MBHDP101 test results debriefing

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TE-MSC-TF

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Thanks to the whole team, specially Jerome and Vincent

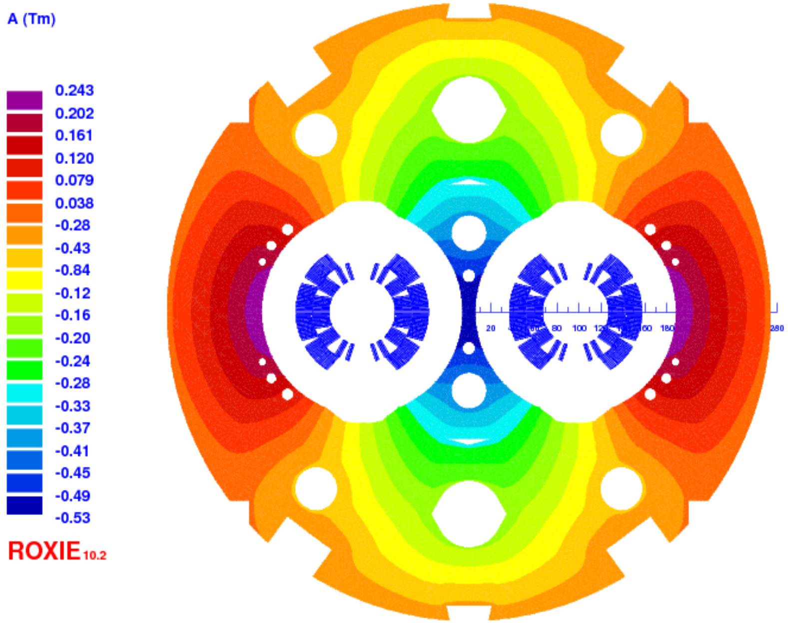
With input from Susana and Antonios

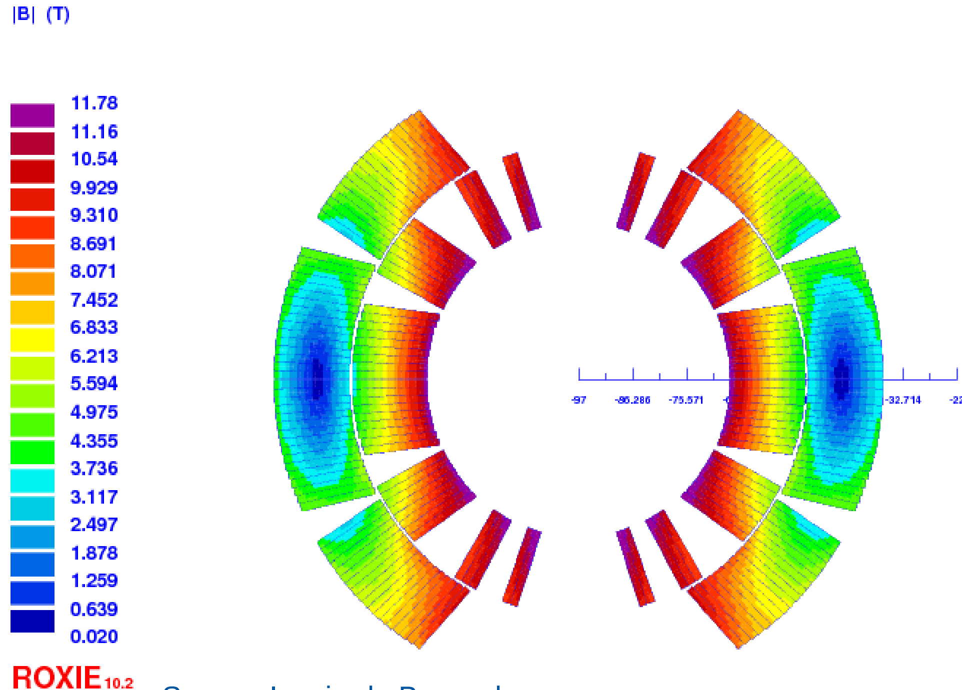
Coils tested at CERN so far

Coil number	MBHSM101	MBHSP101	MBHSP102	MBHSP103	MBHDP101
105	x				
106		x	x		x
107		x			
108			x		x
109				x	x
111				x	x

All coils in MBHDP101 have been tested and trained before in the single aperture configuration

Most important feature of a magnet: the Field



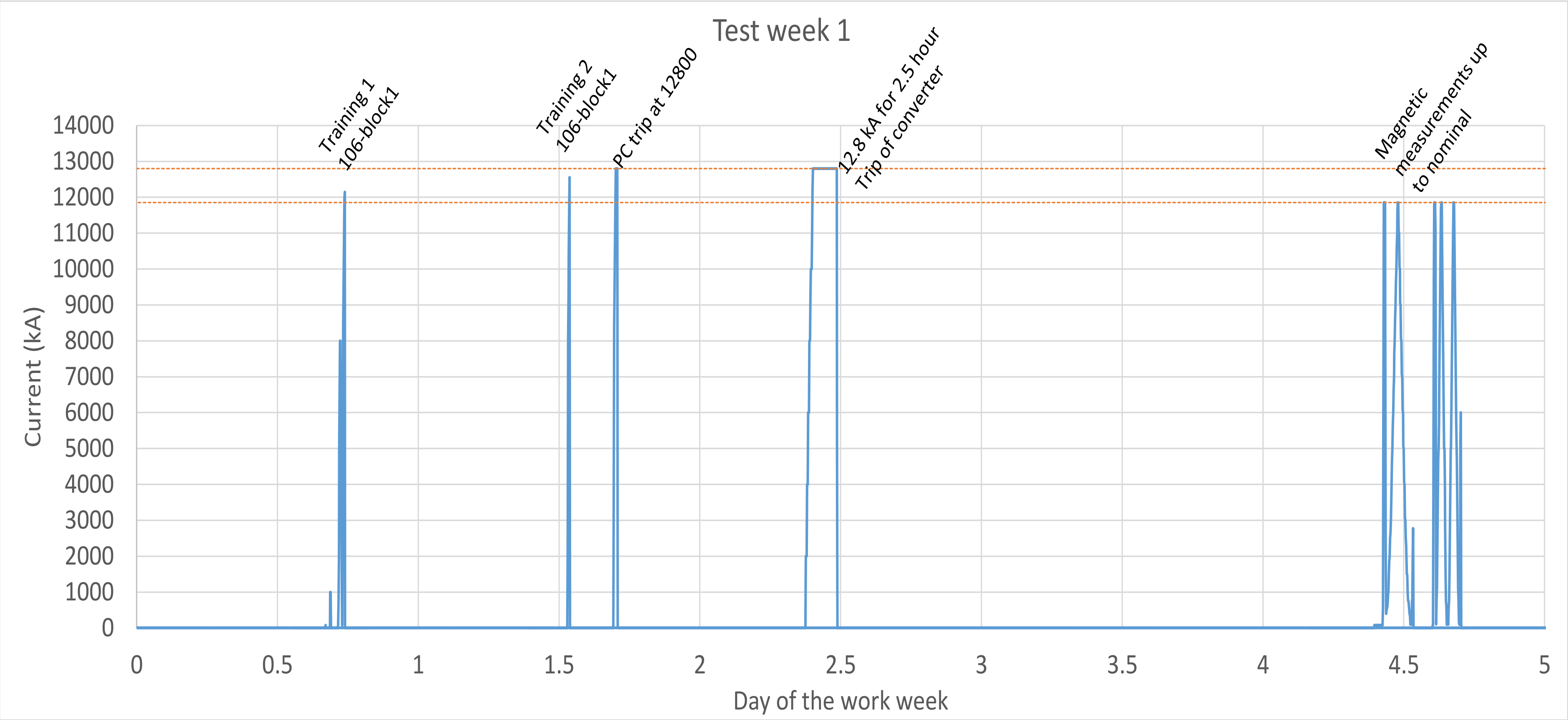


Susana Izquierdo Bermudez

Field on the coil important for testing and calculations.
Field in the bore important for the LHC.
An extended magnetic measurement campaign has been performed. Lucio will report.

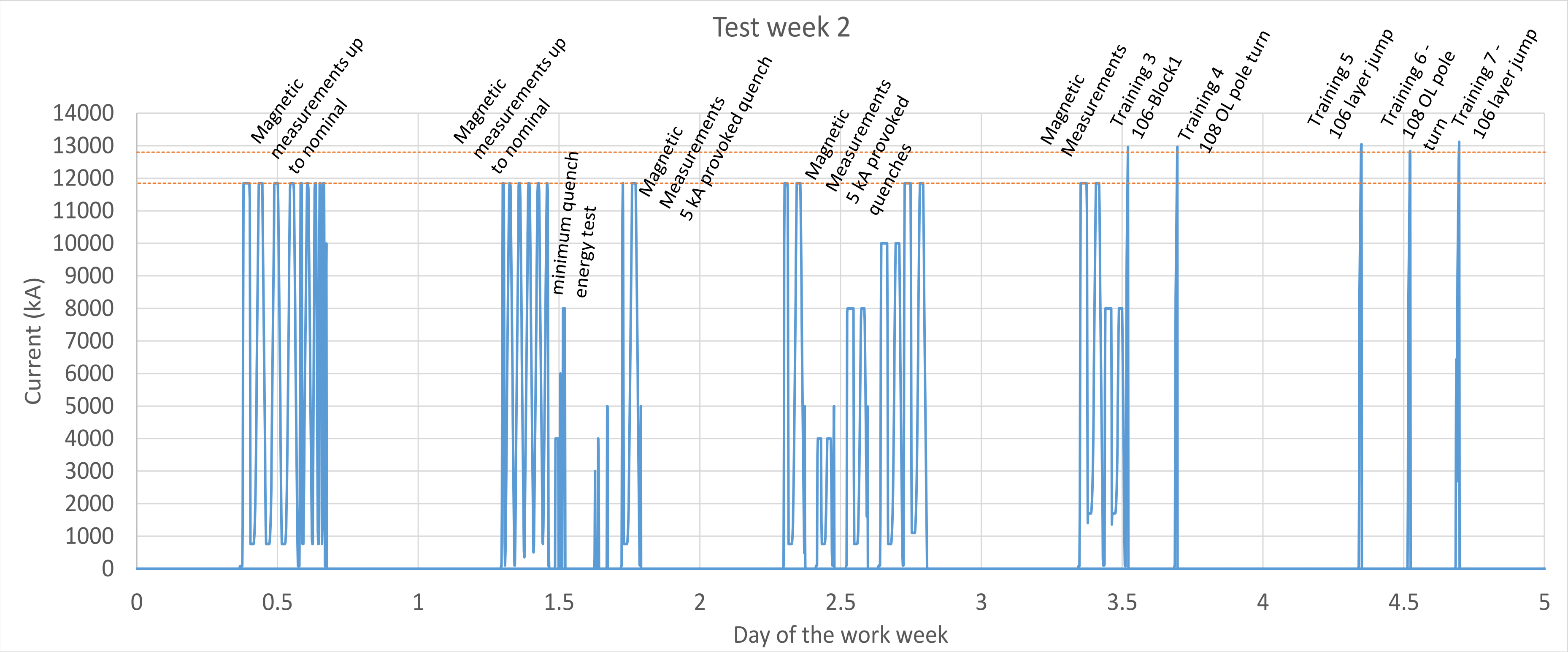
First week test campaign:

- Fast training, followed by magnetic measurements.



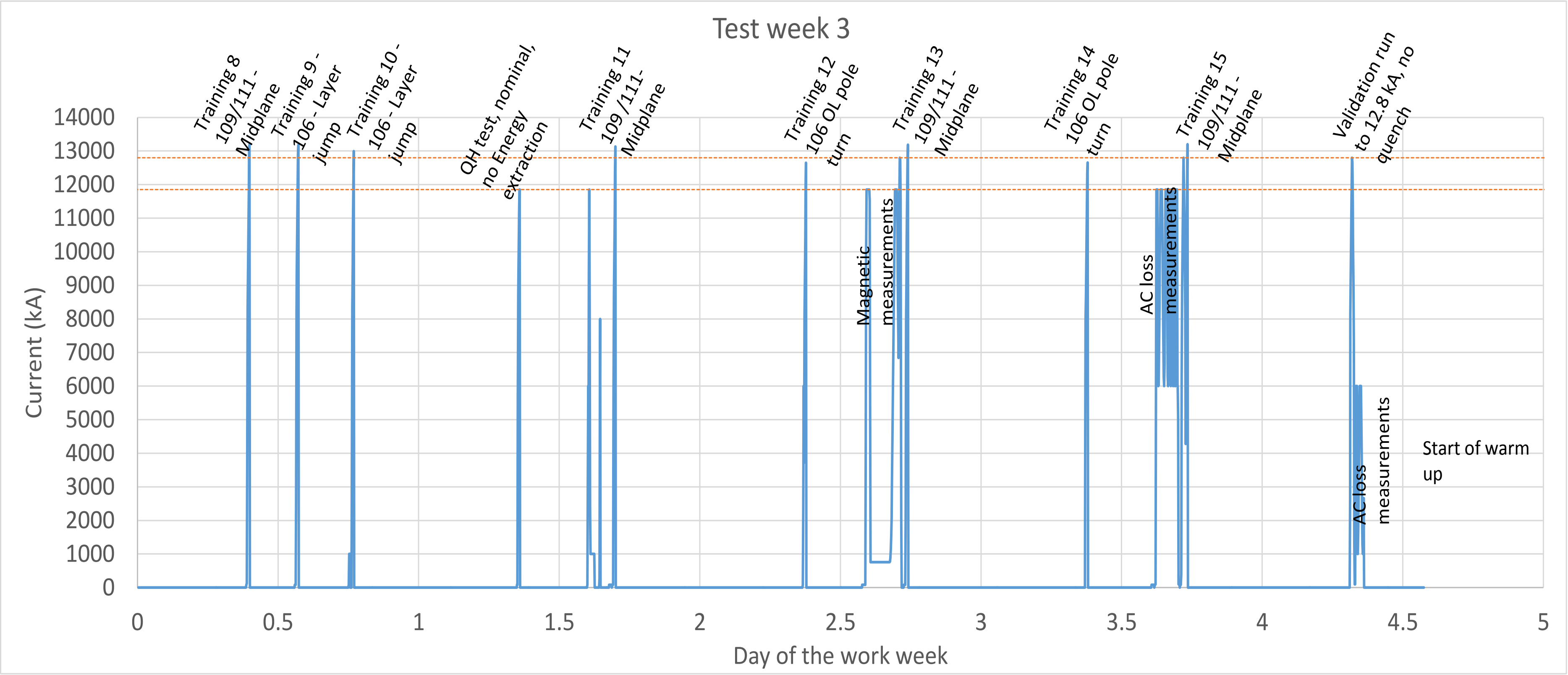
Second week test campaign:

1. Mix of magnetic measurements ad protection studies
2. Start of training above ultimate current.



Third week test campaign:

1. Further training including 3 tests with delayed protection
2. QH test without energy extraction at nominal current
3. Few MM
4. AC loss measurements

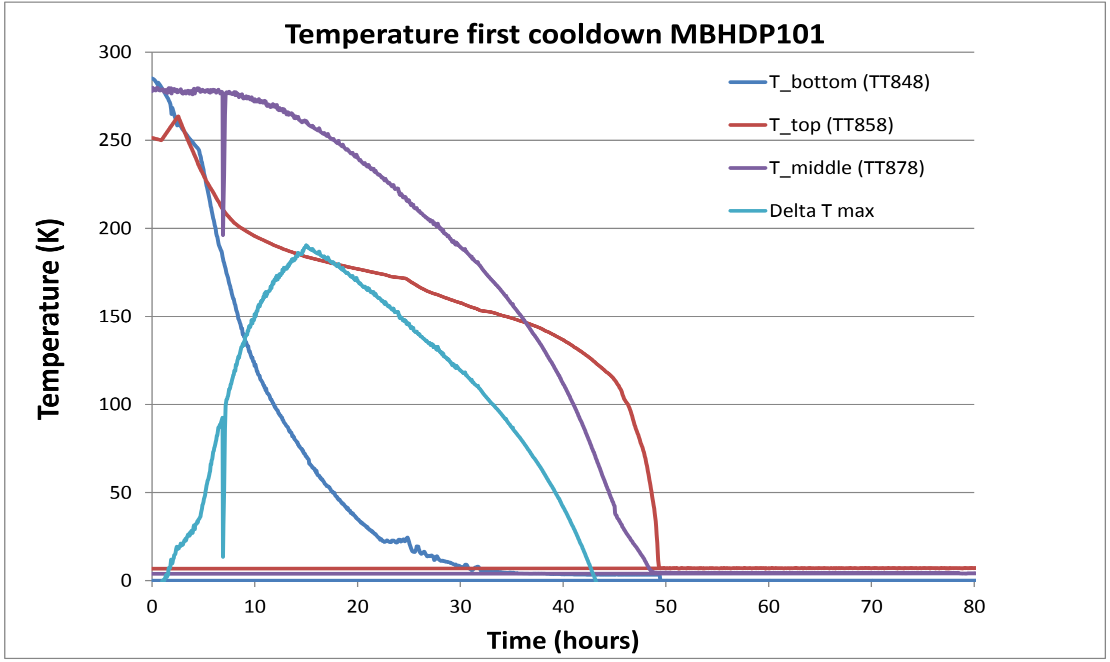


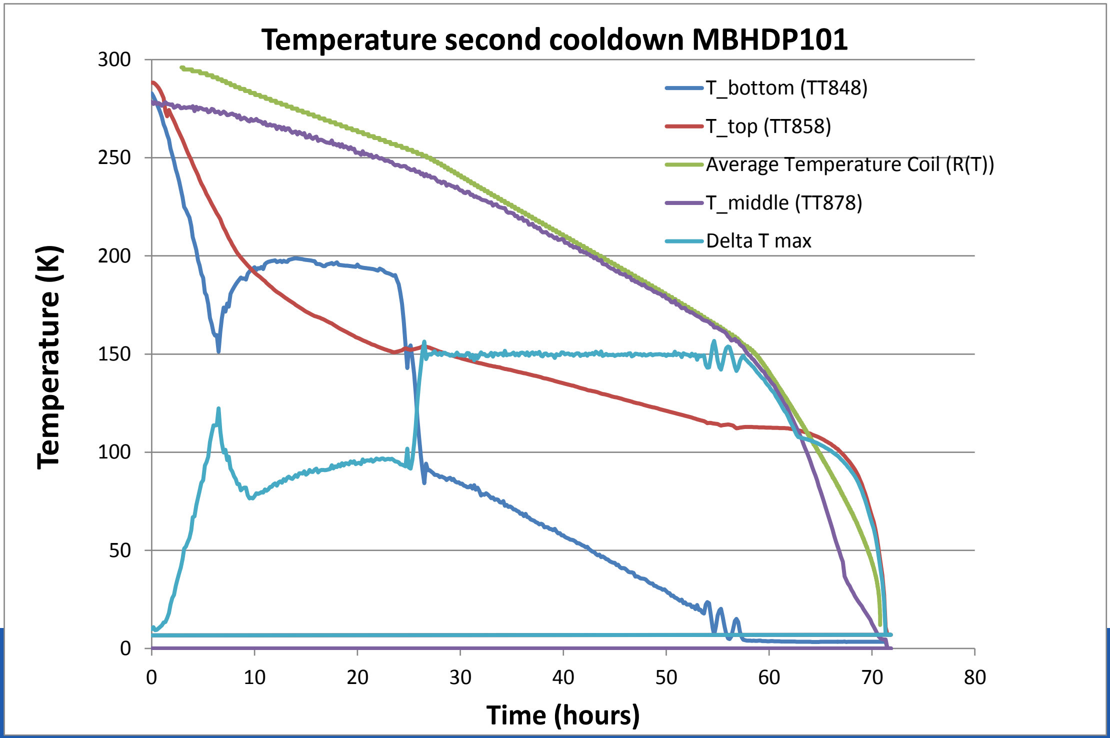
Cooldown

First cooldown:
Delta T between top and bottom at 150 K

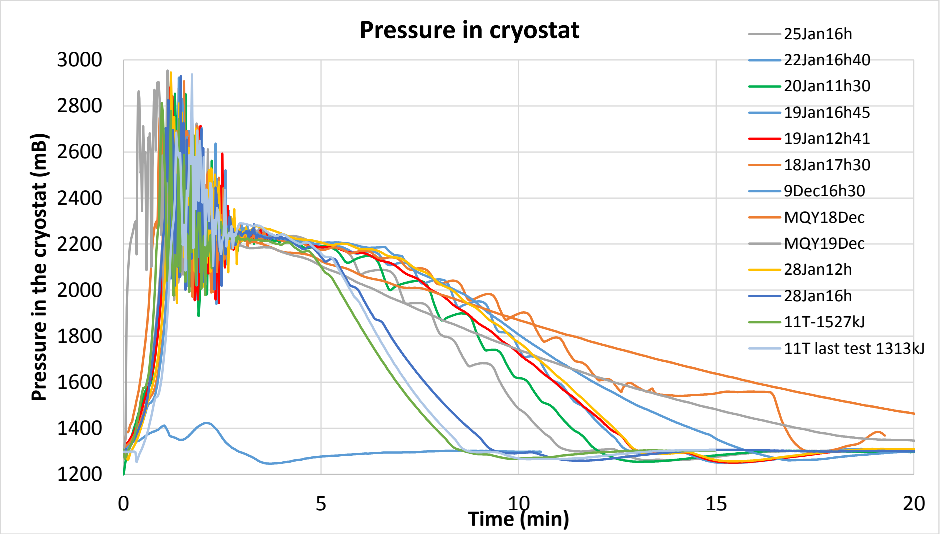
Problem: Middle probe remains the warmest since magnet fills the complete cryostat.

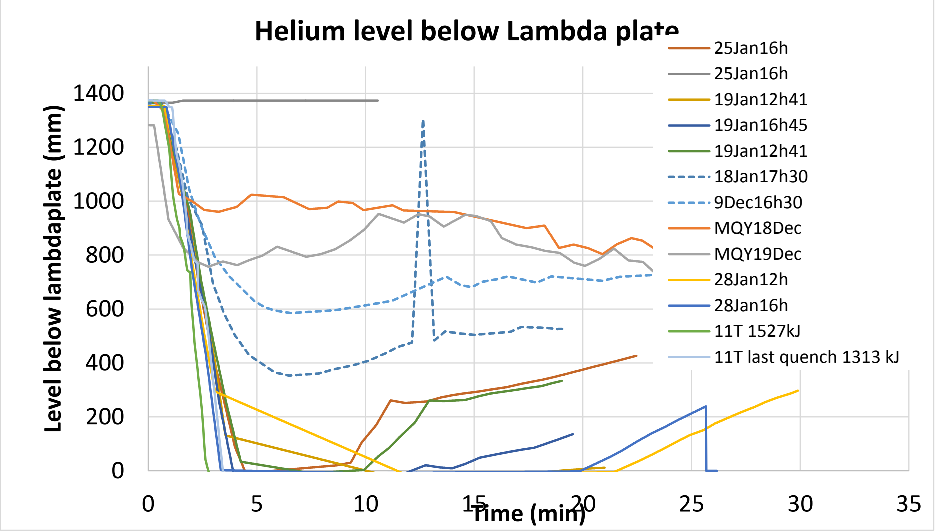
Second cooldown:
Delta T between top, middle and bottom at 150 K (new control conditions).





Pressure in the cryostat, up to 1.5 MJ deposited energy





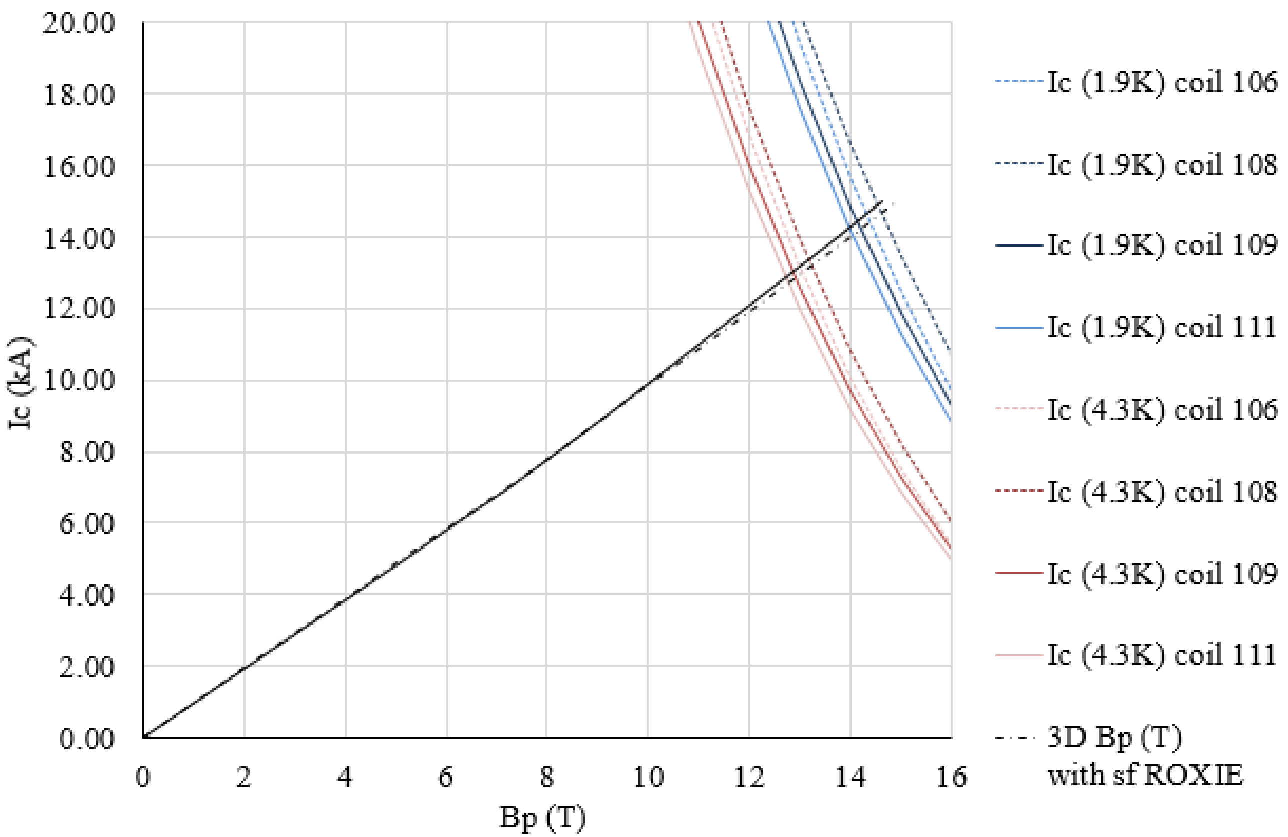
With the amount of energy we keep track of the behaviour of the pressure and helium evaporation

Higher energy deposition:
Faster decrease in He level
Faster decay of pressure

Helium at the level of the coil and higher is all evaporated within 5 minutes at 1500 kJ deposition.

Even with highest cooldown power about 4.5 hours are needed to cool back down the magnet.

Load line and short sample limit:

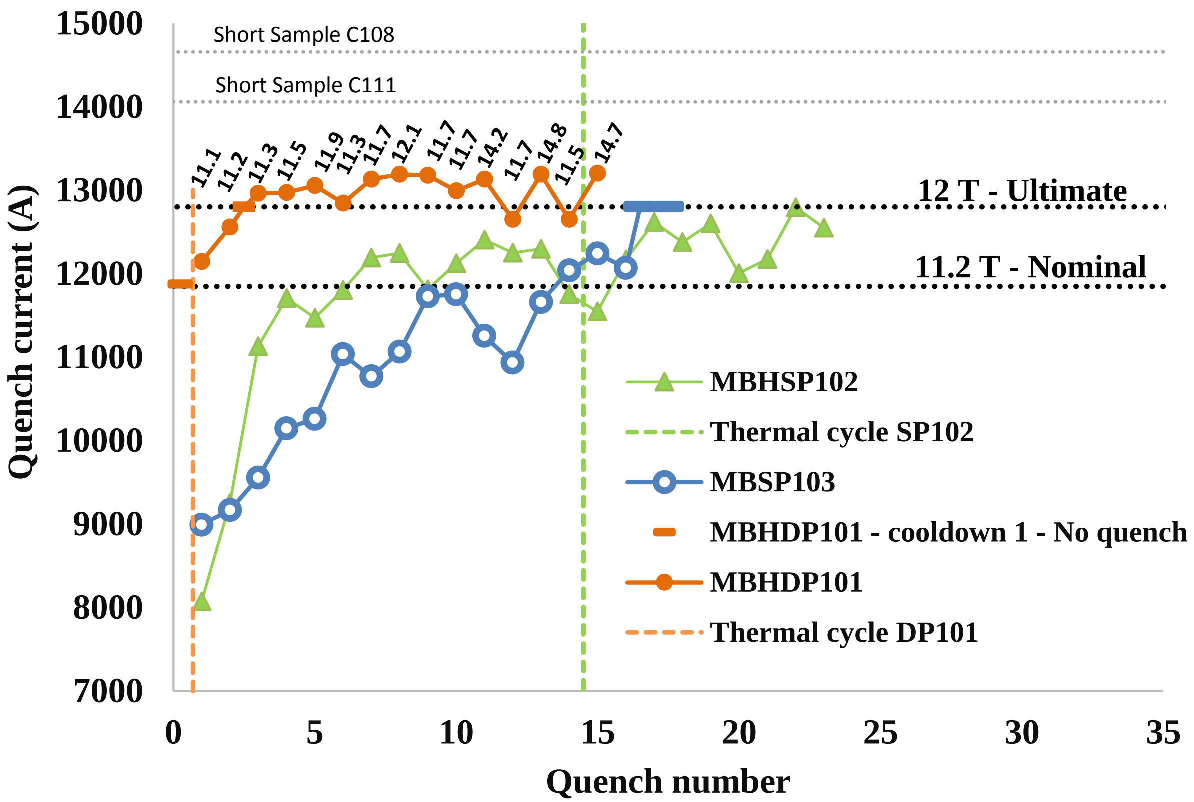


Susana Izquierdo Bermudez and Bernardo Bordini

Measurements of the witness samples give the short sample limit for each coil with about 4 % variation.

Coil	Short sample limit (kA)
106	14.4
108	14.7
109	14.2
111	14.1

Training



Very good result

To be installed in the LHC with nominal operating current of 11850 A

Ultimate design current 12800 A

Long training single apertures

Only 2 training quenches up to ultimate current in double aperture.

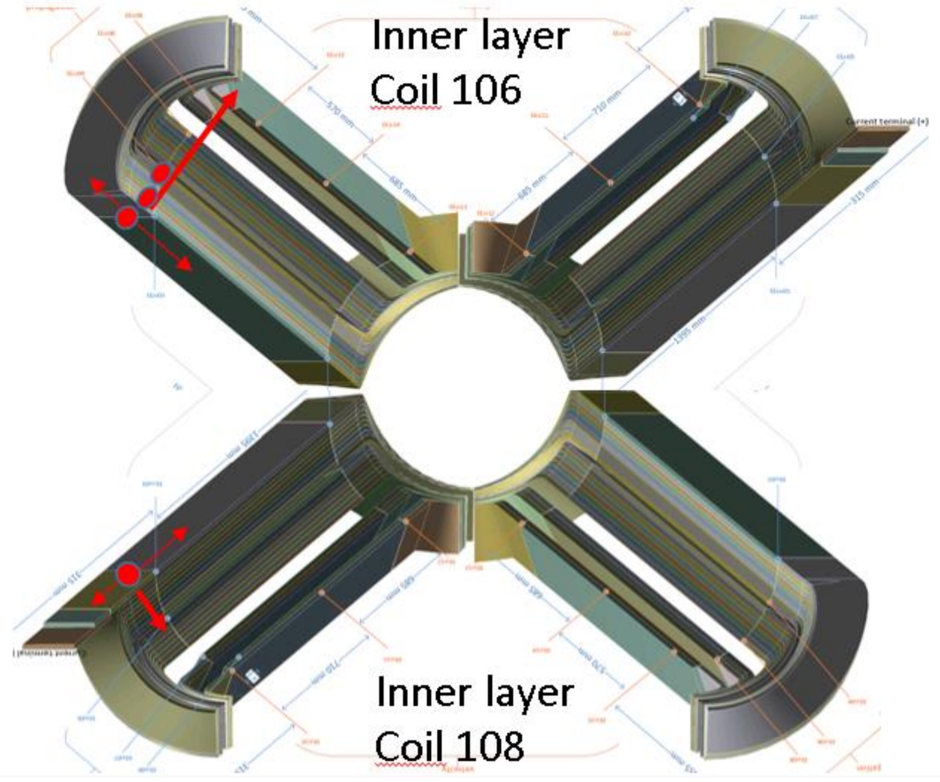
Thermal cycle was done after reaching 11.87 kA.

94 % of short sample limit reached.

First 3 quenches: Midplane

The first 3 quenches were located on the inner layer midplane of coil 106 and coil 108, but with very fast propagation in the blocks of the inner layer.

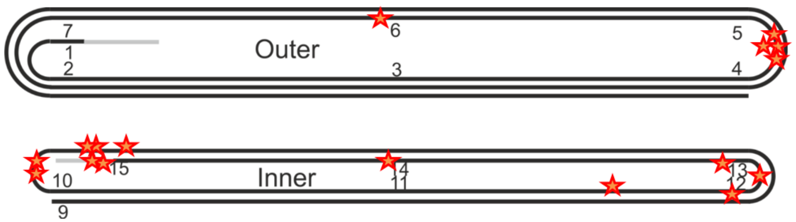
These quenches were close to or including the splice of coil 108



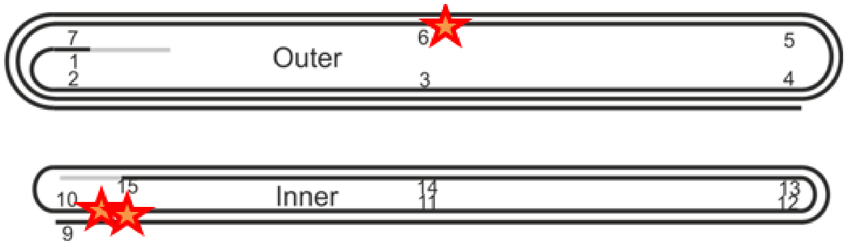
High Field quenches in the same coils while in the single aperture configuration

MBHSP102

COIL 106

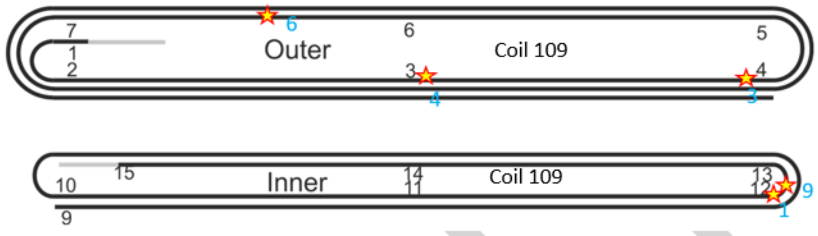


COIL 108

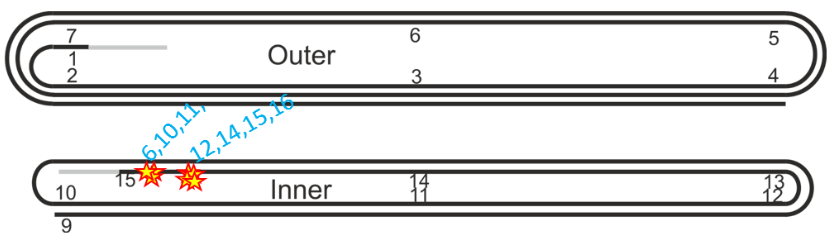


MBSHP103

COIL 109



COIL 111



Additional high field quenches in double aperture configuration

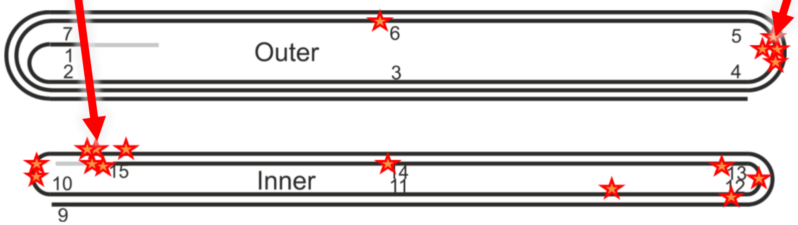
4 Additional quenches in coil 106 I15-O1

MBHSP102

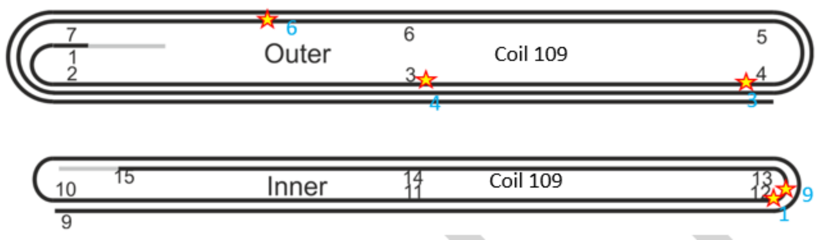
2 additional quenches in coil 106 O4-O5

MBSHP103

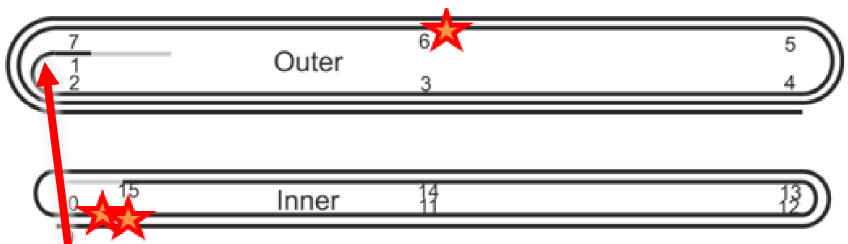
COIL 106



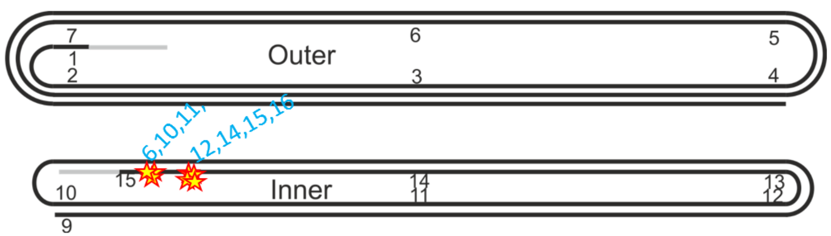
COIL 109



COIL 108



COIL 111



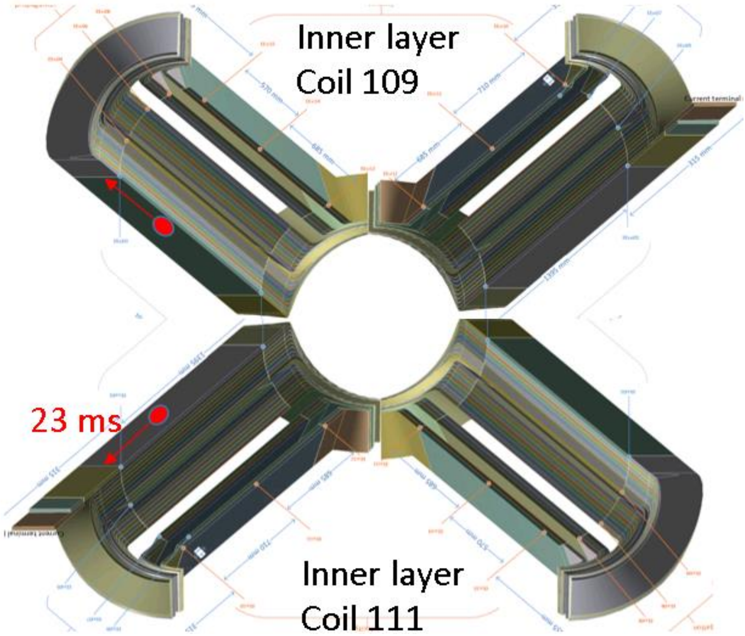
2 additional quenches in Coil 108 O1-O2

Note that the quenches are this time at a higher current than before.

Quenches on the midplane of coil 109 and coil 111

Quenches 8, 11, 13, 15 occurred in the midplane of coil 109 and 111, but those were more "local" quenches compared to the midplane quenches in coil 106 and 108.

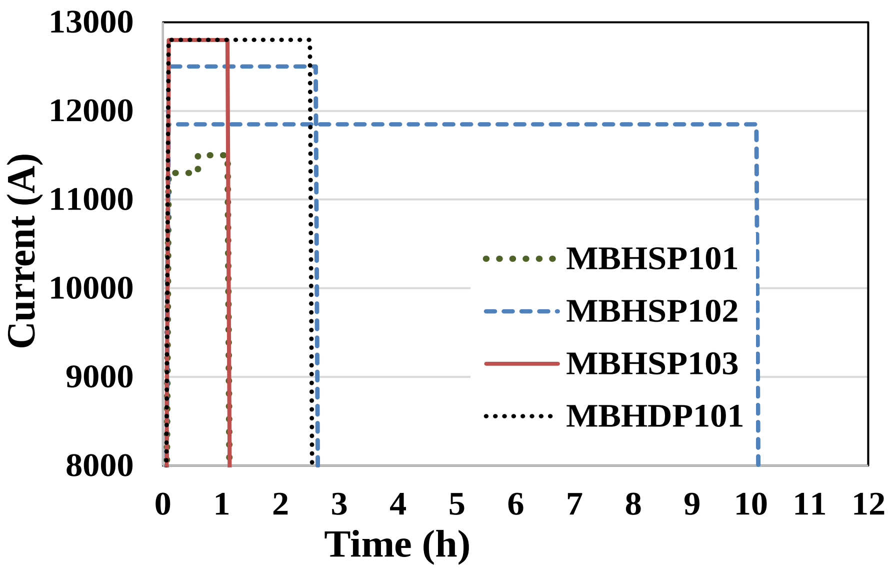
- Typically only 2 turns (1 per coil on the midplane) quenched.
- The quenches occurred all between 13.1 and 13.2 kA, the highest current reached for this magnet.
- Quenches 8, 13 and 15 have exactly the same quench location, with a quench in about the middle (longitudinally) of the midplane, and with 23 ms of propagation time towards the voltage tap of the splice.



This is the limiting point of this specific model.

Endurance test

Double aperture stayed 2.5 hours at ultimate current, followed by an abort due to Cryo loss.
Not a single quench at flattop current was observed in any of the CERN built 11T models.



Splice resistances

Splice resistance (nΩ)			
Coil	**SP102**	**SP103**	**DP101**
106 inner	0.24		0.25
106 outer			0.28
108 inner	0.22		0.32
108 outer	0.39		0.28
109 inner		0.27	0.25
109 outer		0.27	0.21
111 inner		0.21	0.22
111 outer		0.17	
ConLA			7.6
ConLB			12.3

- Clamped joints are OK, 8 and 12 nΩ (in the first cooldown 70 and 150 nOhm)
- Splices are OK, 0.2 to 0.3 nΩ

Thanks to Antonella for calculating the splice resistances

High Voltage test

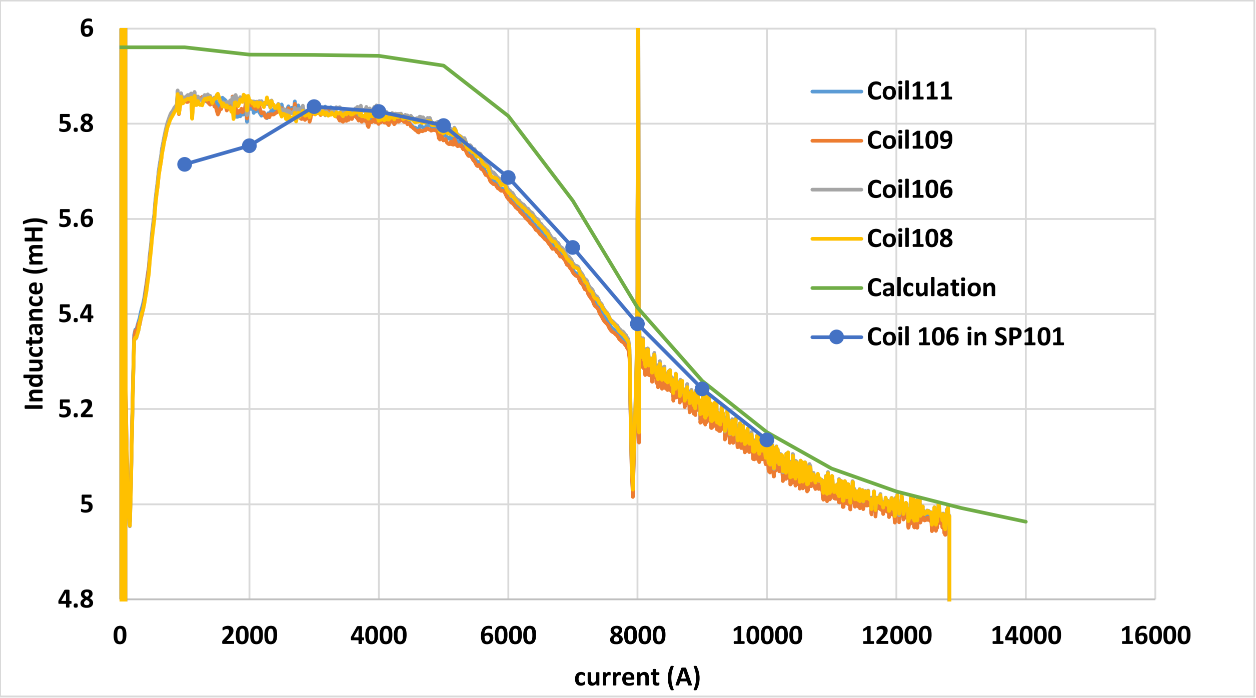
- Magnet to ground insulation (possibly wiring) was not OK before cooldown: now HV test shows 1.9 GΩ at 1 kV.

High-Voltage tests between coil and ground: Criterion > 500 MΩ

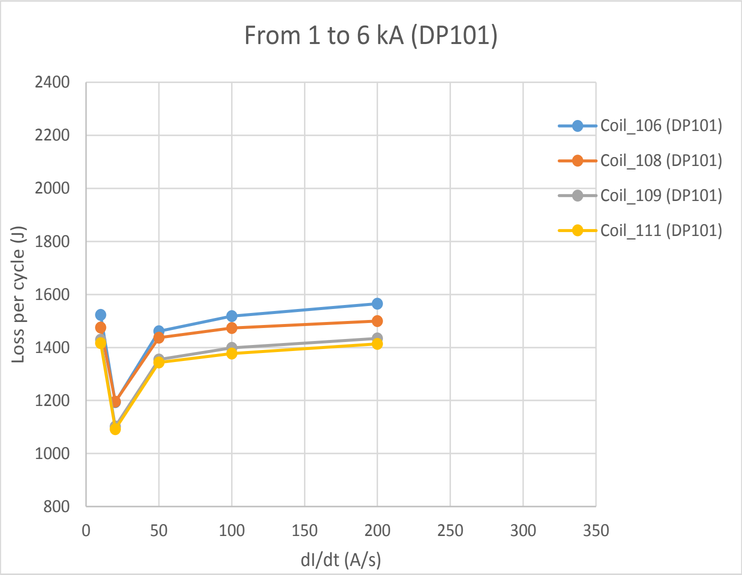
	Date	Result at 1 kV
Reception B180	13 October	260 GΩ
UL7 (Under load before welding)	26 October	10 GΩ
FINAL7 (last test in B927 before shipping to SM18	18 November	83 MΩ
In SM18 after first insertion of MM tubes	24 November	298 MΩ
In SM18 horizontal, before hanging to the insert	26 November 27 November	120 MΩ 151 MΩ
In SM18 in cryostat, warm	1 December	68 MΩ
In SM18 in cryostat, filled with helium	7 December	650 MΩ
In SM18 in cryostat, warm	7 January	250 MΩ
In SM18 in cryostat, filled with helium	18 January	1900 MΩ

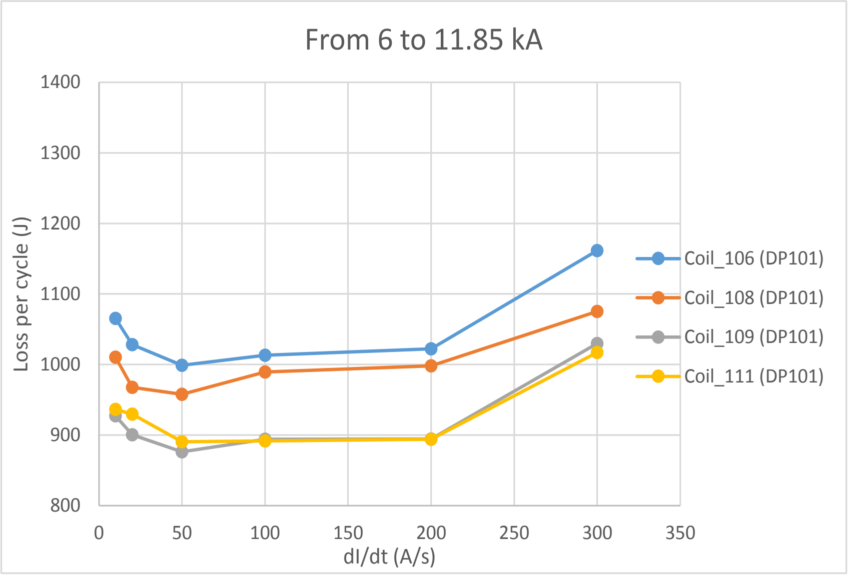
Inductance

- Very good agreement in inductance measurements between the 4 coils, but different from the model.
- Further discussion later.



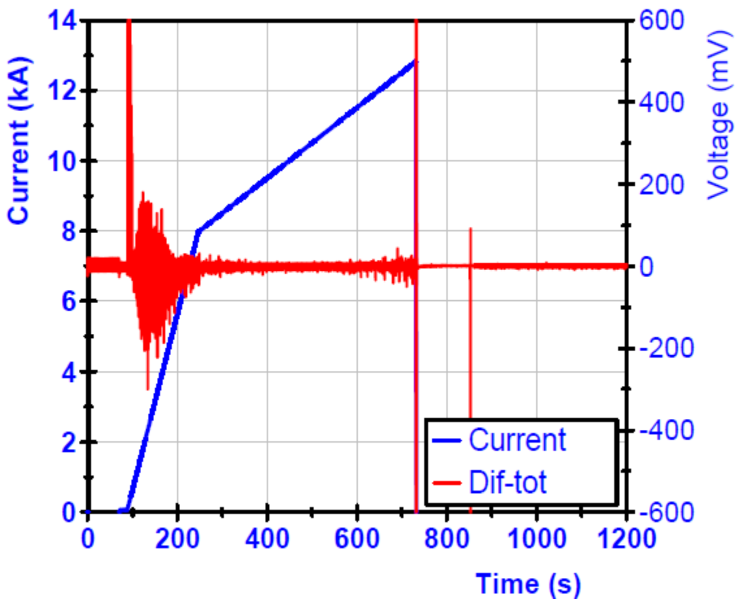
AC loss measurements

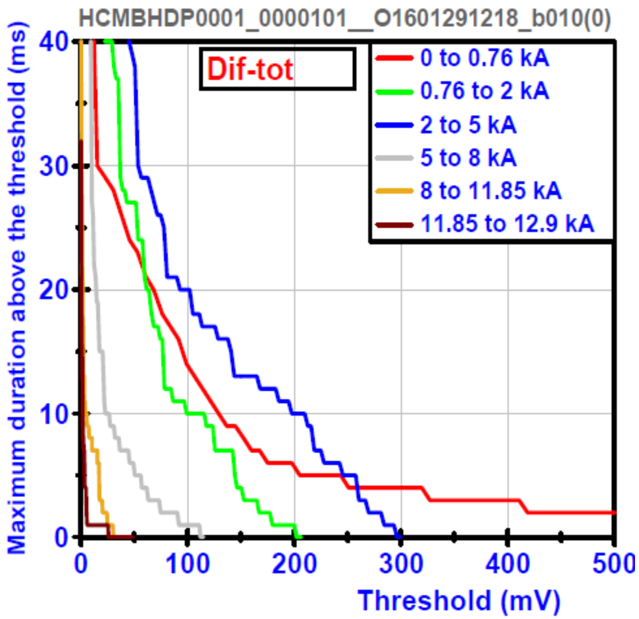




Slope is too small for enough accuracy.
Sign of low interstrand losses and high Rc.

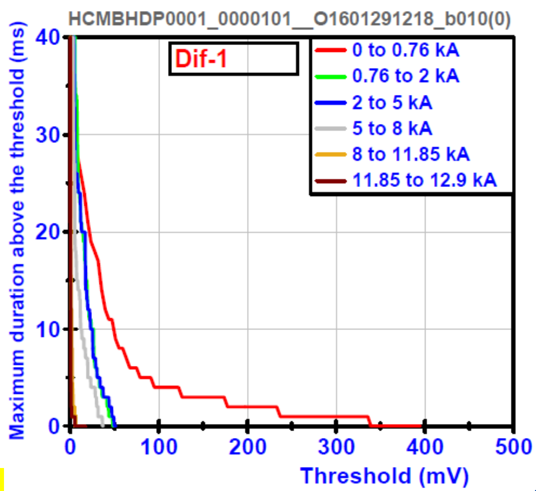
Fluxjump and threshold

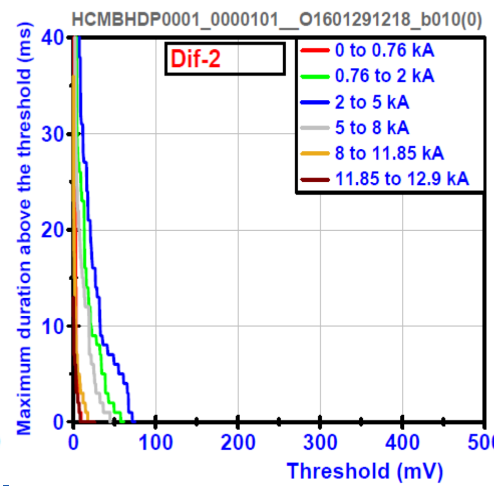




Differential signal between apertures has high Flux Jumps, disturbing protection.

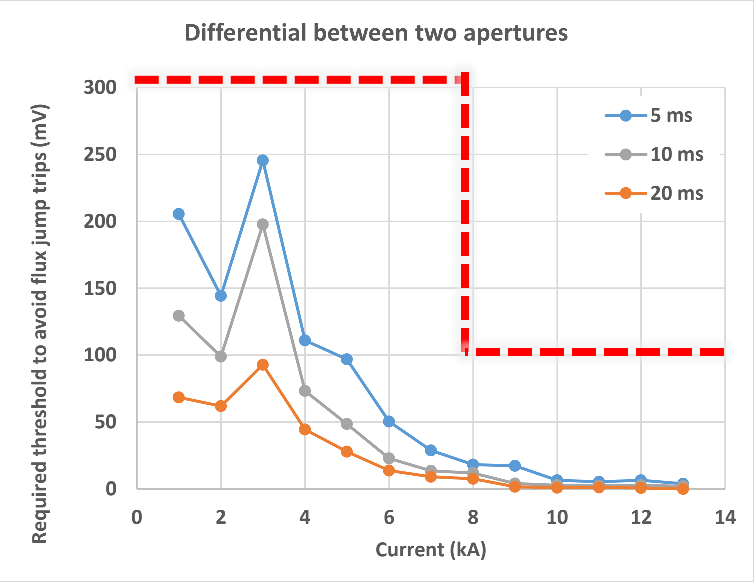
Now protection at 300 mV, 10 ms for total differential,
150 mV, 10 ms, for differential between apertures

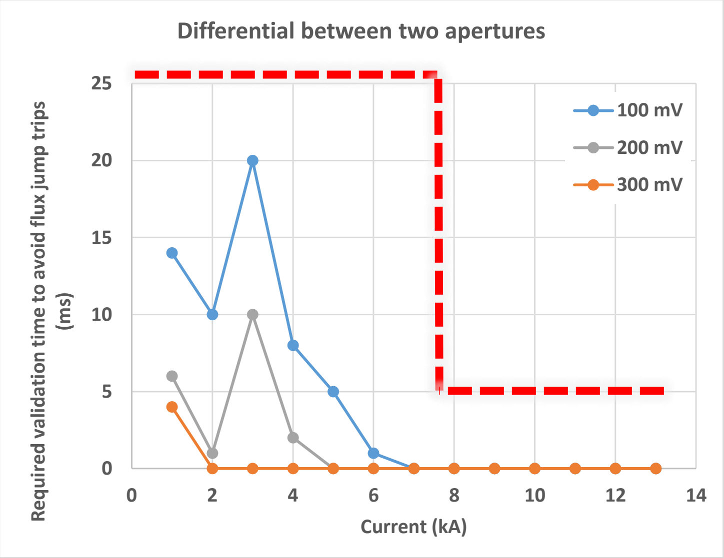




- **Ok for the model test**
- **Important for prototype protection**

Protection solution



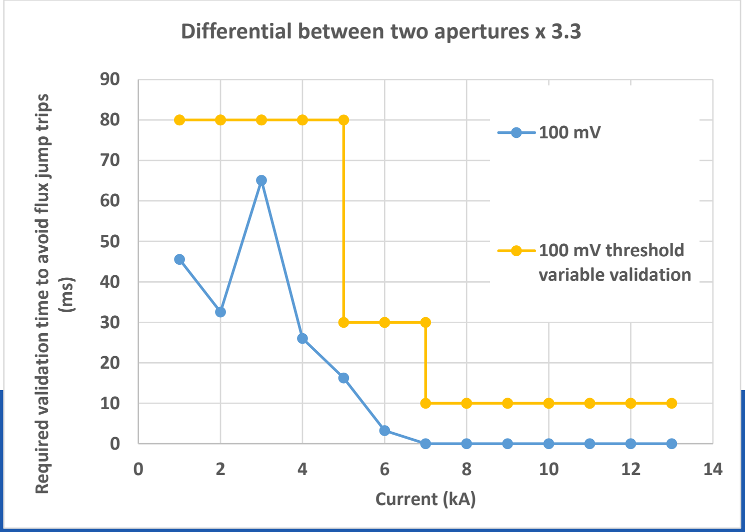


Possible protection strategy for prototype and series:

Solution 1:
Current dependent threshold

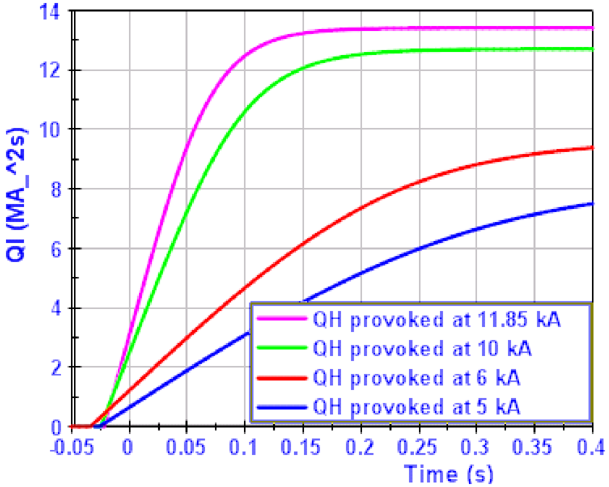
Solution 2:
Current dependent validation time (may save more MIIts at lower and intermediate currents.)

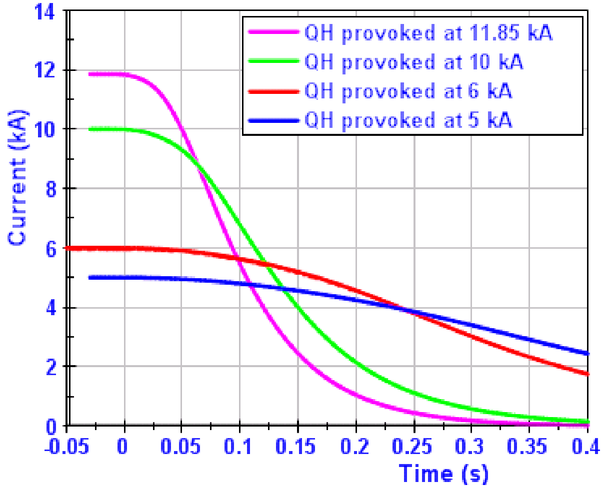
Note: The fluxjumps probably scale up with magnetic length (1.7 m to 5.5 m)



Protection studies

Provoked quenches without Energy Extraction

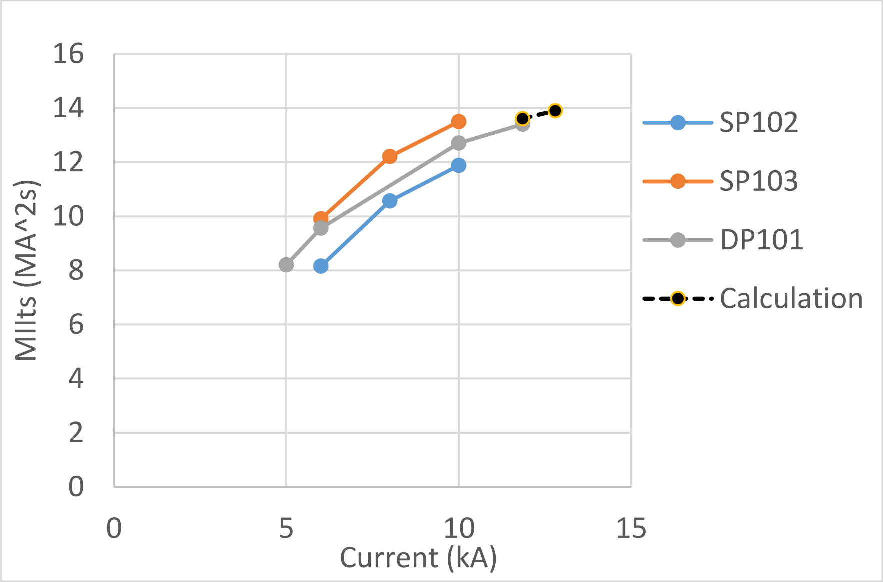


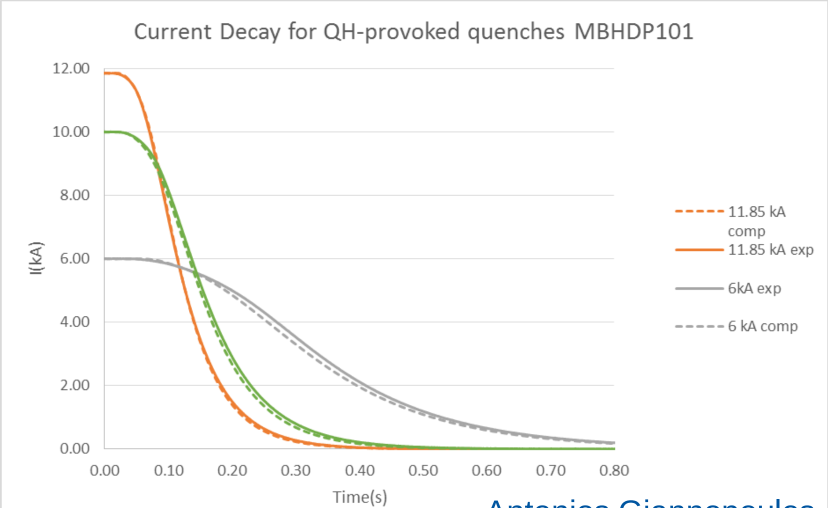


Goal: Further model validation.

NB: conductor properties and QH-coil insulation not all similar to nominal.

Good agreement between model and experiment.





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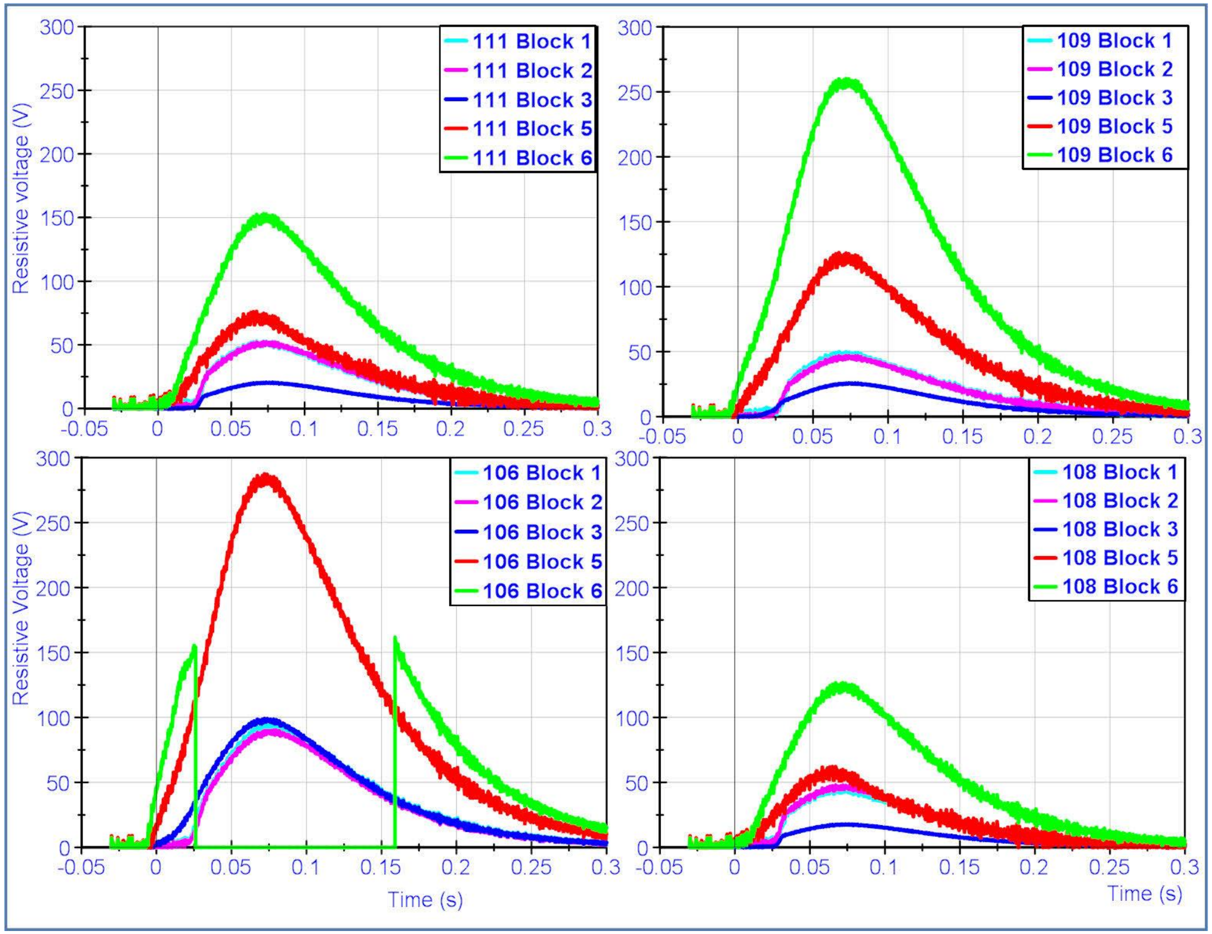
Protection studies



Resistive voltage buildup in the different parts of the coils.

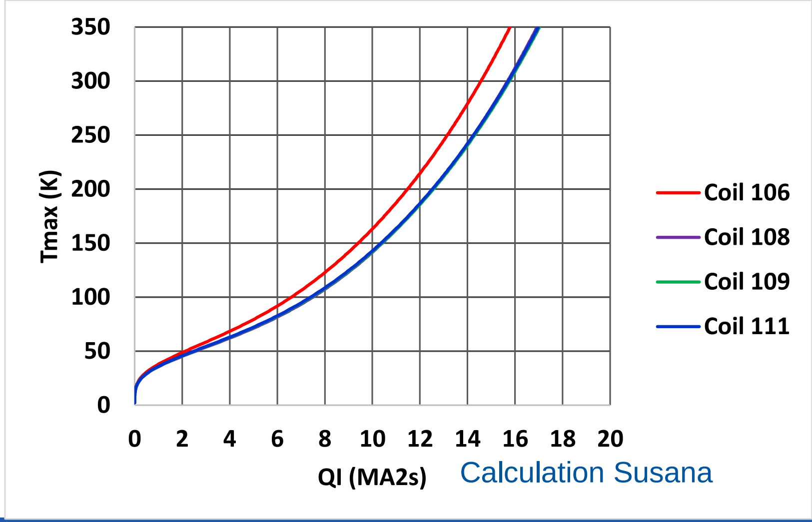
Largest contribution coil 106
Smallest contribution coil 108

This is expected from R, RRR and QH to coil insulation, see next slide.

4 different coils:

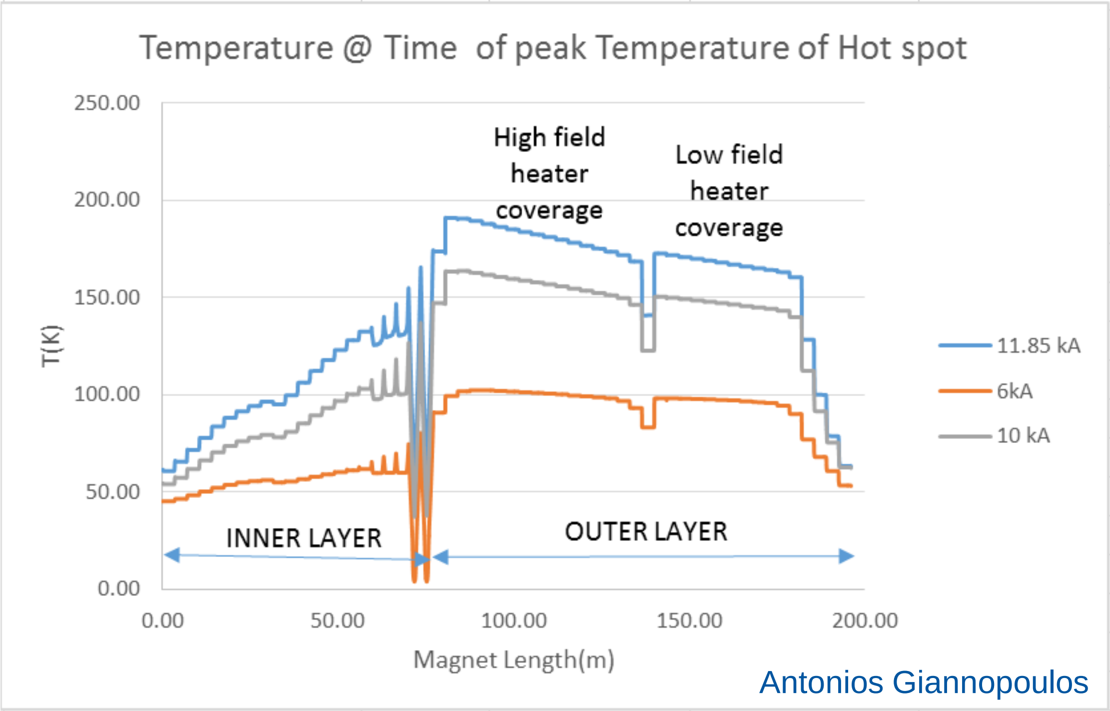
- Low RRR and higher R_{293K} in coil 106 gives much faster resistance and temperature buildup.
- QH onset about 10 ms faster in coil 106 and 109, compared to coil 108 and 111.

Coil	Conductor	$R_{293\,K}$ (mΩ)	RRR	Additional ground wrap outer layer
106	108/127	423	65	None
108	132/169	407	170	Glass 0.1
109	132/169	400	125	None
111	132/169	401	119	Glass 0.2



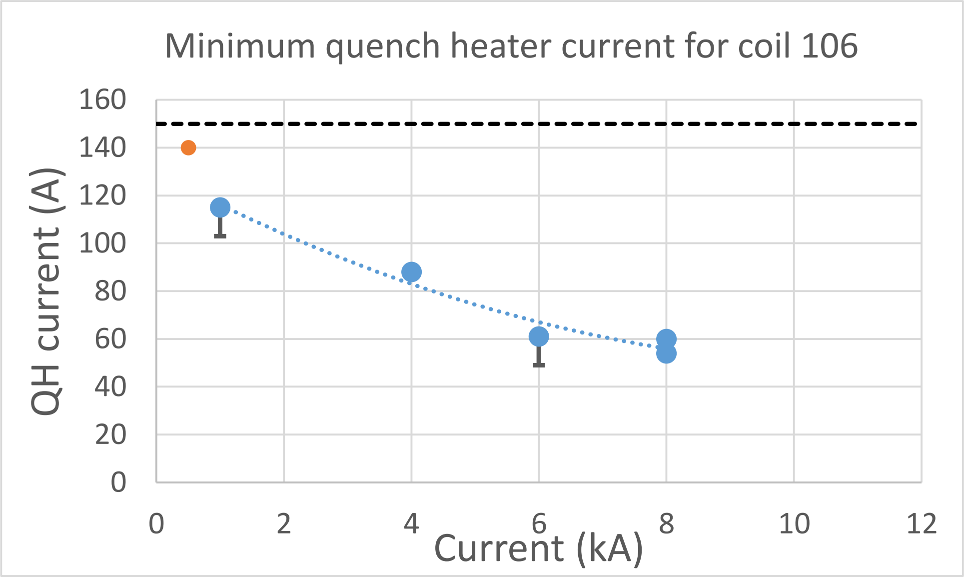
- Coil 106 will reach 300 K in 14.5 MIIts and 350 K in 15.7 MIIts
- About 40 K difference in at 15 MIIts between coil 106 and the other coils.

Protection studies ongoing.



Quench heater provoked quenches, with validation of model in more detail. Temperature of all segments can be used to validate the calculations. (to be done)

Minimum quench heater current to quench the magnet

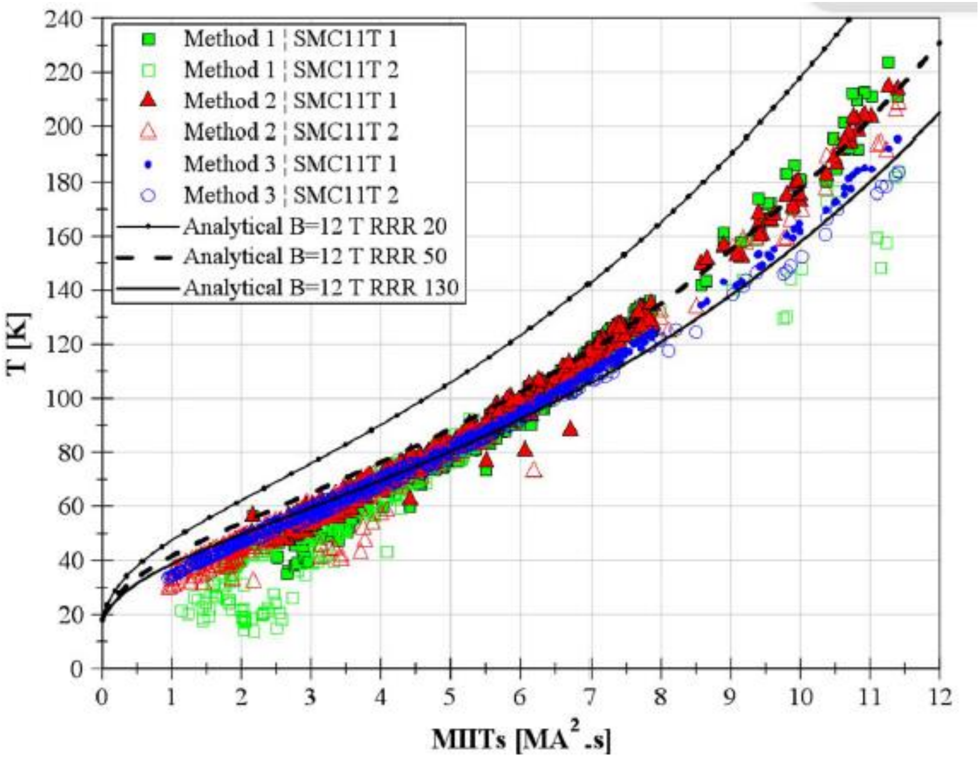


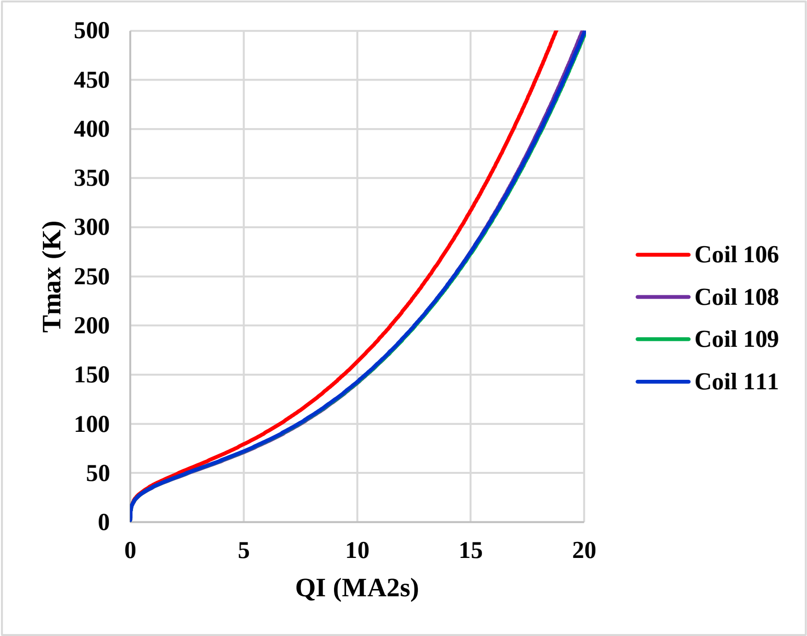
Any pulse above the line will start a quench in coil 106.

Measurent only shows a normal zone in coil 106.

Promising that the coil quenches following a QH discharge at all currents.

Hotspot temperature





Extensive study on Hotspot temperature vs MIIts by H. Bajas on SMC coils

H.Bajas et al., Quench Analyisis of High-Current-Density Nb_3Sn Conductors in Racetrack Coil Configuration, IEEE Trans. Appl. Supercond, Vol 25, No 3, June 2015

Further calculations by S. Izquierdo Bermudez

Coil 106 has a higher R_{293K} and higher R_{4K} and therefore a higher hotspot with similar QI.

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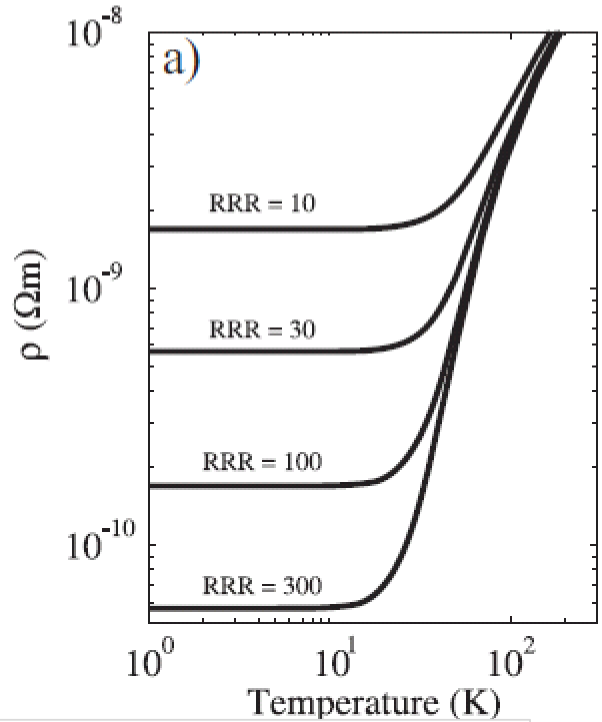
Hot spot temperatures

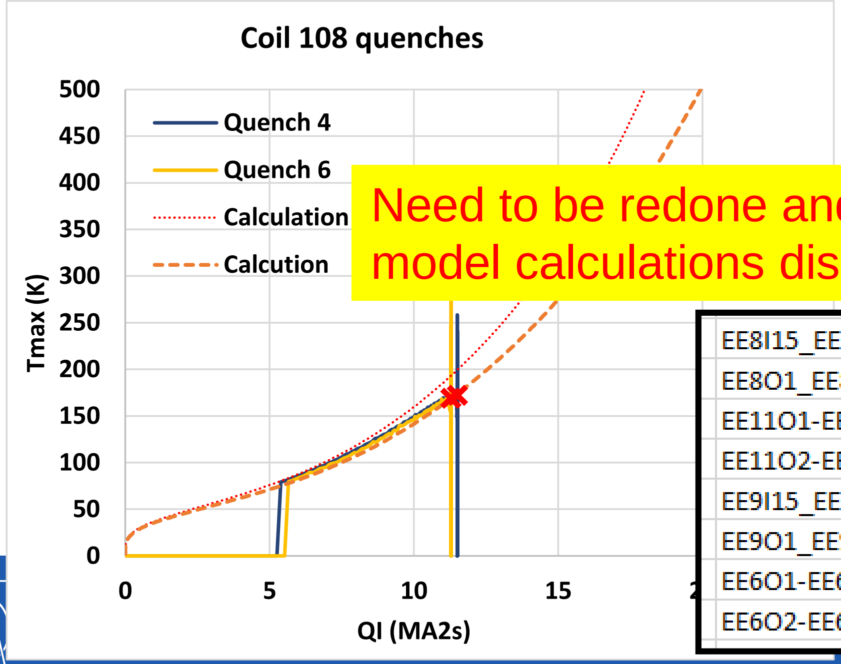
“Measurement” of hotspot temperature using the cable as thermometer.

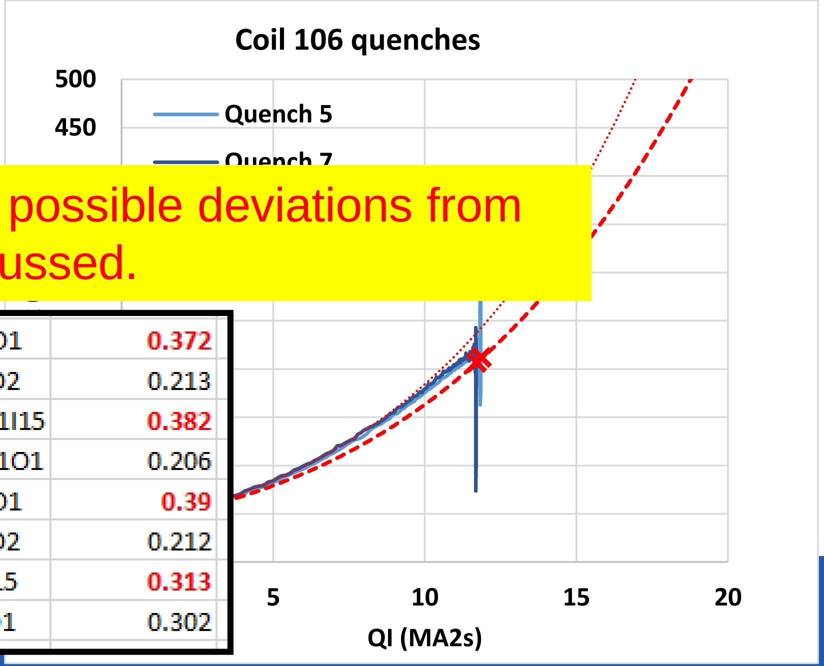
- Measure V
- Subtract V_inductive (inputs L and dI/dt)
- Use room temperature resistance as reference point and deduce T.

Very simple method but requires good input of L and R_{293K}

Images shown before with the best estimate of R_{293K} seem to be optimistic.







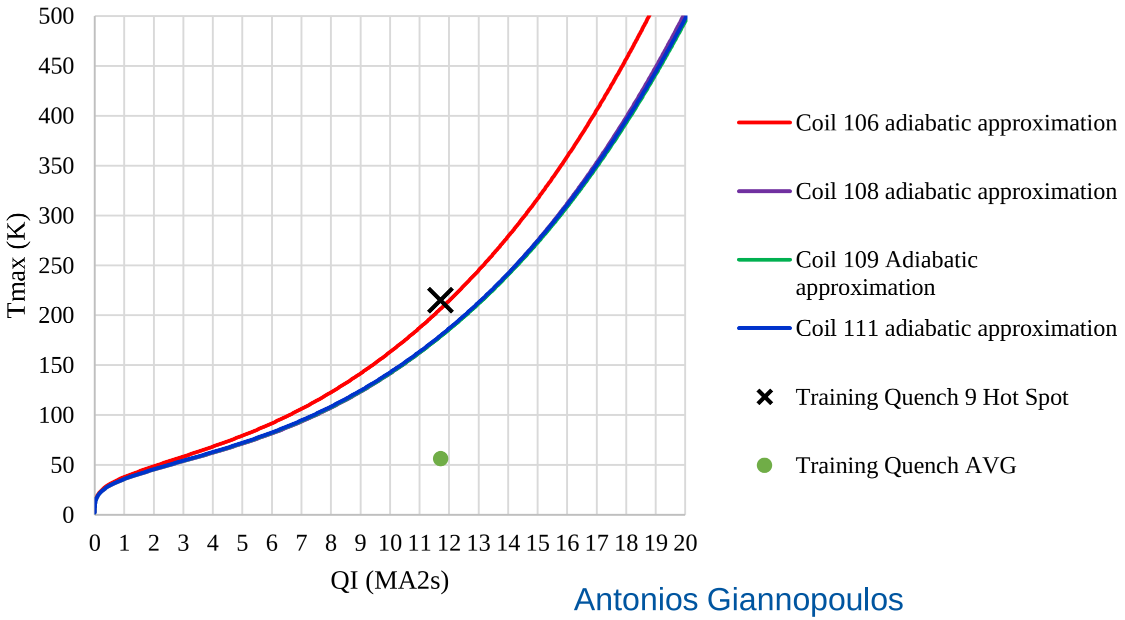
Need to be redone and possible deviations from model calculations discussed.

EE8I15_EE8O1	0.372
EE8O1_EE8O2	0.213
EE11O1-EE11I15	0.382
EE11O2-EE11O1	0.206
EE9I15_EE9O1	0.39
EE9O1_EE9O2	0.212
EE6O1-EE6I15	0.313
EE6O2-EE6O1	0.302

Hot spot temperatures

Modeling still evolving:

- Effort to have a quench starting only in a smal zone with the hotspot
- When the measured curves are recalculated, they will be combined.



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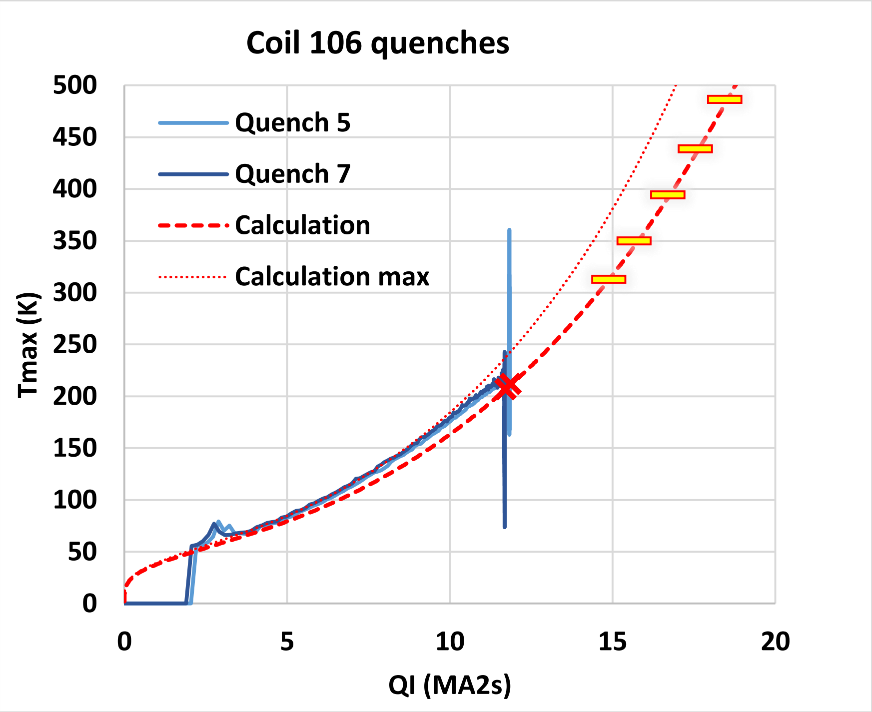
Steps for High MIIts test



Quench in Coil 106 high-field required

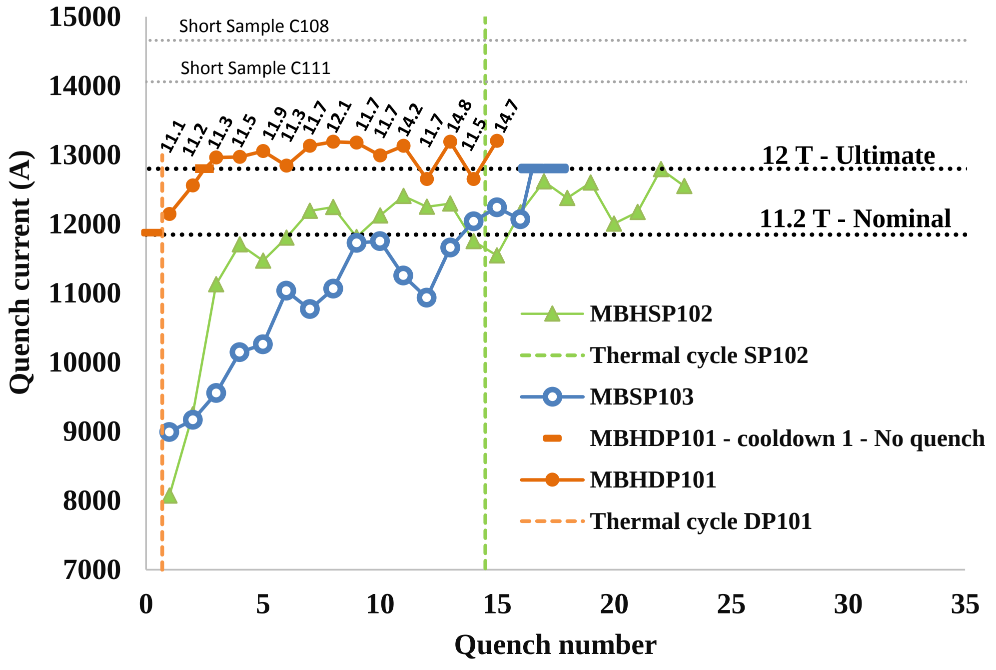
Proposed steps:
- 320 K
- 360 K
- 400 K
- 440 K
- 480 K

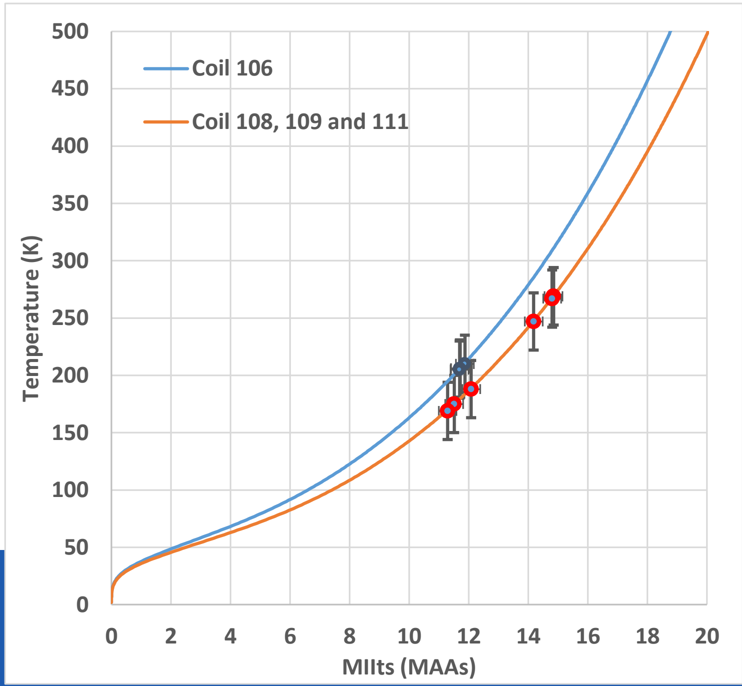
Higher MIIts obtained by delay of protection: 6 ms delay is equivalent to 1 MA^2s at 13 kA.

Some rationals:
- 320 K is the calculated hotspot in nominal conditions
- Resin (CTD-101 K) has a glass transition temperature of 380 K.
- HQ test in USA showed no degradation up to 400 K, but a detraining quench after reaching 460 K (magnet was not pushed later anymore)

Where tests with delayed protection useful?

- Target in MIIts were easily reached (20 ms delay in QH and EE for 15 MIIts).
- As expected 50 % of the quenches were in the high-field region in coil 106
- Unfortunately those quenches happened during the runs without delay in protection, so **target not reached.**
- No test time lost, since it was a nice continuation of the training with only 15 quenches in total.





Suggestions for further testing

MBHDP101

- All test goals have been reached
- Additional goal with higher MIIts not fully reached: the 3 quenches with nominal MIIts were not in the high field location.
- Test station is overcharged already.

For future single apertures

- Take enough test time for a good 4 K measurement series: try to avoid it in double apertures magnets.
- Possibly implement high field spot heaters: For discussion how we can do this.
- Consider performing the training with nominal MIIts. (when using EE, use some delay).

Conclusions

- Great quench performance.
- No degradation seen in the coil after quenches, even in the midplane.
- Large amount of data for protection and magnetic model validation.
- No direct conclusions on protection studies, since 4 different coils were used.

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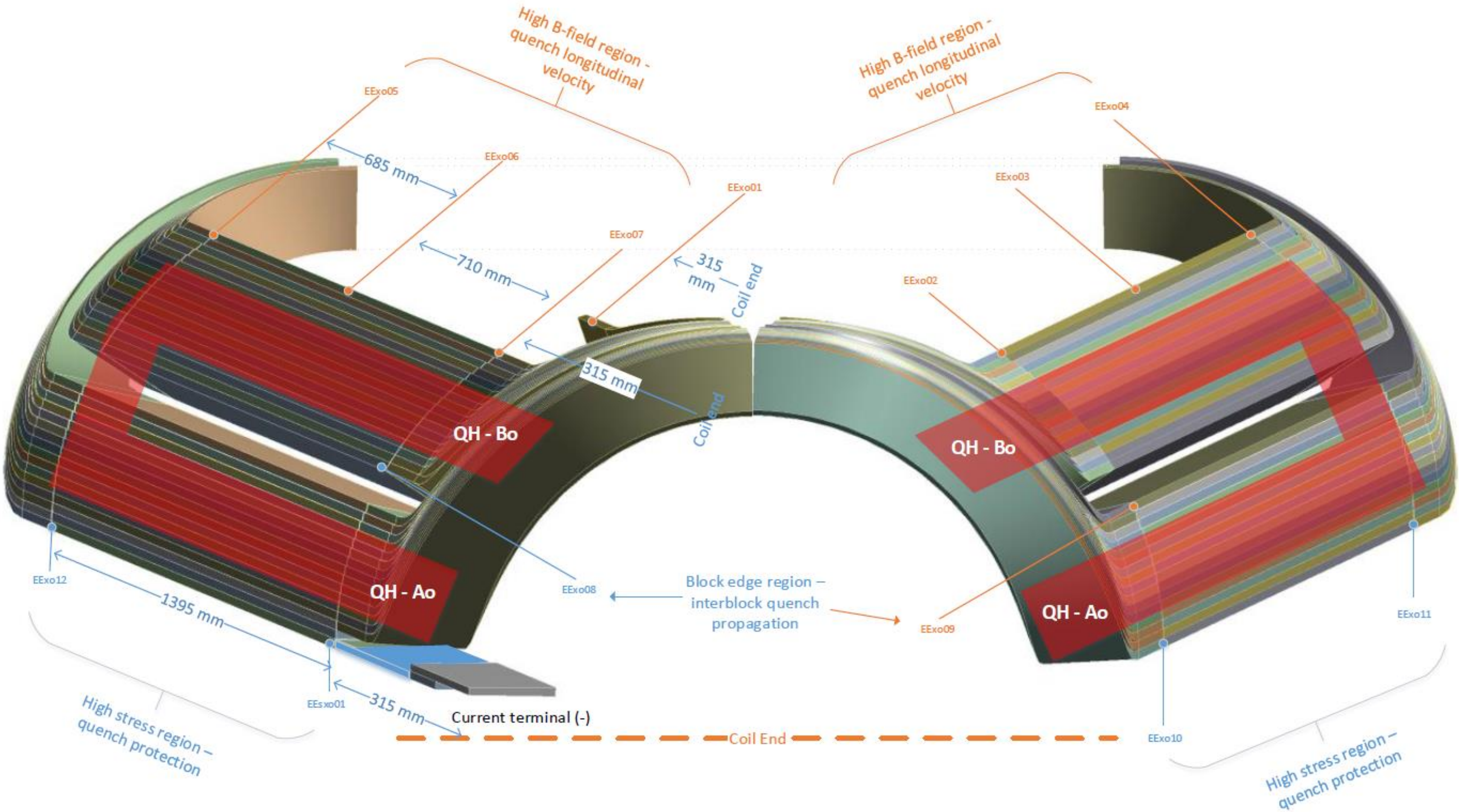
11T Short Dipole – Outer Layer – Instrumentation Voltage Tap Locations



11T Short Dipole – Inner Layer – Instrumentation Voltage Tap Locations