HiLumi US magnet construction and testing plans

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Fermilab

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Acknowledgement

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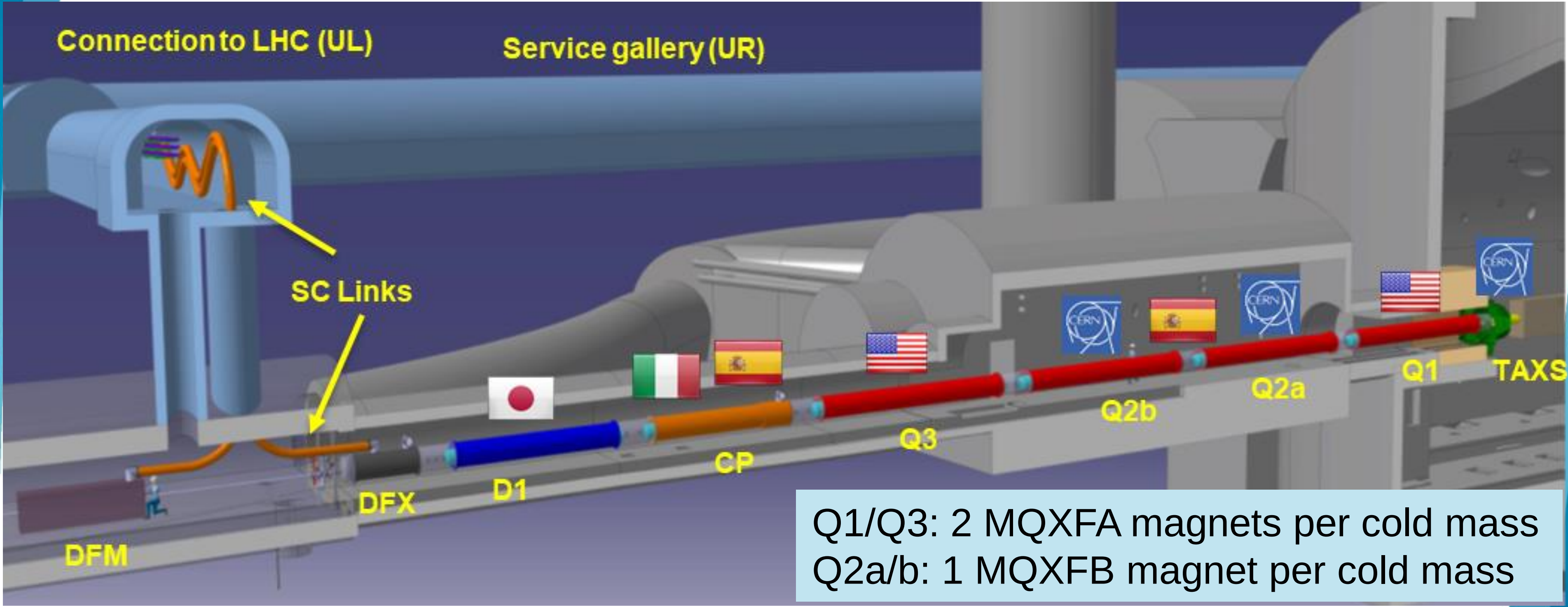
Outline

- Short models & Prototypes
  - feedback & Lessons Learned
- Status and Plans for Magnets
- Quench Heaters
- Status and Plans for Cold Masses
- Status and Plans for Cryo-assemblies
- Status and Plans for tests
- Conclusions

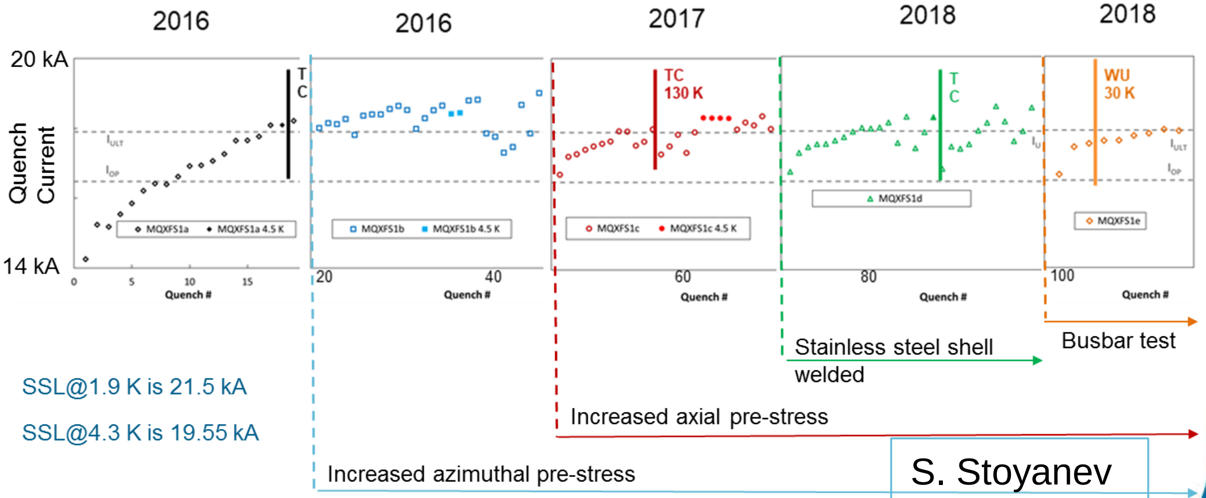
HL-LHC IT region: 50% in-kind from USA
Fundamental role of US for R&D and Design



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

MQXFS1a/b/c/d/e/…

- Reached ultimate current after 350 quenches and 7.5 thermal cycles
- 1st quench after thermal cycle always above nominal current
- Passed proposed test: Heater-Coil High-Voltage
  - 850 V at 100 K in He gas



Quench history of MQXFS1a/b/c/d/e tested at FNAL VMTF

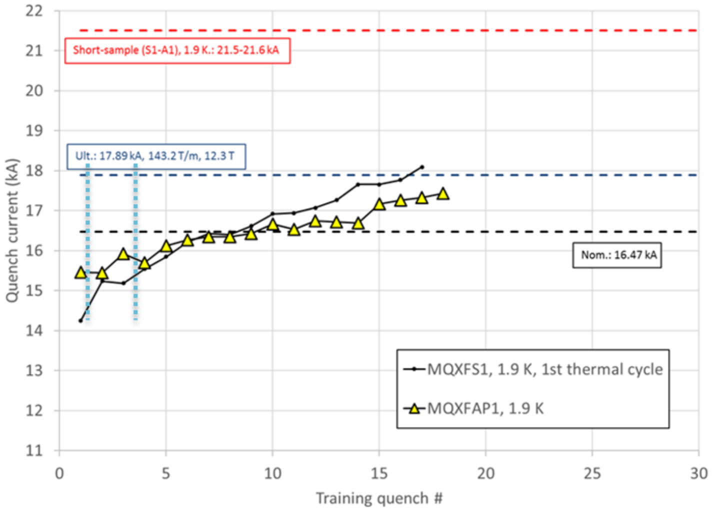
SSL@1.9 K is 21.5 kA

SSL@4.3 K is 19.55 kA

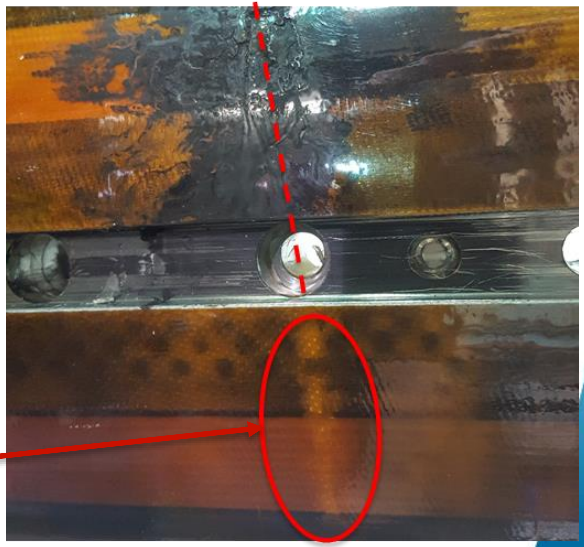
S. Stoyanev

MQXFAP1

- <u>Exceeded nominal current</u>
- 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 <u>Electrical Design Criteria</u> <u>after He exposure</u> (460 V)
    - not yet available for AUP at that time
- Lesson Learned: follow EDC



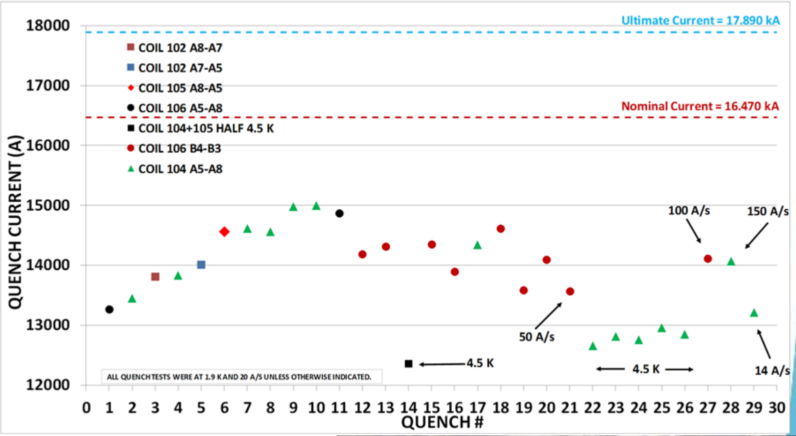
New insulation supplier changed after this coil

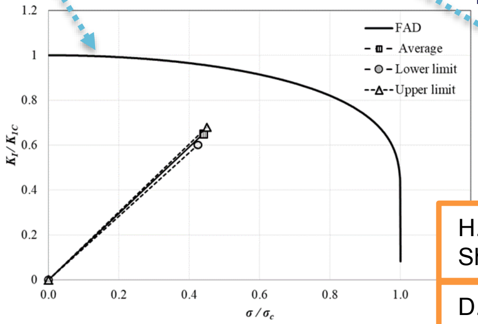


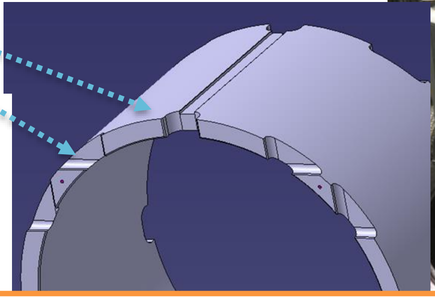
MQXFAP2

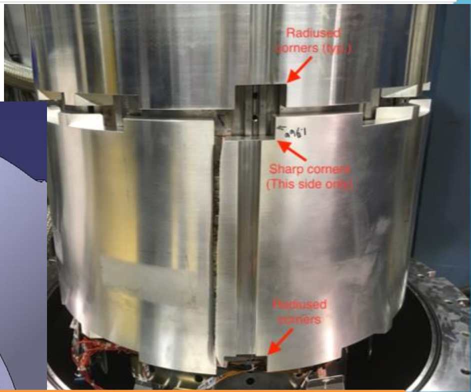
- Design & assembled by LARP
  - Non-conformity (sharp corners) was accepted by L3
- AUP developed Structural Design Criteria based on Failure Assessment Diagram
  - Rounded corners (10-15 mm), Class-AA US inspection, dye-penetrant test
- Lesson Learned:

  follow SDC







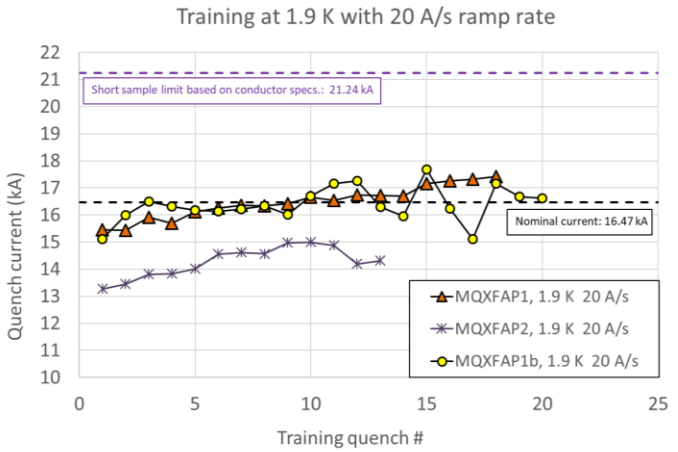


H. Pan, et al., “Fracture Failure Analysis for MQXF Magnet Aluminum Shells”, MT26 paper

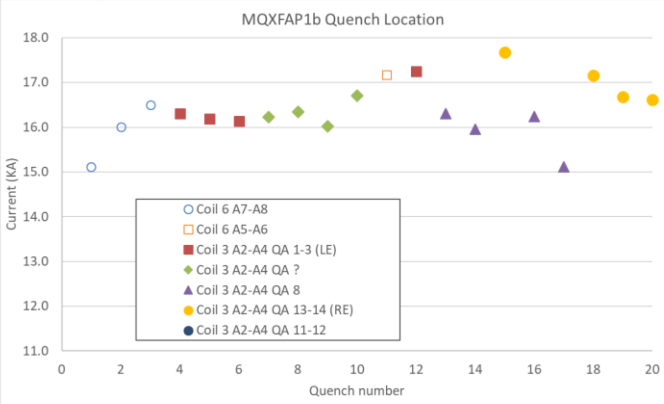
D. Cheng et al., “Mechanical performance of the first two …”, MT26 paper

MQXFAP1b

- <u>Reached nominal current</u> 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”, MT26 paper

J. Muratore, et al. “Test Results of the First Two Full-Length Prototype Quadrupole Magnets for the LHC Hi-Lumi Upgrade”, MT 26 paper

Quench location by Quench Antenna (M. Marchevsky)

Status: Conductor Procurement & QC

- Strand Procurement and QC:
  - 50% strand received
  - 2 contracts remaining, 1 of them has been placed
  - Conductor is being delivered timely
  - No significant issues
  - Helium cap by BOST's helium supplier; Fermilab is providing He gas and getting credit back

Status: Cable Fabrication & Insulation

- Fabricated & Insulated cables:
  - 27 Accepted
  - 1 Rejected
    - Crossover caused by Cu build-up on spool at vendor

- Bare cable fabrication at LBNL: 35 completed
- Insulation braiding at NEWT: 35 completed
- RRR measurements at LBNL: 27 measured

Status: Coil Parts Procurement

	In Stock (set)	Coils in stock Covered from	FY19 Procurement (set)	FY20 Procurement (set)
Pole	12	QXFA 120 QXFA 211	26 (Received 50%, and 25% inspected)	40
End Parts	12		26 (Received 50% and all inspected)	40
Wedges	24		72 (PO placed, expected to receive by Dec. 2019)	0
Pre-series Trace	2	QXFA 119 QXFA 209	**4 in shipment, 2 expected to receive by Nov. 2019**	0
Series Trace	26	-	0	26

- FY20, AUP plans to fabricate 20 coils.
- Pole and end parts in stock, plus 26 sets of pole and end parts that are expected to arrive by Dec. 2019, will cover all the need in FY20.
- Wedges and traces in stock, plus October delivery, will cover all the need in FY20.

Status: Coils at FNAL

AUP Coils to date = 14
8 accepted
2 quarantined
2 rejected
2 underway

Coil Name	Wind Start	Potting Complete	Duration days	DRs	Comments
QXFP01		At BNL			
QXFP02		At BNL			
QXFP03	Jan 4, 2016	Jul 8, 2016	186	7	OK
QXFP04		At BNL			
QXFP05	May 10, 2016	Oct 10, 2016	153	11	OK
QXFP06	Jun 13, 2018	Oct 3, 2018	112	12	OK
QXFA101	July 20, 2016	Apr17, 2017	271	18	Quarantined, electrical
QXFA102		At BNL			
QXFA103	Oct 31, 2016				Rejected
QXFA104	Jan 31, 2017	Jul 10, 2017	160	10	
QXFA105		At BNL			
QXFA106	May 25, 2017	Oct 16, 2017	144	13	OK
QXFA107	Aug 8, 2017	Feb 14, 2018	190	11	Quarantined, electrical
QXFA108	Dec 6, 2017	May 7, 2018	152	11	Rejected
QXFA109	Feb 5, 2018	Jun 25, 2018	140	12	Quarantined, electrical
QXFA110	Apr 23, 2018	Aug 15, 2018	114	10	OK
QXFA111	Jul 5, 2018	Oct 19, 2018	108	6	OK
QXFA112	Aug 22, 2018	Dec 6, 2018	107	4	OK
QXFA113	Oct 11, 2018	Jan 25, 2019	107	8	OK
QXFA114	Dec 11, 2018	Mar 18, 2019	97	6	Quarantined, impreg process
QXFA115	Feb 11, 2019	May 13, 2019	91	7	OK
QXFA116	Mar 26, 2019	Aug 19, 2019	146	8	OK
QXFS10	May 1, 2019	Sep 3, 2019	110	9	OK
QXFA117	May 17, 2019			4	
QXFA118	Jul 24, 2019			2	Rejected
QXFA119	Sep 17, 2019			1	

LARP coils

Notes:

Saddles changed after curing

No more saddle change

May be accepted shortly

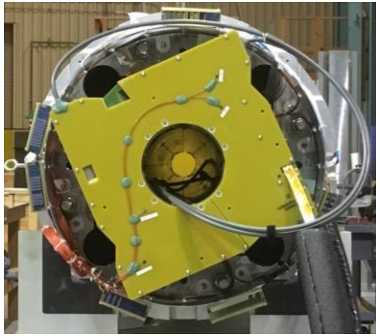
Strand damage during winding

Status: Coils at BNL

- Coils to date = 9 (3 accepted, 1 quarantined, 2 rejected, 3 underway):
  - QXFA202 - Complete and shipped (1st coil fabricated at BNL).
  - QXFA203 - Complete and shipped.
  - QXFA204 - Complete and shipped.
  - QXFA205 - Cable damaged during winding – coil rejected.
  - QXFA206 - Complete and shipped – shipping anomalies, impact is under investigation.
  - QXFA207 - Impregnation complete, final prep underway.
  - QXFA208 - Cable damaged during wind/cure – coil rejected.
  - QXFA209 - Reaction underway.
  - QXFA210 - Winding underway.

Status: Structure Proc. & Magnet Assembly at LBNL

- MQXFA03 Magnet (first Pre-Series) arrived at BNL
  - Coil lead insulation refurbishment to be done at BNL (1 week delay)

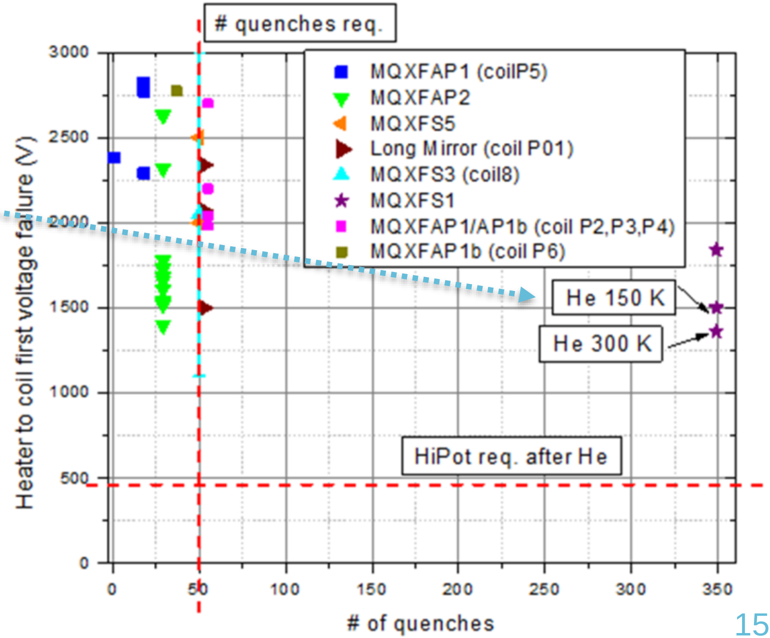


- MQXFAP2 to be disassembled in order to recover parts (~$400k)
- MQXFA04 magnet expected to be ready to ship by end of January 2020
- Parts for structures A04-A08 are arriving
- ARMCO steel (whole production) started arriving

Quench Heaters - I

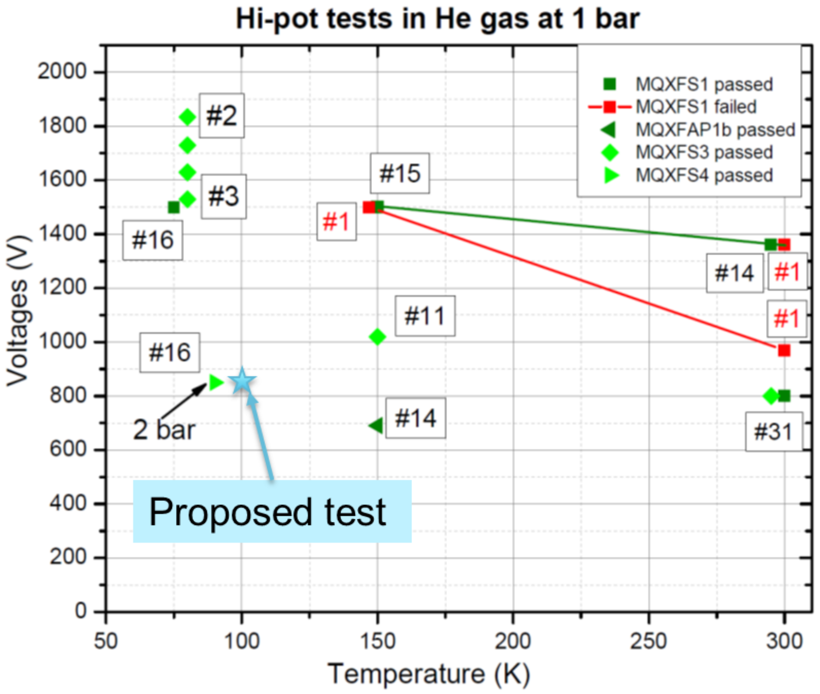
- Hipot after fabrication at 3.7 kV ✓
- Hipot after cold test at 460 V ✓
- Hipot after cold test <u>to failure</u>
  - Minimum: 1.4 kV
  - Consistent with heater-hole minimum distance & He gas
- No degradation after 350 quenches & 8.5 thermal cycles
- Autopsy after cold test showed areas with reduced polyimide thickness

Quench heater detail (end)



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



Heater-Coil Hipot tests in He gas: passed (green) and failures (red) show margin (x2) wrt proposed test

Scope of AUP Q1/Q3 Cryo-Assemblies

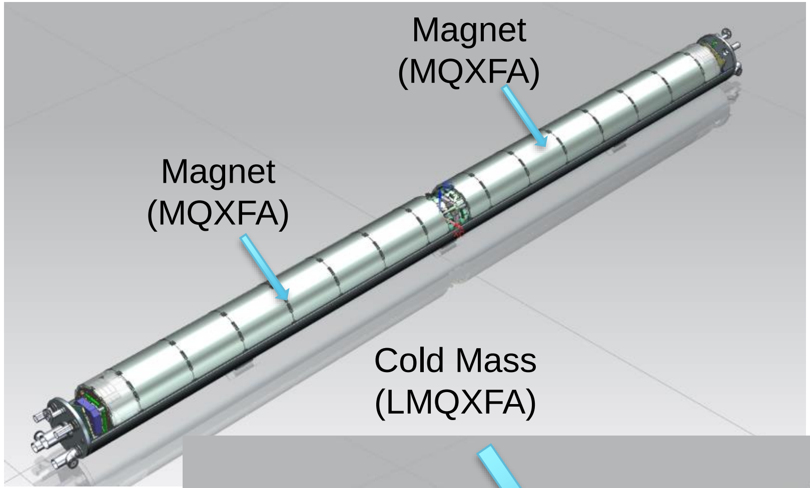
12 Q1/Q3 Cryo-Assemblies

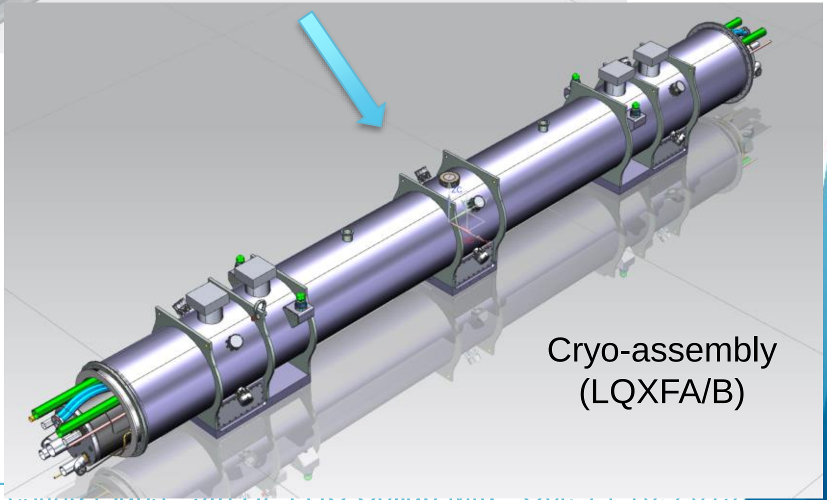
- 2 pre-series
- 9 series production
- re-building one Cryo-assembly assumed

➔ to assure 10 Cryo-assemblies will be delivered

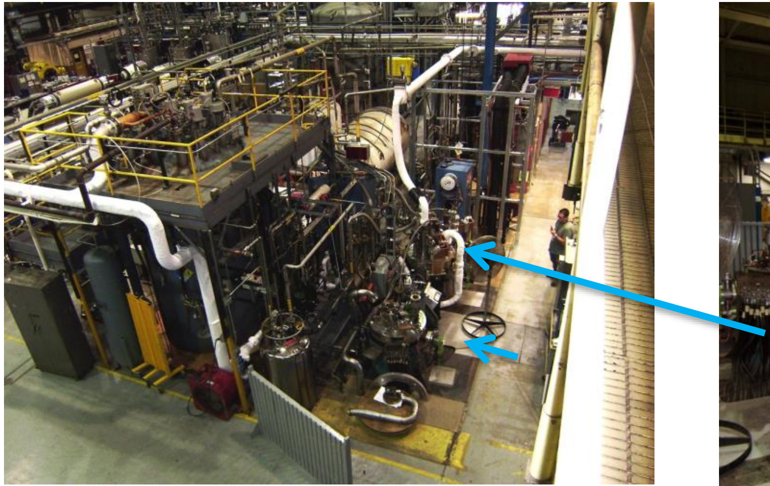
Vertical test of 27 magnets (3 magnets have been tested so far)

Horizontal test of 11 Q1/Q3 Cryo-assemblies





BNL Magnet Test Facility



Vertical Test Facility at BNL, showing two of the five test cryostats and the backup refrigerator. Long arrow points to **Vertical Test Cryostat 2 (1.9K and 24kA)**. Short arrow points to Test Cryostat 3, which is used as a cold buffer for the He return during quenches on future MQXFA tests in Test Cryostat 2.

Vertical Test Cryostat 2, upgraded to provide 1.9 K at 1 bar (nom) and 24 kA, for testing of the 4.2 m-long MQXFA quadrupoles.

Commissioning and validation of upgrades has been done with 4 LARP/AUP magnet tests and 2 zero magnet tests over past 2 years, including most recent test of MQXFAP1b over June 2019.

BNL CRYOGENICS UPGRADES

Linde 1430 Refrigerator/Liquefier 50 L/hr, 114 W

Linde 1610 Liquefier 80-100 L/hr

Linde 1430 is in house, not yet plumbed in.
Linde 1610 being refurbished at Linde.
Together with CTI4000 Refrigerator/Liquefier, total capacity will be about 400 L/hr.

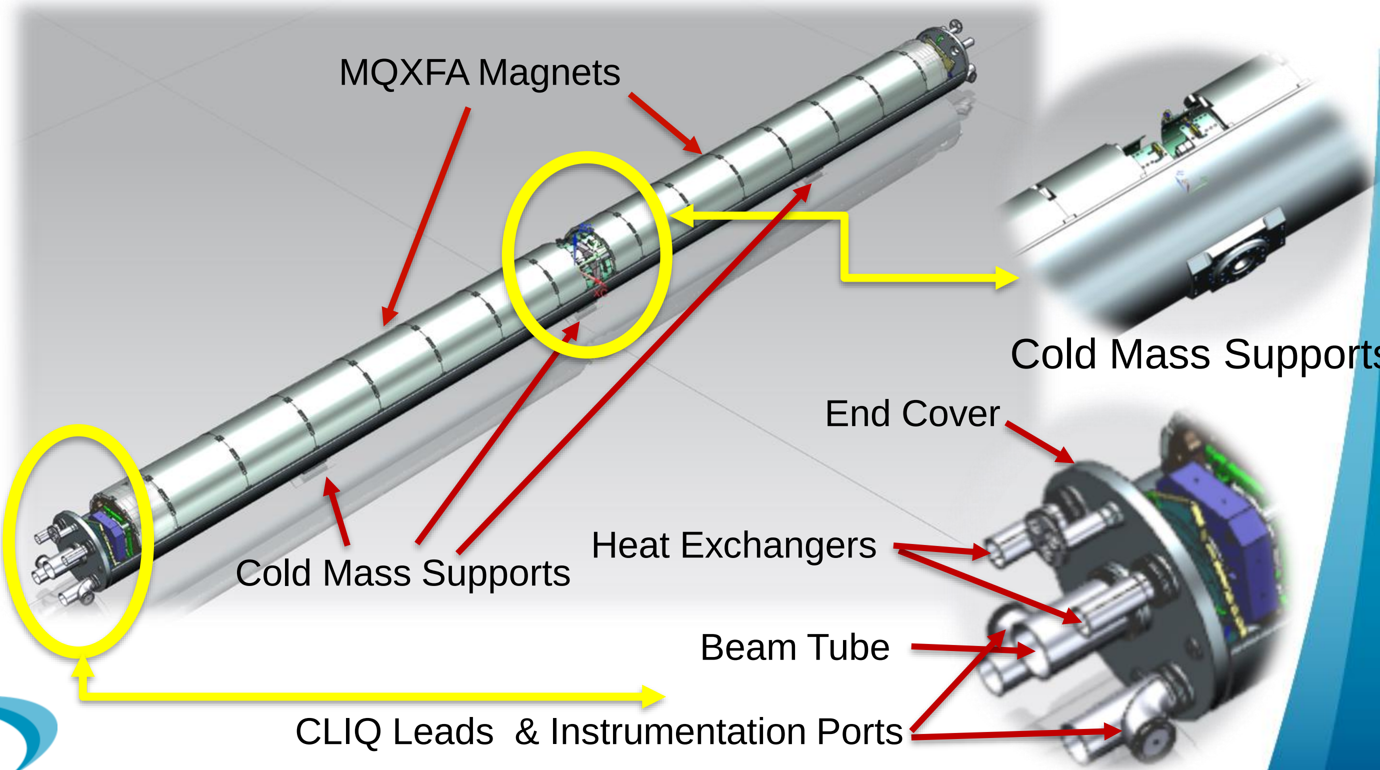
Has been demonstrated to make 3 quenches a day (excellent heat exchanger and pumping capabilities)

For production testing additional liquefaction capacity still needed

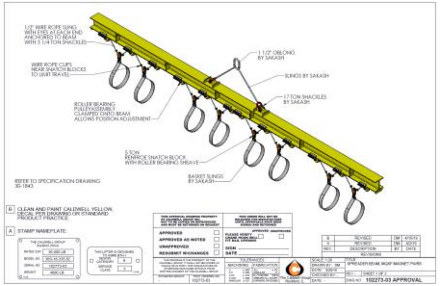
Cold Mass Assembly

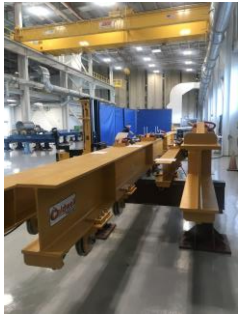
Cold Mass Design and design analysis is close to completion – fine tuning
Detailed Engineering note is under preparation

The design and manufacture of the new HL-LHC cold masses shall be compliant with the Pressure Equipment Directive (PED 2014/68/EU) essential safety requirements (ESR). (LHC-LM-ER-0001 v.4.0, EDMS 1891856 v.4.0). The technical requirement is to use both compliant design and construction standards : EN 13445 and ASME BPVC Section VIII Div. 2 are compatible with PED requirements. (EDMS 1891860/2.0).



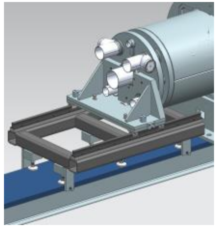
Infrastructure and tooling

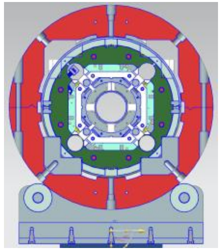




ICBA Completed

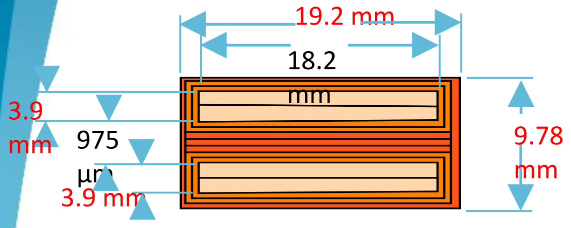
Tooling designed
Procurement in progress

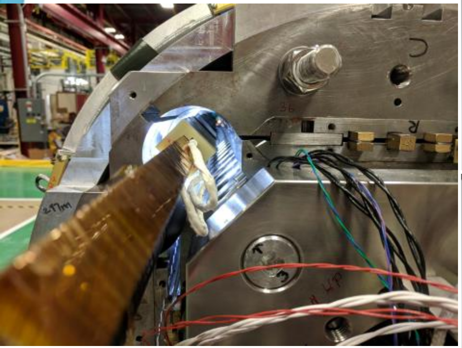


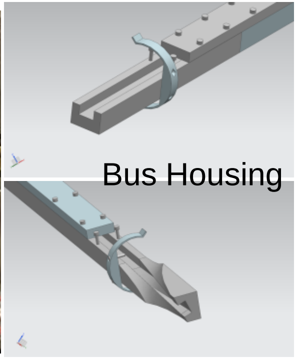


Bus bar for Q1/Q2/Q3

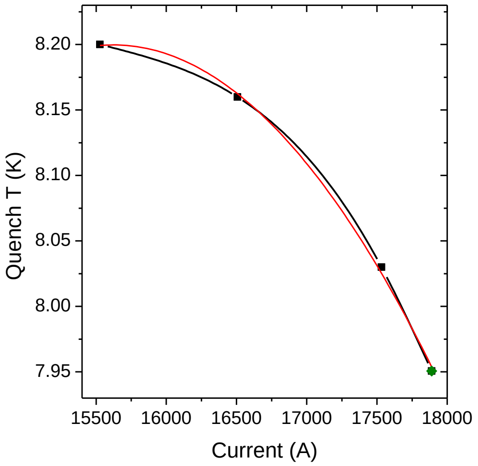
Design has been completed and validated, tooling is close to completion



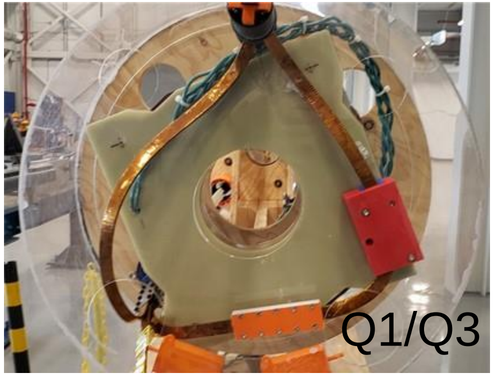




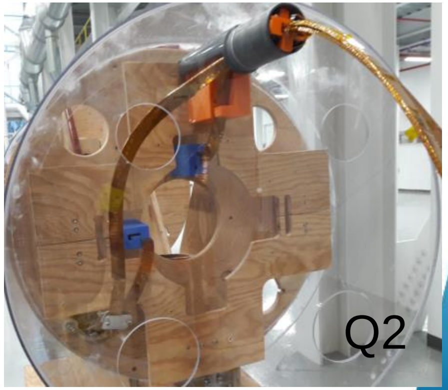
Tested in MQXFS1e magnet (VMTF stand @ IB1 TD)
View of magnet RE + spliced bus



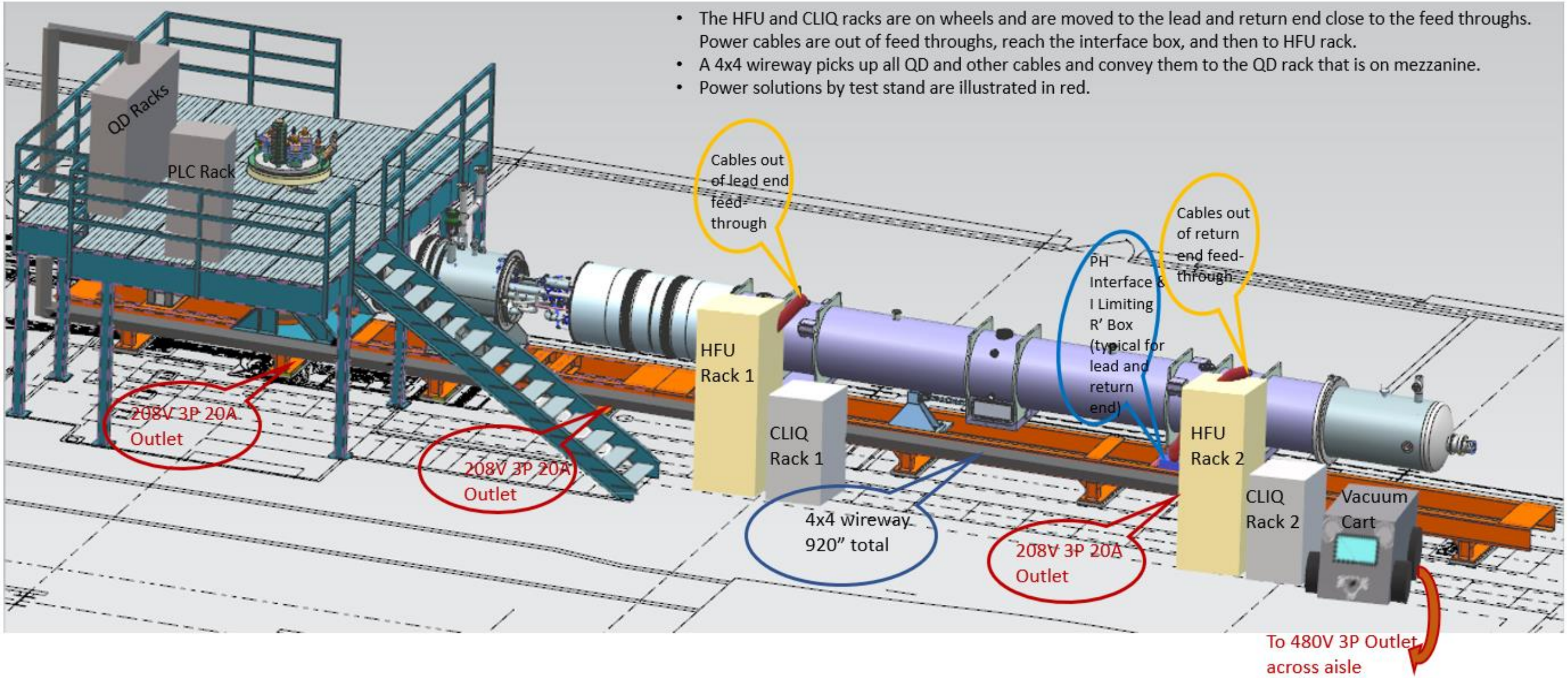
Quench temperature at ultimate current (17890 A), T margin is 6.05 K at ultimate
Detection voltage up to 1 V
<100 K hot spot during bus quench



Expansion loop mockup

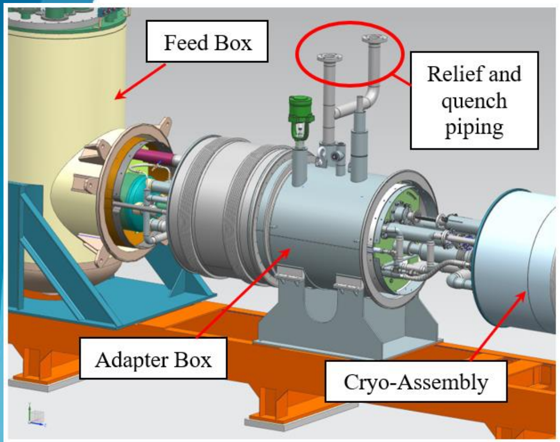


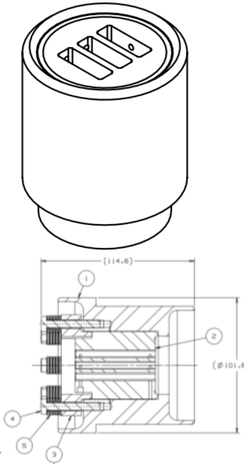
Horizontal Test Stand at Fermilab



Previously used for testing LHC IR Quadrupoles being upgraded

Cryogenic Upgrade

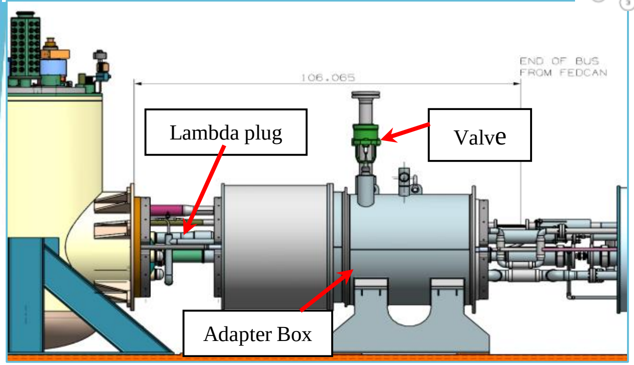




The horizontal test stand will be initially supplied by the existing 300 liter/hr CTI-1500 liquefier.

A new liquefier of the same capacity will be installed and operational at the end of 2021.

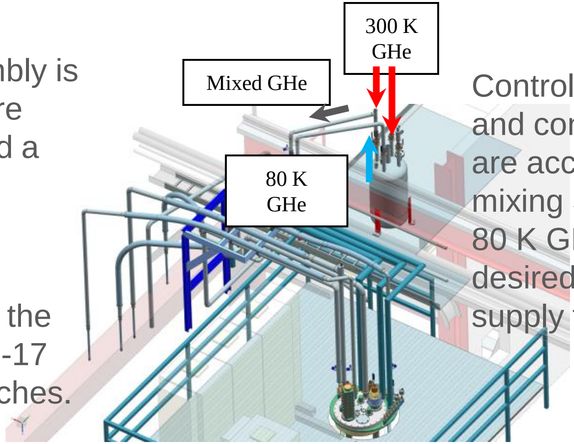
Up to 2 quenches/day at 1.9 K can be supported.



The high-pressure Cryo-Assembly is separated from the low-pressure Feed Box by a lambda plug and a valve.

The lambda plug is a modified CERN design.

Relief valve setpoints will allow the Cryo-Assembly to reach the 16-17 bar expected from tunnel quenches.



Controlled cool-down and controlled warm-up are accomplished by mixing 300 K GHe and 80 K GHe to achieve the desired Cold Mass supply temperature.

QP and MM Upgrade

- QPM system is developed in parallel for the mu2e project and HL-LHC AUP
- QPM Requirements and Specifications are developed
  - A three-tier design will be deployed: Tier 1 – primary QD, Tier 2 – secondary QD, and Tier 3 – System Monitoring and Data Management
- High reliability is achieved with two independent systems: Digital (primary) and Analog (secondary) quench detection
  - Quench detection is accomplished by the standard measurement of voltage signals in coils
- Coupling loss Induced Quench system (CLIQ) is included in the magnet protection along with the quench heater strips
- Rotating coil and Single Stretched Wire Systems are used for alignment and harmonics measurements
  - Rotating coil system internal review successfully passed
  - SSW system is already developed and successfully used for LCLS-II, mu2e and other projects
- Existing 30 kA power system will be used for Q1/Q3 cryo-assemblies horizontal test
  - New 20 kA rated flexible water-cooled power cables connect the bus bar to the top plate

Rotating coil system

PCB probes for rotating coil system

Magnetic Measurements & Power Systems

Conclusions

- Magnet prototyping phase is complete:
  - Lessons learned have improved design and procedures
- Design meets new proposed test in He gas
- Fabrication of magnet components for deliverables is in progress
- Cold Mass design is close to completion, tooling procurement is in advanced stage, Bus bar design is complete
- ICBA completed and tooling installation has started
- VMTF at BNL is fully functional
- HMTF upgrade for AUP is in progress

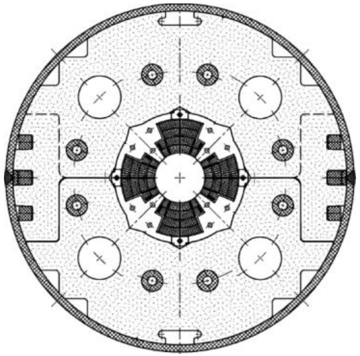
Thank you for your attention

Backup Slides

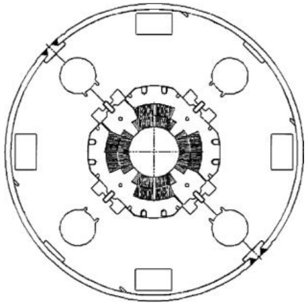
MQXF vs. present LHC low-β quadrupoles

- 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

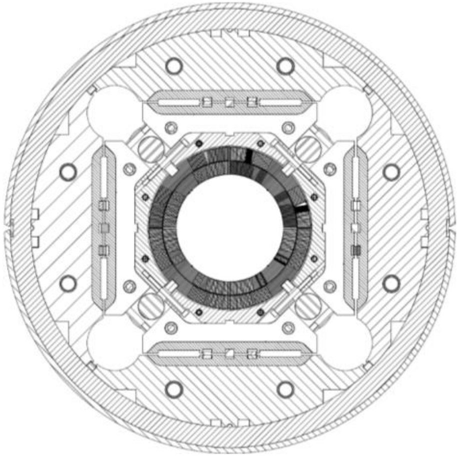
MQXA



MQXB



MQXFA/B

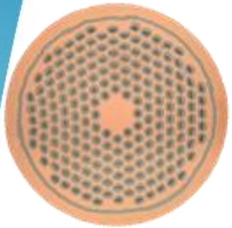


Same scale for all magnets

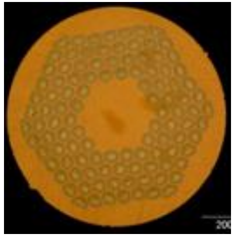
Paolo Ferracin

MQXFA/B Main Parameters

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

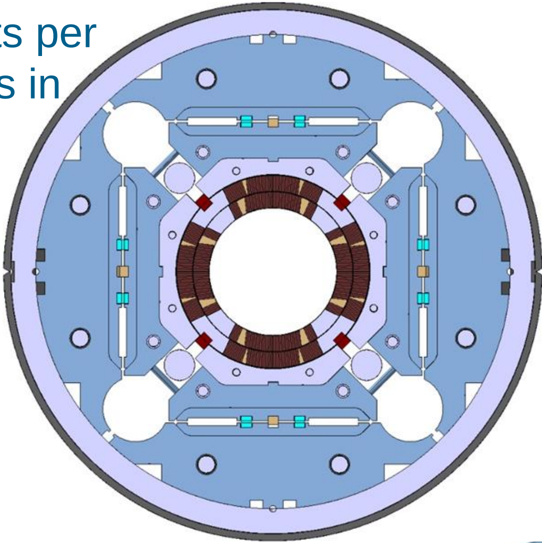


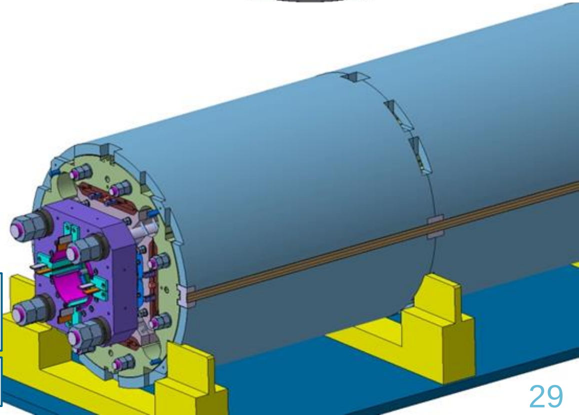
PIT 192
CERN



RRP 108/127
AUP & CERN

2 magnets per cold mass in Q1/Q3

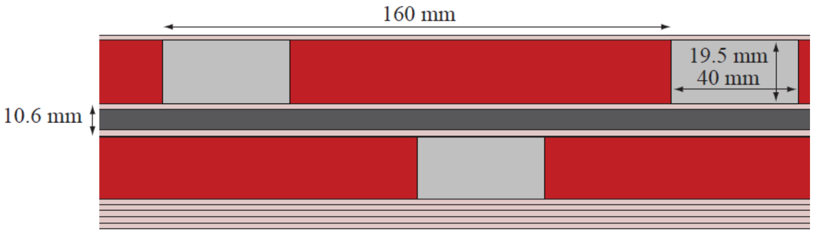




P. Ferracin et al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC " IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

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

MQXF protection strategy: OL quench heaters + CLIQ + Diodes



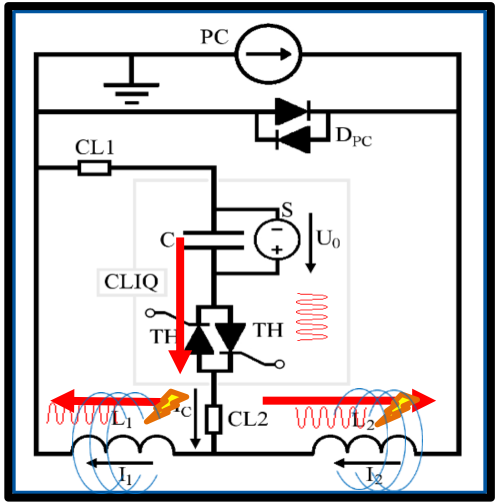
- **50 um polyimide**
- **12 um glue**
- **25 um stainless steel**
- **10 um copper (not in heating zones)**

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

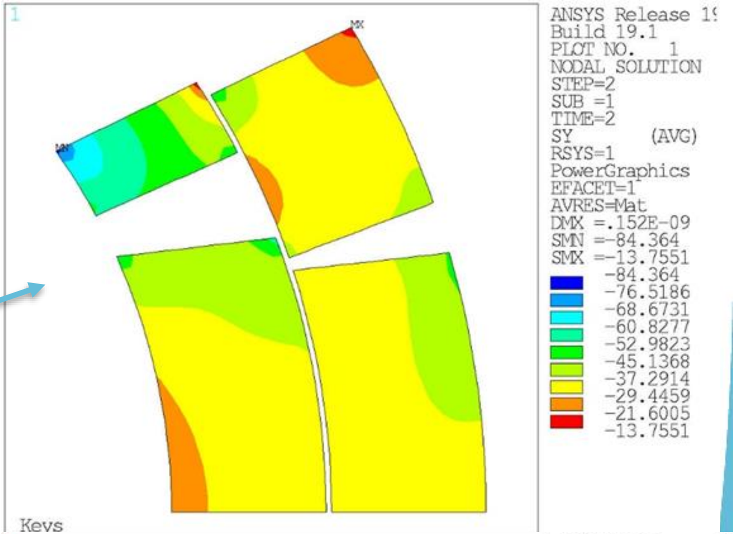
QUENCH

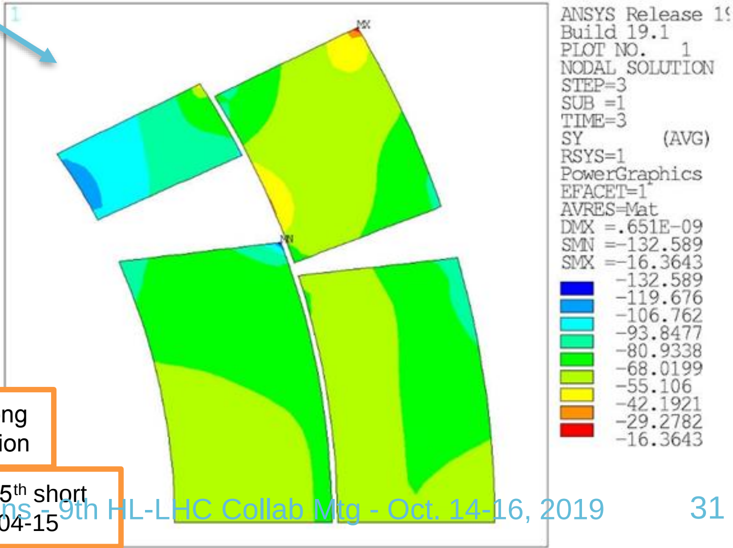
E. Ravaioli

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

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"