MBH – 11T model test results

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Credits go to all involved in magnet design and production

Thanks for the support in testing to Franco Mangiarotti, Jerome Feuvrier, Vincent Desbiolles, Michal Duda, Havard Arnestad, Hugo Bajas, Daniel Turi, Javier Villena, Christian Löffler, Susana Izquierdo Bermudez, Emelie Nilsson, Marta Bajko, Bernardo Bordini, Philippe Grosclaude, et al.

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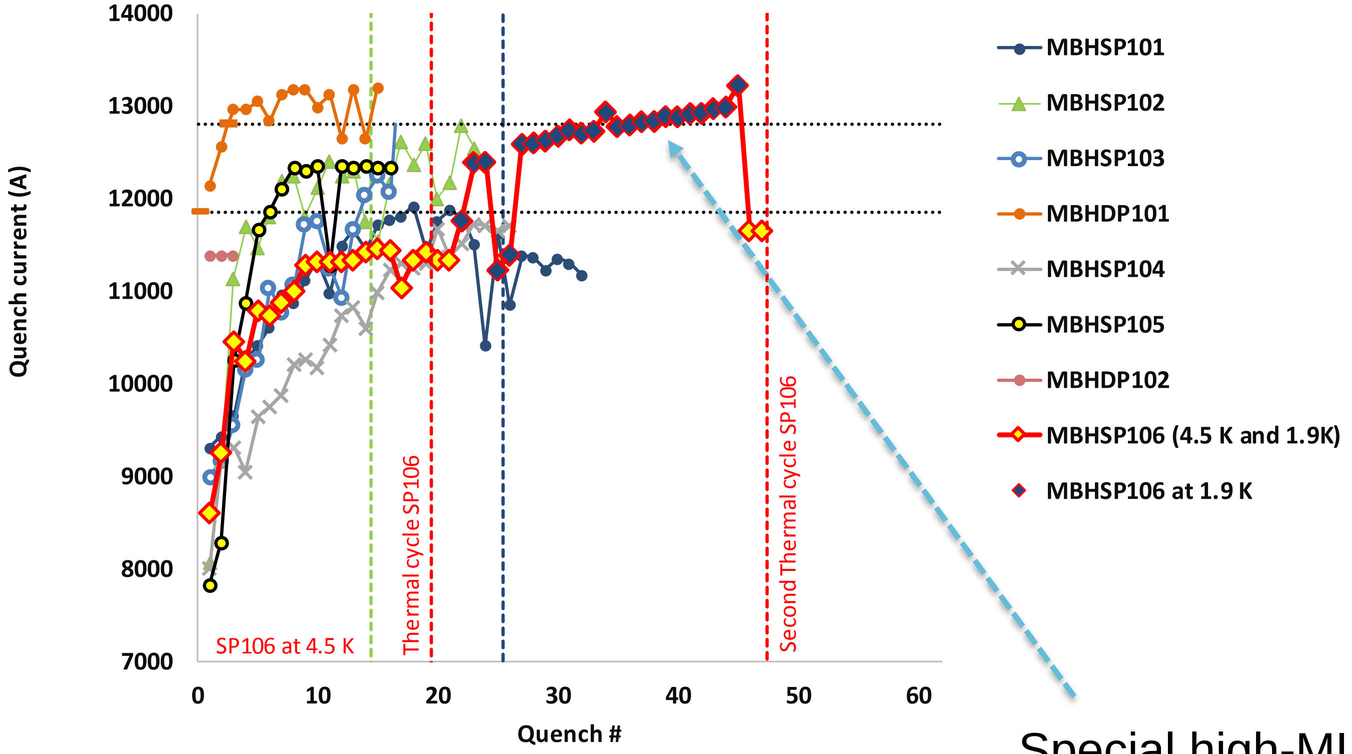
Test overview

- Training
- MBHSP106
  - RR study, training, degradation, High-MIIts studies
- Midplane limit MBHDP102 and Block 3 limit MBHSP106
- Coil limit overview
- Successes
- Conclusions

Training



Training of all models at CERN:

- All single aperture magnets show their first quench between 8 and 9 kA.
- DP101 went immediately to 12.2 kA.
- DP102 went straight to a conductor induced limit.

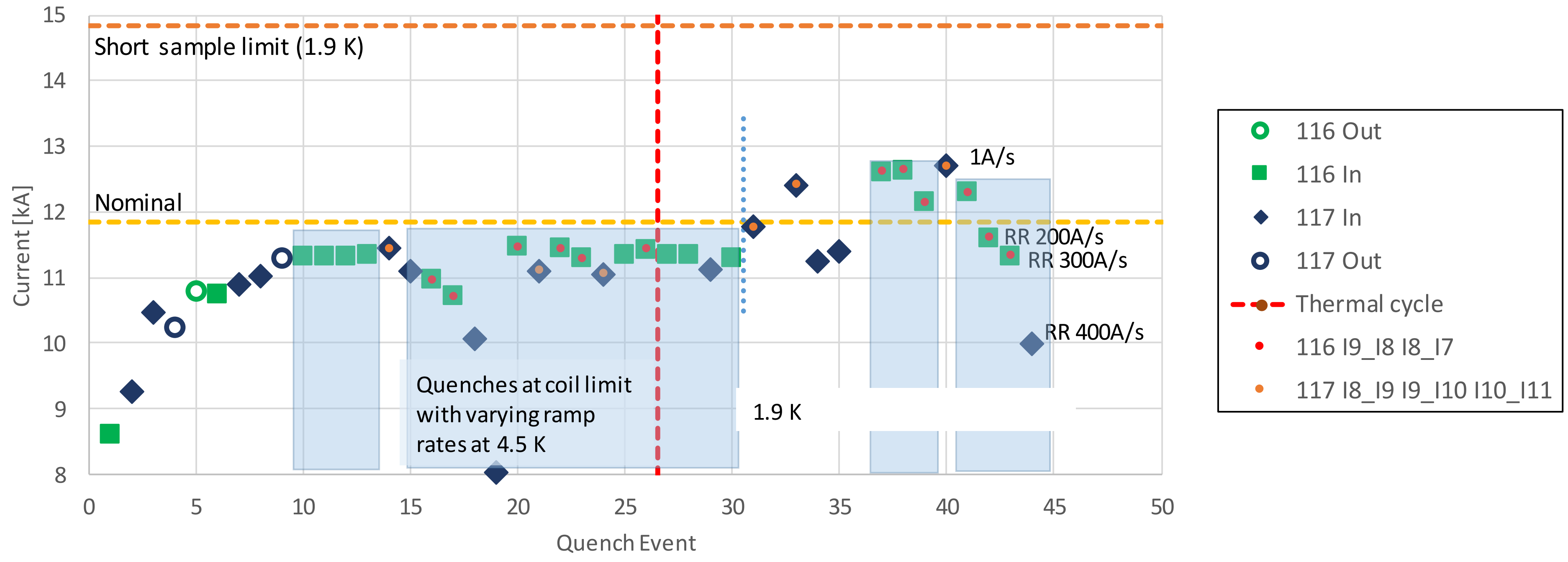
Quench curves give only half the information:
Quenches typically come in two fashions:

- Induced by mechanical movement (slip-stick, epoxy cracking, etc.)
- Induced by conductor limits (degradation, current distribution effects, flux jumps, etc.)

Special high-MIIts training, see later slide

Details of MBHSP106 powering tests

Quench events of the last SP106



Full quench history including ramp rate studies (before high-MIIts studies).
In light-blue are the quenches limited by the conductor.

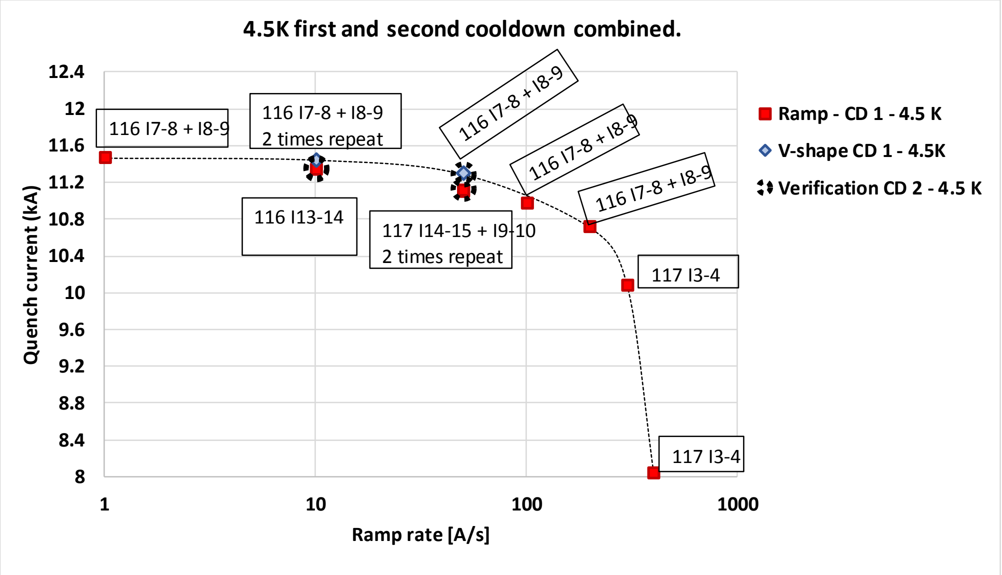
In the following slide the data is split up:

1. Training curve with clear mechanical movements causing the quench.
2. Quench at conductor limit, placed in the ramp rate dependency curve

Ramp rate dependency of model SP106

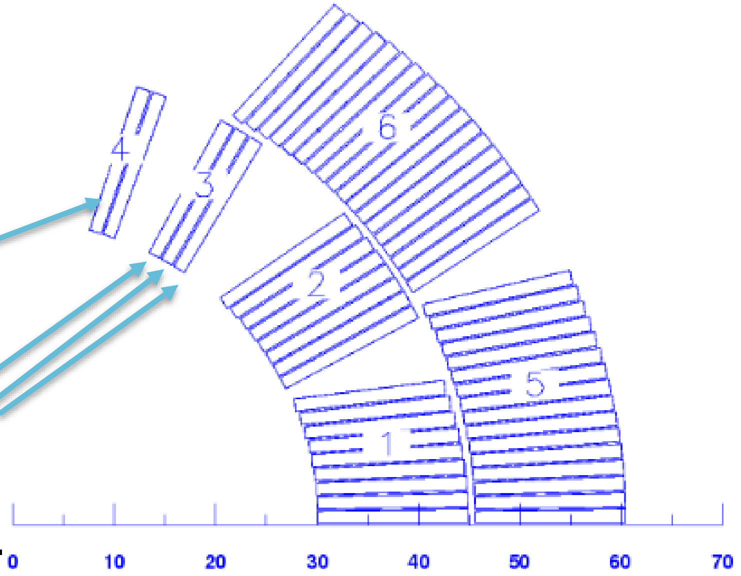
Coil 116 has a clear limit in I7-I8 and I8-I9 at 1.9 and 4.5 K.
At 4.5 K another limit was found in coil 116 I13-I14.

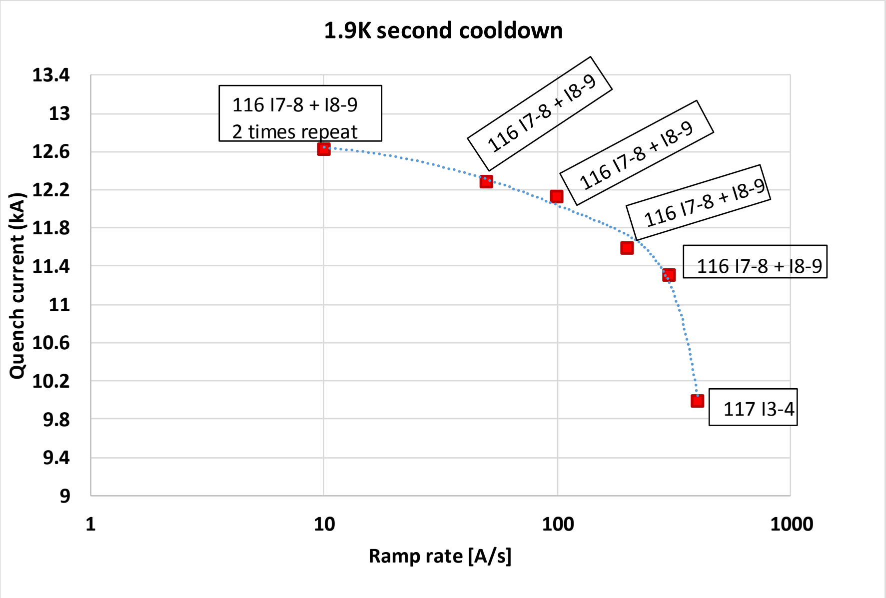
Both are close to the middle of the straight part of the coil.



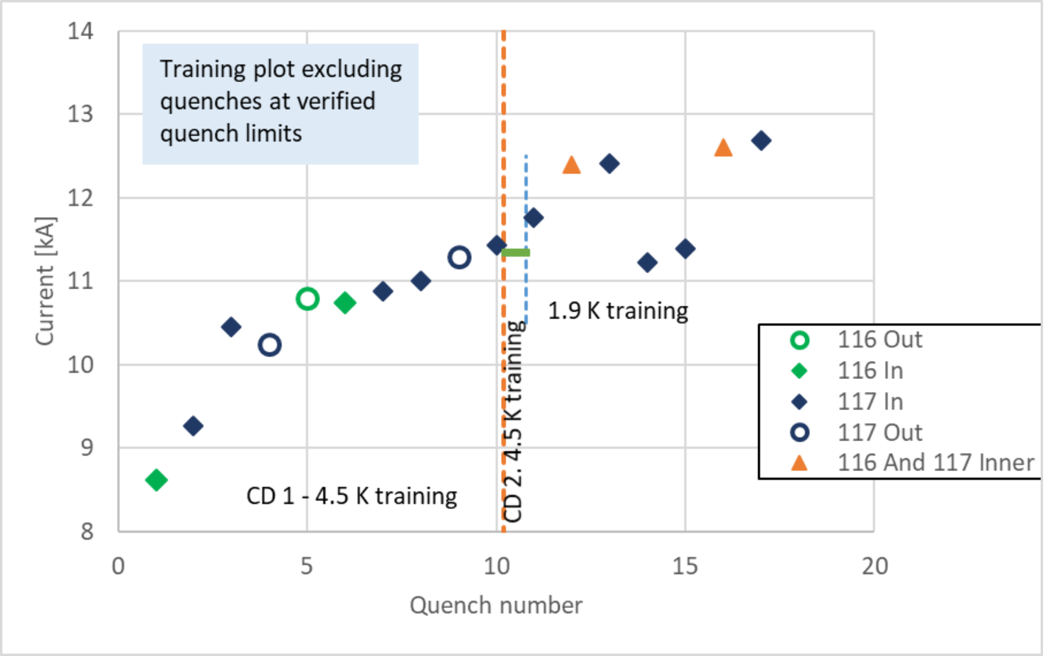
Pole turn I13-I14.

I7-I8 and I8-I9
Three turns of block 3
quench simultaneously.



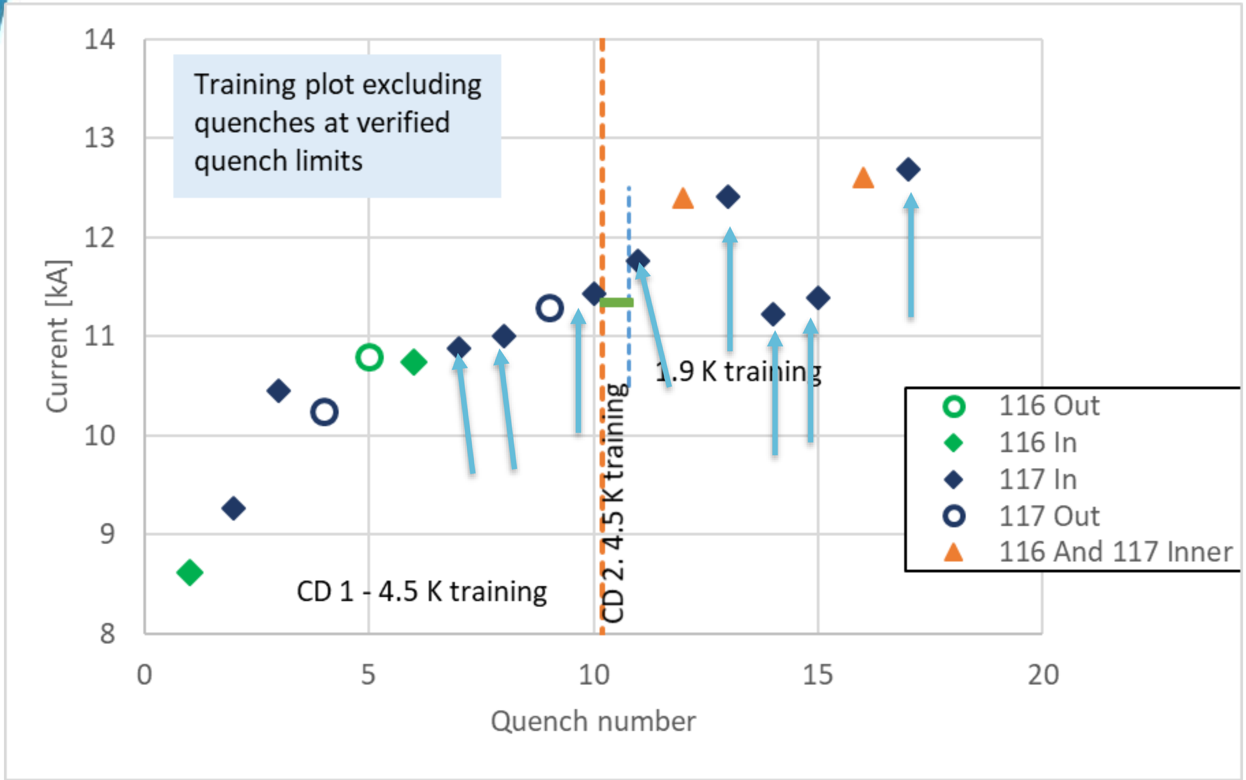


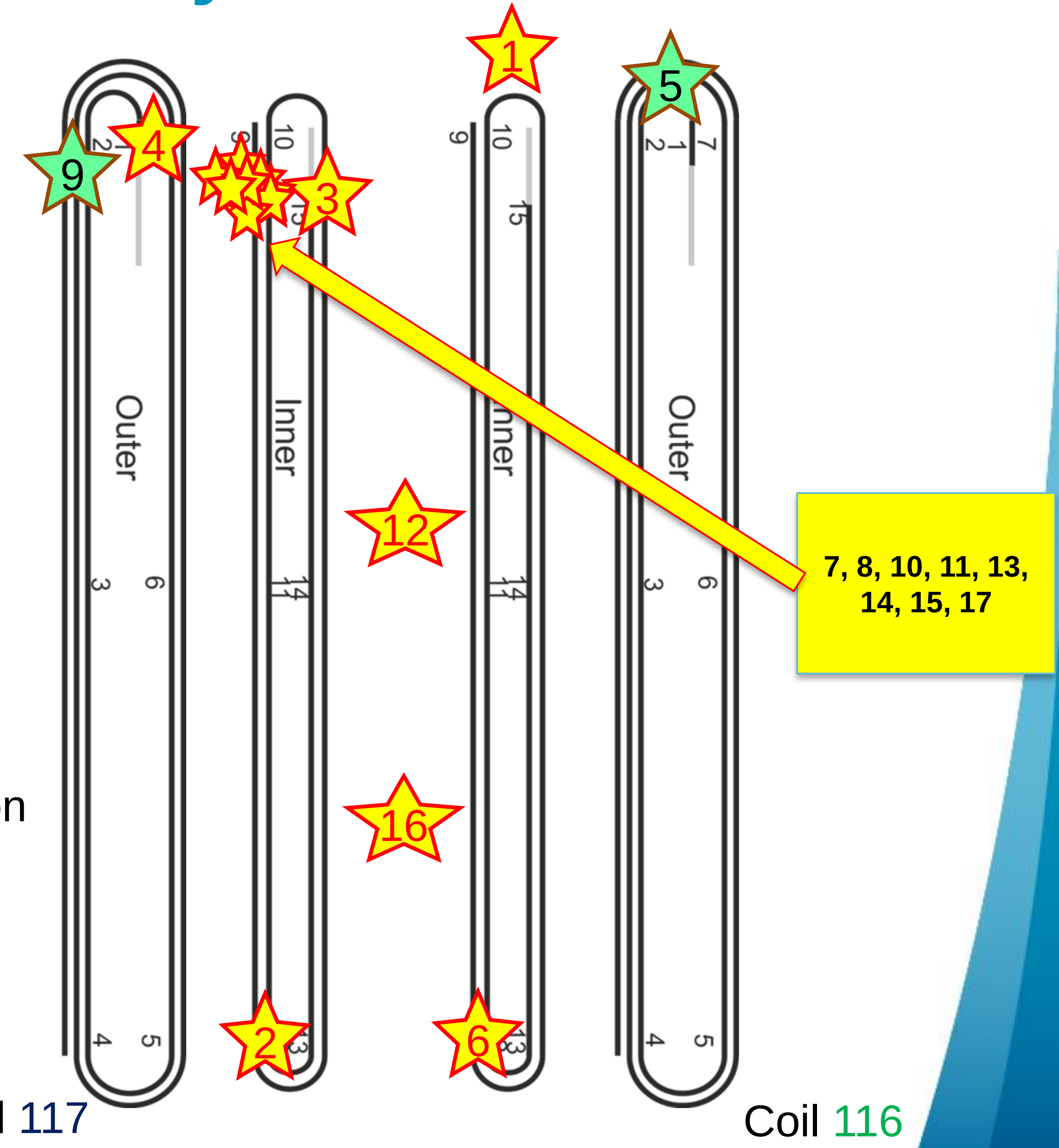
Training of model SP106



- First training was at 4.5 K, looking rather similar to training of other coils at 1.9 K.
- Second training at 4.5 K showed good memory up to 11.3 kA without quench
- Training continued at 1.9 K and showed two important detraining quenches at 11.2 and 11.3 kA, but stable performance after the end of training.

(de)Training in head coil 117 inner layer connection side

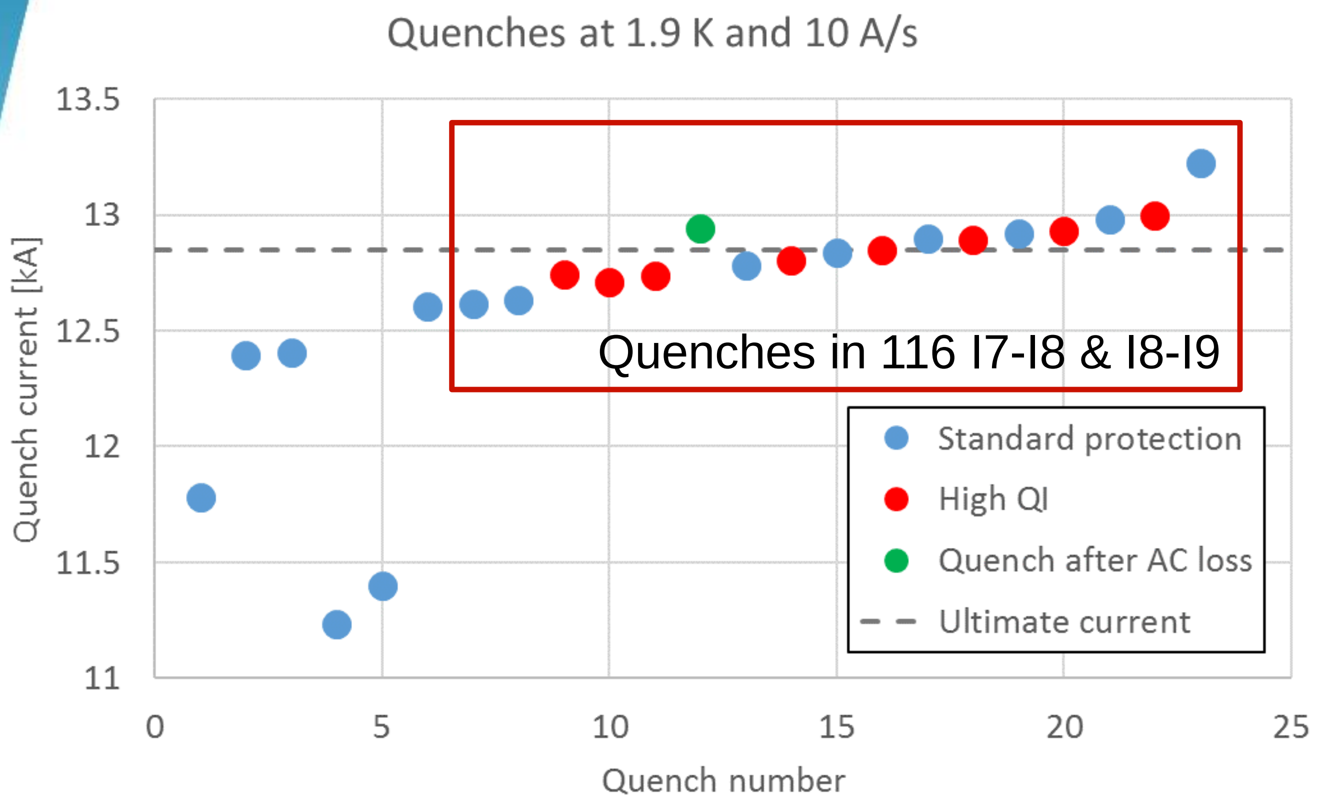


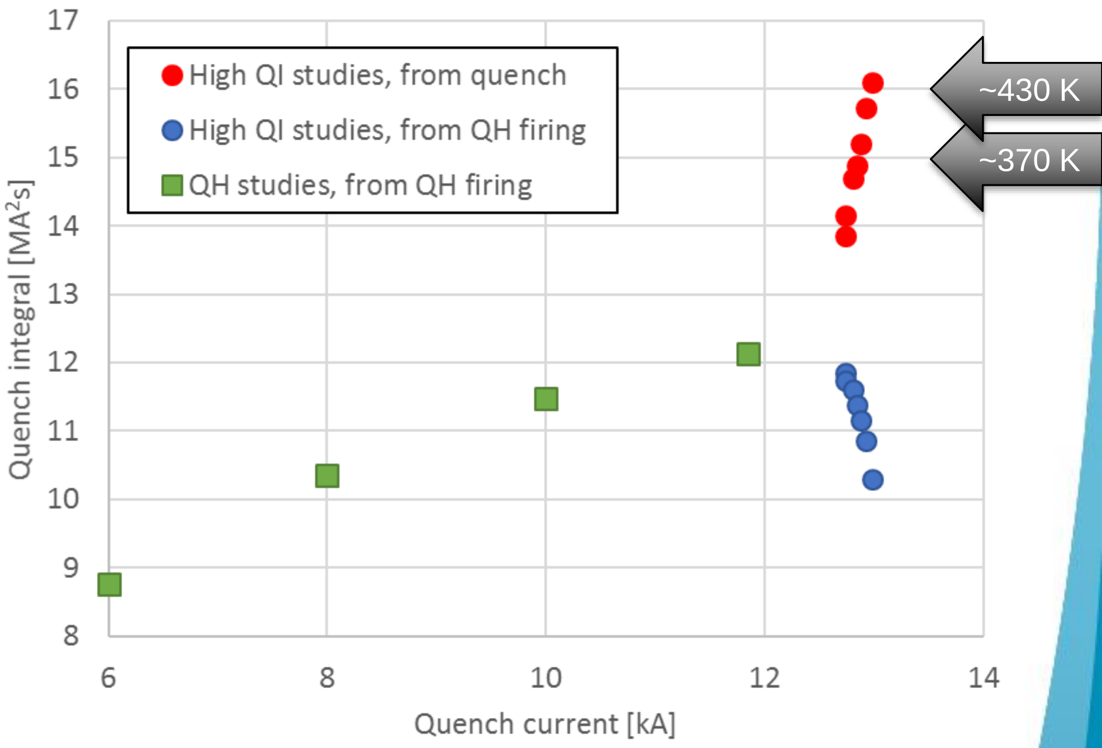


Very prominent training and detraining location is the connection side head of coil 117 where the following quenches originate 7, 8, 10, 11, 13, 14, 15, 17

Quench 12 and 16 started in coil 116 and 117 simultaneously.

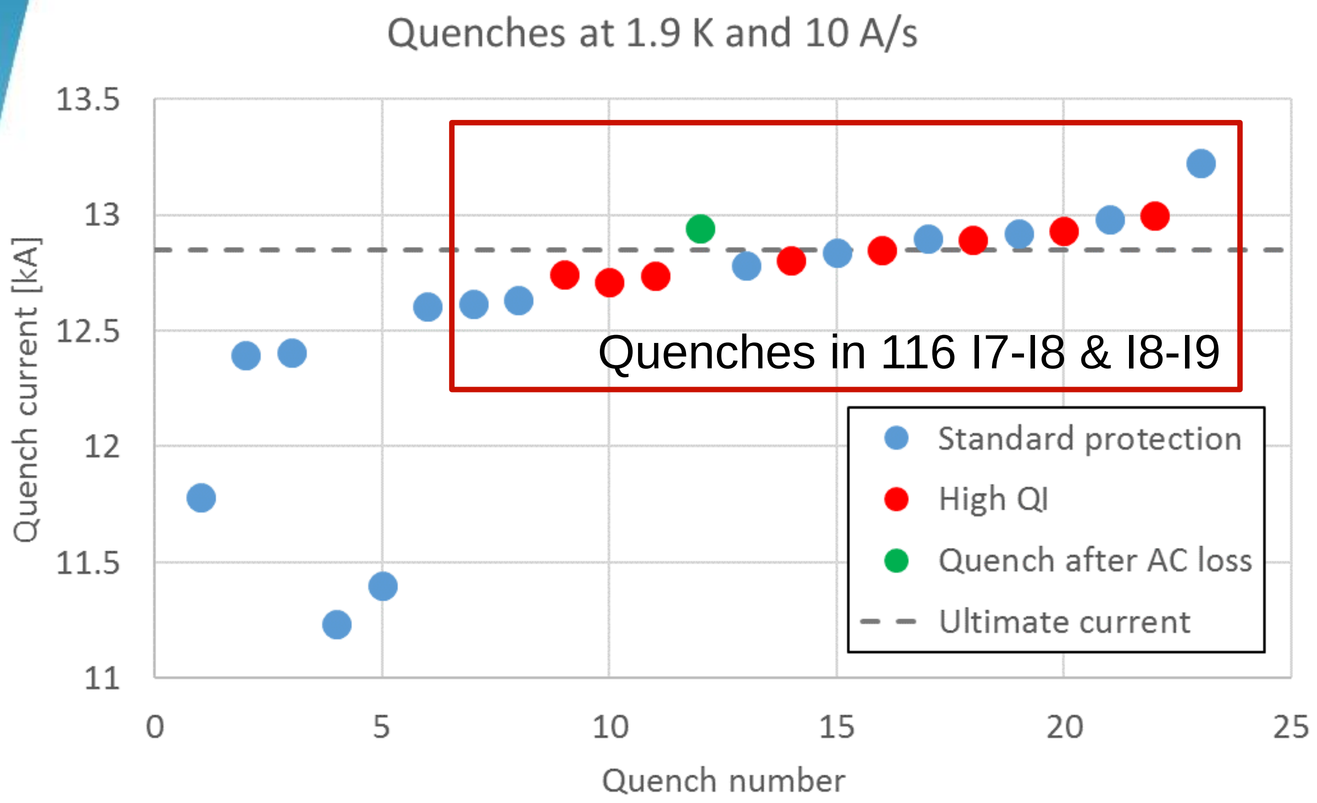
High QI studies



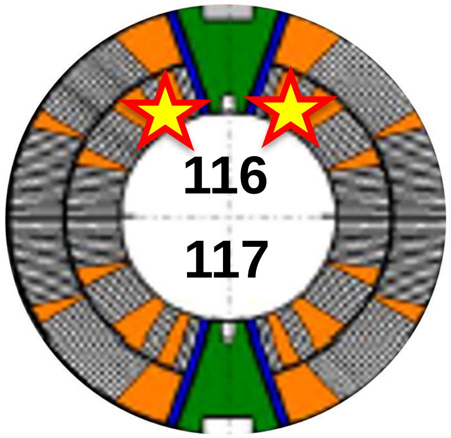


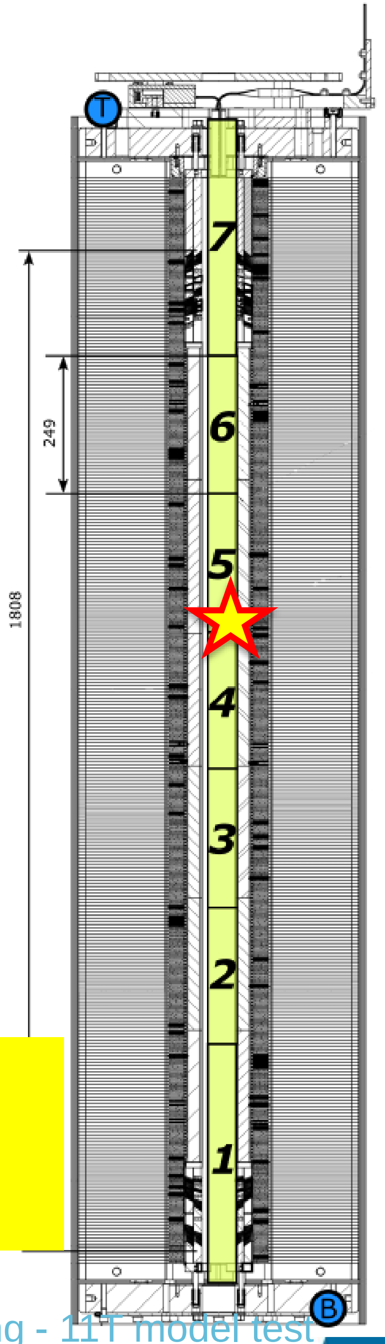
- After all the high QI quenches (except the first one), the quench current increases
- We have reached a maximum quench current of 13.23 kA
- All the high QI & verification quenches were in the same location

High QI studies – location



All those quenches were in the same location, block 3 of coil 116.





Important conclusion: After all these quenches we don't:

- Have any mechanically induced quench (training)
- Have any detraining, even in the "loose head" of coil 117

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How do high-QI studies improve the quench current?

How do high-QI studies improve the quench current?

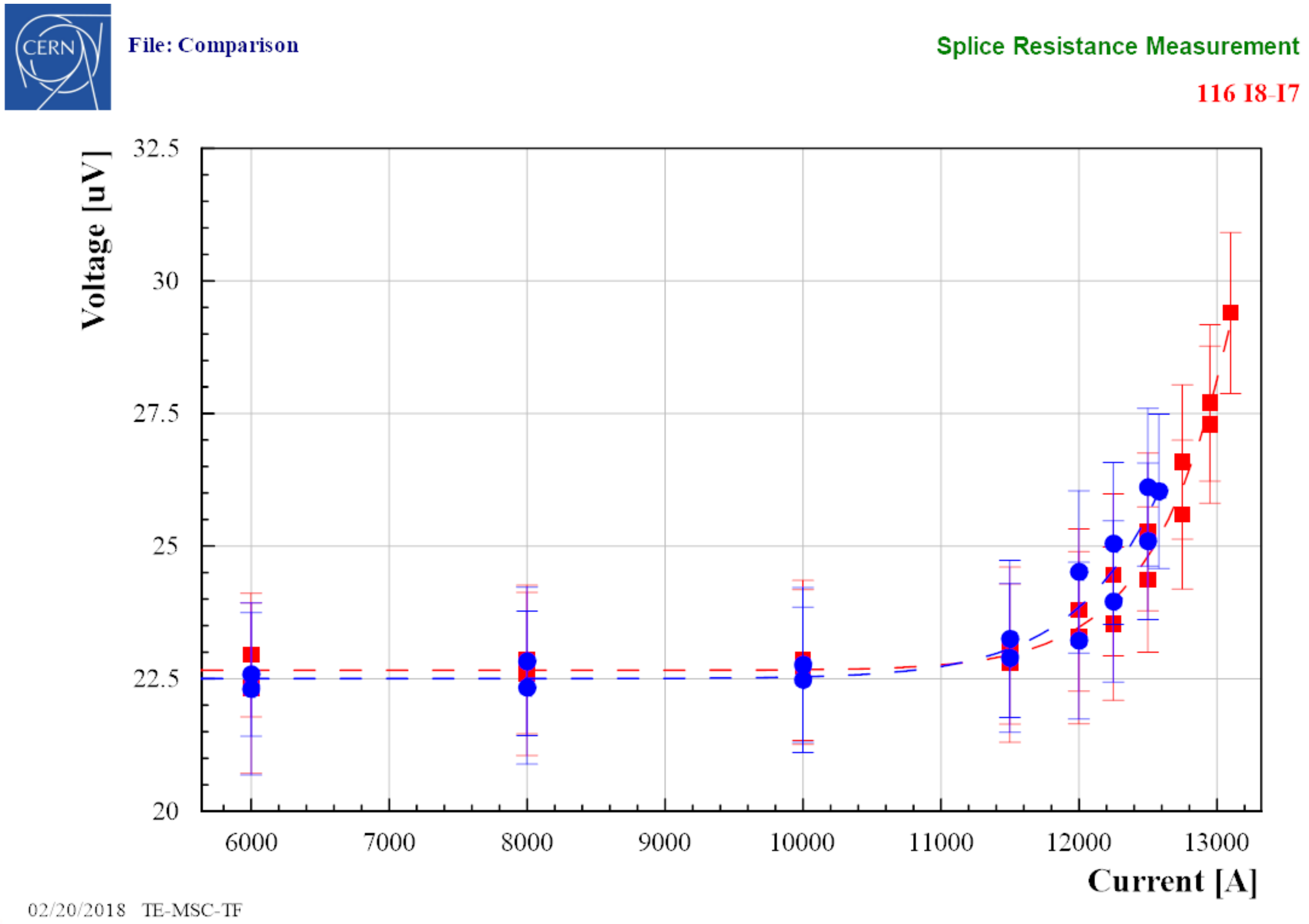
Difficult question to answer.

The only firm conclusion we can draw from the measurements is:
We don't see degradation up to 13.2 kA with hotspot temperatures up to ~430 K.

Can we expect the same phenomena in other coils too?
No statistics: we did not test it in previous models.

Degradation in mid-planes in MBHDP102 and in block 3 of MBHSP106

VI curve – block 3 coil 116



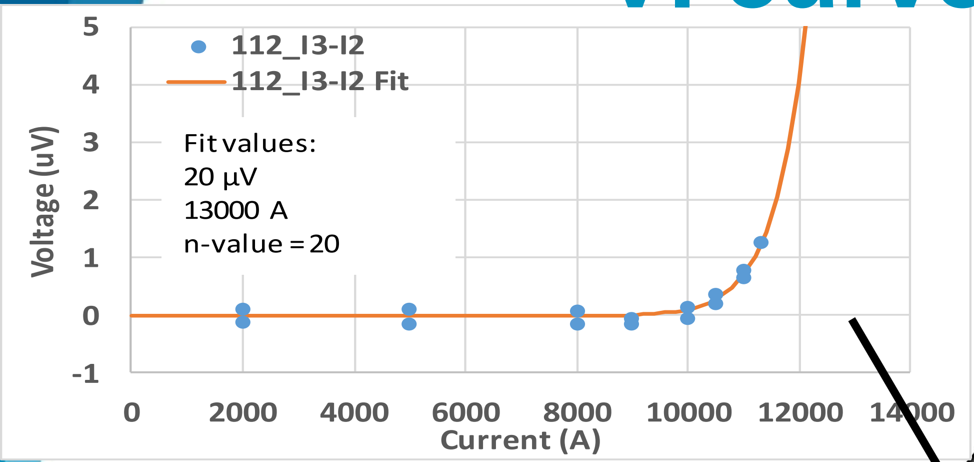
The segments that quenched:

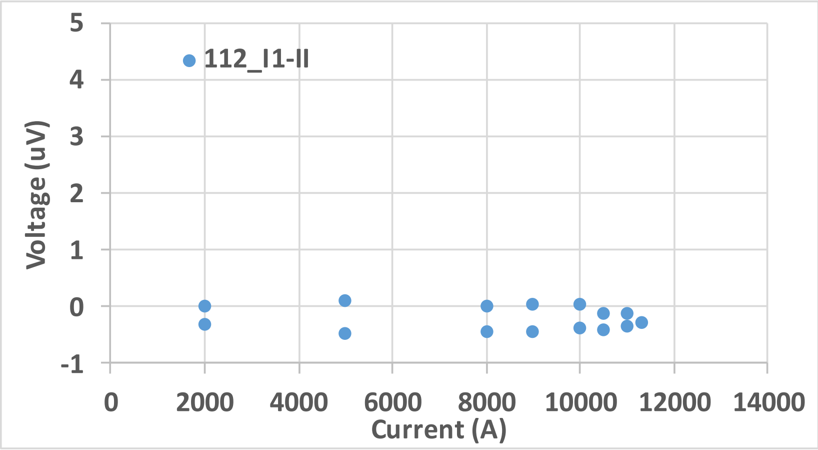
- Segment 116 I7-I8 shows a transition, very similar to the measured before the high QI studies
  - "n" value ~ 20-25
- Segment 116 I8-I9 does not show a superconducting transition

Midplane segments

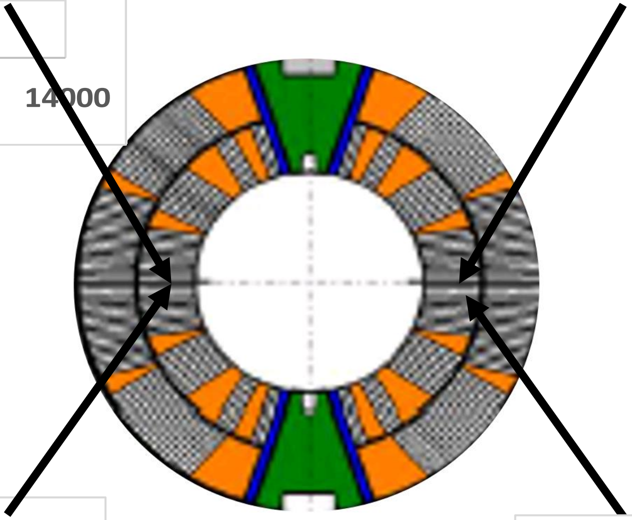
- 116 II-I1, I2-I3 and 117 II-I1, I2-I3 do not show a superconducting transition

VI curves – midplanes DP102





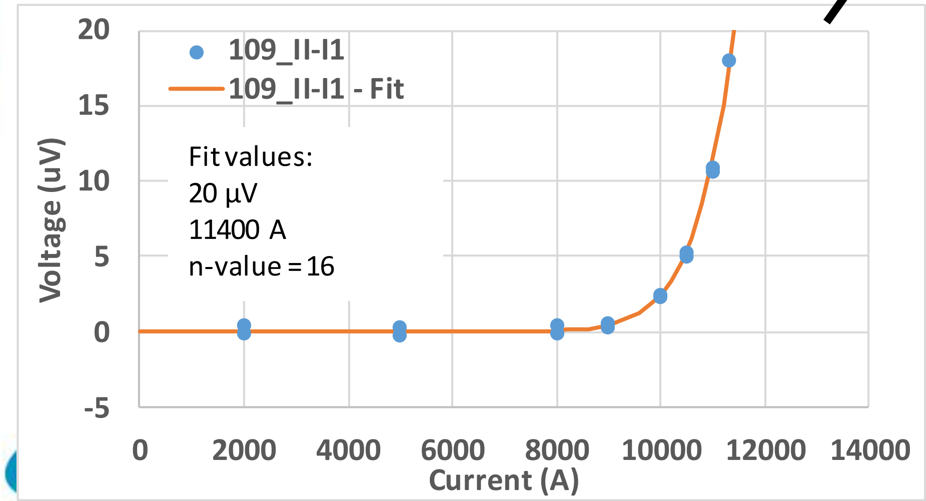
112

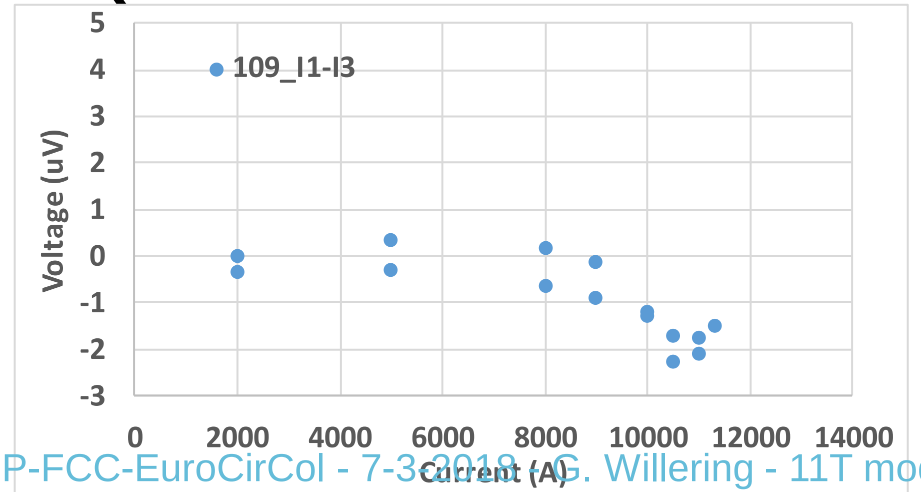


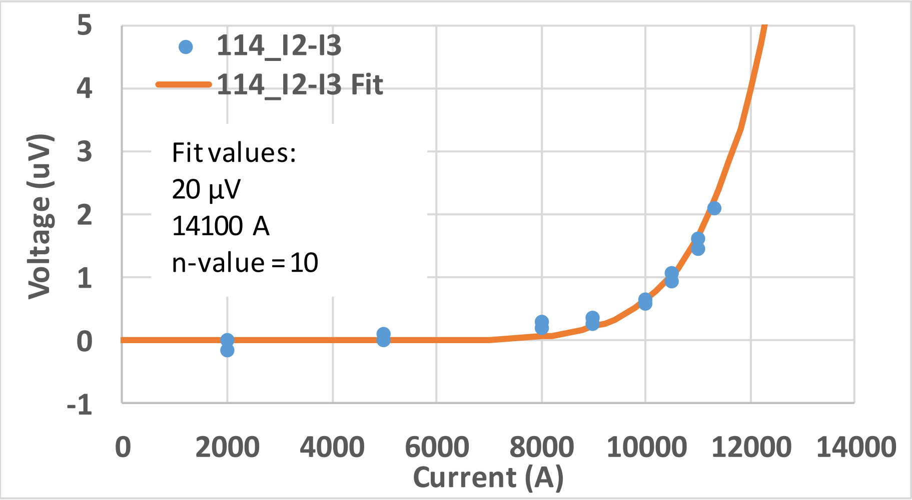
109

Aperture 1 with coil 109 and 112

20 µV at 11400 A

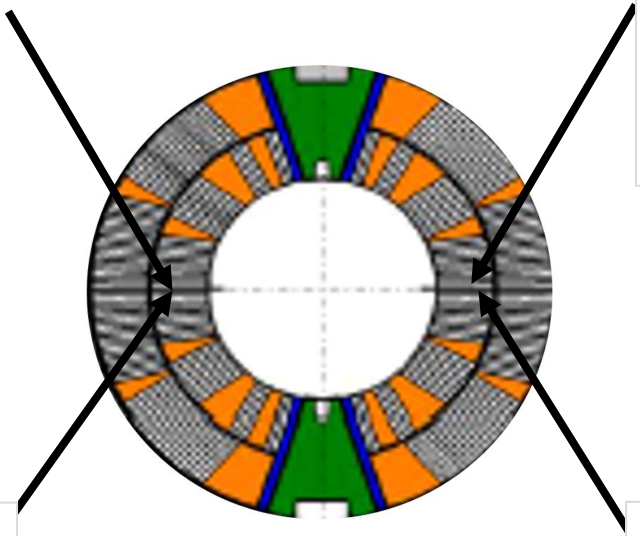




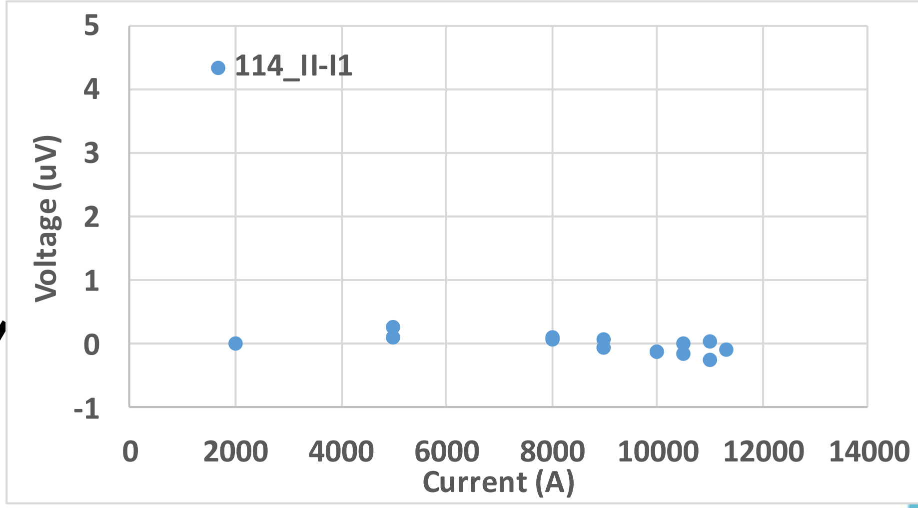


20 µV at 14100 A

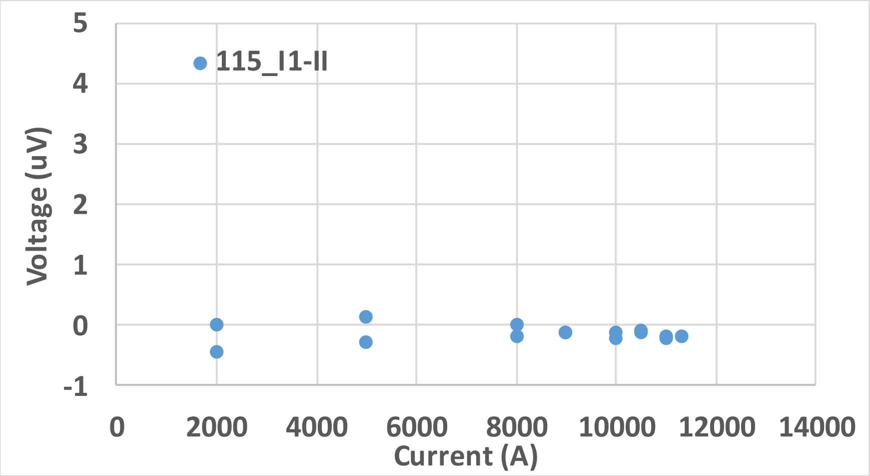
114

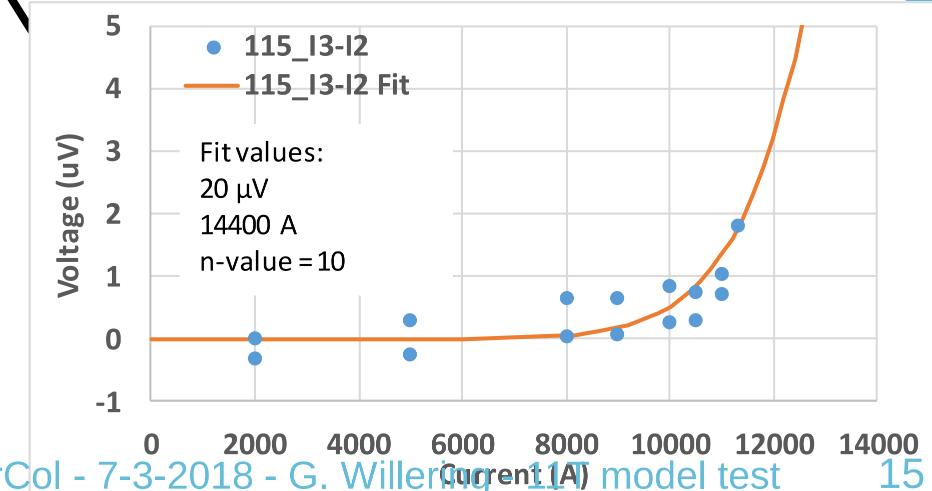


115



Aperture 2 with coil 114 and 115





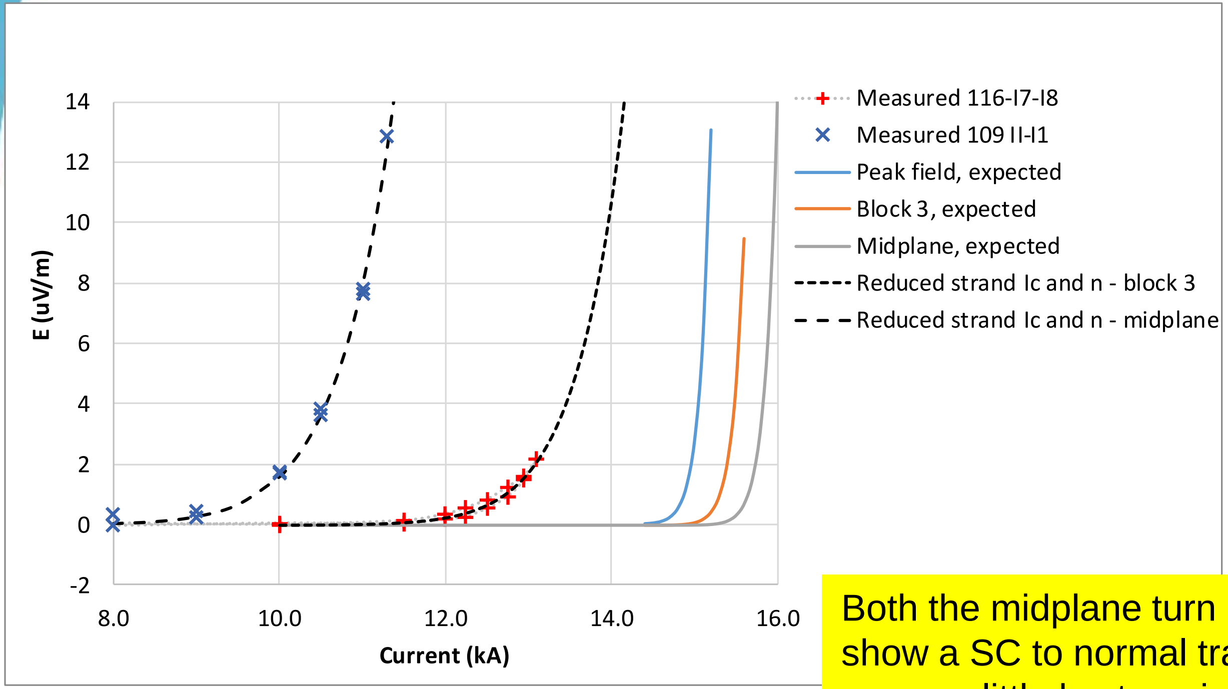
V-I curves and n-value in magnets

Typically n-value is used with constant magnetic field for $(I/I_c)^n$ and cannot be compared to $(I/I_{ss})^n$. However, we can fit the curve with the following formula, using for $I_c(B)$ and $n(B)$ the values from extracted strand data.

Find the best fit for

$$E(I,B) = E_c\left(\frac{I}{f_{I_c} I_c(B)}\right)^{(f_n n(B))}$$

(with E_c = 10 uV/m)



	Block 3 coil 116	Midplane coil 109
I_c reduction factor (f_{Ic})	0.62	0.26
n-value reduction factor (f_n)	0.20	0.12

Note1: Very rough estimate.

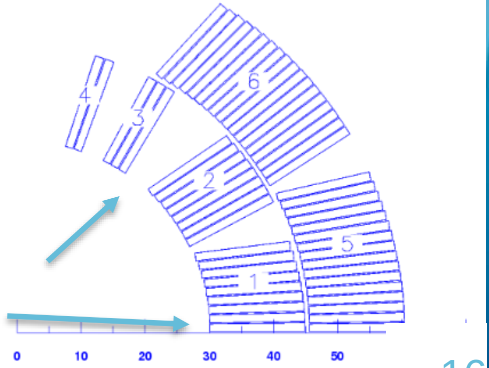
Note2: the approach is very simple, it assumes homogeneous conductor degradation, which in very unlikely.

Note3: The magnetic field gradient over the cable width is taken into account by calculating the average E at the thin edge, the mid point and the thick edge of the cable, all using n(B) and Ic(B). This can be further improved, but it gives a good first order approach.

Both the midplane turn in coil 109 as the block 3 in coil 116 show a SC to normal transition with

- very little hysteresis
- a low n-value
- no decay at constant current.

Interpretation: All this info points to a distributed degradation of the conductor over at least a twistpitch, but likely more.



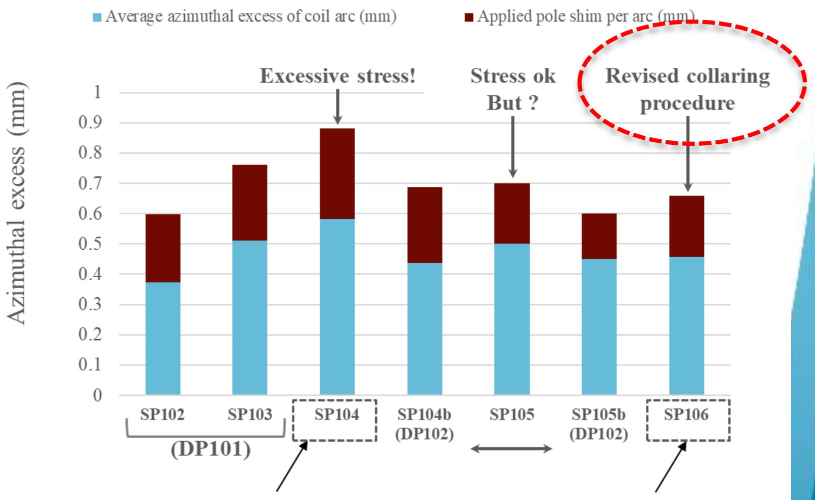
Midplane limit

The V-I measurements were only done for DP102 and SP106 on the 1.4 m straight midplane segments.

DP102:
4 out 8 mid-plane segments showed a SC-NC transition below 11.5 kA

SP106:
0 out of 4 mid-plane segments showed a SC-NC transition up to 13.2 kA.

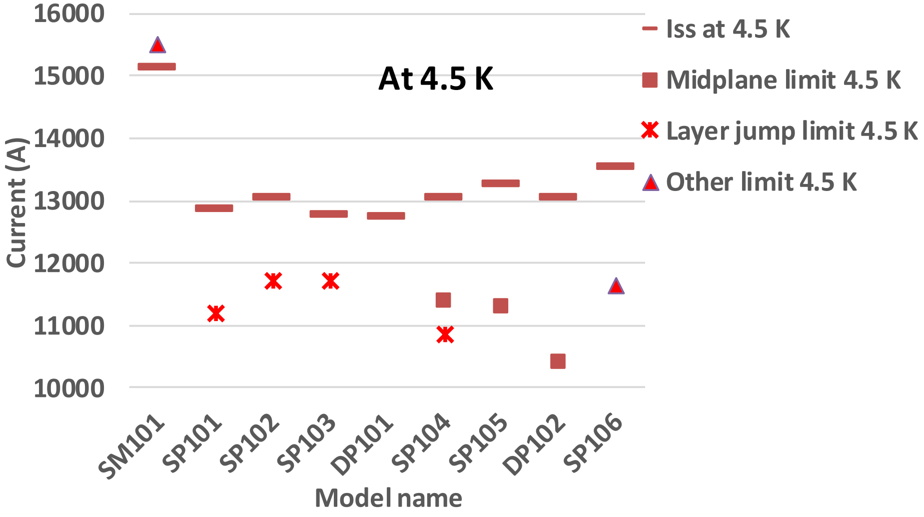
Soft conclusion: the revised collaring procedure seems to give the expected improvement. Would be good to see more statistics.

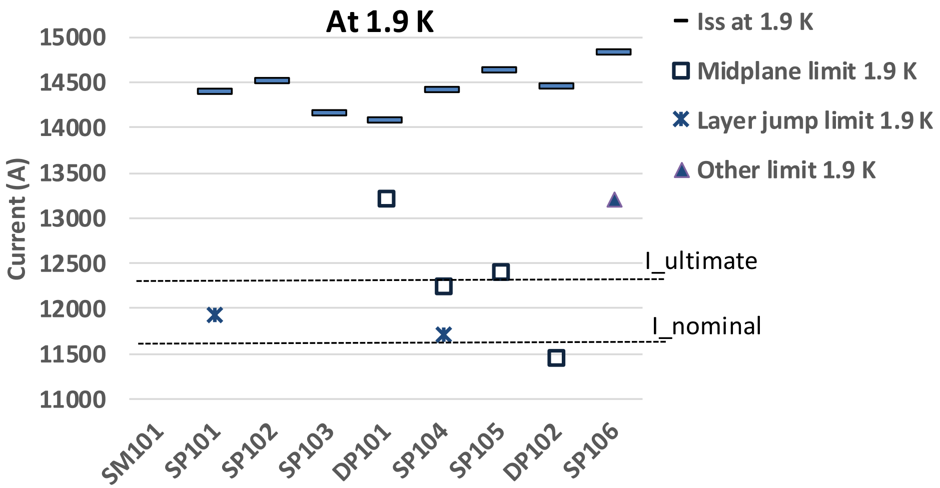


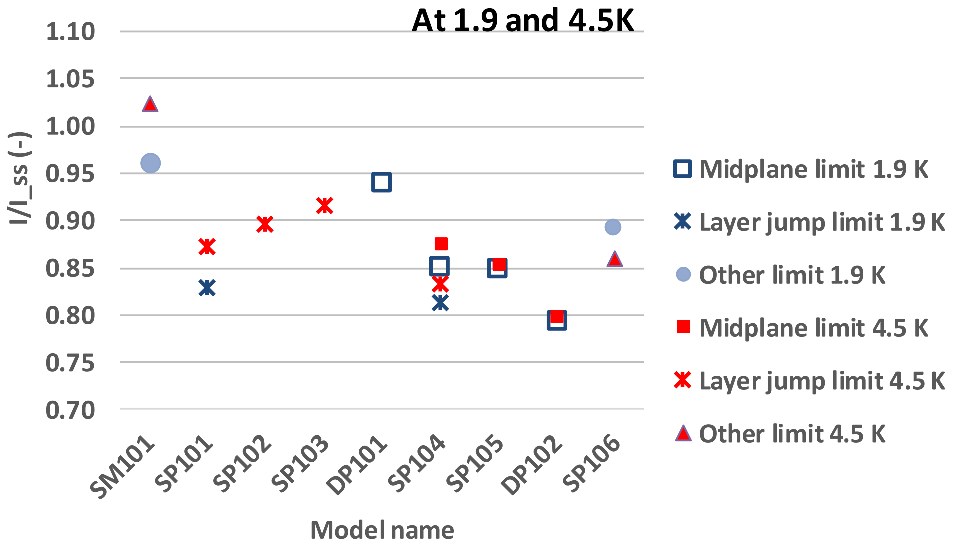
Courtesy C. Löffler, E. Nilsson

Coil limit overview

Coil limits overview







All coils, except the mirror coils, were limited well below the short sample limit, at 4.5 K and at 1.9 K.

The limit location varies.

Many investigations are ongoing to address these limits due to the conductor.

Successes

Successes

Splices

All 24 Nb_3Sn to NbTi splices were excellent with a resistance below 0.5 nOhm.

Holding current tests

Except for coil 113 (layer jump issue) all magnets could hold the current for 1 to 12 hours very close to maximum quench current.

Memory

Every retraining of a coil after thermal cycle, including after re-collaring and re-assembly from single to double aperture, showed a very good memory.

Protectability

The high-MIIts studies for SP106 did not show any degradation up to 13.2 kA up to ~430 K using only nominal protection by the outer layer quench heaters. This gives confidence for the prototypes and series magnets protection.
Flux jumps at low current seem to be easily ignored by variable threshold detection cards.

Understanding

With all effort put in to the measurements throughout the lifecycle of the magnet, issues seem well identified and can be solved.
In MBHSP106 there is no sign anymore of the midplane limit.

Coil performance assessment

Coil	Magnet	12.8 kA reached at 1.9 K?	Memory	Erratic quenches below $I_{ultimate}$	Midplane limit at 1.9 K	(Near) Layerjump limit at 1.9 K	Mid plane limit in % of I/Iss (at 1.9 K / at 4.5 K)	(Near) Layer jump limit in % of I/Iss (at 1.9 K / at 4.5 K)
Coil 105	MBHSM101	-	Good	Good	>16.0 kA	>16.0 kA	> 95 % / >95%	> 102 % / >102%
Coil 106	MBHSP101	No (limit in other coil)	Good to 11.4 kA	Bad	> 11.9 kA	> 11.9 kA	> 82 % / >86%	> 82 % / >86%
	MBHSP102	Yes	Good to 12.2 kA	Bad	>12.8 kA	>12.8 kA	> 88 % / >90%	> 88 % / >90%
	MBHDP101	Yes	Good	Good	> 13.2 kA	> 13.2 kA	> 94% / ?	> 94% / ?
Coil 107	MBHSP101	No	??	Bad	> 11.9 kA	11.9 kA	> 82 % / >86%	82 % / 86%
Coil 108	MBHSP102	Yes	Good to 12.2 kA	Good	>12.8 kA	>12.8 kA	> 88 % / >90%	> 88 % / >90%
	MBHDP101	Yes	Good	Good	> 13.2 kA	> 13.2 kA	> 94% / ?	> 94% / ?
Coil 109	MBHSP103	Yes	??	Good	>12.8 kA	>12.8 kA	> 90 % / >92%	> 90 % / >92%
	MBHDP101	Yes	Good	Good	13.2 kA	>13.2 kA	94% / ?	> 94% / ?
	MBHDP102	No	Good to 11.4 kA	Good to 11.4 kA	11.4 kA	> 11.4 kA	78 % / 78 %	> 78 % / > 78%
Coil 111	MBHSP103	Yes	??	Good	>12.8 kA	>12.8 kA	> 90 % / >92%	> 90 % / >92%
	MBHDP101	Yes	Good	Good	13.2 kA	>13.2 kA	94% / ?	> 94% / ?
Coil 112	MBHSP104	No (limit in other coil)	??	Good to 12.2 kA	> 12.2 kA	>11.7 kA	> 87 % / > 85%	> 87 % / > 85%
	MBHDP102	No (limit in other coil)	Good to 11.4 kA	Good to 11.4 kA	> 11.4 kA	> 11.4 kA	> 78 % / > 78%	> 78 % / > 78%
Coil 113	MBHSP104	No	??	quite ok to 12.2 kA	> 12.2 kA	11.7 kA	> 87 % / 85 %	81 % / 83 %
Coil 114	MBHSP105	No (limit in other coil)	??	Good to 12.4 kA	> 12.4 kA	> 12.4 kA	> 85 % / > 85 %	> 85 % / > 85 %
	MBHDP102	No (limit in other coil)	Good to 11.4 kA	Good to 11.4 kA	> 11.4 kA	> 11.4 kA	> 78 % / > 78%	> 78 % / > 78%
Coil 115	MBHSP105	No	??	Good to 12.4 kA	12.4 kA	> 12.4 kA	85 % / 85 %	> 85 % / > 85 %
	MBHDP102	No (limit in other coil)	Good to 11.4 kA	Good to 11.4 kA	> 11.4 kA	> 11.4 kA	> 78 % / > 78%	> 78 % / > 78%
Coil 116	MBHSP106	Yes	???	Good	> 13.2 kA	> 13.2 kA	> 89 % / > 86 % (other	> 89 % / > 86 % (other
Coil 117	MBHSP106	Yes	???	Good	> 13.2 kA	> 13.2 kA	> 89 % / > 86 % (other	> 89 % / > 86 % (other

Color codes
Green - OK
Red - Bad
Yellow - No conclusion due to limit in other coil

As criterion for Iq >12.8 kA is used as good at 1.9 K
Note that the assessment is made using somewhat arbitrary criteria.

Assessment

Combining the data makes an overview more clear.

Single aperture model SP106 and double aperture DP101 are assessed to be good in all important aspects.

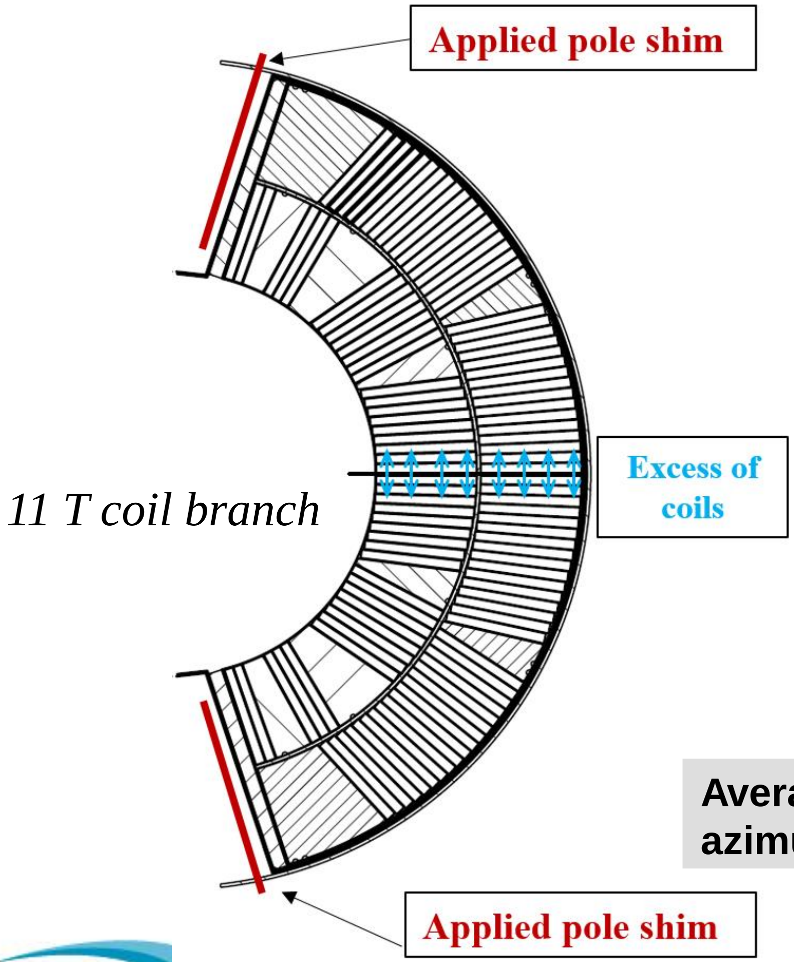
Conclusions

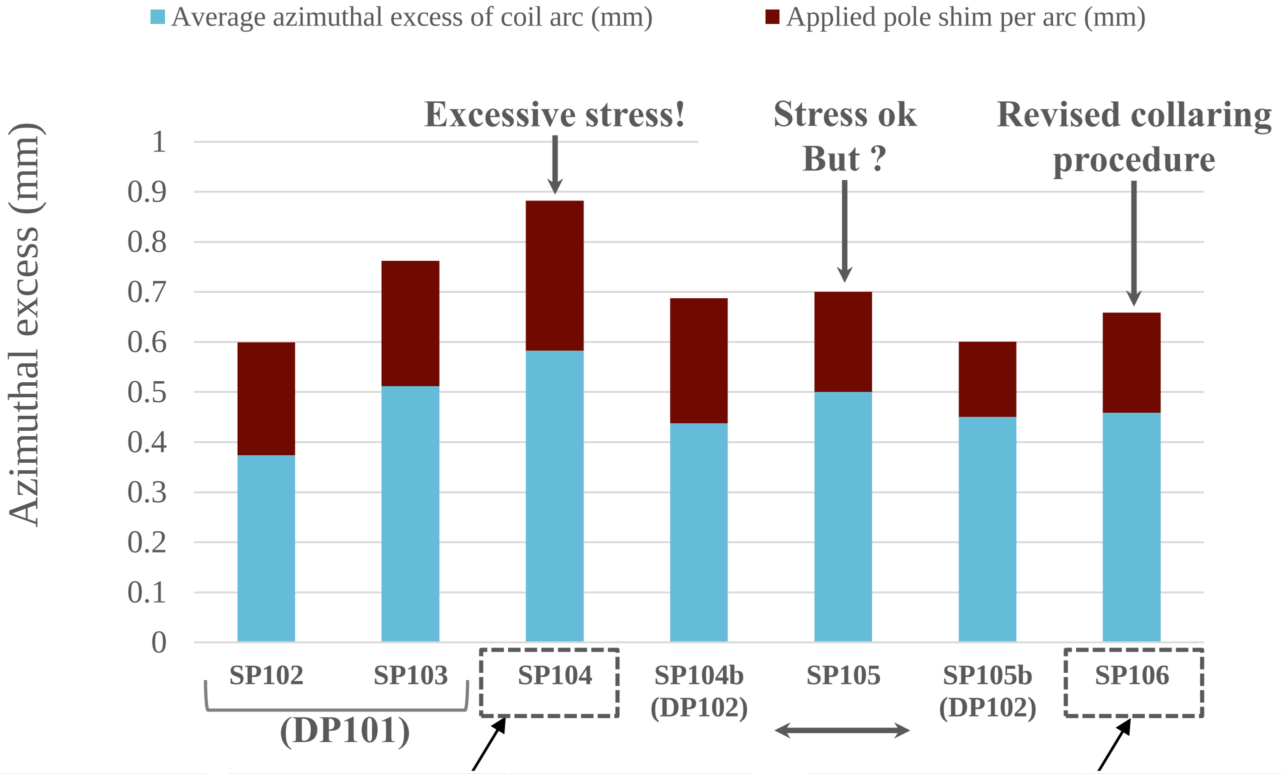
- Last magnet was a good magnet, as was the first double aperture.
- We have a large amount of measurements: understanding so much data is not always easy.
- It is clear from the measurements that the conductor is strongly degraded in the midplane for DP102 and for block 3 in SP106. This is the main issue that is being addressed by all teams at CERN.

Thank you.

Shimming of magnet models

- The pre-stress depends on the sum of the **azimuthal oversize of the coils with the thickness of the pole shims** (… and also on the mechanical properties of the coil)



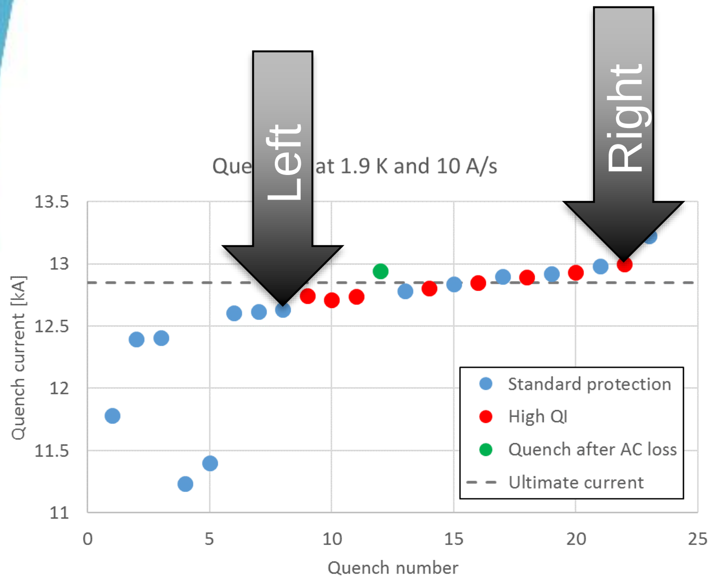


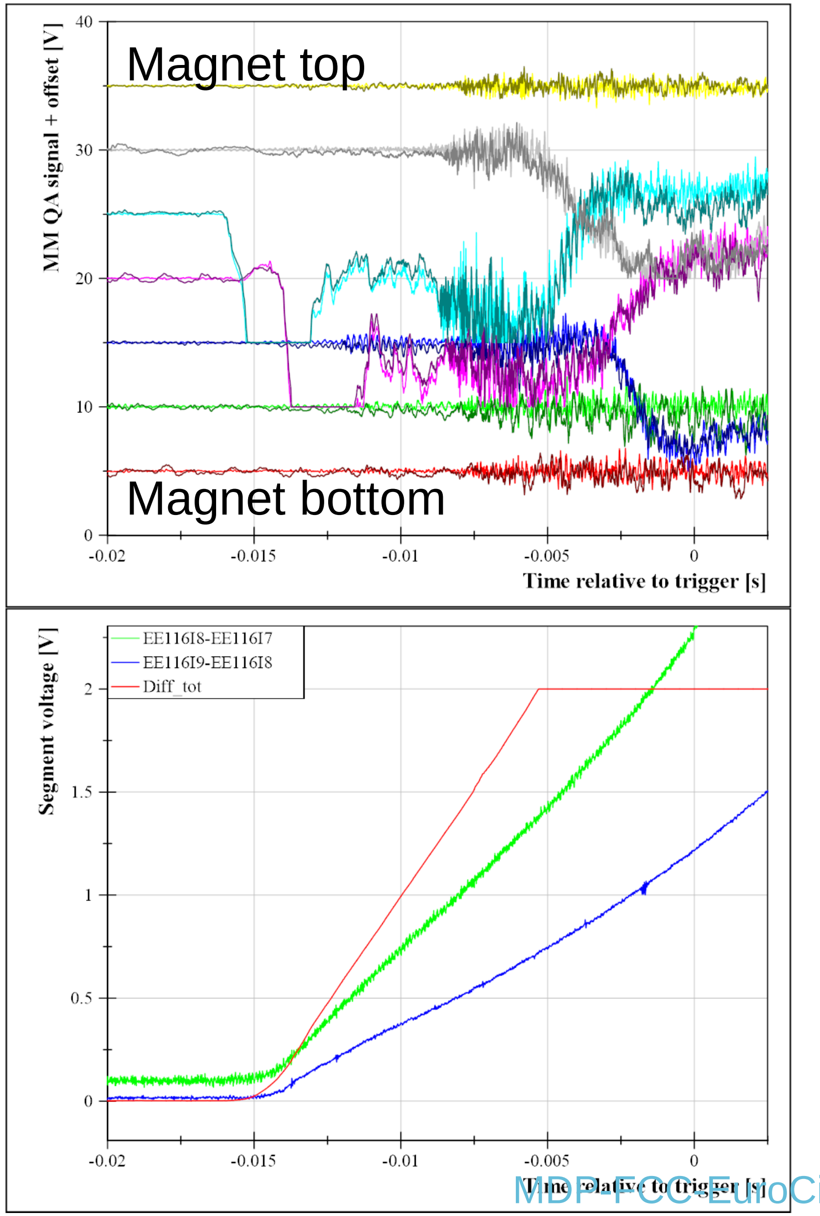
Average inner layer azimuthal stresses @ 12 T	SP104	
	Midplane turn	-147 MPa
	Pole turn	-29 MPa

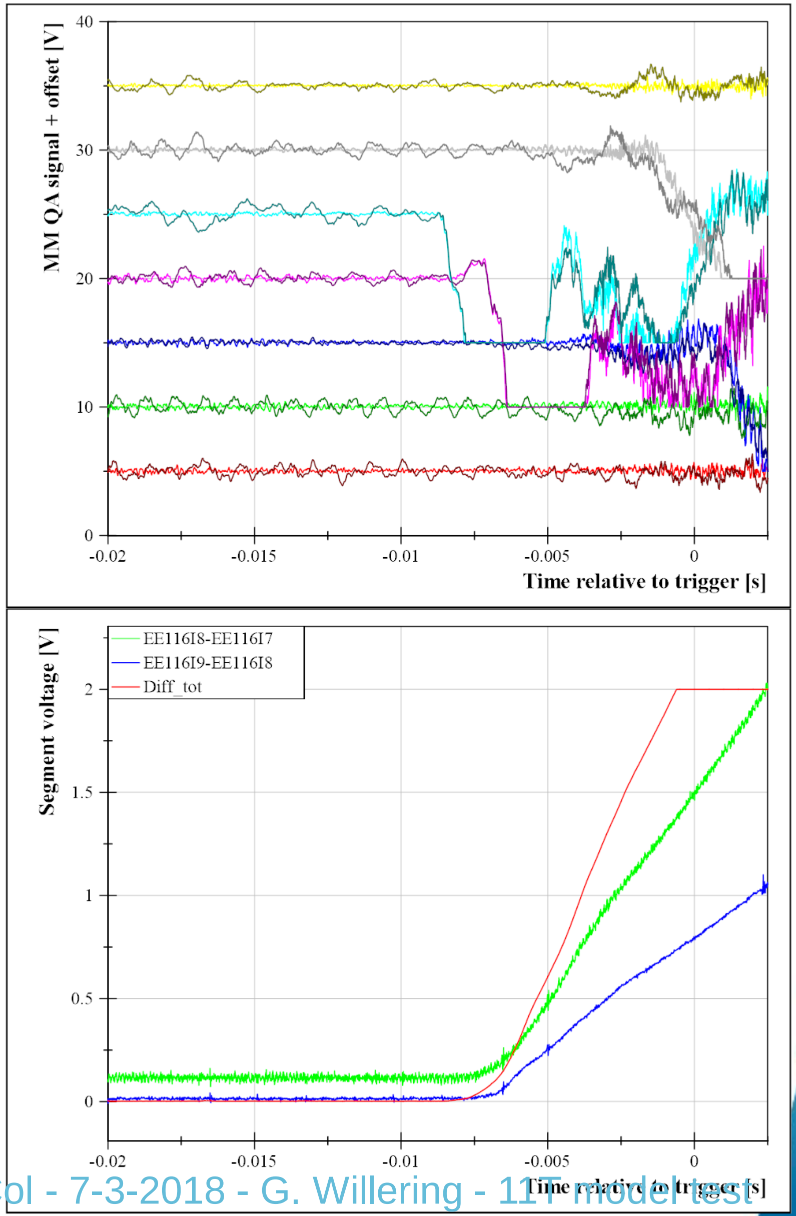
SP106	
Midplane turn	-127 MPa
Pole turn	-7 MPa

Courtesy C. Löffler, E. Nilsson

High QI studies – before and after







High QI studies – before and after