HL-LHC quench heater quality control

11 T dipole prototype quench heater characterisation

C. Scheuerlein, L. Grand-Clement, B. Katzer

Review of 11 T dipole quench protection and electrical tests – 11 January 2019

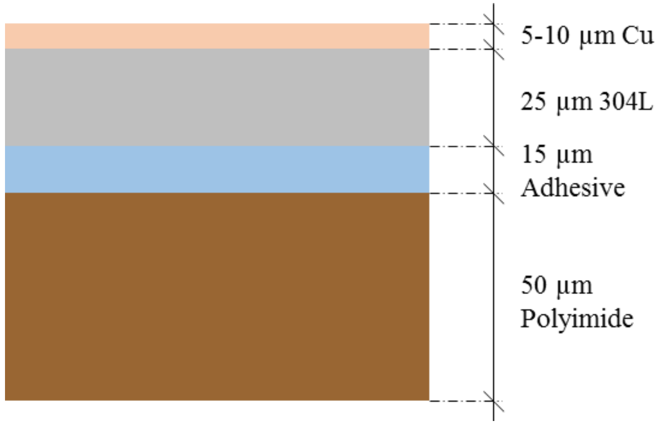
Outline

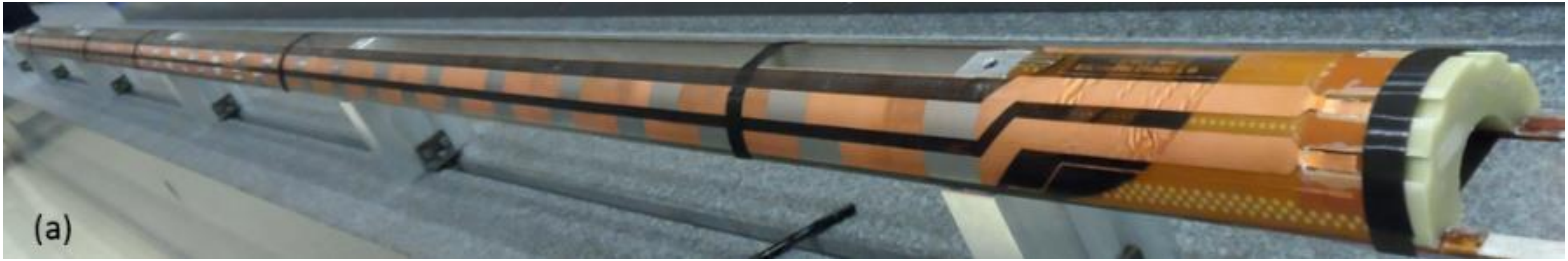
- The HL-LHC quench heaters
- HL-LHC quench heater production status
- HL-LHC quench heater quality control
- Quench heaters installed in the 11 T dipole prototype
  - QC before installation
  - Characterisation of defects provoked during the electrical tests
- 11 T dipole quench heater coverlay option
- Conclusion

The HL-LHC quench heaters

- The HL-LHC quench heaters (QH) are large flexible circuits that are produced in a photolithographic process.
- In order to reduce the overall heater resistance the steel circuits are partially Cu coated.

- The base material of the heaters is a commercially available lamination (GTS laminate L960461), consisting of a **50 µm-thick polyimide film** (Kaneka Apical AV) and a **25-µm thick austenitic stainless steel** EN 1.4307 (304L) hard temper foil.
- The steel foil is glued onto the film with a **15 µm-thick epoxy adhesive** (GTS AS1084). The steel surface of the laminate is electrolytically coated with an approximately **10 µm-thick Cu layer**.





HL-LHC quench heater production status

- The HL-LHC QH series production has started in the beginning of 2018 by the company Trackwise. Production is proceeding as specified (Table 1).
- 11 T dipole QH production is completed.
- 27 out of 105 MQXFA QH were received.
- 36 out of 66 MQXFB QH were received.

Number of 11 T dipole and MQXF quench heaters to be produced per year.

Delivery year	11 T dipole	MQXFA	MQXFB
2018	32	27	22
2019	-	42	29
2020	-	36	15
Total	32	105	66

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HL-LHC quench heater main acceptance tests

<u>Base material</u>

- Before shipping to Trackwise, the Cu coated base material is controlled (visual and geometrical checks, Cu adhesion tests, Cu thickness distribution, Cu RRR measurement of selected samples).

<u>Quench heaters</u>

- Geometrical checks. In particular verification of circuit dimensions, minimum width of polyimide around metallic circuits and Cu pattern.
- Visual QH aspect. In particular verification of the absence of polyimide film defects, delaminations and wrinkles.
- Measure Cu coating thickness distribution (EDMS No. 1759728)
- Measure electrical circuit resistance (EDMS No. 2053975)
- Measure minimum dielectric properties of the polyimide film:
  - 11 T dipole: leakage current measured at 4.2 kV (EDMS No. 1773004)
  - MQXF: leakage current measured at 3.7 kV (EDMS No. 1775188).

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Magnets, Superconductors and Cryostats
TE-MSC

2018
Technical Note 2018-20
EDMS Nr: 2053975

Electrical resistance of the HL-LHC quench heater circuits produced in 2018

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Keywords: Quench heater; HL-LHC; Electrical resistance

1 Introduction

The quench heaters (QH) of the Nb_3Sn superconducting magnets for the High Luminosity upgrade of the LHC (HL-LHC) [1] are large flexible circuits that are produced in a photolithographic process. In order to reduce the overall heater resistance the steel circuits are partially Cu coated [2]. Figure 1 shows an 11 T dipole quench heater, which is impregnated on a reacted coil [3].

Figure 1. 11 T dipole quench heater impregnated on a reacted coil.

The base material of the heaters is a commercially available lamination (GTS laminate L960461), consisting of a 50 µm-thick polyimide film (Kaneka Apical AV) [4] and a 25-µm thick austenitic stainless steel EN 1.4307 (304L) hard temper foil. The steel foil is glued onto the film with a 15 µm-thick epoxy adhesive (GTS AS1084). The steel surface of the laminate is electrolytically coated with an approximately 10 µm-thick Cu layer [5]. Cu coating of the steel-polyimide laminate is performed by the CERN PCB laboratory, and the Cu coated laminate is then provided to the quench heater manufacturer. The specified Cu coating thickness on the heater circuits is between 5-15 µm [6].

At 10 K the specified resistances of the MQXFA and MQXFB outer quench heater circuits are 1.14 Ω and 1.98 Ω, respectively [7]. The nominal 10 K resistance of the 11 T quench heater circuit (sum of circuit resistances on low field and high field blocks) is 3.54 Ω [8].

The series production of the quench heaters for the 11 T dipole and MQXF quadrupole has started in the beginning of 2018 by the company Trackwise. The number of different quench heater types and the delivery schedule as defined in the technical specification [6] are summarised in Table 1. Today the

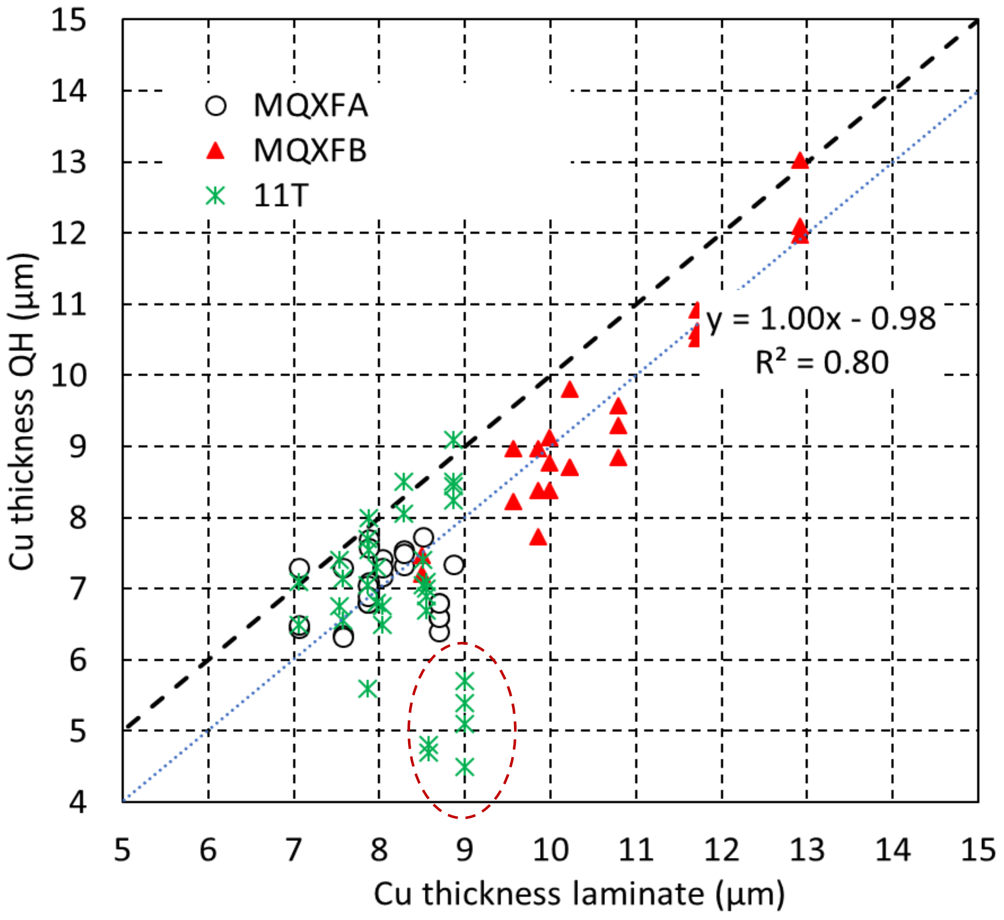
1

Comparison of quality of quench heaters from different manufacturers

- The HL-LHC series QH are produced by the company Trackwise.
- With respect to the quality of the heaters from a previous manufacturer, Trackwise achieved major improvements in terms of:
  - Dimensional tolerances
  - Absence of delaminations between polyimide and steel
  - Absence of bends and wrinkles
  - Cleanliness and visual surface appearance
- The circuit electrical resistance depends on the Cu coating thickness on the base material that is supplied by CERN.
- The dielectric properties of the polyimide film depend on the base material that is supplied by CERN.

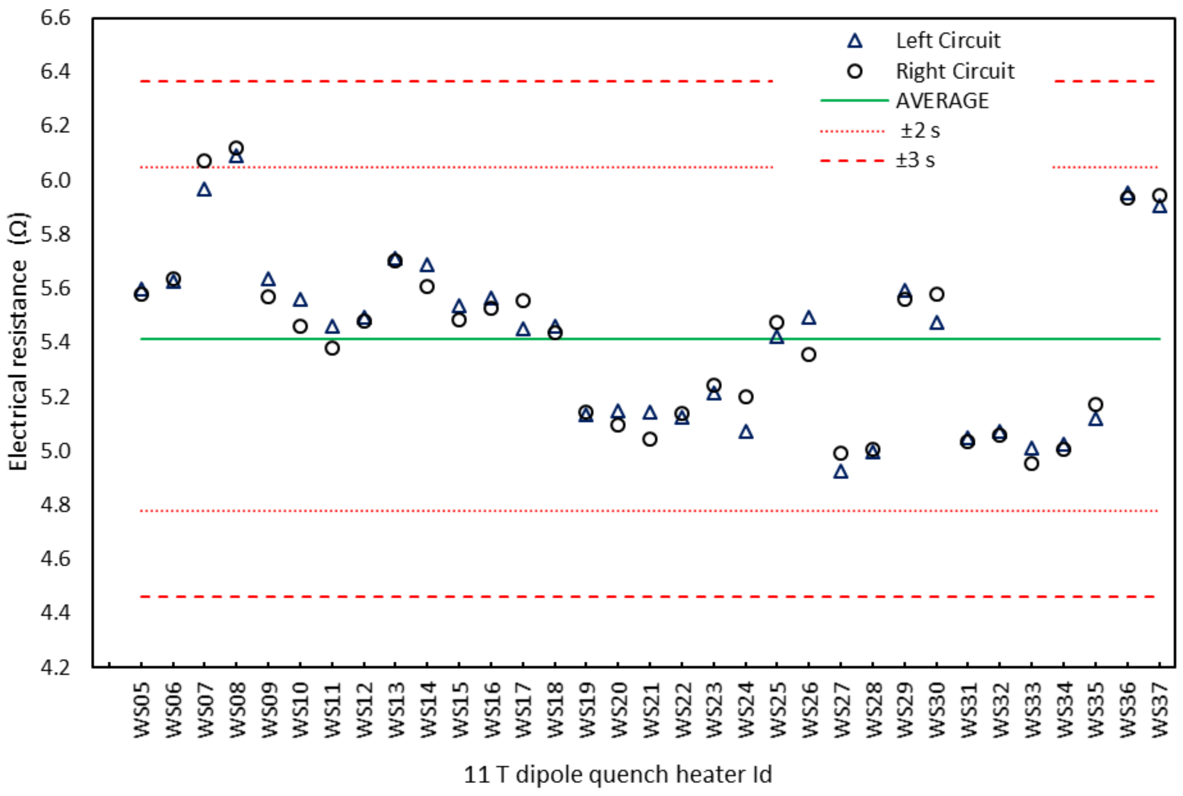
Cu coating thickness reduction during quench heater production

- On the first pre-series heaters produced at Trackwise the Cu coating at the terminals was too thin.
- Therefore, we followed closely the Cu thickness on the base material and on the finished quench heaters.
- The Cu thickness removed is now rather stable.
- In average 0.98±0.64 µm Cu are removed from the laminate during heater production (calculated without taking into account the six encircled data points, which we consider as outliers).

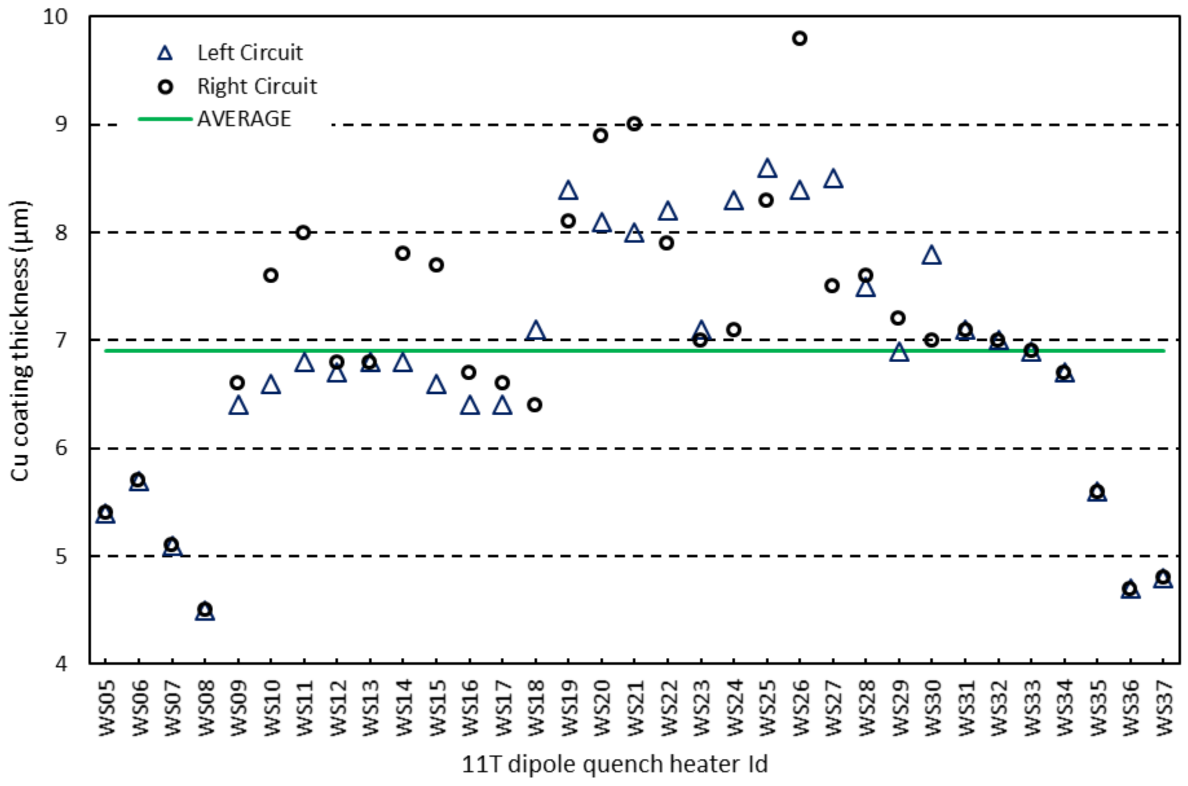


Average Cu coating thickness on QH as a function of the Cu coating thickness on the laminate from which the QH was produced.

11 T dipole heater RT circuit resistance and Cu coating thickness

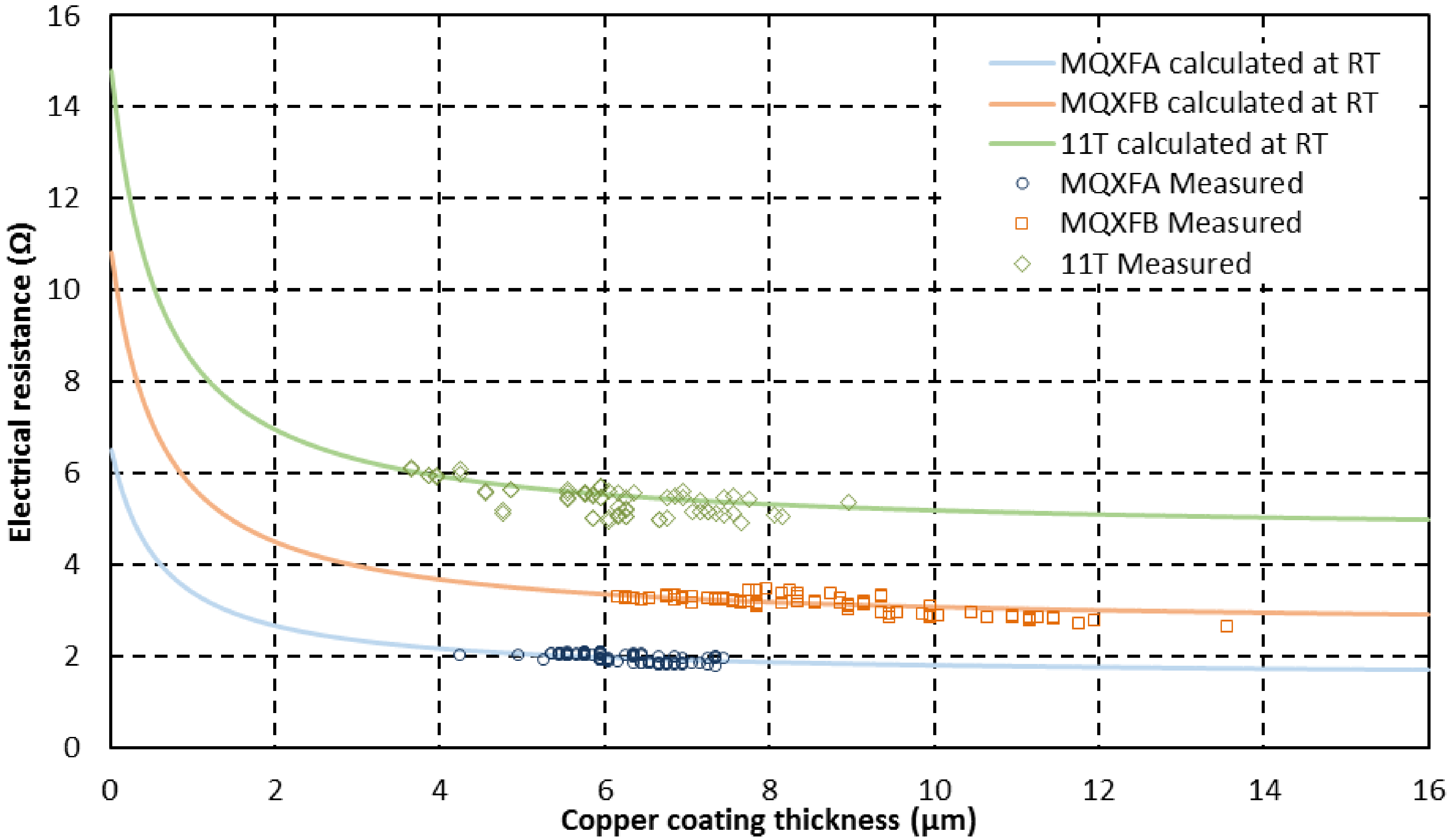


11 T dipole QH circuit RT electrical resistances.



Cu coating thickness on 11 T dipole QH circuits.

Effect of Cu coating thickness on circuit resistance



Comparison of the measured circuit resistance dependence on the measured Cu thickness with the calculated resistance vs Cu thickness dependence.

Measured RT resistance and calculated 1.9 K circuit resistance overview

- The RT circuit resistance variations are mainly caused by Cu coating thickness variations.
- The coefficient of variation of the circuit resistances decreases by more than one order of magnitude when cooling to 1.9 K.

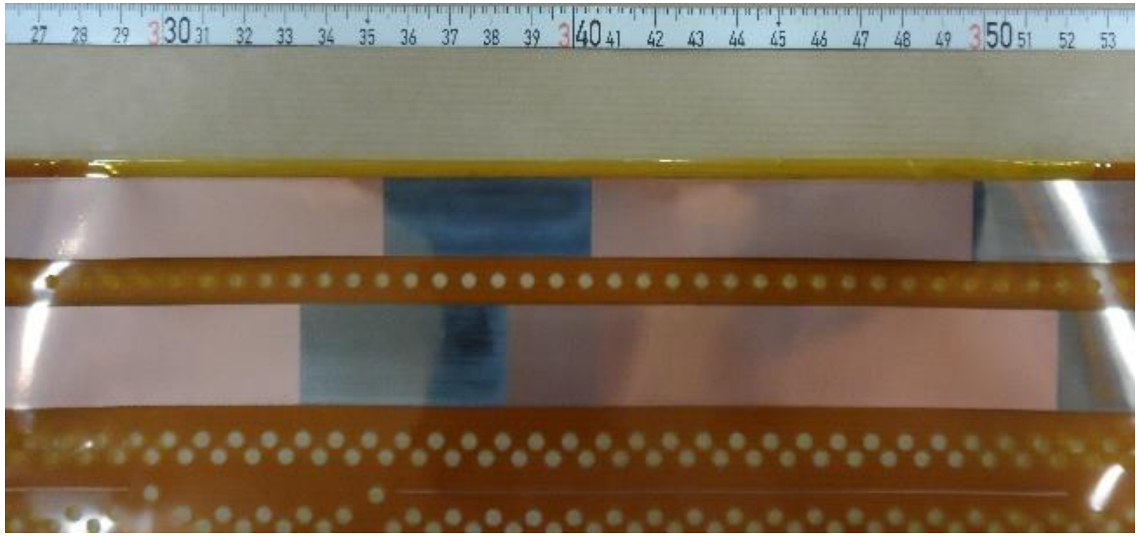
Comparison of the average, maximum and minimum circuit resistances and the coefficient of variation (CV) of the different heater types measured at RT and calculated at 1.9 K.

	Temperature	Circuit resistance				n
		Average± STDEV (Ω)	CV (%)	Max (Ω)	Min (Ω)	
11 T dipole	RT	5.39±0.30	5.66	6.12	4.93	66
	1.9 K	3.45±0.02	0.55	3.41	3.37	
MQXFA	RT	1.95±0.09	4.58	2.08	1.78	108
	1.9 K	1.15±0.01	0.34	1.17	1.14	
MQXFB	RT	3.12±0.19	6.10	3.45	2.64	88
	1.9 K	1.97±0.01	0.44	1.99	1.95	

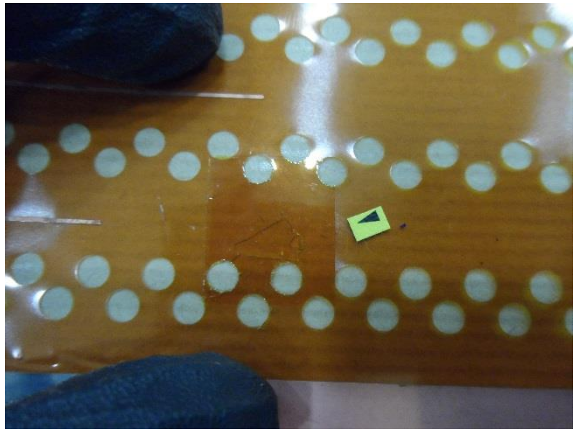
11 T dipole QH with visually detected polyimide defects

3 out of 32 HL-LHC 11 T dipole quench heaters with visible polyimide defect. WS024 was rejected, the other tiny defects were repaired with polyimide tape.

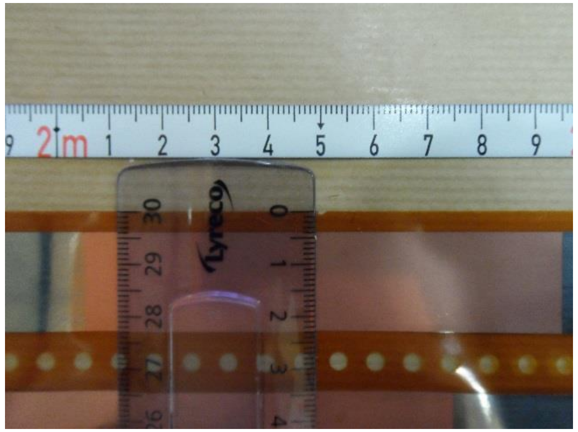
QH ID	location of defect
QH_11T_HCLMBHE050-WS000024 was rejected	3.28 m - 3.53 m (left edge)
QH_11T_HCLMBHE050-WS000025	2.05 m & 3.35 m (left edge)
QH_11T_HCLMBHE050-WS000031	3.05 m (mid)



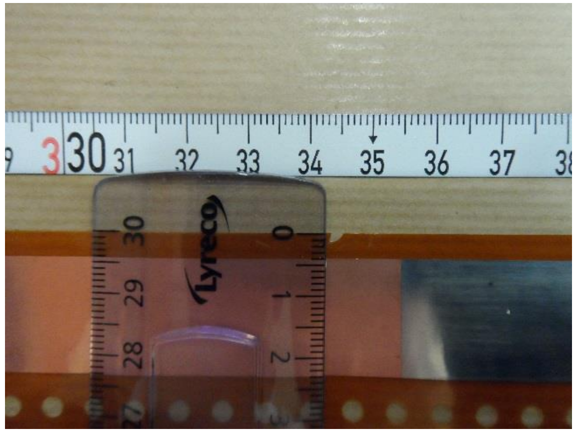
11T WS024 (3.28 m – 3.53 m), heater was rejected.



11T WS031 (3.05 m)



11T WS025 (2.05 m)



11T WS025 (3.35 m)

Set-up for dielectric tests

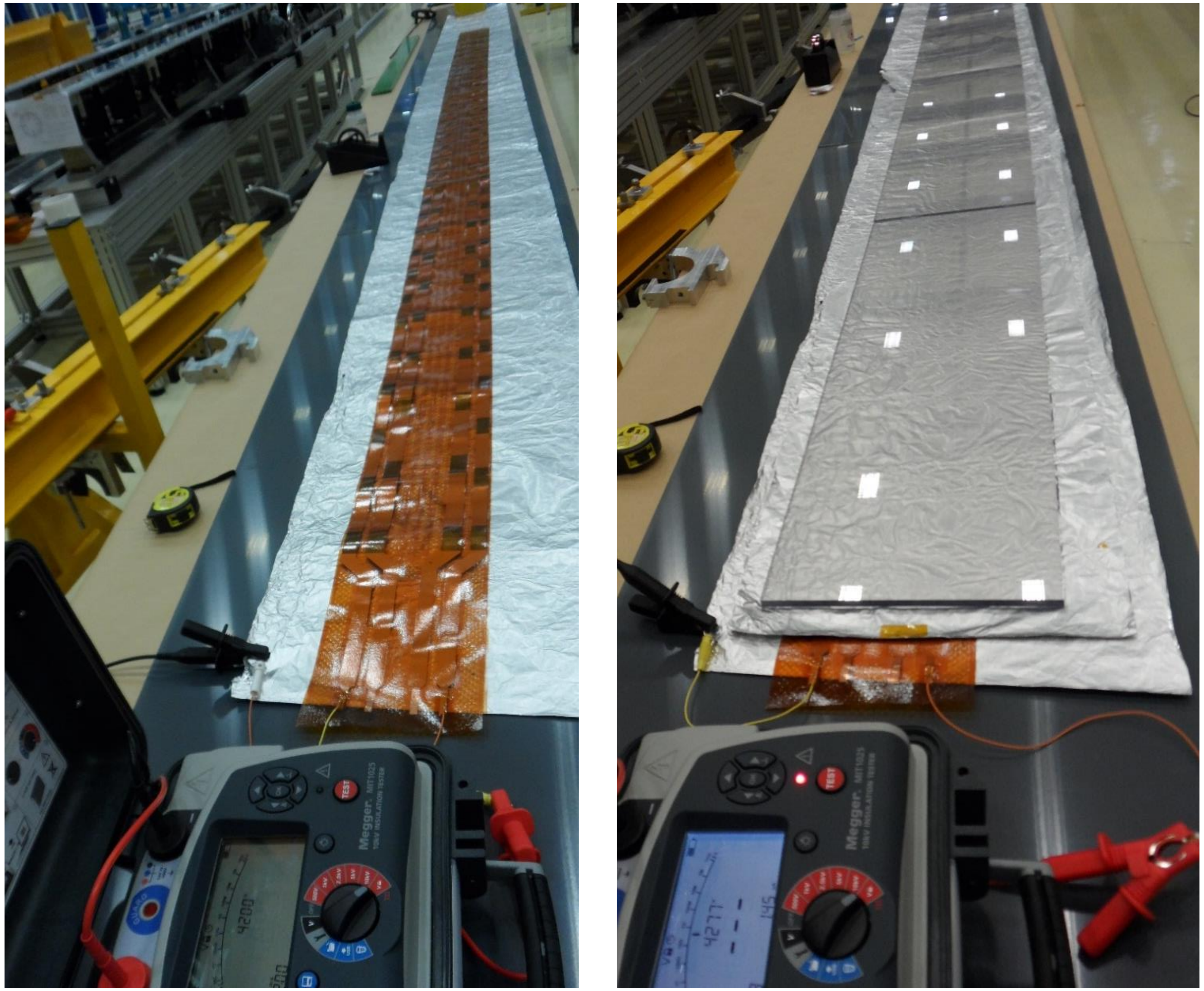
- (a) Leakage current through polyimide film is measured between Al foil and heater circuit, using a Megger MIT1025.

Acceptance criteria (dwell time 120 s):

- 11T dipole QH: max 4.2 μA at 4.2 kV
- MQXF QH: max 3.7 μA at 3.7 kV

→Minimal resistance=1 GΩ

- During the test the electrostatic force attracts the Al foil to the heater.
- For some cases HV tests were repeated with an additional load on top of the heater. → No strong difference between leakage currents measured with and without additional load.
- (b) When testing a heater with coverlay, an Al foil is placed below and above the heater (both foils at ground potential, and the circuit at DC test voltage).



Quench heater high voltage test of (a) series heater and (b) heater encapsulated with polyimide coverlay.

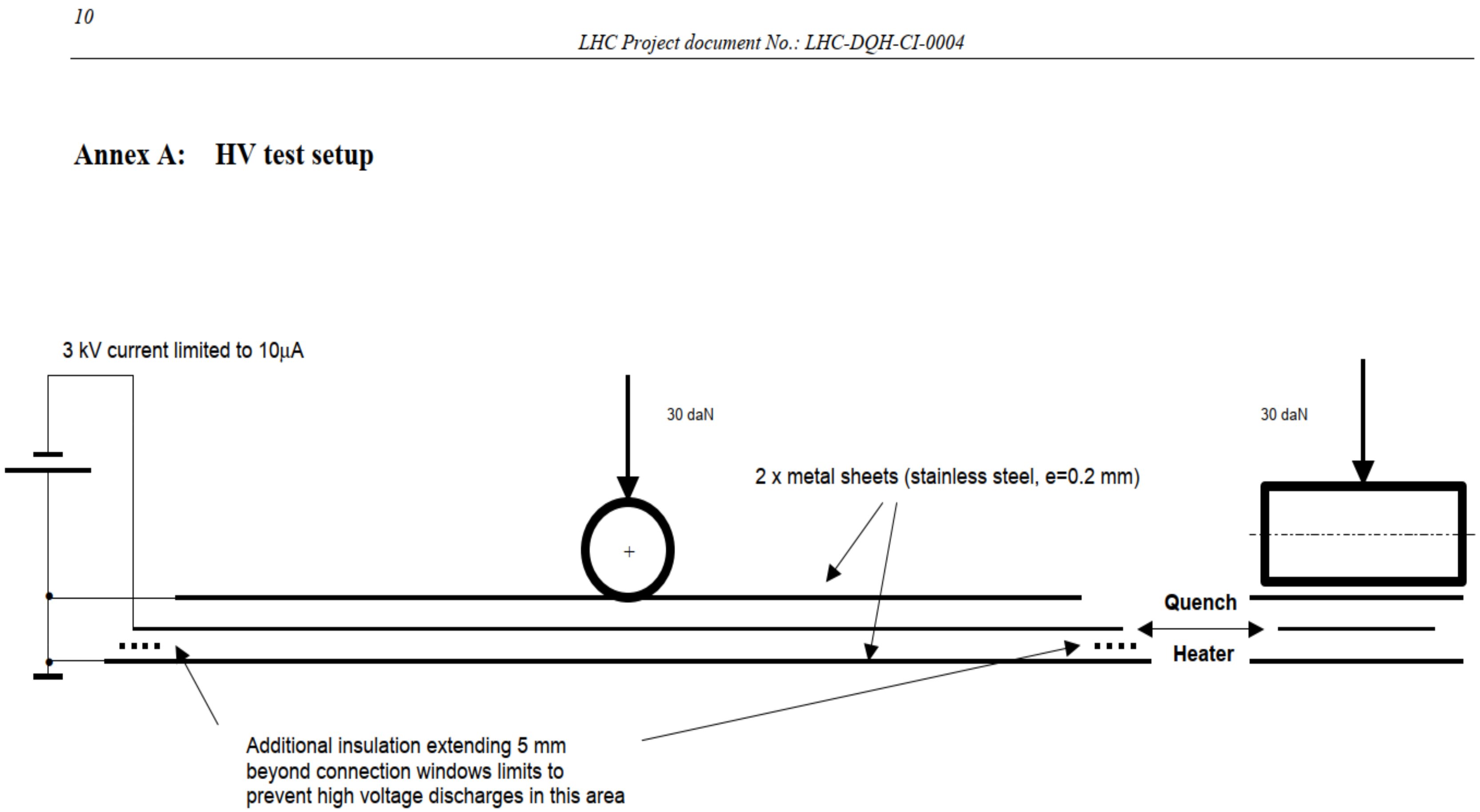
11 T dipole QH with pinholes that were repaired with polyimide tape

- In the polyimide film of 7 out of 32 HL-LHC 11T dipole quench heaters a pinhole was detected during dielectric test with 4.2 kV.
- Pinholes are covered with self-adhesive polyimide and the dielectric test is repeated afterwards.

QH ID	location of pin hole
QH_11T_HCLMBHE050-WS000005	0.36 m
QH_11T_HCLMBHE050-WS000011	2.60 m (right track)
QH_11T_HCLMBHE050-WS000012	2.40 m (right track)
QH_11T_HCLMBHE050-WS000022	1.10 m (right track)
QH_11T_HCLMBHE050-WS000028	3.44 m (left track) 4.60 m (left track)
QH_11T_HCLMBHE050-WS000029	0.30 m (right track)
QH_11T_HCLMBHE050-WS000037	1.25 m (left track)

Proposed test set-up for the LHC quench heater dielectric tests (see EDMS No. 316296)

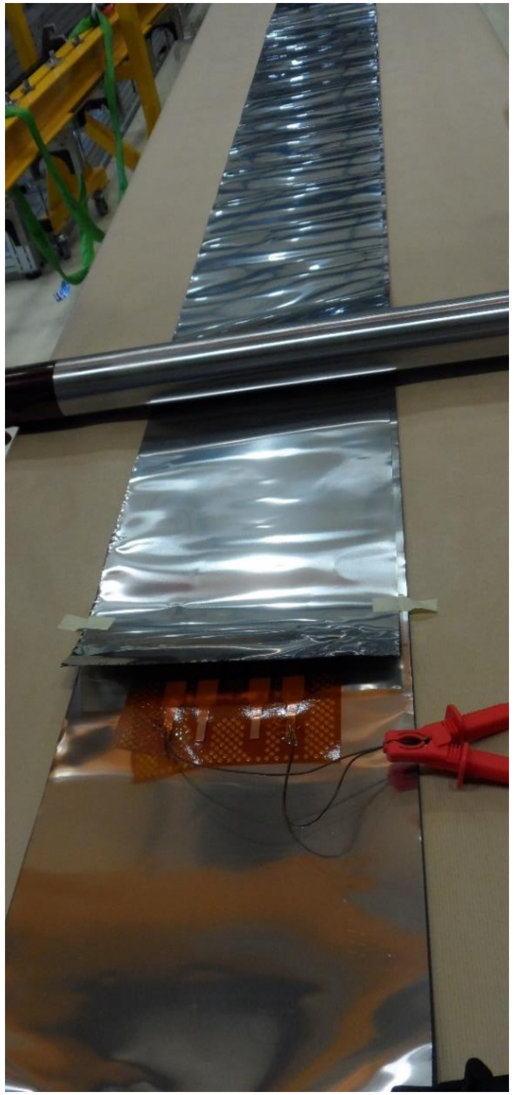
- LHC quench heaters have a coverlay → steel foil is placed below and above the heater.
- A DC voltage of 3 kV is applied to the circuit and the metal foils are grounded.
- During the test a pressure of about 20 MPa is locally applied by means of cylinder that is rolled over the entire heater.



11 T dipole heater dielectric tests with additional load (ongoing)

- Stainless steel cylinder (∅= 80 mm) is rolled over the heater and leakage current measured as described in EDMS No. 316296.
- Tests were performed with a 11 T heater with coverlay
- Test 30th Oct 2018: I leak ≈ 0.2 µA (U = 4.2 kV, 2 min)
- Test 10th Jan 2019 as recommended in EDMS No. 316296 with additional load locally applied by a steel cylinder:
  - I leak ≈ 10 µA during roll movement (unstable)
  - 1.4 µA for spot measurement (short time constant ≈ 5 s instead 2 min)
- NO BREAKDOWN
- Further tests with other heaters will be performed.

Set-up 30th Oct 2018.



Set-up 10th Jan 2019

Quench heater dielectric tests summary

- Test voltage is limited to 4.2 kV in order to avoid surface arching (the distance between metallic circuits and polyimide contours (or holes) is 4 mm, and heaters have no coverlay).
- Tests with set-up where mechanical stress is applied with a massive cylinder are ongoing.
- In some cases break down occurred because of presence of a pin hole in the polyimide. In such cases the pin hole is closed by adding self adhesive polyimide foil (CERN SCEM 04.94.70.150.0), and the dielectric test is repeated afterwards.
- In the more robust LHC quench heaters less pin holes are detected during the LMF dielectric tests (out of 219 spare heater that were re-tested, 13 did not pass the LMF dielectric test because of insulation breakdown, or because the leak current was above specification.
- Discharge test: was abandoned
- Circuit resistance measurement in two different ways:
  - 4-wire method, only the heater circuit resistance is measured (results in note EDMS No. 2053975).
  - The circuit resistance recorded in the electrical test reports includes the resistance of connecting wires.

11 T dipole series quench heater QC reports

QH Id.	QC report	Installed on coil	Comment
HCLMBHE050-WS000005:	EDMS No. 1905951		
HCLMBHE050-WS000006:	EDMS No. 2000027	GE-C01	
HCLMBHE050-WS000007:	EDMS No. 2000034	GE-C02	
HCLMBHE050-WS000008:	EDMS No. 2000044	GE-C05	
HCLMBHE050-WS000009:	EDMS No. 1966584		
HCLMBHE050-WS000010:	EDMS No. 1966587	GE-C08	
HCLMBHE050-WS000011:	EDMS No. 1966558		
HCLMBHE050-WS000012:	EDMS No. 1966589		
HCLMBHE050-WS000013:	EDMS No. 1966591	GE-C03	
HCLMBHE050-WS000014:	EDMS No. 1966592	GE-C06	
HCLMBHE050-WS000015:	EDMS No. 1966595		
HCLMBHE050-WS000016:	EDMS No. 1966596	GE-C07	
HCLMBHE050-WS000017:	EDMS No. 1966865		
HCLMBHE050-WS000018:	EDMS No. 1966866		
HCLMBHE050-WS000019:	EDMS No. 2005709		
HCLMBHE050-WS000020:	EDMS No. 2005711		
HCLMBHE050-WS000021:	EDMS No. 2005712		
HCLMBHE050-WS000022:	EDMS No. 2005713		
HCLMBHE050-WS000023:	EDMS No. 2005714		
~~*HCLMBHE050-WS000024:*~~	~~*EDMS No. 2044133*~~		*NCR. Heater was used for coverlay application test*
HCLMBHE050-WS000025:	EDMS No. 2005720		
HCLMBHE050-WS000026:	EDMS No. 2005719		
HCLMBHE050-WS000027:	EDMS No. 2005718		
HCLMBHE050-WS000028:	EDMS No. 2005717		
HCLMBHE050-WS000029:	EDMS No. 2005716		
HCLMBHE050-WS000030:	EDMS No. 2005715		
HCLMBHE050-WS000031:	EDMS No. 2029034		
HCLMBHE050-WS000032:	EDMS No. 2029262		
HCLMBHE050-WS000033:	EDMS No. 2029263		
HCLMBHE050-WS000034:	EDMS No. 2029264		
HCLMBHE050-WS000035:	EDMS No. 2048605		
HCLMBHE050-WS000036:	EDMS No. 2050891		
HCLMBHE050-WS000037:			*Non standard heater with coverlay.*

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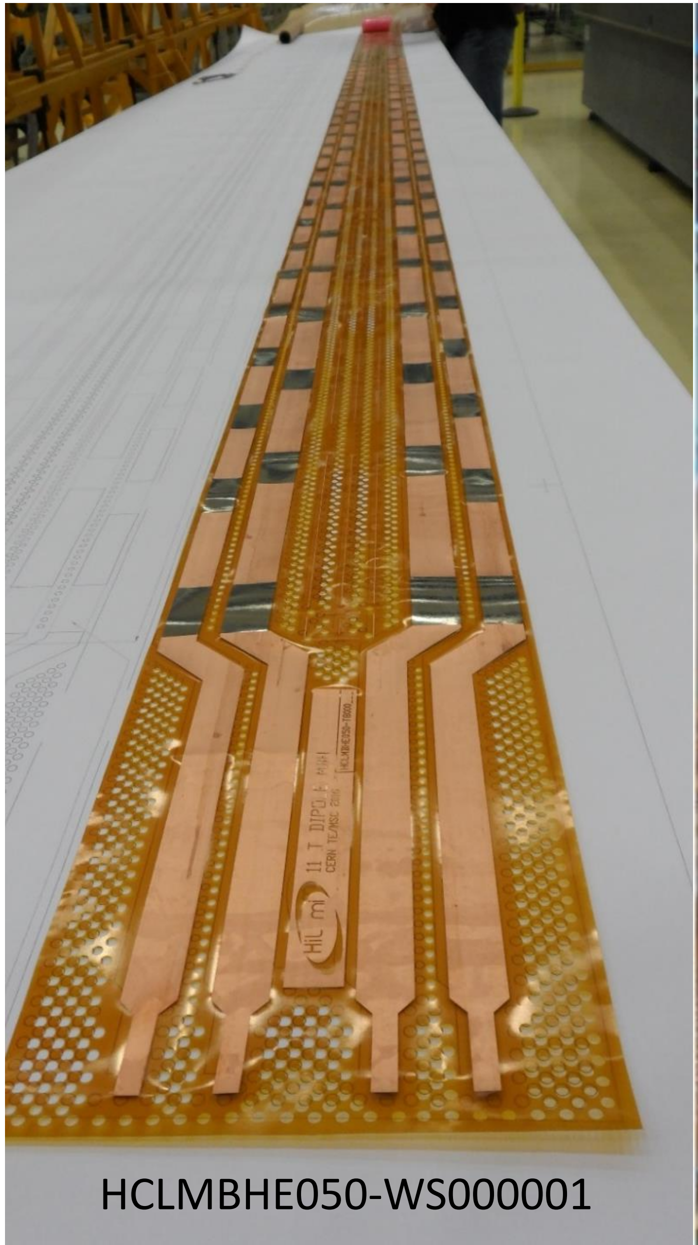
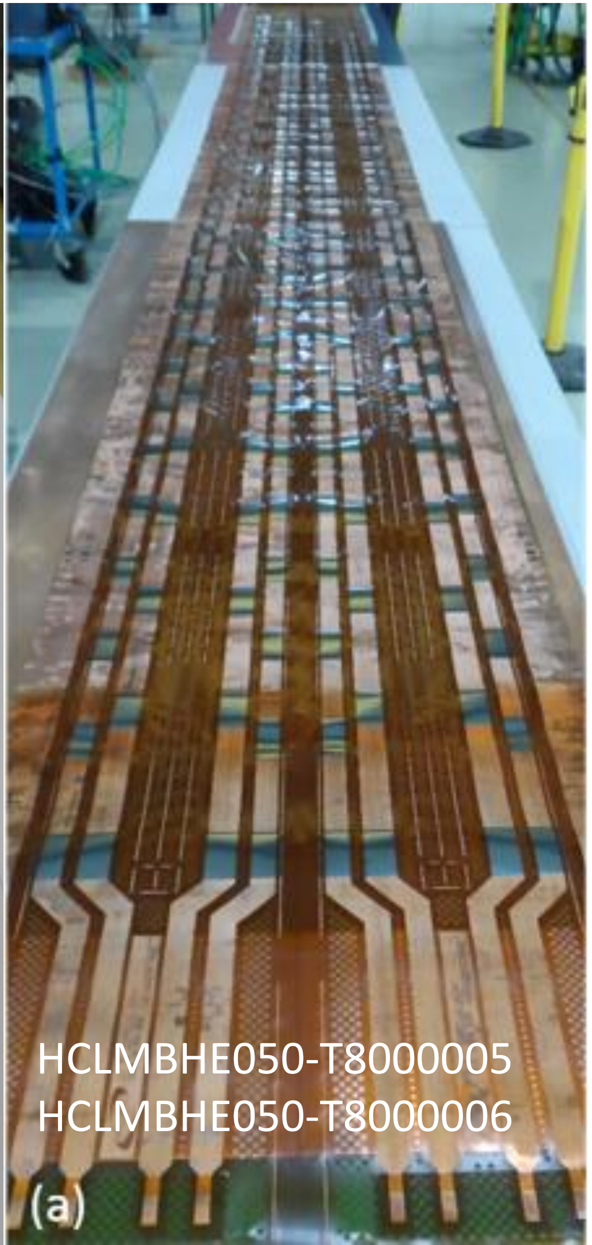
Quench heaters installed on the 11T dipole prototype coils

- Pre-series heaters (about 4 cm shorter than the series production heaters).
- The base material (GTS laminate L960461, Cu coated by CERN PCB lab) for all heaters was supplied by CERN. Prototype QH were produced by two companies:
- Tecnomec
  - HCLMBHE050-T8000005 : CR04
  - HCLMBHE050-T8000006 : CR05
- Trackwise
  - HCLMBHE050-WS000001: CR06
  - HCLMBHE050-WS000002: CR07
- HCLMBHE050-WS000001 and 02 were tested conform (QC reports: WS01 EDMS No. 1802408 and WS02 EDMS No. 1808205). **No pinholes or other polyimide defects were detected.**
- **11 T dipole prototype heaters were tested with a test voltage of 5 kV.**
- **Leakage current through polyimide film of QH WS01, WS02, T805, T806 at 5 kV <1 μA.**





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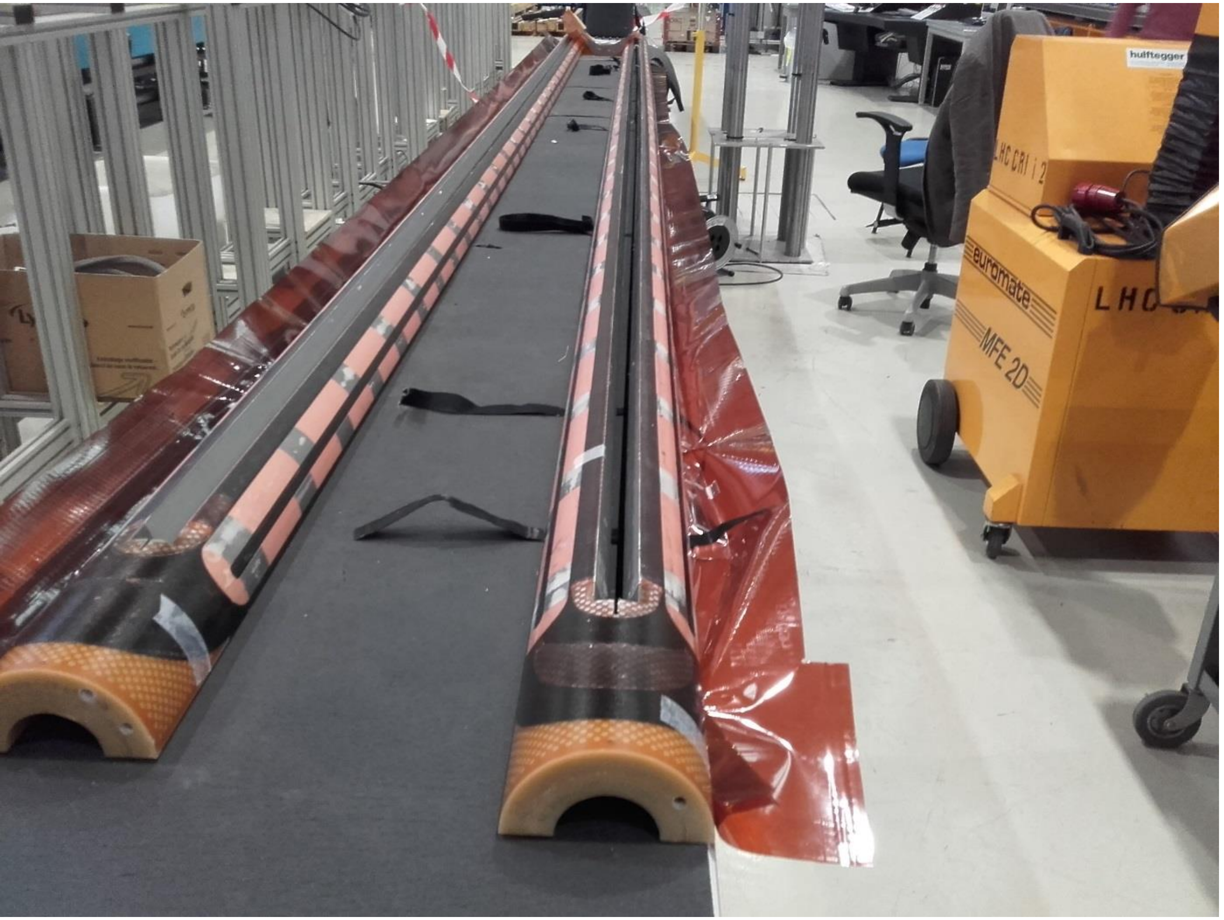
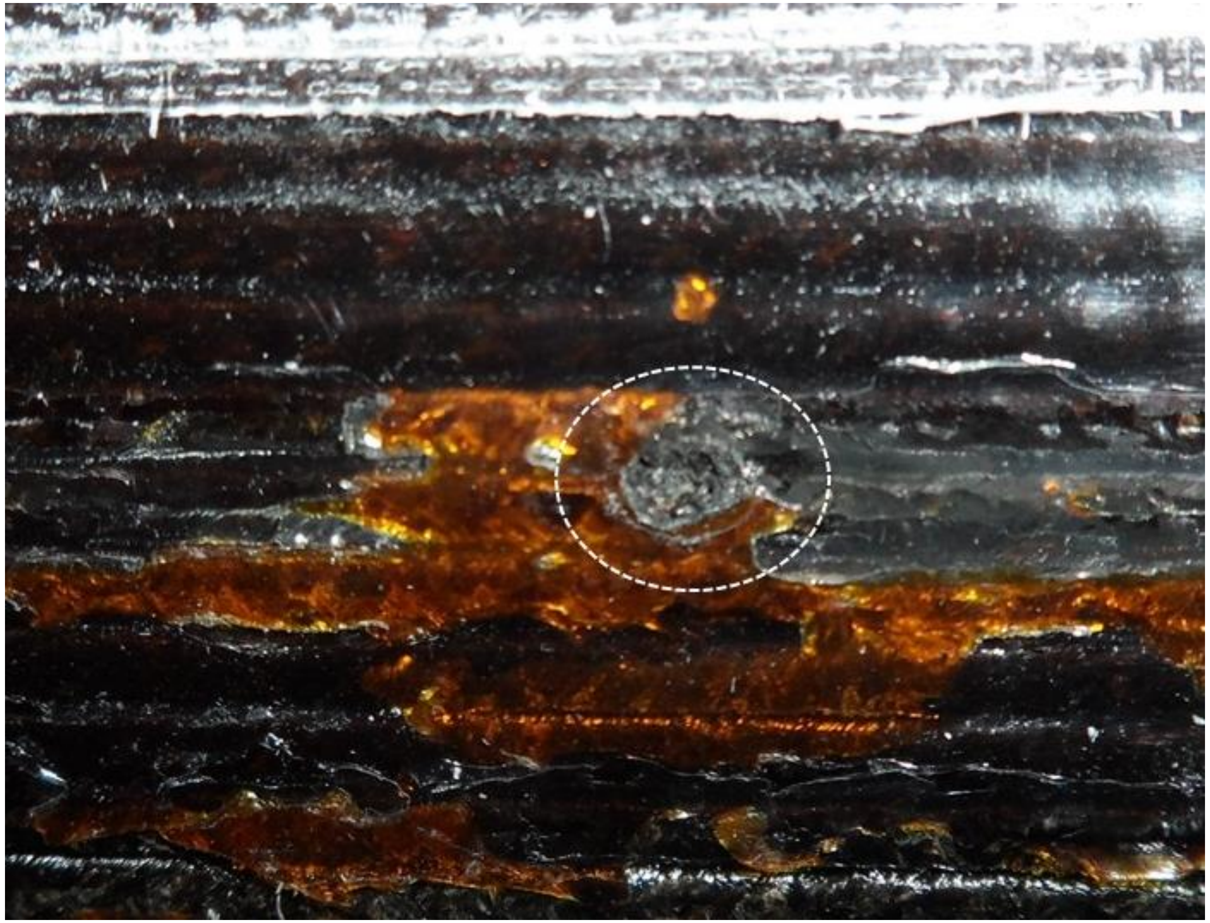
Visual characterisation of quench heater circuit to coil shorts in 11 T dipole prototype coils CR05 and CR06



11 T prototype dipole quench heater defect CR06-2.20 m observed after provoking shorts to coil

Peeled off metallic circuit



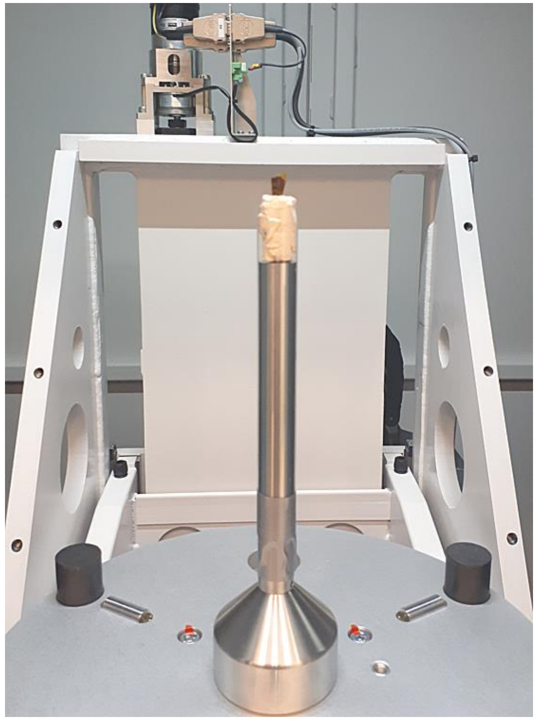
Defect as seen after peeling off the circuit

µ-CT examination of defect CR06-2.20 m

- Precision cutting of 5 mm x 5 mm sample with diamond wire saw, courtesy of S. Caille.
- µ-CT courtesy of M. Jedrychowski, EN-MME.
- Zeiss METROTOM 1500 G2 CT, 215 kV, 7 µm voxel edge size.
- NDT report EDMS No. 2061236.

Rough cutting of coil CR06.

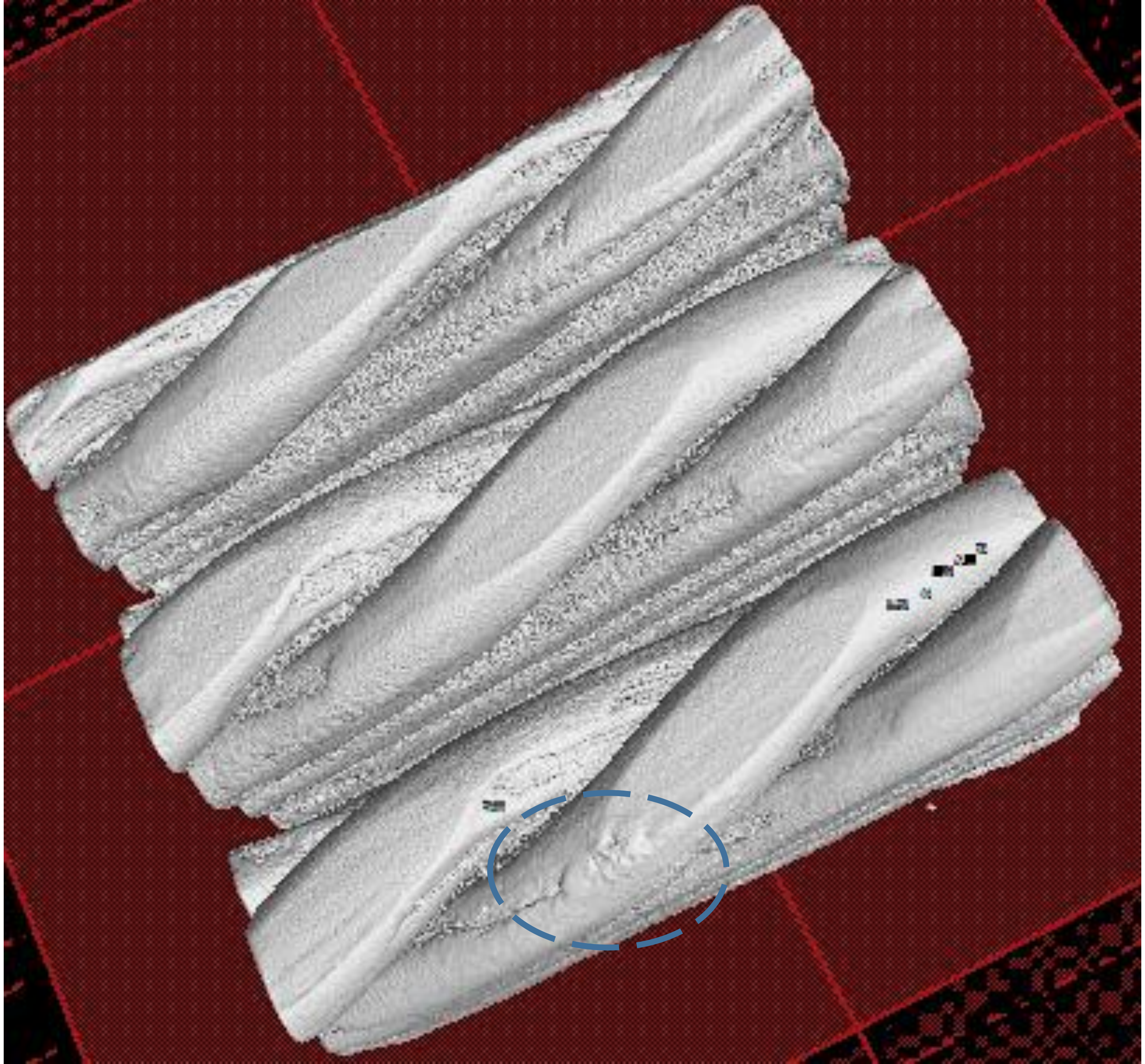
Sample with defect for µ-CT examination



Sample on µ-CT set-up

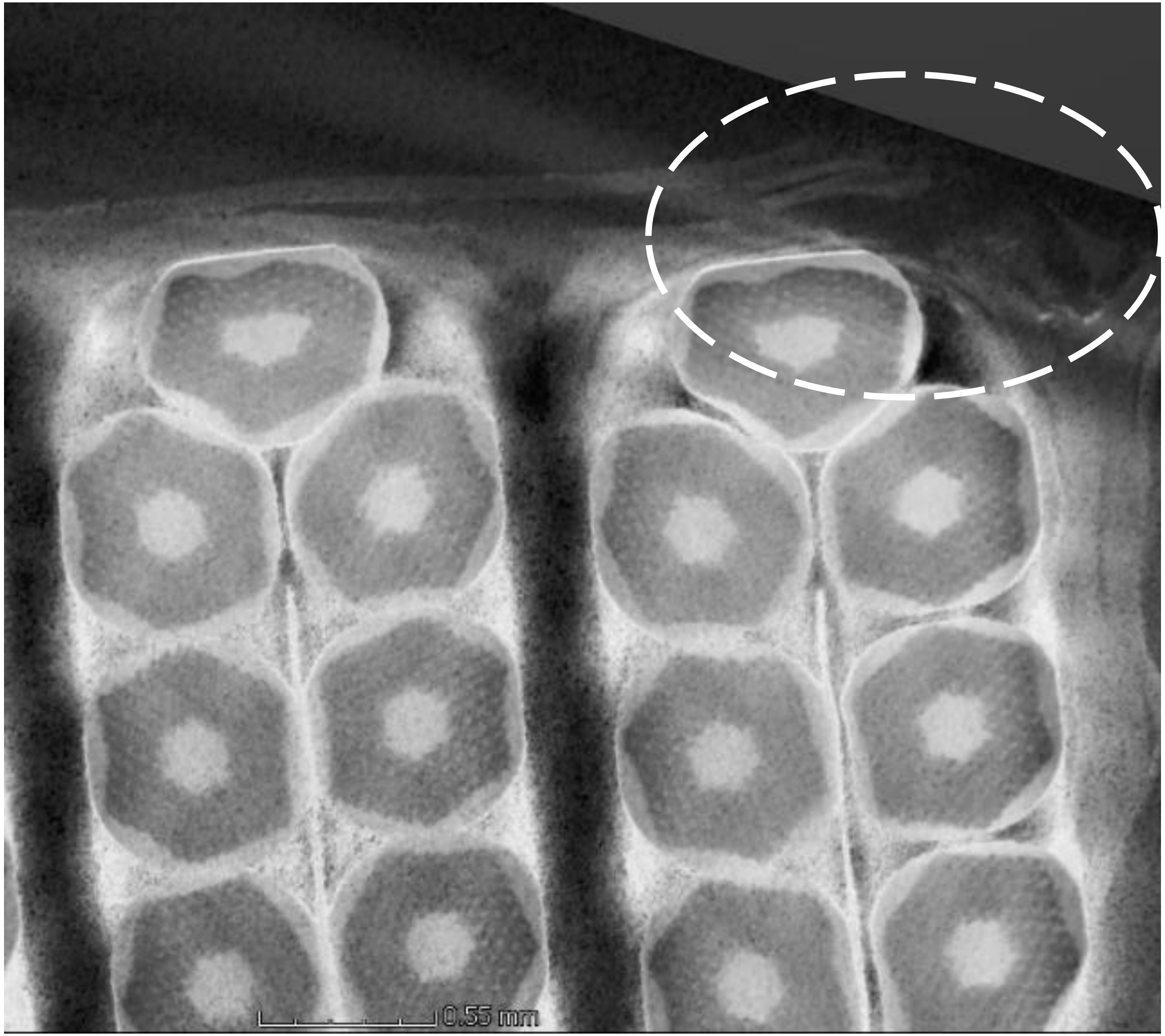
3D rendering of the wires below defect CR06-2.20 m

- Encircled wire region might show signs of Cu melting.



μ-CT cross section of cable and cable insulation

- Cable insulation can be distinguished from background by a slight absorption contrast.
- There are signs of insulation damage in the encircled region.

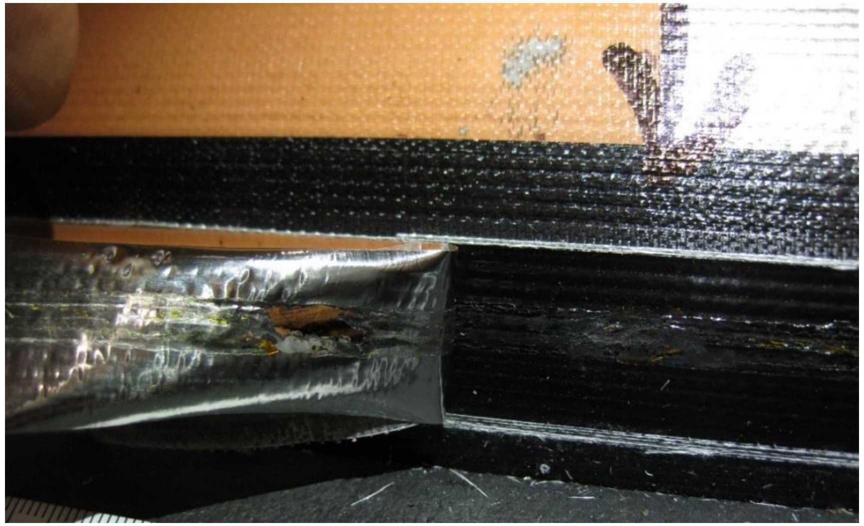


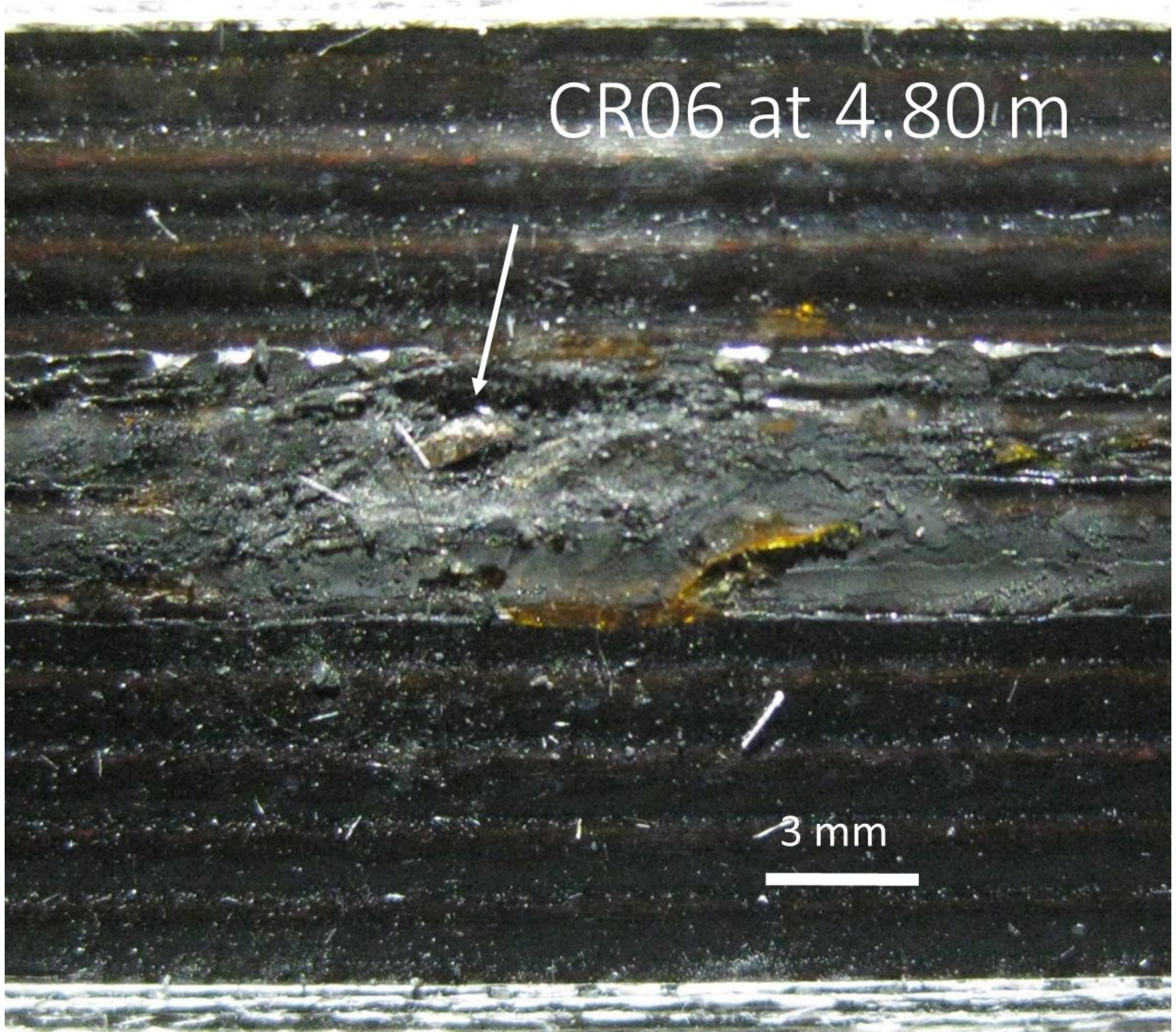
µ-CT examination of defect CR06-2.20 m summary

- The defect CR06-2.20 m between quench heater circuit and Rutherford cables is visualised in the µ-CT images.
- The µ-CT images indicate a direct short between heater circuit and cable through the polyimide foil, as was already speculated from the visual check after peeling off the stainless steel heater strip.
- The origin of the dielectric weakness of the entire insulation system between Rutherford cable and quench heater circuit (i.e. the S2 glass and Mica cable insulation plus the CDT101K epoxy impregnation plus the 50 µm thick polyimide film) was not revealed by the µ-CT examination.

11 T prototype dipole quench heater defect CR06-4.80 m observed after provoking shorts to coil

- Defect CR06-4.80 m: Metal foil is partly melted and bare Cu cable is visible.





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11 T dipole quench heater with coverlay

- If the QH would be installed on the outside of the reacted and impregnated coil, the heater robustness could be improved by encapsulating the circuits with a polyimide coverlay.
- A coverlay 50 µm polyimide + 25 µm glue (Dupont LF) can be applied on the already existing 11 T dipole quench heaters at CERN PCB lab.
- After application of a coverlay on a 11 T dipole QH, the break down voltage increased to >6.5 kV (no surface arching when the circuits are encapsulated).

Conclusion

- The start of the HL-LHC quench heater series production at Trackwise has been followed up closely. The quality of the Trackwise production is very satisfactory.
- Before installing the pre-series quench heaters in the 11 T dipole prototype coils, the leakage current through the polyimide film was tested at 5 kV. Before installation the electrical resistance of the QH polyimide insulation of all four QH circuits was in the order of 10 GΩ.
- Compared to the LHC quench heaters, the HL-LHC quench heaters are less robust (reduced polyimide thickness of 50 µm, no encapsulation).
- The robustness of the HL-LHC insulation system between QH circuit and coil could probably be improved when the QH would be mounted on the outside of the already impregnated coil.
- When applying a coverlay surface arching is avoided and the breakdown voltage in ambient air increases to above 6.5 kV.
- Application of a coverlay on the already existing 11 T dipole heaters is feasible at CERN PCB lab.

Back up slides

Cu coating thickness and Cu RRR on the base material used for the 2018 QH production (see EDMS No. 2053975)

Laminate			Quench heater	
Laminate Id.	Cu thickness (µm)	Cu RRR	QH Id.	Cu thickness
PCB_10m_001	11.71	21.7 *1)	MQXFB WS09	10.6
			MQXFB WS10	10.5
			MQXFB WS11	10.9
PCB_11m_008	12.91	34.7 *1)	MQXFB WS16	13.0
			MQXFB WS17	12.0
			MQXFB WS18	12.1
PCB_11m_013	8.49	23.0	MQXFB WS12	7.5
			MQXFB WS13	7.2
PCB_11m_014	10.22	23.0	MQXFB WS25	8.7
			MQXFB WS26	8.7
			MQXFB WS27	9.8
PCB_11m_018	9.57	23.0 *1)	MQXFB WS14	9.0
			MQXFB WS15	8.2
PCB_11m_020	10.79	27.7	MQXFB WS06	9.6
			MQXFB WS07	8.9
			MQXFB WS08	9.3
PCB_11m_022	9.99	27.7 *1)	MQXFB WS19	8.4
			MQXFB WS20	8.8
			MQXFB WS21	9.1
PCB_11m_023	9.86	27.7 *1)	MQXFB WS22	9.0
			MQXFB WS23	7.7
			MQXFB WS24	8.4
PCB_11m_027 PCB_11m_030	9.00	24.0	11T WS05	5.4
			11T WS06	5.7
			11T WS07	5.1
			11T WS08	4.5
PCB_13m_002	7.06	7.5	MQXFA 01-1	7.3
			MQXFA 01-2	6.5
			MQXFA 01-3	6.5
			11T WS09	6.5
			11T WS10	7.1
PCB_13m_003	7.53	8.7	11T WS11	7.4
			11T WS12	6.8
PCB_13m_004	7.97	8.8	11T WS13	6.8
			11T WS14	7.3
PCB_13m_005	7.57	7.9	MQXFA 02-1	6.4
			MQXFA 02-2	6.3
			MQXFA 02-3	5.8
			11T WS15	7.2
			11T WS16	6.6
PCB_13m_006	8.03	9.5	MQXFA 03-1	7.4
			MQXFA 03-2	7.2
			MQXFA 03-3	7.3
			11T WS17	6.5
			11T WS18	6.8
PCB_13m_007	8.51	18.3	MQXFA 04-3	7.7
			11T WS29	7.1
			11T WS30	7.4
PCB_13m_009	8.87	13.6	MQXFA 06-1	7.4
			11T WS25	8.5
			11T WS26	9.1
PCB_13m_010	8.29	17.1	MQXFA 07-1	7.6
			MQXFA 07-2	7.3
			MQXFA 07-3	7.5
			11T WS21	8.5
			11T WS22	8.1
PCB_13m_011	8.86	19.5	11T WS19	8.3
			11T WS20	8.5
PCB_13m_012	7.86	22.0	MQXFA 09-3	7.1
			11T WS23	7.1
			11T WS24	7.7
PCB_13m_013	7.87	13.1	MQXFA 08-1	7.7
			MQXFA 08-2	7.6
			MQXFA 08-3	7.1
			11T WS27	8.0
			11T WS28	7.6
PCB_13m_014	7.86	20.1	MQXFA 10-1	6.8
			MQXFA 10-2	6.8
			MQXFA 10-3	6.9
			11T WS35	5.6
PCB_13m_018	8.70	11.4	MQXFA 11-1	8.7
			MQXFA 11-2	8.7
			MQXFA 11-3	8.7
			MQXFA 12-1	8.7
			MQXFA 12-2	8.7
			MQXFA 12-3	8.7
PCB_13m_019	8.58	9.9	11T WS36	4.7
			11T WS37	4.8
PCB_13m_023	8.55	21.5	11T WS31	7.1
			11T WS32	7.0
			11T WS33	6.9
			11T WS34	6.7

Electrical circuit resistance of all 11 T dipole quench heaters (see EDMS No. 2053975)

Appendix I: 11 T dipole circuit RT resistances (measured) and calculated at 1.9 K

Laminate Id.	11 T dipole quench heater			Resistance (Ω)		On 11 T coil
	Trackwise Id.	CERN Id.		At RT	Calc. at 1.9 K	
PCB_11m_027 and PCB_11m_030	221-48-1-101	11T WS05	L	5.599	3.473	
			R	5.577	3.473	
	221-48-1-101	11T WS06	L	5.626	3.467	GE-C01
			R	5.637	3.467	
	221-48-1-101	11T WS07	L	5.968	3.480	GE-C02
			R	6.071	3.480	
	221-48-1-101	11T WS08	L	6.092	3.498	GE-C05
			R	6.119	3.498	
PCB_13m_002	221-48-2-101	11T WS09	L	5.634	3.454	
			R	5.569	3.451	
	221-48-2-101	11T WS10	L	5.562	3.451	
			R	5.462	3.438	
PCB_13m_003	221-48-3-101	11T WS11	L	5.461	3.448	
			R	5.378	3.434	
	221-48-3-101	11T WS12	L	5.495	3.449	
			R	5.478	3.448	
PCB_13m_004	221-48-4-101	11T WS13	L	5.710	3.448	GE-C03
			R	5.702	3.448	
	221-48-4-101	11T WS14	L	5.689	3.448	
			R	5.609	3.436	
PCB_13m_005	221-48-5-101	11T WS15	L	5.535	3.451	
			R	5.486	3.437	
	221-48-5-101	11T WS16	L	5.567	3.454	
			R	5.529	3.449	
PCB_13m_006	221-48-6-101	11T WS17	L	5.451	3.454	
			R	5.557	3.451	
	221-48-6-101	11T WS18	L	5.460	3.444	
			R	5.435	3.453	
PCB_13m_011	13←011 221-48-11-2	11T WS19	L	5.134	3.430	
			R	5.144	3.433	
	13←011 221-48-11-1	11T WS20	L	5.150	3.433	
			R	5.095	3.425	
PCB_13m_010	13←010 221-48-10-1	11T WS21	L	5.143	3.434	
			R	5.046	3.425	
	13←010 221-48-10-2	11T WS22	L	5.125	3.432	
			R	5.140	3.435	
PCB_13m_012	13←012 221-48-12-1	11T WS23	L	5.214	3.444	
			R	5.243	3.445	
	13←012 221-48-12-2	*11T WS24*	*L*	*5.071*	*3.431*	***NCR***
			R	*5.198*	*3.444*	
PCB_13m_009	13←009 221-48-09-2	11T WS25	L	5.424	3.428	
			R	5.476	3.431	
	13←009 221-48-09-1	11T WS26	L	5.494	3.430	
			R	5.356	3.419	
PCB_13m_013	13←013 221-48-13-2	11T WS27	L	4.926	3.429	
			R	4.993	3.439	
	13←013 221-48-13-1	11T WS28	L	4.994	3.439	
			R	5.006	3.438	
PCB_13m_007	13←007 221-48-07-1	11T WS29	L	5.592	3.446	
			R	5.561	3.443	
	13←007 221-48-07-2	11T WS30	L	5.474	3.436	
			R	5.581	3.445	
PCB_13m_023	13←023 221-48-15-1	11T WS31	L	5.049	3.444	
			R	5.035	3.444	
	13←023 221-48-15-2	11T WS32	L	5.072	3.445	
			R	5.057	3.445	
	13←023 221-48-16-1	11T WS33	L	5.010	3.446	
			R	4.952	3.446	
	13←023 221-48-16-2	11T WS34	L	5.026	3.449	
			R	5.006	3.449	
PCB_13m_014	13←014 221-48-14-1	11T WS35	L	5.119	3.469	
			R	5.172	3.469	
PCB_13m_019	13←019 221-48-17-1	11T WS36	L	5.955	3.492	
			R	5.933	3.492	
	13←019 221-48-17-2	11T WS37	L	5.908	3.489	
			R	5.946	3.489	

MQXFB and MQXFA series quench heater QC reports

- HCMQXFBC19-WS000006, EDMS No. 2020434
- HCMQXFBC19-WS000007, EDMS No. 2020435
- HCMQXFBC19-WS000008, EDMS No. 2020436 **CR108**
- HCMQXFBC19-WS000009, EDMS No. 2020437
- HCMQXFBC19-WS000010, EDMS No. 2020438
- HCMQXFBC19-WS000011, EDMS No. 2020441 **CR109**
- HCMQXFBC19-WS000012, EDMS No. 2026559
- HCMQXFBC19-WS000013, EDMS No. 2030697
- HCMQXFBC19-WS000014, EDMS No. 2030695
- HCMQXFBC19-WS000015, EDMS No. 2030692
- HCMQXFBC19-WS000016, EDMS No. 2030707
- HCMQXFBC19-WS000017, EDMS No. 2030699
- HCMQXFBC19-WS000018, EDMS No. 2026560
- HCMQXFBC19-WS000019, EDMS No. 2026561
- ~~HCMQXFBC19-WS000020, EDMS No. 2026566~~, heater damaged during discharge test
- HCMQXFBC19-WS000021, EDMS No. 2026567
- HCMQXFBC19-WS000022, EDMS No. 2026568
- HCMQXFBC19-WS000023, EDMS No. 2026571
- HCMQXFBC19-WS000024, EDMS No. 2030698
- HCMQXFBC19-WS000025, EDMS No. 2050328
- HCMQXFBC19-WS000026, EDMS No. 2050378
- HCMQXFBC19-WS000027, EDMS No. 2050414

- MQXFA 1st batch (9 heaters): EDMS No. 2025080
  https://edms.cern.ch/ui/#!master/navigator/document?D:100207330:100207330:subDocs
- MQXFA 2nd batch (9 heaters): EDMS No. 2029799
  https://edms.cern.ch/ui/#!master/navigator/document?D:100238311:100238311:subDocs
- MQXFA 3rd batch (9 heaters): EDMS No. 2048421
  https://edms.cern.ch/ui/#!master/navigator/document?D:100238290:100238290:subDocs

MQXF QH with visually detected small polyimide defects

2 out of 27 MQXFA and 4 out of 22 MQXFB quench heaters with small visible polyimide defect. All were repaired with polyimide tape.

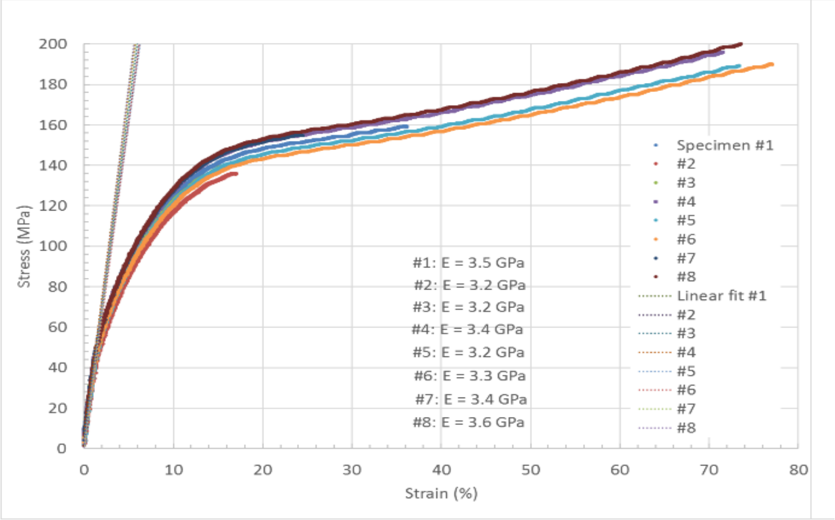
QH ID	location of defect
MQXFA WS000001 - 13←002 221 49-01-1	2.93 m (right edge)
MQXFA WS000001 - 13←002 221 49-01-2	2.14 m (left edge)
MQXFB HCMQXFBC19-WS000015	3.45 m (between mid-left and left track)
MQXFB HCMQXFBC19-WS000016	5.40 m (left edge)
MQXFB HCMQXFBC19-WS000018	2.00 m (right edge)
MQXFB HCMQXFBC19-WS000020	2.20 m (right edge)

MQXF QH with pinholes that were repaired with polyimide tape

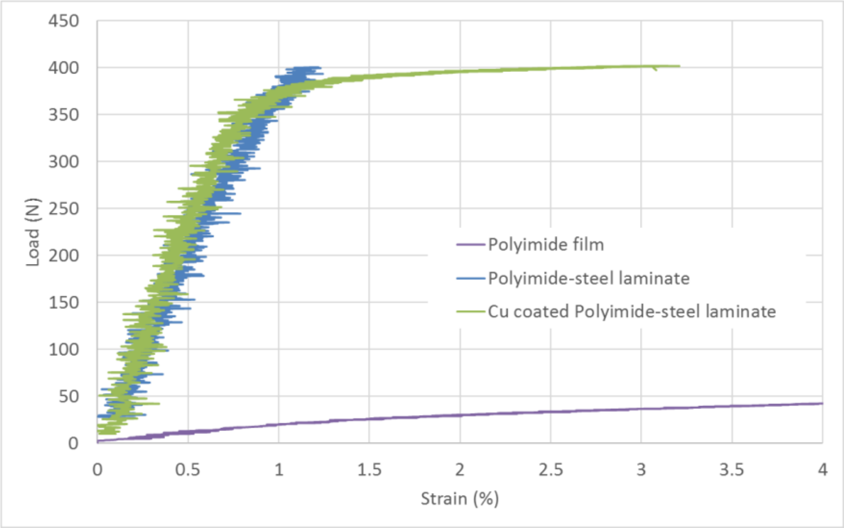
4 out of 27 MQXFA and 3 out of 22 MQXFB quench heaters were repaired with self-adhesive polyimide tape, since a pinhole was detected during dielectric test with 3.7 kV.

QH ID	location of pin hole
MQXFA WS000001 - 13←002 221 49-03-1	1.43 m (mid-left track)
MQXFA WS000001 - 13←002 221 49-06-1	1.65 m (mid-right track)
MQXFA WS000001 - 13←002 221 49-07-2	0.40 m (right track)
MQXFA WS000001 - 13←002 221 49-09-3	2.80 m (mid-left track)
MQXFB HCMQXFBC19-WS000006	2.43 m (mid-left track)
MQXFB HCMQXFBC19-WS000007	0.90 m (mid-right track) 2.55 m (mid-right track)
MQXFB HCMQXFBC19-WS000009	1.26 m (left track)

Tensile properties of heater constituents



Polyimide film Kaneka Apical 200AV stress-strain curves acquired at RT (see EDMS No. 1902426).



Comparison of the RT load vs. strain behavior of the Polyimide film (2 (a)), the laminate GTS L960461 (2 (b)) and the Cu coated laminate (2 (c)).

APICAL AV

APICAL polyimide film possesses an excellent balance of physical, thermal, electrical and chemical properties over a wide range of temperature (-269°C [-452°F] to 400°C [752°F]). More precise thickness control, superior web flatness, plus improved adhesion and excellent dimensional stability are standard features with Apical polyimide films.

Major Applications

- Polyimide base materials for FPC.
- Motor generator insulation.
- Wire and cable insulation.
- Barcode label.
- Pressure sensitive tape.

Thermal Properties

Items	Units	Typical Values	Conditions	Methods
Coefficient of Thermal Expansion	ppm/°C	32	100 to 200°C	TMA

Chemical Properties

Items	Units	Typical Values	Conditions	Methods
Water Absorption	%	2.9	D-24/20	ASTM D-570
Coefficient of Humidity Expansion	ppm/%RH	16	50°C	HMA

Mechanical Properties

Items	Units	Typical Values	Conditions	Methods
Tensile Strength MD & TD	MPa	245	20°C	ASTM D882
Tensile Modulus MD & TD	GPa	3.1	20°C	ASTM D882
Elongation MD & TD	%	115	20°C	ASTM D882

Electrical Properties

Items	Units	Typical Values	Conditions	Methods
Volume Resistivity	Ωcm	$>10^{16}$	20°C	ASTM D-257
Dielectric Constant	-	3.3	20°C, 1 MHz	IPCTM-650
Dielectric Breakdown Voltage	V/μm	320	20°C, 60Hz	ASTM D-149

The data noted in these technical data sheets are given as examples and are not intended to be read as guaranteed values.

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Kaneka Apical AV data sheet (www.kanekatexas.com), 21st February 2017