Status & Plans of the MQXF Low Beta Quadrupoles for HL-LHC

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Fermilab

MT 26
International Conference on Magnet Technology
Vancouver, Canada | 2019

Outline

- HL-LHC Upgrade
- MQXF Requirements
- MQXF Design
- MQXF Design Validation
- Issues & Lessons Learned
- Status
- Conclusions

Acknowledgement

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- US HL-LHC Accelerator Upgrade Project (AUP)
  - BNL: K. Amm, M. Anerella, H. Hocker, P. Joshi, J. Muratore, J. Schmalzle, H. Song, P. Wanderer
  - FNAL: G. Ambrosio, G. Apollinari, M. Baldini, J. Blowers, R. Bossert, R. Carcagno, G. Chlachidze, S. Feher, S. Krave, V. Lombardo, C. Narug, A. Nobrega, V. Marinozzi, C. Orozco, M. Parker, S. Stoynev, T. Strauss, D. Turrioni, A. Vouris, M. Yu
  - LBNL: D. Cheng, M. Marchevsky, H. Pan, I. Pong, S. Prestemon, K. Ray, G. Sabbi, G. Vallone, X. Wang
  - NHMFL: L. Cooley
- CERN
  - A. Ballarino, H. Bajas, M. Bajko, B. Bordini, N. Bourcey, J.C. Perez, S. Izquierdo Bermudez, S. Ferradas Troitino, L. Fiscarelli, J. Fleiter, M. Guinchard, O. Housiaux, F. Lackner, F. Mangiarotti, A. Milanese, P. Moyret, H. Prin, R. Principe, E. Ravaioli, T. Sahner, S. Sequeira Tavares, E. Takala, E. Todesco

US HL-LHC AUP

HiLumi HL-LHC PROJECT

Goal of HL-LHC

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult}$ ≅ 7.5 10^{34} cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**

LHC should not be the limit, would Physics require more…

L. Rossi

HL-LHC IT region: 50% in-kind from USA
Fundamental role of US for R&D and Design

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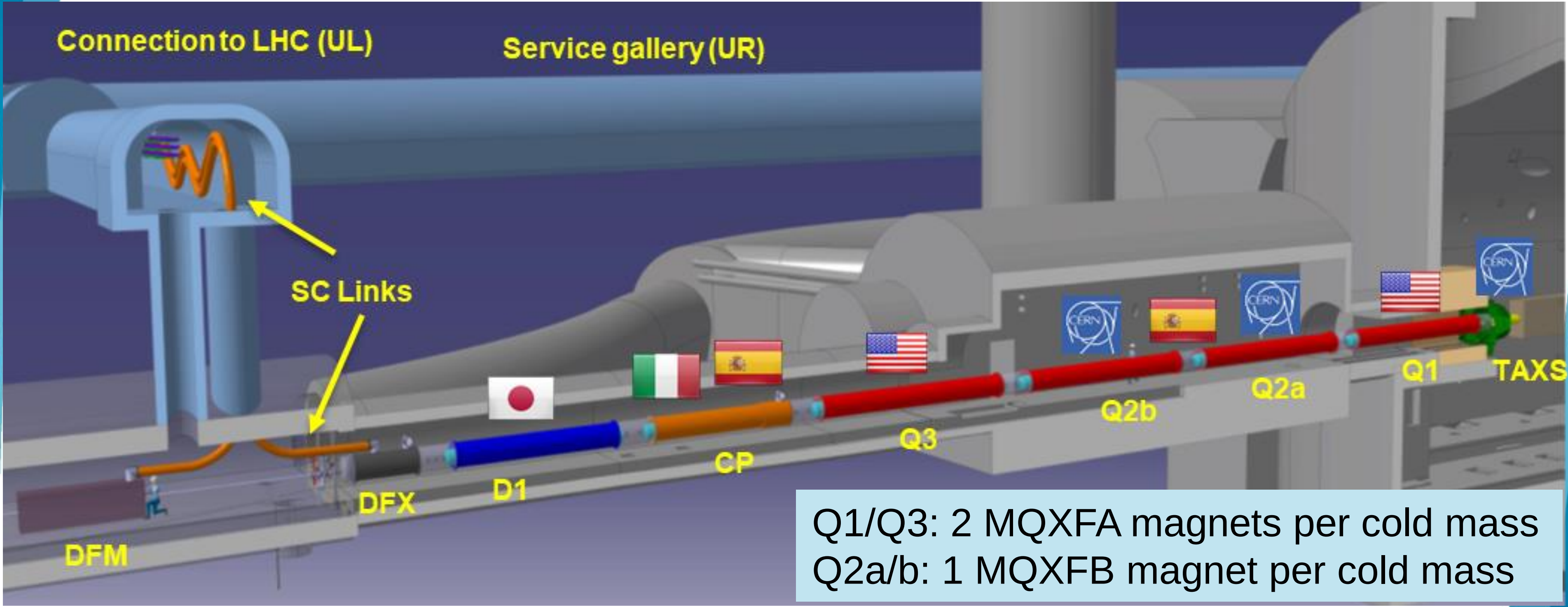

Q1/Q3: 2 MQXFA magnets per cold mass
Q2a/b: 1 MQXFB magnet per cold mass

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HiLumi HL-LHC PROJECT

L. Rossi

Requirements

- **Coil aperture at 300 K w/o preload is 149.5 mm**
- **The MQXF magnet must be capable of operating at steady state providing a gradient of 143.2 T/m**
  - This gradient corresponds to the HL-LHC ultimate gradient, which is 108% of the nominal operating gradient of 132.6 T/m.
- ***R 3.8: Re-evaluate the acceptance criteria of the MQXF magnets to maintain consistency across the HL-LHC magnet production efforts***
  - *In light of the decision not to test the 11T dipole magnets to the ultimate performance criteria, the testing criteria for the MQXF magnets requires re-evaluation*

Report of the
International Review on the Inner Triplet Quadrupoles (MQXF) for LHC

15-17 July 2019

Requirements

- **Memory:** After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current (I_{nom}) with no more than 3 quenches.
- **Lifetime:** MQXF magnets must survive at least 50 quenches ✓
- **Ramp rates:** shell not quench ramping up at 30 A/s; and down at150 A/s from nominal ✓
- **Radiation:** All MQXFA components must withstand a radiation dose of 35 MGy ✓
- **Splice resistance:** must be less than 1.0 nΩ at 1.9 K. ✓

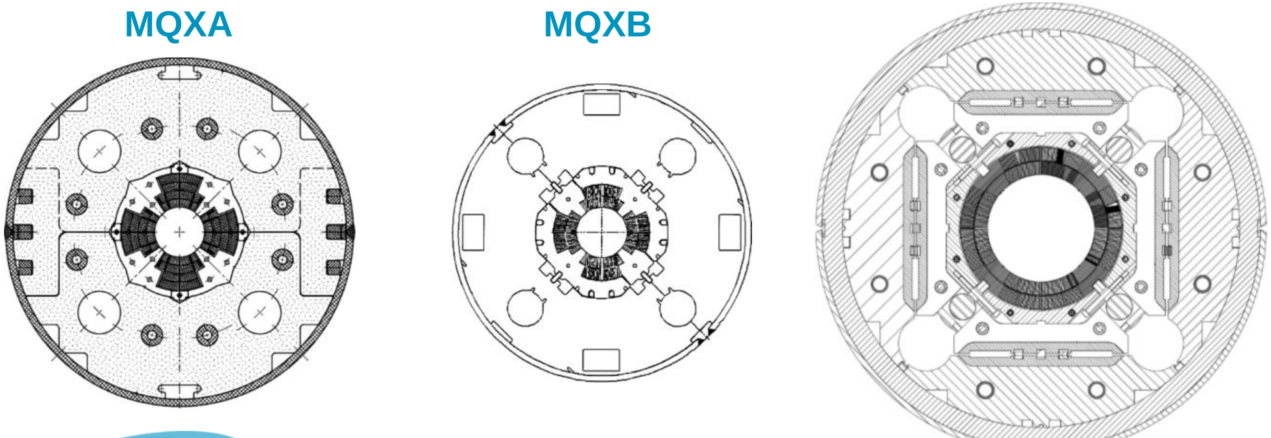
MQXF vs. present LHC low-β quadrupoles

- More than **double** the aperture: from 70 to 150 mm
- **~4 times** the e.m. forces in straight section
- **~6 times** the e.m. forces in the ends
- Cold mass OD from 490/420 to 630 mm

MQXA

MQXB

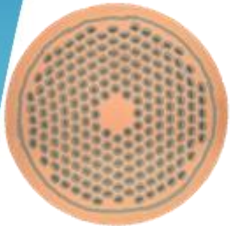
MQXFA/B



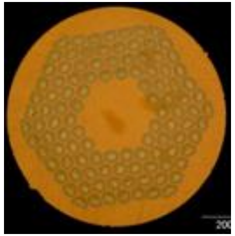
Same scale for all magnets

Paolo Ferracin

MQXFA/B Main Parameters



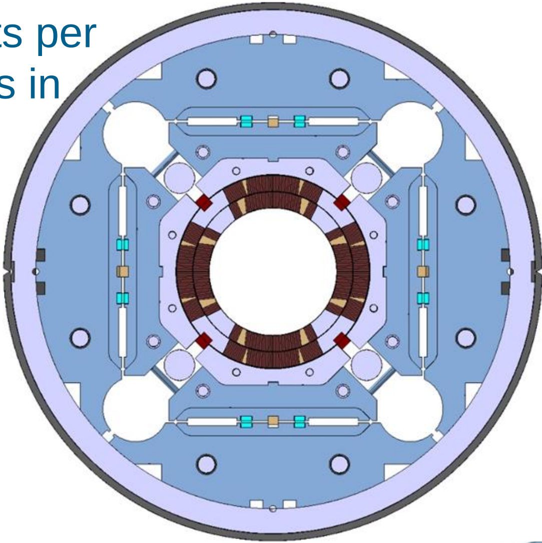
PIT 192
CERN

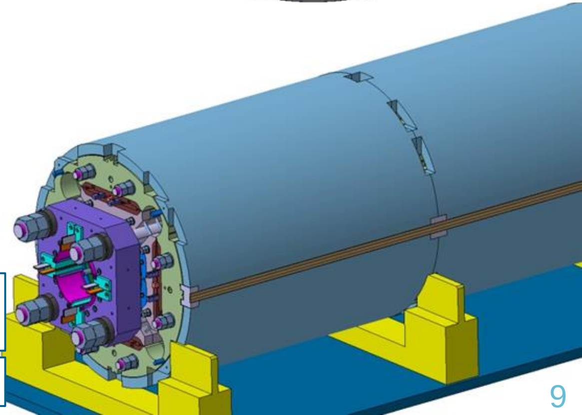


RRP 108/127
AUP & CERN

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nom. current	T	11.4
Stored energy at nom. curr.	MJ/m	1.2
Diff. inductance	mH/m	8.2
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle		0.4

2 magnets per cold mass in Q1/Q3



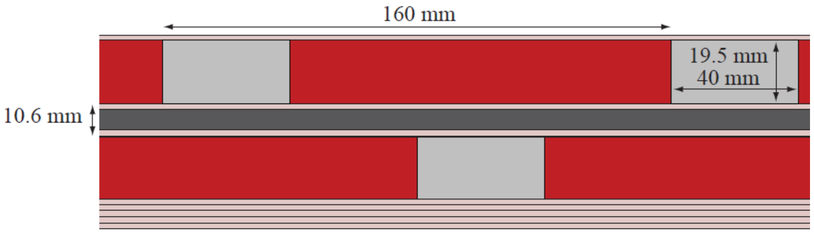


P. Ferracin et al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC " IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

G. Ambrosio et al., "MQXFS1 Quadrupole Design Report" LARP DocDB 1074

US HL-LHC AUP

MQXF protection strategy: OL quench heaters + CLIQ + Diodes

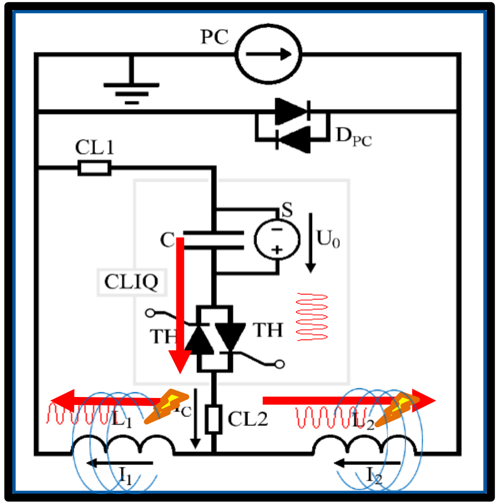


- **50 um polyimide**
- **12 um glue**
- **25 um stainless steel**
- **10 um copper (not in heating zones)**

Connection scheme:
- compensates the voltages induced by CLIQ and QH,
- reduces the effects of failures
- reduces the effects on the LHC beam of a QH supply spurious triggering (dipole kick)

Courtesy of D. Cheng

Coupling-Loss Induced Quench (CLIQ): a capacitive discharge into the coil results in high inter-filament and inter-strand coupling losses



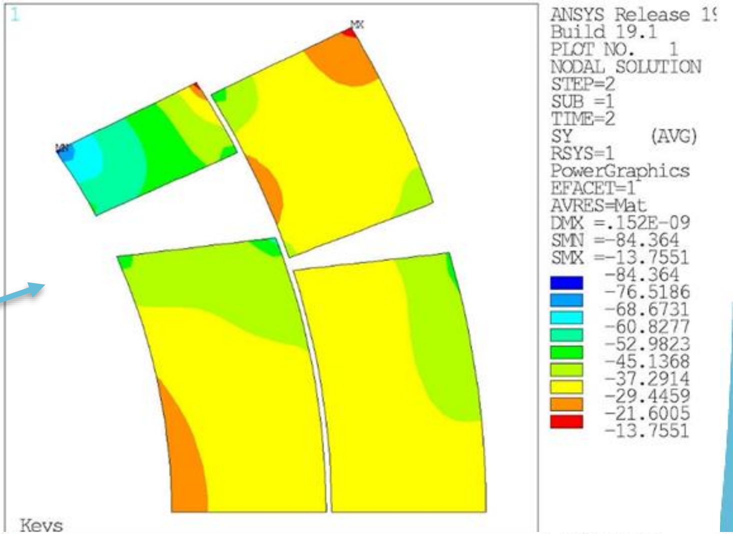
Current change
Magnetic field change
Coupling losses (Heat)
Temperature rise
QUENCH

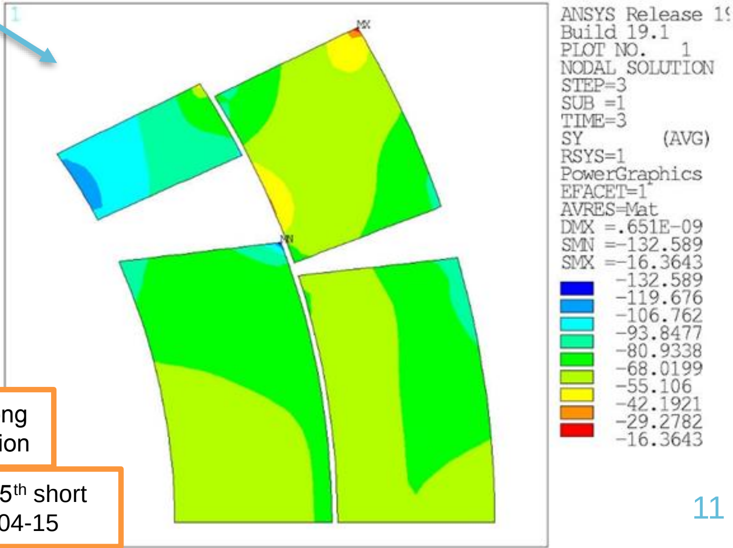
E. Ravaioli

M. Mentink, et al. "Protection Studies of the HL-LHC circuits with the STEAM Simulation Framework" Mon-Af-Po1.16-04

Structural Design

- Pre-stress targets (azimuthal stress at pole) for I_{nom}:
  - After assembly: 80 MPa
  - After cooldown: 110 MPa
    - Expected range +/- 10 MPa
- Axial preload:
  - After cooldown: 1 MN
    - ~80% of axial force at I_{nom}





Final design based on MQXFS4

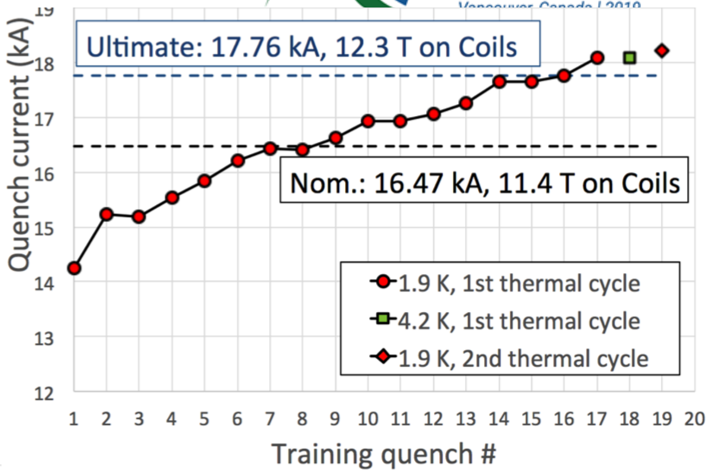
D. Cheng et al., "Mechanical performance of the first two prototype 4.5 m long Nb3Sn low-β quadrupole magnets for the Hi-Lumi LHC Upgrade", this session

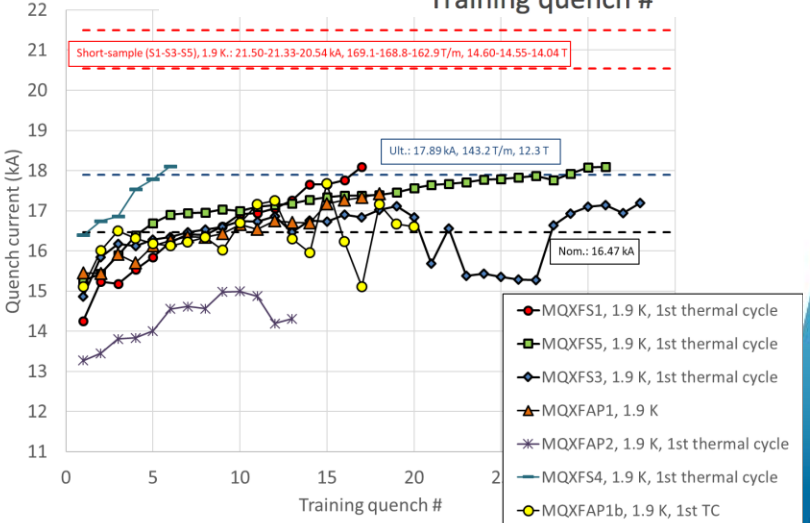
G. Vallone et al. "Mechanical analysis and measurements of MQXFS6, the 5th short model of the Nb3Sn Low-β Quadrupole for the Hi-Lumi LHC" Mon-Mo-Po1.04-15

Validation: Gradient

- Excellent 1st short model
- All but one MQXF magnets with RRP conductor exceeded I_{nom}
- 3 short models exceeded I_{ult}
- 2 magnets showed detraining after I_{nom}

Quench history of MQXFS1 tested at FNAL VMTF

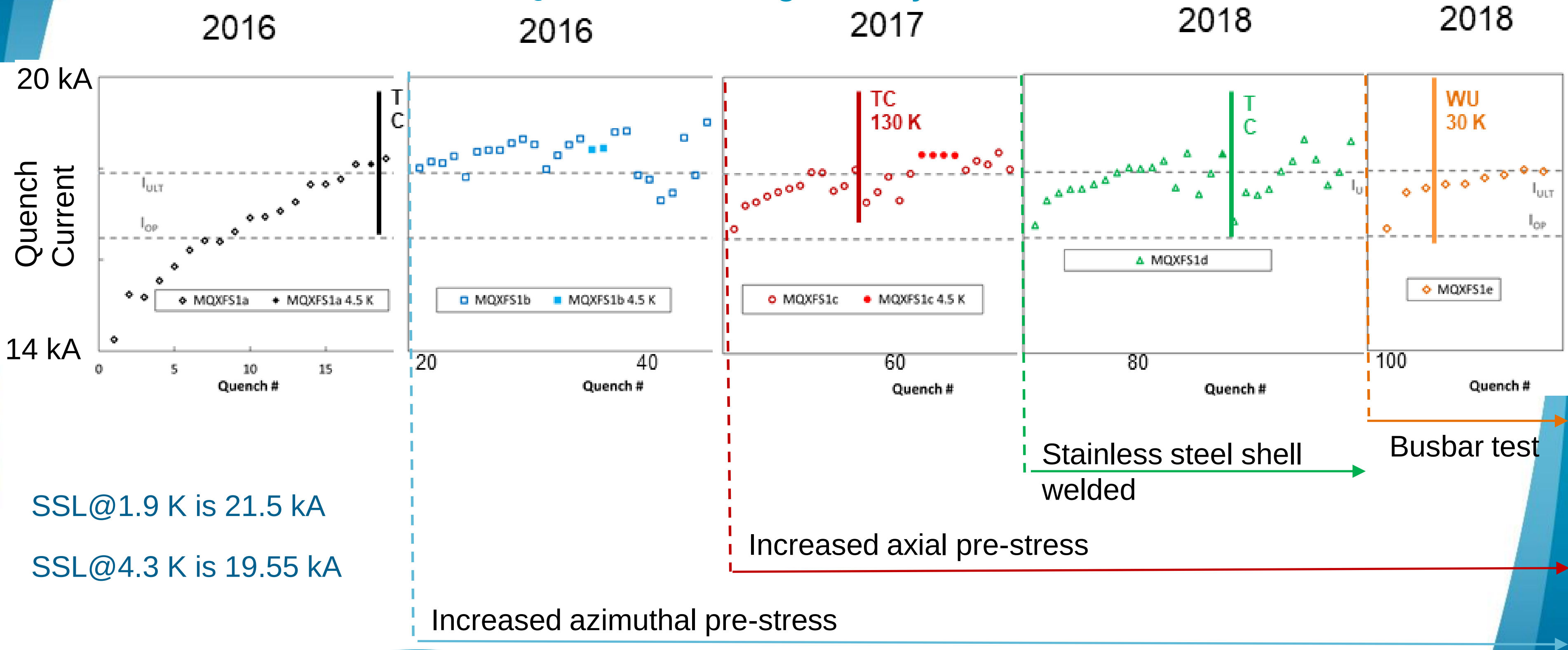




J. Muratore, et al. "Test Results of the First Two Full-Length Prototype Quadrupole Magnets for the LHC Hi-Lumi Upgrade" this session

Validation: Memory & Endurance

MQXFS1 Training History

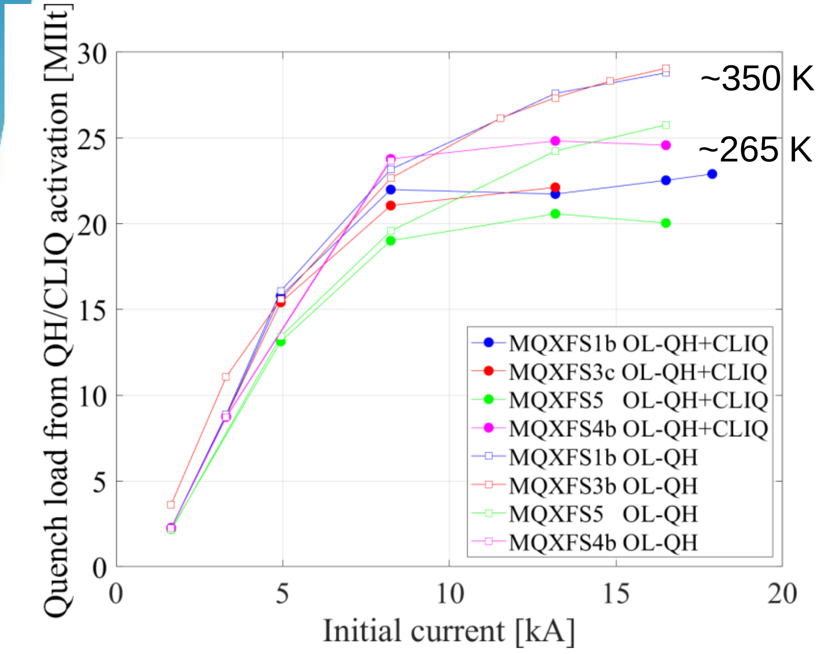


SSL@1.9 K is 21.5 kA

SSL@4.3 K is 19.55 kA

S. Stoynev

Validation: Quench Protection



Data: H. Bajas, S. Izquierdo Bermudez, F. Mangiarotti (CERN), G. Chlachidze, S. Stoynev (FNAL)

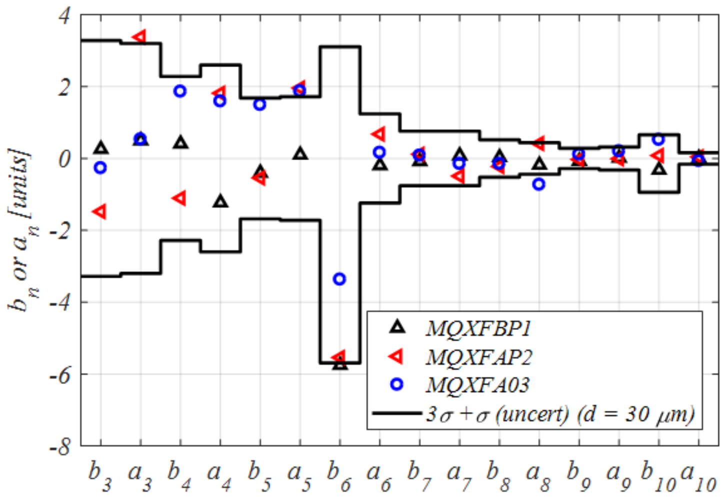
Temperature computed after adding 4.5 MIIt for detection + validation time + triggering time (approx. 5+10+2 ms)

- Quench protection demonstrated up to I_{ult}
- At I_{nom}, CLIQ reduced the quench load by 20-25%
- If coils have very different RRR & Cu/NCu, voltages may increase by ~45%
  - ➔ Coil Ordering = position of coils in each magnet based on conductor property (if needed)

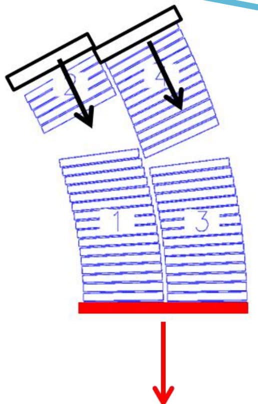
E. Ravaioli

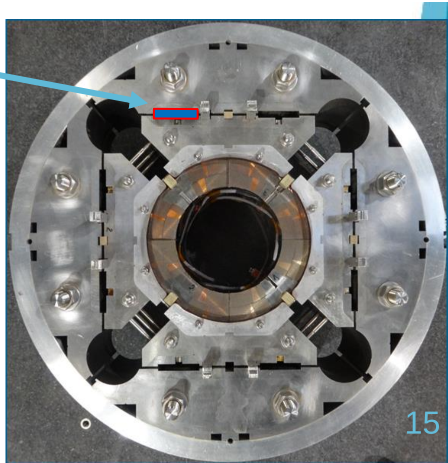
Validation: Field Quality

- FQ better in prototypes than in short models
- FQ only slightly affected by magnet pre-load
- Good warm-cold correlation
- Magnetic shims used to correct low-order harmonics
- X-section correction to adjust b6 in production coils
  - 125 um shims adjustment



Average measured harmonics in the magnet straight section after pre-loading vs. targets





Data: G.L. Sabbi, X. Wang (LBNL), S. Izquierdo Bermudez (CERN), J. Muratore, H. Song (BNL)

X. Wang et al., "Magnetic Measurements of MQXFA Prototype Quadrupoles during Magnet Assembly", Thu-Mo-Po4.07-03

H. Song, et al. "Vertical Magnetic Field Measurements of Full-Length Prototype MQXFAP Quadrupoles at Cryogenic Temperatures for Hi-Lumi LHC" Wed-Af-Po3.20-07

Issues & LL: MQXFAP2

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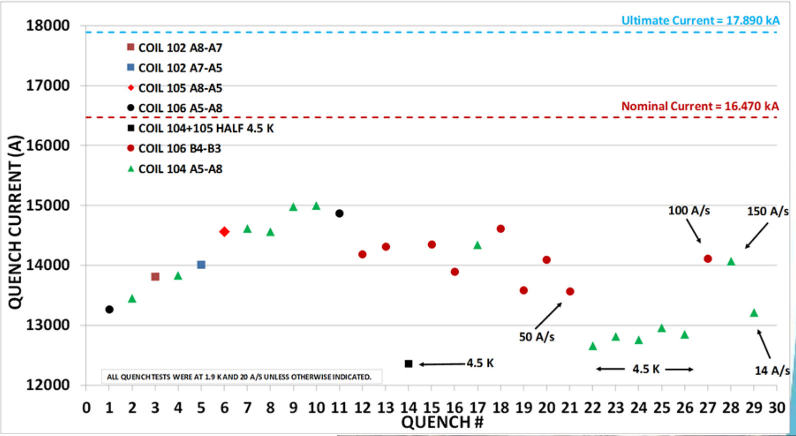
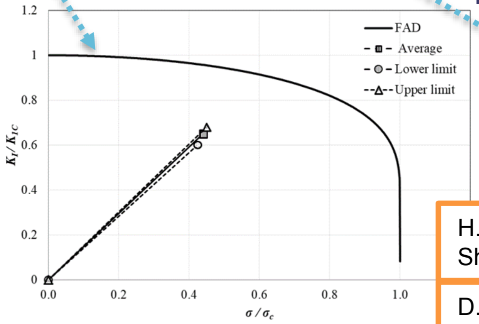
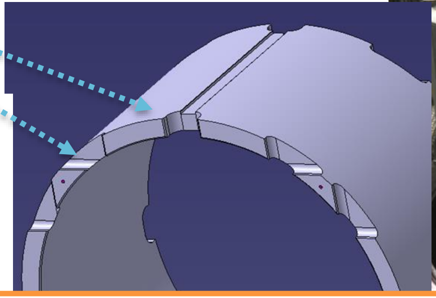
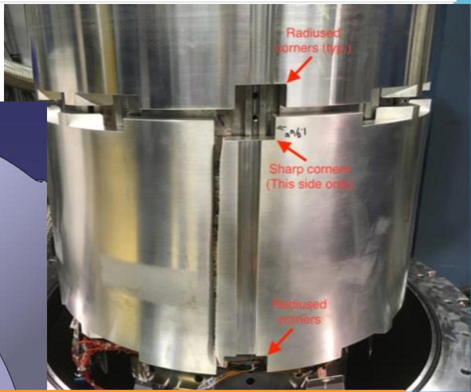
- Design & assembled by LARP
  - Non-conformity (sharp corners) was accepted by L3
- AUP developed <u>Structural Design Criteria</u> based on Failure Assessment Diagram
  - Rounded corners (10-15 mm), Class-AA US inspection, dye-penetrant test
- Lesson Learned:

  follow SDC









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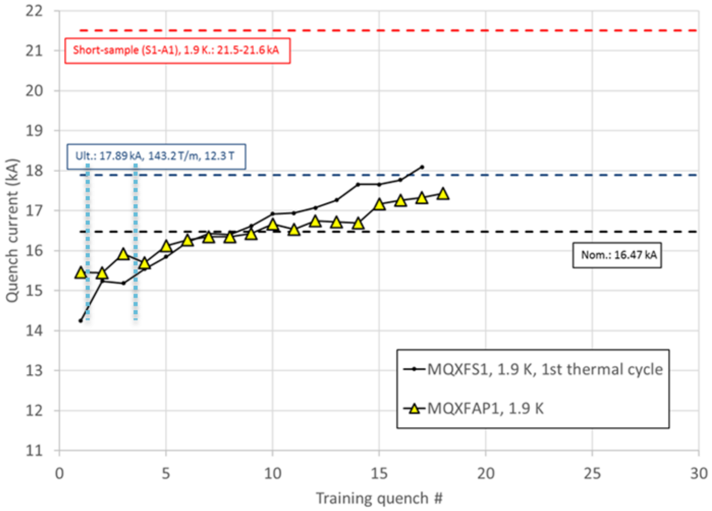
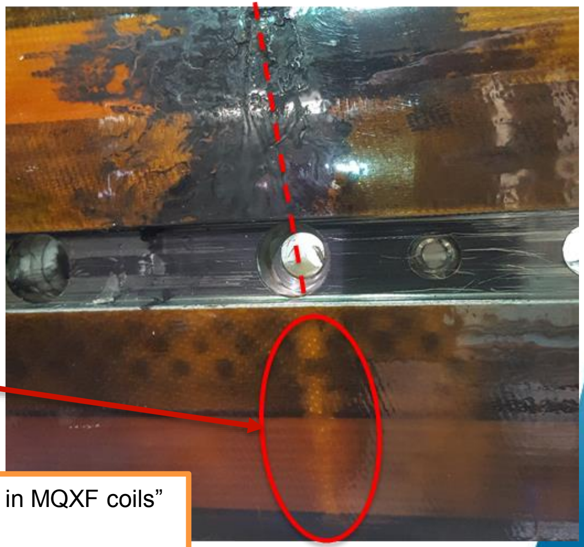
H. Pan, et al., "Fracture Failure Analysis for MQXF Magnet Aluminum Shells", Mon-Mo-Po1.03-02

D. Cheng et al., "Mechanical performance of the first two …" this session

Issues & LL: MQXFAP1

- Coil-Ground short caused by Coil-Heater double short caused by HiPot at 300 K after He exposure,
  - HiPot performed at 2.4 kV well above Electrical Design Criteria after He exposure (460 V)
    - not yet available for AUP at that time
- Lesson Learned: follow EDC



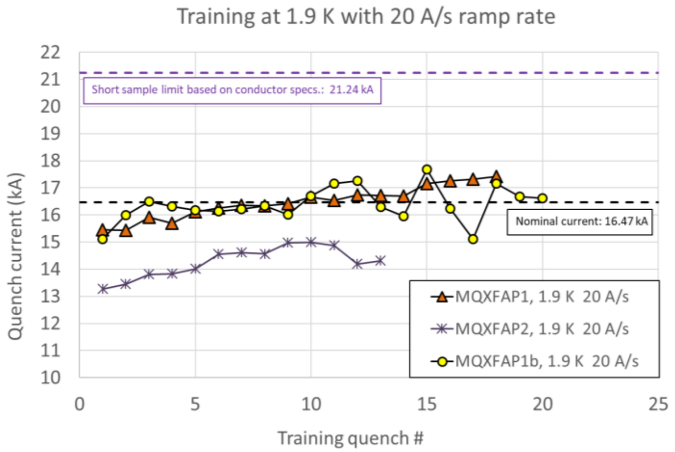


New insulation supplier changed after this coil

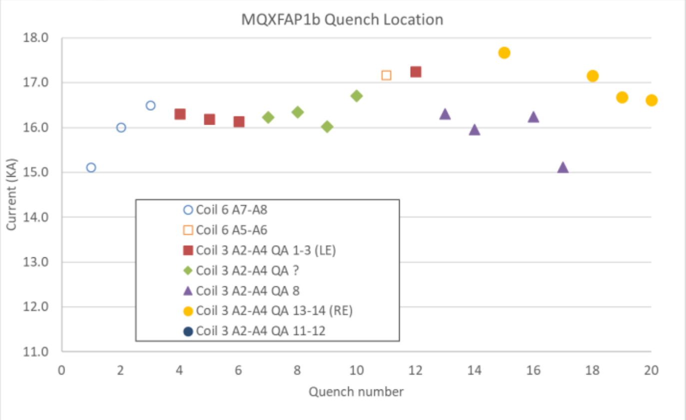
V. Marinozzi et al., “Analysis of the heater-to-coil insulation in MQXF coils” Mon-Mo-Po1.03-07

Issues & LL: MQXFAP1b

- Nominal current in 3 quenches
  - All of them in the new coil (P6)
- All detraining quenches in an old coil (P3)
  - Detraining quenches moved from Lead to Return end
- Possible causes:
  - Preloading sequence: Az 0/100% Ax 0/100%
  - Epoxy impregnation issue in coil P3
- Lessons Learned:
  - New Preloading sequence: Az 50% Ax 50% Az 100% Ax 100%
  - Analysis of epoxy T_g in progress & for QC



Training by J. Muratore



D. Cheng et al., “Mechanical performance of the first two prototype 4.5 m long Nb3Sn low-β quadrupole magnets for the Hi-Lumi LHC Upgrade”, this session

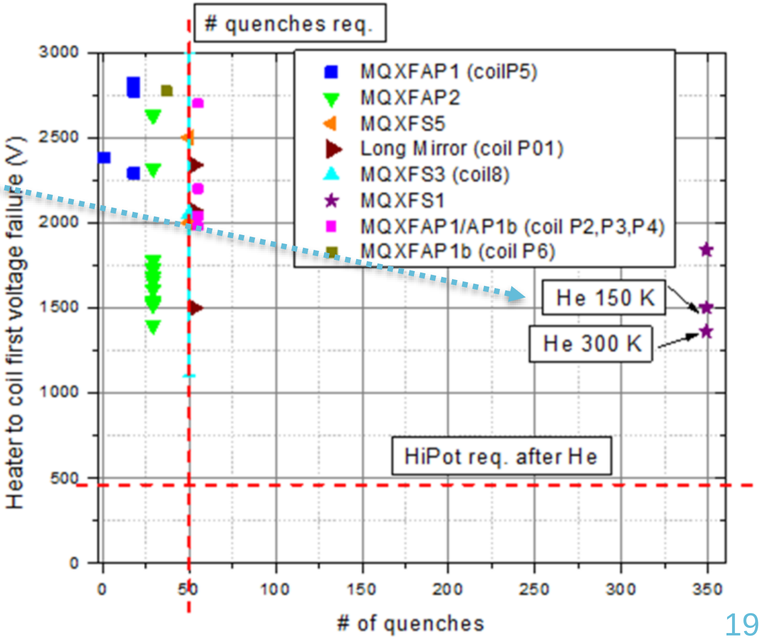
J. Muratore, et al. “Test Results of the First Two Full-Length Prototype Quadrupole Magnets for the LHC Hi-Lumi Upgrade”, this session

Quench location by Quench Antenna (M. Marchevsky)

Quench Heaters - I

- Hipot after fabrication at 3.7 kV ✓
- Hipot after cold test at 460 V ✓
- Hipot after cold test to failure
  - Minimum: 1.4 kV
  - Consistent with heater-hole minimum distance & He gas
- No degradation after 350 quenches & 7 thermal cycles
- Autopsy after cold test showed areas with reduced polyimide thickness on top of small bubbles in the epoxy between turns

Quench heater detail (end)



V. Marinozzi et al., "Analysis of the heater-to-coil insulation in MQXF coils" Mon-Mo-Po1.03-07

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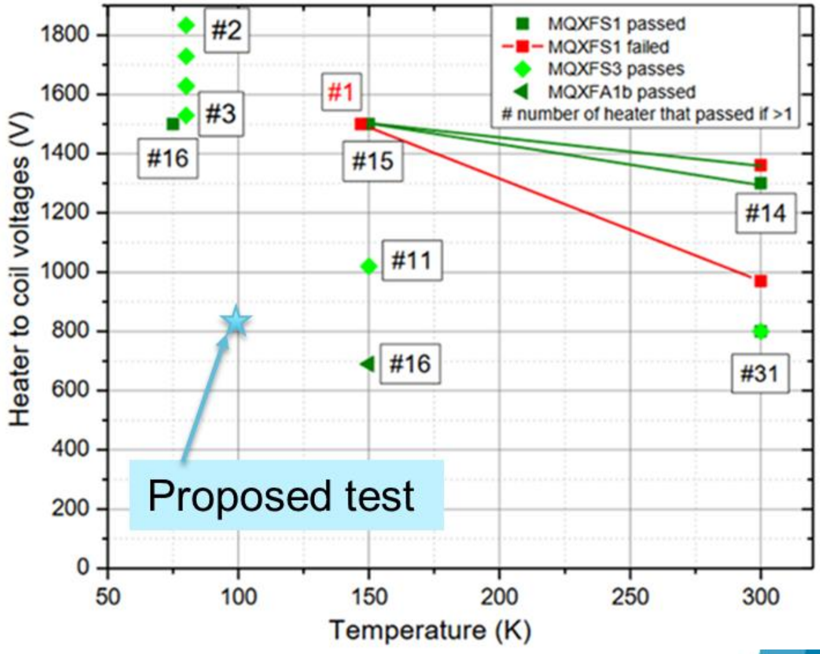
Quench Heaters - II

- New test proposed to demonstrate Heater-Coil dielectrical strength after magnet training:
  - Heater-Coil Hipot at 850 V in He gas (1 bar) at 100 K
  - Peak Heater-Coil voltage during quench is ~350/650 V in MQXFA/B at 100 K
- He pressure increase during quench will give additional dielectric strength:
  - More than 1 kV (10 bar, 100 K)
- Alternative procedures for QH installation are under development



MAXFA/B Status

- Status of components for deliverables:

	MQXFA (AUP)	MQXFB (CERN)
Strand Received	50%	95%
Cables accepted	27	15
Coils accepted	10	5
Magnets assembled	1	1

- RRP strand procurement is going very well
- Cabling is going very well
- Coil fabrication still through *learning curve*

Milestones

- First test of deliverable magnets:
  - MQXFA03 “pre-series” vertical test start: October 2019
  - MQXFBP1 “prototype” horizontal test start: December 2020

MQXFA03

D, Cheng, et al. “Mechanical performance of the first two prototype 4.5 m long Nb_3Sn low-β quadrupole magnets for the Hi-Lumi LHC Upgrade”, this session

MQXFBP1

F. Lackner, et al. “Assembly of MQXFBP1 prototype, the Nb_3Sn Q2 quadrupole for HL-LHC”, this session

Conclusions

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- Tests of short models and prototypes have validated main features of MQXF magnets
- Lessons learned from issues during these tests have improved design and procedures
- New Hipot in He gas at 100 K has been proposed to assure Heater-Coil dielectric strength after magnet training
- Fabrication of deliverable components has started

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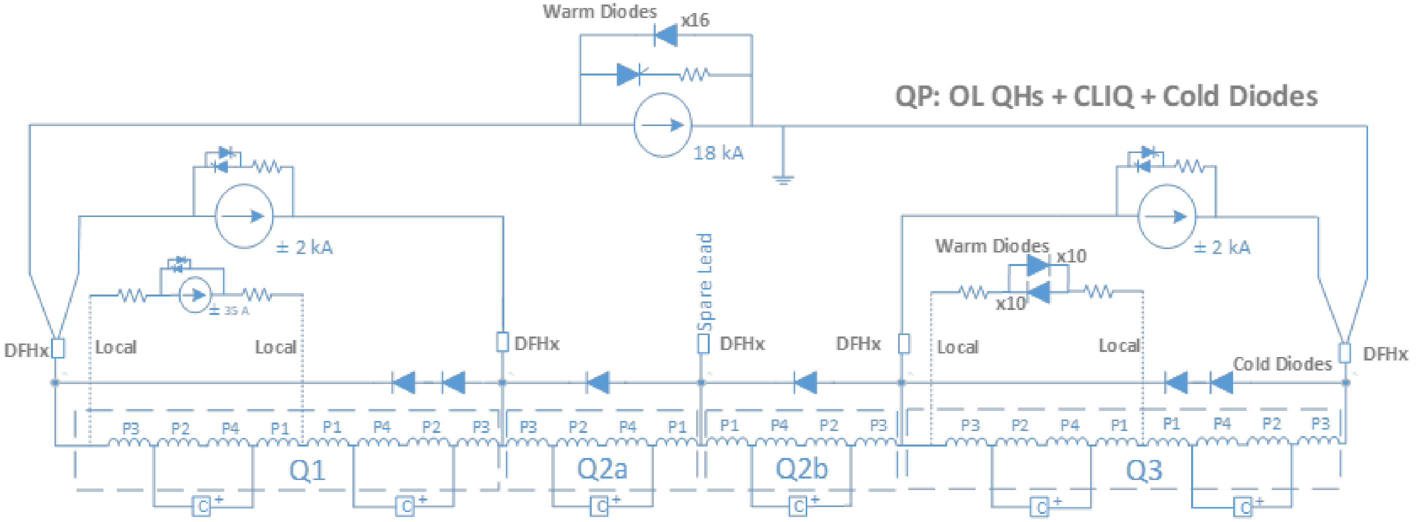
Thank you for your attention

Backup Slides

RQX+RTQX1/3+RTQXA1 (Triplet – main quads)



The circuit went through several iteration steps in the last years.

Protection studies have been performed by M. Mentink and E. Ravaioli, and lately also by V. Marinozzi (FNAL). Latest simulation results were presented by E. Ravaioli at the 'Intl review on the IT Quadrupoles for HL-LHC' (July 2019), see: https://indico.cern.ch/event/828604/contributions/3471709/

Quench Heaters - IV

Possible alternative designs under development:

1. **Swap** one layer of fiberglass cloth from above Quench Heater to under Quench Heaters
   - Higher Hot-Spot temperature (≥ 60 K with CLIQ failure)
   - Small impact on cost & schedule
     - Assuming already fabricated coils (by AUP) accepted for deliverables

2. Put Quench Heaters **outside** of potted coils
   - Higher Hot-Spot temperature (≥ 60+ K with CLIQ failure)
   - Significant impact on cost & schedule (prototypes needed)
     - Assuming already fabricated coils (by AUP) accepted for deliverables

"The better is the worst enemy of good enough"