Overview of the Quench Heater Performance for MQXF, the Nb_3Sn low-β Quadrupole for the High Luminosity LHC

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Outline

- Introduction
- Quench Heater Performance
- Quench Heater Failures
- Conclusions

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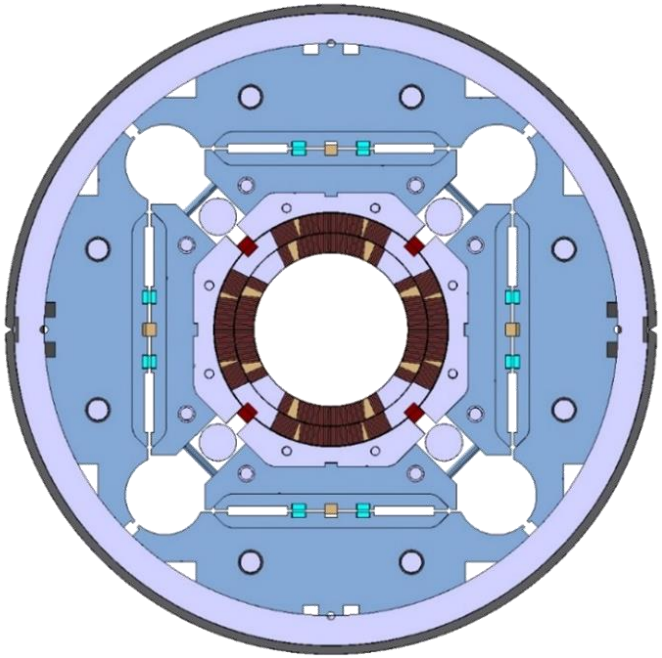
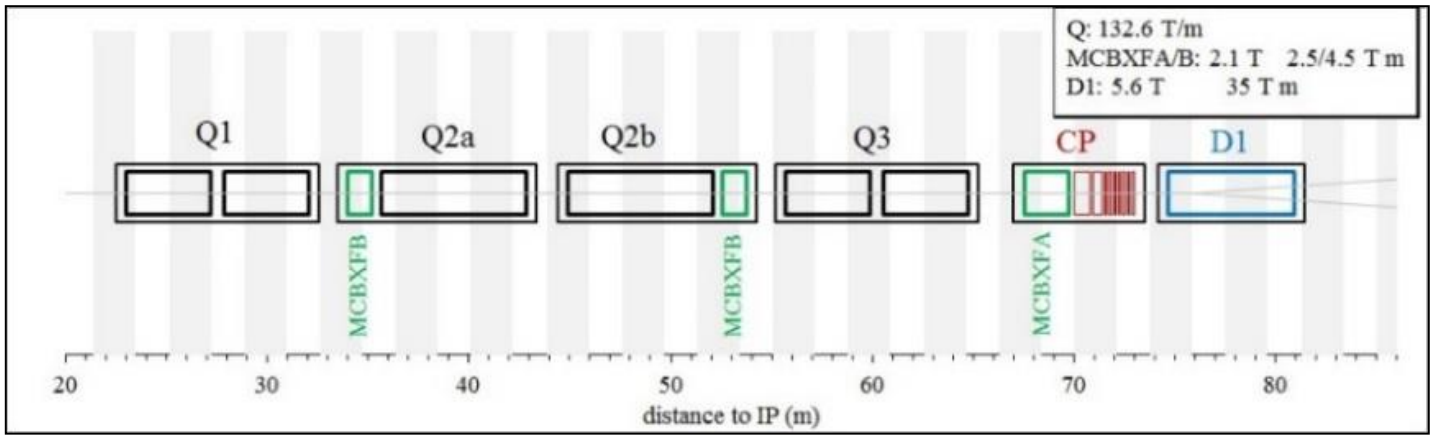
- **Introduction**
- Quench Heater Performance
- Quench Heater Failures
- Conclusions

MQXF

- LHC IR upgraded as a part of HiLumi project
  - Quadrupoles: NbTi → Nb_3Sn
- Target: 132.6 T/m
  - 150 mm coil aperture, 11.4 T B_{peak}
- Q1/Q3 (by US-AUP Project)
  - 2 magnets **MQXFA** with 4.2 m
- Q2a/Q2b (by CERN)
  - 1 magnet **MQXFB** with 7.15 m
- Different lengths, same design

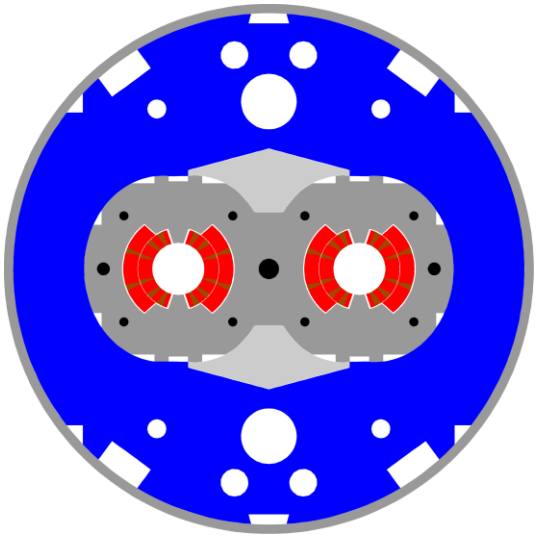




Overview of Magnet Parameters

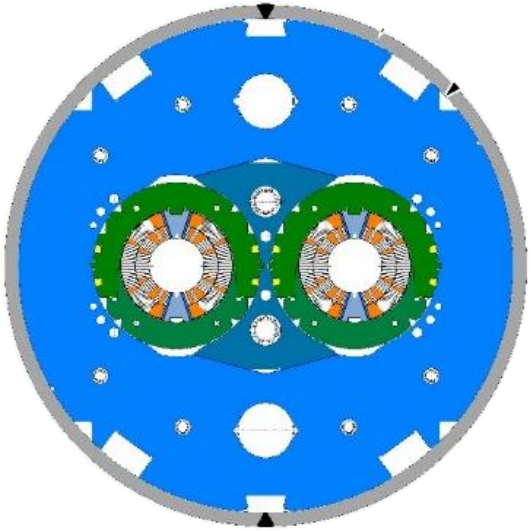
Due to the high stored energy density (130 MJ/m^3) and the low copper stabilizer fraction (55 %), quench protection is particularly challenging.

LHC-MB



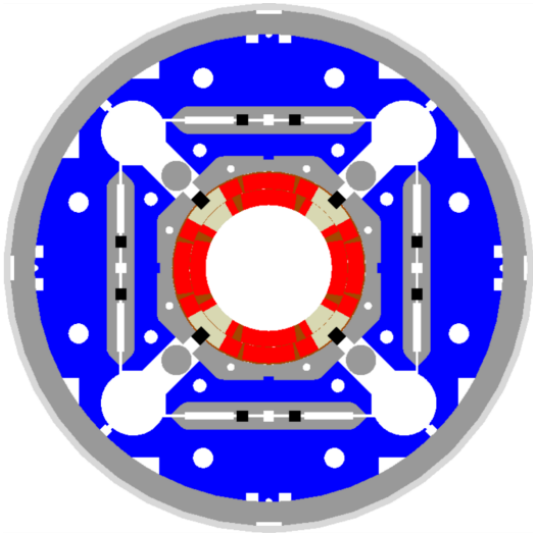
- $B_p(I_{nom})$= 8.6 T
- $J_{overall}(I_{nom})$= 356/442 A/mm^2
- $J_{cu}(I_{nom})$= 763/932 A/mm^2
- e_m (I_{nom})= 71 MJ/m^3

HL-LHC 11 T



- $B_p(I_{nom})$= 11.8 T
- $J_{overall}(I_{nom})$= 523 A/mm^2
- $J_{cu}(I_{nom})$= 1439 A/mm^2
- $e_m(I_{nom})$= 130 MJ/m^3

HL-LHC MQXF

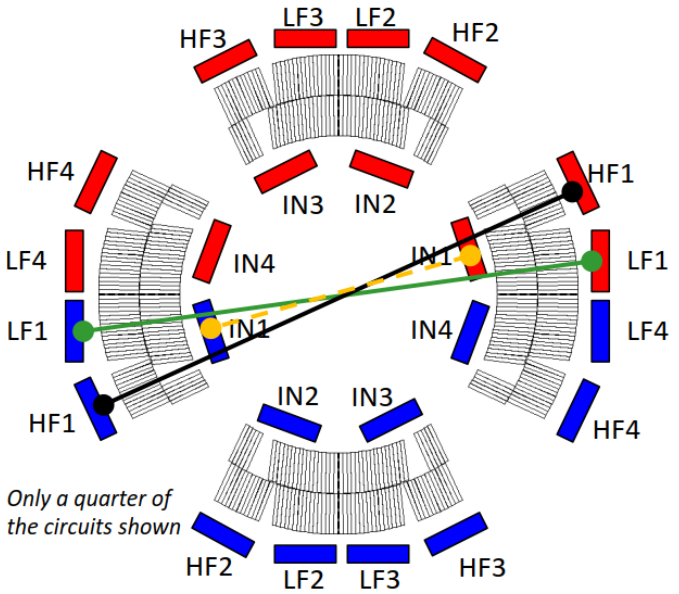


- $B_p(I_{nom})$= 11.4 T
- $J_{overall}(I_{nom})$= 469 A/mm^2
- $J_{cu}(I_{nom})$= 1330 A/mm^2
- $e_m(I_{nom})$= 129 MJ/m^3

MQXF – Key protection features

Quench heaters

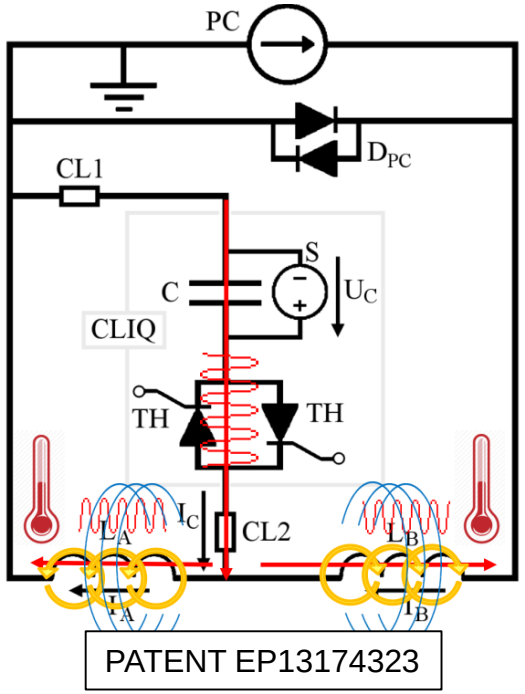
Temperature rise in the conductor through due to the heating of metal strips attached to the coil.



CLIQ

(Coupling-Loss Induced Quench)

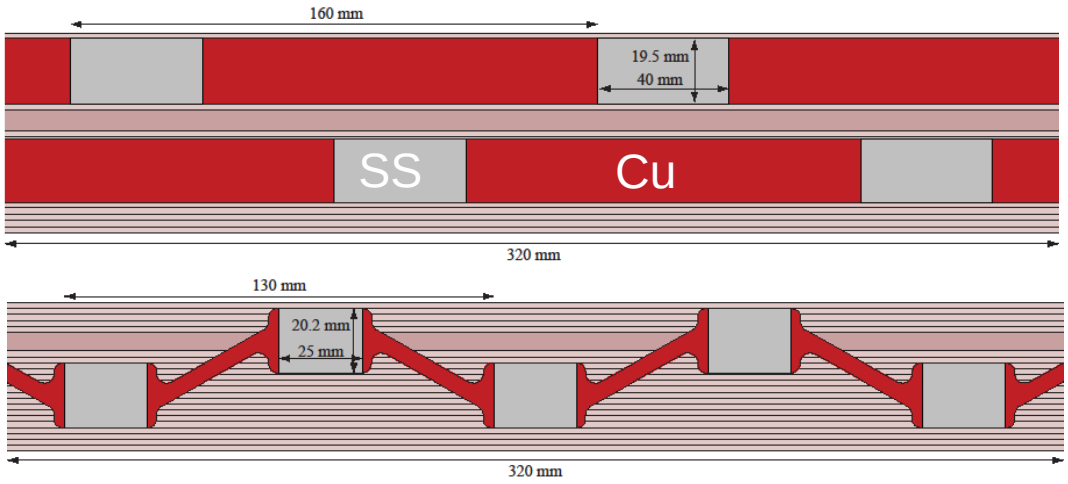
Temperature rise in the conductor due to the coupling current losses arising from a change on the magnetic field.

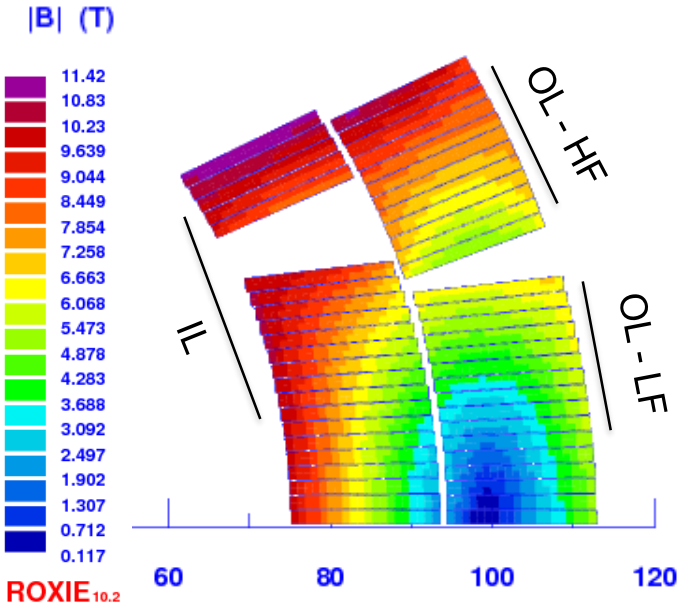


PATENT EP13174323

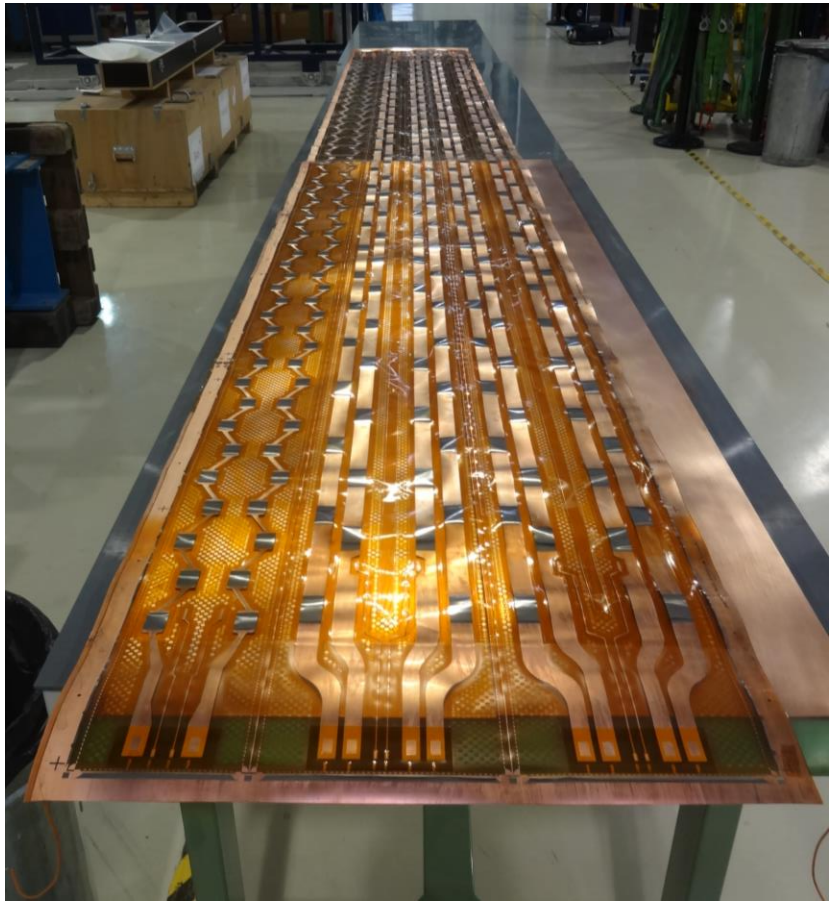
Quench Heater Design Criteria

- In order to minimize the time needed to start a quench (quench heater delay):
  - Heater power and energy sufficiently high → 150 – 200 W/cm^2
  - Insulation heater to coil shall be minimized, without compromising the electrical integrity → 0.050 mm of polyimide
- Peak voltage heater to coil ± 450 V → Copper platting to reduce overall strip resistance.
- Quench shall propagate in between heater stations within ~ 5 ms → Distance in between stations ~ 100 mm
- Shall cover a large portion of the coil (~ 80 %)

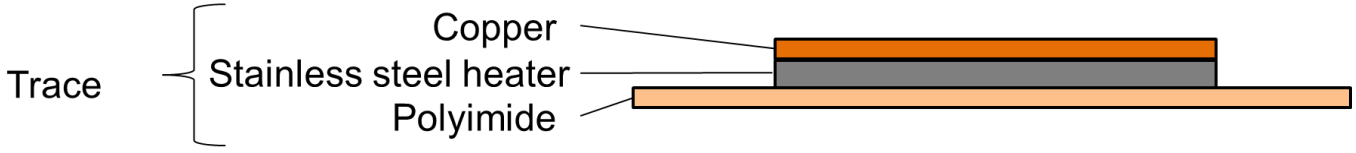




Quench Heater (Trace) Fabrication



- PCB Technology
  - Copper electroplated to the stainless steel-polyimide base material.
  - Etching of the copper, nickel and stainless steel to the required heater pattern.
  - RRR_{Cu} = 25-40
- Polyimide is perforated:
  - Prevent detachments on the inner surfaces, experienced in previous LARP magnets.
  - Improve adhesion during coil impregnation.
  - Better cooling during magnet operation.
- DC voltage test (3 kV under slight pressure) at the end of the trace fabrication process.

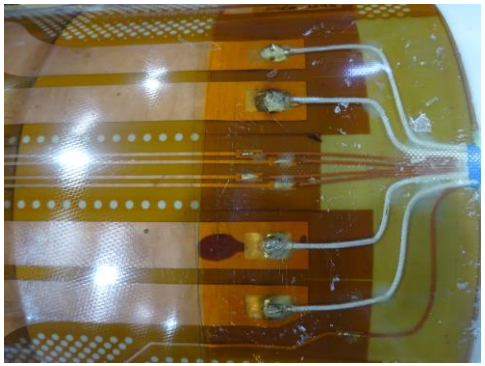


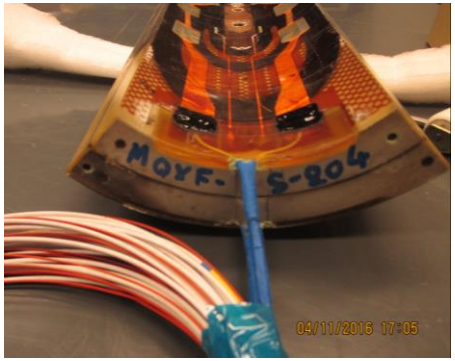
Coil Fabrication

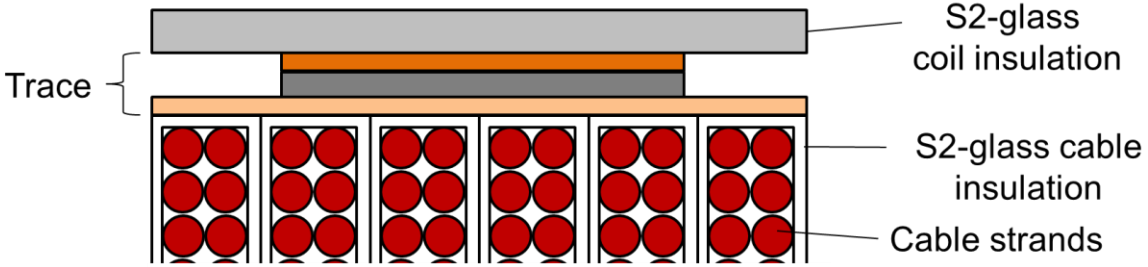
Coil after reaction

Coil after impregnation

- Trace installed in the coil before impregnation, covered by a layer of S2-glass insulation.
- Heater powering wires soldered to the heater strips “splice block soldering pockets”

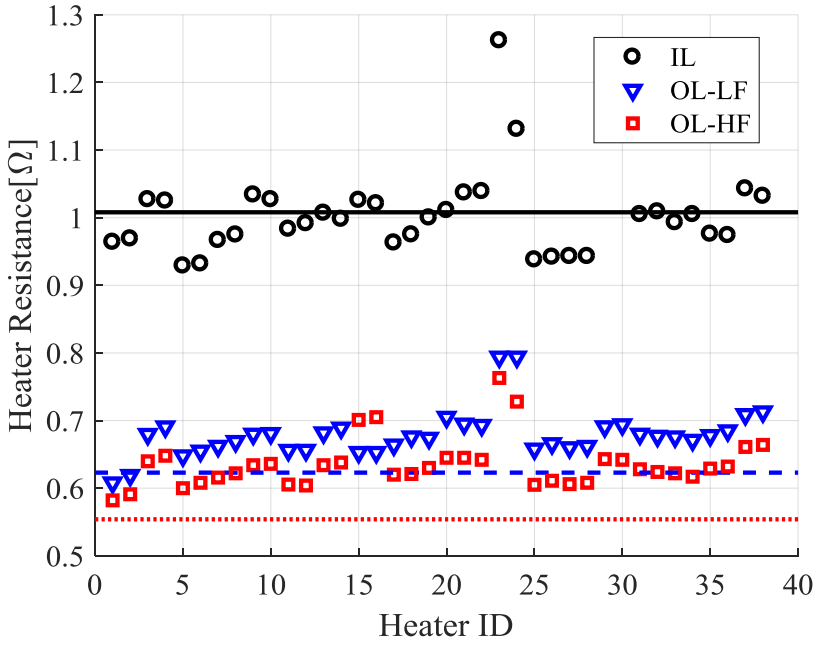






Quench Heater Electrical Verifications

- Resistance measurements.
- Electrical insulation, 2.5 kV DC voltage test (3 kV from summer 2017)
  - All coils passed (22 produced by CERN, 9 produced by LARP)
  - Two practice coils were pushed to the limit, showing good heater to coil electrical insulation up to 5 kV.
- Heater discharge tests
  - 80 A current discharge (23 J)
  - All coils passed.



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- **Quench Heater Performance**
- Quench Heater Failures
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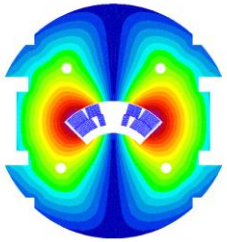
Overview on magnets tested

Single Coil Assemblies

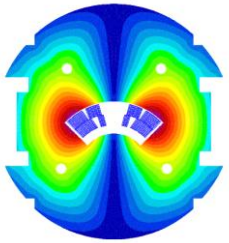
MQXFSM1 (1.2 m)



Tested @ FNAL, 2015

- ✓ Scalability of coil technology
- ✓ Scalability of quench heater performance

MQXFPM1 (4 m)

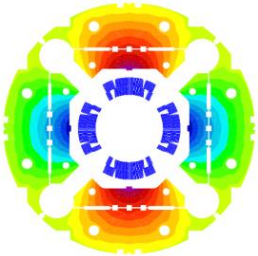


Tested @ BNL, 2016

Short Models (1.2 m length)

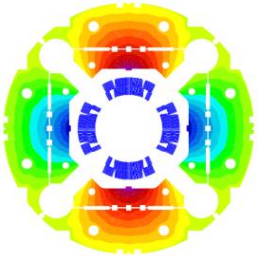
Goal of quench protection tests: Verify that the baseline quench protection parameters are suitable for quench protection performance

MQXFS1a/b/c



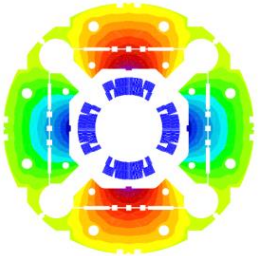
Tested @ FNAL, 2016-2017

MQXFS3a/b



Tested @ CERN, 2016

MQXFS5a

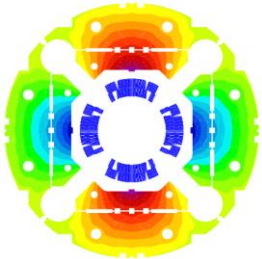


Tested @ CERN, 2017

Prototypes (4/4.2/7.15 m)

Final validation of the quench protection performance.

MQXFA1 (4 m)



Test in progress @ BNL

Short Model Magnets - MQXFS

MQXFS1

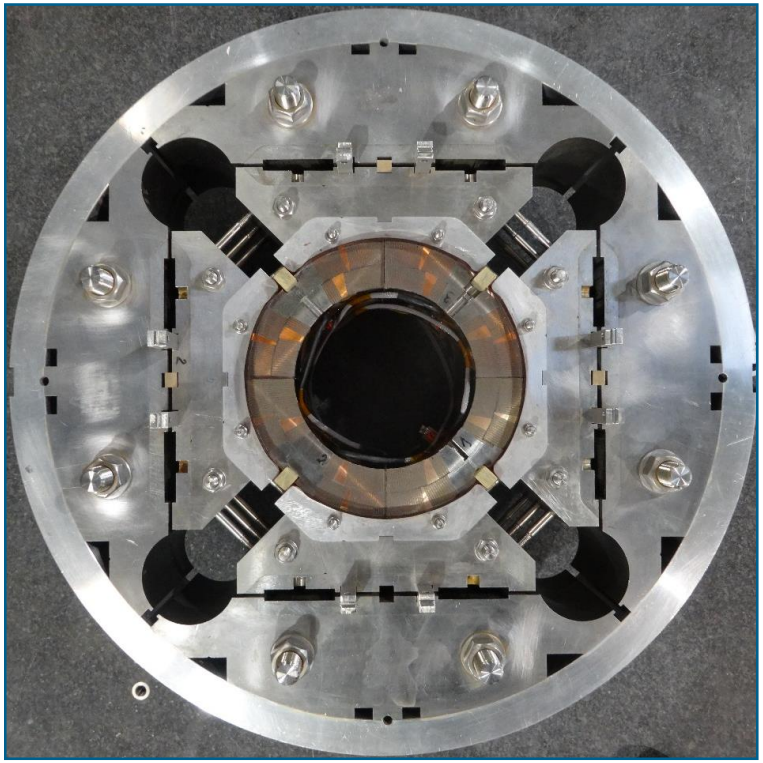
- RRP Nb_3Sn conductor
- 1st generation coils
- 2 coils produced by CERN/
  2 coils produced by LARP

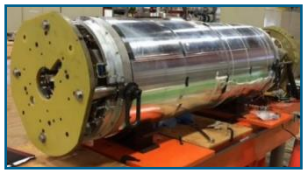
MQXFS3

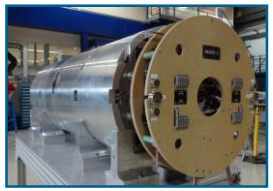
- RRP Nb_3Sn conductor
- 2nd generation coils, baseline quench heater lay-out
- 3 coils produced by CERN/
  1 coil produced by LARP

MQXFS5

- PIT Nb_3Sn conductor
- 2nd generation coils, baseline quench heater lay-out
- 4 coils produced by CERN







MQXFS quench heater protection studies

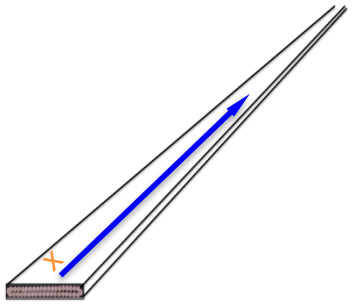
- Goal of short model quench protection tests → Verify that the baseline quench protection parameters are suitable for quench protection performance:
  - Assumptions on quench detection and validation (5 + 10 ms) are adequate.
  - Quench heaters are able to:
    - Quench a large portion of the coil in a sufficiently short time.
    - Quench the magnet at all operating current levels.

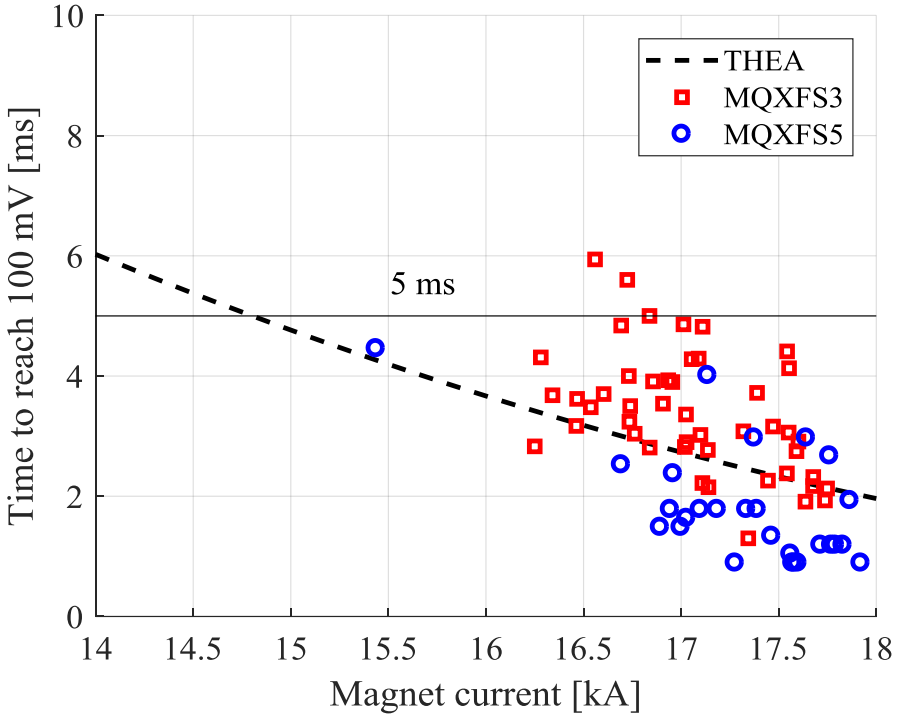
	MQXFS1	MQXFS3	MQXFS5
Quench Heater Delays	✓	✓	Not yet
Quench Integral Studies (QH)	~	✓	Not yet
Minimum Quench Energy	✓	Not yet	Not yet
Quench Integral Studies (QH+CLIQ)	✓	Not yet	Not yet
CLIQ studies	✓	Not yet	Not yet
EE discharge (quench back)	✓	Not yet	Not yet

Initial quench propagation and detection

- A good characterization of the initial quench propagation is important because it determines the time needed to detect a normal zone:
  - Cable level: measurements on FRESCA [1].
  - Magnet level: analysis on natural quenches during training.

THEA 1-D conductor model: conductor is a continuum solved with accurate (high order) and adaptive (front tracking) methods:





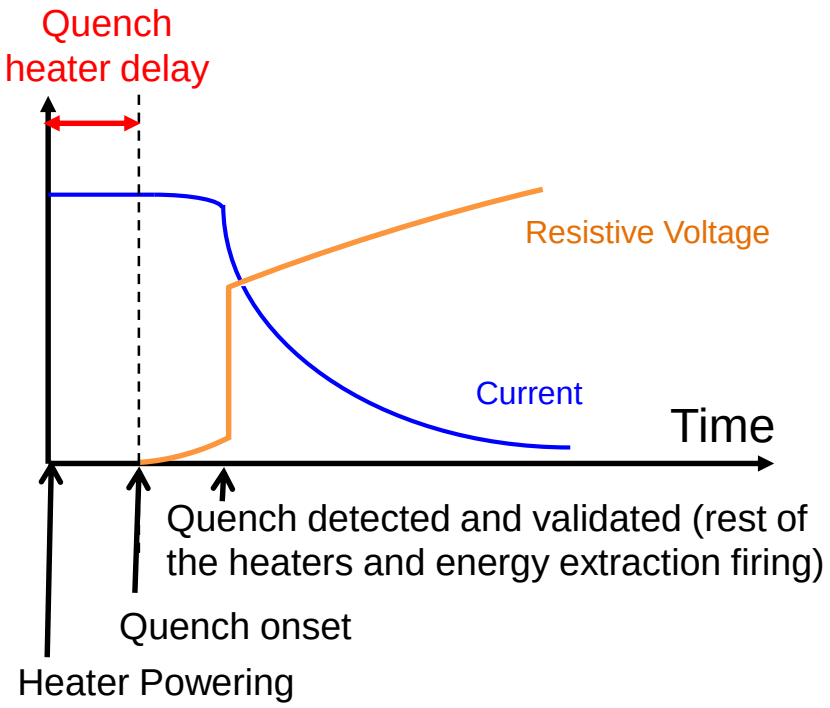
Experimental data from H. Bajas.

[1] J. Fleiter, et al., Quench Propagation in Nb_3Sn Rutherford Cables for the Hi-Lumi Quadrupole Magnets. IEEE Trans. Appl. Superconductivity

Quench heater delay

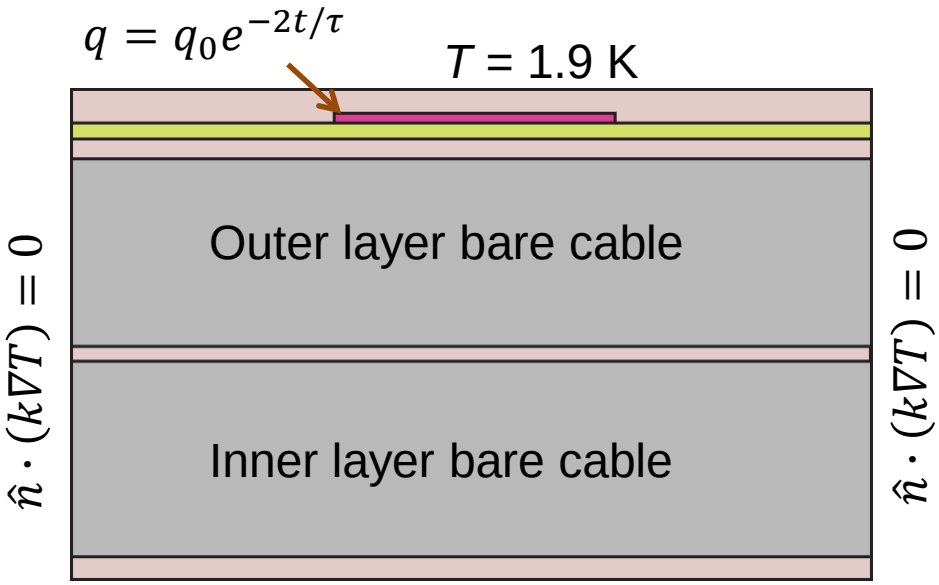
The experiment

- Magnet ramped to a specific current level.
- Quench induced on the magnet, through the firing of a heater strip.
- Upon quench detection, firing of the rest of the quench protection elements (energy extraction and rest of the heater strips)



The model

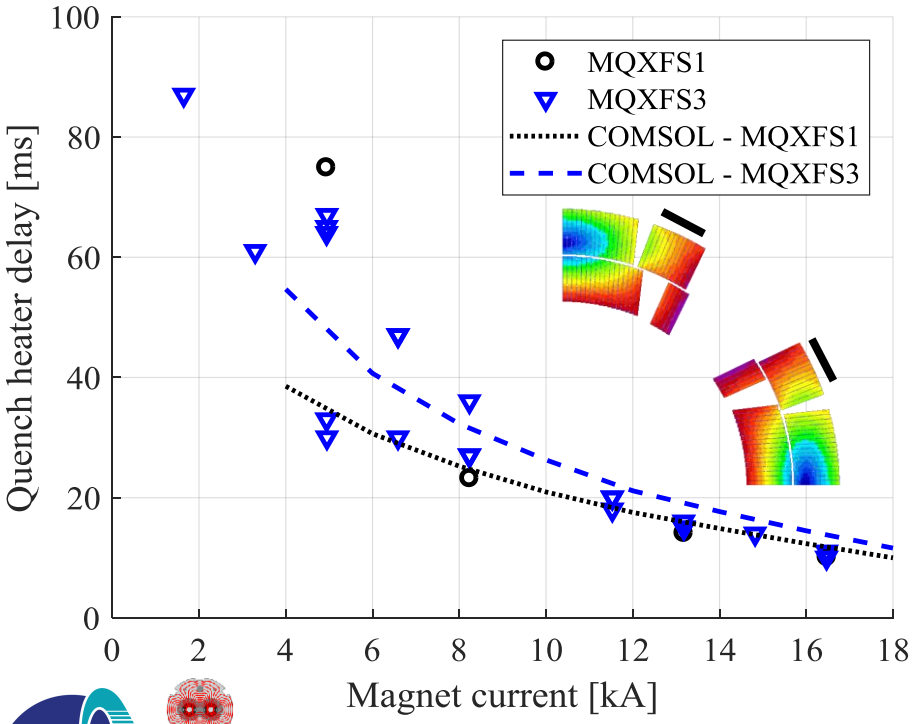
- 2D FEM simulation (COMSOL), solving the heat equation until first point in the cable reaches T_{cs}
- One turn at a time.
- Half of heater period is enough due to symmetry.



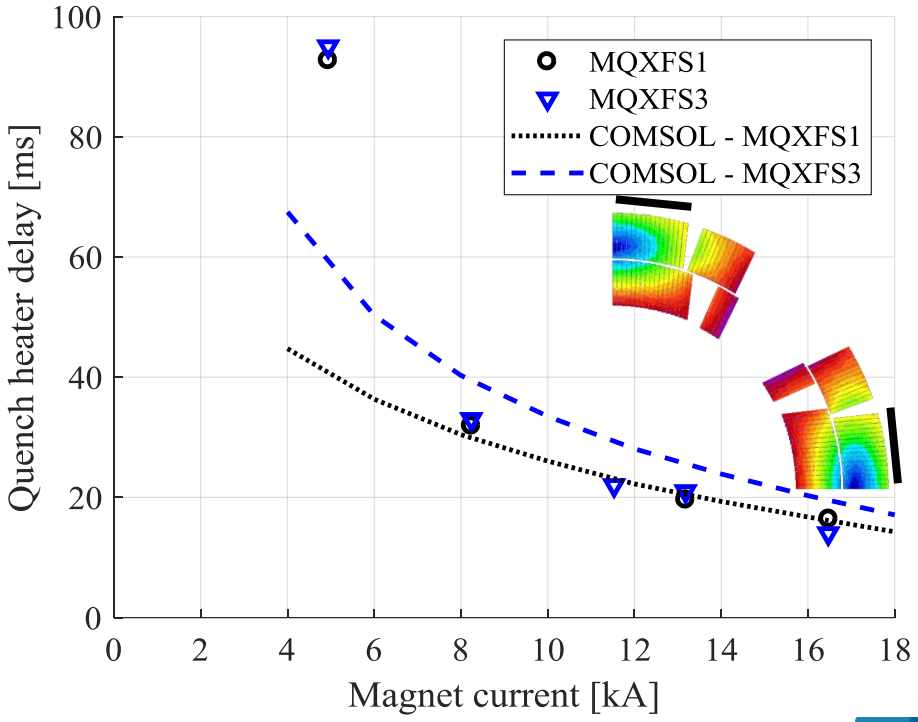
Outer layer quench heater delay

- Measured delays in agreement with expectations.
- Good reproducibility at high current.
- Larger spread at lower current not critical since we have a lot of margin in terms of protection.

Outer Layer – High Field Block



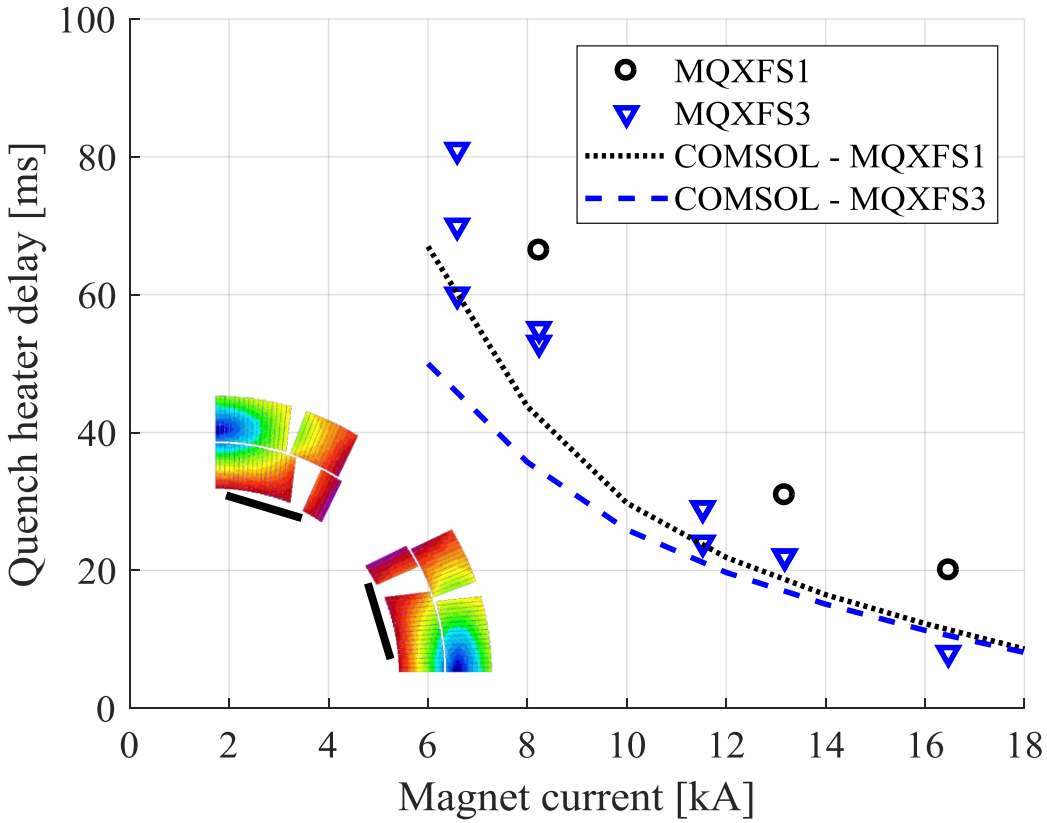
Outer Layer – Low Field Block



Experimental data from G. Chalchidze, S. Stoynev and H. Bajas.

Inner layer quench heater delay

- In MQXFS1, inner layer heater delays are around 10 ms longer than expected.
- Delays in agreement with the model for MQXFS3.

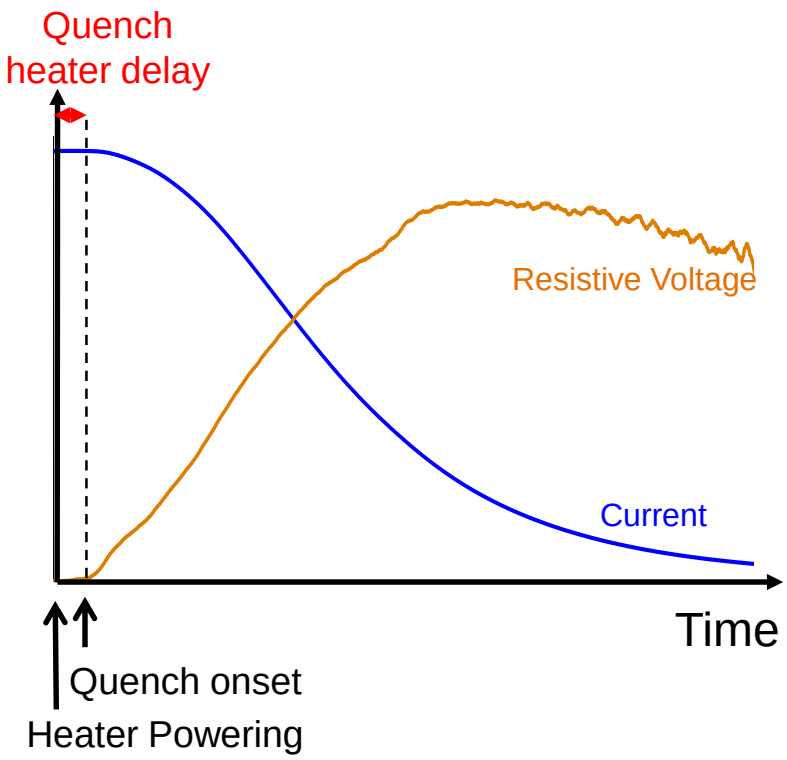


Experimental data from G. Chalchidze, S. Stoynev and H. Bajas.

Quench integral studies

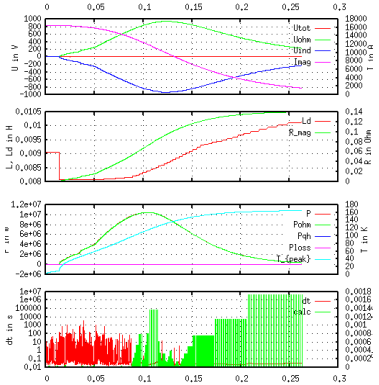
The experiment

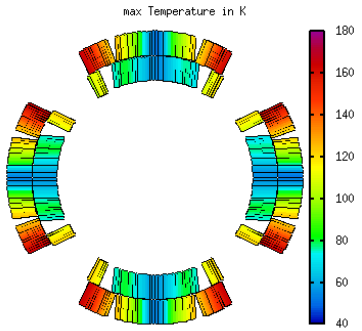
- Magnet ramped to a specific current level.
- Quench induced on the magnet, through the firing of OL or OL+IL heaters.
- Study of the current decay, resistance growth and temperature rise.



The models

- **0-D model (running time: seconds)**
  - Computes current decay and resistance growth assuming that the magnet is fully or partially quench at the minimum quench heater delay.
- **ROXIE 2D (running time: minutes)**
  - Includes heat propagation from heater to coil
  - Includes electromagnetic and thermal transients occuring during quench.





- **Supermagnet 3D (running time: hours)**
  - THEA-POWER coupling, using a second order thermal network among coil turns [1]

[1] S. Izquierdo Bermudez, et al., Quench modeling in high-field Nb_3Sn accelerator magnets, in Proc. 25th ICEC 25 ICMC 2014

Quench integral studies at nominal current

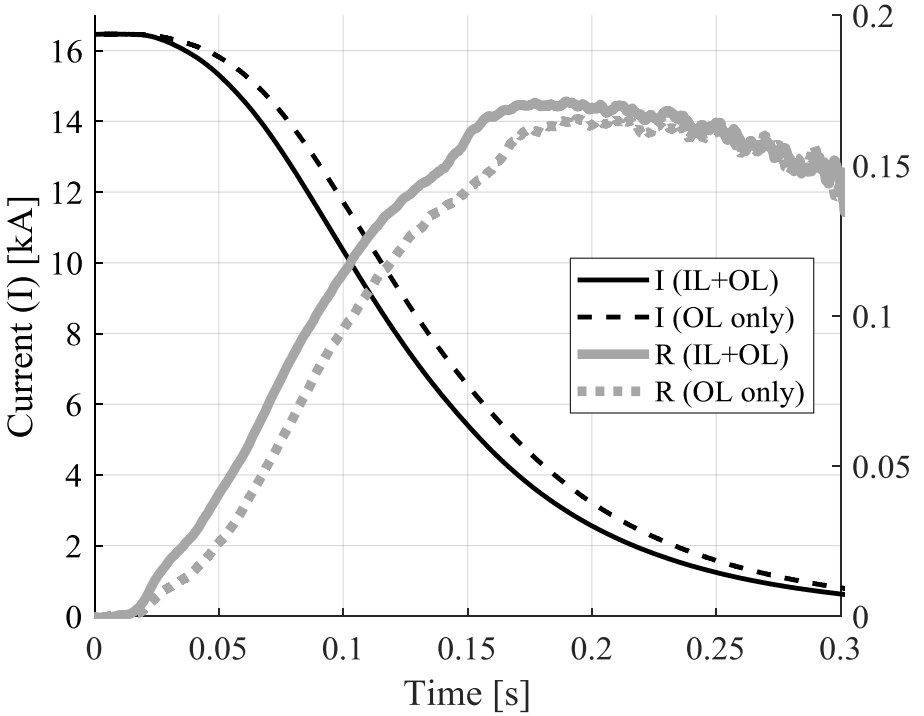
$$\int_0^{\infty} [I(t)]^2 \, dt = A_{total} A_{Cu} \int_{T_0}^{T_\infty} \frac{C_p^{ave}(T)}{\rho_{Cu}(T)} \, dT$$

Circuit response (QI)

Cable material properties

	QI [MA^2]	T_{adi} [K] (B_p = 13 T, RRR = 140)
OL only	28.9	240
OL + IL*	25.7	200

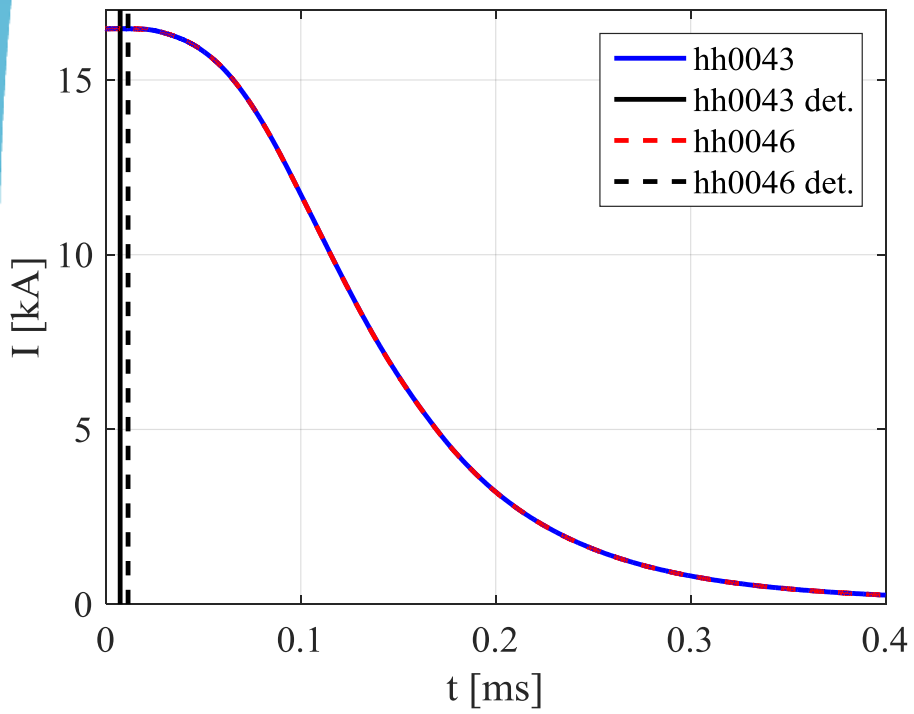
* 3 inner layer strips not operating

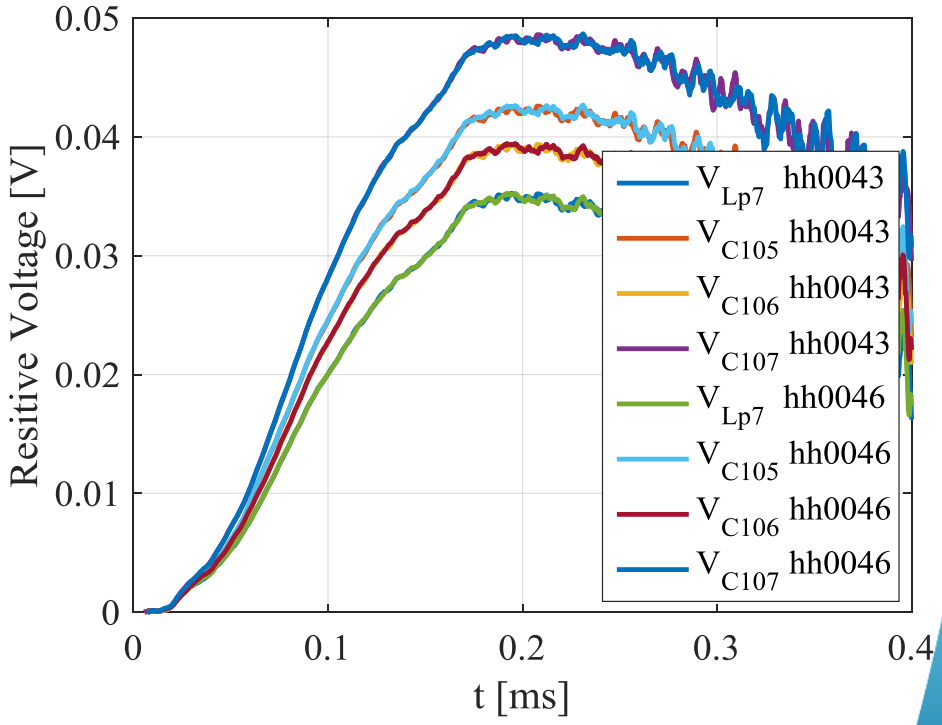


- In case of a natural quench, QI about 5 MA^{2}s larger at nominal current (~ 70 K):
  - Detection time (~ 5 ms)
  - Validation time (10 ms)
  - Heater firing time (~ 1-4 ms)
- The average coil temperature at the end of the current decay is 100-120 K.

Reproducibility at nominal current

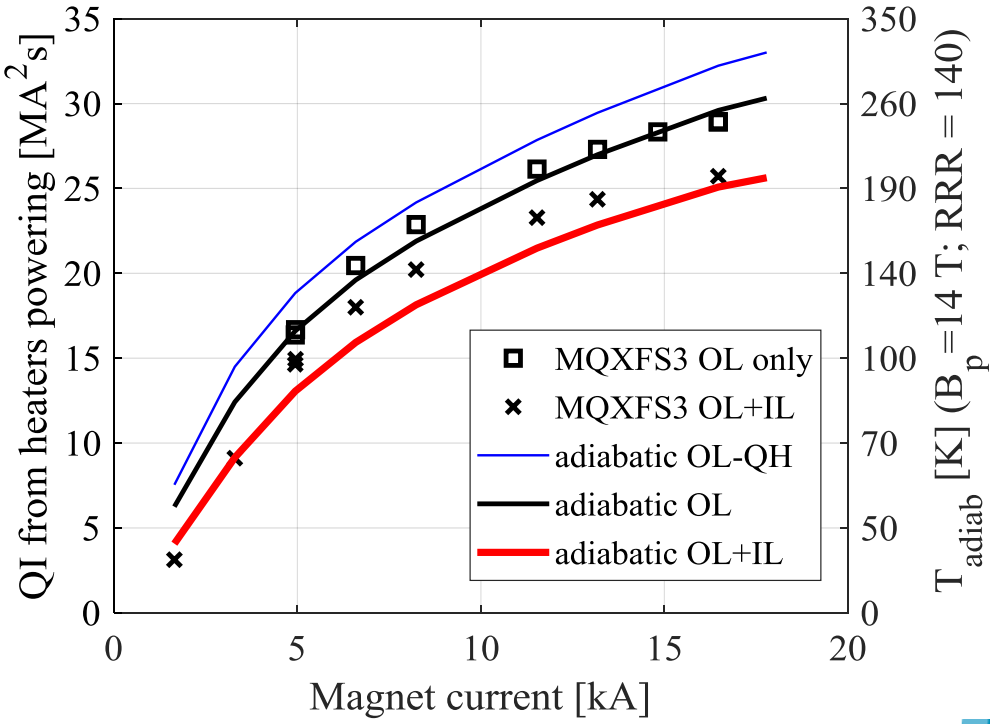
- Current decay and resistance growth is very reproducible for two quenches at nominal using only OL heaters
  - QI from QH fired (excluding heater firing delay):
    - hh0043 = 28.94 MA^2s
    - hh0046 = 28.91 MA^2s





Quench integral – 0D

- Assumption: magnet is fully or partially quench at the minimum quench heater delay.
- Cases:
  - OL-QH: Only turns in contact with the outer layer quench heaters
  - OL: All outer layer turns quench
  - OL+IL: All coil turns quench
- Very simple approach, only a zero-order approximation of the effectiveness of the heaters!!

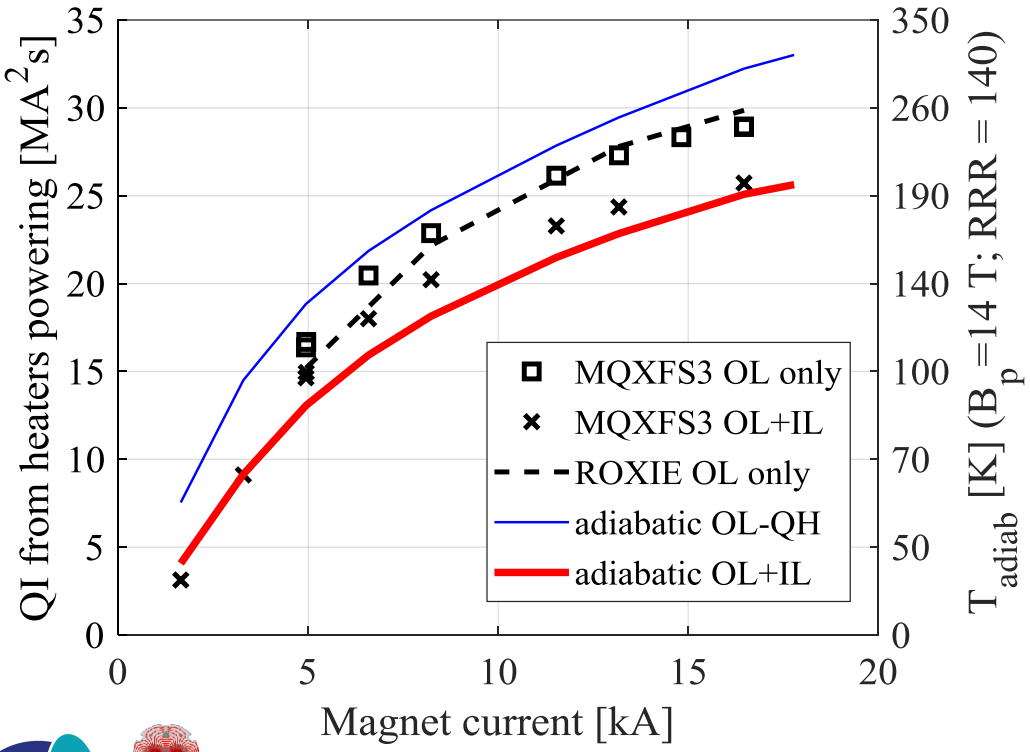


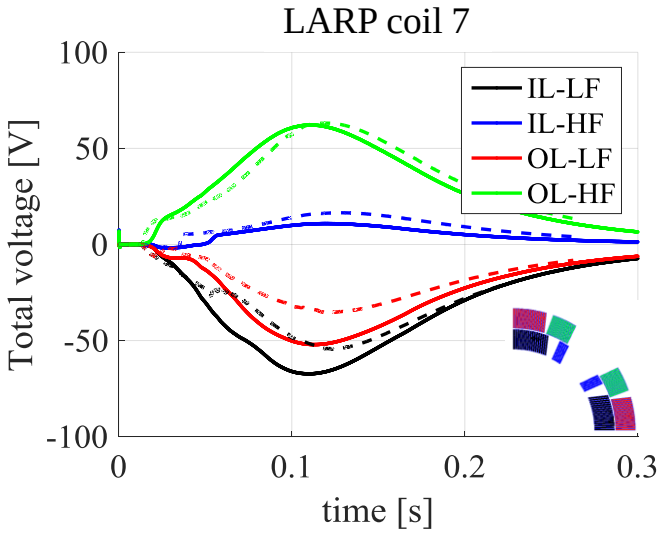
Experimental data from H. Bajas.

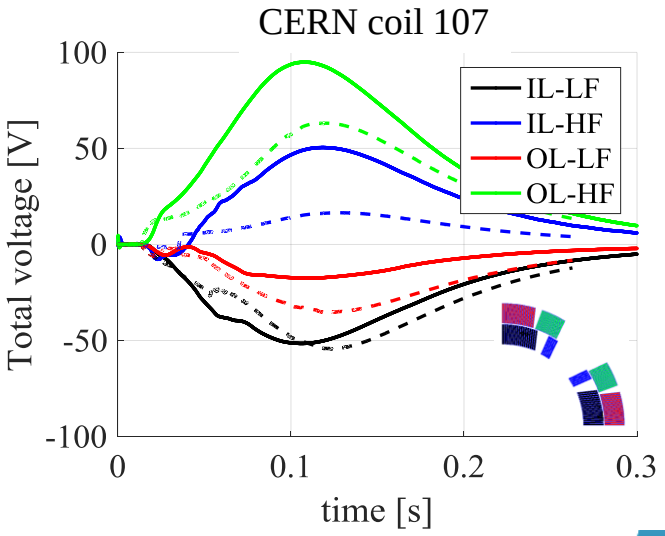
→ Inner layer heaters considerably reduce the quench load, in particular at high current

Quench integral – ROXIE 2D

- Good agreement on the quench integral and magnet resistance at the end of the decay at different current levels.
- When comparing total voltage per coil block, large imbalance among coils in the same magnet not captured by the model.







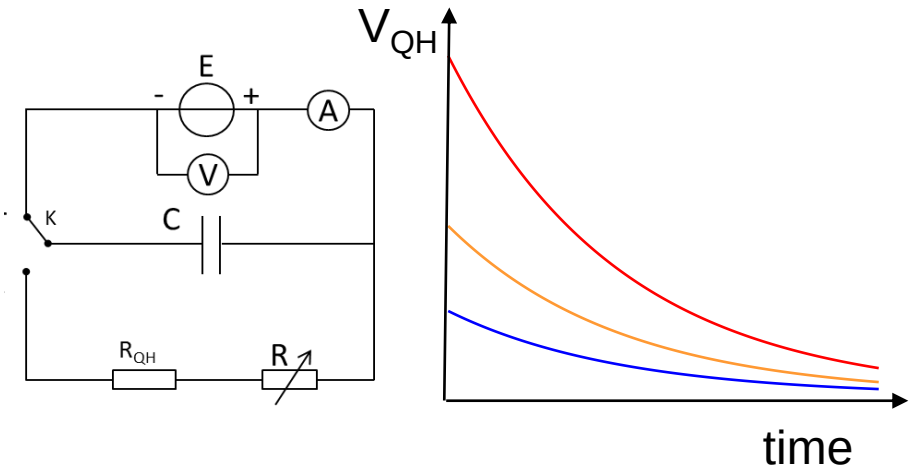
Dotted lines: ROXIE

Continuous lines: Measurements

Minimum Quench Energy

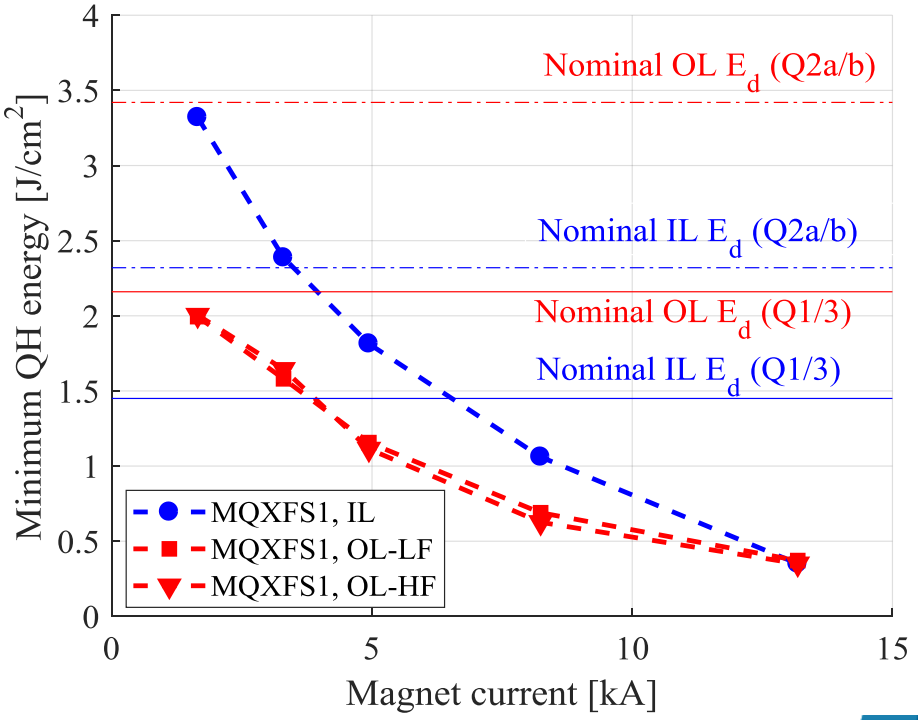
The experiment

- Magnet ramped to a specific current level.
- Heater power supply voltage gradually increase to find the minimum voltage required to start a quench (R, C constants)



The results

- Outer layer quench heaters can quench the magnet at all current levels.
- With the nominal heater powering parameters, inner layer heaters cannot quench the magnet at current levels lower than 4 kA (Q2a/b) and 7 kA (Q1/3)

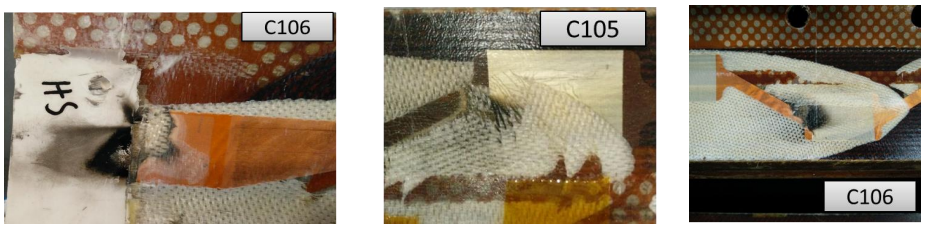


Experimental data from G. Chalchidze and S. Stoynev

Outline

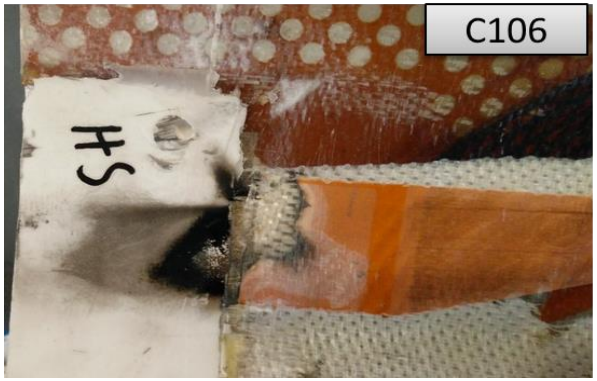
- Introduction
- Quench Heater Performance
- **Quench Heater Failures**
- Conclusions

Overview on quench heater failures

	OUTER LAYER	INNER LAYER
MQXFS1	All OK	3 out of 8 heater strips weak electrical insulation to coil at cold, never powered during test (failure at 750 V instead of 1kV)
MQXFS3	All OK	3 out of 8 heater strips failed during powering test 
MQXFS5	All OK	Inner layer heaters not powered, to decouple the effect of the heater powering and the magnet quench.

Failure modes

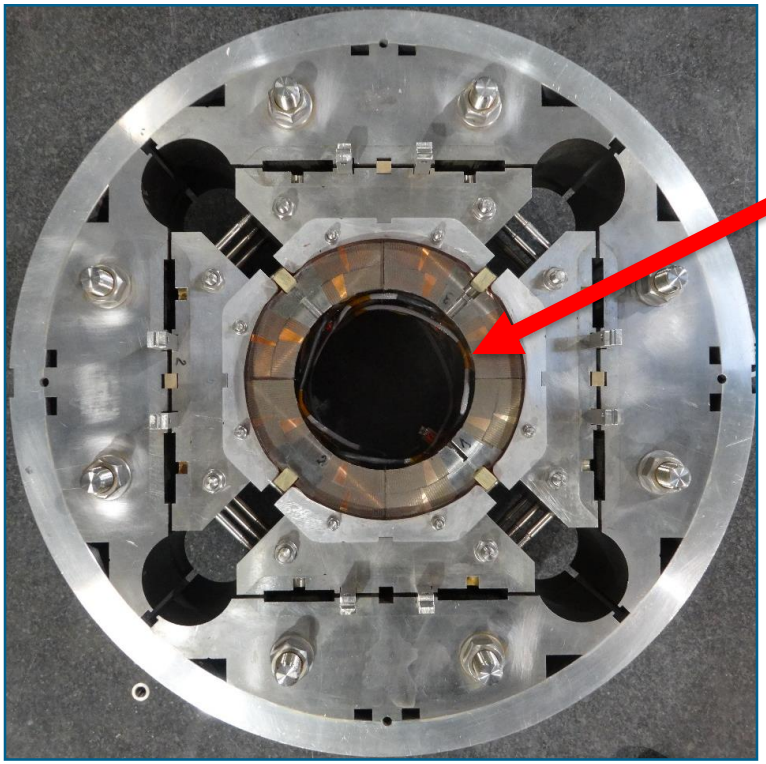
- Failure in the extremities, at the connexion level:
  - Heater strips were shorter than the coils, resulting on a mechanically weak assembly.
  - Heater design was updated, and this weakness is not present in the recent coils.

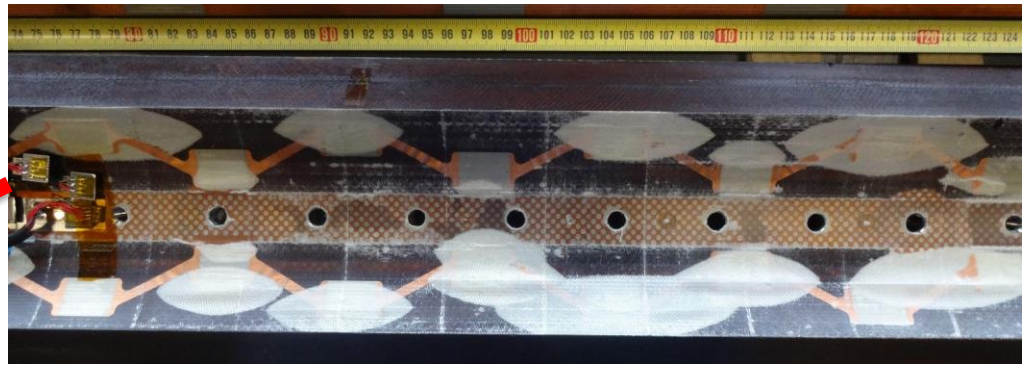


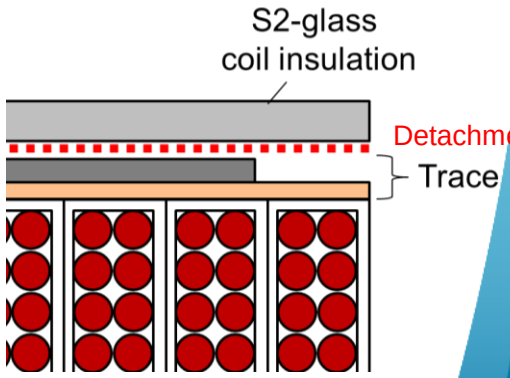
- Failures on the magnet straight part. Possible sources:
  - Heater fabrication defaults (unlikely).
  - Heater damage following a S2-glass to heater detachment.

Detachments - Observations

- After powering test, strong signs of delamination on the coil inner surface, mainly on the stainless steel heater stations.
- Destructive inspection of LARP coil 7 have shown that the source of delamination is the S2-glass to metal interface.







Detachments - Observations

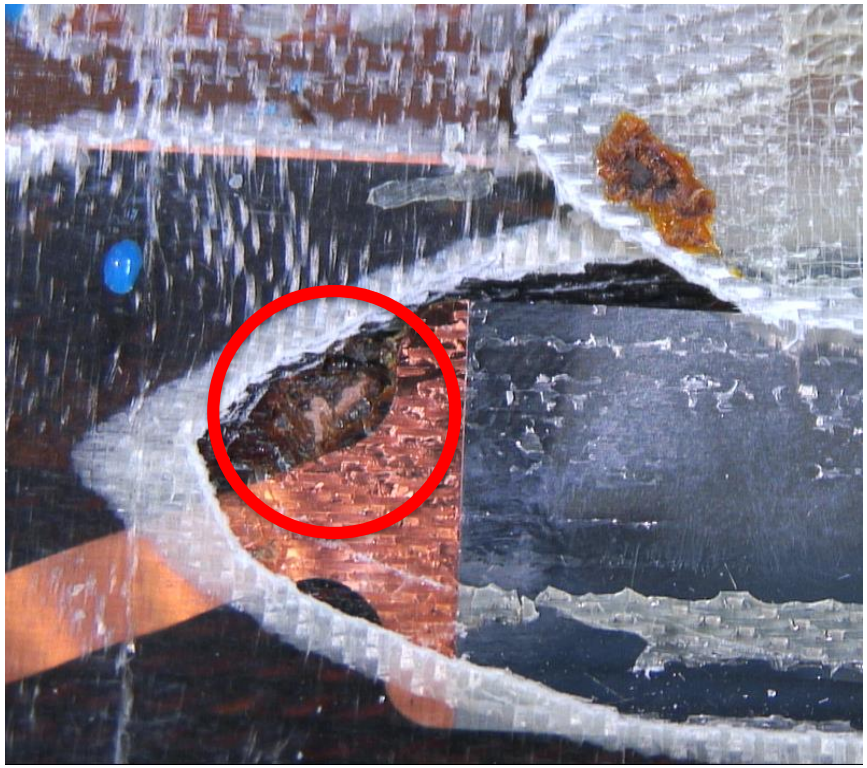
- Detachments are not only present on the heater stations, also in the coil ends.
  - A coil without inner layer trace is under production to study the “bubbles” formation in absence of the trace.

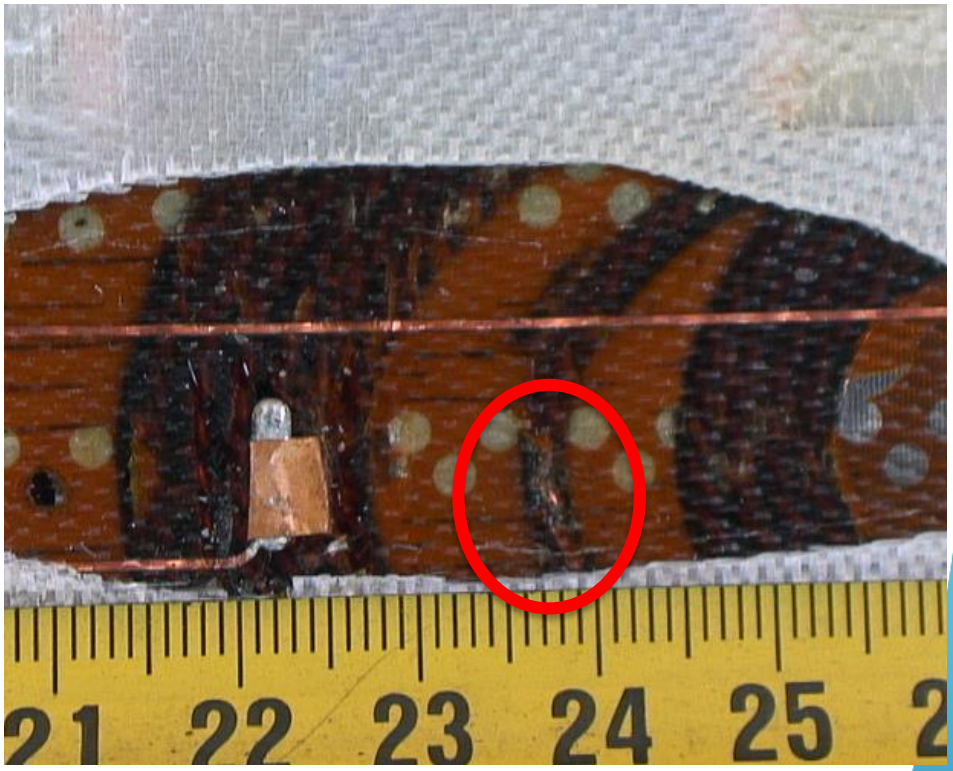
Coil LARP 7 before powering test

Coil LARP 7 after powering test

Delamination - Risks

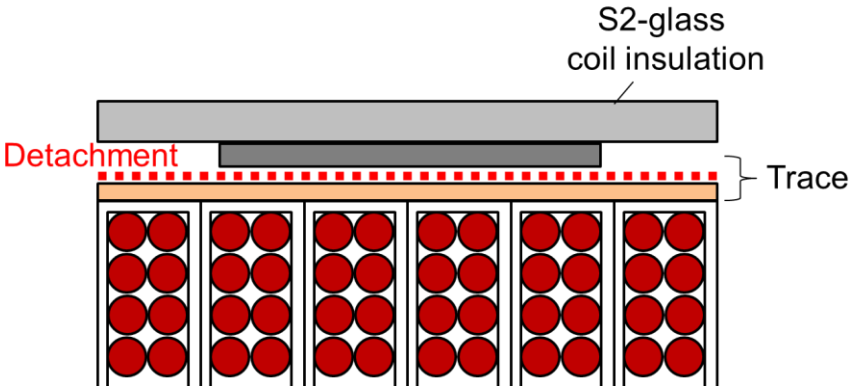
- Highest risk→ degradation of the conductor insulation.

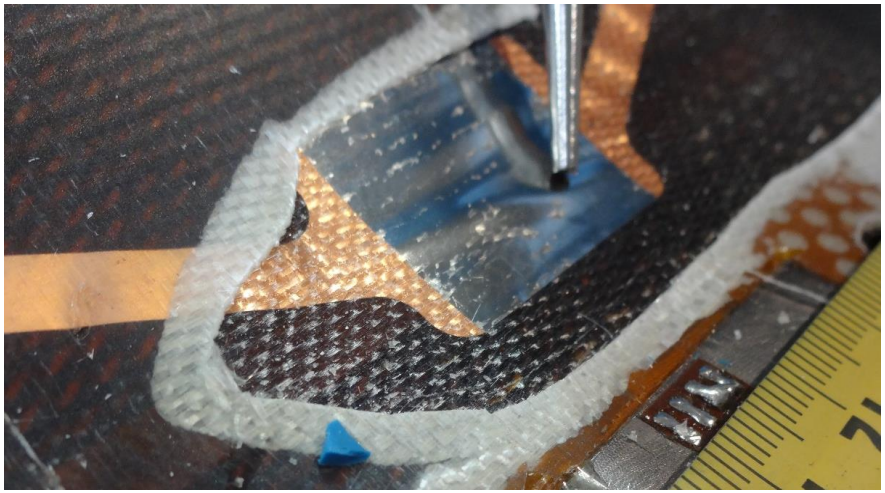




Heater to Polyimide Detachments

- Even if the primary source of delamination is the weak metal to glass adherence, heater to polyimide delamination was also observed in several locations.
  - A trace made with a stronger polyimide-metal base material under production.

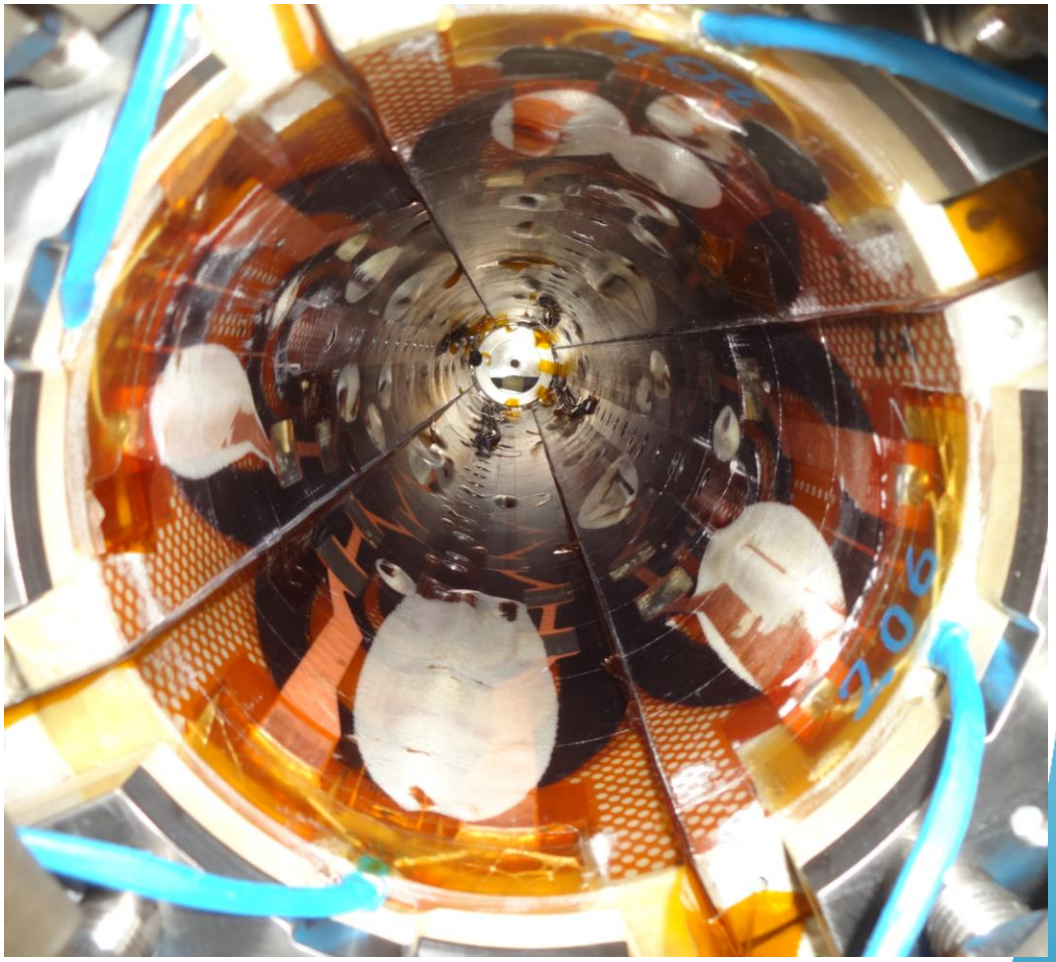




MQXFS5 - Detachments

- Inner layer quench heaters were not powered in MQXFS5, to decouple the effect of the heater powering and the magnet quench.
  - Detachments in the heating stations and coils ends.
  - The main source of the bubbles formation is the increase of the coil temperature during quench and not the heater powering.

View of MQXFS5 aperture after powering test



Electrical Integrity after Powering Test

- In MQXFS1, heaters were tested only up to 1 kV.
  - All passed.
- In MQXFS3, electrical insulation was verified up to 2.5 kV:
  - All outer layers heaters passed.
  - 7/8 of the inner layer heaters failed.
- In MQXFS5, only inner layer heater were tested:
  - All heaters failed the 3 kV insulation test, with a breakdown voltage 2.6-2.9 kV.
  - When re-tested at 1 kV, 3/8 heaters were strongly degraded

    (leakage current > 4mA at 0.2 kV).

Insulation Voltage [KV] QH to coil

		OL-HF		OL-LF		IL	
Magnet	**Coil**	**R**	**L**	**R**	**L**	**R**	**L**
MQXFS1	3	> 1 kV				>1.0[3]	>1.0[3]
	5					>1.0[1]	>1.0
	103					>1.0	>1.0[1]
	104					>1.0	>1.0[1]
MQXFS3	7	**> 2.5 kV**				<2.5	<2.5
	105					0.1[2]	0.1
	106					<2.5[2]	<2.5[2]
	107					0.5	**>2.5**
MQXFS5	203	Insulation test not performed after cold powering test				>1.0[3]	0.2[3]
	204					0.2[3]	>1.0[3]
	205					0.2[3]	>1.0[3]
	206					>1.0[3]	>1.0[3]

1. Did not pass electrical tests at 1.9 K, so never powered at 1.9 K.
2. Failed during powering test.
3. Heaters never powered at cold.

Outline

- Introduction
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Conclusions

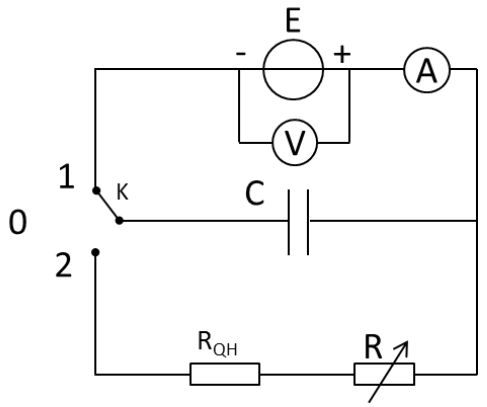
- Outer layer quench heaters are able to quench a large portion of the coil is a sufficiently short time, behaving as expected.
  - Combination of outer layer heaters and CLIQ (also behaving as expected) provides a reliable and fully redundant protection system.
- About 30 % of the inner layer quench heaters failed during magnet powering.
  - In spite of the failures, inner layer quench heater significantly contributed to a reduction of the quench load.
- We have a delamination problem on the inner surface of the coils, which is being addressed. Several coils are under production with different insulation and heater lay-out to find a solution.

THANK YOU

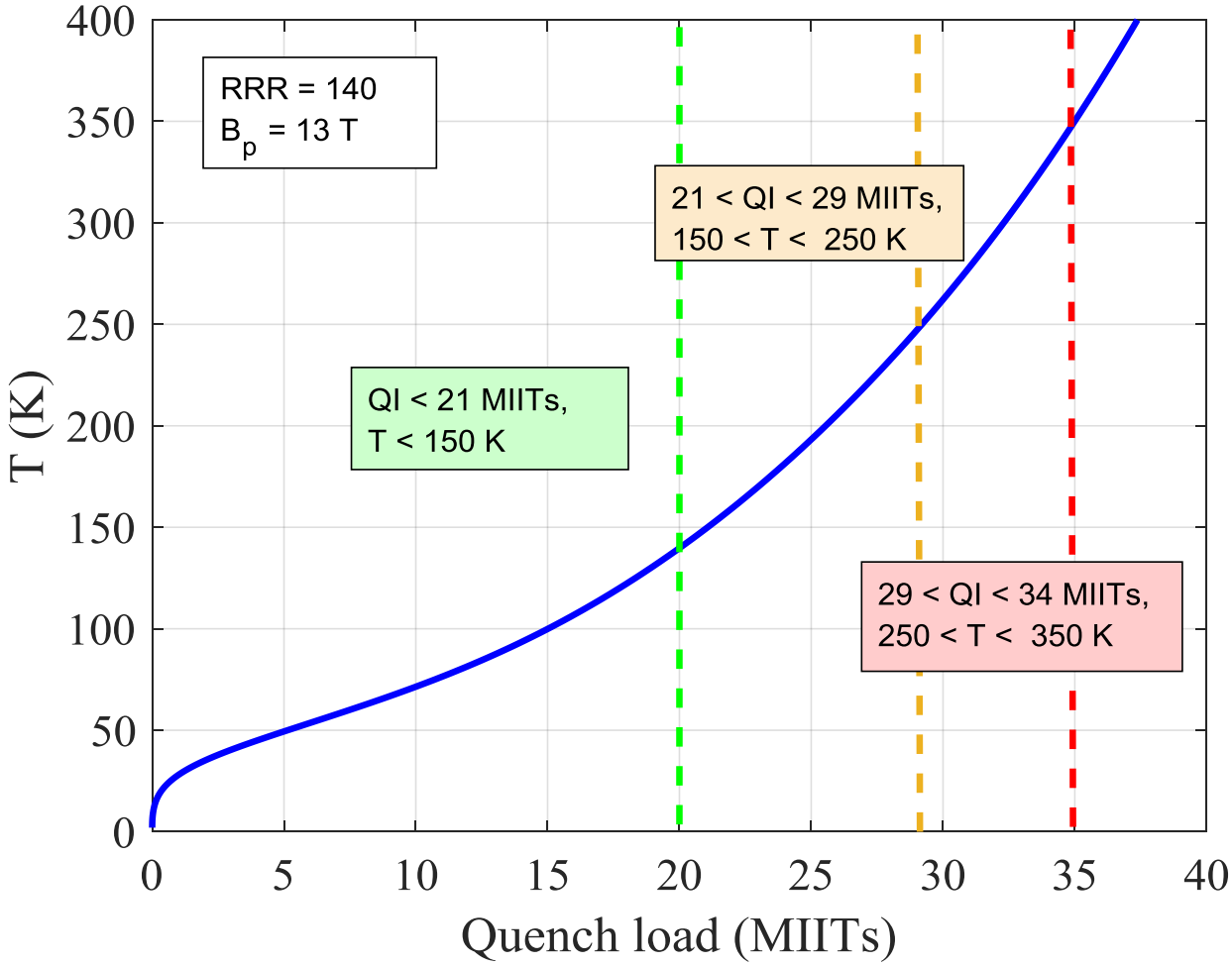
Quench heater powering

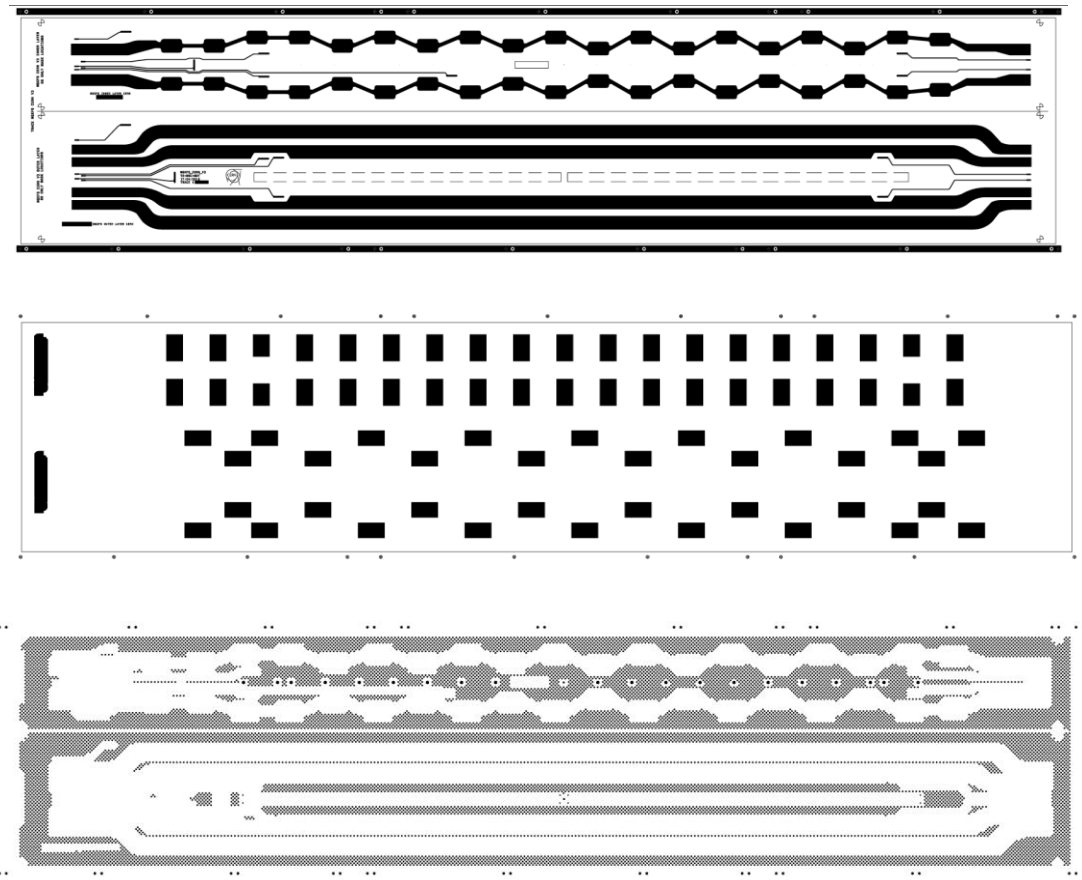
- For HL-LHC, **"Standard"** LHC quench heater power supply:
  - Charging voltage: ± 450 V
  - Maximum current through the heaters: **200 A** (instead of 80 A)
  - Capacitance: 7.05 mF
  - Improvement of the heater firing unit expected to **reduce the heater firing delay from 5 ms to 1 ms.**
- For short models, powering parameters adapted to have powering conditions as close as possible to HL-LHC nominal operation.

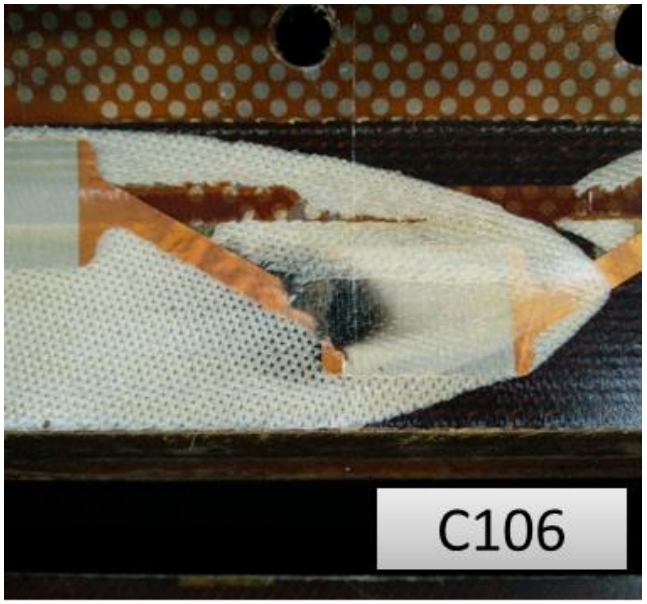
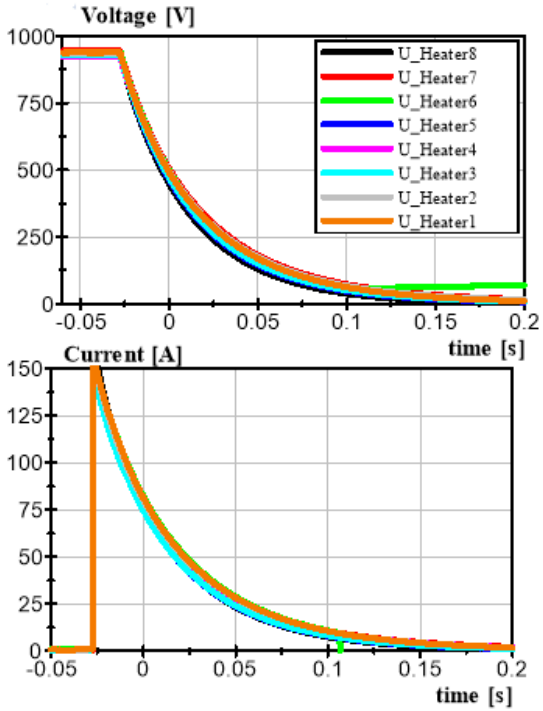
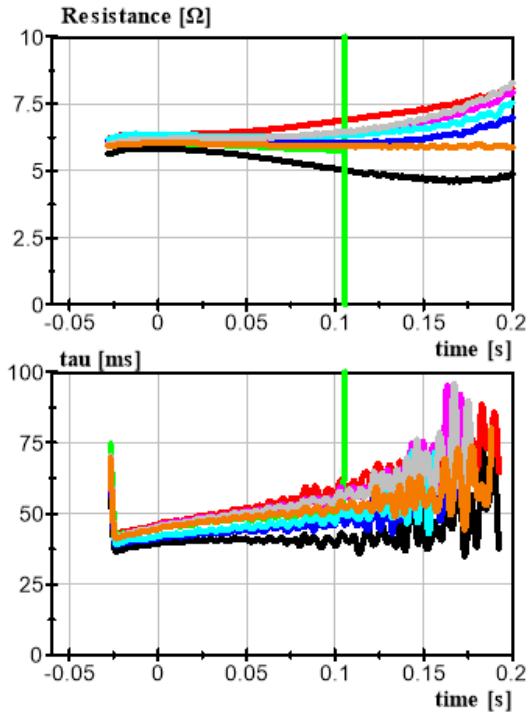
		Q1/3	Q2a/b	MQXFS1	MQXFS3
OL	**P_d, W/cm²**	213	213	209	123
	E_d, J/cm²	2.16	3.42	3.39	2.59
IL	**P_d, W/cm²**	98	98	97	123
	E_d, J/cm²	1.45	2.32	2.31	2.59



Material properties





Inner layer heater failures

- Failure detected during cold powering test in the quench heater monitoring tool.
- There is not signature of failure on the previous quench to the one where the heater fails.