The long shutdown 1 (LS1) of LHC a reliable energy upgrade

ARW 2015

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outline

☑ Introduction

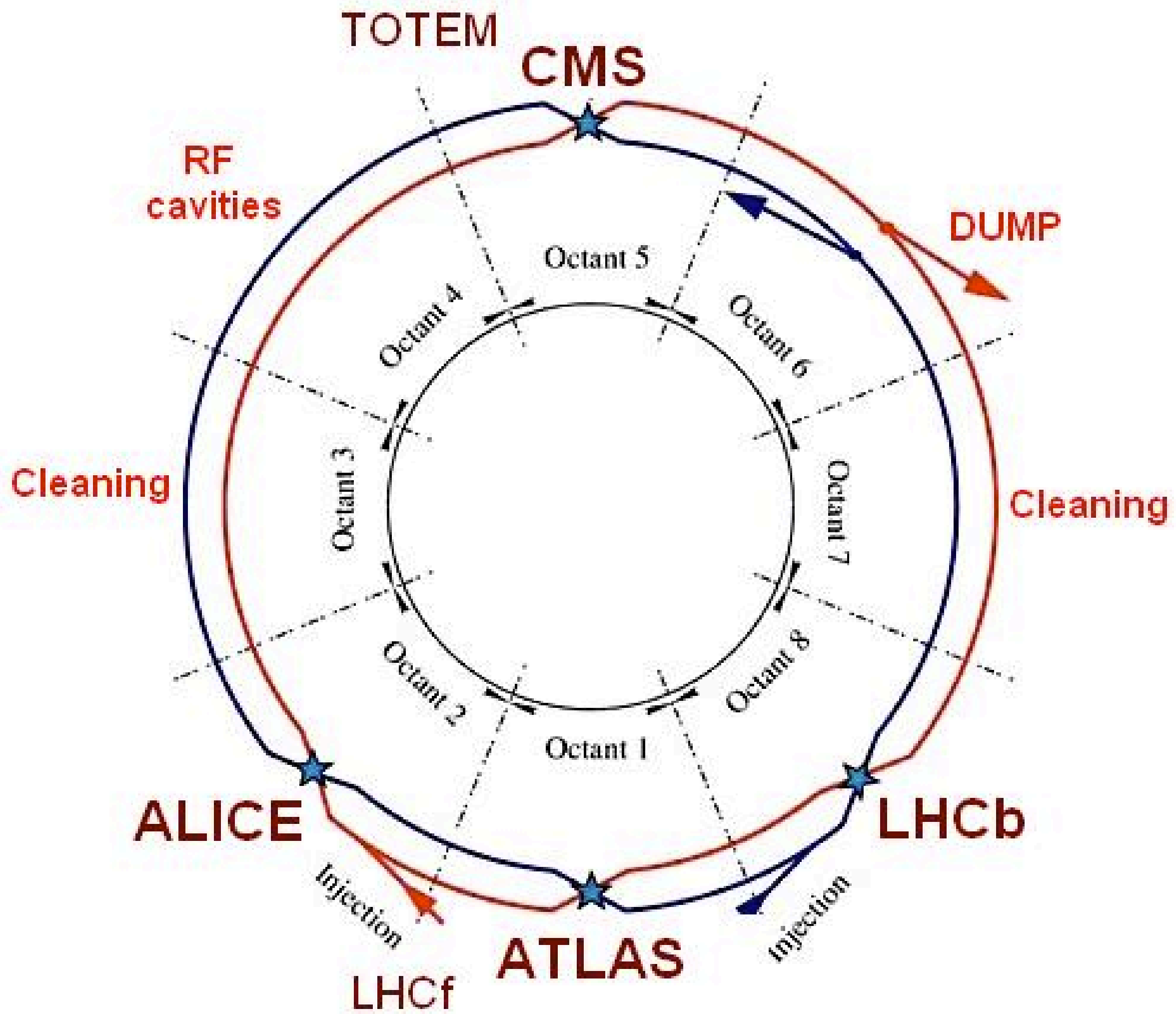
- The LHC layout
- The superconducting circuits
- The 2008 incident

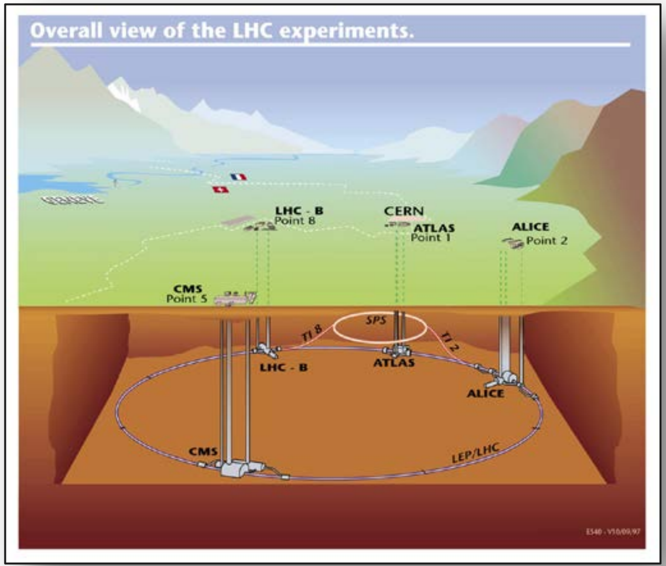
☑ The LS1 @LHC

- The Superconducting Magnet And Circuit Consolidation project (SMACC)
- The superconducting circuits re-validation:
    - The Copper Stabilizer Continuity Measurement (CSCM)
    - The Powering tests

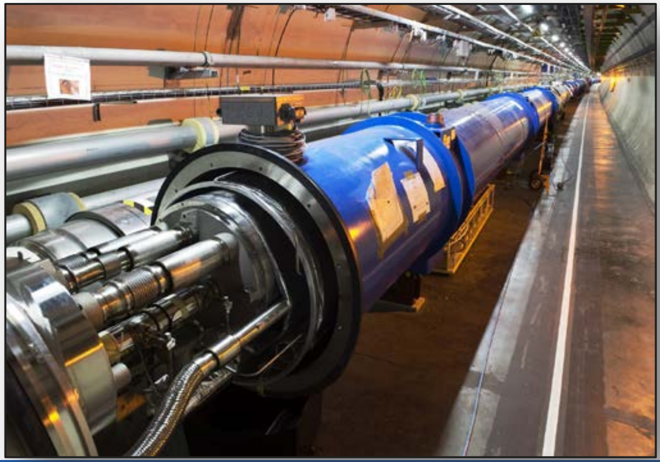
☑ Conclusions

The LHC layout





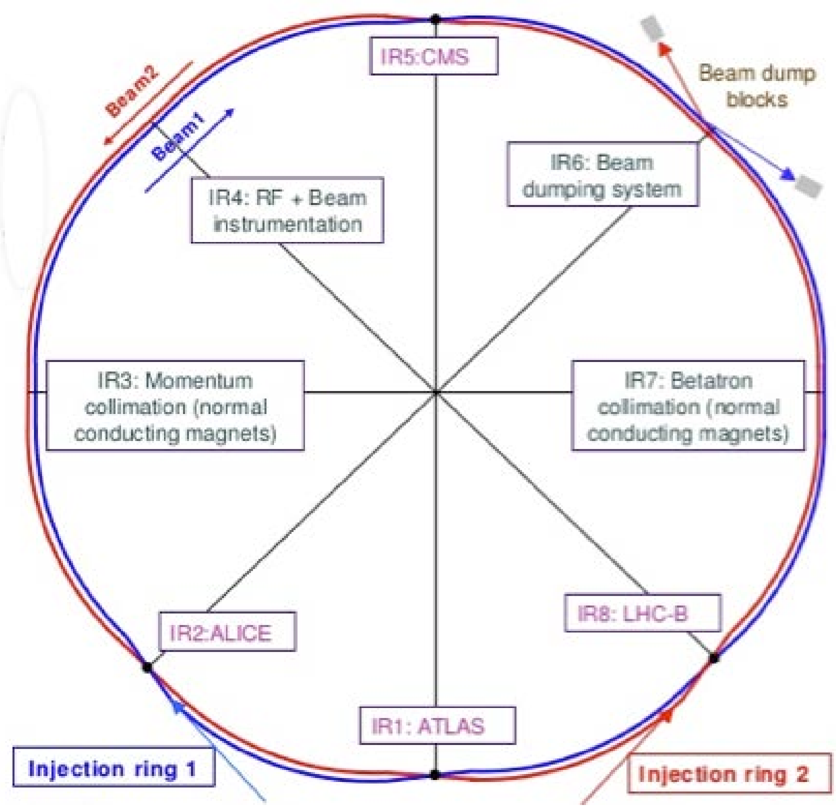
27 km circumference
50 to 170 m underground



2 counter-rotating beams
14 TeV collision energy

4 interaction points
6 experiments

The superconducting circuits



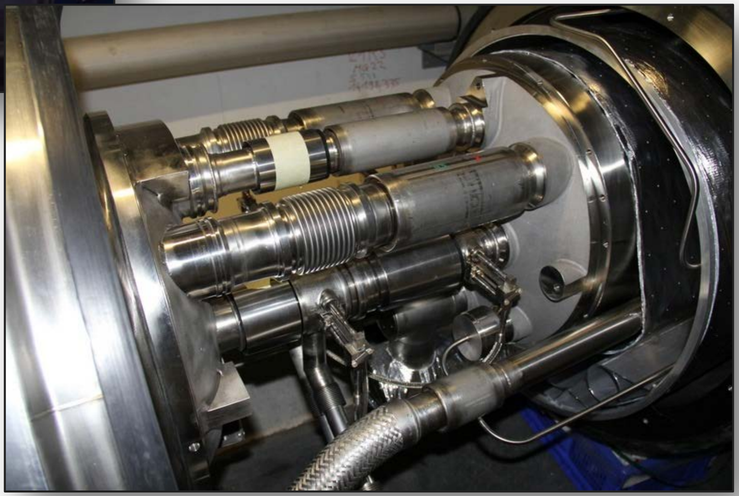
- Almost **1600** superconducting circuits operating mostly at **1.9 K**
- **8** sectors cryogenically and electrically separated

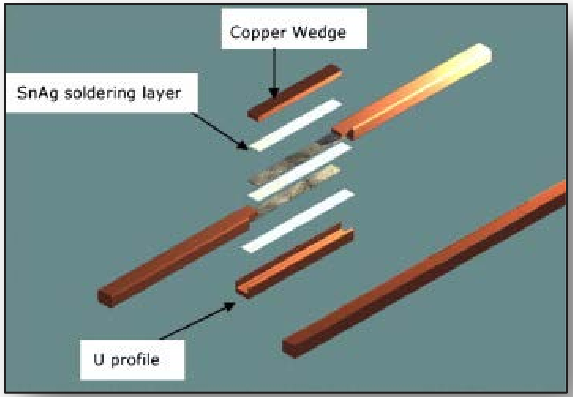
Per sector a unique cryostat containing:

- One 13 kA dipole circuit (**154** magnets)
- Two 13 kA quadrupole circuits (**49** magnets)
- Large variety of corrector magnets

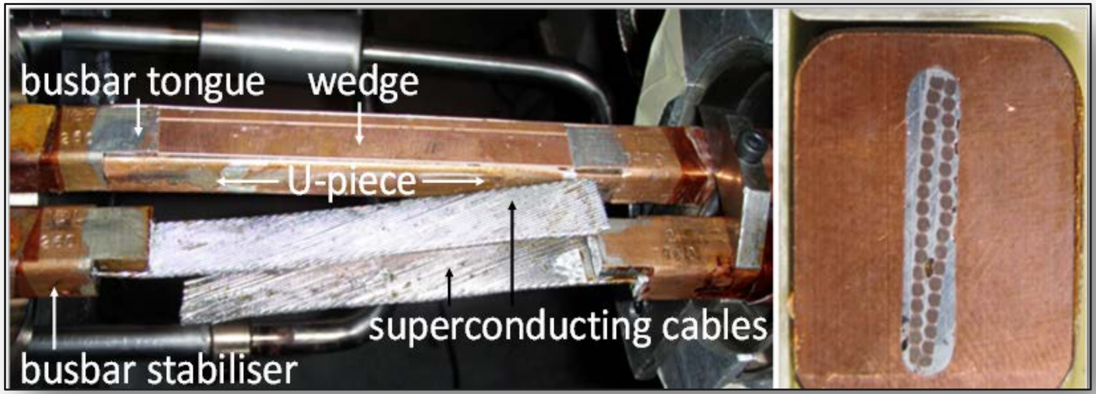
LHC FODO cell

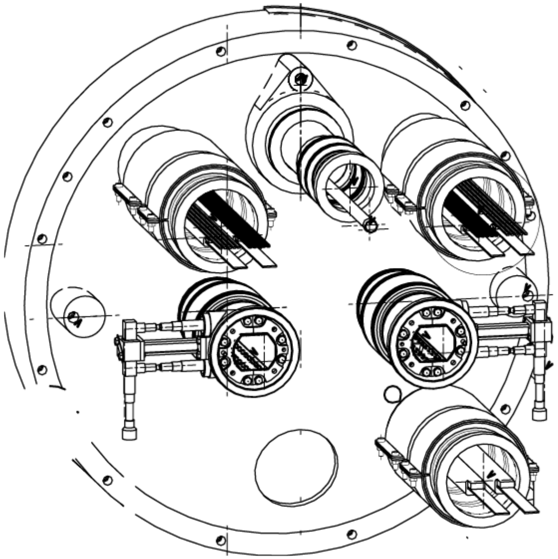
The magnet interconnects



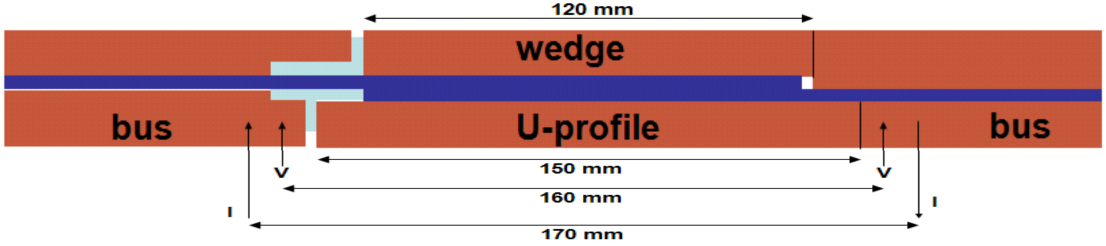


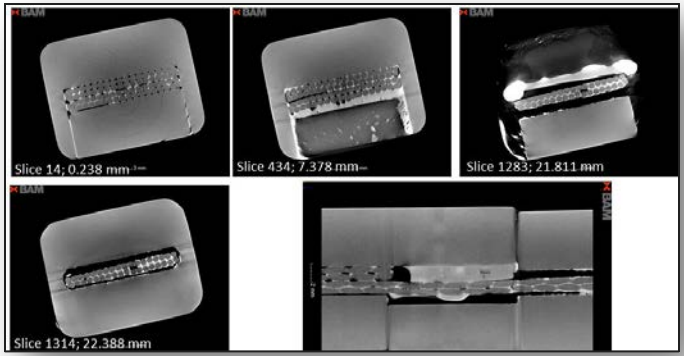
- **1695** magnet interconnects
- **10170** main superconducting splices carrying a current of about **13 kA**
- NbTi filaments surrounded by copper stabilizer filled with tin

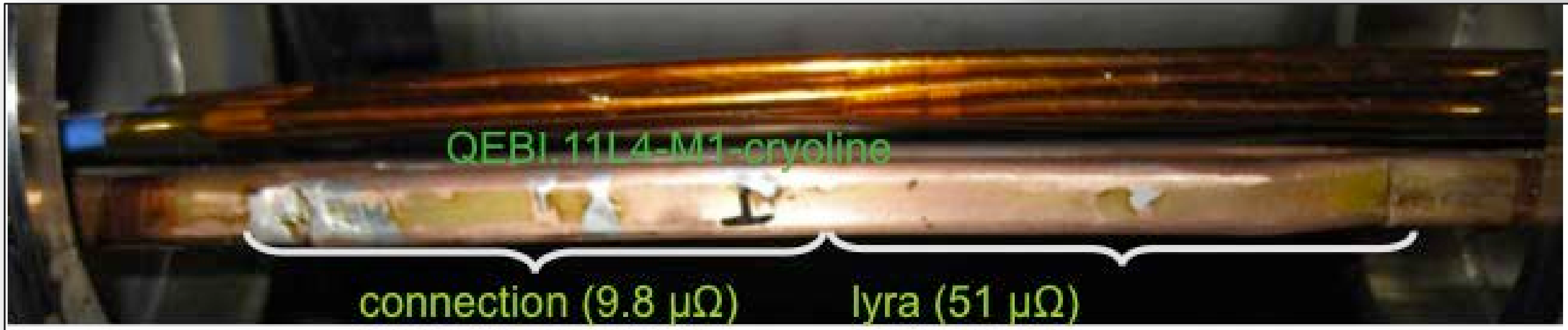


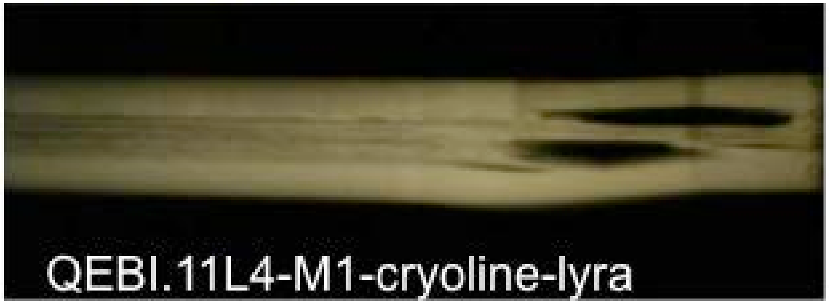


The 2008 incident

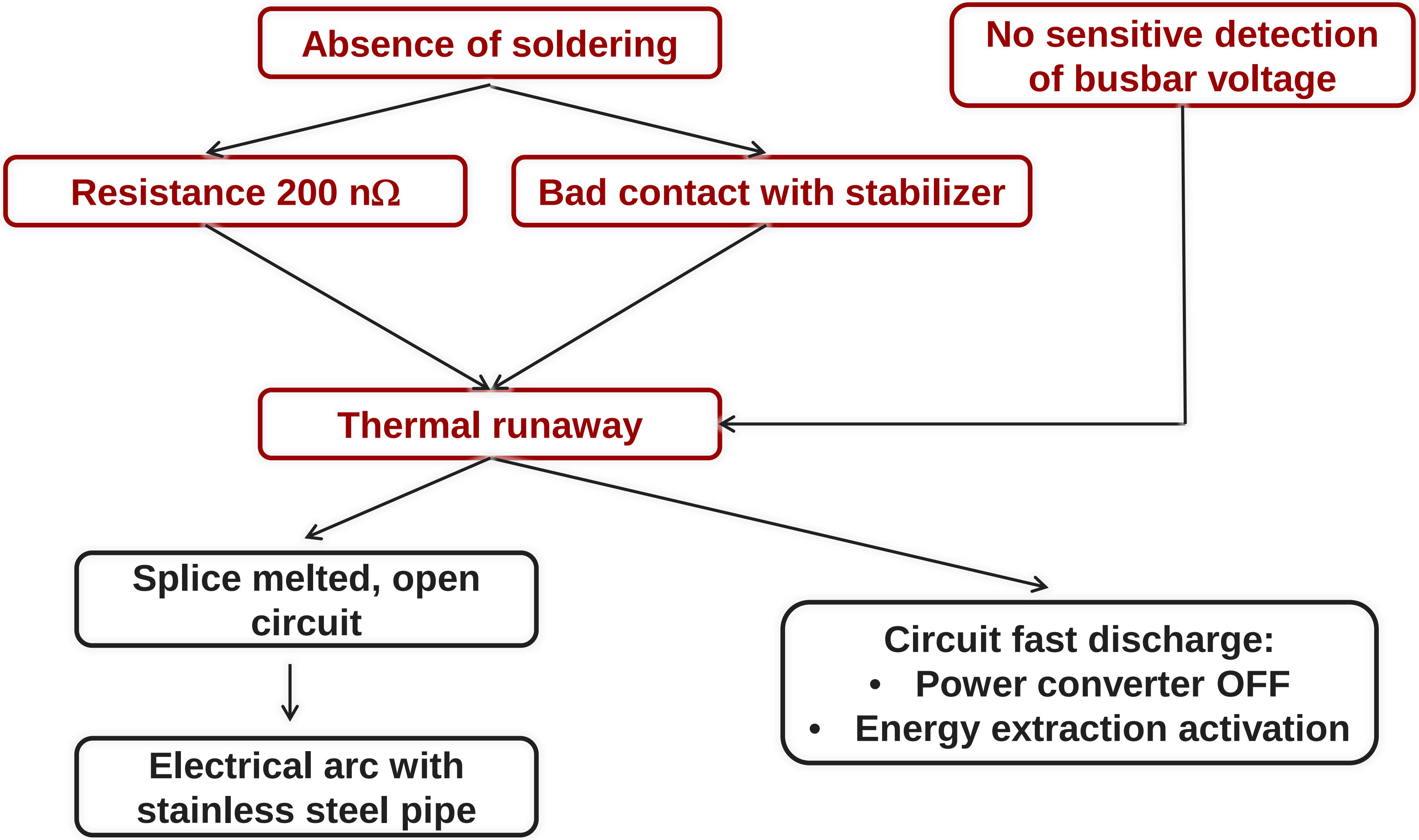




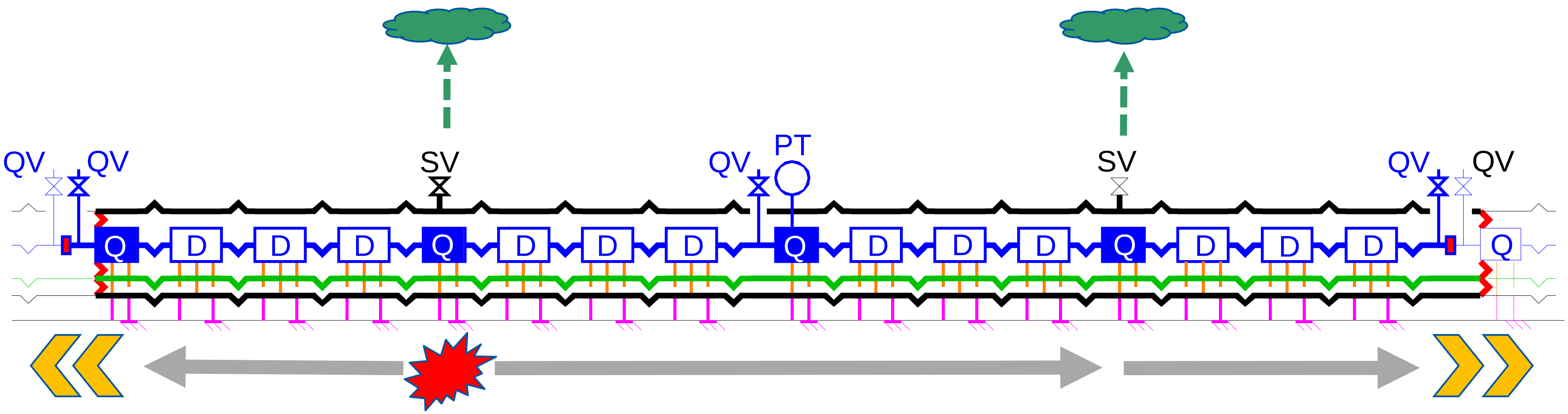




The 2008 incident



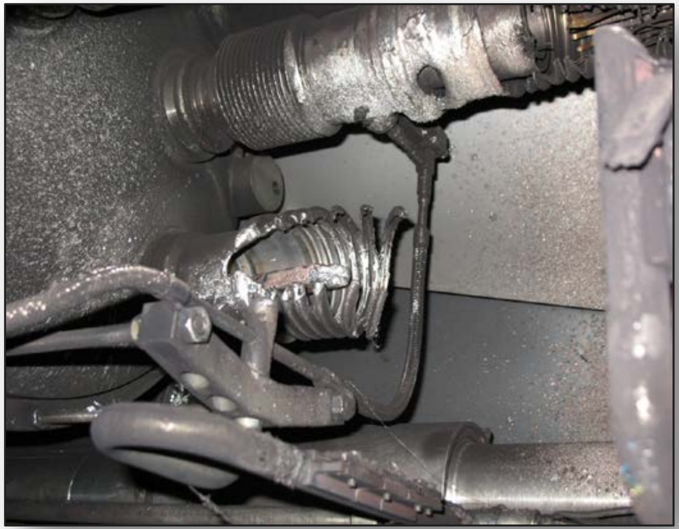
The 2008 incident

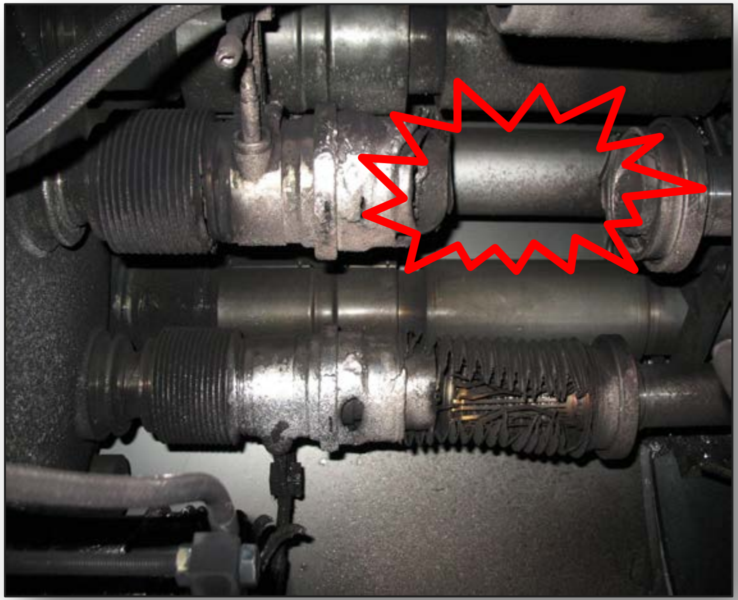


- Cold-mass
- Vacuum vessel
- Line E
- Cold support post
- Warm Jack
- Compensator/Bellows
- Vacuum barrier

- **Pressure wave propagates along the magnets inside the insulating vacuum enclosure**
- **Rapid pressure rise:**
  - **Self actuating relief valves could not handle the pressure**
    designed for 2 kg He/s, incident ~ 20 kg/s
  - Large forces exerted on the vacuum barriers (every 2 cells)
    designed for a pressure of 1.5 bar, incident ~ 8 bar
  - Several quadrupoles displaced by up to ~50 cm
  - Connections to the cryogenic line damaged in some places
  - Beam vacuum to atmospheric pressure

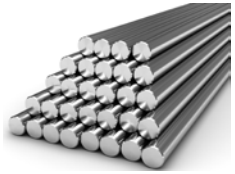
The 2008 incident





- **6** tons of He released
- He volume increased **~4800**
- **600 MJ** energy released

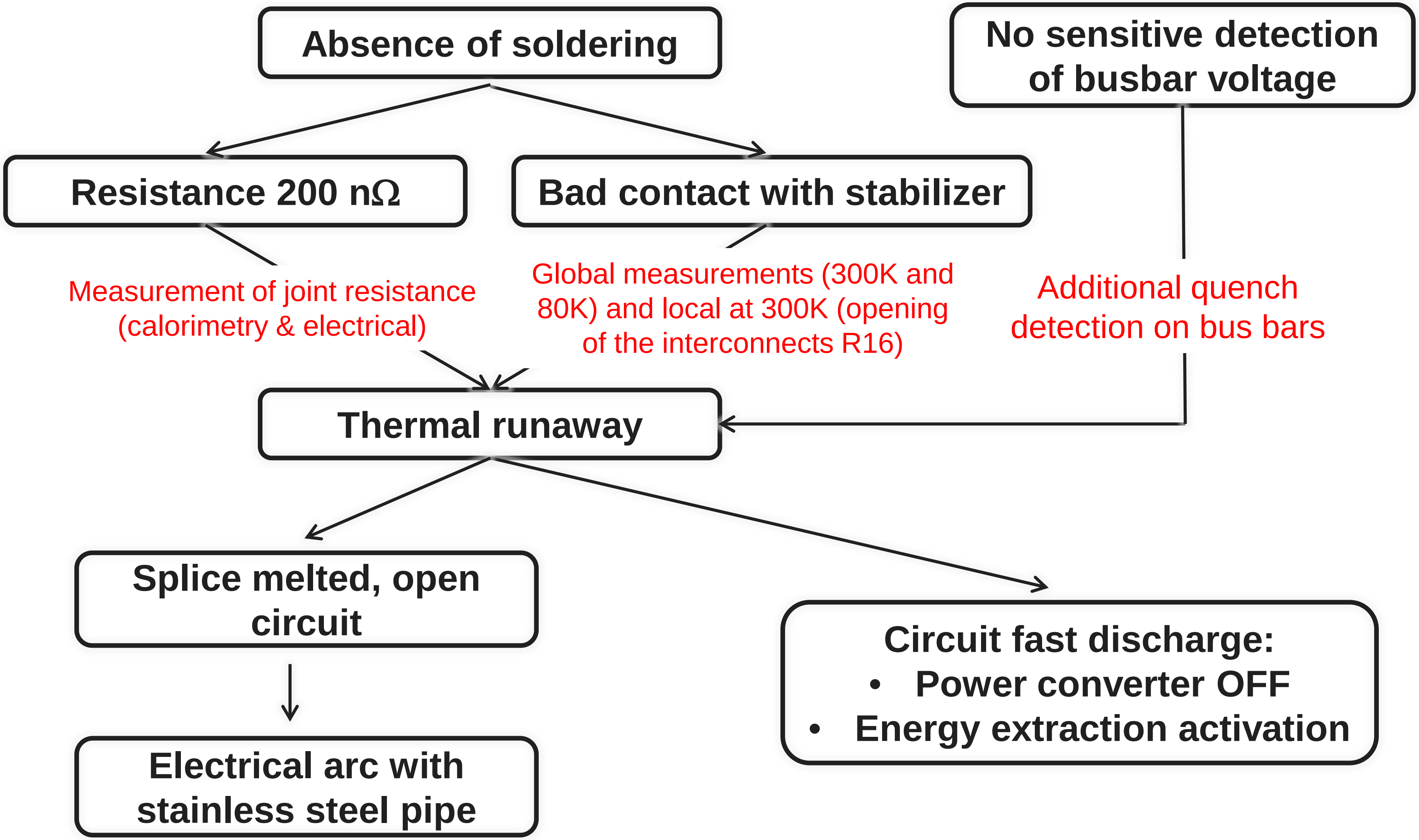
130 kg of TNT



to melt 750 kg of steel

The 2008 incident

Maximum safe energy 3.5 - 4 TeV



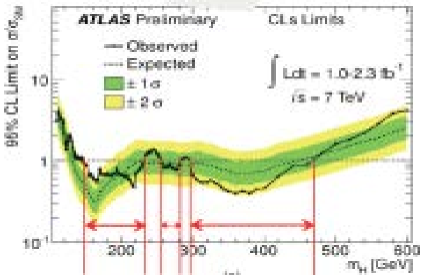
The LHC timeline

3.5 TeV

4 TeV

September 10th, 2008
First beams circulating

November 29th, 2009
Beams back



August, 2011
2.3e33, 2.6 fb^{-1}
1380 bunches

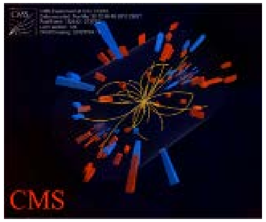
July 4th, 2012
Higgs discovery

2008 | 2009

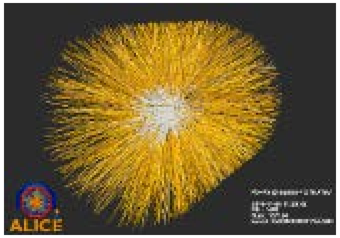
September 19th, 2008

Accidental release of 600 MJ stored in one LHC dipole magnets

March 30th, 2010
First collisions at 3.5 TeV



November 2010
Ions



7 TeV

(6.5)

outline

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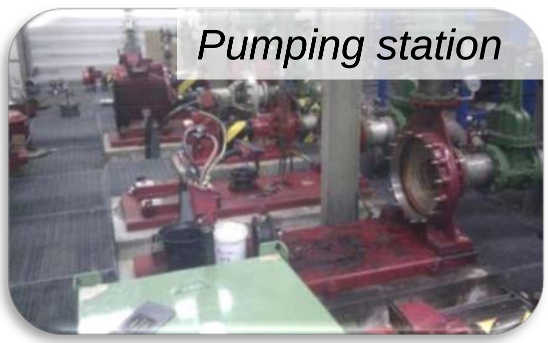
  - **The 2008 incident**
- ☑ **The LS1 @LHC**
  - **The Superconducting Magnet And Circuit Consolidation project (SMACC)**
  - **The superconducting circuits re-validation:**
    - **The Copper Stabilizer Continuity Measurement (CSCM)**
    - **The Powering tests**
- ☑ **Conclusions**

LS1 @LHC


The main 2013-14 LHC consolidations
1 1695 Openings and final reclosures of the interconnections
2 Complete reconstruction of 1500 of these splices
3 Consolidation of the 10170 13kA splices, installing 27 000 shunts
4 Installation of 5000 consolidated electrical insulation systems
5 300 000 electrical resistance measurements
6 10170 orbital welding of stainless steel lines
7 18 000 electrical Quality Assurance tests
8 10170 leak tightness tests
9 4 quadrupole magnets to be replaced
10 15 dipole magnets to be replaced
11 Installation of 612 pressure relief devices to bring the total to 1344
12 Consolidation of the 13 kA circuits in the 16 main electrical feedboxes


P7 enclosure

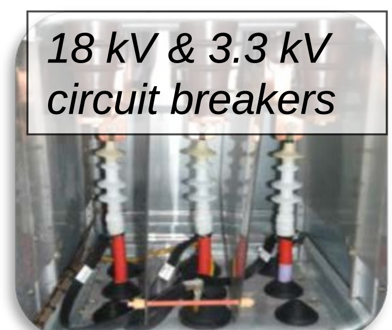

Vacuum


Pumping station


UPS


Cryogenics


ACS Exchange

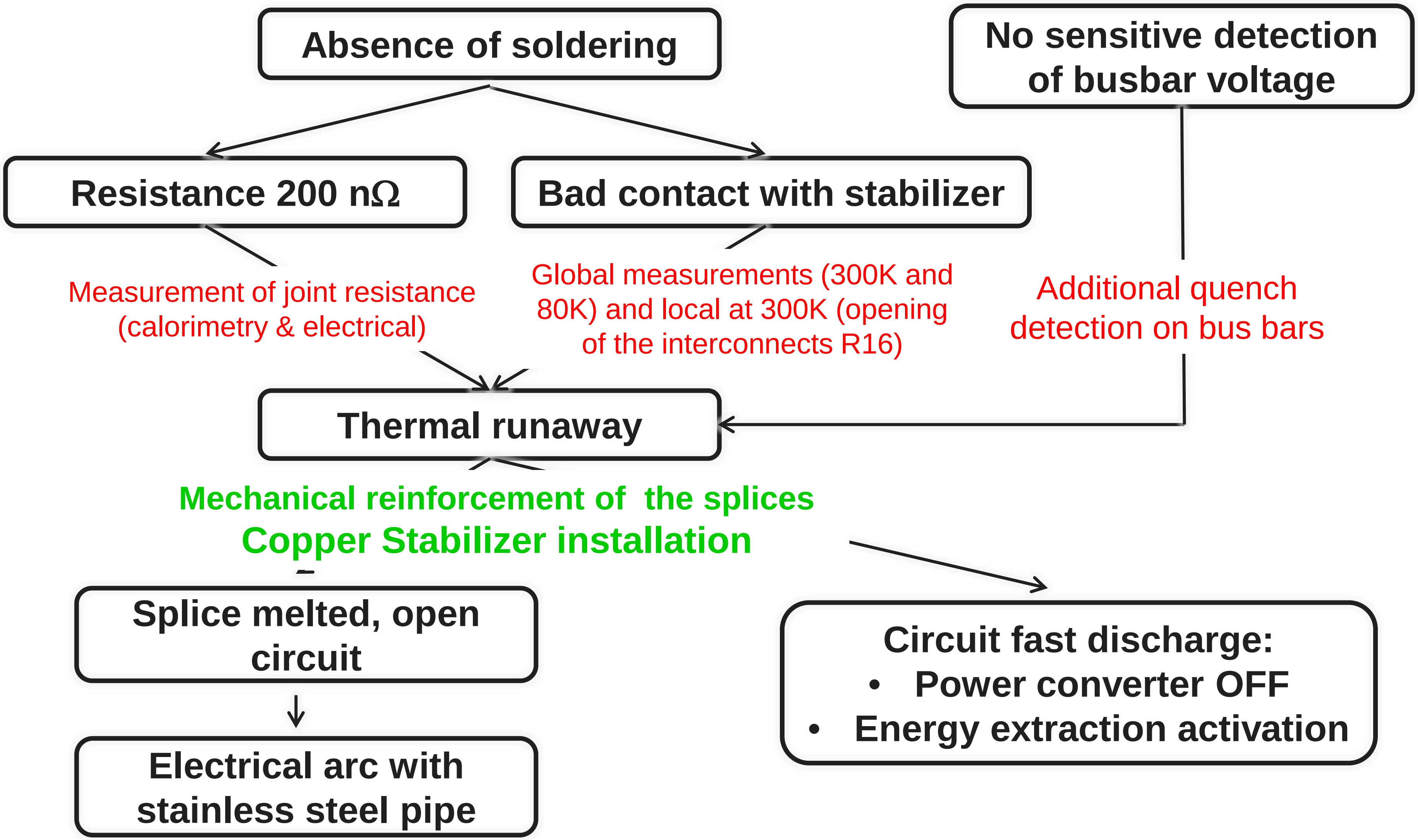

18 kV & 3.3 kV circuit breakers

The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 3000 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines

7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 3 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

The 2008 incident



The splice consolidation - strategy

1. **Measure** all pre-LS1 splices
2. **Repair** NON-conform splices:
   - **> 10.6 μΩ** for dipoles (5.6 μΩ)
   - **> 14.3 μΩ** for quadrupoles (9.3 μΩ)
3. **Consolidate ALL** splices

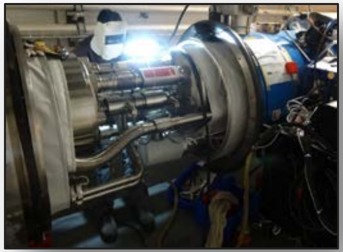
Interconnect opening (warm-up, W bellow opening, lines cut, splice insulation removal,...)

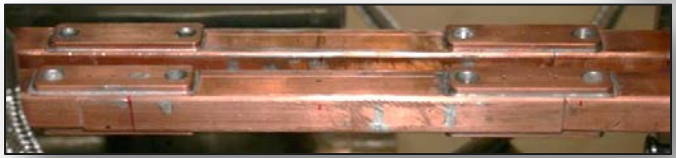
Quality control of existing splices

GOOD?

NO (about 30%) → **Splice de-soldering & re-assembly**

YES → **Splice consolidation**

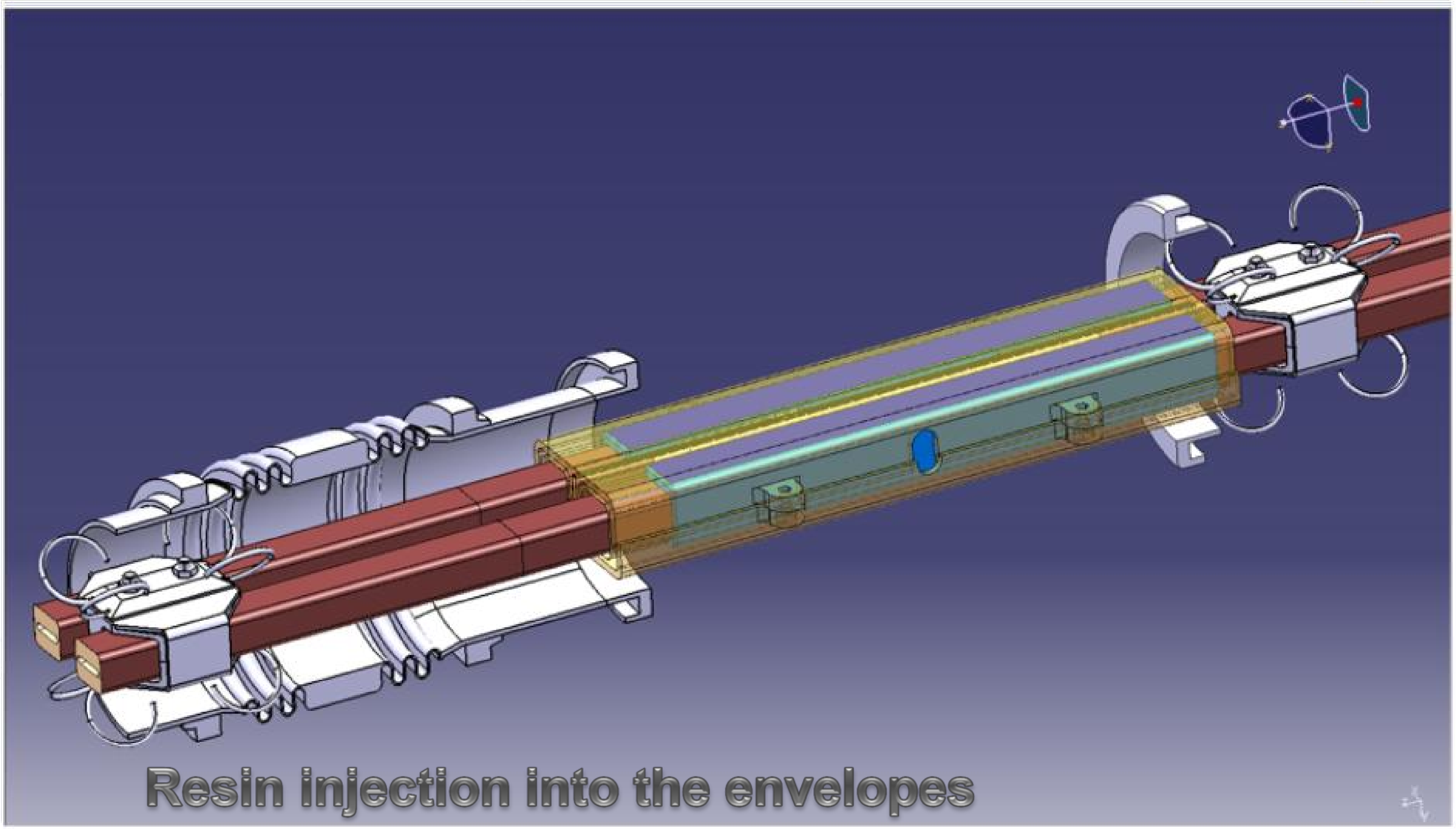




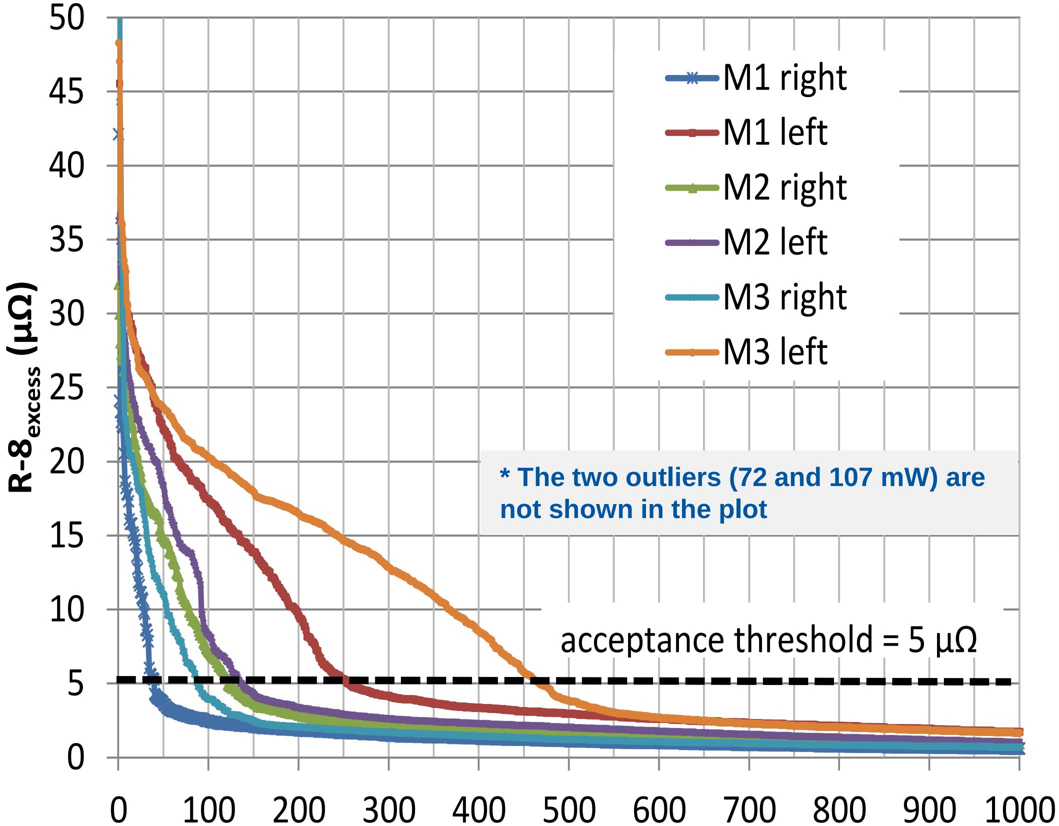
Interconnect re-closure (insulation installation, lines welding leak test,…)

- **10170** superconducting splices
- **6** consolidation steps
- **5** Quality Assurance steps
- **> 2700** shunts installed
- **> 300.000** electrical measurements

The splice consolidation



The splice consolidation – before LS1



S. Heck, M. Solfaroli, O. Andreassen, P. Thonet, C. Scheuerlein, A. Ballarino, F. Bertinelli, L. Bottura, P. Fessia, J.-Ph. Tock, "*Non-destructive testing and quality control of the LHC main interconnection splices*", IEEE Trans. Appl. Supercond.

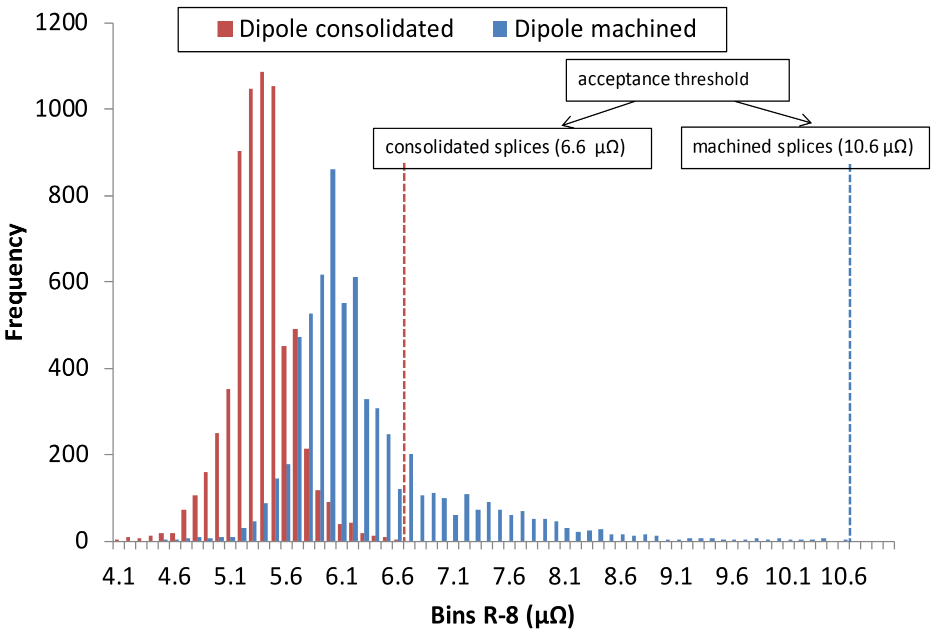
$$R_{excess} = R_{meas} - R_{nominal\_max}$$

$R_{nominal\_max\ (RB)}$ = **5.6 μΩ**
$R_{nominal\_max\ (RB)}$ = **9.3 μΩ**

Sector	RB	RQ
	R_{excess} max [μΩ]	
56	28.6	21.1
67	35.0	32.4
78	71.9 OK for 3.5 TeV	107
81	41.8	34.4
12	29.6	45.5
23	27.8	43.2
34	33.6	36.3
45	48.3	34.9

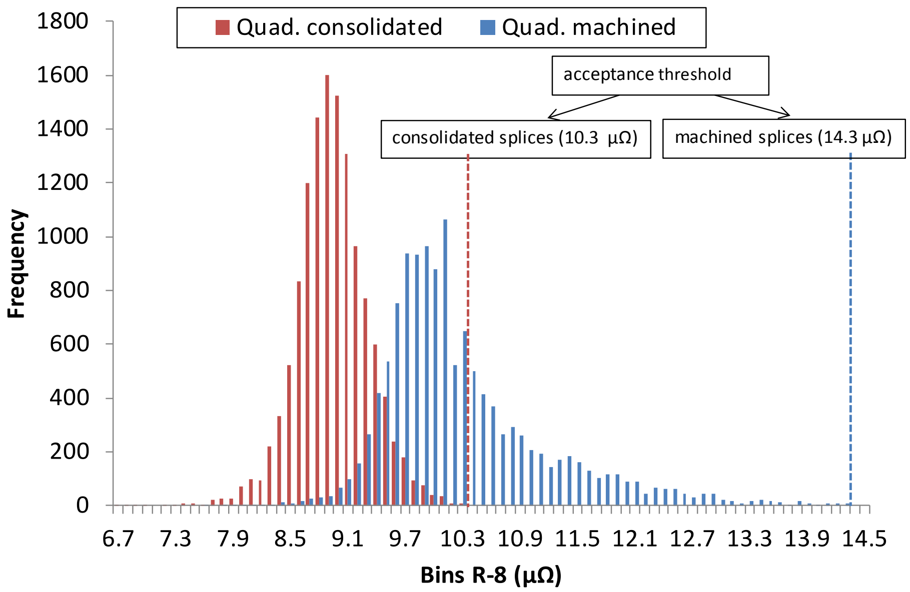
Splice	R_{excess} >5 μΩ (%)
M1-Left	8.2
M1-Right	1.3
M2-Left	4.4
M2-Right	3.8
M3-Left	15
M3-Right	2.7

The splice consolidation – after LS1

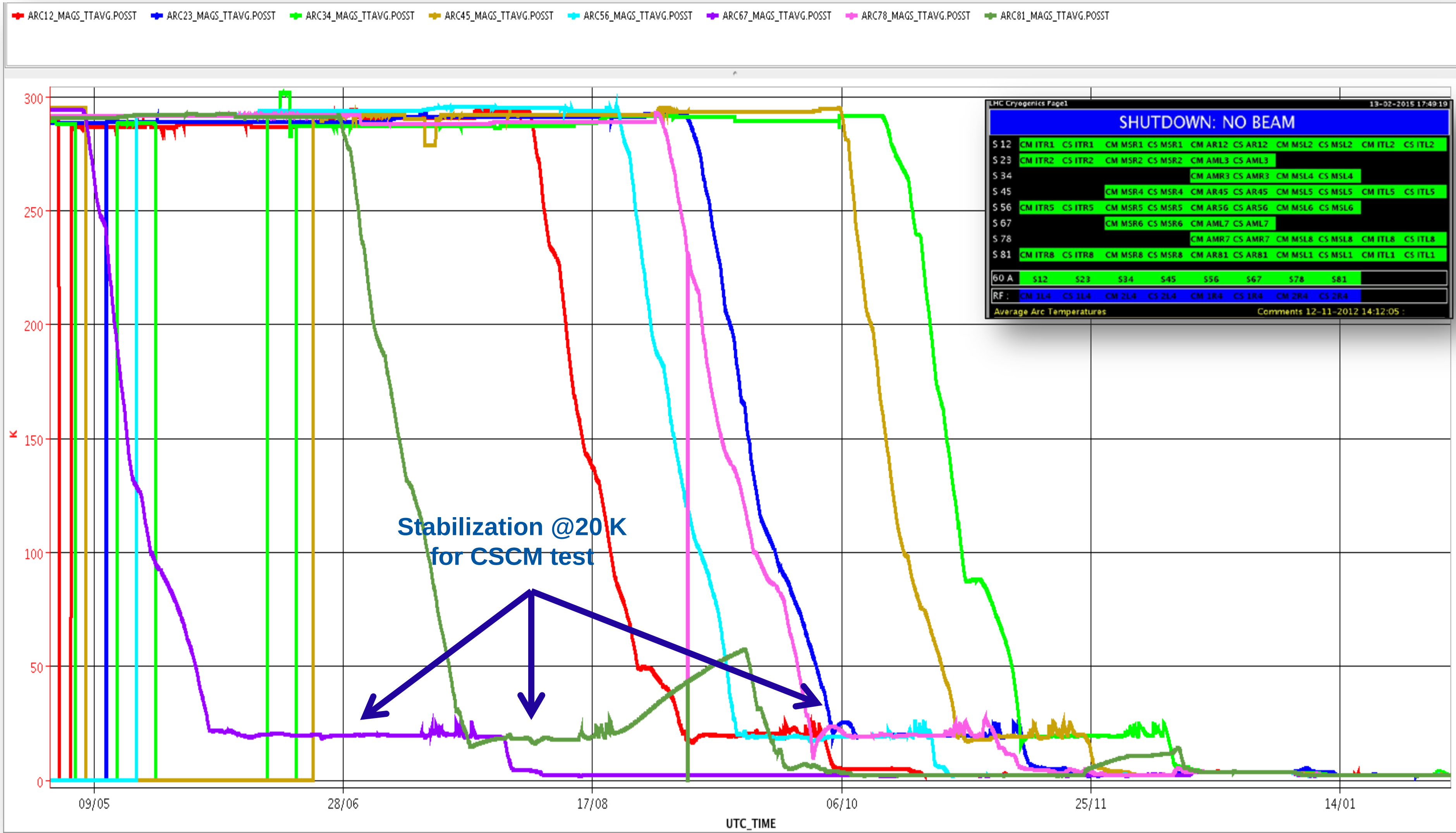


Dipoles: $R_{acceptance}$ = **6.6 μΩ**

Quads: $R_{acceptance}$ = **10.3 μΩ**



Cool-down



ARC12_MAGS_TTAVG.POSST
ARC23_MAGS_TTAVG.POSST
ARC34_MAGS_TTAVG.POSST
ARC45_MAGS_TTAVG.POSST
ARC56_MAGS_TTAVG.POSST
ARC67_MAGS_TTAVG.POSST
ARC78_MAGS_TTAVG.POSST
ARC81_MAGS_TTAVG.POSST
K
300
250
200
150
100
50
0
09/05
28/06
17/08
06/10
25/11
14/01
UTC_TIME
Stabilization @20 K
for CSCM test
SHUTDOWN: NO BEAM
Average Arc Temperatures

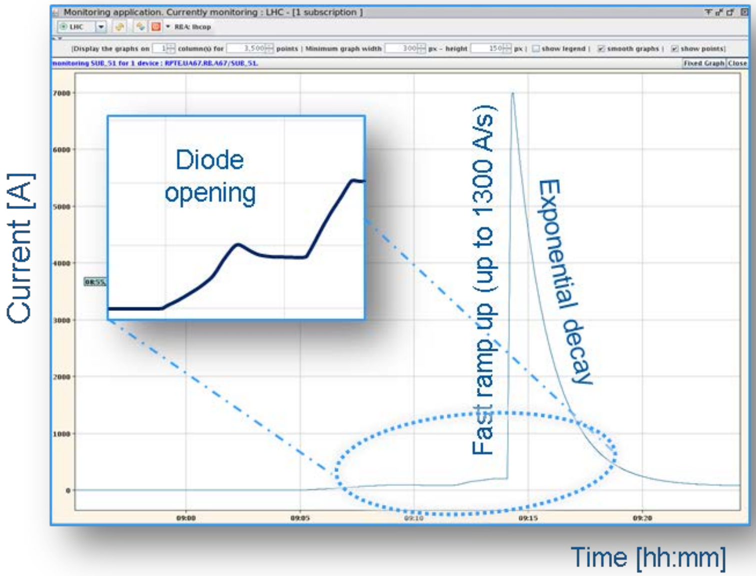
Validation: the CSCM

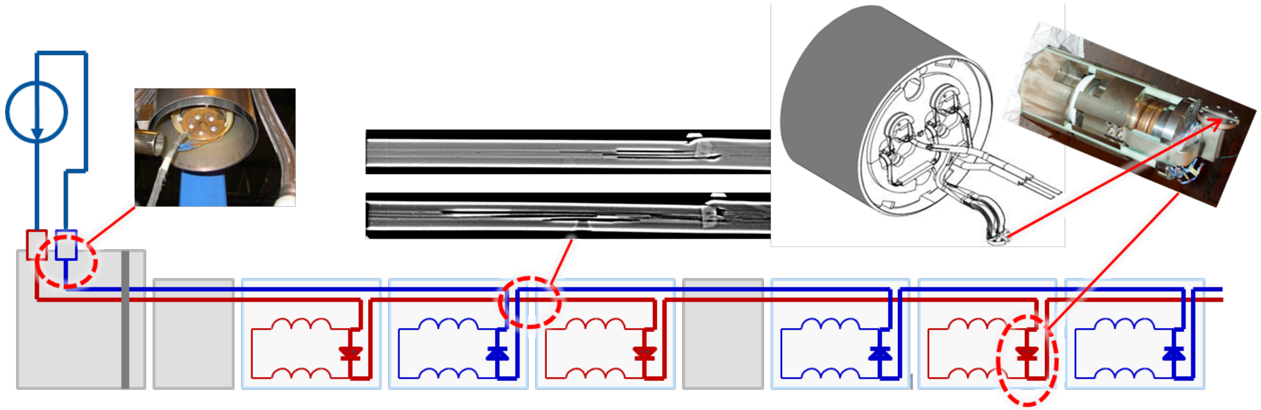
The ***Copper Stabiliser Continuity Measurement*** is a test that aims to validate:

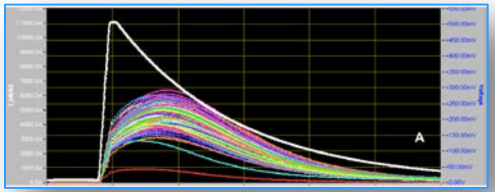
- All interconnection splices
- All current lead–busbar connection on the DFBA
- All bypass diodes paths

Principle: **NO thermal runaway = good result**

- Stabilize the entire sector at **20±5** K (magnets no longer superconducting)
- Apply few hundred A current to open the bypass diodes
- Apply a current pulse, max. **6.5 TeV** equivalent, **t = 100 s**





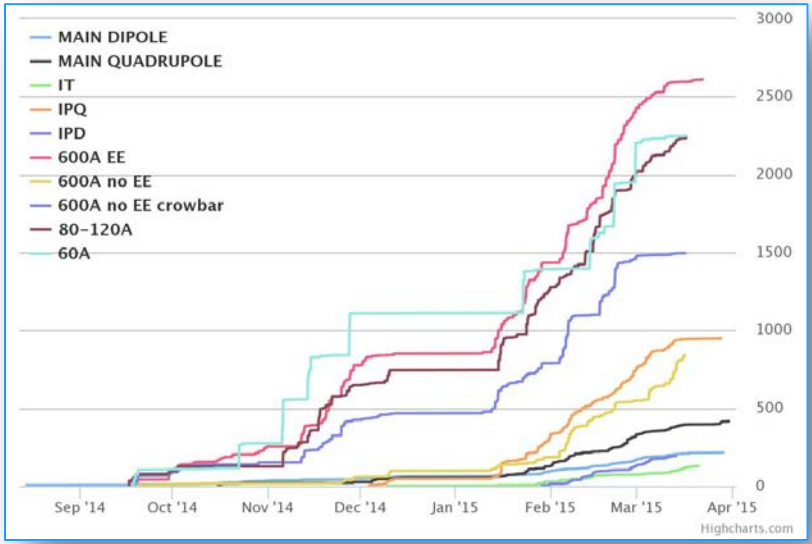


Voltages on bus bar segments of a sector

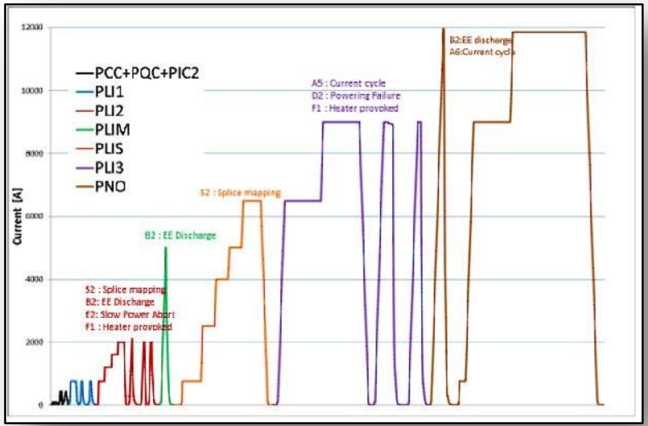
(spread is due to RRR and segment length differences)

Validation: the powering tests

Electrical Quality Assurance (check of insulation integrity) followed by a series of current cycles to test the powering interlocks, the protection functionality and the capability of all magnets to reach the required current

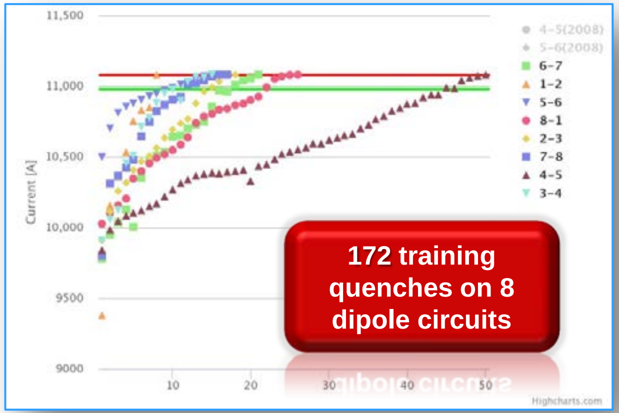


LHC powering tests evolution

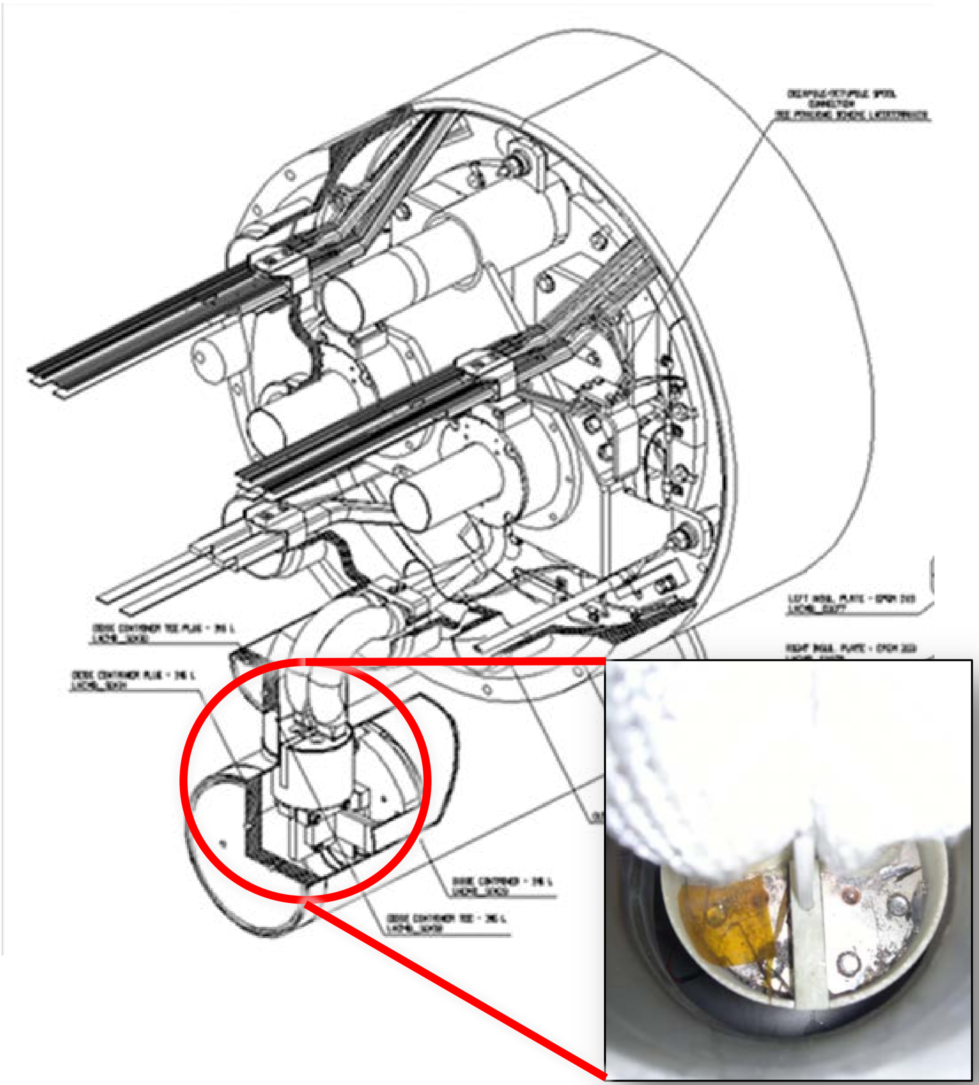


Commissioning plan for the main dipole circuits

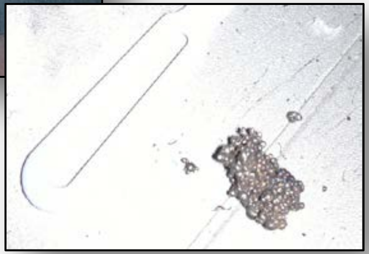
From September 15th 2014 to April 03rd 2015, **1566 superconducting circuits** have been commissioned through execution and analysis of **about 13.800 test steps** at increasing current level



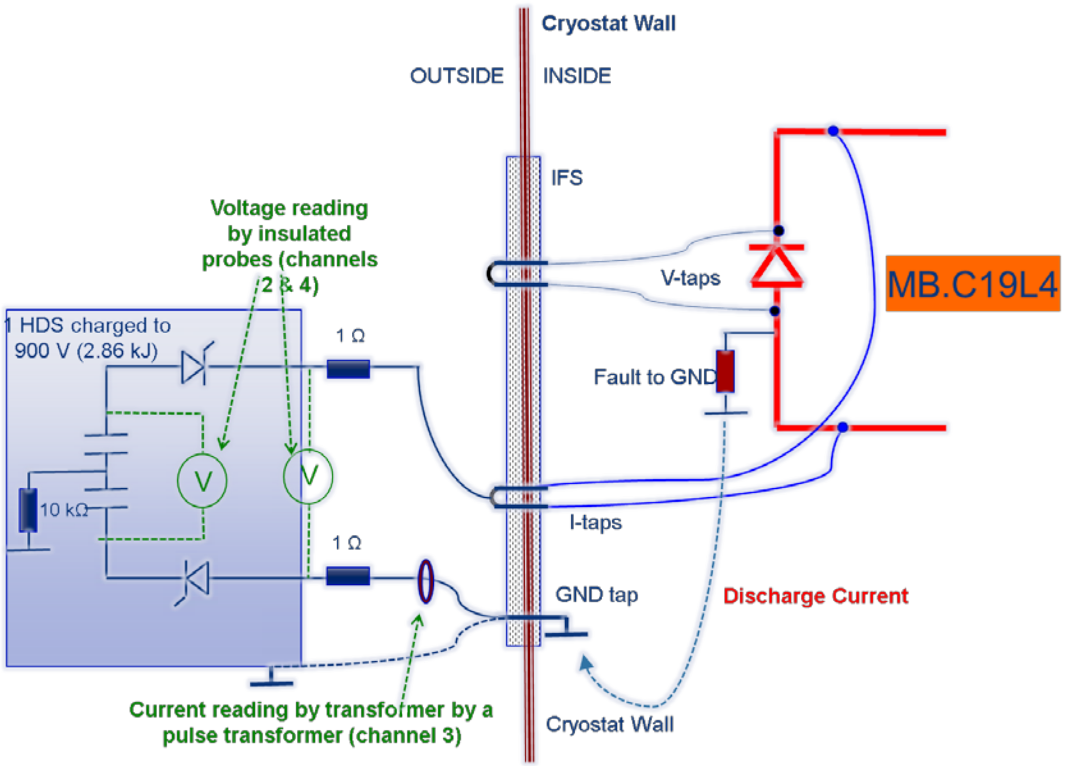
Short – the problem

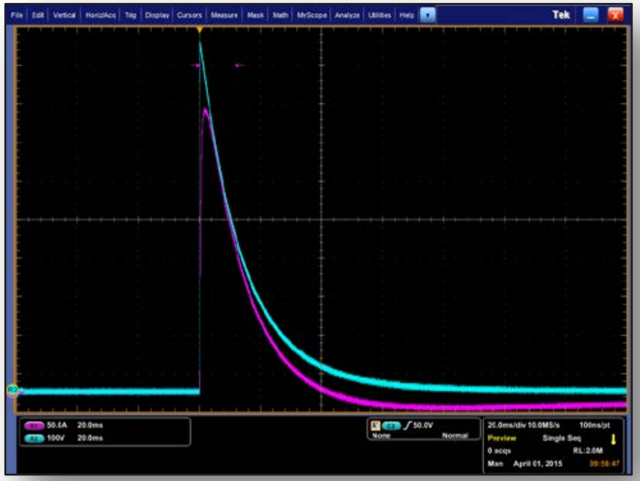


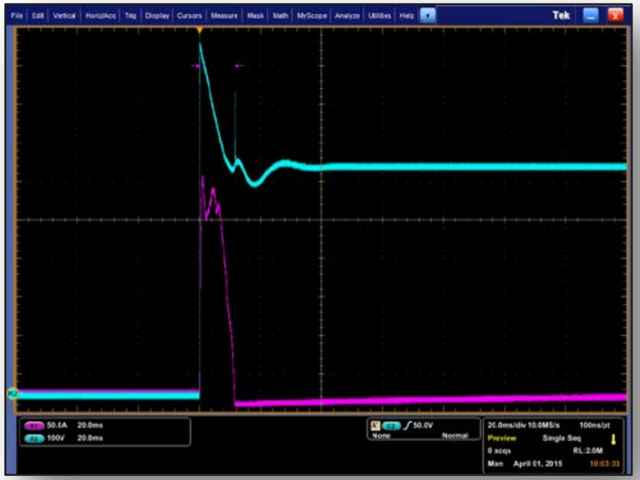
- During the powering test of one of the main dipole circuits a Earth fault appear
- After investigation the fault was localized in the cold part of the circuits on the diode connection to the magnet (R ~**1 Ω**)
- The short was very likely caused by a small metallic debris, bridging the half moon with the diode tube



Short – the solution







- Dissipated energy **~1.5 kJ**
- Discharge voltage **906 V to 578 V**
- Short resistance **~1 Ω**
- Energy dissipated in short **~500 J**
- Discharge time **~11.5 ms**

Conclusions

- The measurements taken during the LS1 proved the importance of the splice consolidation…a long upgrade process, mandatory to operate the machine at higher energy
- The work done has been electrically validated!
- The LHC is now ready to take the challenge to reliably operate at 6.5 TeV

Thank you for the attention!

SC circuits consolidation - beyond splices

- **18** cryo magnet replaced
- **612** missing Safety Relief Valves
- Consolidation of **135** splices in Distribution FeedBox
- Replacement of several cryogenic bellows
- Quadrupole diodes consolidation
- Installation of cryogenic Beam Loss Monitors
- Main quadrupole circuits modification
- Electrical non conformity repair
  - Low beta insertions
  - Cryogenic lines
  - …

Validation: the short-circuit tests

Tests with current performed on the warm part of the circuits:

- Dielectric strength check for cables and energy extraction systems
- Energy extraction current sharing verification
- Interlock signals verification
- Conical connection resistance verification
- Heat run (**12h** or **24h**)