QH strip resistances and circuit parameters in the MQXF magnets

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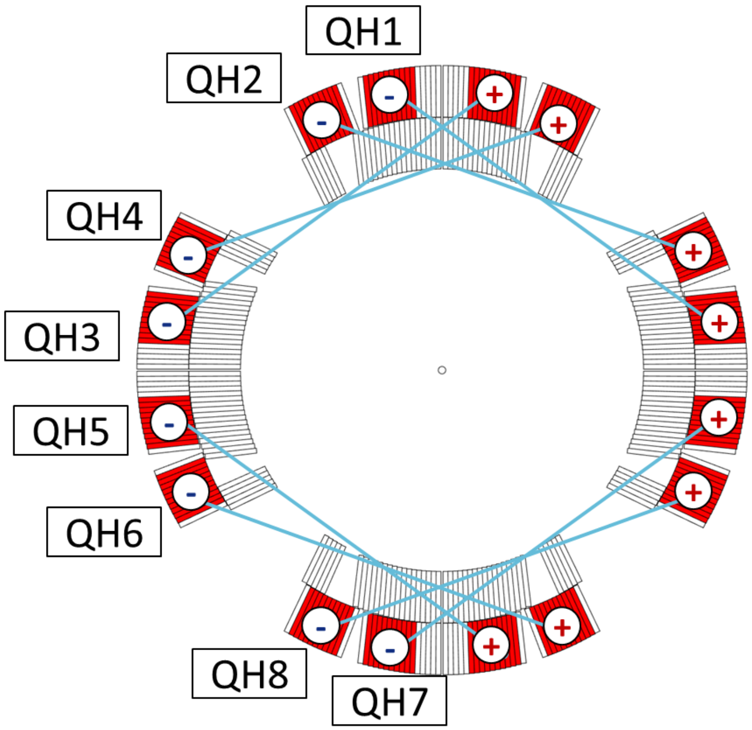
Outline

- **Introduction**
- Statistics on quench heater resistance measurements
- Circuit parameters
- Conclusions

Introduction

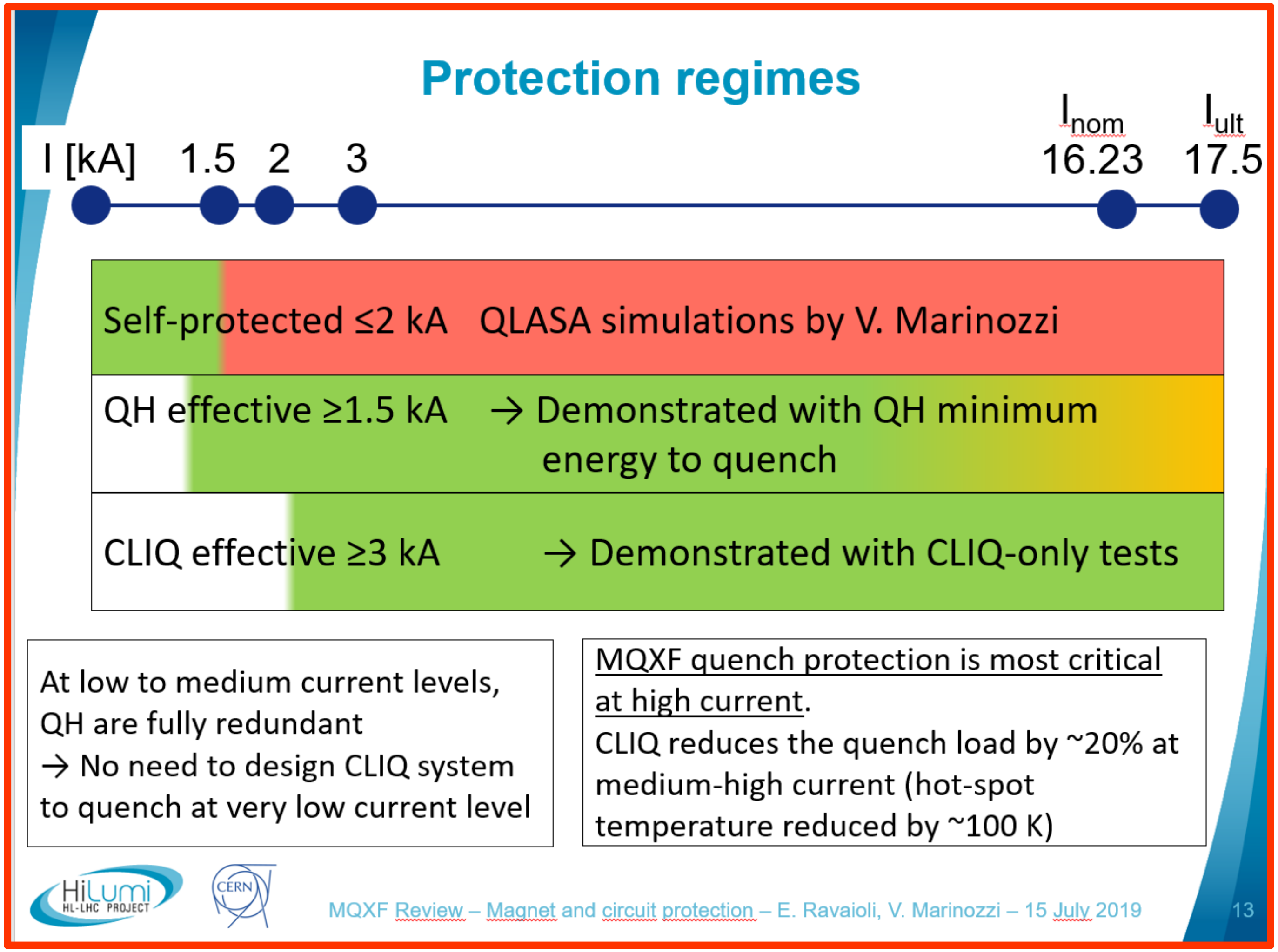
- Each MQXF magnet has 8 quench heater circuits, with a wiring configuration optimized to minimize the peak voltage and impact to the beam in case of spurious firing.

- Each QH strip before coil fabrication (4W measurements)
- After magnet assembly, heater strips are connected in series
- Each circuit is measured at different steps of fabrication/test, here we focus only on the final measurements in the test facility (RT and 1.9 K)



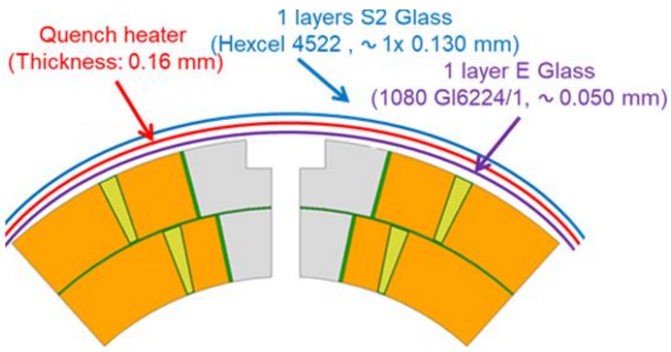
Introduction - Requirements

- Protection heaters shall:
  - Initiate a quench in the low current regime where CLIQ is not effective (1.3-3 kA)
  - Quench the largest portion of the coil as quick as possible at high current, where the protection of these magnets is critical

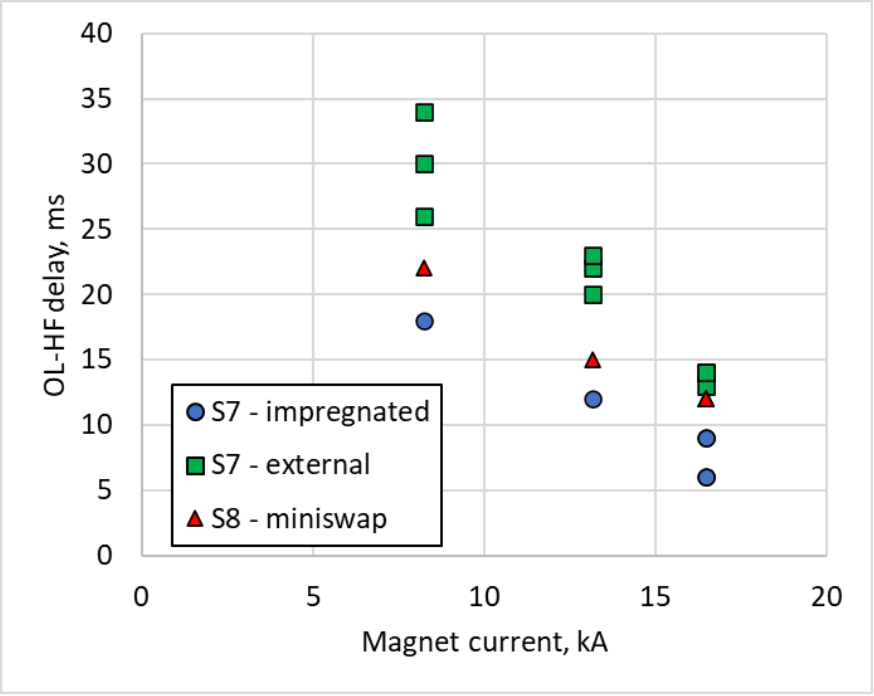


Introduction – Requirements: MQXFA vs MQXFB

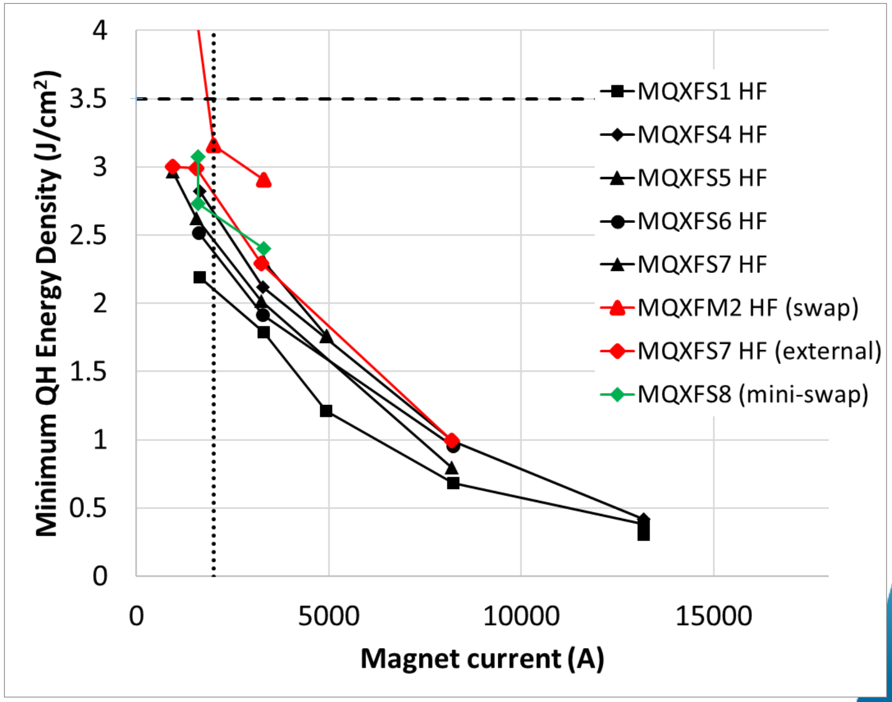
- In 2021, CERN decided to implement the so-called 'mini-swap' in MQXFB magnets (see EDMS 2646046). Consequences:
  - Increase the hot spot temperature by 30 K in case of CLIQ failure (no change for the nominal protection increase)
  - Small increase of the minimum QH energy density to start a quench at low current.
- The mini-swap was not implemented in MQXFA magnets



Measured QH delay in MQXFS magnets with different heater layout



Measured minimum energy density in MQXFS magnets with different heater layout



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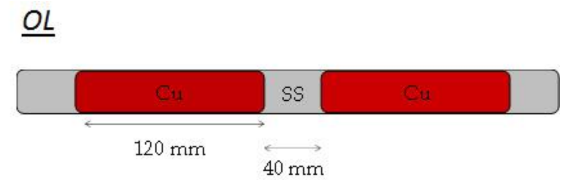
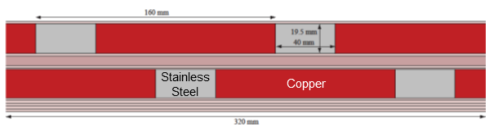
- Introduction
- **Statistics on quench heater resistance measurements**
- Quench heater circuit parameters
- Conclusions

Quench heater design – nominal parameters initial design phase

Nominal design parameters (30 RRR Cu, 1.34 RRR SS)

			MQXFA	MQXFB
Geometry	Magnet length	(m)	4.2	7.15
	Heater SS width	(mm)	20	20
	Heater Cu width	(mm)	20	20
	Heater SS thickness	(mm)	0.025	0.025
	Heater Cu thickness	(mm)	0.01	0.01
	Station length	(mm)	40	40
	Station period	(mm)	160	160
	Number of stations		25	44
Room temperature strip resistance	SS resistivity at RT	(Ω m)	7.30E-07	7.30E-07
	Cu resistivity at RT	(Ω m)	1.80E-08	1.80E-08
	SS station resistance at RT	(Ω)	5.84E-02	5.84E-02
	Cu station resistance at RT	(Ω)	1.08E-02	1.08E-02
	Total strip resistance at RT	(Ω)	1.73E+00	3.05E+00
Cold strip resistance	SS resistivity at 10 K	(Ω m)	5.45E-07	5.45E-07
	Cu resistivity at 10 K	(Ω m)	6.00E-10	6.00E-10
	SS station resistance at 10 K	(Ω)	4.36E-02	4.36E-02
	Cu station resistance at 10 K	(Ω)	3.60E-04	3.60E-04
	Total strip resistance at 10 K	(Ω)	1.10E+00	1.93E+00
Circuit resistance (nominal)	Number of strips in series		2	2
	Resistance of the warm leads	(Ω)	2.3	0.6
	Total resistance	(Ω)	4.5	4.5
Powering parameters (nominal)	Voltage	(V)	900	900
	Capacitance	(mF)	7.1	7.1
	Peak current	(A)	200	200
	RC	(ms)	32	32
	Peak power density	(W/cm^2)	218	218
	Energy density in the heater stations	(J/cm^2)	3.46	3.46



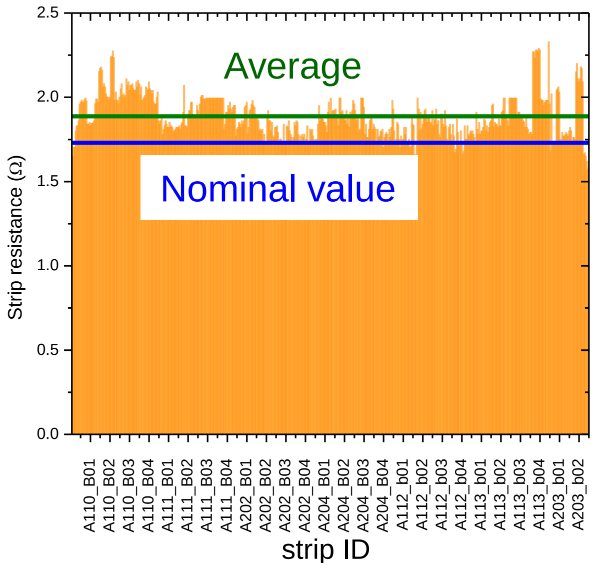


~ 6.1 Ω (2 strips) @ RT

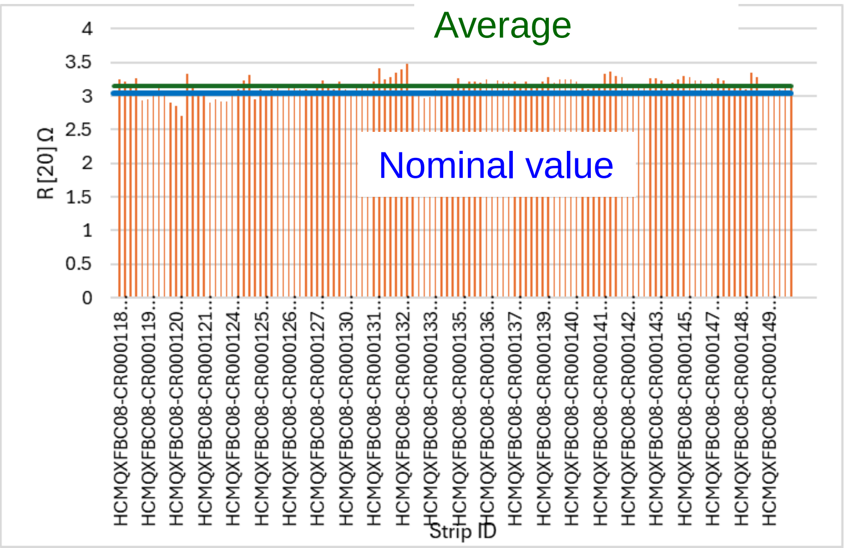
~ 3.9 Ω (2 strips) @ 1.9 K

QH resistance – individual strips

MQXFA: Data collected at FNAL with 4W measurements over 532 strips



MQXFB: Data collected at CERN-TE/MSC/LMF with 4W measurements, 124 strips measured

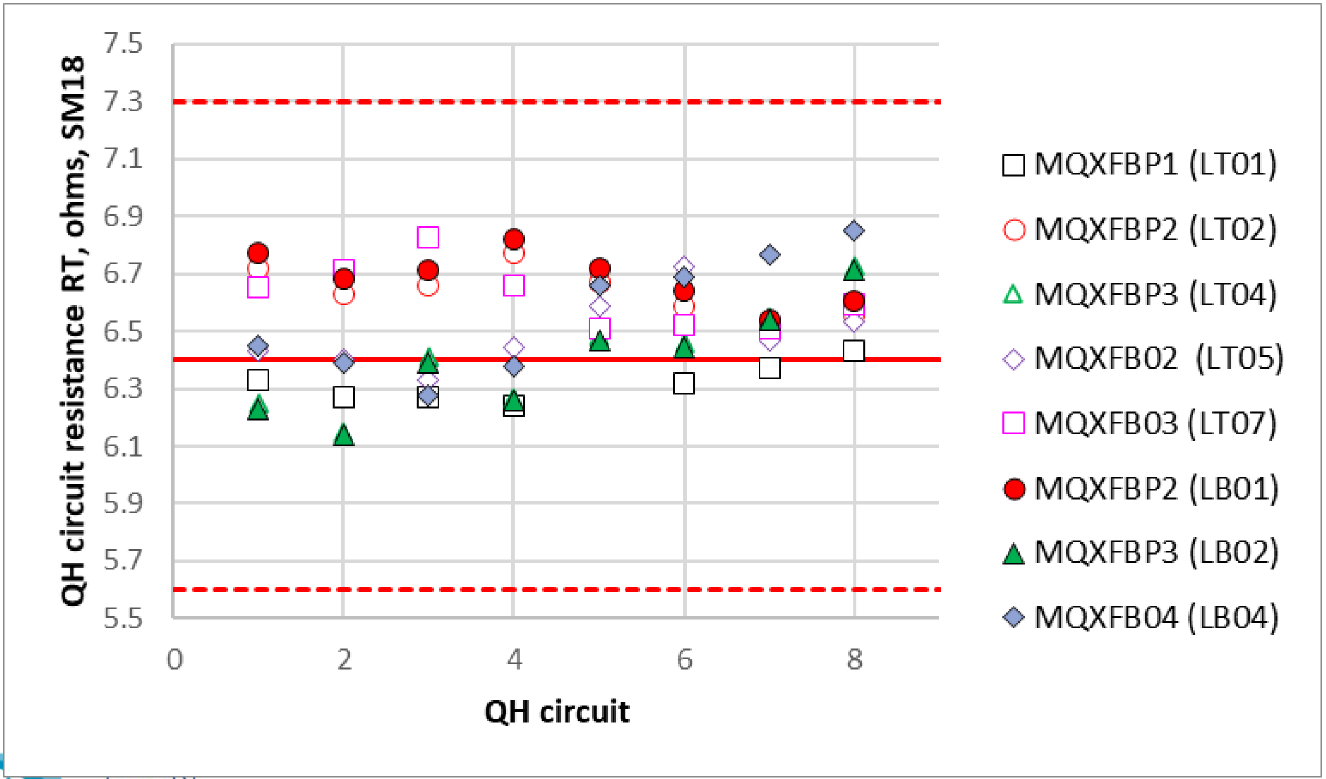


Room Temperature Single Strip Resistance [Ω]		
	MQXFA	**MQXFB**
Nominal	1.73	3.05
Avg. strip	**1.89**	**3.16**
St. Dev	**0.13**	**0.12**
Max	2.33	3.48
Min	1.57	2.71
Range	0.76	0.77
Range (%)	40	24

- Measured average strip rather close to initial estimates in the design phase (average resistance ≈ 0.1 Ω higher that initial design value)
- As expected, similar spread of the measured resistance for MQXFA and MQXFB since heaters are all produced by CERN

MQXFB: heater circuit resistance at RT

- Requirements at room temperature RT ([EDMS 2873724]):
  - Quench heater resistance at 293 K between 5.6 and 7.3 Ω
  - Difference of quench heater resistance at 293 K before and after tests less than 0.15 Ω
- Measured values are well within the specification.
- Very consistent measurements between magnets assembled in temporary and final cold mass.



Circuit Resistance [Ω]	
Nominal*	6.10
Avg. circuit	6.51
St. Dev	0.17
Max	6.85
Min	6.15
Range	0.70
Range (%)	10.75

*Consider only heater strips

Remark 1: empty markers corresponds to magnets assembled in temporary cold mass configuration

Remark 2: for the statistics, if a magnet is assembled in temporary and Q2 cold mass is considered only once

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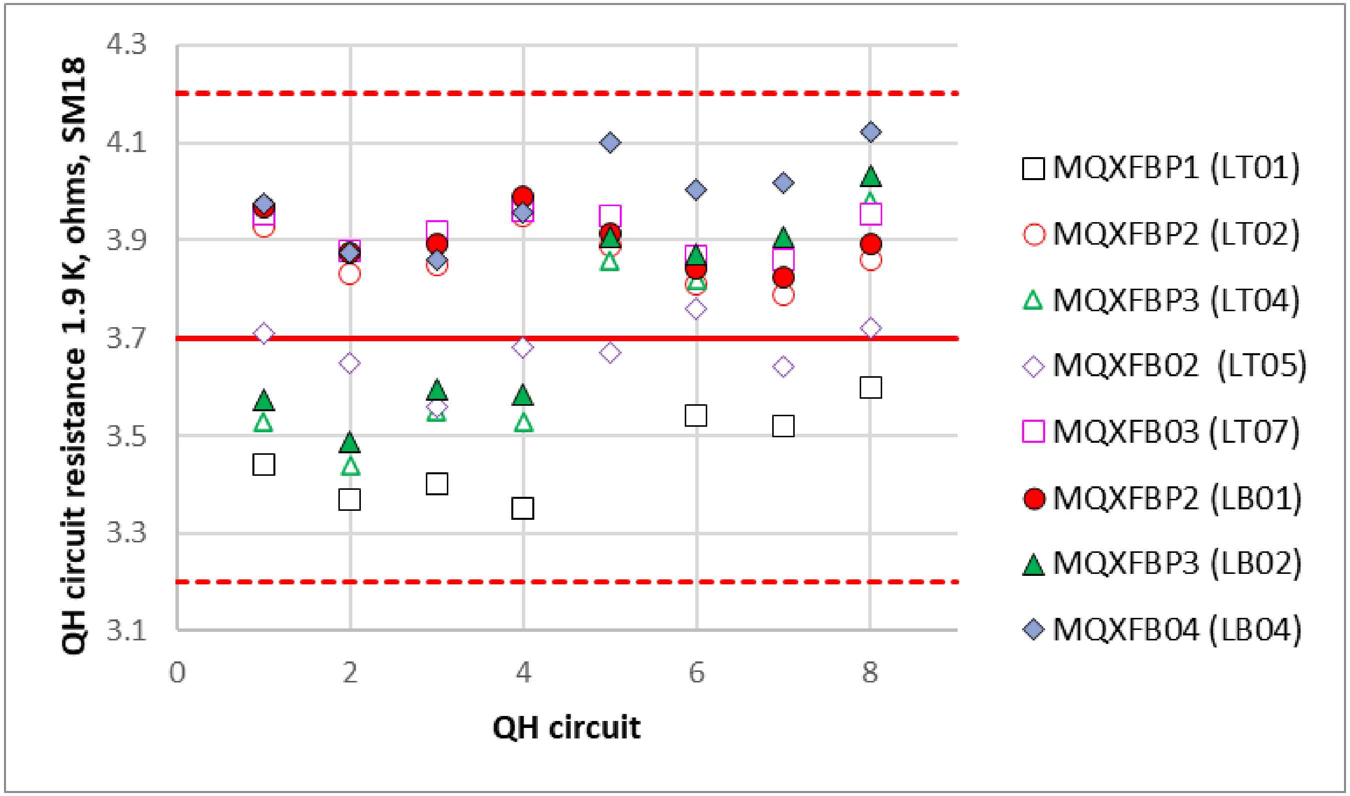
MQXFB: heater circuit resistance at 1.9 K

- Requirements at 1.9 K (EDMS 2873724):
  - Quench heater resistance at nominal operation conditions between 3.2 and 4.2 Ω
  - At least 6 quench heater circuits with at least 3.4 Ω resistance at nominal operation conditions
- Measured values so far are well within the specification.



Circuit Resistance [Ω]	
Nominal*	3.90
Avg. circuit	3.77
St. Dev	0.20
Max	4.12
Min	3.35
Range	0.77
Range (%)	20.43

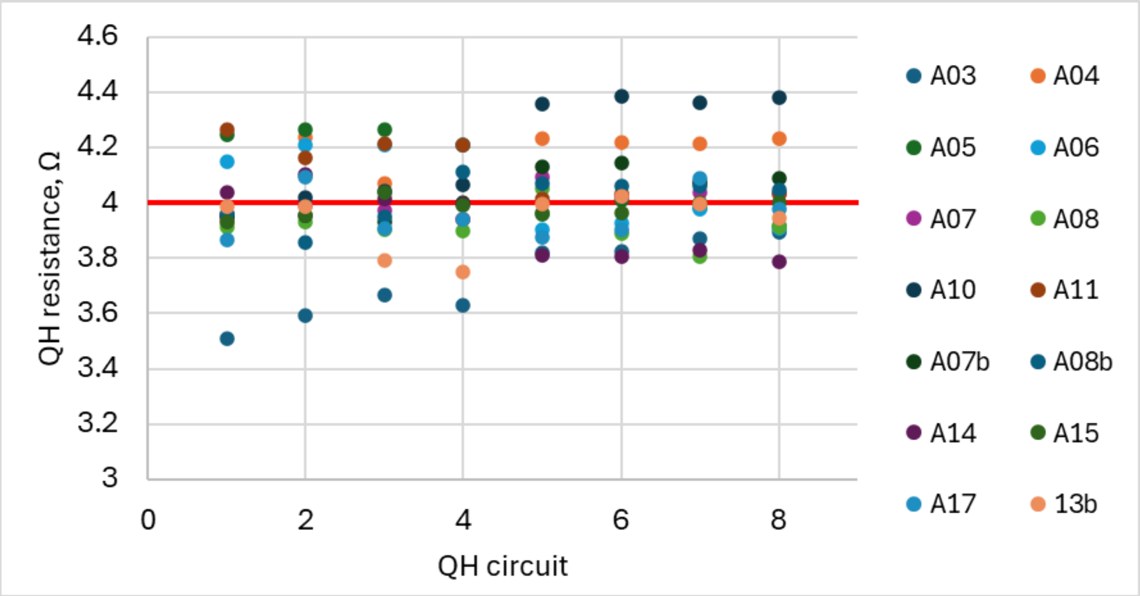
*Consider only heater strips

Remark 1: empty markers corresponds to magnets assembled in temporary cold mass configuration

Remark 2: for the statistics, if a magnet is assembled in temporary and Q2 cold mass is considered only once

MQXFA: heater circuit resistance at warm

- AUP has limited statistics on Q1/Q3 configuration, so for the moment we focus on the measurements on individual MQXFA magnets in vertical configuration
- Average measured value close to the expected, and spread consistent with MQXFB experience
  - Slightly larger variation on the first magnets (iterations on the length of the QH wires)

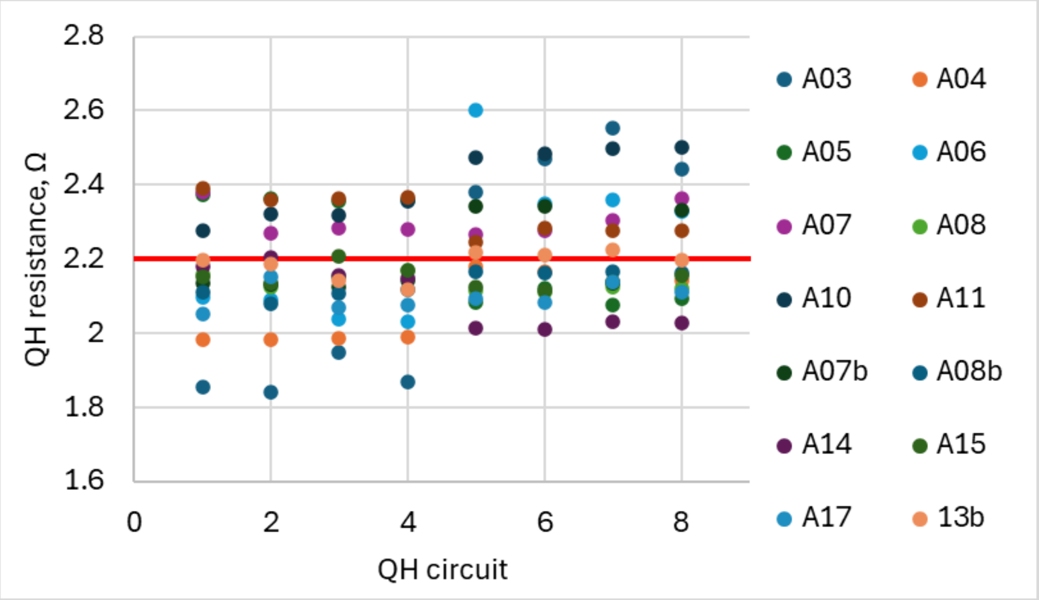


Circuit Resistance RT [Ω]		
	All	Exclude A03 to A06
Nominal*	3.86	3.86
Avg. circuit	4.01	4.01
St. Dev	0.16	0.13
Max	4.39	4.39
Min	3.51	3.75
Range	0.88	0.64
Range (%)	22	16

*Consider only heater strips

MQXFA: heater circuit resistance at cold

- AUP has limited statistics on Q1/Q3 configuration, so for the moment we focus on the measurements on individual MQXFA magnets in vertical configuration
- Average measured value close to the expected, and spread consistent with MQXFB experience
  - Slightly larger variation on the first magnets (iterations on the length of the QH wires)



Circuit Resistance Cold[Ω]		
	All	Exclude A03 to A06
Nominal*	2.20	2.20
Avg. circuit	2.20	2.20
St. Dev	0.15	0.11
Max	2.60	2.50
Min	1.84	2.01
Range	0.76	0.49
Range (%)	35	22

*Consider only heater strips

Summary

- Average measured value close to the expected and spread consistent in MQXFB and MQXFA magnets.
- Slightly larger variation on the first magnets (iterations on the length of the QH wires, less mature quench heater fabrication process)

MQXFB Circuit Resistance [Ω]		
	RT	1.9 K
Nominal*	6.10	3.90
Avg. circuit	6.51	3.77
St. Dev	0.17	0.20
Max	6.85	4.12
Min	6.15	3.35
Range	0.70	0.77
Range (%)	11	20

MQXFA Circuit Resistance [Ω]		
	RT	1.9 K
Nominal*	3.86	2.20
Avg. circuit	4.01	2.20
St. Dev	0.16	0.15
Max	4.39	2.60
Min	3.51	1.84
Range	0.88	0.76
Range (%)	22	35

MQXFB Circuit Resistance [Ω] (excluding BP1-BP2-BP3)		
	RT	1.9 K
Nominal*	6.10	3.90
Avg. circuit	6.56	3.86
St. Dev	0.15	0.15
Max	6.85	4.12
Min	6.28	3.56
Range	0.57	0.56
Range (%)	9	15

MQXFA Circuit Resistance [Ω] (excluding A03 to A06)		
	RT	1.9 K
Nominal*	3.86	2.20
Avg. circuit	4.01	2.20
St. Dev	0.13	0.11
Max	4.39	2.50
Min	3.75	2.01
Range	0.64	0.49
Range (%)	16	22

*Consider only heater strips

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- **Quench heater circuit parameters**
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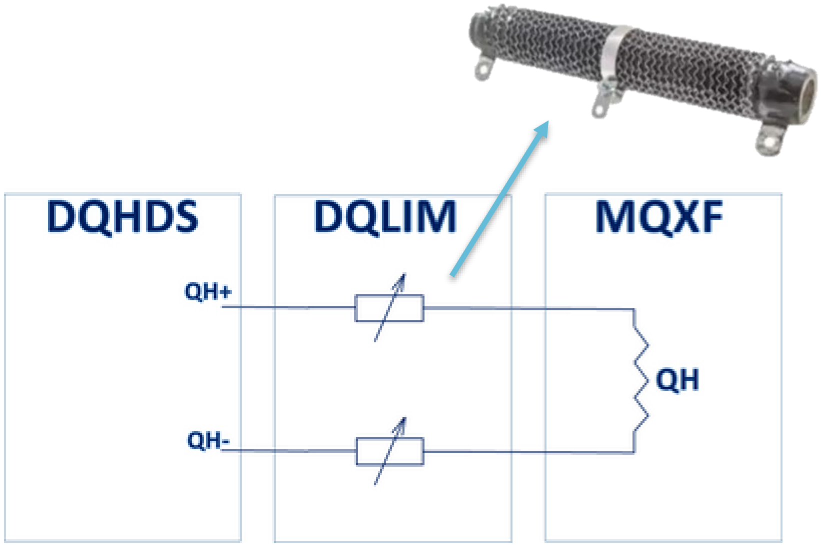
Quench heater circuit parameters

- A resistor in series with the quench heaters to adjust circuit parameters such that we are under acceptable limits including the expected spread on capacitance/voltage/resistance
  - Capacitance: 7.05 mF +0, -5 % (initially was ± 20 %, ± 5 % expected but to be revised when we receive series units)
  - Voltage: ± 450 V. For an average of 900 V, the range is set to 880 V – 950 V.
  - Resistance: to the heater circuit resistance, one needs to add the resistance of the wiring in the tunnel, which is not the same for the different circuits.



Quench heater circuit parameters

- For MQXFA, spread based on individual magnets vertically tested, needs to be confirmed once more data in Q1/Q3 configuration is available
- We might be able in the future to slightly narrow the spread on QH circuit resistance since the current spread includes also the first magnets

	Q1-Q3				Q2a-Q2b			
	Nominal	Average	Min	Max	Nominal	Average	Min	Max
Quench heater resistance 1.9 K, Ohm	2.2	2.2	1.7	2.7	3.9	3.7	3.2	4.2
QH circuit warm resistance (cabling and series resistance), Ohm	2.2	2.2	1.64	2.76	0.7	0.9	0.34	1.46
Total resistance, Ohm	4.4	4.4	4.34	4.46	4.6	4.6	4.54	4.66
Charging voltage, V	900	900	880	950	900	900	880	950
Capacitance, mF	7.05	6.87	6.70	7.05	7.05	6.87	6.70	7.05
Peak current, A	205	205	197	219	196	196	189	209
RC, ms	31	30	29	31	32	32	30	33
Peak power density, W/cm2	230	230	165	323	212	201	162	261
Energy density, J/cm2	3.57	3.48	2.47	4.95	3.44	3.18	2.53	4.18
QH Strips Parameters (per Circuit)								
SS resistivity at NOC (1.9 K)	0.000000545				0.000000545			
QH Length, m	2				3.52			
QH Width, m	2.00E-02				2.00E-02			
QH Thickness, m	2.50E-05				2.50E-05			
QH Reference Resistance, Ohm	2.18E+00				3.84E+00			
QH Area, cm2	4.00E+02				7.04E+02			
Min distance DQHDS to magnet, m	40				40			
Max distance DQHDS to magnet, m	150				110			
Min cabling resistance, Ohm	0.12				0.12			
Max cabling resistance, Ohm	0.45				0.33			
Min resistance value in the DQLIM, Ohm	0.595				0.005			
Max resistance value in the DQLIM, Ohm	1.320				0.670			

Variations linked to WP7	**Nominal**	**Average**	**Min**	**Max**	**Comments**
Circuit resistance variation, Ohm	0	0	0.06	0.06	Variation of +/- 60 mOhm (+/- 5 %), requires fine tuning of DQLIM resistance based on QH circuit resistance value (incl. cabling)
DQHDS charging voltage variation, V	900	900	880	950	Variation based on observations from the LHC RQX U_HDS. Design Value of the DQHDS = 940 V, reduction due to losses in feeding cables
Capacitance variation, mF	7.05	6.87375	6.6975	7.05	Variation of -5, 0 % of nominal (based on measurements from existing batches, could evolve - Specs -20, +20 %)

Wire section for DQHDS to magnet, mm2	6

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Conclusions

- We analyzed the spread on the quench heater circuit resistance based on the MQXFA/MQXFB magnets built so far.

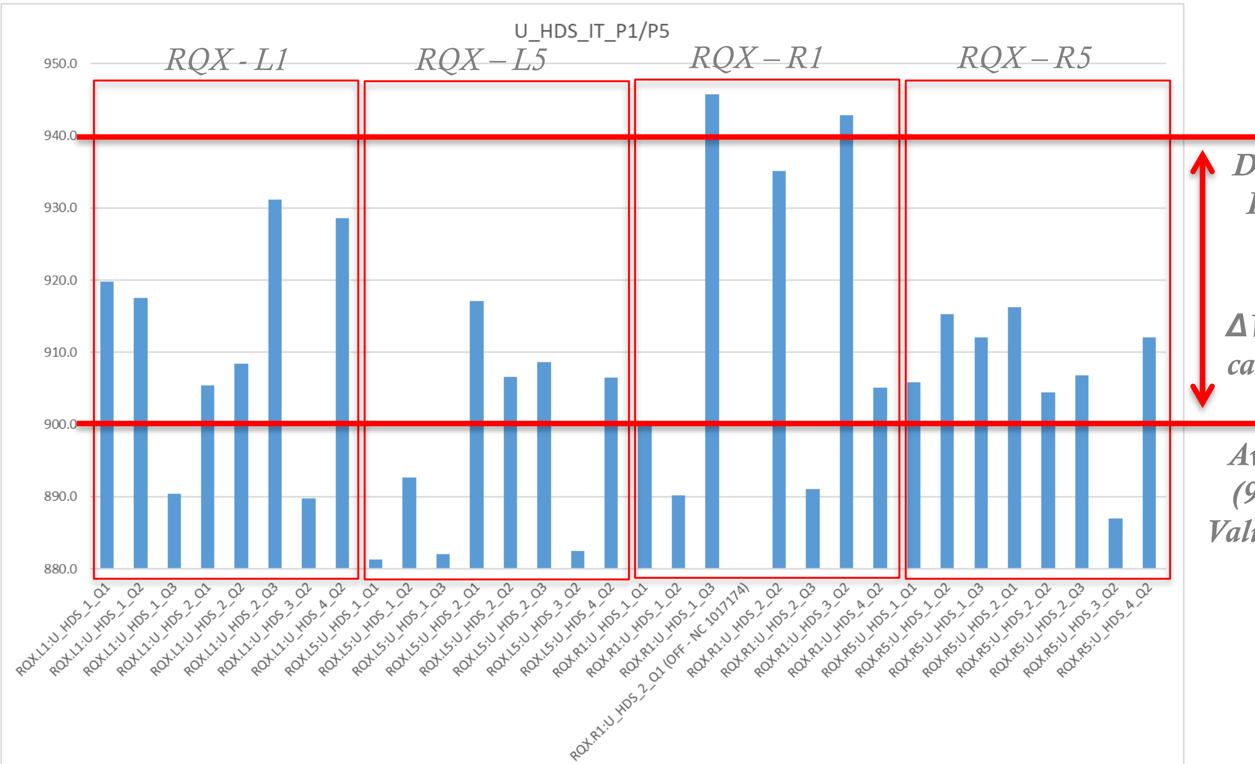
- The average measured value close to expectations and the measured spread is consistent in MQXFB and MQXFA magnets.

- We observe slightly larger variation on the first magnets (iterations on the length of the QH wires, less mature quench heater fabrication process)
  - We might be able in the future to slightly narrow the quench heater resistance range, but we need more data before proposing a modification on the quench heater circuit parameters.

Additional slides

DQHDS Charging Voltage

Comparative study started in collaboration with WP17/EN-EL (to be finalized in 2022) for HL-LHC vs. LHC, but no major change is expected.



Design Value of the LHC DQHDS (at 230 V)

ΔV related to cabling losses

Average = 902 V (900 V Nominal Value for HL-LHC)

Extract of the LHC's RQX Values on 2021-10-21
Confirmed by different weekly samples (Variation of few Volts)

Capacitance of the DQHDS - Update

- Nominal value of the Capacitance is 7.05 mF with a range in the Technical Specs of ±20%
- Capacitance measurement show typically +0, -3 % (vs. +0, -7 % previously)
- An additional +0, -2 % is typically attributed to the ageing of the capacitor bank
- Sorting of capacitance within +0, -5 % has been discussed for the MQXF magnets

References

- Quench heater parameters MQXF (22/01/2022) https://indico.cern.ch/event/1119409/
- NCR MQXFBP3 QH resistance EDMS 2782298
- Quench heater parameters MQXF (09/07/2021) https://indico.cern.ch/event/950696/
- NCR MQXFBP2 QH resistance EDMS 2643444