

HL-LHC 26th Technical Committee

11 T Dipole Model MBHSP102 - Cold Test Results

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27 August 2015





OUTLOOK

- Main features cable and conductor characteristics
- Test plan
- Powering tests
 - Training
 - Quench location
 - Stability tests
 - Ramp-rate dependence
- Magnetic measurements and analysis
- Quench protection studies
- Conclusions

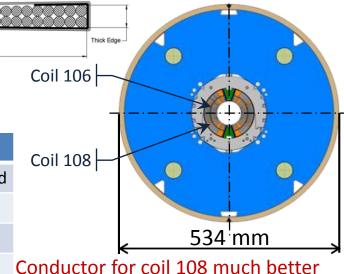


Main features, cable & conductor characteristics,

- Single aperture
- 6-block Nb₃Sn coils of Ø 60 mm aperture
- Coil 106 recovered from previons model MBHSP101
- Coil 108 new

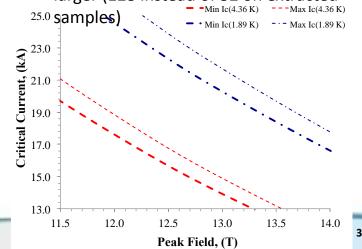
Conductor characteristics	Coil 106	Coil 108	
Strand type	RRP 108/127, Ta-Dope	ed RRP 132/169, Ti-Doped	
Billets	13925, 13926	15917, 15918, 15919	
$Max I_C$ (4.22 K, 12 T) – Virgin wire	480 A	472	
Min I_C (4.22 K, 12 T) – Virgin wire	466 A	417	
Max RRR – Virgin wire	230	271	
Min RRR – Virgin wire	88	103	
Copper – Non Copper ratio	1.22	1.22	
Cable above stavistics	Coil 10C	Seil 100	

	• • •			
	Cable characteristics	Coil 106	Coil 108	
	Transposition pitch	100 mm	100 mm	
	Mid thickness	1.2491 mm	1.2460 mm	
	Width	14.717 mm	14.696 mm	
	Keystone angle	0.783 deg	0.787 deg	
	Number of strands	40	40	
	Core width	12 mm	12 mm	
	Core thickness	25 μm	25 μm	



(thanks to adequate HT parameters):

- The critical current is at least 4.5 % larger
- The minimum integral RRR is significantly larger (128 instead of 32 on extracted



Test plan

- PART I: Powering tests (with mechanical measurements included)
 - Training at 1.9 K, 10 A/s, including a thermal cycle
 - First target current of 12.5 kA, giving some margin w.r.t. the limit resulting from the mechanical design
 - Then, after thermal cycle, target current pushed to 12.8 kA (12 T) corresponding to the mechanical design limit (not 'sharp')
 - Holding current tests included
 - Ramp-rate dependence
 - Training at 4.2 K in the end of the test campaign
 - Training not mixed with other tests, only splice measurement

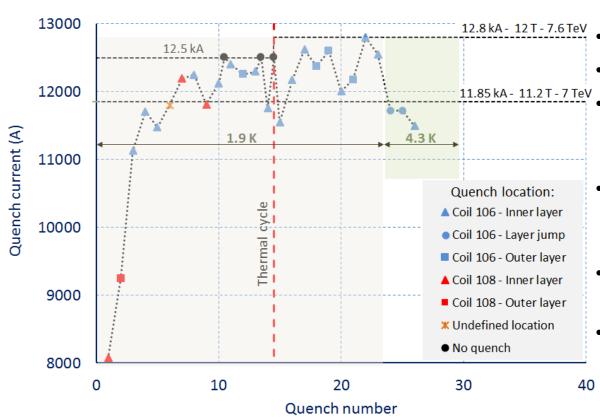
PART II: Magnetic measurements

- Transfer function
- Allowed multipoles, and non-allowed
- Comparison with ROXIE model, with MBHSP101
- Influence of coil geometry on harmonics
- Inter-strand coupling currents
- Ramp-rate dependence
- Integral field
- Cold/warm correlation

PART III: Protection studies

- Initial quench propagation
- Quench heater performance
- Assessment of AC losses contribution
 - Quench integral studies

Training - MBHSP102



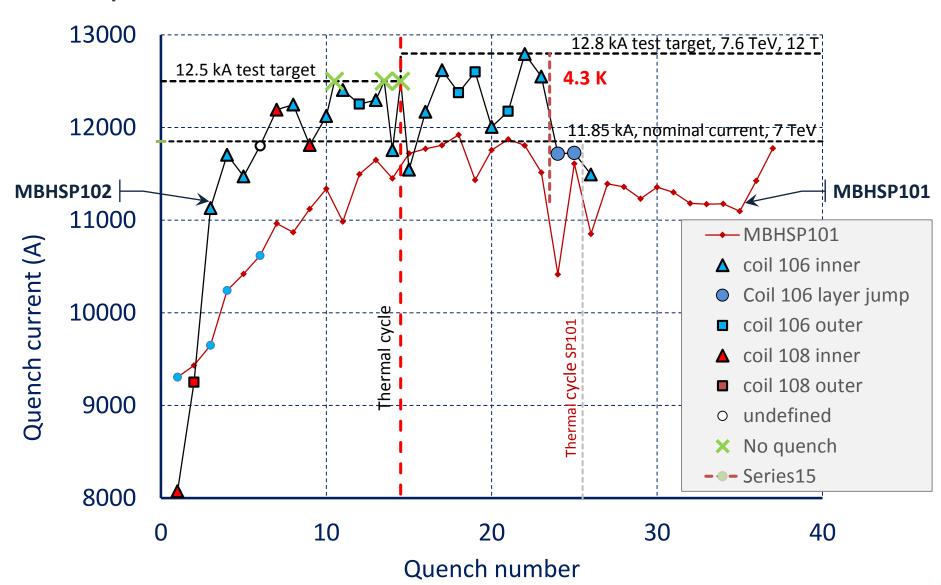
In brief:

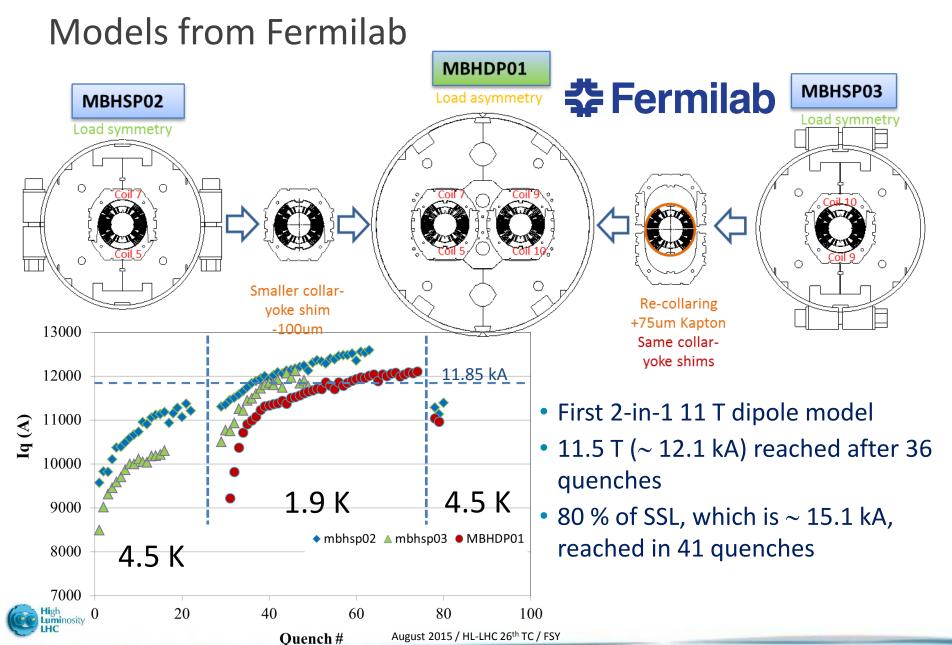
- 6 quenches to I_{NOM} of 11.85 kA
- 10 quenches to 1st target of 12.5 kA
- Only 3 or 4 re-training quenches for coil 106 after de-collaring and recollaring
- Coil 108 had only 4 or 5 (de)-training up to 12.3 kA, it never quenched again up to 12.8 kA
- Memory after thermal cycle is good, with one quench just below nominal
 - Target of 12.8 kA (12 T) reached after thermal cylce

Very good compared to previous models

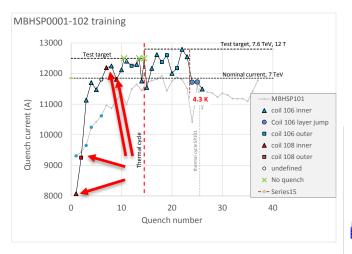


Comparison with MBHSP101

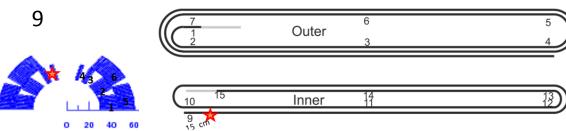


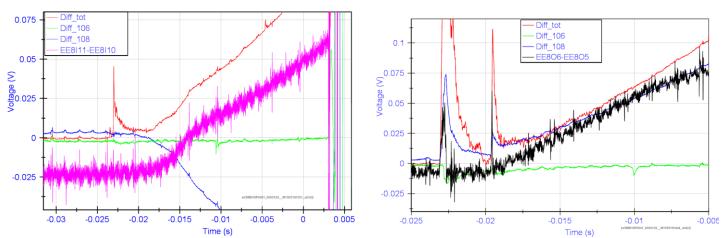


Quench location - Coil 108



4 quenches in coil 108: Quench 1, 2, 7, 9

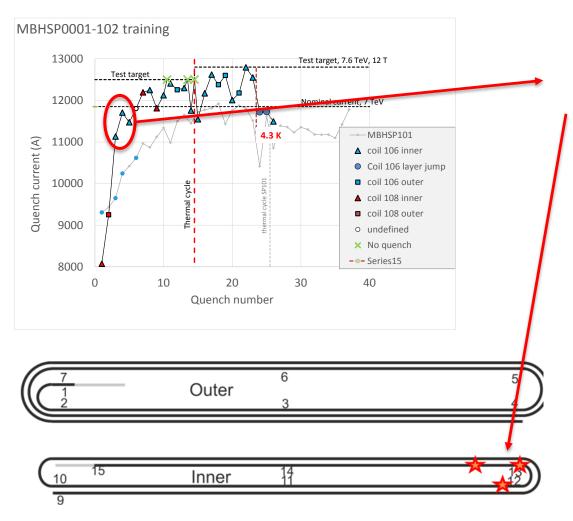




- Large precursors in the two low-current quenches (8 and 9.2 kA)
- 4 different quench locations



Quench location – Coil 106, first 3 quenches

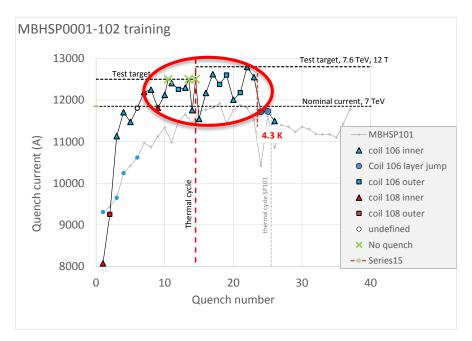


Quenches close to the head of the inner layer, high-field turn

Confirms the quench location of the training of coil 106 in MBHSP101



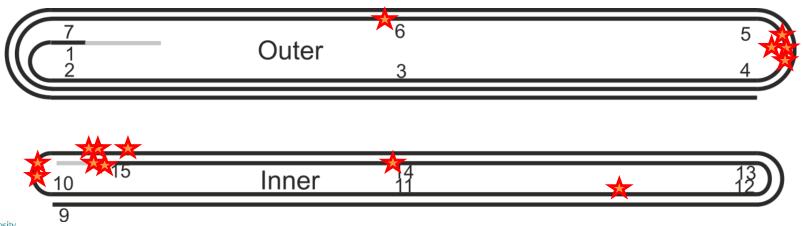
Quench location - Coil 106, further training @ 1.9 K



Quench location different from that

- * of the first 3 training quenches and
- * of the training quenches in MBHSP101

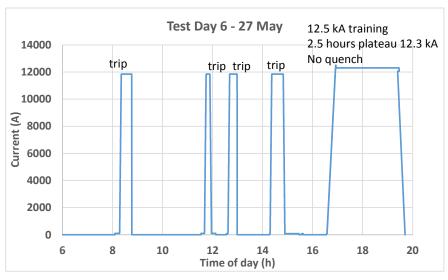
Analyses of the V-tap signals and of the magnetic measurements shaft give consistent results in terms of quench localisation

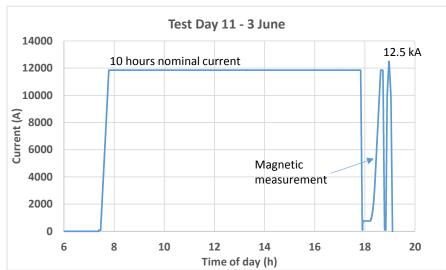


Stability test

2.5 hours at 12.3 kA, no quench

10 hours at nominal current, 11.85 kA, followed by a magnetic measurements cycle and a ramp to 12.5 kA without quench



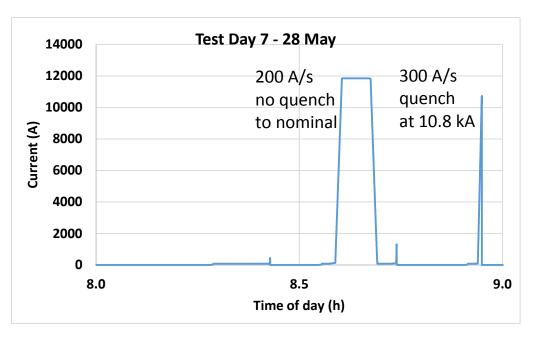


Note the length of the test days from 8 h to 20 h

No sign of any instability



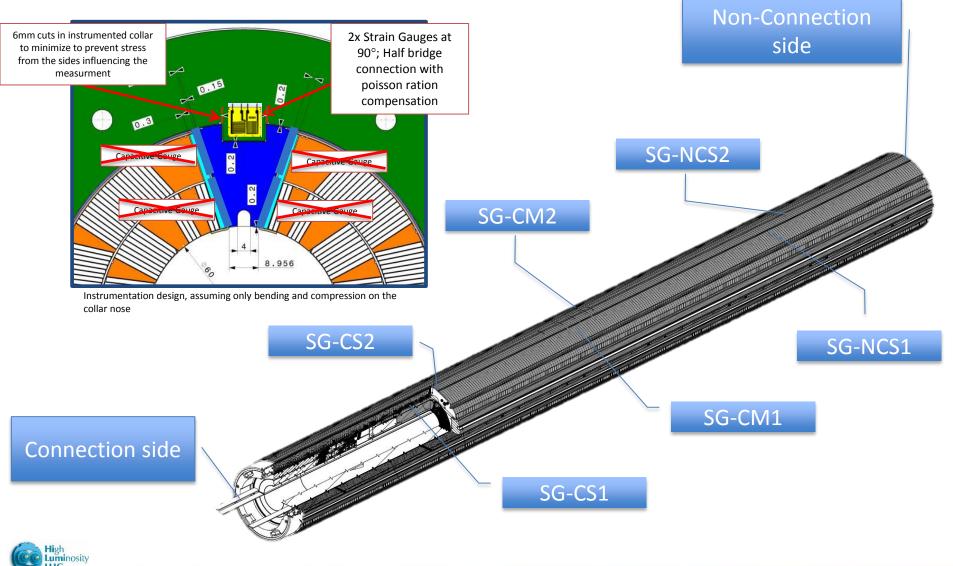
Ramp-rate dependence



- No quench at 200 A/s up to nominal current
- Quench at 300 A/s at 10.8 kA
- ➤ No further ramp rate dependence tests were done, considering:
 - Quench back results
 - High ramp rate without quench
 - Limited test time



Mechanical measurements

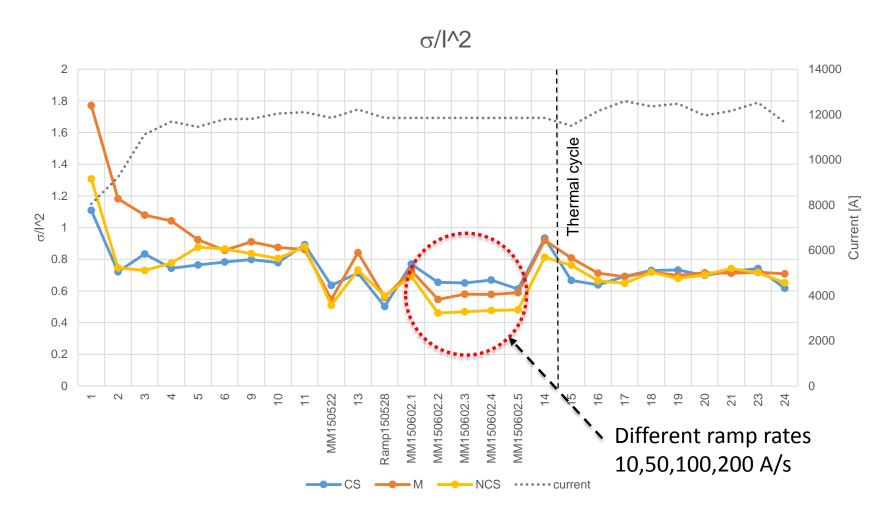


Stress history MBHSP101&102 // Stress collar-nose (error +-1 stdev)



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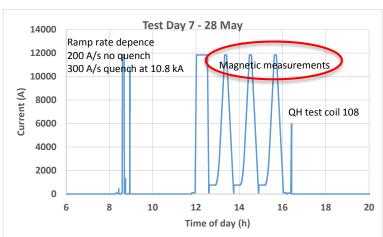
Settling of mechanical system





Magnetic measurements

- Measurements @ RT and cryogenic T
- Measurements cycle:
 - At 1.9 K
 - Stair-step cycle
 - 3 x machine simulation cycles
 - Ramp-rate study at 20, 50, and 100 A/s
 - Long flat-top (10 h) before a machine cycle
 - No measurement at 4.3 K



A measurement is the average over 250 mm

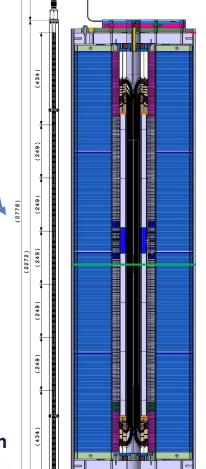
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Standard

program



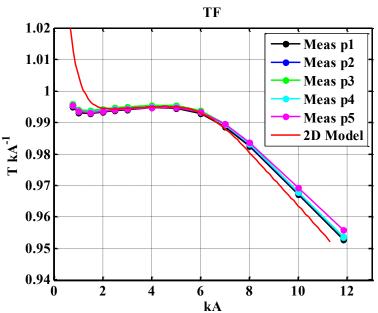
A measurement is the average over 1.2 m



L. Fiscarelli



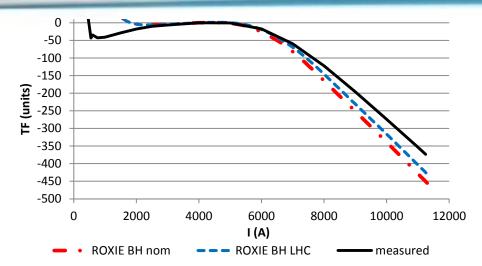
Transfer function



Possible sources of errors:

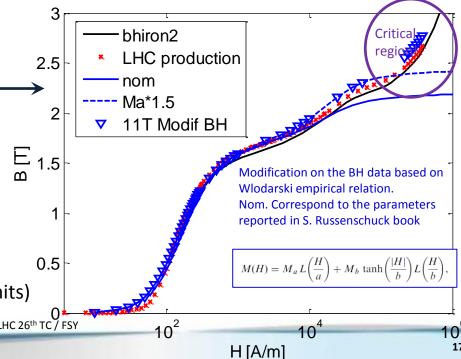
- Iron properties (the main source of errors)
 - When using data measured during the LHC production, discrepancy decreases by 20 units (from ~70 to ~50 units)
- Packing factor of the yoke laminations
 - Can explain up to ~15 units
- Geometric
 - Rather big displacements are needed to explain
 other 35 units (350 μm smaller coil gives ~15 units)

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- Measurements and ROXIE model in agreement for geometric TF
- Saturation overestimated by the model

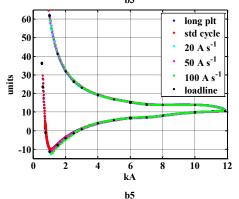
Results of measurements on MBHSP101 and MBHSP102 are consistent (not shown here)



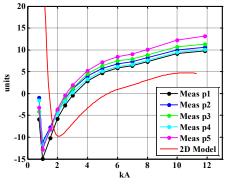
Reference radius 17 mm

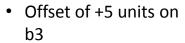
Allowed multipoles

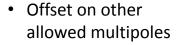
Comparison with ROXIE (2D)

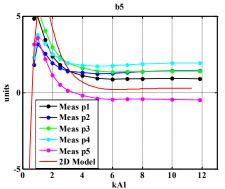


- b3 changes by ~22 units during ramp
- Offset on allowed multipoles after long plateau at nominal

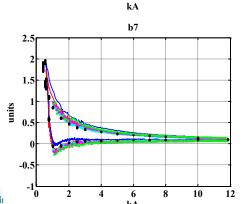








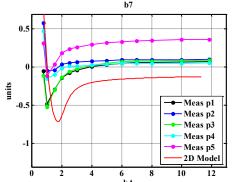
 Discrepancy on persistent currents



6

10

-10^L



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Ramp-rate dependence

	20 A s ⁻¹	50 A s ⁻¹	100 A s ⁻¹		20 A s ⁻¹	50 A s ⁻¹	100 A s ⁻¹	
n		ΔBn	Bn Δ An			ΔAn		
2	-0.01	-0.07	-0.06		-0.13	-0.31	-0.42	
3	0.08	0.16	0.27		-0.02	0.02	0.06	
4	0.01	0.02	0.04		-0.08	-0.14	-0.19	
5	-0.07	-0.04	0.01		-0.03	-0.01	-0.01	T
6	0.00	0.01	0.03		0.01	-0.01	-0.03	mT
7	0.01	0.01	0.02		0.00	0.00	0.00	
8	0.00	0.01	0.04		0.00	-0.01	0.00	
9	0.01	0.00	-0.01		0.00	0.01	0.01	

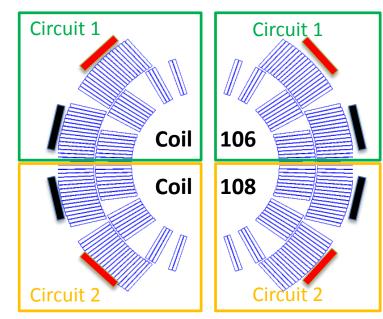
$$\Delta C_n = C_n^{dynamic}(I) - C_n^{static}(I) \Big|_{I=5 \ kA}$$

Small effects: the cored cable is well performing



Quench heater test set-up in SM18 - layout in model

- Coil 108 has a ground wrap between the QH and the outside surface of the outer layer (0.1 mm S2 Glass)
- No ground wrap in coil 106
- Standard LHC Quench Heater Power Supply: $V = \pm 450 \text{ V, C} = 7.05 \text{ mF}$
- Maximum current = 150 A
- Voltage is fixed to a total of 900 V, additional resistance in series with the circuit is setting the current
- In the previous assemblies, three different current levels in the heaters were explored: 80 A, 100 A and 150 A. For MBHSP102, quench heater tests were



Pave

[W/cm²]

34

52

118

/cm²]

perfo	rmed only	for I _{QH} = 150 A	\ \				
		Radd)	Ι [A]	P _{LF} [W/cm ²]	P _{HF} [W/cm ²
	+ F	$\stackrel{\perp}{=}$ C	RLF		80	41.3	25.9
	-		■ R _{HF}		100	64.5	40.4
			TIME	>	150	145.1	91.0
High							



RC

(ms)

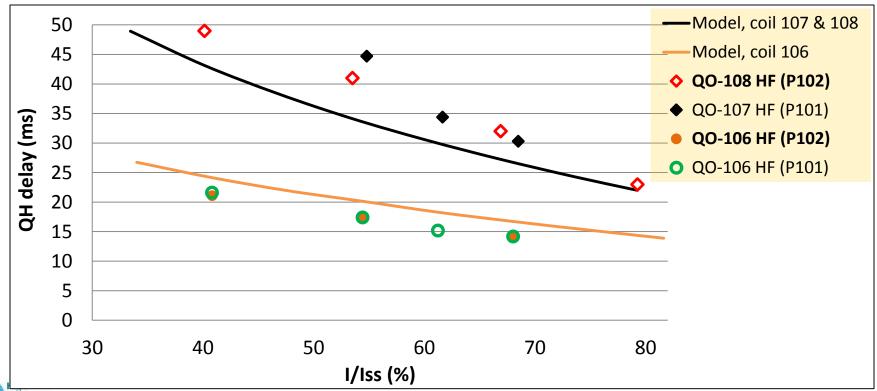
80

64

42

Quench heater test plan - Results in high field region

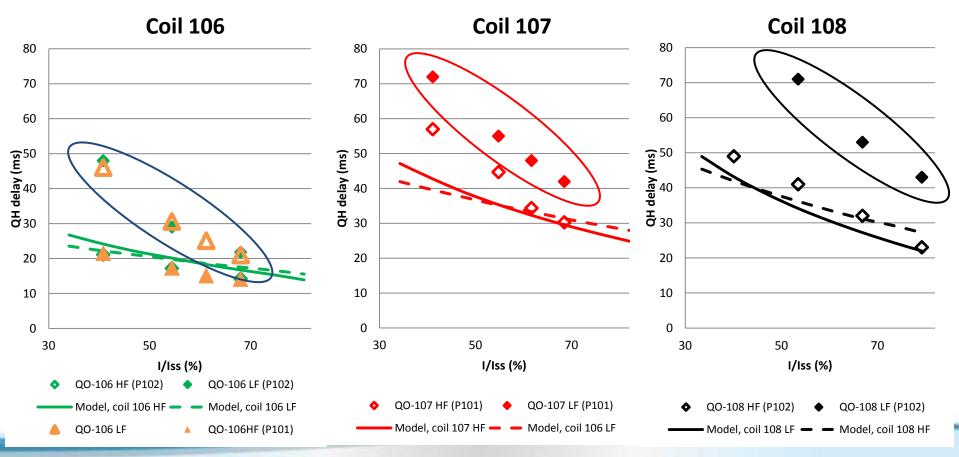
- Measure QH delay as a function of the magnet current for a quench heater current of 150 A
- Compare the performance of the heaters in coils 106 and 108
- Quench onset delay consistent with the measurements in MBHSP101





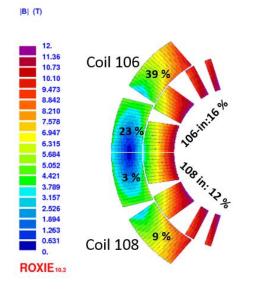
Quench heater efficiency

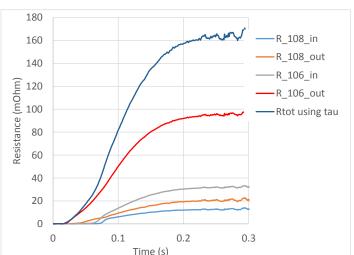
- The quench heater delay for the low field region is much longer than expected
- The behaviour is reproducible in coil 106
- The discrepancy is stronger for coil 108 than for coil 107 but both coils have the same insulation scheme so in principle the behaviour should be similar



Quench heater efficiency

- Quench heaters of coil 108 are much less efficient than those of coil 106
- In coil 108, the energy dissipated in the inner layer is about the same as the energy dissipated in the outer layer → quench back is observed and its contribution is not negligible





60 — 108 HF 50 — 106 HF — 106 LF (a40 — 106 LF — 106 LF 10 — 106 LF — 106 LF — 106 LF — 106 LF

Heat deposition distribution, 10 kA, all heaters fired simultaneously, I_{OH} = 150 A

Resistance growth inner and outer layers, 10 kA, all heaters fired simultaneously, $I_{OH} = 150 \text{ A}$

Resistance growth HF and LF blocks, 10 kA, all heaters fired simultaneously, $I_{OH} = 150 \text{ A}$



Conclusions

Quench performance

- Rather fast training curve up to nominal current
- A few detraining quenches in coil 106 up to nominal current
- Only 4 quenches in coil 108 (consistant with cable of better quality/performance)
- Stable powering during 10 hours

Magnetic measurements and analysis

- TF in agreement for geometric
- Model overestimates saturation
- Offset on allowed multipoles

Quench protection studies

- The important differences in the two conductors and coil insulation layout complicates the quench protection analysis
- Behavior of coil 106 is very reproducible in aperture MBHSP101 and MBHSP102
- Heater performance in coil 108:
 - Heater delay as expected (very close to coil 107 measured in MBHSP101 with the same insulation layout)
 - Heater efficiency lower than expected. Not clear reason to explain the differences between low field guench heater delay observed in coil 107 and 108



'Much' more information available in Indico:

- http://indico.cern.ch/event/406942/
 Debriefing on cold tests of 11T model MBHSP102 Part 1
- http://indico.cern.ch/event/407058/
 Debriefing on cold tests of 11T model MBHSP102 Part 2
- Including further details, and additional topics as:
 - Mechanical measurements and analysis
 - Analysis of non-allowed harmonics
 - Inter-strand coupling currents
 - Assessment of AC losses contribution:
 - Magnetic measurements
 - Ramp rate study
 - Energy extraction tests
 - Quench integral studies





Next model, MBHSP103
is nearly finished
will be installed on the test bench in week starting 7 September 2015



