Performance of the cold powered diodes and diode leads in the main magnets of the LHC

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Acknowledgment

In the past 25 years many persons have been involved in the design, production, testing, consolition, and quality assurance of the diodes in the LHC.

Contents

- Cold diode bypass circuit for main LHC magnets
- Diode stack design
- Diode wafer performance
- Diode leads performance
- Conclusions

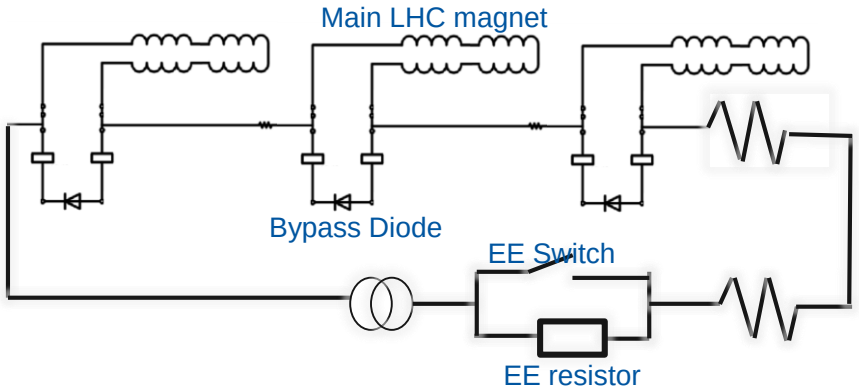
Cold diode bypass protection circuit for main LHC magnets

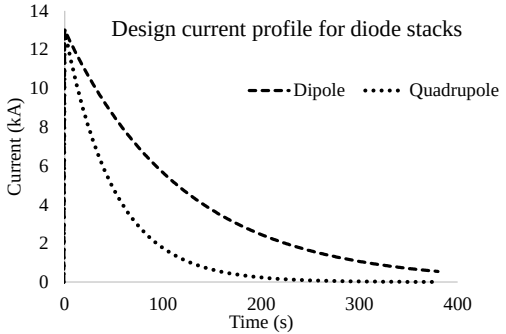
Superconducting magnet operation
- Diode bypass not used, switch closed.

Magnet quench
- Quench heaters fired, magnet becomes resistive
- Diode bypass takes all current
- Circuit Energy Extraction switch opening
- Exponential current decay in the circuit and in the diode parallel to quenched magnets.

LHC main magnet circuit characteristics

	Dipole	Quadrupole
Number of magnets in series	154	47 or 51
Circuit length	About 3 km	About 3 km
I_{Design} and τ_{design}	13 kA, 120 s	13 kA, 50 s
I and τ at 6.5 TeV	11 kA, 100 s	9.9 – 10.4 kA, 30 s
Energy deposition	1.7 MJ	0.72 MJ

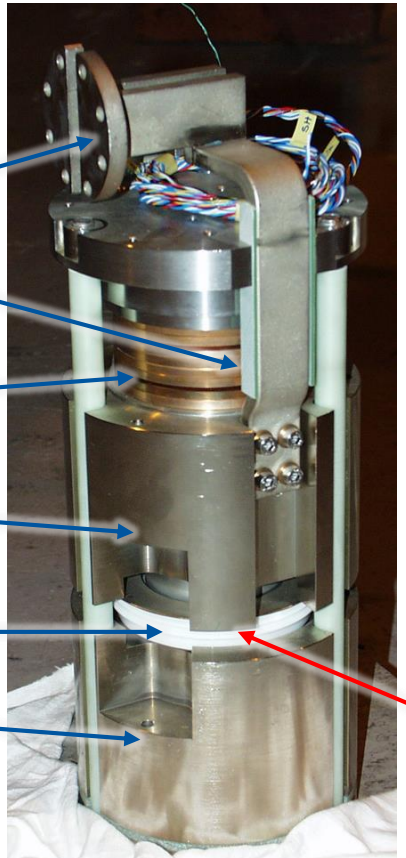




Diode stack

Components

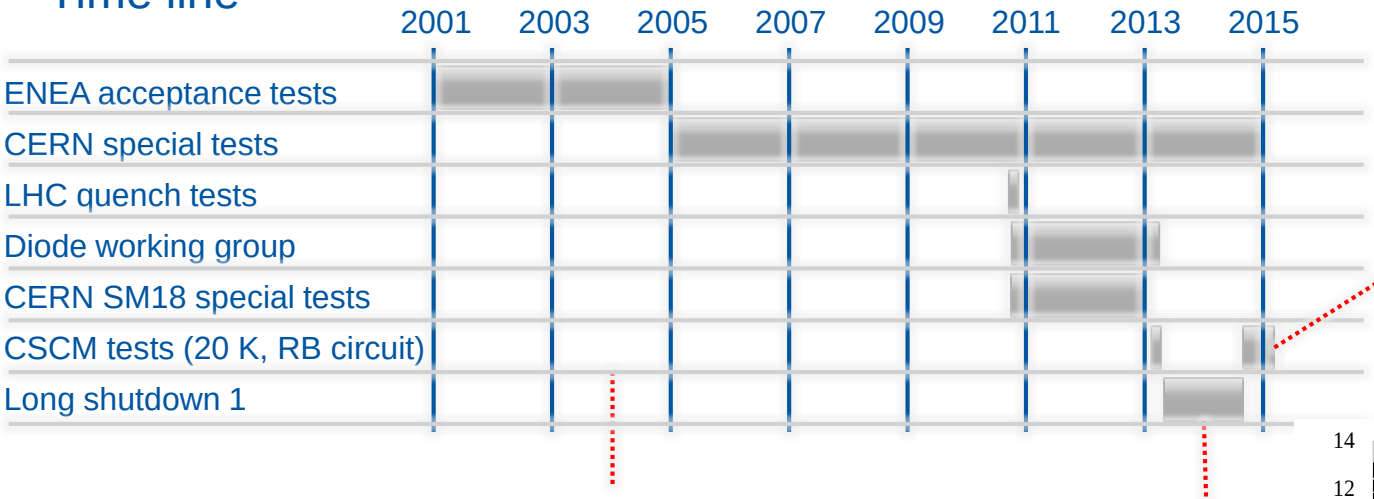
- Half-Moon
- Bus bar
- Washers apply constant 40 kN pressure
- Heat sink
- Diode pack
- Heat sink



Dipole diode stack

Focus in this presentation:
- Diode wafer
- Contact resistance of bolted and clamped contacts

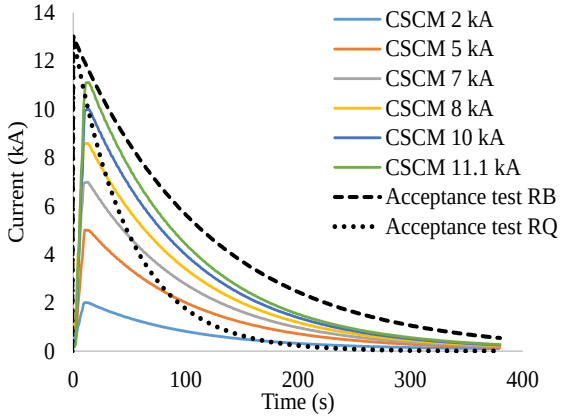
Time line



- Diode bypasses of all dipole diodes qualified at high current.

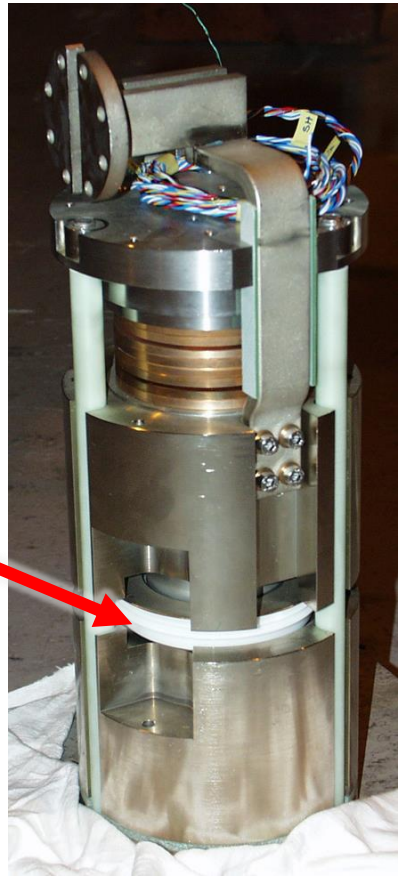
Half Moon contacts in about 200 stacks redone with updated procedure

- All contact resistances measured direct or indirect.
- All quadrupole busbar-busbar connections redone



Performance of:

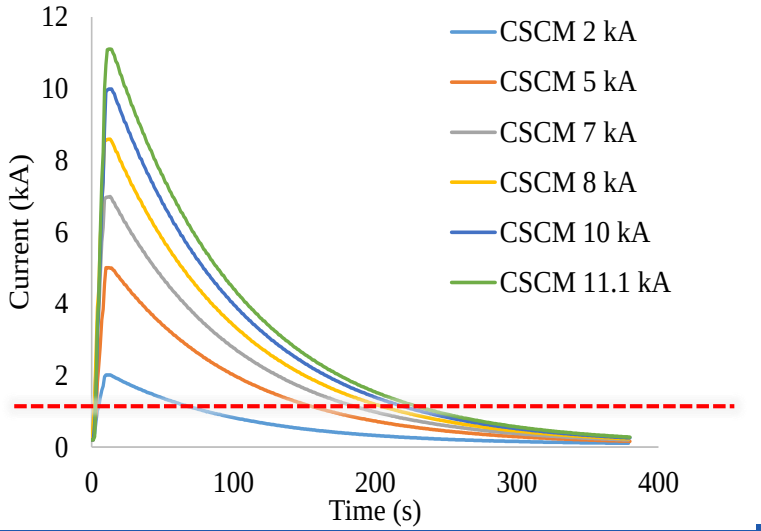
1. Diode wafer
2. Diode-heatsink contact
3. Heatsink-busbar contact
4a. Dipole busbar to busbar contact
4b. Quadrupole busbar to busbar contact

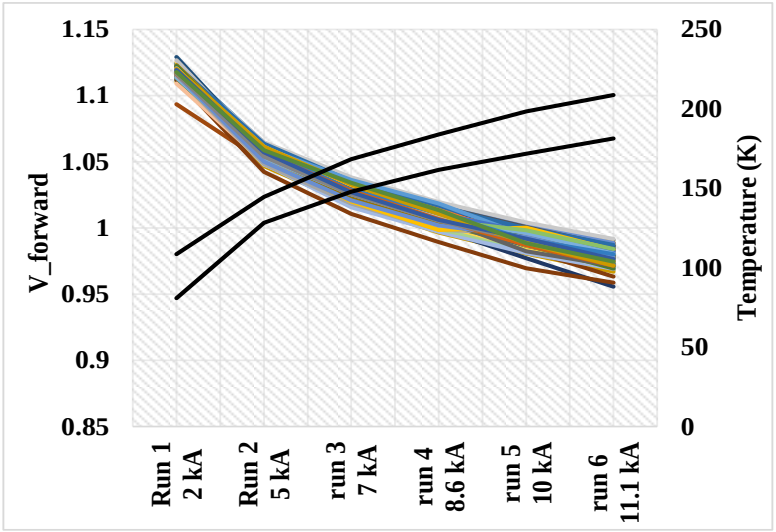


Diode wafer performance

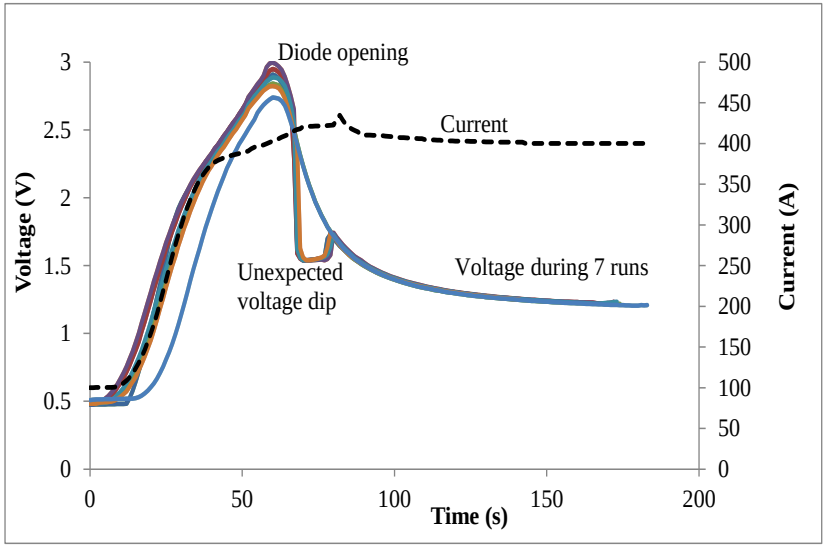
- 2.3 % in acceptance tests (2001 - 2005) rejected due to V_f failures.and V_r
- No failures seen in all qualification and special tests of the diode wafer.
- No failures during special tests nor in > 800 quenches of LHC dipole magnets in 2014-15

- Temperature calculated during all CSCM discharges at 1 kA





Diode wafer performance



Interesting feature during CSCM test at a current of 400 A (3 % of nominal current).

- Sudden dip in the voltage just after the start of conduction.
- Return to nominal voltage after about 10 s.
- Very repeateble and occurring in about 13 % of the tested diodes.
- Explained by local start of conduction, followed by quick local heating, followed by conduction of the full diode.

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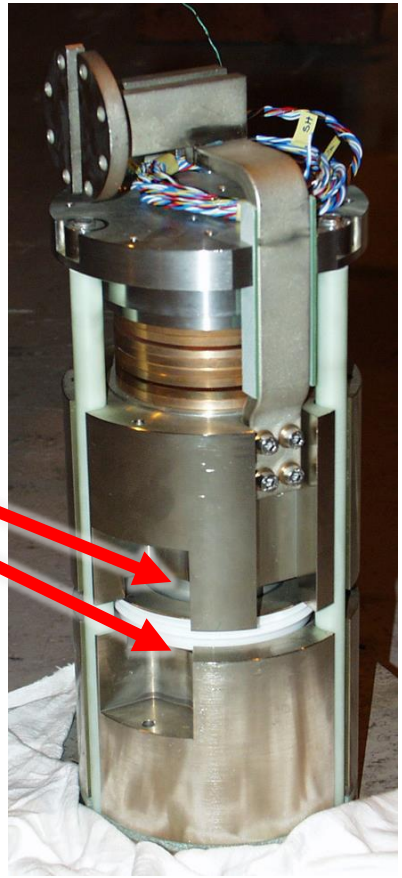
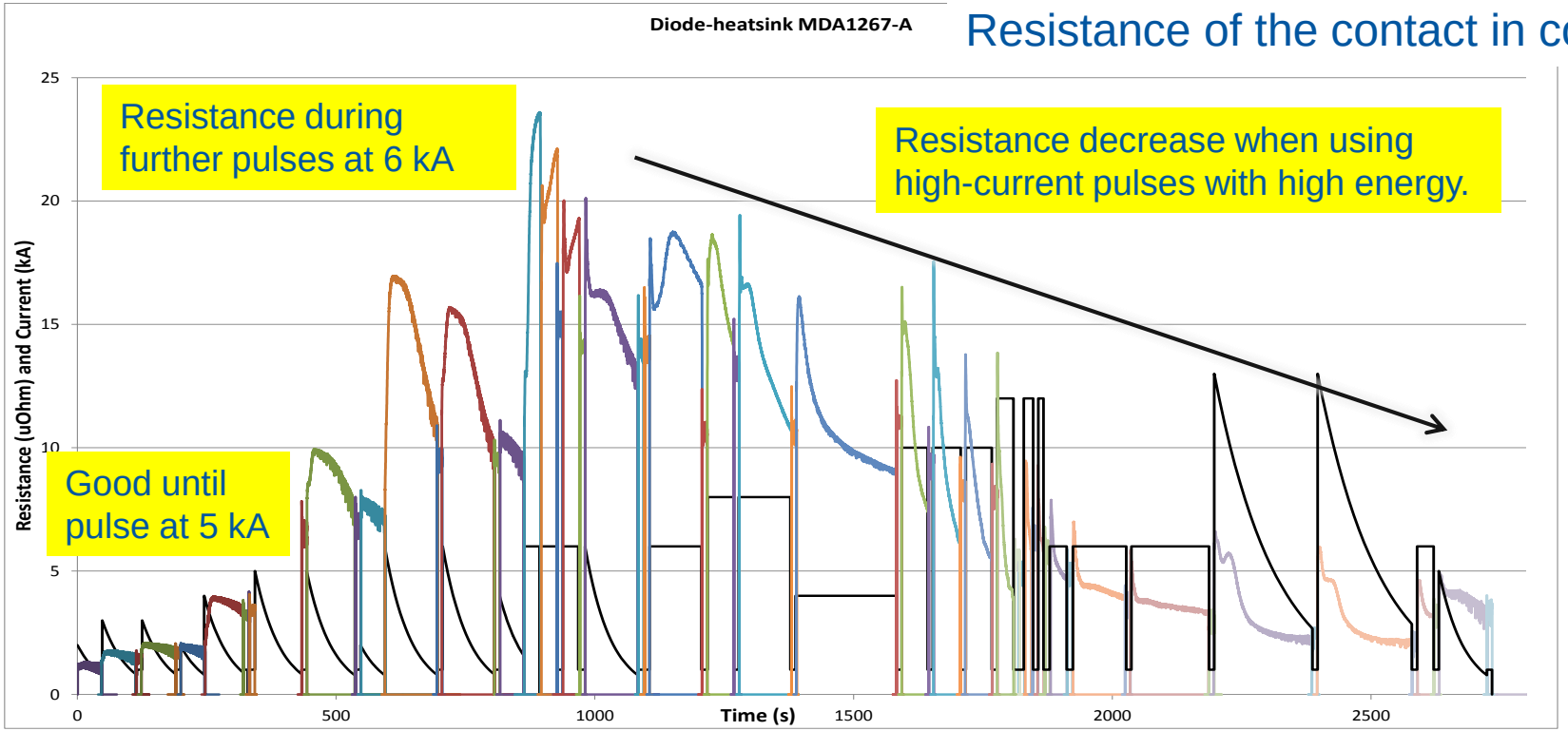


Diode to heat sink contact

- Clamped contact Ni-coated to Ni-coated Cu parts.
- Since 2010 resistance jumps and very high resistances have been measured, nominal is below 5 μΩ, a high value of more than an order of magnitude has been seen many times.
- Many special tests focusing on this contact have been performed, not a single test has shown any negative effect on diode functioning or overheating of any part.

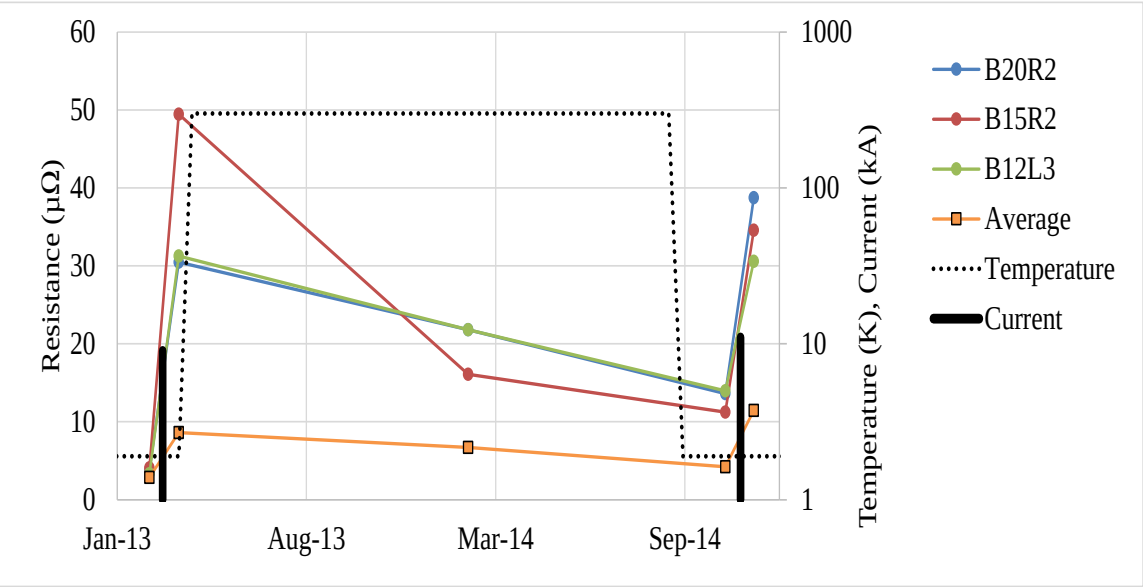
Diode to heat sink contact

Current during different tests in black
Resistance of the contact in colours.



Diode to heat sink contact

- Largest statistics before and after the CSCM test in 154 dipole diodes in 2013 and 2015
- The CSCM cycles increase the resistance.
- The long shutdown has a positive effect on the resistance of the leads, which is thought to be linked to diode-heatsink contact.



- Cyclic effect.
- Reason has never been fully explained, probably due to Ni-O layer and diffusion processes.

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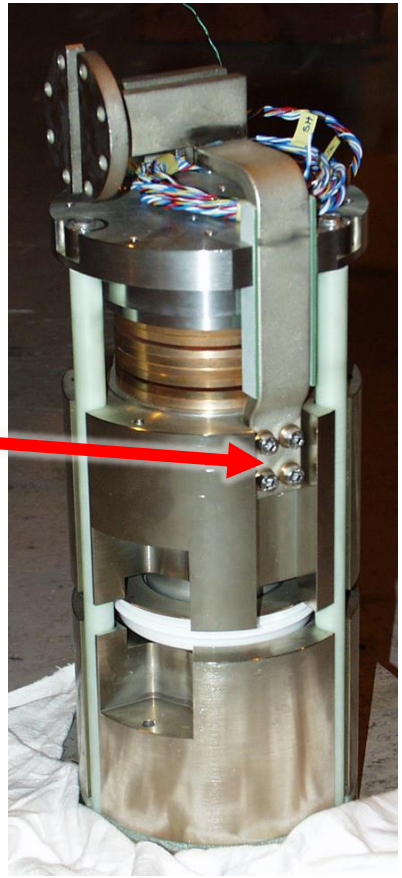
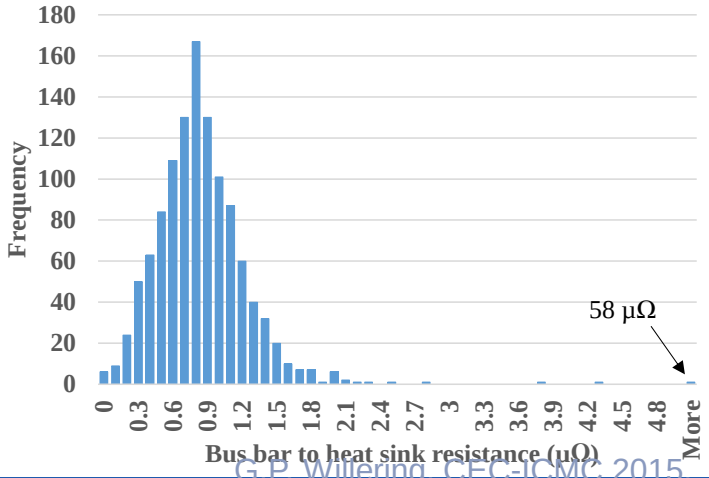


Bus bar to heat sink contact

4-screw bolted contact on **dipole** diode stacks

3-screw bolted contact on **quadrupole** diode stacks

- Some contacts have been measured during special investigation tests. 3-screw bolted contact was part of some concern.
- These contacts have been measured directly for the quadrupole stacks in the LHC during the Long Shutdown in 2013-14
- 7 Quadrupole stacks have been extracted to redo these connections because of resistance above spec of 2 µΩ, one having a critical resistance of 58 µΩ.



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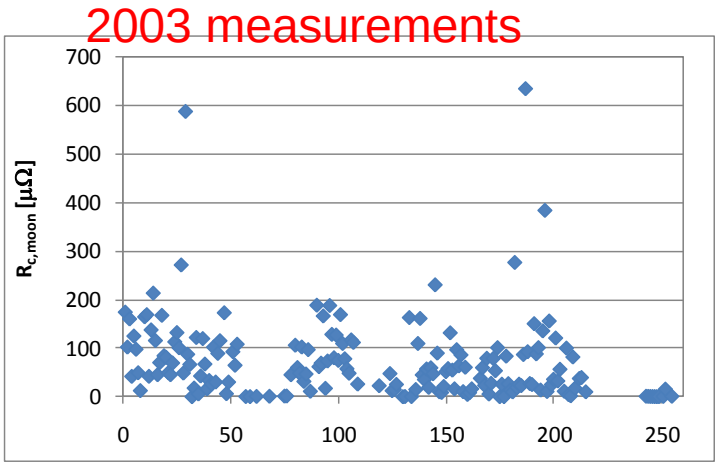
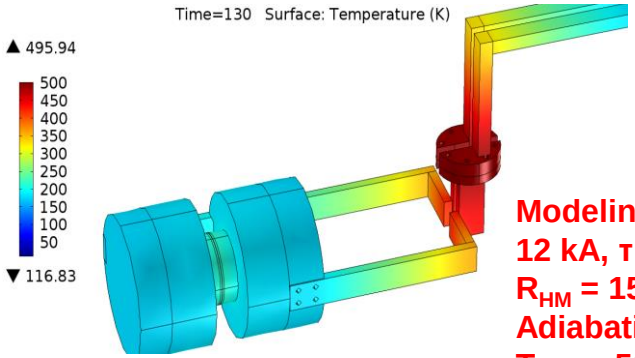
Dipole busbar to busbar contact

- Historic problem: in 2003 the contacts in about 200 stacks were redone due to excessive resistance of up to 600 μΩ.
- New procedure applied since then with a resistance of below the acceptance limit of 2 μΩ.
- During LS1 in 2014, one diode stack had half-moon resistances of 90 and 210 μΩ.





Courtesy Z. Charifoulline

Modeling
12 kA, τ = 100 s
R_{HM} = 15 μΩ
Adiabatic conditions
T_{max} = 500 K

- CSCM test has after consolidation fully qualified the dipole circuit, including this contact up to 6.5 TeV operation (11.1 kA)

A. Verweij and Z. Charifoulline, "Hot spot temperatures in the MB and MQ diode stacks (comsol simulations)," CERN internal note, to be published, 2015.

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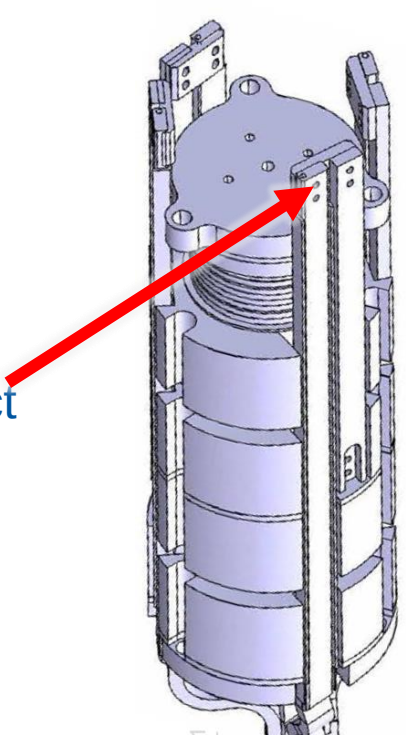
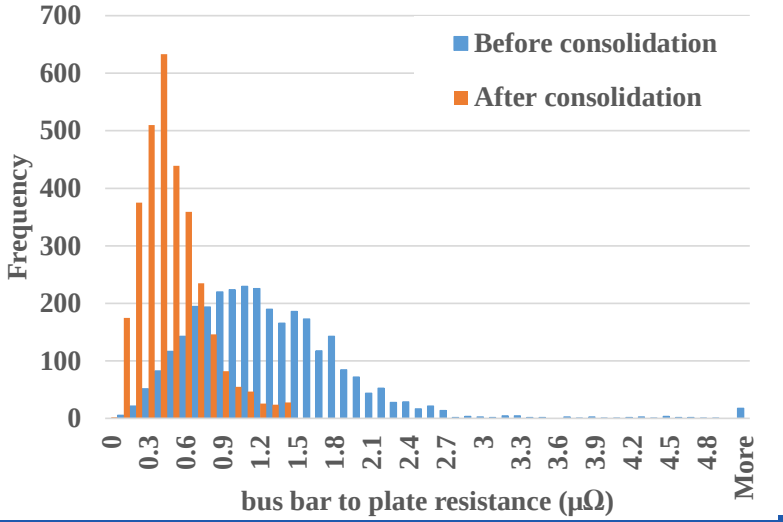
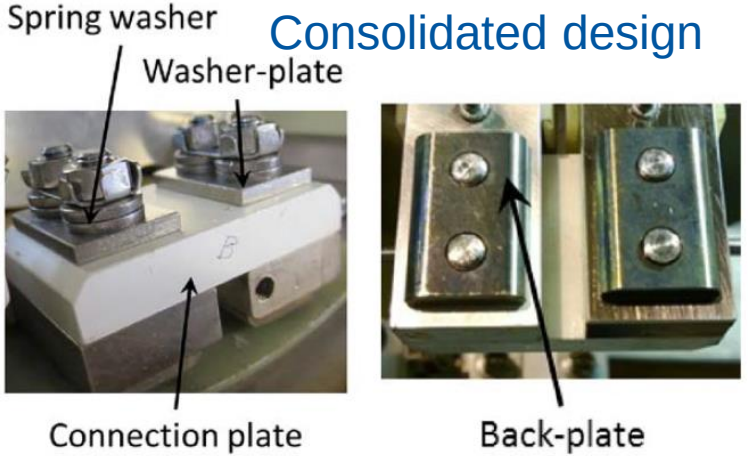


Quadrupole heat sink to bus bar contact

- Investigations triggered by quench tests in 2011 showed that this contact was mechanically underdesigned.
- All contacts redone in 2013-2014 consolidation.
- Before consolidation up to 26 µΩ, after consolidation resistance all below 1.5 µΩ, with a criterion of 2 µΩ



Consolidated design



Conclusions

- No performance issues of the 2024 diode wafers protecting the LHC main diodes have been discovered between acceptance test starting in 2001 and now.
- Detailed measurement of all contact resistance during the Long LHC Shutdown revealed a few critical issues.
- Quality control with detailed contact resistance measurements in 392 Quadrupole diode stacks proved the quality of contacts after consolidation.
- Full discharge tests at 20 K in all dipole circuits qualified all 1232 dipole diode stacks.

We have now strong confidence in the protection of the LHC magnets in operating conditions.

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More information

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