MQXF Quench Heaters Assessment

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with contributions from many colleagues

9th HL-LHC Collaboration Meeting,
Fermilab, USA, 14-16 October 2019

Outline

- **Requirements**
- Design
- Measurements
- Inspection
- Analysis
- Conclusions

Electrical Requirements

- EDMS# 1963398

- Summary Table:

EDMS NO. 1963398 | REV. 2.0 | VALIDITY APPROVED

REFERENCE : US HL-LHC-AUP#: US-HiLumi-doc-879

ENGINEERING SPECIFICATION

ELECTRICAL DESIGN CRITERIA FOR THE HL-LHC INNER TRIPLET MAGNETS

Component	V_max @ nominal current	V_test @ 1.9 K	V_test @ 300 K	V_test @ 300 K after He
Coil-Ground	670 V	1840 V	3680 V	368 V
Coil-Heater	900 V ✓	2300 V* ✓	3680 V** ✓	460 V ✓

Maximum leakage current to ground (μA) – not including leakage of the test statation	10
Test voltage duration (s)	30

Notes:
*Some coils/magnets did not meet it: test facility limitation found/assumed
**Value agreed in order not to exceed the test voltage coil to ground.

See talk *"Voltage Withstand Levels"*

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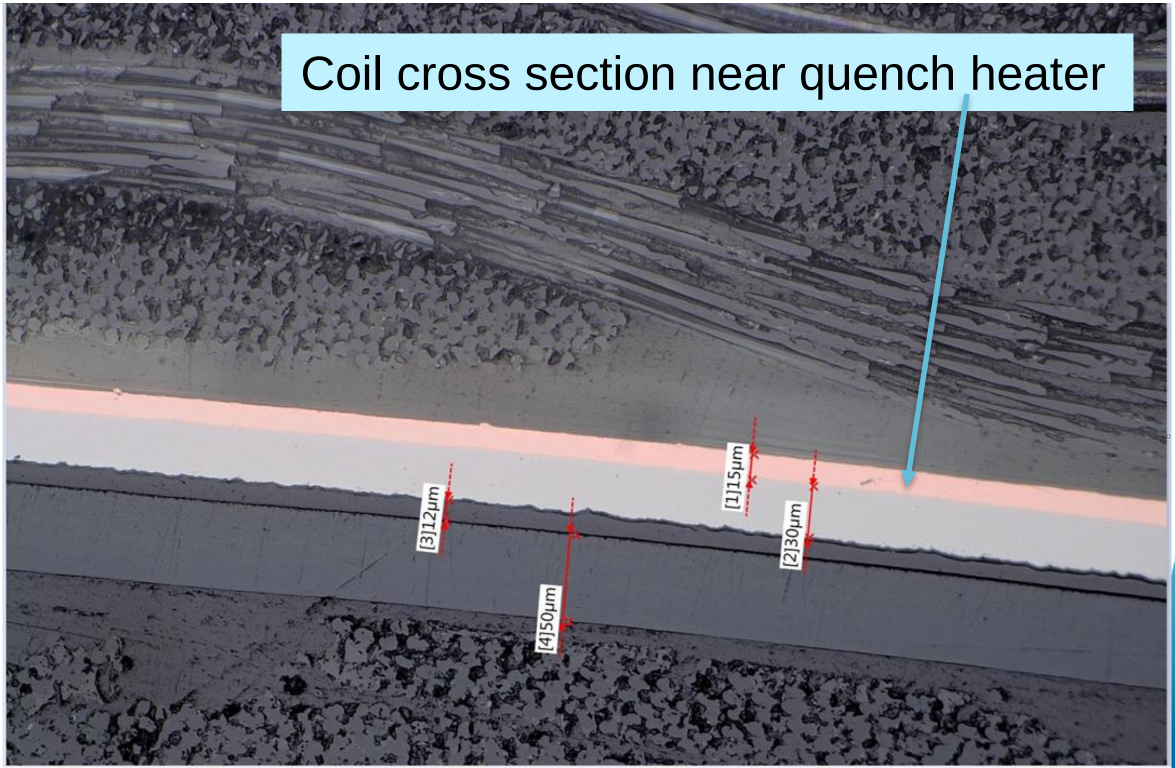
MQXFA Quench Heater Design

- MQXFA Quench Heaters:
  - 50 um polyimide + 12 um glue + 25 um steel + 10 um copper (in some areas) ➔ **<u>200 um</u>** Heater-Coil distance (including 145 um cable insulation)
  - Additional 50 um polyimide in the ends
  - Holes in polyimide at **<u>4 mm</u>** from heaters ➔ Max V at 300 K in He gas is **900 V**



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Heater-Coil HiPot Results

- Test methods and results reported in: "Hi-Pot tests of MQXF Quench-Heaters to coils"

US HL-LHC AUP	Hi-pot tests of MQXF Quench-Heaters to coils	US-HiLumi-doc-2293 Other: Date: 06/28/2019 Page 1 of 26

US HL-LHC Accelerator Upgrade Project

Hi-pot tests of MQXF Quench-Heaters to coils

M. Baldini

Abstract- The United States High Luminosity Large Hadron Collider Accelerator Upgrade Project (US-HL-LHC AUP) is designing and fabricating 10 Q1/Q3 cold masses for the interaction regions of the LHC. Each cold mass contains two 4.2 m quadrupole magnets (MQXFA). The Nb_3Sn quadrupole MQXFA magnets operate in superfluid He at 1.9 K with a nominal field gradient of 132.6 T/m. The MQXF protection system is based on CLIQ (Coupling-Loss Induced Quench system) and outer layer quench heaters [1].

This note reports a summary of the quench heaters to coil high voltage (Hi-pot) tests performed on MQXF short and long coils. A total of 104 heaters were taken into consideration. All heaters passed qualification test after fabrication (at different thresholds because many of them were tested before threshold finalization). Some heaters failed after magnet cold powering test. In this note first voltage failures after cold powering have been identified. No first failures were observed below 1100 V in air at 300 K. Among all the heaters: 48 passed the high voltage tests above 2300 V and 6 failed below 2000 V in air.

This analysis helps to determine a range of voltage target values to perform high voltage tests without compromising the insulation integrity after exposure to liquid He.

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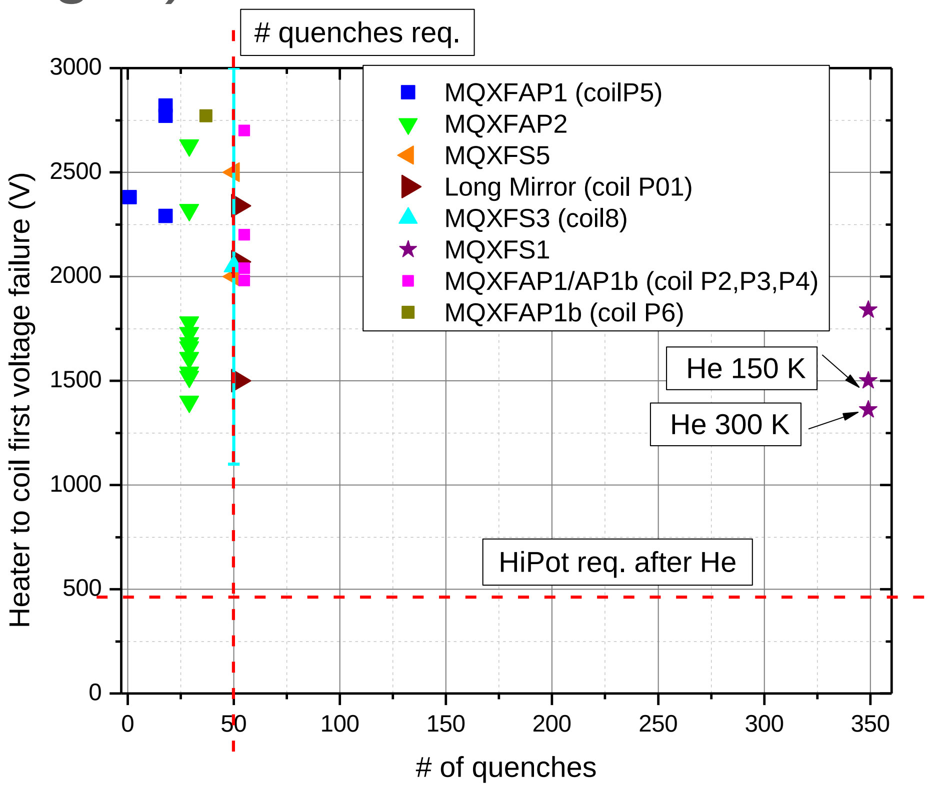
Available at:
http://us-hilumi-docdb.fnal.gov/cgi-bin/ShowDocument?docid=2293
EDMS# 2229465

HiPot after He Exposure – Above Requirement

- 28/106 heaters failed HiPot below 3 kV in air at 300 K after cooldown and magnet training (in plot)
- Minimum voltage of first failure: 1400 V
- No further degradation after 350 quenches (tested in He gas)

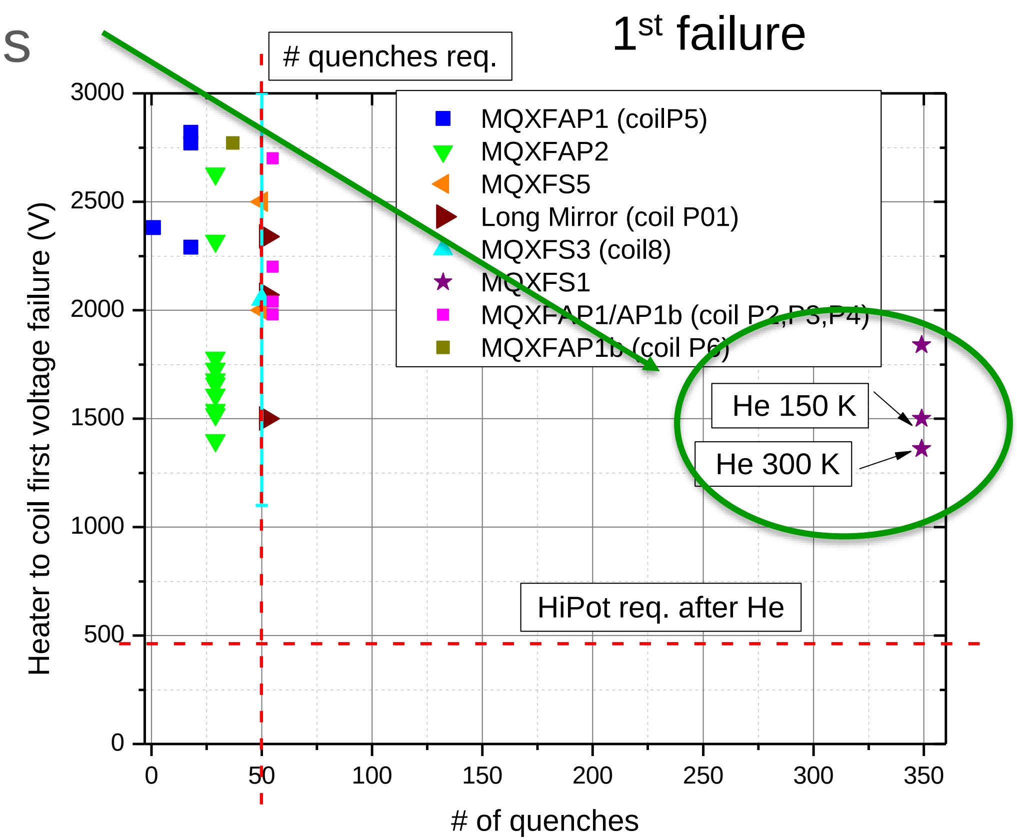


Observations:

- Design meets requirements with x3 margin
- Possible explanation of failures above 900 V at 300 K is through holes in polyimide and cracks in epoxy because of trapped He

Long Term Reliability

- Is QH insulation performance getting worse with number of quenches or thermal cycles?
- Answer: No
  - MQXFS1: 350 quenches
  - and 7.5 thermal cycles



Hipot Tests in He gas

- 60 heaters tested in He gas after magnet training
- No failure below 1.5 kV at 150 K

* 2 heaters of MQXFAP1b were disconnected because of old design

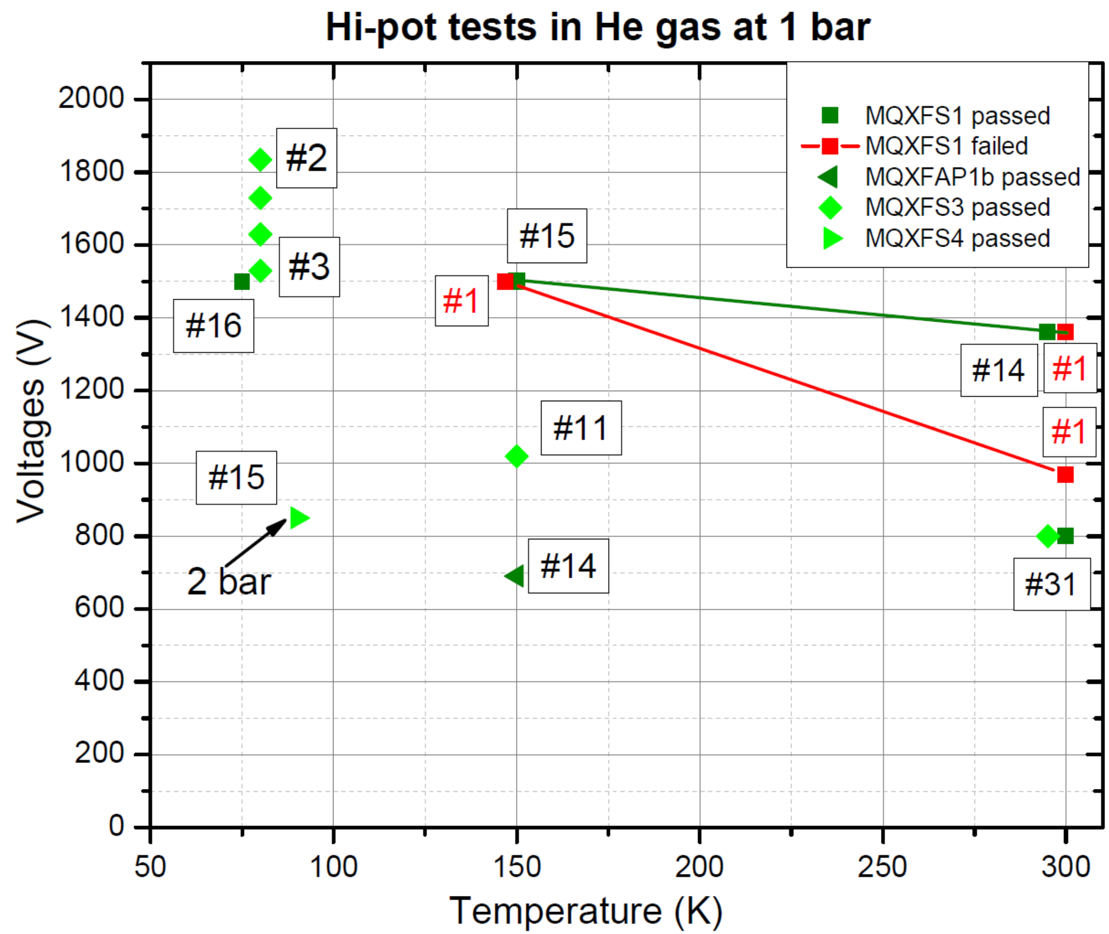


Fig 5. Heater-Coil HiPot in He gas (1 bar) after magnet training

Outline

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- **Inspection**
- Analysis
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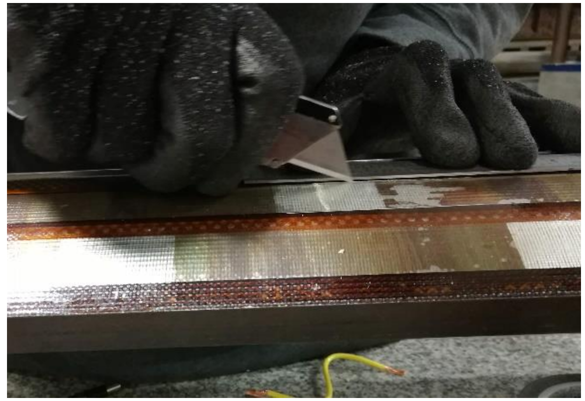
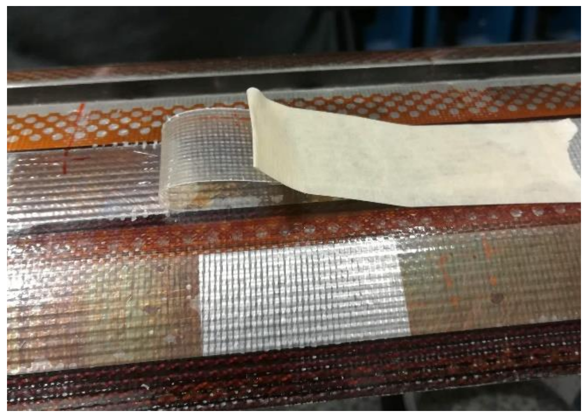
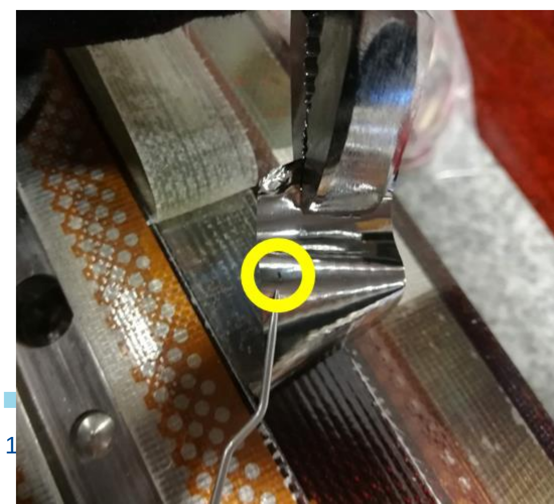
Coil QXFP01 autopsy: Heater removal at 1st Hipot failure location

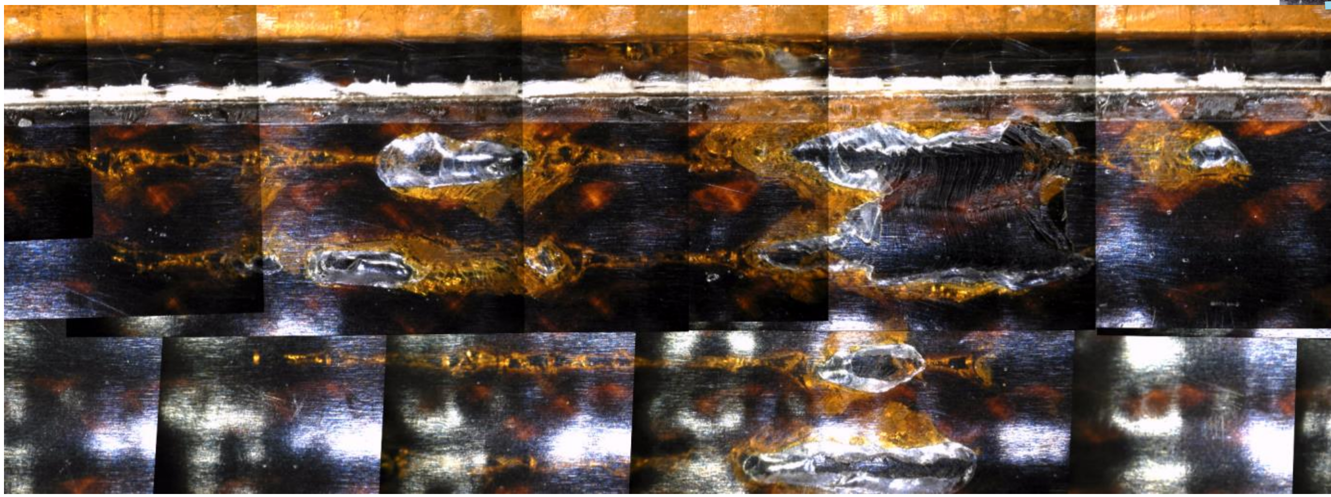




Second Hipot failure location

Heater peel-off damaged polyimide:
Polyimide found on heater after removal

2nd Hipot failure location



Observations:

- Polyimide is thinner than nominal in some areas (white areas)
  - A few measurements: 17-20 um
- All white areas are on top of bubbles in epoxy (yellow areas)
- These bubbles are set between turns and run along turns

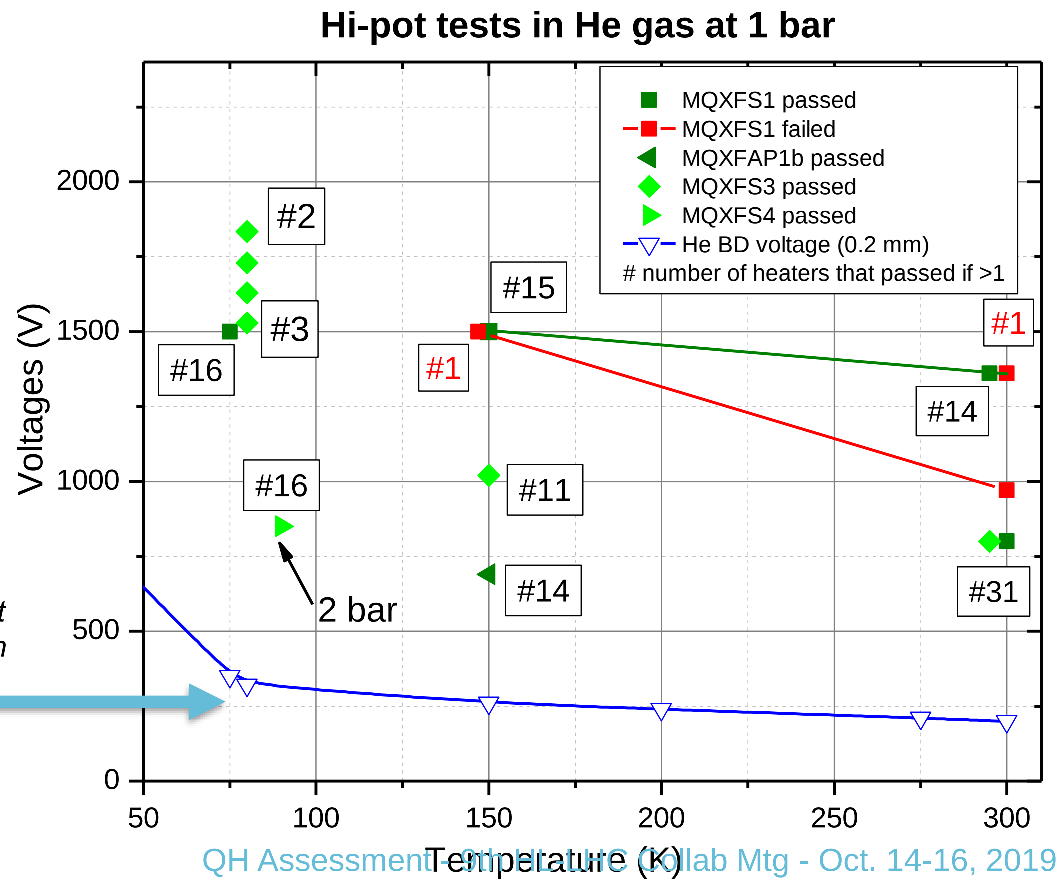
Mechanism:

- **Blisters due to helium pressure during quench**
  - Helium is “stored” in bubbles btw turns
- ~~No cracks propagating from epoxy into polyimide~~

Feedback from measurements - I

- Measurements in He gas demonstrate <u>NO breaching of polyimide (0/60)</u>
  - Direct path breakdown voltage < 300 V at 150 K

Fig 5. Heater-Coil HiPot <u>in He gas (1 bar) after magnet training</u>



P. Fessia, G. Kirby, J.C. Perez, and F.O. Pincot, *"Guidelines for the insulation design and electrical test of superconducting accelerator magnets during design assembly and test phase"* CERN EDMS# 1264529.

Feedback from measurements - II

- 1^{st} failure in He gas consistent with 4 mm path

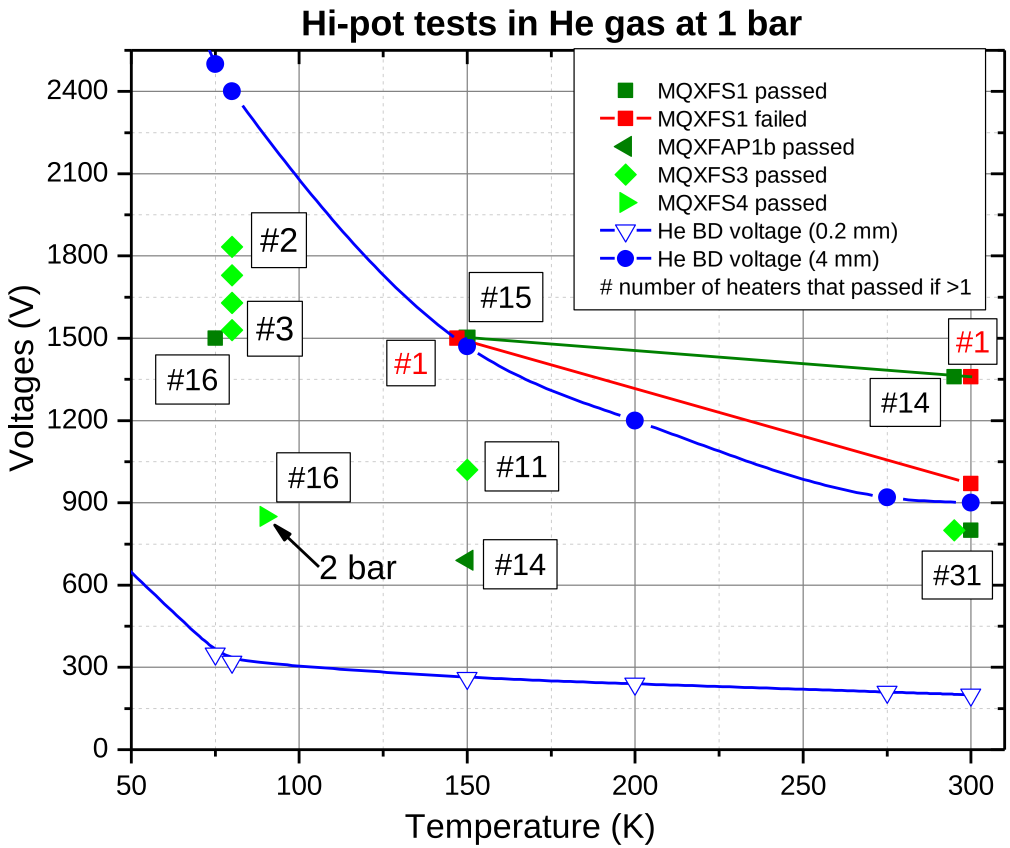


Fig 5. Heater-Coil HiPot <u>in He gas (1 bar) after magnet training</u>

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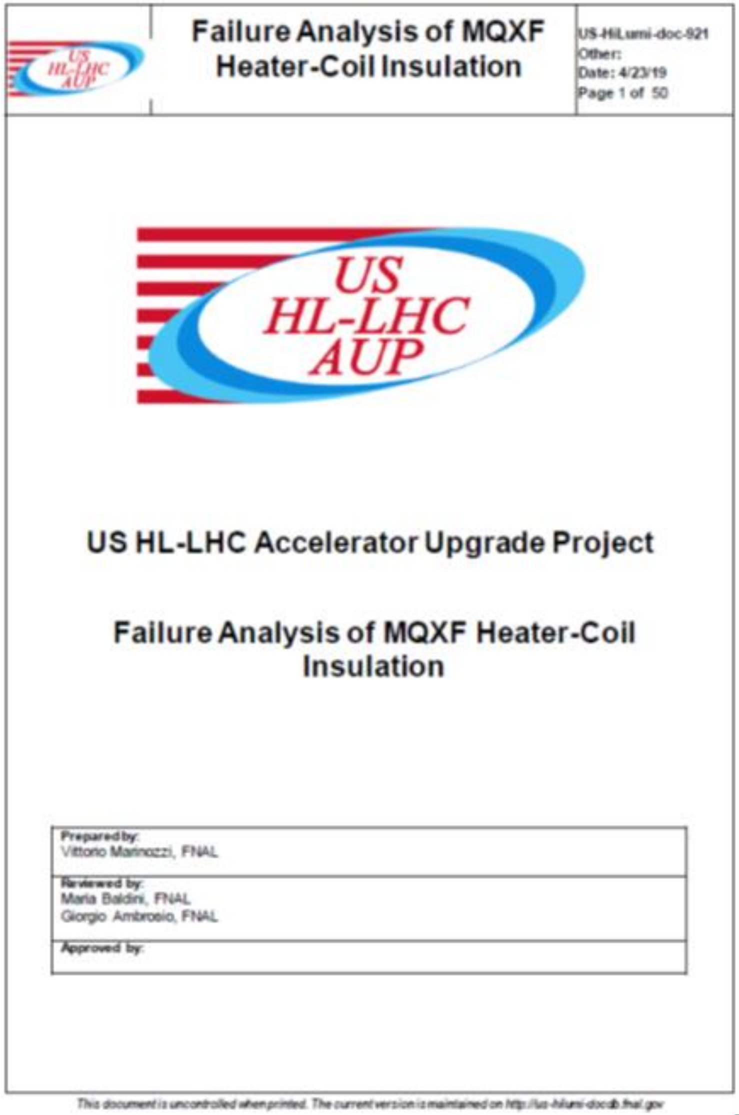
Failure Analysis

- What may happen if polyimide fails and there is a direct path Heater to Coil?
- Minimum path: 200 um
- MQXFB: 660 V at 100 K
- MQXFA: 390 V at 100 K
  - Peak Heater-Coil Voltage (I_nom) with 2 QH failures, realistic conductor parameters NOT uniformly distributed and coil ordering.

A. Verweij
https://indico.cern.ch/event/835702/contributions/3503953/


Failure Analysis of MQXF Heater-Coil Insulation

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Other:
Date: 4/23/19
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US HL-LHC AUP

US HL-LHC Accelerator Upgrade Project

Failure Analysis of MQXF Heater-Coil Insulation

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Approved by:

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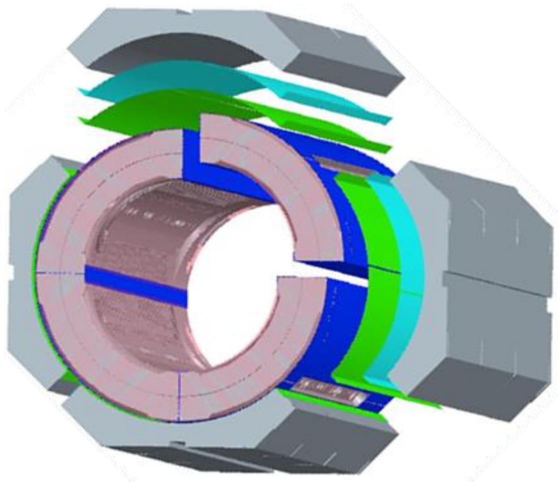
He Pressure

- During quench the pressure of He trapped in bubbles is going to increase significantly
- Note: if there is no He under pressure there is no blistering of polyimide
- Contact pressure between coil (outer layer) and structure is always above 10 MPa, or **100 bar**
  - He isochoric expansion (1.9-100 K): 530 bar



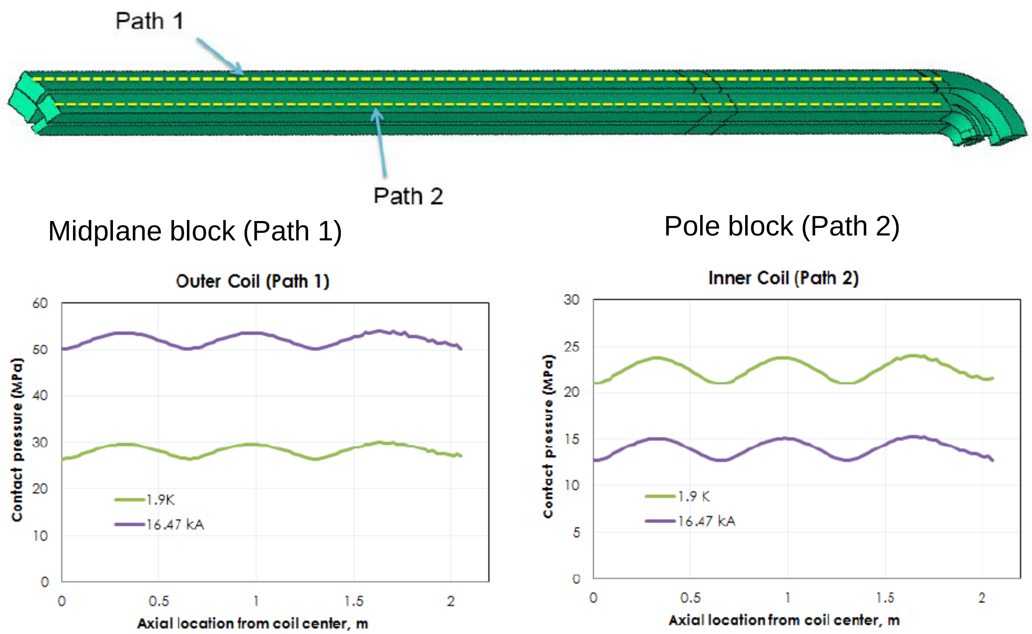
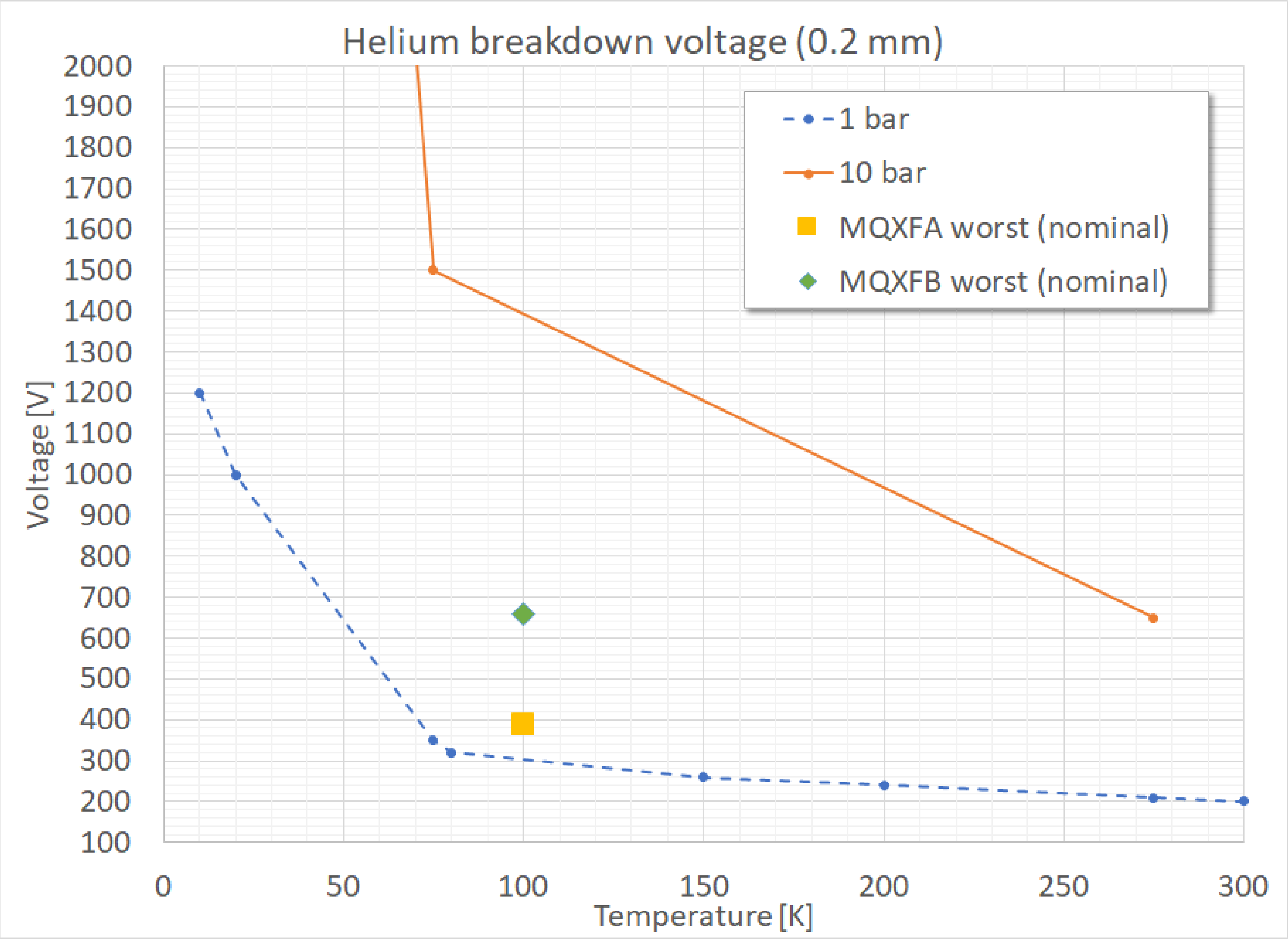


Figure 7: Average contact pressure between MQXF coil (outer layer) and structure on the midplane block (path 1) and on the pole block (path 2). Green curves show the contact pressure after cool-down (1.9 K), purple curves show the contact pressure after energization at nominal current (16.47 kA). The pressure is always higher than 10 MPa in all considered scenarios.

Helium Pressure During Quench

- Assuming only **10 bar** pressure for trapped He during quench ➔ margin against voltage breakdown: **~1.4 kV** at 100 K



Proposed Intermediate-Temperature HV Test on HL-LHC Nb_3Sn Magnets

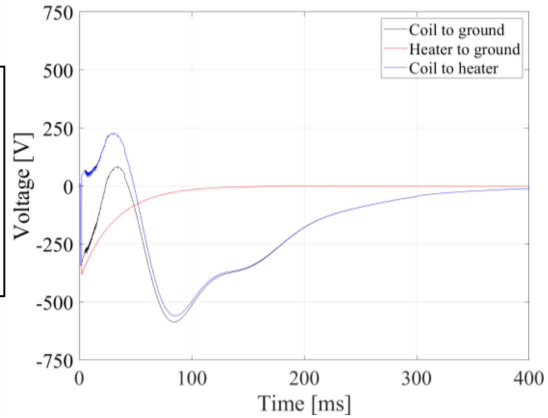
- It has been proposed to apply a 20% margin on top of the considered maximum voltage at quench
- However, we have to make sure that a) non-homogeneity of conductor parameters is considered and b) ultimate current values without margin are covered

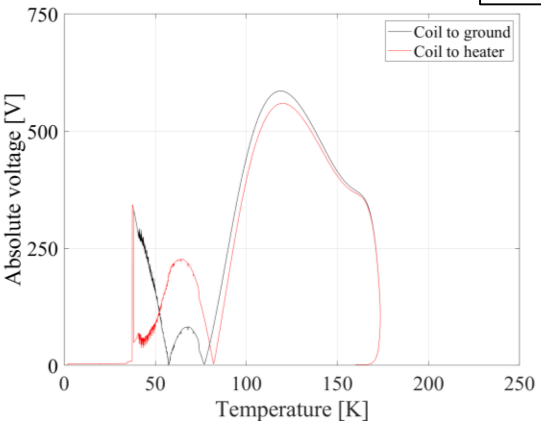
Magnet	1.2 * $V_{max\ @nominal}$	$V_{max\ @ultimate}$	Maximum value at I_{nom} with conductor variations
11T MBH	1.2*1400 = **1680 V**	1519 V	1560 V
MQXF	1.2*670 = 804 V	850 V	**850 V (*)**

(*) MQXF- For realistic parameters, in case of up to two failures, with coil **ordering within the same magnet**:
$U_{coil-gnd}$ <670 V at $I_{nominal}$
$U_{coil-gnd}$ <850 V at $I_{ultimate}$

See [3]

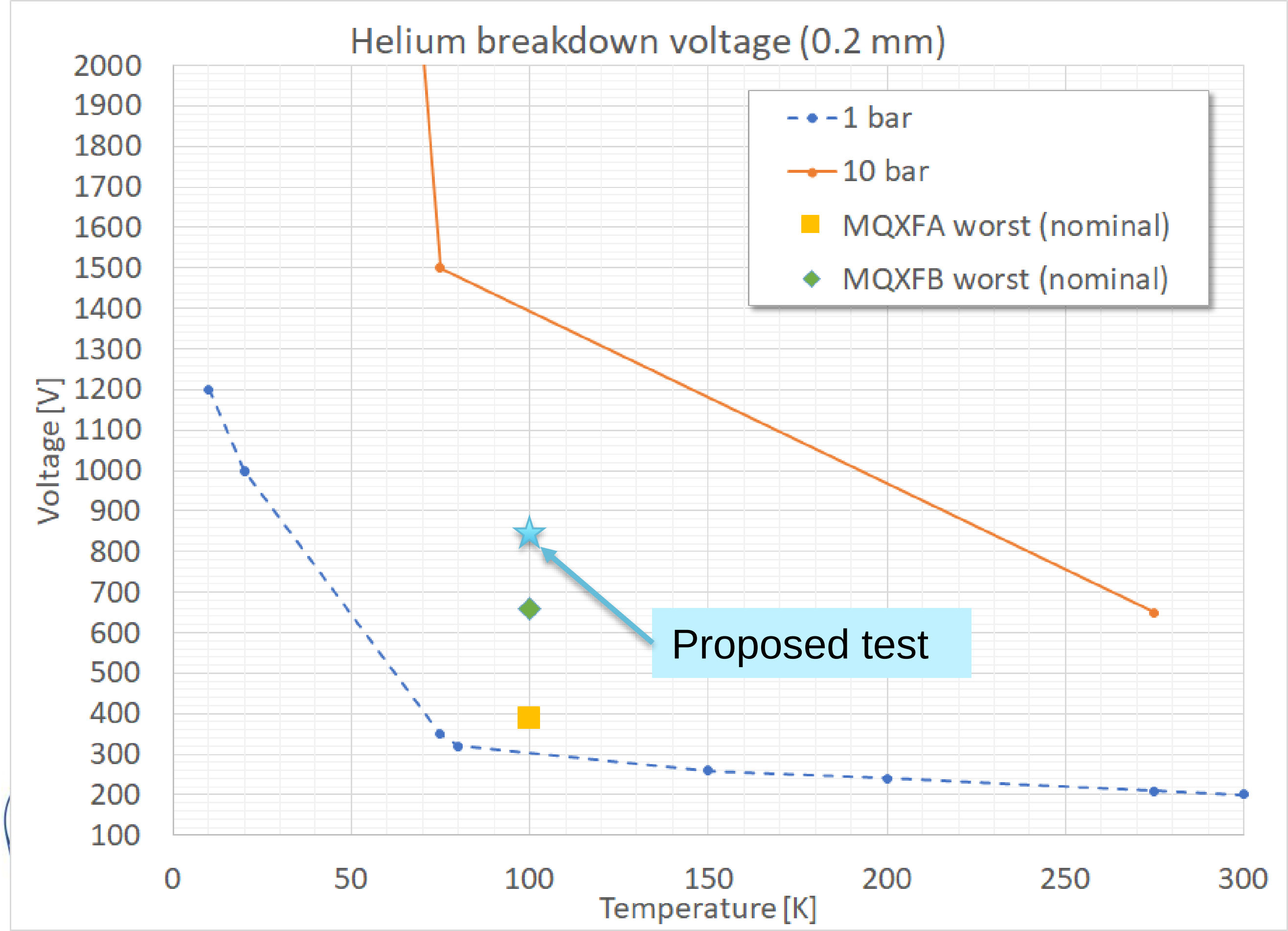
Voltages as a function of time and the local conductor temperature (not the worst case is shown).
Courtesy: E. Ravaioli





Intermediate Temperature Test in He

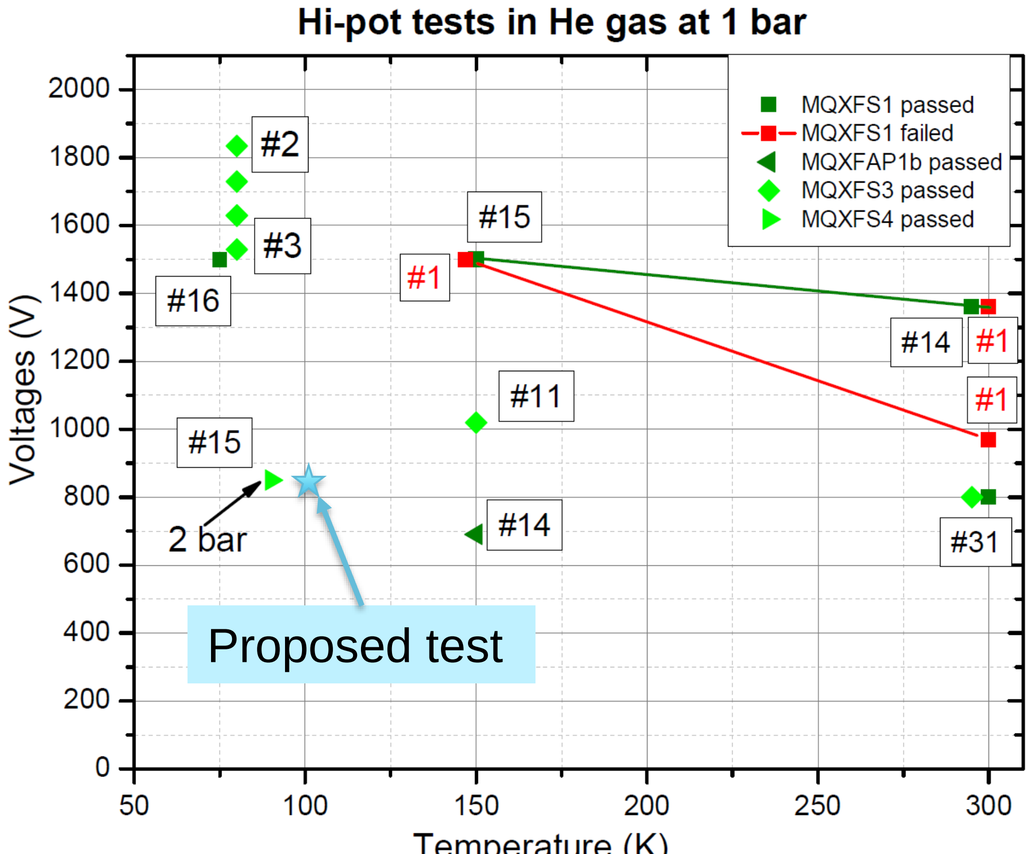
- Demonstrates:
  - No breaching of polyimide
  - Margin w/o pressure effect above max voltage



New Test & Present Design

- Does the present design meet the proposed test/requirement?
- Answer: yes (with limited statistic: 60/60)

Fig 5. Heater-Coil HiPot <u>in He gas (1 bar) after magnet training</u>



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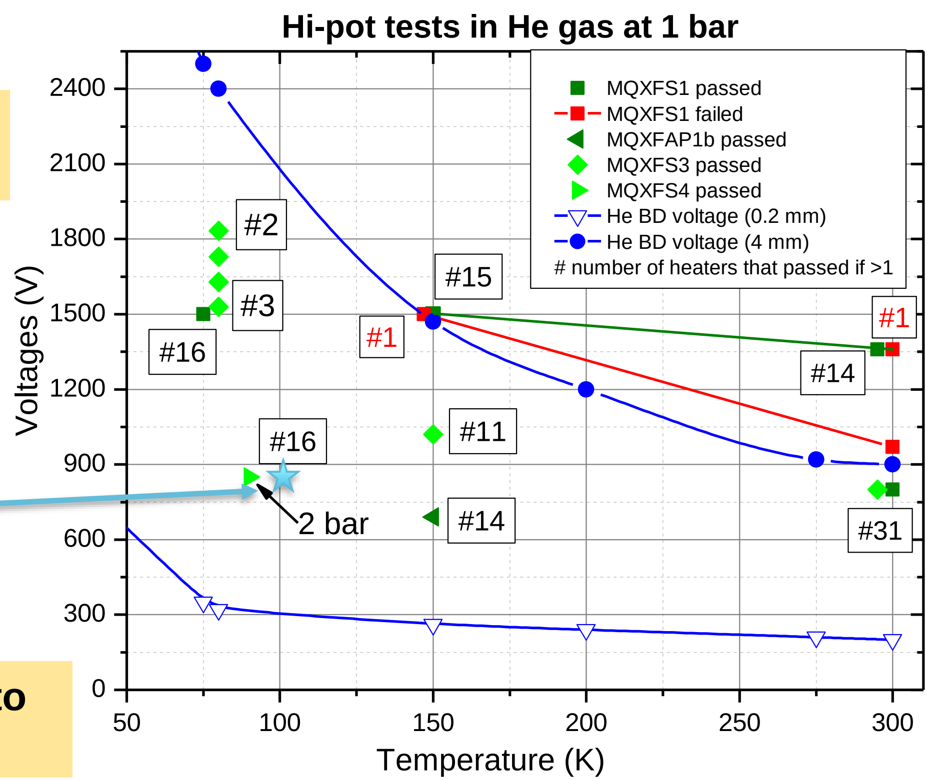
Summary

- Present design meets requirements
- Measurements (Heater-Coil Hipot after training & TC):
  - No 1st failure in air < 1.4 kV at 300 K
  - No 1st failure in He gas < 1.4 kV at 150 K
- Inspection:
  - Blistering makes polyimide thinner
  - Blisters caused by expansion of He in bubbles btw turns
- Analysis:
  - Helium expansion during quench is going to increase helium voltage breakdown to ~1.4 kV at 100 K
    - Under assumptions presented

Technical Proposal* - I

- Add test proposed by Felix during Circuit Review
  - Heater-Coil Hipot at 850 V, 100 K in He (~1 bar)
  - At the end of Magnet/Coldmass training & Therm Cycle
  - Assures NO polyimide BREACHING
  - The additional margin provided by He pressure during quench will assure no issue during whole HL-LHC life

Fig 5. Heater-Coil HiPot in He gas (1 bar) after magnet training



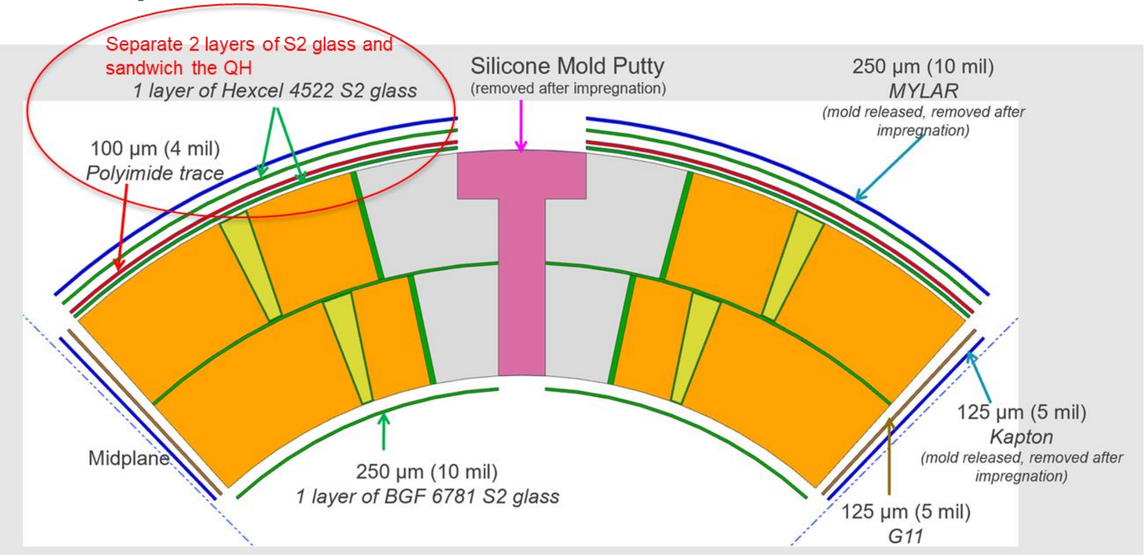
Proposed test

***Cost & Schedule implications to be addressed by Project Office**

Technical Proposal - II

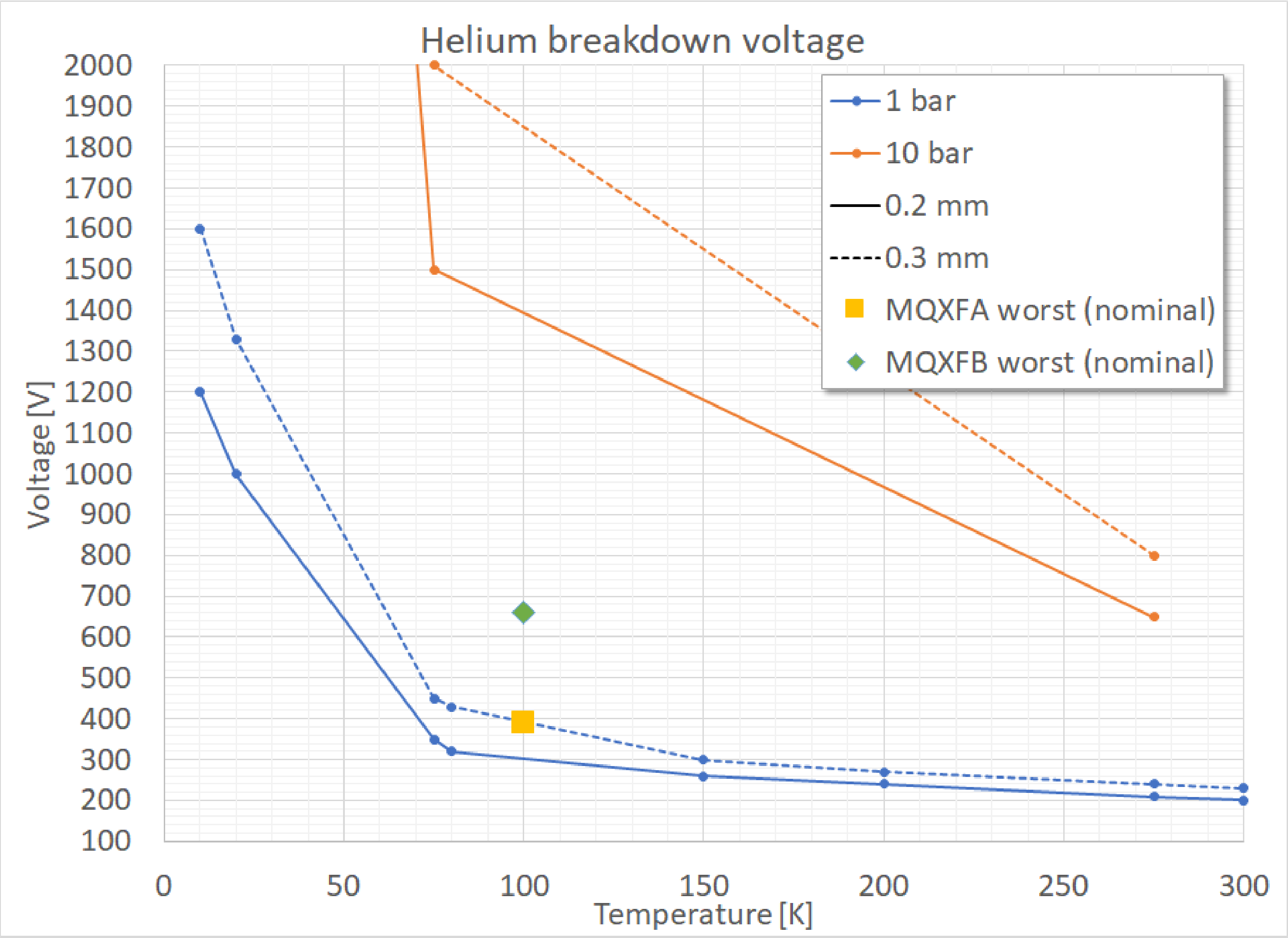
- Swap one layer of fresh fiberglass with QH
  - It will reduce risk that some coils may not pass "Felix test"
  - It will make a G11 layer separating polyimide from the bubbles btw turns (➔ prevent polyimide blistering)
  - It will increase Coil-Heater distance (➔ increased He voltage breakdown)

Swap performed on coils QXFS04 & 10.
No issues with epoxy impregnation.
Passed all Electrical Tests.
QXFS10 to be tested in Mirror Magnet in Jan 2020

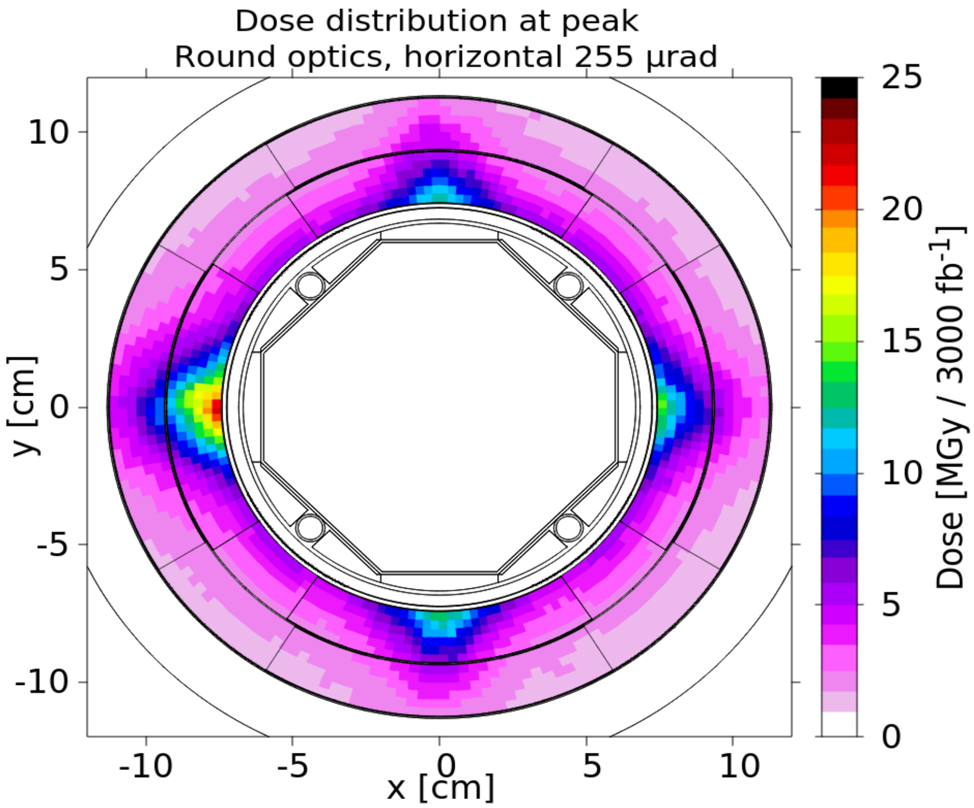


Back up Slides

He VB with 0.2 & 0.3 mm distance



Radiation Dose



F. Cerutti, M. Sabate Gilarte, G. Lerner, A. Tsinganis, RADIATION LOAD ON THE NEW MAGNETS OF THE EXPERIMENTAL INSERTIONS, EDMS#**2136375**

HiPot after Coil Fabrication at 300 K

- 220 MQXF heater strips tested at room temperature
- All heaters passed HiPot after coil fabrication before He exposure
  - Present requirement in magnet: 3680 V

	#coil	2000 V	2500 V	3000 V	3200 V	3680 V	3700 V	5000 V
Short model	29	1	23 (17*)	3	1			1
MQXFA	18		2 (2*)		11 (8*)	5		
MQXFB	8			4			4	

* assembled and tested in a magnet.

Table 5: Voltage targets used in high voltage heater to coil tests prior to Electrical QA criteria approval.

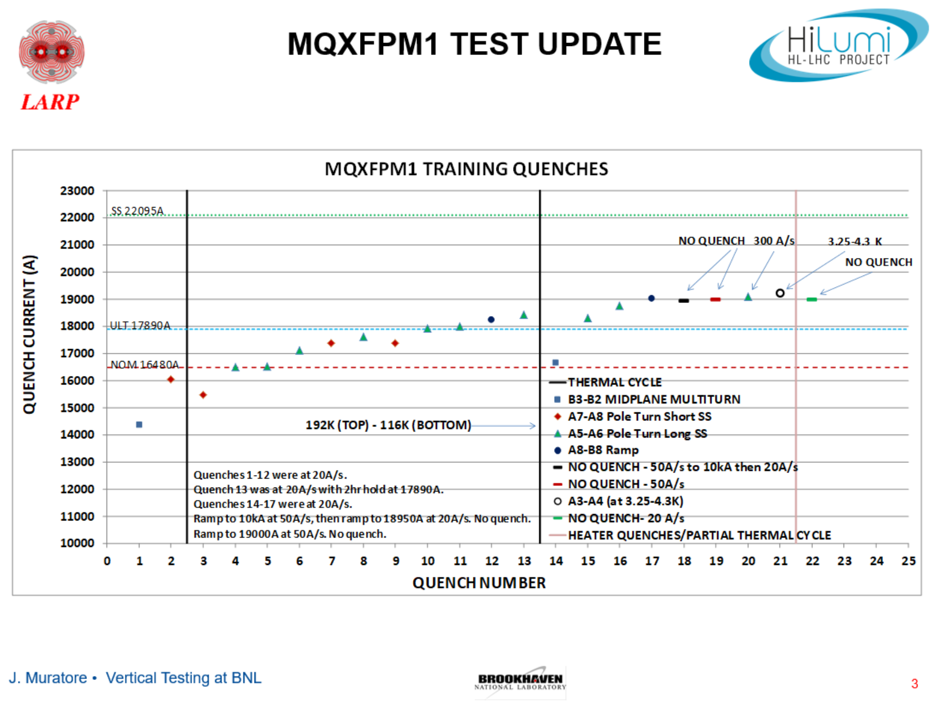
HiPot after He Exposure - I

- 106 heaters experienced cooldown and magnet training
- All 106 heaters passed HiPot requirement
  - **460 V** in air at 300 K

➔ There is no issue wrt present Electrical Requirements

Background

- QXFP01 was the first long prototype coil
- All traces passed electrical test at 2500 V before testing
- Successfully tested in mirror configuration
- The coil had 22 training quenches, and 30 QH induced quenches



- **One of the OL midplane traces never failed**
- **The other OL midplane trace failed at 2340 V (breakdown) immediately after warm up,**
- **The two pole traces failed after warm up respectively at 1500 V and 2070 V (breakdown).**

Background

After Disassembly and Hipot testing heater 2 (Pole, Transition), a short was created at a location that was determined by thermal imagery. This location was later verified by poking it and watching the resistance change

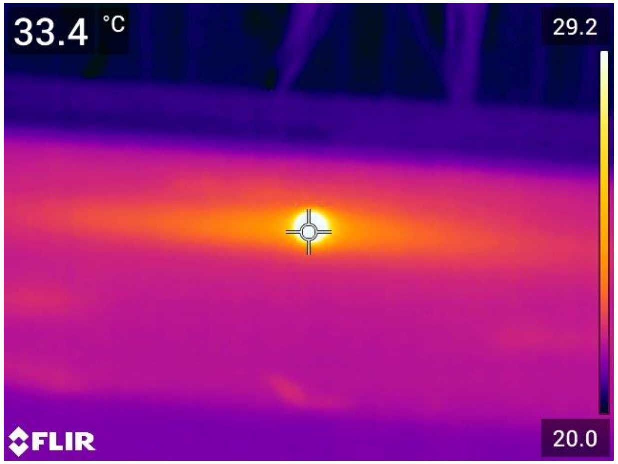
A plan was determined as follows:

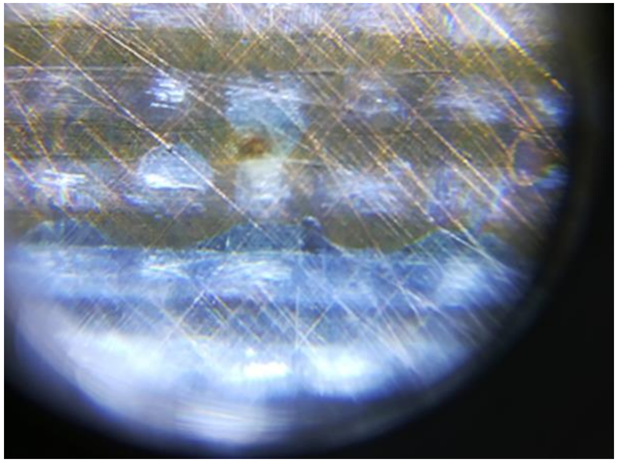
- Peel glass off of heater and observe location, check if short is still there
- Separate heater from trace and examine area
- Check for other shorts

And after discussion

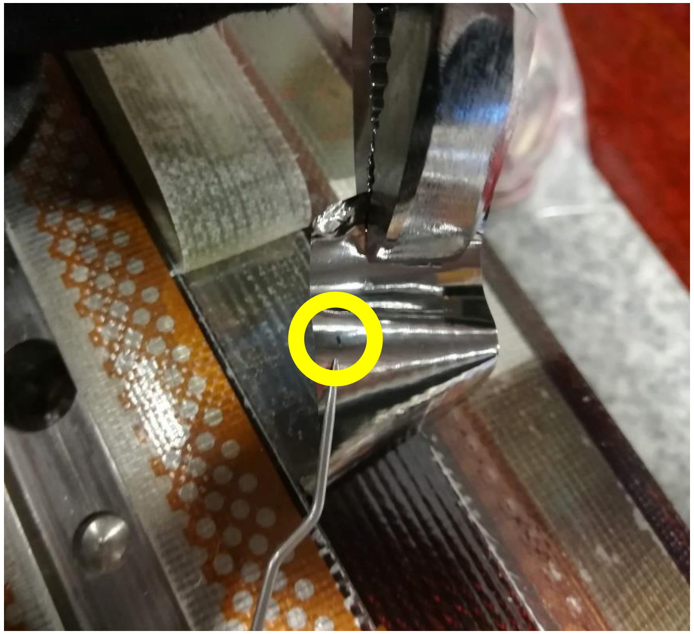
Work to develop and identify more shorts

Practice heater and glass removal was completed on inconsequential areas of the coil and practice traces.





The First Hipot failure location



Short caused by series of HiPot tests (first failure at V > 1.5 kV) and thermal image analysis

Subsequent locations found by acoustic analysis and pick-up coils

Peak Heater-Coil Voltages

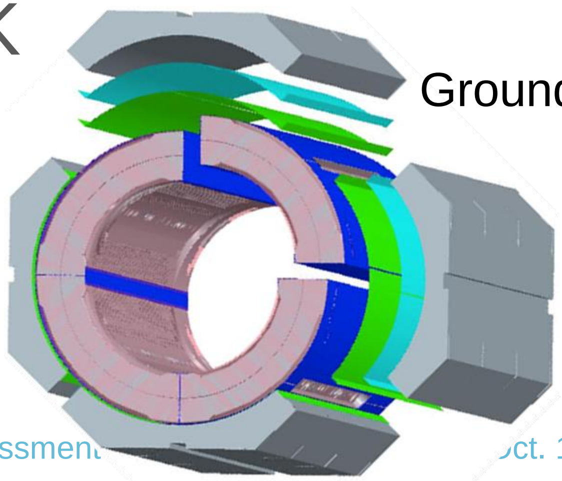
- Peak Heater-Coil Voltage (I_nom):
  - With 2 QH failures, realistic conductor parameters NOT uniformly distributed and coil ordering:

- MQXFB: 660 V at 100 K
- MQXFA: 390 V at 100 K

A. Verweij *https://indico.cern.ch/event/835702/contributions/3503953/*

He Pressure

- Since the roughness of the two surfaces in contact is low, it is reasonable to assume that they act as a good seal able to sustain a helium pressure of ~ 100 bar.
  - He isochoric expansion (1.9-100 K): 530 bar
- Assuming that only a fraction of this pressure (10% equivalent to ~10 bar) can be actually sustained by the "seal", the helium breakdown voltage is **~ 1.4 kV** at 100 K



Ground Insulation