S. Izquierdo Bermudez, with many contributions from WP11, WP7 and the FNAL collaboration. 29th October 2015.

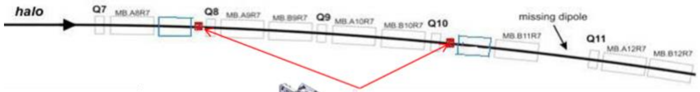
Quench Protection of the 11 T Nb_3Sn Dipole for the LHC Luminosity Upgrade

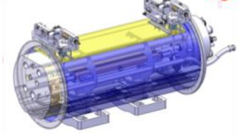
Acknowledgements

Bernhard Auchmann, Hugo Bajas, Marta Bajko, Bernardo Bordini, J. Blomberg Ghini, Lorenzo Bortot, Luca Bottura, G. Chlachidze, Ludovic Grand-Clement, Mikko Karppinen, Juan Carlos Perez, Francois-Olivier Pincot, Herve Prin, Felix Rodriguez Mateos, Jacky Mazet, Ana Teresa Perez Fontela, Juho Rysti, Frederic Savary, Emmanuele Ravaioli, David Smekens, Gerard Willering, A. V. Zlobin…

And many other people involved in the design, construction and test of the magnet.

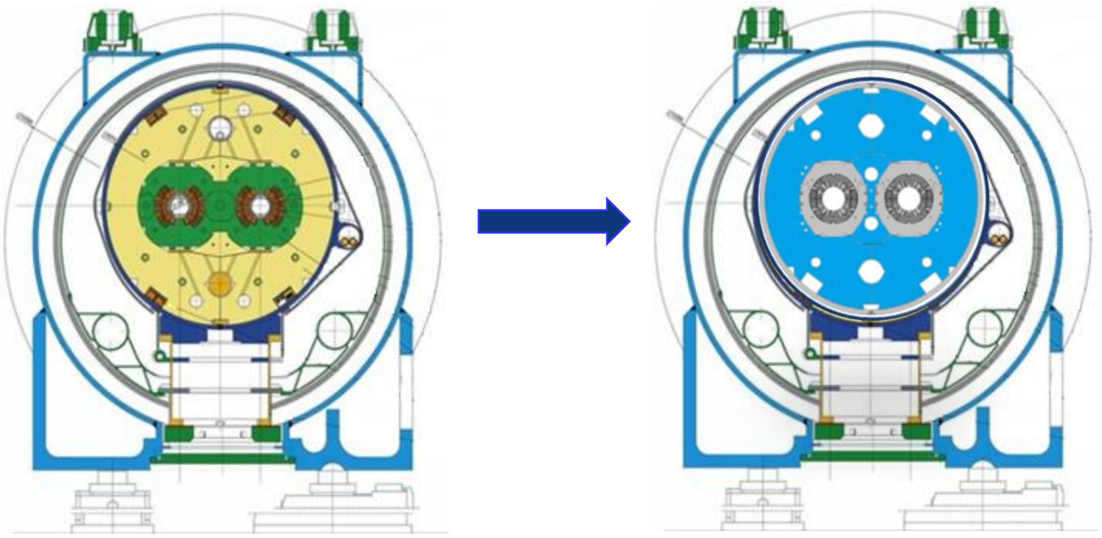
Introduction





5.5 m Nb_3Sn | 3.5 m Collim | 5.5 m Nb_3Sn

5.5 m Nb_3Sn | 3.5 m Collim. | 5.5 m Nb_3Sn



DS-11 T magnet must be 100 % compatible with the LHC lattice and main systems

This has important consequences, as it is setting (many) important constrains in the design:

- Integrated field (pair of DS-11T dipoles): **118.8 Tm**
- Operational point
- Yoke dimension/geometry
- Aperture
- Length
- …

Challenges: high field, forces, stored energy!

Contents

Contents

1. Magnet Parameters

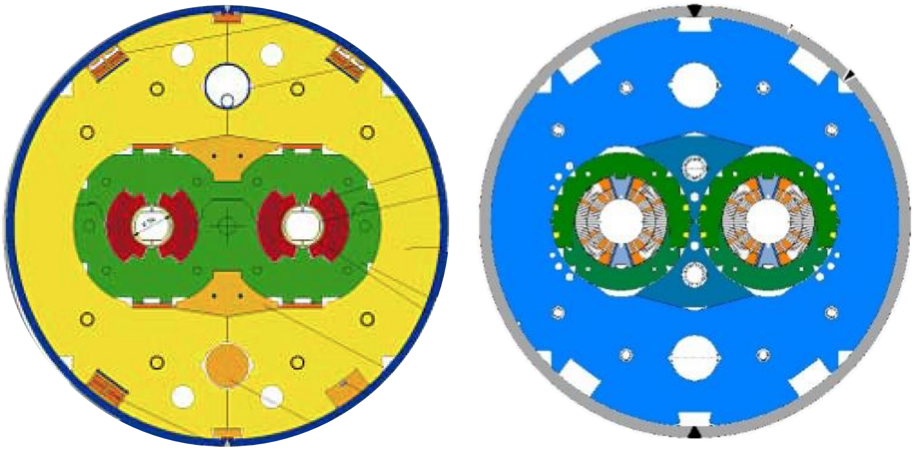
Comparing to the Main Bending LHC dipoles:

- **High stored energy density**

(compact winding for cost reduction)

- **Low stabilizer fraction**

(to achieve the desired margins)



Magnet parameters at nominal current I_{nom} = 11.85 kA	**LHC MB dipole**	**DS-11T dipole**
Field in the aperture at I_{nom} (B_0), (T)	8.3	11.2
Peak field in the conductor at I_{nom} (B_p), T	8.6	11.6
Engineering current density (J_{eng}), A/mm^2	**500**	**790**
Stored energy in the conductor volume at I_{nom}, MJ/m^3	**60**	**130**
Differential inductance at I_{nom}, mH/m	6.9	11.7
Magnetic length, m	14.3	2 x 5.3
Temperature margin, K	1.8-6.5	4.5-14.5
Copper area in the cable (A_{Cu}), mm^2	15.53 (IL)/13.43 (OL)	8.23

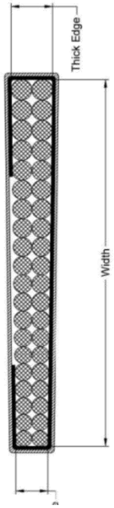
1. Magnet parameters – Insulation Scheme

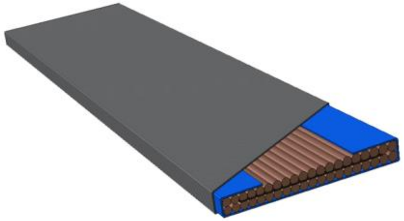
Insulation designed to withstand a turn to turn voltage of **1.2 kV**:

Cable insulation lay-out

- Mica tape, COGEBI FIROX®, thickness 80μm
- S2 glass braided sleeve
- Resin impregnation, CTD-101K

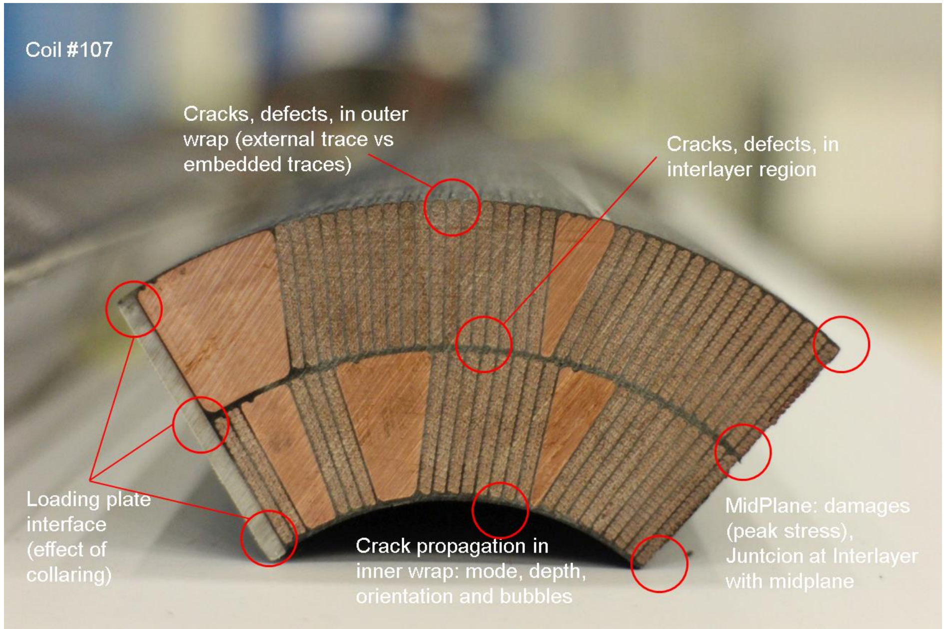
(total thickness after reaction, 35 MPa = 100-μm)





Work in progress to understand:

- Actual limit in terms of dielectric strength
- Effect of voids/cracks



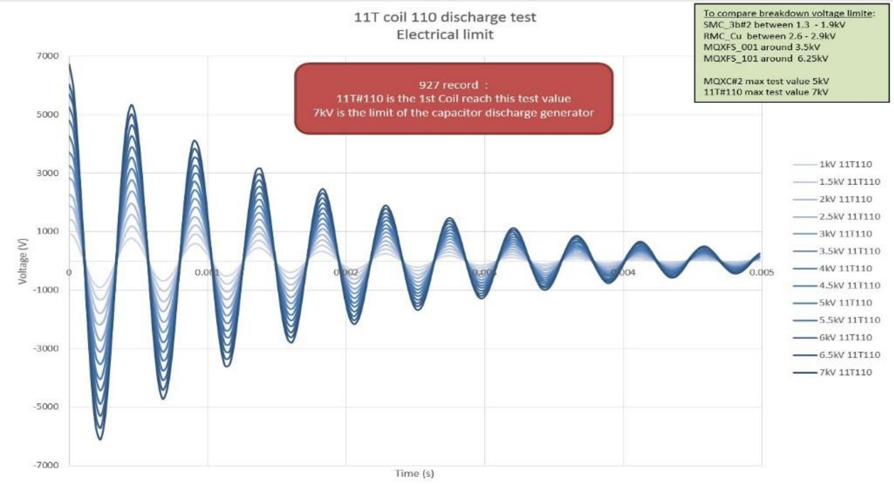
More details [D. Smekens]
http://indico.cern.ch/event/434223/

1. Magnet parameters – Insulation Scheme

Destructive tests on coil 110 and 107 show great electrical performance!

Impulse test

- Coil 110 (virgin coil) > **7 kV** (limit of the power supply)
- Coil 107 (after cold testing and decollaring) > **6 kV**



927 record :
11T#110 is the 1st Coil reach this test value
7kV is the limit of the capacitor discharge generator

To compare breakdown voltage limite:
SMC_3b#2 between 1.3 - 1.9kV
RMC_Cu between 2.6 - 2.9kV
MQXFS_001 around 3.5kV
MQXFS_101 around 6.25kV

MQXC#2 max test value 5kV
11T#110 max test value 7kV

Quench heaters:

Failure at **7 kV** the level of the connectors

Weakest point:

Coil to loading plate (floating), leakage at 2 kV

Additional information:
https://indico.cern.ch/event/395351/

1. Magnet parameters – Electrical QA

Standard tests – Short model program

Dielectric:*

- Current leakage test:
    - Magnet to ground at 1 kV.
    - QH to magnet at 1 kV.

Pole inter-turn discharge:*

- Impulse test at 1 kV.

Quench heaters:

- Before installation, quench heaters tested under pressure up to 3 kV.

*Test performed at every step of the assembly process (after coil impregnation, after collaring, after shell welding …)

Towards LHC MB standard?

REF: IT-2997/LHC/LHC. TECHNICAL SPECIFICATION FOR THE SUPPLY OF 1158 COLD MASSES OF THE SUPERCONDUCTING DIPOLE MAGNETS FOR THE LHC COLLIDER

Dielectric:

- Current leakage test:
    - Magnet to ground at 5 kV.
    - QH to magnet at 3 kV.

Pole inter-turn discharge:

- Impulse test at
    - 4 kV after winding
        - 1.8 kV IL, 3 kV OL
    - 2.8 kV after shell welding.
    - 2 kV before cold test

Quench heaters:

- Before installation, quench heaters tested under pressure up to 5 kV.

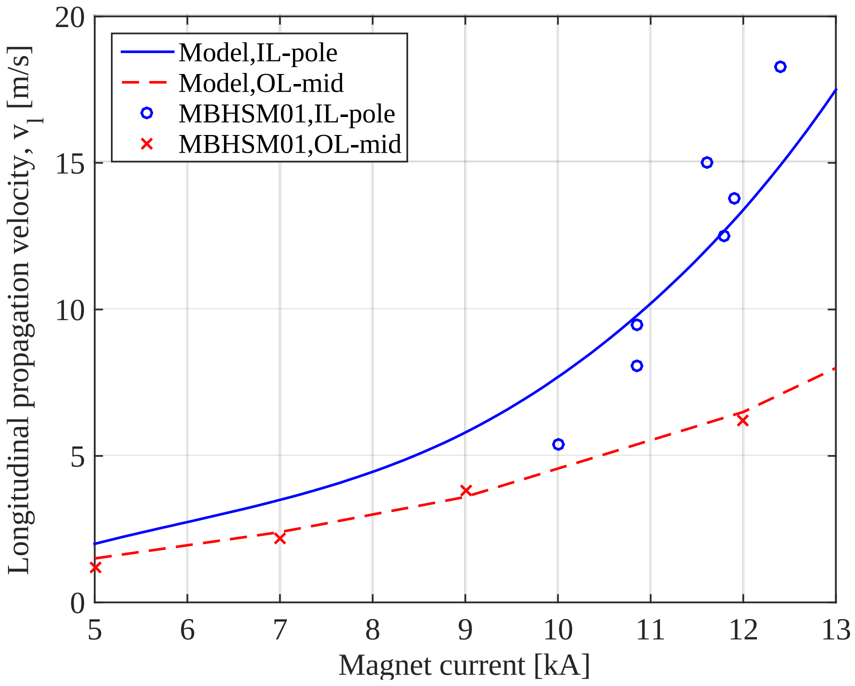
+ inductance measurements + resistance measurements + QH discharge (identical in 11T and standard LHC dipole)

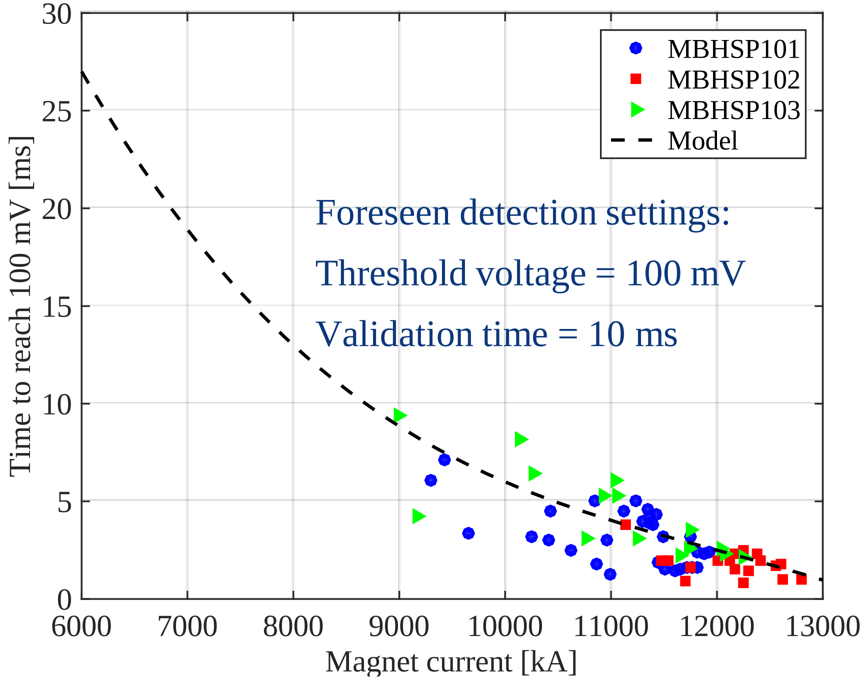
Contents

2.1 Initial quench propagation and detection

A good characterization of the initial quench propagation is important because it determines the time needed to detect a normal zone:

- **Cable level**: measurements on FRESCA [1]
- **Magnet level:**
  - **R&D Magnets**: measurements on the Short Model Racetrack Coil (SMC) [2]
  - **Magnet models**: measurements on FNAL and CERN 11T magnets [3]





Foreseen detection settings:

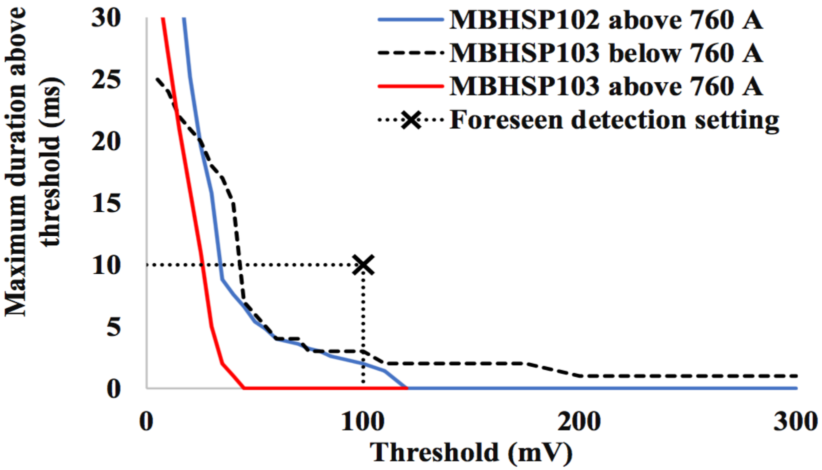
Threshold voltage = 100 mV

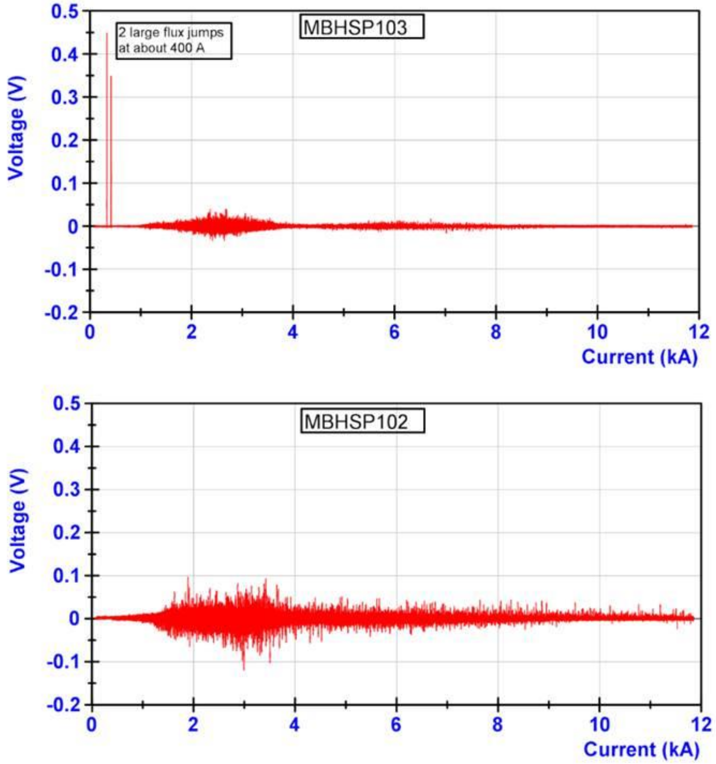
Validation time = 10 ms

[1] J. Fleiter, et al., Quench Propagation in Nb3Sn Rutherford Cables for the Hi-Lumi Quadrupole Magnets. IEE Trans. Appl. Superconductivity
[2] S. Izquierdo Bermudez, et al., Quench modeling in high-field Nb3Sn accelerator magnets, in Proc. 25th ICEC 25 ICMC 2014
[3] S. Izquierdo Bermudez, et al., Quench Protection Studies of the 11 T Nb3Sn Dipole for the LHC Upgrade, Submitted for publication

2.1 Initial quench propagation and detection

- In Nb_3Sn, **voltage spikes** at low field are typically observed due to the **flux jumps** on the superconductor.
- This might require the use of a **threshold** voltage/validation delay which is **a function of the magnet current.**
- For the first single apertures tested at CERN, 100 mV threshold and 10 ms delay can by used to protect the magnet in the full range of currents.
- The situation might be different for full length double aperture magnet (as very likely this effect scales with the coil volume).



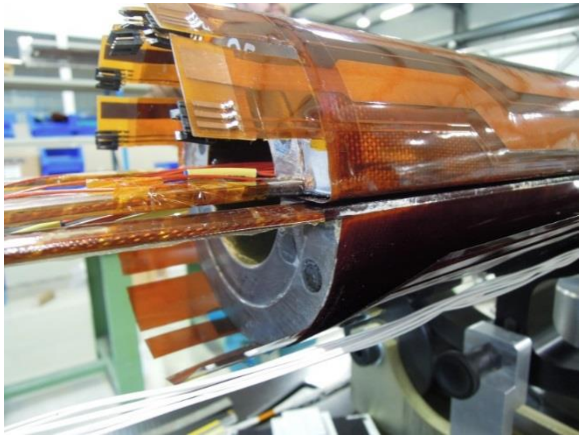


[G. Willering]

2.2 Quench heater performance

Original design, quench heaters **glued after coil impregnation**. Total insulation from heater to coil:

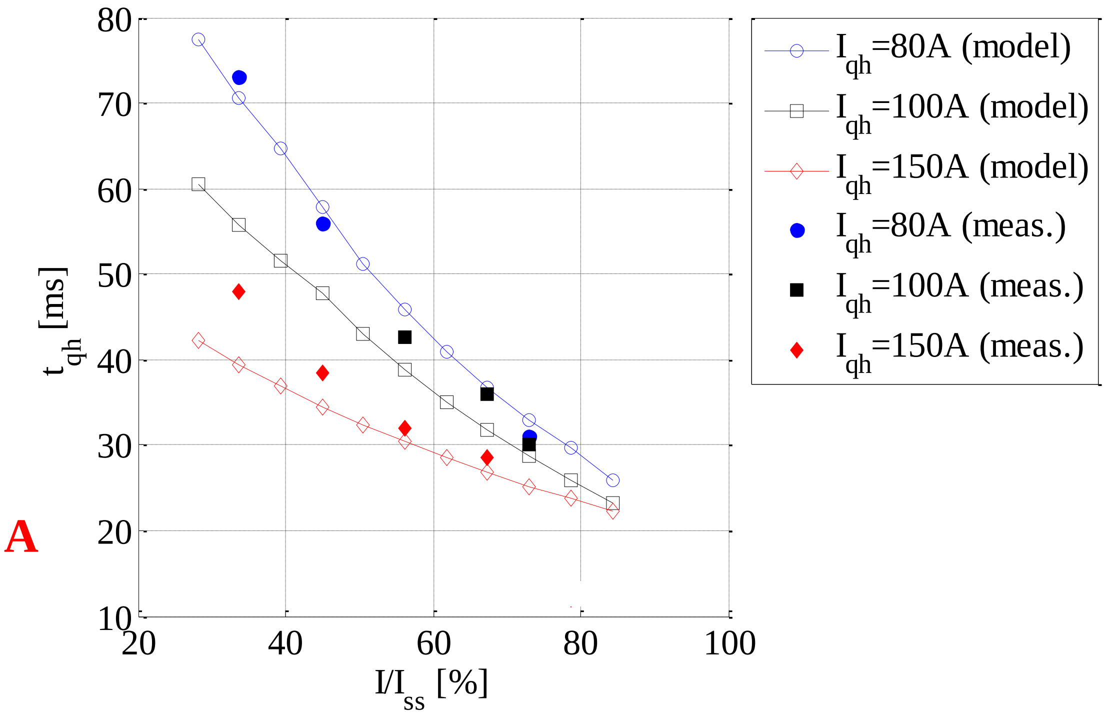
- 0.05 mm polymide (Kapton $^{(R)}$)
- 0.1-0.2 mm glass protection sheet
- 0.1 mm cable insulation



Extensive tests performed on the single coil model assembly to validate the quench heater performance

I [A]	P_{LF} [W/cm^2]	P_{HF} [W/cm^2]	P_{ave} [W/cm^2]
80	41	26	34
100	65	40	52
150	**145**	**91**	**118**

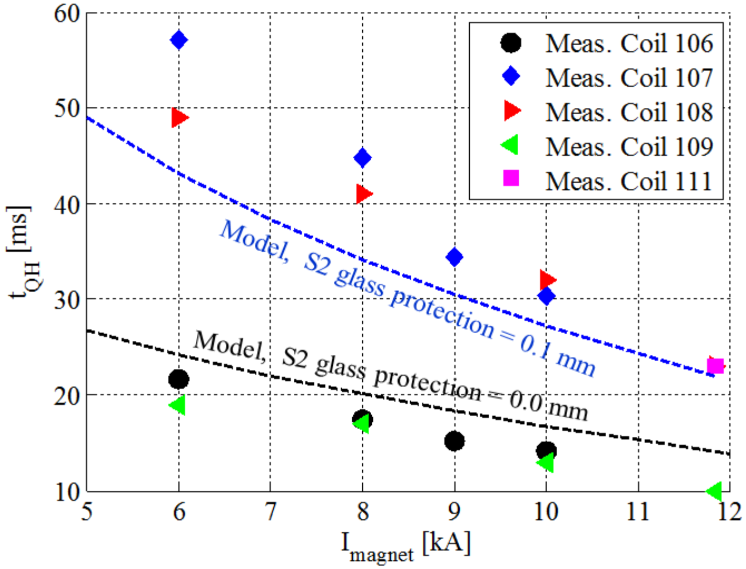
Baseline quench heater current = **150 A**



2.2 Quench heater performance

Different insulation schemes tested in the first short magnets, and as expected, significant decrease of the quench heater delay → **New baseline**: quench heaters **impregnated with the coil** (S2 glass protection = 0.0 mm)

	Strand lay out	Coil R at 300 K mΩ	Average coil RRR	S2 glass mm
Coil 105	RRP 108/127	426	77	0.1
Coil 106	RRP 108/127	423	62	0
Coil 107	RRP 108/127	426	91	0.1
Coil 108	RRP 132/169	407	165	0.1
Coil 109	RRP 132/169	400	125	0
Coil 111	RRP 132/169	401	119	0.1



P_d=90 W/cm^2 HF, 145 W/cm^2 LF

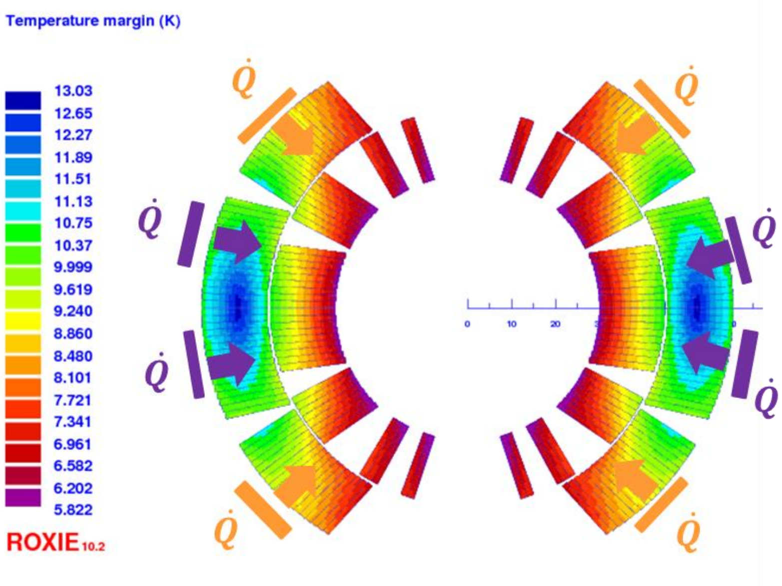
MBHSM101 (coil 105); MBHSP101 (coil 106 &107); MBHSP102 (coil 106&108); MBHSP103 (coil 109 &111)

More details:

http://indico.cern.ch/event/365072/
http://indico.cern.ch/event/407058/

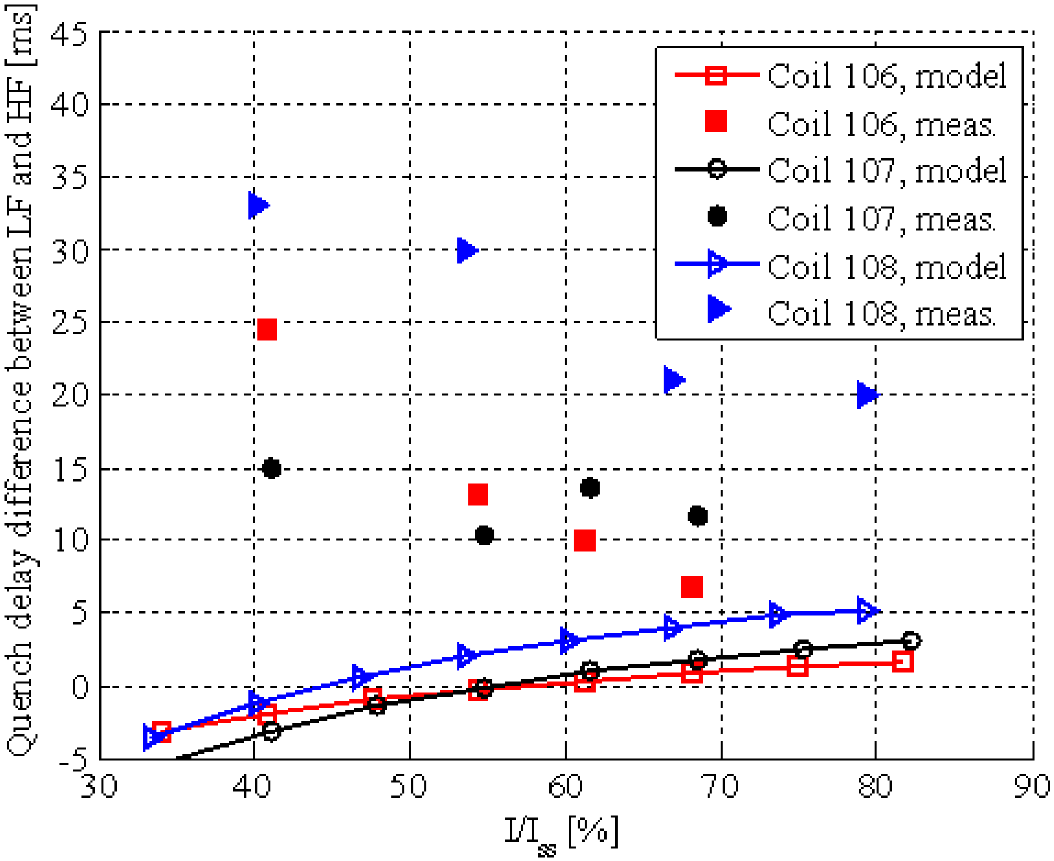
2.2 Quench heater performance

- Even if the agreement between measurements and model is reasonable good for the heater delay in the high field area, the delay to quench the low field block is longer than expected.
- It varies significantly from coil to coil to coil
  - Coil manufacturing?
  - Test data interpretation?



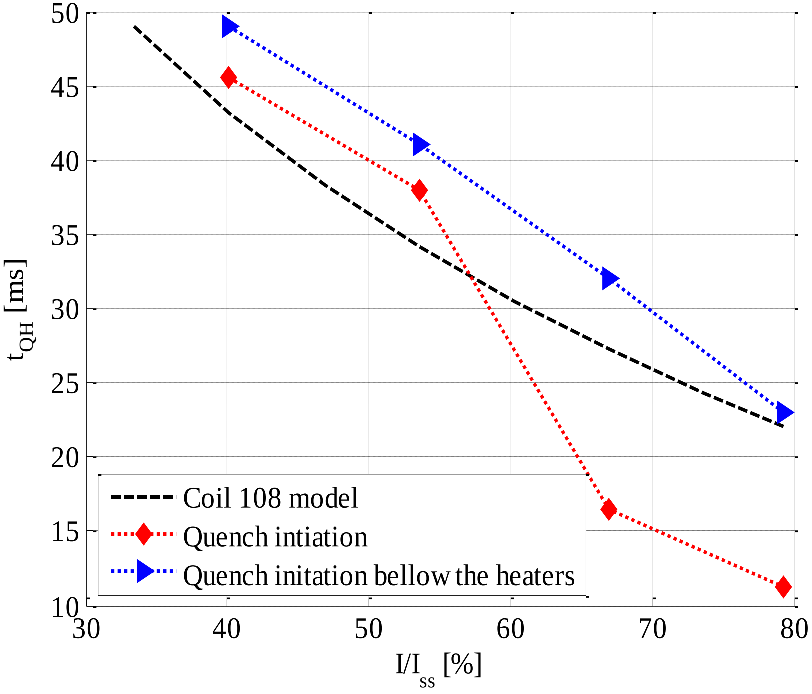
Quench heaters on the high field blocks

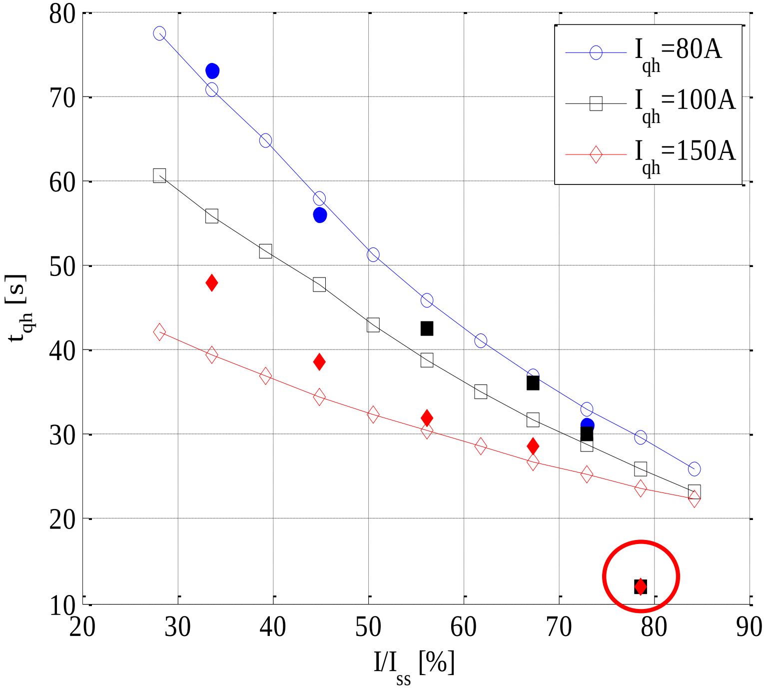
Quench heaters on the low field blocks



2.2 Quench heater performance

- At high magnet currents, a fast quench starts after quench heater firing. The conductor where the quench starts is not bellow the heaters, so it is difficult to explain it through thermal heat conduction from heater to coil.
- The same effect was observed in coil 105, tested in single coil configuration.
- This effect was not observed in MBHSP103 (coils 109 and 111)

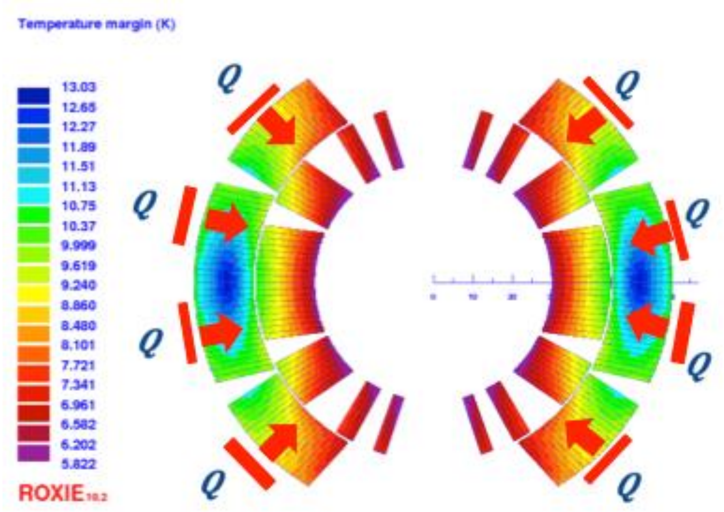




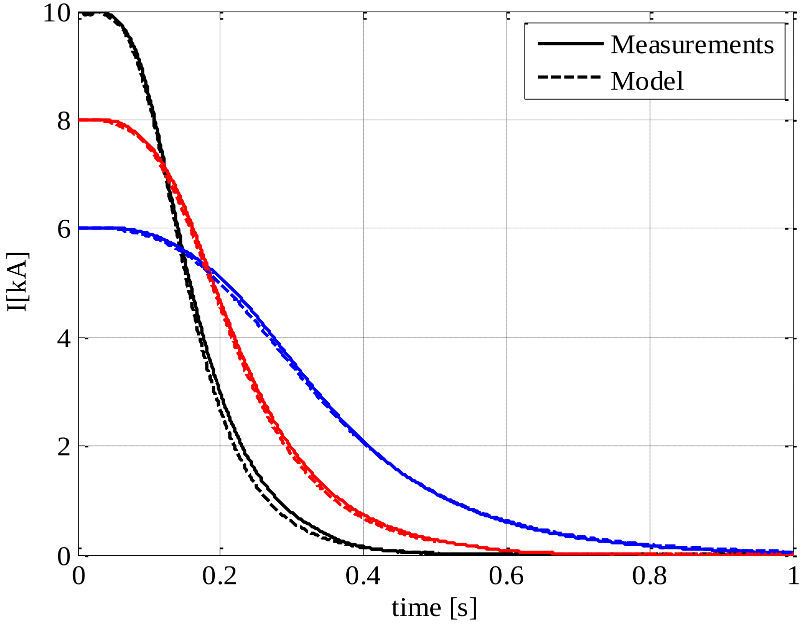
2.3 Quench propagation within the coil

Once the quench heaters introduced a distributed quench in the magnet cross section, it is important to study the quench propagation within the magnet cross section:

- Manual trip at different currents
- Dump delay 1000 ms
- Study the quench heater delay, layer to layer propagation, resistance growth and current decay.



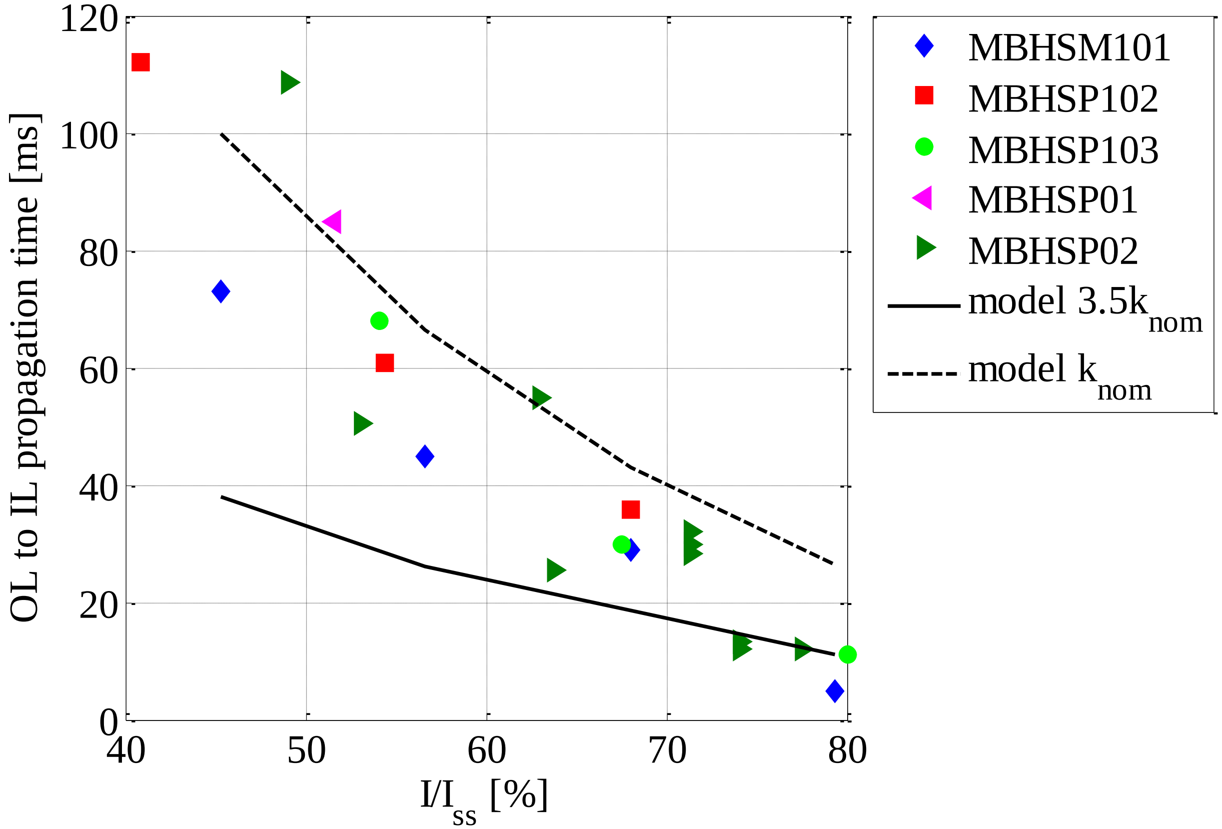
Current decay for quench heater provoked quench in MBHSP102



2.3 Quench propagation within the coil

- Layer to layer propagation delays in the different magnets tested are comparable
- Work on-going to further refine the model including AC loss and reduce the level of uncertainty on the thermal material properties of the insulation.

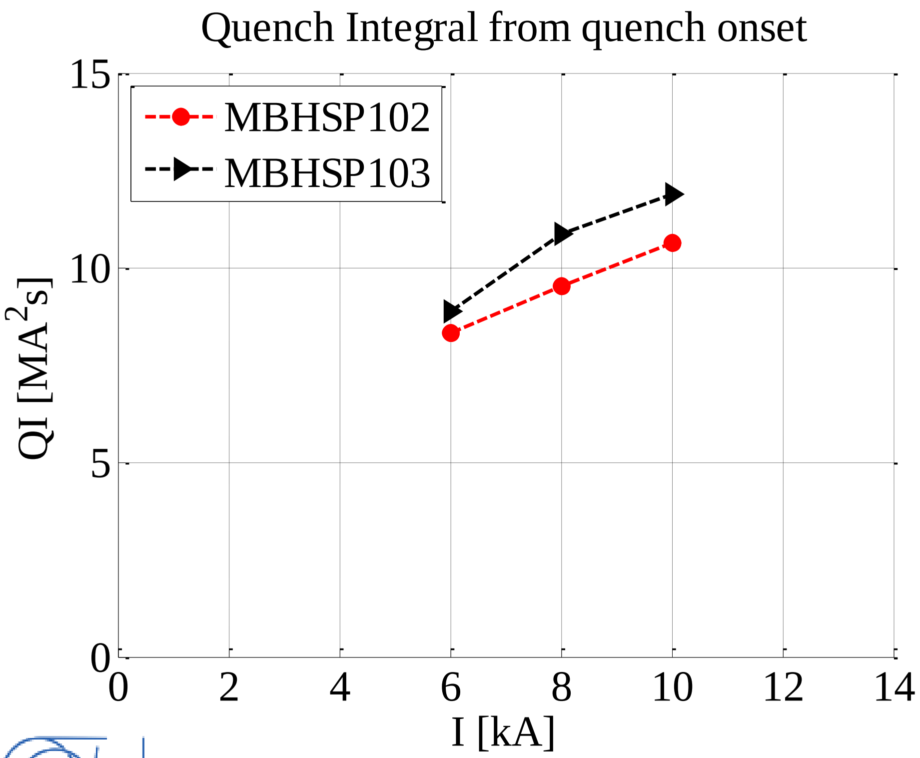
<u>Outer layer to inner layer propagation delay</u>

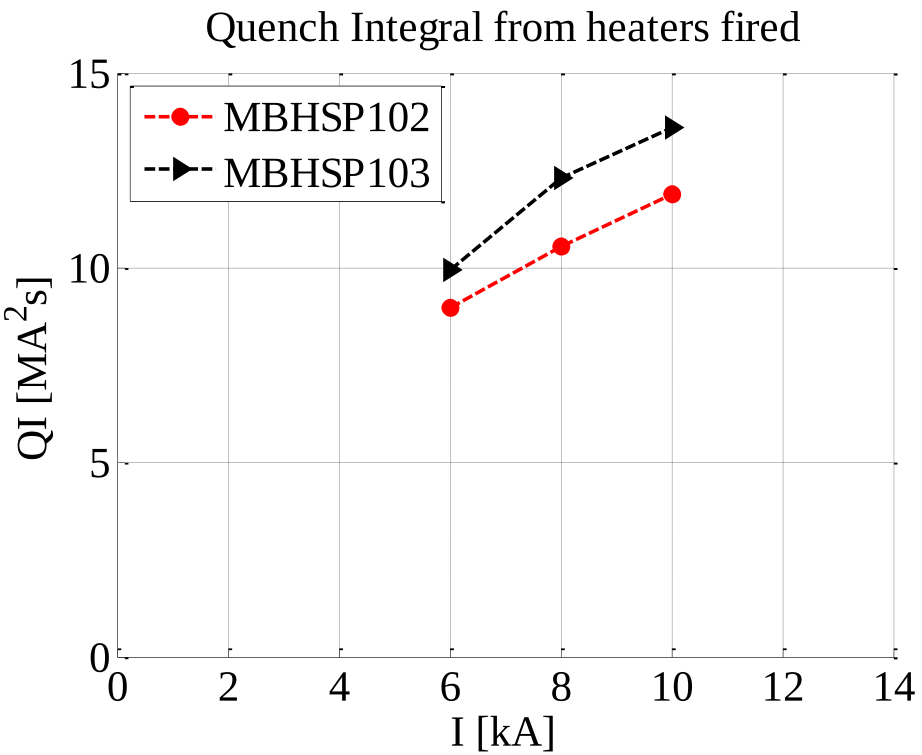


2.3 Quench propagation within the coil

The large differences on the QI are explained by the low RRR and higher resistivity of coil 106.

		Strand lay out	Coil R at 300 K mΩ	Average coil RRR	S2 glass mm
MBHSP102	**Coil 106**	RRP 108/127	423	62	0
	Coil 108	RRP 132/169	407	165	0.1
MBHSP103	**Coil 109**	RRP 132/169	400	125	0
	Coil 111	RRP 132/169	401	119	0.1

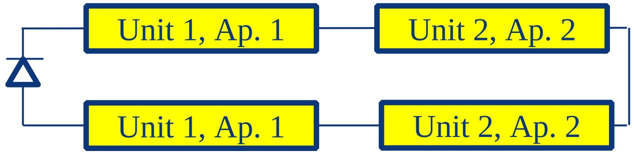

Quench Integral from quench onset


Quench Integral from heaters fired

Contents

3. Baseline protection scheme

- Each 11 T cryo-assembly is made out of 2 x 5.5 m magnets connected in series and protected by one standard LHC cold diode
  - Resistance to radiation at the level o of the diode needs to be confirmed. 1 MGy?

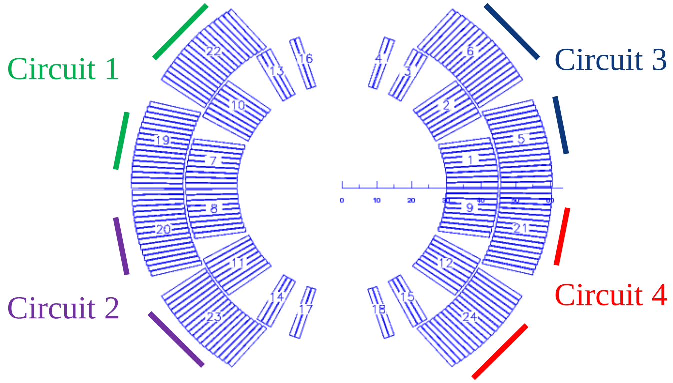

Unit 1, Ap. 1

Unit 2, Ap. 2

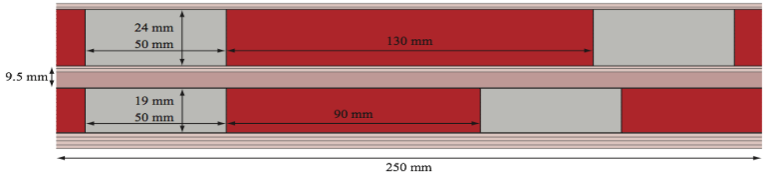
Unit 1, Ap. 1

Unit 2, Ap. 2

- Each aperture is protected with 4 quench heater circuits (2 heater circuits per coil)



- Heater geometry optimized to have a uniform quench in the magnet cross section and a propagation in between stations faster than 5 ms.

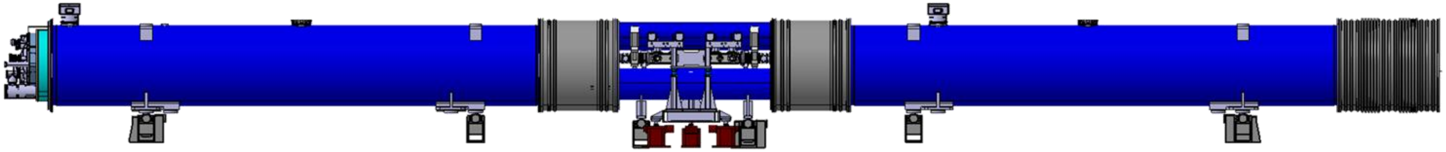


- High field and low field quench heater in series (better for redundancy)

- S. Izquierdo Bermudez et al., Quench Protection Studies of the 11T Nb_3Sn Dipole for LHC Upgrades, IEEE Trans. Appl. Supercond., submitted for publication

3. Baseline protection scheme

- **“Standard”** LHC quench heater power supply:
  - Charging voltage: ± 450 V
  - Maximum current through the heaters: **150 A** (instead of 80 A)
  - Capacitance: 7.05 mF
  - Improvement of the heater firing unit expected to **reduce the heater firing delay from 5 ms to 1 ms.**
  - Integration study needed to fit 16 heater power supplies for each cryo-assembly



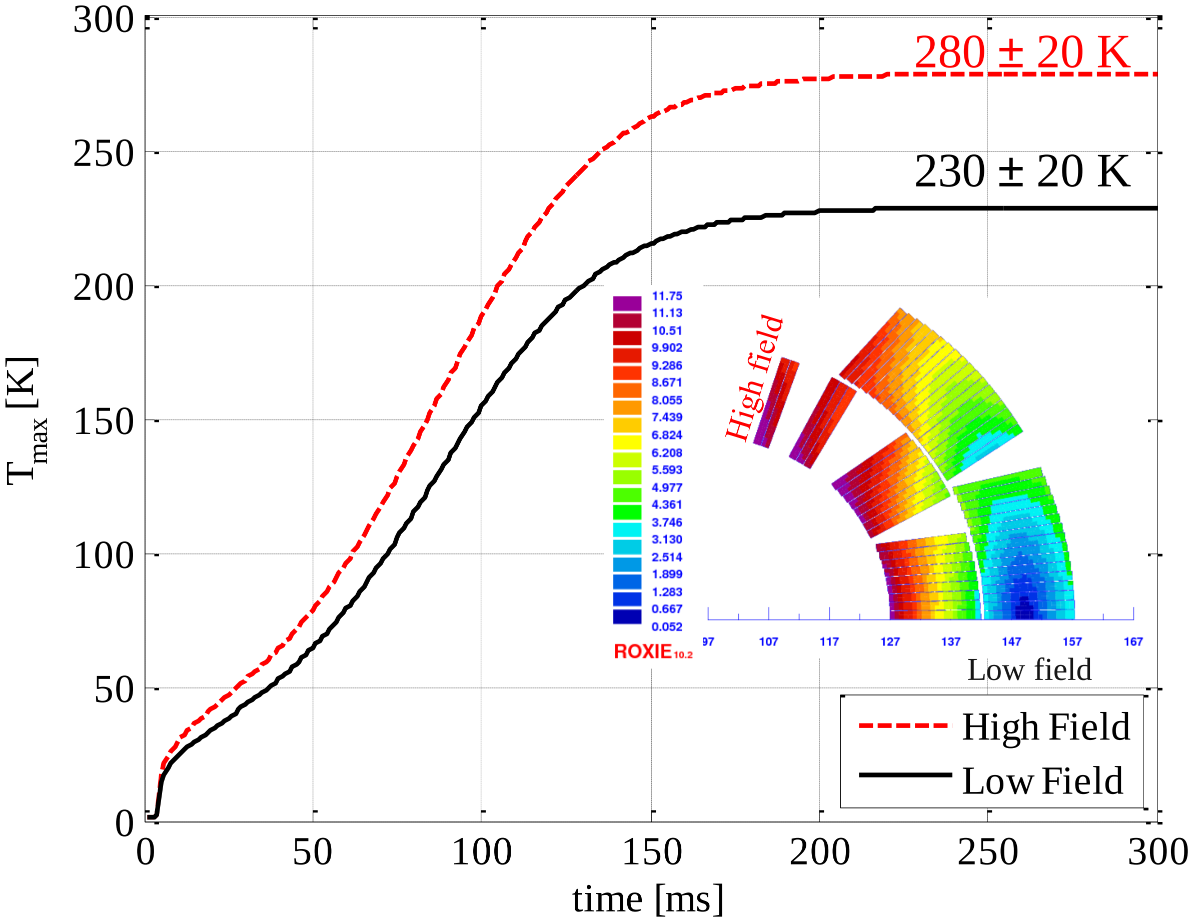
3. Baseline protection scheme

Expected hot spot temperature under accelerator conditions:

- 100 mV threshold, 10 ms validation
- **1 ms** heater firing delay
- Assumed heaters impregnated with the coil.

  (heater delay ~ **14 ms**).

  Total insulation from heater to coil :
  - 50 µm of kapton
  - 100 µm conductor insulation
- Nominal conductor parameters, RRR=100
- All quench heaters fired



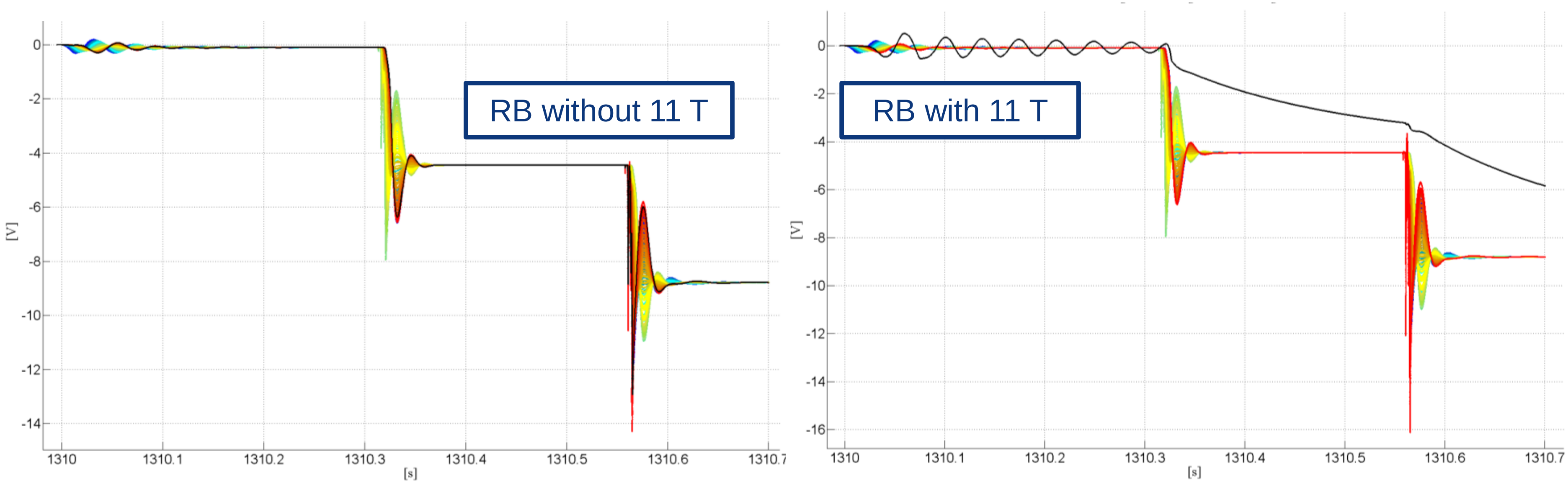
What we have today:

- Heater firing delay = 5 ms
- Heaters delay = 20 ms

T_{max} = 320 ± 20 K

3. Baseline protection scheme

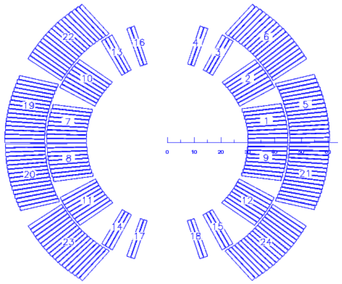
- The behavior of the 11 T in the circuit is different from the rest of the magnets due to the presence of the trim.
- Requires the change of RB symmetric quench protection around 11 T.
- Small impact of the 11 T on the rest of the circuit.



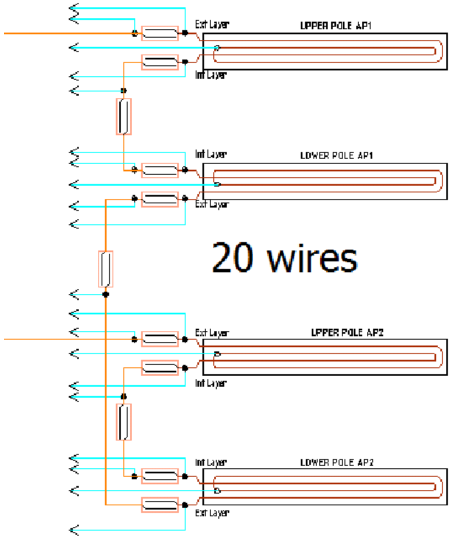
Black line: 11-T location. Preliminary studies.
[Lorenzo Bortot]

3. Baseline protection scheme

- A fast detection of symmetric quenches is a must for the 11 T (current thresholds in the RB circuits of 400 mV are not applicable)
- Careful design of the detection system is needed.
- Planned voltage tap lay-out for the prototype:
  - Fully monitoring of all the splices
  - Additional voltage tap in between the two coil layers



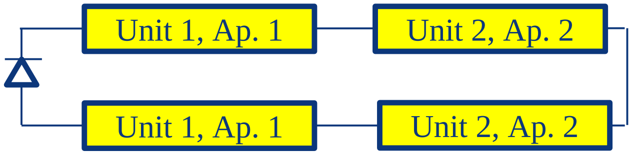
Voltage tap lay out per aperture



[L. Grand-Clement]

3. Baseline protection scheme - Redundancy

- Baseline circuit configuration: 2 units of 5.5 m connected in series and protected with an unique diode



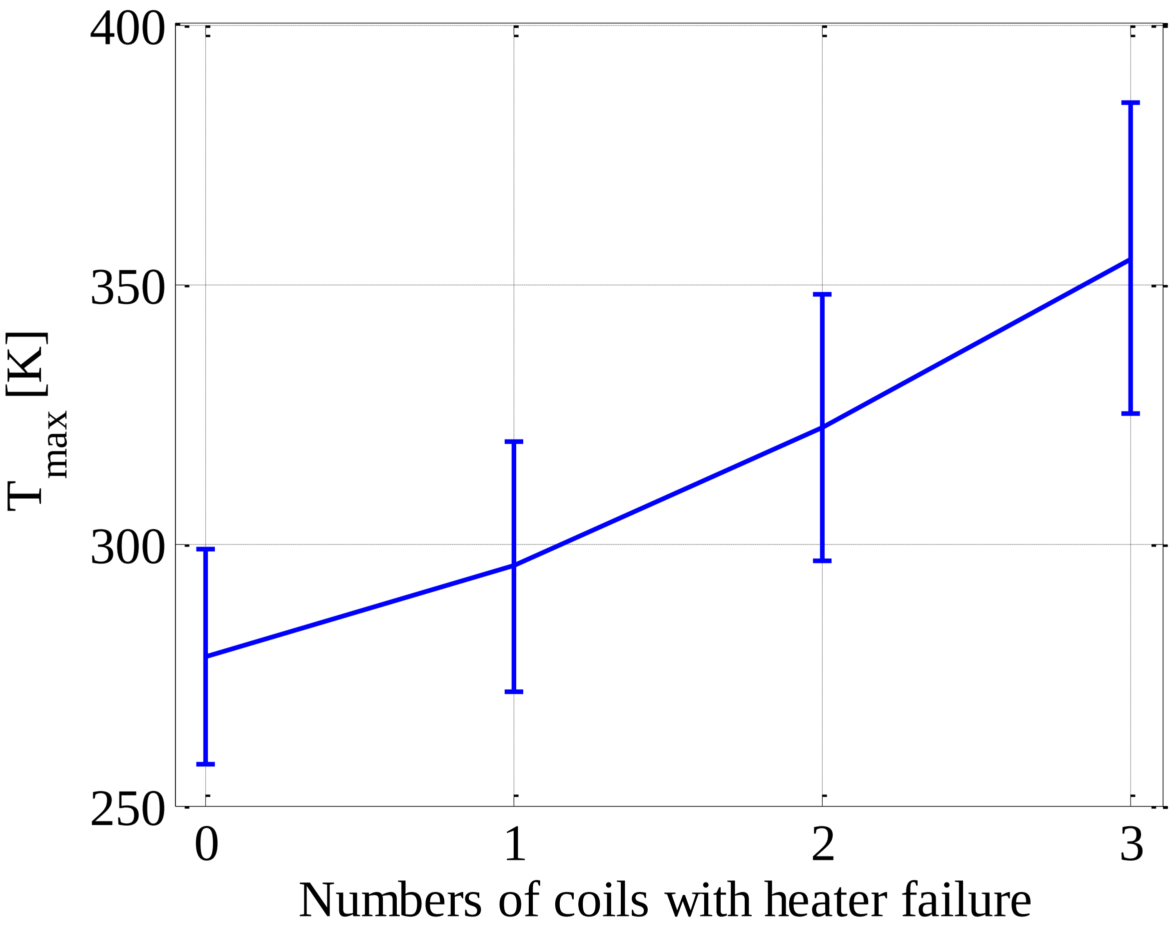
Unit 1, Ap. 1

Unit 2, Ap. 2

Unit 1, Ap. 1

Unit 2, Ap. 2

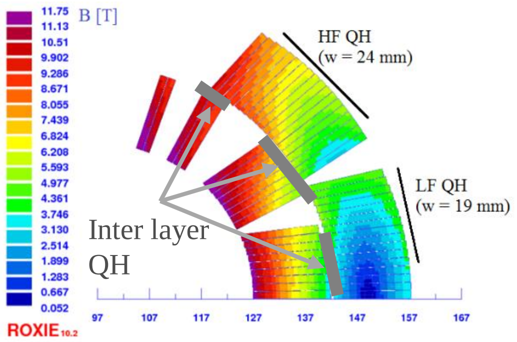
- For this analysis, we consider that **all the heaters in a coil fail** (very pessimistic scenario as the baseline configuration considers 2 quench heater circuits per coil, and the possibility to have 4 quench heater circuits per coil is being explored)
- Remark: this situation becomes critical not only from the hot spot temperature point of view, but also from the peak voltages!

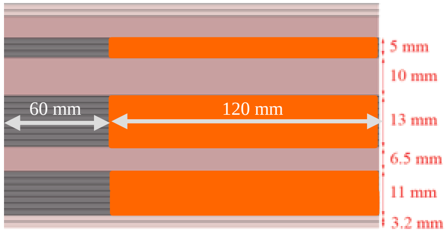


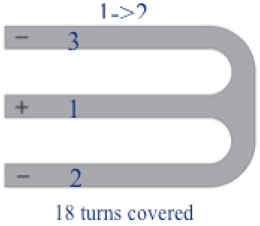
Contents

4. R&D activities: Inter layer quench heaters

- Design approach: Maximize the number of turns covered
- Heater power density → P_d = **50-100 W/cm^2**
- Design constraints:
  - Voltage < 450 V
  - Current < 150 A

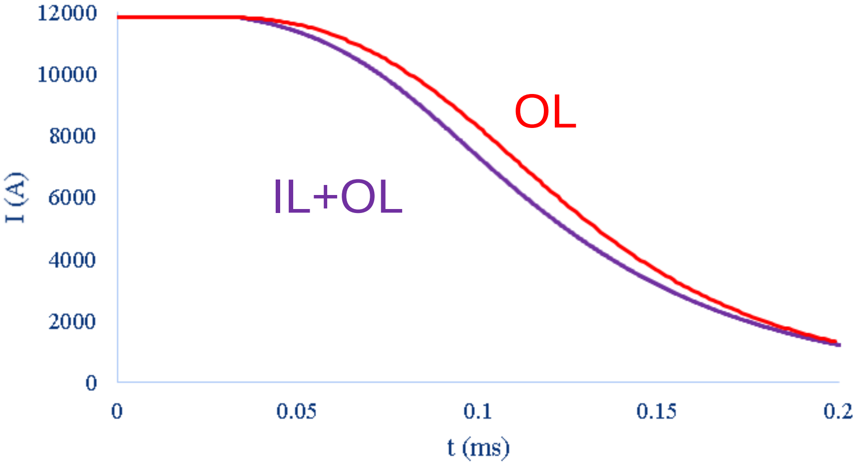


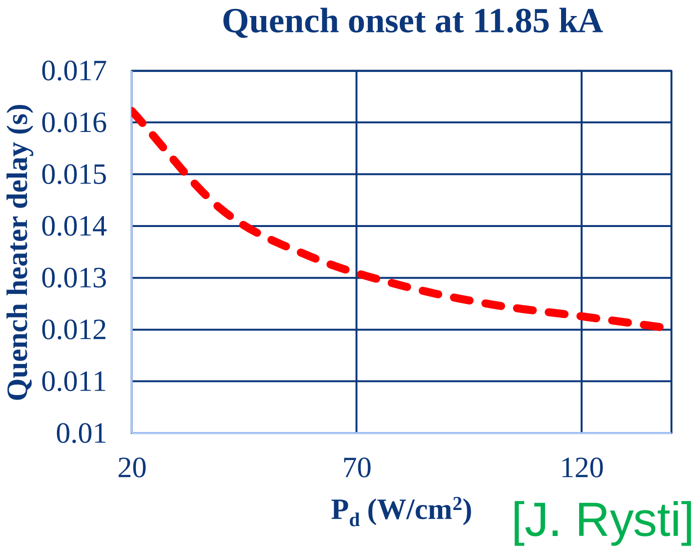




- Expected maximum tempearture with outer layer + inter layer heaters:

T_{max} = 240 ± 20 K



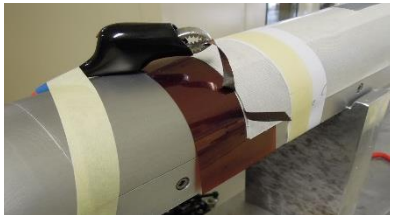


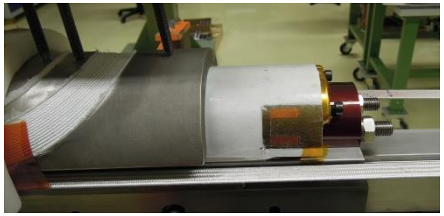
[J. Rysti]

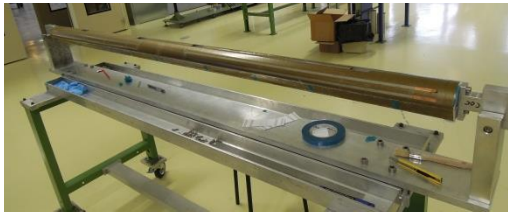
4. R&D activities: Inter layer quench heaters

Technical challenges:

Electrical Robustness







- Inter layer heaters installed in coil 110
  (heaters follow the full coil manufacturing process)
- Embedded in a S2-glass – Mica sandwich
- Total thickness = 0.5 mm
- Breakdown voltage heaters2coil = 9 kV ☺
- Challenge: find mica full length (max. length available of the preferred product is about 1 m, alternative options under procurement)

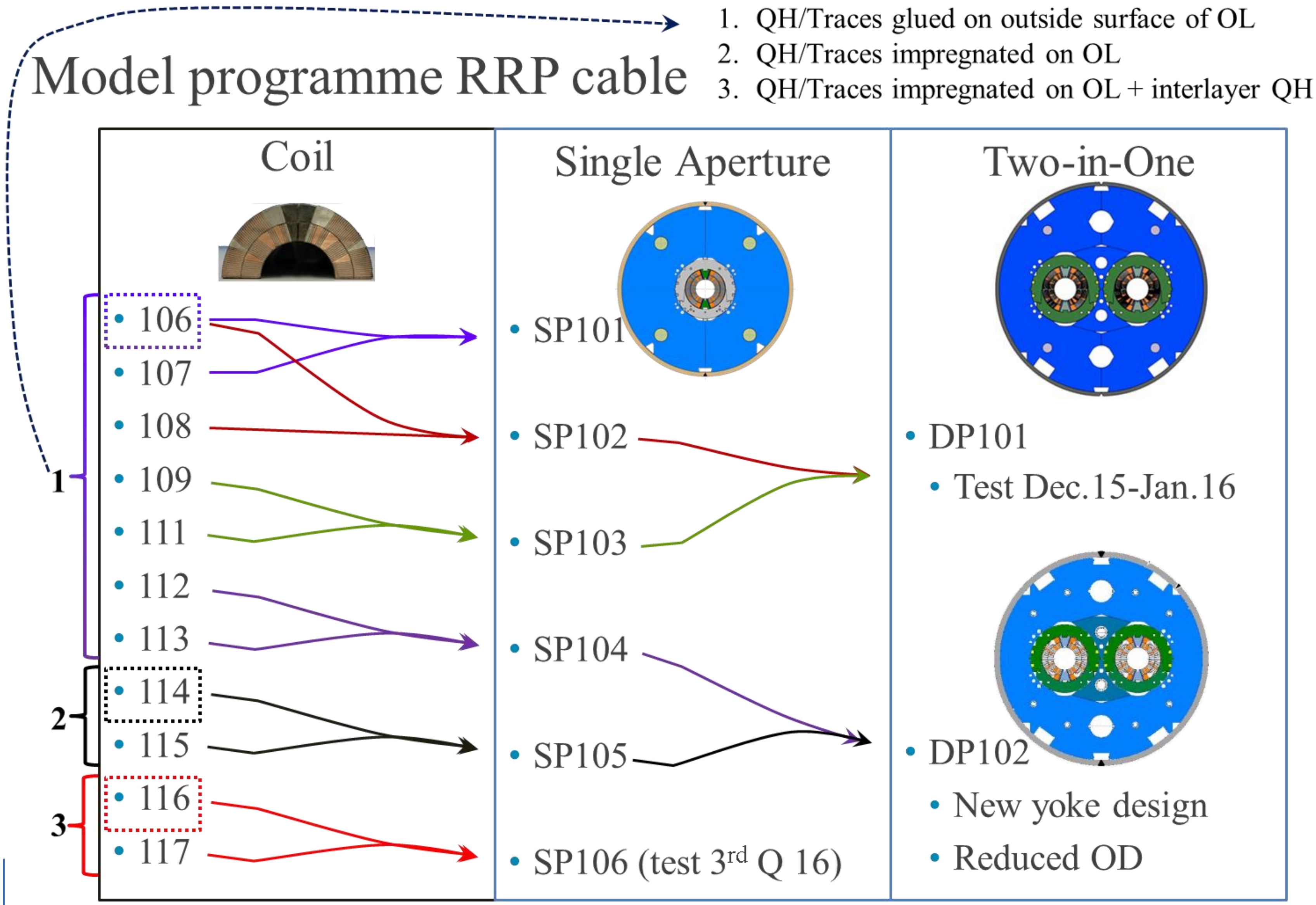
Copper plating

- Copper plating (needed to reduce the overall strip resistance) requires a thin layer of nickel
- During heat treatment, the nickel diffuses in to the copper, increasing significantly the electrical resistivity
- Solutions under study:
  a) Increase the thickness of the copper plating
  b) Find a method to deposit non-resistive material on a resistive material without the nickel interface

More details EDMS 1541876

[J. Rysti and Ana Teresa Perez Fontela]

4. R&D activities: Inter layer quench heaters



Model programme RRP cable

1. QH/Traces glued on outside surface of OL
2. QH/Traces impregnated on OL
3. QH/Traces impregnated on OL + interlayer QH

Coil

- 106
- 107
- 108
- 109
- 111
- 112
- 113
- 114
- 115
- 116
- 117

Single Aperture

- SP101
- SP102
- SP103
- SP104
- SP105
- SP106 (test 3rd Q 16)

Two-in-One

- DP101
  - Test Dec.15-Jan.16
- DP102
  - New yoke design
  - Reduced OD

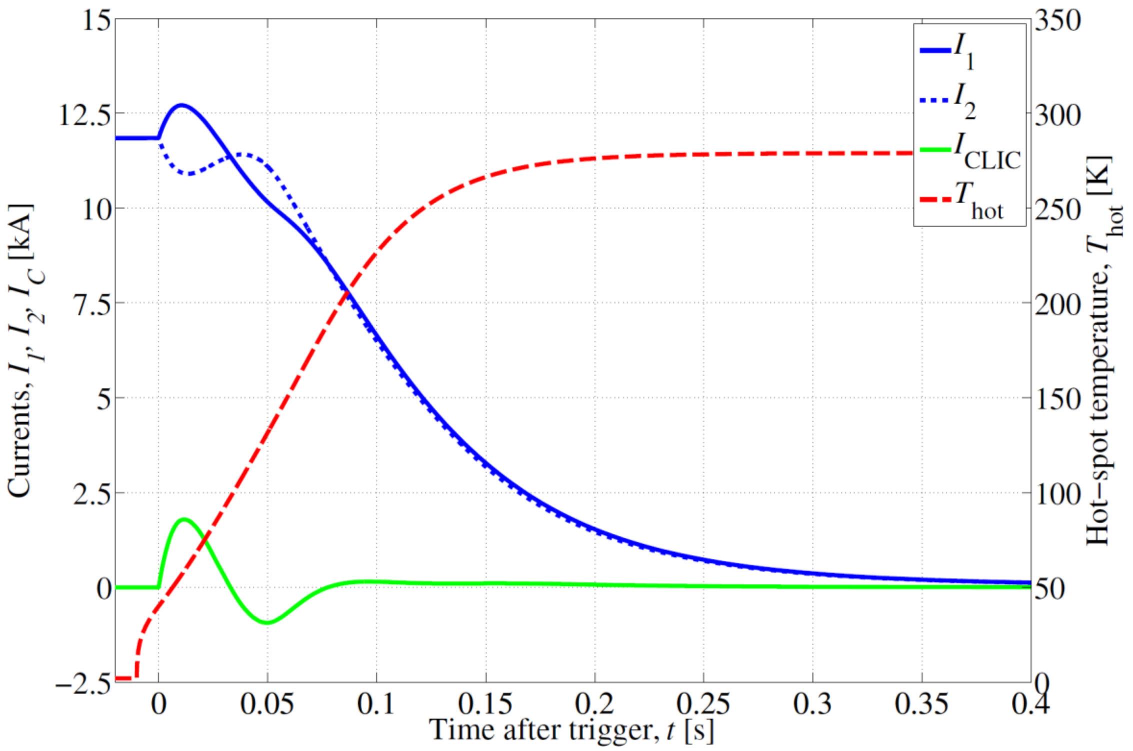
4. R&D activities: CLIQ

[E. Ravaioli, J. Blomberg Ghini]

Hot-spot Temp **290 K**

Peak voltage to ground **650 V**

- Time to detect and validate the quench = 15 ms
- 1 CLIQ unit per aperture
- CLIQ unit delay = 1 ms
- Charging voltage 500 V
- Capacitance 60 mF



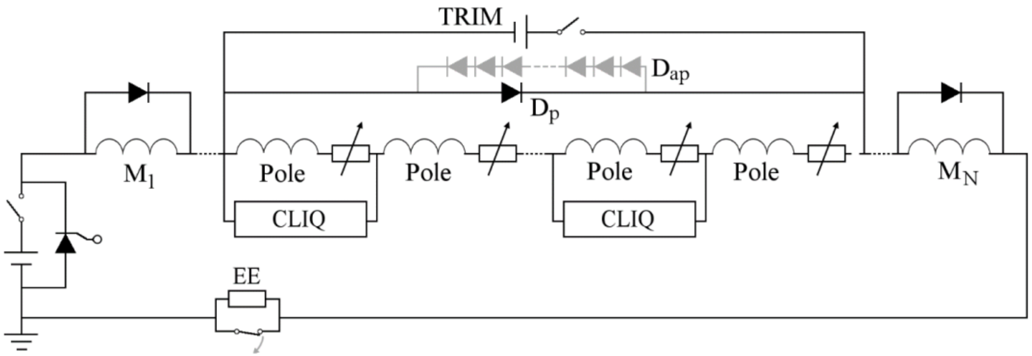
- J. Blomberg Ghini and E. Ravaioli, “Protecting the superconducting 11T Hi–Lumi LHC dipole with the new coupling–loss induced quench protection system”, CERN internal report, 2015

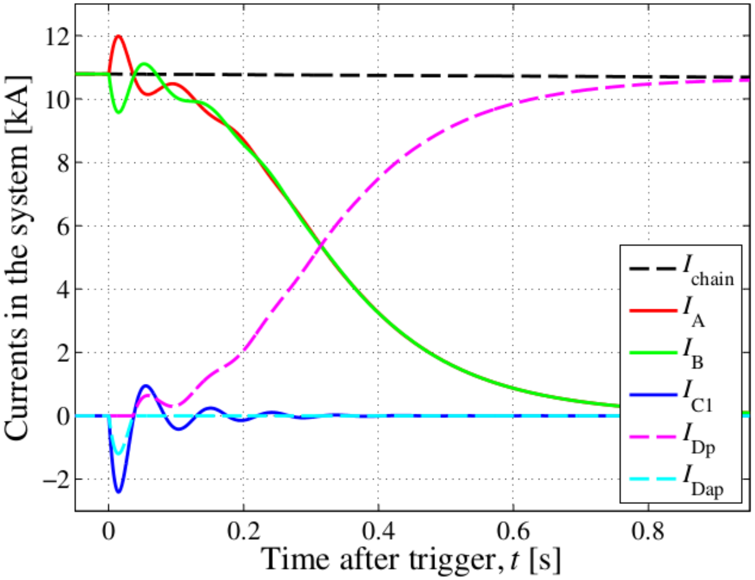
4. R&D activities: CLIQ

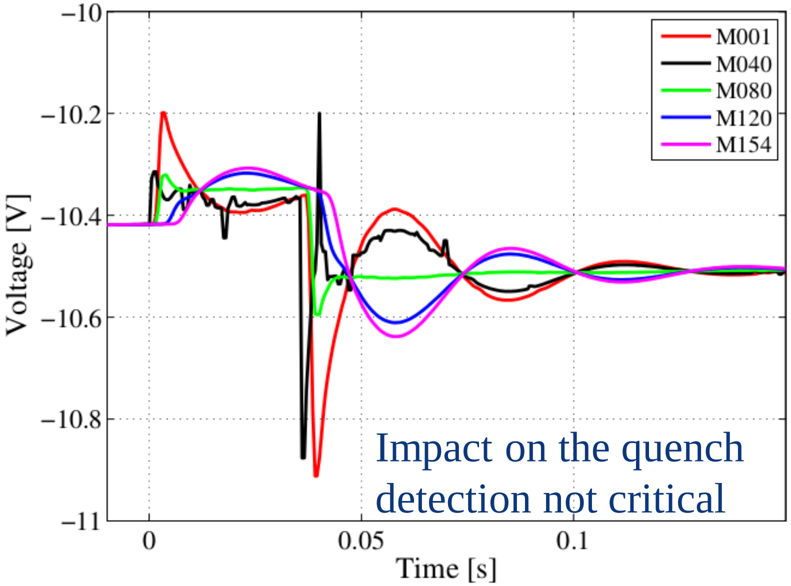
[E. Ravaioli]

To avoid conduction after activating the energy-extraction ➔ warm diode in parallel sufficiently high ($>2R_{EE}I_0/N_M \sim 11$V, proposal = 20 V)

Coupled electro-thermal simulations using TALES







Impact on the quench detection not critical

- E. Ravaioli et al., CLIQ-based Quench Protection of a Chain of High-field Superconducting Magnets, IEEE Trans. Appl. Supercond., submitted for publication
- E. Ravaioli, CLIQ, PhD thesis, Ch. 8, 2015

Contents

5. Summary

- The expected hot spot temperature for the current configuration of the 11 T is **320 K ± 20 K**.
- The baseline configuration considers a reduction of the quench heater delay (reducing the insulation from heater to coil) and the heater firing delay (through a hardware improvement) → **T_{max} = 280 K ± 20 K.**
- **R&D** work on-going to **reduce the hot spot temperature** and improve the system **redundancy**.
- We have a good set of data for the first magnets tested
    - Everyone is very welcome to study it!
    - If additional studies are needed, now is a good moment to ask for them ☺

5. Summary

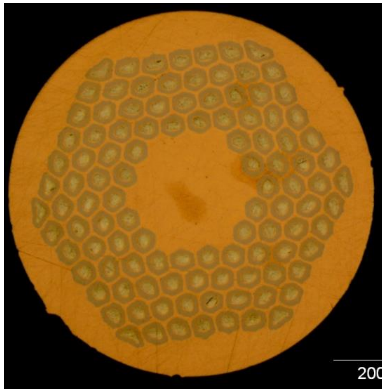
- A fast detection of the quench is a must:
  - Effort needed on the development of quench detection systems that can cope with the flux jumps typically observed in Nb_3Sn (variable threshold/validation time as a function of the magnet current)
  - The detection of symmetric quench protection should be carefully study to define the optimal/minimum required voltage signal for a safe operation

THANK YOU!

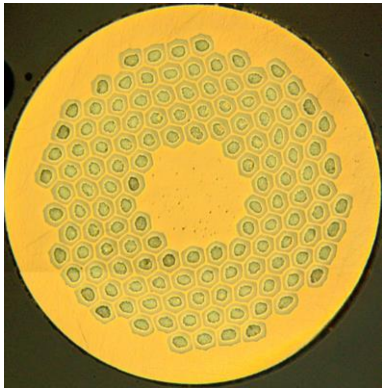
Additional slides

0.7 mm Wire Received so far

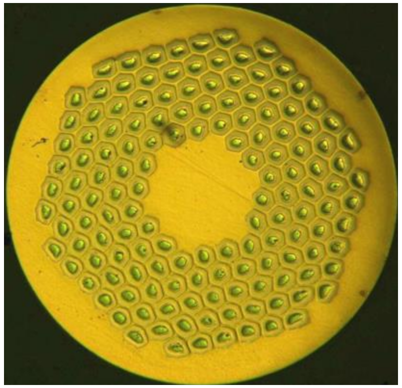
RRP 108/127



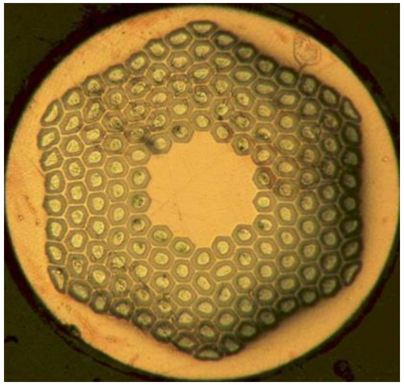
RRP 132/169



RRP 144/169

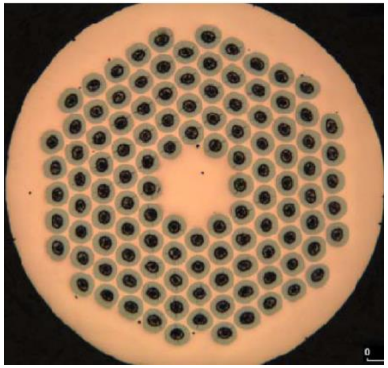


RRP 150/169

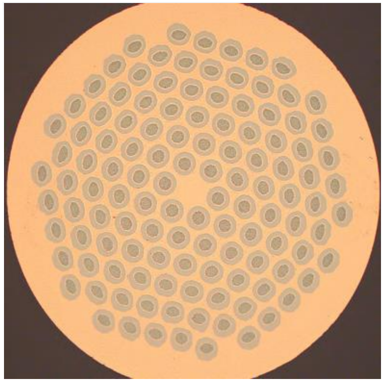


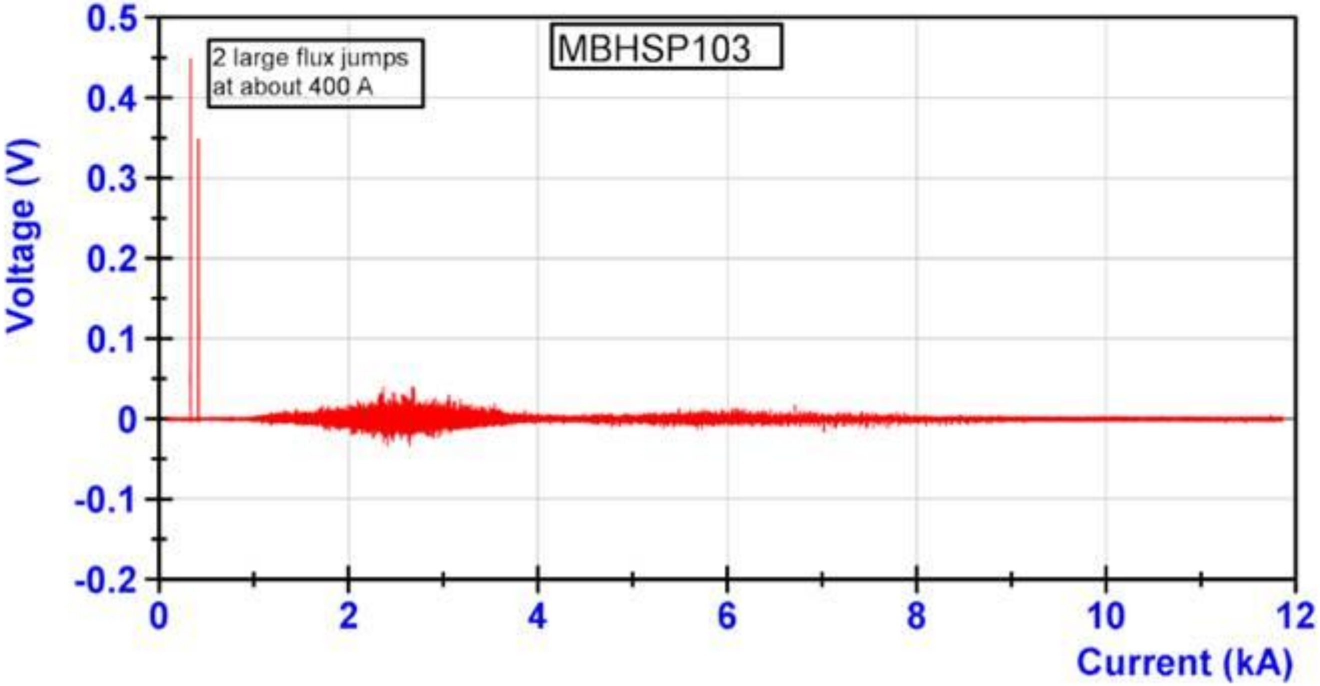
	Layout	Cu to non-Cu	Sub-Element size	SE shape
RRP	108/127	1.19	46 µm	Hex
	132/169	1.28	41 µm	
	144/169	1.08		
	150/169	1		
PIT	114	1.25	44 µm	Circular
	120	1.15		

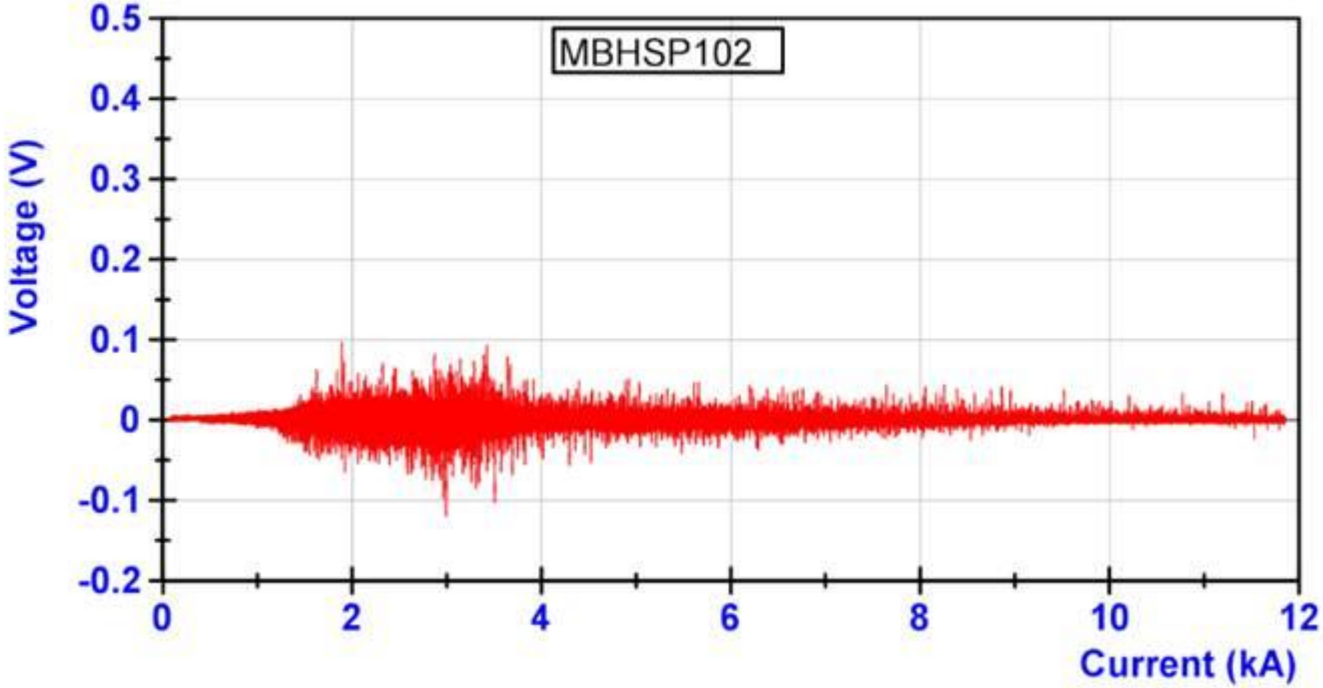
PIT 114



PIT 120

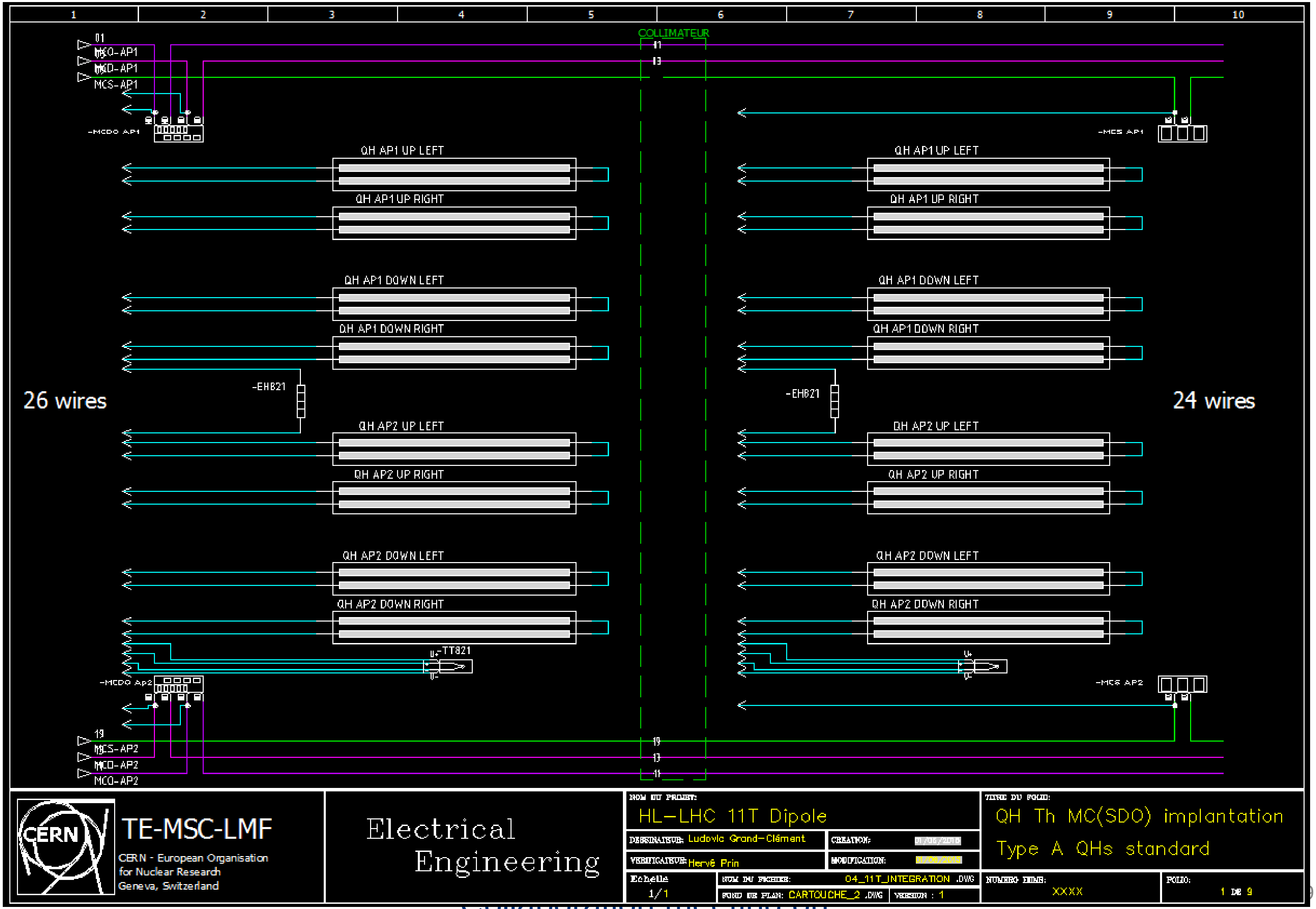



MBHSP103
2 large flux jumps
at about 400 A
Voltage (V)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
2
4
6
8
10
12
Current (kA)


MBHSP102
Voltage (V)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
2
4
6
8
10
12
Current (kA)

Electrical circuit – Quench heaters and

L. Grand-Clement



26 wires

24 wires

Collaboration meeting on

		Nom.	Coil 106	Coil 108	Coil 109	Coil 111
rand			RRR 108/127 Ta-Dopped	RRP 132/169 Ti Dopped	RRP 132/169	RRP 132/169
ı/nCu	--	1.15±0.1	1.22	1.22	1.27	1.27
il R @ RT	mΩ	404	423	406	404	405
verage Coil RR	--	>100?	62	165	125	119