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Lessons learned from the prototypes of the MQXFA Low Beta Quadrupoles for HL-LHC and plans for production in the US

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US HL-LHC AUP

HiLumi HL-LHC PROJECT

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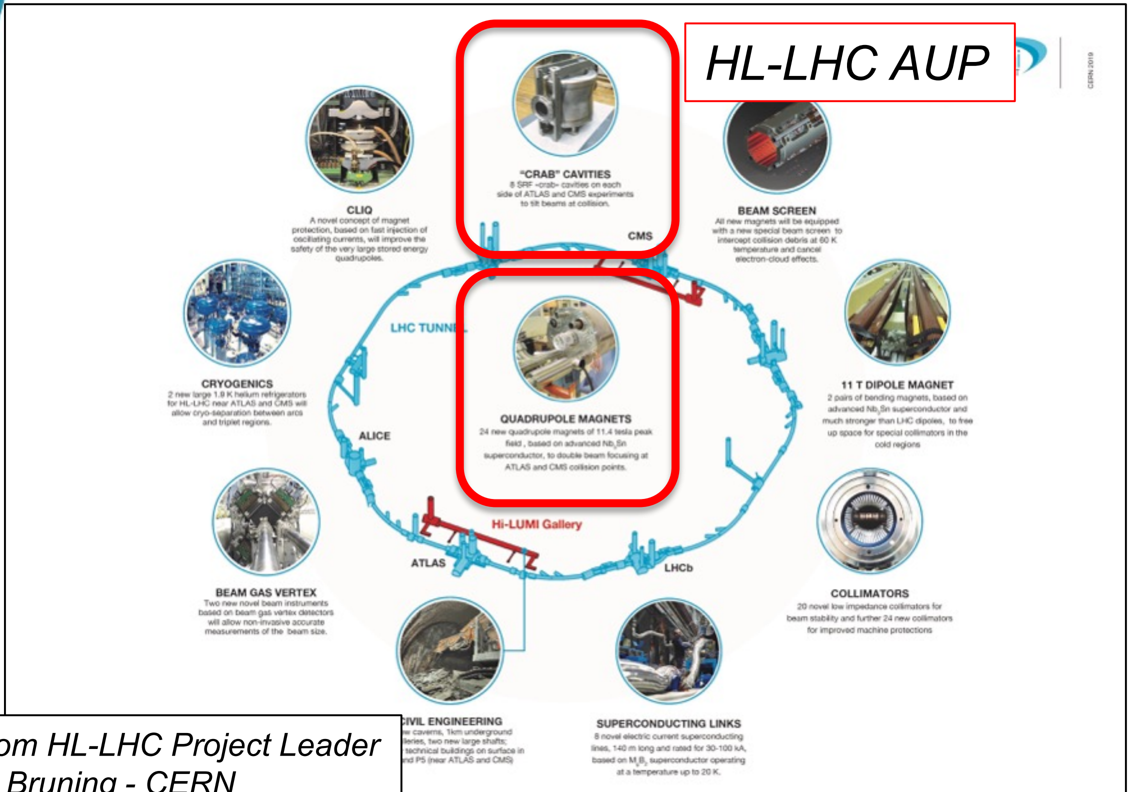
Outline

- AUP Scope & MQXFA Magnets
- MQXFA Magnet Production status
- Lessons Learned
- Conclusions

US Contribution to HL-LHC



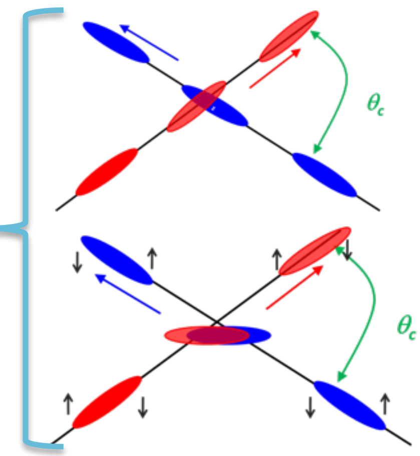
From HL-LHC Project Leader O. Bruning - CERN

Quad Magnets

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

Beam size

Crab Cavities

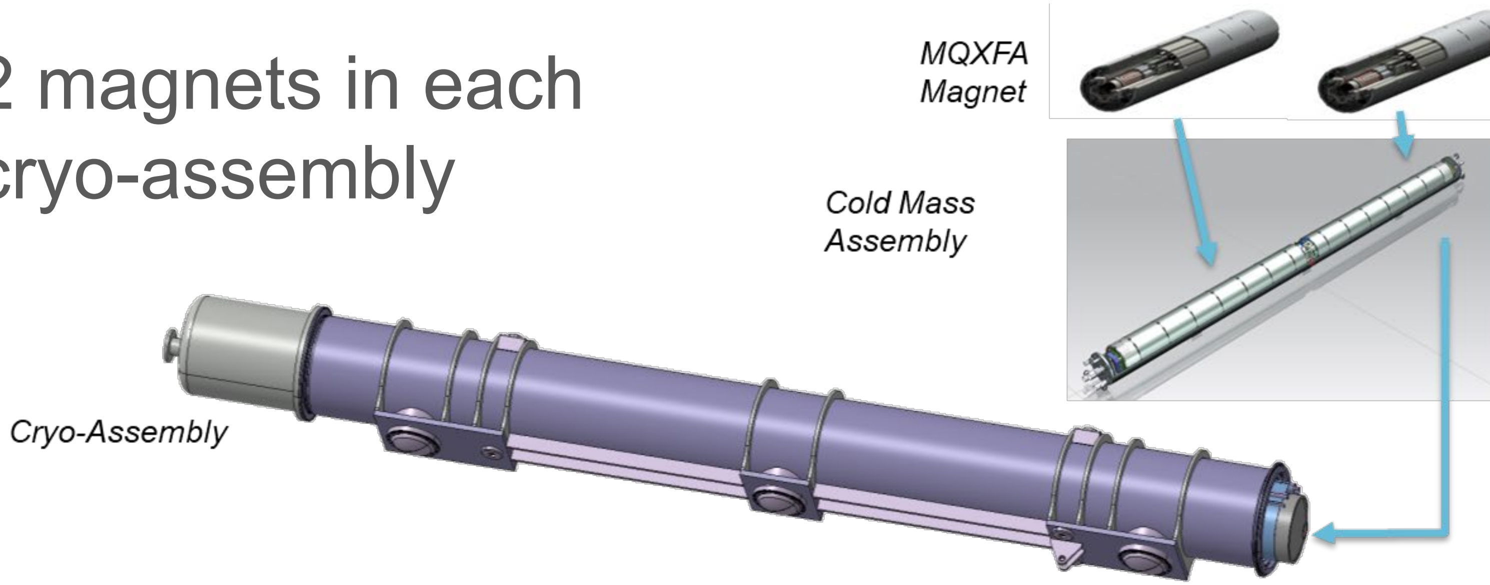


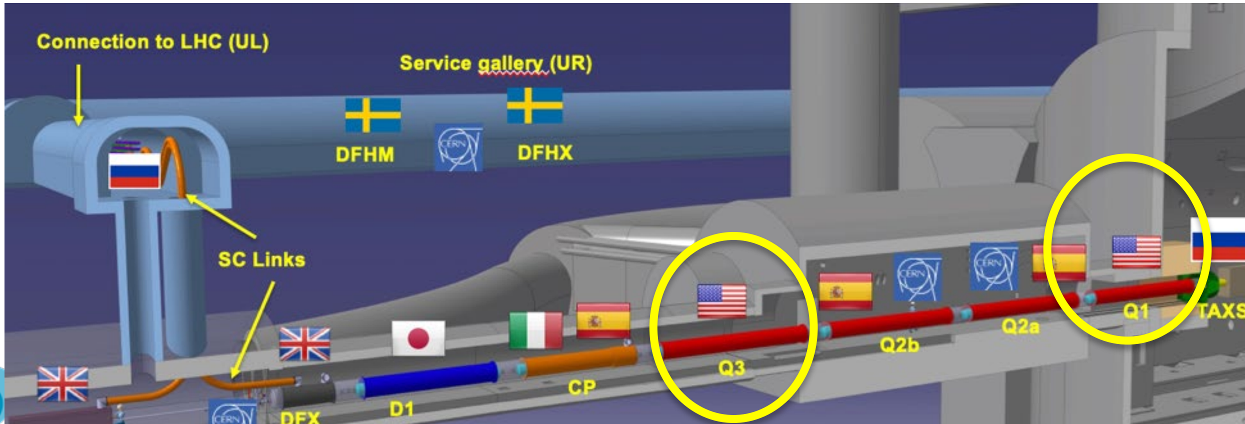
- HL-LHC: from 300 fb^{-1} to 3000/4000 fb^{-1}
- LARP (DOE supported R&D Program) established the necessary technology for the HL-LHC Focusing Magnets and Crab Cavities
- DOE baselined **HL-LHC AUP** Project, coordinating efforts from US Labs (FNAL, BNL, LBNL with contributions from SLAC, JLAB, ODU & FSU)

Slide by G. Apollinari

MQXFA Magnets for HL-LHC Inner Triplets

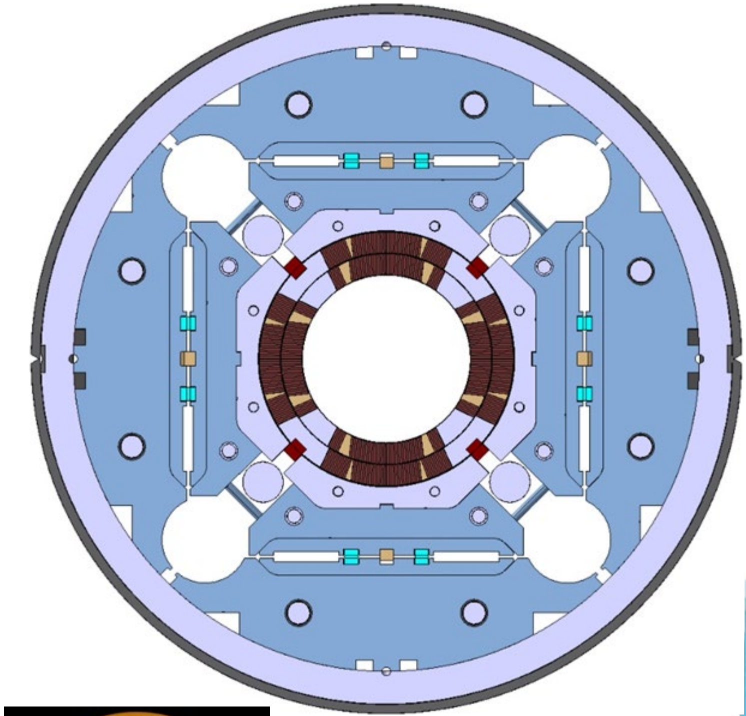
- 10 Q1/Q3 Cryo-assemblies (including 2 spares)
  - 2 magnets in each cryo-assembly

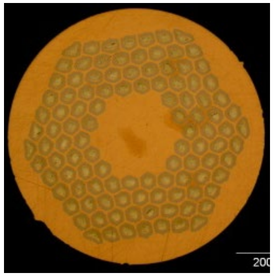




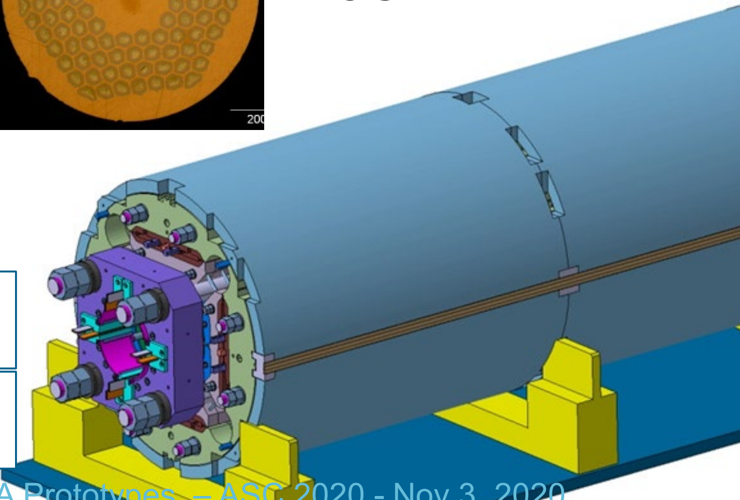
MQXFA/B Design

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	132.2
Nominal current	kA	16.23
Peak field at nom. current	T	11.3
Stored energy at nom. curr.	MJ/m	1.15
Diff. inductance	mH/m	8.26
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle		0.4





Nb_3Sn Conductor
B-OST RRP



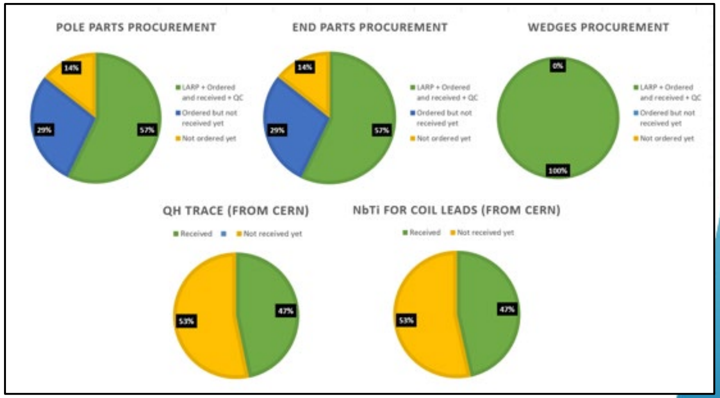
P. Ferracin et al., “Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC ” IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

G. Ambrosio et al., “First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC” NAPAC16, FERMILAB-CONF-16-440-TD

Technical Progress: Nb_3Sn Superconductor, Coil Parts and Coils Assembly

- All Nb_3Sn Conductor is under procurement.
  - Delivered according to plans and meeting technical specs.
- Cable fabrication ~50% complete with 98% yield [1]
- Coil parts in stock at ~50+% level
- Coil fabrication is ~34% complete with yield *improving* to 78-80% levels (up from 75% in early stages of production).

LBNL FY18 order (100km)		B-OST dates	UL #	Piece Length
20% milestone A		Jan-19		
20% milestone B		Jan-19		
60% balance upon delivery and acceptance	Shipment A	Jan-19	28	1
	Shipment B	Feb-19	29-32	4
FNAL FY18 base order (300km) - PO646116		B-OST dates	UL #	
20% milestone A		Sep-18		
20% milestone B		Sep-18		
60% upon delivery and acceptance		Jan-19	13-27	15
FNAL FY18 option order (580km) - PO646116		B-OST dates	UL #	
20% milestone A		Feb-19		
		May-19		
20% milestone B		Mar-19		
		Jul-19		
60% upon delivery and acceptance	Shipment A	Mar-19	33,34	2
	Shipment B	Apr-19	35,36,37	3
	Shipment C	Jul-19	38,39,40,41	4
	Shipment D	Oct-19	42-51	10
	Shipment E	Nov-19	52-61	10
FNAL FY19 base order (400km) - PO655175		B-OST dates	UL #	
20% milestone A		Jan-20		
		Apr-20		
20% milestone B		Feb-20		
		Jun-20		
60% upon delivery and acceptance	Shipment A	Apr-20	62,63,64,65	4
	Shipment B	Jun-20	66,67,68,69	4
You are here	Shipment C	Aug-20	70,71,72,73	4
	Shipment D	Oct-20	74,75,76,77	4
	Shipment E	Dec-20	78,79,80,81	4
FNAL FY20 base order (420km+120km=540km) - PO667037		B-OST dates	UL #	
20% milestone A		Oct-20		
		Dec-20		
20% milestone B		Nov-20		
		Jan-21		
60% upon delivery and acceptance	Shipment A	Feb-21	82,83,84,85,86a	4.5
	Shipment B	Apr-21	86b,87,88,89,90	4.5
	Shipment C	Jun-21	91,92,93,94,95a	4.5
	Shipment D	Aug-21	95b,96,97,98,99	4.5
	Shipment E	Oct-21	100,101,102,103,104a	4.5
	Shipment F	Dec-21	104b,105,106,107,108	4.5
	TOTAL			96



1) I. Pong et al., “Bare Cable Fabrication Statistics for the AUP MQXF Magnet Coils at 50% Milestone” this conference Wk2LPo3F-04

MQXFA Pre-Series Magnet Status

- **MQXFA03**:
  - 1st pre-series magnet
  - 1st magnet completely fabricated by AUP

  Status: cold test is complete, magnet is at FNAL

  accepted for use in 1st Cold-Mass
- **MQXFA04:**

  Status: cold test at BNL is complete
- **MQXFA05:**

  Status: assembly is complete, magnet is at BNL
- **MQXFA06:**

  Status: assembly to be completed at LBNL in Dec 2020
- **MQXFA07 and Series Magnets:**

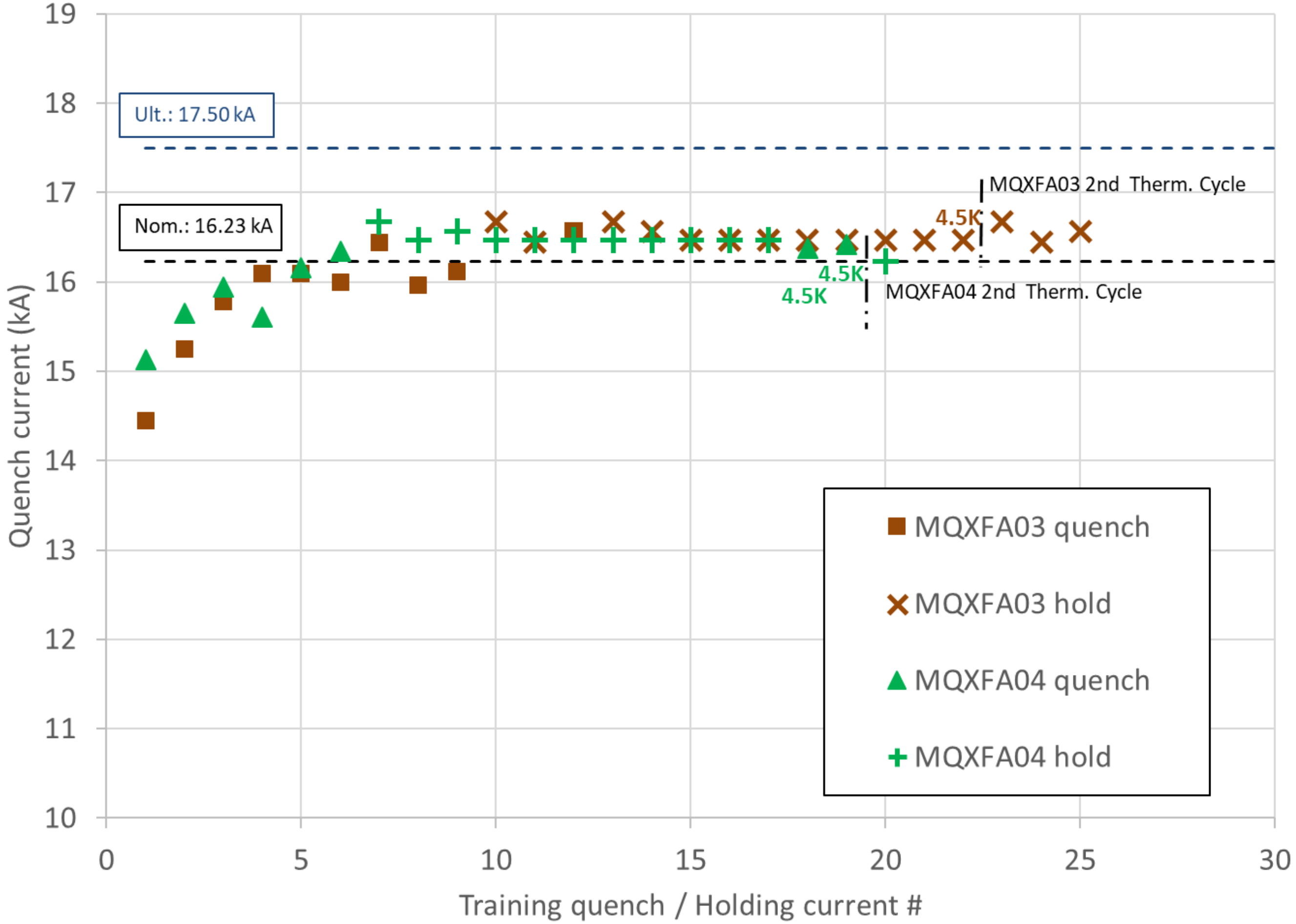
  Plans: a new magnet completed every other month


MQXFA magnet at BNL after shipment

MQXFA03 & MQXFA04 Quench History [1]

Requirement MQXFA-R-T-03: The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 556.9 T in superfluid helium (HeII) bath at 1.3 bar and at a temperature of 1.9 K. ➔ 16230* A + 300 A (margin) = **16530 A for 300 minutes**

Requirement MQXFA-R-T-17: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with **no more than 3 quenches.**



Nominal and ultimate currents of WP3 magnets
CERN-EDMS 2114564

1) J. Muratore et al., "Test Results of the First Pre-Series Quadrupole Magnets for the LHC Hi-Lumi Upgrade." this session

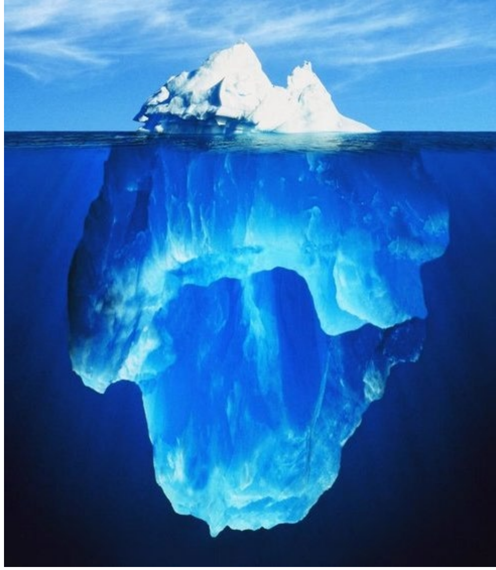
MQXFA03 & A04 Test Summary

- Requirements & Test Goals:

Requirement	A03	A04
Hold current at nominal current + 300 A (T-3)	✓	✓
Ramp to/from I_nom at ±30 A/s (T-11)	✓	✓
150 A/s ramp down w/o quench (T-18)	✓	✓
Temperature margin	✓	✓
Magnetic measurement (O-2)	✓	✓
Splice resistance < 1 nΩ (T-29)	✓	
Training memory (T-17)	✓	✓
All other requirements	✓	

- <u>MQXFA03 was accepted for use in 1st LMQXFA Cold Mass</u>

Below the Surface…



- Before MQXFA Pre-Series Magnets:
  - Several Nb_3Sn quadrupoles magnets with bladder & Key structure by the LHC Accelerator Research Program (LARP)
  - One MQXF short coil and one long coil tested in “mirror magnet” by LARP
  - Five MQXFS short models, many re-assemblies and many tests by LARP/CERN/AUP (S1a/b/c/d/e) and CERN (S3a/b/c, S4a/b/c, S5, S6a/b/c)
  - Two MQXFA prototypes by LARP and one re-assembly by AUP
  - One MQXFB prototype by CERN

Lesson Learned #1 – The Issues

- Issue #1: In 1st prototype Coil-Ground short
  - Causes: a dry spot after impregnation (experimental insulation) plus a high-voltage test (Hipot) at 300 K after He exposure performed at pre-cooldown value ➔ caused a double Heater-Coil short [1], that caused Coil-Ground short
  - Solution: Electrical Design Criteria has lower Hipot values after He exposure, and additional Hipot at 100 K in He gas after training and thermal cycle [2,3].
  - Now: all quench heaters meet requirements
- Issue #2: Some early coils had coil-pole or coil-saddle electrical weakness
  - Causes: excessive binder at coil-pole interface; saddle exchange after winding
  - Solution: reduced binder amount close to pole; no more saddle exchange after winding

1) J. Muratore et al., "Test Results of the First Two Full-Length Prototype Quadrupole Magnets for the LHC Hi-Lumi Upgrade" IEEE Trans App. Supercond. Vol. 30, no. 4, 4004205

2) M. Baldini et al., "Assessment of MQXF Quench Heater Insulation Strength and test of Alternative Design" this conference Wk2LOr1B-06

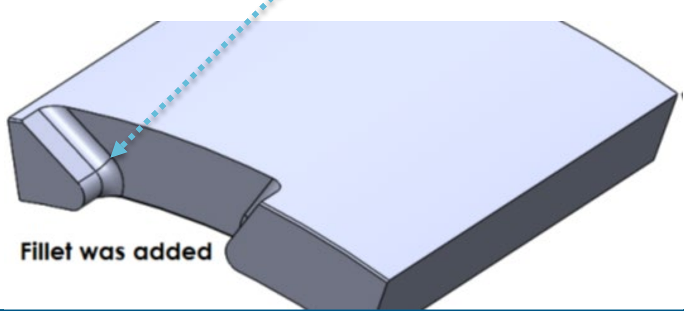
3) V. Marinozzi et al., "Study of the heater-coil electrical insulation for the HL-LHC low beta quadrupoles" this conference Wk2LPo2I-08

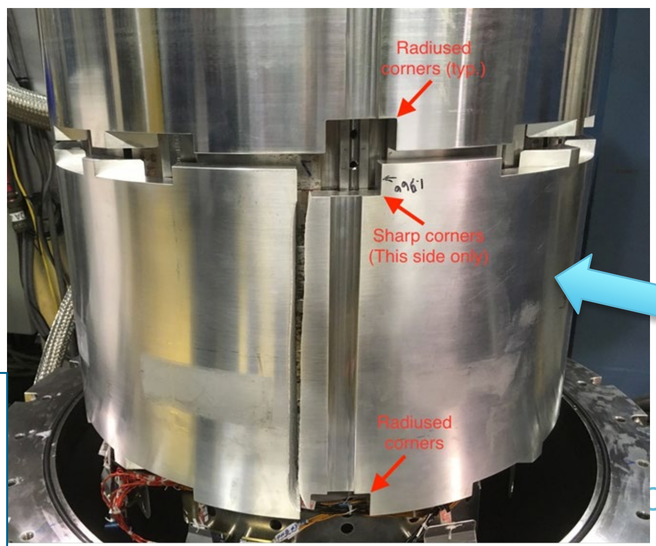
Lesson Learned #1 – The Lesson

- Background info: Fabrication technology in use for MQXF coils was developed by LARP (LHC Accelerator Research Program). LARP performed Hipot test at 1 kV, which was the max at vertical test facilities used at that time
- Lesson Learned: During R&D make estimate of peak voltages <u>plus margin</u> for all high-voltage tests (Hipot, Impulse test, …); and <u>perform tests at these levels as early as possible</u>.

Lesson Learned #2 – The Issue

- Issue: In 2nd prototype bottom Al shell fractured during/after cooldown [1]
  - Causes: shell manufactured incorrectly (sharp corners) and non-conformity was accepted based on past experience
  - Solution: AUP Structural Design Criteria require large fillet radii (min 10 mm), ultrasound tests, die penetrant tests, cold property tests





1) 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 " IEEE Trans App. Supercond. Vol. 30, no. 4, 4000906

Lesson Learned #2 – The Lesson

- Background info: Successful use of Al shells in many LARP short and long models generated confidence, but the addition of accelerator-quality features (cutouts) and the acceptance of a non-conformity generated this issue.
- Lesson Learned: Develop Design Criteria (Structural/Electrical/...) in the early phase of the R&D

- ➔ *Al-shell-based structures can be used for accelerator magnets*

Lesson Learned #3 – The Issues

- Issue: Actual coil yield (80%) is lower than in project baseline (87%)
  - Causes: Several different causes; only one station (winding at FNAL) had more than one issue per station
  - Solution: Winding equipment at FNAL was replaced; Corrective Action & Preventive Action implemented after every issue; Lessons Learned are shared in AUP and with CERN; increased QA resources; performed Electrical QA assessment; …
  - Now: Coil yield is getting better

Lesson Learned #3 – The first Lesson

- Original assumption: after fabrication of coils for short models and prototypes, production coil yield is expected to be higher than in the R&D (LARP) phase. I.e. "*we will be out of the learning curve after prototype phase*"
- First Lesson Learned: equipment changes from short to long coils, and need to increase technician number may negatively affect coil yield in the early phase

Lesson Learned #3 – The second Lesson

- Second Lesson Learned: present coil fabrication technology for Nb_3Sn accelerator magnets is very labor intense
  - ➔ it is fine for a small series production (HL-LHC)
- A large-scale production of Nb_3Sn accelerator magnets must be preceded by the development of <u>2nd generation Nb_3Sn coil fabrication technology</u> that should be <u>much less labor intense</u>
  - Automation may be part of the solution, nonetheless it will require significant effort to prepare the coil fabrication technology for this step

Conclusions

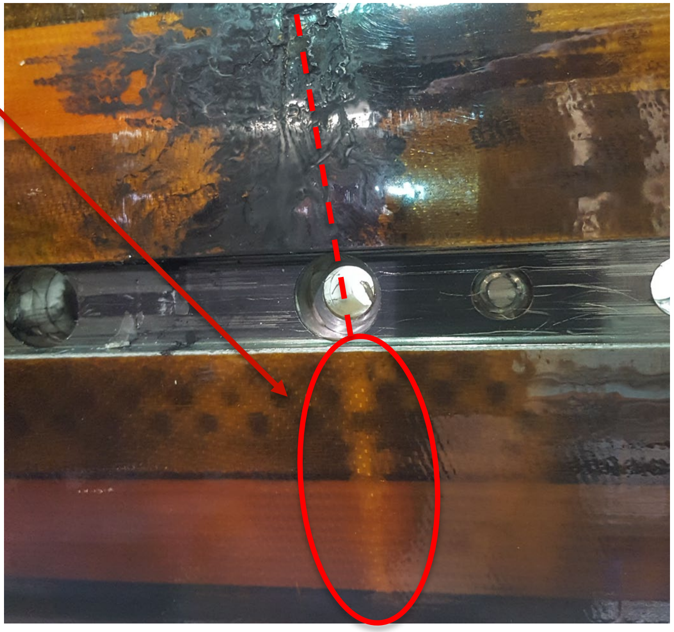
- Successful test of the first two MQXFA Pre-Series magnets for HL-LHC has demonstrated AUP readiness for Series production
- Some Lessons Learned have been instrumental to this progress
- … and may be useful for future projects

Thank you!

Back up Slides

MQXFAP1 Short to Ground: Causes & Prevention

- Short was caused by a series of (now) well-understood events:
- Coil 5 impregnation was poor in the short area:
  - Increased possibility of helium trapped after cold test
  - Insulation brand/vendor no more used after this coil



- Between quench 1 and quench 2, magnet was hi-potted with high voltage (2.5 kV) at room temperature, after helium exposure
  - Coil 5 failed during this hi-pot test
  - Helium at warm is a poor insulator
  - This procedure will not be repeated, according to AUP Electrical Design Criteria
- Hi-pot during training was performed because of rupture of the burst disk and subsequent warm-up
  - Helium relief system was upgraded and demonstrated

➔ The issue was caused by a combination of well-understood events, and each one will be prevented in future tests

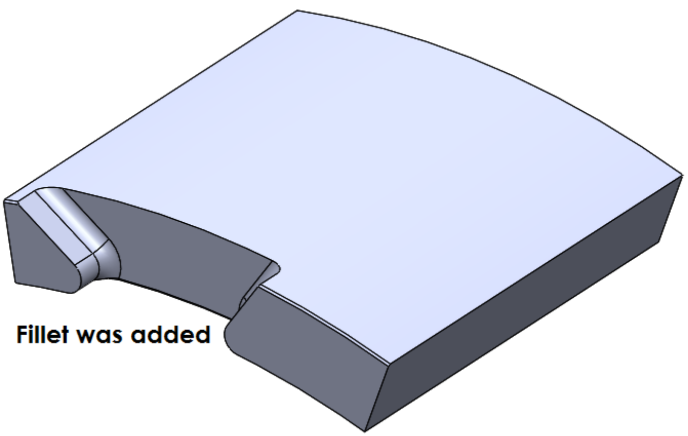
- **Design weakness is excluded**

Analysis on MQXFAP1 Short-to-Ground: US-HiLumi-doc-897
Failure Analysis of MQXF Heater-Coil Insulation: US-HiLumi-doc-921

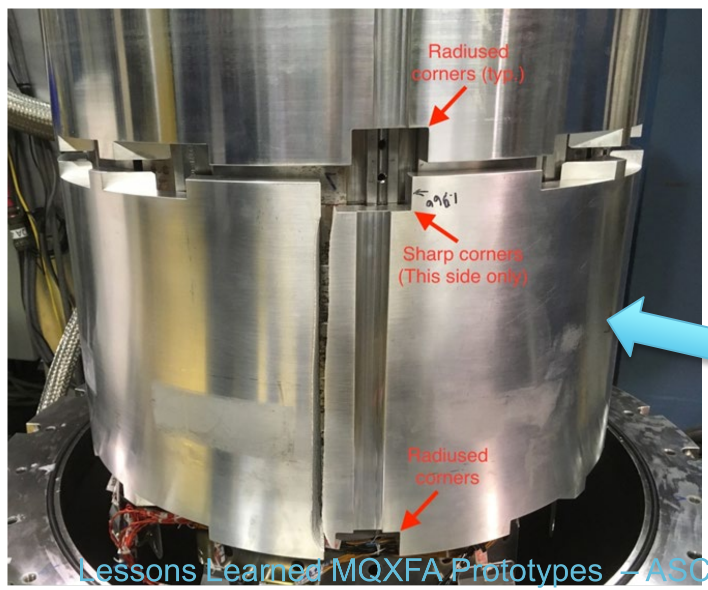
MQXFAP2 Broken Shell

- Root cause:
  - LARP structure with bottom shell manufactured incorrectly and inspected before Final Design Report was completed
  - Non-conformity (sharp corners) accepted (June 2017)
  - Material temper different from other shells (under investigation)
- Issue addressed in FDR (May 2018)
  - 10 mm min fillet radius at critical corners
  - Lesson learned: non-conforming parts will be rejected

Picture from MQXFA FDR, showing 10 mm fillet radius



Longitudinal fracture in return-end shell with crack start at sharp corner

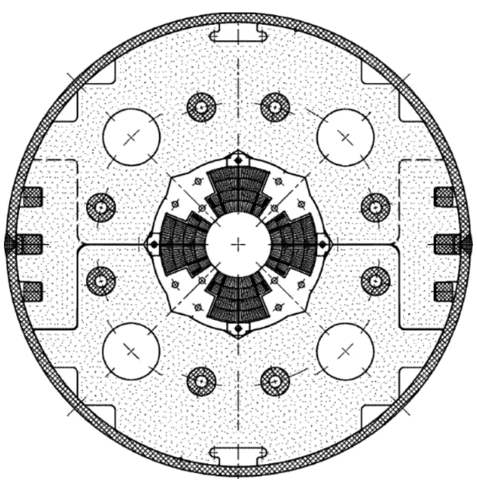


Low-β quadrupole magnets from LHC to HL-LHC

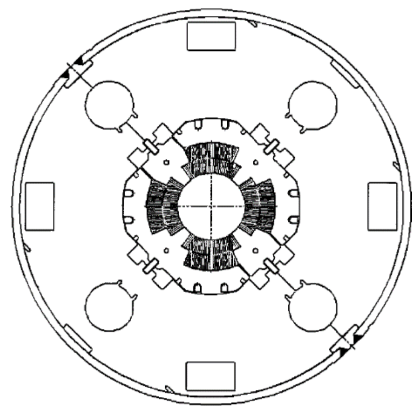
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

State of the art quadrupoles at the time of LHC construction

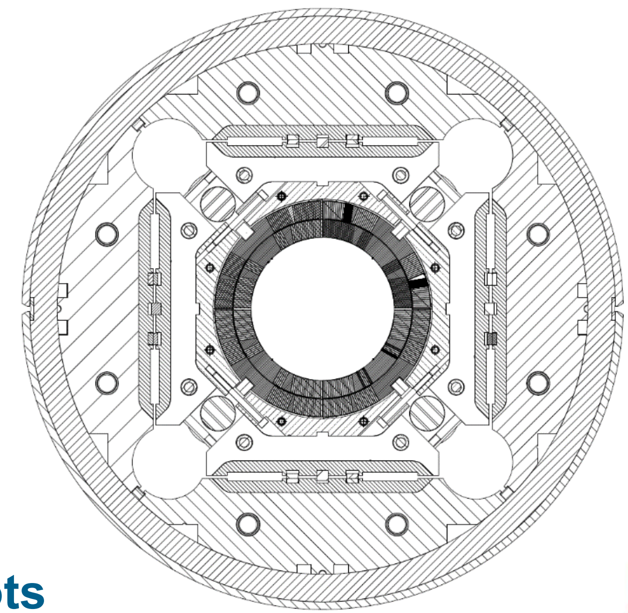
MQXA



MQXB



MQXF



Same scale for all 3 plots