# IT quadrupoles: summary of test results

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on behalf of the MQXF collaboration

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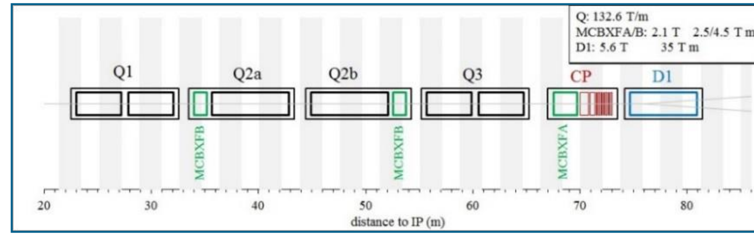
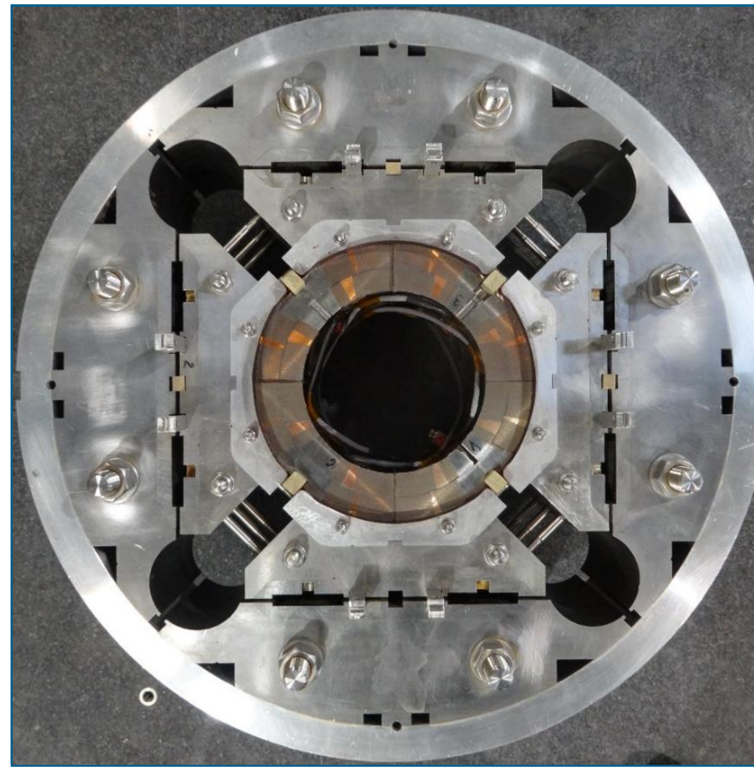
# Outline

- Introduction
- Assembly and loading
- Test results

# Introduction
# HiLumi low-β quadrupole MQXF

- Target: 132.6 T/m
  - 150 mm aperture, 11.4 T $B_{peak}$
- Q1/Q3 (by AUP)
  - 2 magnets MQXFA with 4.2 m
    - Series: 20 magnets
- Q2a/Q2b (by CERN)
  - 1 magnet MQXFB with 7.15 m
    - Series: 10 magnets
- Different lengths, same design
  - Identical short models



# Introduction

- Tests
  - **2 single-coil tests**
    - MQXFSM1 (1.2 m)
    - MQXFAM1 (4.0 m)
  - **4 short models (1.2 m)**
    - MQXFS1
    - MQXFS3
    - MQXFS5
    - MQXFS4
  - **2 MQXFA prototypes**
    - MQXFAP1 (4.0 m)
    - MQXFAP2 (4.2 m)
- Assembly **MQXFB prototype** (7.15 m) in progress
- Total of 31 coils "used"

PARAMETERS OF COIL USED IN SHORT MODELS AND PROTOTYPES

| Coil | Laboratory[a] | Strand | Cross-section | $L_c^b$ (m) | Magnet |
|---|---|---|---|---|---|
| 2 | LARP/AUP | RRP 108/127 | 1st gen. | 1.19 | MQXFSM1 |
| 103 | CERN | RRP 132/169 | 1st gen. | 1.19 | MQXFS1a-d |
| 104 | CERN | RRP 132/169 | 1st gen. | 1.19 | MQXFS1a-d |
| 3 | FNAL/BNL | RRP 108/127 | 1st gen. | 1.19 | MQXFS1a-d |
| 5 | FNAL/BNL | RRP 108/127 | 1st gen. | 1.19 | MQXFS1a-d |
| 105 | CERN | RRP 132/169 | 2nd gen. | 1.19 | MQXFS3a-c |
| 106 | CERN | RRP 132/169 | 2nd gen. | 1.19 | MQXFS3a-c |
| 107 | CERN | RRP 132/169 | 2nd gen. | 1.19 | MQXFS3a-c |
| 7 | FNAL | RRP 108/127 | 2nd gen. | 1.19 | MQXFS3a-b |
| 8 | FNAL/BNL | RRP 144/169 | 2nd gen. | 1.19 | MQXFS3c |
| 203 | CERN | PIT 192 | 2nd gen. | 1.19 | MQXFS5 |
| 204 | CERN | PIT 192 | 2nd gen. | 1.19 | MQXFS5 |
| 205 | CERN | PIT 192 | 2nd gen. | 1.19 | MQXFS5 |
| 206 | CERN | PIT 192 | 2nd gen. | 1.19 | MQXFS5 |
| 108 | CERN | RRP 108/127 | 2nd gen. | 1.19 | MQXFS4 |
| 109 | CERN | RRP 108/127 | 2nd gen. | 1.19 | MQXFS4 |
| 110 | CERN | RRP 108/127 | 2nd gen. | 1.19 | MQXFS4 |
| 111 | CERN | RRP 108/127 | 2nd gen. | 1.19 | MQXFS4 |
| QXFP01 | FNAL/BNL | RRP 108/127 | 1st gen. | 4.00 | MQXFAM1 |
| QXFP02 | FNAL/BNL | RRP 132/169 | 1st gen. | 4.00 | MQXFAP1 |
| QXFP03 | FNAL | RRP 144/169 | 2nd gen. | 4.00 | MQXFAP1 |
| QXFP04 | FNAL/BNL | RRP 132/169 | 2nd gen. | 4.00 | MQXFAP1 |
| QXFP05 | FNAL | RRP 108/127 | 2nd gen. | 4.00 | MQXFAP1 |
| QXFA101 | FNAL | RRP 108/127 | 2nd gen. | 4.20 | MQXFAP2 |
| QXFA102 | FNAL/BNL | RRP 108/127 | 2nd gen. | 4.20 | MQXFAP2 |
| QXFA104 | FNAL | RRP 108/127 | 2nd gen. | 4.20 | MQXFAP2 |
| QXFA105 | FNAL/BNL | RRP 108/127 | 2nd gen. | 4.20 | MQXFAP2 |
| 104 | CERN | RRP 108/127 | 2nd gen. | 7.15 | MQXFBP1 |
| 105 | CERN | RRP 108/127 | 2nd gen. | 7.15 | MQXFBP1 |
| 107 | CERN | RRP 108/127 | 2nd gen. | 7.15 | MQXFBP1 |
| 108 | CERN | RRP 108/127 | 2nd gen. | 7.15 | MQXFBP1 |

# Electrical tests

- Coil to QH (requirement)
  - 52 coils, tested in the range 2500-3700  V, all passed
- Coil to floating part (QC)
  - Coil to end-shoe
    - 2 MQXFA coils did not pass (binder issue)
  - Coil to pole
    - Weak insulation (from 20 to 800 MΩ) coil to pole in CERN coils
    - No issue for US coils except 1

# Outline

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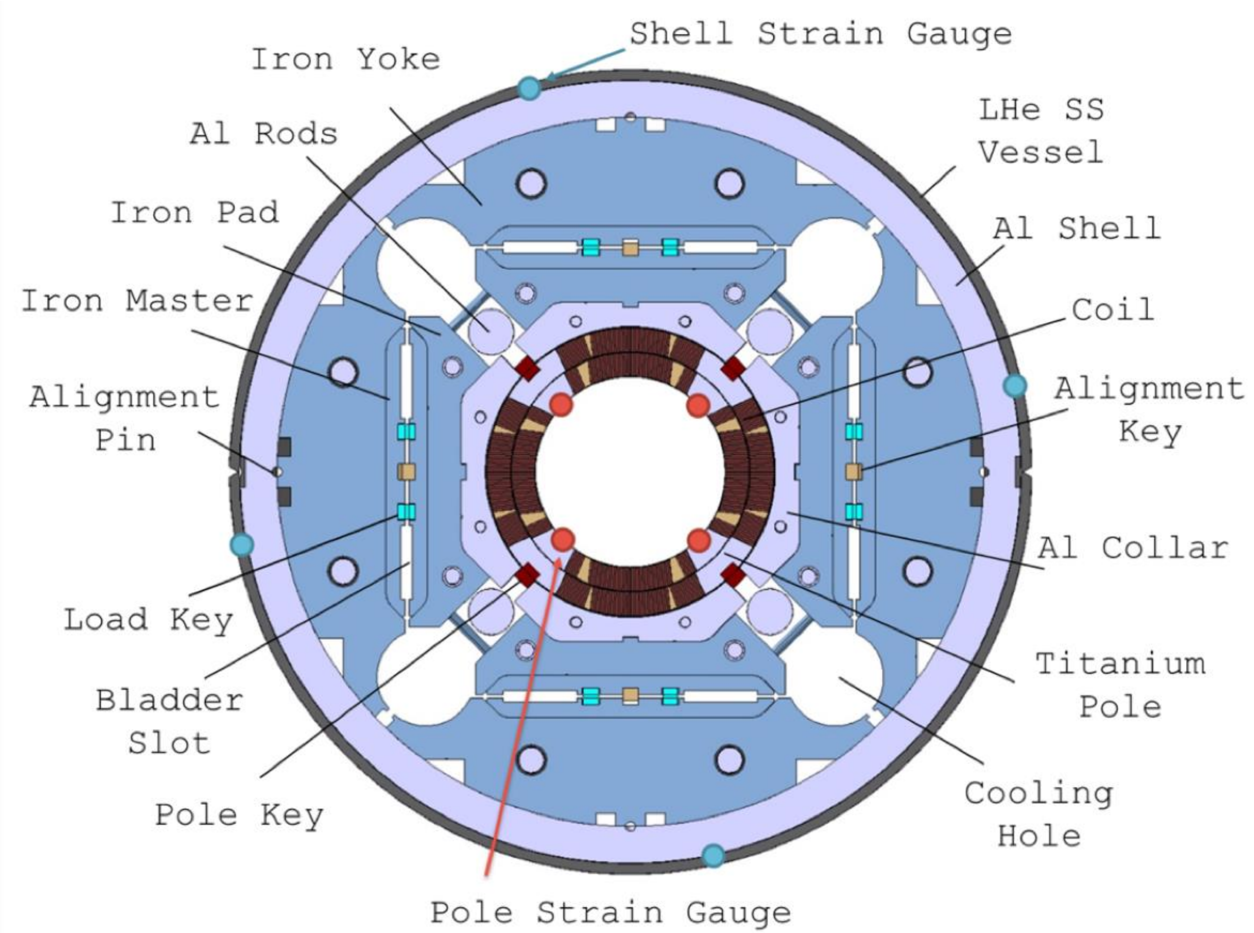
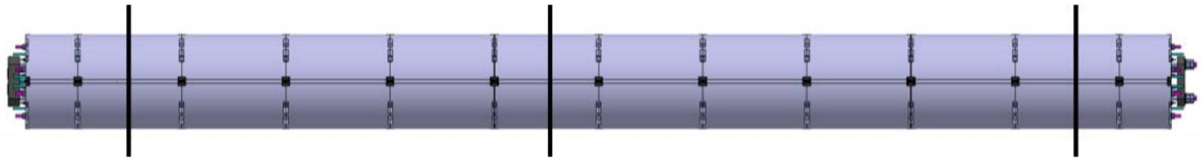
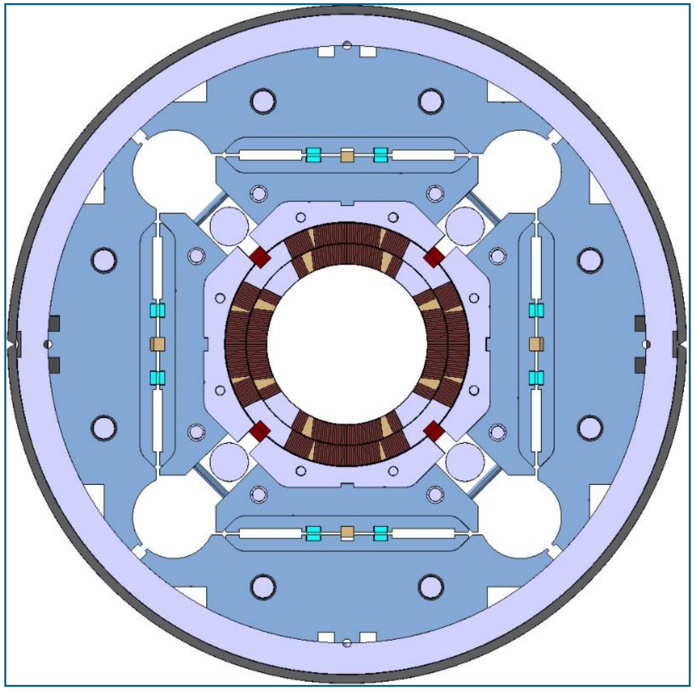
# MQXF mechanical structure

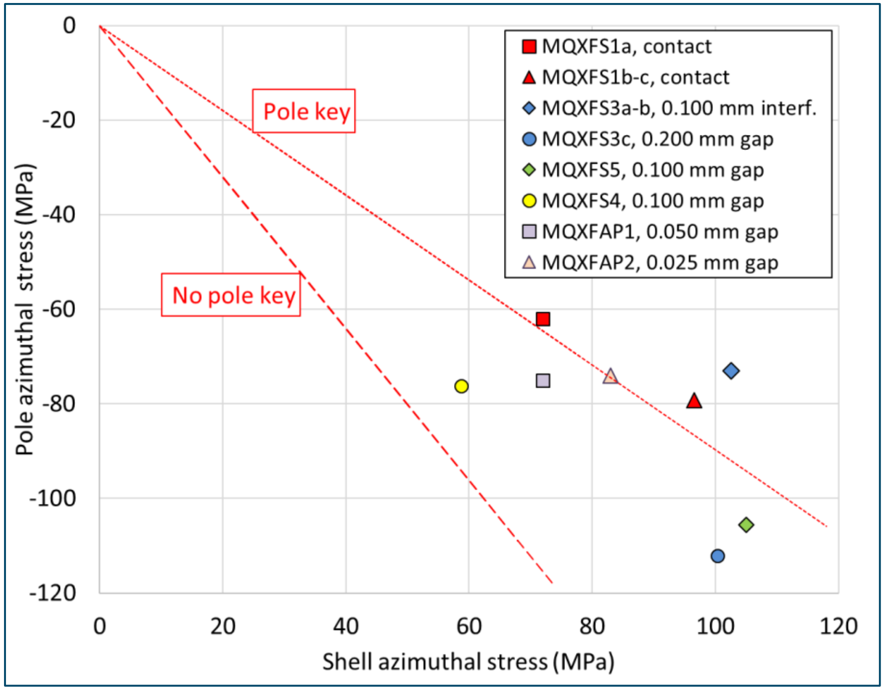


# Room temperature pre-load

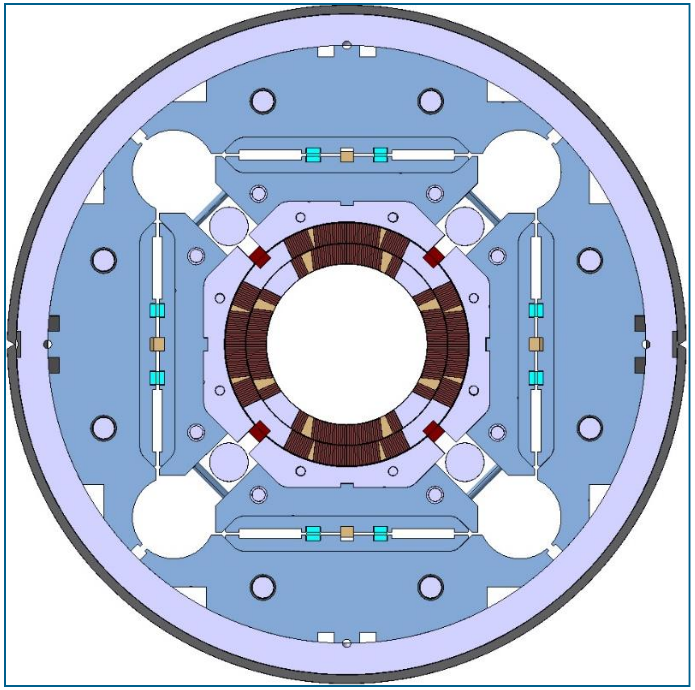
- Pole key – collars
  - from 0.100 interf to 0.200 mm gap.
- Coil pre-load
  - from -60 to -110 MPa

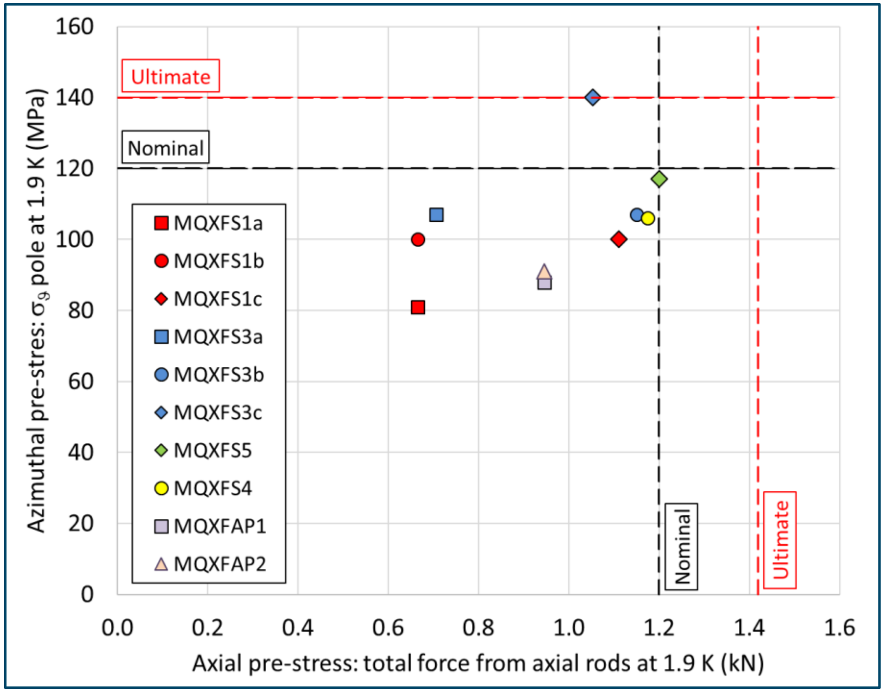




# Pre-load after cool-down

- Different level of pre-load achieved
  - Low pre-load in MQXFS1a → unloading before $I_{nom}$
  - Full pre-load in MQXFS3s → unloading at $I_{ult}$
- Same approach axially





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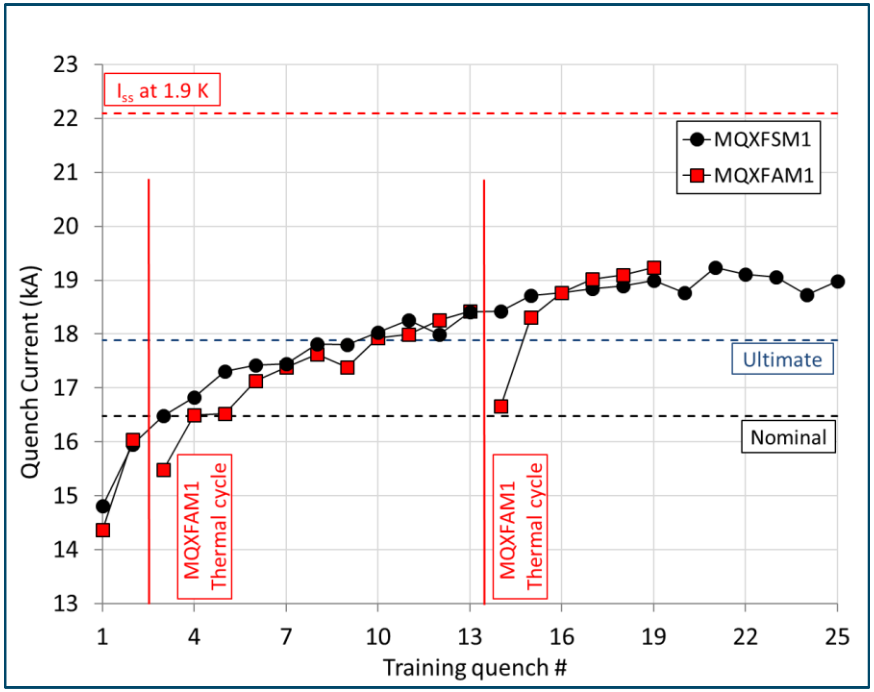
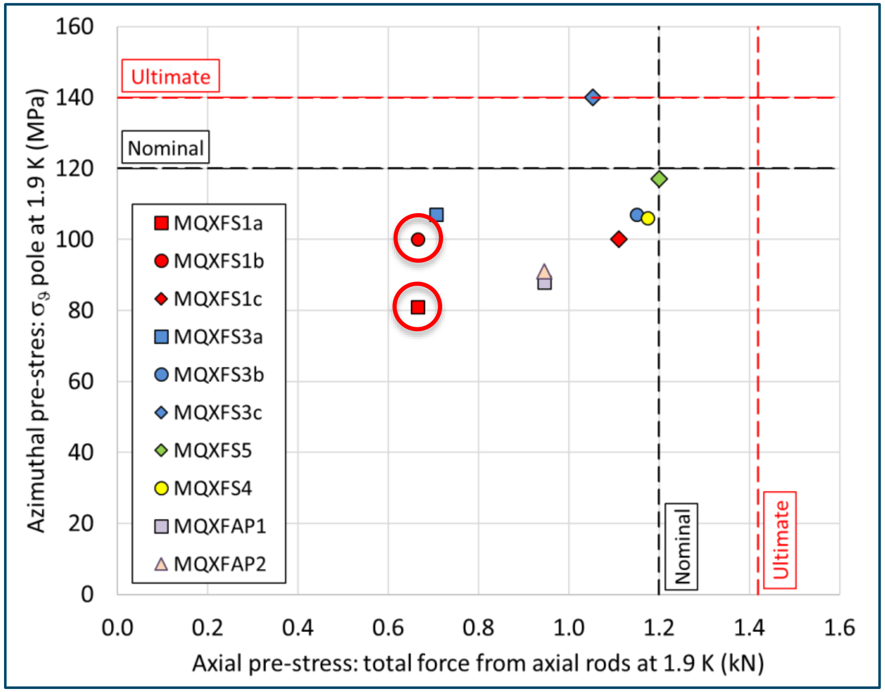
# Test results
# Single coil tests

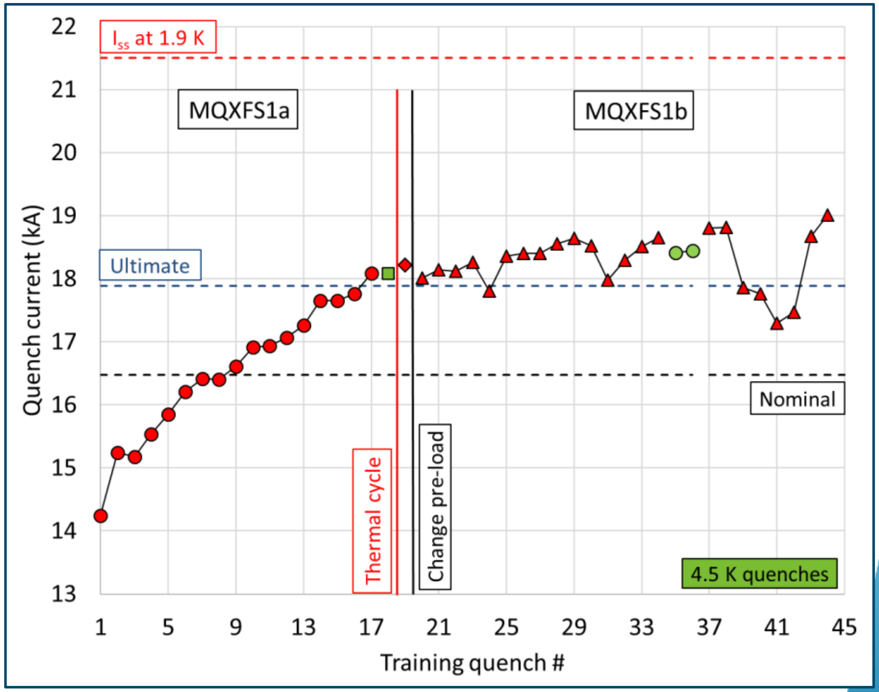
- MQXFSM1, 1.2 m and MQXFAM1, 4.0 m
- Iron structure ("mirror"), load-line similar to MQXFS
- Successful validation of coil design and fabrication procedure → bout 87% of $I_{ss}$



# Test results
# MQXFS1

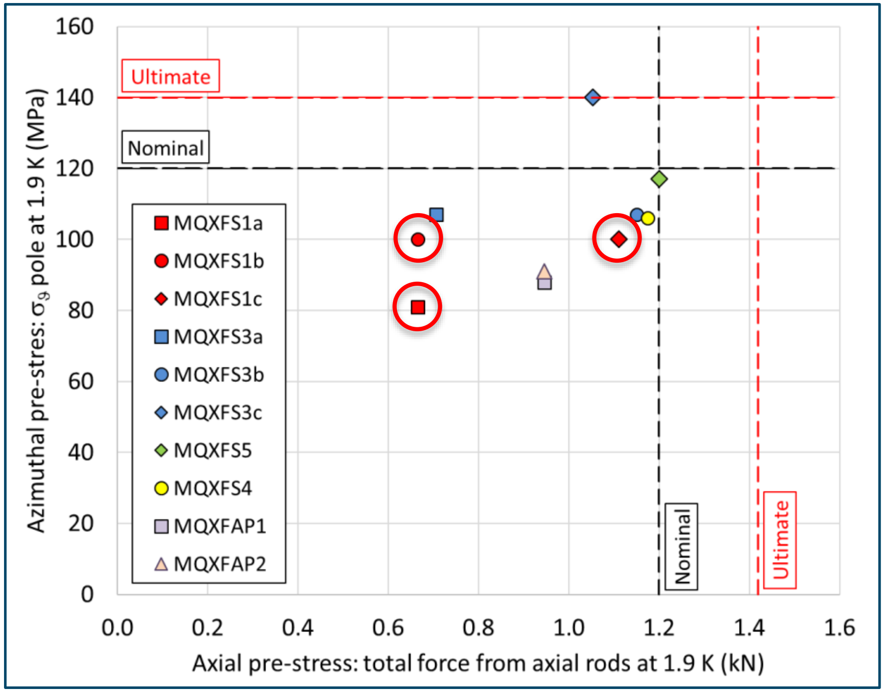
- 1st generation coils, RRP 108/127 and 132/169
- MQXFS1a, then increase of azimuthal (MQXFS1b)
  - $I_{ult}$ reached in all tests (some detraining quenches)
  - Up to 19 kA (highest current reached so far)

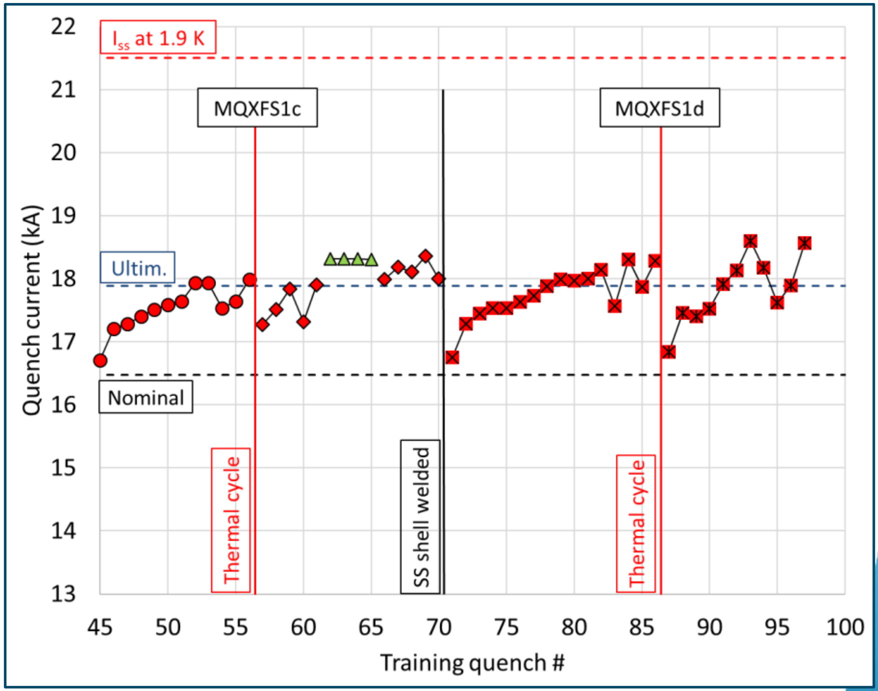


# Test results MQXFS1

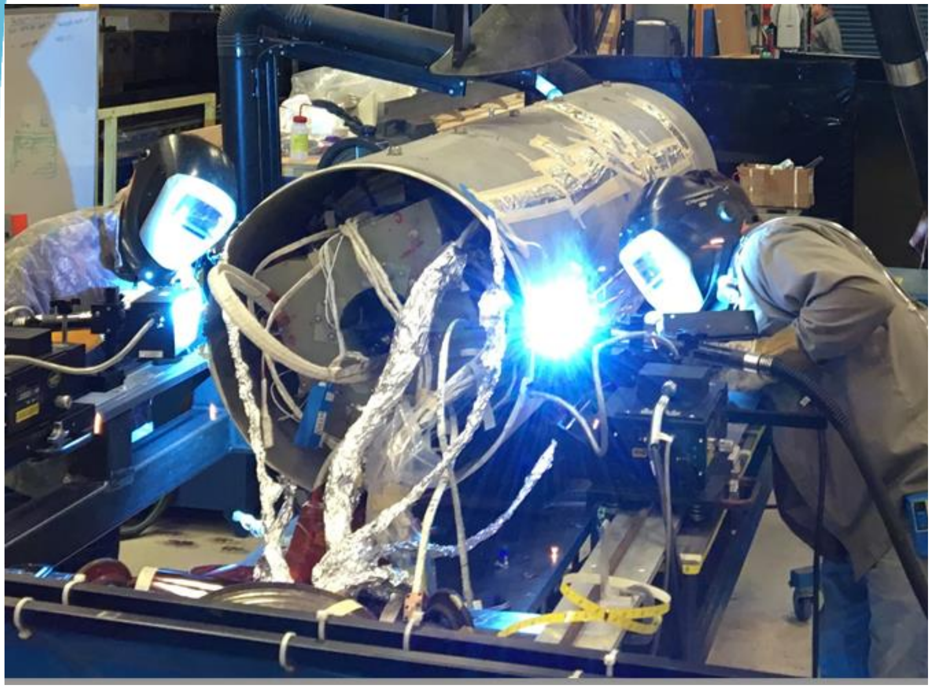
- Then…
  - Increase of axial pre-load (MQXFS1c)
  - $I_{ult}$ reached at 1.9 K and 4.2 K (some detraining and loss of memory)

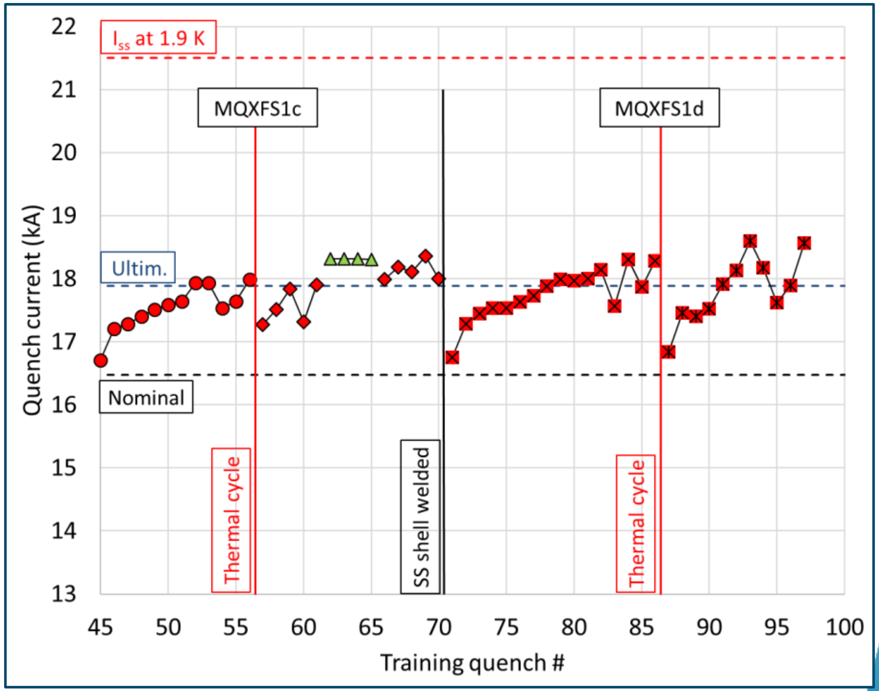


# Test results
# MQXFS1

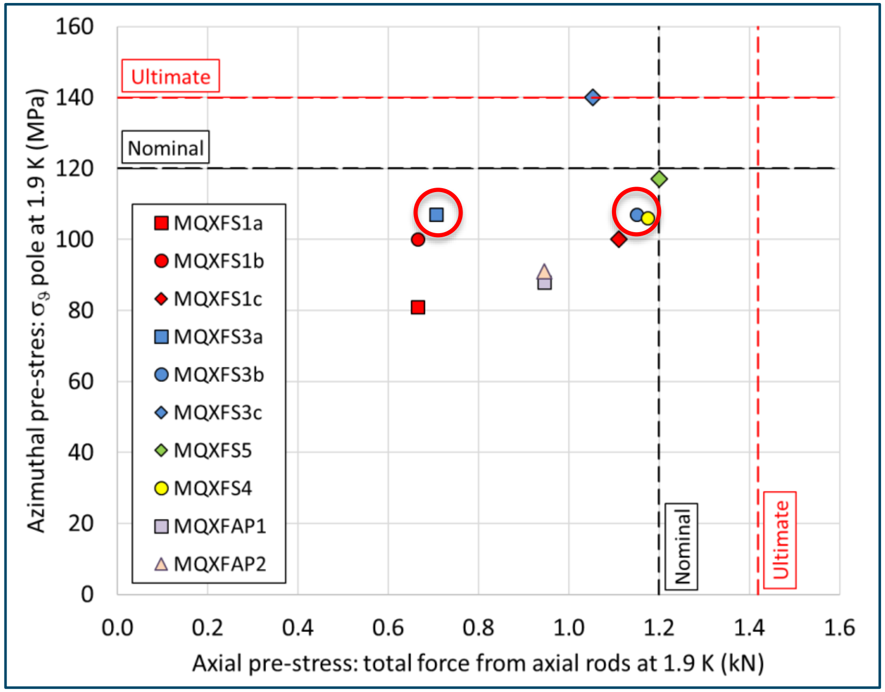
- Then…
  - Stainless steel shell welding (MQXFS1d)
  - Process demonstrated, limited pre-load increase at warm and no pre-load increase at cold

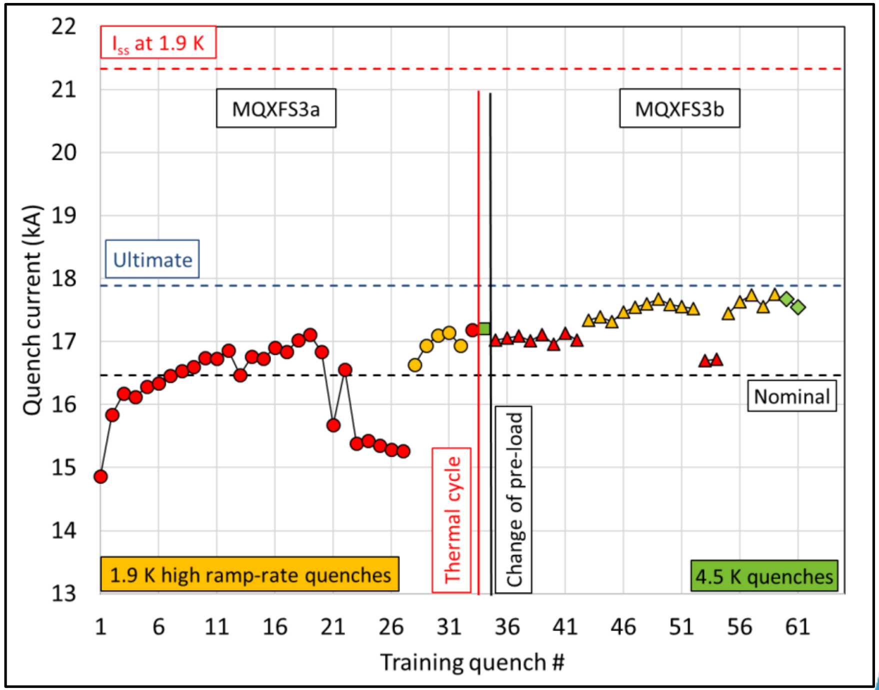




# Test results
# MQXFS3

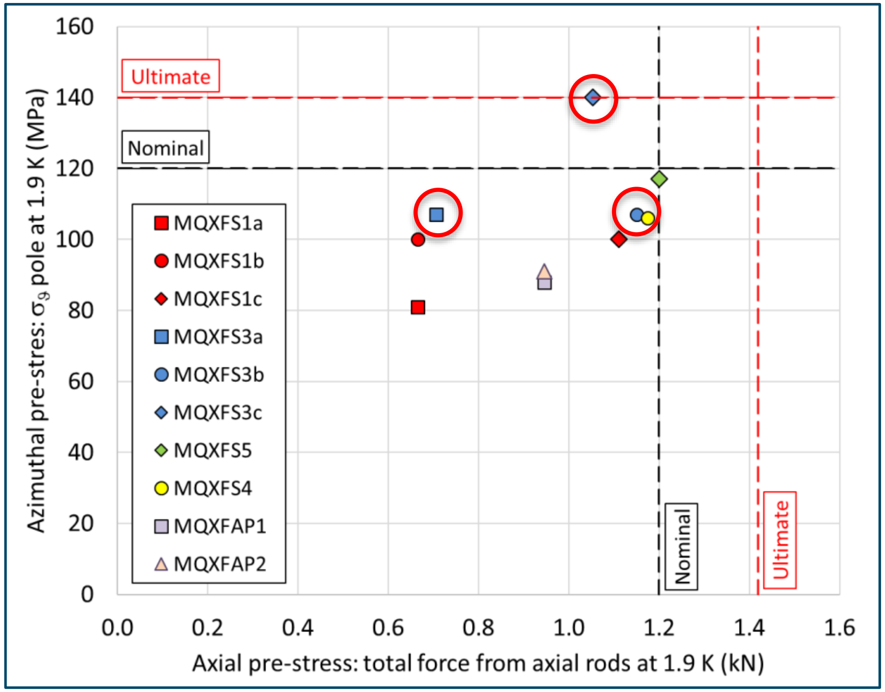
- 2nd generation coils, RRP 108/127, 132/196, 144/169
- MQXFS3a
  - Degradation in end region of coil 7, bypassed at high ramp rates
- Then increase axial (MQXFS3b)
  - Better, but similar behavior

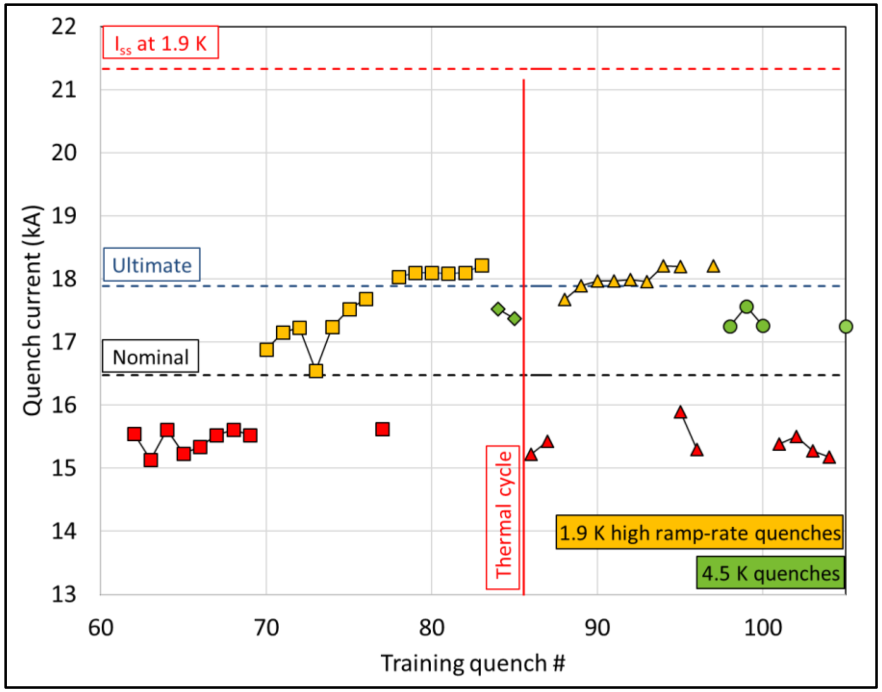


# Test results
# MQXFS3

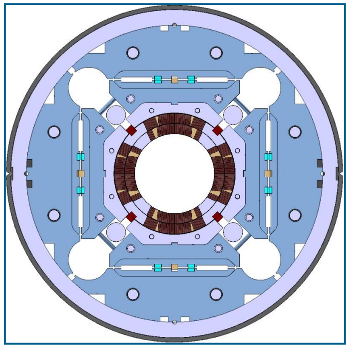
- Then
  - Change of coil and increase azimuthal (MQXFS3c)
  - $I_{ult}$ only at high ramp-rate → limited by "old" coil (106)
    - Interpretation: degradation triggering self-field instability

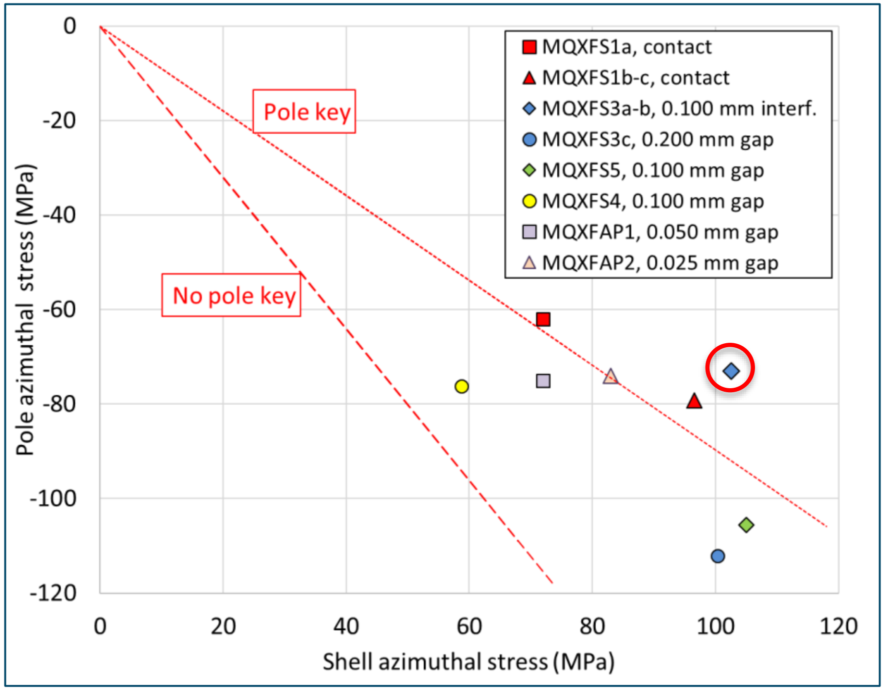


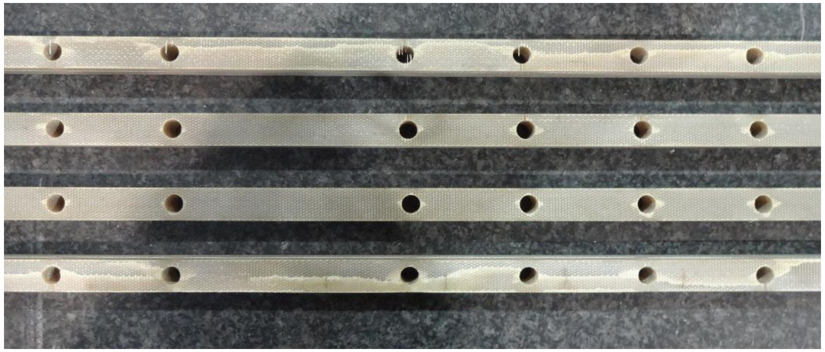



# Test results MQXFS3

- MQXFS3a assembled with pole key to collar interference
  - Major damage in pole key

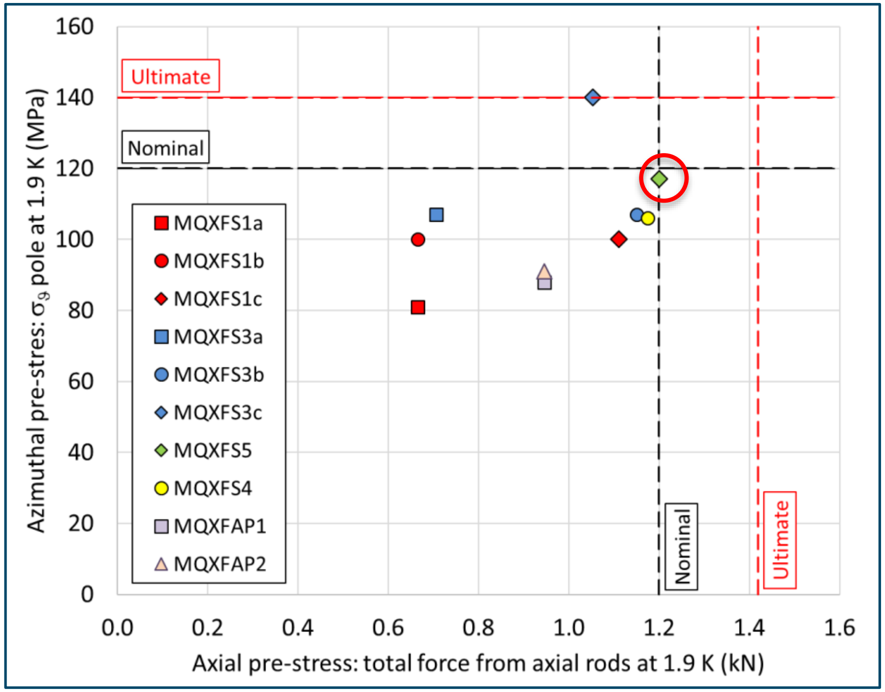


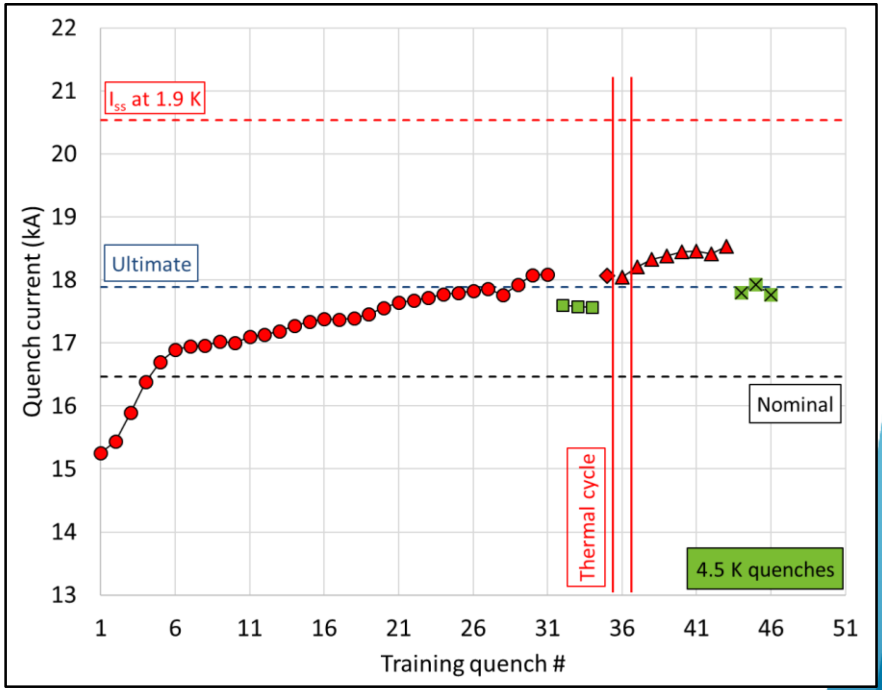


# Test results
# MQXFS5

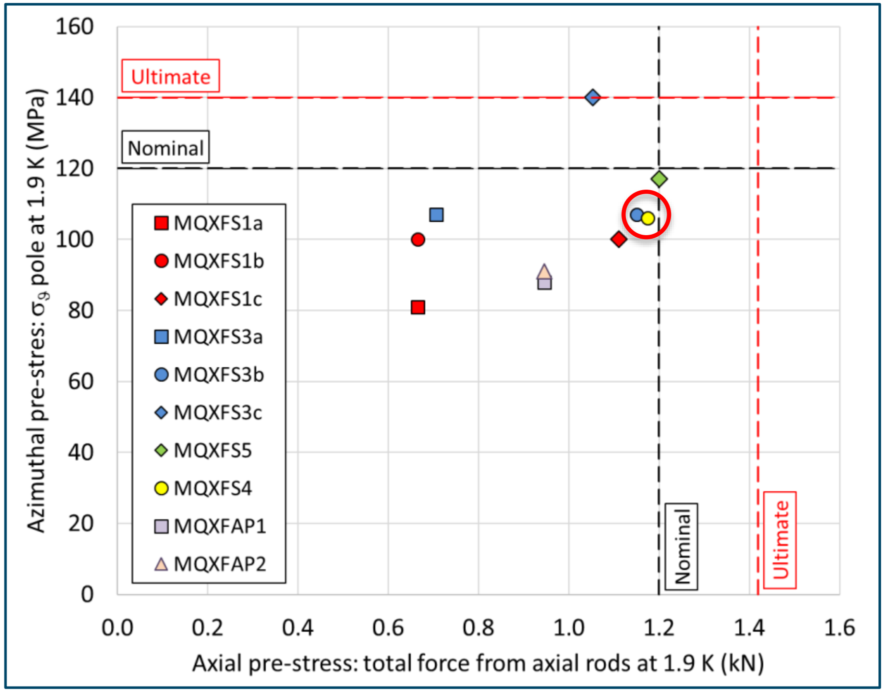
- 2nd generation coils, PIT 192
  - "Nominal" pre-load
  - $I_{ult}$ reached, both at 1.9 K and 4.5 K, with full memory
  - Change of slope during training

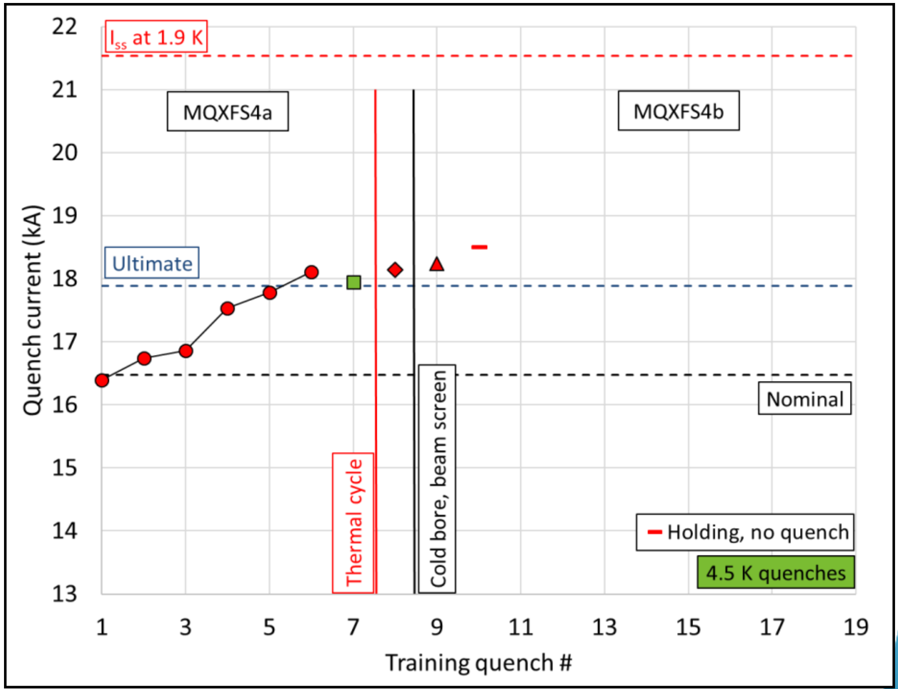


# Test results
# MQXFS4

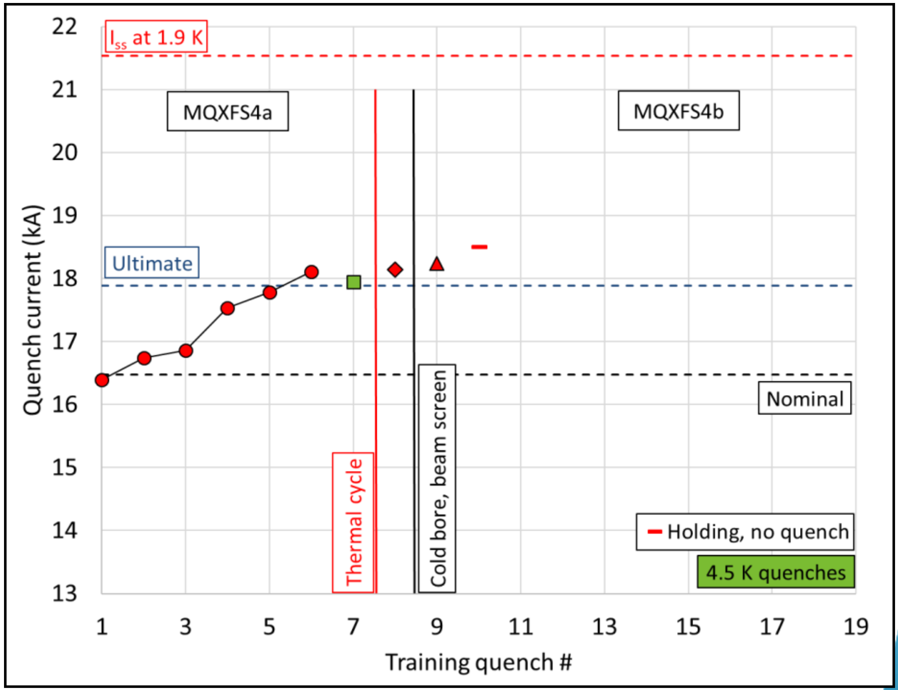
- $2^{nd}$ generation coils, RRP 108/127
  - "Nominal" pre-load
  - $I_{ult}$ reached, both at 1.9 K and 4.5 K, with full memory
  - Fastest training



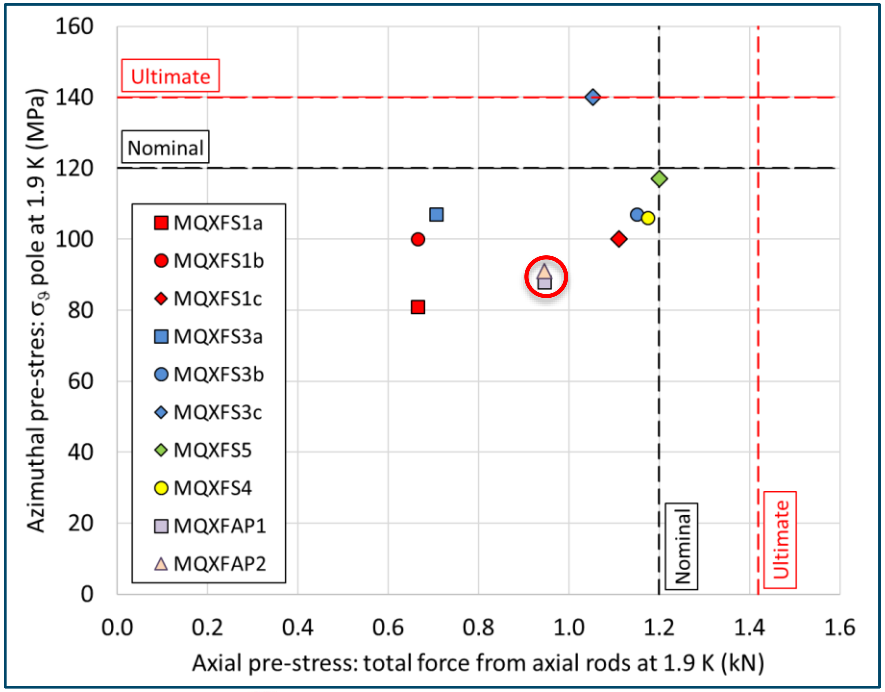
# Test results
# MQXFS4

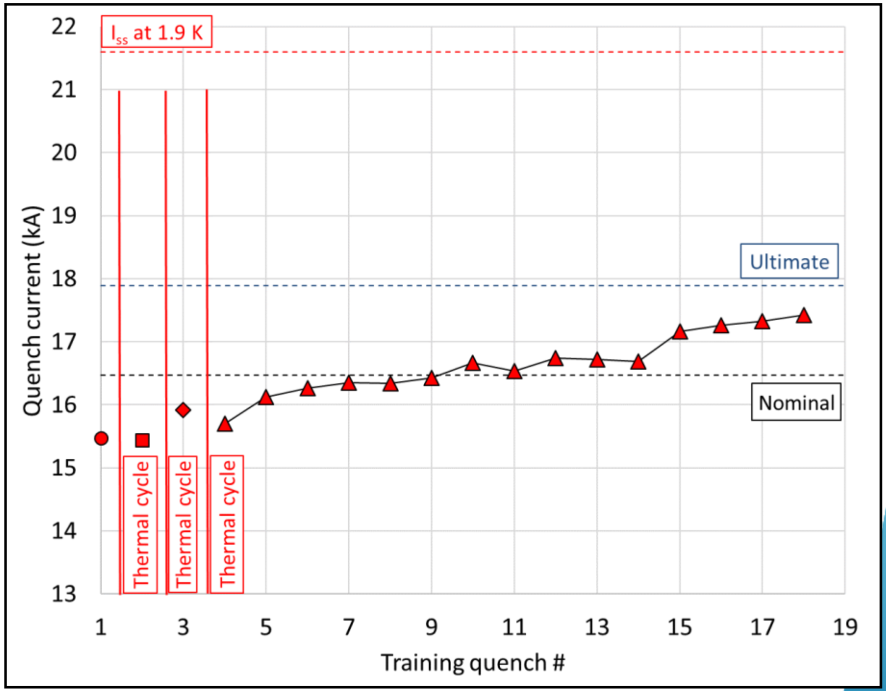
- Then…
  - Insertion of cold bore and beam screen
    - Validation of process
  - No effect on magnet performance



# MQXFAP1

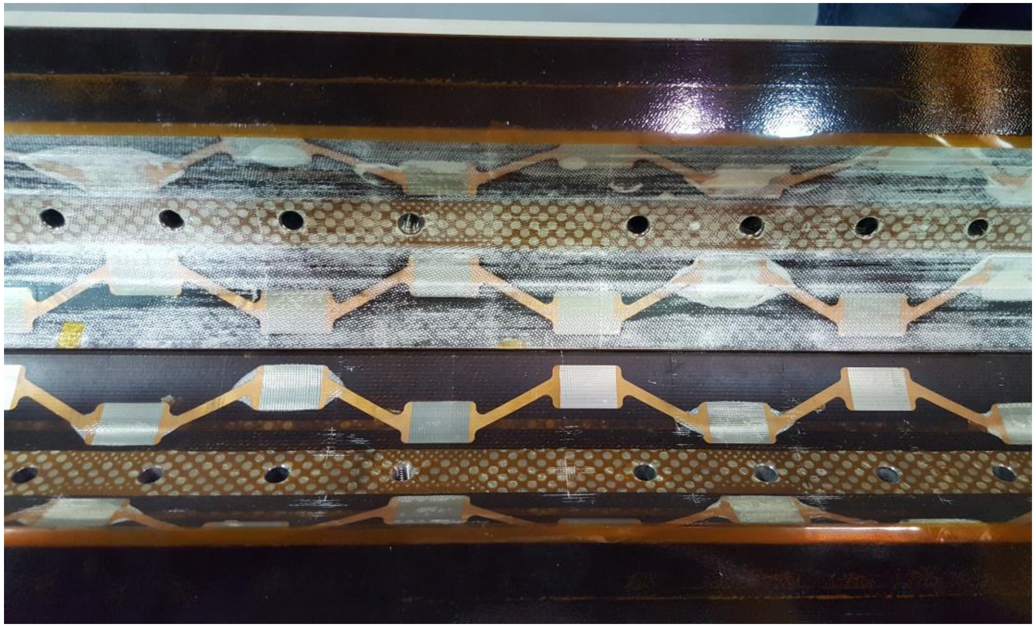
- 1st generation coils, 4.0 m, RRP 108/127, 132/169, 144/169
- 3 thermal cycles for problems in cryogenic system
- $I_{nom}$ reached, training stopped because of a short to ground caused by previous double-short QH to coil



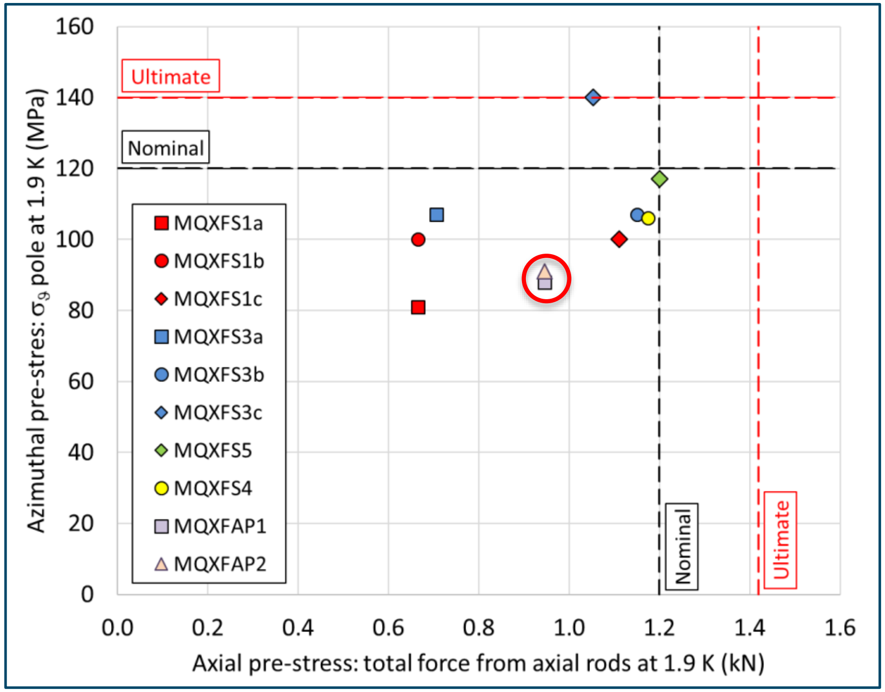
# MQXFAP1

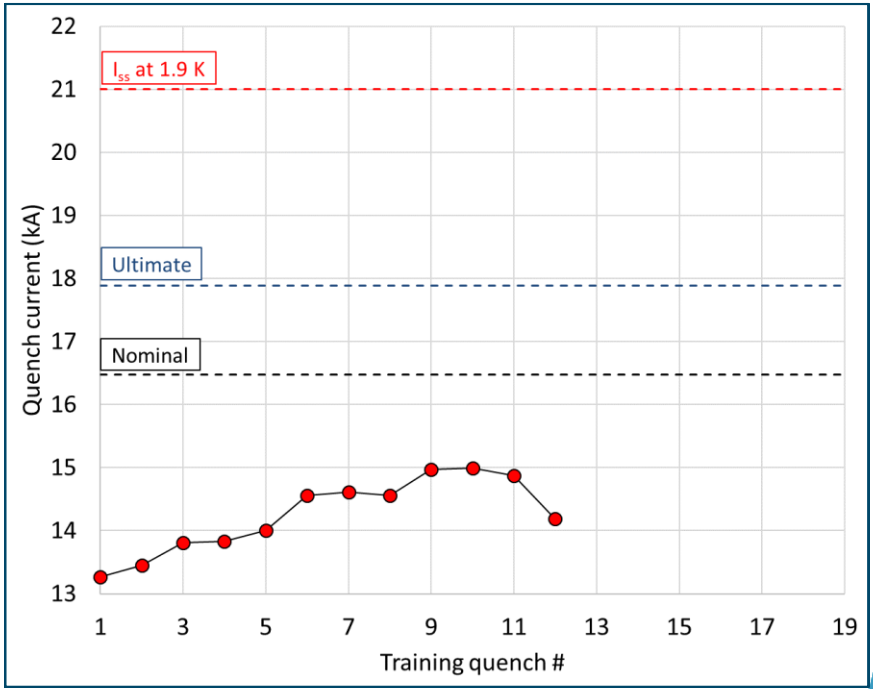
- Short was caused by a series of events
  - Coil 5 impregnation was poor in the short area:
    - Increased possibility of helium trapped after cold test
  - Between quench 1 and 2, magnet hi-potted with high voltage (2.5 kV) at 293 K, after helium exposure
- Design weakness is excluded



# MQXFAP2

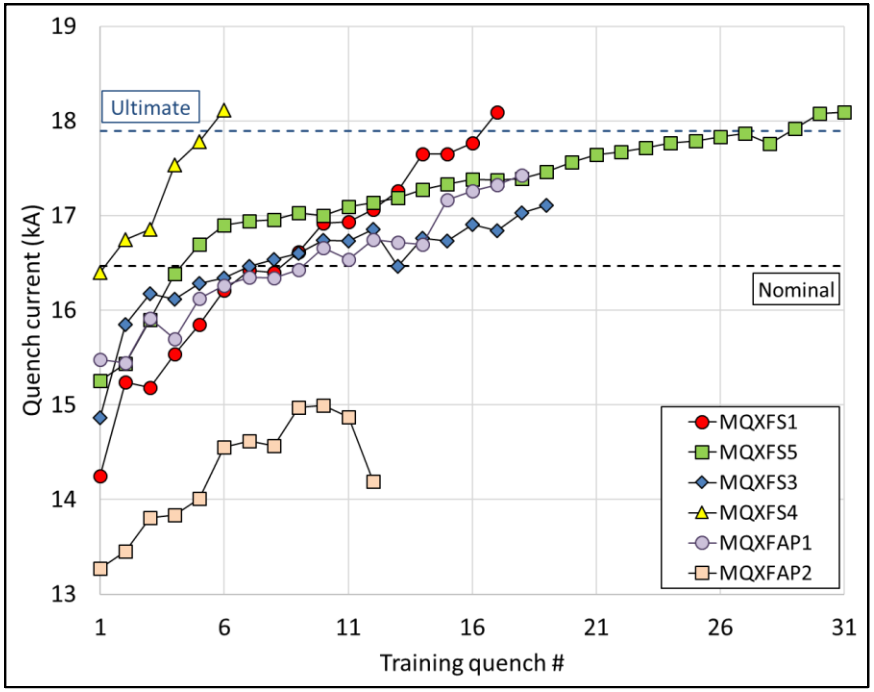
- $2^{nd}$ generation coils, 4.2 m, RRP 108/127
- Same pre-load as MQXFAP1
- Test in progress

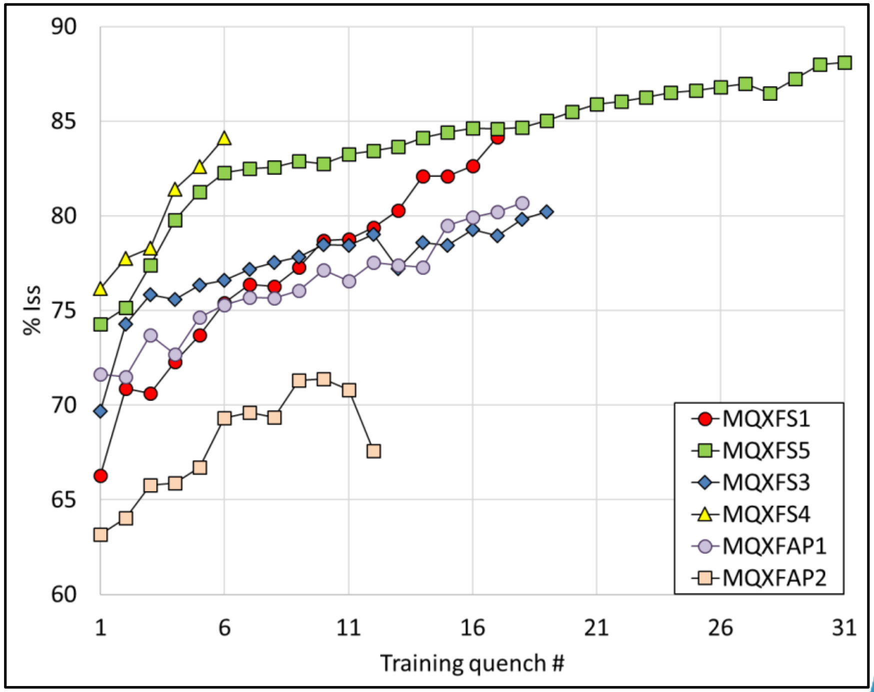


# Comparison/conclusions

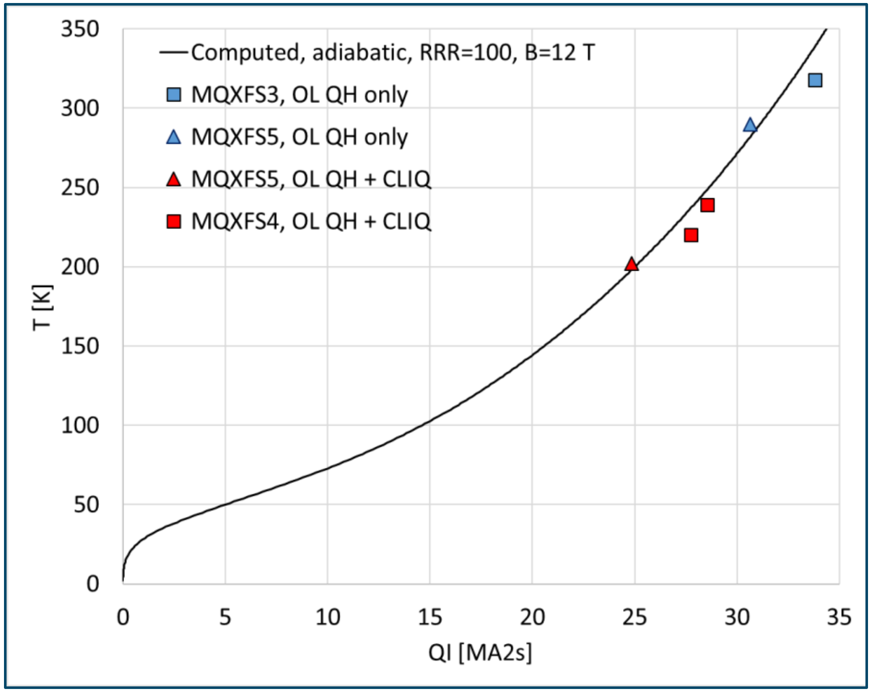
- All short models and MQXAP1 reached $I_{nom}$
- 3 short models reached $I_{ult}$
  - MQXFS3 only at high ramp-rate and MQXFAP1 stopped by electrical short
- MQXFS4 fastest training (6 quenches to 85% of $I_{ss}$)



# Quench protection

- Inner layer quench heaters abandoned
  - Issue of delamination not solved
- Protection with outer layer QH and CLIQ



# Next steps

- Assembly of MQXFBP1


- Assembly of MQXFS6: PIT with bundle

# Appendix

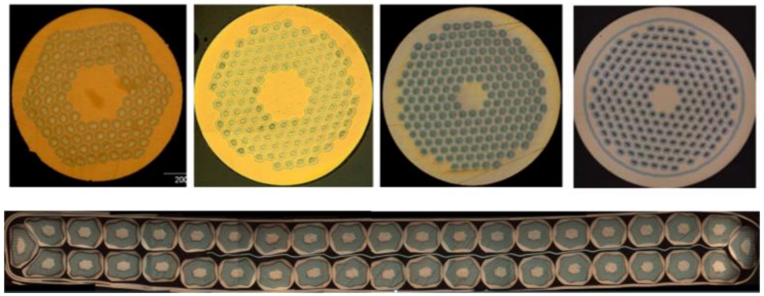
# Conductor and cable

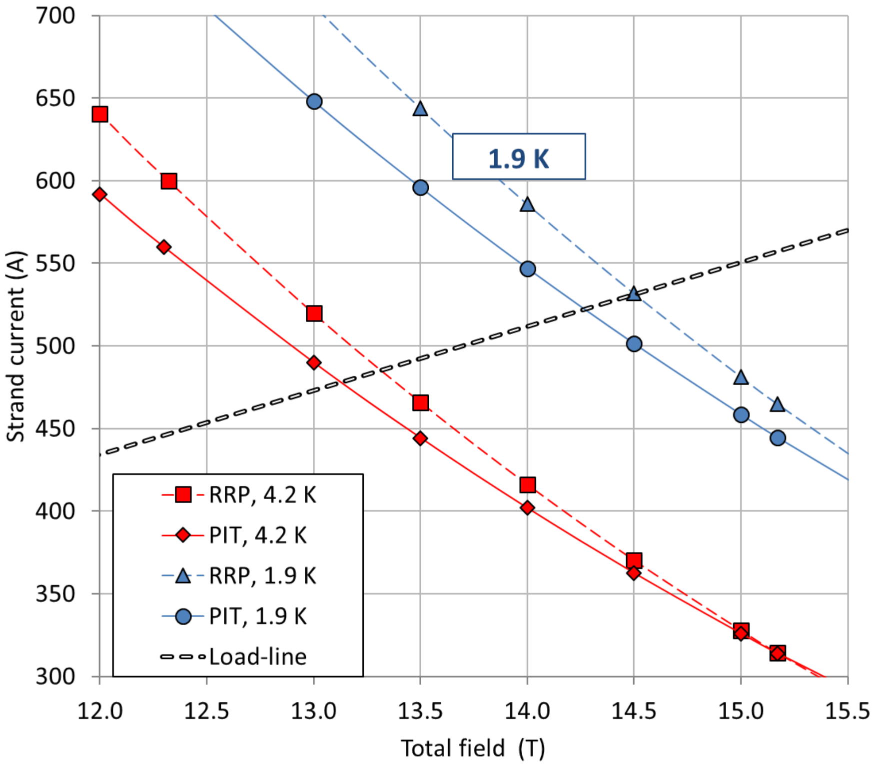
- Two final strands
  - RRP 108/127 (MQXFA/B)
  - PIT 192 with bundle barrier (MQXFB)
- Also used
  - 132/169 and PIT without bundle barrier

- So, $I_{nom}$ correspond to
  - 77% of $I_{ss}$ for RRP
  - 79% of $I_{ss}$ for PIT

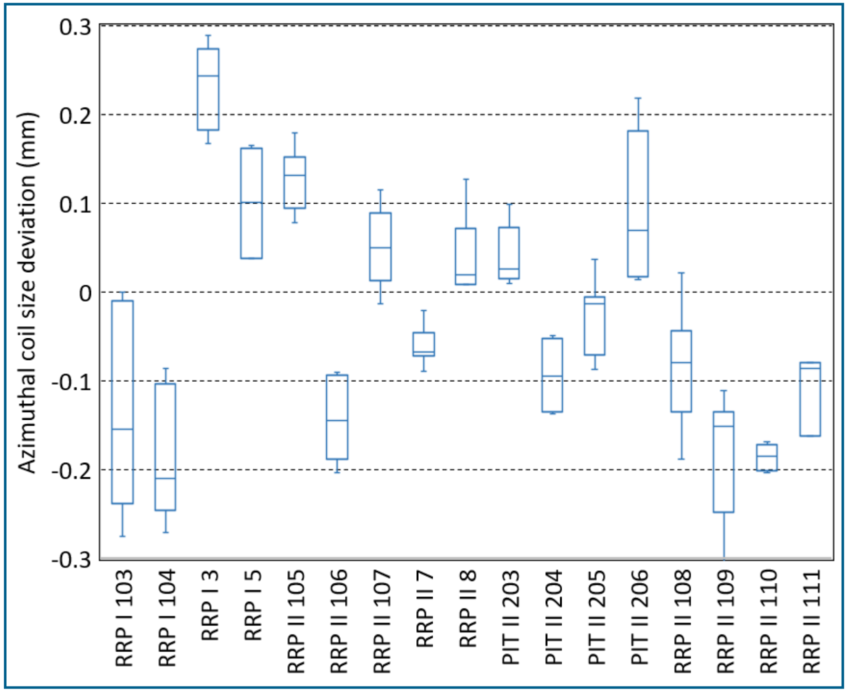
- And $I_{ult}$ → 84-86%

- 1st and 2nd gen. cables
  - From 0.55° to 0.40 ° keystone angle

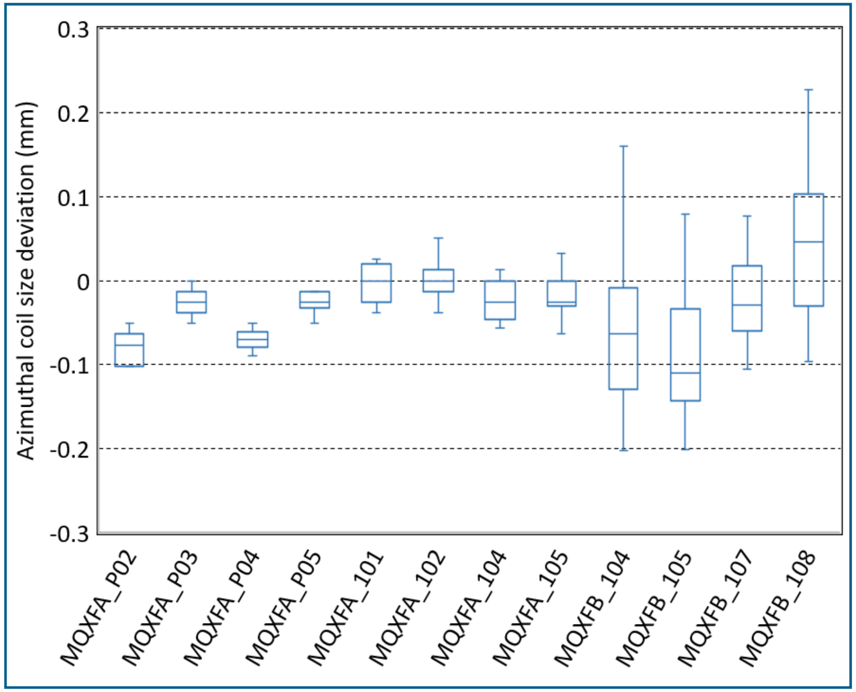




# CMM



Azimuthal coil size deviation (mm)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
RRP I 103
RRP I 104
RRP I 3
RRP I 5
RRP II 105
RRP II 106
RRP II 107
RRP II 7
RRP II 8
PIT II 203
PIT II 204
PIT II 205
PIT II 206
RRP II 108
RRP II 109
RRP II 110
RRP II 111

Azimuthal coil size deviation (mm)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
MQXFA_P02
MQXFA_P03
MQXFA_P04
MQXFA_P05
MQXFA_101
MQXFA_102
MQXFA_104
MQXFA_105
MQXFB_104
MQXFB_105
MQXFB_107
MQXFB_108

# Field quality