LMBXFP1
D1-prototype cold mass – test at CERN
MTF: HCLMBXF004-KJ000001

Test results – Final Report
28 February 2024

Reporting to WP3 meeting, https://indico.cern.ch/event/1379959/

MBXFP1
At KEK - vertical

MBXFP1 in D1proto cold mass
At CERN - horizontal

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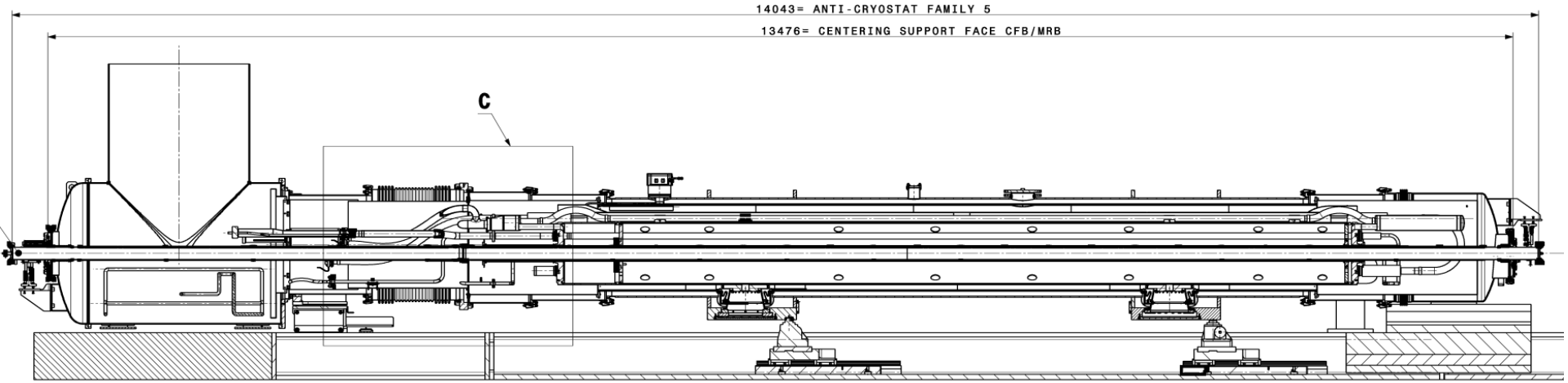
Gaëlle Ninet, Raphaël Bouvier, Franco Mangiarotti, Piotr Rogacki, Lucio Fiscarelli

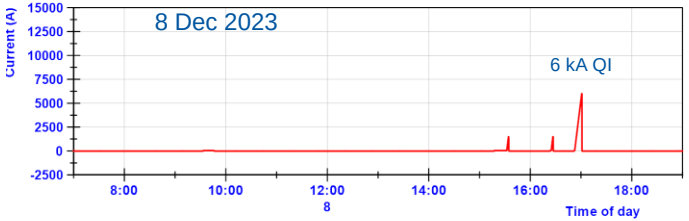
D1-prototype on the SM18 test bench

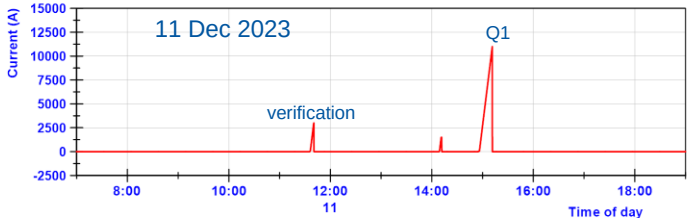


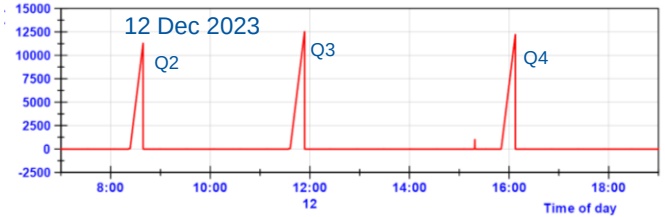
References:
Test report KEK tests: EDMS 2747573 and Indico 1077539
Test plan CERN tests: EDMS 2952771
Test report CERN tests: EDMS **3015584**
Acceptance criteria: EDMS 2045899

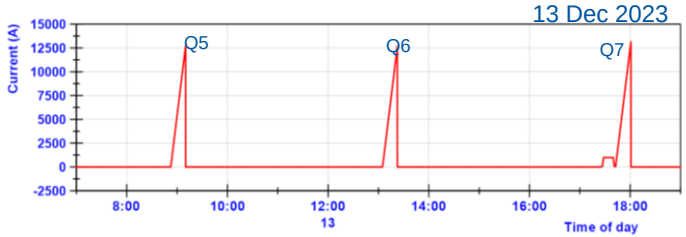
Test overview

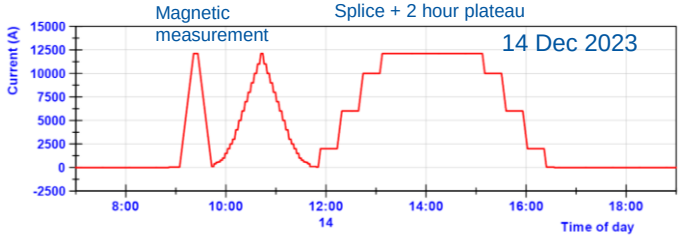
Powering – first cool down







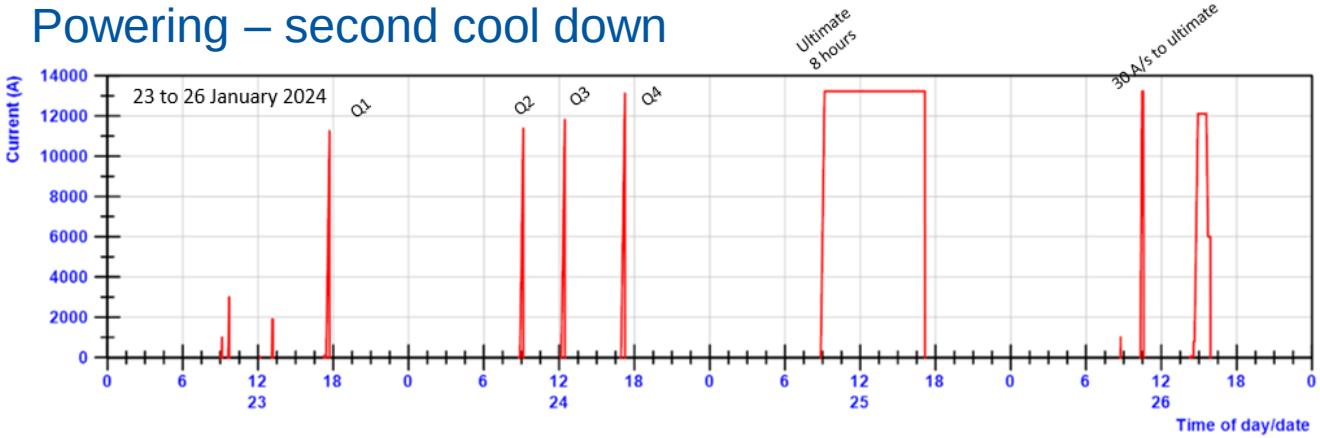




All tests at 1.9 K (4.5 K not possible in current setup).

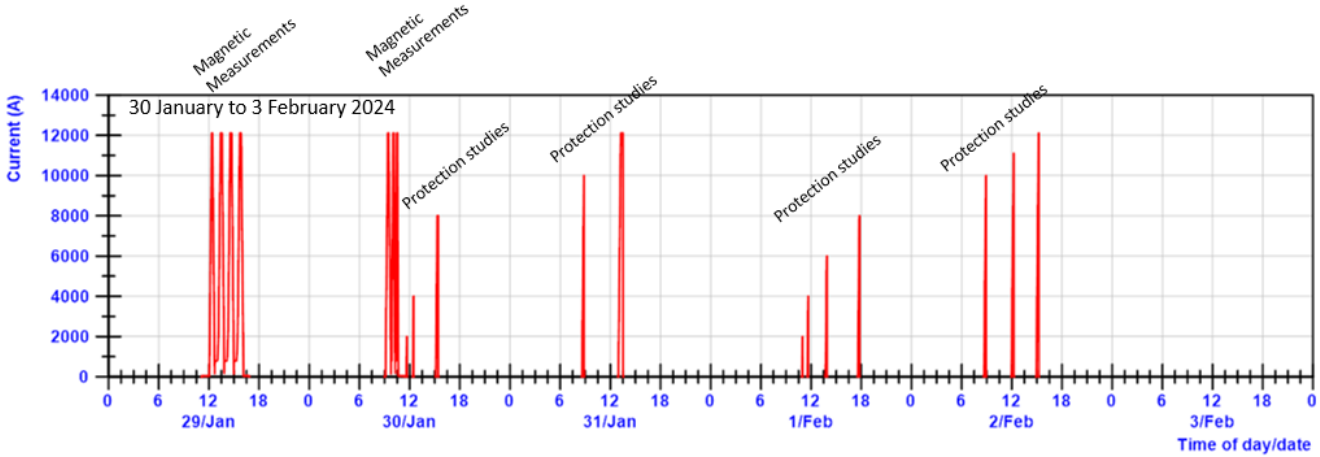
- Five days with powering tests
- Some delays due to setup, debugging and verification of quench protection
- 6 quenches done (max rate is 3 per day).
- Magnetic measurements and 2 hours plateau done.

Powering – second cool down



23 – 26 January

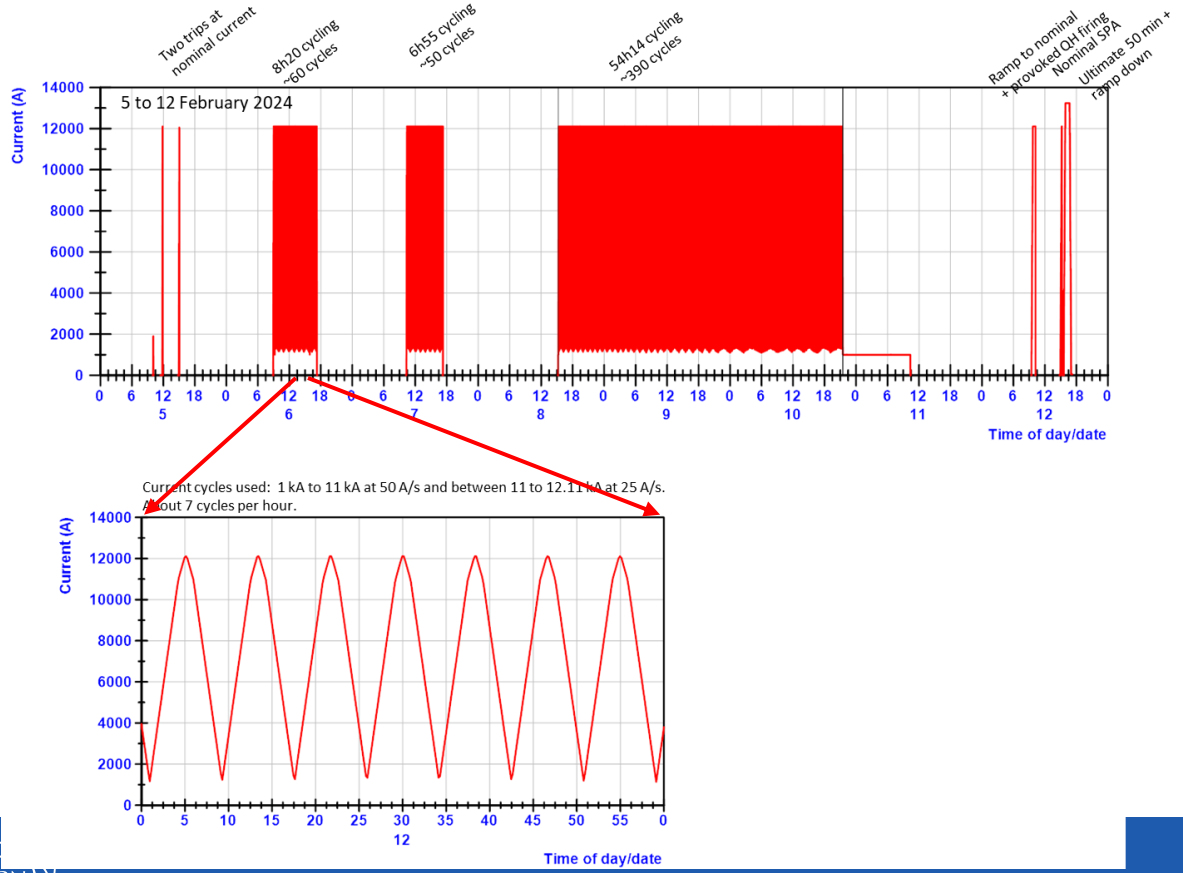
- 4 training quenches
- 8 hour ultimate current – OK.
- 30 A/s to ultimate
- Nominal current cycle.



29 January to 2 February

- Magnetic measurement cycles
- Nominal QH protection studies.
- Worst case 2 out of 4 QH protection studies up to nominal current.

Powering – second cool down



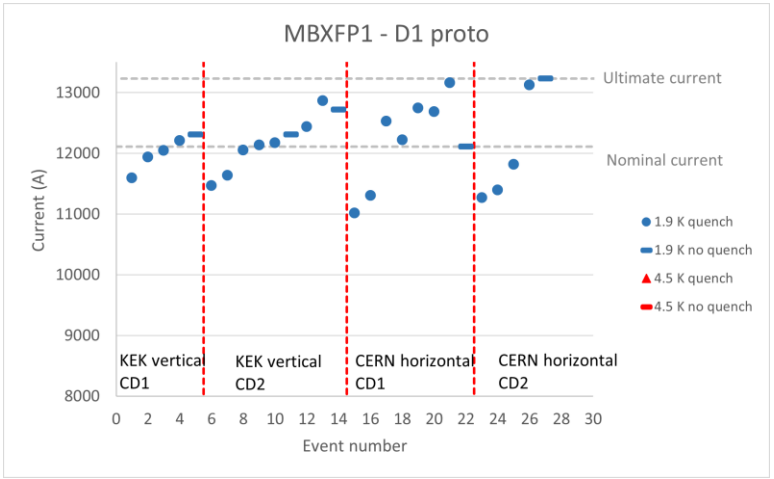
5 to 12 February

- Two trips during setup of fast cycles.
- 500 cycles done between 1 kA and 12.11 kA at 50 A/s – continuous cycling for in total ~ 70 hours.
- Verification test ramp to nominal + provoked QH firing.
- Nominal current SPA test
- Ultimate current verification with ramp down.
- Powering tests completed
- Nominal HV tests performed in nominal 1.9 K conditions.

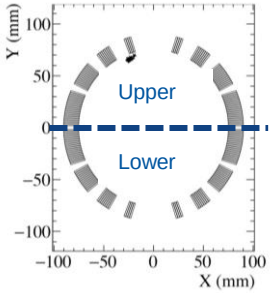
Conclusion:
After the 4 training quenches, the magnet powering was stable and reliable.

Training

Magnet training

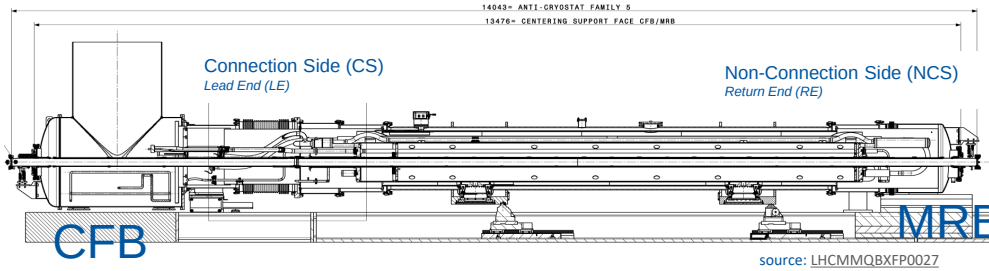


Event number	Temperature (K)	Ramp rate (A/s)	Type	Current (A)	Coil	Longitudinal location
1	1.9	20	Training	11589	U	CS
2	1.9	20	Training	11934	U	CS
3	1.9	20	Training	12042	L	CS
4	1.9	20	Training	12209	U	CS
5	1.9	20	Reached	12310		
6	1.9	20	Training	11466	U	CS
7	1.9	20	Training	11634	L	CS
8	1.9	20	Training	12052	U	CS
9	1.9	20	Training	12132	L	CS
10	1.9	20	Training	12169	U	CS
11	1.9	20	Reached	12310		
12	1.9	20	Training	12436	L	CS
13	1.9	20	Training	12866	L	CS
14	1.9	20	Reached	12716		
15	1.9	12	Training	11010	L	CS
16	1.9	12	Training	11300	L	CS
17	1.9	12	Training	12525	L	CS
18	1.9	12	Training	12220	L	CS
19	1.9	12	Training	12741	L	NCS
20	1.9	12	Training	12680	U	CS
21	1.9	12	Training	13160	L	CS
22	1.9	12	Reached	12110		
23	1.9	12	Training	11267	U	CS
24	1.9	12	Training	11392	L	CS
25	1.9	12	Training	11816	L	CS
26	1.9	12	Training	13120	U	NCS
27	1.9	12	Reached	13231		



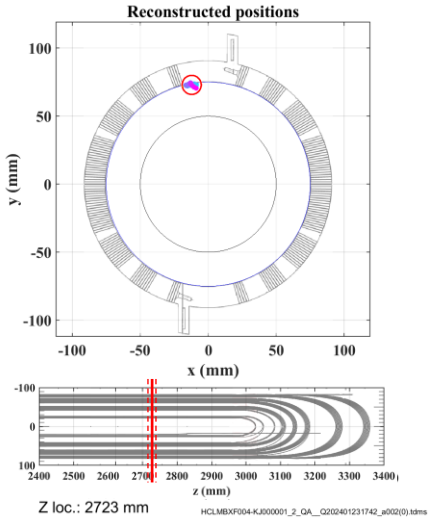
All training done at 1.9 K, no powering at 4.5 K.

- 3 quenches were needed in the second horizontal cool down to reach nominal current.
- In both the first and second horizontal test, the first two quenches were lower than recorded in the vertical test.
- The training slope up to ultimate current increases throughout the 4 cool downs, but with limited memory.
- The training quenches are mostly in the connection side of the magnet (20 out of 22), distributed over the upper (9) and lower coil (13). There is no sign of a specific weak spot.

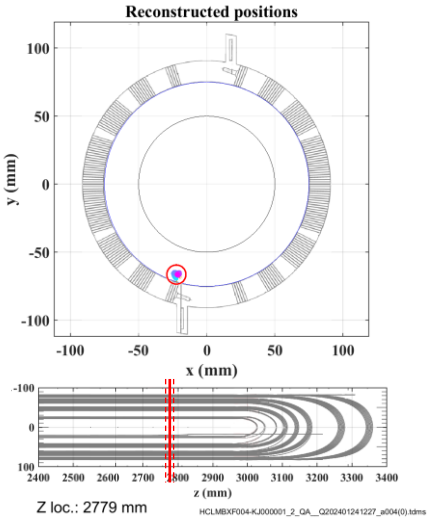


source: LHCMMQBXFP0027

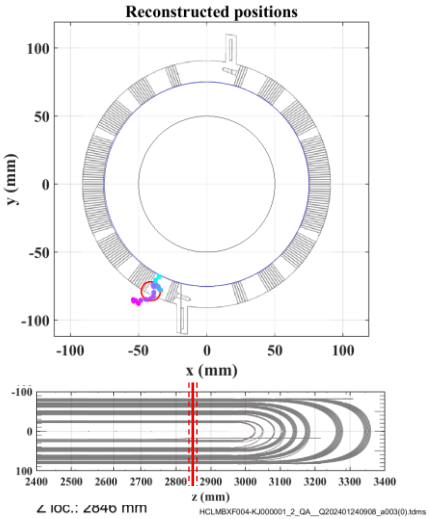
Quench location – CD2



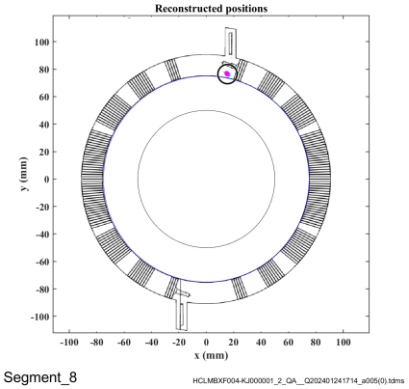
CD2 – Q1 at 11.26 kA
Upper coil, connection side
2723 mm from magnetic center



CD2 – Q2 at 11.39 kA
Lower coil, connection side
2779 mm from magnetic center



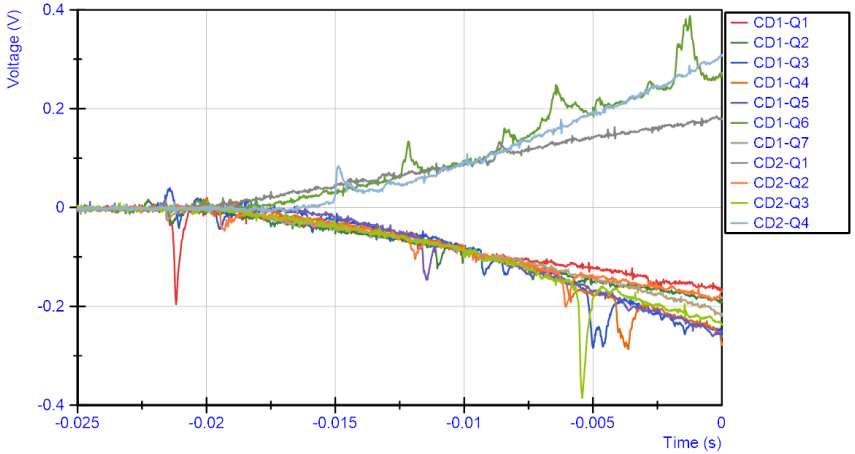
CD2 – Q3 at 11.82 kA
Lower coil, connection side
2846 mm from magnetic center



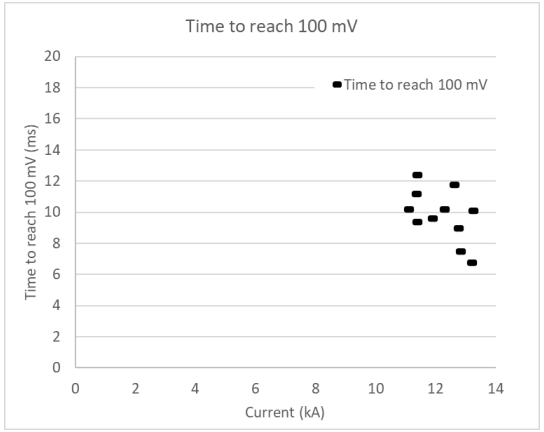
CD2 – Q4 at 13.12 kA
Upper coil, non-connection side
No longitudinal position possible

Courtesy Piotr Rogacki

Voltage during quench



Differential voltage (V_{upper}-V_{lower}) for all 11 quenches in horizontal tests at CERN. Positive voltages are quenches in the upper coil, negative in the lower coil.

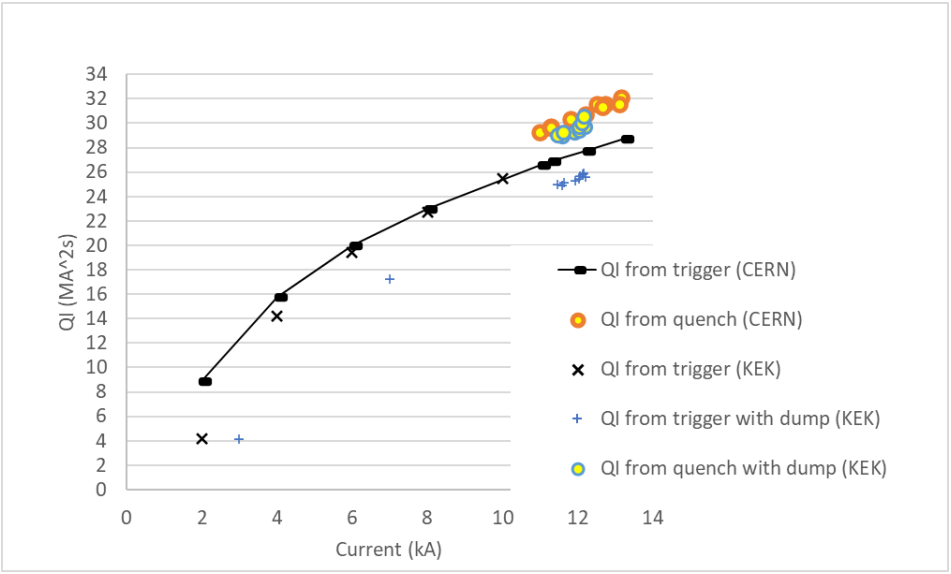


Time from quench start to reach the detection threshold of 100 mV for all 11 quenches in horizontal tests at CERN.

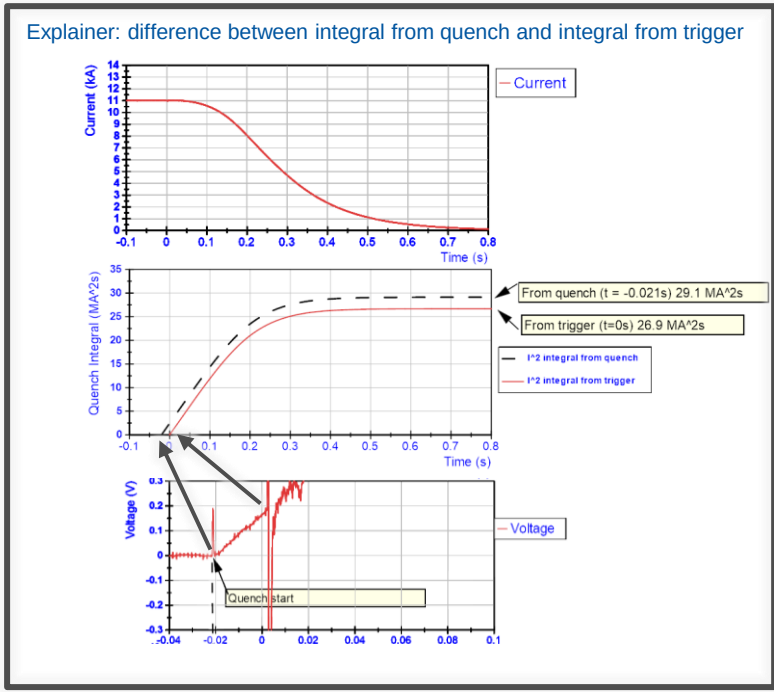
Protection studies

MBXFP1 – nominal protection

Plots with all 4 QH used



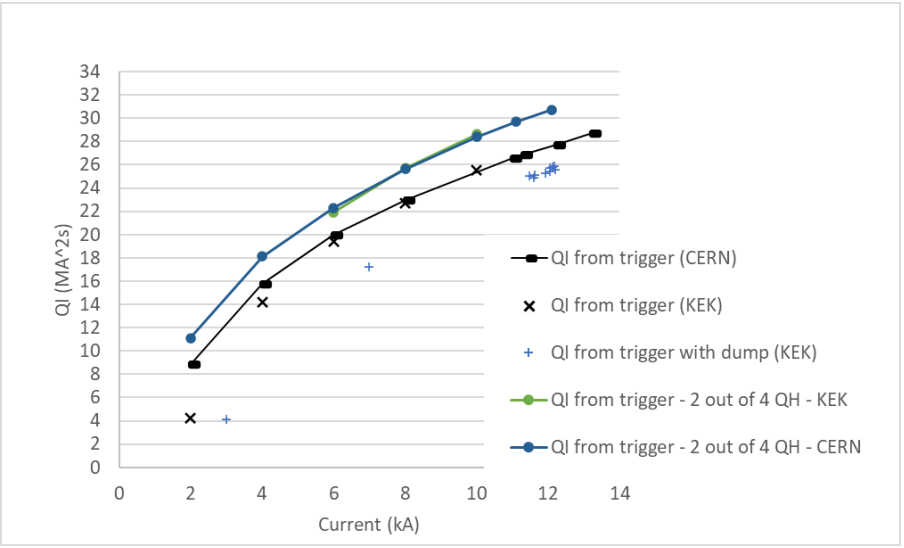
Explainer: difference between integral from quench and integral from trigger



- Protection studies redone up to ultimate current.
- Data at CERN consistent with data from KEK (thanks to Kento Suzuki for the data)
- The dump at KEK reduces the $QI_{from\ trigger}$ by about 2 MA^2s.
- At CERN the time to reach threshold at ultimate current is ~ 10 ms with 10 ms validation time.
  This gives a difference between $QI_{from\ quench}$ vs $QI_{from\ trigger}$ ~ 2.5 MA^2s.

MBXFP1 – protection

Data including 2 out of 4 quench heaters



Data from KEK: Courtesy Kento Suzuki

- Data with 2 out of 4 QH at CERN consistent with that of KEK.
- At nominal current, QI from trigger is 2.8 MA^2s higher when only using 2 out of 4 QH, compared to nominal case
- Maximum QI recorded is 30.7 MA^2s from trigger. In case of quench, the QI would be about 33.2 MA^2s with the used quench detection settings.

TABLE I
PARAMETERS OF THE RUTHERFORD CABLE USED IN THE D1 MAGNET

Copper to SC ratio	1.9
Strand diameter (mm)	0.825
Number of strands	36
RRR	190
Cable thin edge (mm)	1.362
Cable thick edge (mm)	1.598
Cable width (mm)	15

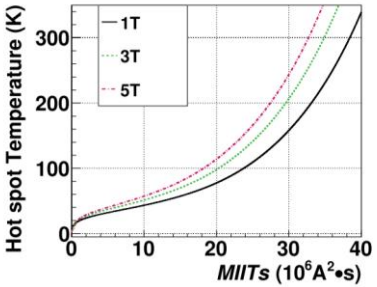


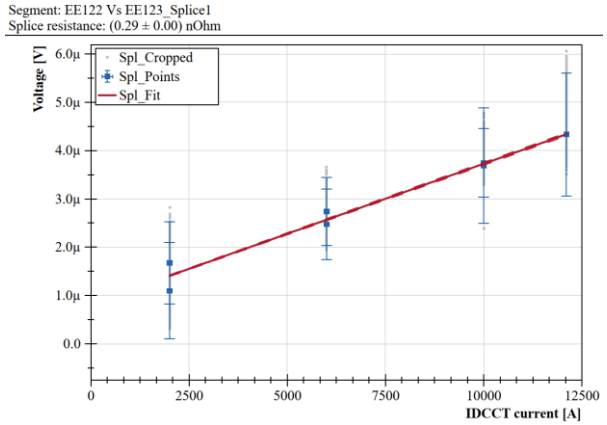
Fig. 1. Calculated hot spot temperature as a function of $MIITs$ for the cable in the D1 magnet.

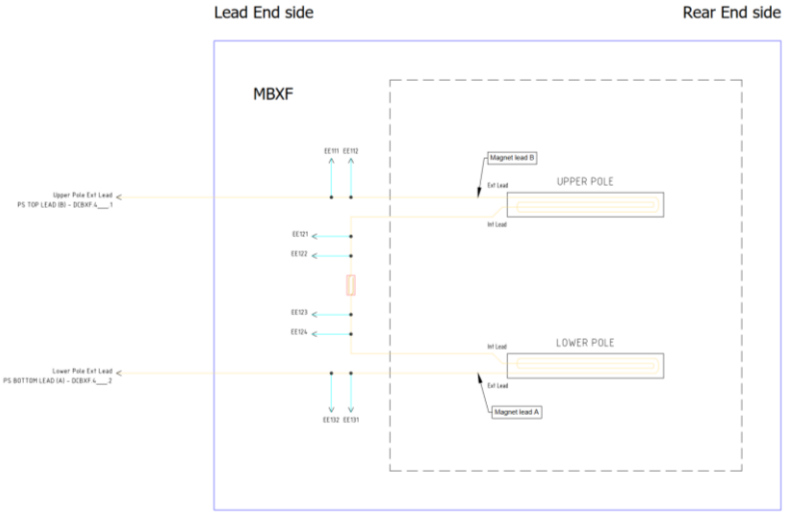
K. Suzuki, et al. *"Quench Protection Heater Study With the 2-m Model Magnet of Beam Separation Dipole for the HL-LHC Upgrade"* IEEE Trans. Appl. Supercond., Vol. 28, No. 3, April 2018

Other tests

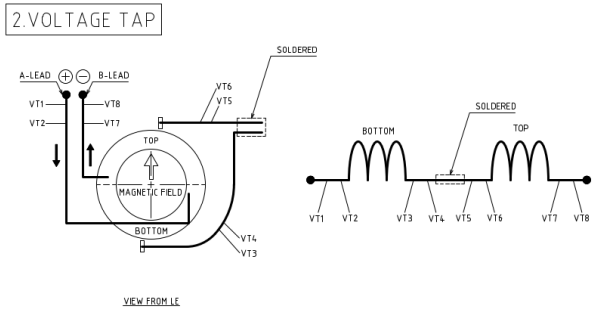
MBXF - splice

One inter-coil splice between Vtaps EE123 and EE122.
Its resistance is 0.29 nΩ and shows linear behavior up to nominal current. (measured in CD 1)





LHCLMBXFE0024



HV insulation test

Test status

Warm initial: **OK**
At 1.9 K, CD1, before powering: **OK**
At 1.9 K, CD1, after powering: **OK**
At 1.9 K, CD2, before powering: **OK**
At 1.9 K, CD2, after powering: **OK**
Warm final: **OK**

Test result

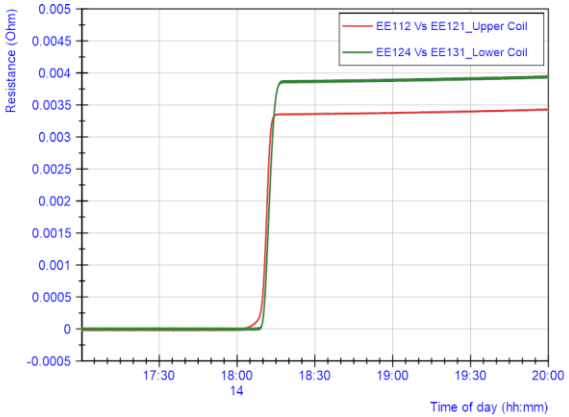
Test	(MBXF+QH) to ground at 1300 V R (GΩ)	QH to (MBXF+ground) at 2300 V R (GΩ)
CD1 at 1.9 K, before powering	>32*	>750*
CD1 at 1.9 K, after powering	>21	>450
CD2 at 1.9 K, before powering	> 34	> 310
CD2 at 1.9 K, after powering	>31	>790

*Part of the leakage current is related to the test bench, measurements vary due to varying humidity in the hall.

Table with testlevels from test plan.

Polarity +	Polarity -	Warm initial	1.9 K LHe	Warm Final	Imax [uA]
MBXF, QH	Ground	260	260/800/**1300**	370	10
QH	MBXF, Ground	460	460/1300/**2300**	460	10
Cryogenic Heater	MBXF, QH, Ground	---	675	---	70
TT821	Ground	---	25	---	2

Resistance at transition SC-NC



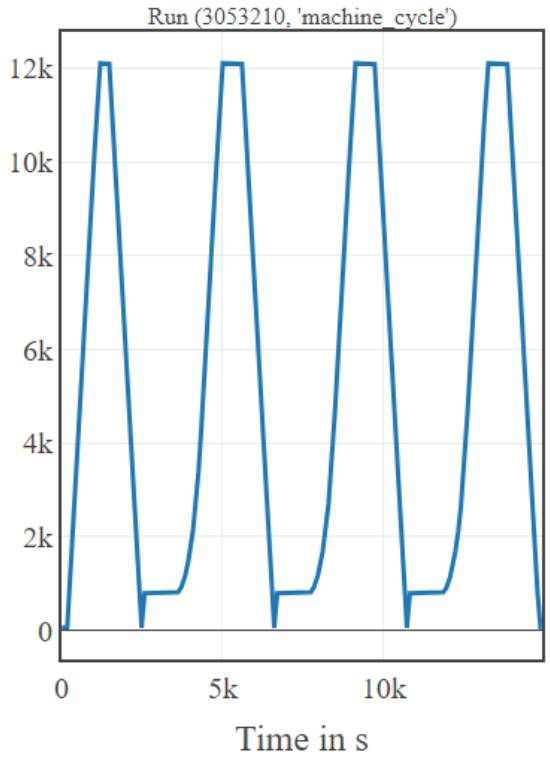
Coil resistance measurement during warm up.

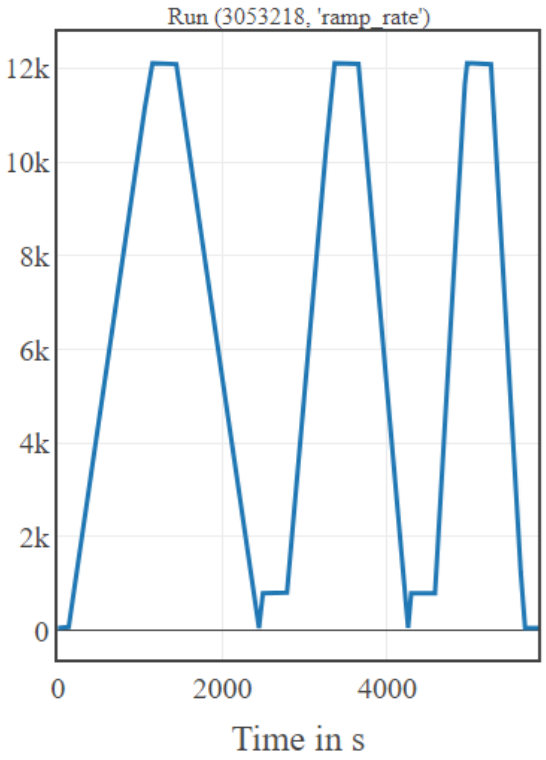
Coil	R_{293K}(mΩ)	R_{10K}(mΩ)	RRR
Lower	772.8	3.86	200
Upper	773.2	3.37	229

Magnetic measurements

Powering cycles for MM

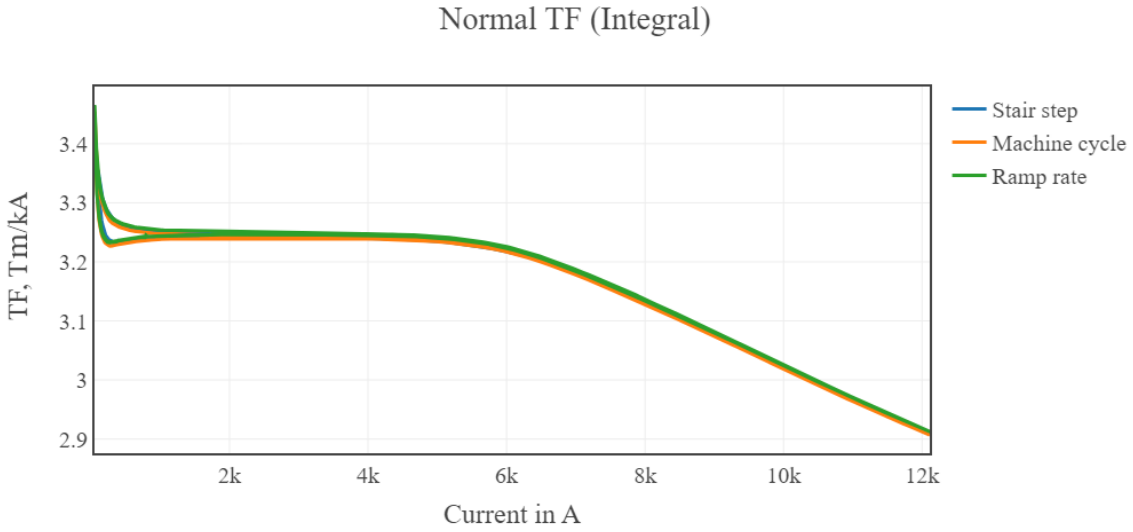
- Measurements performed during CD2:
  - Machine cycles
  - Ramp-rate cycles
  - Stretched wire
- Stair-step cycle was performed during CD1





By Lucio Fiscarelli and Piotr Rogacki
See also https://indico.cern.ch/event/1360284/

MM: Integral transfer function



With stretched wire:

Integral field is **35.188 Tm** at **12.110 A**, +53 units wrt specifications

(the measurement with rotating coils is confirmed by the stretched wire)

By Lucio Fiscarelli and Piotr Rogacki
See also https://indico.cern.ch/event/1360284/

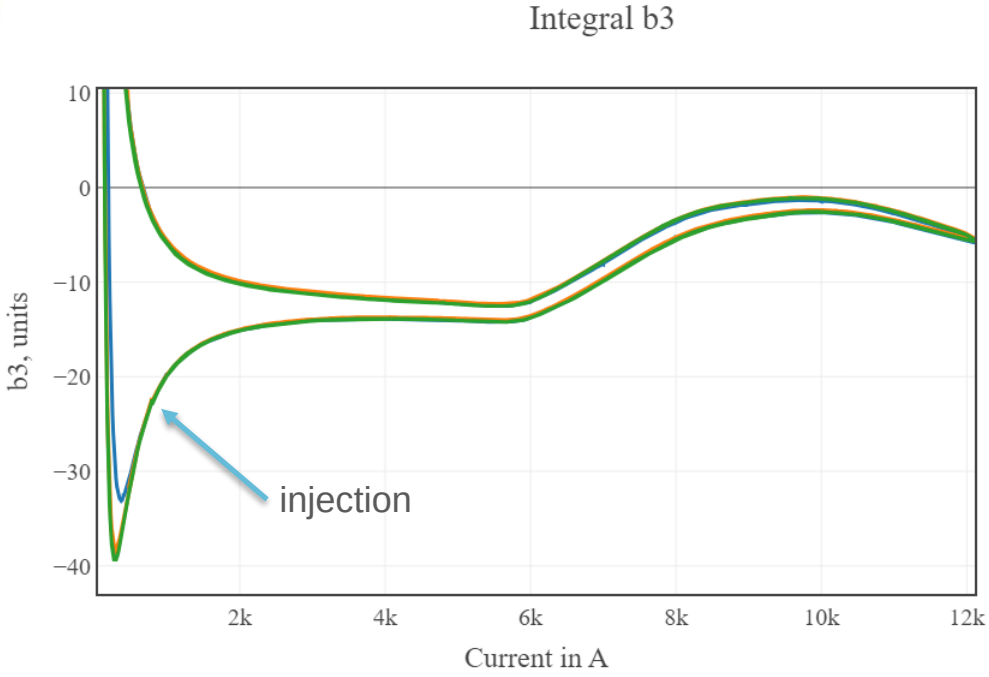
MM: Field at injection and nominal

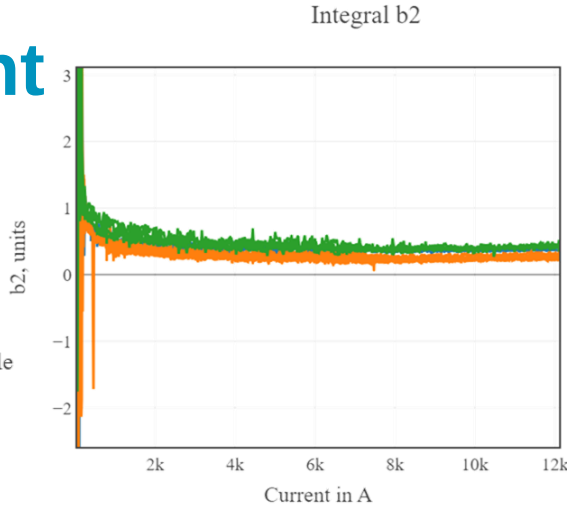
	Current: 790 A		Current: 12110 A	
Quantity	**Unit**	**Value**	**Unit**	**Value**
I	A	790	A	12110
Int. field	Tm	2.5562	Tm	35.188
Int. TF	Tm/kA	3.2357	Tm/kA	2.9057

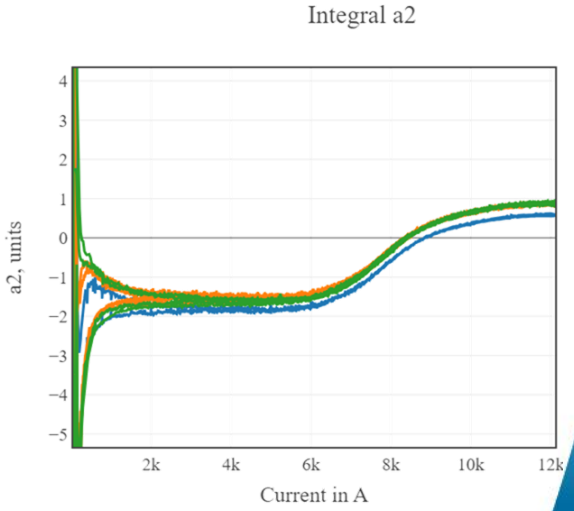
	Current: 790 A		Current: 12110 A	
n	**bn**	**an**	**bn**	**an**
2	0.45	-1.05	0.27	0.88
3	-22.35	2.09	-5.44	1.95
4	0.16	-0.33	0.05	0.12
5	2.04	-0.12	6.68	-0.19
6	-0.01	0.05	0.05	0.00
7	0.24	0.19	0.35	0.20
8	0.06	0.22	0.04	0.15
9	0.35	0.02	0.76	0.00
10	0.03	0.10	0.04	0.10
11	-0.15	0.05	-0.13	0.07
12	0.01	0.05	0.03	0.03
13	-0.69	0.05	-0.73	0.05
14	0.00	0.00	0.00	0.00
15	-1.11	0.02	-1.18	0.03

By Lucio Fiscarelli and Piotr Rogacki
See also https://indico.cern.ch/event/1360284/

MM: Multipoles vs current







By Lucio Fiscarelli and Piotr Rogacki
See also https://indico.cern.ch/event/1360284/

Conclusion

MBXFP1 – D1 prototype horizontal test

- First and second cool down completed.
- Training and holding current tests done.
- 500 powering cycles performed, no issues.
- Behavior as demonstrated by KEK tests confirmed for:
  - Instrumentation, Quench Heater, Quench Integral, Splice, Insulation, Magnetic field

Magnet is being shipped to SMI-2 for preparation for the IT-String: it is the first magnet ready for the IT-String.

Appendix

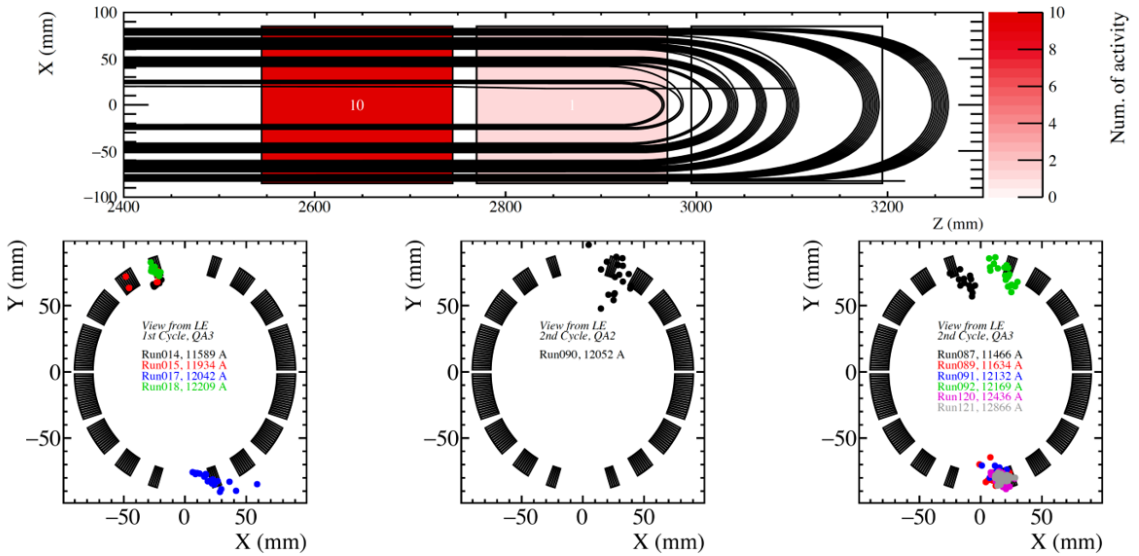
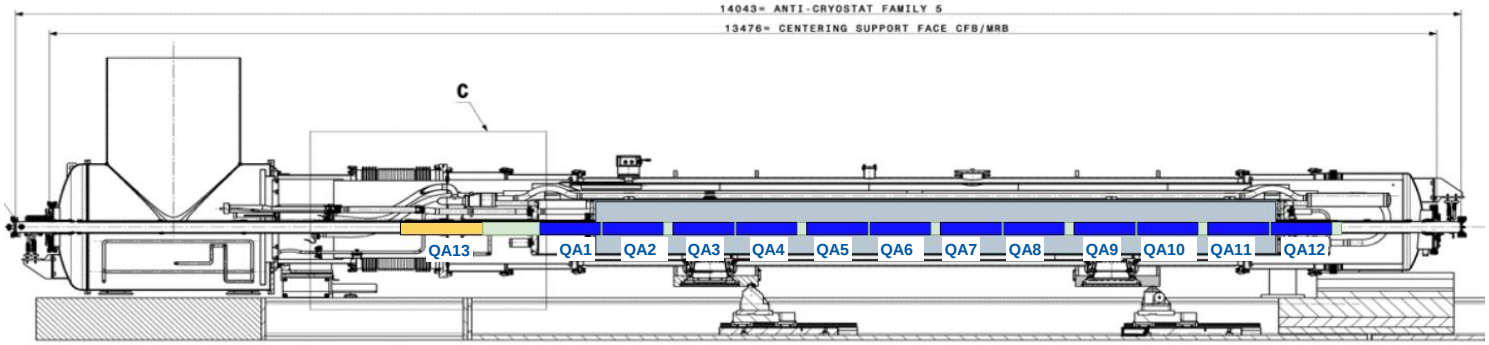


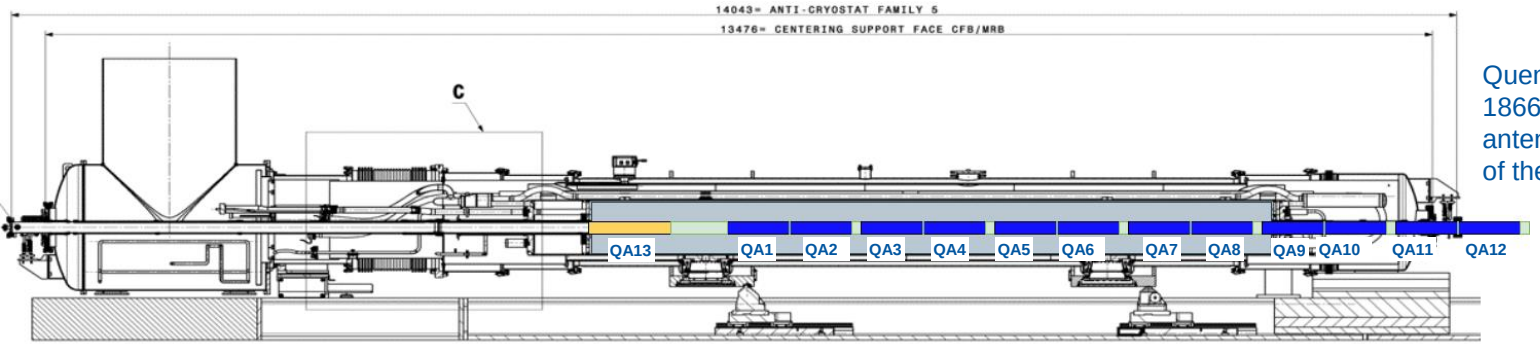
Figure 14: Summary of the quench location analyzed by signals of the quench antennas.

Extract on quench location from KEK test report: EDMS 2747573 and Indico 1077539



D1 nominal position			
PCB	segment start	segment end	
13	-5261	-4461	mm
1	-3920	-3310	mm
2	-3300	-2690	mm
3	-2598	-1988	mm
4	-1978	-1368	mm
5	-1276	-666	mm
6	-656	-46	mm
7	46	656	mm
8	666	1276	mm
9	1368	1978	mm
10	1988	2598	mm
11	2690	3300	mm
12	3310	3920	mm

Position with respect to magnetic center.



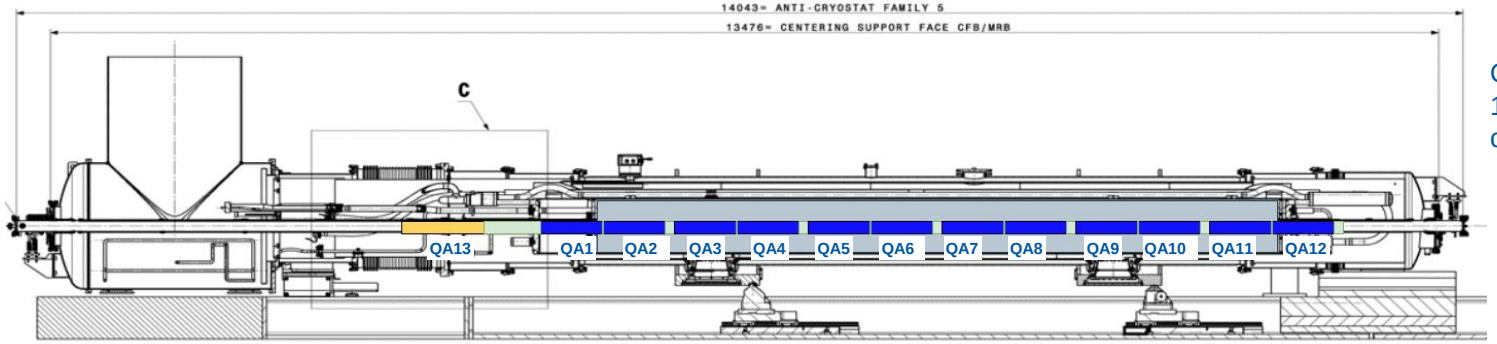
Quench 3 to 6: QA shifted by 1866 mm to have prototype antenna QA13 covering the head of the magnet.

D1 position with 1866 mm shift			
PCB	segment start	segment end	
13	-3395	-2595	mm
1	-2054	-1444	mm
2	-1434	-824	mm
3	-732	-122	mm
4	-112	498	mm
5	590	1200	mm
6	1210	1820	mm
7	1912	2522	mm
8	2532	3142	mm
9	3234	3844	mm
10	3854	4464	mm
11	4556	5166	mm
12	5176	5786	mm

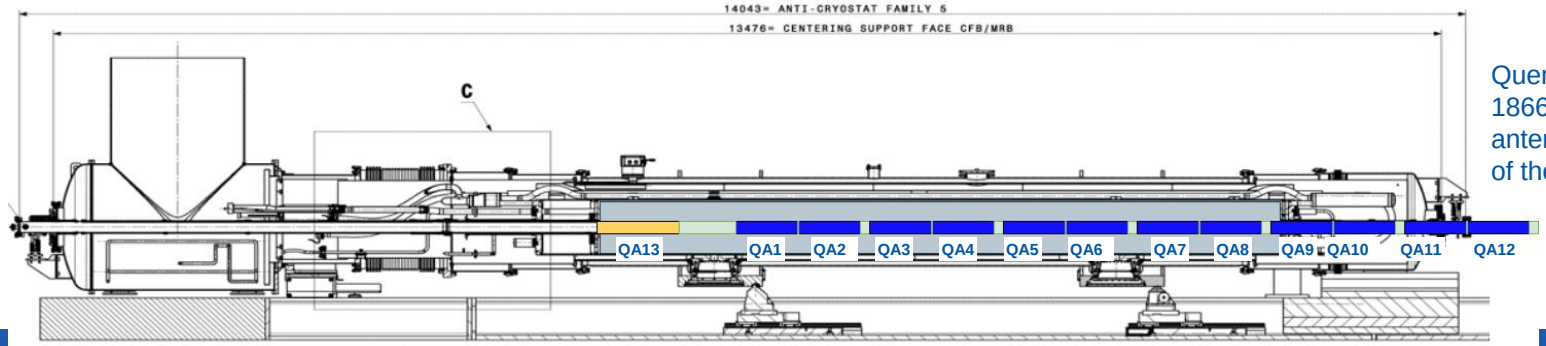
Position with respect to magnetic center.

Magnet training location at CERN

Same Quench Antenna system as for MQXF magnets.



Quench 1 and 2: QA segment 1 to 12 centered with the magnetic field center between QA6 and QA7



Quench 3 to 6: QA shifted by 1866 mm to have prototype antenna QA13 covering the head of the magnet.

Quench 7: no QA because rotating shaft was installed

Magnet training location at CERN

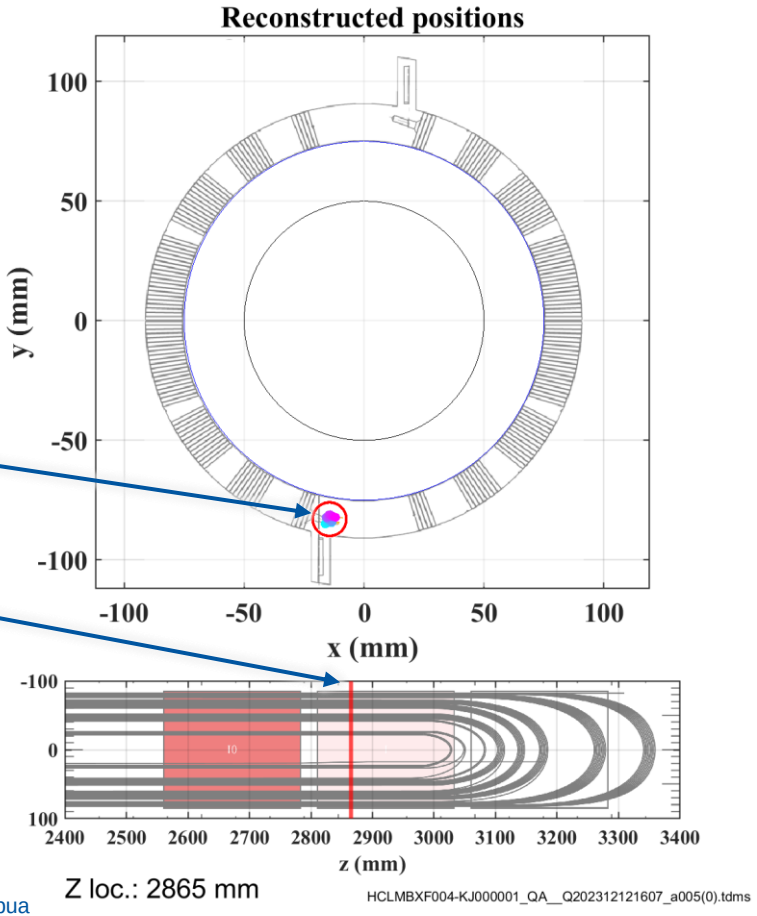
More precise localization: Work in progress and focus for next cool down.

Example for quench 15 (4th quench this cool down)
Main focus on the pole turn and layer exit.

Quench	I (kA)	Coil	Side
1	11.59	U	CS
2	11.93	U	CS
3	12.04	L	CS
4	12.21	U	CS
5	11.47	U	CS
6	11.63	L	CS
7	12.05	U	CS
8	12.13	L	CS
9	12.17	U	CS
10	12.43	L	CS
11	12.87	L	CS
12	11.01	L	CS
13	11.30	L	CS
14	12.53	L	CS
15	12.22	L	NCS
16	12.74	U	CS
17	12.68	L	CS
18	13.16	L	

Azimuthal quench start location.

Longitudinal quench location as identified using the prototype quench antenna, within a few cm precision. Location is around the red line.
Not easy due to a lot of signal from vibrations.

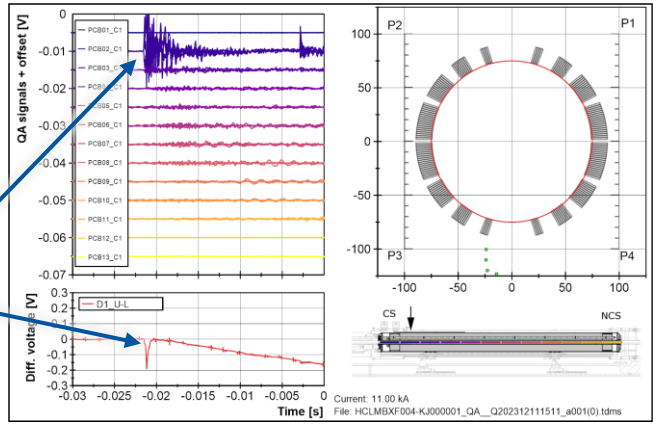


Thanks to Piotr Rogacki and Vincenzo di Capua

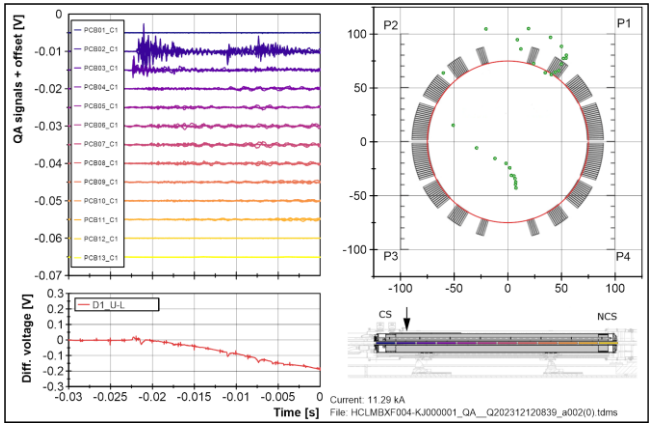
Magnet training location at CERN

Quench	I (kA)	Coil	Side
1	11.59	U	CS
2	11.93	U	CS
3	12.04	L	CS
4	12.21	U	CS
5	11.47	U	CS
6	11.63	L	CS
7	12.05	U	CS
8	12.13	L	CS
9	12.17	U	CS
10	12.43	L	CS
11	12.87	L	CS
12	11.01	L	CS
13	11.30	L	CS
14	12.53	L	CS
15	12.22	L	NCS
16	12.74	U	CS
17	12.68	L	CS
18	13.16	L	

Precursor motion



Quench 12
Clear motion and precursor
Difficult azimuthal localization



Quench 13
Clear motion – difficult azimuthal localization

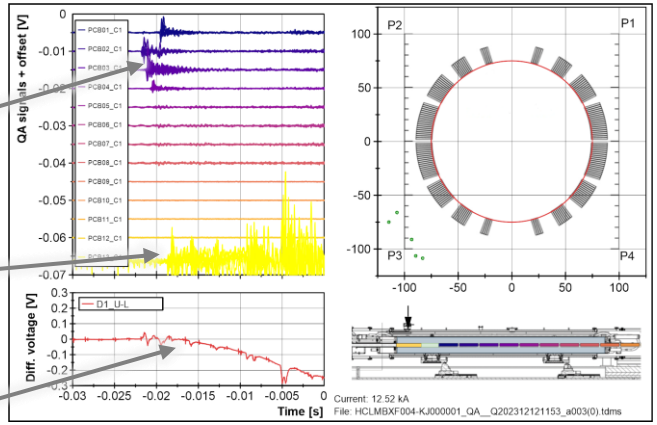
Magnet training location at CERN

Quench	I (kA)	Coil	Side
1	11.59	U	CS
2	11.93	U	CS
3	12.04	L	CS
4	12.21	U	CS
5	11.47	U	CS
6	11.63	L	CS
7	12.05	U	CS
8	12.13	L	CS
9	12.17	U	CS
10	12.43	L	CS
11	12.87	L	CS
12	11.01	L	CS
13	11.30	L	CS
14	12.53	L	CS
15	12.22	L	NCS
16	12.74	U	CS
17	12.68	L	CS
18	13.16	L	

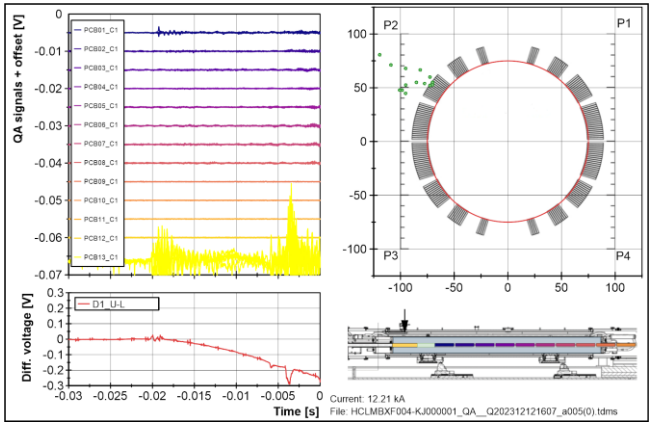
Motion more towards the center, likely unrelated to quench start.

Motion leading to the quench, in segment 13.

Voltage build up.



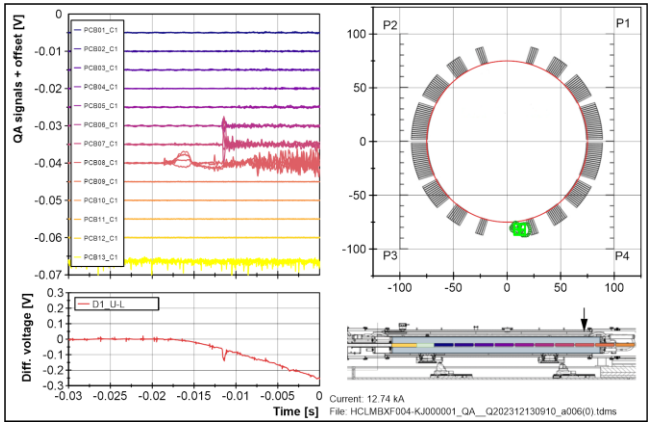
Quench 14
Shifted quench antenna (new segment has different number of turns and larger amplitude signal)
Clear motion



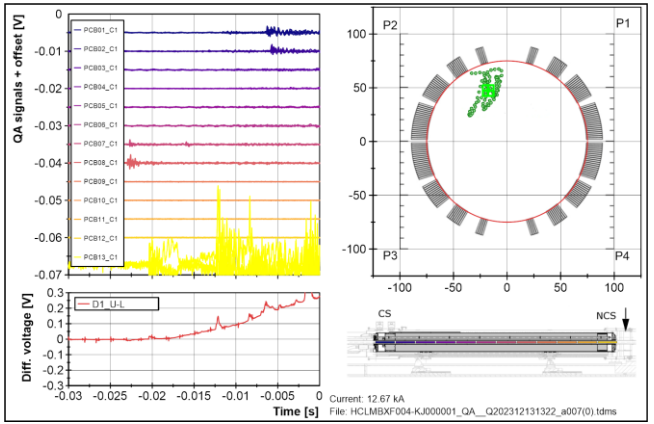
Quench 15
Clear motion – difficult azimuthal localization

Magnet training location at CERN

Quench	I (kA)	Coil	Side
1	11.59	U	CS
2	11.93	U	CS
3	12.04	L	CS
4	12.21	U	CS
5	11.47	U	CS
6	11.63	L	CS
7	12.05	U	CS
8	12.13	L	CS
9	12.17	U	CS
10	12.43	L	CS
11	12.87	L	CS
12	11.01	L	CS
13	11.30	L	CS
14	12.53	L	CS
15	12.22	L	NCS
16	12.74	U	CS
17	12.68	L	CS
18	13.16	L	



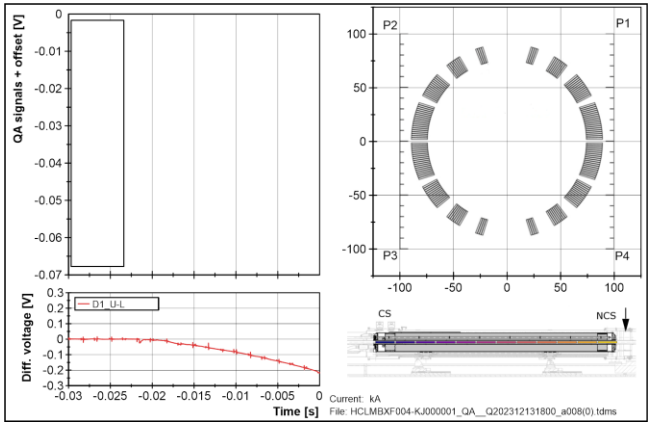
Quench 16
First quench in NCS
Localized in pole turn



Quench 17
Clear motion – difficult azimuthal localization
Head CS

Magnet training location at CERN

Quench	I (kA)	Coil	Side
1	11.59	U	CS
2	11.93	U	CS
3	12.04	L	CS
4	12.21	U	CS
5	11.47	U	CS
6	11.63	L	CS
7	12.05	U	CS
8	12.13	L	CS
9	12.17	U	CS
10	12.43	L	CS
11	12.87	L	CS
12	11.01	L	CS
13	11.30	L	CS
14	12.53	L	CS
15	12.22	L	NCS
16	12.74	U	CS
17	12.68	L	CS
18	13.16	L	



Quench 18

No quench antenna installed