MQXF (results of all type of tests and global plan CERN/AUP)

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On behalf of the whole MQXF team

7th HL-LHC Collaboration Meeting -- CIEMAT, Madrid -- Nov. 13 -16, 2017

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Outline

- Cold Powering Tests:
  - Performance vs. Requirements
- To Do List
  - Requirements to be Demonstrated
  - Components to be Fixed
- Status & Plans

Cold Powering Tests

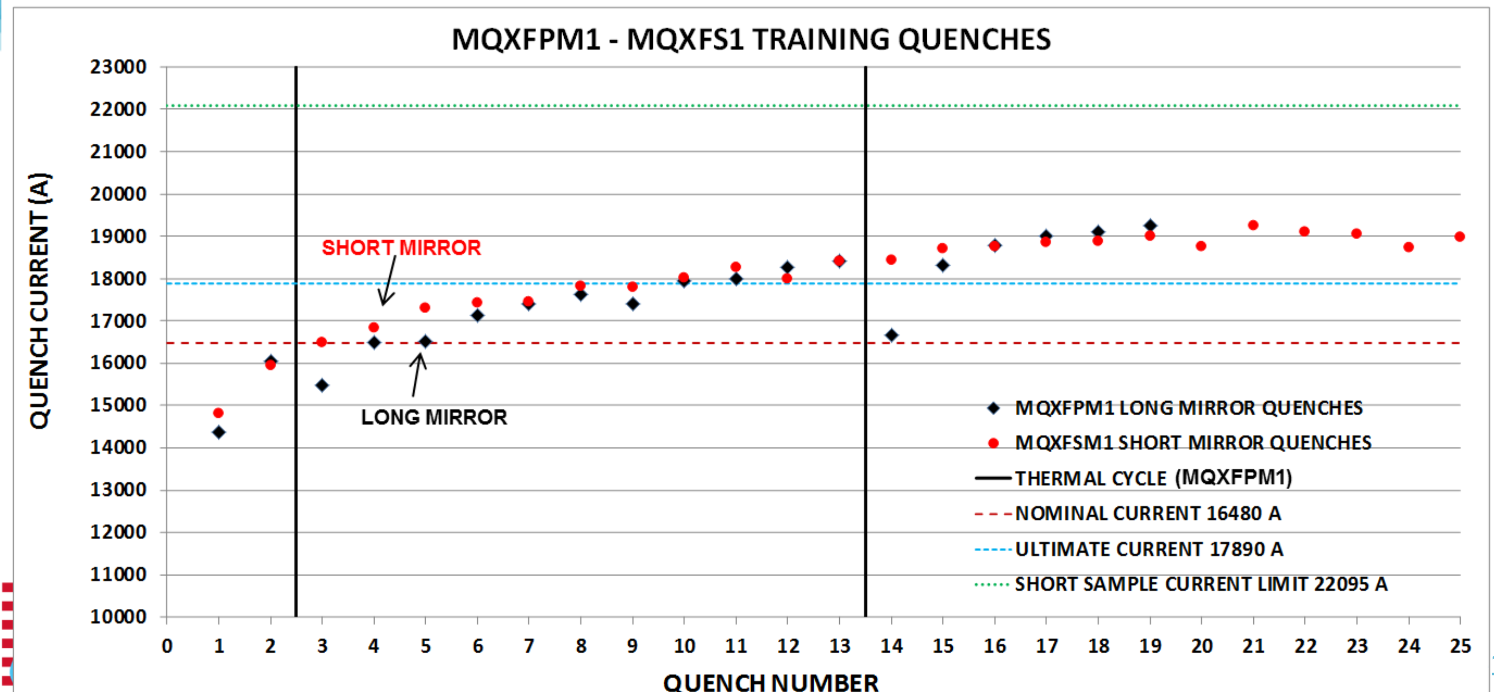
- Single Coil Tests:
  - MQXFS1M: 1.2 m, 1st generation, RRP 108/127
  - MQXFP1M: 4.0 m, 1st generation, RRP 108/127
- Short models (1.2 m):
  - MQXFS1a/b/c: 1st generation, RRP 108/127 & 132/169
    - Coil fabrication: LARP (2) & CERN (2)
  - MQXFS3a/b: 2nd generation, RRP 108/127 & 132/169
    - Coil fabrication: CERN (3) & LARP (1)
  - MQXFS5: 2nd generation, PIT no-bundle-barrier
- Prototypes:
  - MQXFAP1: 4.0 m, 1st & 2nd generation,
    RRP 108/127, 132/169, 144/169,

Gradient & Memory Requirements

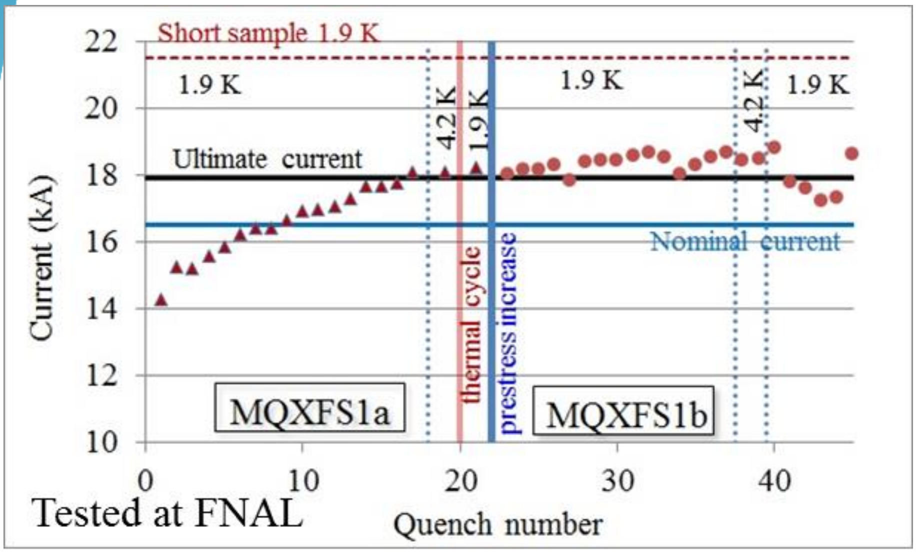
- Ultimate operating gradient
  - "R-T-03: The MQXFA magnet must be capable of reaching a gradient of 143.2 T/m in superfluid helium at 1.9 K (…)"
- Good memory
  - "R-T-17: After a thermal cycle to room temperature, MQXFA magnets should attain the nominal operating current with no more than 3 quenches."
  - Target (objective req.) is no more than 1 quench

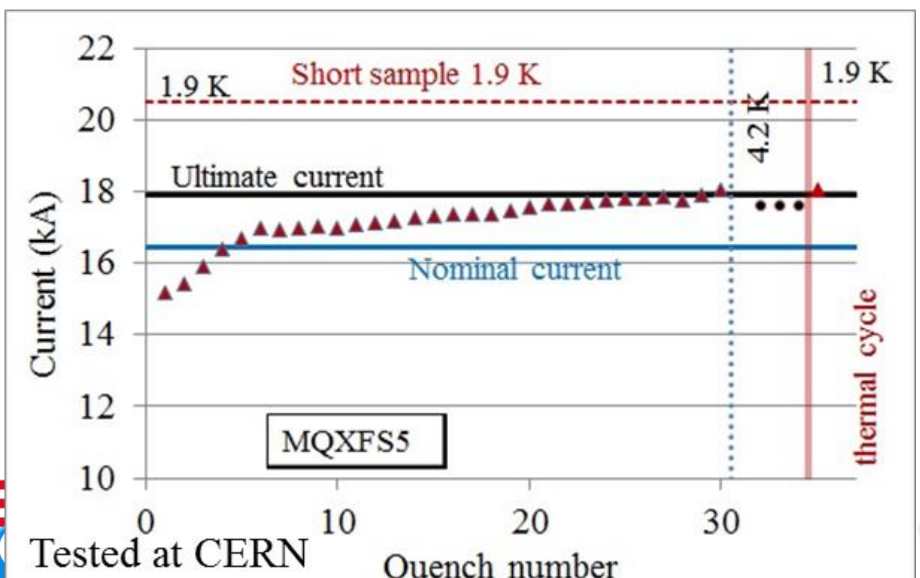
Single Coil Tests

- We can make coils up to 4 m long, with small/no degradation ➔ coils can meet requirements
  - Successful test of single short (1.2m) and long (4.0m) coil in mirror structure

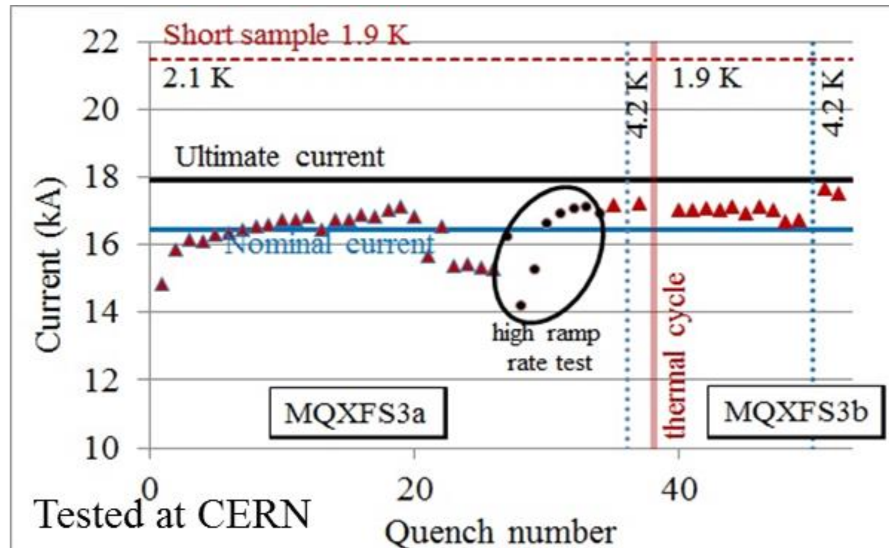


Short Model Tests: Quench History



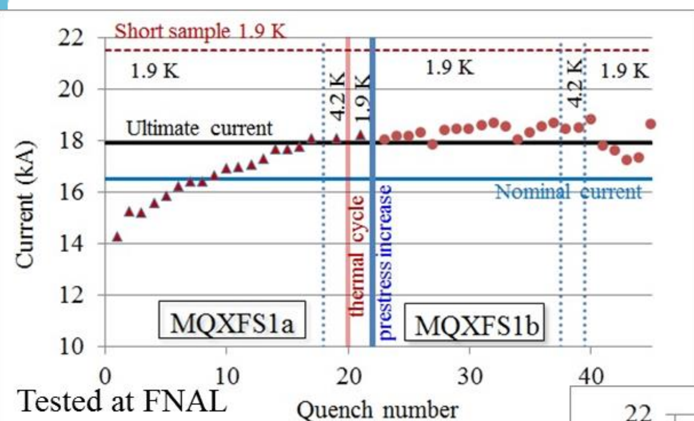


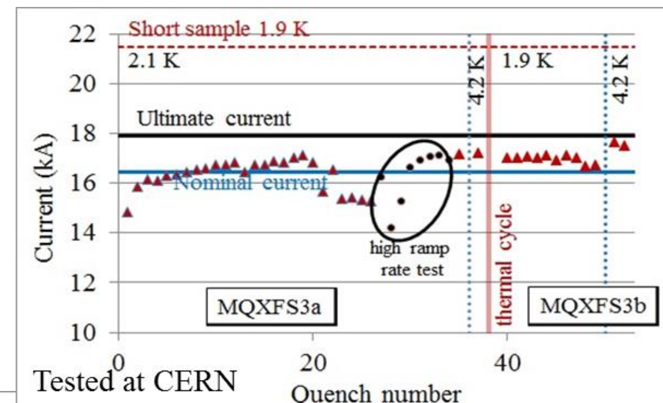
Time

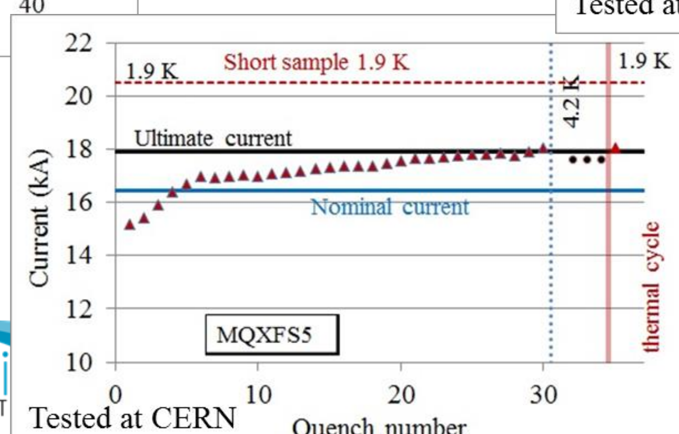


Short Model Tests: Quench History

- MQXF magnets can meet gradient & memory requirements ✔ ✔
- Understanding safe pre-stress range & application
  - MQXFS3 lesson learned: do not over-compress pole keys

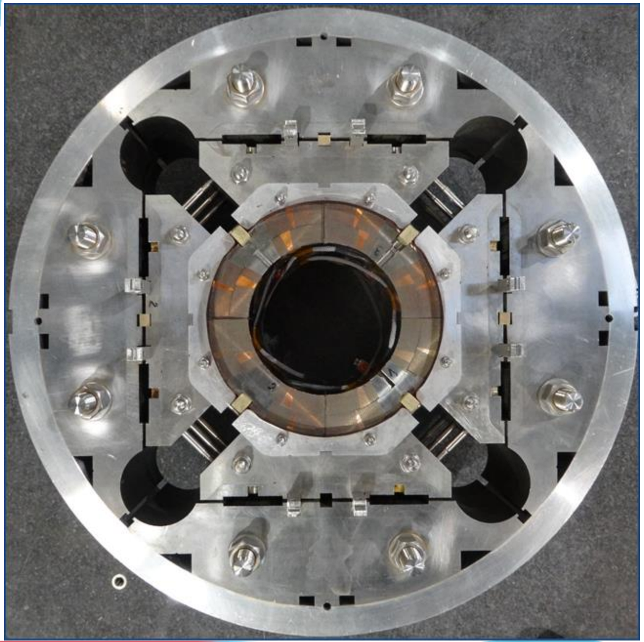


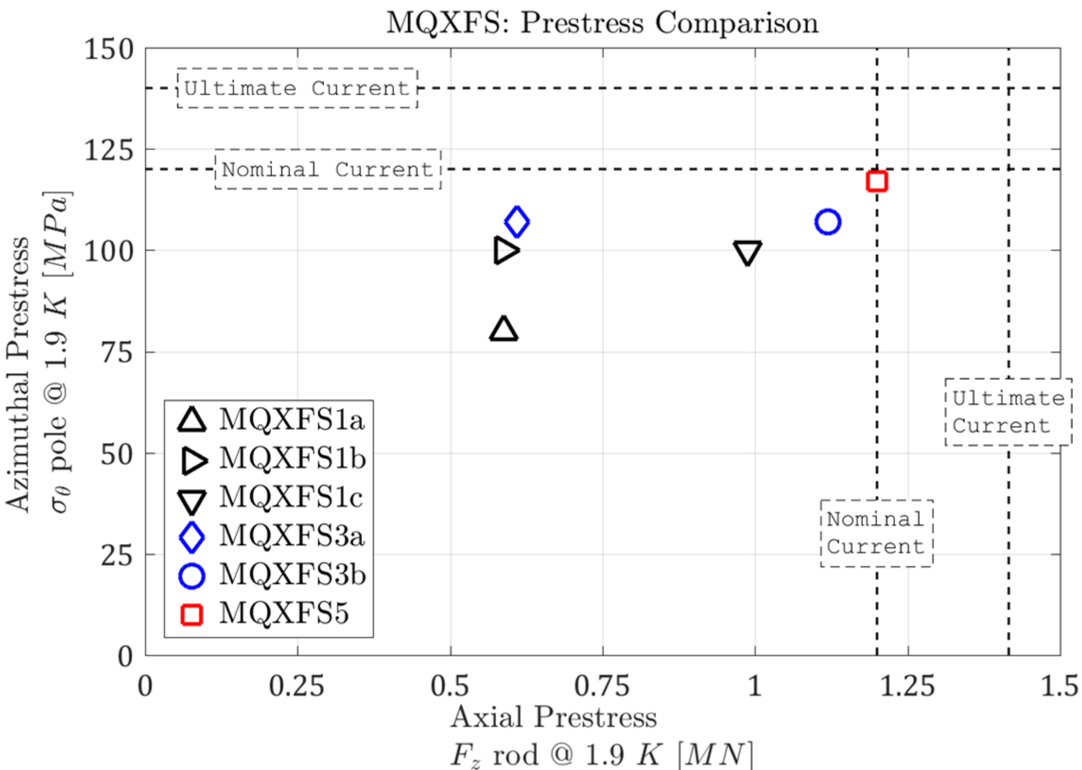




Pre-Stress

- Large safe pre-stress window
  - Loading new coils ≠ loading tested coils
- Pre-stress strategy: small gap around pole keys, that will close during cooldown

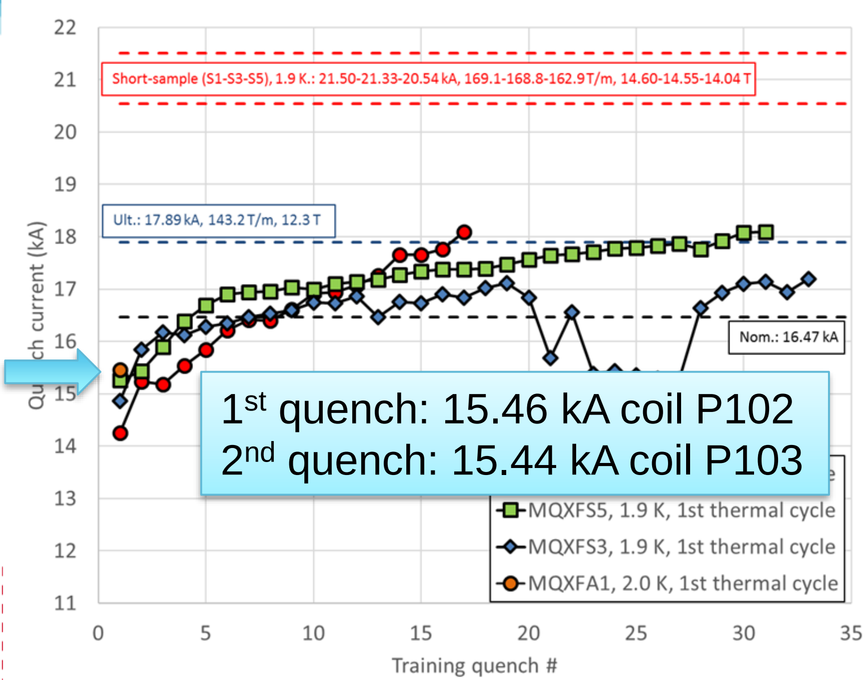


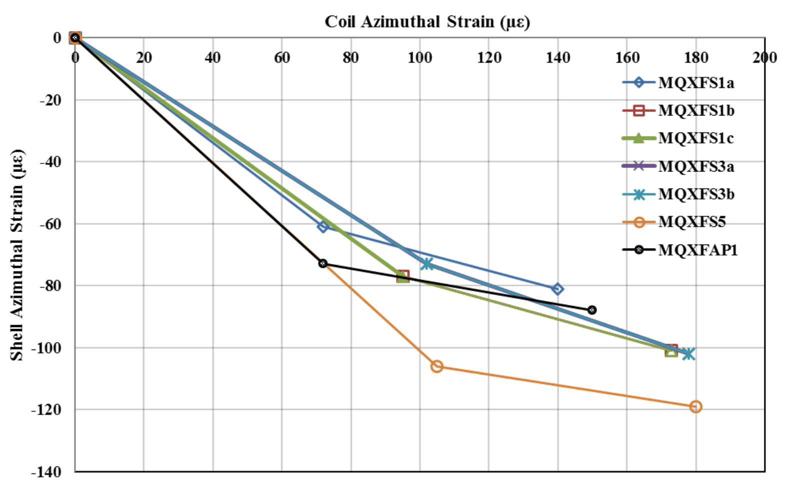


First MQXFA Prototype

- MQXFAP1 pre-load based on MQXFS
  - First quench at end of August
- Upgrades to helium-recovery line, quench protection system, DAQ
  - Training restarted this Monday

Quench History, 1st thermal cycles





Because we don't have a clear coil strain in MQXFAP1 after cool-down, the value of MQXFAP1 coil stress at 1.9 K is calculation result.

Quench Protection Requirements

- Compatibility with CERN protection systems
  - R-T-19 : The MQXFA quench protection components must be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN [3].
  - R-O-06 (target): MQXFA magnets shall survive at least 50 quenches after the acceptance test.

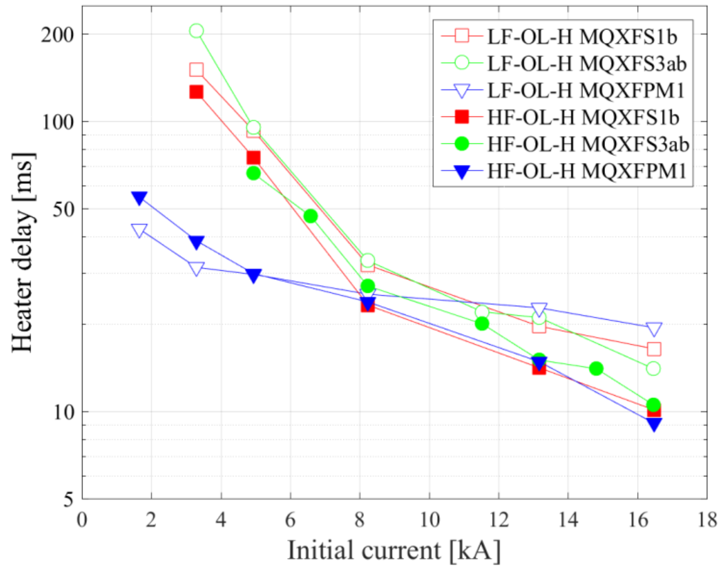
MQXF quench protection studies

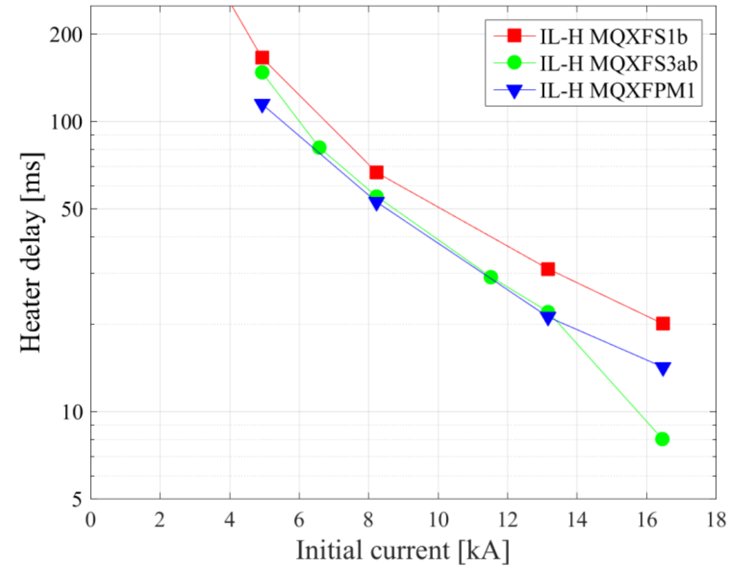
QH delays

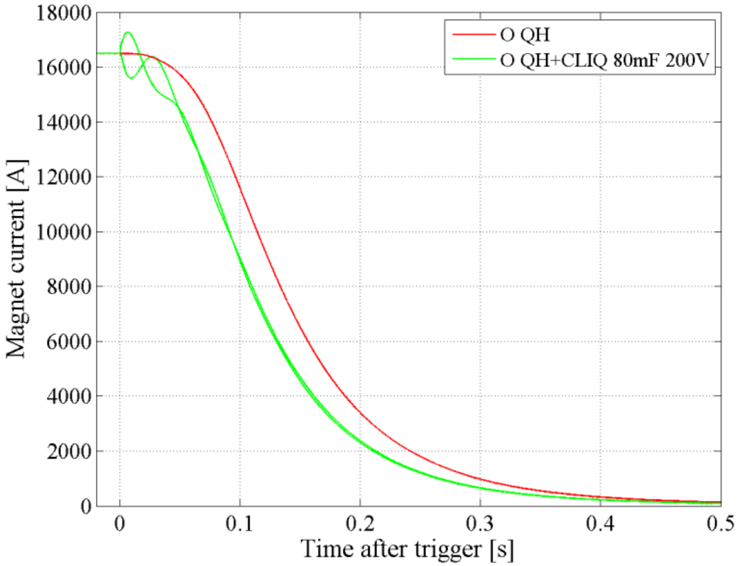
HF-OL: 9-11 ms

LF-OL: 14-19 ms

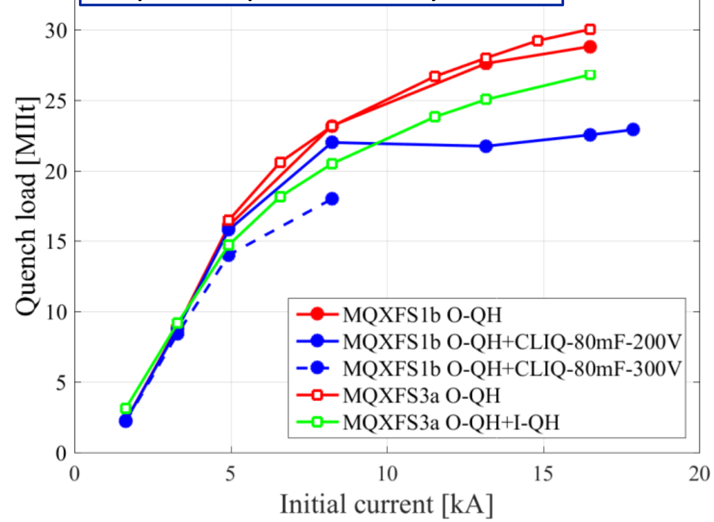
IL: 8-20 ms







Calculated from triggering of quench protection system



Quench integrals

Magnet protected in the entire current range

Quench Protection

- **Outer Layer Heaters are performing as expected**
- **CLIQ is performing as expected**
  - ➔ **<u>We can protect triplet magnets with redundancy</u>** ✔
- Inner Layer Heaters have some issues
  - Bubbles/delamination and some heater failures
  - ➔ Work in progress

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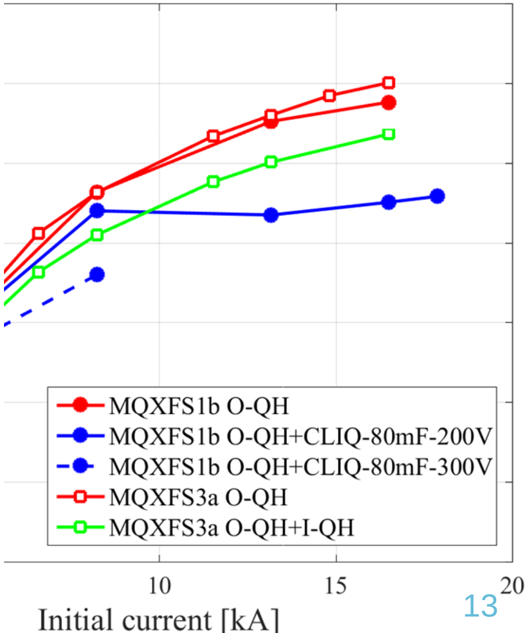
Table 11. Failure case analysis. Simulated hot-spot temperature, peak voltage to ground and peak turn to turn voltage obtained for one failure or two simultaneous failures of QH circuits, at nominal and at ultimate current. Uncertainty ranges are due to the different locations of the initial quench and of the failing QH circuits

Configuration	T_{hot} [K]			$U_{g,peak}$ [V]			$U_{t,peak}$ [V]		
	No f	1	2	No f	1	2	No f	1	2
Nominal current									
O-QH	330-345	345-362	363-384	577	702	868	113	122	132
O-QH + I-QH	251-253	255-266	277-283	561	716	928	83	90	100
O-QH + CLIQ	236-237	238-240	239-242	641	668	666	83	84	86
Ultimate current	Req. T_{hot} < 350 K								
O-QH	352-369	364-385	379-406	808	916	1068	133	141	152
O-QH + I-QH	276-279	279-292	301-310	725	898	1128	101	109	120
O-QH + CLIQ	260-262	261-264	262-267	874	910	909	101	103	105

MIIts measured during protection tests on MQXFS1/3



Field Quality Requirements

- Field Quality targets:
  - R-O-02: The MQXFA field harmonics must be optimized at high field. Table 2 provides specific target values for field harmonics at a reference radius of **50 mm.**
- Thresholds to be set in Acceptance Plan
  - Draft under discussion

WORK IN PROGRESS

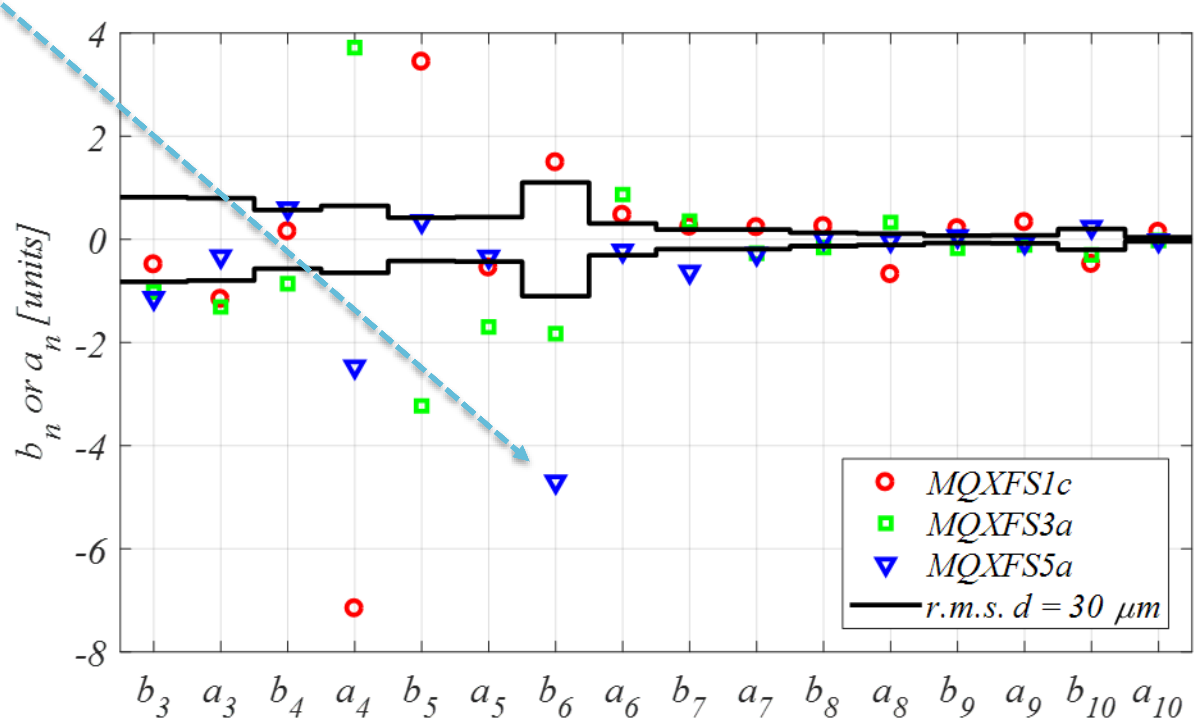
Random components are estimated for a 25 µm random error in the block positioning for non-allowed, and 100 µm for the allowed

	Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm																
	Straight part										Ends		Integral				
	Systematic						Uncertainty		Random				Q1/Q3		Q2a/b		
Normal	Geometric	Ass. & cool	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	Conn. Side	Non conn. Side	Injection	High Field	Injection	High Field
2									10	10						
3	0.000	0.000	0.000	0.000	0.000	0.000	0.820	0.820	0.820	0.820			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.570	0.570	0.570	0.570			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.420	0.420	0.420	0.420			0.000	0.000	0.000	0.000
6	-2.200	0.900	0.660	-20.000	-21.300	-0.640	1.100	1.100	1.100	1.100	8.943	-0.025	-16.692	0.323	-18.593	-0.075
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.130	0.130	0.130	0.130			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.070	0.070	0.070			0.000	0.000	0.000	0.000
10	-0.110	0.000	0.000	4.000	3.890	-0.110	0.200	0.200	0.200	0.200	-0.189	-0.821	3.119	-0.175	3.437	-0.148
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009			0.000	0.000	0.000	0.000
14	-0.790	0.000	-0.080	1.000	0.210	-0.870	0.023	0.023	0.023	0.023	-0.545	-1.083	0.033	-0.856	0.106	-0.862
Skew																
2									10.000	10.000	-31.342		-2.985	-2.985	-1.753	-1.753
3	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.430	0.430	0.430	0.430			0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.310	0.310	0.310	2.209		0.210	0.210	0.124	0.124
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080	0.080	0.080			0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040	0.065		0.006	0.006	0.004	0.004
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.014	0.014			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010			0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	-0.222		-0.021	-0.021	-0.012	-0.012
	Magnetic length straight part				Q1/Q3	3.459	Q2a/b	6.409	Mag. Len. Ends		0.400	0.341				

Short Models: Field Quality

Geometric field errors at nominal operating conditions:

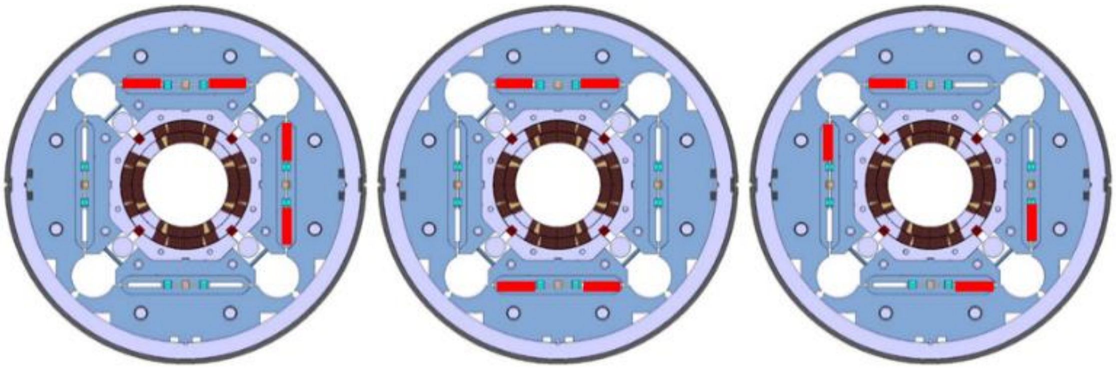
- a_4 and b_5 above targets in MQXFS1 and MQXFS3.
- MQXFS5, the first magnet assembled with four coils produced in the same manufacturing line, has a remarkable better field homogeneity
  - b_6 is above targets in MQXFS5, consistent with expectations due to coil shimming.



Magnetic Shimming

- Ferromagnetic shims inserted in the bladder slots can correct up to ± 5 units of b_3/a_3, ± 5 units of b_4 and +-1 unit of a_4
- Three different magnetic shimming layout have been tested in the short model assemblies.
- Obtained correction is in agreements with expectations.

MQXFS1c **MQXFS3a** **MQXFS5a**



n		MQXFS1c		MQXFS3a		MQXFS5a	
		Δb_n	Δa_n	Δb_n	Δa_n	Δb_n	Δa_n
3	**Measured**	**3.51**	**-3.92**	1.17	-0.59	-0.40	-0.40
	Computed	**4.22**	**-4.24**	0.00	0.00	0.00	0.00
4	**Measured**	0.01	-1.69	**-2.55**	0.83	-0.22	**0.71**
	Computed	0.00	0.00	**-2.88**	0.00	0.00	**0.84**

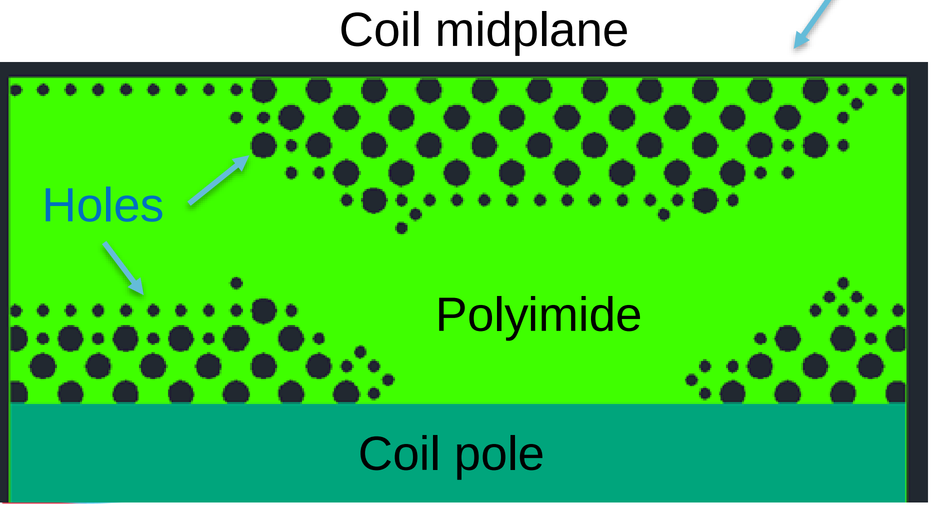
Other Requirements: Splices

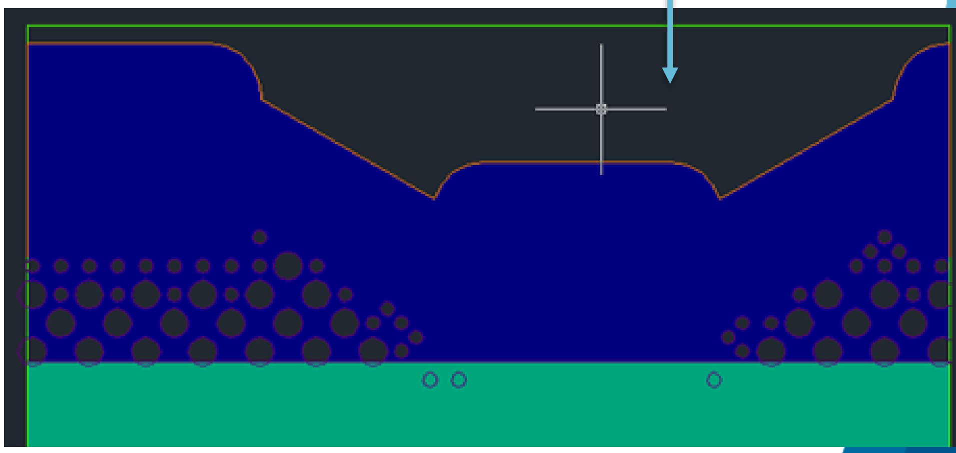
- Splices
  - R-T-14: Splices are to be soldered with CERN approved materials.
  - R-O-04: Splice resistance target is less than 1.0 nΩ at 1.9 K.

- Measurements:
  - All splices are made with <u>CERN approved materials</u> and show <u>resistance < 1.0 nΩ</u> with margin ✓

Other Requirements: Cooling

- Coil inner surface: 40% polyimide free
  - **R-T-07: At least 40% of the coil inner surface must be free of polyimide.**
- Actual: present traces have 18-20% of conductor surface polyimide free
- Latest computations show that 24% is OK
- By trimming present traces we may have >30%





Other Requirements: Electrical

- Electrical tests:
  - **R-T-16: The MQXFA magnet coils and quench protection heaters must pass a hi-pot test specified in Table 3.**

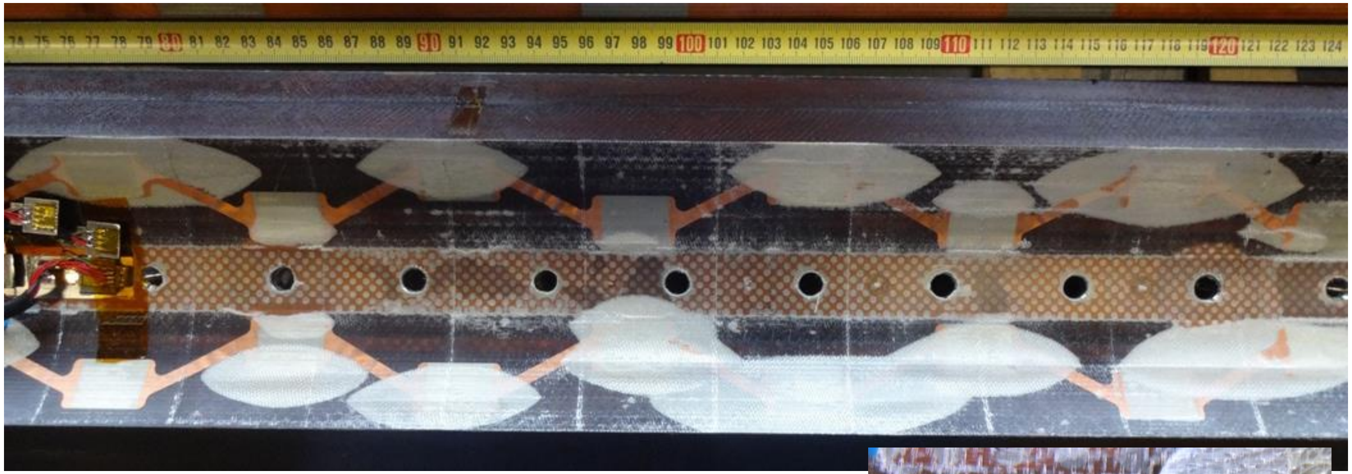
Circuit Element	Expected Vmax [V]	V hi-pot	I hi-pot [μA]	Minimum time duration [s]
Coil to Ground at RT *	n.a.	3.7 kV	10	30
Coil to Quench Heater at RT *	n.a.	3 kV	10	30
Coil to Ground at cold **	670	1.8 kV	10	30
Coil to Quench Heater at cold **	900	2.3 kV	10	30

- Actual: Fine at room temperature; hard at cold
  - More details in parallel session tomorrow

To be Demonstrated / Fixed

To be fixed: Inner Layer Quench Heaters

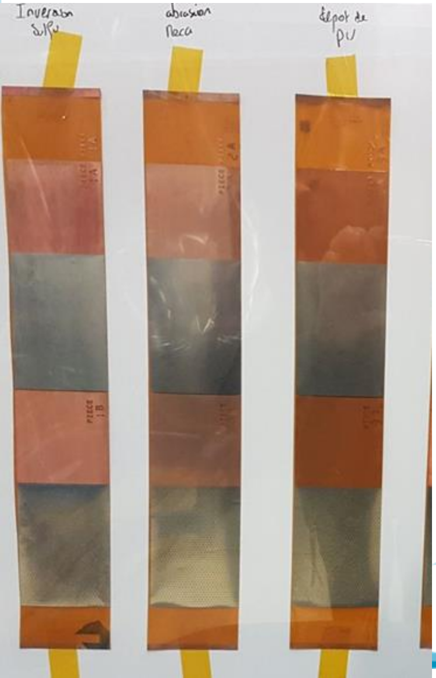
- Issue: Delamination (“bubbles) may cause heater failure and compromise cable insulation
- Study: Weak bonding btw fiberglass sheet and metal on trace; even if heaters are not fired



Plan to fix Inner Layer Quench Heater - I

On going R&D to address issue:

- Encapsulated trace (polyimide on both side)
  - Short model trace fabricated
- Surface treatment of metal parts
  - Samples under preparation for de-bonding test
    - sample 1: *inversion sulfurique*
    - sample 2: *abrasion mécanique*
    - sample 3: *deposit of thin layer of Polyuréthane on ss*
    - sample 4: *Cleaning of ss (with Acide Fluoridrique)*
    - sample 5: *Laisser le Ni de wood*
    - sample 6: no treatment
    - sample 7: encapsulated trace (polyimide coverlay pressed)



Plan to fix Inner Layer Quench Heater - II

Schedule:

- De-bonding tests completed by Jan-Feb 2018
- Test in MQXF4
  - Coil 108: standard trace, heat cleaned fiber
  - Coil 109: No inner layer trace (only VT)
  - Coil 110: encapsulated trace
  - Coil 111: surface treated trace
- Results in summer 2018
  - NOTE: AUP has already started coils for MQXFA03

?

To be demo: Welding of SS shell on MQXF

- Welding tests are almost completed
- AUP:
  - Welding of SS shell on MQXFS1: in 2-3 weeks
  - Test planned in January (MQXFS1d)
- CERN:
  - Welding and test to be done on MQXFS5b (Jan-Feb) or MQXF3d (~April)

More details Wednesday afternoon in Herve' and Sandor talks

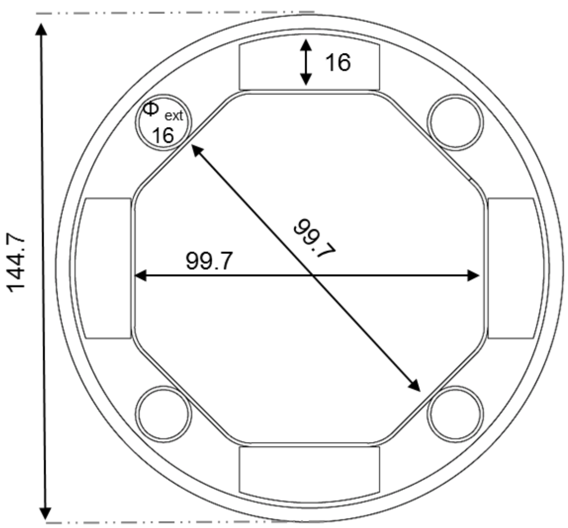
To be demo: Alignment

- AUP plans to use MQXFAP2 to demonstrate alignment
  - MQXFAP2 assembly completed by Feb-March 2018
- CERN plans to use the mechanical assembly test to demonstrate alignment
  - Mechanical test completed by April 2018

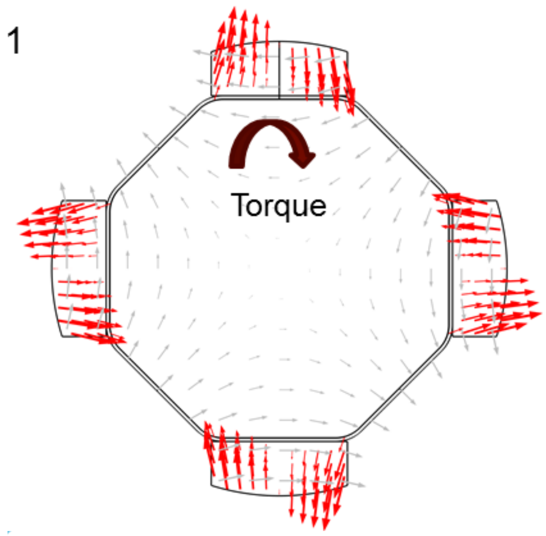
To be demo: Cold Bore & Beam Screen Integration

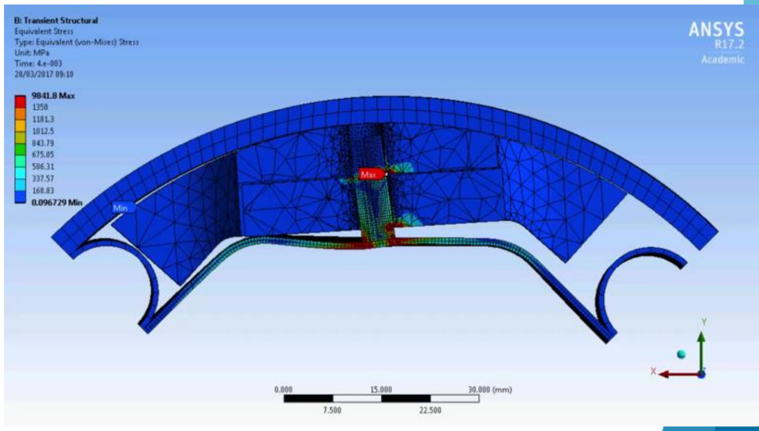
- Cold Bore with Beam Screen will be heavy (16 mm tungsten blocks in Q1)
  - Coil bumpers on poles
- Significant forces during quench & CLIQ discharge
  - FEM and design adjustments in progress

Q1



*The dimensions are given in mm

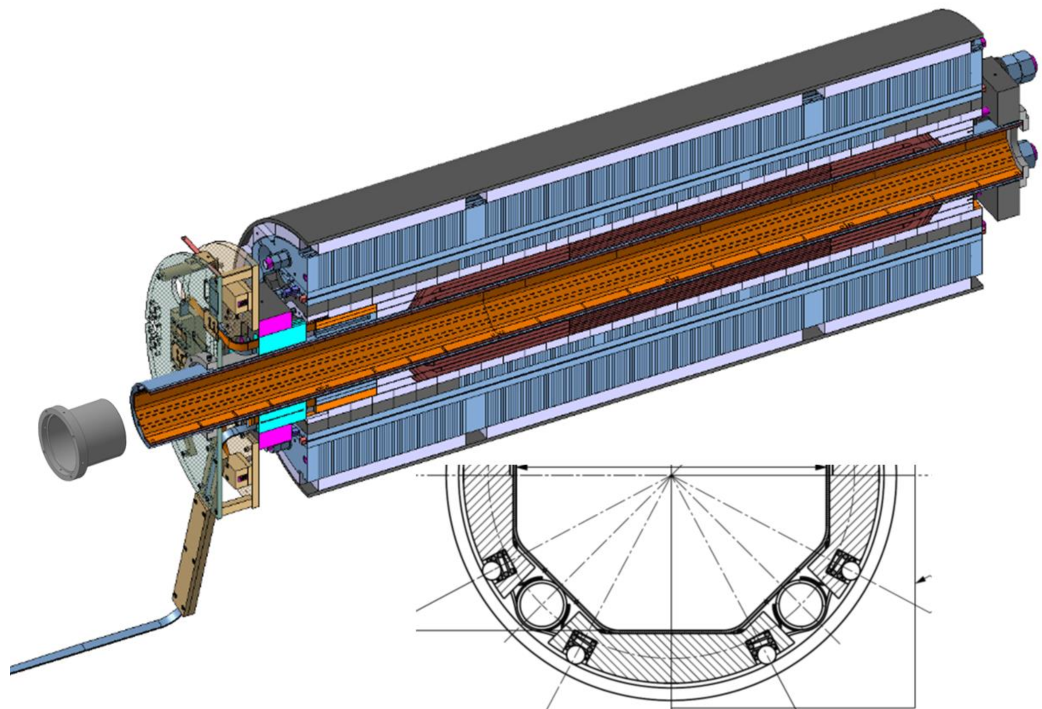




To be demo: Cold Bore & Beam Screen Integration

Short Models:

- Cold bore insertion in vertical condition, and vertical cold test: MQXFS5b (Jan-Feb)
- Cold bore insertion in horizontal condition (with coil bumpers), and vertical cold test: MQXFS3d (Mar-Apr)

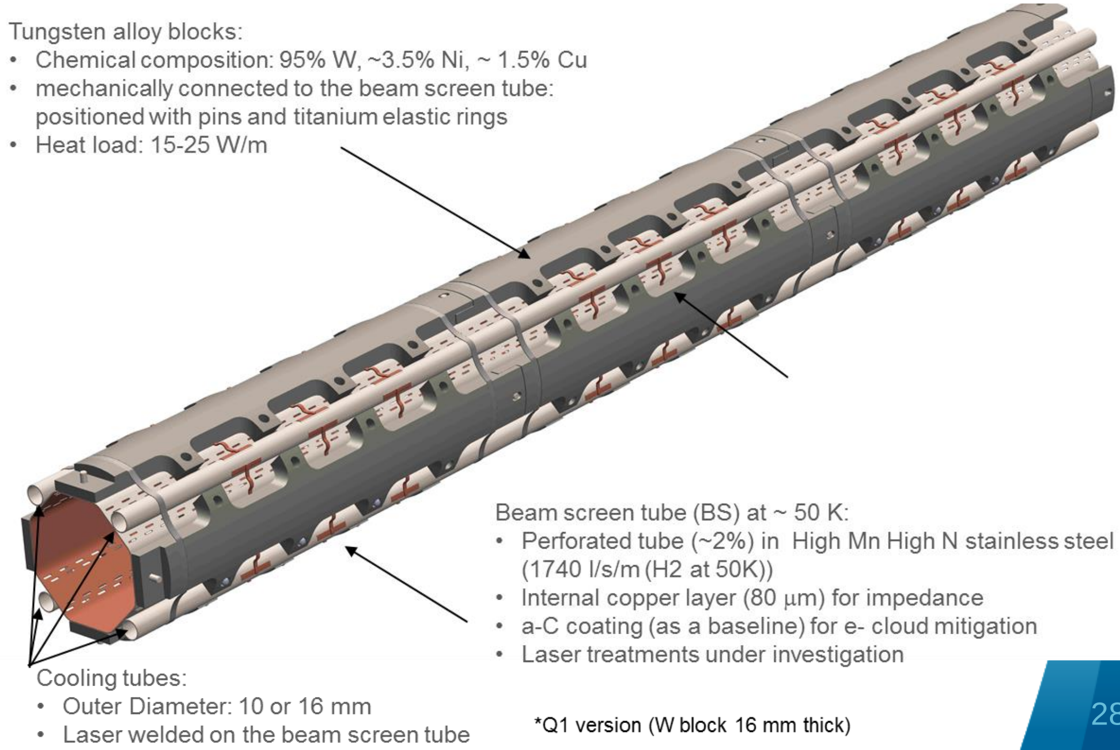


To be demo: Cold Bore & Beam Screen Integration

Prototypes:

- MQXFBP1 w Cold Bore, w/o Beam Screen
  - May 2019
- **PROPOSAL**: MQXFBP1 w Cold Bore & Beam Screen
  - After 1st thermal cycle

Goal: test possible impact on magnet training/performance of Beam Screen shaking due to CLIQ discharge, w/o dumping effect of helium (in vertical tests)



Status & Plans

AUP Status & Plans

- Short models:
  - MQXFS1d with SS welded shell in January
  - Coil QXFS9 with alternative wedges & one end part is under fabrication
  - MQXFS1e with QXFS9 test: depends on MQXFAP1
- Prototypes & Pre-series:
  - MQXFAP1: under test
  - MQXFAP2: 4 coils completed (spare in progress), structure procured, pre-assembly started, test in April
  - MQXFA03: coils started, structure procurement starting soon

US HL-LHC AUP

HiLumi HL-LHC PROJECT

AUP: from Prototype to Pre-series

Feature	MQXFAP2	MQXFA03
Coil midplane shims meet requirements*	NO	YES
Polyimide free inner coil surface	18%	TBD†
Holes on coil poles (hole per pole part)	7/8	8/8
Wires according to CERN specs	NO	YES
Solution for IL QH “bubbles”	NO	TBD†
Provision for coil bumpers	NO	YES
Strain gauges interference w CB integration	YES	NO
Fabricated according to MIPS**	NO	Planned

*Approved list of MQXFA materials

**Cable and Coil MIPS under approval; Magnet MIP in progress

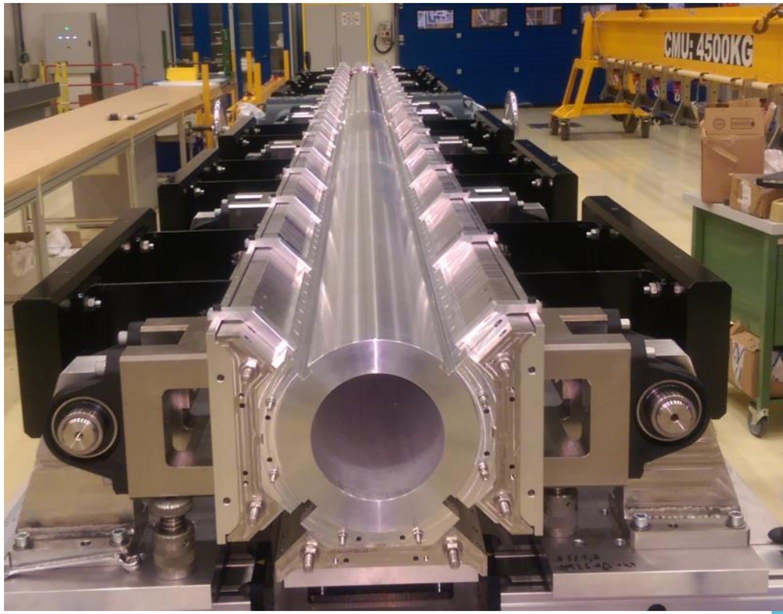
†Need decision by end of Dec 2017

CERN Status & Plans

- Short models coils:
  - 108-111 in progress
  - 112, 210-212 to be started
- Short model tests:
  - MQXFS3c: (w new coil) Dec 2017
  - MQXFS5b (w beam screen): Jan-Feb 2018
  - MQXFS3d (w beam screen): Mar-Apr 2018
  - MQXFS4 (w RRP coils & IL QH opts): summer 2018
  - MQXFS6 (w PIT bundle coils): Nov-Dec 2018

CERN Status & Plans

- Prototype RRP coils:
  - 103 completed as practice coil
  - 3 coils under fabrication
  - 2 coils starting soon
- Mechanical assembly test:
  - Oct 2017 – April 2018
- First prototype:
  - Magnet assembly & loading: Apr-Sept 2018
  - Cryo-assembly: Sept 2018 - Apr 2019
  - Test: May 2019



Conclusions

- Short models have demonstrated that MQXF magnets can meet gradient and memory requirements
- Quench protection is fine, but a solution is needed for Inner Layer quench heaters
- Short models and Prototypes tests are being used to complete readiness demonstration
  - To be completed by summer 2018
  - Fabrication of coils for MQXFA03 has started, so we need to be careful not to miss opportunity to use these coils in HL-LHC

Back up slides