Cold powering test results of the 11 T cosθ model magnets at CERN

Gerard Willering

With thanks to Jerome Feuvrier, Vincent Desbiolles, Hugo Bajas, Marta Bajko, Francois-Olivier Pincot for the work on the tests and Susana Izquierdo Bermudez and David Smekens for providing feedback with the design data

Many thanks to all the persons that delivered the magnets with all its instrumentation for the test

High Luminosity LHC

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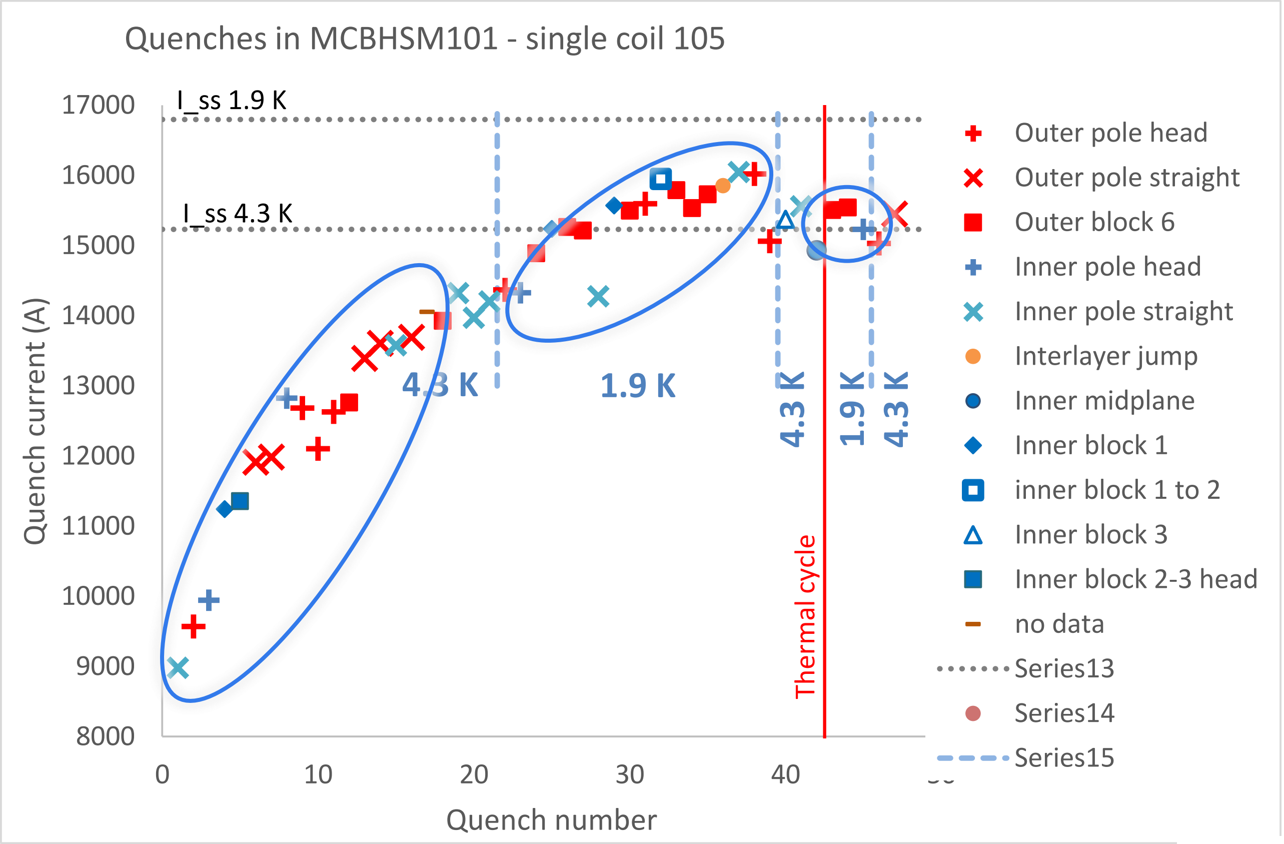
CAPACITIES

Focus

- Training and quench location
  - Coil 105
  - Coil 106-107
- Quench localisation and “weak points”
- Conductor
- Resistance box
- Electrical integrity.

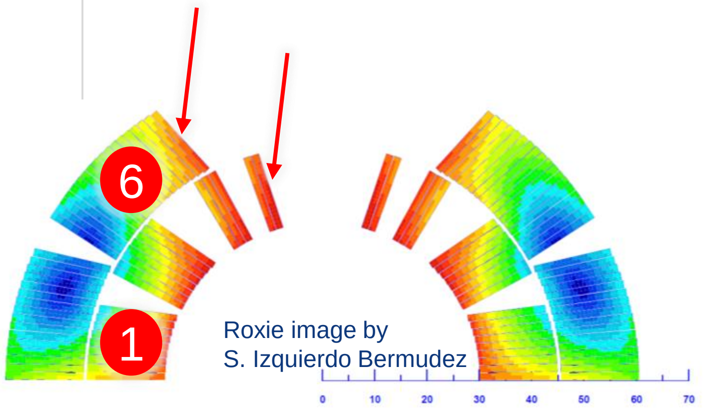
About training: single coil HCMBHSM101- coil 105



Initial training 4.3 K mainly around the pole, but spread around

Initial training 1.9 K mainly in outer block 6 and a few in inner block 1

Slight detraining after the thermal cycle for 1.9 K, not for 4.3 K.



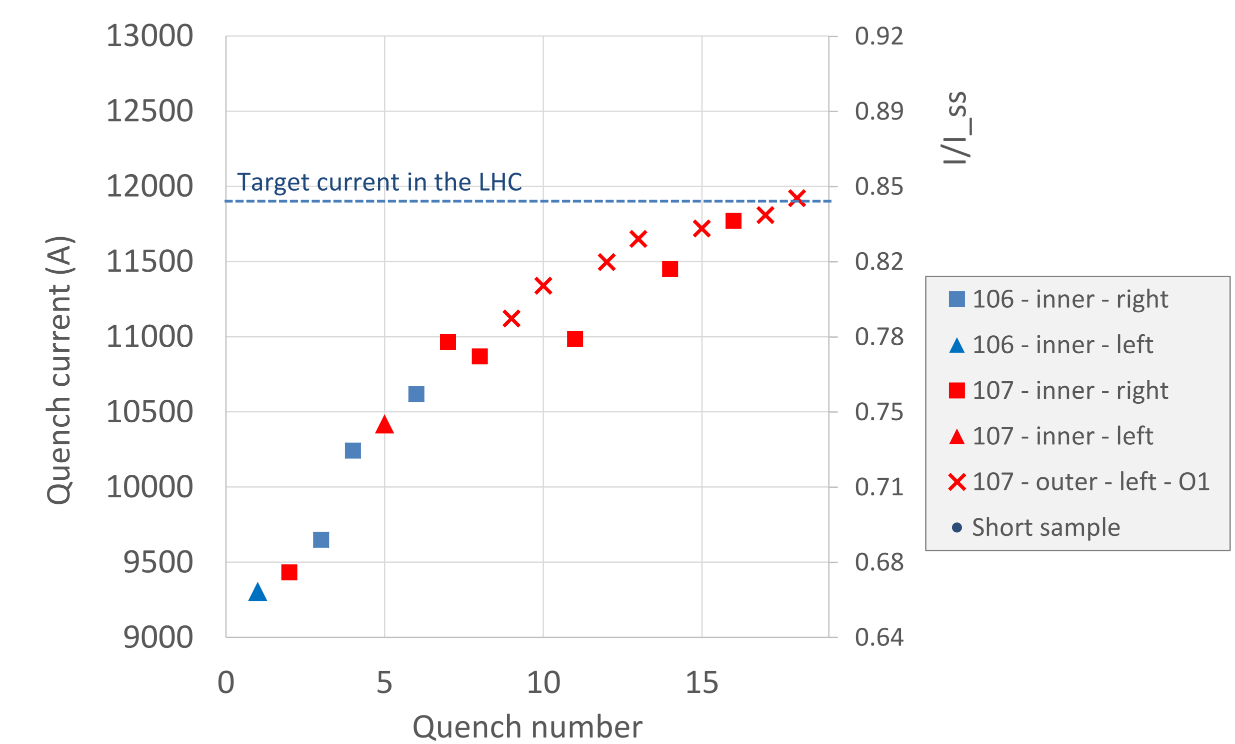
Conclusion

The training is rather random without real ‘weak spots’

No major memory loss

About training: :single aperture MBHSP101- coil 106-107

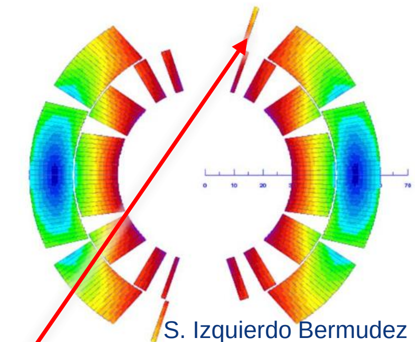
Initial training in the single aperture at 1.9 kA



4 quenches initiated in coil 106, no more quenches from 10.6 to 11.9 kA!!

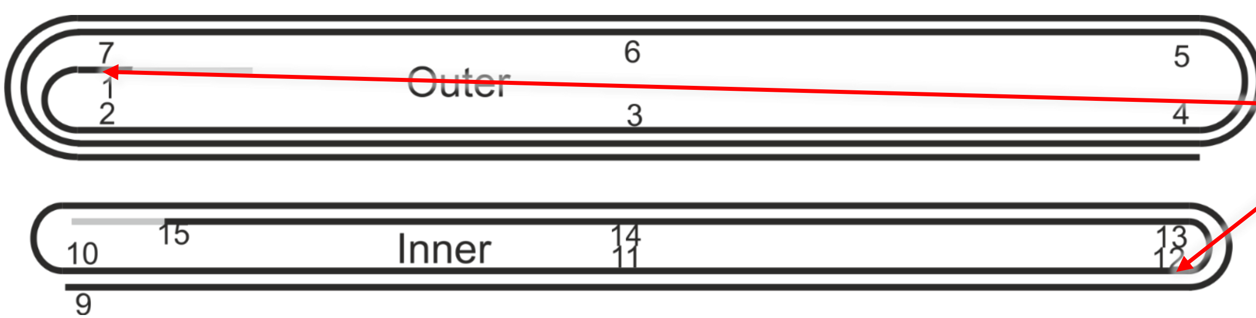
Initial training looks OK for coil 107 except for 2 specific spots.

Target of 11.85 kA is reached.

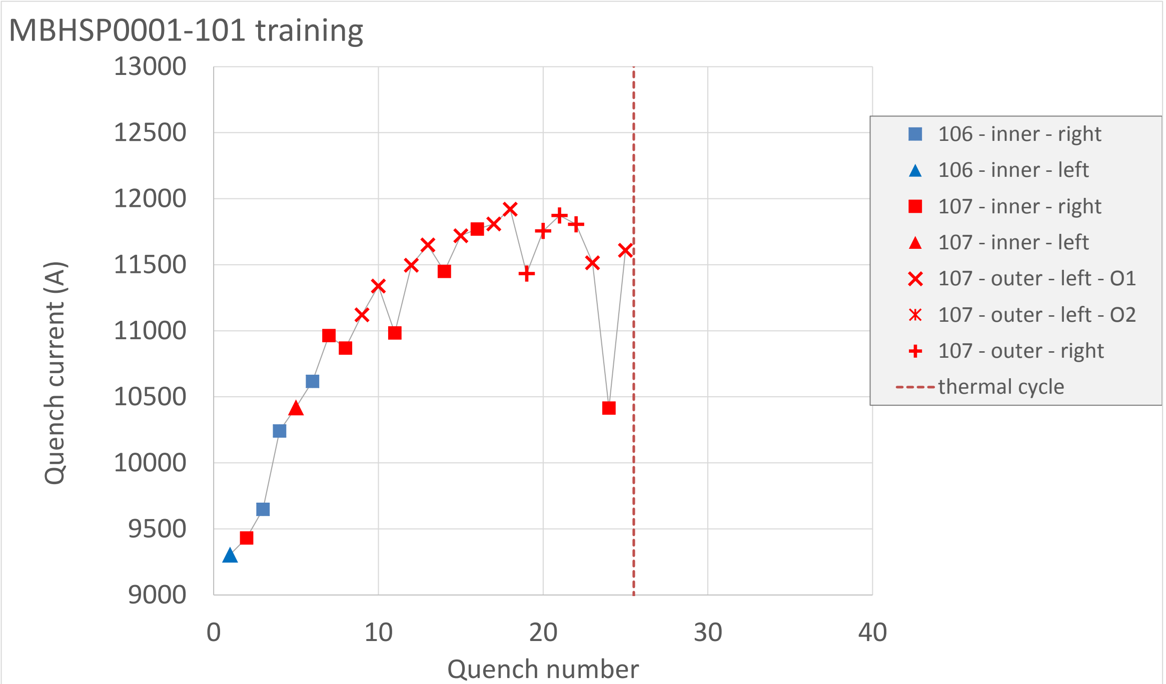


Initial training

Location	# quenches
Coil 106	4
Coil 107 at O1	7
Coil 107 inner layer pole head	6
Coil 107 around I12	1

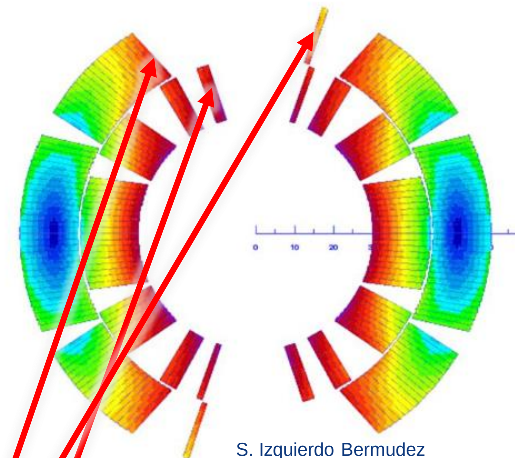


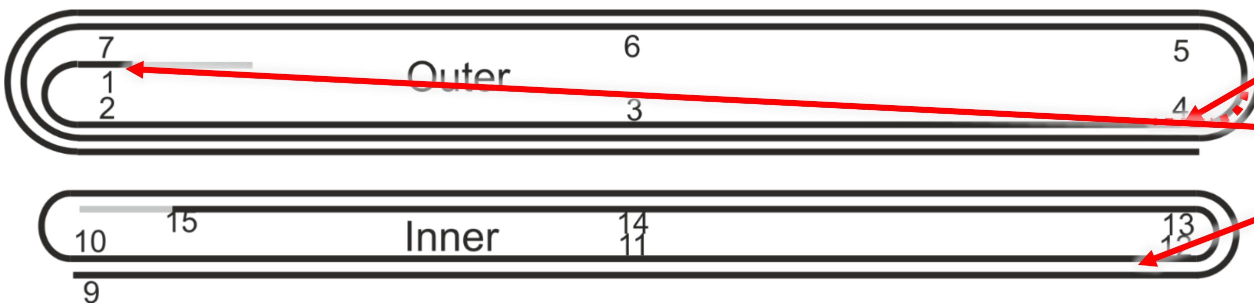
About training: detraining or possible degradation in the single aperture at 1.9 K



The detraining and quenches around voltage tap O4 are remarkable in quench 19 to 22

A strong detraining quench followed in quench 24.





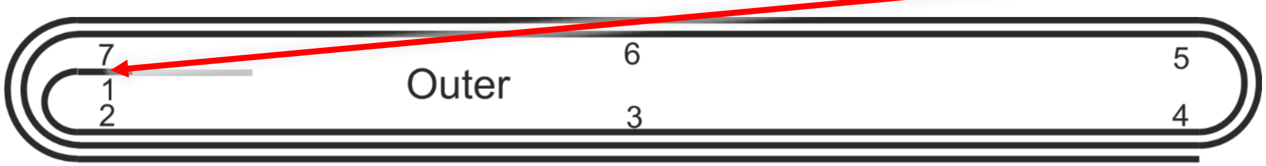
Quench 19 to 22	Outer layer, close to Vtap O4
Quench 23, 25	At Vtap O1
Detraining 24 (50 A/s)	Close to Vtap I12

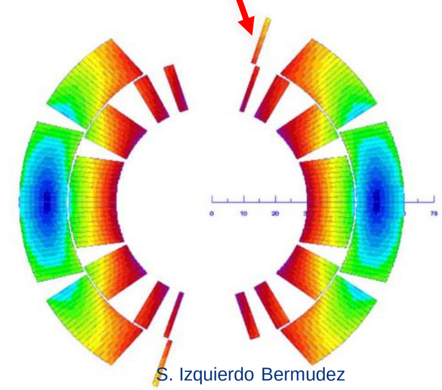
About training: after thermal cycle at 1.9 K

Quench 26 to 31 at 1.9 K show a rather limited quench current, always quenching in the same location.

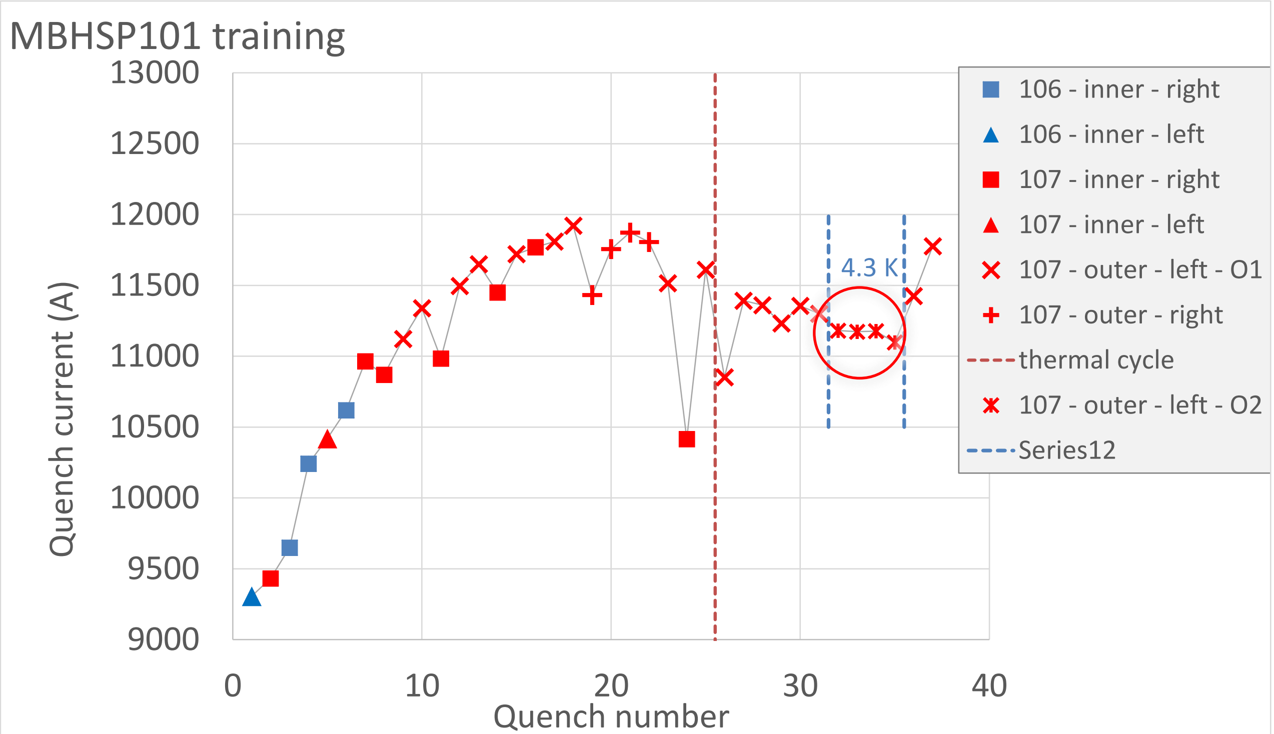
Apparently the coil was degraded after thermal cycle for 6 quenches, but after the tests at 4.3 K the quench level increased to 11.76 kA.

All quenches from quench 25 at 1.9 K in O1





About training: 4.3 K powering

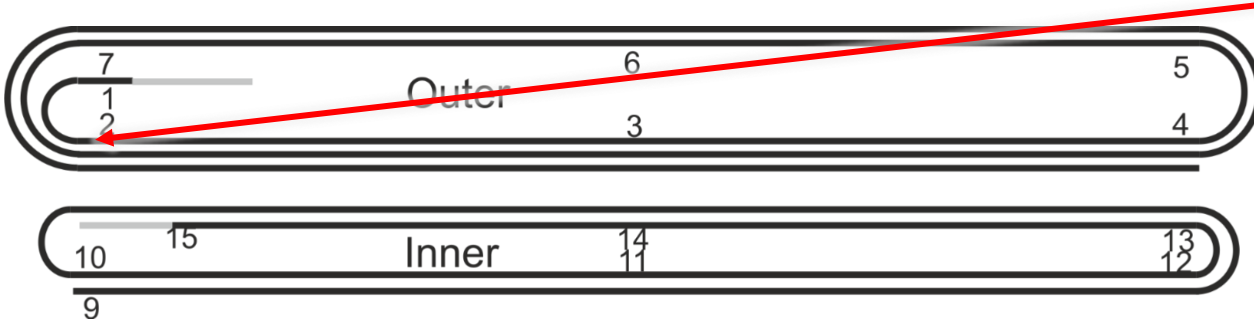


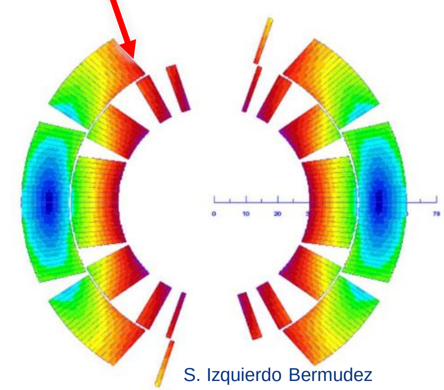
The lower quench current at 4.3 K at 0.85^*I_{ss} is not expected.

At 10 A/s 3 quenches at 11177 ± 4 A with identical quench location and pattern.

The quench at 50 A/s occurred at 11095 A with similar quench pattern.

Quench location is at voltage tap O2





S. Izquierdo Bermudez

About quench localisation: overall impression and understanding

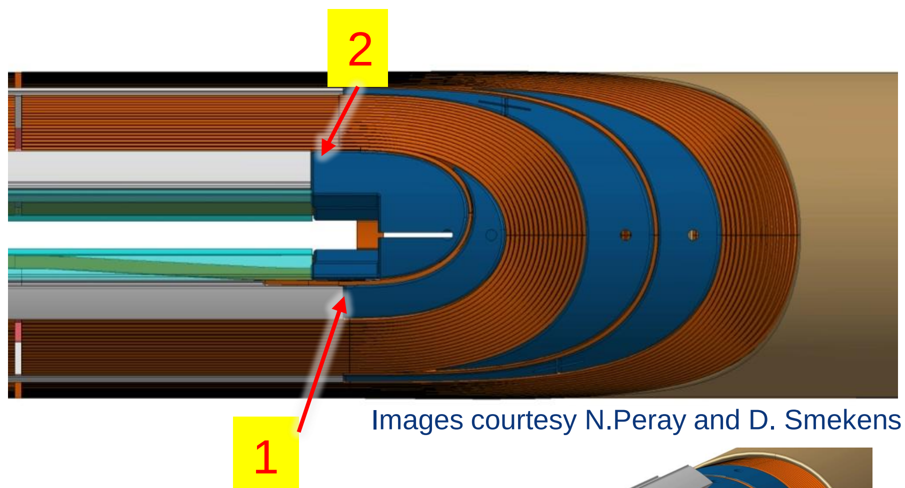
Quenches in coil 105 were rather random, no “weak spots”
Quenches in coil 106 were only 4 up to the target current of 11.85 kA, no “weak spots”
Many quenches in coil 107 with 3 main “weak spots”.

1 at 1.9 K limited at the end of the layer jump in the outer layer, at voltage tap 107-O1.
2 at 4.3 K limited at the first turn of the outer layer, just next to the head, at voltage tap 107-O2.
3 Detraining occured many times around the pole close to voltage tap I12.

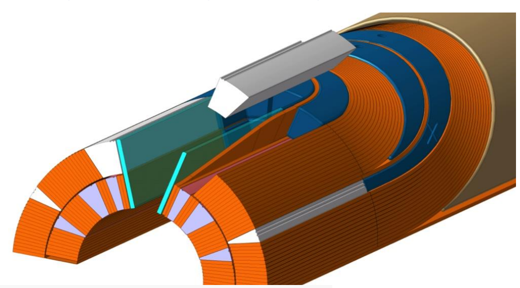
What is the origin of the limitation in the weak points?

Mechanics?
The quench is located at the points with discontinuation of the pole and shims, see image.
This is true for all 3 weak points.

Is the precompression sufficient?
Is the epoxy OK?



Images courtesy N.Peray and D. Smekens



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1. at 1.9 K limited at the end of the layer jump in the outer layer, at voltage tap 107-O1.
2. at 4.3 K limited at the first turn of the outer layer, just next to the head, at voltage tap 107-O2.
3. Detraining occured many times around the pole close to voltage tap I12.

What is the origin of the limitation in the weak points?

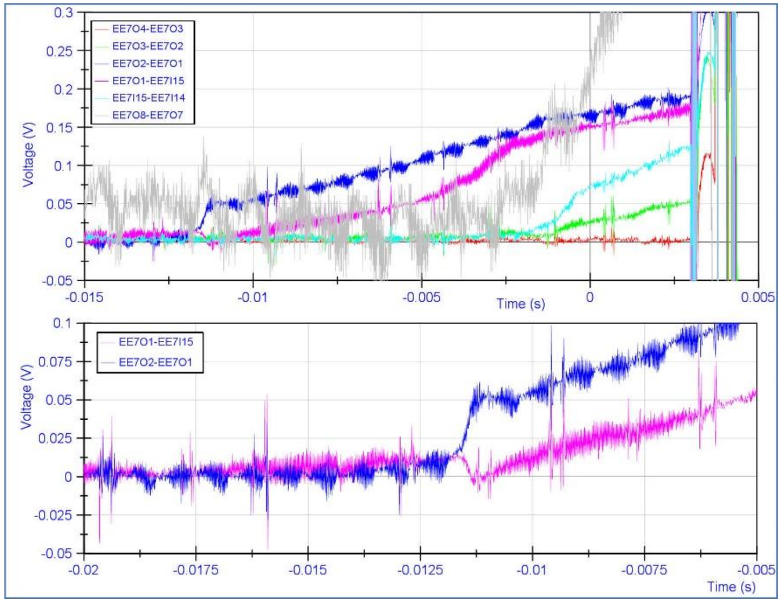
Voltage taps ?

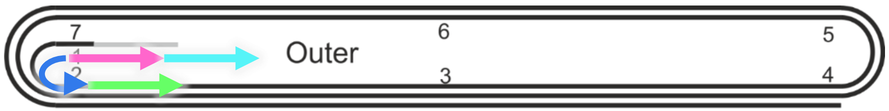
For weak point 1 and 2, the quench is localised always at the voltage taps (precision about 1 cm).

In addition all the quenchs voltage around O1 give a very supicious jump up and down. This may indicate that the quench localizes around the strand where the voltage tap is placed on.

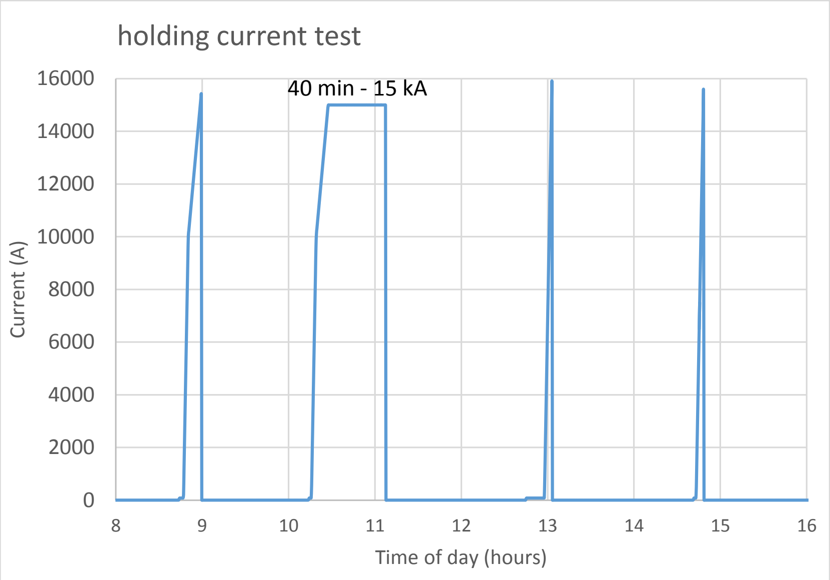
Can voltage taps have influence in the quench initiation or is this a coincidence?

In the next coil these voltage taps may be moved closer towards the center of the magnet or removed to avoid these questions.





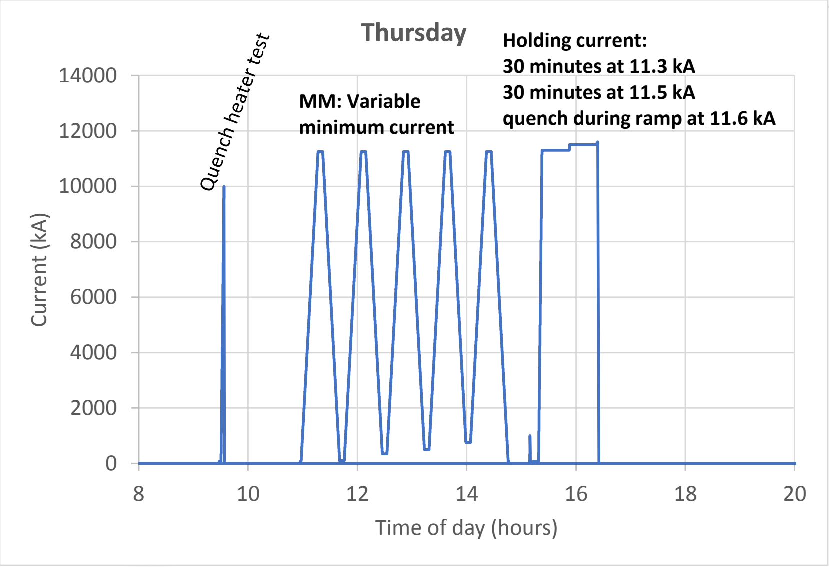
About the conductor : Holding current tests



Single coil MBHSM101 – coil 105

40 minutes at 15 kA at 1.9 K.

(trip after 40 minutes due to warming of the Cu current leads)



Single aperture MBHSP101 – coil 106-107

30 minutes at 11.3 kA

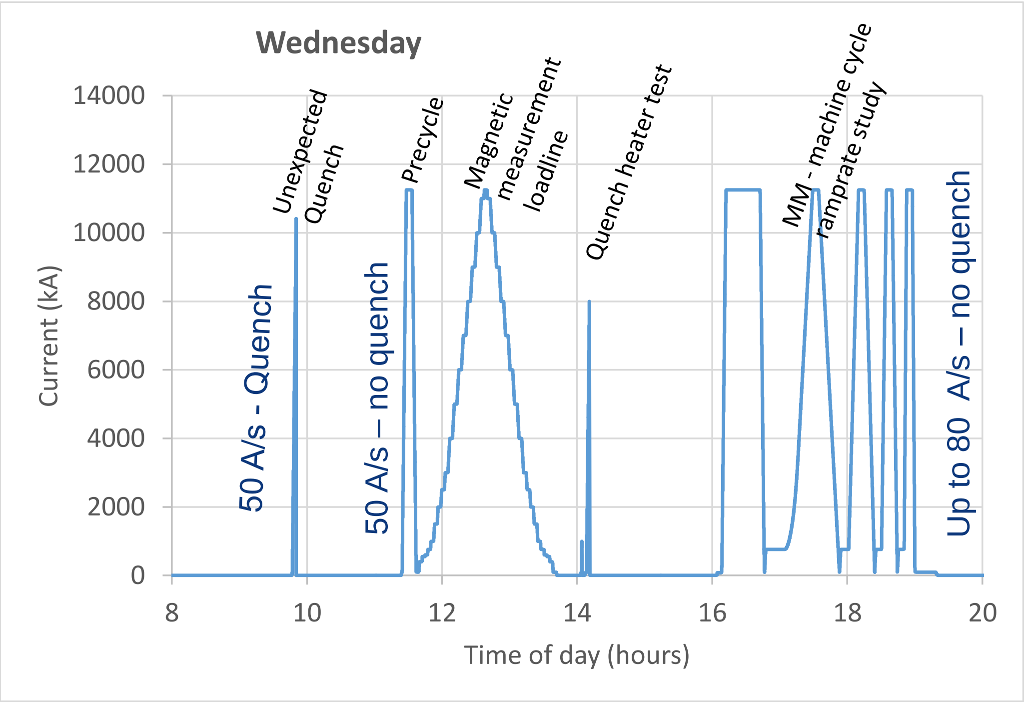
followed by 30 minutes at 11.5 kA

Followed by quench during ramp at 11.6 kA

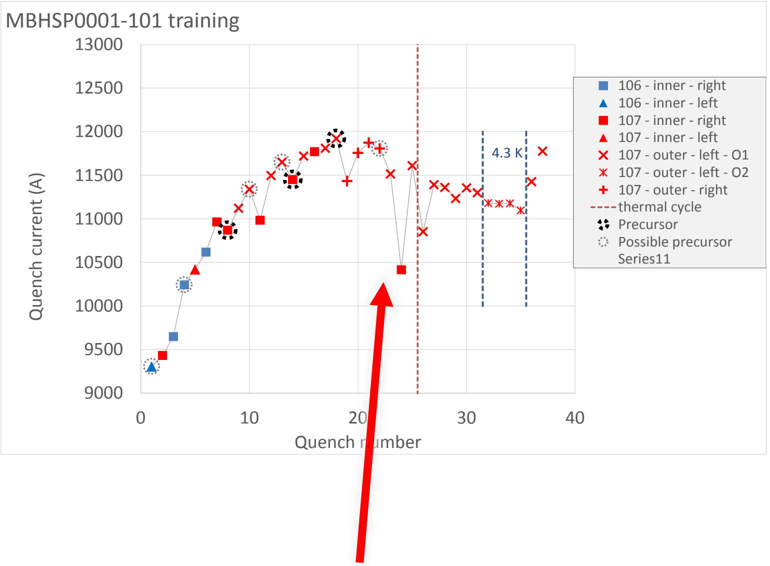
Both coil 105 and coils 106-107 had showed holding quench.

Short conclusion: No apparent conductor issue?

About the conductor: ramp rate dependency



No ramprate effect recorded up to 80 A/s at 1.9 K up to nominal current.



Detraining at 50 A/s

The detraining quench (23) at 10.4 kA at 50 A/s, the others were at 10 A/s. Afterwards during the same day, the current was ramped up to 11.25 kA multiple times with a ramp rate of up to 80 A/s without quench.

The detraining quench has a similar signature as the other (detraining) quenches, so at this level of current ($0.72*I_{ss}$) we can conclude that there is no repetitive ramp rate effect.

Also the last quench at 11.76 kA was at 50 A/s.

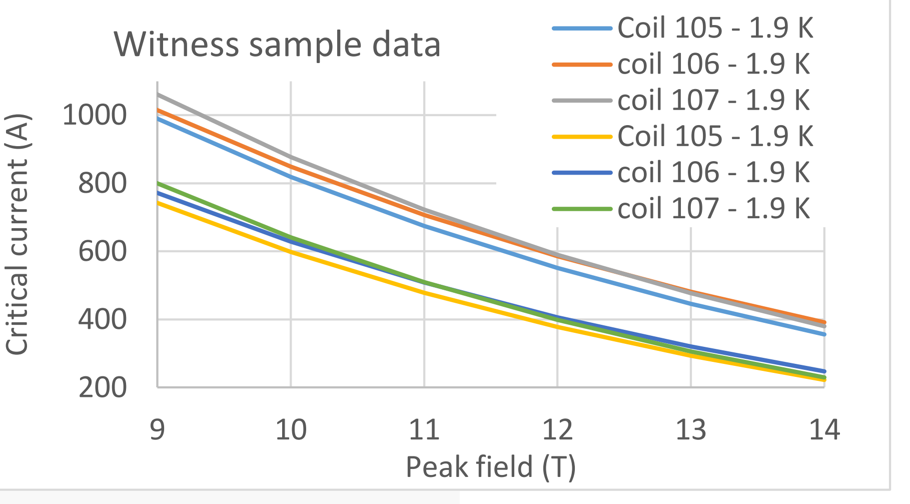
About the Conductor: RRR and Ic

RRR measurements are done on the whole coil, but also on short segments. The short segments show the same value as for the whole coil.

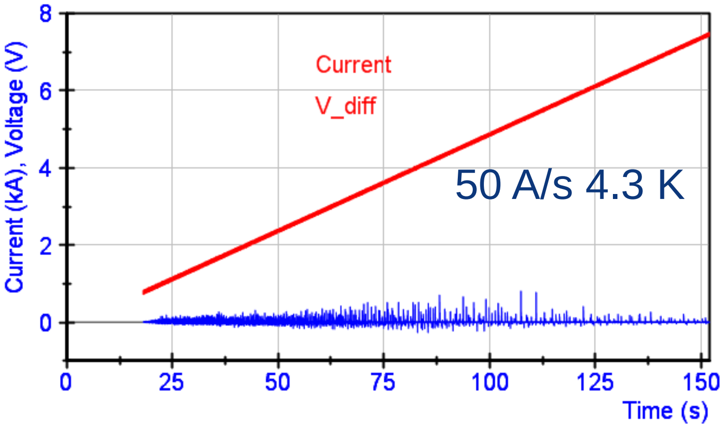
Expected values are from the notes by B. Bordini and are valid for single wires.

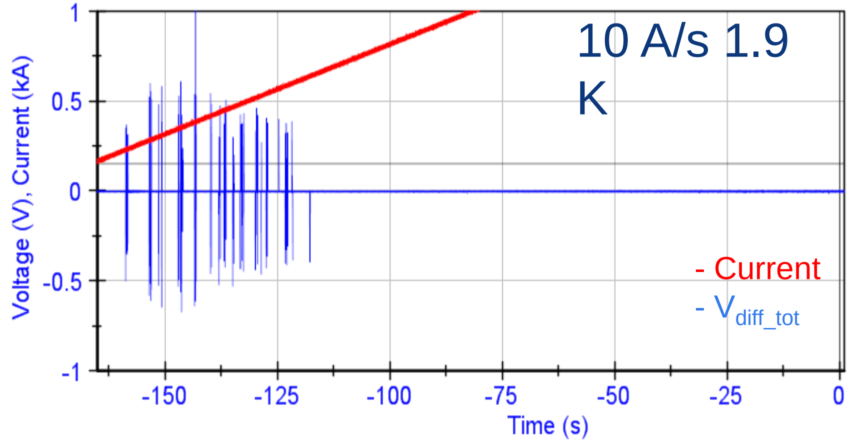
	Expected min – max RRR	RRR Measured SM18
Coil 105	88-230	77 ± 5 %
Coil 106	88-230	65 ± 5 %
Coil 107	143-230	95 ± 5 %

Looking at the lowest measured I_c in the witness samples, coil 105 is performing about 6 % less than coil 106 and 107. No

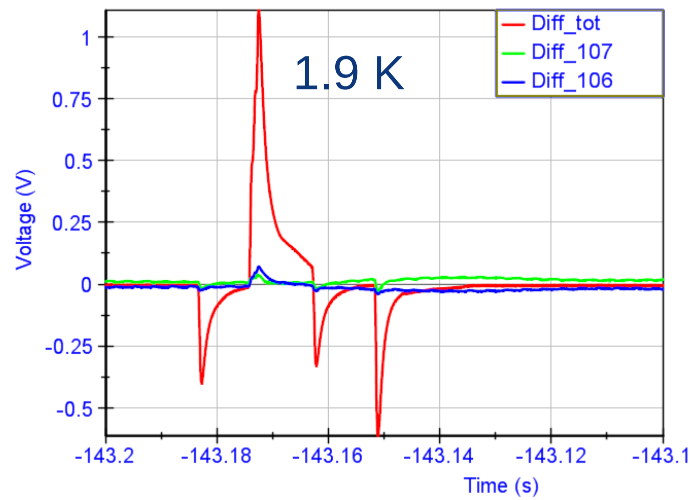


About the Conductor: Protection and flux jumps





Flux jumps at 1.9 K up to injection current.
Flux jumps at 4.3 K up to about 8 kA

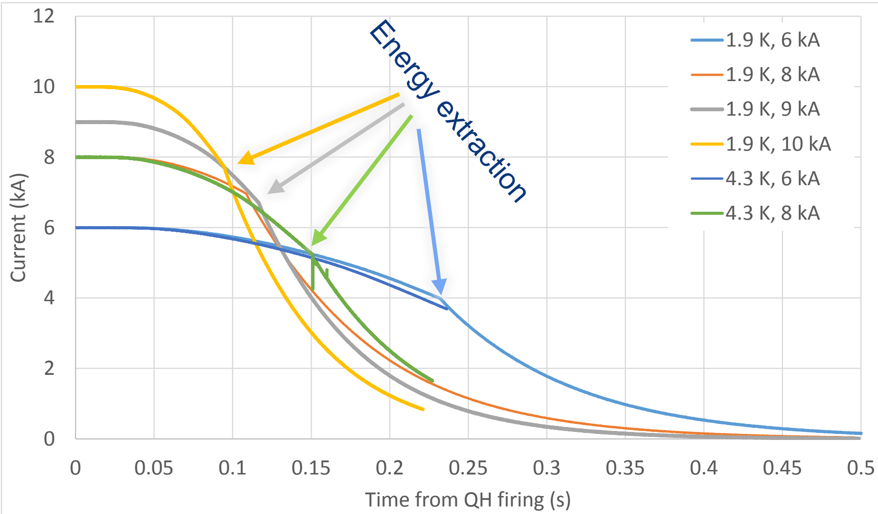


Threshold and validation time are a trade-off between tight protection and avoiding unwanted trips.

During the test of the MBHSP101 single aperture at 4.3 K the test was perturbed by trips and the threshold needed to be increased.

For reference see talk by B. Bordini for the flux jumps in wires observed at 1.9 K and 4.3 K on 9-12-2014

About the quench heaters: Quench heater efficiency tests



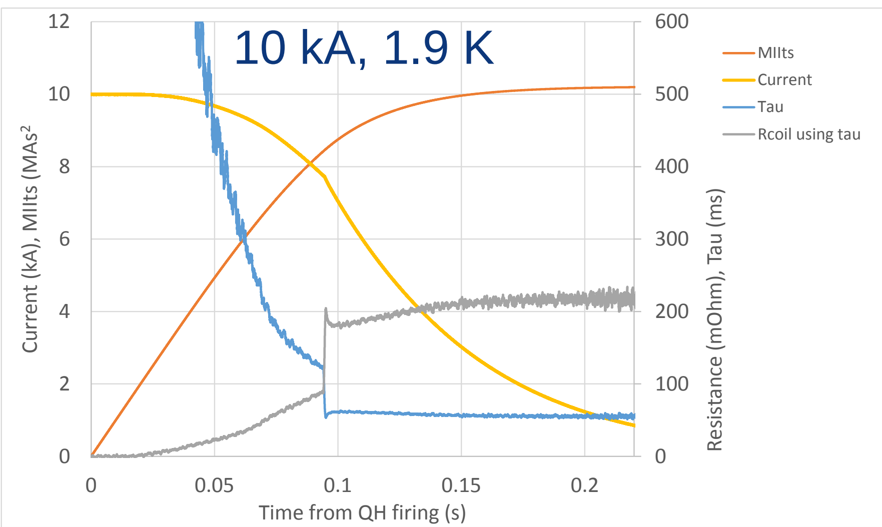
Quench heater efficiency test, test station point of view

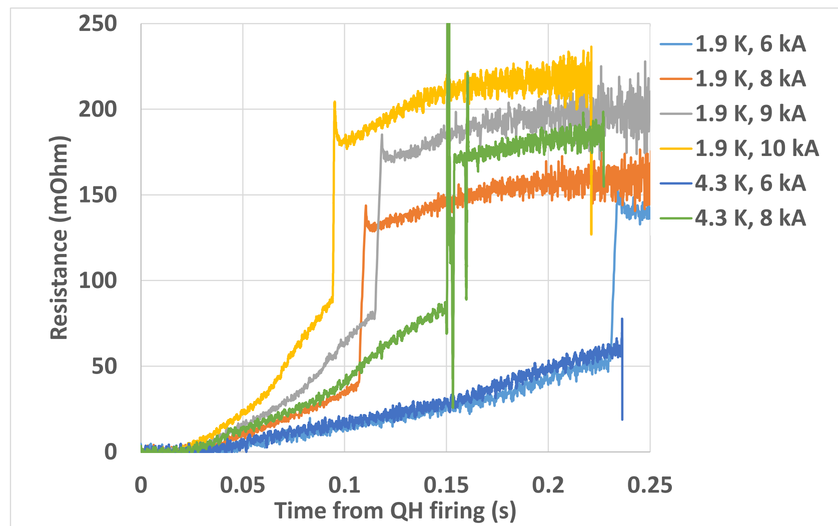
Test sequence

- Provoke heater discharge manually at the desired current
- Detect the heater provoked quench
- After a set delay, switch in the energy extraction.

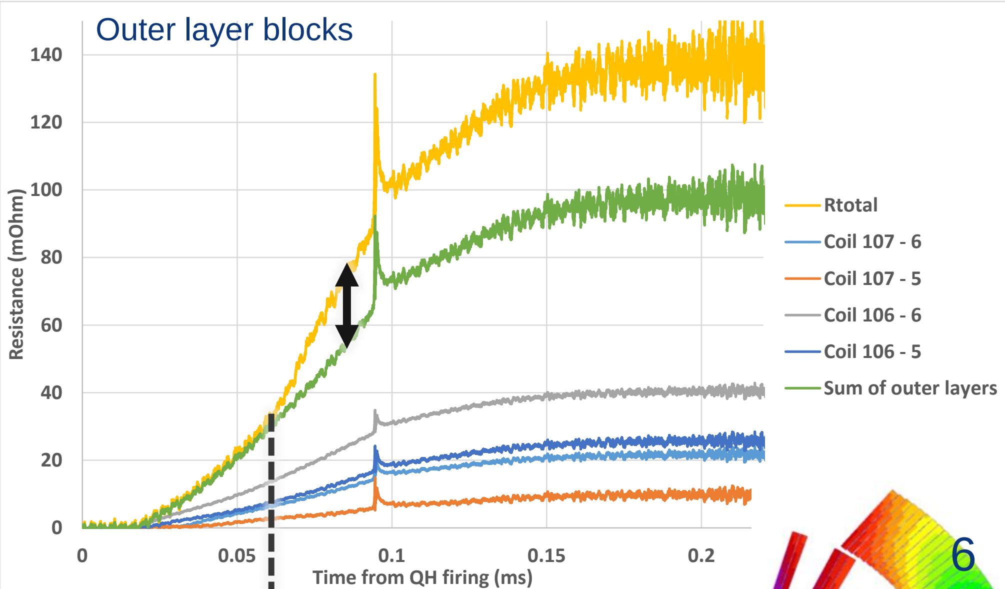
Direct data that can be extracted from the current decay in the magnet are

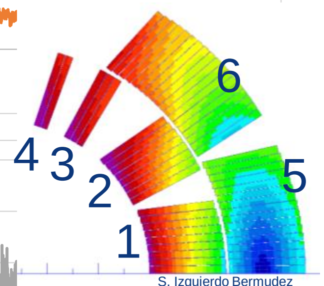
- MIIts
- Time constant of current decay
- Total circuit resistance (including dump resistance)

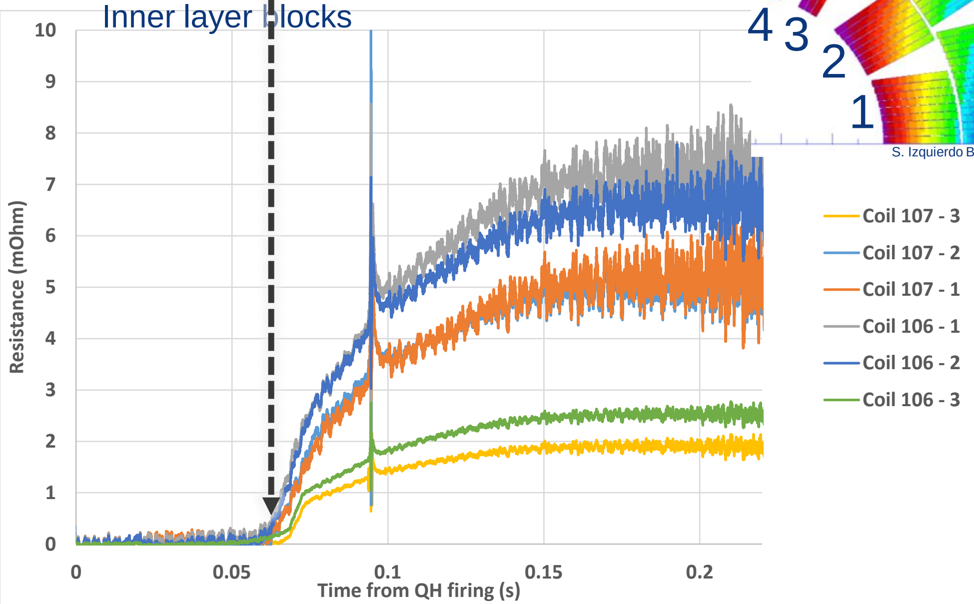




About the quench heaters: Resistance growth in the coils







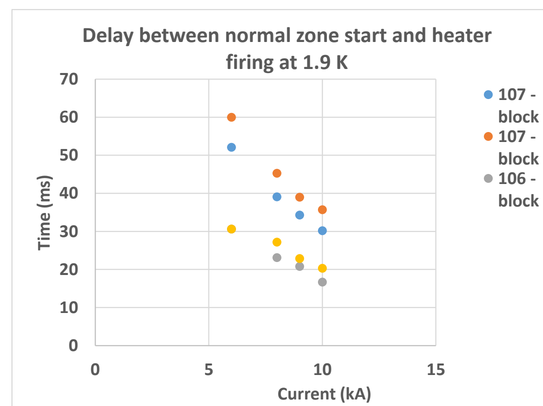
Outer layer quench heaters only MBHSP101

Resistance growth in the coils at 10 kA, 1.9 K, quench heaters on blocks 5 and 6.
I_{QH} = 150 A.

The peaks at 90 ms correspond to the opening of the energy extraction.

Quicker initiation in coil 106 due to thinner insulation layer.
Faster resistance buildup in coil 106 due to low RRR.

The contribution of the inner layers is measured clearly. It will form the base for model validations.

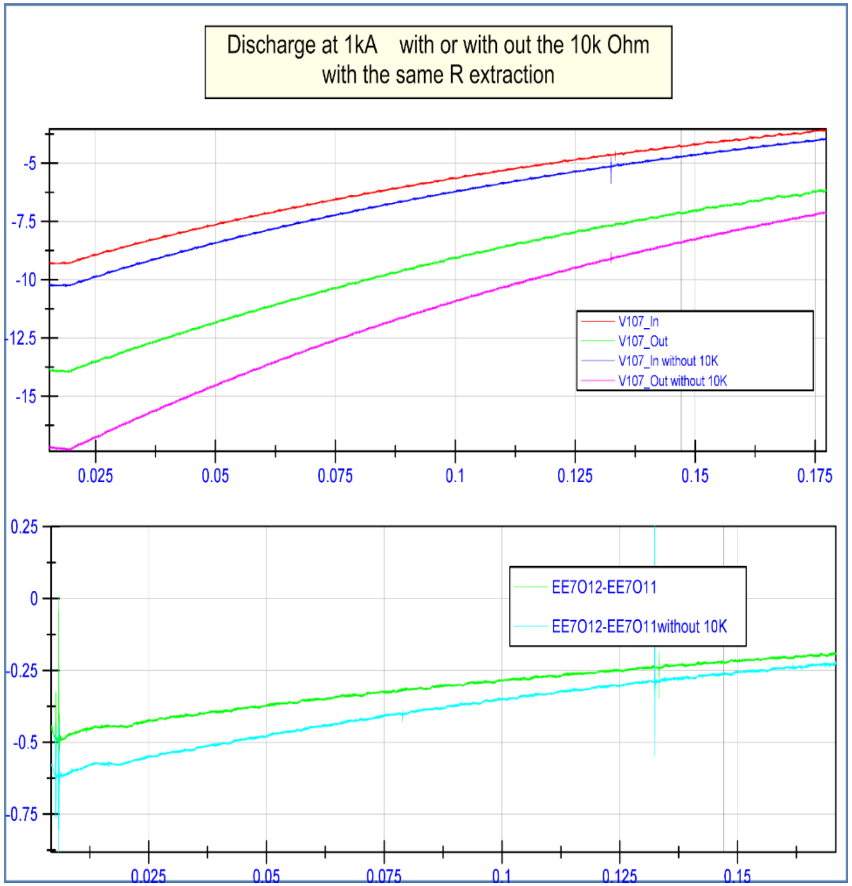


See for calculations of QH efficiency and protection studies the presentation by S. Izquierdo

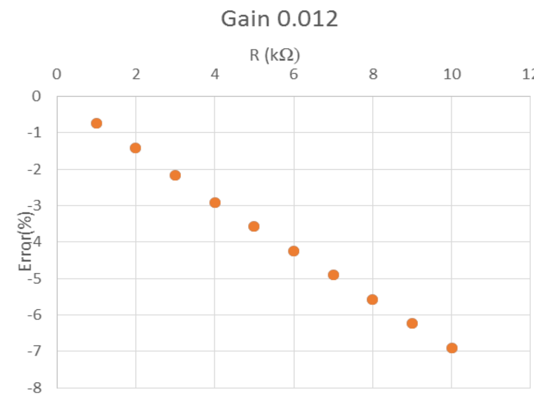
About the resistance box

During the last test campaign we sorted out the impact of the 10 kΩ resistance added to the wiring.

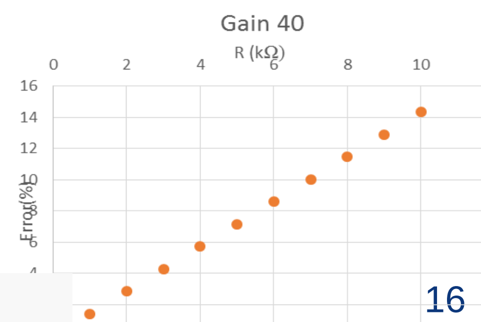
It was validated that over the whole voltage range a linear compensation factor can be applied (hardware or software).



G = 0.012			
Vin [V]	R [kohms]	Vout [V]	Diff [%]
100	0	1.203	
100	1	1.194	-0.74813
100	2	1.186	-1.41313
100	3	1.177	-2.16126
100	4	1.168	-2.90939
100	5	1.16	-3.5744
100	6	1.152	-4.2394
100	7	1.144	-4.90441
100	8	1.136	-5.56941
100	9	1.128	-6.23441
100	10	1.12	-6.89942



G = 40			
Vin [V]	R [kohms]	Vout [V]	Diff [%]
0.1	0	4.008	
0.1	1	4.065	1.422156
0.1	2	4.122	2.844311
0.1	3	4.18	4.291417
0.1	4	4.238	5.738523
0.1	5	4.295	7.160679
0.1	6	4.353	8.607784
0.1	7	4.41	10.02994
0.1	10	4.582	14.32136



Images by Jerome Feuvrier

About the electrical integrity coil 106-107

Test show **no variations** before and after the cold powering in:

- Inductance
- Capacitance
- Capacitif discharge on QHs
- Capacitif discharge on coil
- Resistance measurement
- Dielectric measurement
- Insulation of Quench Heater to coil

Coil to ground resistance at room temperature

Before cold powering – 30 GΩ
During thermal cycle – 30 GΩ
After last test – **70 MΩ (coil 106)**

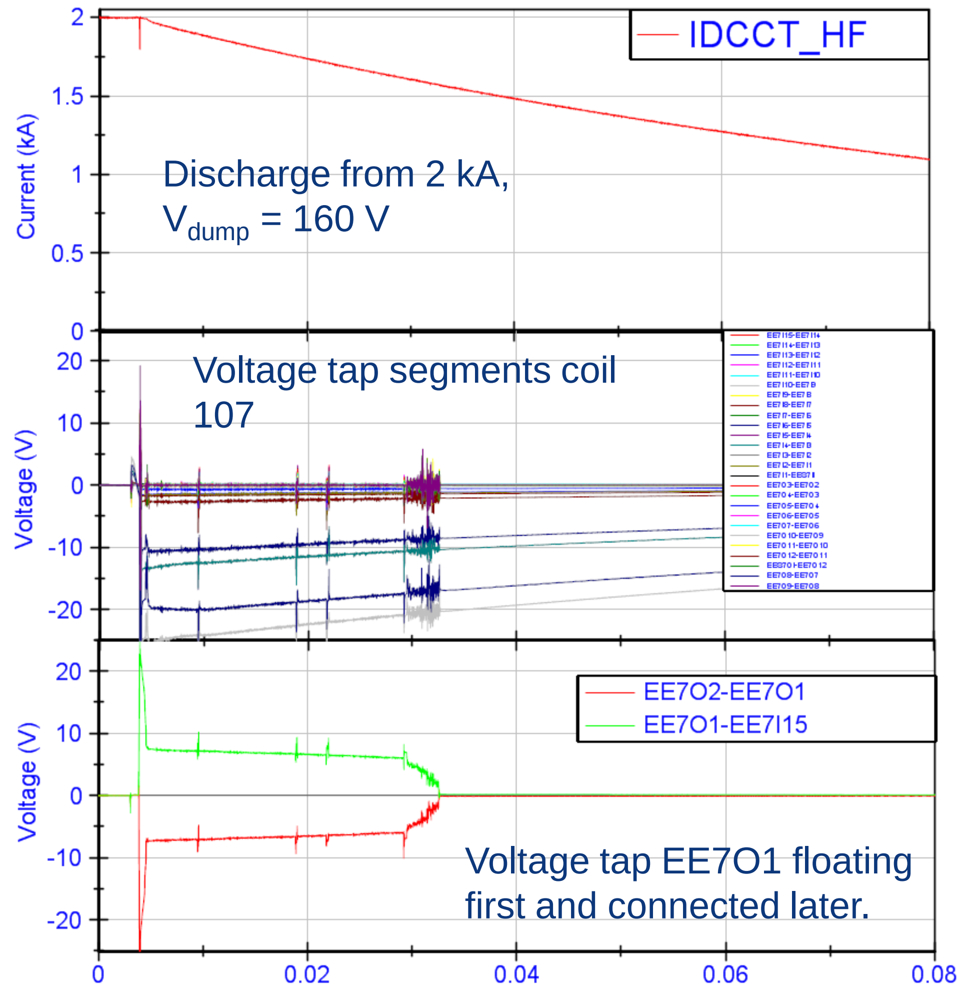
About the electrical integrity

Loss of voltage taps

Due to a cabling error on the SM18 side, 2 voltage taps were lost (wiring burned through) in coil 106, namely taps O1 and OI.
Relation to voltage to ground insulation problem?

Voltage breakdown in the last quench

1. HV test OK at 1.9 K, 0 A for 900 V.
2. During the last discharge a voltage to ground breakdown occured (more than 1 A and blowing the fuse in the Power Converter) at the location of **coil 107 – voltage tap O1 and I15** at about 700 V
3. HV test OK at 1.9 K, 0 A for 900 V.
4. Discharge from 2 kA: Again short to ground, Fuse of PC broken again.
5. HV test still OK at 1.9 K, 0 A for 900 V.
6. Testing stopped.



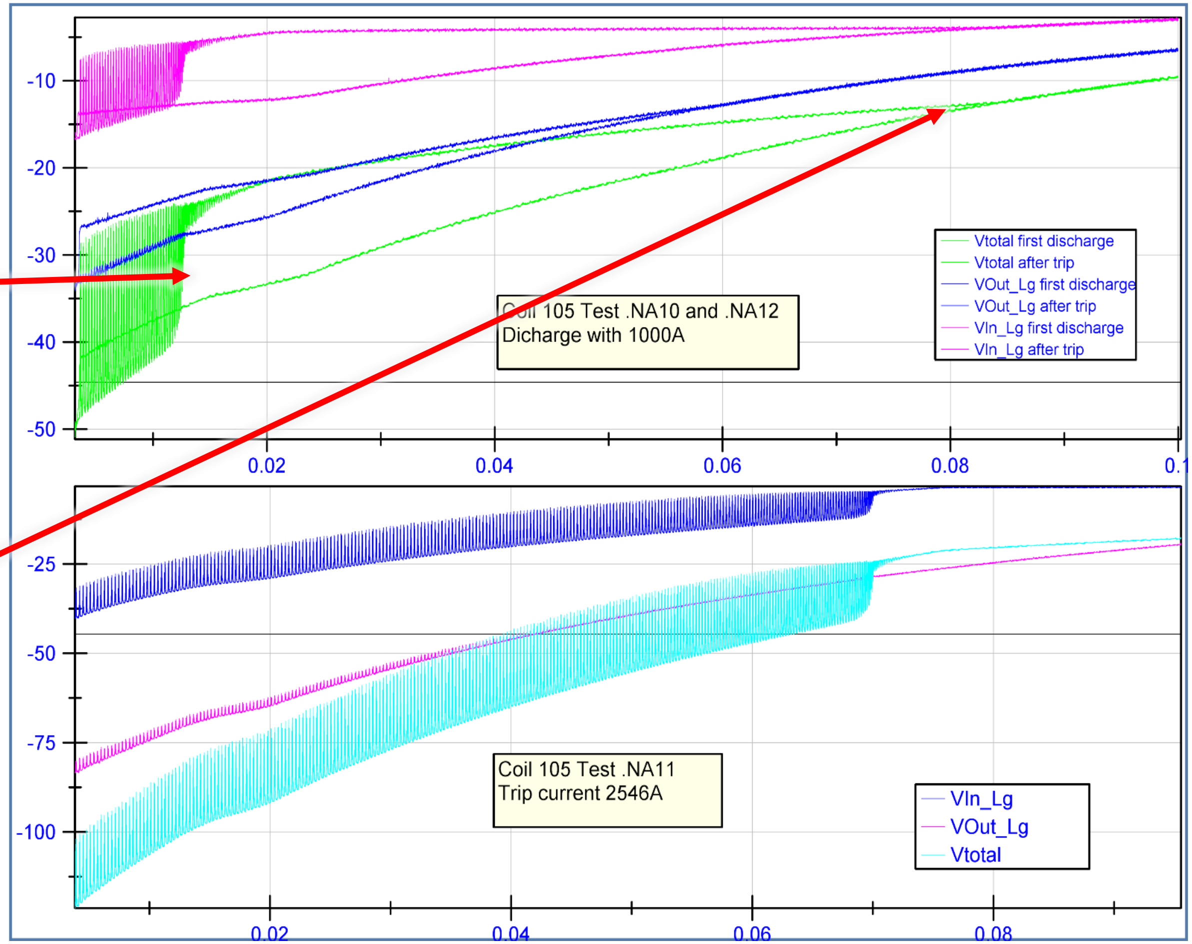
Coincidence with the weak spot in the magnet?

About the electrical integrity, coil 105

Quick reminder for completeness

In coil 105 we had a short through voltage tap wires.

This problem solved itself, since the short-current has burned away in a discharge from 2.5 kA.



What was not tested and should be tested next time:

What could have been done if we would not have had the problem with the short to ground

- Protection only by the Quench heaters (gives high MIIts, up to 300 K hotspot and large energy deposition in the bath). *Adaptations are done to our insert such that high energies can be handled more safely*
- Studies related to losses and cooling in the magnet
    - Ramp rate dependency studies and AC loss
    - Quench back

What remains important:

- Training
- RRR
- Quench protection (only protected by QH)
- Ramp rate dependence and quench back.
- Magnetic measurements (new shaft)
- Mechanical measurements

Summary in short

Coil 105
- trained up to 97 % of I_{ss} at 1.9 K
- good memory

Coil 106 assembled in MBHSP101
- 4 training quenches up to nominal current

Coil 107 assembled in MBHSP101
- 19 training quenches up to nominal current
- Limiting points at 1.9 K and 4.3 K are well localized

Large amount of data is available for protection studies

Thank you.

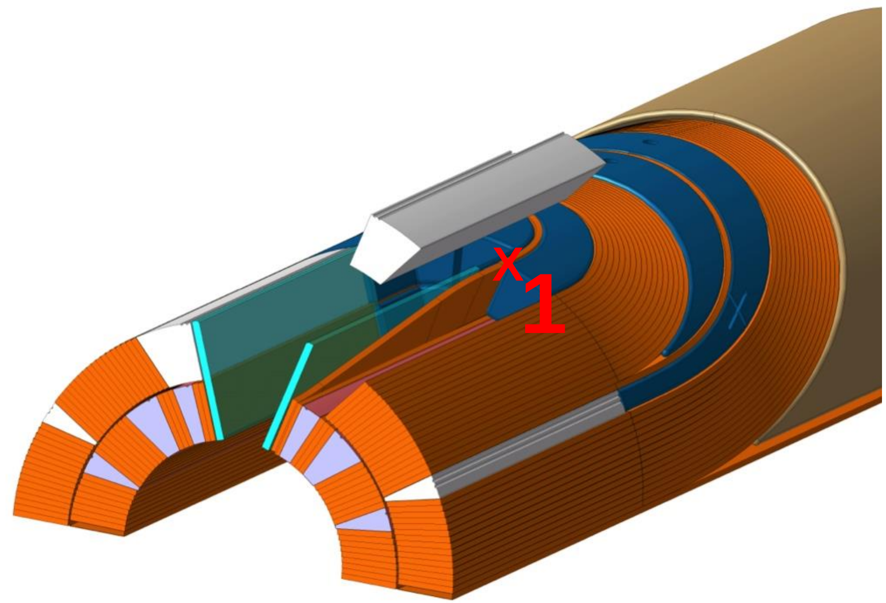
Backup slides

Summary of weak locations in coil 107

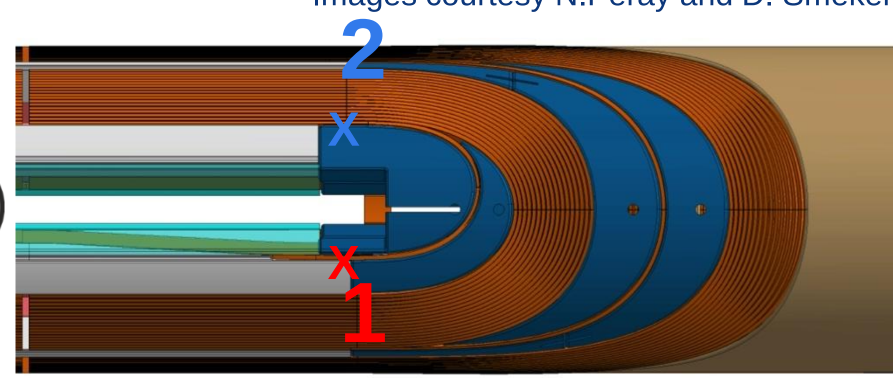
1. At voltage tap O1, just out of the layer jump.
   7 quenches during initial training
   Limiting point later on at 1.9 K

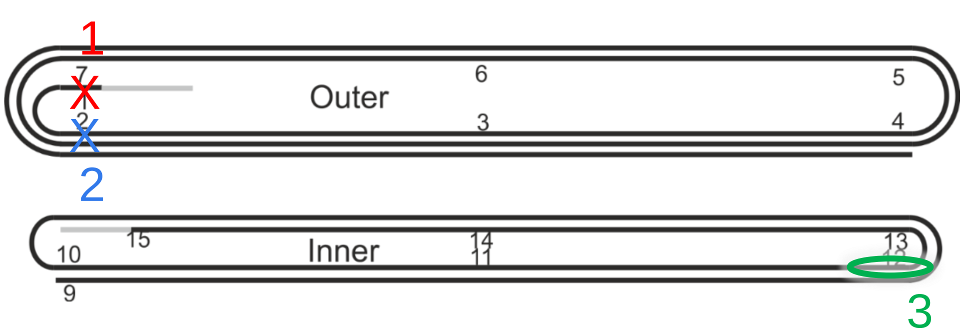
2. At voltage tap O2, opposite of O1.
   Limiting point at 4.3 K

3. Around voltage tap I12, close to the pole head with 6 training quenches and detraining.

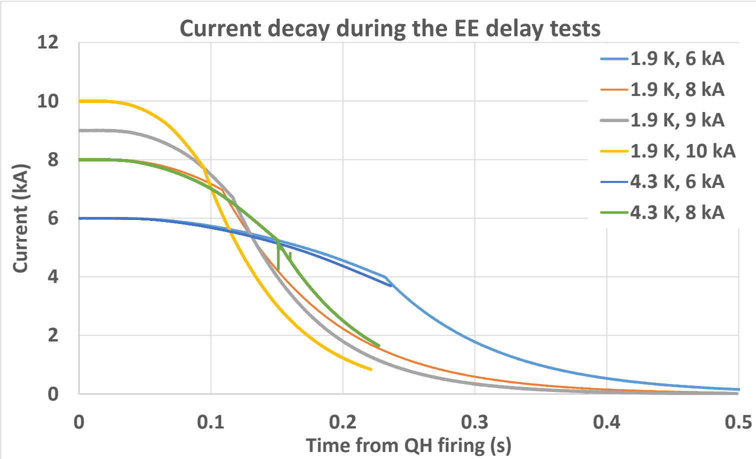


Images courtesy N.Peray and D. Smekens





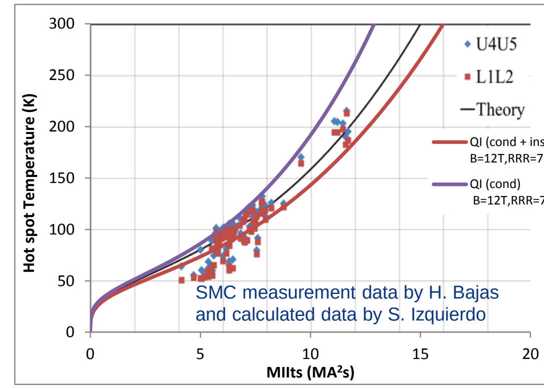
Quench heater efficiency testing

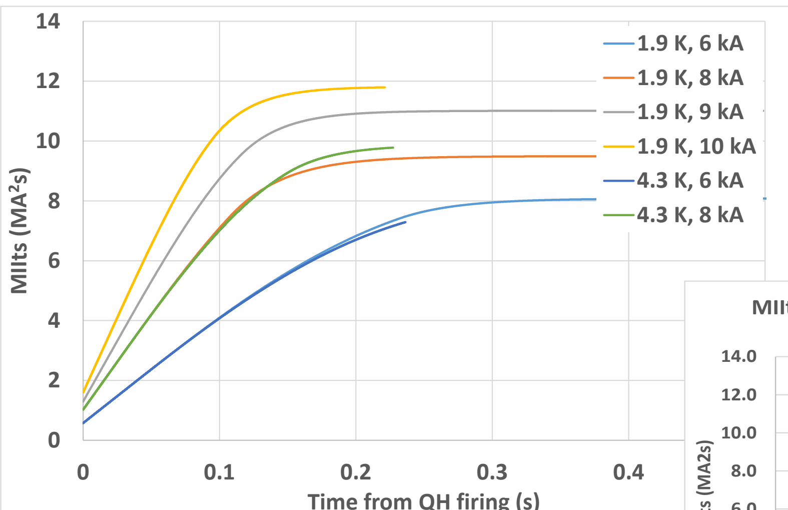


In case of a natural quench quench heater firing is about 16 ms after the start of the normal zone with the current setup.
This will give for example 1.6 MIIts at 10 kA.

T K	I kA	MIIts MA²s	T_hotspot K
1.9	6	8.1	127 ± 16
1.9	8	9.5	156 ± 22
1.9	9	11.0	193 ± 30
1.9	10	11.8	217 ± 37
4.3	6	7.9	123 ± 14
4.3	8	9.8	163 ± 24

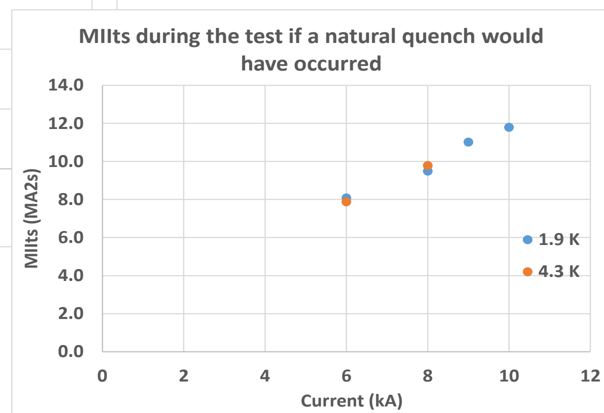
More indepth study on the hotspot temperature has been done with the SMC coils, see talk by H. Bajas

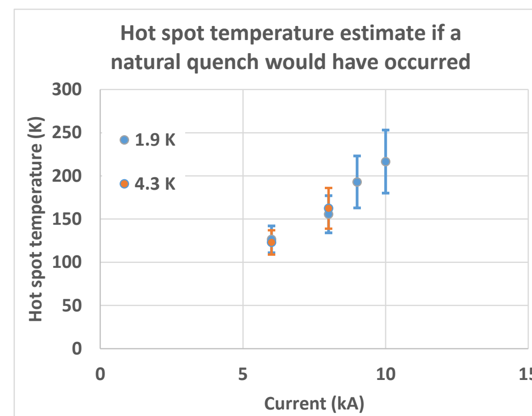




There is no consensus on the hotspot temperature level to cause damage to the coil. For this magnet test the goal is to be conservative.

One more test at 11 kA at 1.9 K was foreseen.

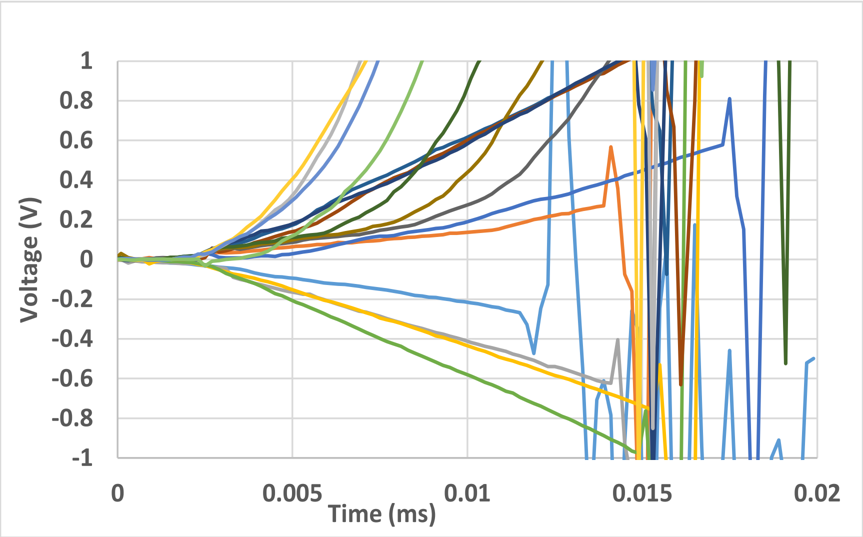


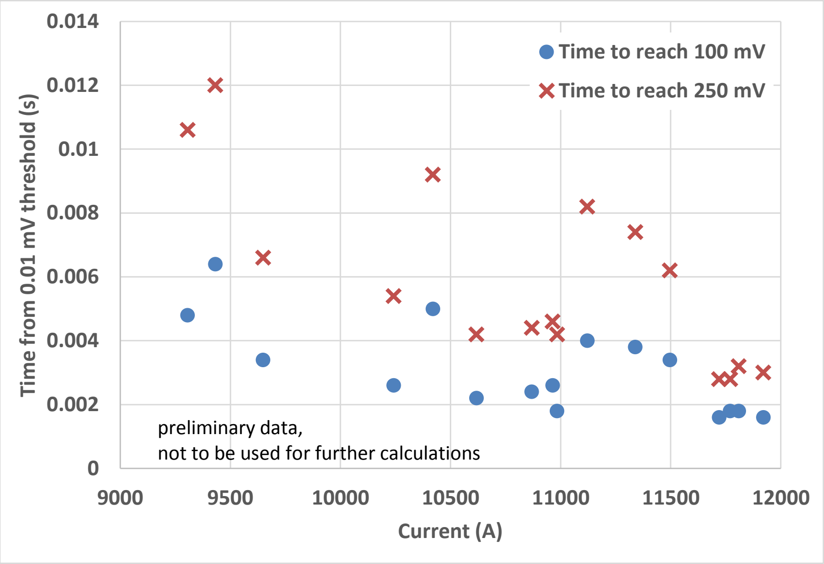


Note that this data is specific to the test, depending on protection settings and energy extraction.

Protection and voltage detection

Differential voltage during initial training quenches





Typical magnet protection uses a differential, here $V_{107} - V_{106}$

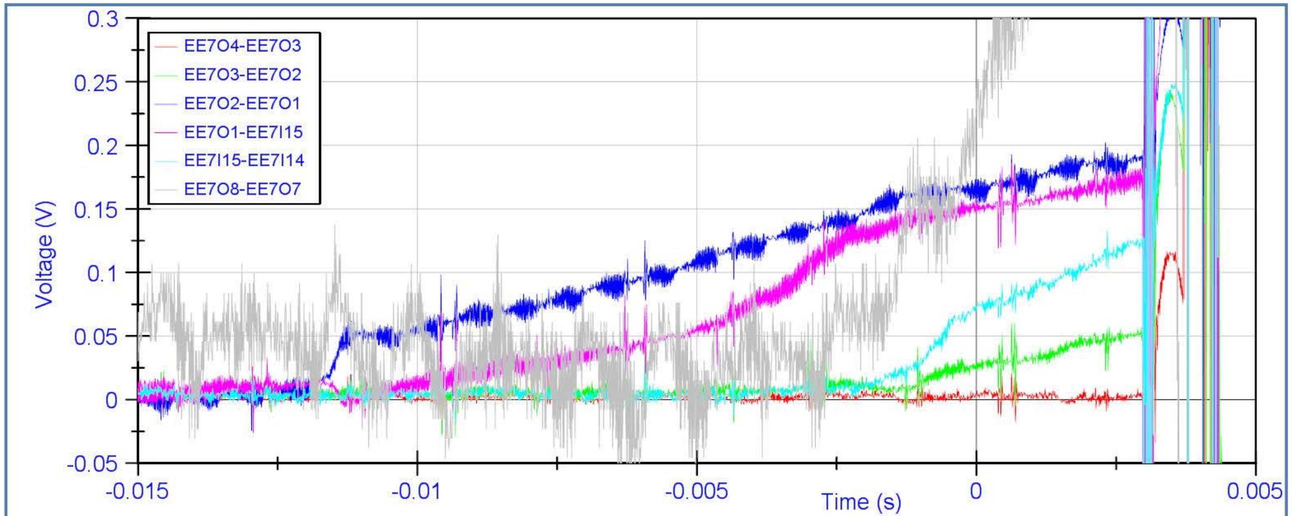
A negative voltage occurs for a quench in coil 106, positive for coil 107.

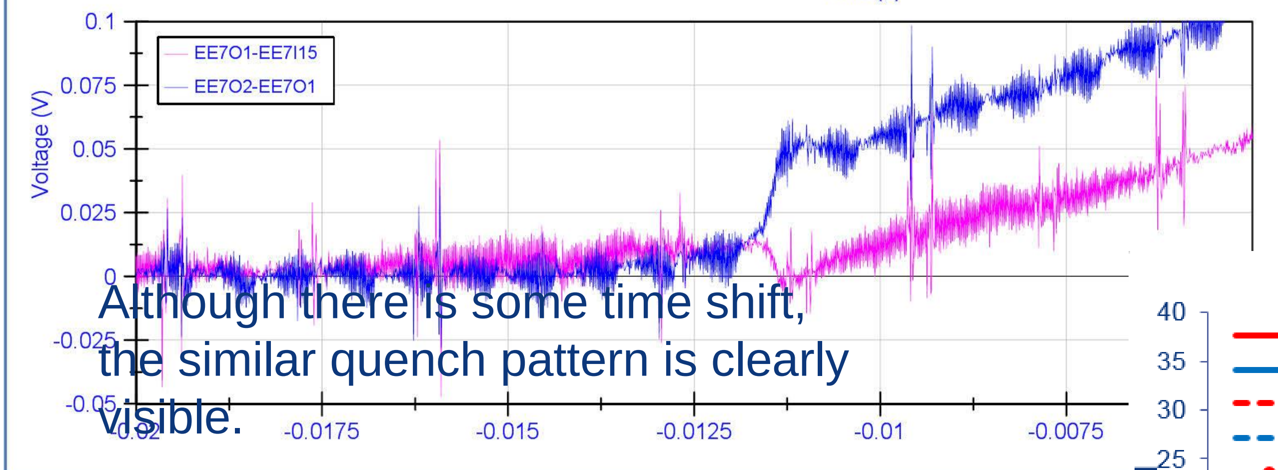
Typical voltage threshold for protection is 100 to 250 mV.

Time to reach the threshold depends on current and quench location.

In the curve a compilation of data is given, based on time between quench start (10 mV) to 100 mV and 250 mV.

Fresh data, further validation and investigation needed.





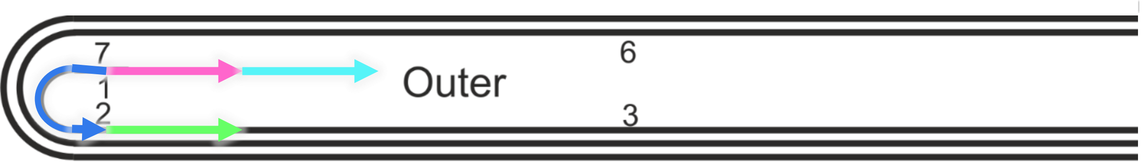
Although there is some time shift, the similar quench pattern is clearly visible.

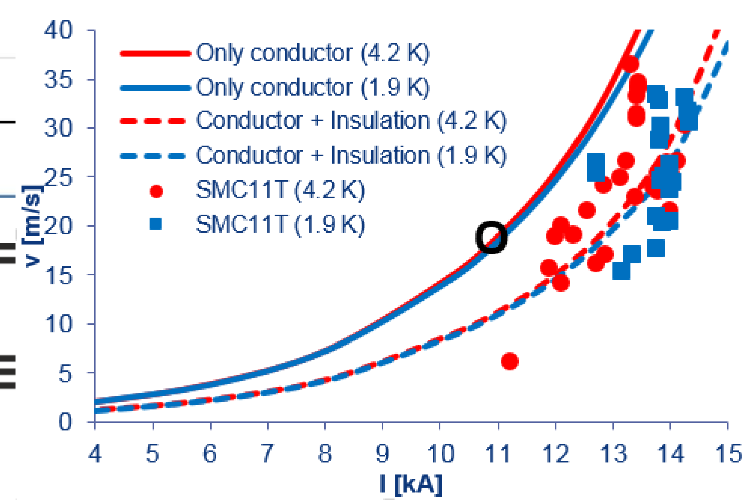
Clear propagation of quench into the next segments
O2-O3 8.4 ms
I14-I15 8 ms

Both segment lengths are 15 cm
Quench propagation velocity 18 – 19 m/s at 10.8 kA in the high-field zone.

Voltage signal suspicious

More data to be extracted. Preliminary data is shown below with respect to data from SMC (H.Bajas) and calculations (S.Izquierdo Bermudez), see the respective talks.



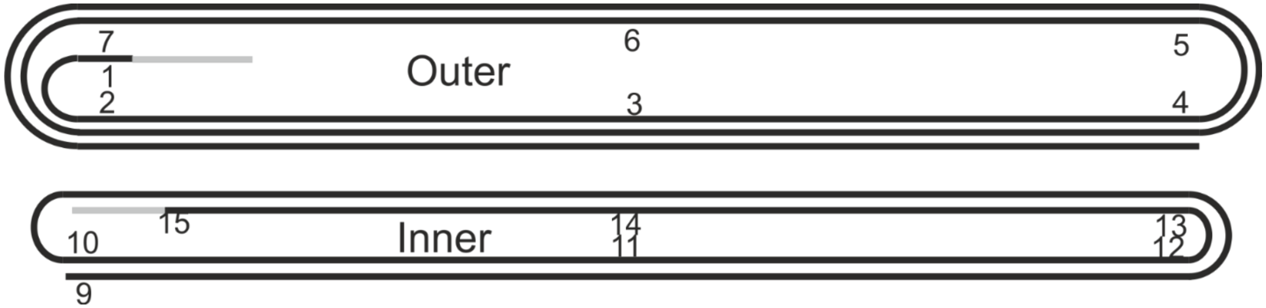


Quench localisation results and discussion

- **Important findings that were not reported in the international review:**

"Weak" locations are around voltage taps close to the turns.

Coil 107 O1, O2, O4.

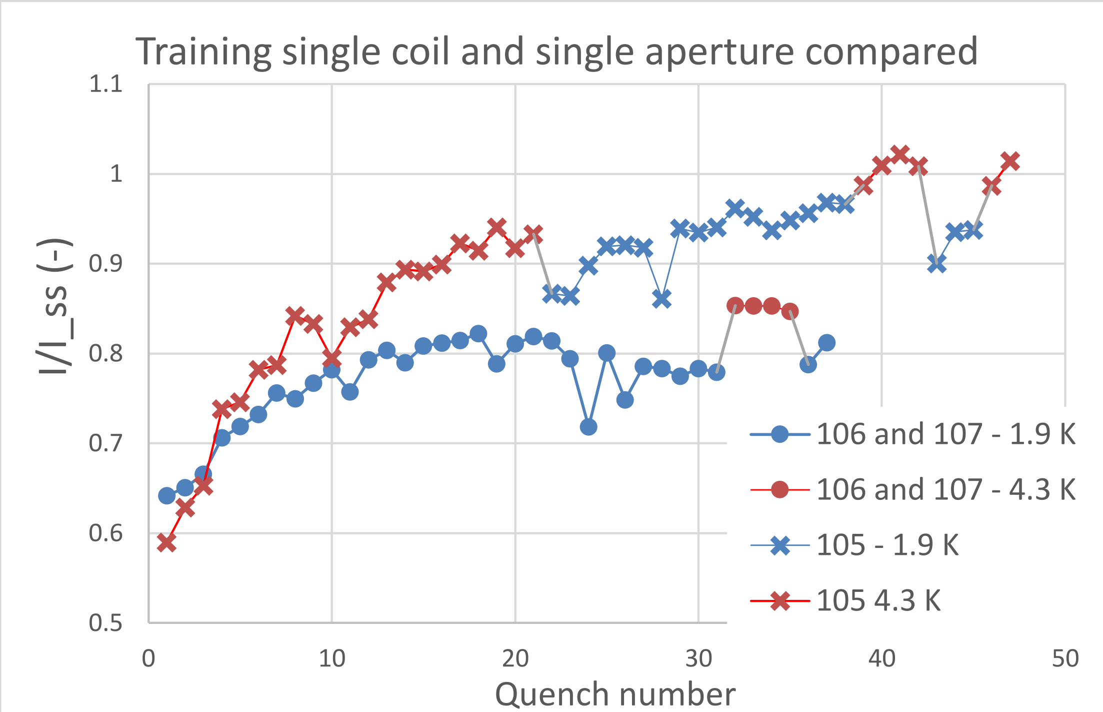


Voltage to ground breakdown during the last discharge at about 700 V in 107-O1 that damaged this voltage tap and prevented from further powering.

Without powering voltage to ground level repeatedly tests before and after this issues up to about 900 V. During powering later on, even to 2 kA there was a voltage breakdown.

Shorts in Coil 105 at O1 and I15.

Training MBHSP101 and MBHSM compared



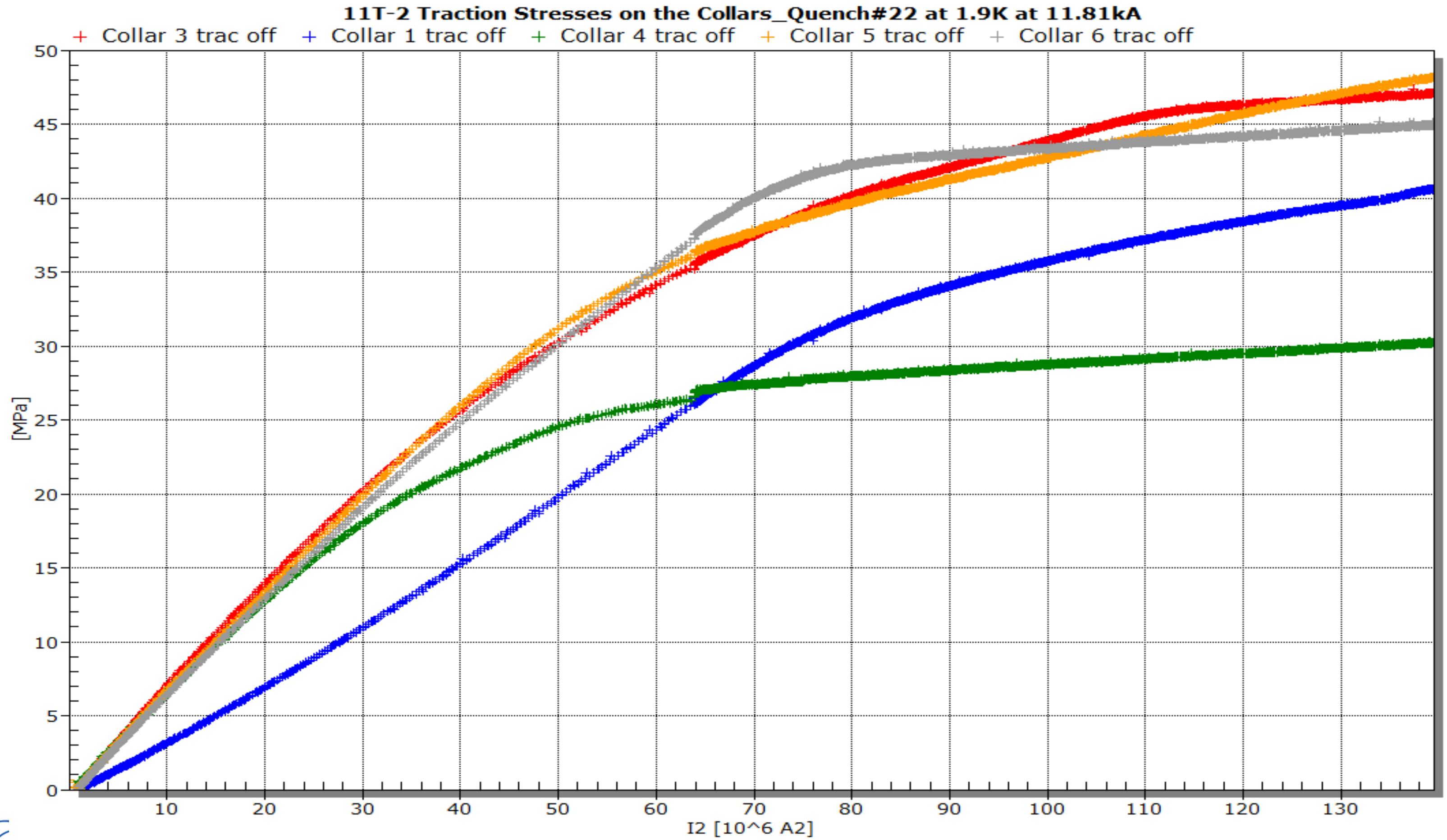
Short sample limit is calculated by combining calculated loadline (Roxie, see presentation S.Izquierdo) and the measured critical current density of short samples (see presentation Bernardo).

Short sample limit for MBHSM has been passed by 2 %. Variations and calculations errors apply.

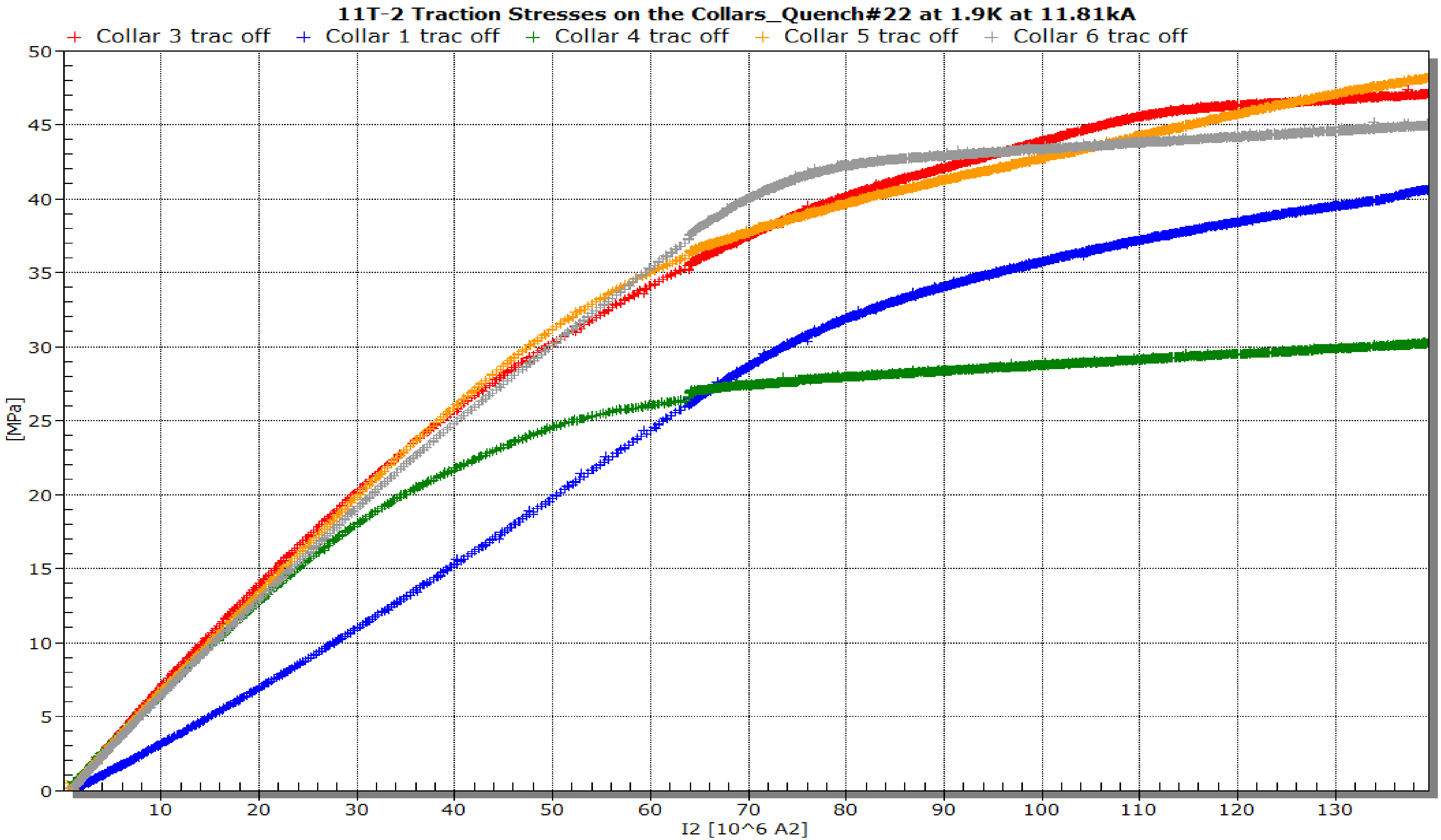
Coil 105 has a better performance than coil 107.
Note that coil 106 only showed 4 quenches before reaching $0.82{*}I_{ss}$

Correlation between mechanics of the collar and yoke to be analysed, see EDMS 1387744

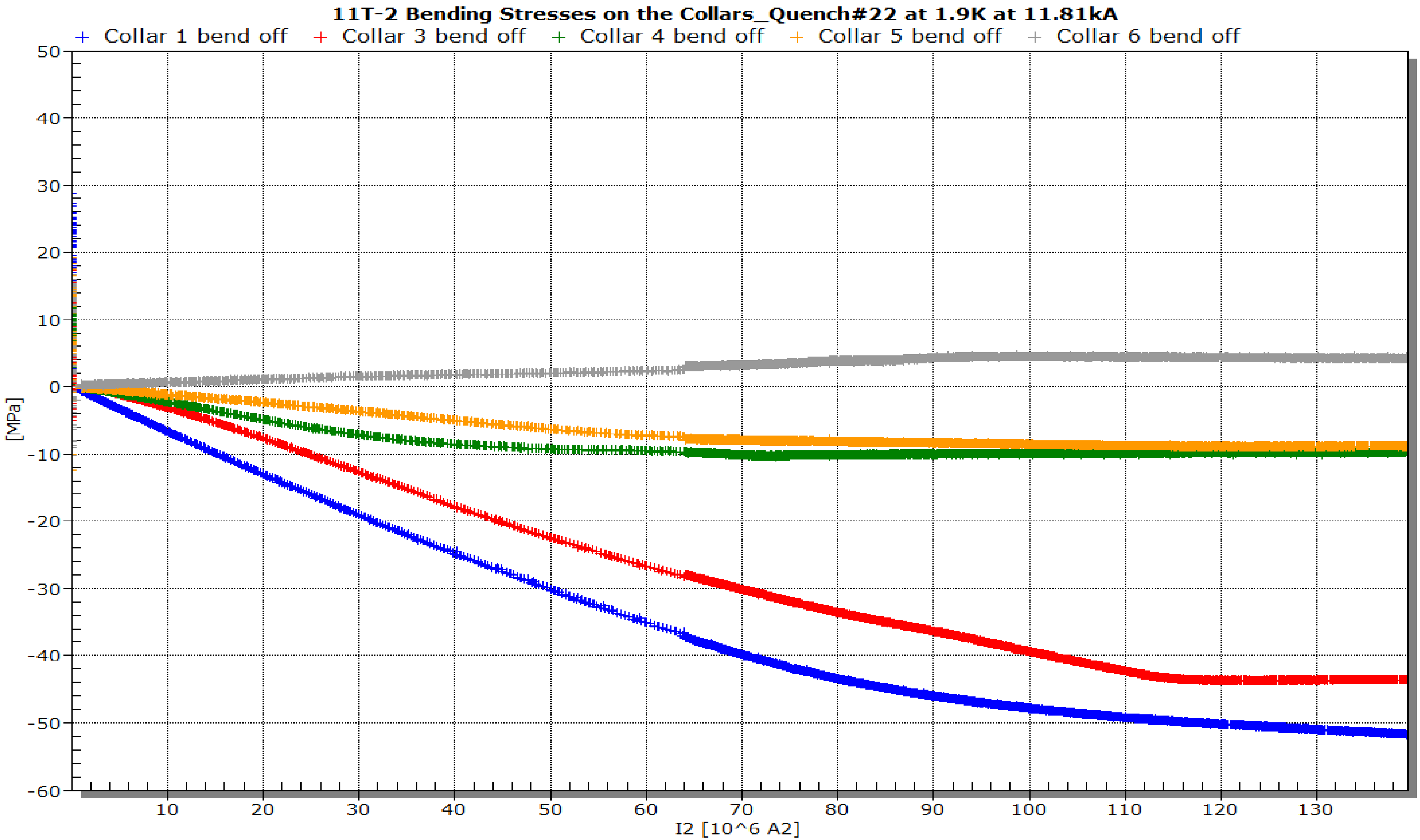
Behavior of the collars during a Quench



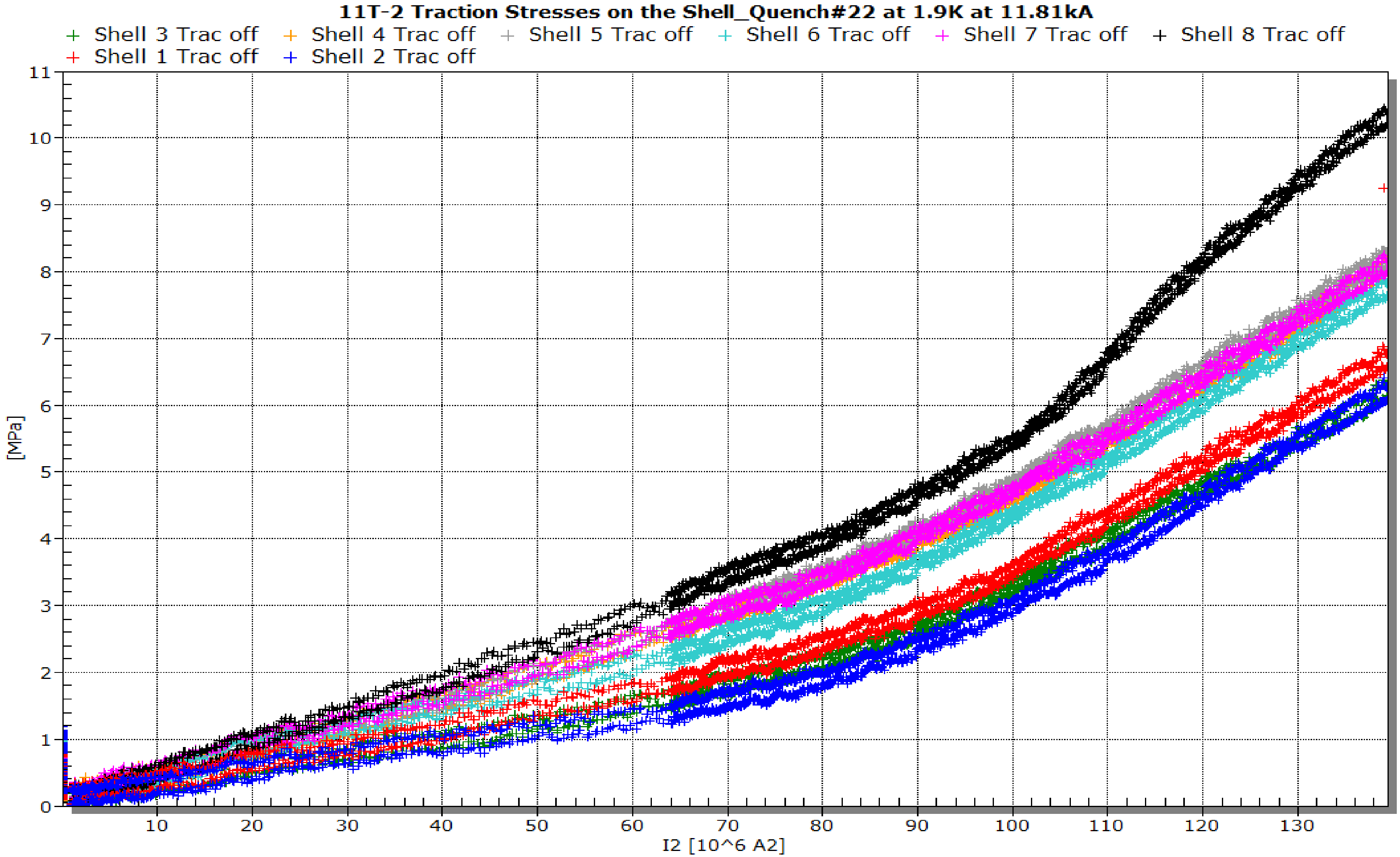
Behavior of the collars during a Quench



Behavior of the collars during a Quench



Behavior of the shells during a Quench



Behavior of the shells during a Quench