Assessing Resin and insulation limits and improving electrical robustness

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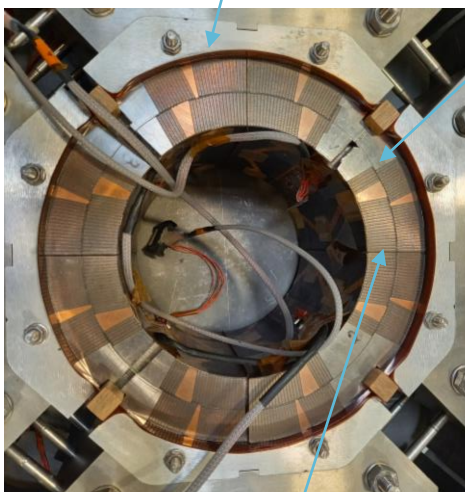
April 29th 2022 – Report on Ongoing actions for MQXFB

MQXF: dielectric challenges in a nutshell

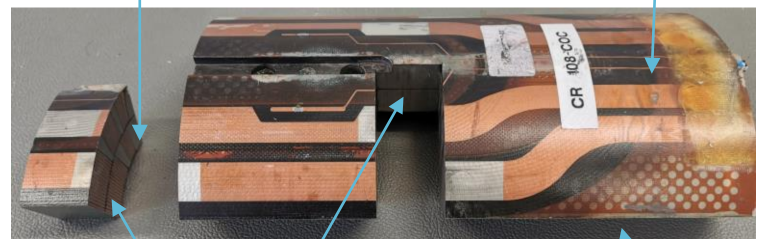
Coil to Structure

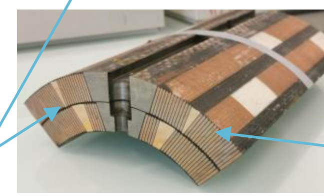


Coil to Coil

Coil to pole
5x125 microns S2 glass

Coil to endshoe





Interlayer insulation
Fiberglass layers (2x250+2x175 microns) impregnated with binder CTD1202

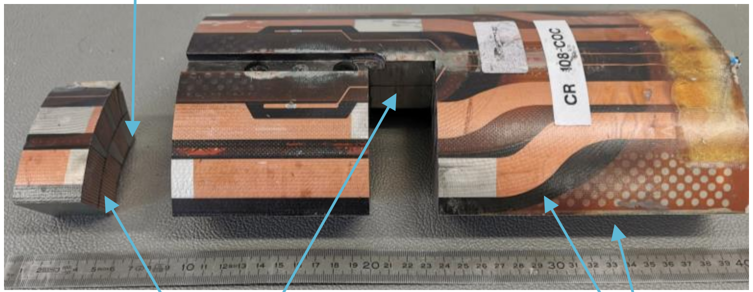
Quench heater to coil

+ vacuum impregnation with CTD 101K

Dielectric strength in the coil depends on our ability to preserve the **mechanical integrity of the insulation** at each stage of the coil, magnet fabrication and magnet operation

Context

Coil to pole
5x125 microns S2 glass



Interlayer insulation
Fiberglass layers (2x250+2x175 microns) impregnated with binder CTD1202

Quench heater to coil

- MQXFS : short model – 1.2 m magnetic length
- MQXFA : USA magnet – 4.2 m magnetic length
- MQXFB : CERN magnet – 7.15 m magnetic length

Key processes and materials inherited from LARP

- **CTD 1202 Binder** used in the interlayer insulation and during the winding to stiffen the fiberglass. Impact on fiber mechanical integrity
- **QH technology impregnated with the coil**: Cu/Stainless steel/polyimide laminate
- **CTD 101K** for vacuum impregnation

=> Production based on these processes and materials. Some improvements have been implemented during the MQXFB production

Dielectric status of fabricated coils/magnets (1/4) Coil to Ground

Electrical Acceptance based on a series of tests performed during coil, magnet, cold mass and cryostated magnet fabrication Flowchart of the electrical tests throughout the production - 2447487-v3

Voltage withstand levels for the magnet are set based on the HL-LHC Electrical Design Criteria for the IT magnets - 1963398 v6

Table 5. IT magnets electrical test values at *'Manufacturing Facilities and Test Stations'* stage.

Test name		**Test voltage**	**Value**
Test voltage at NOC at *'Manufacturing Facilities and Test Stations'* stage (V)	Coil to ground (5)	$V_{test1\ (ground)}$	1840
	Quench heater to coil (6)	$V_{test1\ (heater)}$	2300
Test voltage at gaseous helium conditions(2) (V) *At 100 K during warm-up*	Coil to ground (5)	V_{test5}	425 (MQXFA) 850 (MQXFB)
	Quench heater to coil (6)		
Test voltage at warm(3) before first helium bath (V)	Coil to ground (5)	$V_{test2\ (ground)}$	3680
	Quench heater to coil (6)	$V_{test2\ (heater)}$	3680(4)
Test voltage at warm(3) after helium bath (V)	Coil to ground (5)	$V_{test3\ (ground)}$	368
	Quench heater to coil (6)	$V_{test3\ (heater)}$	460
Maximum leakage current (µA) – not including leakage of the test station			10
Test voltage duration (s)			30

Dielectric status of fabricated coils/magnets (2/4) Coil to Ground

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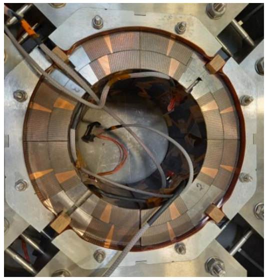

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Coil to ground

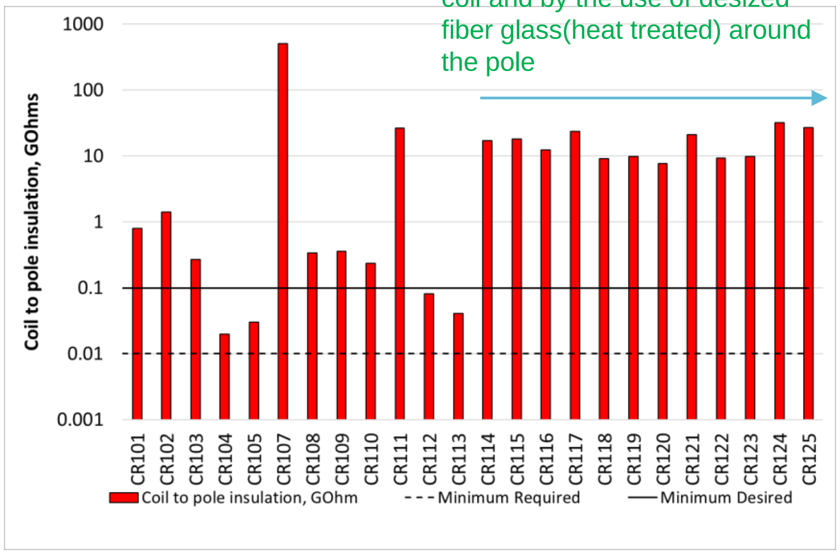
All the MQXF magnets passed these tests

except MQXFAP1 due to heater failure (see slide xx)

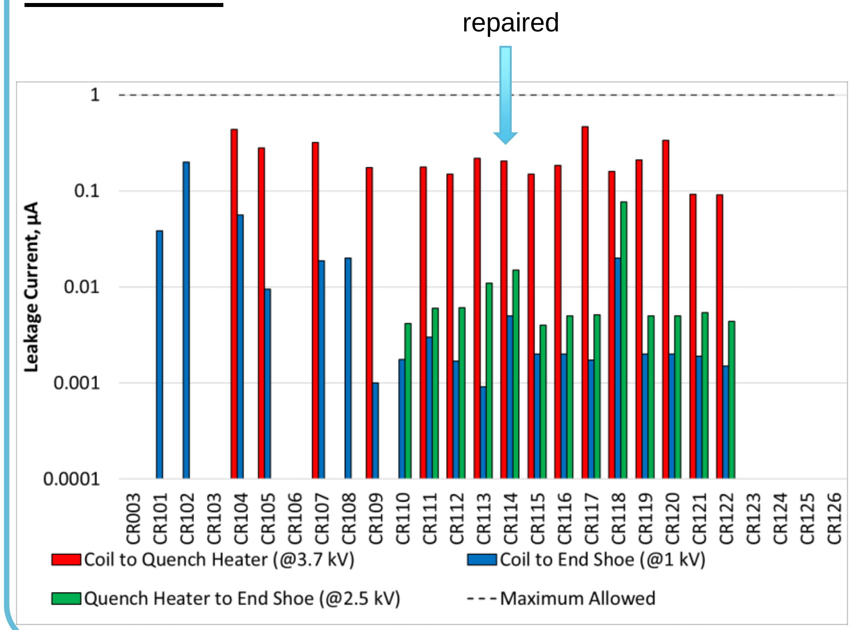
Dielectric status of fabricated coils/magnets (3/4) Coils after impregnation before assembly

MQXFB Coil winding to Pole – 100 V – 30 s

Improvement by reducing amount of ceramic binder in the coil and by the use of desized fiber glass(heat treated) around the pole



MQXFB - Coil winding to Endshoe/QH and QH to endhsoe



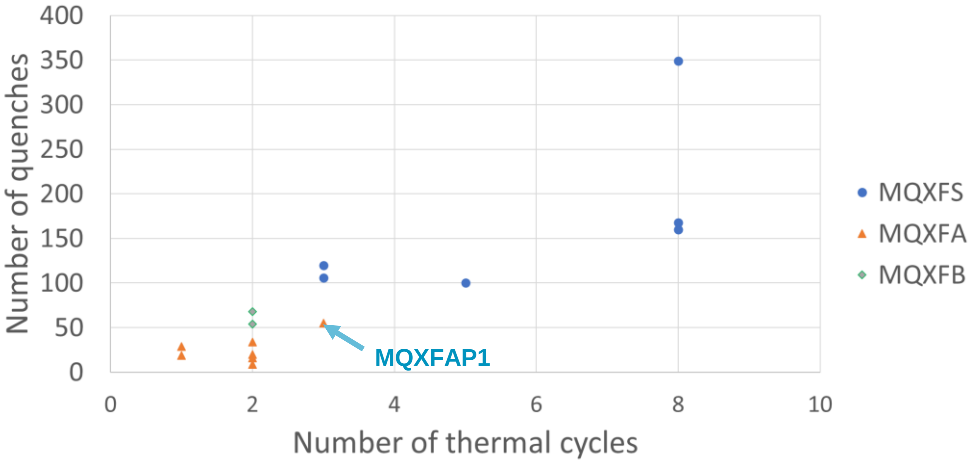
Coil to pole / coil to endshoe / endshoe to QH: leakage test passed for all coils after fabrication

Coil to QH:

- MQXFB: 1 coil out of 35 coils showed a defect after coil fabrication (including PIT and Cu coils)
- MQXFA: 2 coils out of 72 coils showed a defect after coil fabrication

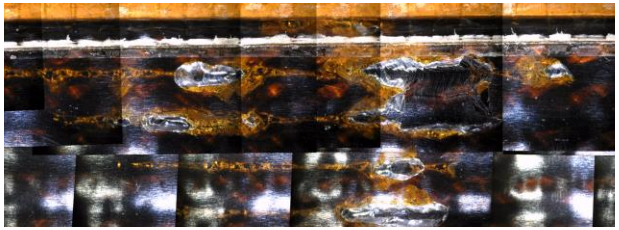
Dielectric status of fabricated coils/magnets (4/4) the specific case of QH

- At least 253 heaters experienced cooldown and training, assembled in short and long magnets
  - All passed 2.3 kV in LHe
  - All passed 460 V in air at room temperature after test
- 1 heater failure detected before test in MQXFAP1a
  - isolated but causing a short to ground



⇒ V breakdown values do not seem to be affected by the number of quenches or thermal cycles
EDMS 2229465 v.3

- Investigation on MQXFAP1a heater failure
https://ieeexplore.ieee.org/document/9366979
- Additional tests at high voltage to probe the limit of the dielectric insulation between coil and heaters were performed on tested coils
EDMS 2229465 v.3
- Blistering effect:
  - polyimide gets thinner by a rapid expansion of GHe trapped in bubbles in the impregnation => requires quenching and impregnation defects.

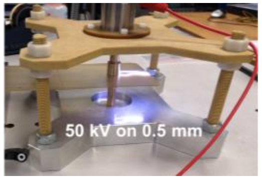


Decision to act on impregnation and QH design

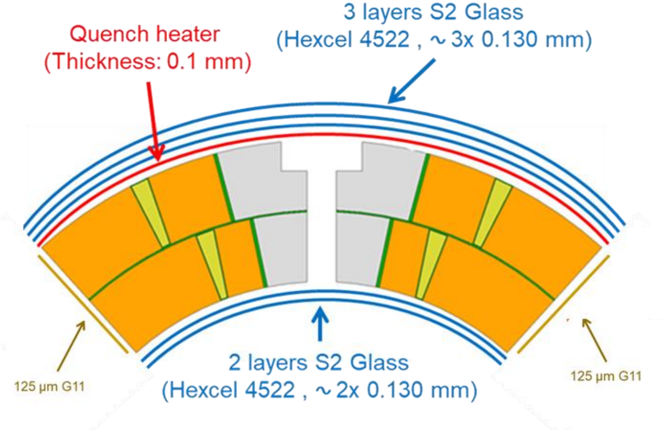
Improvements in QH robustness

To improve the reliability of the Quench heaters:

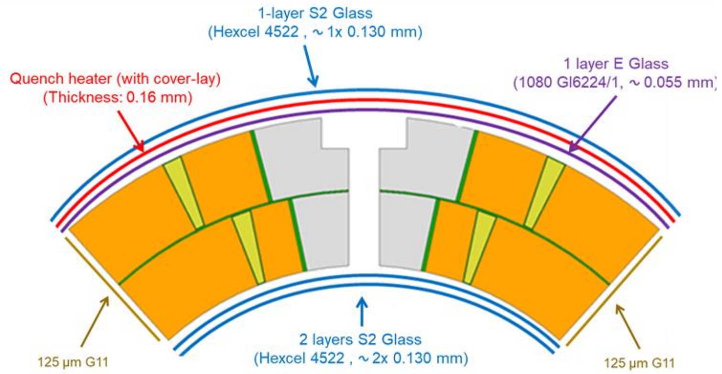
- Sandwich construction: addition of a Polyimide coverlay to improve the mechanical robustness of the QH (heaters circuit on the neutral axis)
- 0.055 mm E-glass (EDMS 2519642 (v.1)) added after reaction between heater and coil to :
  - Facilitate resin impregnation
  - Provide additional dielectric insulation heater to coil
- HV qualification tests on QH before installation from 3.7 kV to 5 kV



Initial Design



New Design

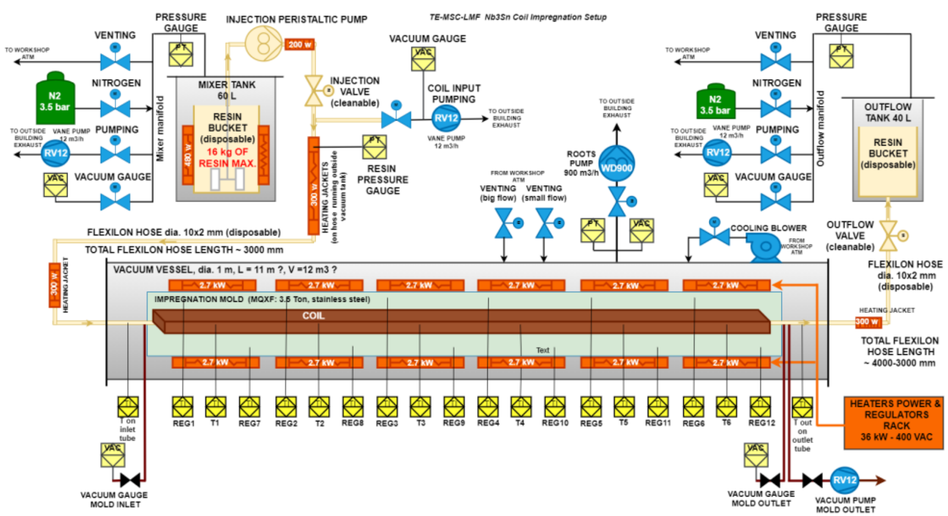


Presently implemented in coils 115/116 for MQXFS8
To be implemented in MQXFB from coil 126
Already implemented in 2 MQXFB Cu coils 004 and 005

MQXF QH Technical Meeting
https://indico.cern.ch/event/1077589/

Improvement of the impregnation process starting from coil 120

1. **Better degassing**
   a. installation of an additional pumping unit at the mould exit
   b. better monitoring of local mould pressures with the introduction of local (at the mould inlet and outlet) pressure pickups and, consequently, adjustment of degassing time
   c. better conditioning of the injection tank
2. **Increase of degassing temperature (coil + mould) from 80°C to 110°C**
3. **Tighter monitoring and control of the impregnation process**, new rule of iteration of the milking process based on 100% absence of bubbles at the outlet resin tank



All these improvements are implemented from coil 120 (i.e., coils for MQXFB02 already produced)

In summary: status in MQXFB

In MQXFB

- **CTD 1202 Binder** used in the interlayer insulation and during the winding to stiffen the fiberglass. Impact on fiber mechanical integrity => minimization of amount of binder use
- **QH technology** : Cu/Stainless steel/polyimide laminate => increase robustness of QH
- **CTD 101K** for vacuum impregnation => improvement of impregnation process

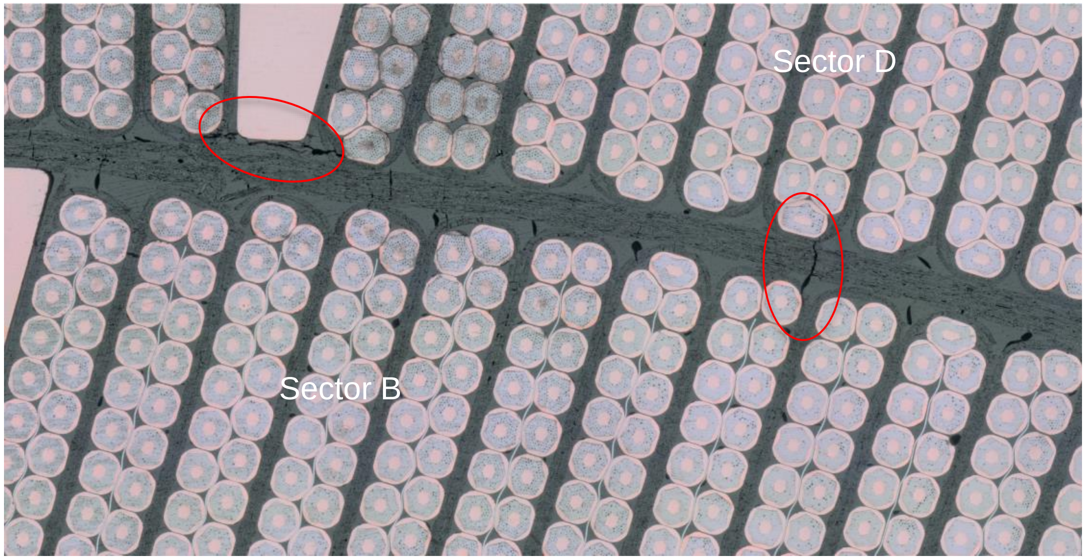
A few numbers

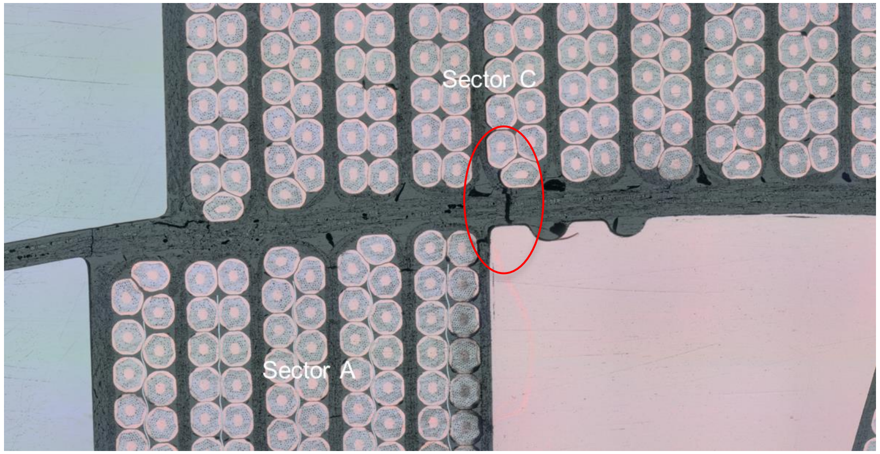
- 89 out of 91 long coils passed the required HV test before assembly (as of 10/2021)
- 38 long coils have been assembled in a magnet and tested at 1.9 K (as of 10/2021)
  - 30 for MQXFA => 1 out of 30 showed a defect QH2coil which became coil2GND defect
  - 8 for MQXFB => no defect
- MQXFB prototypes (P1 and P2) had 2 thermal cycles each and respectively 68 and 50 quenches

Improvements implemented
Low rejection rate for MQXF but additional possible improvement looking ahead

Recent observations

Courtesy of M. Crouvizier





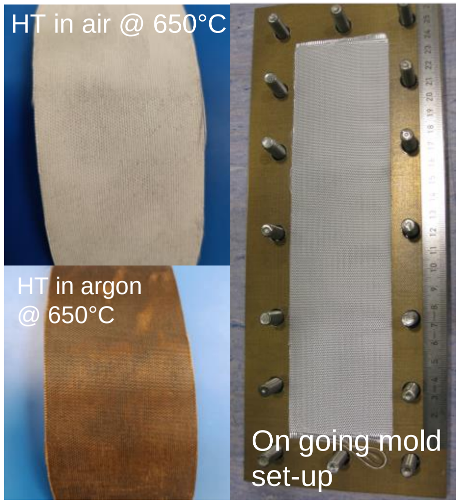
Recent in-depth observations show:
1) Interlayer and various cracks
2) Resin to components decohesion

Problematics to investigate:
- ✓ Impregnation process
- Mechanical and dielectric strength of the interlayer insulation and of the cable insulation
- Adhesion resin to components
- Resin thoughness

Systematic characterization of material

Tight connexion with HFM

Interlayer and cable insulation dielectric strength



Interlayer insulation

Questions to address:

- What happens to the organic part of the binder during heat treatment?
- Is the binder preventing a satisfying impregnation?

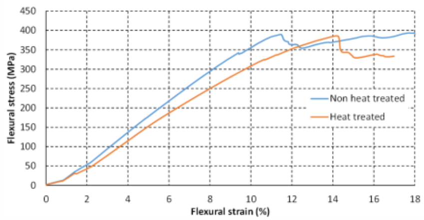
Ongoing studies: Dielectric, mechanical and chemical characterizations

- Understand the effect of the binder on the fiber
- Optimize the fabrication process of the interlayer

Cable insulation (braided fibre)

Ongoing studies

- Dielectric characterization before and after heat treatment
- Mechanical characterization (flexural tests)



Preliminary results indicate that the cable insulation dielectric strength and mechanical strength is not affected by the HT
Impact of the binder to be evaluated

Adhesion

Phase 1: benchmarking

- understand how to measure and characterize the adhesion strength of impregnation systems
- Production of reference samples: copper, stainless steel, glass tissue, polyimide…

Phase 2: characterization of adhesion in the coil components

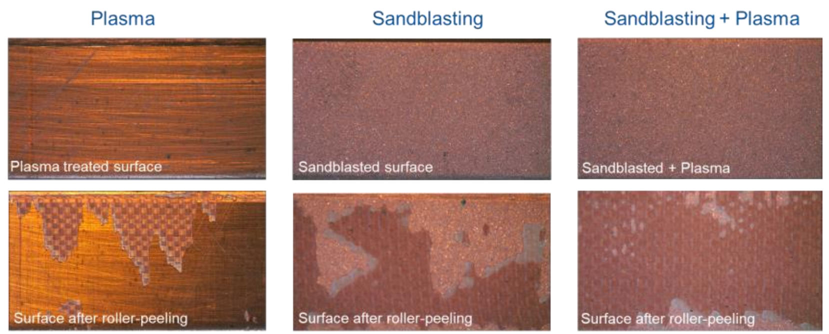
- characterize of adhesion strength towards, virgin and heat treated cable insulation, interlayer material (with binder), pole material, wedge material, mica sheets, Teflon coating…
- Identify and measure parameters which can be exploited in FEM

Ongoing Phase 1 activities

Sample design and test methods:

- Discussion with TE-VSC-SCC (Surfaces, Chemistry and Coatings)
- peel-off strength, shear strength, pull-off strength

Example of adhesion of CTD101K to copper, fiberglass-copper impregnated sandwich with various surface preparation

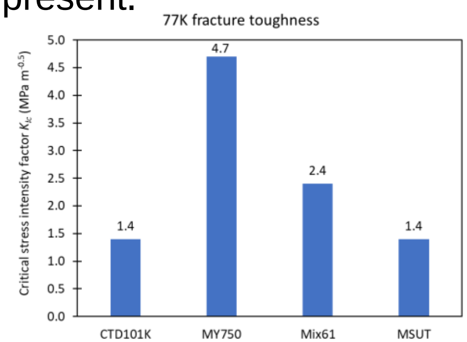


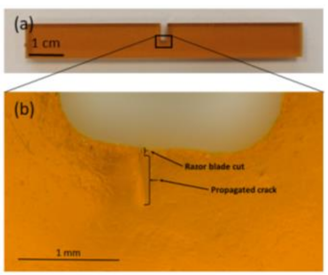
Courtesy of B. Verma

Adhesion studies are going on with first results expected by Q4 2022

Resin Fracture Toughness

The Fracture Toughness describes the ability of a material to resist fracture propagation when a defect is present.



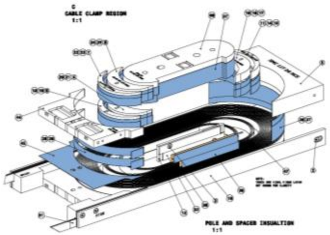


Courtesy of A. Garuud

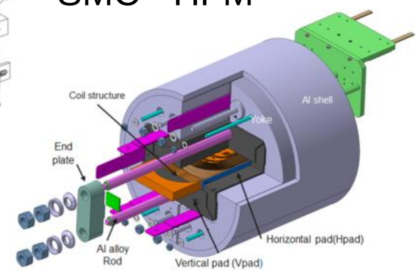
Example of CTD101 K single edge notched bending (SENB) specimen for 3-point bending experiment

https://edms.cern.ch/document/2715073/1

Beyond the measurement of the fracture toughness for each resin, the challenge is to understand the role of this parameter in the magnet performance

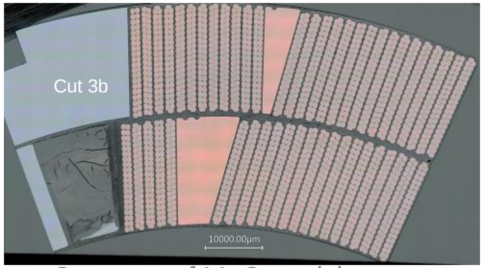


SMC - HFM



Courtesy of JC Perez

Resin rich area observed
Importance to reinforce with fibres
Issue with accessibility of some areas => Crushed S2 glass to fill in the gaps



Courtesy of M. Crouvizier

Minimization of the resin rich areas

Resin Fracture thoughness is not the only parameter which matters, radiation hardness and processability are also being investigated

Timeline for improvements

Adhesion

- Interim report 1 on adhesion studies (Q3 2022)
- Interim report 2 on adhesion studies (Q4 2022)

Interlayer

- Report on HT coil interlayer (Q3 2022)

In case of convincing results, compatible with HL-LHC timescale

Q2 2022 | Q3 2022 | Q4 2022 | Q1 2023 | Q2 2023

HFM

Cable insulation

- Report on HT impregnated braid (Q2 2022)

Resin development

- Interim report 1 on tougher resin (Q3 2022)
- Prelim report on irradiation of impregnation system in air (Q4 2022)
- Interim report 1 on tougher resin (Q1 2023)
- Start of irradiation campaign at cold (Q2 2023)

In Summary

- Coils and magnets are meeting the dielectric requirements
- Along the production, improvements have been made to increase the mechanical robustness and therefore the dielectric strength inside the coils
  - Additional studies on interlayer and adhesion are ongoing and could lead to further improvements in the timescale of HL-LHC MQXFB coil production.
  - Characterization of resins are ongoing but the switch to another resin than CTD101K is not considered in the timescale of HL-LHC
- Irradiation tests under various radiation sources, temperatures and atmospheres have been initiated but timeline to get meaningful results is of the order of about 2 years.
- So far, tests performed on short model magnets and MQXFA05 (endurance test) do not show evidence of degradation. Importance to perform this type of tests (thermal and powering cycles) in upcoming short models and long magnets.