Report on Ongoing Actions for MQXFB

New test and measurement techniques

S. Russenschuck, F. Mangiarotti, G. Willering
with the contribution of (at least) 32 staff from TM, MSC, TE

Overview

MQXFS/P test history and lessons learnt (limitation versus degradation versus defect, homogenous or local)

Software for QA, safety, database, and reporting (Carpenter)

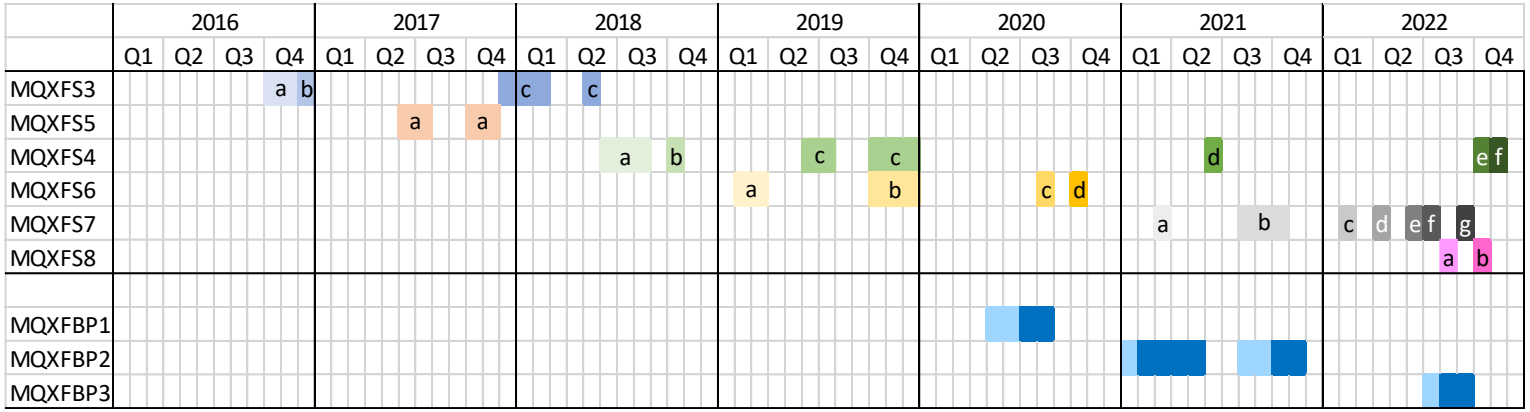
New quench antenna systems to enable longitudinal and transveral quench localization in coils without local voltage taps

Upgraded trim powering for the assessment of coil performance with a short lead time

V-I measurements (pole turn versus full coil)

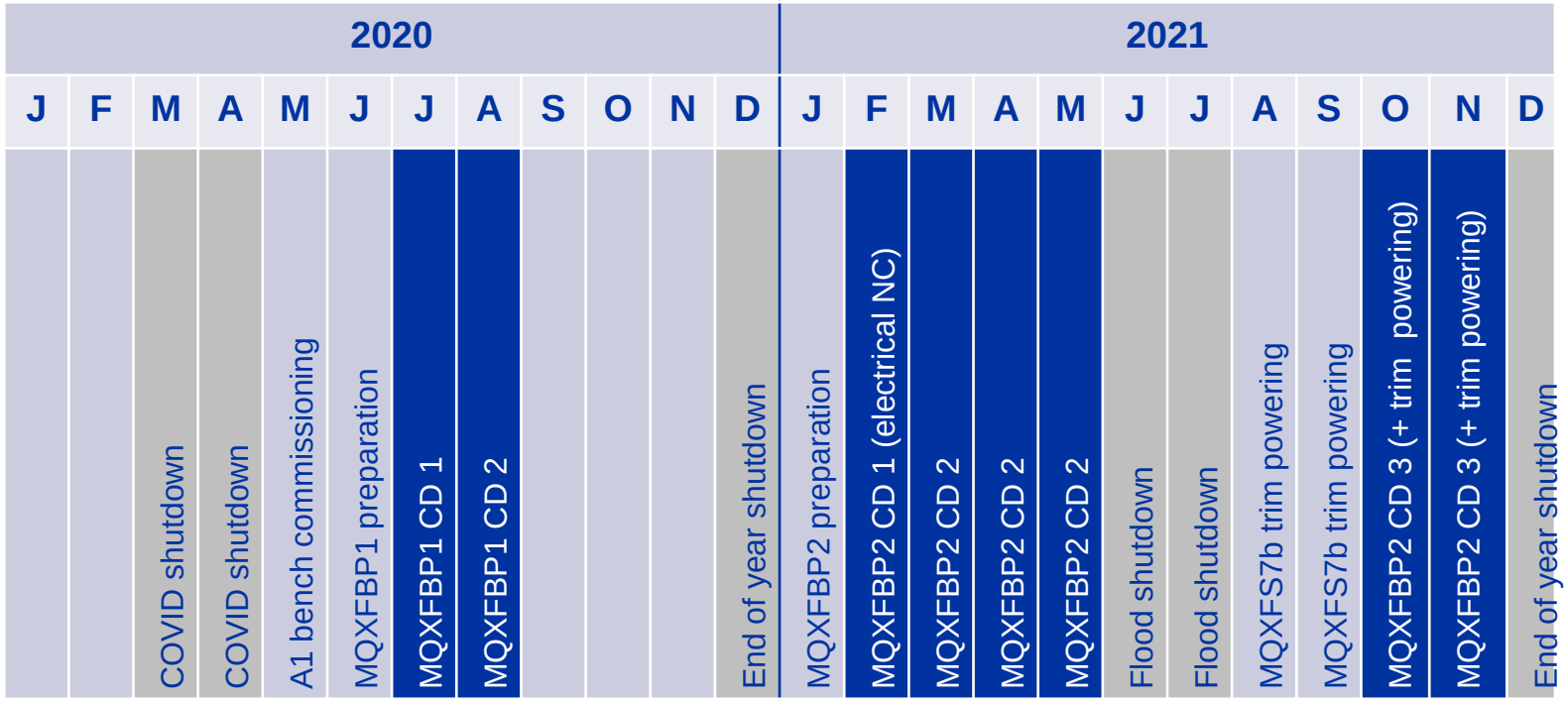
Safety issues have been addressed (but not here). Presentation TE-TM 2.05.2022

MQXF test history

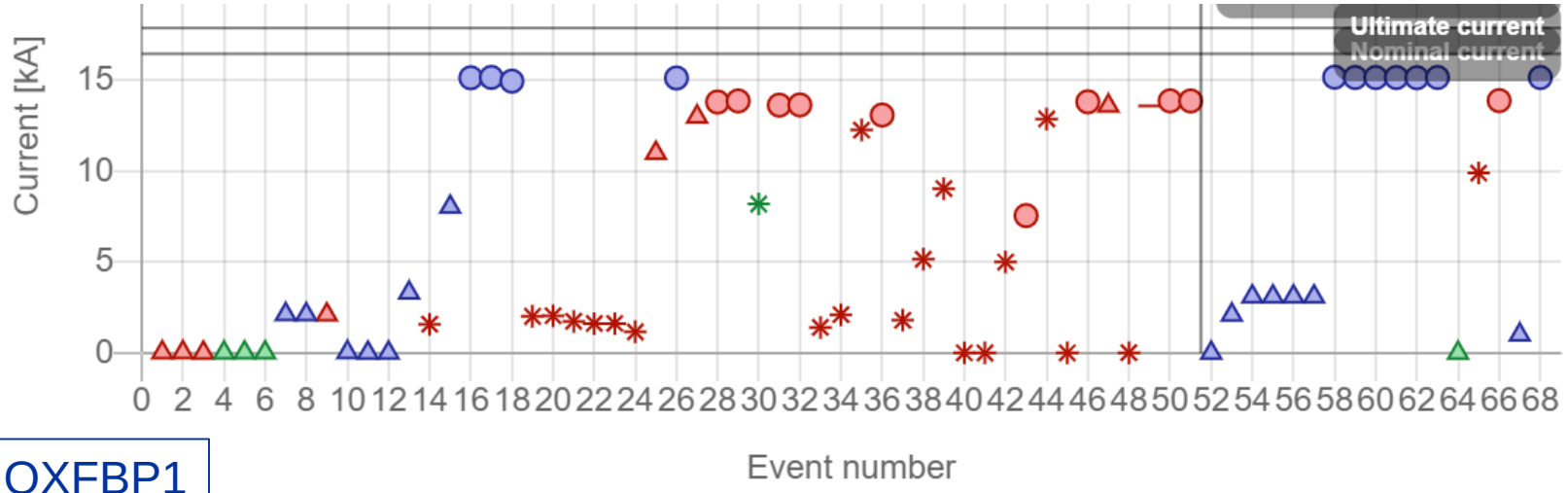


Timeline of activities for MQXFBP1 and BP2

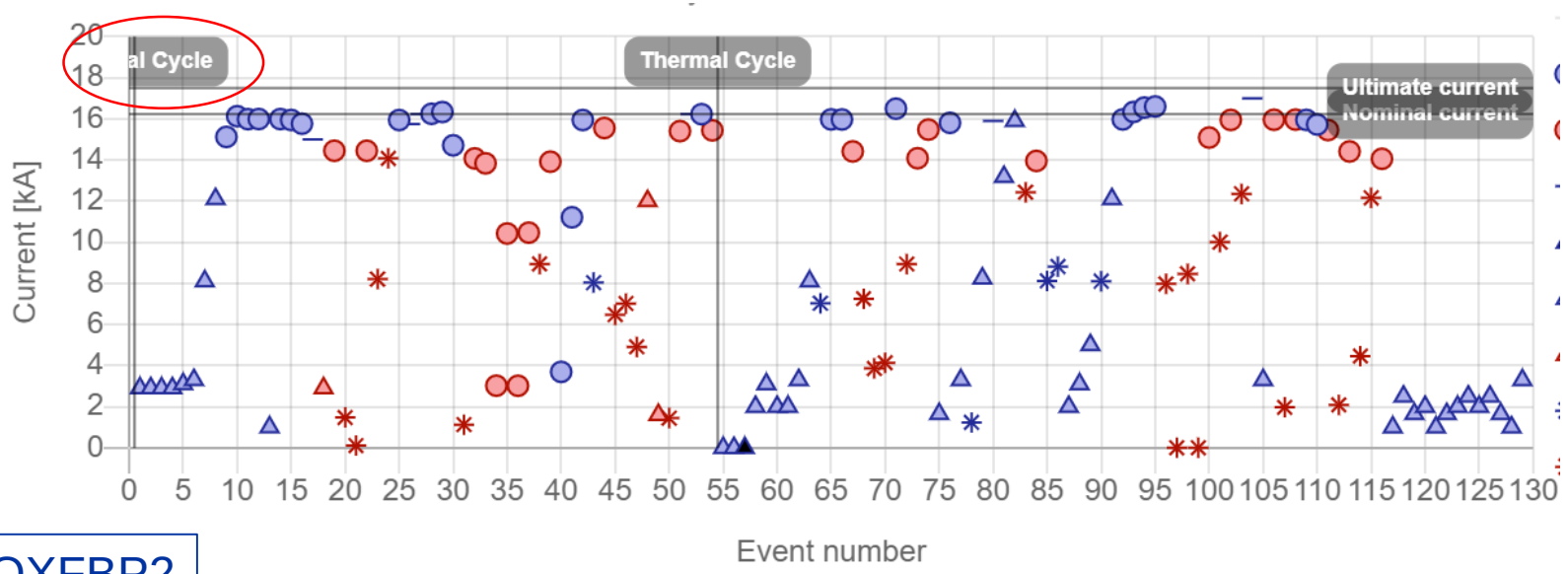
10 months of cold testing for the MQXFB(S&P) in 2020-2021



MQXFP Event history



MQXFBP1



MQXFBP2

- No quench
- Natural quench
- Provoked quench
- Trip

T = 1.9 K

1.9< T <4.5 K

T = 4.5 K

Almost 200 quenches in total

Carpenter as a QA and safety tool

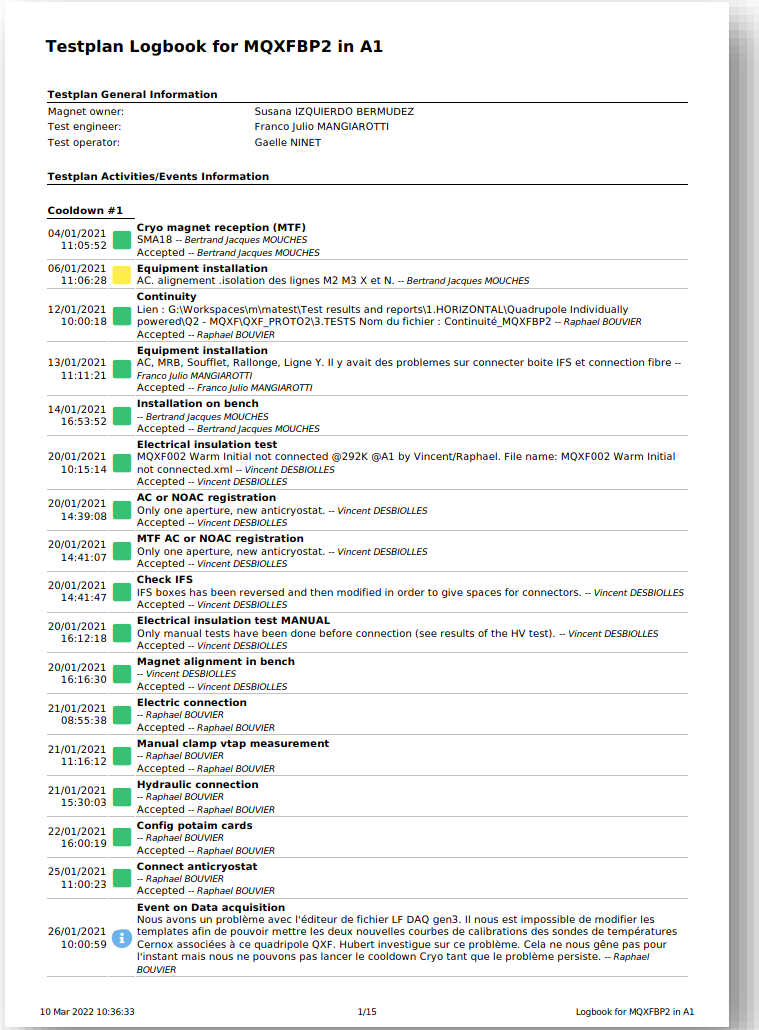
All tests done are stored in the database, including status and comments

Test order imposed by the approved test procedure

Levels imposed by the test plan

Easy to follow up the test chronology

Sign off at the control points



Testplan Logbook for MQXFBP2 in A1

Testplan General Information

Magnet owner:	Susana IZQUIERDO BERMUDEZ
Test engineer:	Franco Julio MANGIAROTTI
Test operator:	Gaelle NINET

Testplan Activities/Events Information

Cooldown #1

04/01/2021 11:05:52 — **Cryo magnet reception (MTF)**
SMA18 -- *Bertrand Jacques MOUCHES*
Accepted -- *Bertrand Jacques MOUCHES*

06/01/2021 11:06:28 — **Equipment installation**
AC. alignement .isolation des lignes M2 M3 X et N. -- *Bertrand Jacques MOUCHES*

12/01/2021 10:00:18 — **Continuity**
Lien : G:\Workspaces\m\matest\Test results and reports\1.HORIZONTAL\Quadrupole Individually powered\Q2 - MQXF\QXF_PROTO2\3.TESTS Nom du fichier : Continuité_MQXFBP2 -- *Raphael BOUVIER*
Accepted -- *Raphael BOUVIER*

13/01/2021 11:11:21 — **Equipment installation**
AC, MRB, Soufflet, Rallonge, Ligne Y. Il y avait des problemes sur connecter boite IFS et connection fibre -- *Franco Julio MANGIAROTTI*
Accepted -- *Franco Julio MANGIAROTTI*

14/01/2021 16:53:52 — **Installation on bench**
-- *Bertrand Jacques MOUCHES*
Accepted -- *Bertrand Jacques MOUCHES*

20/01/2021 10:15:14 — **Electrical insulation test**
MQXF002 Warm Initial not connected @292K @A1 by Vincent/Raphael. File name: MQXF002 Warm Initial not connected.xml -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

20/01/2021 14:39:08 — **AC or NOAC registration**
Only one aperture, new anticryostat. -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

20/01/2021 14:41:07 — **MTF AC or NOAC registration**
Only one aperture, new anticryostat. -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

20/01/2021 14:41:47 — **Check IFS**
IFS boxes has been reversed and then modified in order to give spaces for connectors. -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

20/01/2021 16:12:18 — **Electrical insulation test MANUAL**
Only manual tests have been done before connection (see results of the HV test). -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

20/01/2021 16:16:30 — **Magnet alignment in bench**
-- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

21/01/2021 08:55:38 — **Electric connection**
-- *Raphael BOUVIER*
Accepted -- *Raphael BOUVIER*

21/01/2021 11:16:12 — **Manual clamp vtap measurement**
-- *Raphael BOUVIER*
Accepted -- *Raphael BOUVIER*

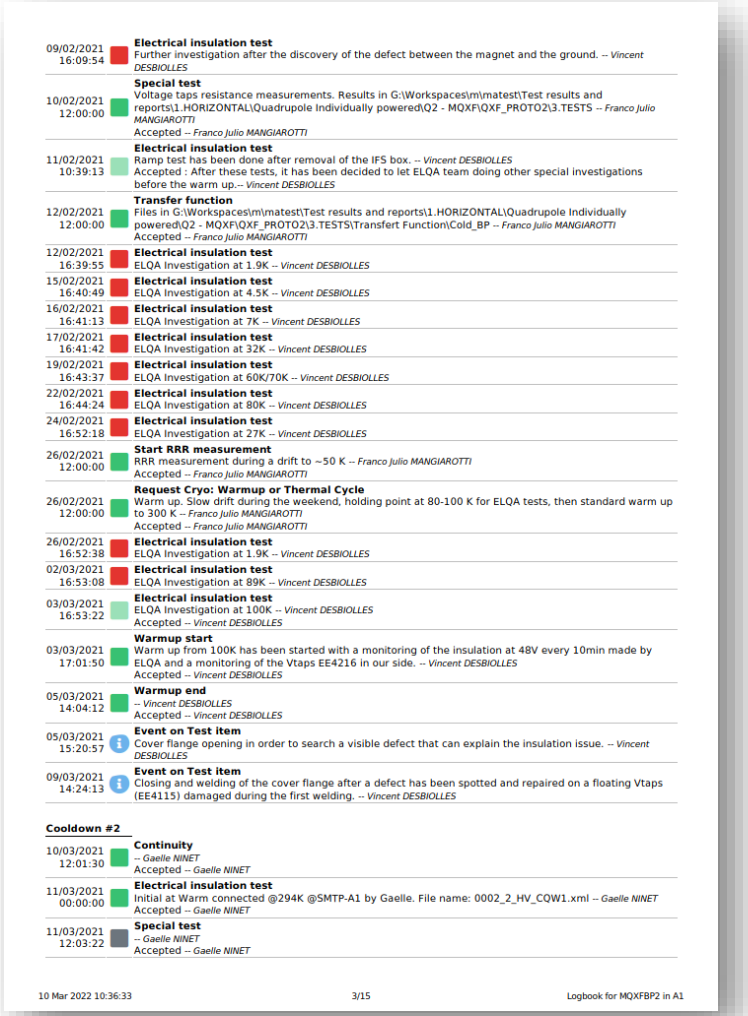
21/01/2021 15:30:03 — **Hydraulic connection**
-- *Raphael BOUVIER*
Accepted -- *Raphael BOUVIER*

22/01/2021 16:00:19 — **Config potaim cards**
-- *Raphael BOUVIER*
Accepted -- *Raphael BOUVIER*

25/01/2021 11:00:23 — **Connect anticryostat**
-- *Raphael BOUVIER*
Accepted -- *Raphael BOUVIER*

26/01/2021 10:00:59 — **Event on Data acquisition**
Nous avons un problème avec l'éditeur de fichier LF DAQ gen3. Il nous est impossible de modifier les templates afin de pouvoir mettre les deux nouvelles courbes de calibrations des sondes de températures Cernox associées à ce quadripole QXF. Hubert investigue sur ce problème. Cela ne nous gêne pas pour l'instant mais nous ne pouvons pas lancer le cooldown Cryo tant que le problème persiste. -- *Raphael BOUVIER*

10 Mar 2022 10:36:33 1/15 Logbook for MQXFBP2 in A1



09/02/2021 16:09:54 — **Electrical insulation test**
Further investigation after the discovery of the defect between the magnet and the ground. -- *Vincent DESBIOLLES*

10/02/2021 12:00:00 — **Special test**
Voltage taps resistance measurements. Results in G:\Workspaces\m\matest\Test results and reports\1.HORIZONTAL\Quadrupole Individually powered\Q2 - MQXF\QXF_PROTO2\3.TESTS -- *Franco Julio MANGIAROTTI*
Accepted -- *Franco Julio MANGIAROTTI*

11/02/2021 10:39:13 — **Electrical insulation test**
Ramp test has been done after removal of the IFS box. -- *Vincent DESBIOLLES*
Accepted : After these tests, it has been decided to let ELQA team doing other special investigations before the warm up.-- *Vincent DESBIOLLES*

12/02/2021 12:00:00 — **Transfer function**
Files in G:\Workspaces\m\matest\Test results and reports\1.HORIZONTAL\Quadrupole Individually powered\Q2 - MQXF\QXF_PROTO2\3.TESTS\Transfert Function\Cold_BP -- *Franco Julio MANGIAROTTI*
Accepted -- *Franco Julio MANGIAROTTI*

12/02/2021 16:39:55 — **Electrical insulation test**
ELQA Investigation at 1.9K -- *Vincent DESBIOLLES*

15/02/2021 16:40:49 — **Electrical insulation test**
ELQA Investigation at 4.5K -- *Vincent DESBIOLLES*

16/02/2021 16:41:13 — **Electrical insulation test**
ELQA Investigation at 7K -- *Vincent DESBIOLLES*

17/02/2021 16:41:42 — **Electrical insulation test**
ELQA Investigation at 32K -- *Vincent DESBIOLLES*

19/02/2021 16:43:37 — **Electrical insulation test**
ELQA Investigation at 60K/70K -- *Vincent DESBIOLLES*

22/02/2021 16:44:24 — **Electrical insulation test**
ELQA Investigation at 80K -- *Vincent DESBIOLLES*

24/02/2021 16:52:18 — **Electrical insulation test**
ELQA Investigation at 27K -- *Vincent DESBIOLLES*

26/02/2021 12:00:00 — **Start RRR measurement**
RRR measurement during a drift to ~50 K -- *Franco Julio MANGIAROTTI*
Accepted -- *Franco Julio MANGIAROTTI*

26/02/2021 12:00:00 — **Request Cryo: Warmup or Thermal Cycle**
Warm up. Slow drift during the weekend, holding point at 80-100 K for ELQA tests, then standard warm up to 300 K -- *Franco Julio MANGIAROTTI*
Accepted -- *Franco Julio MANGIAROTTI*

26/02/2021 16:52:38 — **Electrical insulation test**
ELQA Investigation at 1.9K -- *Vincent DESBIOLLES*

02/03/2021 16:53:08 — **Electrical insulation test**
ELQA Investigation at 89K -- *Vincent DESBIOLLES*

03/03/2021 16:53:22 — **Electrical insulation test**
ELQA Investigation at 100K -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

03/03/2021 17:01:50 — **Warmup start**
Warm up from 100K has been started with a monitoring of the insulation at 48V every 10min made by ELQA and a monitoring of the Vtaps EE4216 in our side. -- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

05/03/2021 14:04:12 — **Warmup end**
-- *Vincent DESBIOLLES*
Accepted -- *Vincent DESBIOLLES*

05/03/2021 15:20:57 — **Event on Test item**
Cover flange opening in order to search a visible defect that can explain the insulation issue. -- *Vincent DESBIOLLES*

09/03/2021 14:24:13 — **Event on Test item**
Closing and welding of the cover flange after a defect has been spotted and repaired on a floating Vtaps (EE4115) damaged during the first welding. -- *Vincent DESBIOLLES*

Cooldown #2

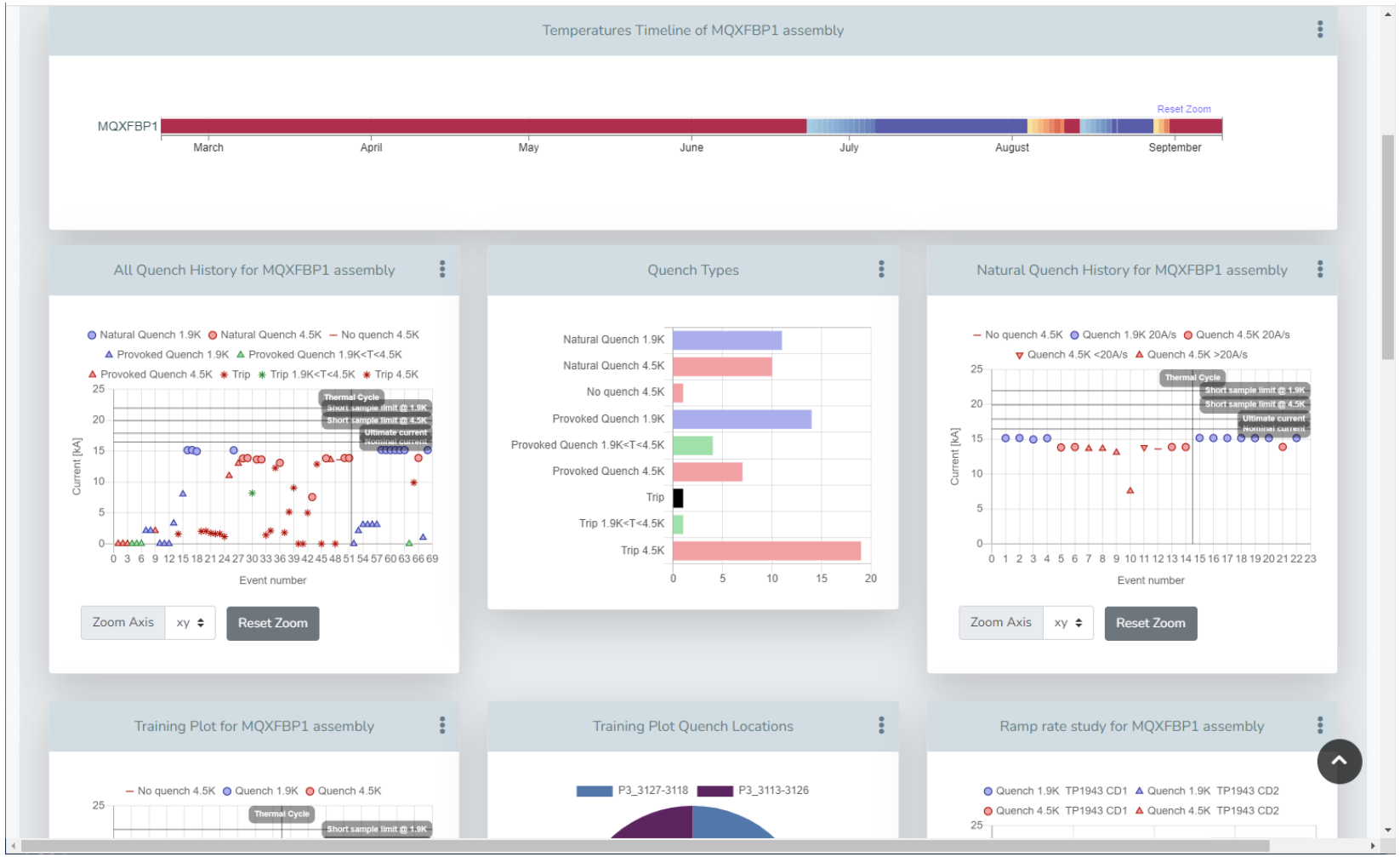
10/03/2021 12:01:30 — **Continuity**
-- *Gaelle NINET*
Accepted -- *Gaelle NINET*

11/03/2021 00:00:00 — **Electrical insulation test**
Initial at Warm connected @294K @SMTP-A1 by Gaelle. File name: 0002_2_HV_CQW1.xml -- *Gaelle NINET*
Accepted -- *Gaelle NINET*

11/03/2021 12:03:22 — **Special test**
-- *Gaelle NINET*
Accepted -- *Gaelle NINET*

10 Mar 2022 10:36:33 3/15 Logbook for MQXFBP2 in A1

Carpenter for data visualization



Main test data uploaded to the database, which allows to automatically generate standard plots (Protocols)

Take home messages – MQXF testing overview

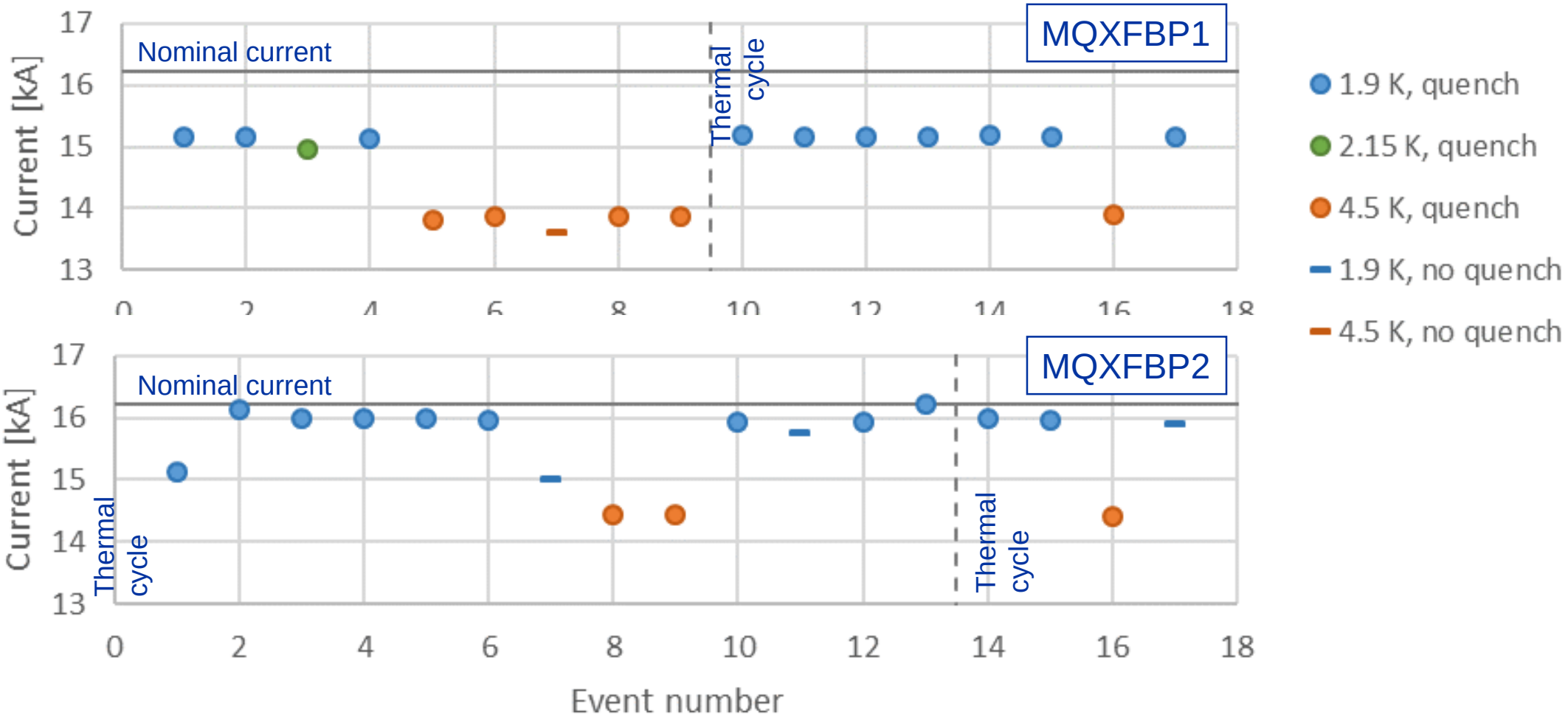
7 years experience with testing of MQXF magnets. Highest priority during all this time, short of the 11 T, which adds to the experience

At least 23 TM staff and FSU directly involved in the MQXF prototype tests; more for the short model campaign (bench and instrumentation preparation, calibration and commissioning, testing new procedures)

Synergies identified between former TF and MM section already before (grand) unification: quench antennas, DAQ, and instrumentation. And now, of course, the upgrade for WP3

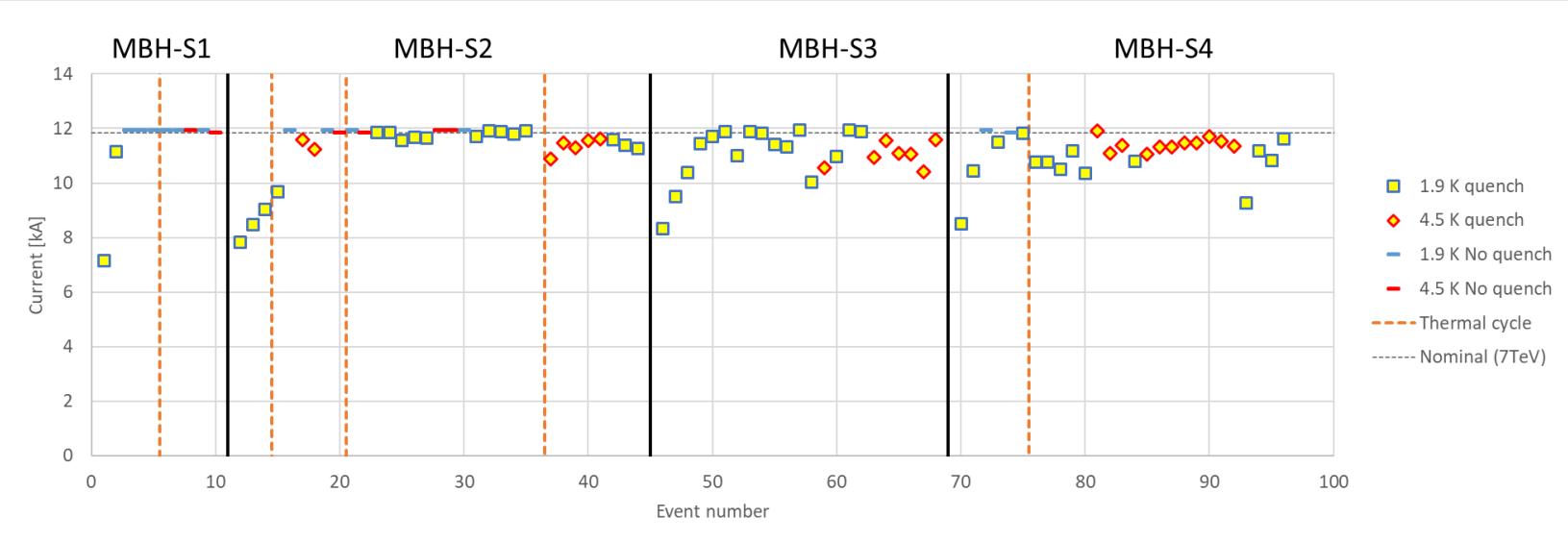
10 months of MQXF cold testing in 2020-2021

Quench performance limitation (MQXFB prototypes)

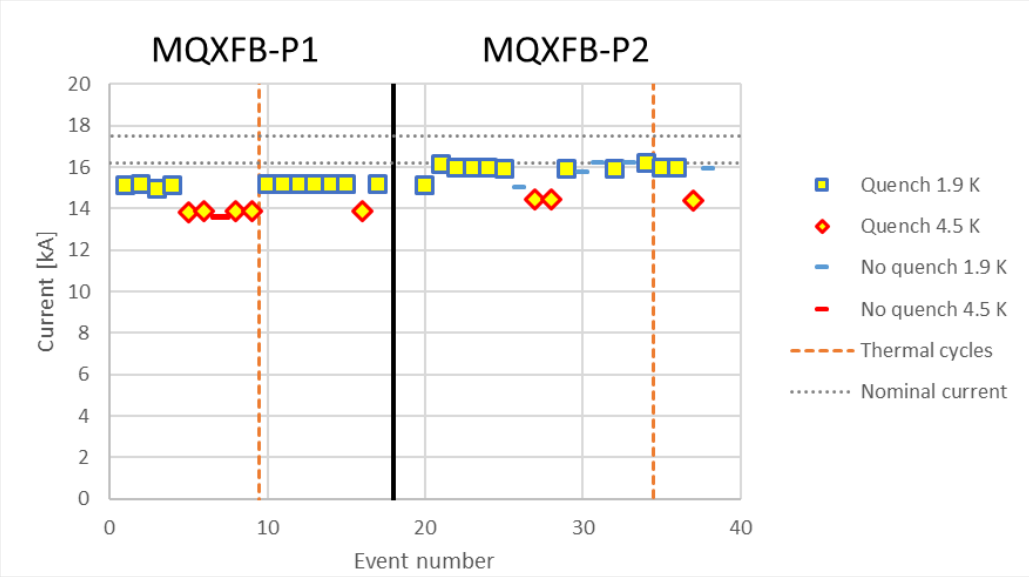


The magnets reach a quench limit in the first or second quench: same current, voltage signature and quench antenna signals.

Quench performance limitations versus degradation (11 T series)

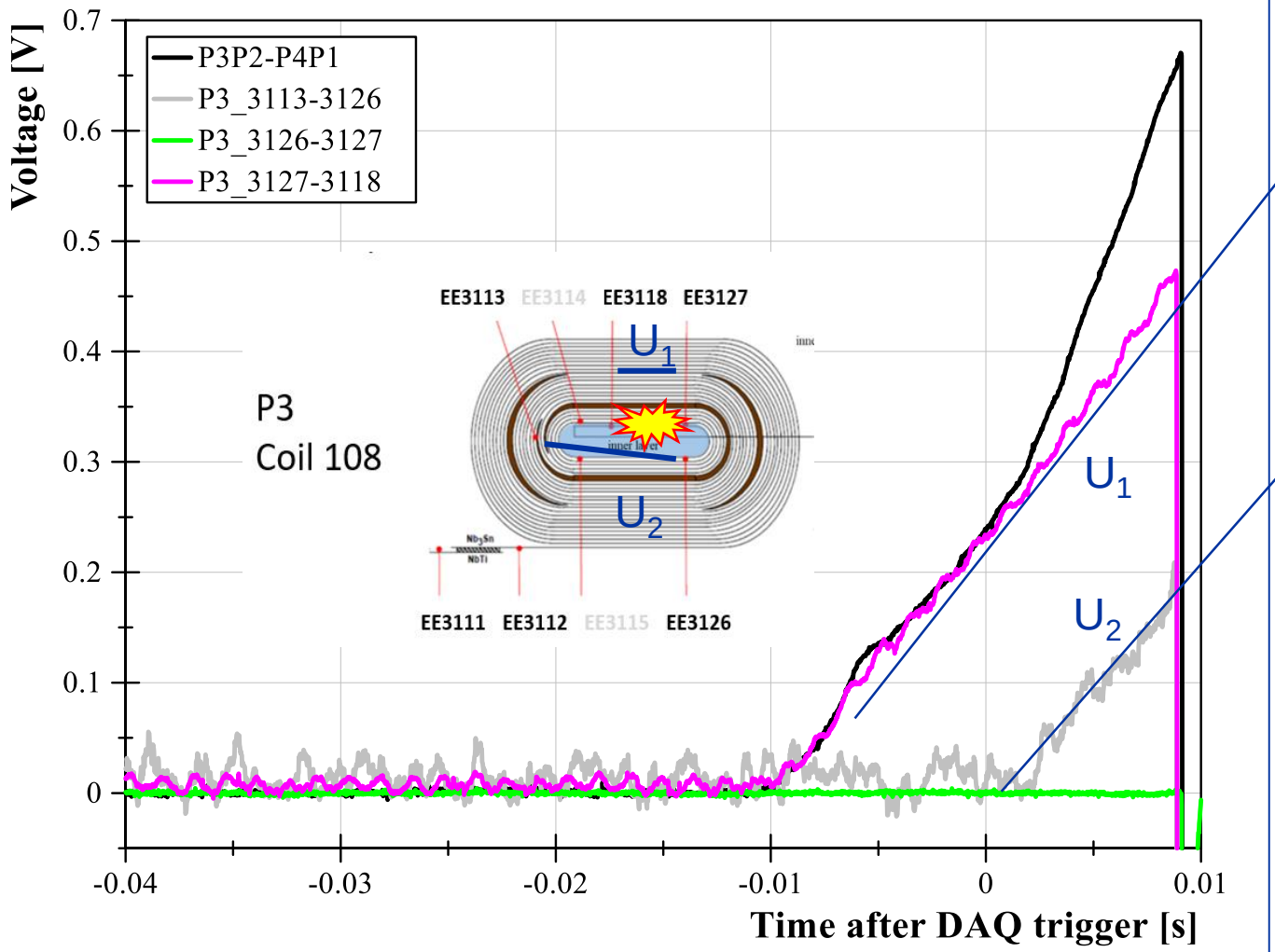


In these plots: tests at nominal ramp rate



The type of degradation in the 11 T (gets worse after each thermal cycle) is different from that of the MQXF (no further degradation so far)

Quench location 1.A – Voltage signals



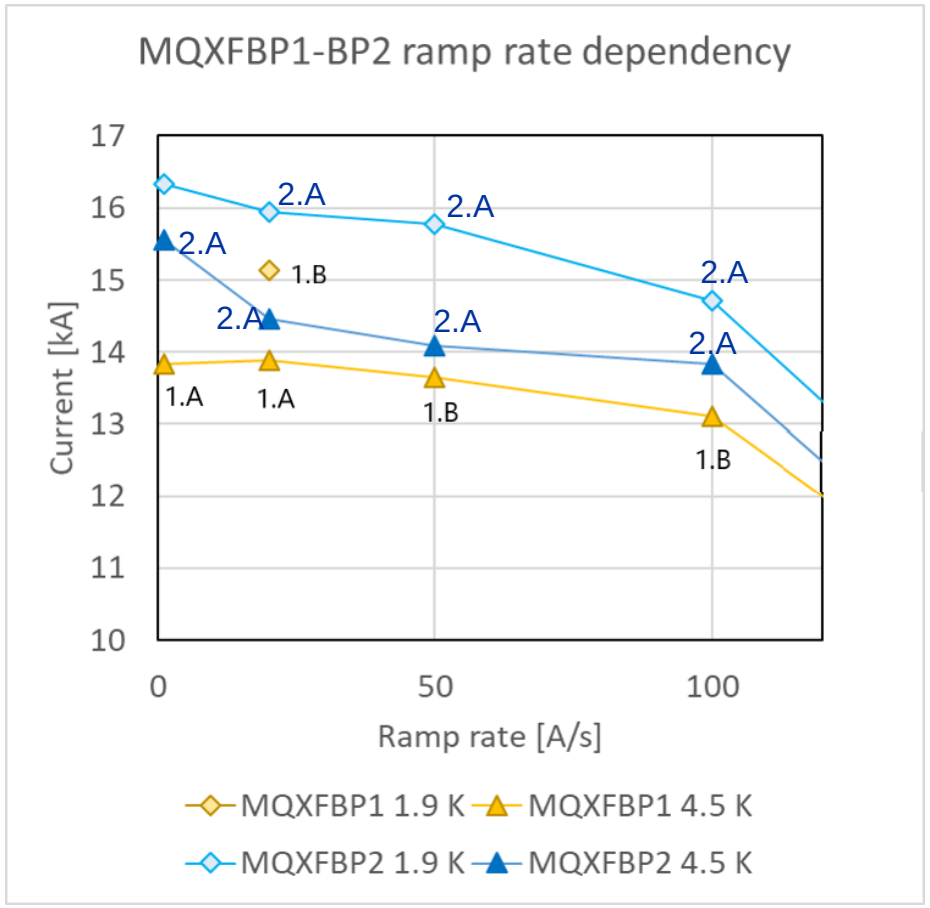
Quench starts between 3127-3118 (pole turn center)

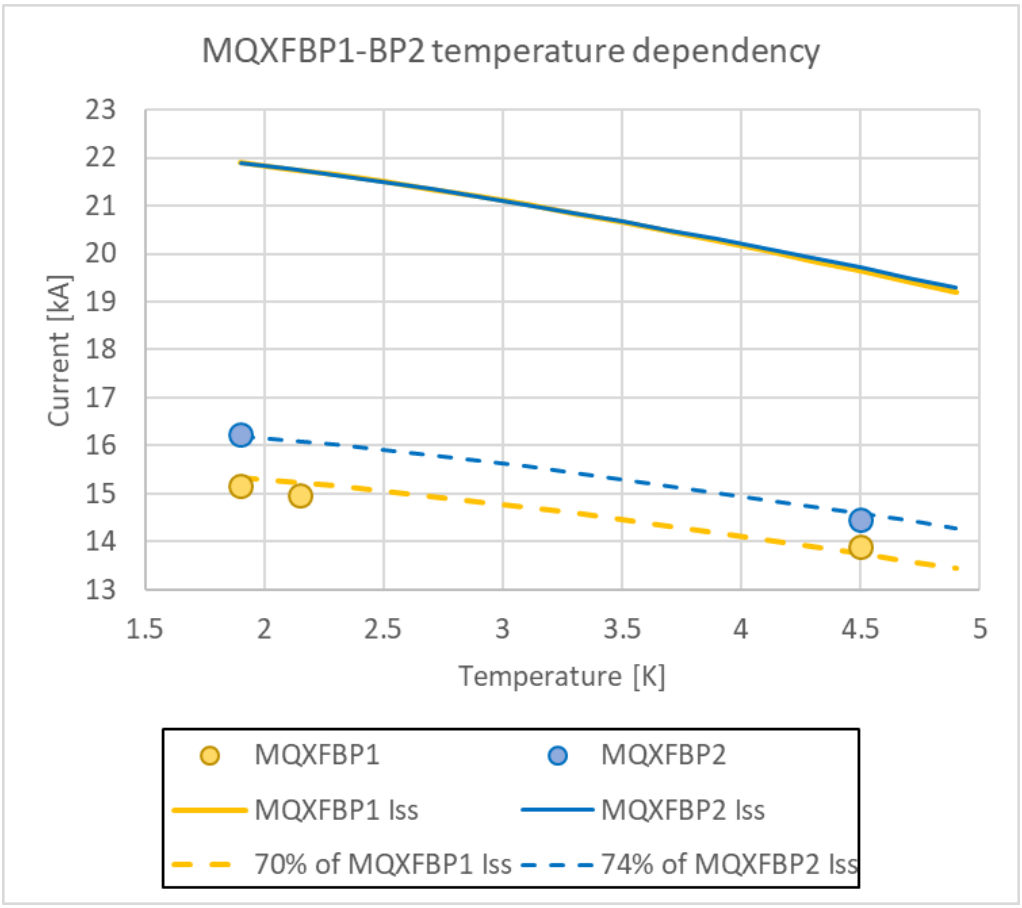
After ~13 ms it propagates transversally to 3113-3126

Quench does not reach longitudinally neighboring segments (3126-3127 and 3118-3212)

QPV: ~15 m/s at 15 kA, 1.9 K

Ramp rate and temperature dependence





Normal temperature dependence in both magnets, -> not mechanically limited. Ramp rate dependence for BP1: insufficient data. For BP2, low RR at 4.5 K may hint at non-homogeneous defect. Ongoing R&D: Special test foreseen on a SMC with artificially degraded conductor

Take home message – performance characterization (ramp rates, quench propagation)

The magnets show almost no training; they reach a current limit at the first or second quench

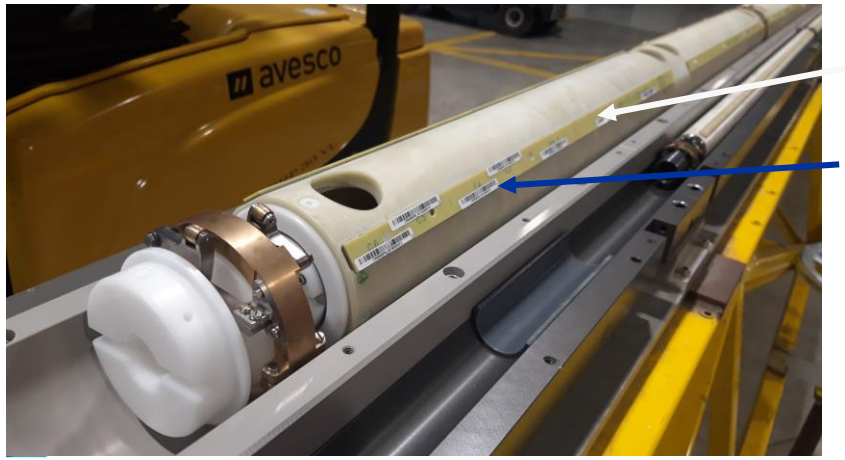
The current limit did not change after one thermal cycle (as opposed to the 11 T where it got worse after successive thermal cycles (degradation versus limitation)

Temperature dependence is normal – conductor limitation, no mechanical limitation

Quench propagation velocity: similar to other (not limited) short models – indicates local conductor degradation

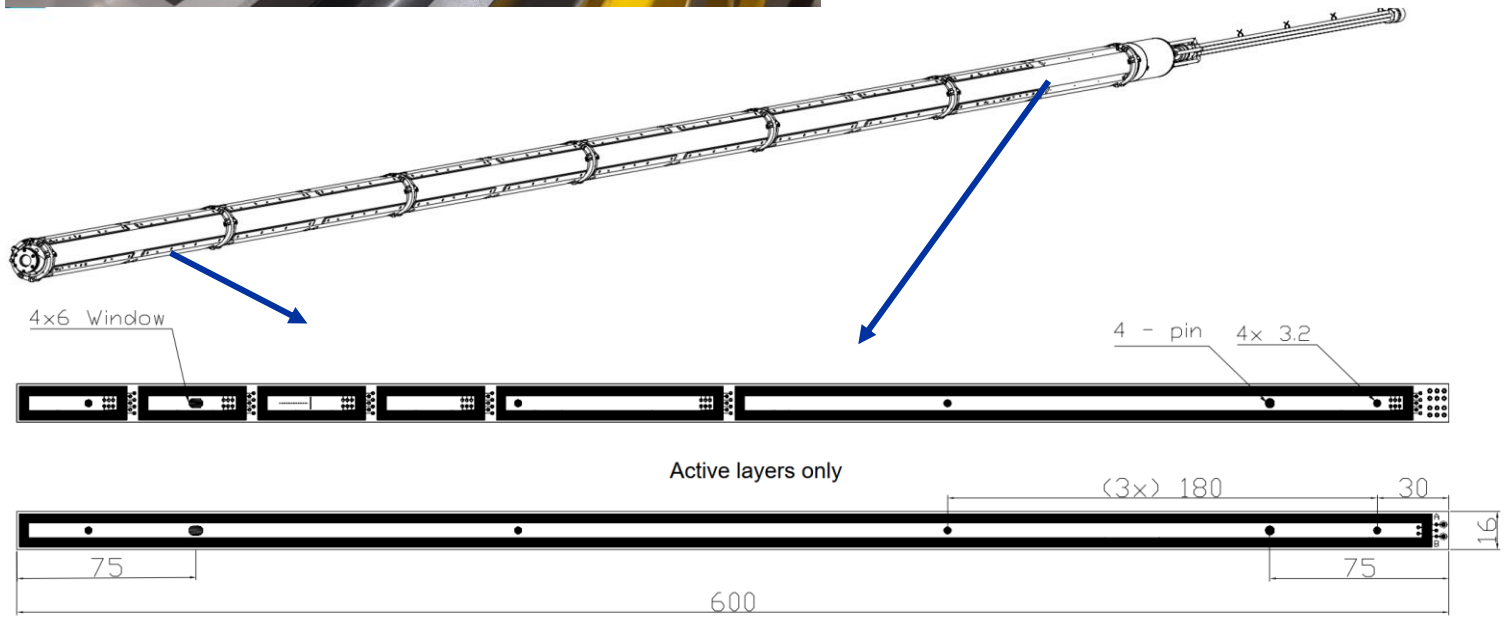
More information on these techniques here: https://indico.cern.ch/event/820811/

Quench Antenna (B2 sensitive)

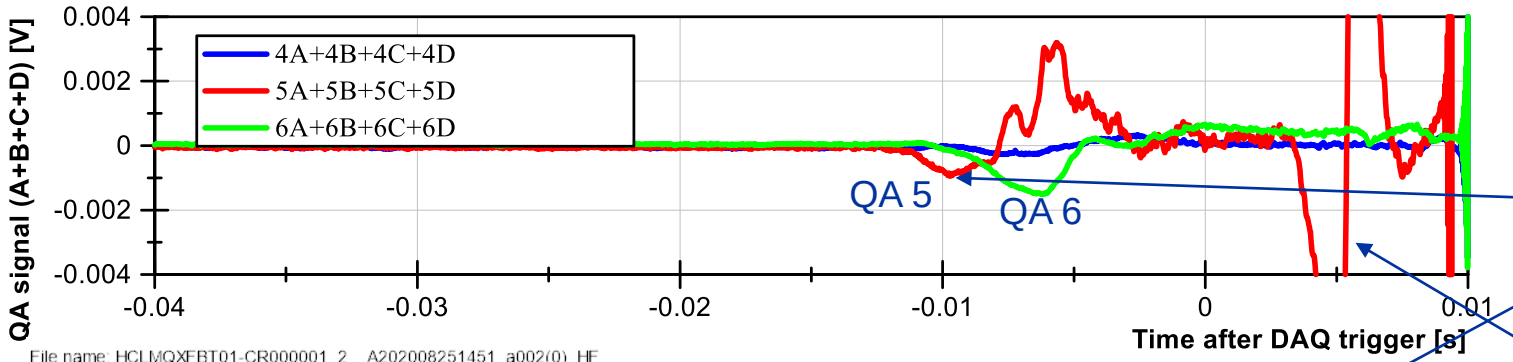


6 support tubes of 1.27 meter

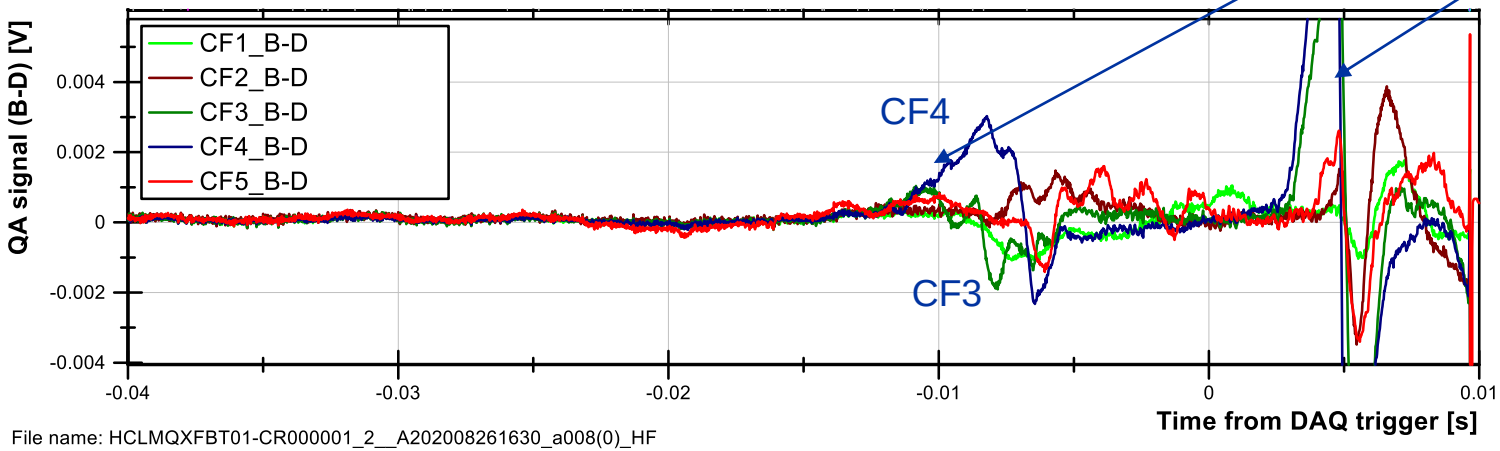
4 times 11 PCB’s of 0.6 meter



Quench location 1.B – QA signal



File name: HCLMQXFBT01-CR000001_2__A202008251451_a002(0)_HF
Quench 2, CD2. QA shifted 300 mm

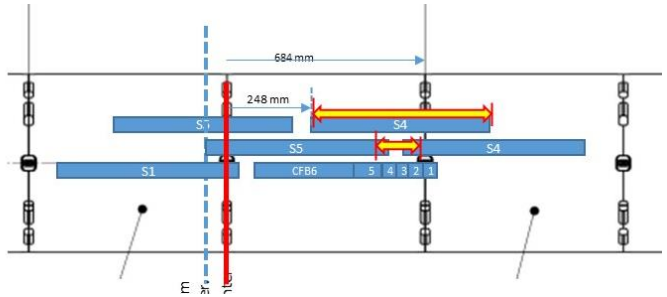


File name: HCLMQXFBT01-CR000001_2__A202008261630_a008(0)_HF
Quench 6, CD2. QA shifted -3392 mm

Six quenches with different QA position. In each, we observe where the quench starts.

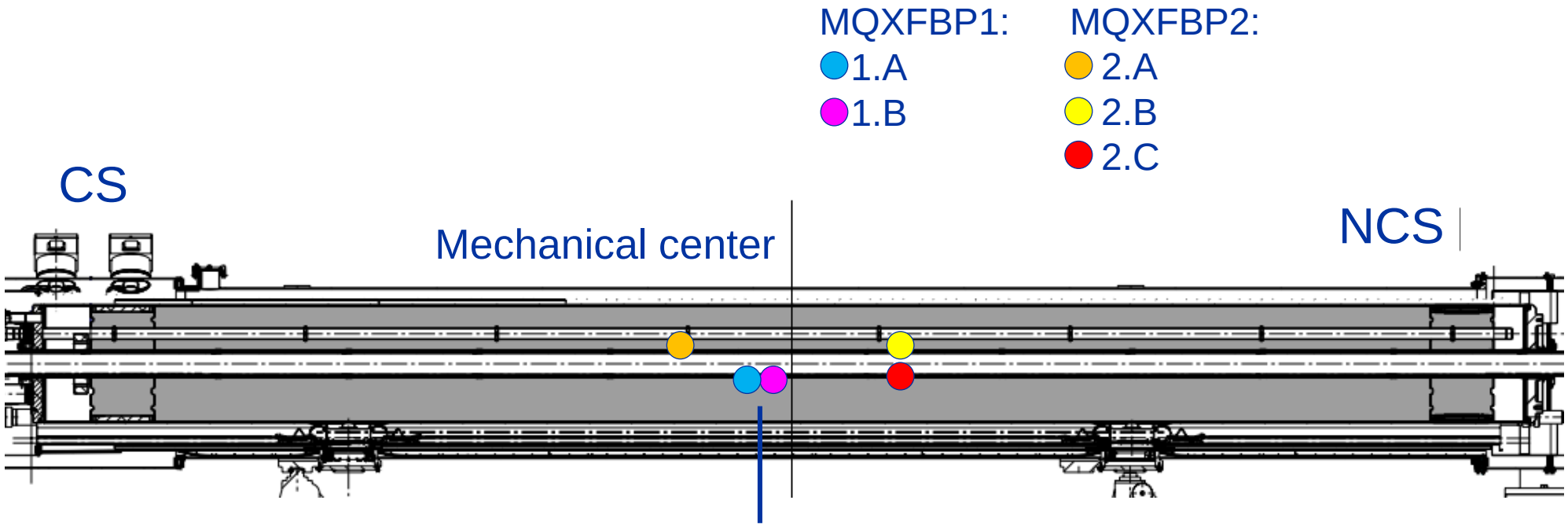
- Example top: starts in QA 5
- Example bottom: starts in CF 4

After ~13 ms we see the transverse quench propagation



Quench localization

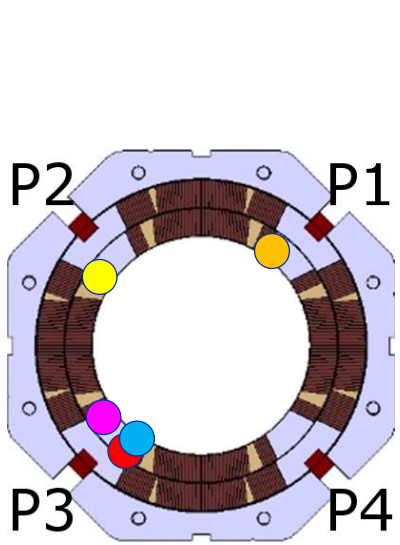
The recurring quench locations are in the inner layer, pole turn, straight segment, near the mechanical center. In MQXFBP1 in coil P3, in MQXFBP2 in coil P1.
Longitudinal localization within ±50 mm from quench antenna data.



Quench localization

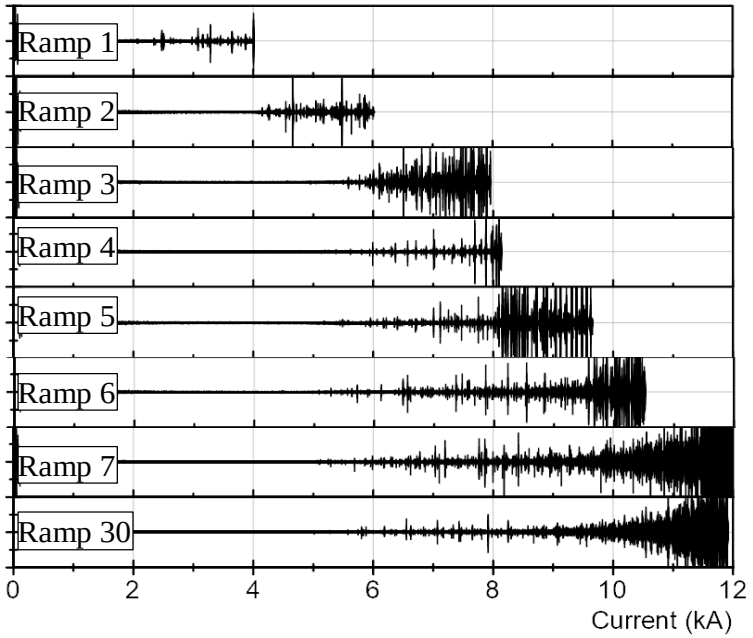
MQXFBP1:
- 1.A
- 1.B

MQXFBP2:
- 2.A
- 2.B
- 2.C



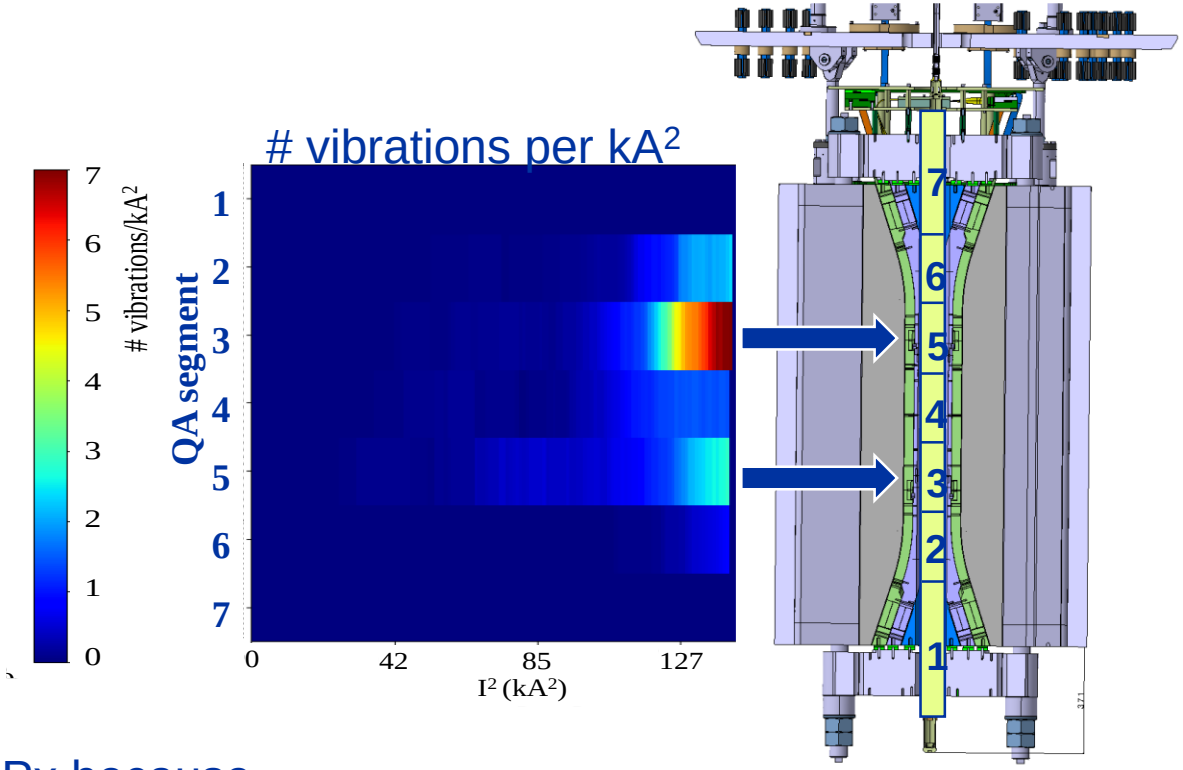
Vibration analysis for Fresca2

Investigation of all vibrations picked up by the MM shaft used as a quench antenna).
Training effect: less vibrations after consecutive ramps.



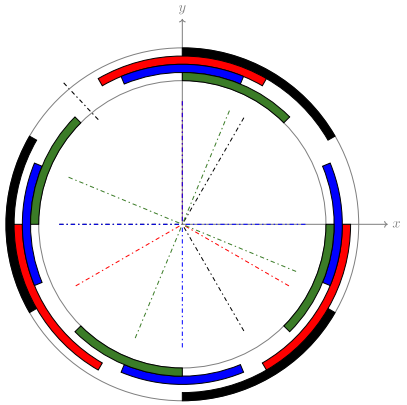
Signals for QA5

Vibration analysis fully trained magnet
Highest activity seen by QA 5, consistent with quench locations in the magnet.

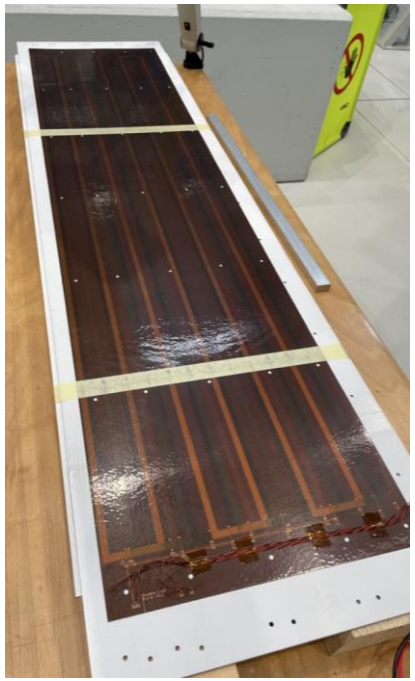


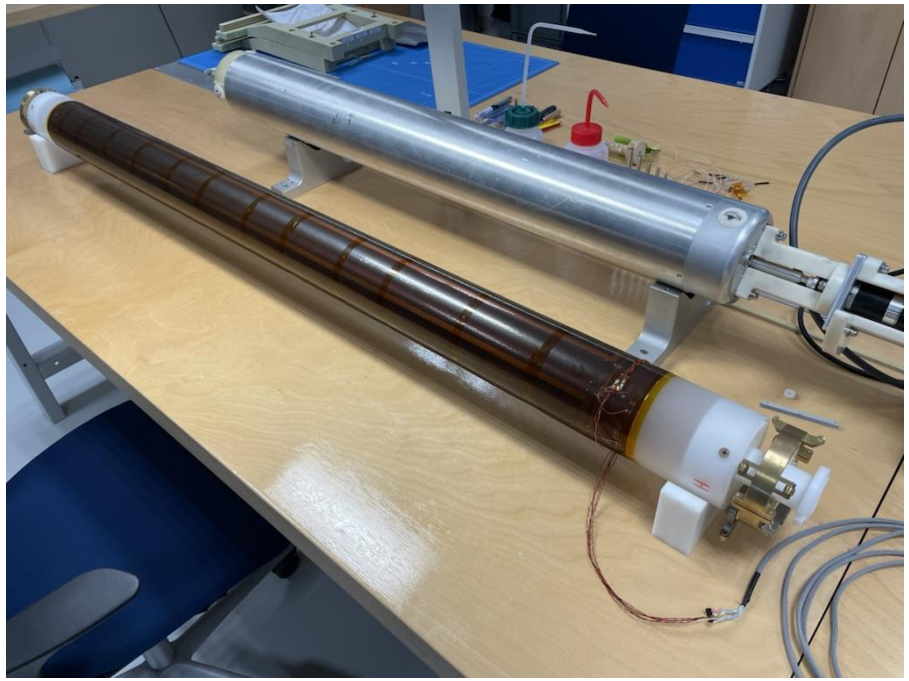
This type of analysis was not needed in the MQXFBPx because they were not limited mechanically. However, we have this tool at our disposal if needed

Multipole Sensitive Quench-Antenna
(prototype segment)



Clean B3,A3,B4,A4 sensitive through coil design
(analogue bucking -> Flex PCB design)
Compromise between noise (PC, vibrations etc), resolution in radial direction, and signal strength.

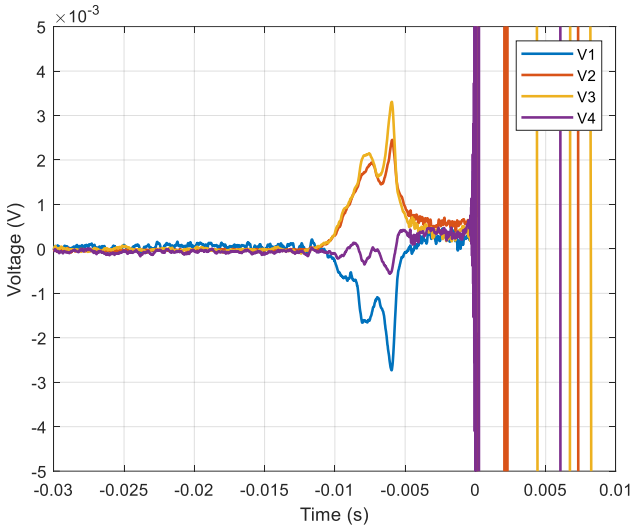


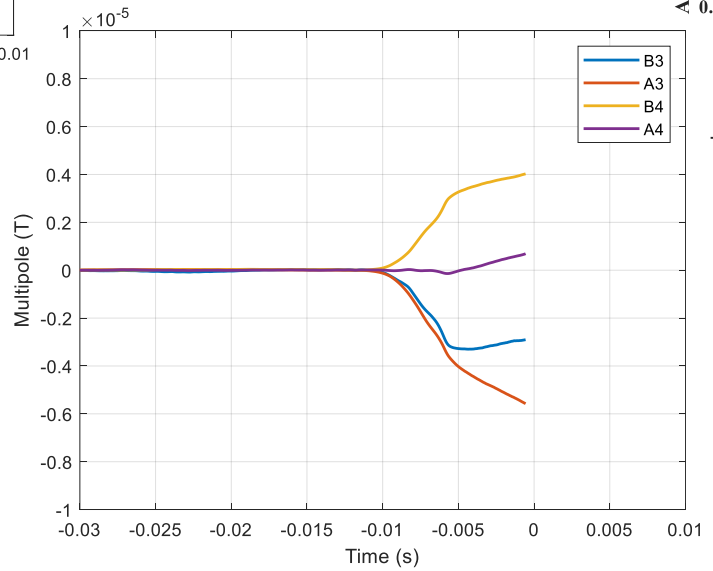


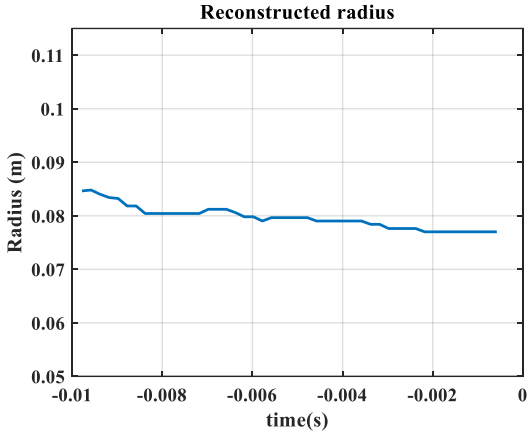
Leroy et al. 1993, Ogitsu et al. 1996, Bossert et al. 2011

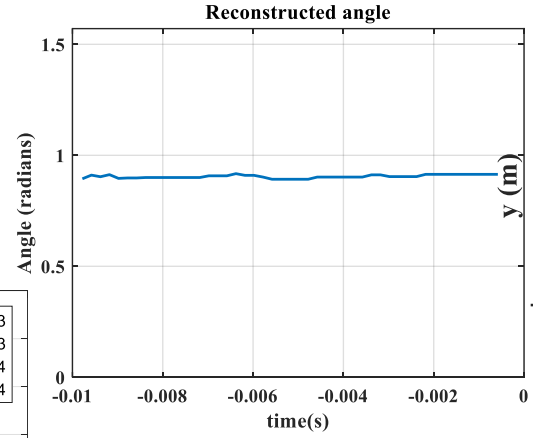
Data from quench

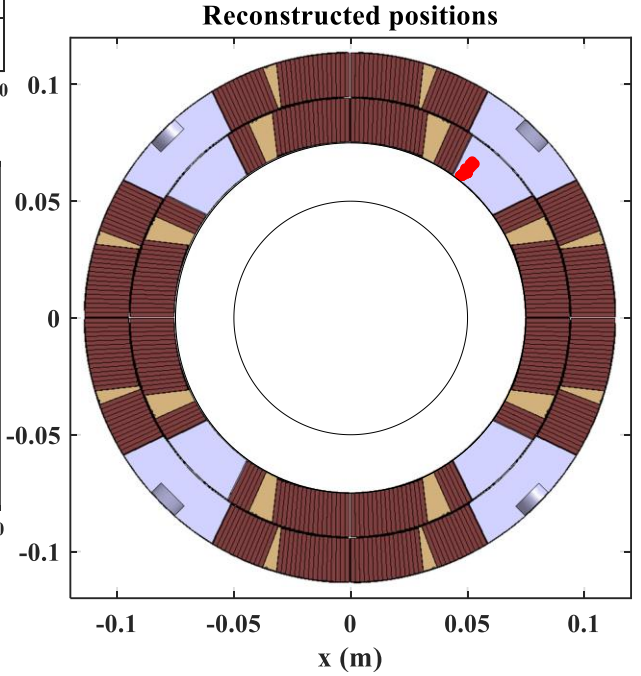
@ 4.5 K, 1 A/s, I_{quench} = 15455 A, trim circuit disconnected









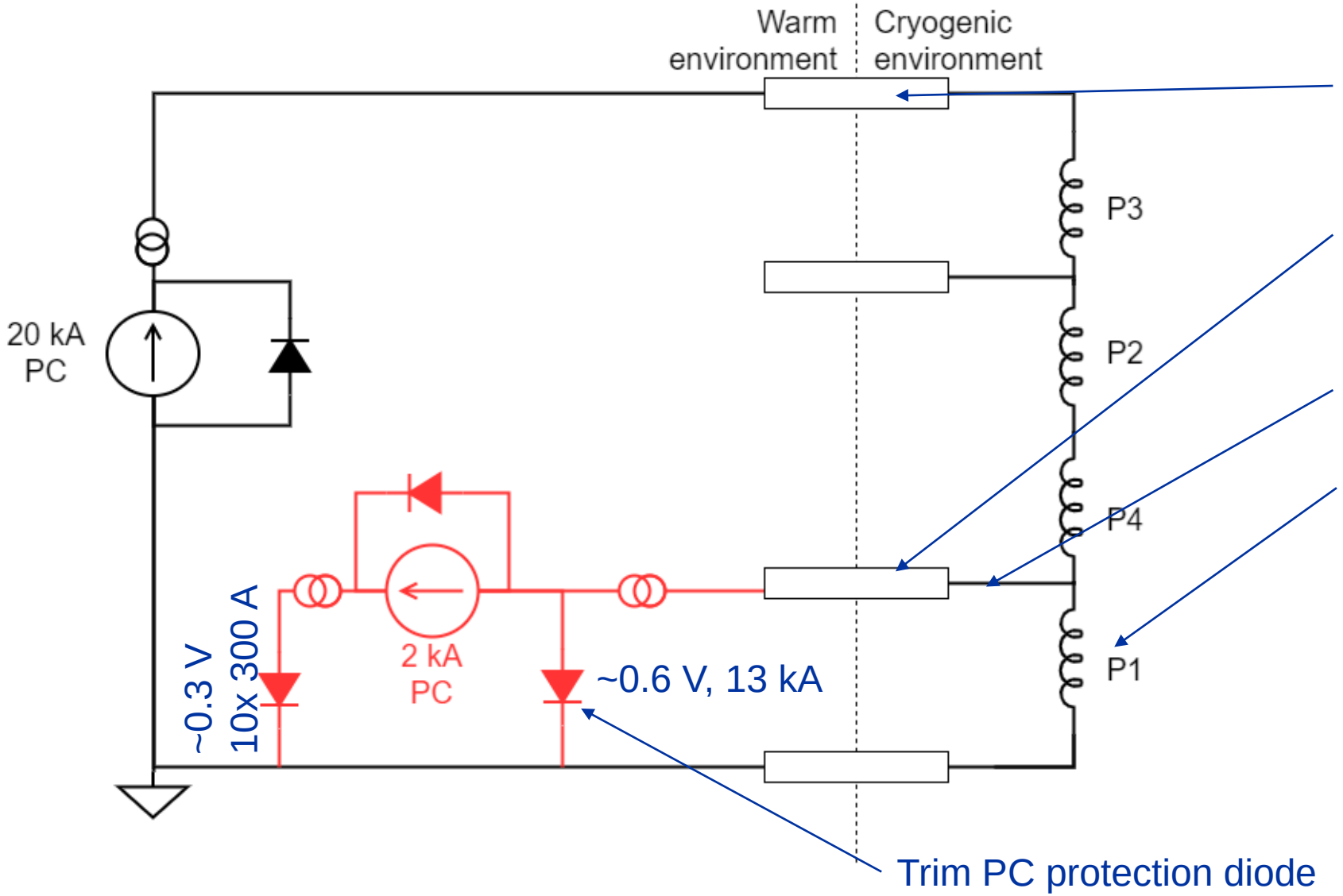


Take home message – Quench antenna

Standard 4-coil (B2 sensitive – 64 channels) quench antenna effective to localize the longitudinal quench location within +/- 45 mm for reproducible quench positions. Also, most probably, effective for recording field changes due to vibrations (in case of structural limitations)

Multipole quench antenna (with 12 x 600-mm segments = 48 channels) will allow us to localize the quench in the cross section, in particular for magnets with fewer voltage taps. If needed shorter flex PCB can be retrofitted.

Circuit diagram, trim powering



Main current leads (20 kA)

Auxiliary current leads (600 A) used for CLIQ in the temporary cold mass configuration

Superconducting CLIQ leads

Coil to trim down

Next step: Double the leads to allow up to 2 kA trim powering

Initial tests on MQXFS7

2 kA Trim PC

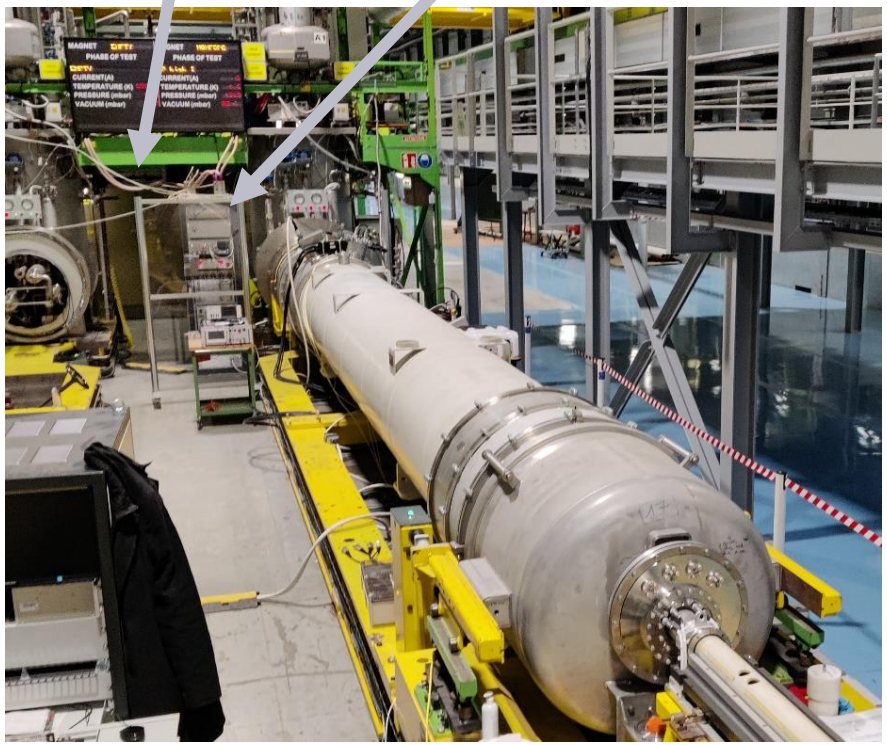
Additional DCCT (to measure trim current)

Protection diode

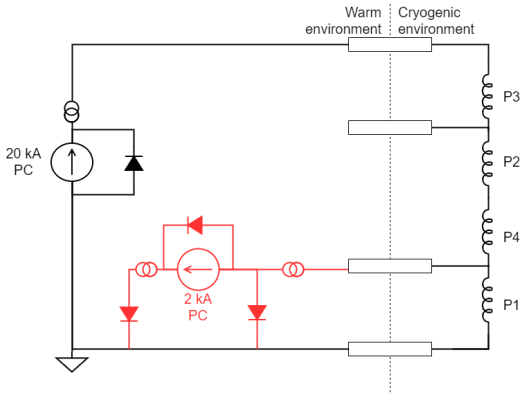
Test of MQXFBP2

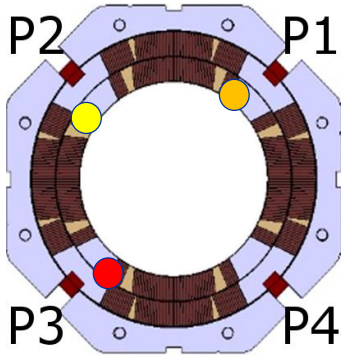
2 kA cables going to the mezzanine

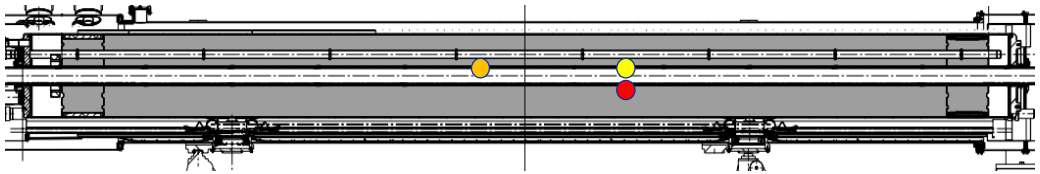
2 kA Trim PC

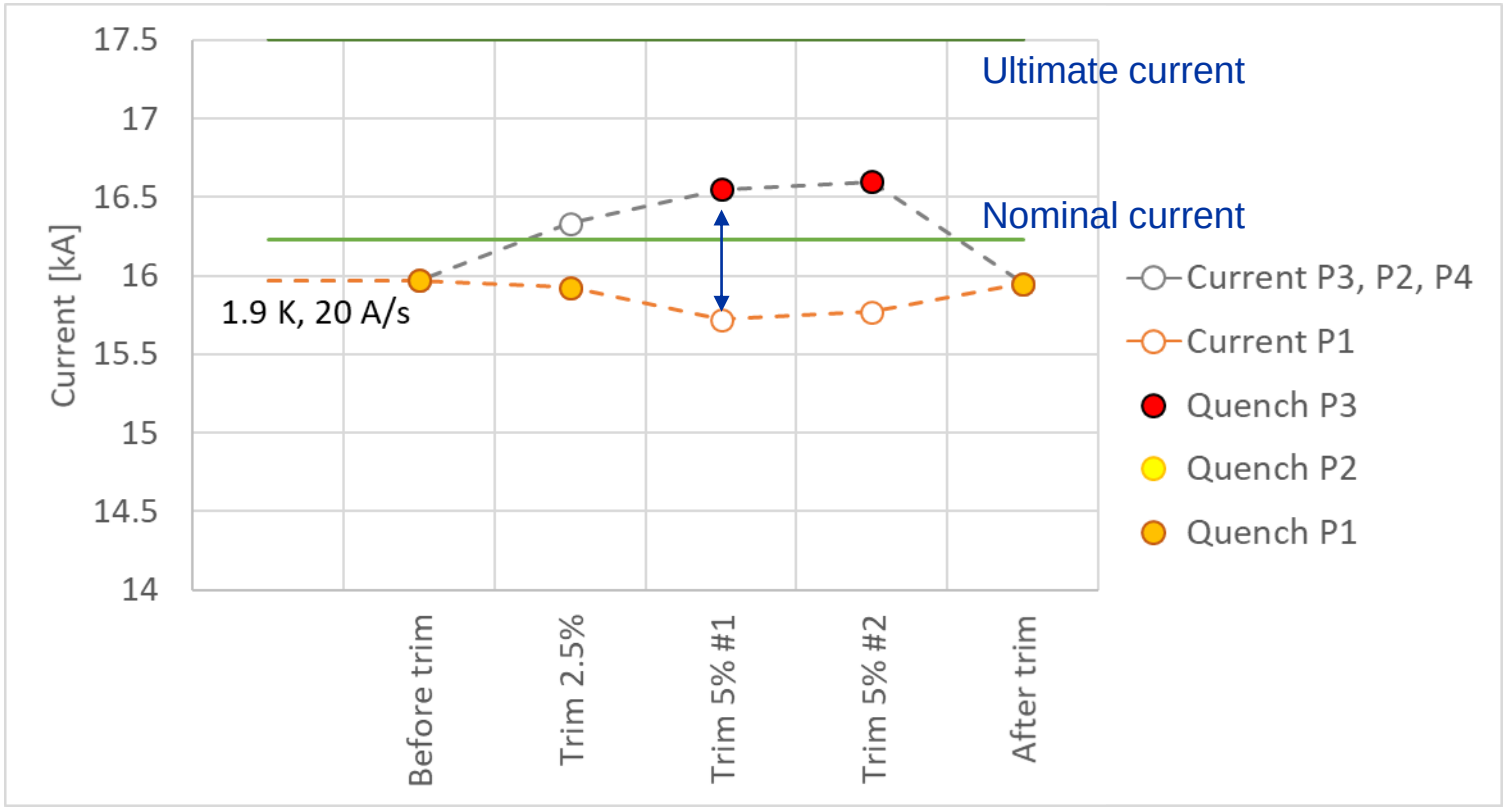


Trim powering results

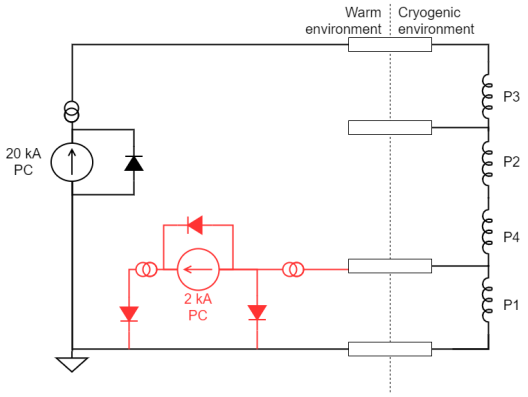


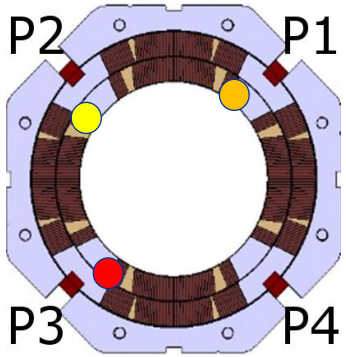


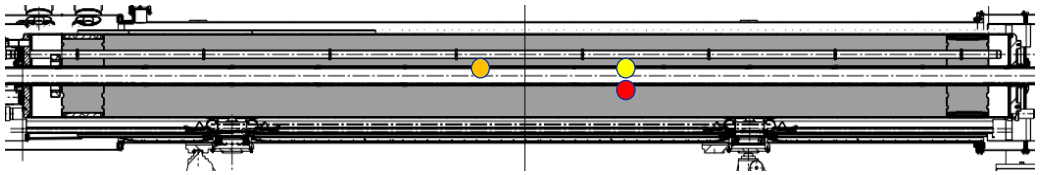


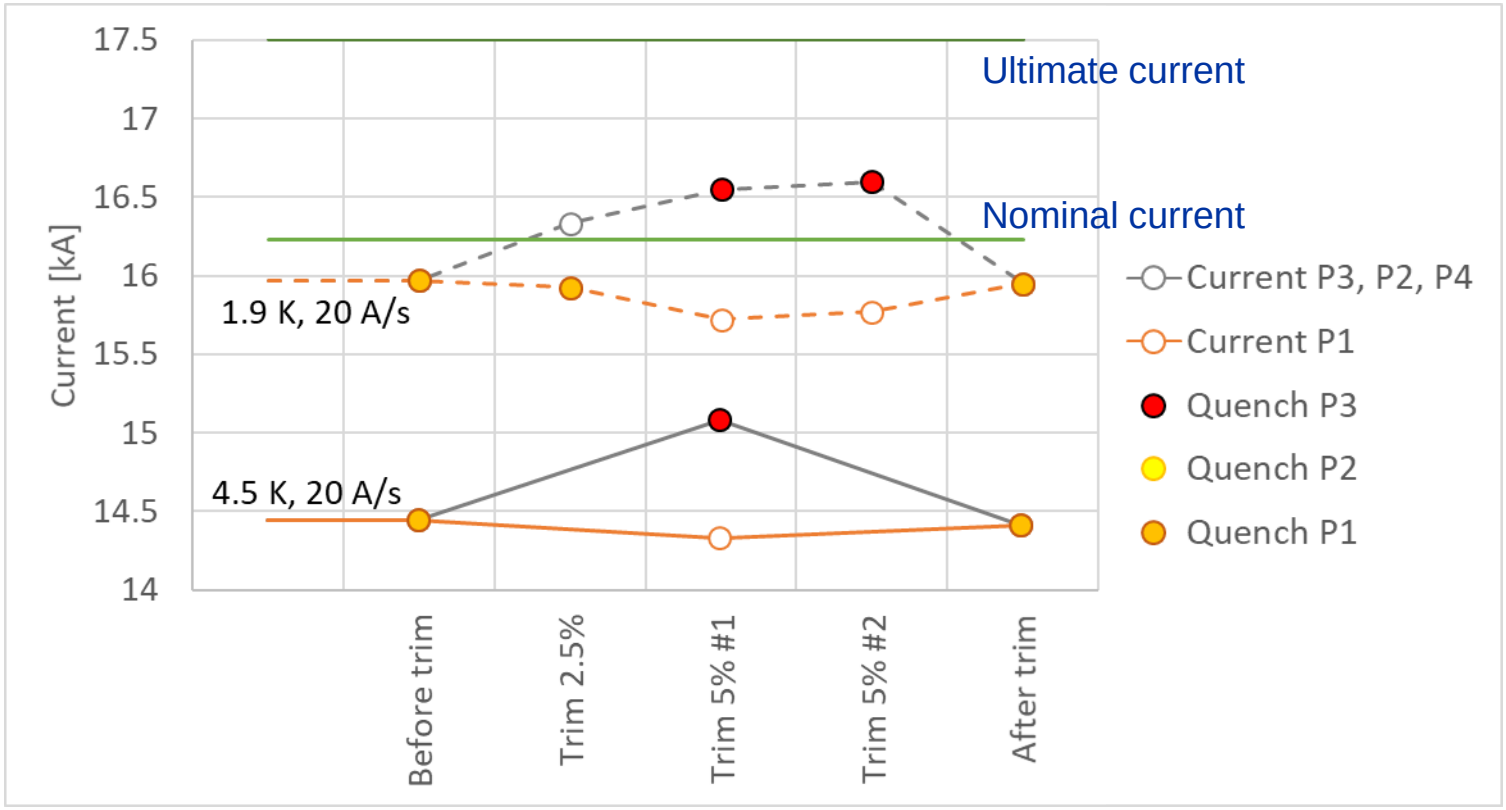


Trim powering results

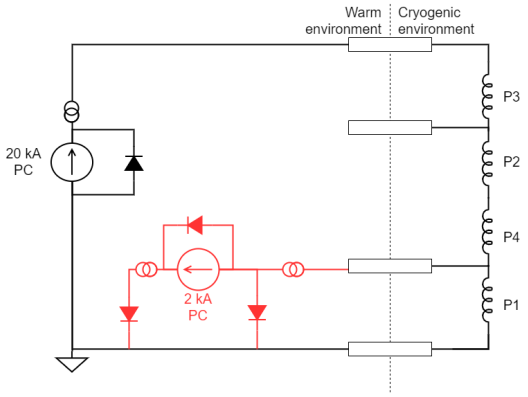


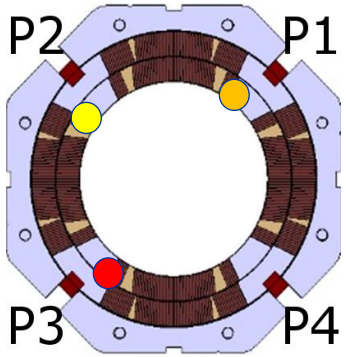


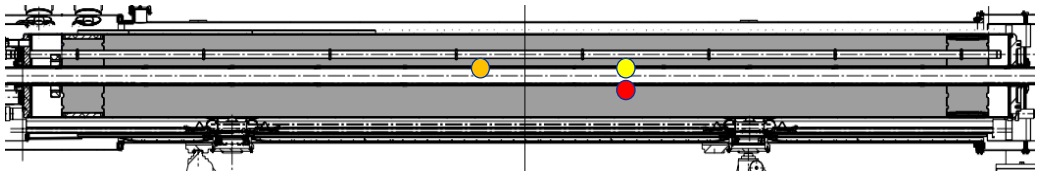


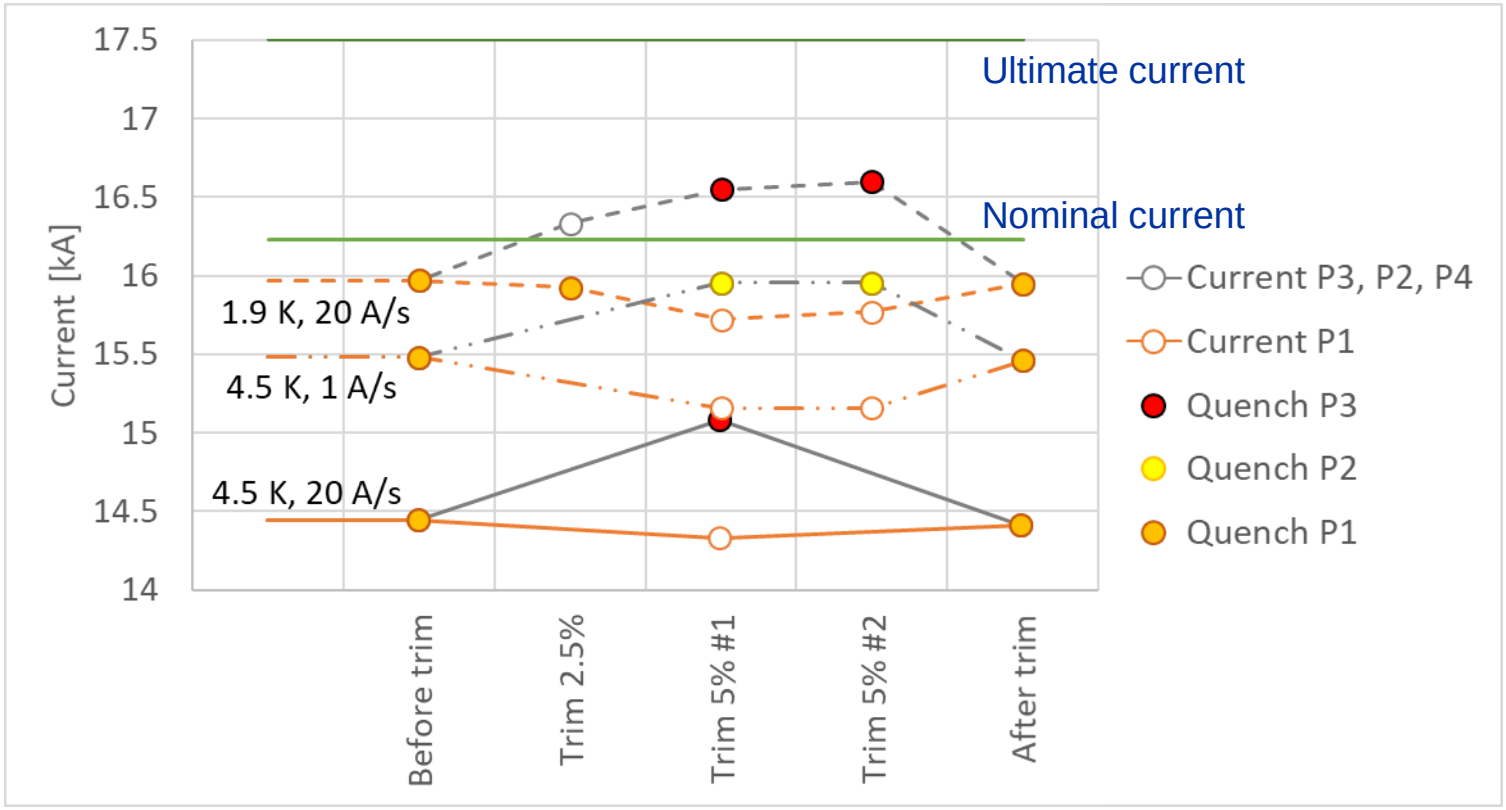


Trim powering results

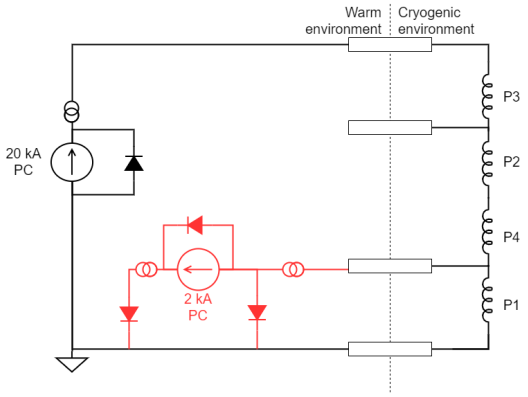


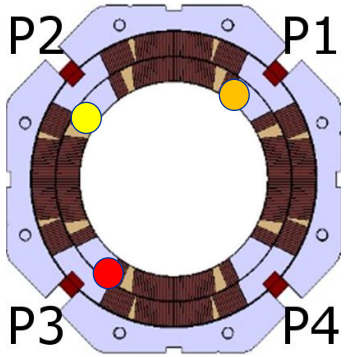


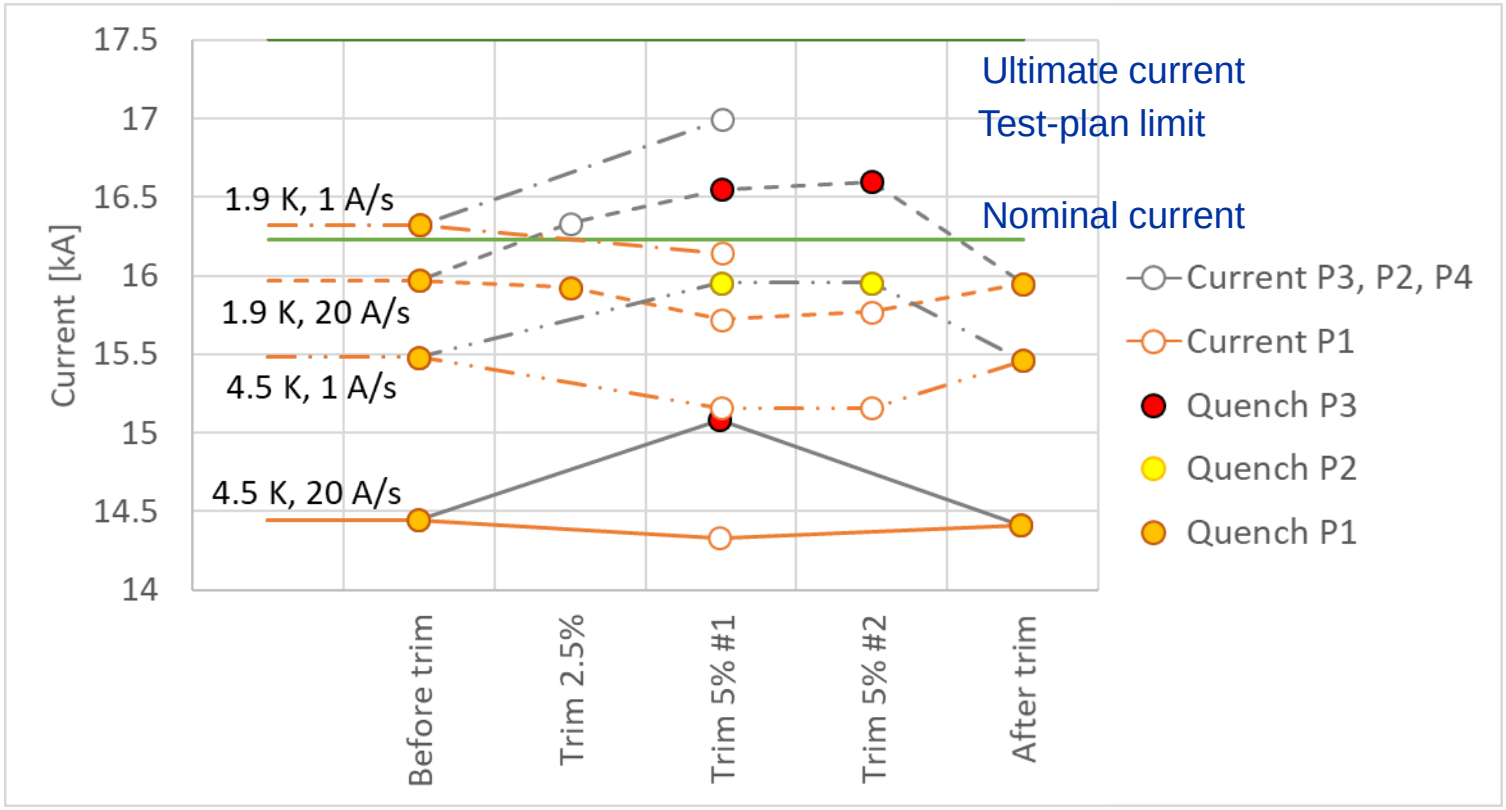




Trim powering results







Take home message – Trim powering

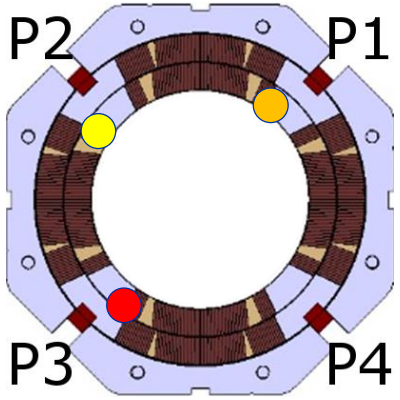
Trim powering validated on a short model and implemented in the MQXFBP2 prototype. Procedures, circuit analysis (with support from MPE), validation through short model testing, and risk mitigation measurements developed

Trimmed powering of MQXFBP2 allowed us to see the quench limit in at least two other coils. At least 3 limited at various levels of severity.

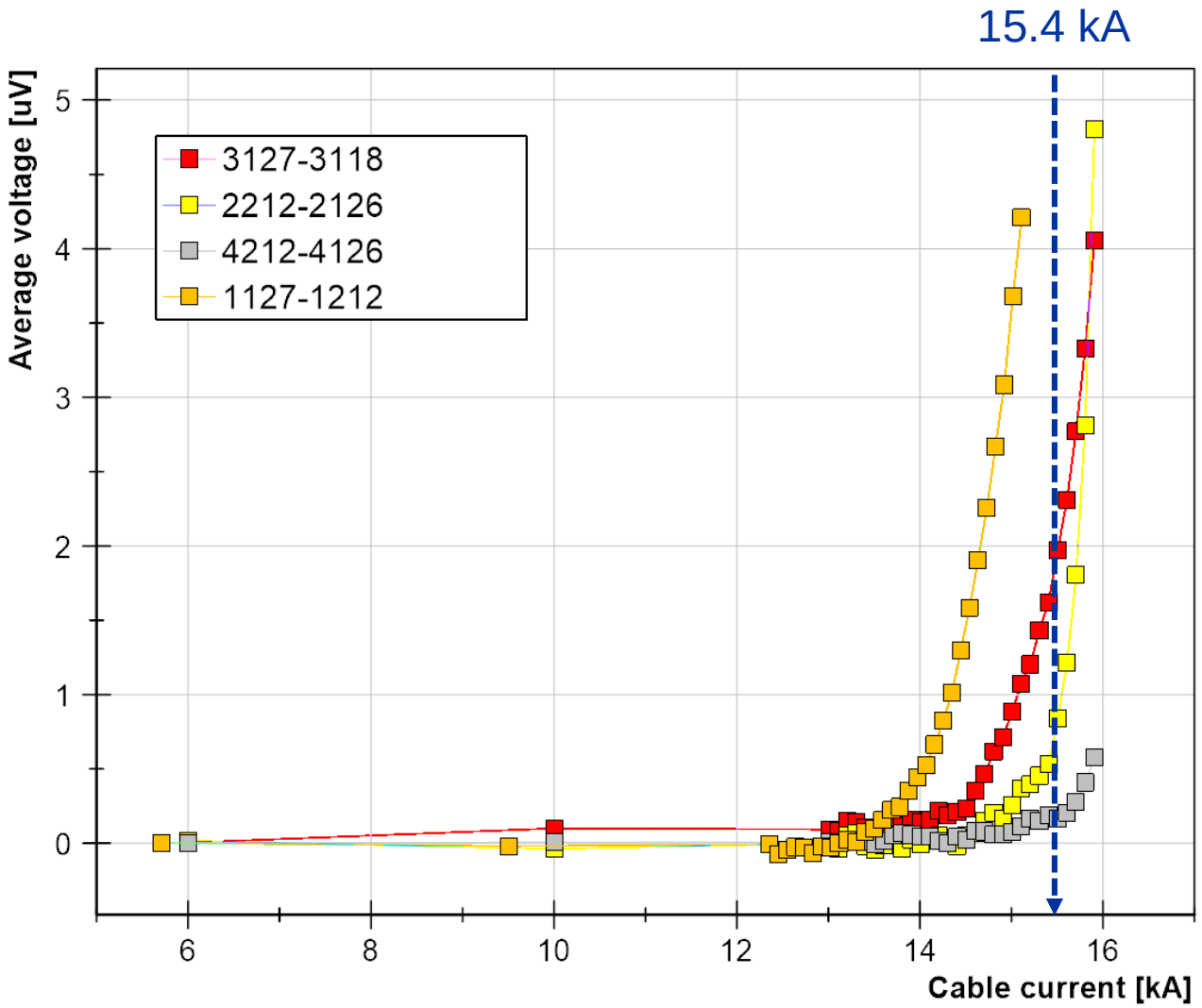
Enhanced trim powering (up to 2 kA) for the next magnets to have a lower lead-time assessment of the new coil manufacturing procedure

V-I measurements with 5% trim at 4.5 K

Inner pole turn segments in the four coils show same transition. In the quenching coils ~5 uV, in P4 ~0.6 uV

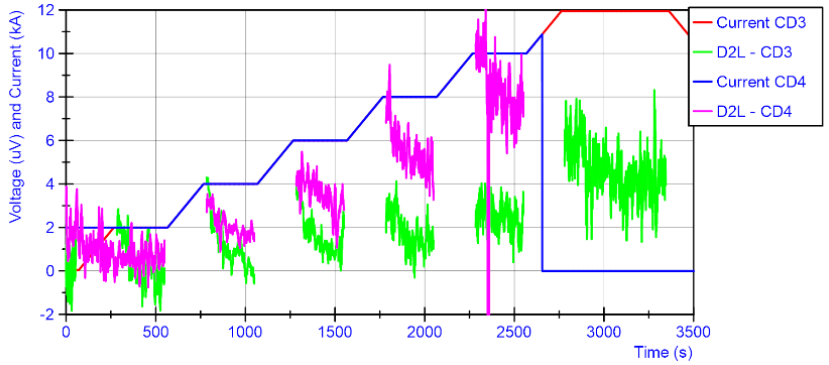


N-value strongly depends on B (~60 at 10.5 T ~45 at 12.3 T) which in turn depends strongly on position in the coil

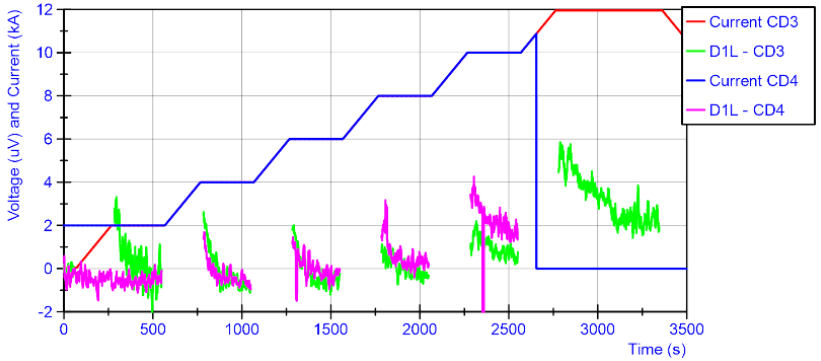


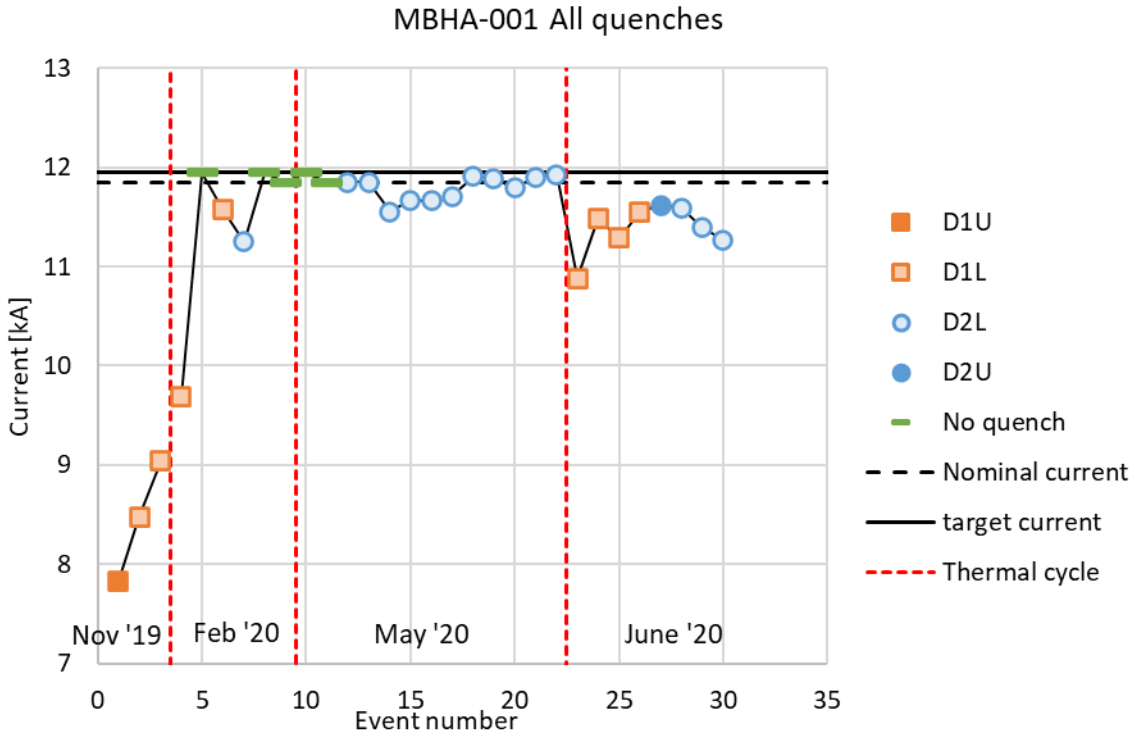
MBHA-001

Lower coil aperture 2



Lower coil aperture 1





11T from 2018 to 2021: V-I over full coil gave conclusive results. MQXFBP2, april 2021: V-I measurements on full coil were disturbed. MQXFBP2, November 2021: Issue solved by putting less voltage measurements in parallel and better cable routing

V-I measurements – MQXFBP01

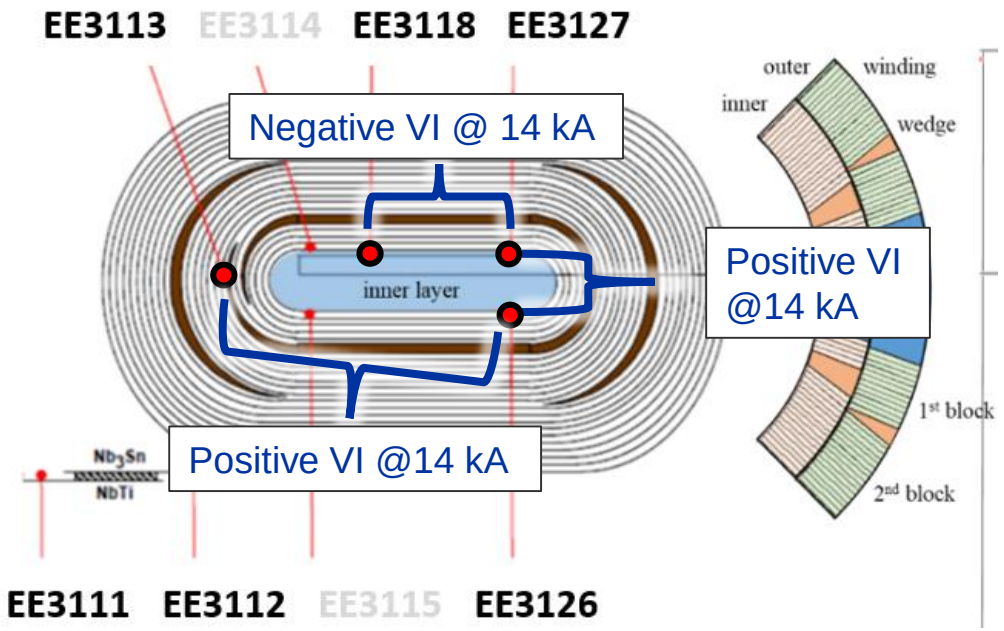
Magnet always quenched at same current level: 15.1 kA (1.9 K) Voltage taps within the coil. Decaying voltage signals on current plateau of 14 kA

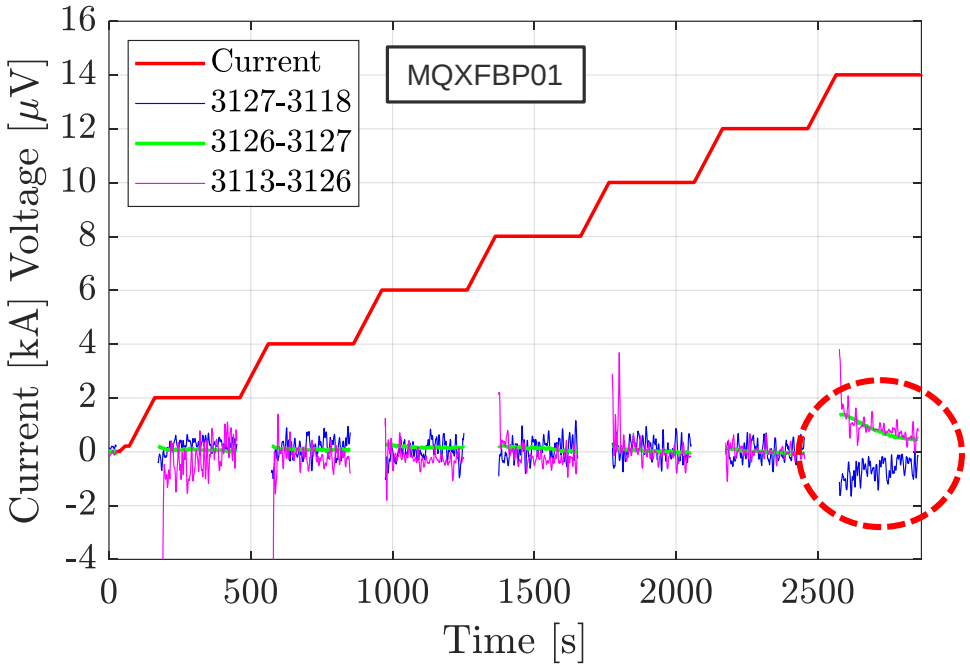
Negative on straight segment (3127-3118)

Positive in the head (3126-3127) and multiturn (3113-3126)

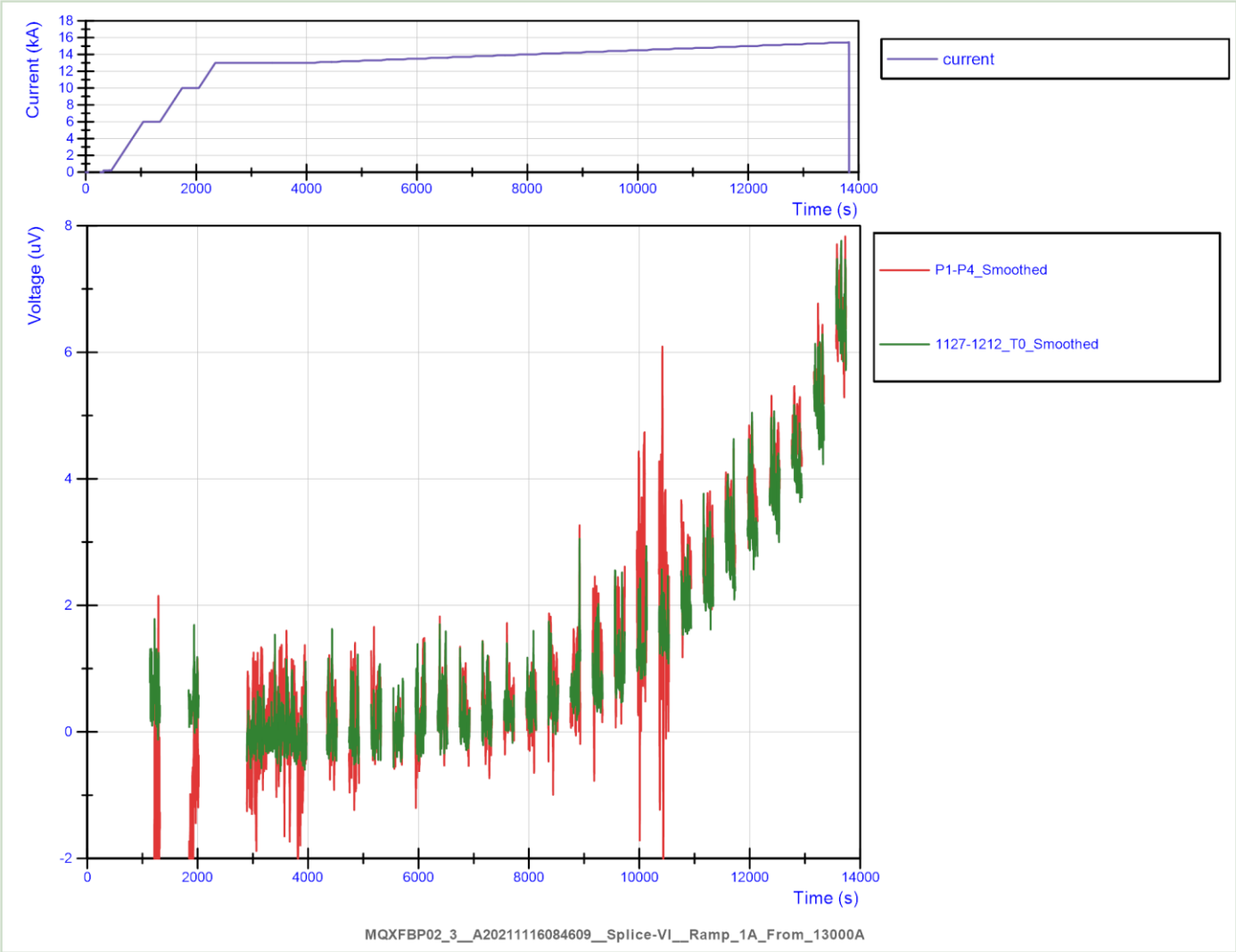
According to simulations, negative voltage is possible when measuring in front or after the defect. Ongoing R&D, special test foreseen on a SMC with artificially degraded conductor

P3
Inner layer
108





Comparison pole turn versus full coil measurement



Direct measurement of the pole turn (voltage tap 1127-1212) and V(P1) – V(P4)

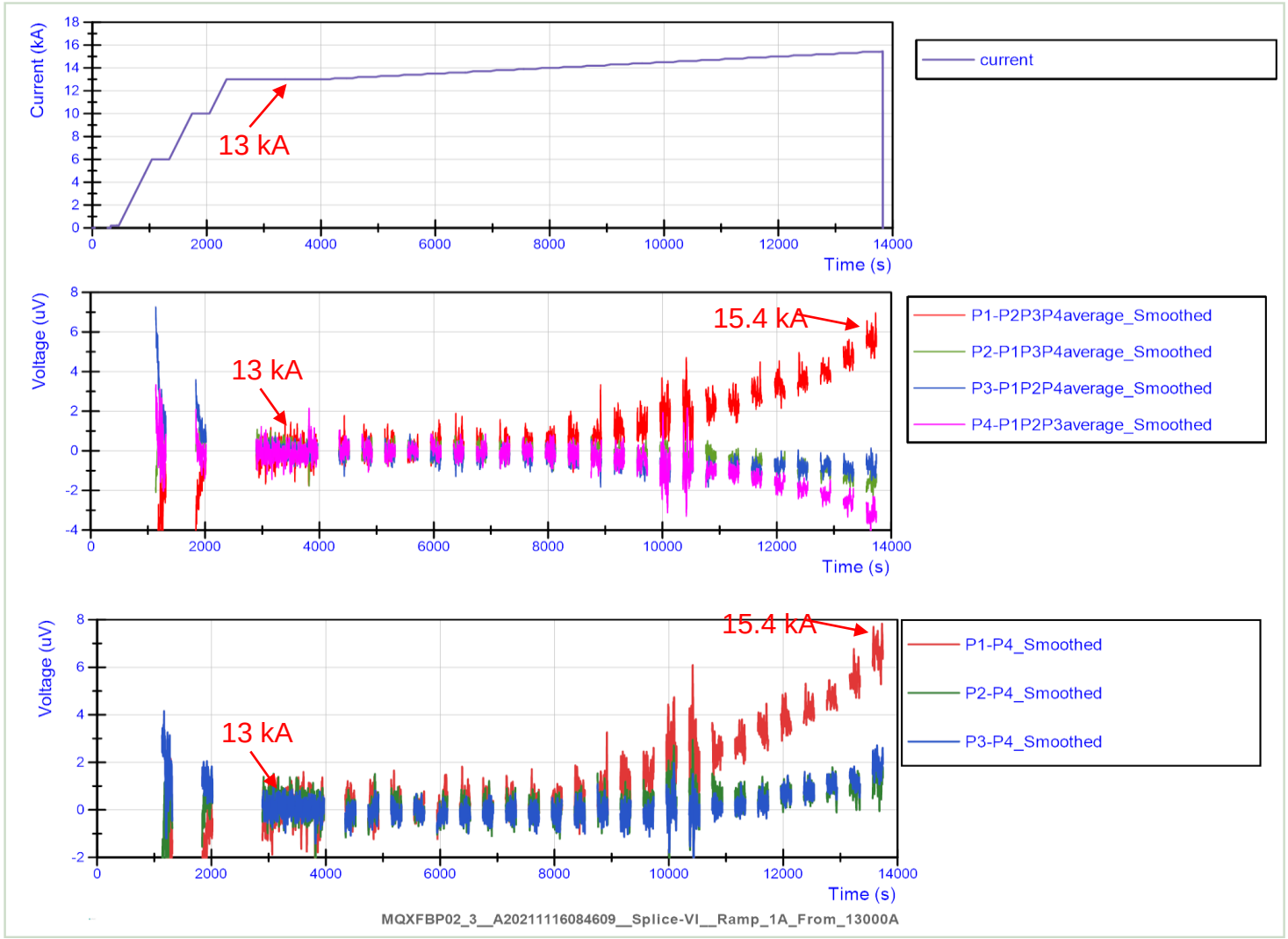
The direct measurement has slightly less noise, but the final result is not significantly different.

Conclusion:

For P1 all degradation is in the pole turn, not in any other turn.

Full-coil V-I

Example MQXFBP2, November 2021



Current plateaus at 4.5 K, each 100 A
Ramp of 1 A/s between plateaus.
(good setting for non-decaying signals; for decays use a faster ramp).

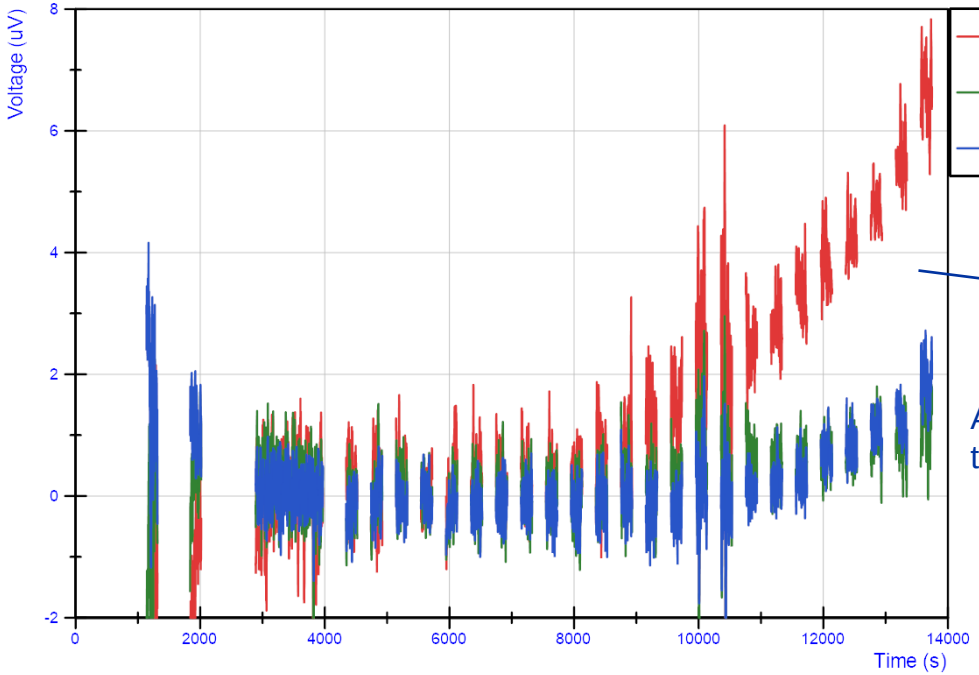
Remove inductive voltage from signals.

Identify the coil with least degradation (P4 in this case).

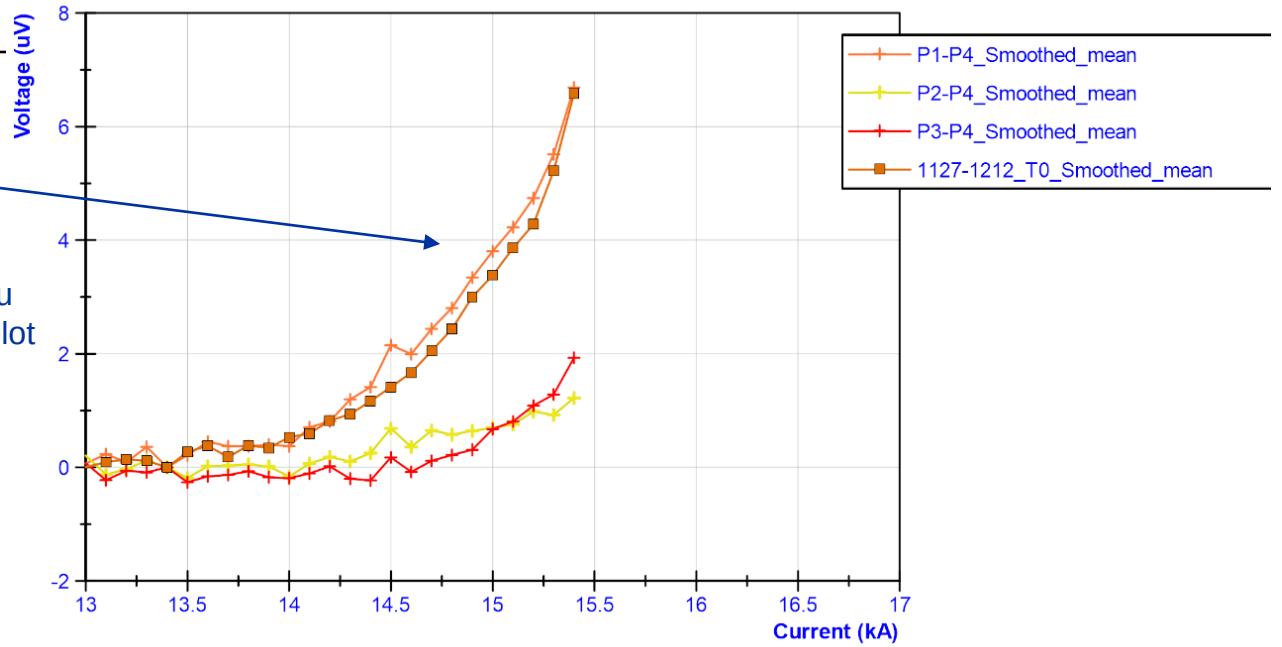
Buck the average voltage to this coil (removes noise, magnetization decay, noise from power converter, etc.)

P1 has the most degradation, P2 and P3 show some degradation at about 14 kA

Comparison pole turn vs full coil measurement (2)



Average per plateau translates to a V-I plot



Measurements without trim up to 15.4 kA show that a voltage buildup starts also in P2 and P3 from about 15 kA.

In a test without trim, even the full coil measurement can show the start of voltage build up.

Take home message – V-I measurements

Decaying signal in MQXFBP1 indicates local conductor defect, stronger at quench location 1.B (a bit closer to center) than 1.A

Numerical modelling can qualitatively explain the phenomenon and predicts a few broken strands. Special test foreseen on a SMC with artificially degraded conductor

Assuming that not all coils are limited, even full-coil measurements can reveal defects without trim powering.

V-I Measurements are a good example for operation at 4.5 K.

- No overstressing as SS is about 10% less for Nb3Sn
- Conductor more stable which helps measurements close to SS limit
- Check the operational margin
- Distinguish between conductor limitation/degradation/defectation

Summary

SM18 upgrade for HL-LHC magnet testing according to plan and no more on the critical path

Safety issues are addressed (objective and subjective risks). Presentation TE-TM 2.05.2022

Large experience accumulated on the testing and diagnostics of Nb_3Sn magnets

New diagnostics tools (V-I, quench antenna) allow better understanding and localization of the quench phenomenology of Nb_3Sn magnets

Trim powering enables us to probe coil-by-coil