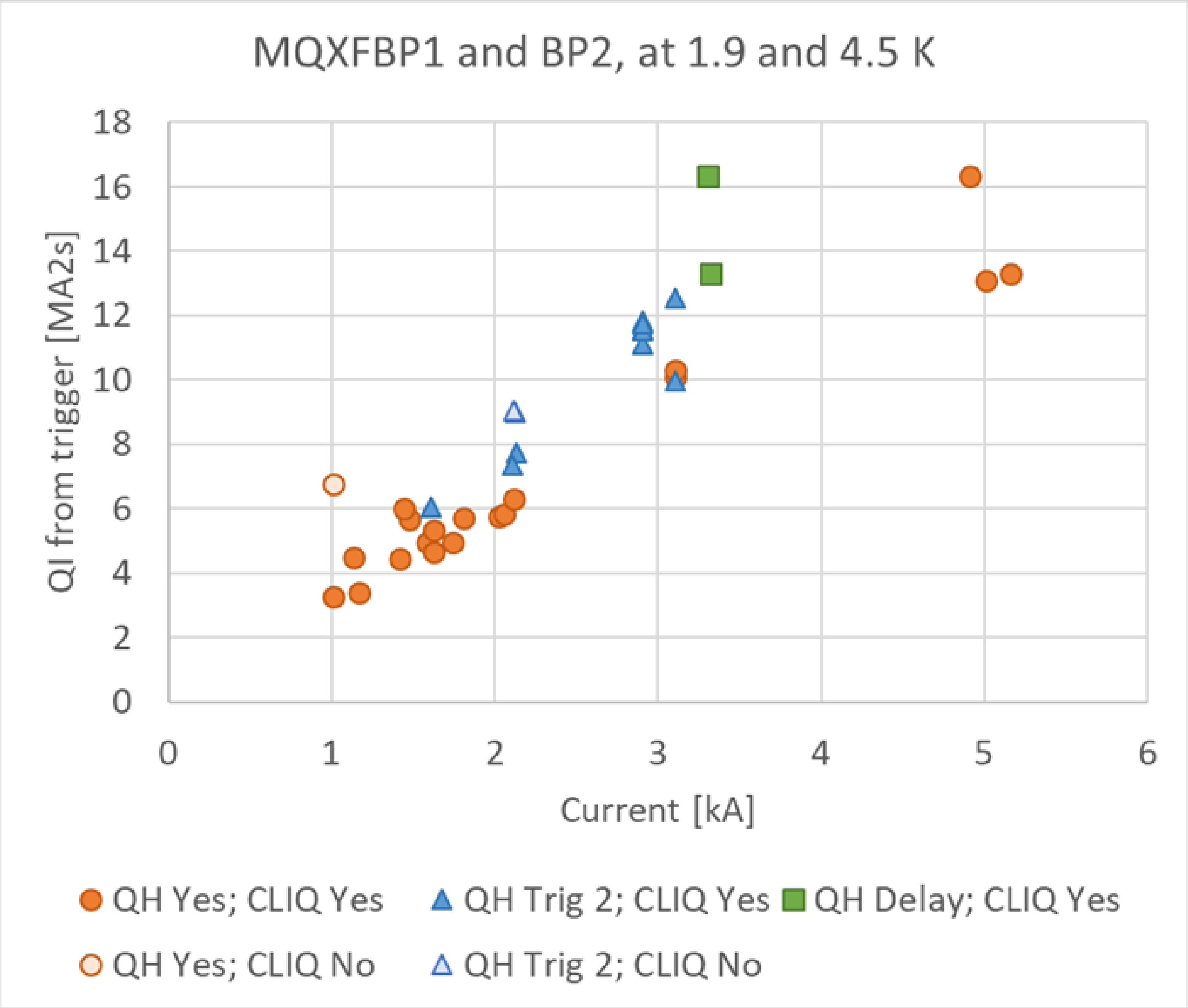
→ Minimum quench-heater energy density (MQE) to start a quench was systematically measured on model magnets

→ QH configurations featuring additional 0.1 mm S2 glass (“swap”/”external”) tested on a mirror coil and a model coil

→ QH design provides sufficient energy density to protect the magnet

Franco Mangiarotti, Michal Duda, Stoyan Stoynev, Maria Baldini

MQXFB prototype quench protection tests at low current



→ Based on the experience with two MQXFB prototypes, the magnet is well protected at low current.

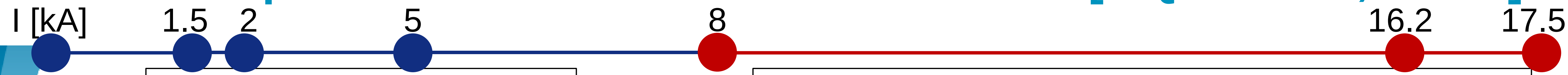
Manual trigger without quench

2 QH circuit powered to start quench, rest triggered upon detection

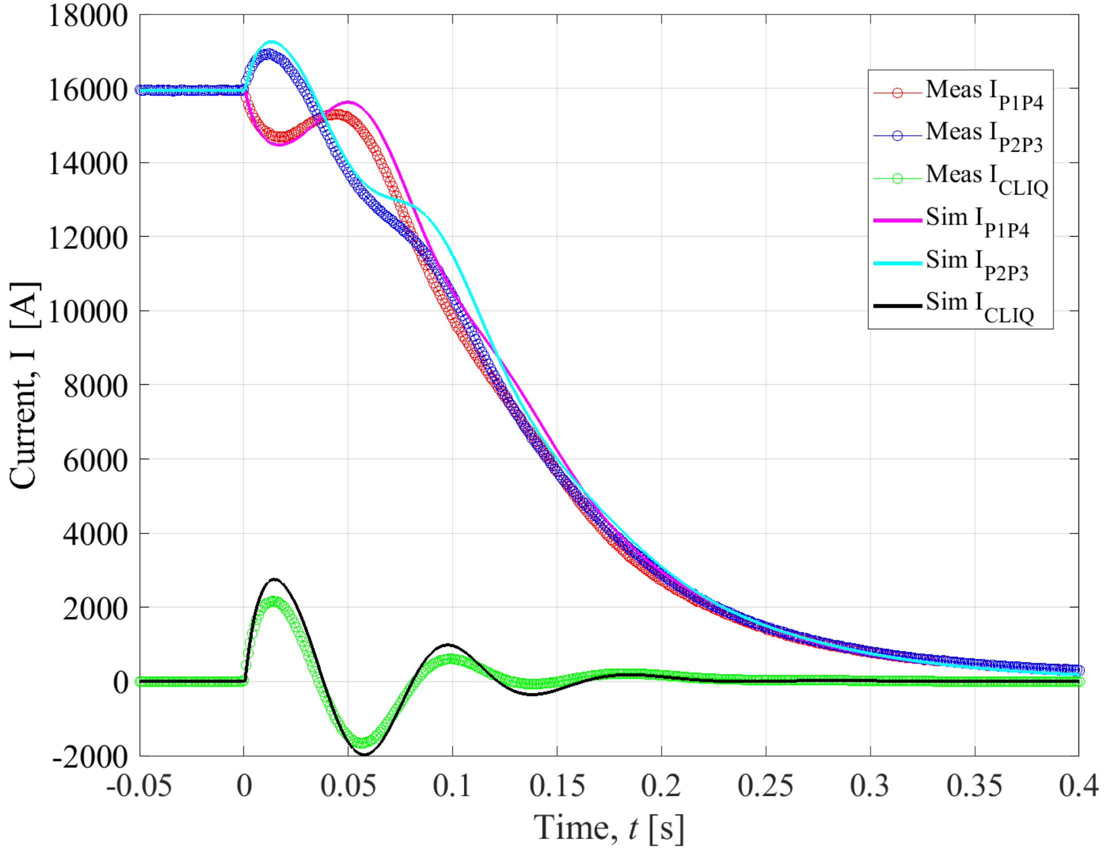
Manual trigger without quench, QH delayed 500 ms

Franco Mangiarotti

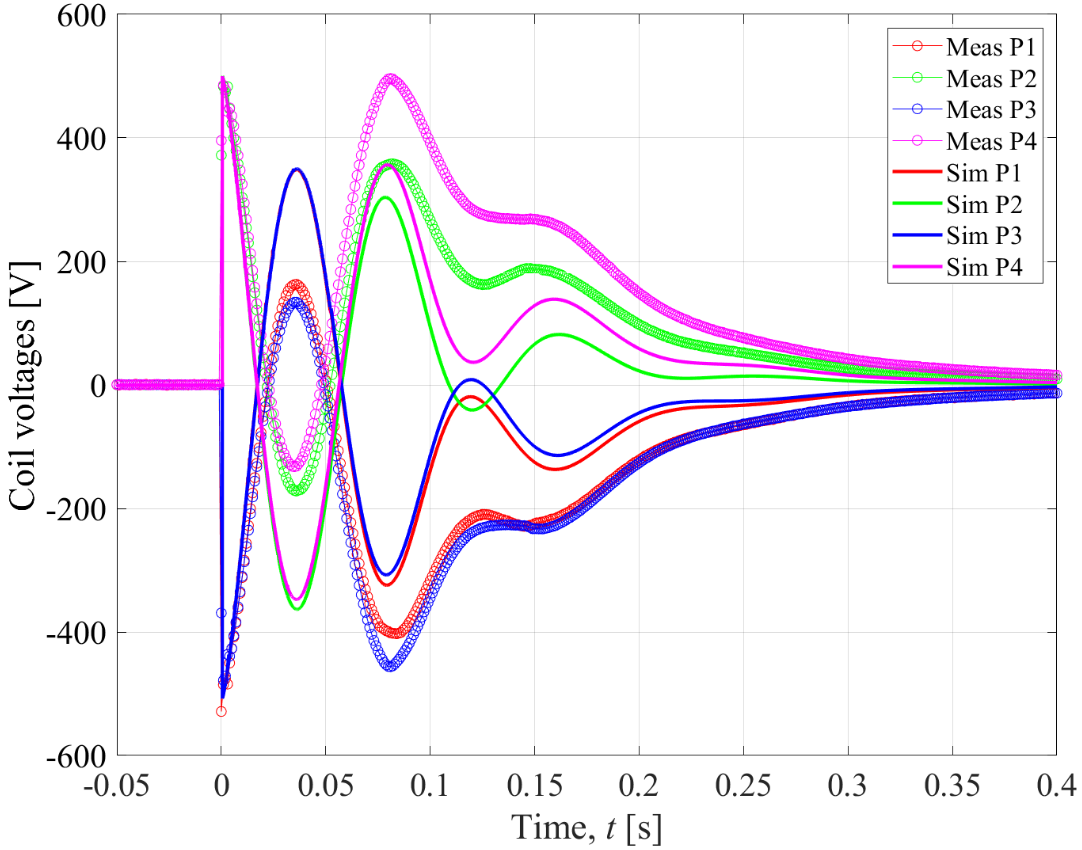
Example of validation of simulation model [MQXFBP02, 16 kA]



Currents in the system



Voltages across the four coils

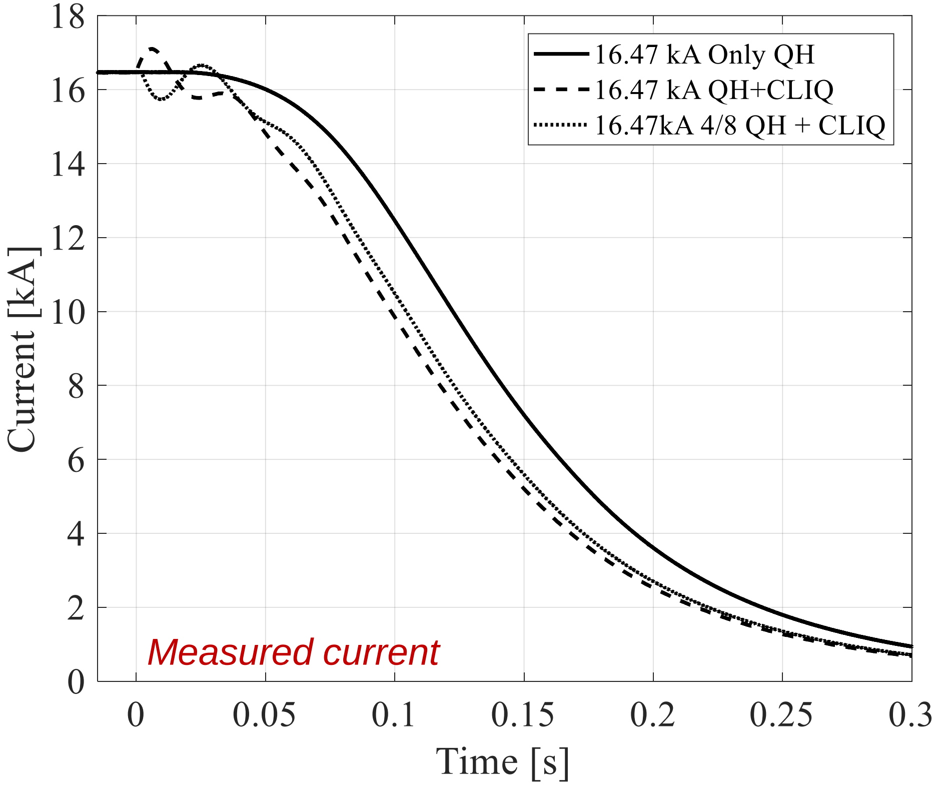


→ Typical expected error, before applying any fitting parameters:
<10% error on the quench load and <20% error on the coil voltages

Measurements: Franco Mangiarotti
STEAM-LEDET simulations

[8-17.5 kA] Redundancy of the quench protection at high current

I [kA] — 1.5 — 2 — 5 — 8 — 16.2 — 17.5



Measured quench integral (MA^2s) from protection triggering

Case	CLIQ	Low-field QH	High-field QH	I, kA	QI, MA^2s
No failure	Yes	4oo4	3oo4 [1 strip unavailable]	16.47	24.8
4 QH failures	Yes	4oo4	0oo4	13.2	27.8
				16.47	26.2
CLIQ failure	No	4oo4	3oo4 [1 strip unavailable]	13.2	28.9
				16.47	30.9

Note: In the first test, CLIQ unit U=200 V, C=40 mF. In the other four tests: CLIQ unit U=200 V, C=50 mF.

- → Redundancy demonstrated at 80%-100% of nominal current on MQXFS4 short model
- → Tests more conservative than realistic worst-case, i.e. two simultaneous failures (no CLIQ and 7oo8 QH)
- → If CLIQ doesn't fail, failure of 4 QH circuits increases quench load by ~1.5 MIIt (~20 K), consistent with model

Franco Mangiarotti, Jose Ferradas Troitino

Simulated hot-spot temperature – Reference and worst-case

I [kA] 1.5 2 5 8 16.2 17.5

Reference case: No failures. All coils have reference conductor parameters (RRR, Cu fraction).
Worst-case: Worst combination of two failure cases. Coils have largest expected spread of conductor parameters [see Annex]. Optimum electrical order of four coils within each magnet selected.

Hot-spot temperature [K]	**Reference case**		**Worst case**	
	I_{nom}	I_{ult}	I_{nom}	I_{ult}
Impregnated heaters [previous baseline]	227	250	346	374
Mini-swap heaters (0.055 mm G10 layer)	231	253	375	404

→ New QH design increases the hot-spot T only by <5 K in the reference case, and <30 K in the worst-case
→ Temperature of 370-400 K considered acceptable for a one-in-a-lifetime event such as a double failure

STEAM-LEDET simulations

Simulated peak voltage to ground – Reference and worst-case

Reference case: No failures. All coils have reference conductor parameters (RRR, Cu fraction).
Worst-case: Worst combination of two failure cases. Coils have largest expected spread of conductor parameters [see Annex]. Optimum electrical order of four coils within each magnet selected.

Peak voltage to ground [V]	Reference case		Worst case	
	I_{nom}	I_{ult}	I_{nom}	I_{ult}
Impregnated heaters [previous baseline]	589	751	639	818
Mini-swap heaters (0.055 mm G10 layer)	+2%	+3%	+2%	+3%

→ Confirmed that the expected worst-case at nominal current is within electrical design criteria (<670 V)
→ The new QH design increases the peak voltage to ground only by 2-3%
→ In first approximation, MQXFA voltages are scaled with the magnetic length, i.e. they are ~40% lower

STEAM-LEDET simulations

List of simulated cases

Assumptions to identify the worst-cases

Power supply initial currents

Conductor parameters

Complete magnet quenches

Diode forward voltage

Failure cases

#	I_main [kA]	I_Q1 [kA]	I_Q3 [kA]	I_Q1a [A]	fCu [-]	RRR [-]	Quench	Cold Diode OV [V]	Failure
1	16.23	0	0	0	ref	ref	no	6	no
2	17.5	0	0	0	ref	ref	no	6	no
3	17.5	0	0	0	↑all	↑all	no	6	no CLIQ-Q2a +QH-Q2a
4	0.05	0	0	0	ref	Ref	no	6	No
5	16.23	0	0	0	ref	Ref	no	6	Spurious CLIQ-Q1a
6	16.23	0	0	0	ref	Ref	no	6	Spurious CLIQ-Q1b
7	16.23	0	0	0	ref	Ref	no	6	Spurious CLIQ-Q2a
8	16.23	0	0	0	ref	Ref	no	6	Spurious CLIQ-Q2b
9	16.23	0	0	0	ref	Ref	no	6	Spurious CLIQ-Q3a
10	16.23	0	0	0	ref	Ref	no	6	Spurious CLIQ-Q3b
11	15.5	2	0	0	↓Q1a, ↑others	↓Q1a, ↑others	full Q1a	6	No
12	15.5	2	0	-35	↓Q1b, ↑others	↓Q1b, ↑others	full Q1b	6	No
13	17.5	-2	-2	-35	↓Q2a, ↑others	↓Q2a, ↑others	full Q2a	6	No
14	17.5	-2	-2	-35	↓Q2b, ↑others	↓Q2b, ↑others	full Q2b	6	no
15	15.5	0	2	-35	↓Q3a, ↑others	↓Q3a, ↑others	full Q3a	6	no
16	15.5	0	2	-35	↓Q3b, ↑others	↓Q3b, ↑others	full Q3b	6	no
17	16.23	-2	0	-35	↓Q1a, ↑others	↓Q1a, ↑others	no	6	no CLIQ-Q1a +QH-Q1a
18	16.23	-2	0	35	↓Q1b, ↑others	↓Q1b, ↑others	no	6	no CLIQ-Q1b +QH-Q1b
19	14.23	2	2	0	↓Q2a, ↑others	↓Q2a, ↑others	no	6	no CLIQ-Q2a +QH-Q2a
20	14.23	2	2	0	↓Q2b, ↑others	↓Q2b, ↑others	no	6	no CLIQ-Q2b +QH-Q2b
21	16.23	0	-2	0	↓Q3a, ↑others	↓Q3a, ↑others	no	6	no CLIQ-Q3a +QH-Q3a
22	16.23	0	-2	0	↓Q3b, ↑others	↓Q3b, ↑others	no	6	no CLIQ-Q3b +QH-Q3b
23	17.5	0	0	0	ref	ref	no	6	short in Q1 crowbar
24	15.5	2	0	-35	↓Q1b, ↑others	↓Q1b, ↑others	full Q1b	6	short in Q1 crowbar
25	16.23	-2	0	35	↓Q1b, ↑others	↓Q1b, ↑others	No	1	no CLIQ-Q1b +QH-Q1b
26	16.23	0	-2	0	↓Q3b, ↑others	↓Q3b, ↑others	No	1	no CLIQ-Q3b +QH-Q3b
27	15.5	2	0	-35	↓Q1b, ↑others	↓Q1b, ↑others	full Q1b	1	no
28	15.5	0	2	-35	↓Q3b, ↑others	↓Q3b, ↑others	full Q3b	1	no