MQXFB test results at CERN

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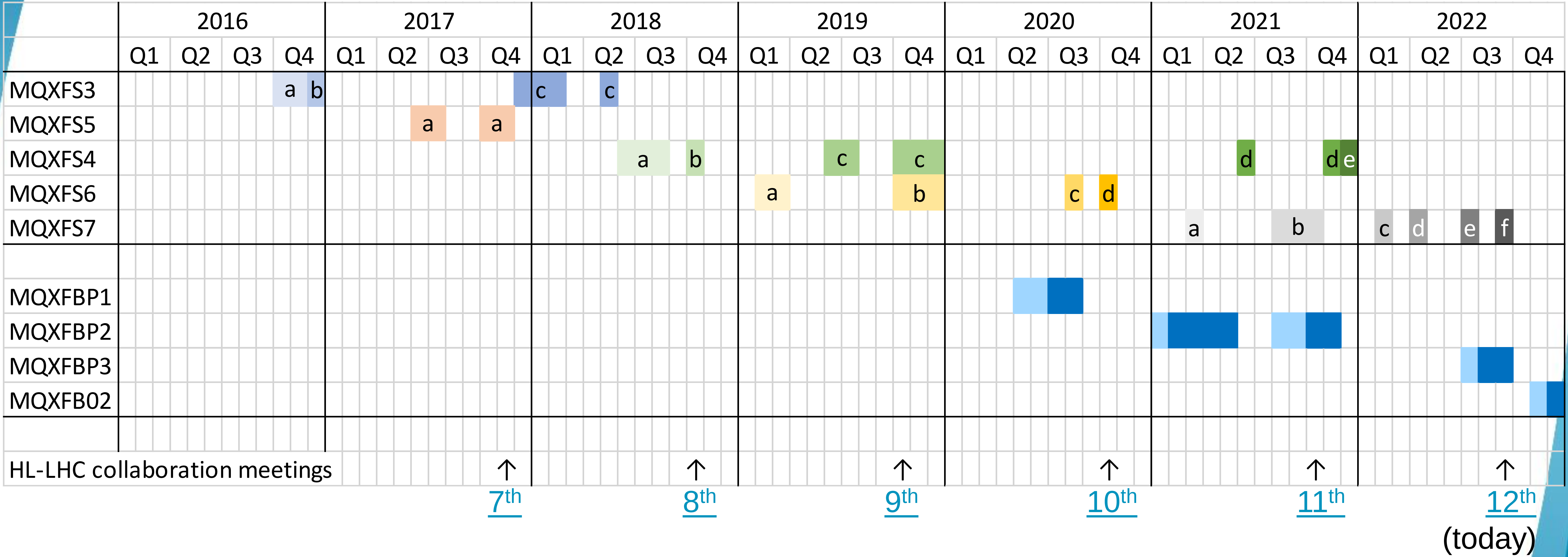
on behalf of the test & measurements team

Thanks to support throughout the section, group and project.

2022.09.21, 12th HL-LHC Collaboration Meeting

MQXF test history at CERN



Focus of today's talk: MQXFBP2 and BP3

MQXFB tested at CERN so far

MQXFBP1

MQXFBP3

MQXFBP2

Same test bench,
same cryostat,
three different magnets

Each magnet in one word

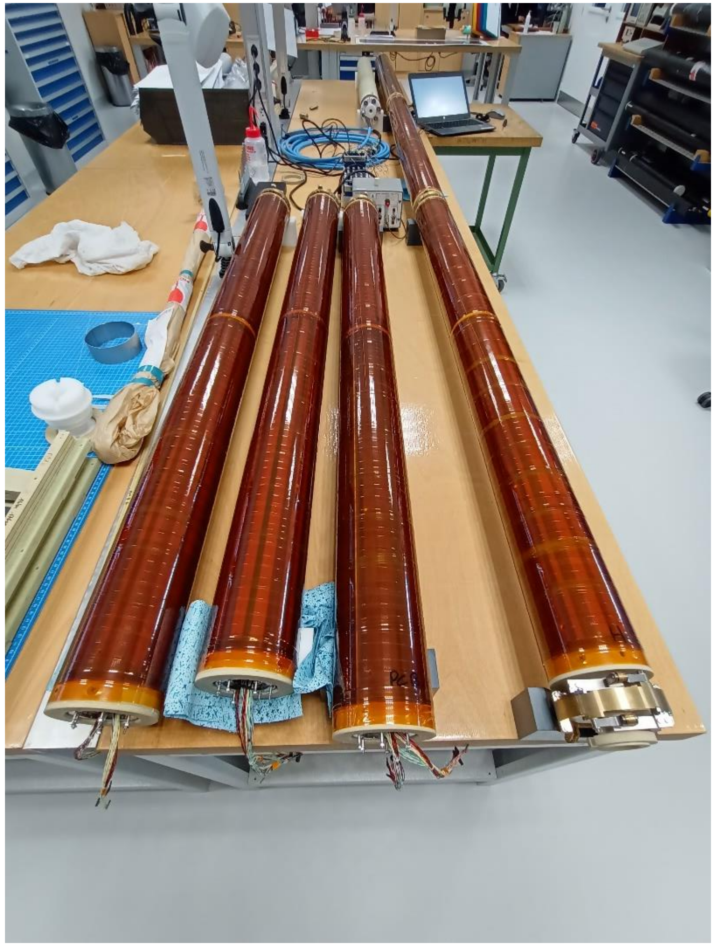
- MQXFBP1: first prototype
- MQXFBP2: improved coil heat treatment
- MQXFBP3: lower stress during steel shell welding. Test ongoing

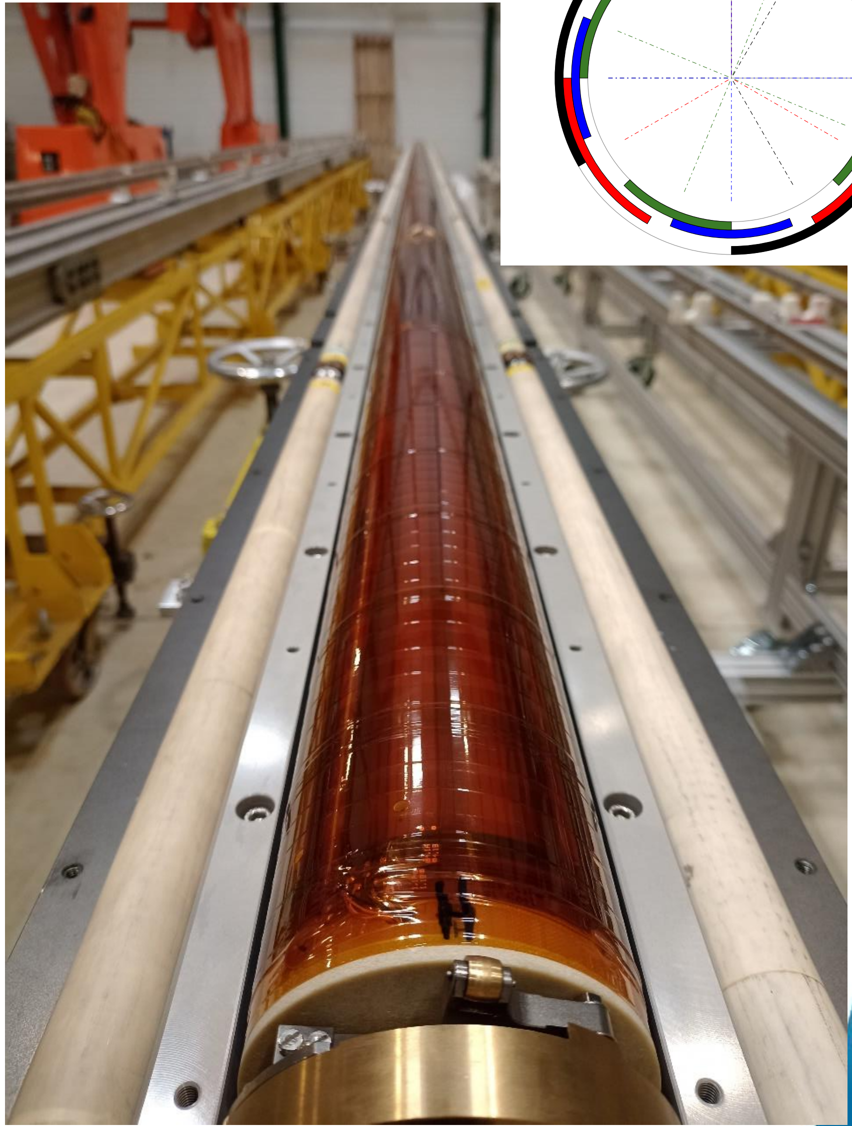
More information:
MQXFBP2: https://indico.cern.ch/event/941940/
MQXFBP3: https://indico.cern.ch/event/971956/, https://indico.cern.ch/event/964272/

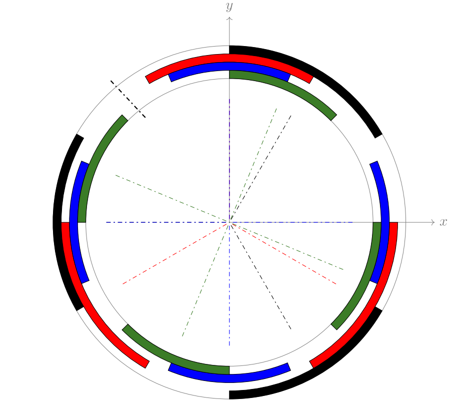
New tools

Multipole Sensitive Quench-Antenna

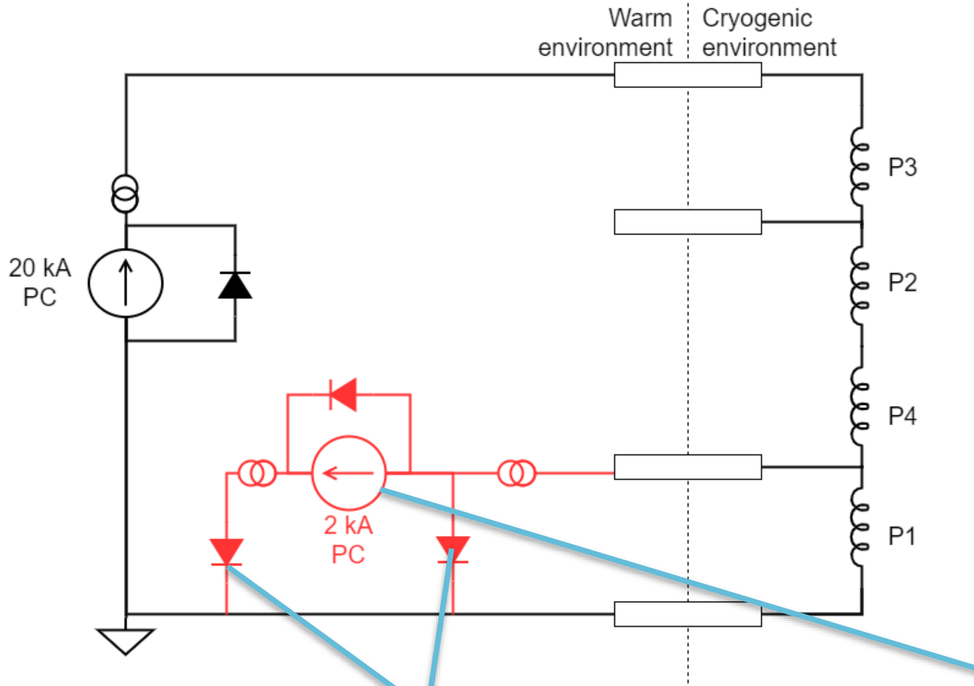
Sensitivity mostly to B3, A3, B4, A4 through coil design (analogue bucking and use of Flex PCBs)
Compromise between noise (PC, vibrations, etc), resolution in radial direction, and signal strength.







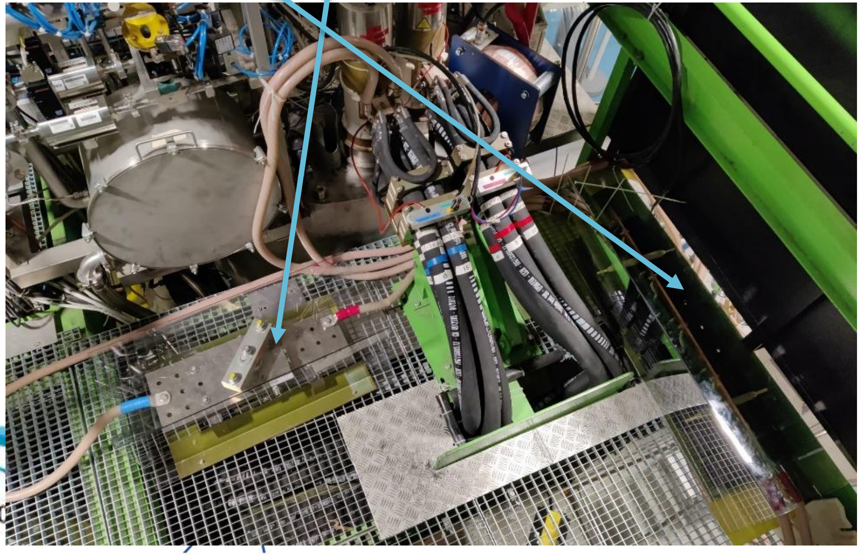
Trimmed powering

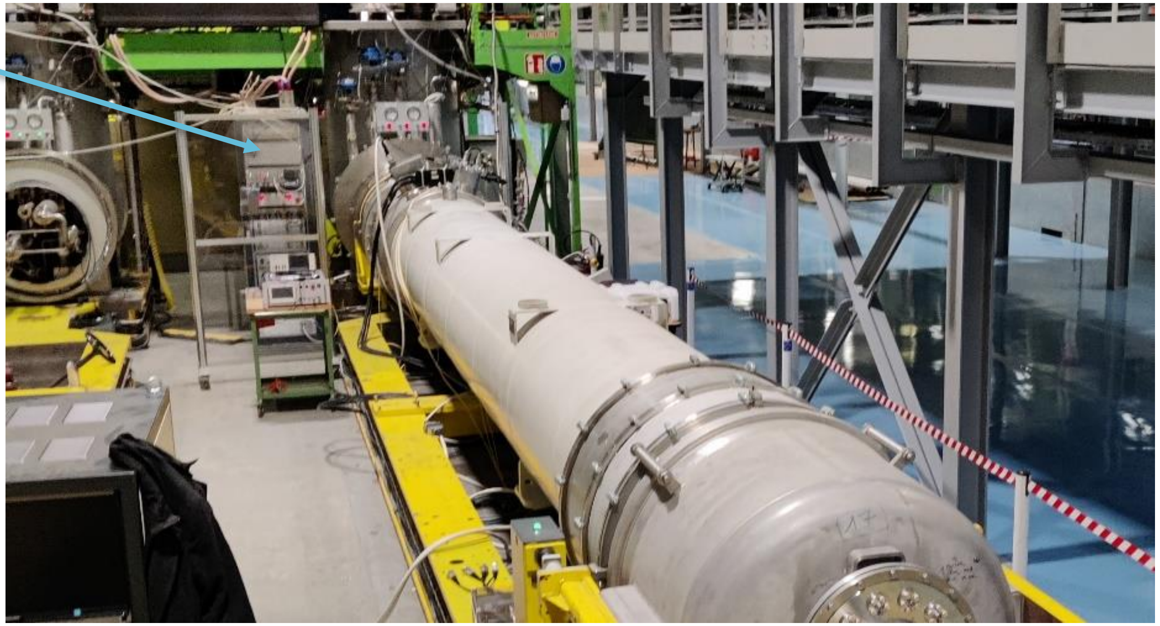


Power circuit modification (in red) to evaluate the performance of non-limiting coils.

Implemented in MQXFBP2, where coil P1 (limiting coil) was powered with less current than the other three.

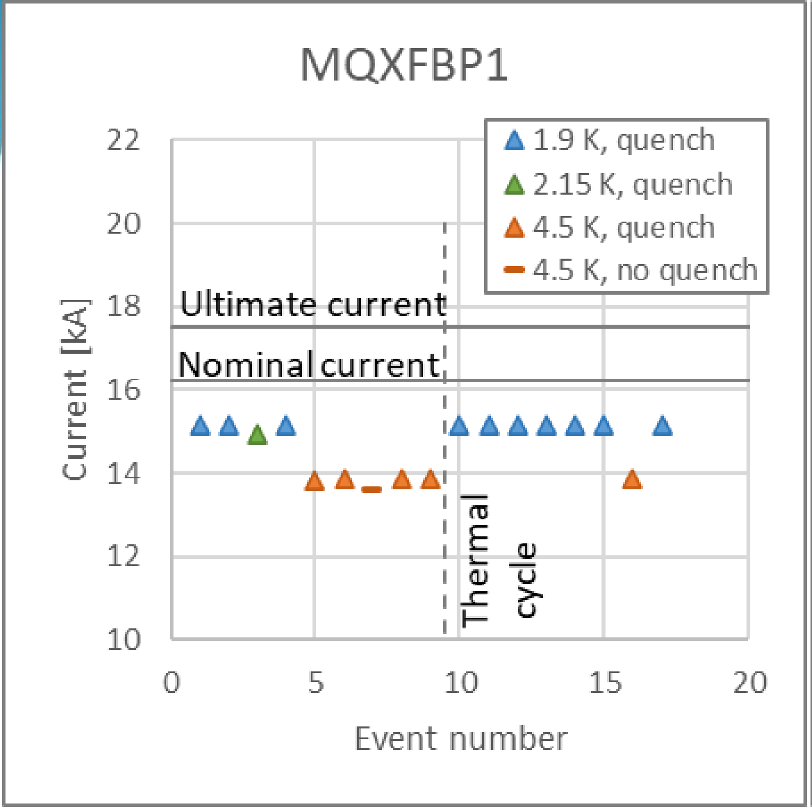
Improvements made at the cold mass level to allow, if necessary, trimmed powering of any coil up to 2-3 kA in MQXFBP3.

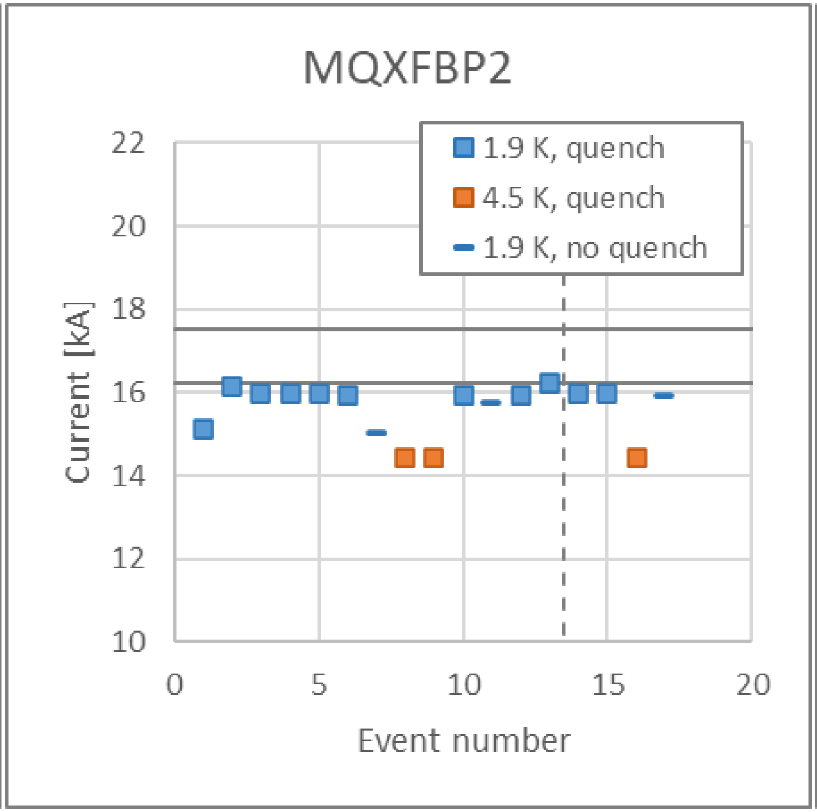


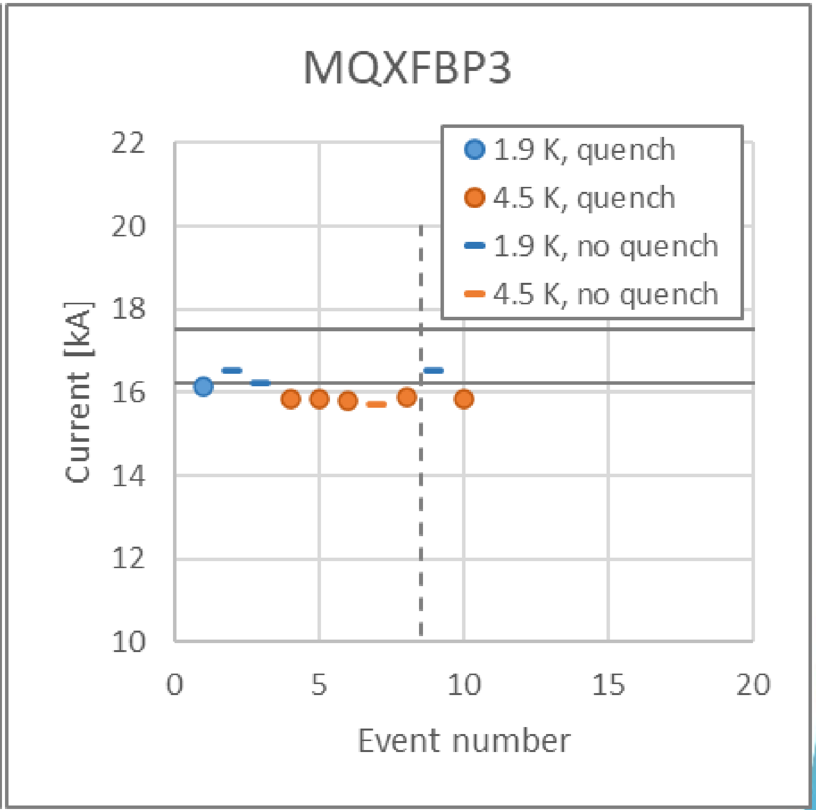


Quench performance

Quenches at nominal ramp rate





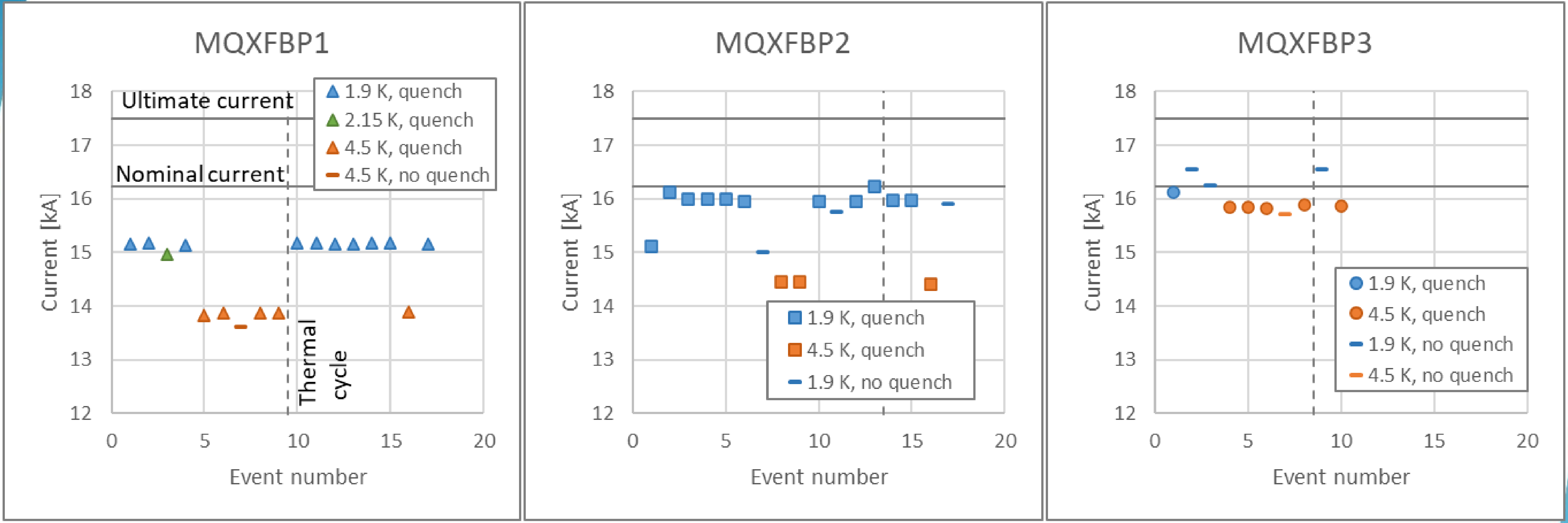


At 1.9 K: MQXFBP1 and BP2 were limited below nominal current (~15 and ~16 kA respectively). BP3 reached the target current (nominal + 300 A)

At 4.5 K: the three magnets are limited below nominal current: 13.8, 14.2 and 15.8 kA respectively.

All magnets kept perfect training memory after thermal cycle.

Quenches at nominal ramp rate



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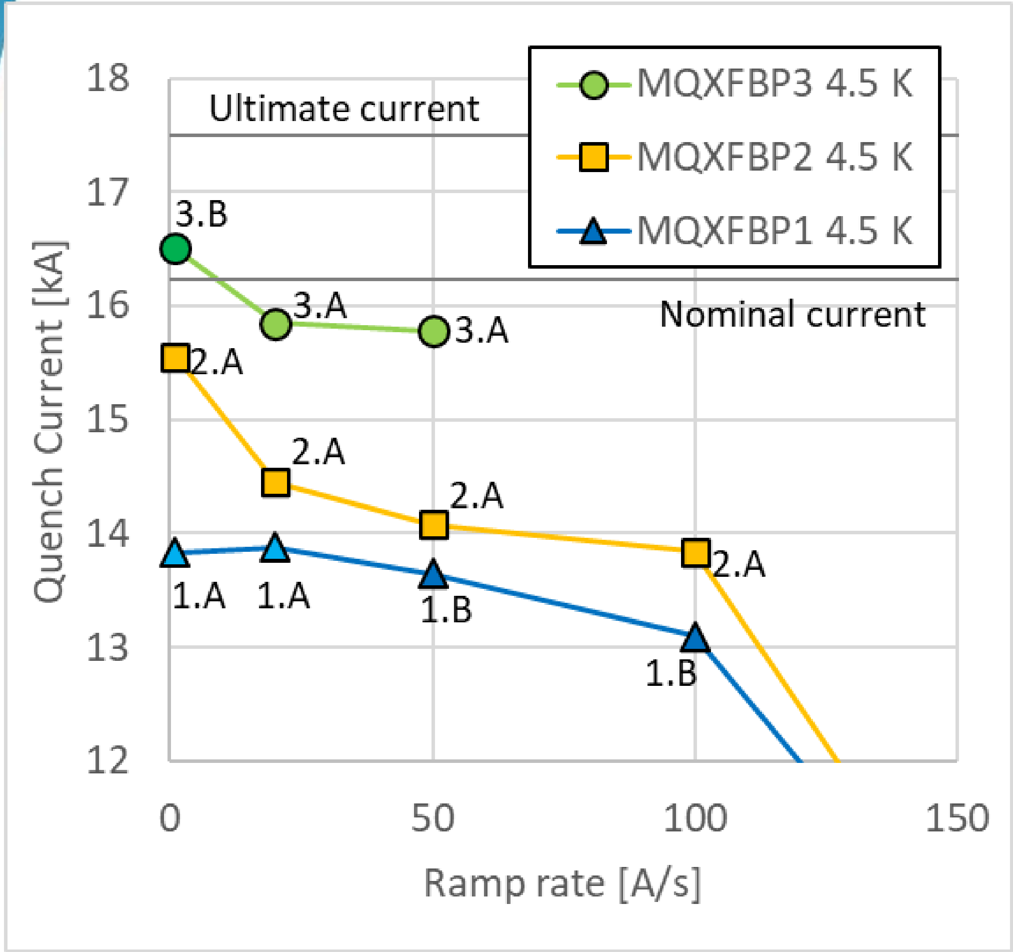
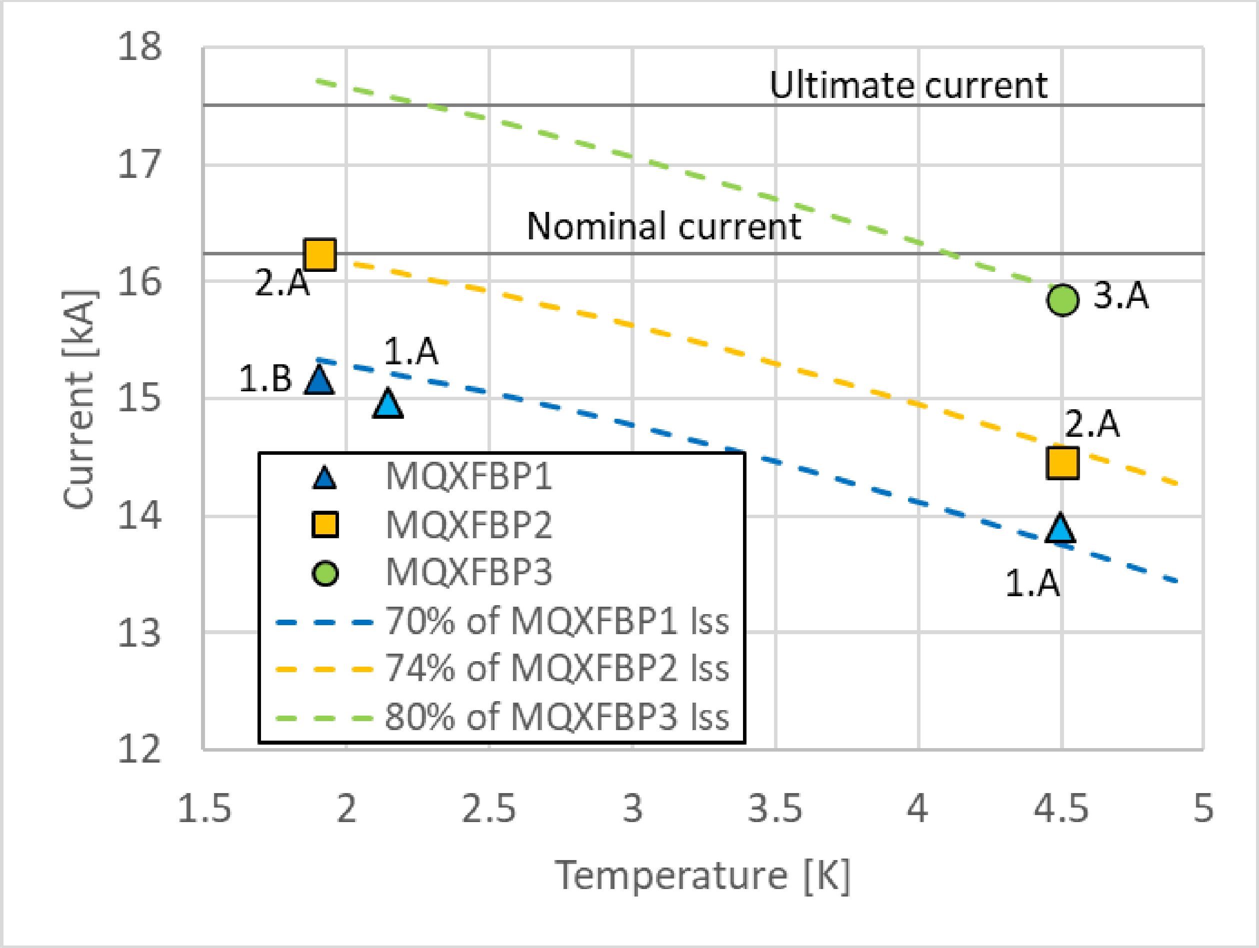
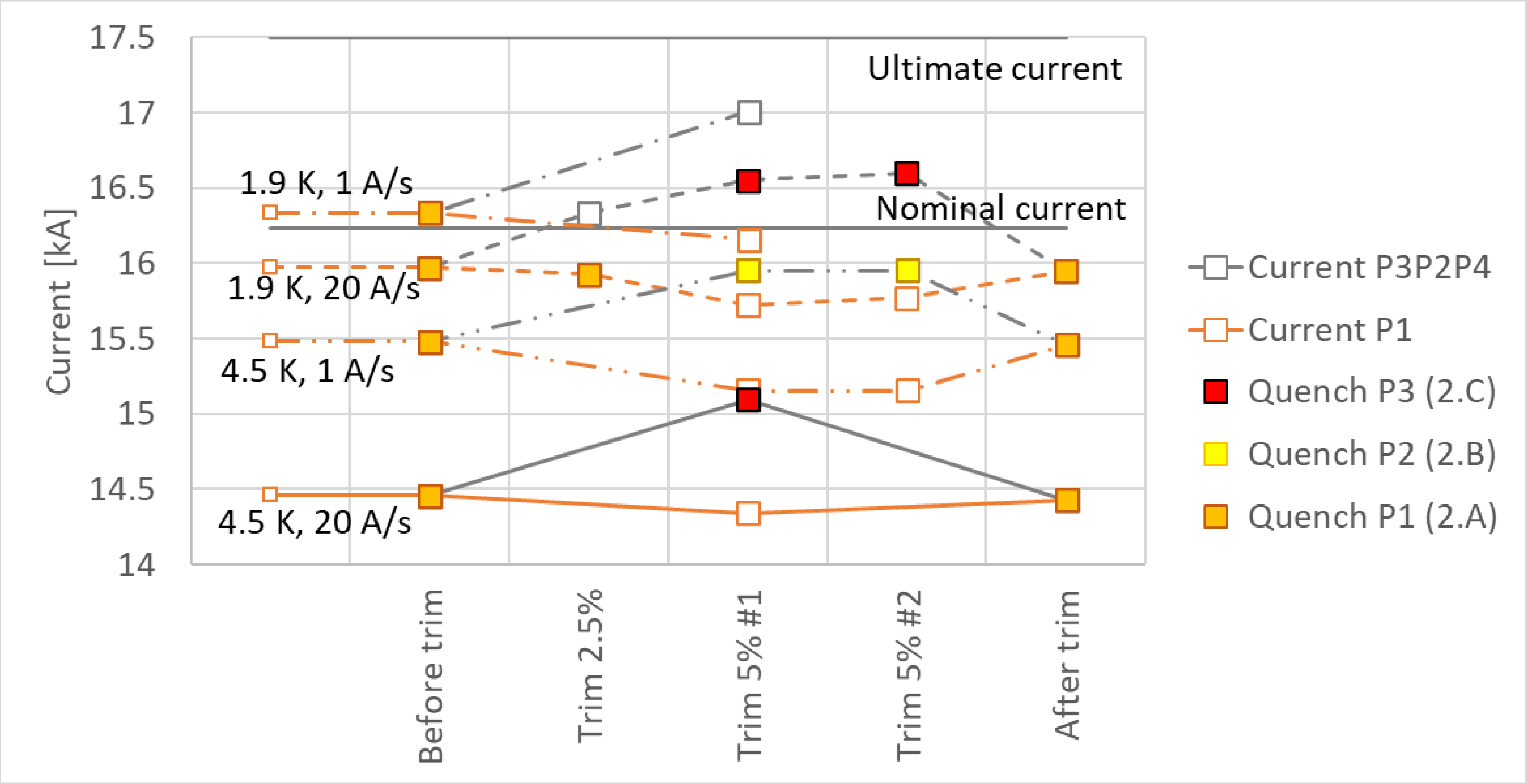
Ramp rate and temperature dependency





Point labels indicate quench location.
Ramp rate and temperature dependency very similar between the three magnets.
Quench level extrapolation for BP3 at 1.9 K: above ultimate current.

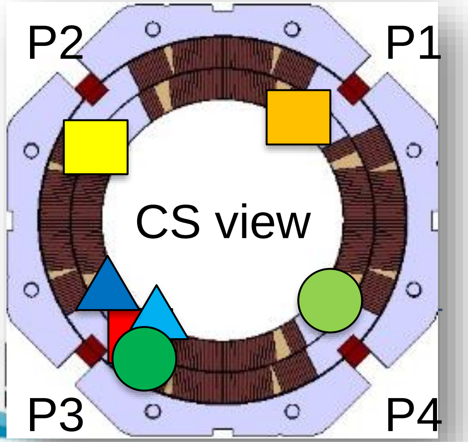
MQXFBP2 trim powering main results

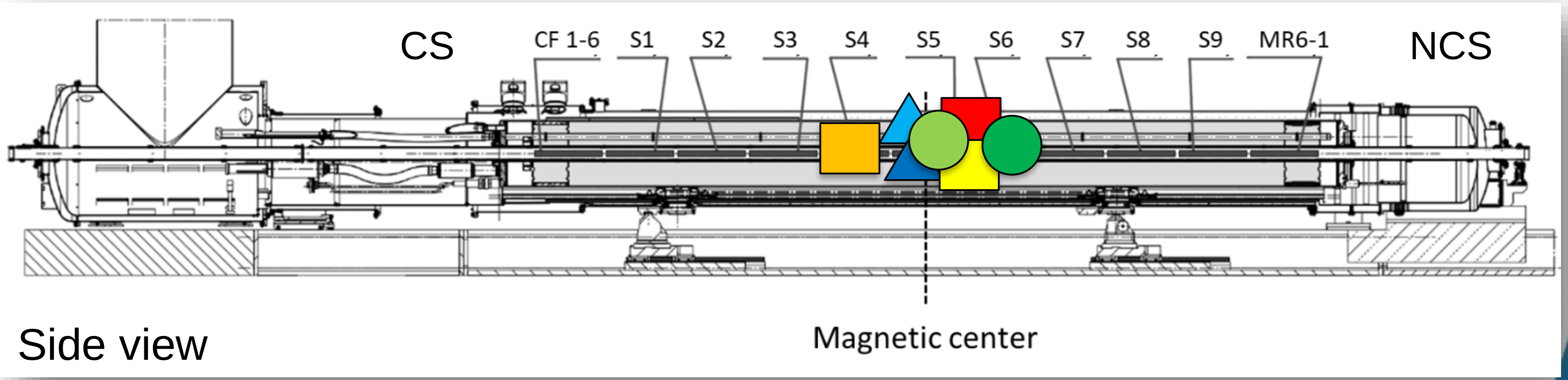


In parenthesis: quench location.
MQXFBP2 coils P2 and P3 showed a similar limitation signature as coil P1 at a higher current

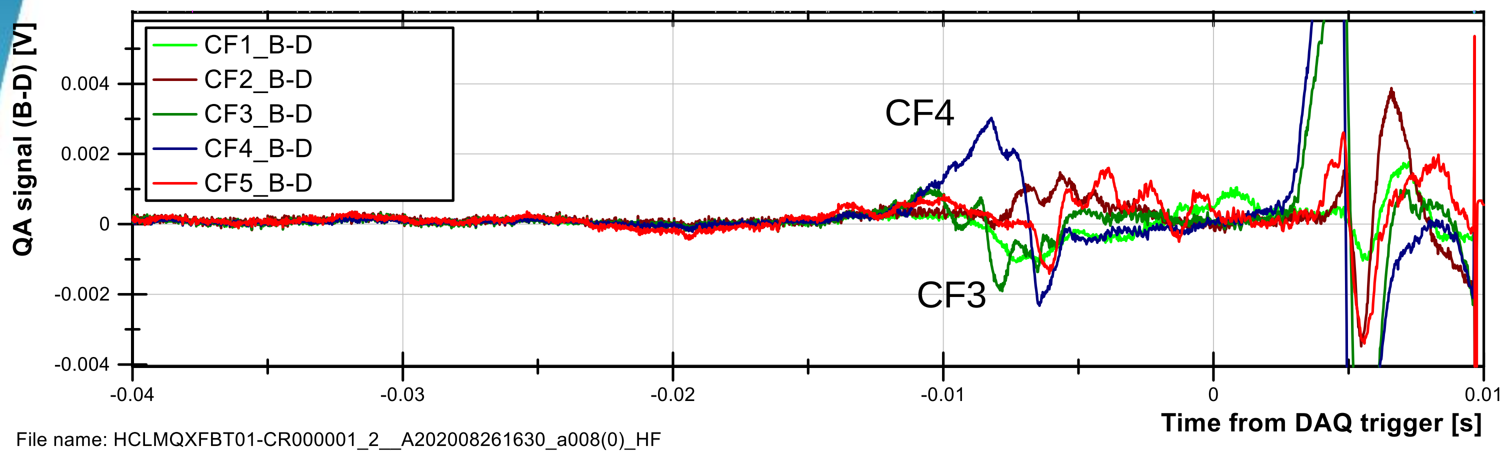
Recurring quenches at limiting locations

MQXF…		1 A/s	20 A/s (VI)	20 A/s	50 A/s	100 A/s
BP1	1.9 K		1.A	1.B		
	2.15 K		1.A			
	4.5 K	1.A	1.A	1.A	1.B	1.B
BP2	1.9 K		2.A	2.A	2.A	2.A
	1.9 K trim			2.C		
	4.5 K	2.A		2.A	2.A	2.A
	4.5 K trim	2.B		2.C		
BP3	4.5 K	3.B		3.A		





Longitudinal quench localization



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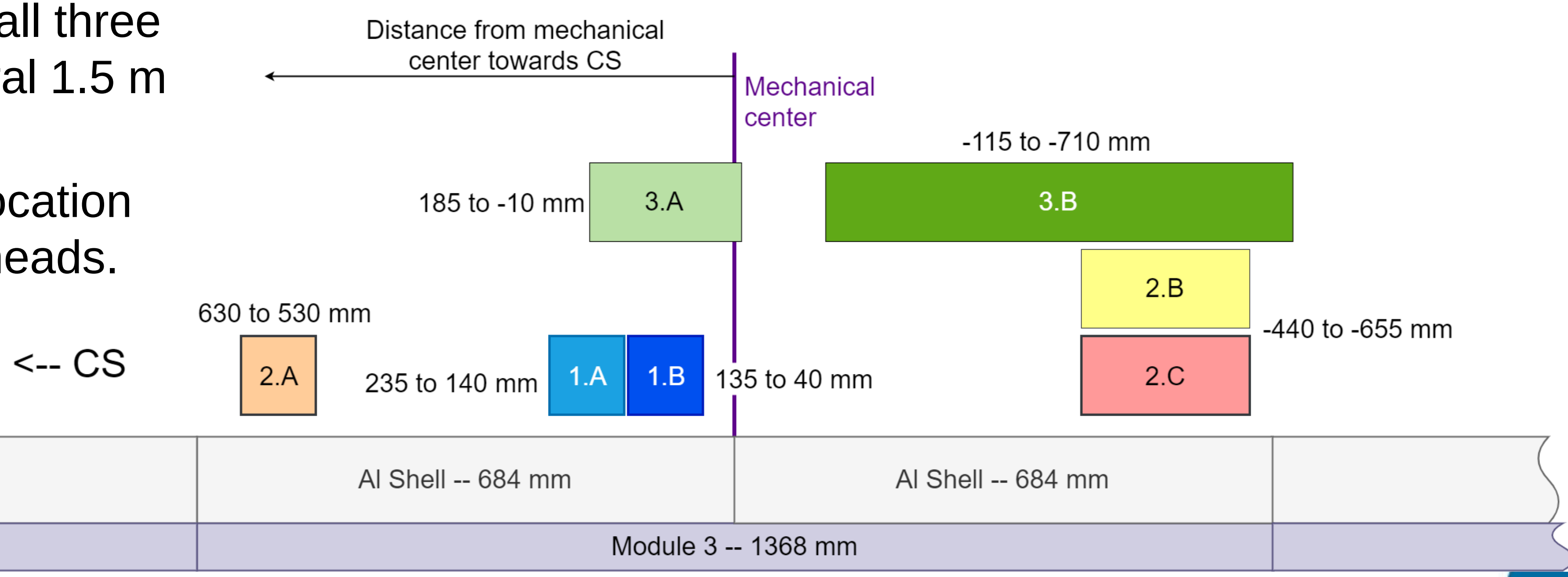
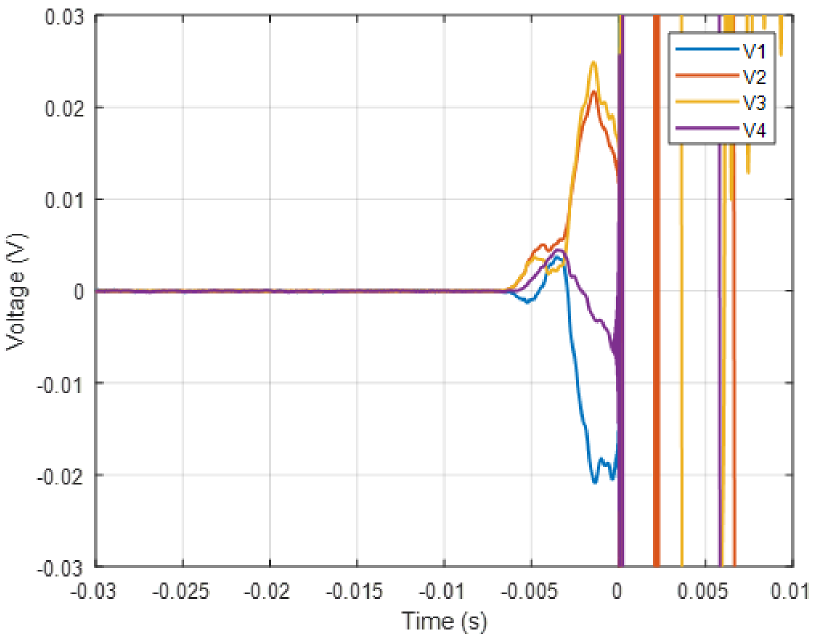
Quench 6, CD2. QA shifted -3392 mm

- On repetitive quenches we can narrow down the longitudinal position of the quench by shifting the quench antenna position.
- Higher precision (±50 mm) with the standard quench antenna due to higher density of coils.

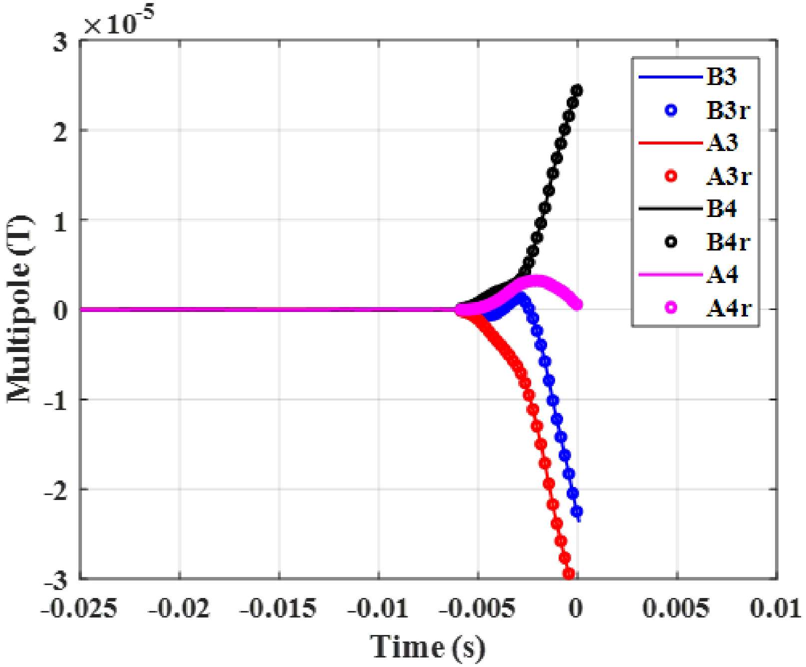
- The limiting locations in all three magnets are at the central 1.5 m of the magnet.
- No quench, no limiting location found at any of the coil heads.



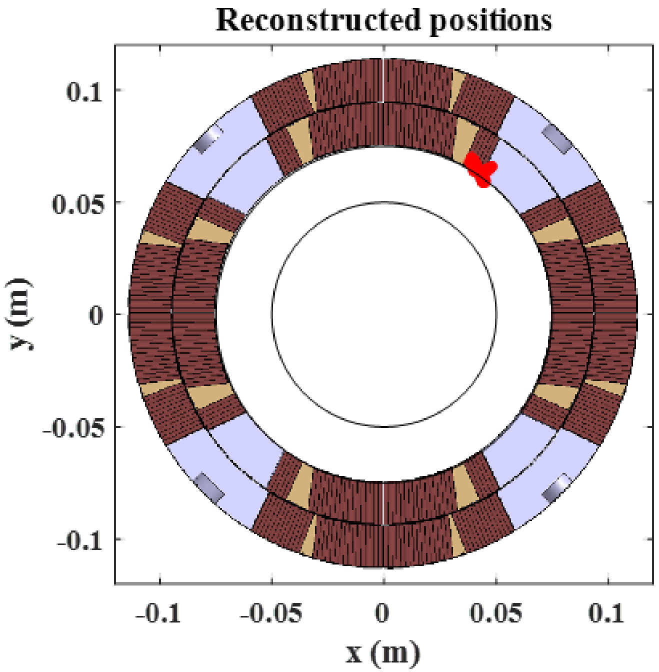
Cross-section quench localization



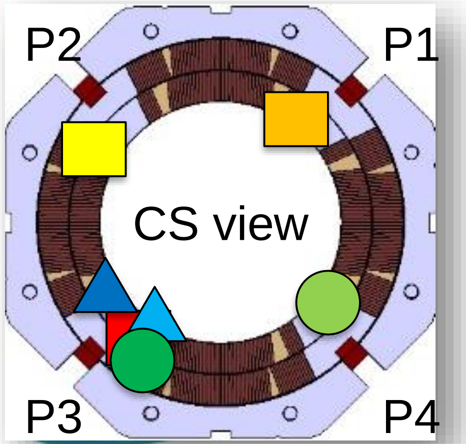
QA voltage signals



Reconstructed multipoles

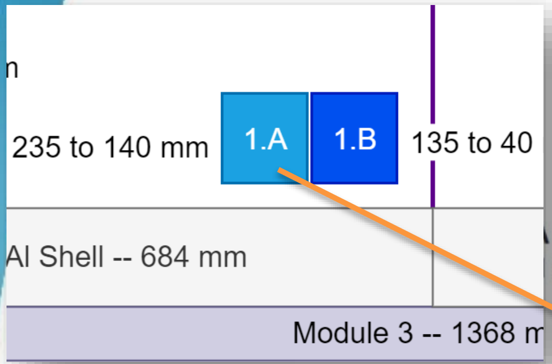


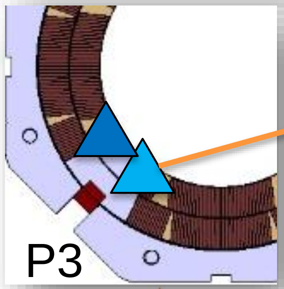
Reconstructed quench position



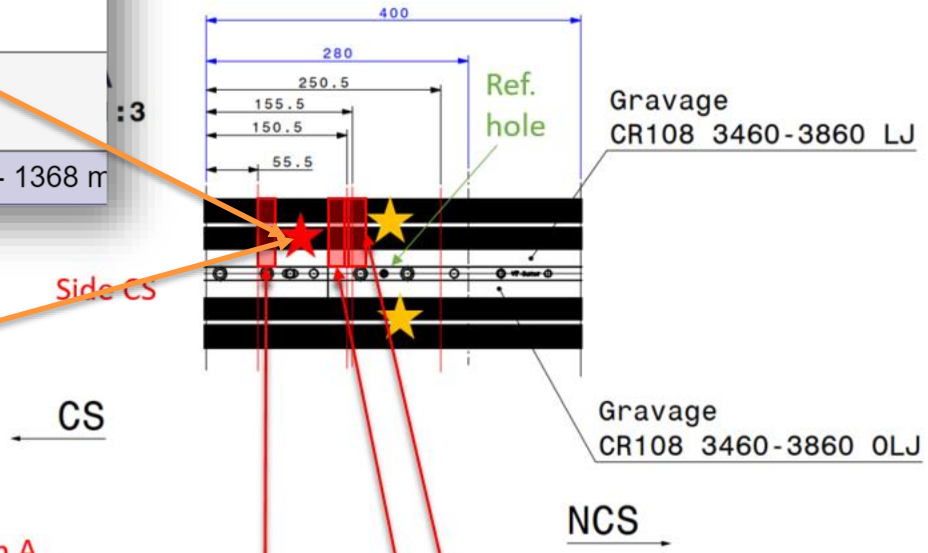
- In MQXFBP1 and BP2 we relied on voltage taps for quench localization in the cross section.
- In MQXFBP3 we use the multipole quench antenna. A first prototype was validated in MQXFBP2 (see above) and implemented as main QA in MQXFBP3. Quench location can be identified within a few turns.
- In all cases, the performance limiting location is in the inner layer pole turn (BP1 and BP2) or pole turn block (BP3).

Quench localization for destructive studies



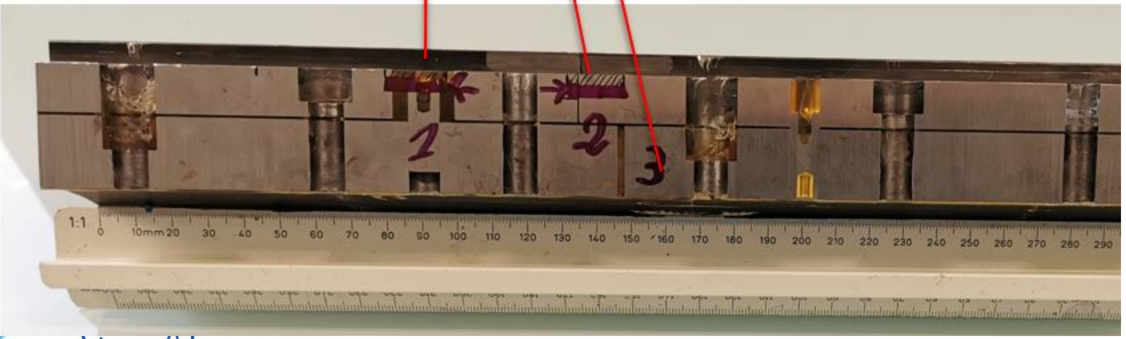


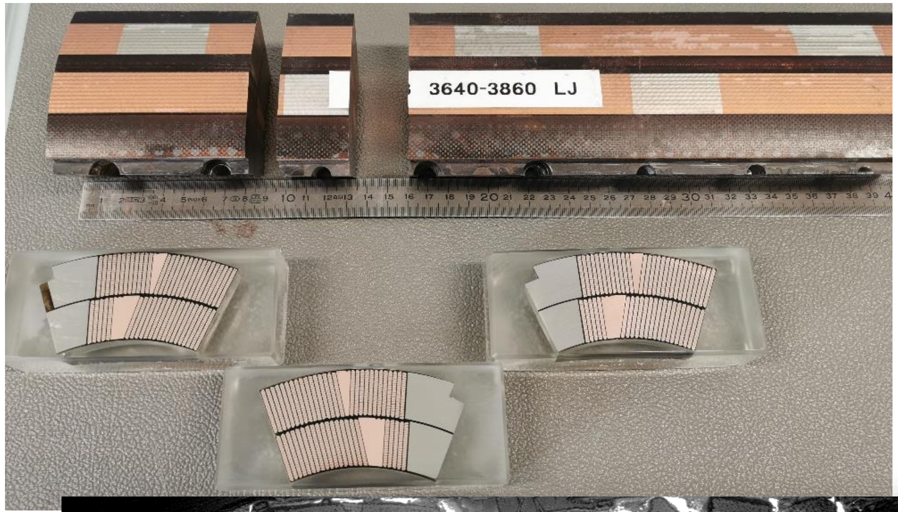
See more on A. Moros' talk on Thursday

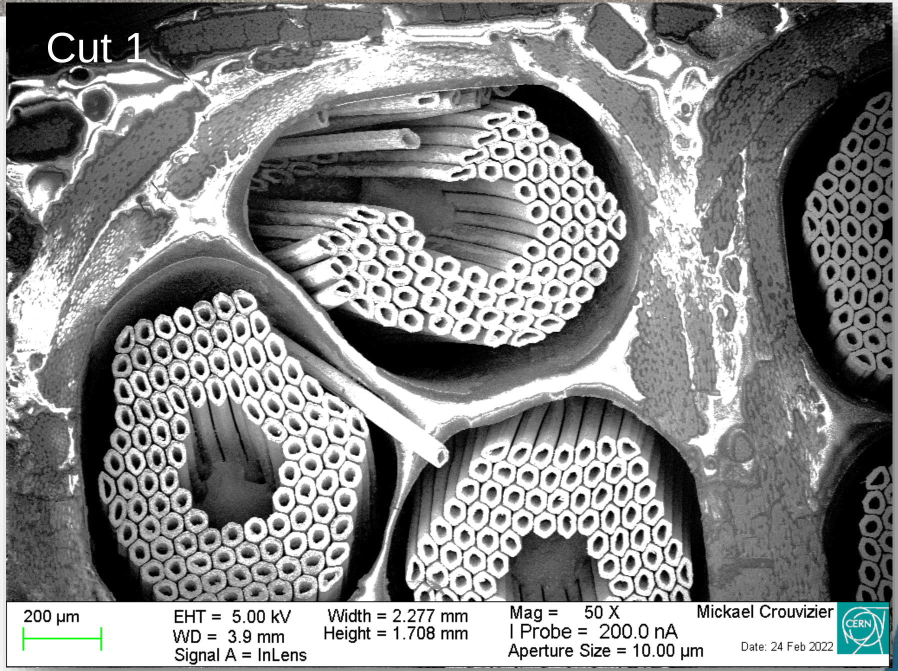


Quench location A

Quench location B



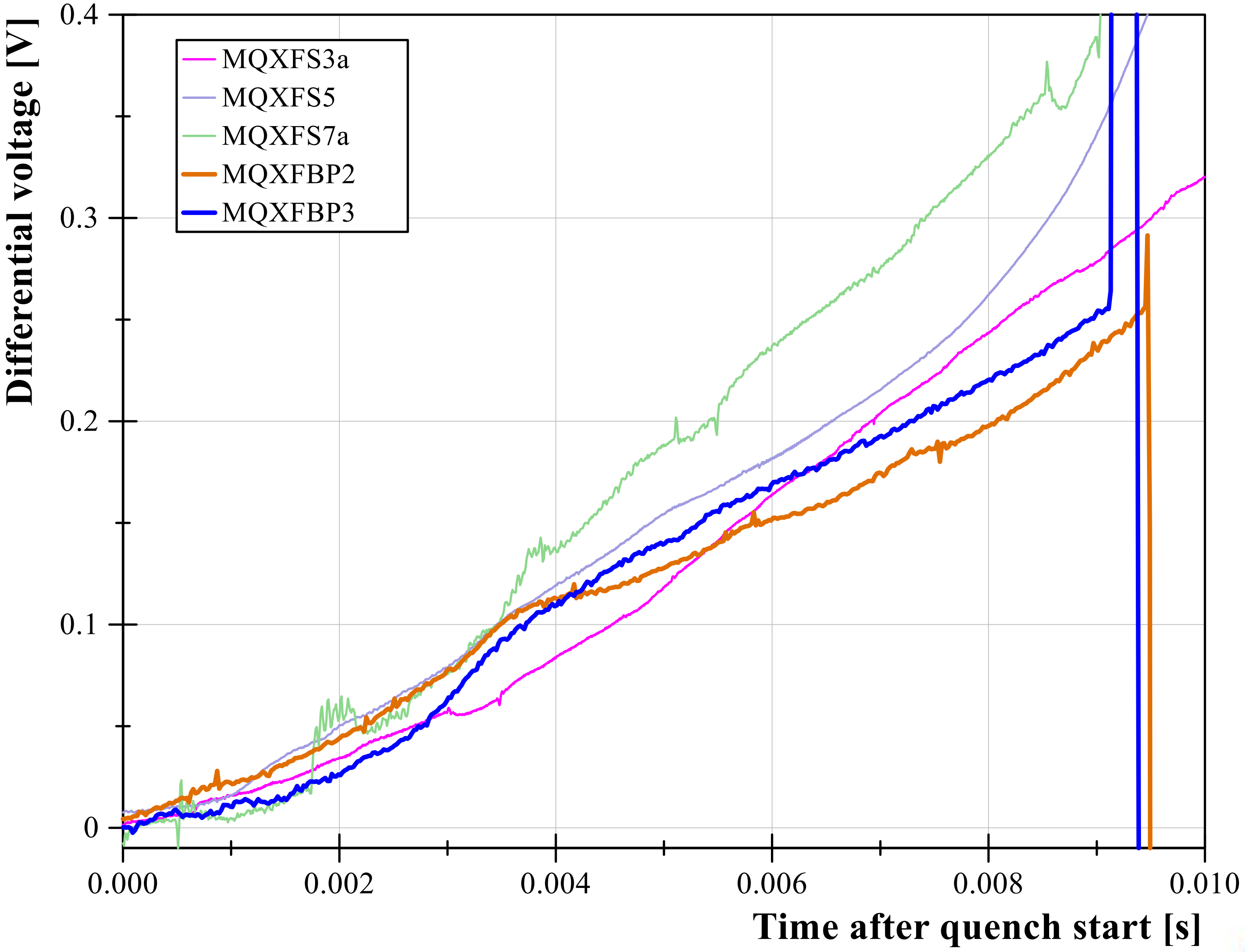




Voltage buildup during quench

- Shown: quenches in short models and prototypes BP2 and BP3 around 16 kA, inner pole turn or pole turn block

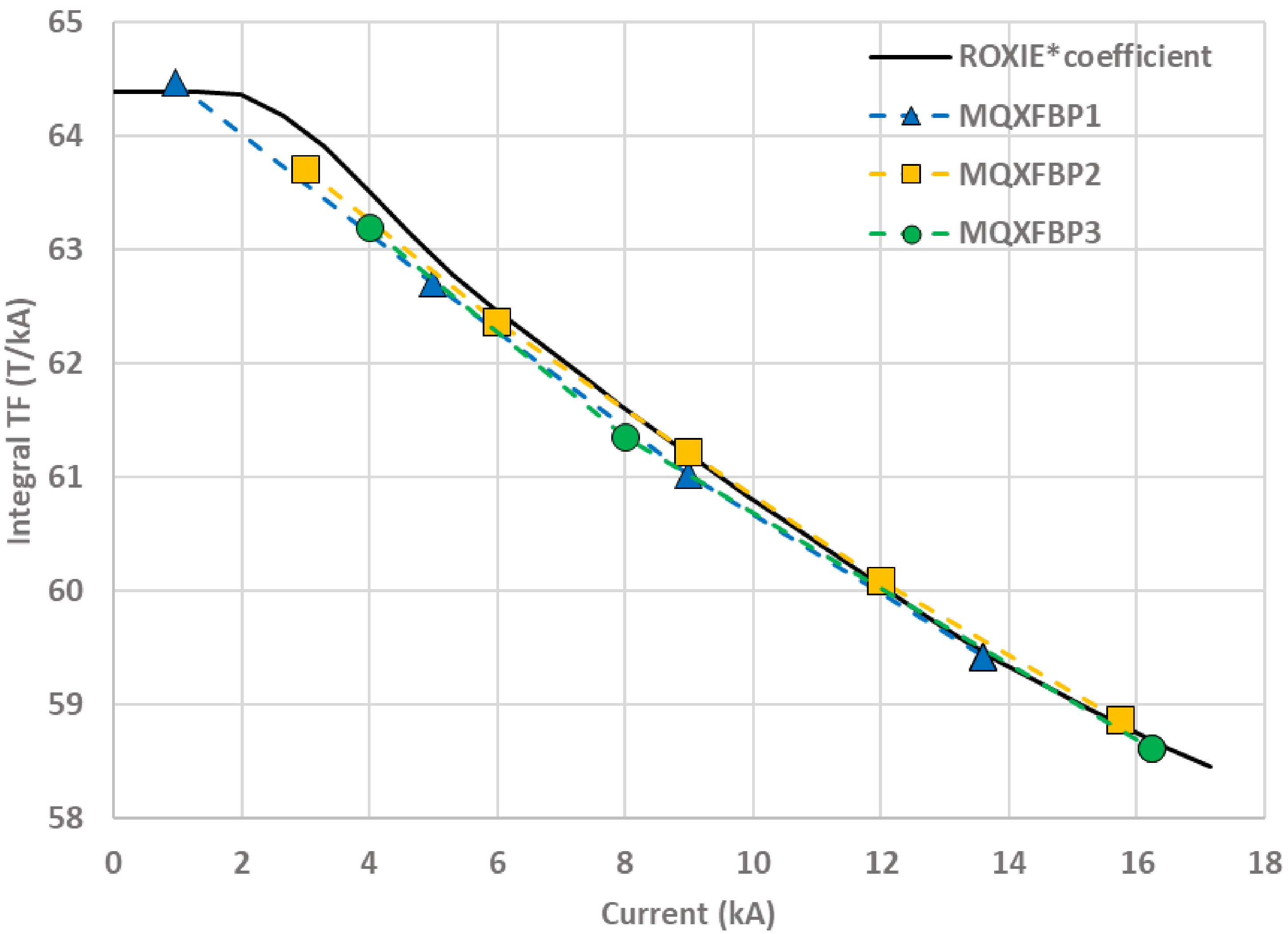
- Voltage buildup in both prototypes is similar to that of short models, hinting towards local limitation in the prototypes



Magnetic field quality

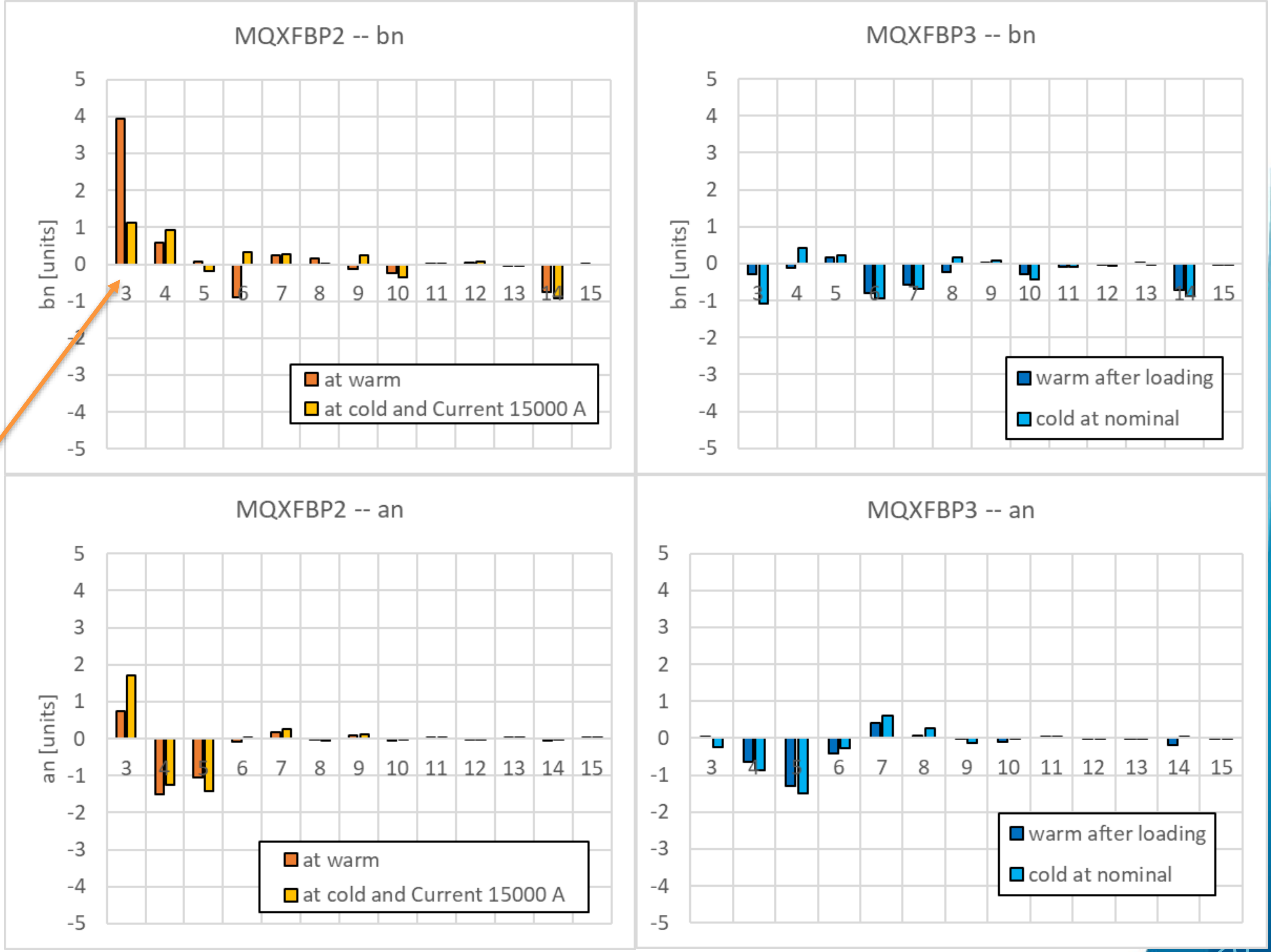
Transfer function of MQXFBP magnets

- Transfer function measured with stretched wire.
- The measurements from the three magnets agree within 10 units at high current.
- MQXFBP3 reaches 951.4 Tm/m integral field at nominal current (specification: 948.1 Tm/m)
- During a 8h endurance test at nominal current, the magnetic field (measured with the rotating magnetometer) was stable within the measurement precision of 1 unit.



Field quality of MQXFBP magnets

- MQXFBP1 only measured at room temperature – results not shown today.
- MQXFBP2 and BP3: field quality well within the specifications
- At nominal level, all multipoles are well controlled including b6
- Based on measurements at ambient temperature, magnetic shims were applied in MQXFBP2 to correct b3. It was not necessary in MQXFBP3



More information in E. Todesco’s talk this afternoon

Mechanical measurements

MQXFB – Coil mech. behavior

MQXFBP1:

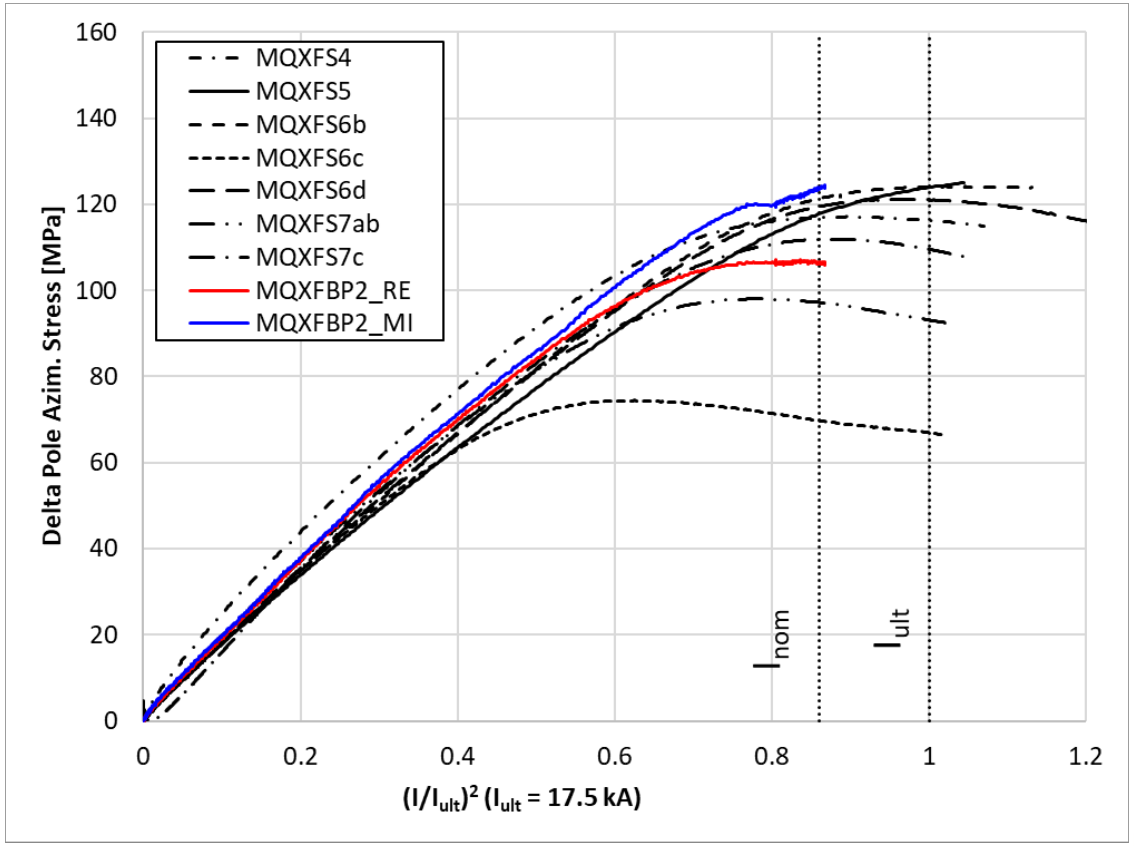
- No coil strain data available at cold.

MQXFBP2:

- Strain measurements available in the return and middle magnet sections.
  - Note: In MQXFBP2, the increase of the coil stress during welding was larger than expected. As a result, the final stress of the coils at cold is 15-20 MPa higher than the initial target.
  - Un-loading of the winding pole, when approaching the nominal current, is as expected from the RT pre-load when including the additional stress from the welding.

MQXFBP3:

- Most of the coil strain data at cold is not available (See EDMS #2400116, attempts on-going to recover signals a 4.5 K)
  - Comparison with MQXFBP2 can be established based on the strain measurements before cool-down. The average azimuthal preload in MQXFBP3 is ~ 30-40 MPa lower than in MQXFBP2 (absolute strain).



Change of azimuthal pole pre-stress during powering, as a function of the square of the current. Average among the 4 coils in the magnet. Measurements by M. Guinchard and team

More information in H. Prin's talk on Thursday

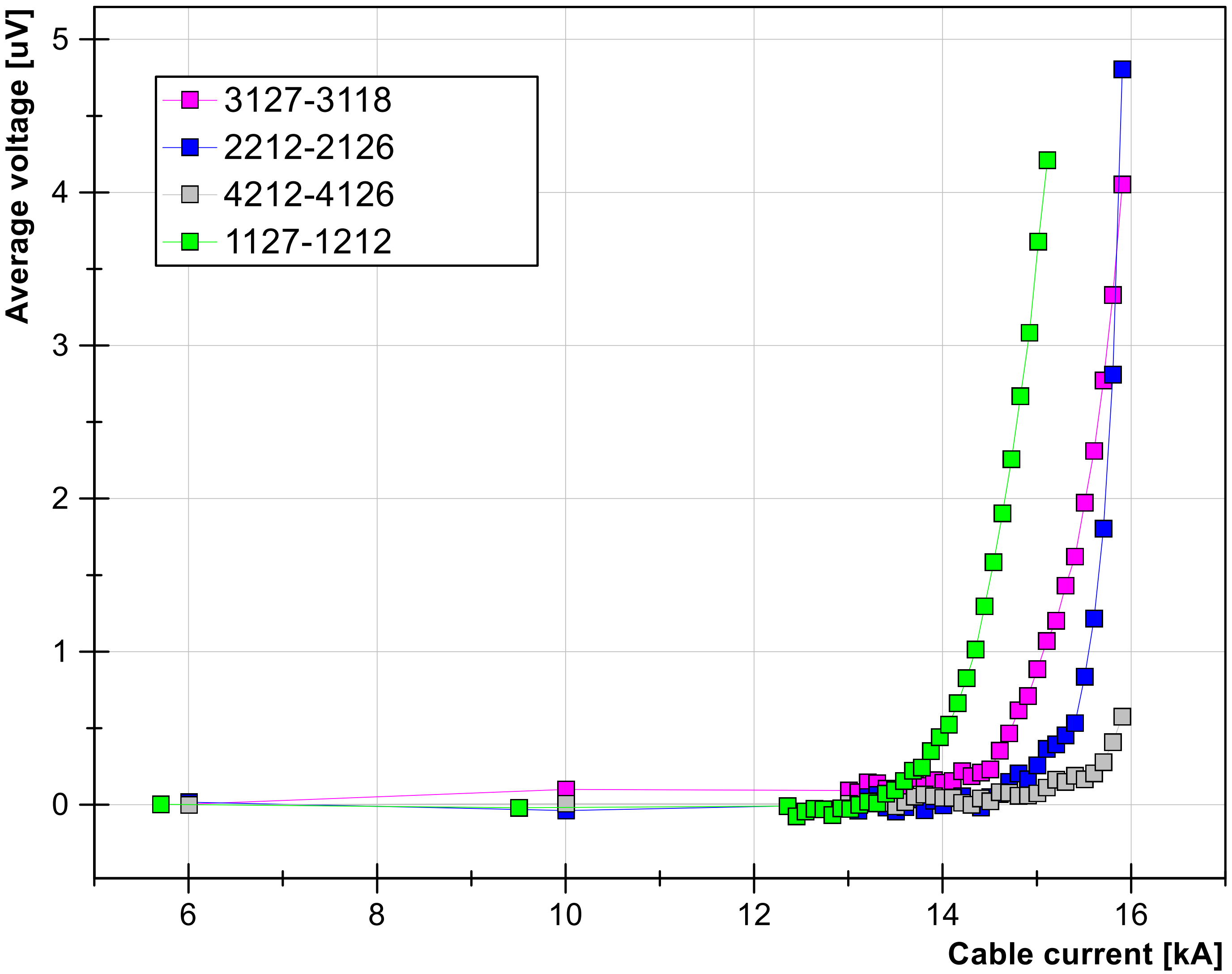
V-I measurements

MQXFBP2 VI measurements with trim

Tests done with coil P1 trimmed down 5% at 4.5K

Inner pole turns segment in the four coils show some transition.
In the quenching coils ~5uV, in P4 ~0.6 uV

X axis corresponds to the current in each location



MQXFBP2 vs BP3 VI measurements

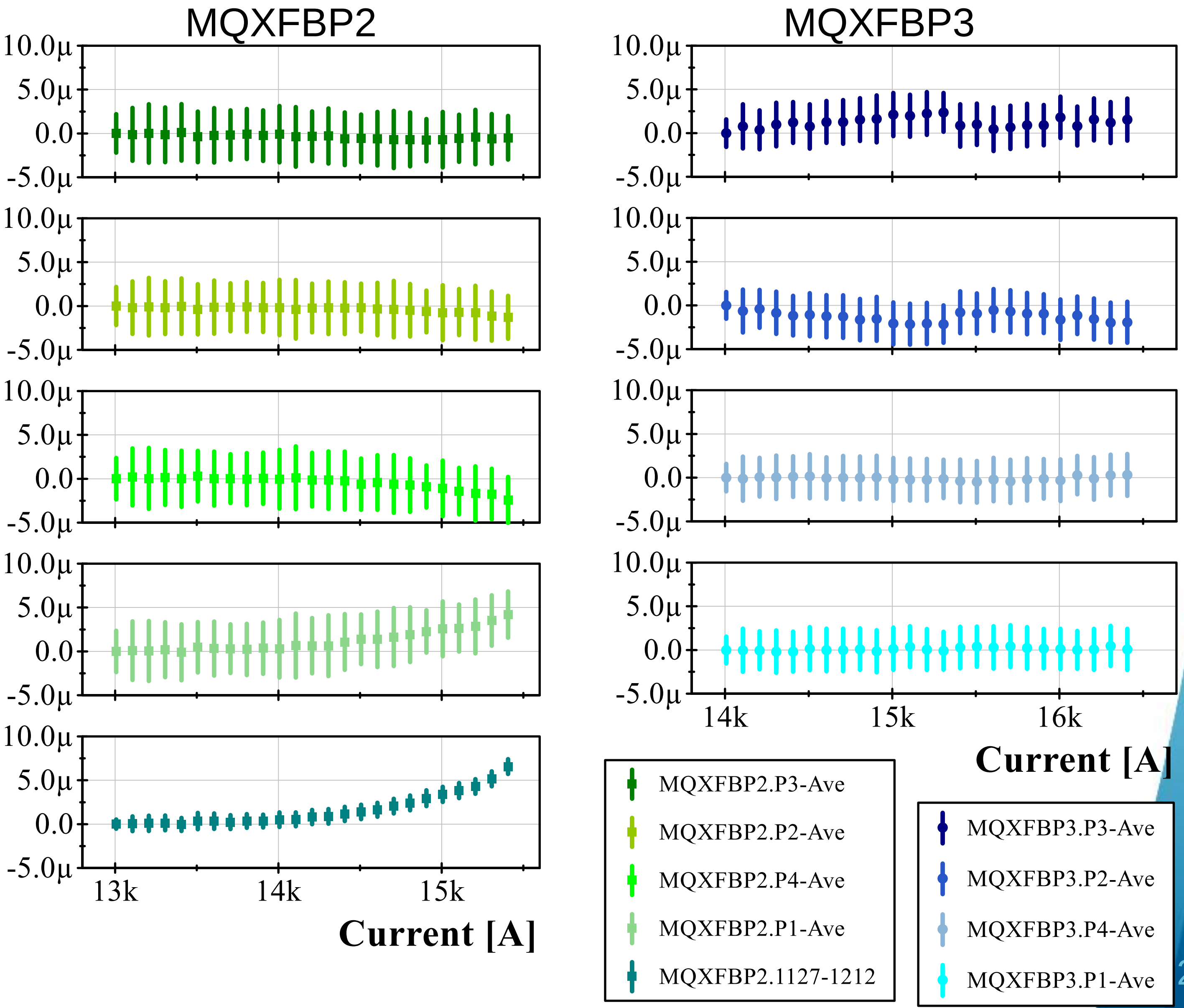
Tests done at 4.5K

Shown: coil voltage – average coil voltage. Offset corrected at the first plateau.

In MQXFBP2 the coil voltage mirrors the single segment voltage (1127-1212).

In MQXFBP3 no early superconducting transition was observed.

We are working on reducing the measurement noise level.



Conclusions

Conclusions

- Performance:
  - Increasing performance MQXFBP1 → BP2 → BP3.
  - MQXFBP3 reached the target current (nominal current + 300 A) at 1.9 K and 20 A/s ramp. It operated during 4.5 hours at target current and during 8 hours at nominal current.
  - All MQXFB magnets tested so far show a very fast training (maximum 1 quench)
  - The magnetic field quality of the magnets is within specifications.
- Thermal cycle:
  - All magnets showed perfect training memory after thermal cycle
  - The coils limitation level, ramp rate dependency, and V-I measurements unchanged after thermal cycle
- Limitation:
  - All MQXFB magnets so far show a performance limitation in one or more coils, in the inner layer pole turn or pole turn block, near the mechanical center of the magnet.
  - Coil heads are consistently performing well
- New tools developed and implemented to improve our understanding of these magnets' performance and limits.

Extra slides

Mech meas

MQXFB – Rods and vessel mech. behavior

SS-vessel:

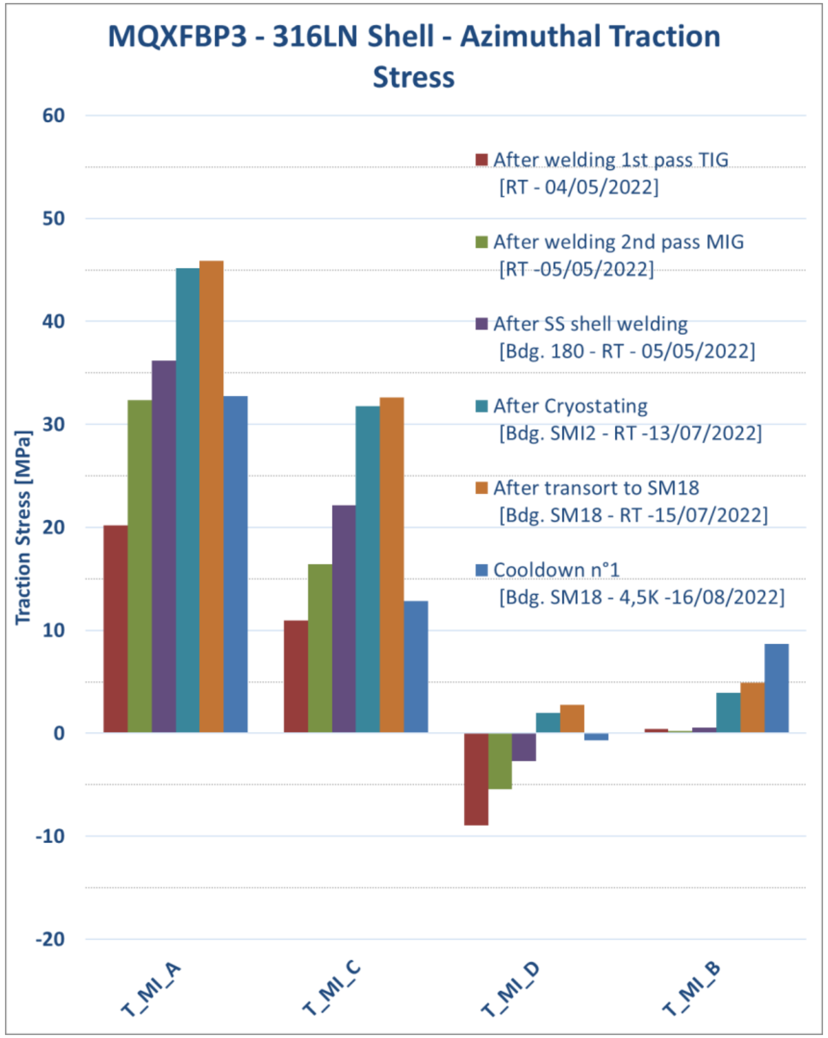
- SS – vessel in contact with the magnet at cold for MQXFBP1 and MQXFBP2.
- Detailed instrumentation installed in MQXFBP3, confirming the de-coupling of the vessel to the magnet structure, both in the azimuthal and longitudinal directions (as desired with the new cold-mass preparation procedure, **see talk from H. Prin "Cold mass assembly at CERN"**).

Rods:

- Data summarized in the table below.

The increase of strain in the rods during cool down for BP3 is 10 % higher than BP1&BP2, still 20 % lower than the FE predictions (FE ∆rods CD = 680 με)

		Avg. Rod Strain [με]		Avg. Rod Stress [MPa]		Δ Rod Strain CD [με]	Δ Rod Strain 16.23 kA [με]
		RT	1.9 K	RT	1.9 K		
Magnet	MQXFBP1	603	1055	116	222	**452**	**70**
	MQXFBP2	551	1012	106	213	**461**	**55**
	MQXFBP3	416	933	80	196	**517**	**100**

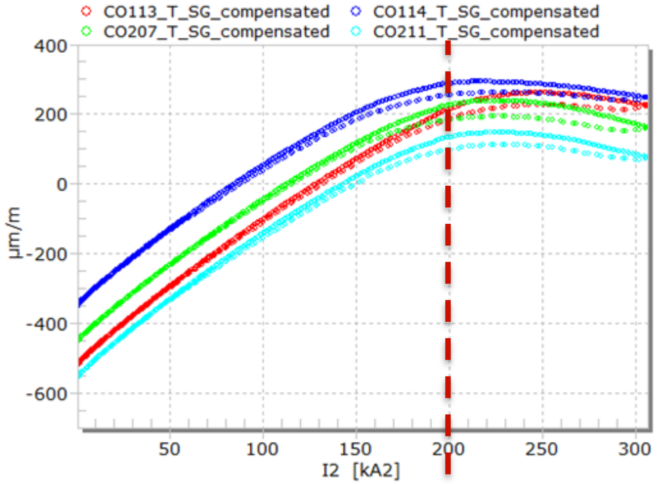


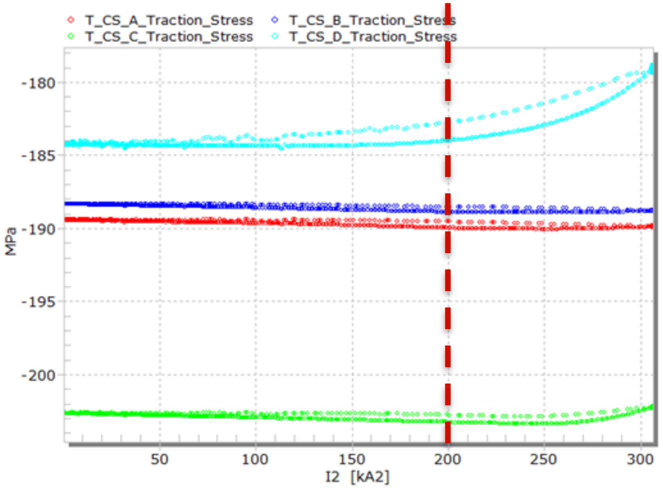
HL-LHC PROJECT

MQXFBP3 – An attempt to estimate coil preload at cold

See EDMS #2400115

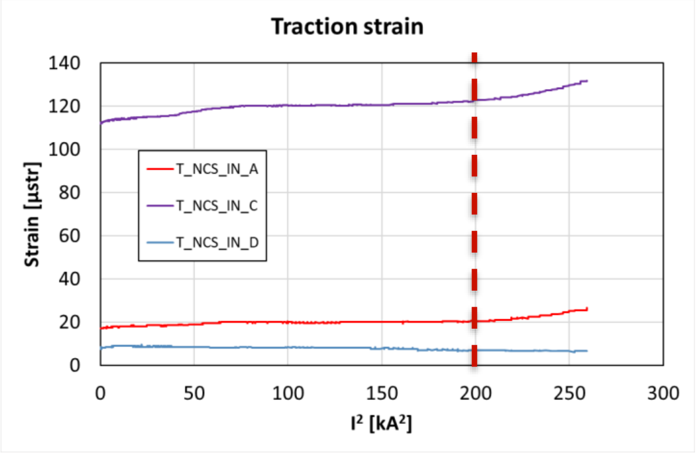
MQXFS7b





MQXFBP3

Non-connection side (NCS)



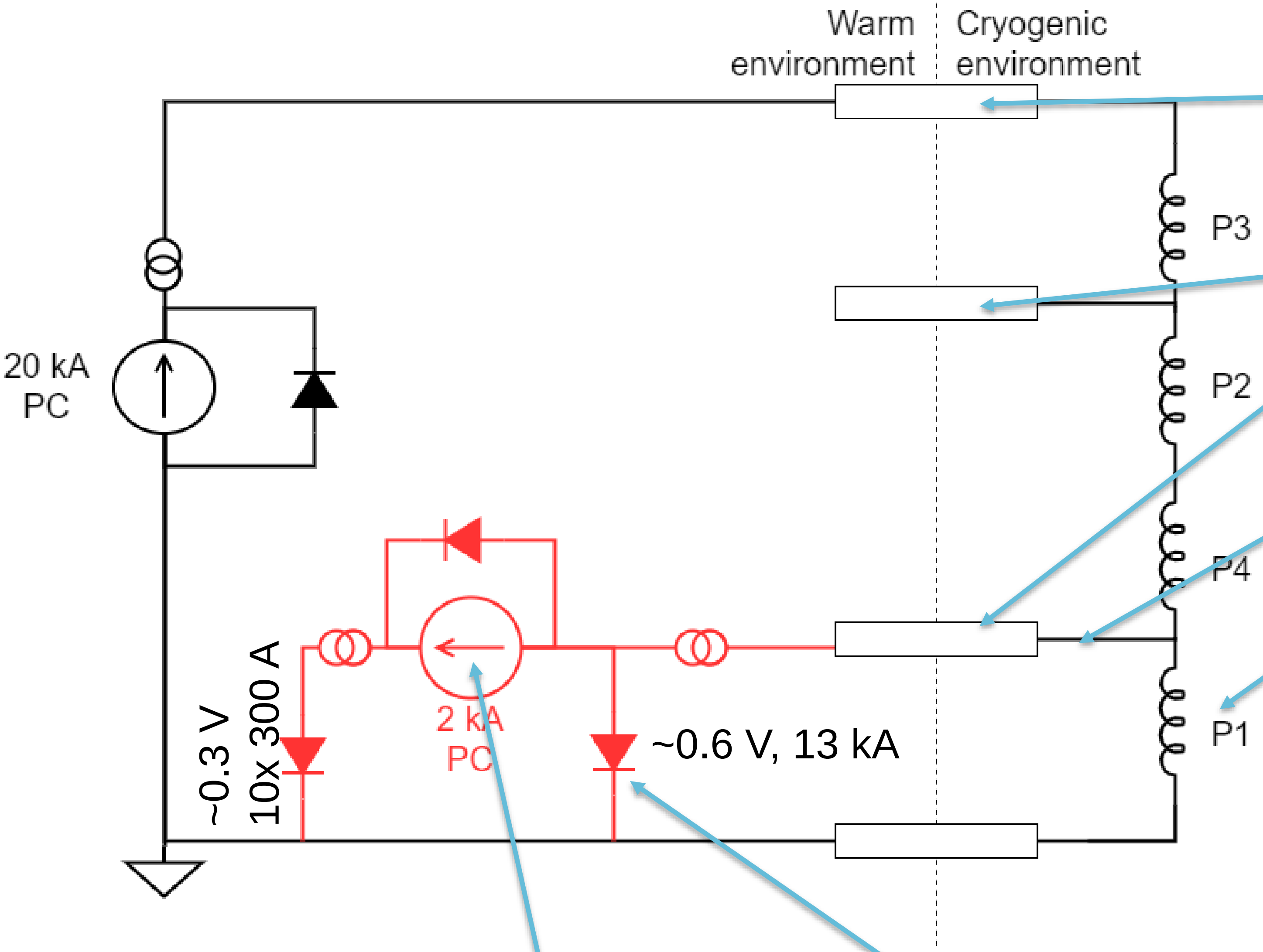
- In MQXFS7b, we could perceive the "pole unloading" in some of the SS vessel strain gauges. Specifically, in those located in the bottom of the magnet (during welding).
- In MQXFBP3, one could also see the same effect in the A and C gauges (bottom).

Application to MQXFBP3:

- Using this logic for the magnet extremities, the "pole unloading" would happen at 0.7 * $(I/I_{ult})^2$ (≈90-100 MPa pole unloading, very similar to S7b)
- No visible signs in the center of the magnet.

Trim

Trimmed powering -- circuit diagram



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

Trim PC is floating

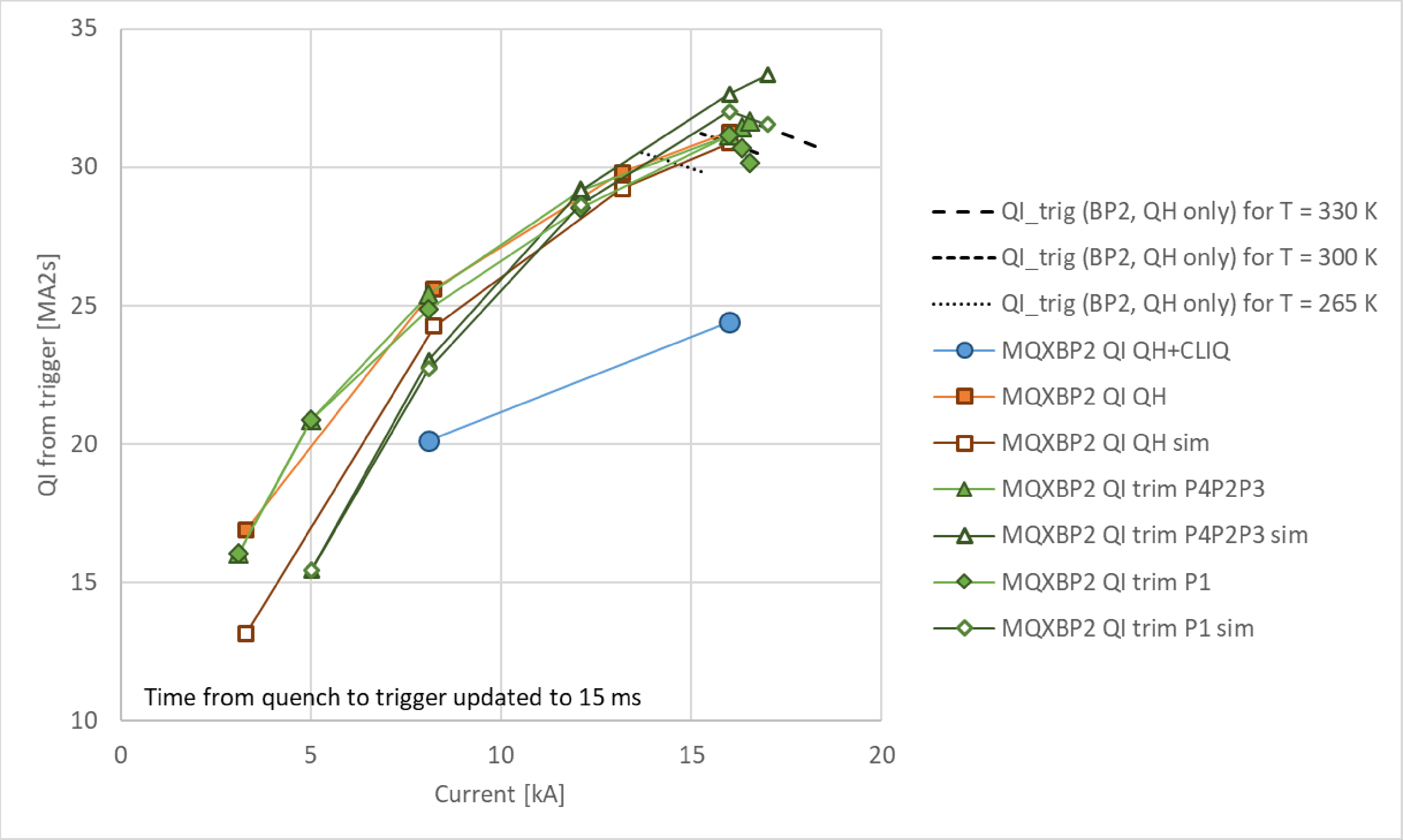
Trim PC protection diode

QI_trigger vs current

Measurements and simulations agree very well, specially at high currents.

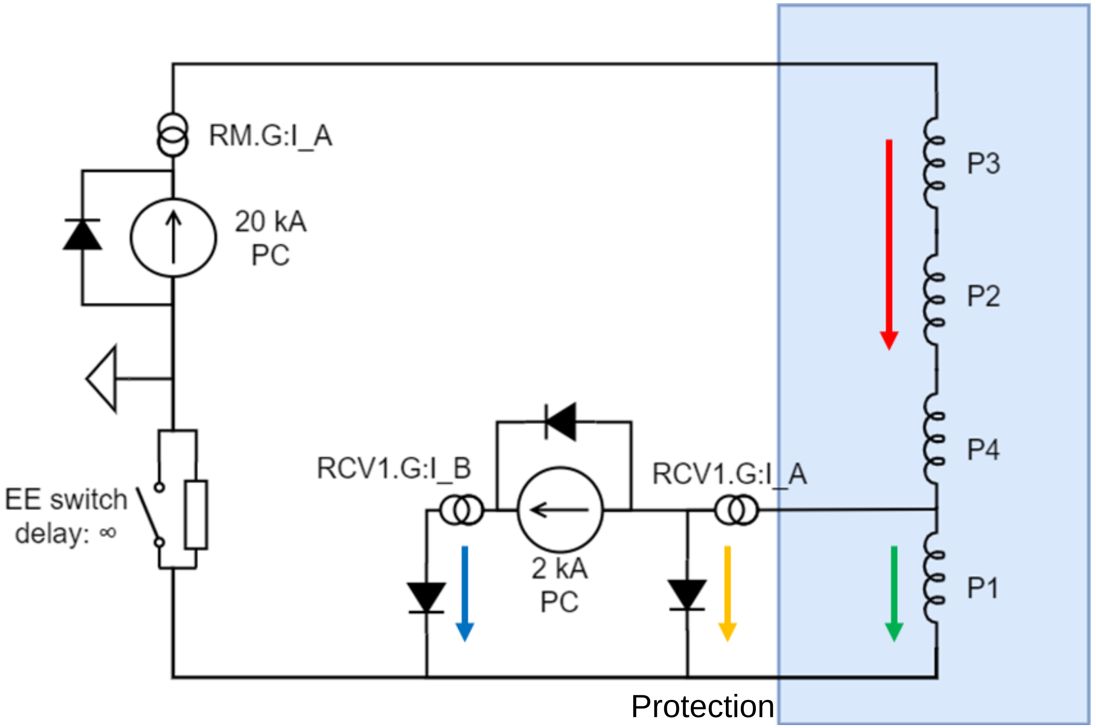
The QH only test was very representative of the trim tests in this magnet.

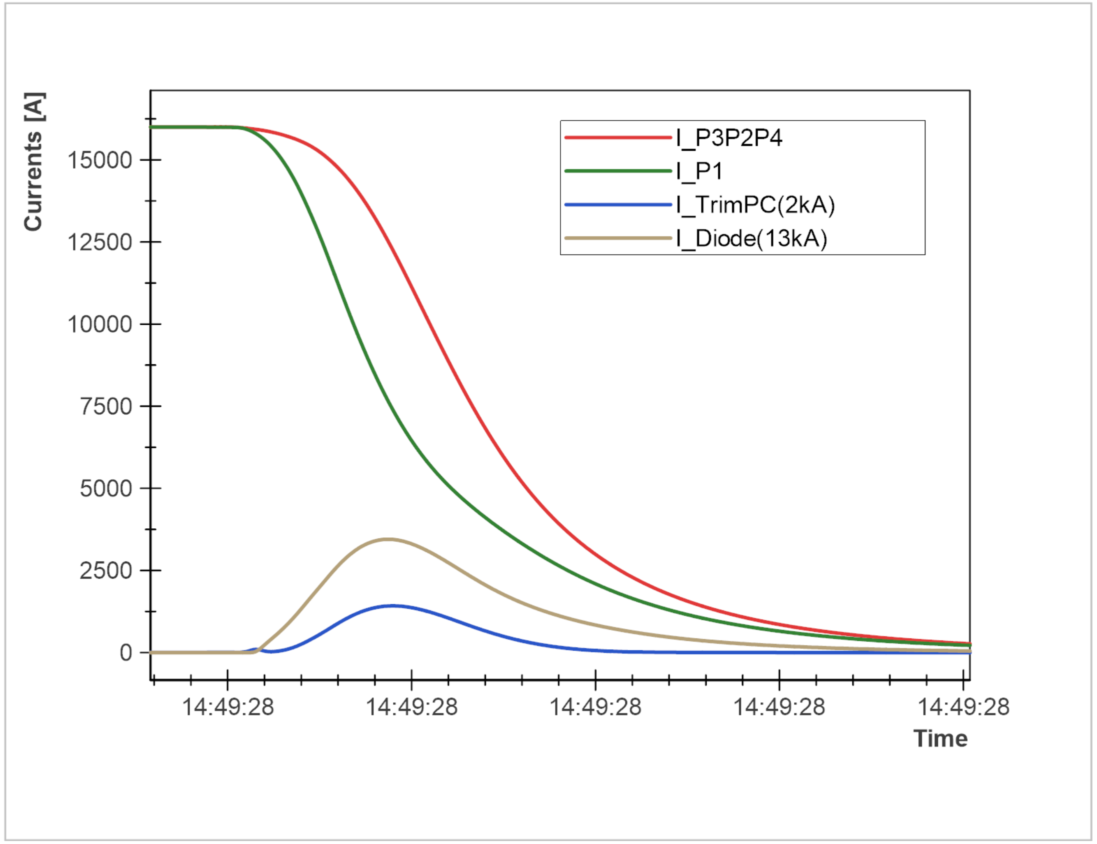
Maximum hotspot temperature reached ~330 K.



Simulations by E.Ravaioli with STEAM-LEDET + PSPICE coupled using STEAM-COSIM

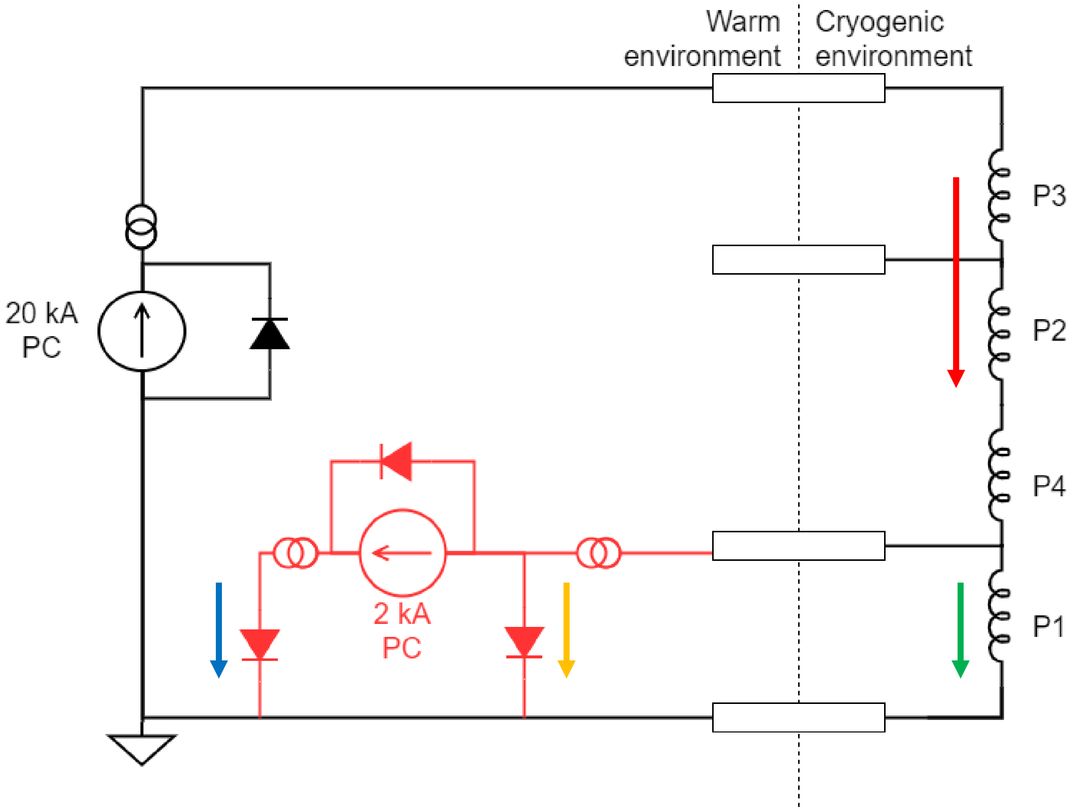
Why use the PC protection diode?

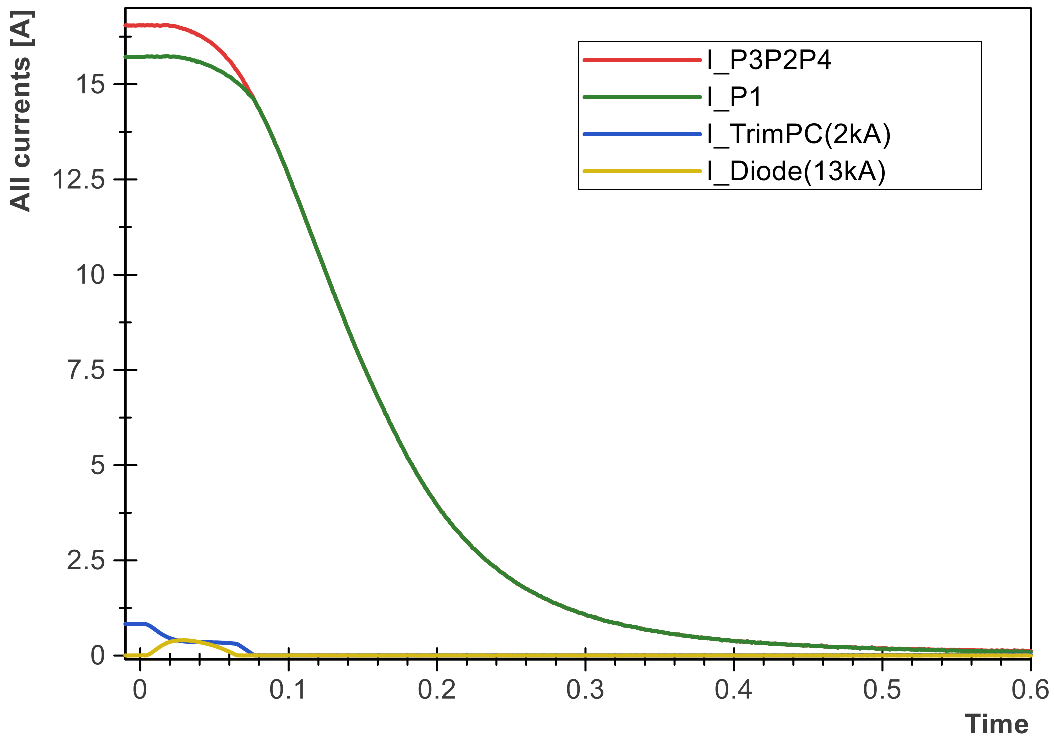




Results from MQXFS7b test (note slightly different circuit)
Peak current in the trim branch is 1.4 kA (through PC, blue) + 3.4 kA (through protection diode, gold)
P1 develops resistance faster than the other coils

In MQXFBP2: protection diode not necessary





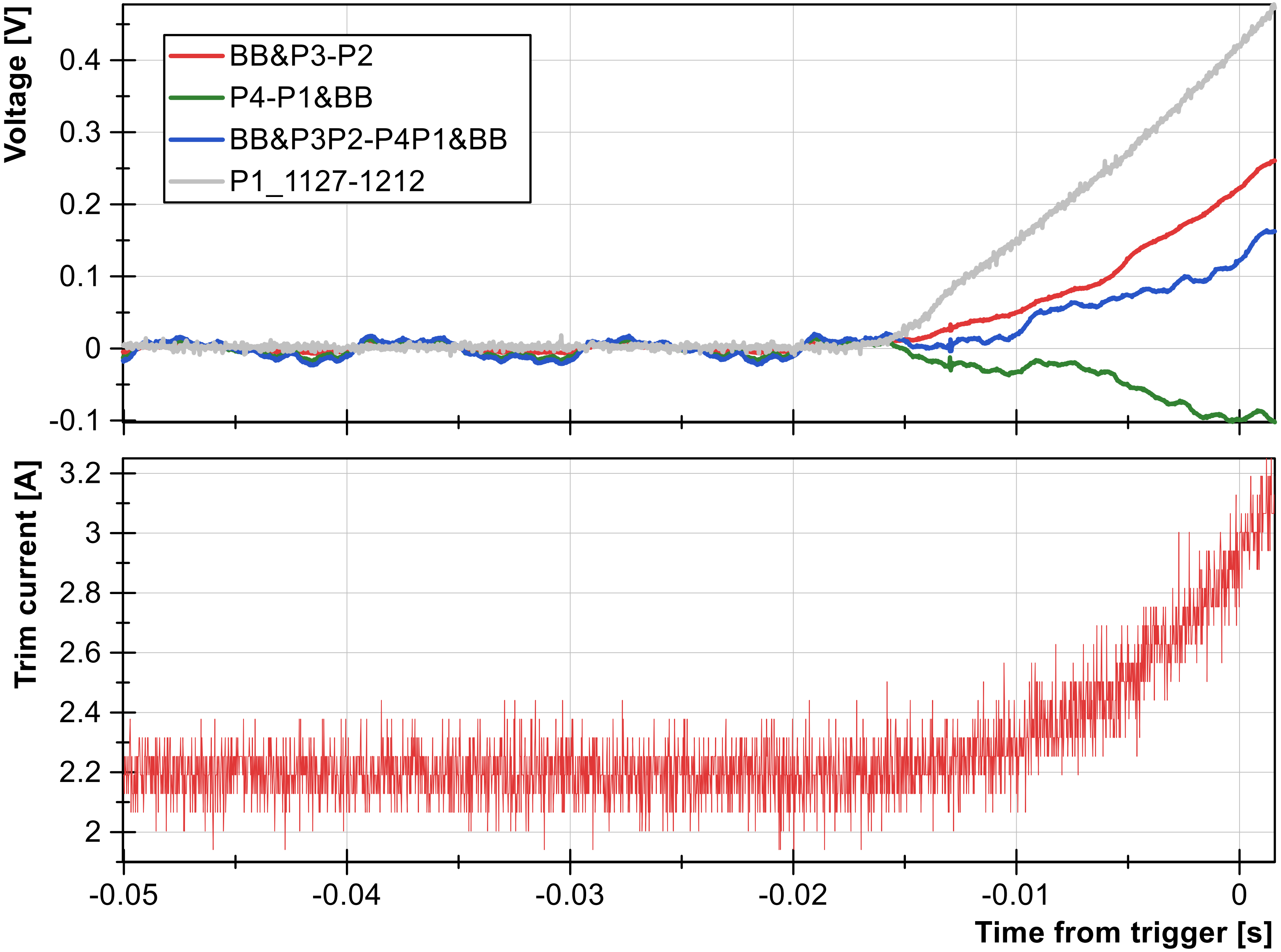
In MQXFBP2, the peak trim current happens before QH trigger and not during the discharge
Resistance balance in this magnet is different (P1 develops resistance slower than average)

Coil cross-talk during quench

A quench in P1 causes an increase in the trim current (i.e. a reduction of P1 current).

This induces a voltage in the other three coils, and the differential signal used for quench detection is reduced.

Quench detection was delayed by ~6 ms.



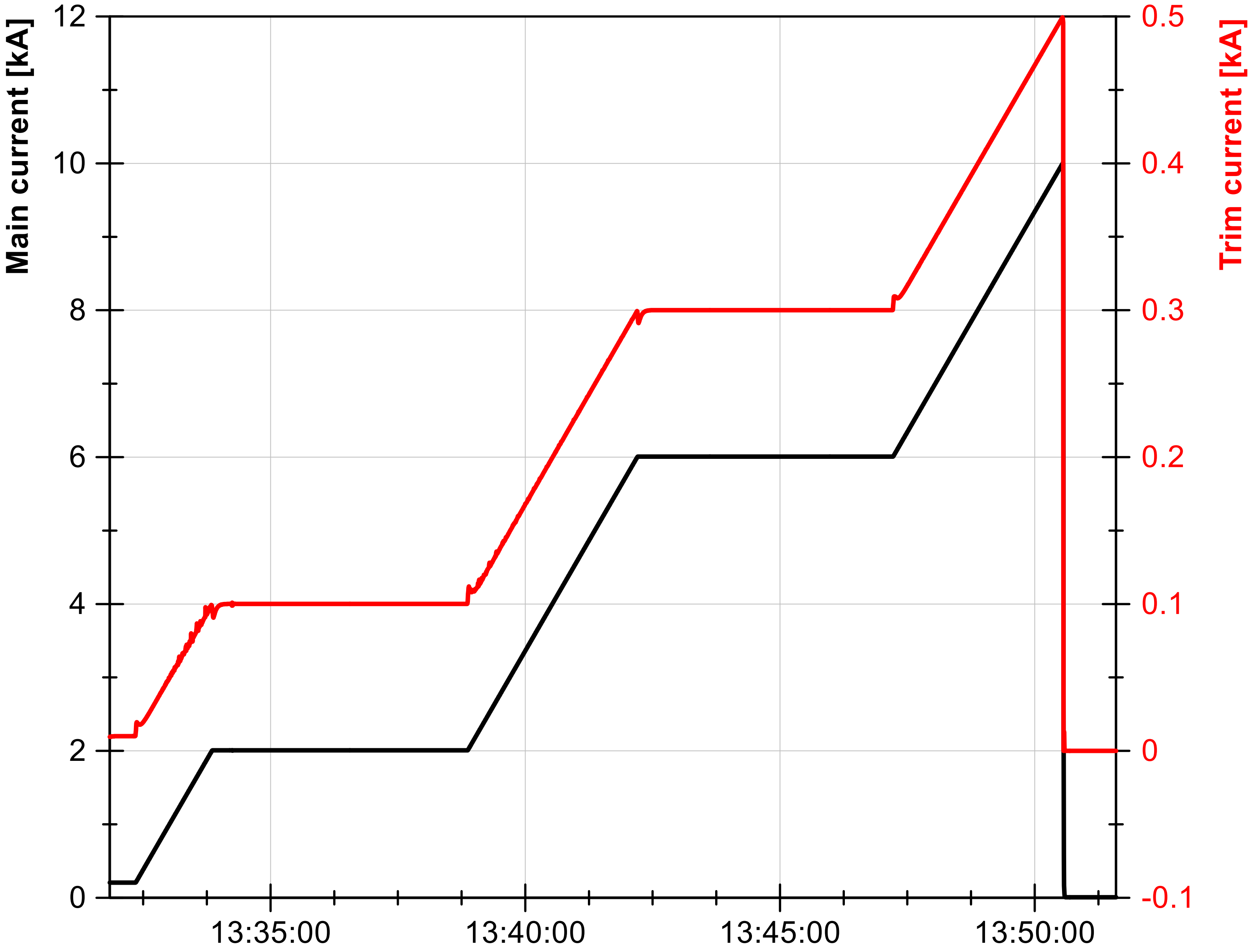
PC cross-talk during ramp rate change

Changes in the ramp rate of the main PC caused a fluctuation in the trim PC current
This triggered the uQDS above 8 kA

This is essentially a regulation issue between the PCs

Solutions:

- de-synchronize PCs
- Reduce acceleration and deceleration



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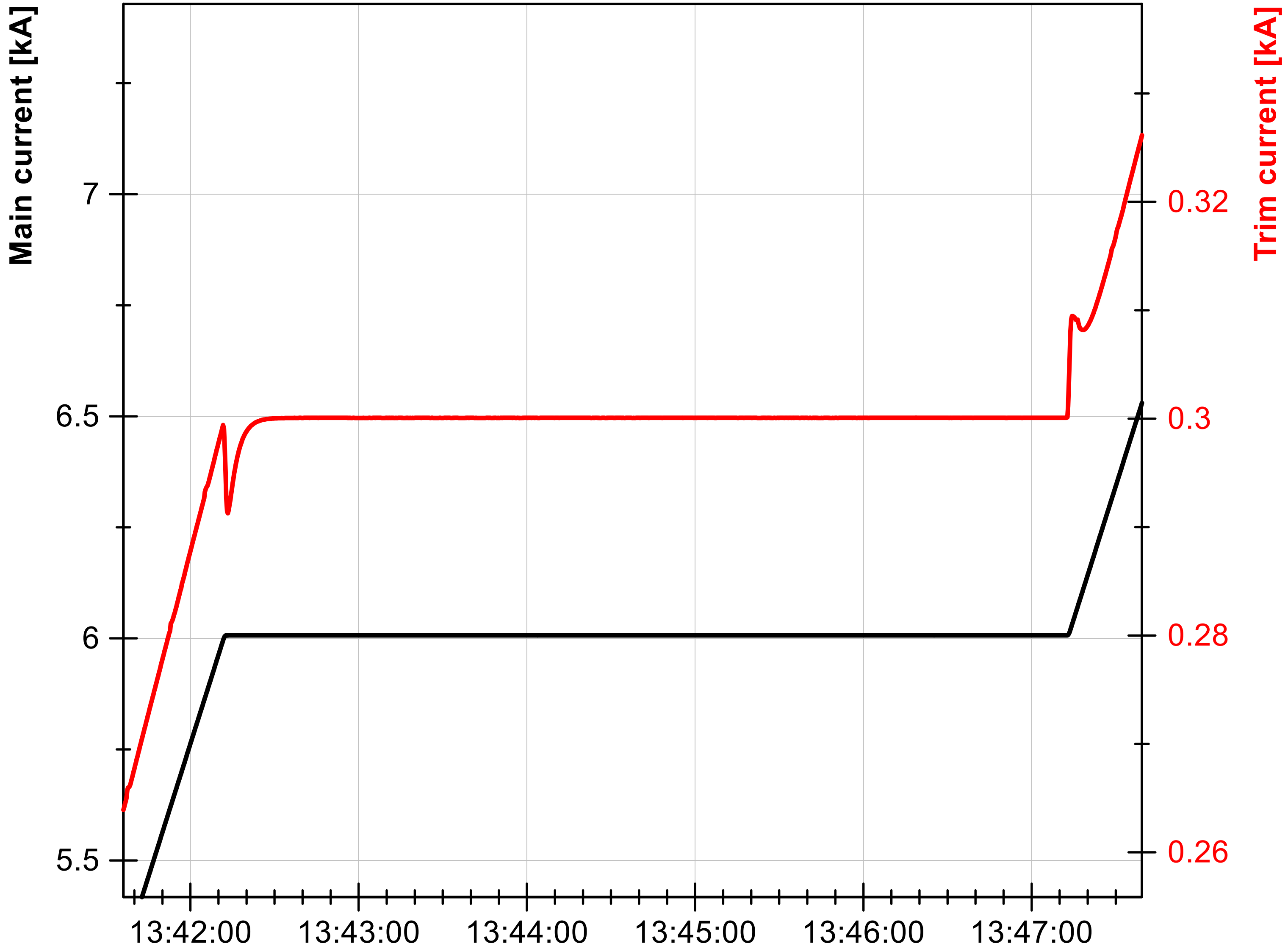
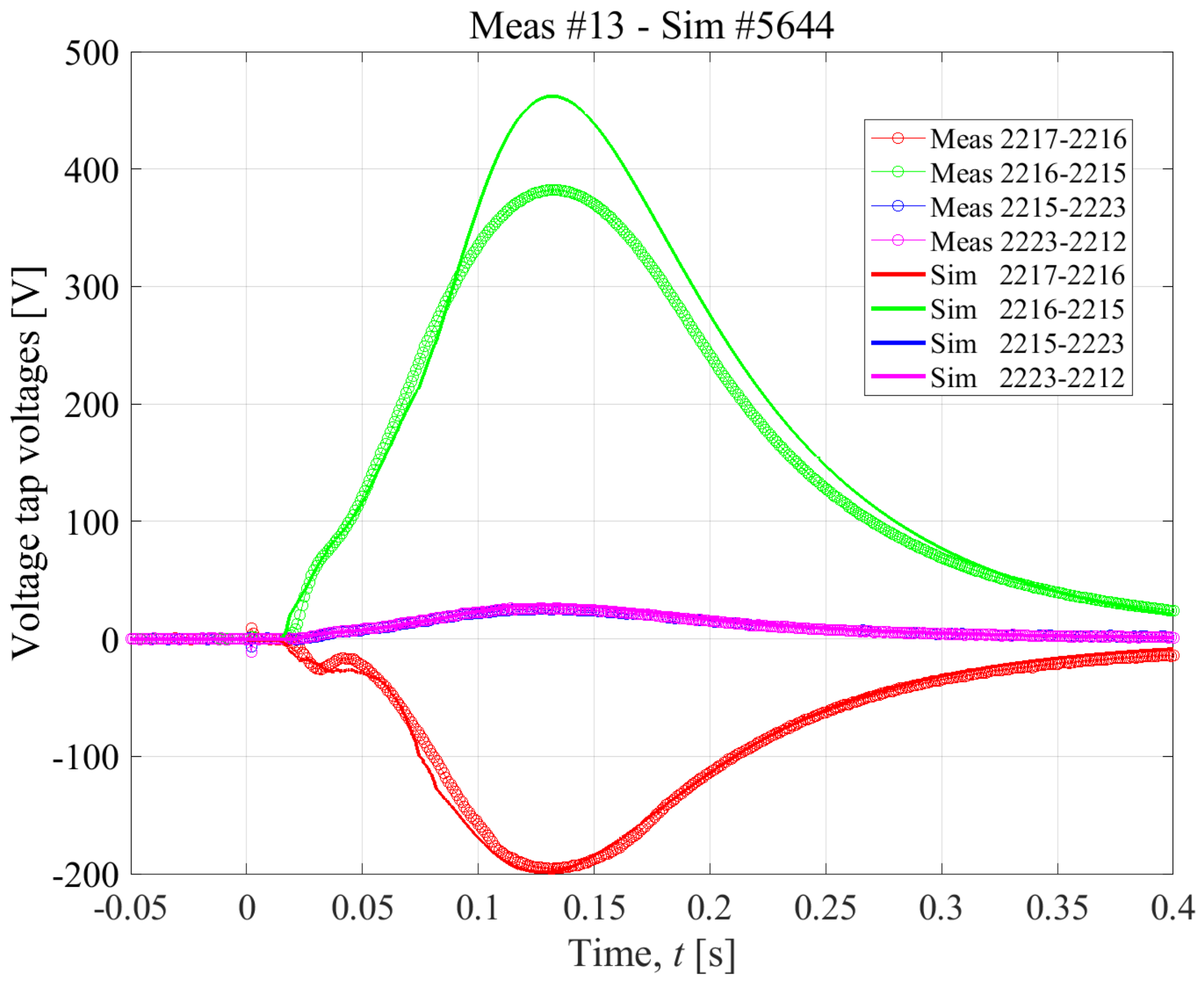
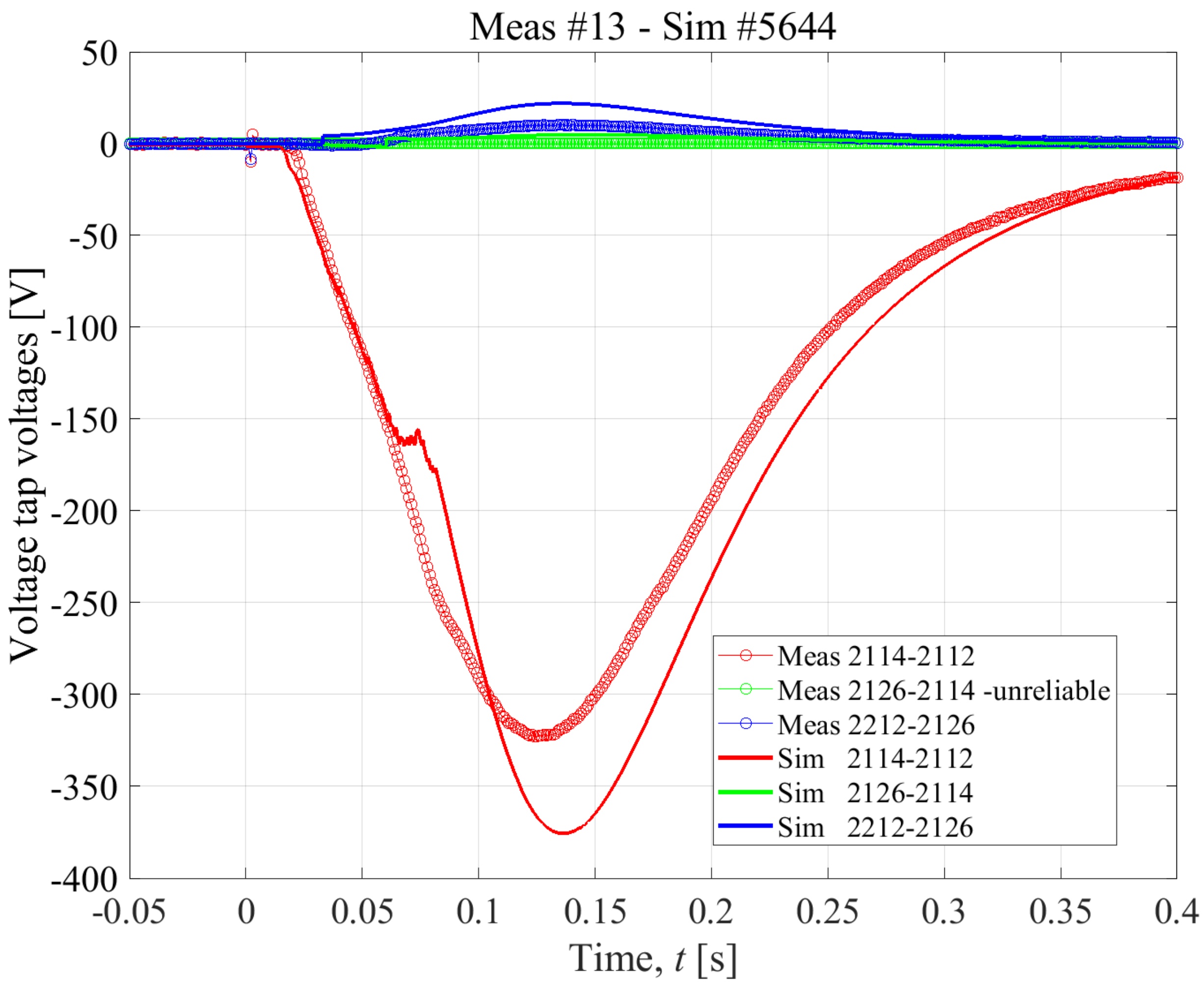
- de-synchronize PCs
- Reduce acceleration and deceleration



Voltages after quench. 16 kA, QH (no CLIQ)

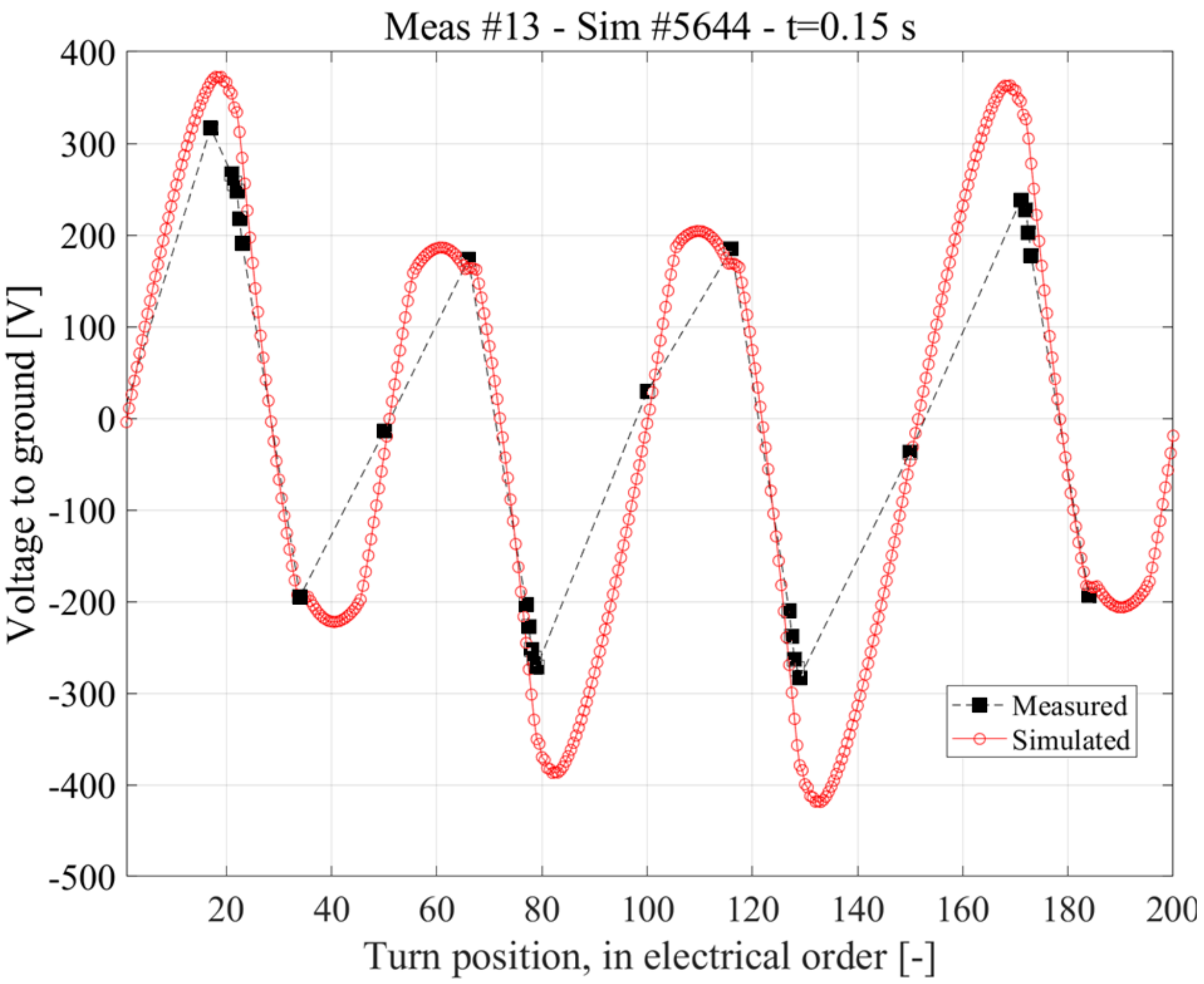


P2 outer-layer voltage taps

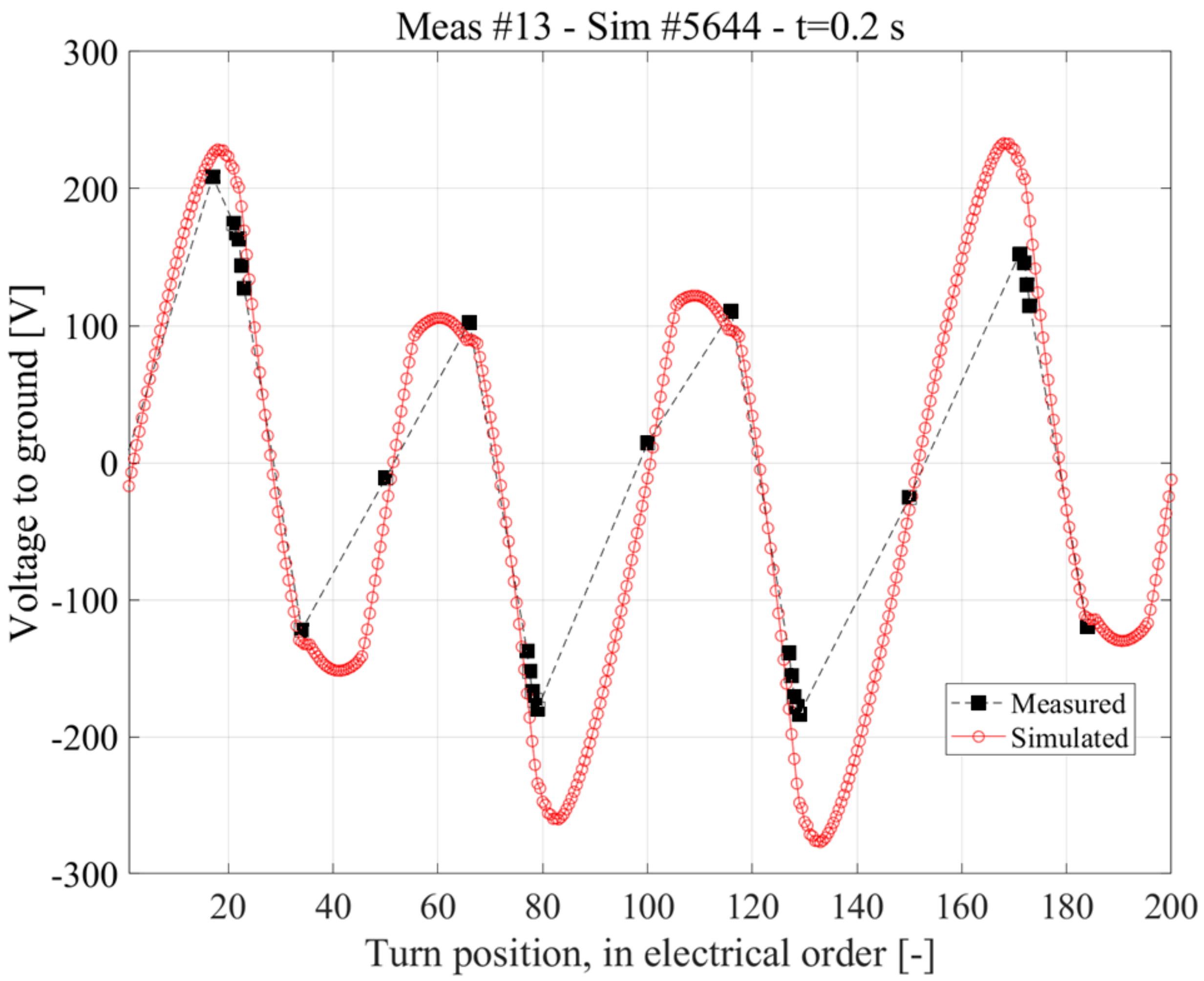


P2 inner-layer voltage taps

Voltages after quench. 16 kA, QH (no CLIQ)



Voltage to ground distribution, at t=150 ms



Voltage to ground distribution, at t=200 ms

Measured voltage to ground distribution 16.6 kA, 5% trim