HFM

High Field Magnets Programme

RMM1e
Cold Test results

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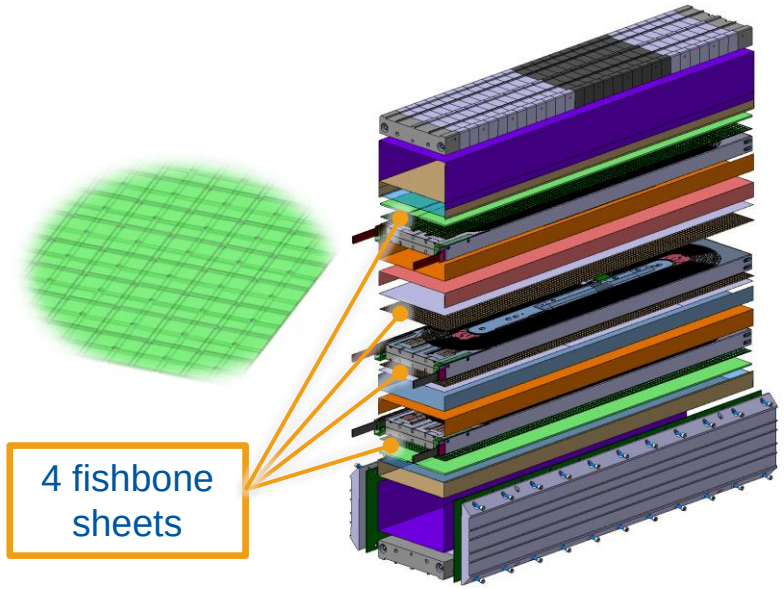
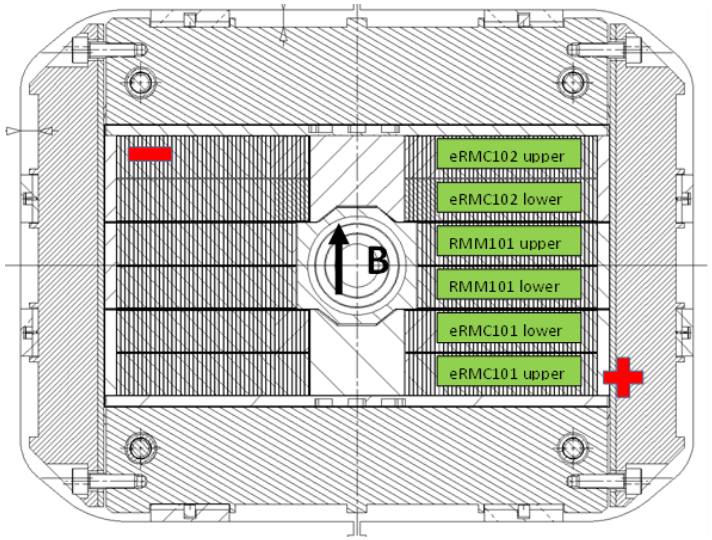
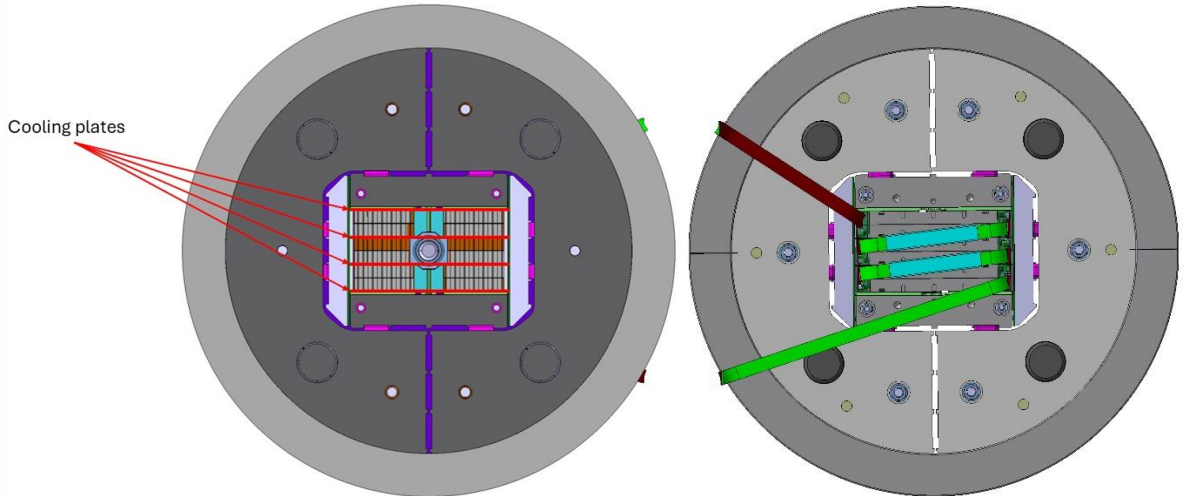
EDMS: 3397157

The Magnet

Main magnet parameters





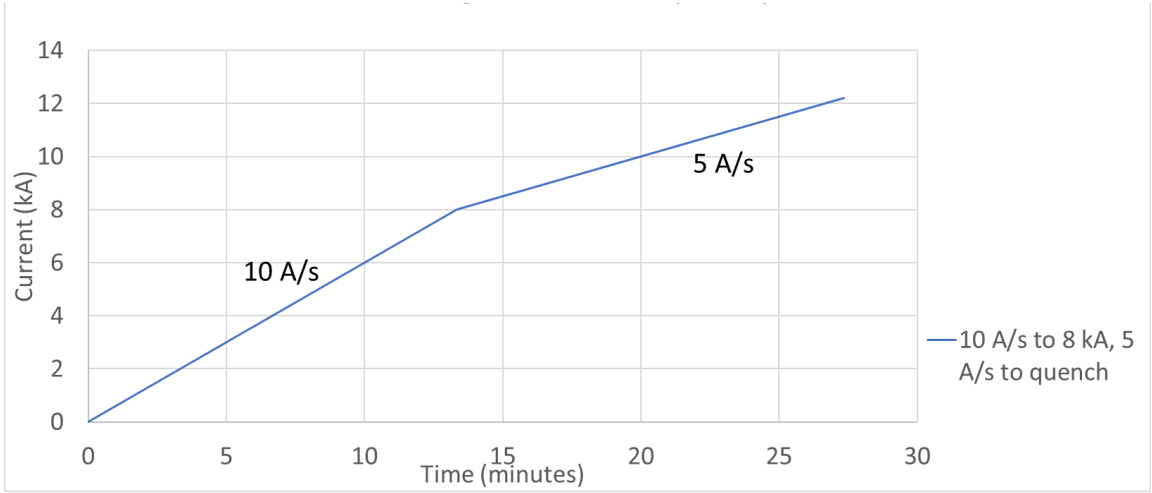


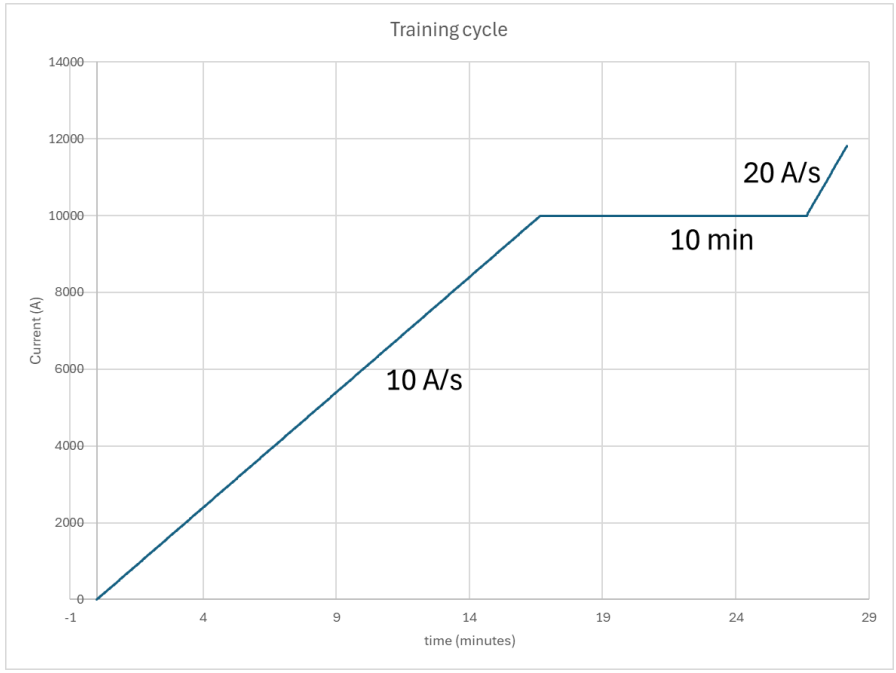
Powering parameters:	**1.9 K**	**4.5 K**
Nominal Current	11.4 kA	
Target Current	11.81 kA	-
Short sample limit	13.64 kA	12.15 kA
Nominal stored energy	1.17 MJ	-
Peak field on coil	17 T at 11.81 kA	
Target bore field	16.5 T	
Maximum QI, hotspot temperature	25 MA^2s, 97 K	
Baseline protection	Dump: 80 mOhm	
Instrumentation	Strain gauges, magnetic measurements, acoustic emission sensors	

Training

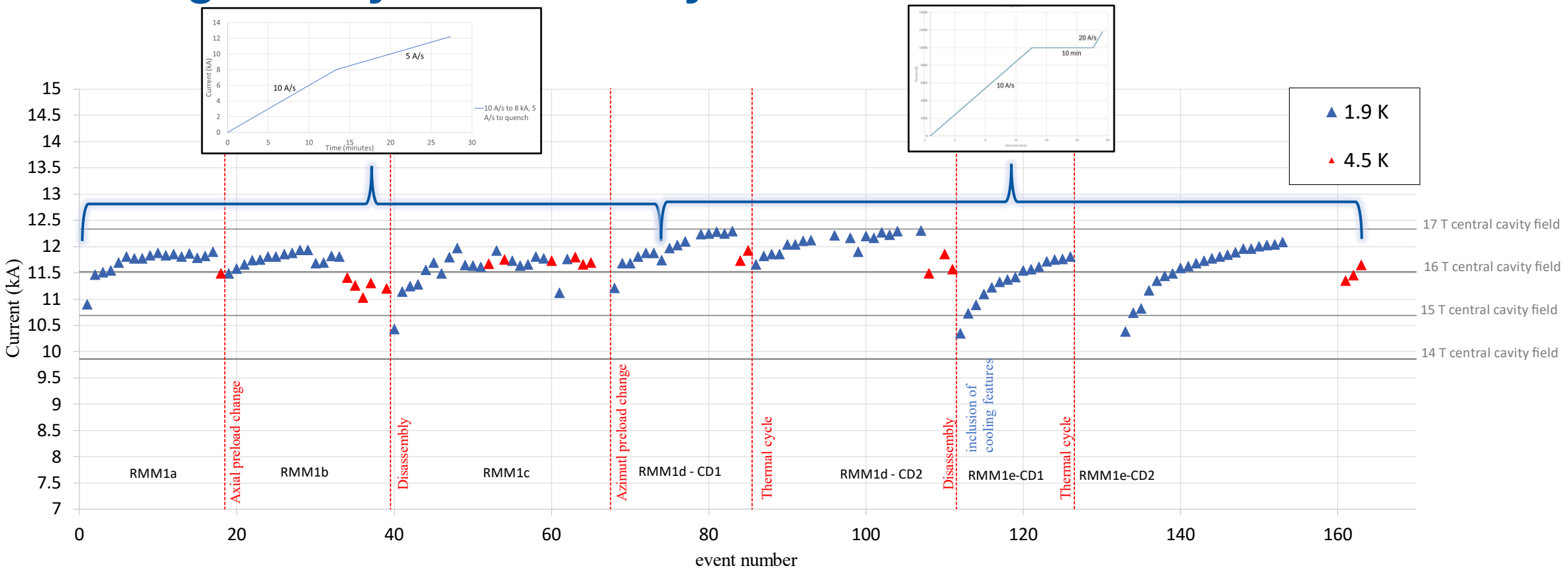
Training cycles

- RMM1a, b, and c were trained with a **two slopes ramp.**
- 10 A/s up to 8 kA and then 5 A/s until quench.
- This approach have **been kept for the first eight quenches in RMM1d** before to move to a different **strategy to avoid the occurrence of quenching in the low field region** (conductor limitation).
- Low field region quenches during ramps occurring from **RMM1c from 11.6 kA.**
- Not visible in RMM1a and RMM1b up to respectively 11.9 kA and 11.93 kA.



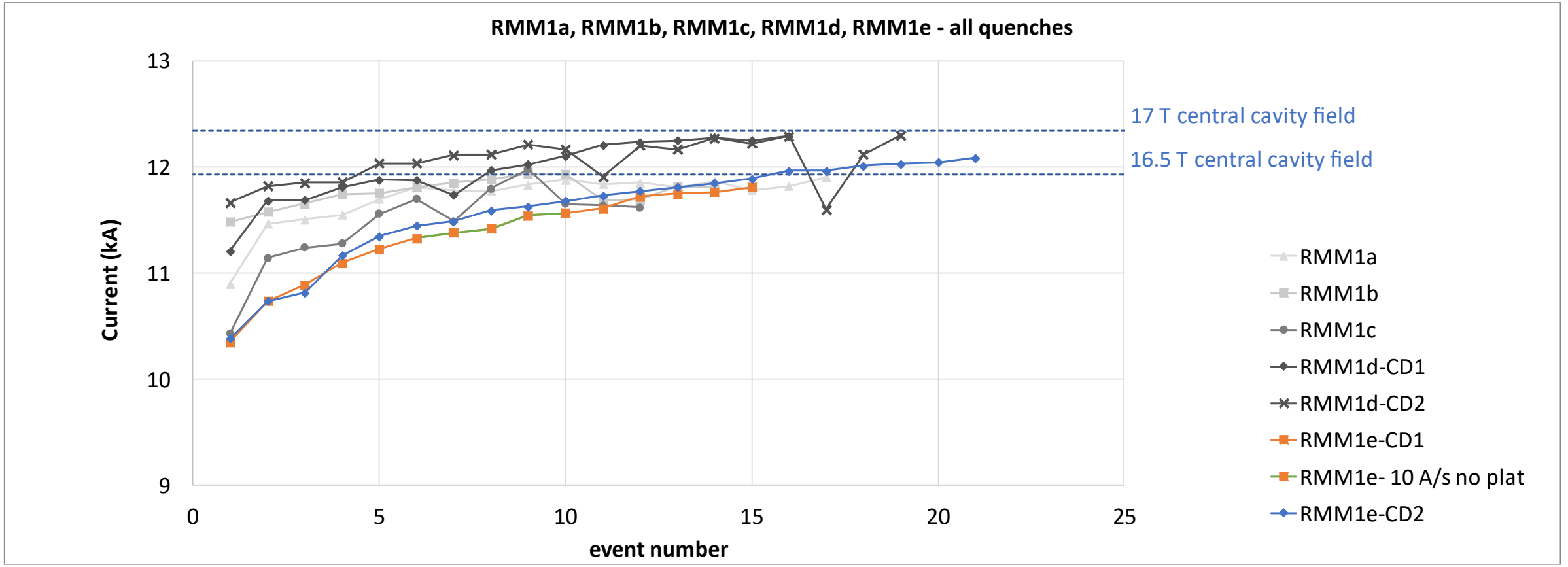


Training history RMM1 family



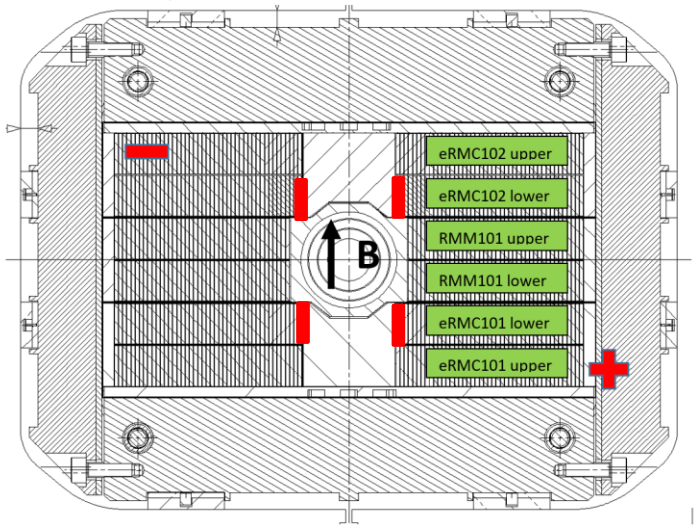
- **Slower training** (more quenches needed to reach target field).
- **Less erratic** (No detraining events).

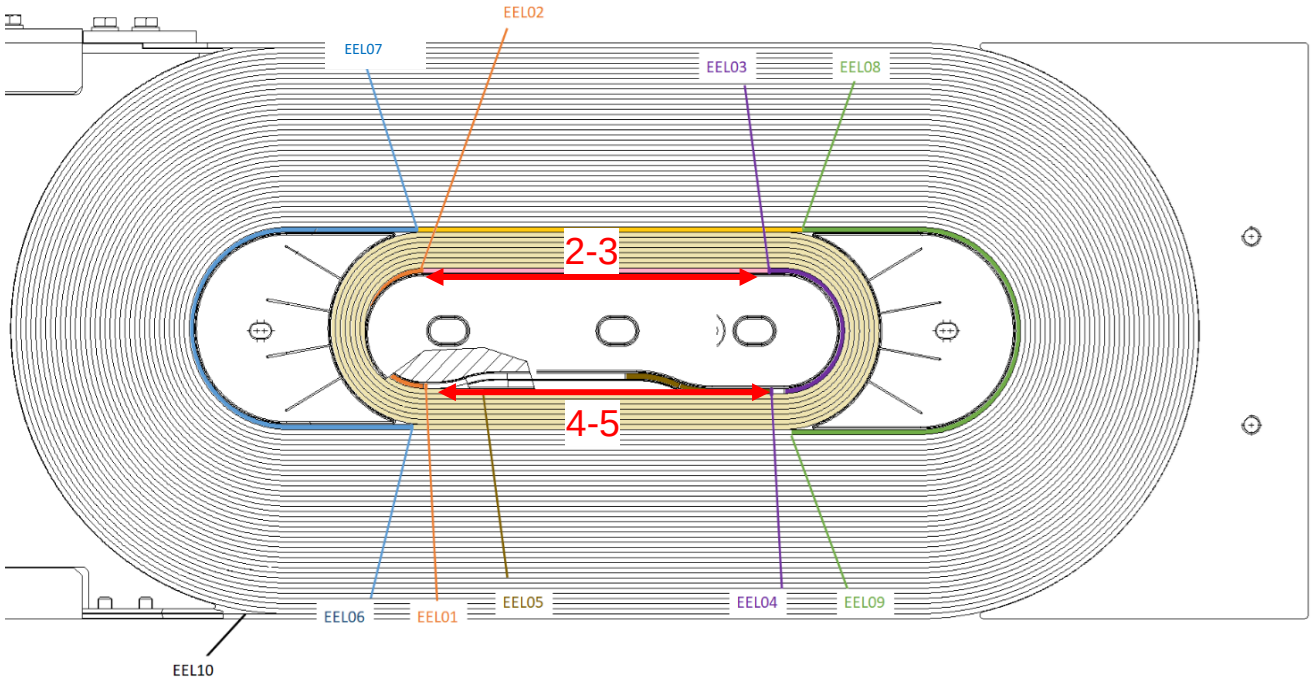
Training history RMM1e



- First quench at **10.35 kA.**
- **Monotonic** training.
- Complete **loss of memory** after thermal cycle.
- Re-training with **same slope.**

Quench location



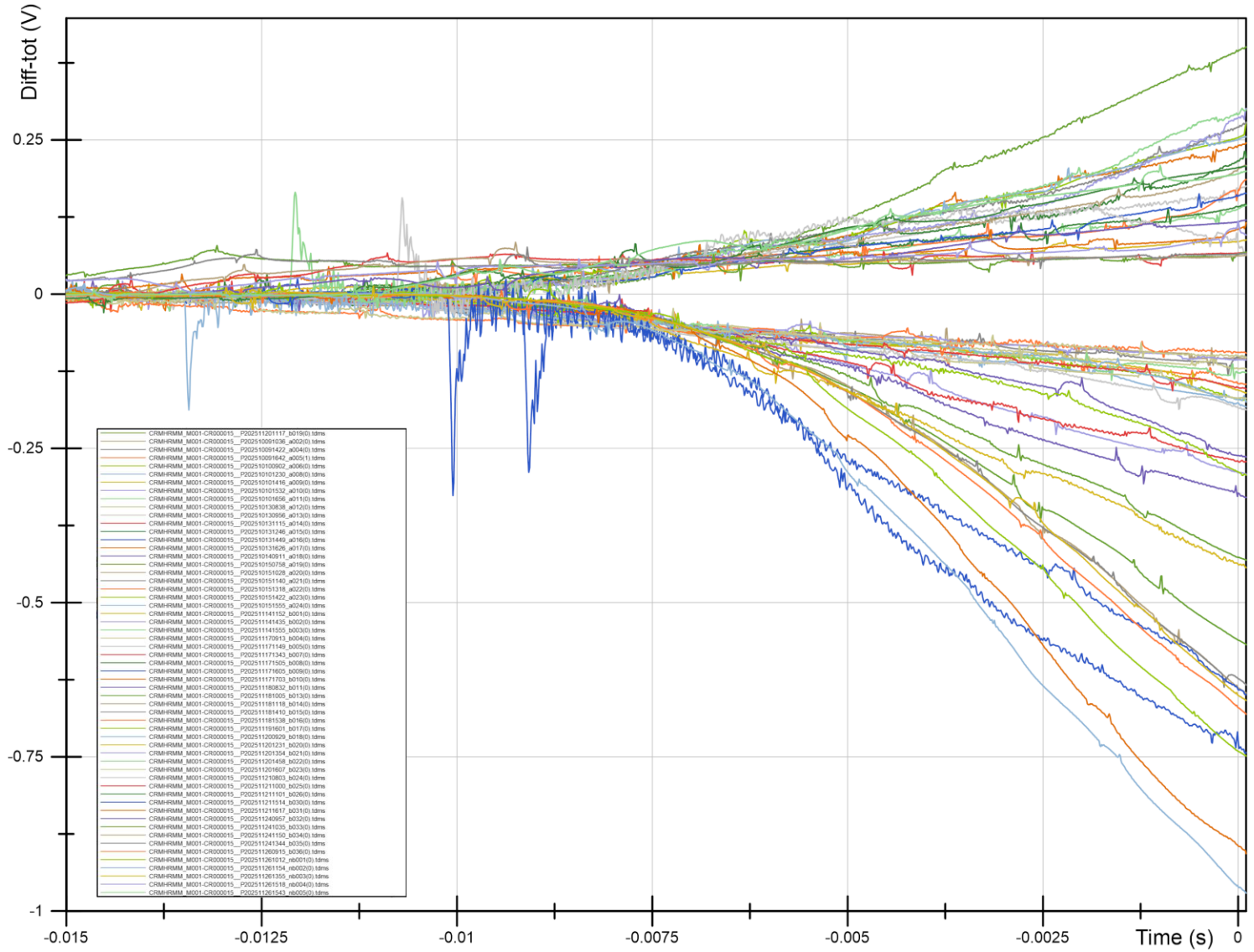


- Most of the quenches started in **eRMC101** and **eRMC102**.
- Most of the quenches in the lower layers and in the **straight regions identified by EEL05-EEL04** (with propagation to **EEL06-EEL05**) and **EEL03-EEL02.**
- **Three quenches occurred in the upper layer** in both coils eRMC101 and eRMC102.

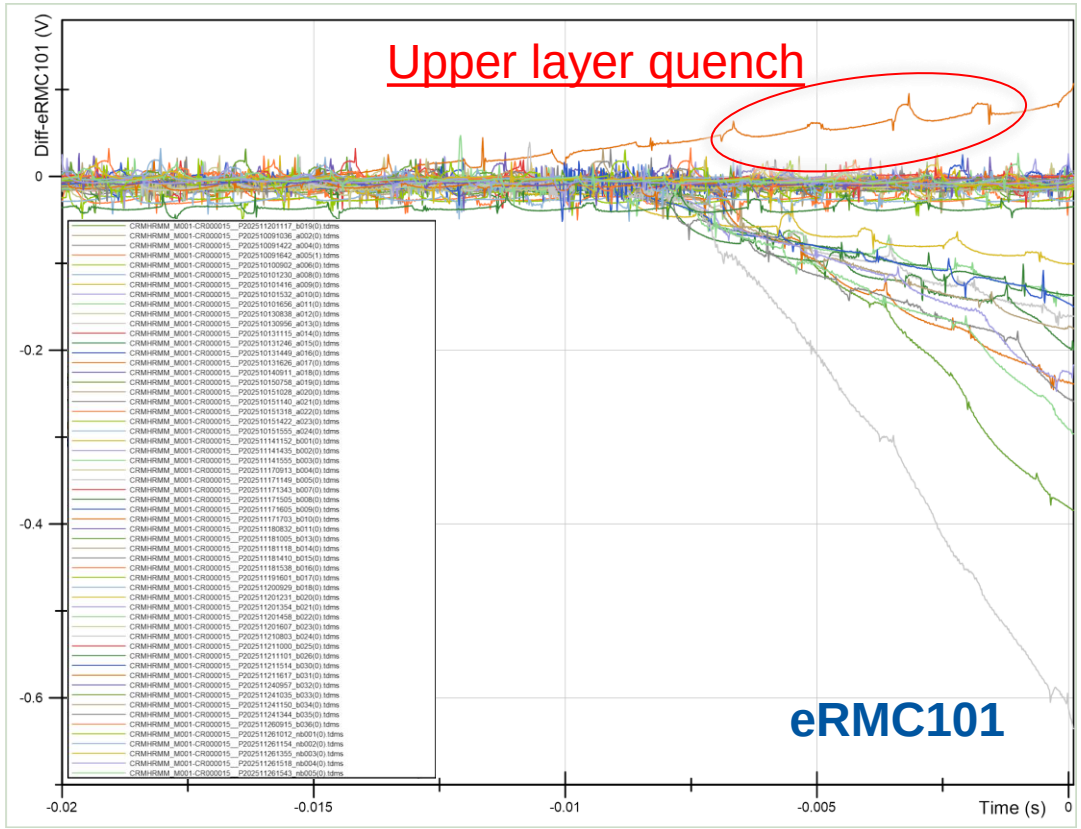
Quench signatures

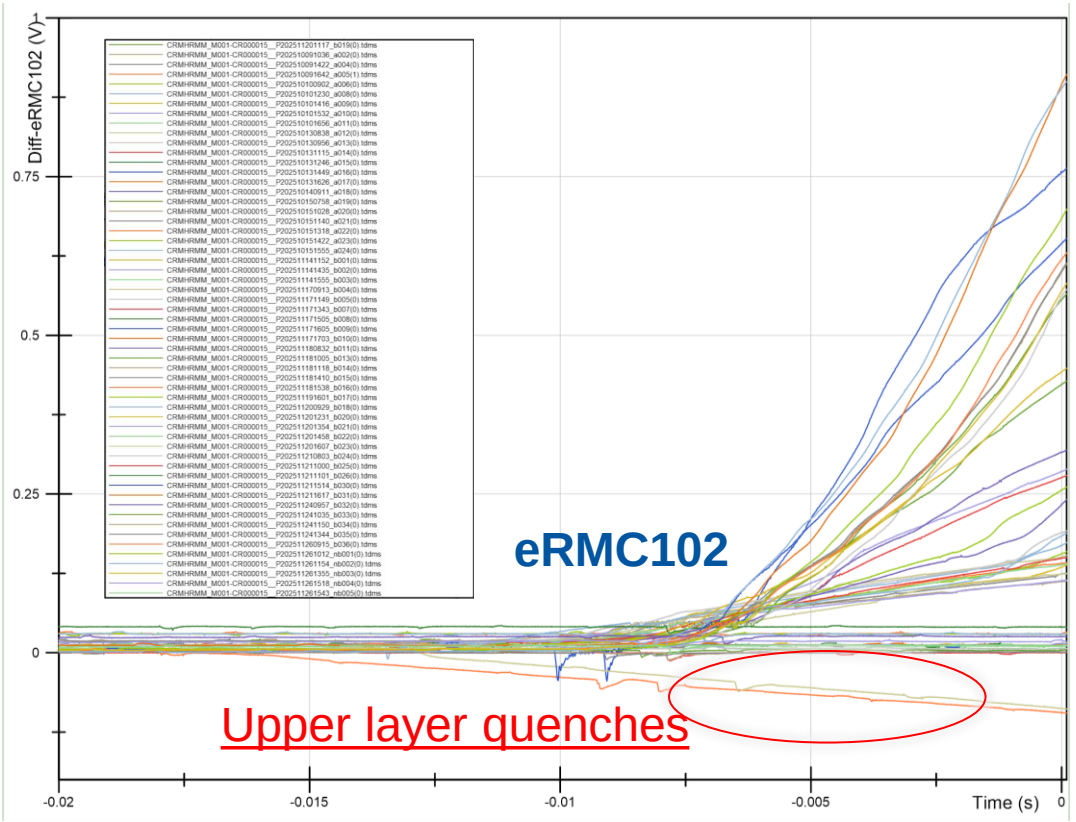
- Almost **all** the **quenches** showed a very **similar behaviors** in terms of quench start and propagation.

- Only **five of the quench showed a precursor**, one in the first cool down and four in the second one.



Quench signatures – eRMC coils

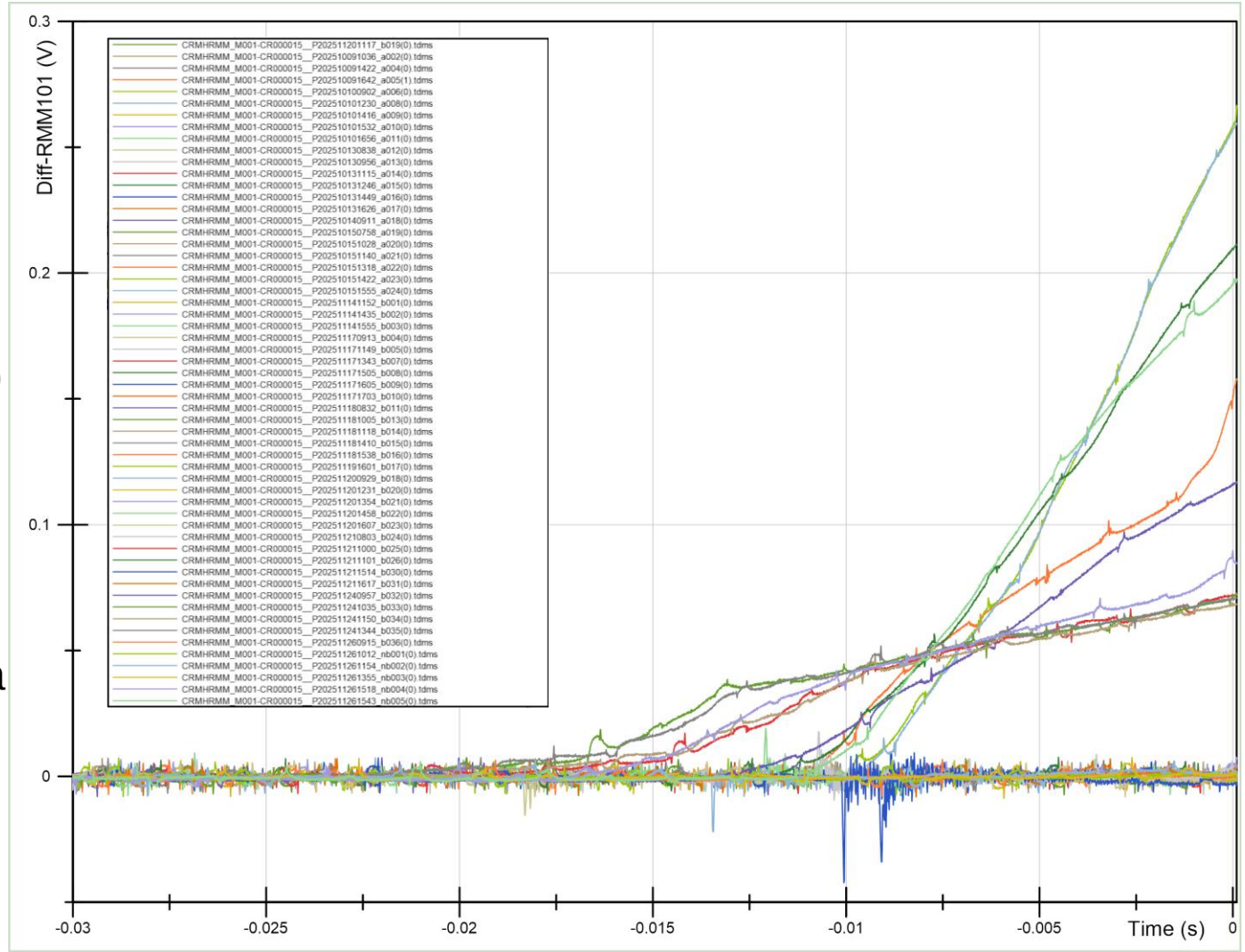




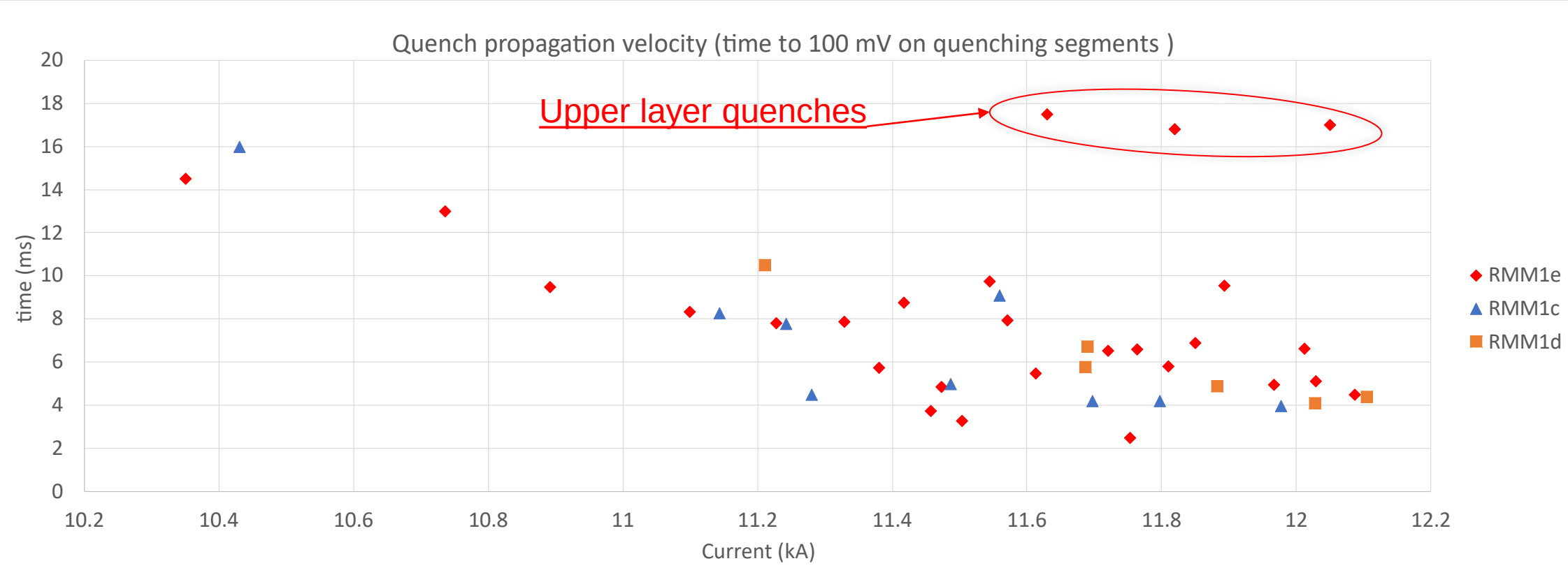
- **Three of the precursors** occurred in the **eRMC102** coil with a very similar quench propagation.
- **First time** a quench start in the **upper plates** (lower field region compared to lower plates) .
  - **Quench propagation is slower** than the rest of the quenches developed in the lower plates.

Quench signatures – RMM coil

- **Twelve** quenches in **RMM** coil.
- All of them developed during the **ramp rate** studies (above 40 A/s) or **flat top** quenches.
- **Ramp rate quench location:** L07-L06
- **Holding current quench location:** L11-L09
- NO Quench of the RMM coil happened during the standard training.
- In two cases the Quench was preceded by a precursor.
- A reaction to the precursor in the eRMC102 is visible.



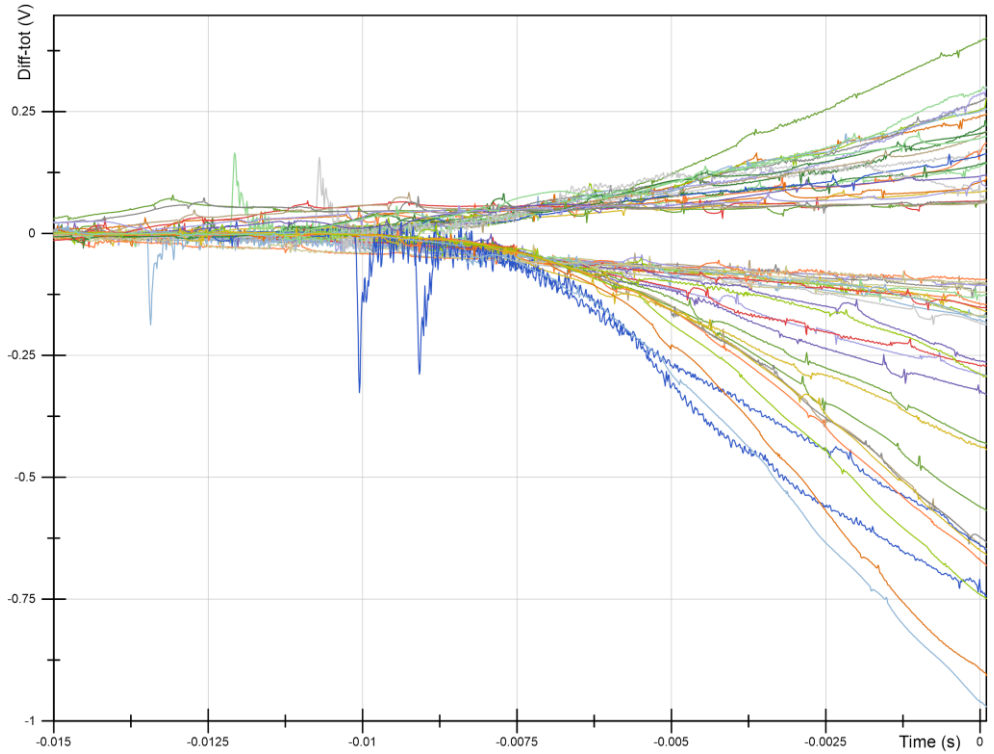
Quench propagation velocity RMM1



- **Quench propagation velocity is comparable** for the last three RMM iterations.
- **Variability** due to the different **quench location.**

Quench precursors energy

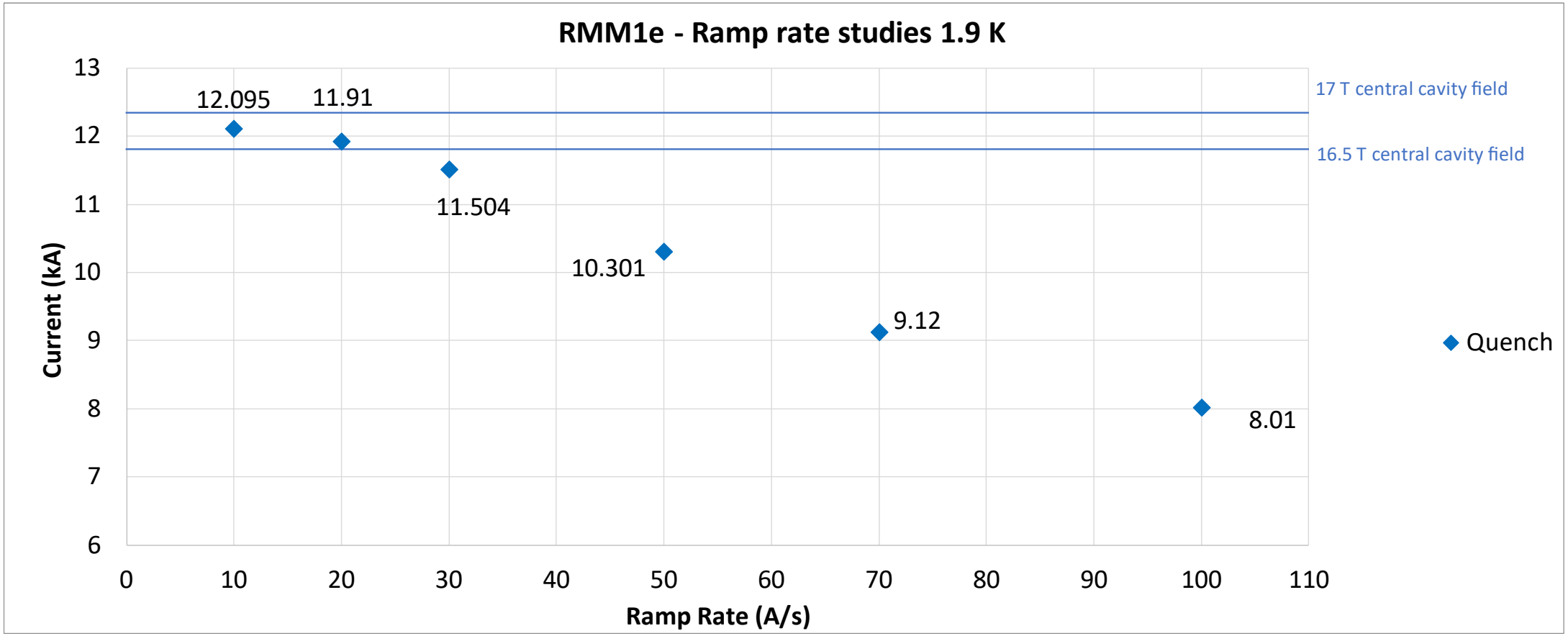
- **Energy of the precursor** computes as:
  - $\mathrm{E} = \int_{T_{start}}^{T_{end}} V_{prec} \cdot I \, \mathrm{dt}$
- Energy of the precursors compatible within the RMM1c and RMM1d
- Lower precursors energy in RMM1e with respect to the last two predecessors.
- Deviation within the same iteration is also compatible with the predecessors.



Magnet	Mean energy (mJ)	Std energy (mJ)
RMM1c	1.4	0.14
RMM1d	0.98	0.62
RMM1e	0.44	0.12

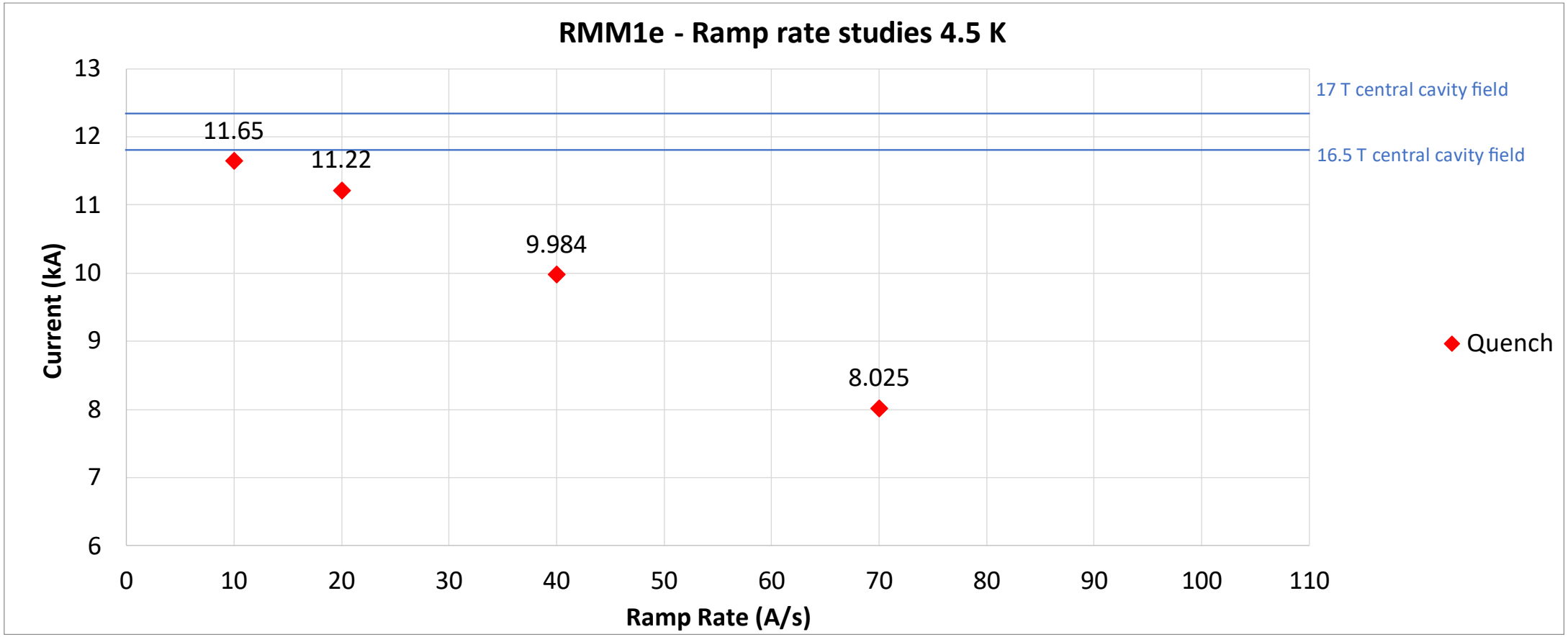
Ramp rate studies

Ramp rate studies – RMM1e 1.9 K



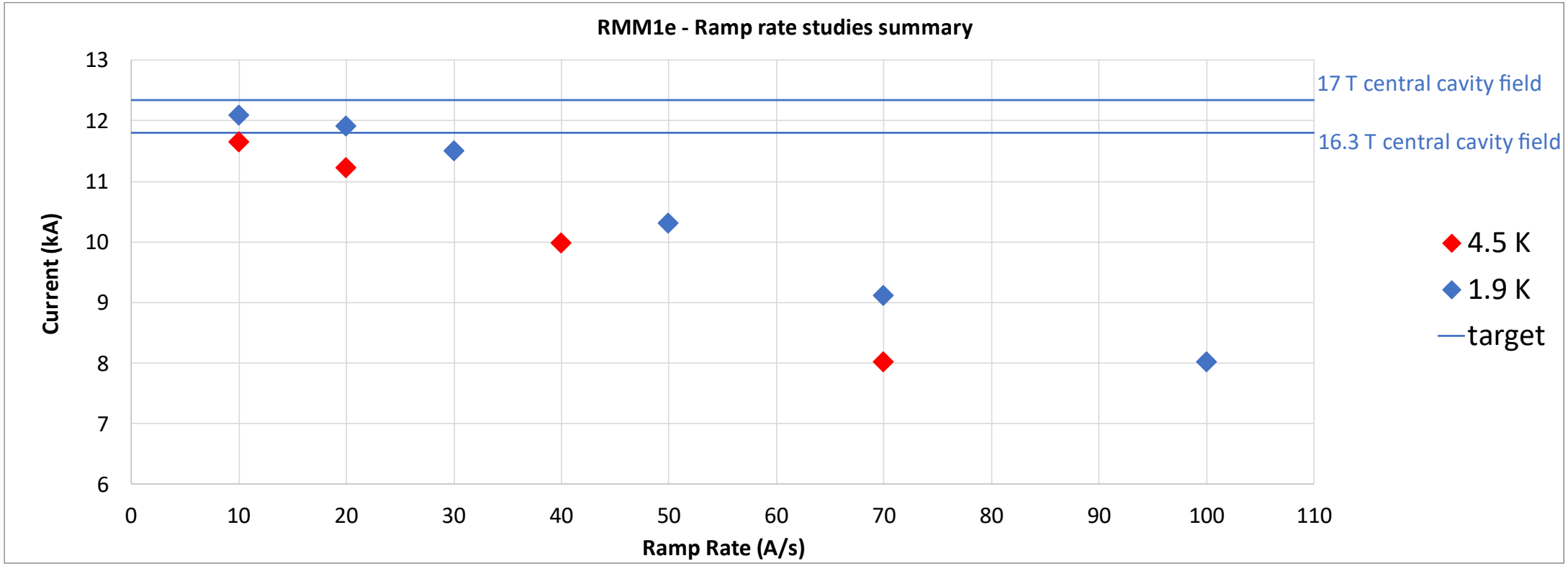
- Not possible to compare with any predecessor.
- Useful as a reference.
- ~ 1.2 kA lost each 20 A/s

Ramp rate studies – RMM1e 4.5 K



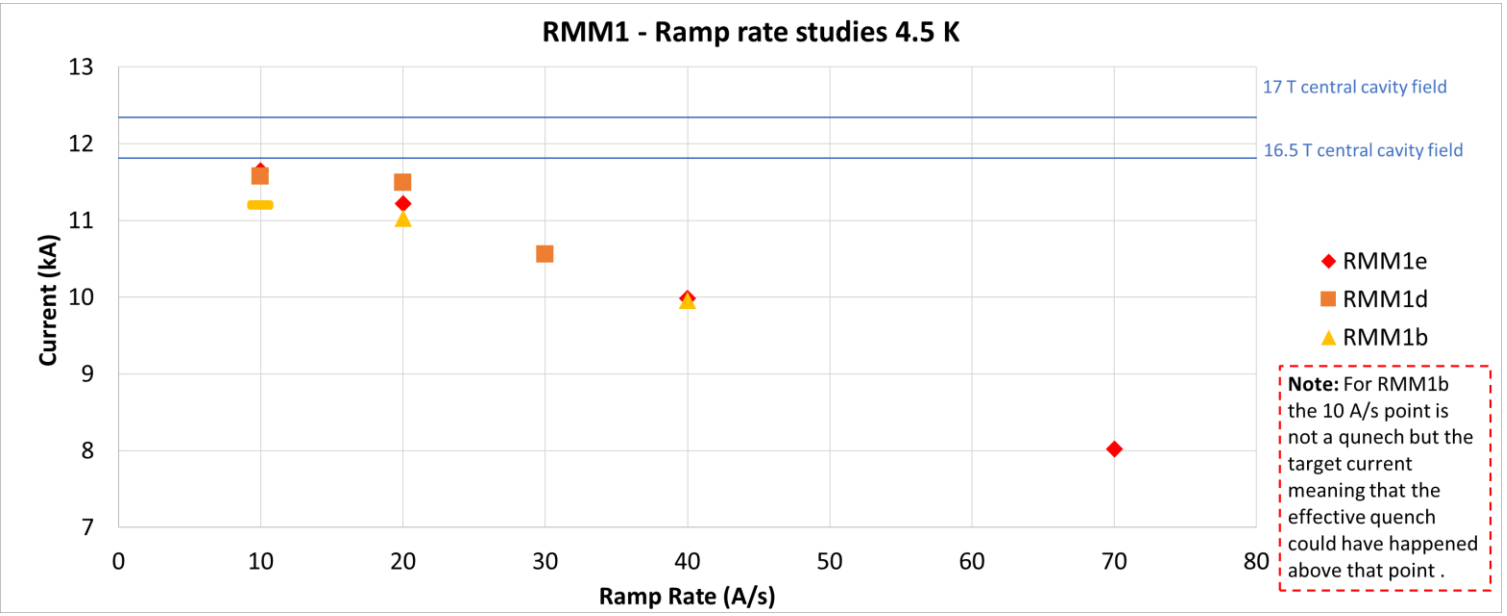
- At 4.5 K it seems that we have ~ 1.2 kA lost each 20 A/s

Ramp rate studies – RMM1e



- Less than 10 % of difference between 1.9 K and 4.5 K at 10 A/s.
- Difference increase at higher ramp rates.

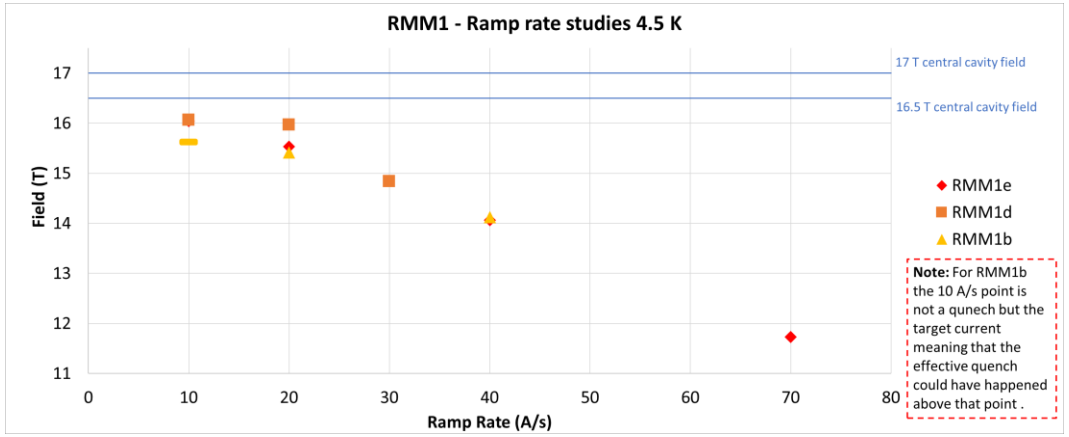
Ramp rate studies – RMM1 4.5 K



- RMM1a => No ramp rate studies.
- **RMM1b =>** Ramp rate studies at 4.5 K (20 A/s and 40 A/s).
- RMM1c => No ramp rate studies.
- **RMM1d =>** Ramp rate studies at 4.5 K (10 A/s 20 A/s and 30 A/s).
- **RMM1e =>** Ramp rate studies at both 1.9 and 4.5 K.
  - **1.9 K**
    - 10 A/s, 20 A/s, 30 A/s, 50 A/s, 70 A/s, 100A/s
  - **4.5 K**
    - 10 A/s 20 A/s, 40 A/s, 70 A/s

- In field the results match even closer.

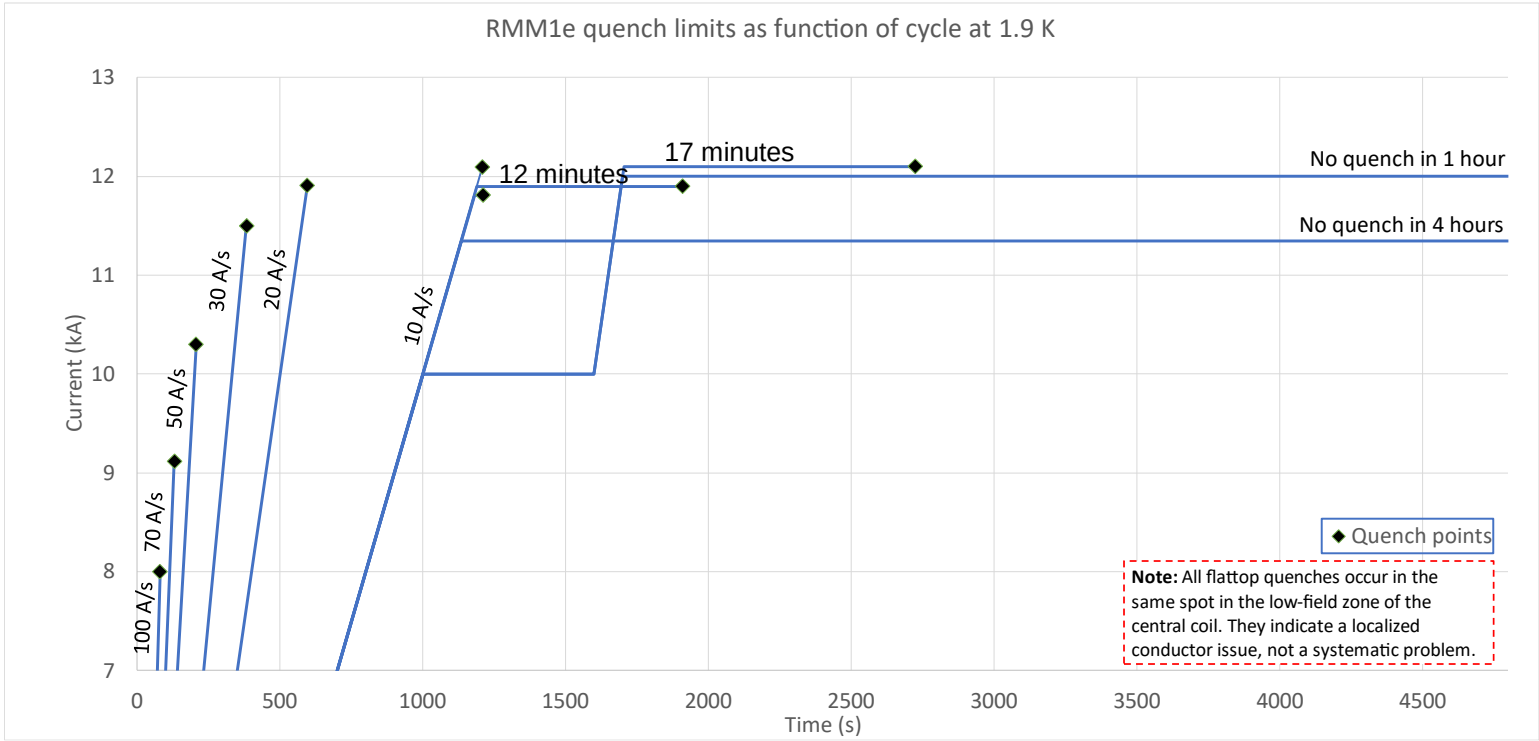
- Given that in **RMM1e** for a given current **the field in the cavity is slightly lower** with respect to the previous iterations due to **the fishbone presence.**



Holding current

Holding current and quench limits

- Holding current studies only at 1.9 K.
- All quenches occurred in **RMM101 L11-L09 as for all the predecessors.**
- Low field region (RMM101 L11-L09) affected by **conductor limitations visible from RMM1b.**
- **Holding current quenches due to current redistribution.**



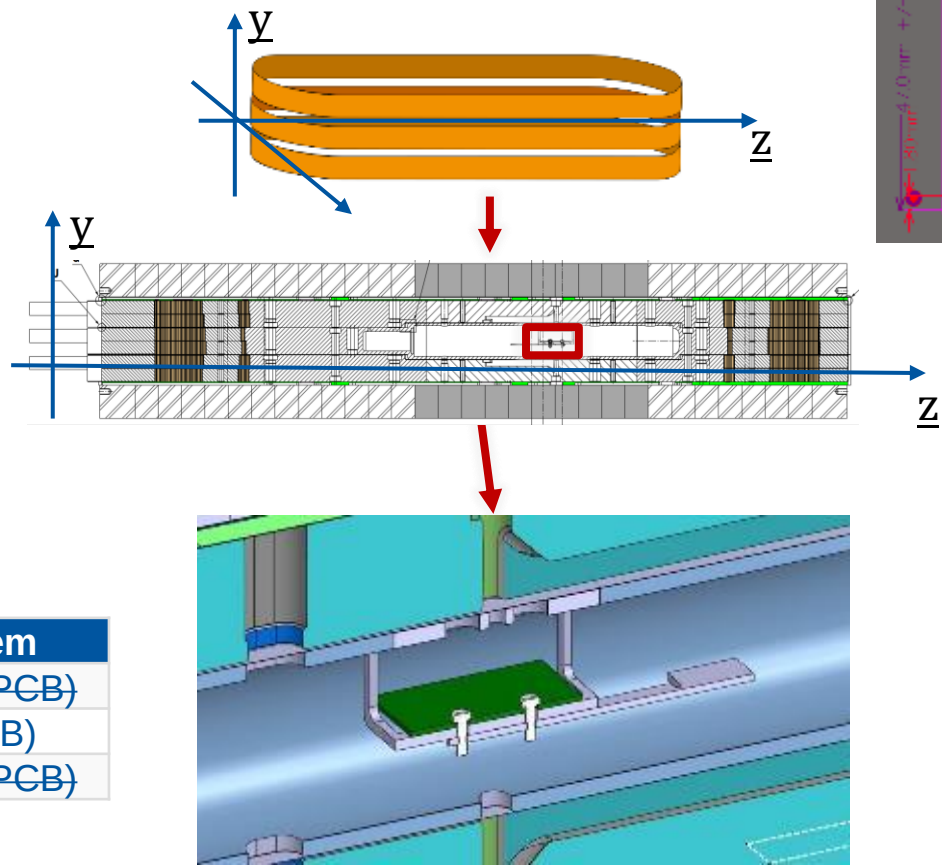
	Current (kA)	B (T)	Time before quench (min)	Intermediate plateau
RMM1e	12.1	16.64	17	YES
	12.0	16.57	No quench (1h)	YES
	11.9	16.34	12	NO
	11.35	15.73	No quench (4h)	NO

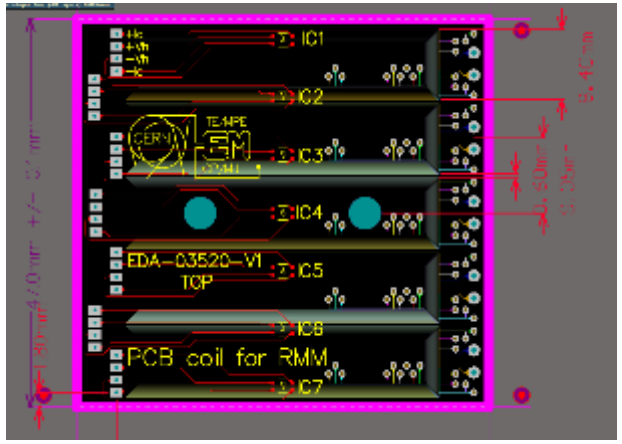
	Current (kA)	B (T)	Time before quench (min)	Intermediate plateau
RMM1d	12.1	16.71	0.14 (8.5 s)	YES
	12.0	16.59	11.3	YES
	11.8	16.34	48	YES

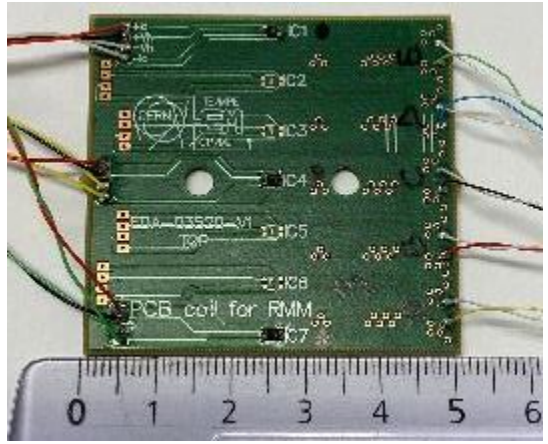
Magnetic measurements

The setup

- **Same measurement setup used for RMM 1a, 1b, 1c, 1d.**
- **Induction coils** used to measure **central field and homogeneity** in correspondence with quench/extraction events (≈ 5.5 T/s).
- **Central coil lost**. Replaced with **extrapolation of the remaining ones.**
- **Hall sensors** acquired but not used in this iteration.



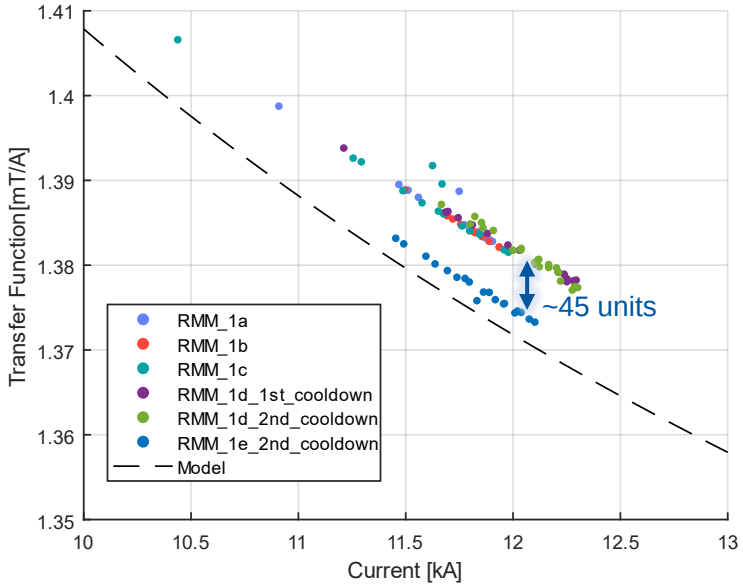


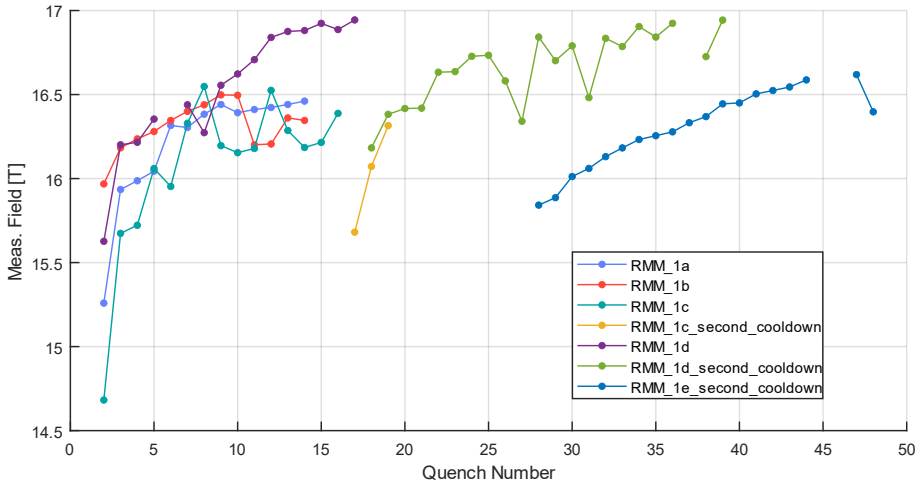


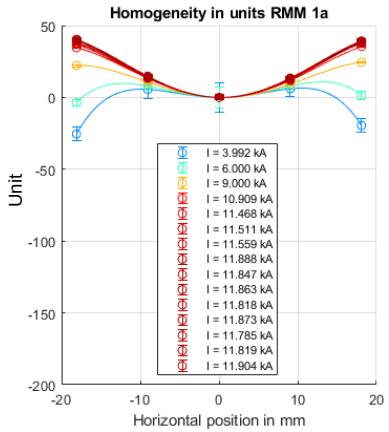
Quantity of interest	Measurement system
Central field	~~Central induction coil (PCB)~~
Homogeneity	4 induction coils (PCB)
DC transfer function	~~Central induction coil (PCB)~~

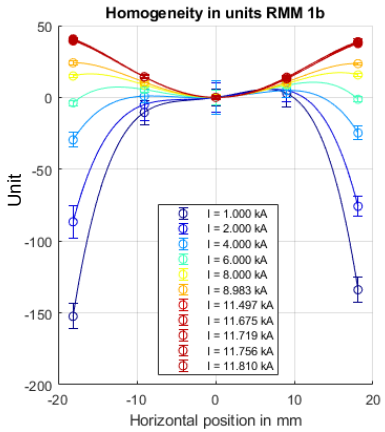
Magnetic measurements results

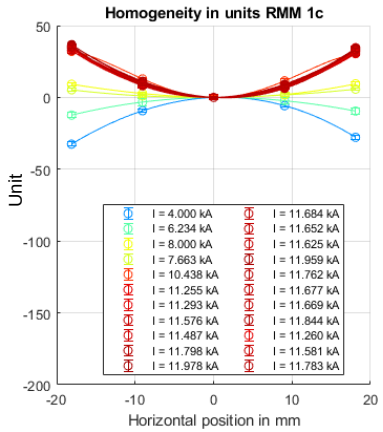
- **~15 units** of difference with respect to the model
- **~45 units** of difference between RMM1e and predecessors**.**
- Homogeneity in line with the predecessors up to the measured level.

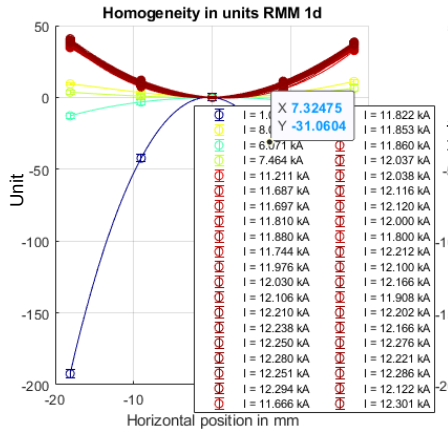


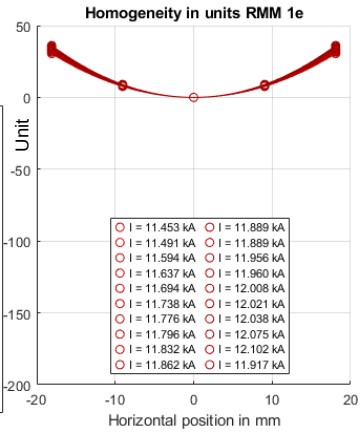








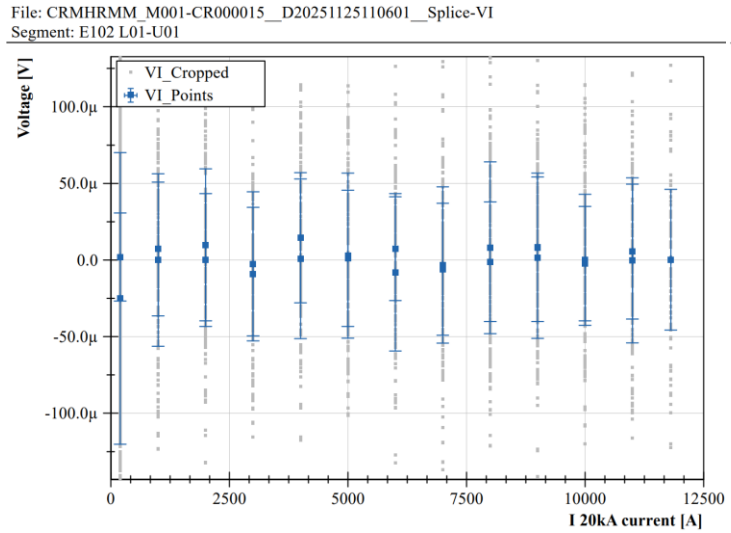


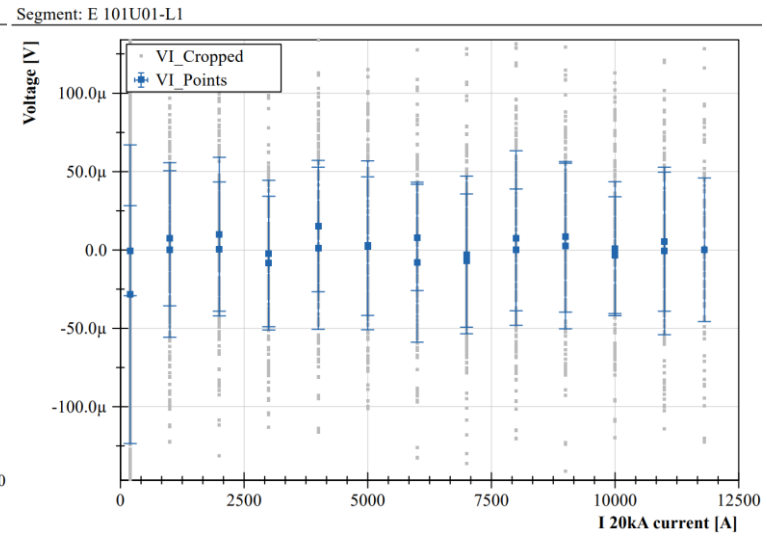


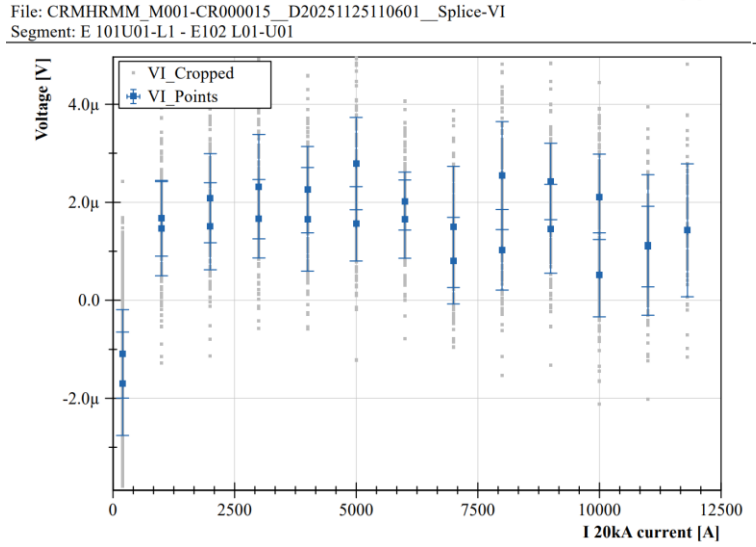
Electrical stability

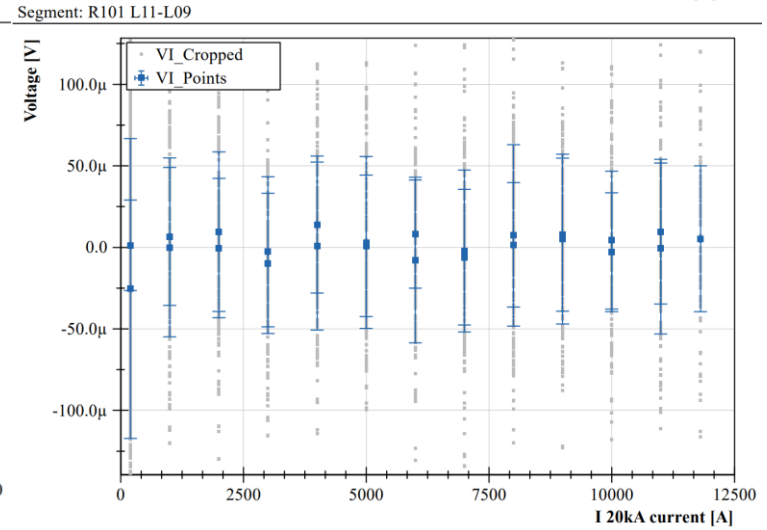
V-I measurements

- V-I measurement performed at the end of the 1.9 K powering.
- Performed up to 11.81 kA
- No signs of performance degradation compared to the beginning of the tests.
- No V-I measurements have been performed at the end of the 4.5 K powering.









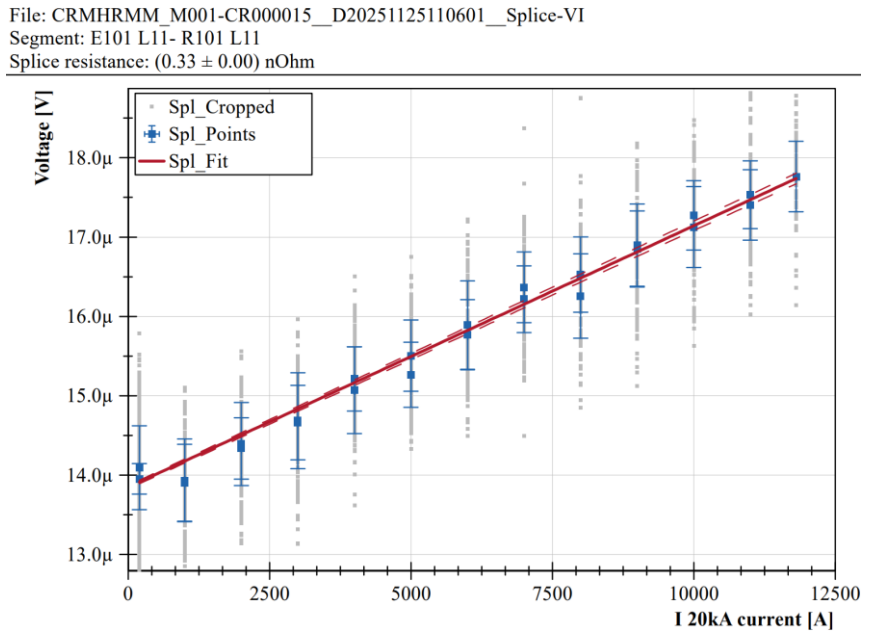
Splices resistance measurement

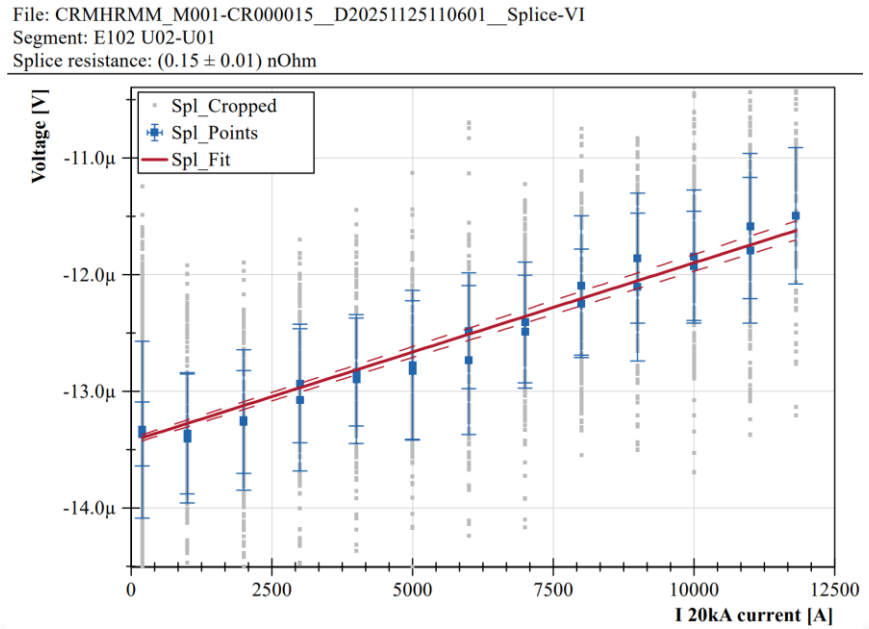
- Splice resistance values measured on a stair step cycle.

- Four splices measured individually.
  - Two inter coil.
  - Two Nb3Sn-NbTi

- No surprise, values compatible with previous iterations.

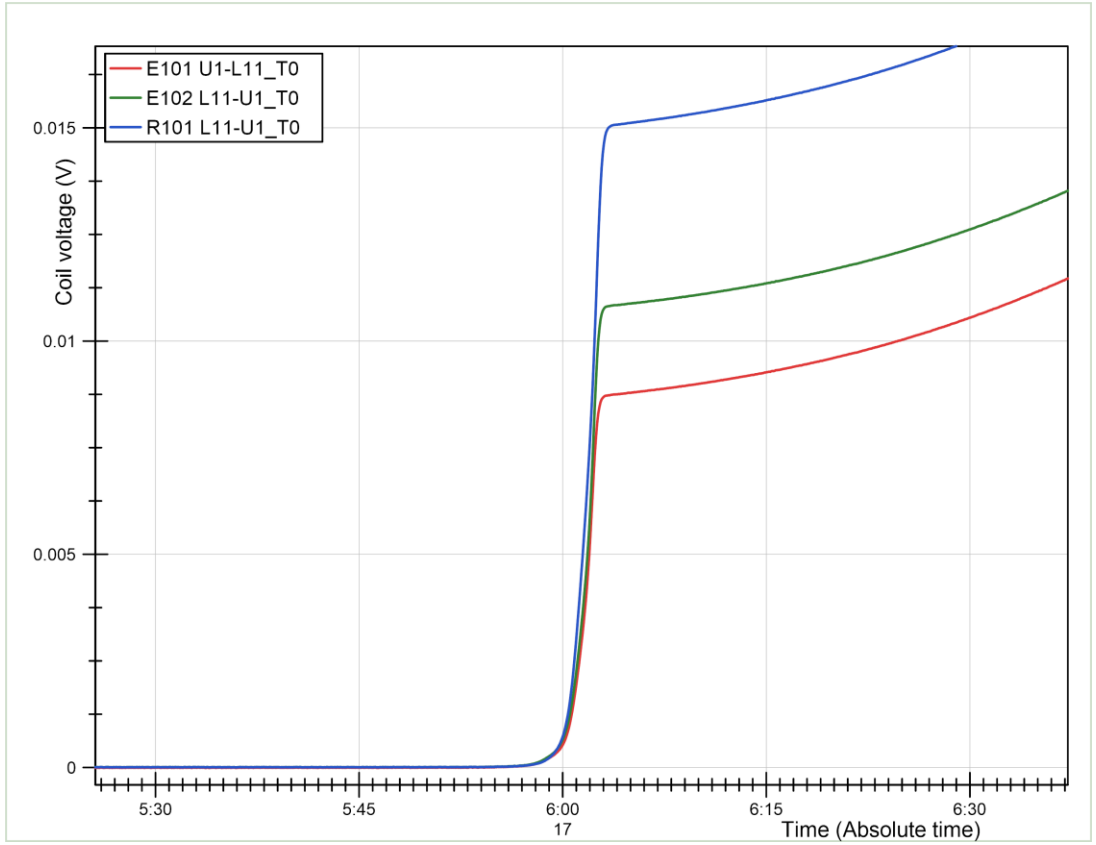
Voltage taps	Splice type	R (nOhm)	std (nOhm)
E102 L11-L10	Nb3Sn-NbTi	0.16	0.01
E102 U02-U01	Nb3Sn-NbTi	0.15	0.01
E101L11- R101L11	Inter-coil	0.33	0.01
R101U01-E102L11	Inter-coil	0.36	0.01





Residual Resistance Ratio (RRR)

- The residual resistance ratio have been measured for all the block coils individually during the first warm up (thermal cycle).
- 6 A were injected int the coils.



Coil:	ERMC101	ERMC102	RMM101
V taps	E101U1-E101L11	E102L11-E102U1	R101L11-R101U1
RRR	150	119	85

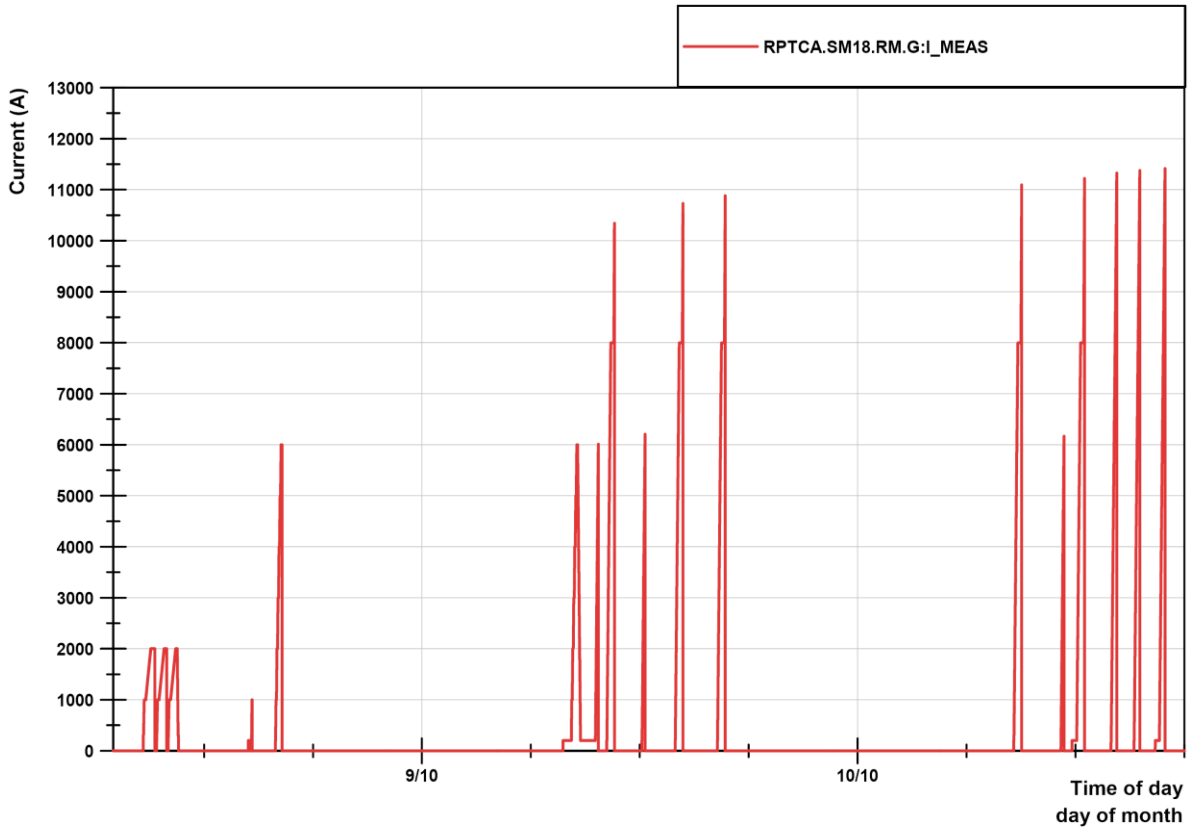
Conclusions

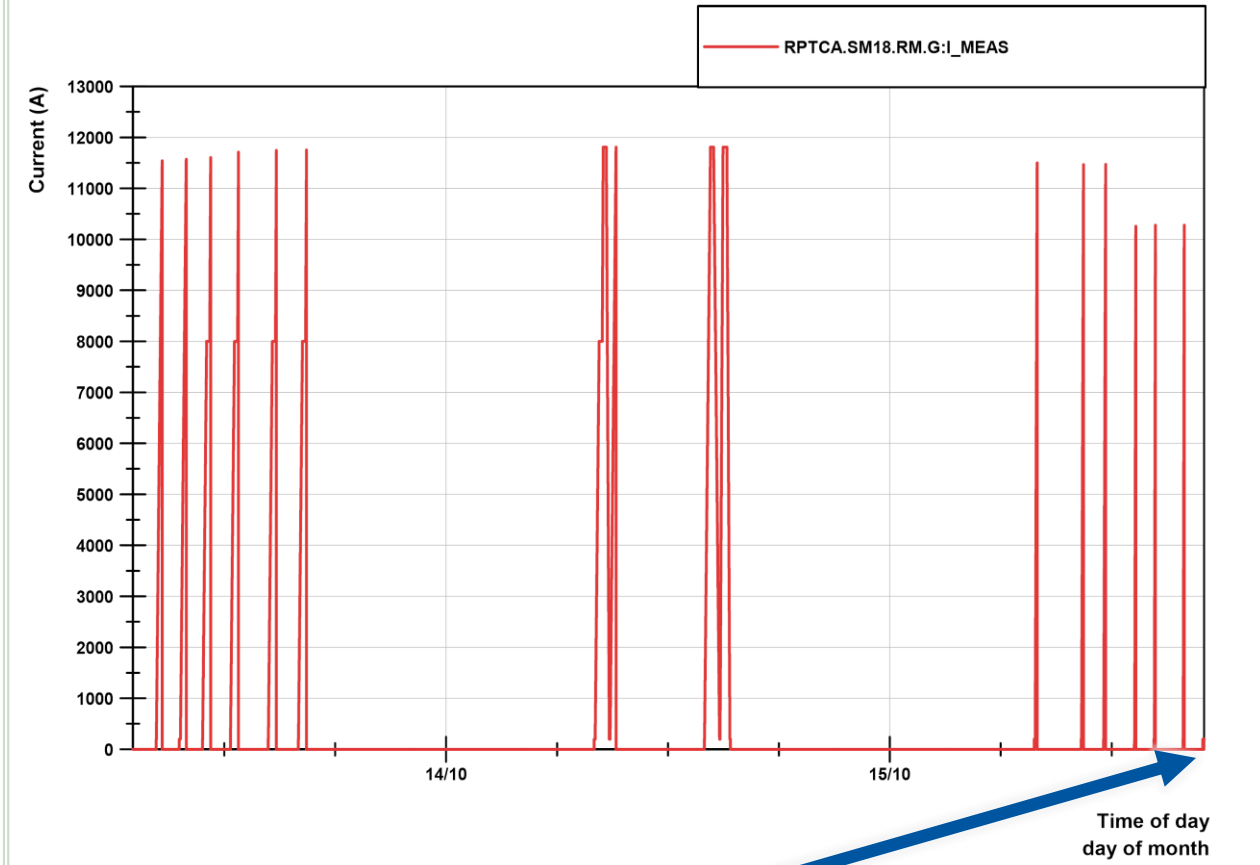
- The magnet trained up to 16.58 T (Bore field)
- Most of the quenches happened in the usual locations with a few exceptions (Upper layer training quenches).
- Quench behavior compatible with the previous iterations.
- Impact of the fishbone at 1.9 K in cooling from AC losses difficult to assess due to lack of references.
- Fishbone seems to not have an impact on the cooling during the ramp rate studies at 4.5 K.
- No signs of degradations visible after the tests at 1.9 K.
- V-I, Splice, and RRR measurements were normal as per the other RMM1 magnets.

Appendix

Powering overview

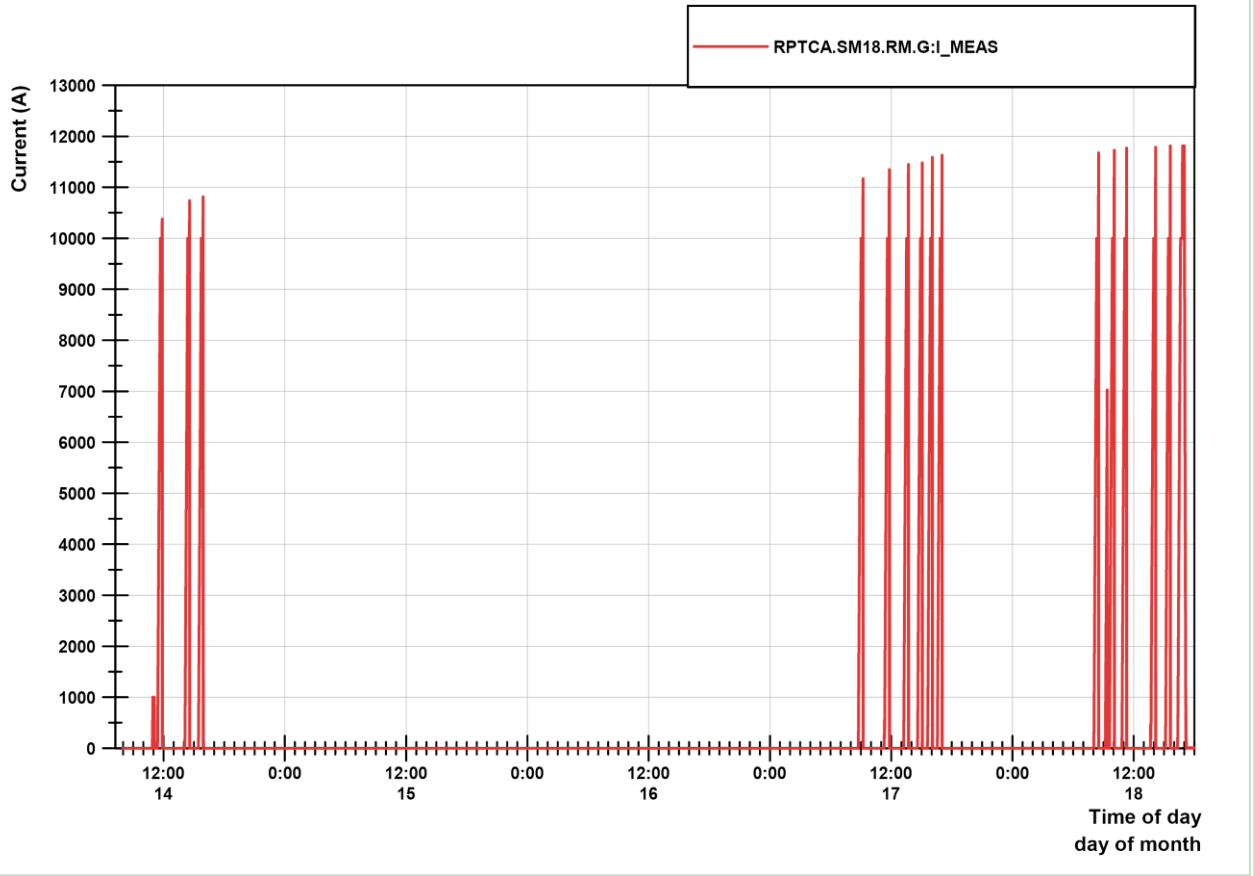
Powering overview CD1 1.9K

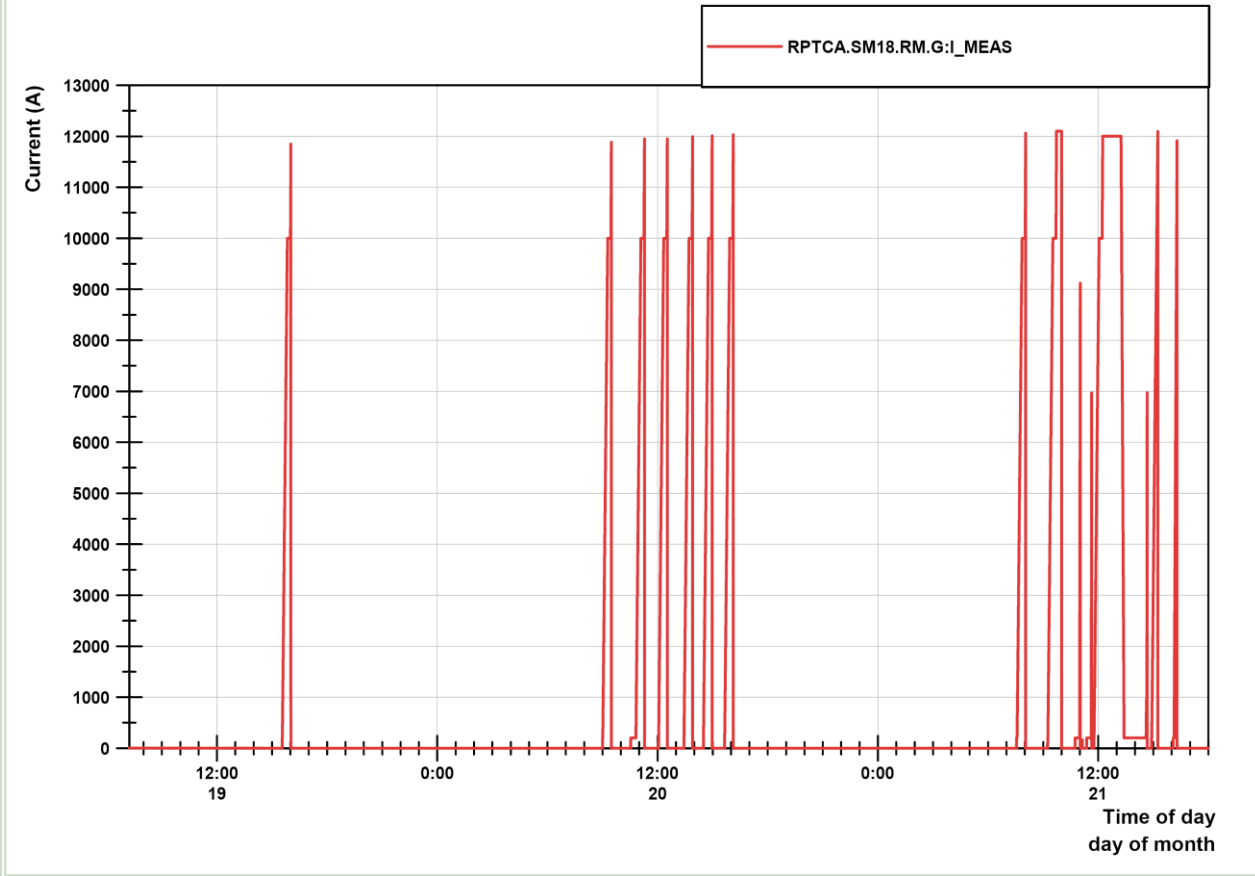




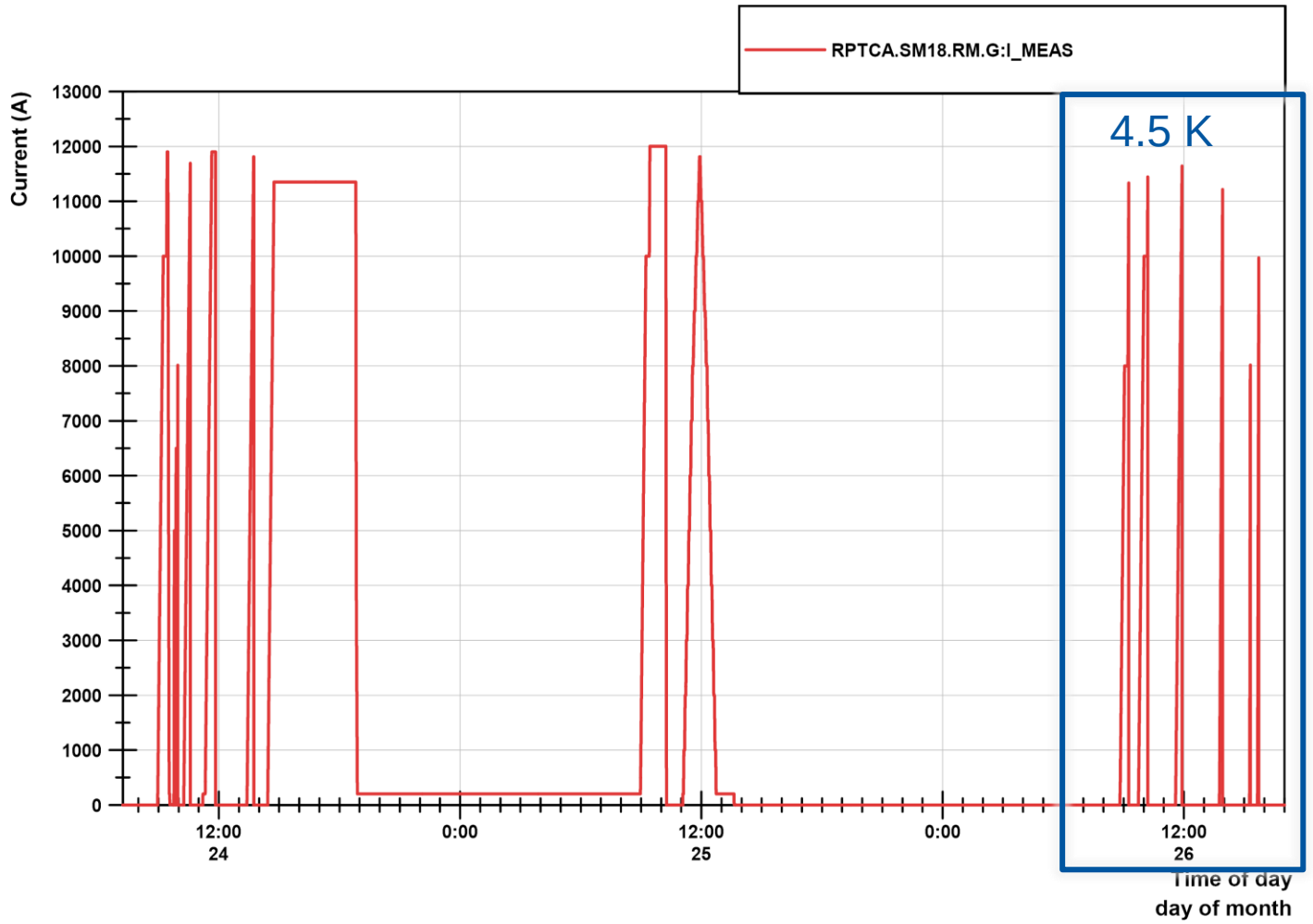
CD1 interrupted by Helium leak issue due to bellow crack

Powering overview CD2 1.9 K



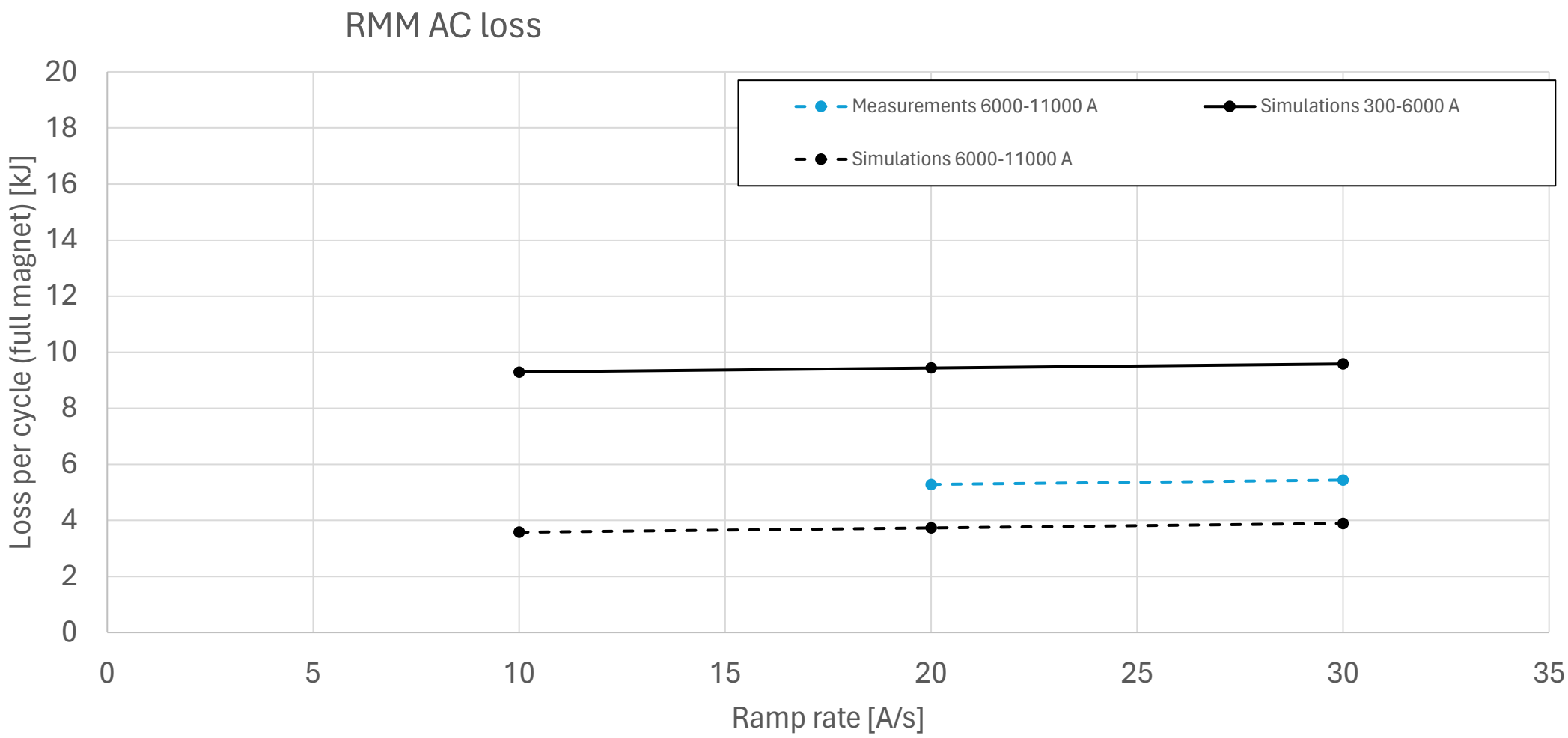


Powering overview CD2 1.9 K and 4.5 K



Hysteresis losses

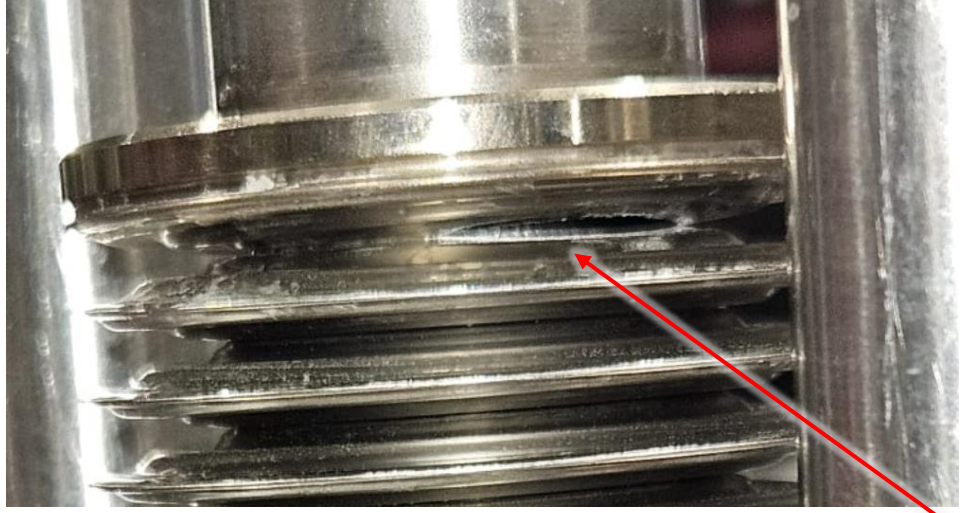
Hysteresis losses as measured in RMM1d



Helium Leak

Helium leak in the valve bellow

Temporary sealing by polymerlab team.



Leak

- This is the valve on the lambda plate that is closed during 1.9 K operation and open during 4.5 K operation. After each quench at 1.9 K it also opens.
- In the photo the open position.
- After the quench, the sound of helium exiting was heard

Main leak but also other developing