Splice Consolidation:

What we will do: status of main technical solutions.

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Probably at least 45 CERN staff members
Plus external experts, plus FSUs

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Presented by P. Fessia

Contributors

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- Development of new cutting tool for sleeves: M. Duret TE-MSC
- Electrical HV qualification of insulation system: R. Lopez, J. Kosek TE-MSC-MNC
- Electrical characterization of solders and electrical quality control, RRR investigations: C. Scheuerlein, S. Heck, TE-MSC-SCD section
- Lyre force computations: Bernard Auchmann TE-MSC-MDA
- Hydraulic verification of the insulation : A. Perin TE-CRG
- Evaluation of radiation dose to insulating material: F. Cerutti and his team EN-STI
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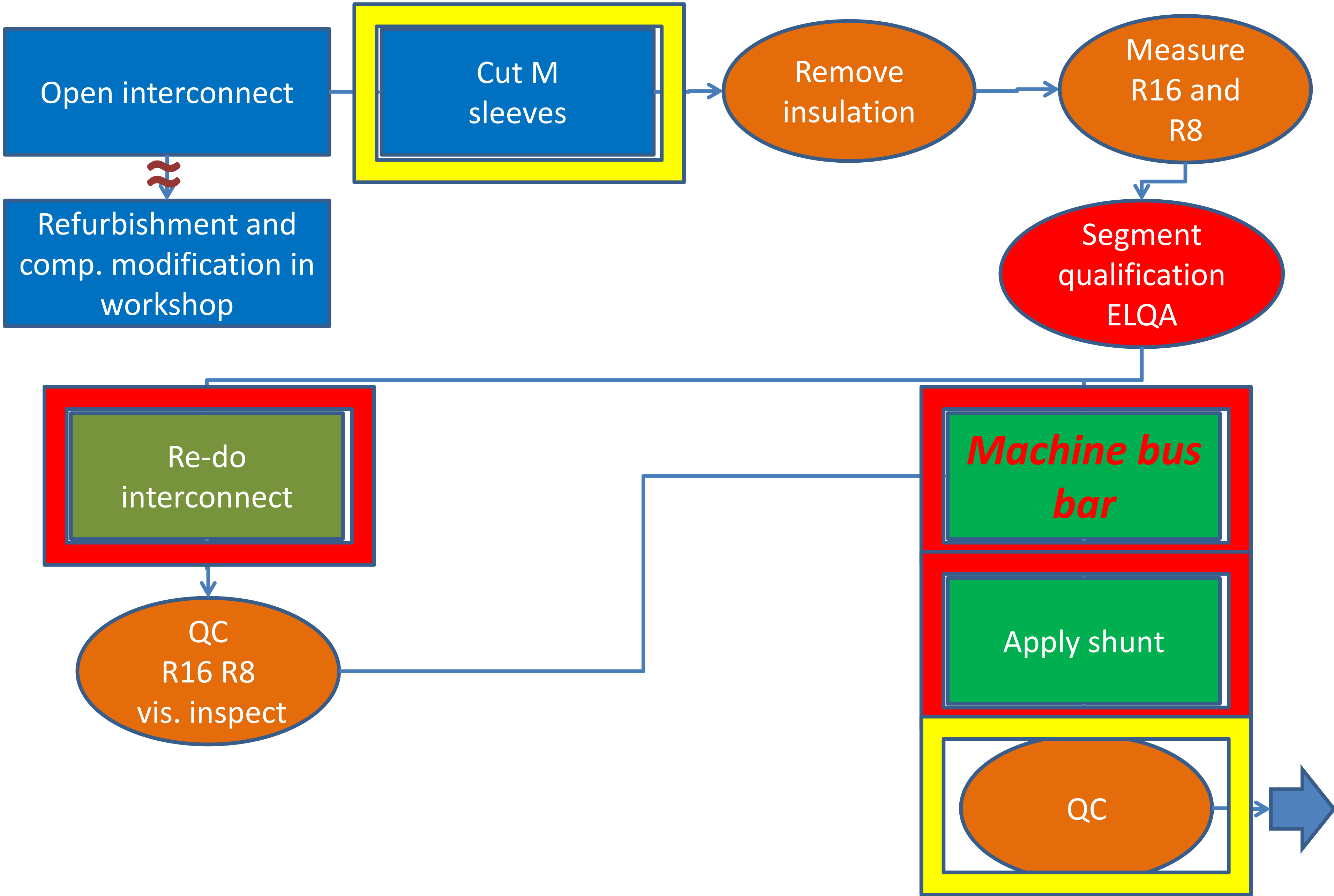
One step at a time … I



Open interconnect

Refurbishment and comp. modification in workshop

Cut M sleeves

Remove insulation

Measure R16 and R8

Segment qualification ELQA

Machine bus bar

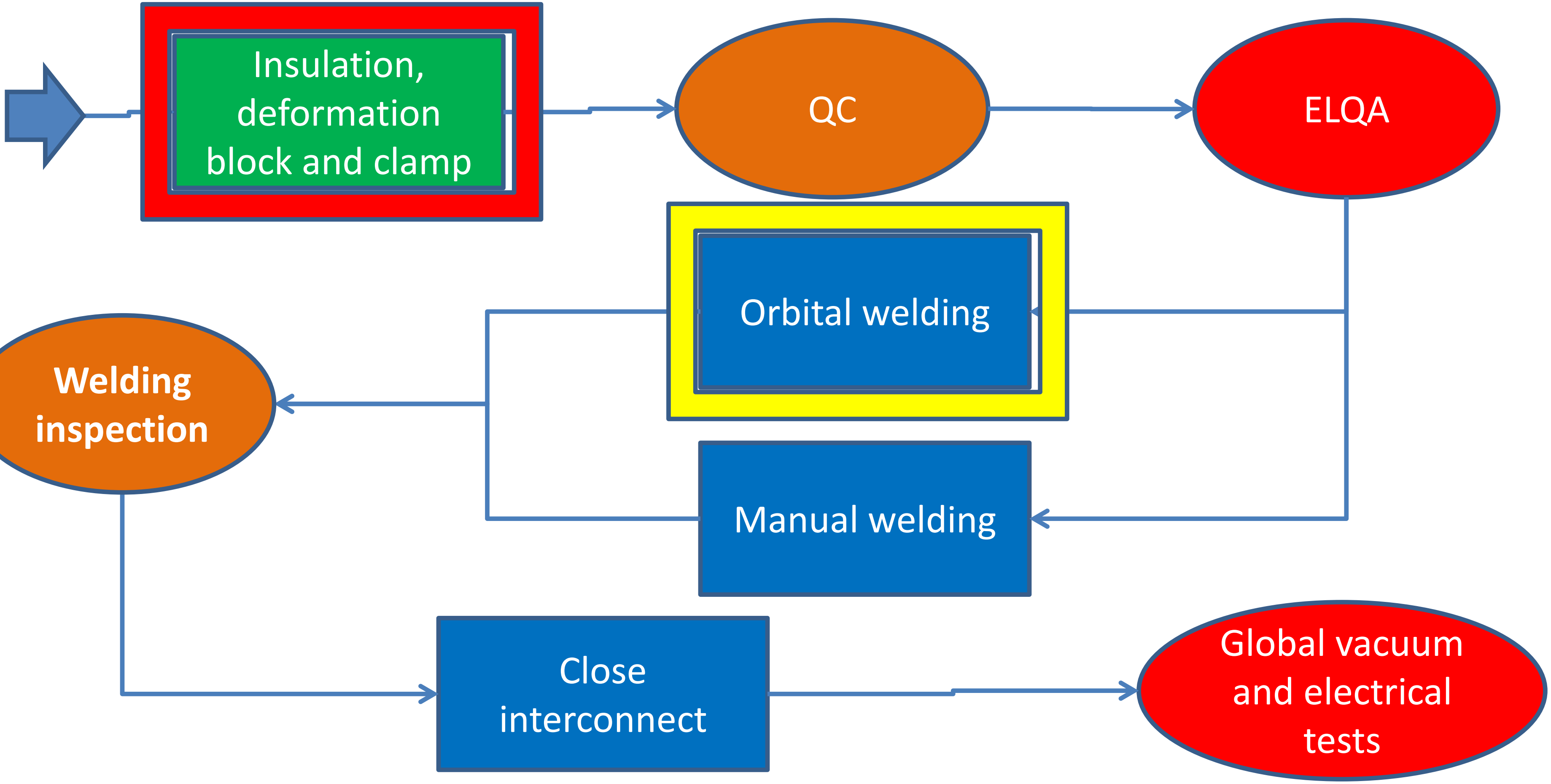
Apply shunt

QC

Re-do interconnect

QC R16 R8 vis. inspect

One step at a time … II

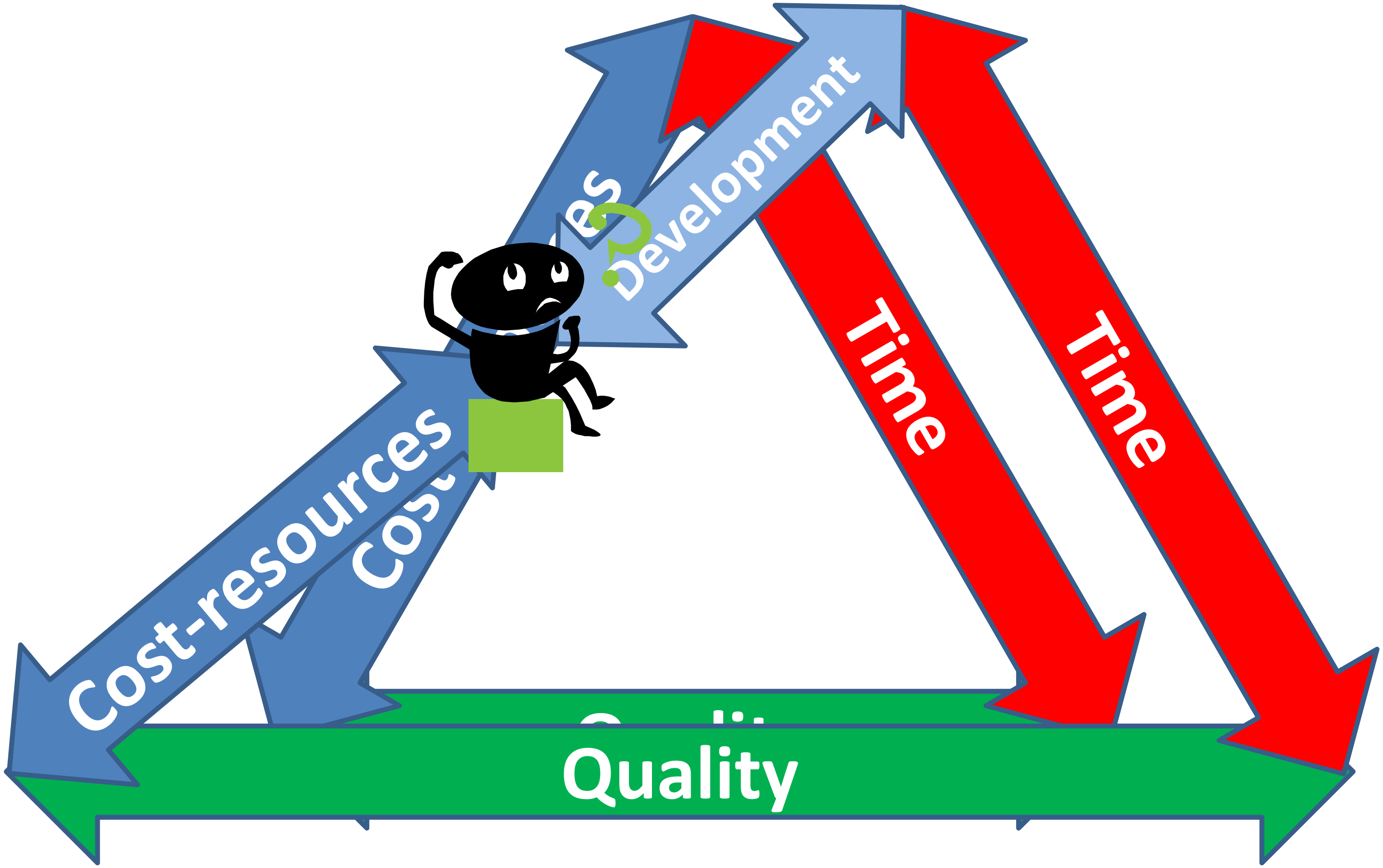


Number of joints to be redone: 1.500 (estimation 15% of the total volume)

Number of shunts to be applied: about 27.000

If we take 52 weeks of work it means a shunt every 5 minutes

Development directions



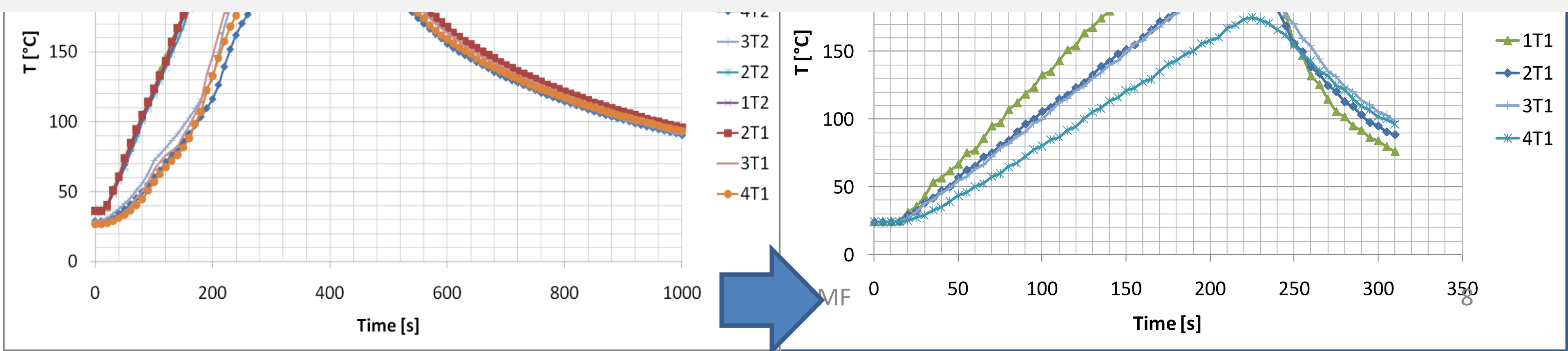
A Summary *inspired by an old management book*

- Redoing the 13 kA interconnect
  - Can we do better (or avoid to do worst) and how ? *Or Is the better the enemy of the good?*
- Shunt
  - The shunt: a “stupid” piece of copper. *Or the devil is in the details*
  - Where do I solder this damn thing ? *Or if Mahomet does not go the mountain the mountain goes to Mahomet*
- Insulation and clamp
  - High voltage Insulation, restraining magnetic forces, provide cooling without blocking the He flow, is it possible ?? *Or Can you keep your barrel full and have your wife (husband) drunk?*
- Tests: proving the that the shunt works *or I do not believe if I do not touch with my hand*
- What an external eye thought of our ideas (the international external review 18-22 October 2010)
- The nearby future

Redoing the 13 kA interconnects

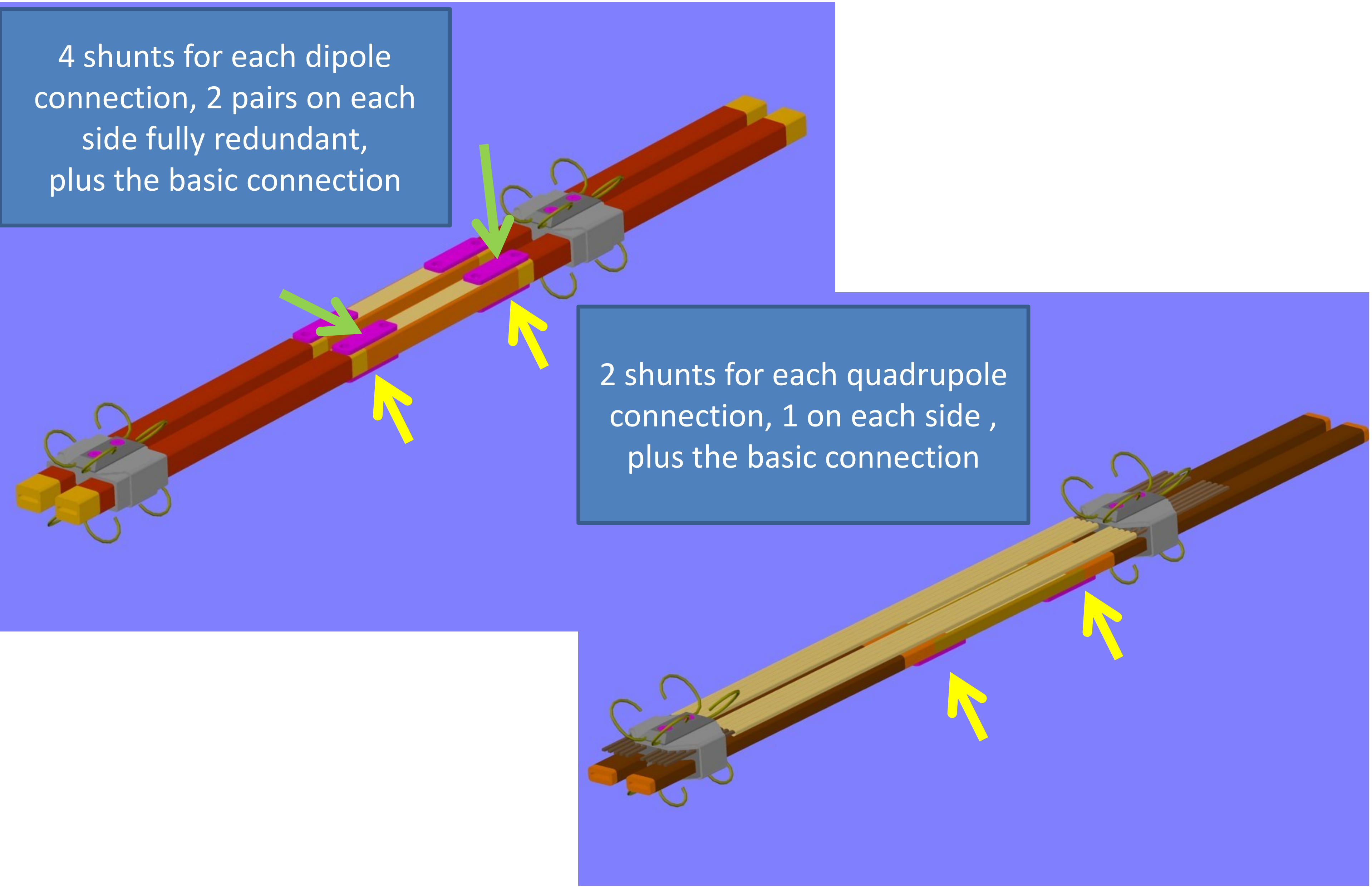
Re-optimizing the soldering process

We are today positive about the possibility to un-solder and re-solder without opening the spools connection



Shunt design

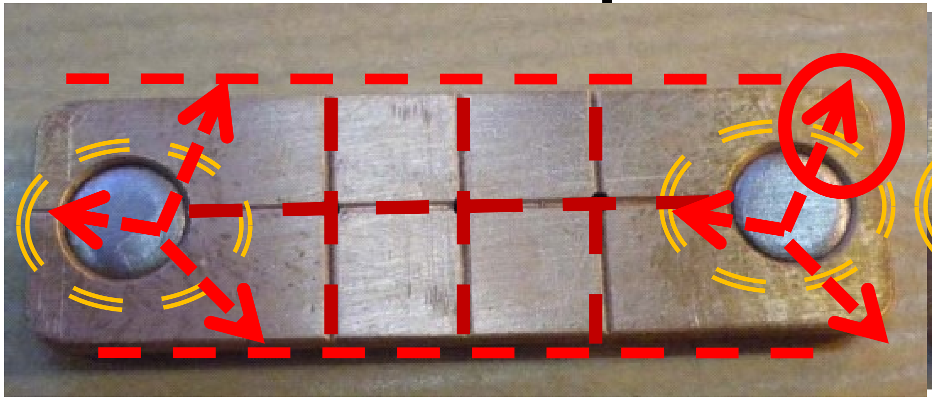
Shunt

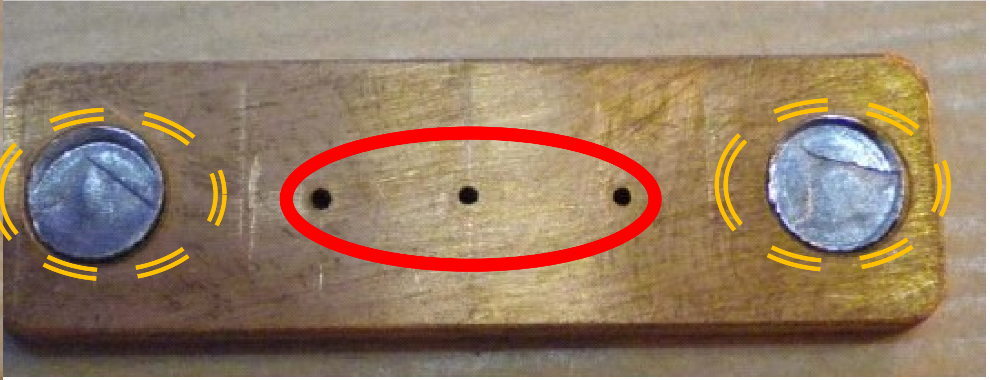


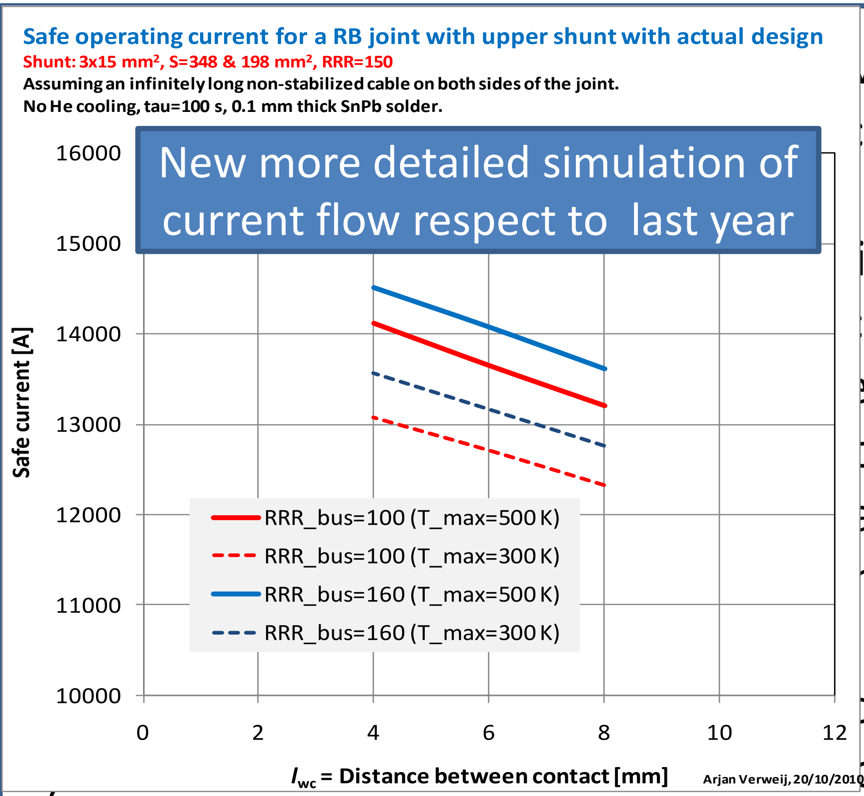
4 shunts for each dipole connection, 2 pairs on each side fully redundant, plus the basic connection

2 shunts for each quadrupole connection, 1 on each side , plus the basic connection

Shunt present configuration







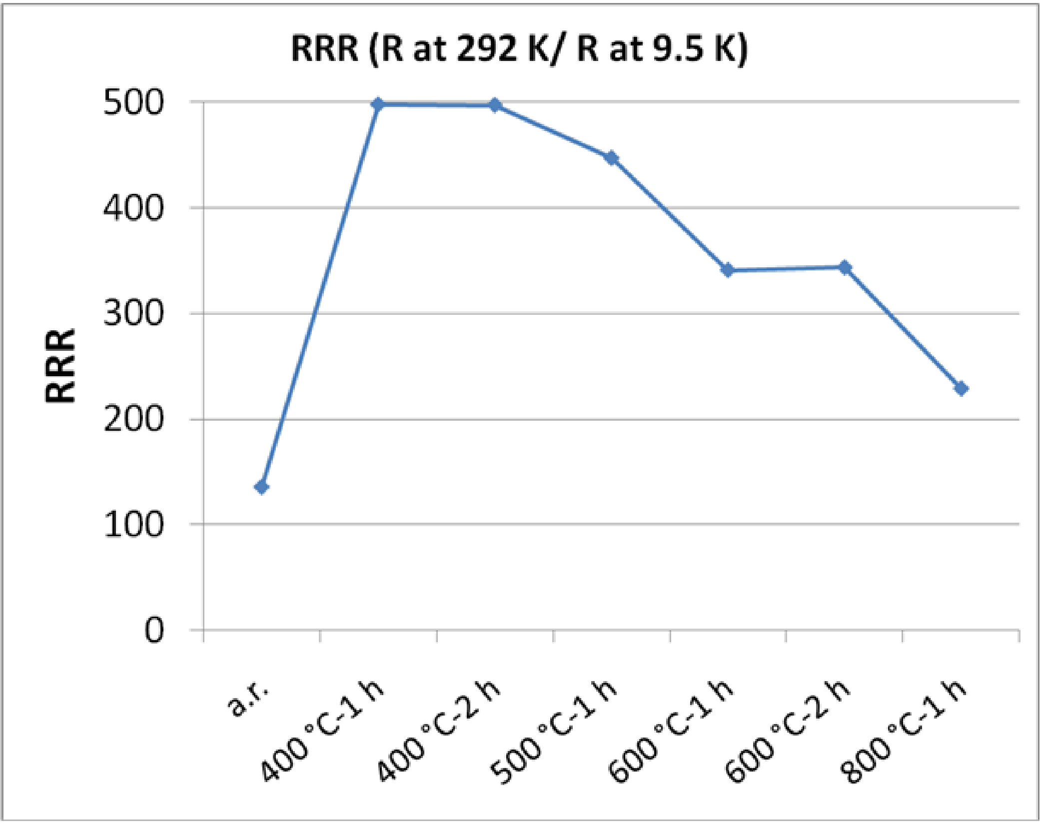
Safe operating current for a RB joint with upper shunt with actual design

Shunt: 3x15 mm², S=348 & 198 mm², RRR=150

Assuming an infinitely long non-stabilized cable on both sides of the joint.

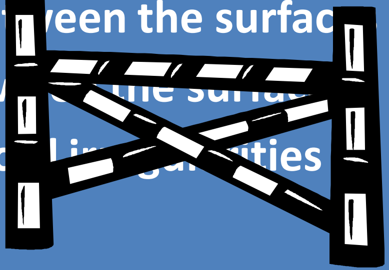
No He cooling, tau=100 s, 0.1 mm thick SnPb solder.

New more detailed simulation of current flow respect to last year



RRR (R at 292 K/ R at 9.5 K)

Adapting the shunt to the surface, *Mahomet goes to the mountain*



Interconnection geometrical defects:

- **Shift between the surfaces**
- **Tilt between the surfaces**
- **Superficial irregularities**

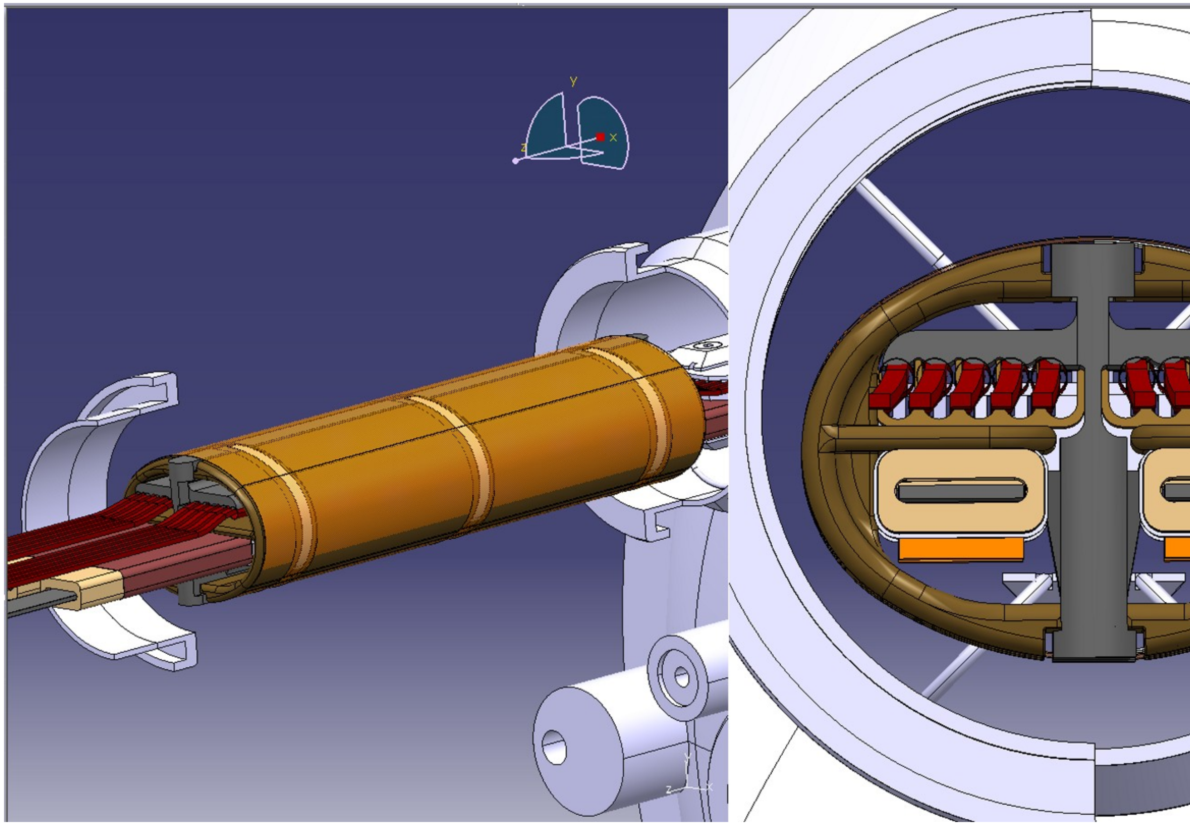
Adapting the surface to the shunt or bringing the

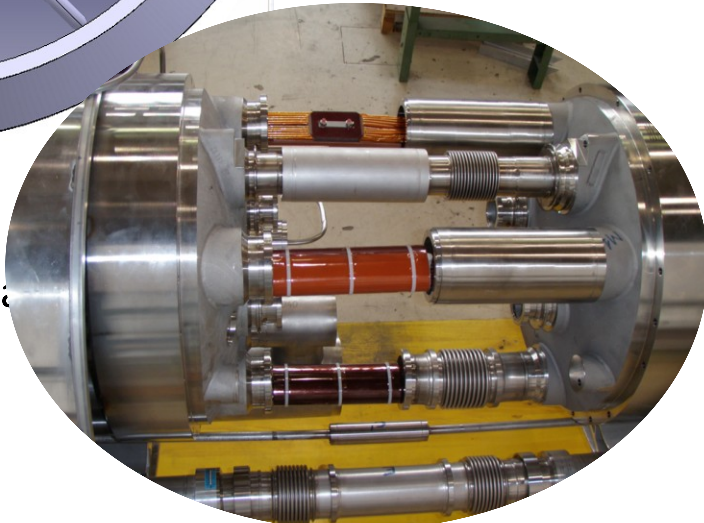
The insulation box
And the clamping

Requirements

- Provide the following insulation capacity
  - Better or equal to previous insulation if possible
  - Respect document LHC-PM-ES-0001 (“VOLTAGE WITHSTAND LEVELS FOR ELECTRICAL INSULATION TESTS ON COMPONENTS AND BUS BAR CROSS SECTIONS FOR THE DIFFERENT LHC MACHINE CIRCUITS”)
- Restrain the lateral deformation of the interconnect in order to significantly reduce associated stresses
- Of easy assembly, not constraining the bus bar in unnatural position that could generate new unforeseen stresses, complying with bus bar shape defects *up ±3 mm in horizontal and ±5 mm in vertical*
- Fulfill cryogenic conduction and hydraulic impedance requirements (computed and verified by TE-CRG as acceptable)
- Withstand radiation dose of the worst arc interconnect for 20 years (1 MGy including safety factor 10 verified by EN-STI)
- Providing enhanced cooling
- Improve electrical separation between spools and main circuits

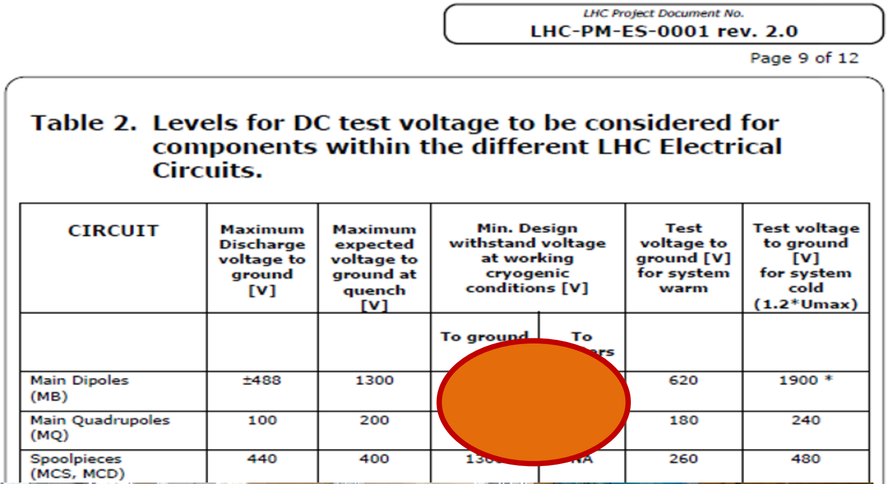
Design & assembly procedure
MQ and spools bus bars





1) Shunt soldering in position
2) Spool bus bars “comb” pieces introduction
3) Central insulation piece introduction between the bus ba
4) Lateral insulation pieces introduction
5) Polyimide foil wrapping around insulation pieces
6) 316L collars tie clamping around

Electrical and mechanical requirements



LHC Project Document No.
LHC-PM-ES-0001 rev. 2.0

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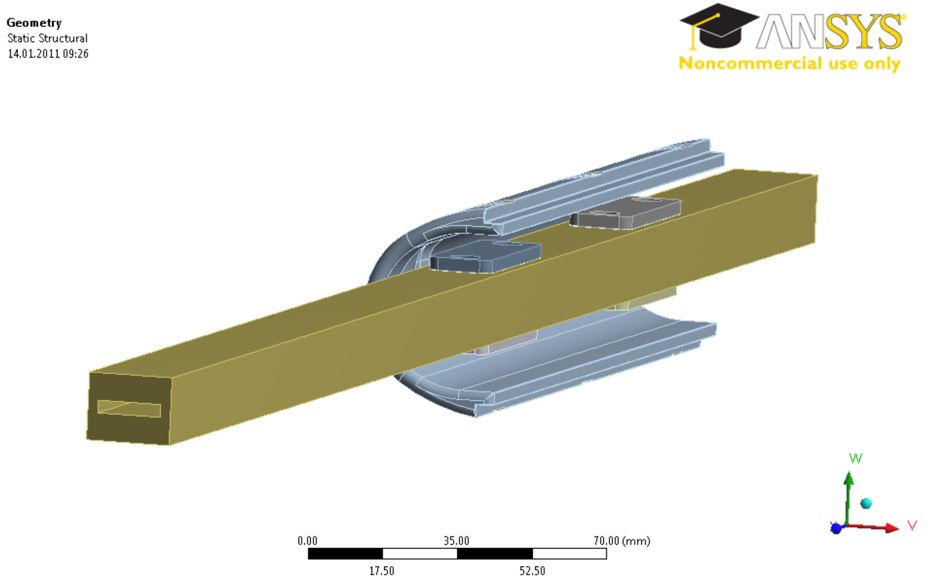
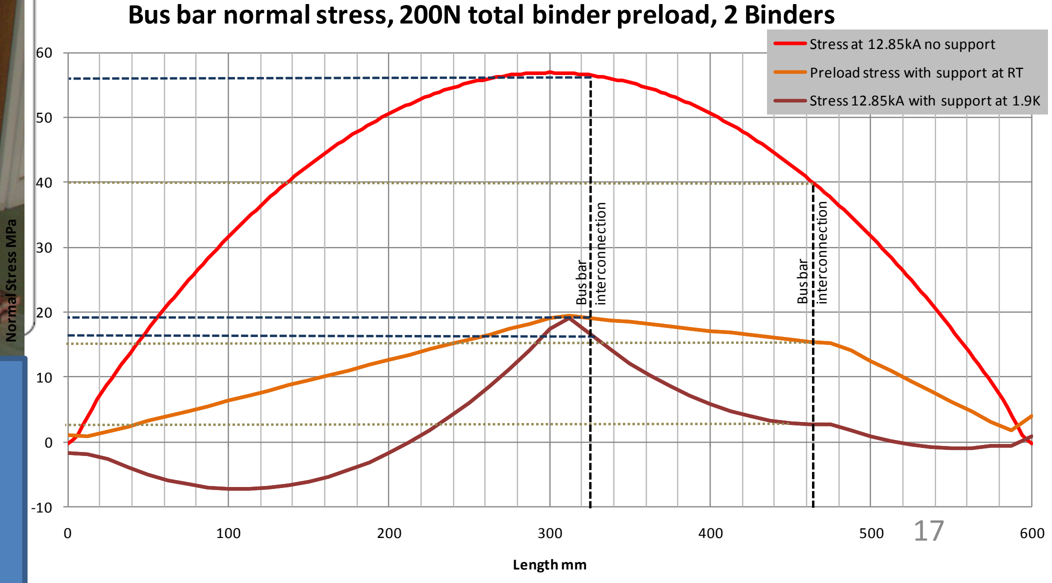
Table 2. Levels for DC test voltage to be considered for components within the different LHC Electrical Circuits.

CIRCUIT	Maximum Discharge voltage to ground [V]	Maximum expected voltage to ground at quench [V]	Min. Design withstand voltage at working cryogenic conditions [V]		Test voltage to ground [V] for system warm	Test voltage to ground [V] for system cold (1.2*Umax)
			To ground	To [illegible]rs		
Main Dipoles (MB)	±488	1300	[illegible]	[illegible]	620	1900 *
Main Quadrupoles (MQ)	100	200	[illegible]	[illegible]	180	240
Spoolpieces (MCS, MCD)	440	400	130	NA	260	480





New insulation withstand between 3.3 kV and 6.8 kV a 1 bar He. In next future we will try improvement to increase margin on the lower bound

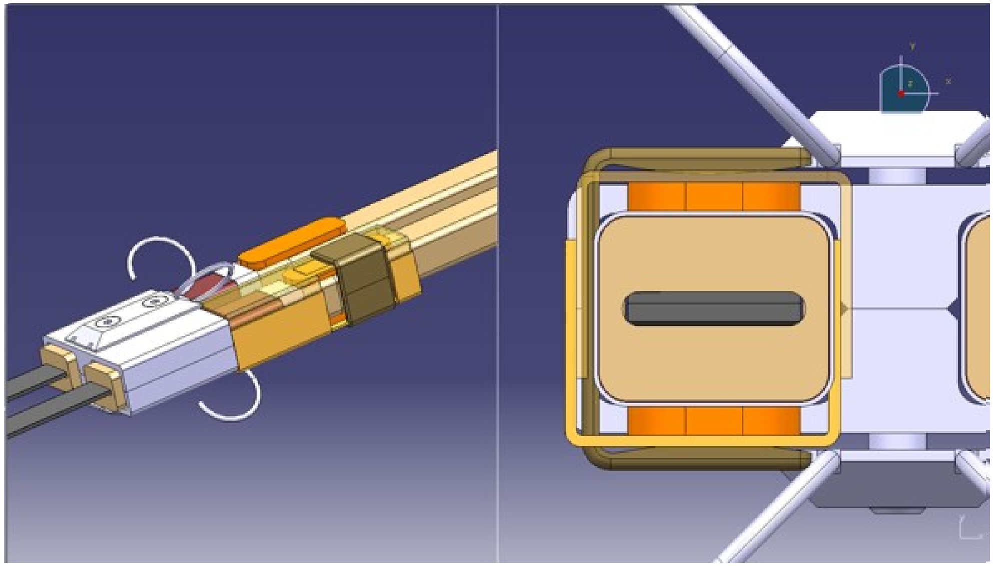
Reinforcement of the connections

13 kA connection

We would use a steel cable tie with a spring blade the possible longitudinal movement will be blocked by the insulation positioning pads

Shunt

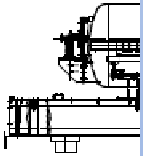
Mandatory not to deplete the electrical insulation and to integrate the system in the whole redesign of the connection.

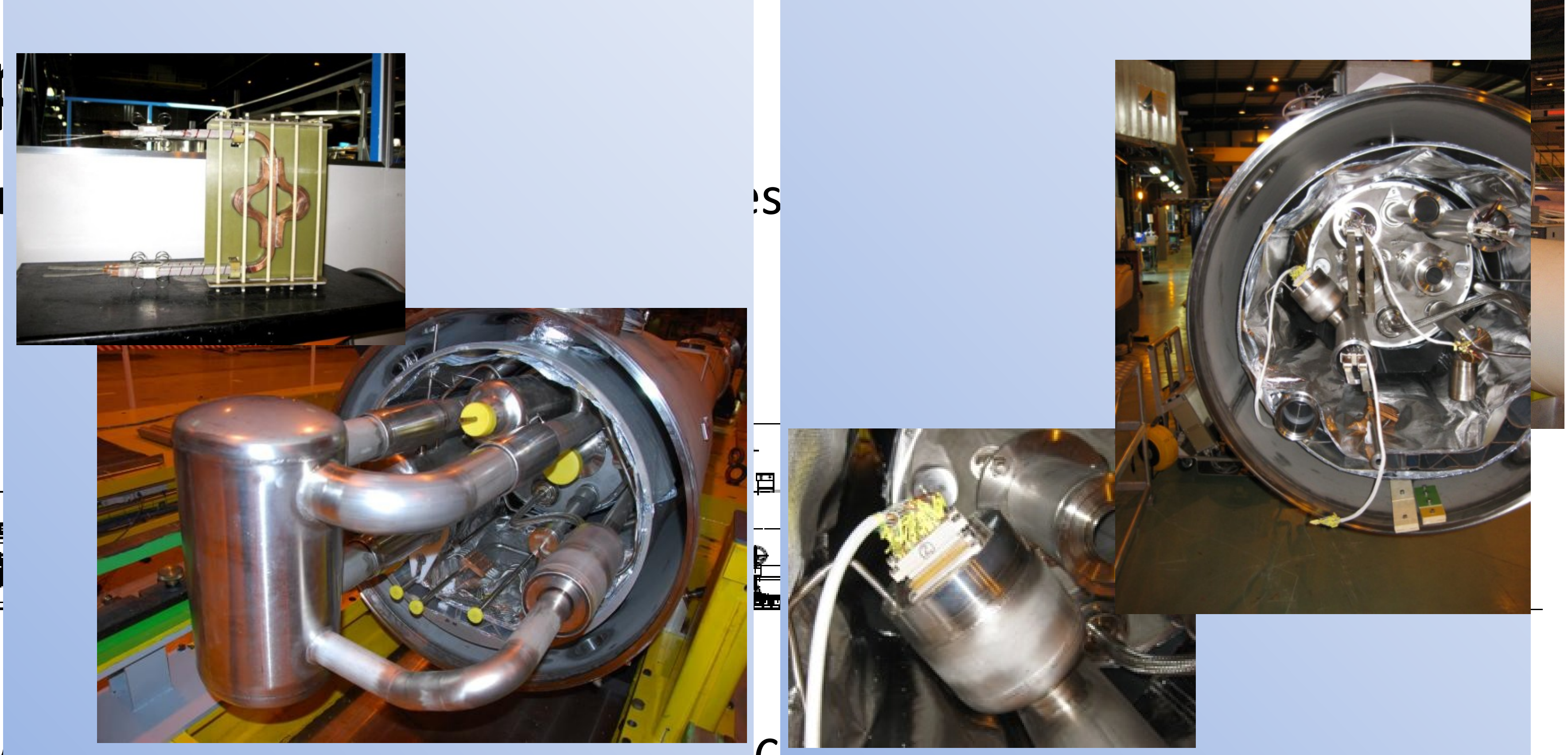


Shunt test

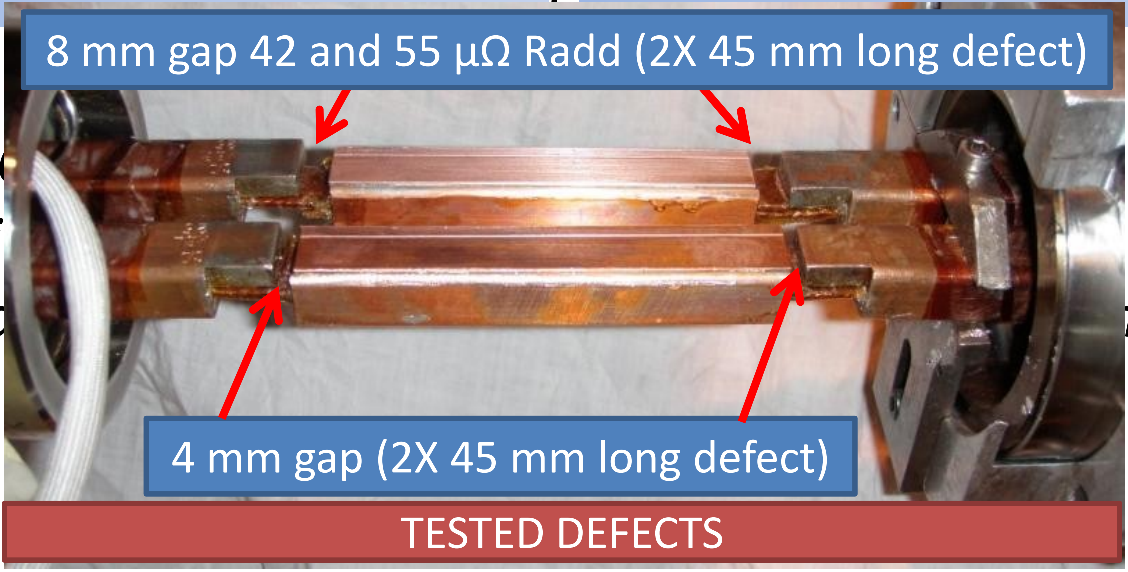
Exp

- Fi es





- *Su c*
  of 2.1 m
- *Use of two M are passing*
  through provi magnet and
  the its inducto nt shape as
  we want

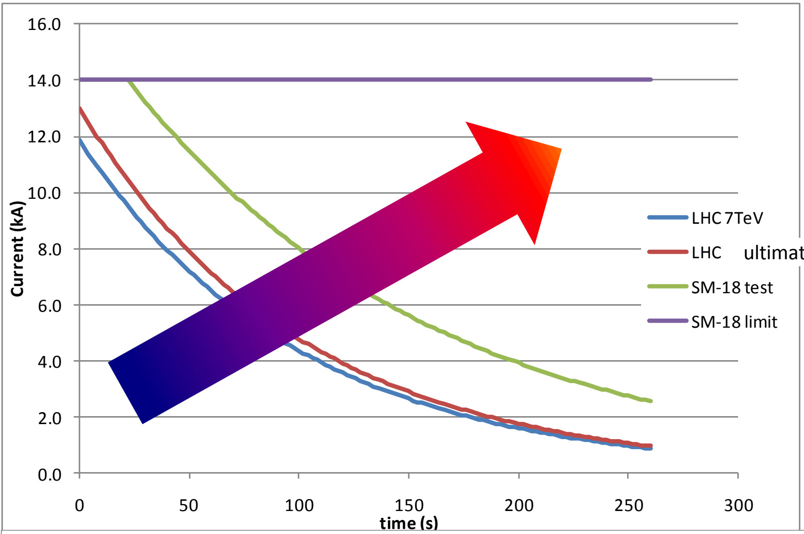


8 mm gap 42 and 55 μΩ Radd (2X 45 mm long defect)

4 mm gap (2X 45 mm long defect)

TESTED DEFECTS

Thermal runaways in the interconnections



LHC 7TeV and LHC ultimate

Very quick recovery of the normal zone, no thermal runaway

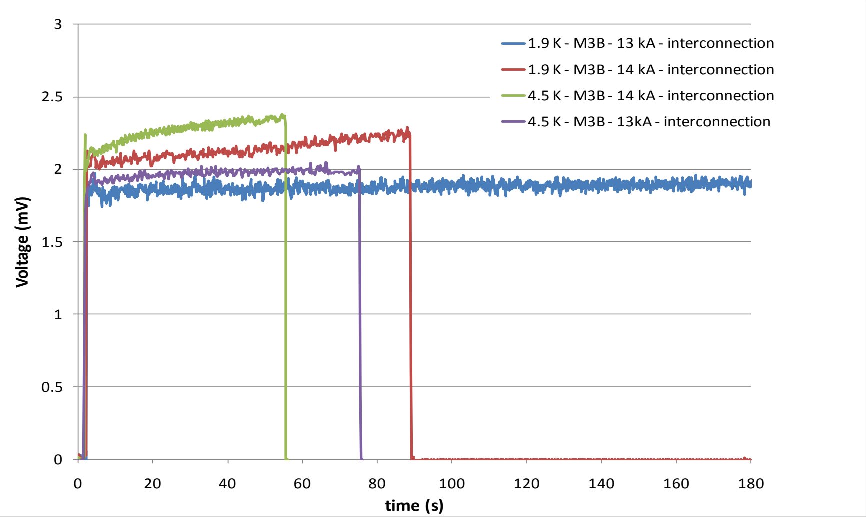
Test cycle: 14 kA, τ = 100 s

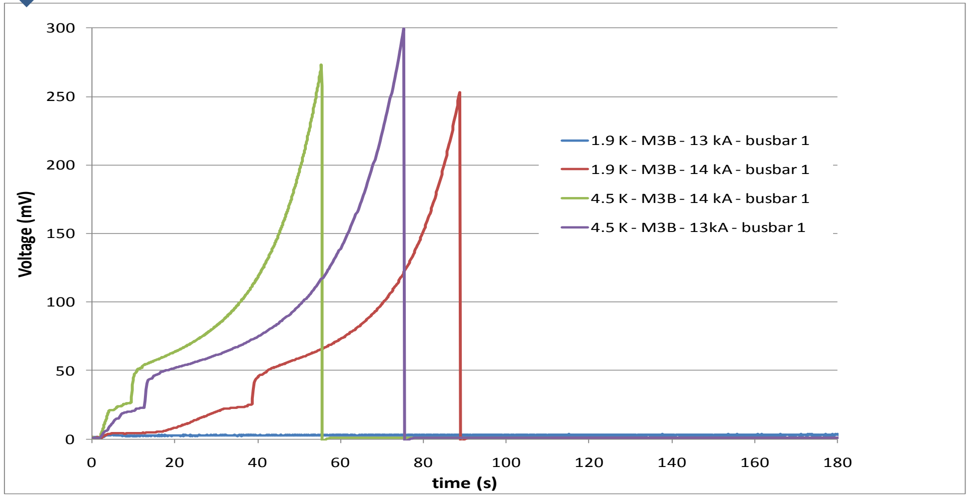
Test cycle: 14 kA, τ = 140 s

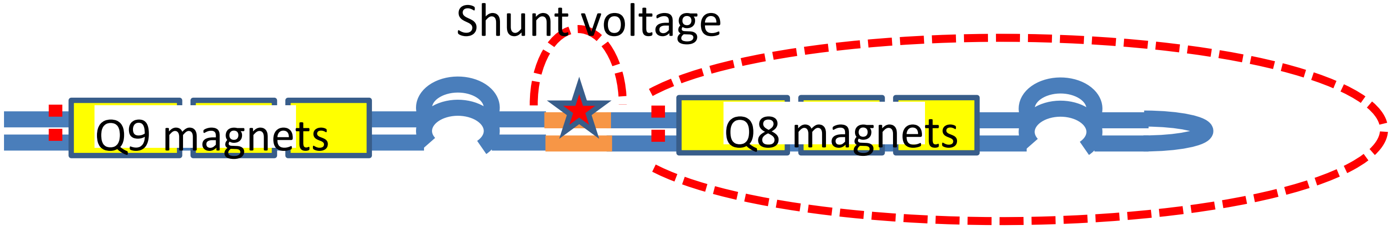
Test cycle (Sm18 test): 14 kA for 22 s, then τ = 140 s.

Still no signs of thermal runaway in the most critical shunt!!

Therefore we went to constant currents of 13 and 14 kA (power supply limit) and increased bath temperature







busbar voltage

Review recommendations

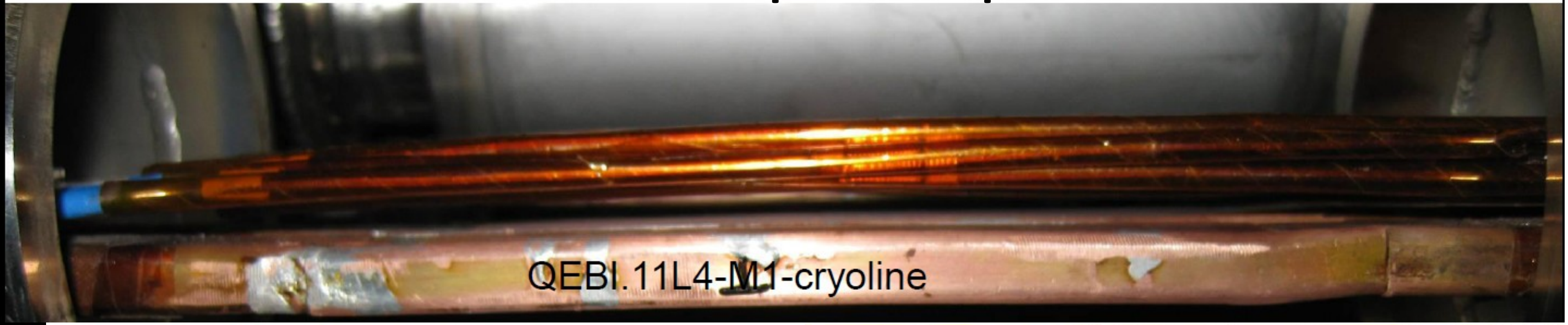
(18-22 October 2010)

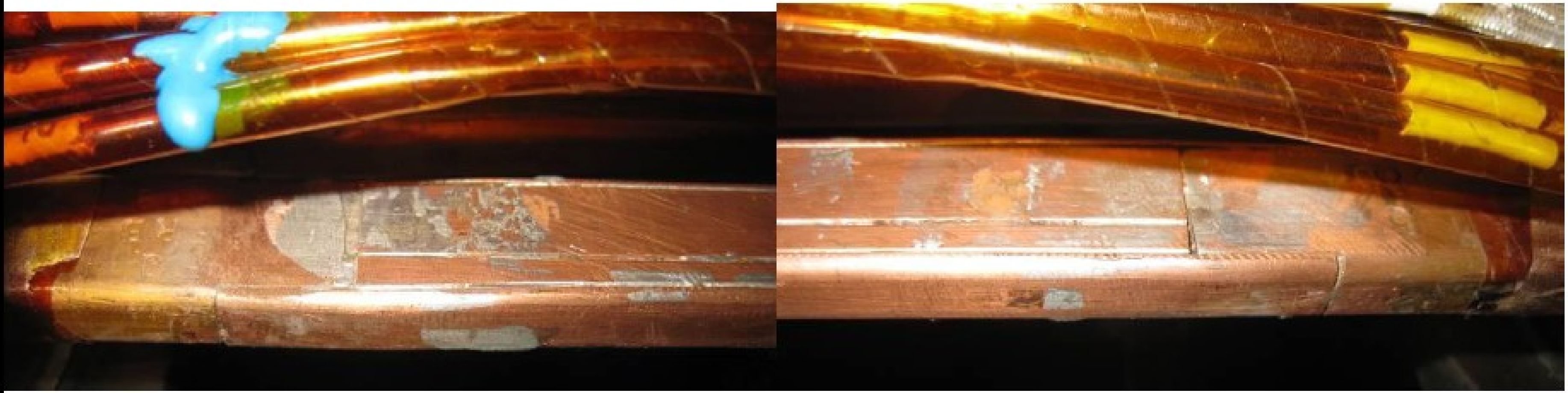
And nearby future

Review: technical recommendations

- The present LHC splice is not a reliable system also when rebuilt and the use of redundant shunt is recommended also for quadrupole line
  - See next 2 slides
- Pursue the development of a clamp to hold together the system (without providing preload and not ensuring the same level of electrical resistance of soldered connection)
  - See previous slides, design ongoing
- Improve understanding of tests pushing to a full adiabatic case testing
  - SM18 is going ahead with life simulation tests, 5,900 *(objective 10,000)* current cycles have been performed *(14kA, force 40% higher then 11.85kA)* up to now without showing deterioration of electrical resistance. Full adiabatic condition are not applicable because we cannot eliminate the solid conduction through the bus bars. We will investigate possibility to make the test even more severe if we deem representative of the machine possible conditions. Installed insulation in the interconnection provide today already much worst condition respect to the future tunnel installation. We still need full modelling of SM18 validation test.
- Consider testing of shunt applying non destructive mechanical tests to verify its correct application
  - We estimate that systematically applying a mechanical load for testing is a risky approach (could cause non detectable flaws, i.e. crack initiation). Stress levels are very low. We will qualify the correlation electrical resistance – soldered surface. We will consider other approaches (random mechanical sampling, develop novel technology?)

Redundant shunt on quadrupole connection I





Issue number 1

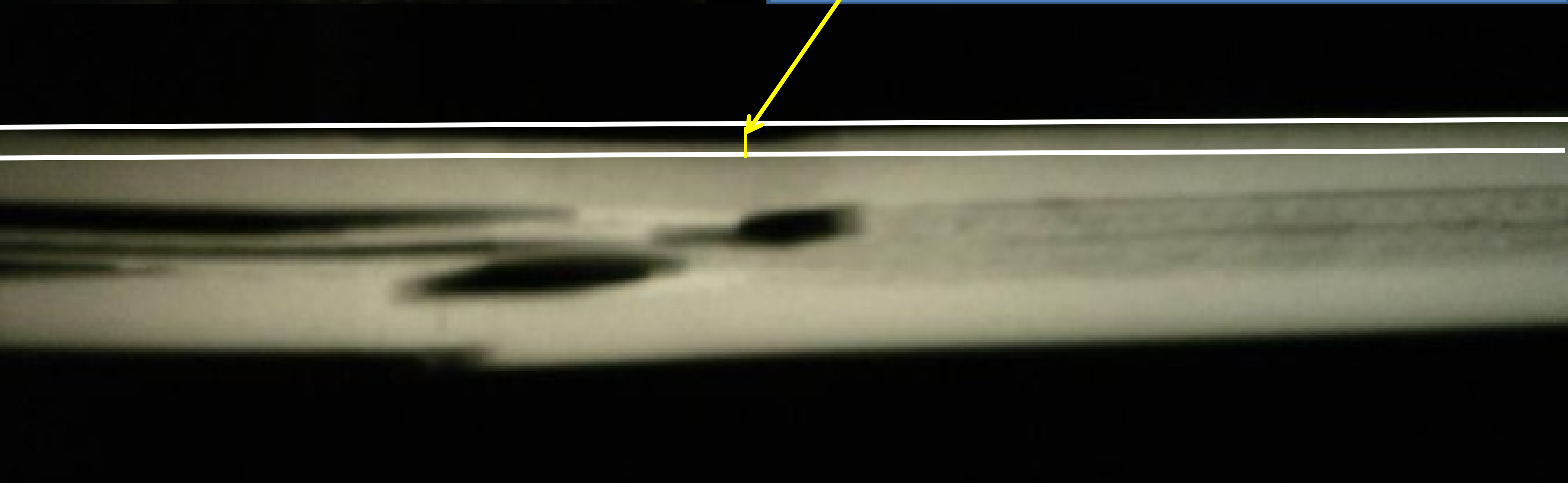
The limited vertical space below the spools (20 mm on one side and 10 mm on the other side). does not allow the machining of copper to provide a flat surface without risks for the spools connection and cable integrity itself.

The soldering of the shunt with the present techniques is also not possible because of space constraints.

Redundant shunt on quadrupole connection II

Tooling used in the series assembly was pressing on the “tongues” of the bus bar (see marks on left photo) and creating a difference of level that should be machined out i.e. in the γ-ray **1.3 mm.** This would leave only 2 mm of bus bar copper.

Application of redundant quadrupole shunt requires the development of a complete different approach, requiring a different extra production step in the activity and probably not insuring the same quality of electrical contact

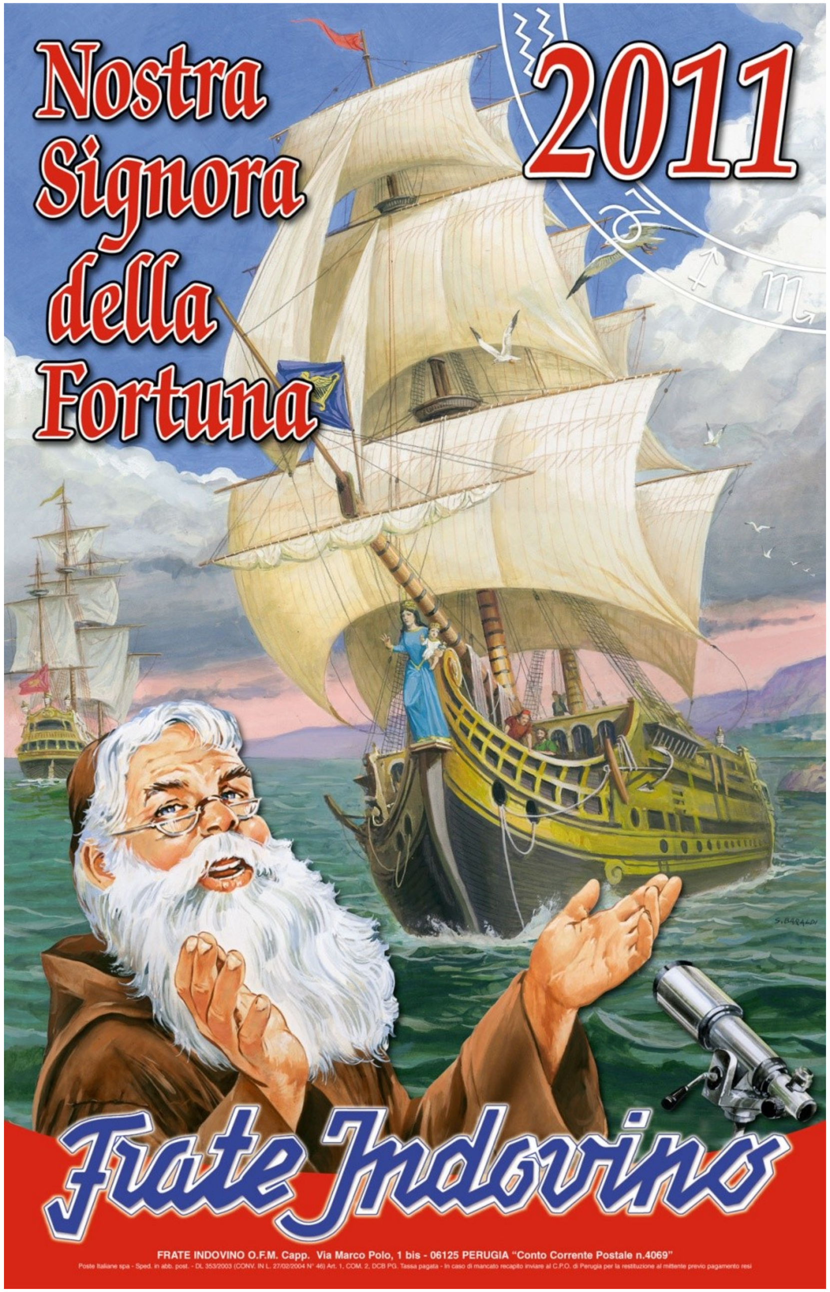


If the 2012 shut down is confirmed, we can be ready, but resource allocation has to be prioritized because of other TE-MSC-LMF section main tasks:

1) **Repairs of dipoles from 3-4 to replace defective units**
2) **Repairs of quadrupoles from sector 3-4 to re-establish nominal optics**
3) **Construction of bus bars for the collimation in point 3**

item	End of development	End of technical qualification	End of full procedure test with repeatability	Technical specification	Pre-series at CERN (1 sector)	Series at CERN
quadrupole present shunt (tooling and comp)						
Quad redundant shunt	*June 2011*	*September 2011*	*November 2011*	*October 2011*	*January 2012*	*March 2012*
Orbital cutting	May 2011	June 2011	June 2011	July 2011	September 2011	October 2011
Orbital welding	May 2011	June 2011	September	NA	NA	November

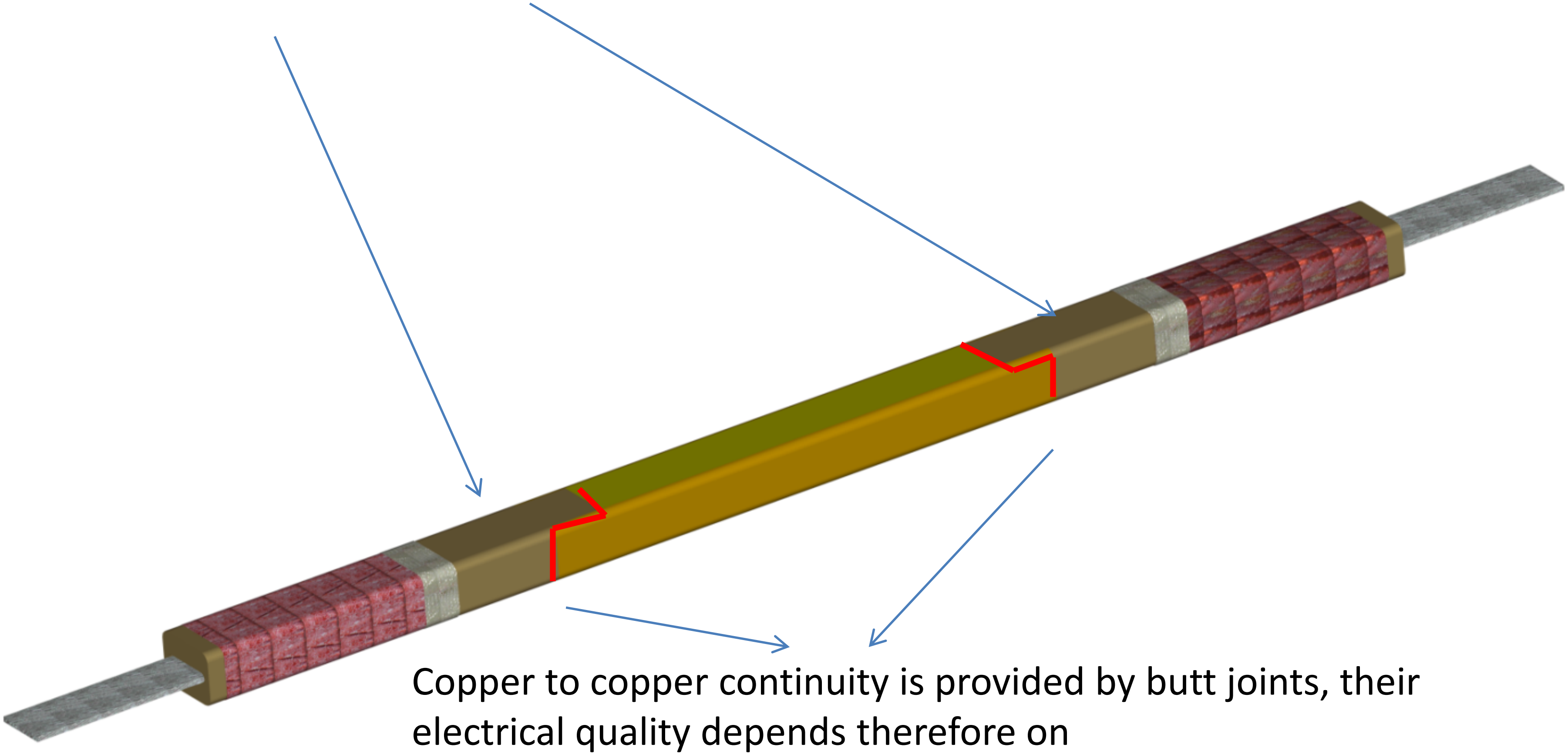
The old Grandma’s management book



Extra slides for questions

The problem

Partial melting of the Sn-Ag in the bus bar during connection soldering, loss of solder, lack of contact between copper and Sc cable over XX mm

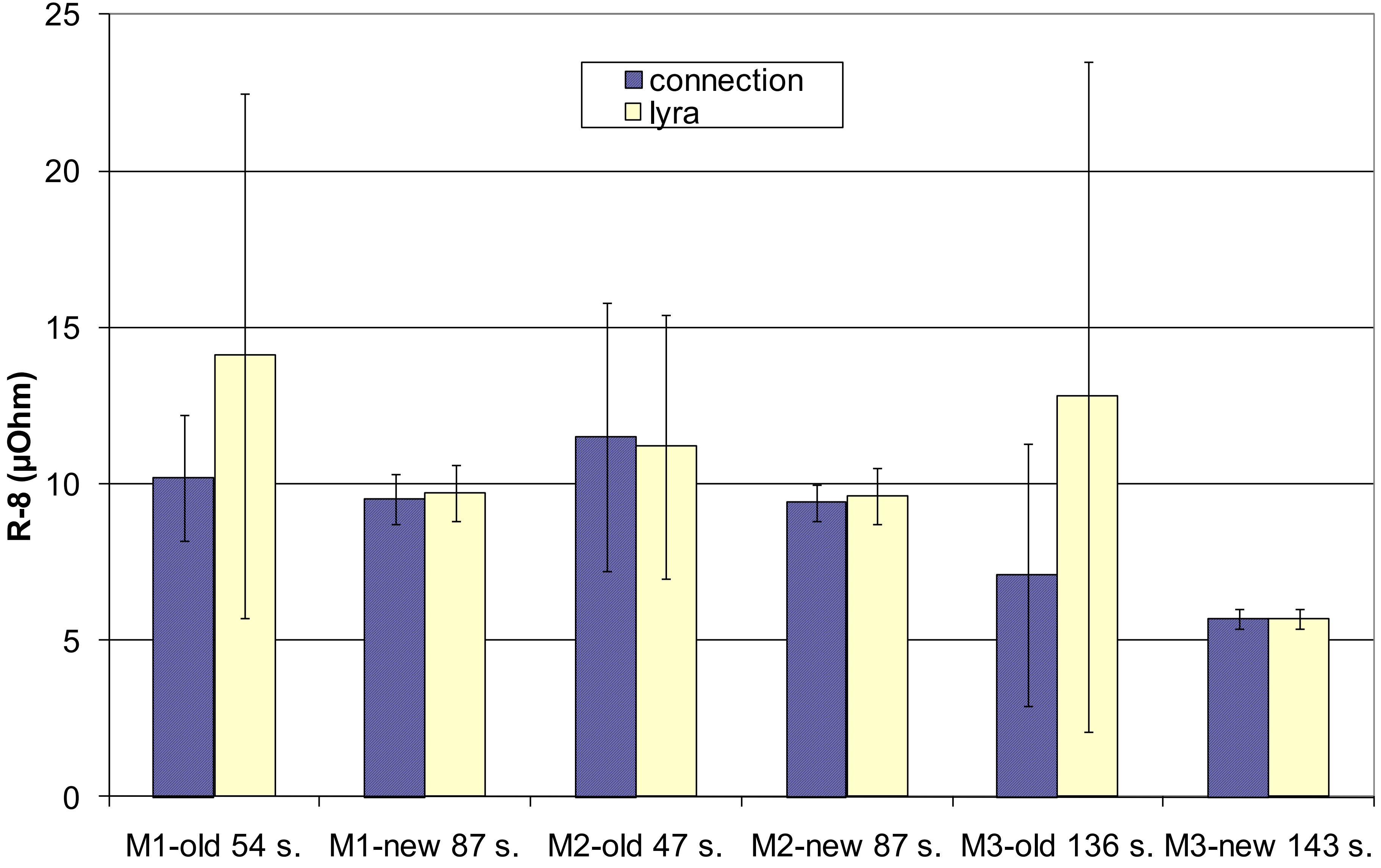


Copper to copper continuity is provided by butt joints, their electrical quality depends therefore on

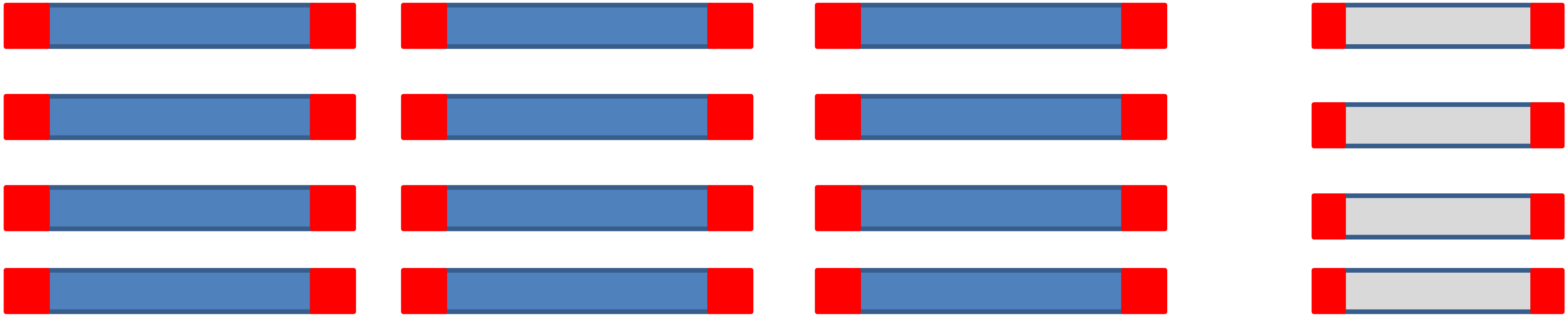
1) The tolerances of the mating surface
2) The respective tolerances between 2 paired bus bars
3) The cleaning of the surfaces
4) The capacity of the soldering to fill the gap providing good contact
5) Correct execution of the soldering

Redoing the 13 kA interconnect can we do better ?

Comparing the connection quality between the series production and the 3-4 reassembly



Re-building a piece of LHC machine

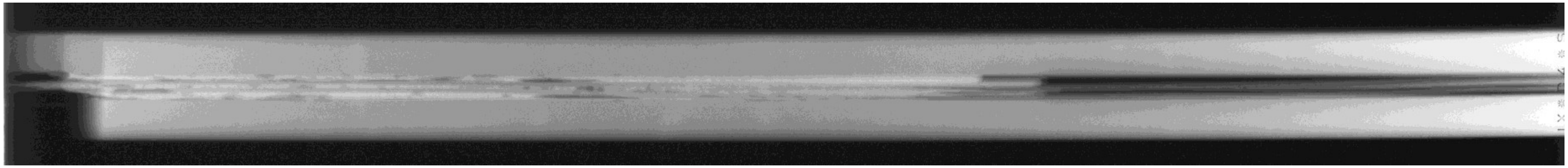


Gamma rays on MB interconnection samples

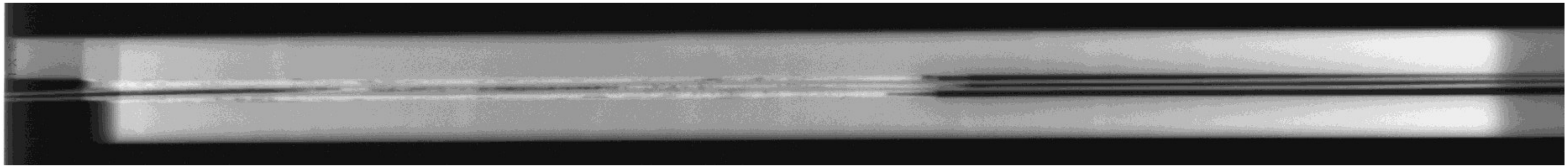
Best Result

Test Dipole Bus-Bar, inductor v.4, t_o=15 s, T_o = 240˚C

Left Side

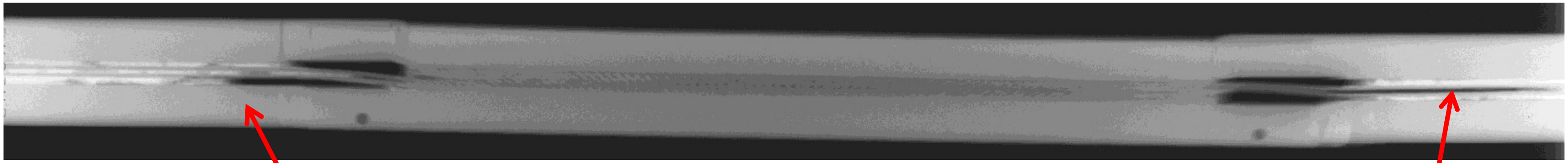


Right Side



L.S.

R.S.



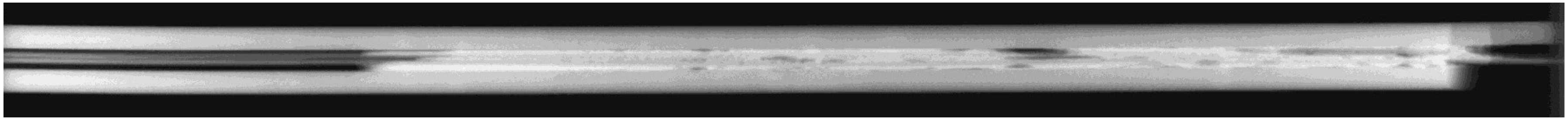
Acceptable Sn96Ag4 missing

≈5mm, no soldering material

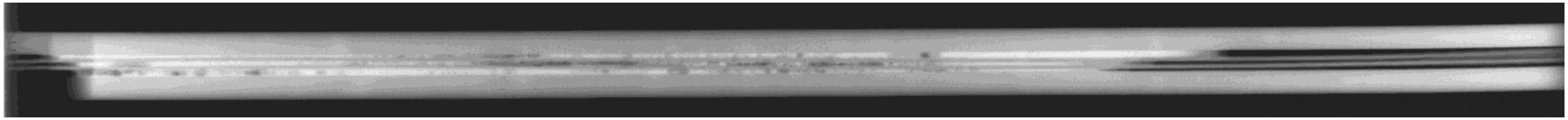
Gamma rays on MQ interconnection samples

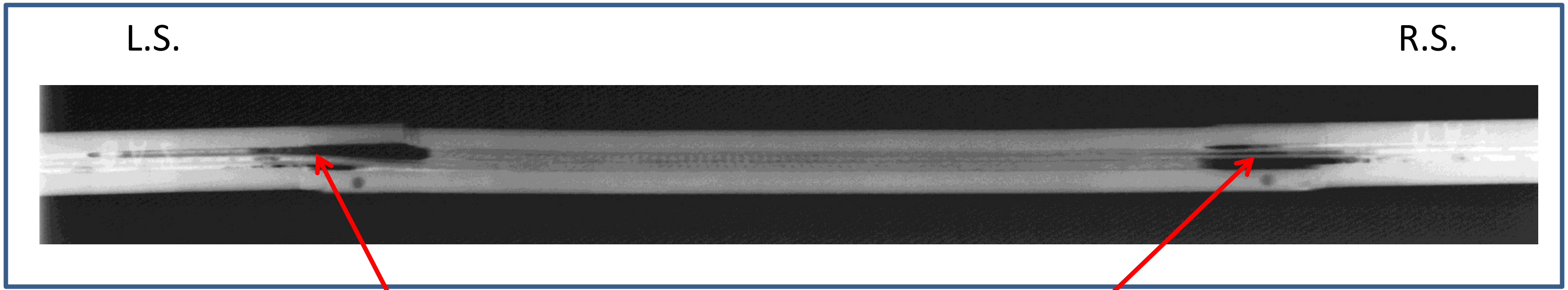
Test Quadrupole Bus-Bar, inductor v.4, t_o=15 s, T_o = 240˚C

Left Side



Right Side

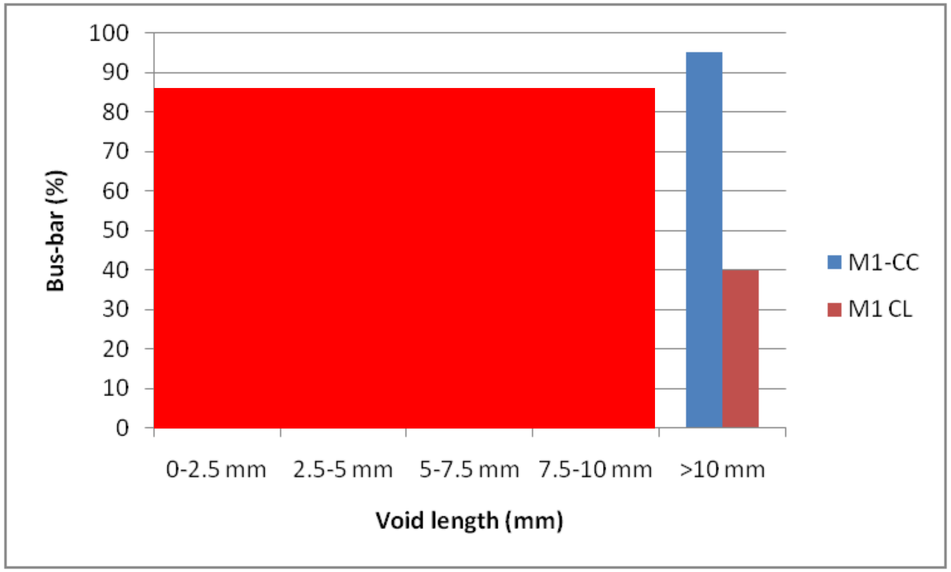


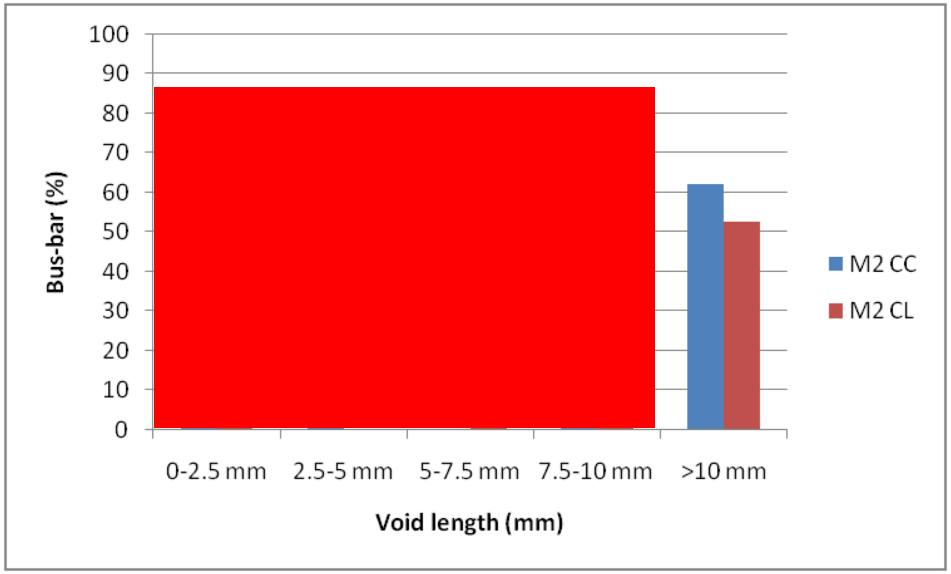


Void length < 10 mm

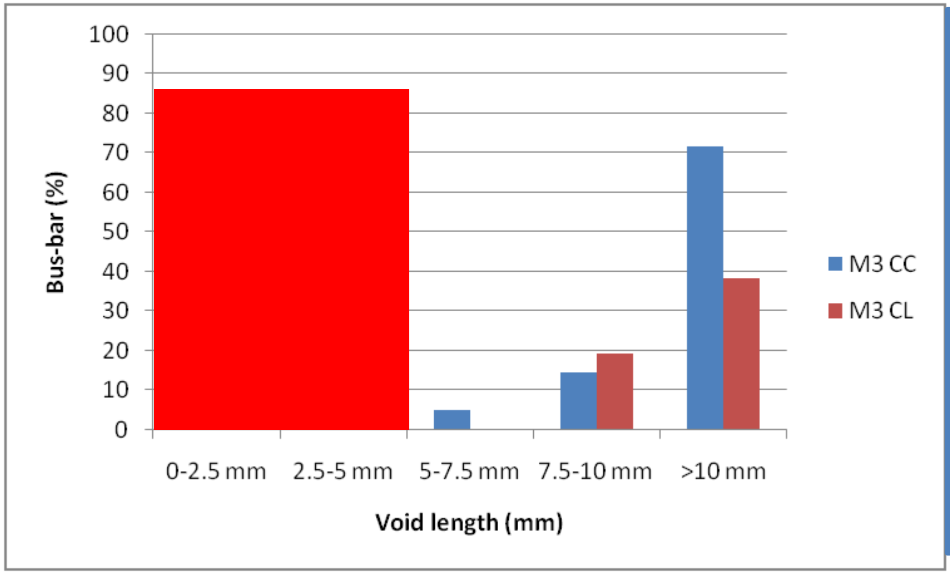
Estimated impact of the optimized soldering process

Data from 21 magnets experiencing problems after 3-4 accident



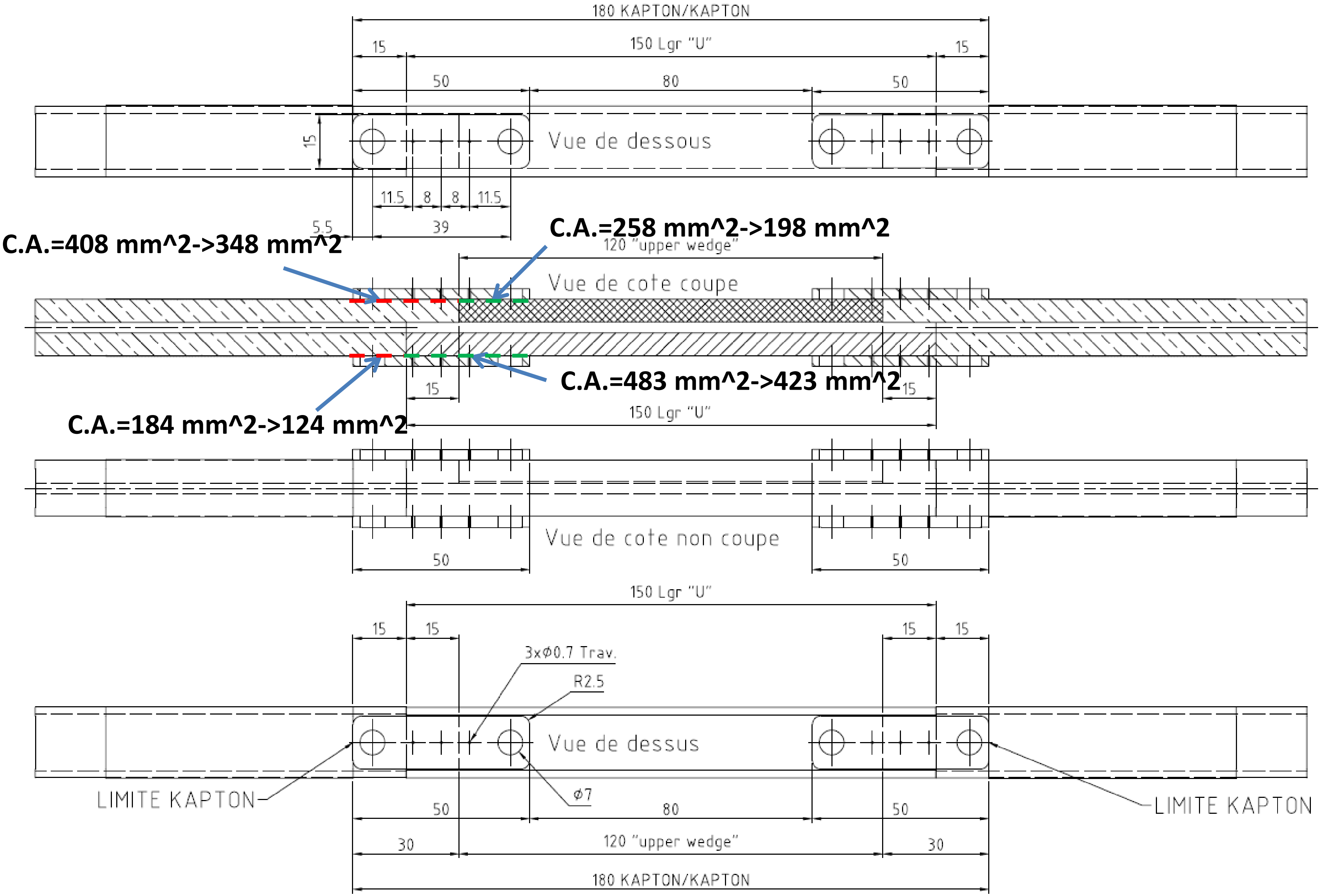


The void length has been averaged on the two connection sides.



- The overall average of the interconnection that could be affected by the new procedure is about
  - M1 60% CL 5% CC
  - M2 45% CL 40% CC
  - M3 40% CL 8% CC
- Indeed, what it could change is the distribution of connections having a void length below 5 mm for MB and 10 for MQ.

The shunt



C.A.=408 mm^2->348 mm^2

C.A.=258 mm^2->198 mm^2

C.A.=483 mm^2->423 mm^2

C.A.=184 mm^2->124 mm^2

The soldering process I

Reflow

- **A band of solder is positioned between the shunt and the bus bar and melted in situ**

Capillarity

- **The solder is contained in 2 “reservoir”, the 2 copper surfaces are in contact and the melted solder migrates and wet the surfaces by capillarity**

The soldering process II

Reflow

- possibility to accommodate more irregular surface
- More regular solder thickness but normally thin 0.03-0.08 (good for electrical properties **but not for mechanical**)

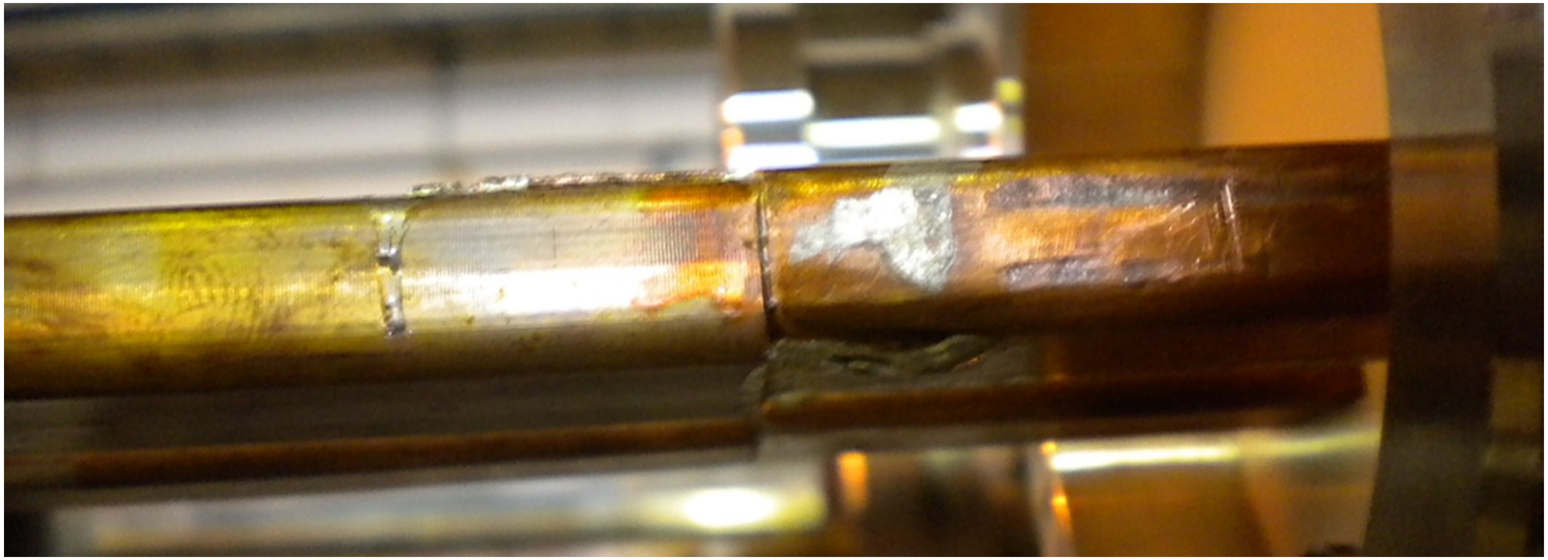
- Risk of surface de-wetting due to the flux trapped
- Need to follow temperature profile by operator that needs to act in order to press the pieces together when the solder melts
- Change of heat conduction in the moment when pieces are pressed together with T overshooting

Capillarity

- The melted solder moves as a wave pushing ahead the flux and reducing the risk of trapped flux (Swiss cheese defect)
- Impossible to forget the solder during mass production, quantity of solder pre-determined
- Easier visual inspection (solder comes from the centre so if the fillet on the edge is good the solder has passed by)
- No need to compensate the solder melting mechanically pushing down the shunt

- Strongly affected by the surface quality
- More irregular solder thickness, but thicker 0.07-0.11 mm

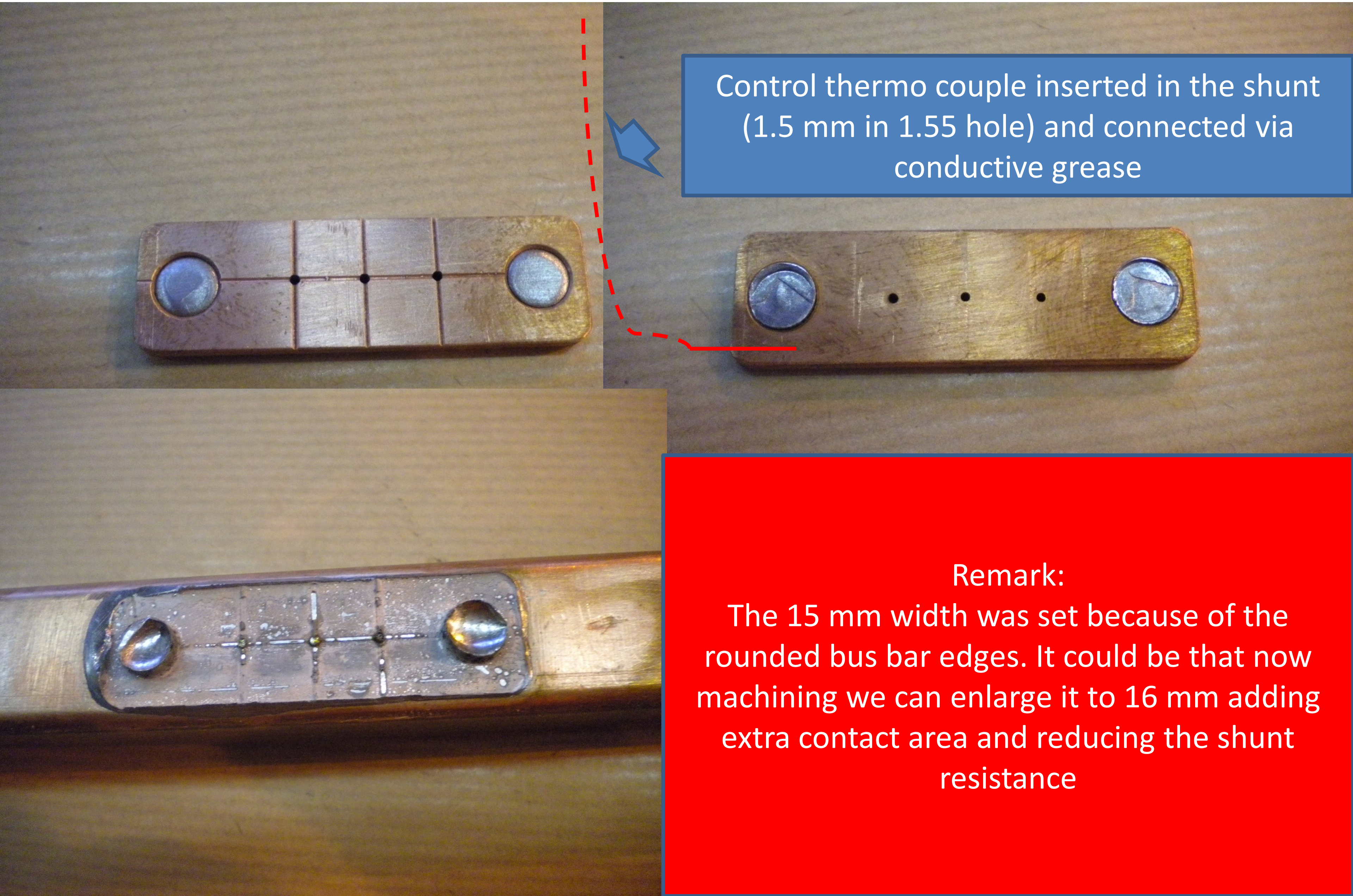
A typical tunnel bus bar connection



Interconnection geometrical defects strongly reduce the quality of the fitting between the shunt and the bus bar affecting the mechanical and electrical quality of the joint. This defect is the sum of 3 types of defects

- Shift between the surfaces
- Tilt between the surfaces
- Superficial irregularities

Shunt present configuration and joint quality



Control thermo couple inserted in the shunt (1.5 mm in 1.55 hole) and connected via conductive grease

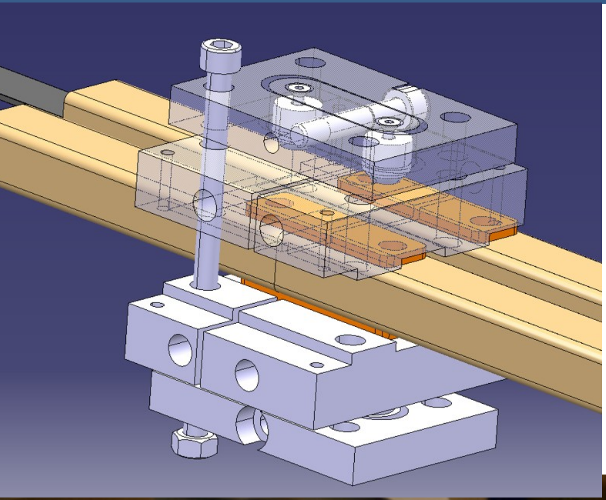
Remark:
The 15 mm width was set because of the rounded bus bar edges. It could be that now machining we can enlarge it to 16 mm adding extra contact area and reducing the shunt resistance

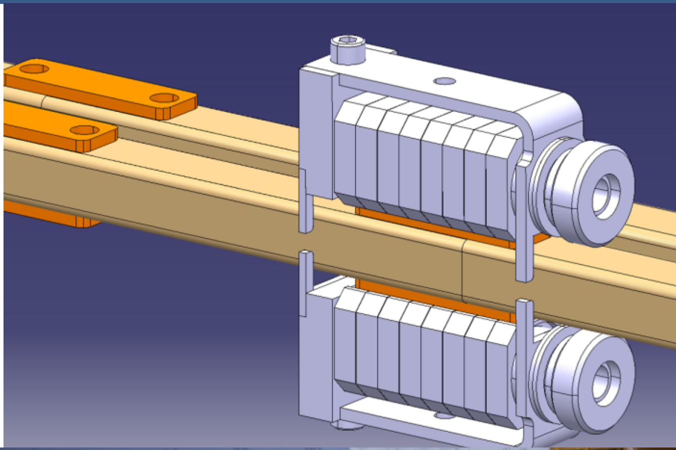
Heating

We tried successfully micro welding techniques, but this technology cannot be used due to the decision of doubling the shunt.

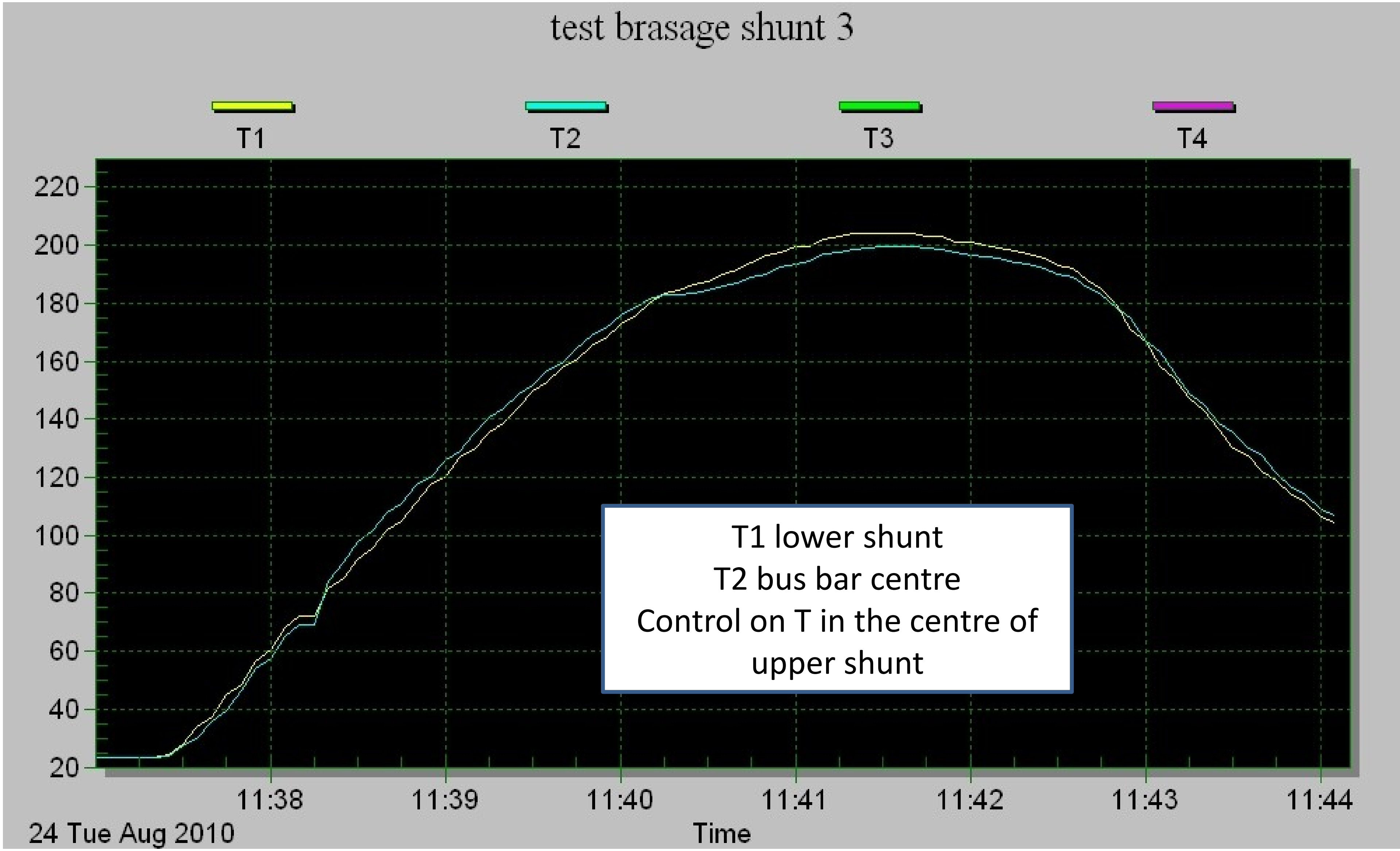
At the moment we have tested successfully 2 types of ovens

And exploring other non contact technologies





Temperature profiles during soldering



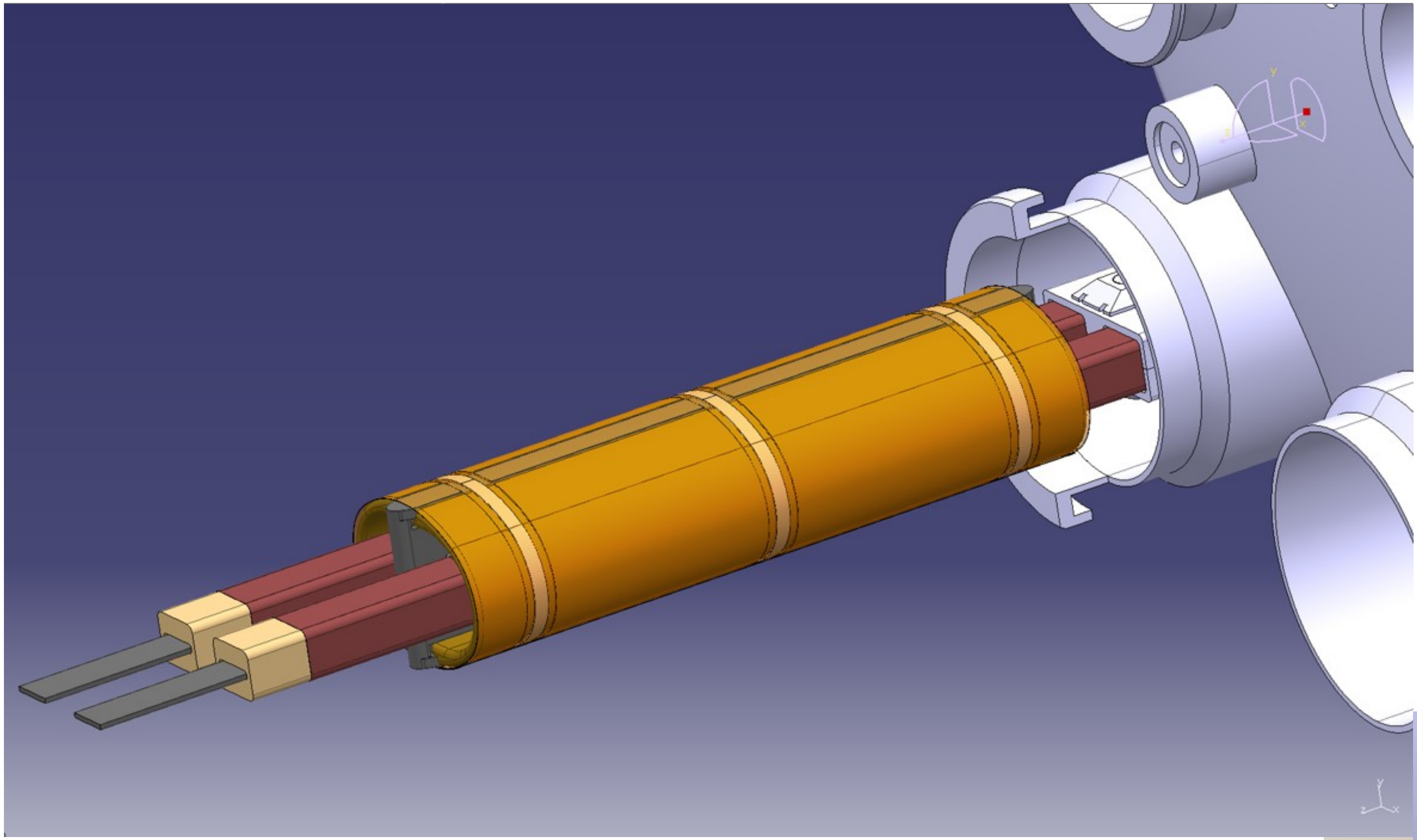
T1 lower shunt
T2 bus bar centre
Control on T in the centre of upper shunt

Shunt: the mechanical loads

Cause-situation	Repetition time	Description	Load type
Incident	Exce		ompression
Soldering	Once		f thermal contraction etween copper and during cool down to RT this state of stress y the creep
Cooling down-warm up	Few year		thermal contraction etween copper and
Current ramping	Few hundred times per year	Normal operation	-Stress distribution due to deformation induced by Lorentz forces between bus bar (repulsive force) -Electromigration effect in the shunt

The insulation box

Design & assembly procedure
MB bus bars



Isostatic assembly

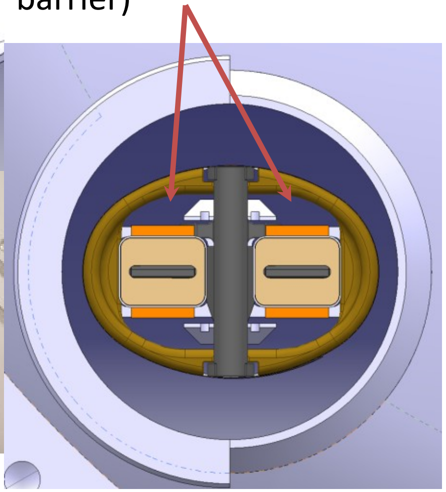
Mirror symmetry across H and V planes (assembly facilitate and cost saving)

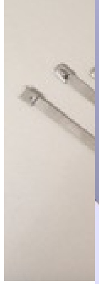
Allowed misalignment default V±5 mm, H±3 mm

Second insulation skin

Pre-stress adjusted with accurate tooling (5kg)

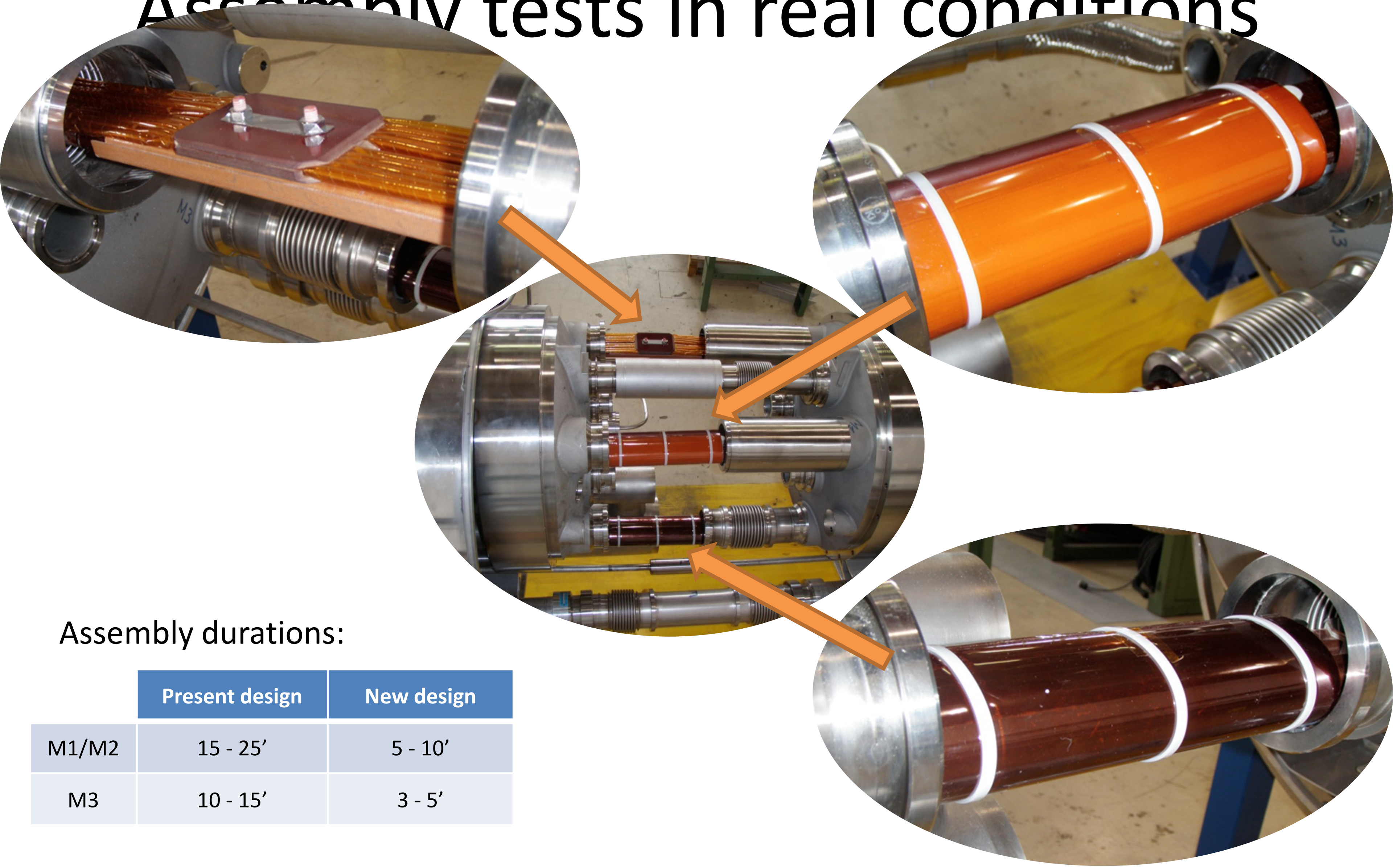
Helium ducts in order to give good cooling for the bus bars (no thermal barrier)





1) Shunt soldering in position
2) Central insulation piece introduction between the bus bars
3) Lateral insulation pieces introduction
4) Kapton foil wrapping around insulation pieces
5) 316L collars tie clamping around

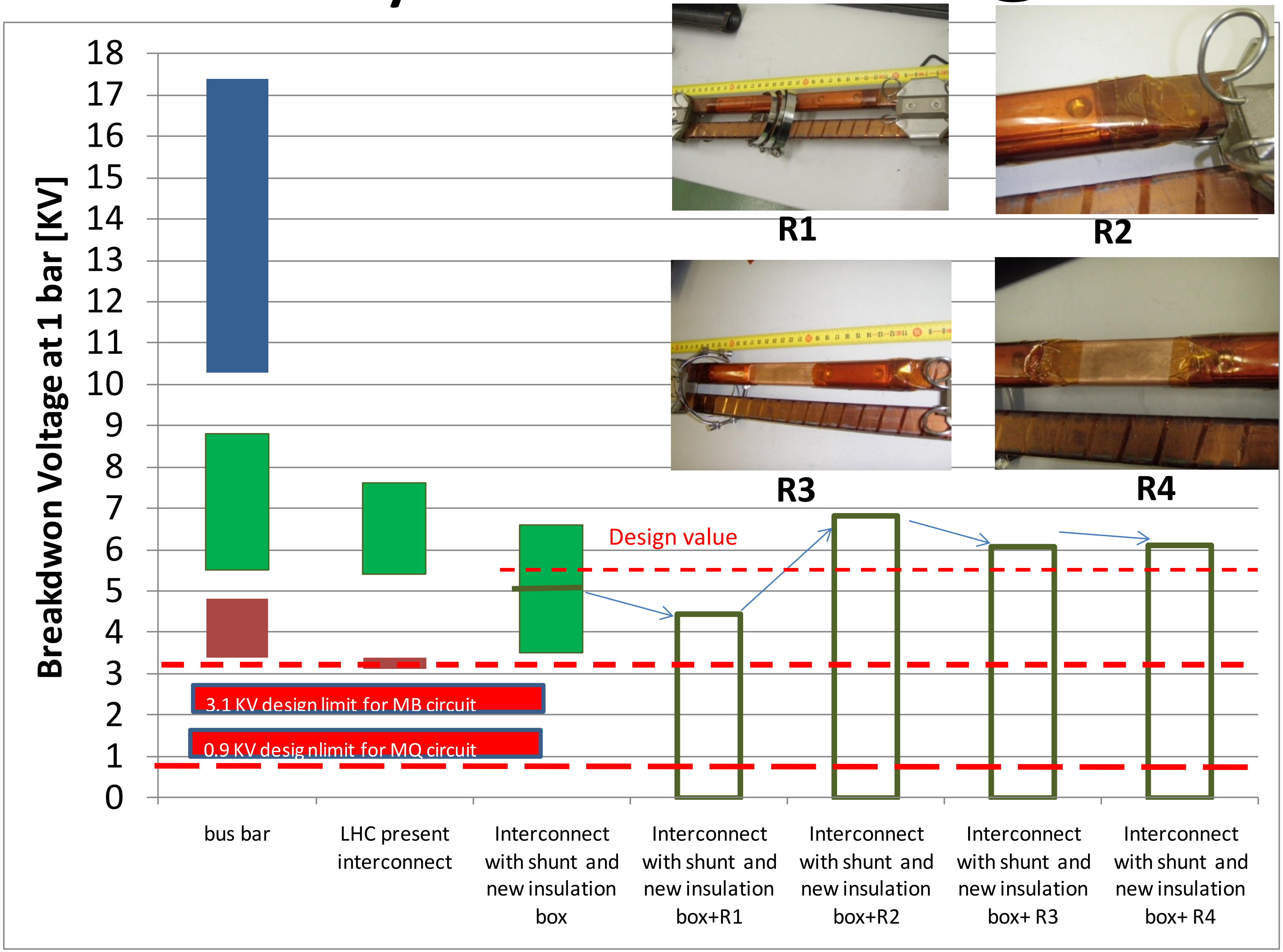
Assembly tests in real conditions

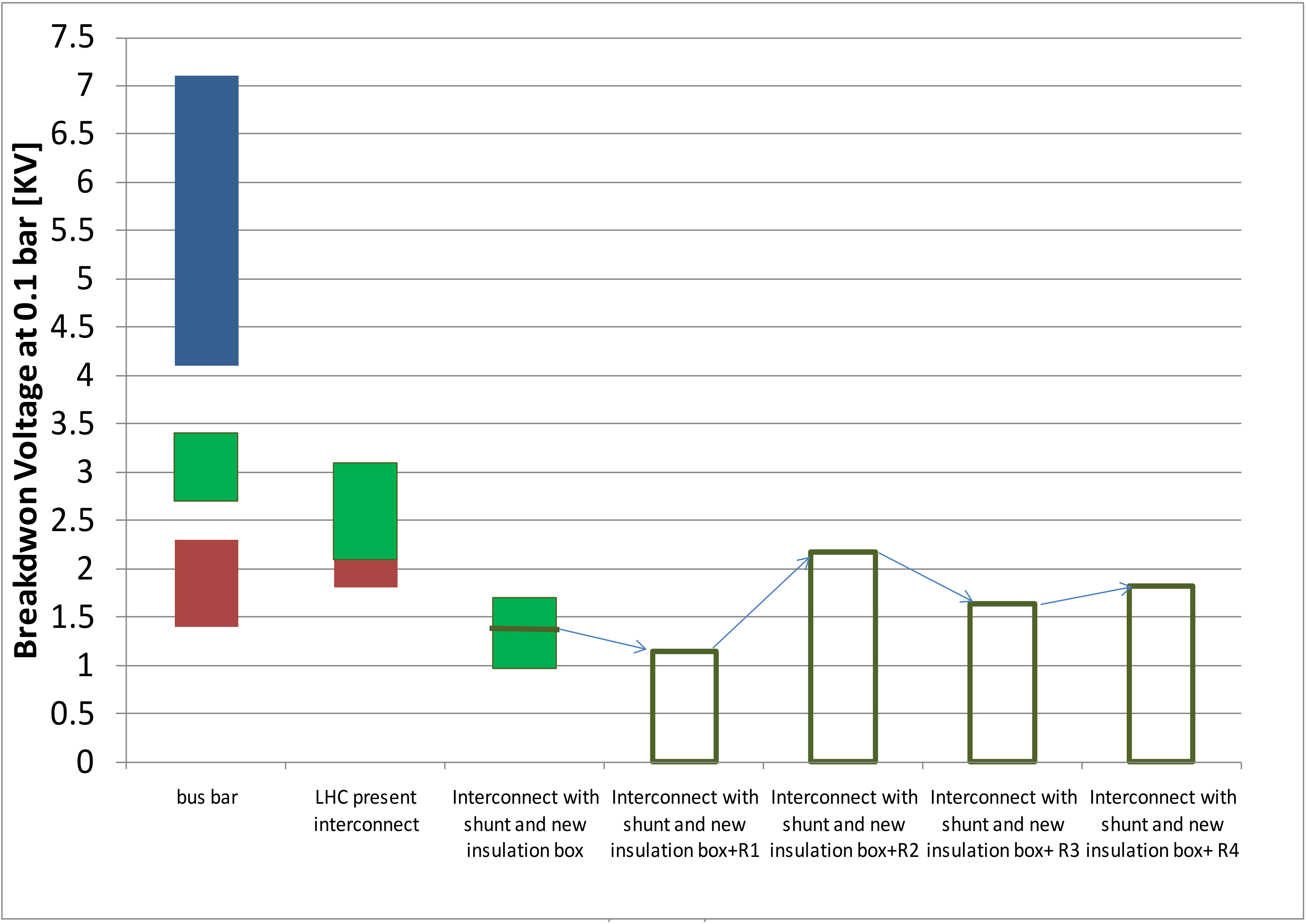


Assembly durations:

	Present design	New design
M1/M2	15 - 25’	5 - 10’
M3	10 - 15’	3 - 5’

Summary of test results @ 1bar




Breakdwon Voltage at 0.1 bar [KV]
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
bus bar
LHC present interconnect
Interconnect with shunt and new insulation box
Interconnect with shunt and new insulation box+R1
Interconnect with shunt and new insulation box+R2
Interconnect with shunt and new insulation box+ R3
Interconnect with shunt and new insulation box+ R4

Electrical requirements

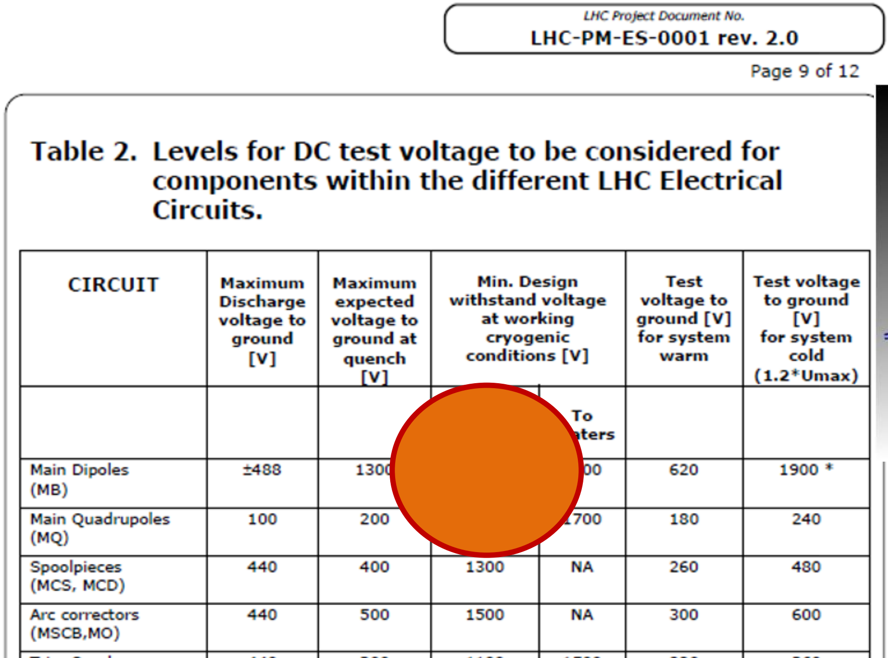


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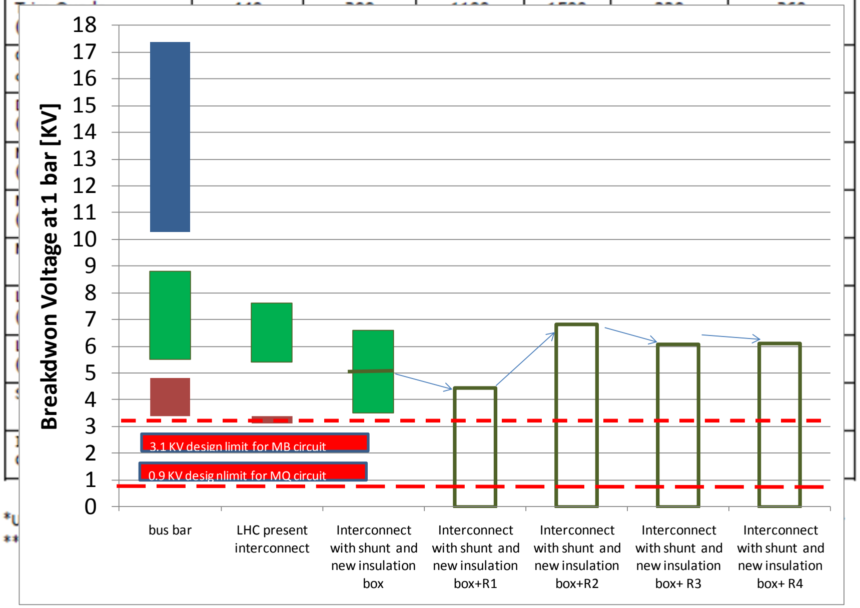
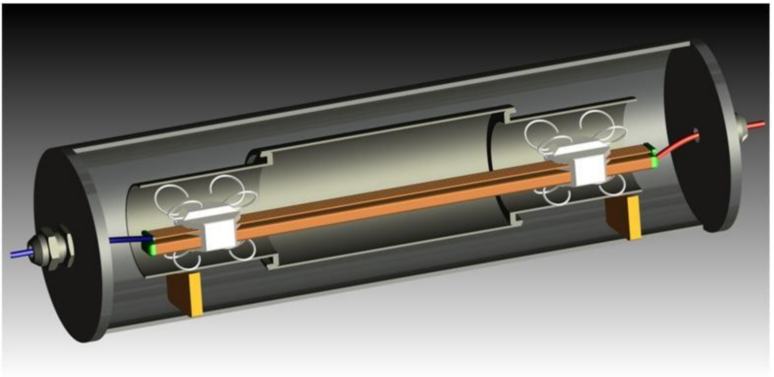
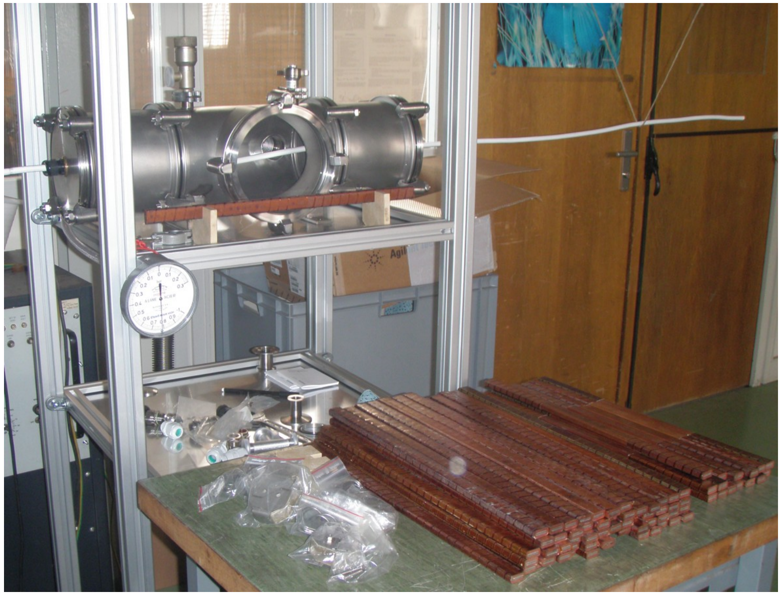
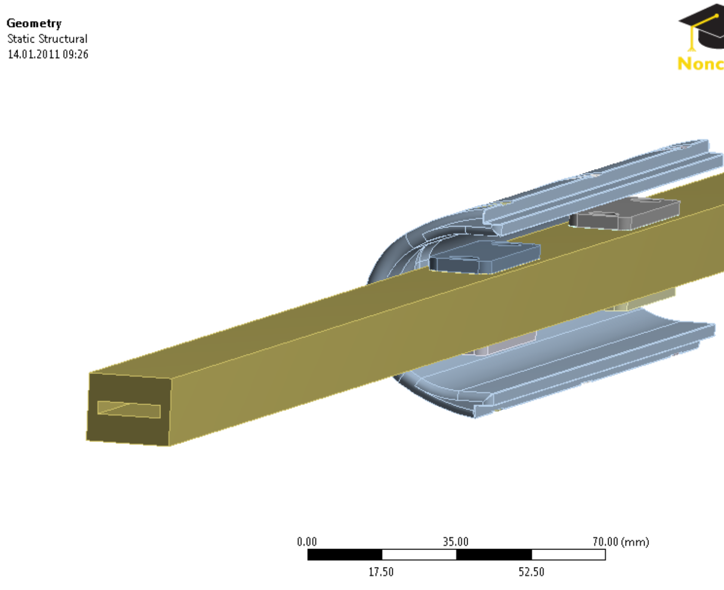
Table 2. Levels for DC test voltage to be considered for components within the different LHC Electrical Circuits.

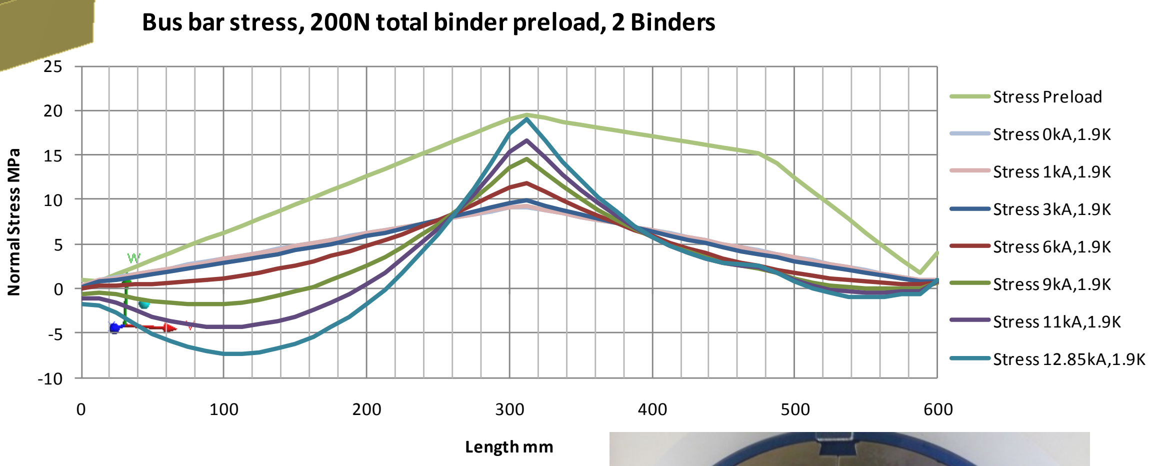
CIRCUIT	Maximum Discharge voltage to ground [V]	Maximum expected voltage to ground at quench [V]	Min. Design withstand voltage at working cryogenic conditions [V]		Test voltage to ground [V] for system warm	Test voltage to ground [V] for system cold (1.2*Umax)
				To aters		
Main Dipoles (MB)	±488	1300		00	620	1900 *
Main Quadrupoles (MQ)	100	200		700	180	240
Spoolpieces (MCS, MCD)	440	400	1300	NA	260	480
Arc correctors (MSCB,MO)	440	500	1500	NA	300	600

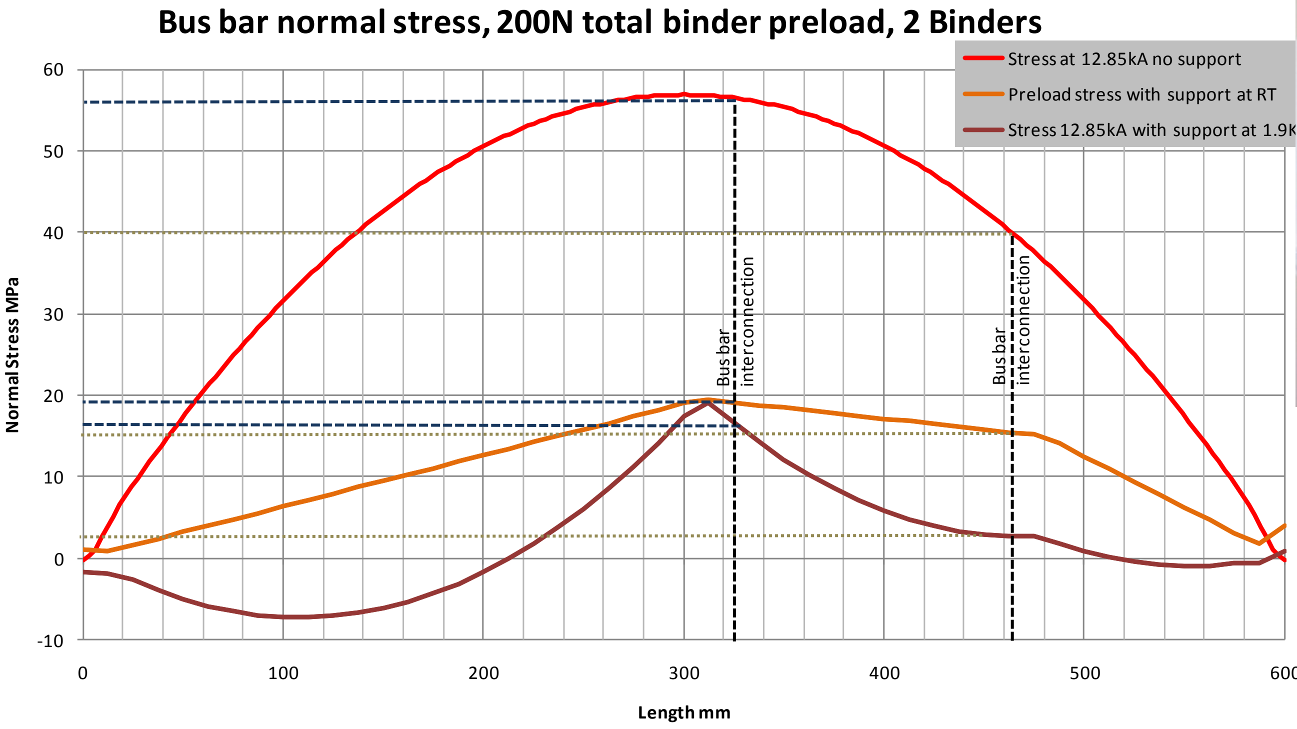


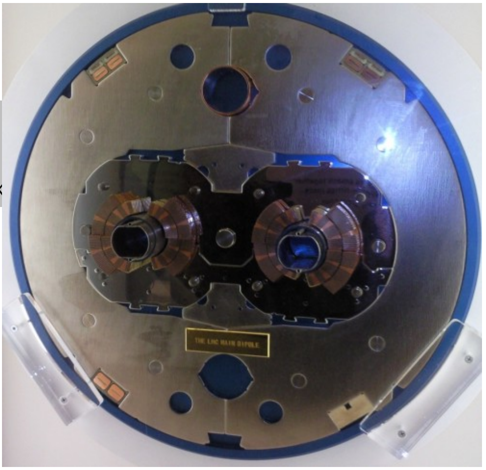




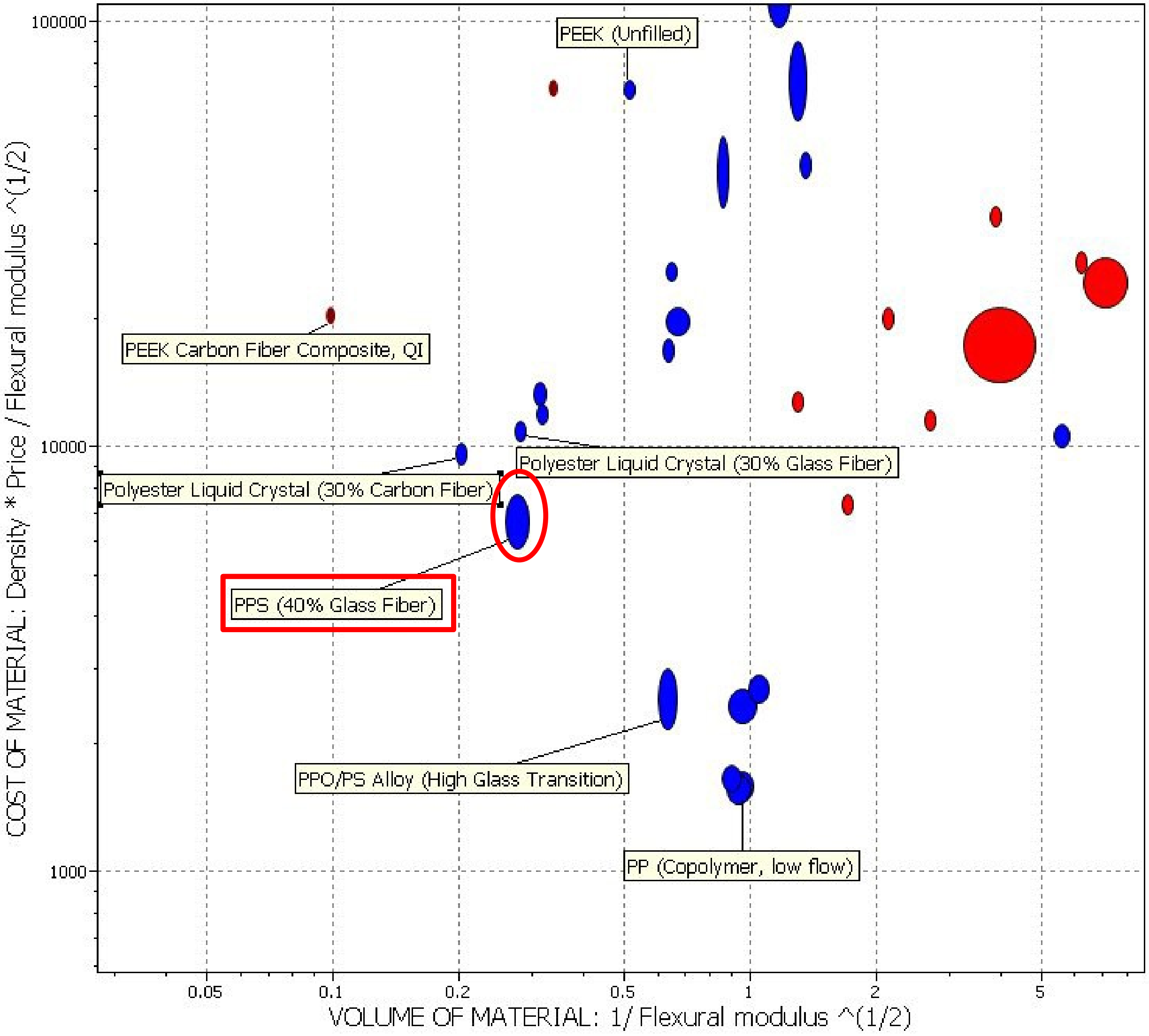

Geometry
Static Structural
14.01.2011 09:26
ANSYS
Noncommercial use only
0.00
35.00
70.00 (mm)
17.50
52.50


Bus bar stress, 200N total binder preload, 2 Binders
Normal Stress MPa
25
20
15
10
5
0
-5
-10
0
100
200
300
400
500
600
Length mm
Stress Preload
Stress 0kA,1.9K
Stress 1kA,1.9K
Stress 3kA,1.9K
Stress 6kA,1.9K
Stress 9kA,1.9K
Stress 11kA,1.9K
Stress 12.85kA,1.9K


Bus bar normal stress, 200N total binder preload, 2 Binders
Stress at 12.85kA no support
Preload stress with support at RT
Stress 12.85kA with support at 1.9K
Normal Stress MPa
60
50
40
30
20
10
0
-10
0
100
200
300
400
500
600
Length mm
Bus bar interconnection
Bus bar interconnection

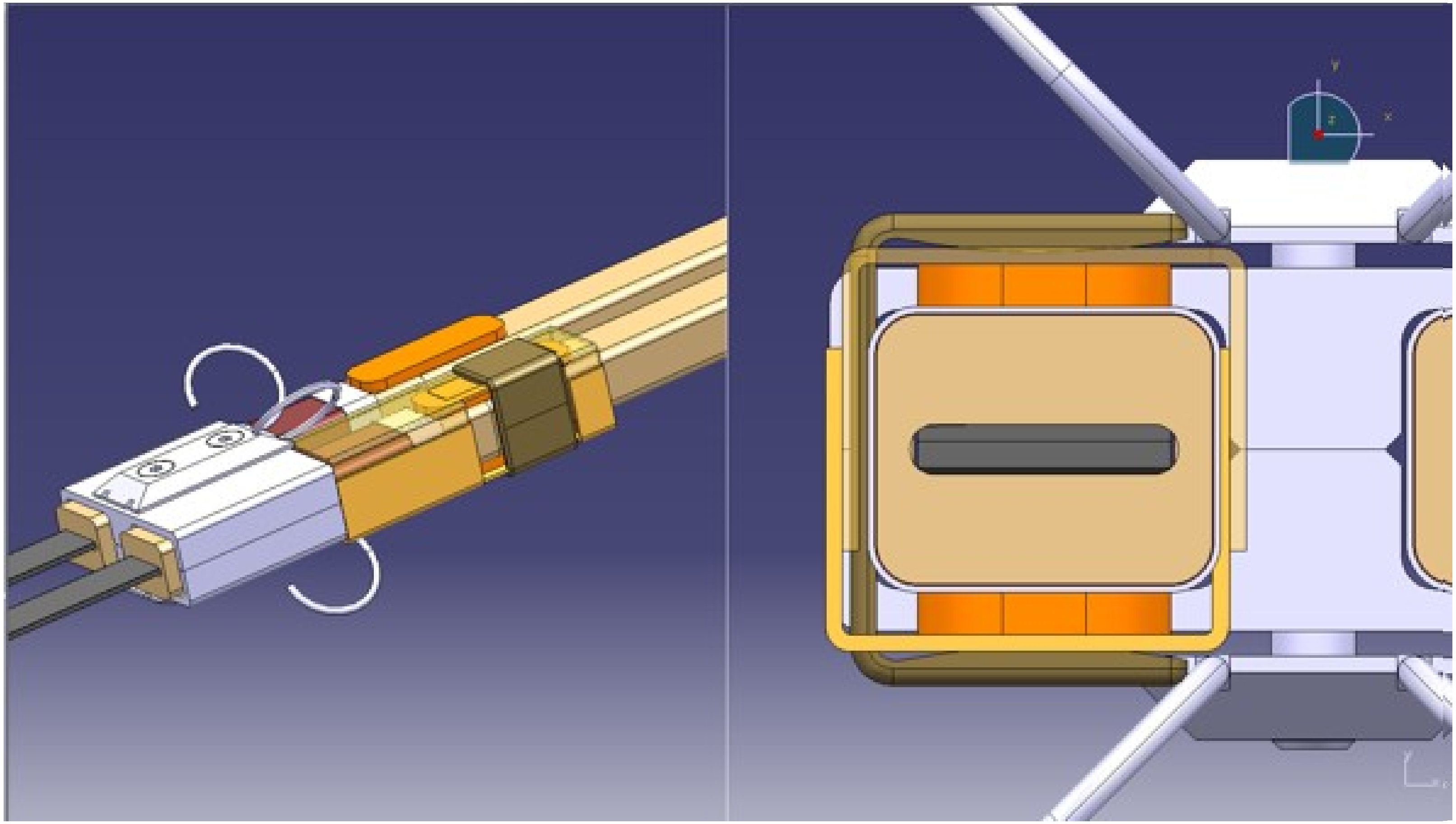


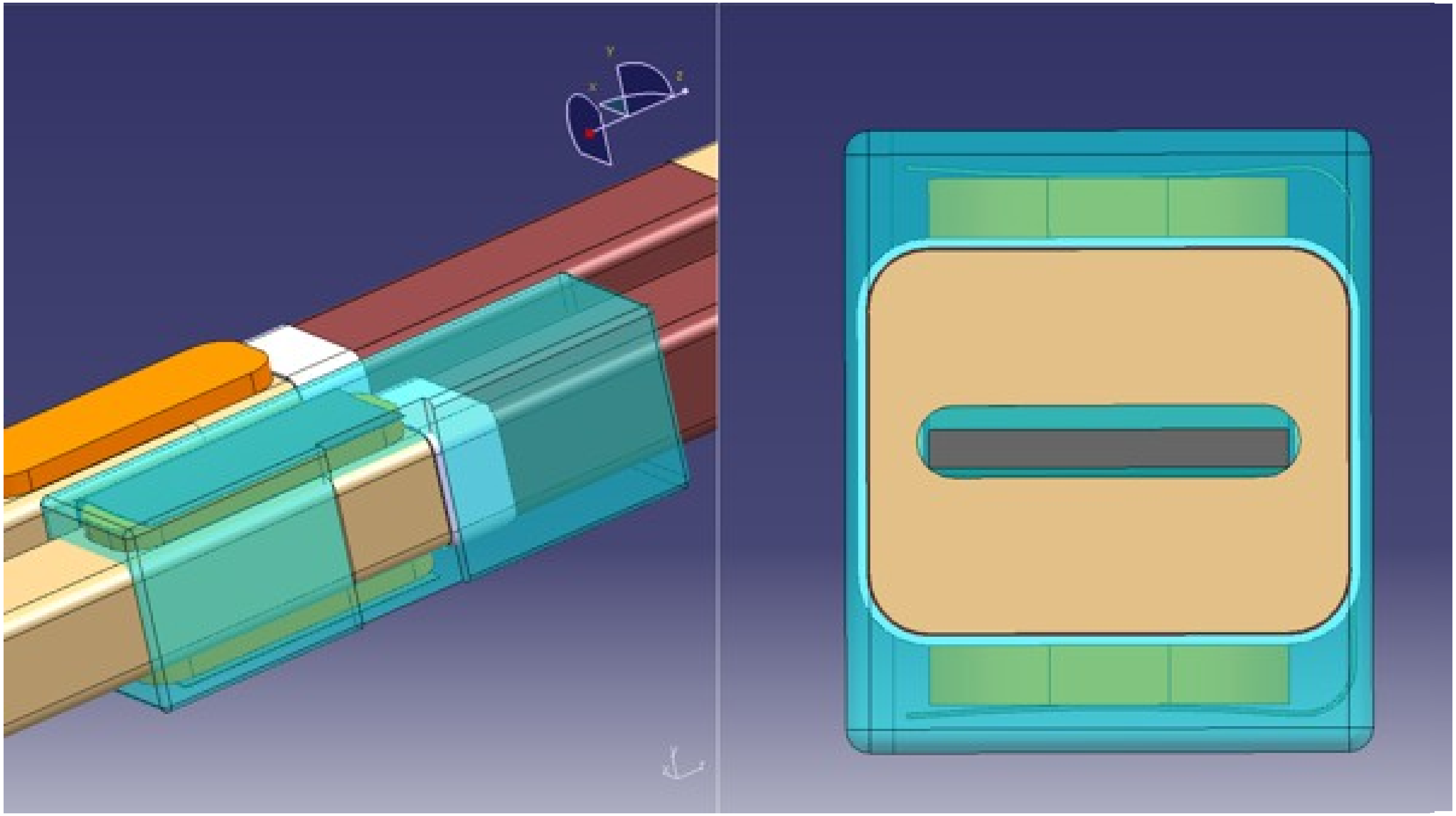
Material selection chart



Comparison with other materials in question:

	PPS	PEEK	PAA	G11
Price [€/kg]	~10	~70-100	~10.5	~ 460 Hollow tube Da156, Di 117, 1000mm
Dielectric strength [kV/mm]	22	17	31	31.5
Mold shrinkage ASTM D 955 [mm/mm]	0.003-0.005	0.01 - 0.02	0.001 to 0.003	-
Water absorption 24h [%]	0.02	0.125	0.2	0.2
Physical Properties	Stable and sufficient	sufficient	Time stability less good than for PPS	sufficient
Arc resistance [s]	125	40	Not commonly used for insulation	120
Molding	Good injection molding characteristics	less good molding characteristics and high mold shrinkage	Good	-
Radiation [Mgy]	10	8	5	5 … 20


y
x
z

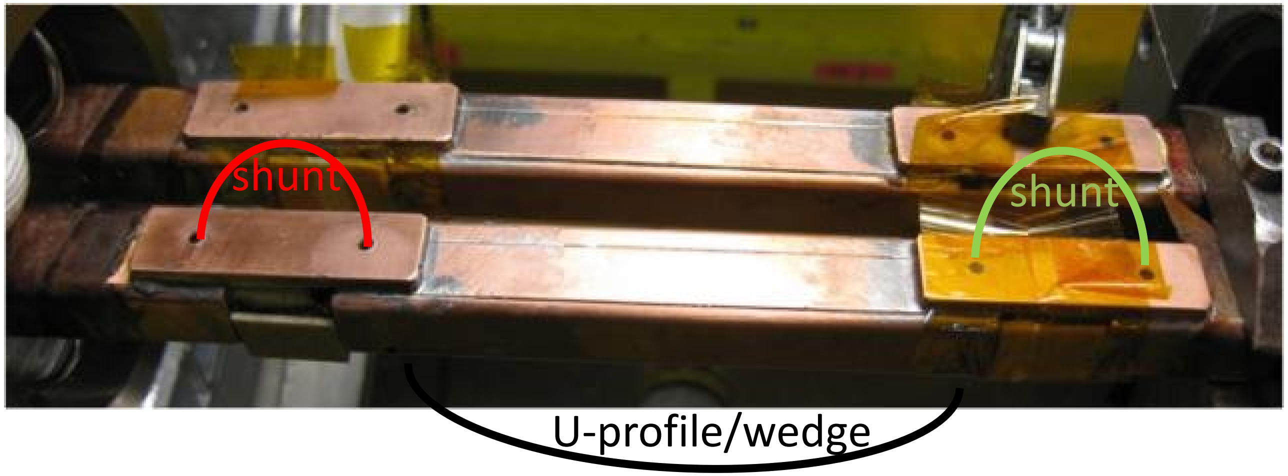


The SM18 test

1. RRR measurements

High precision measurements on resistance.
-In the test the U-profile/wedge have a low RRR
- In the tests the shunts have a much lower RRR than foreseen for the LHC conditions.

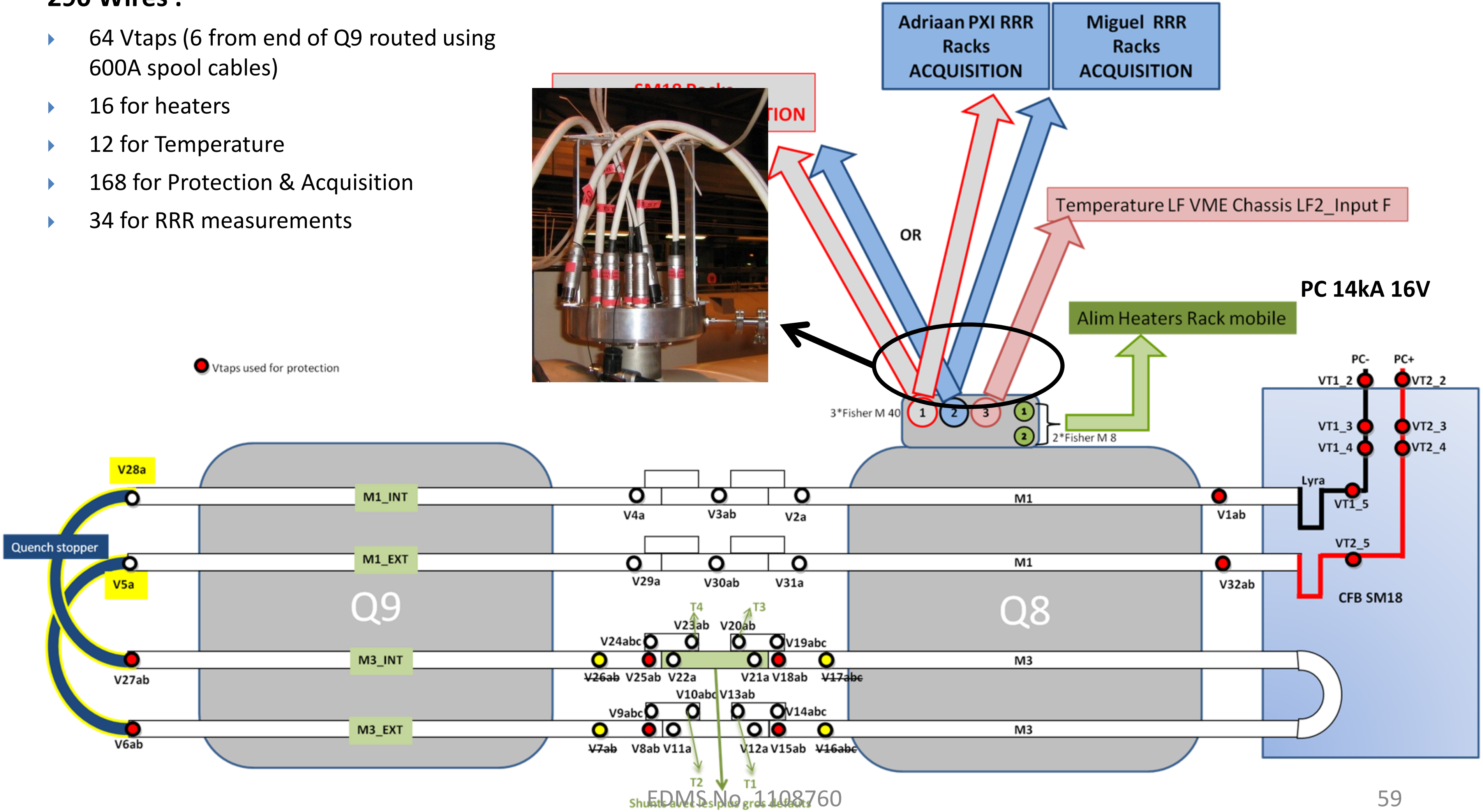
type	RRR	Typical LHC value
U-profile RQ	174, 176, -, -	> 200
U-profile RB	182, -	> 200
Shunt RB	156, 156, 160, 160	> 300
Busbar RQ	252, 264, - , -	> 200 (lab tests)
Busbar RB	258, 303, -	> 200 (lab tests)



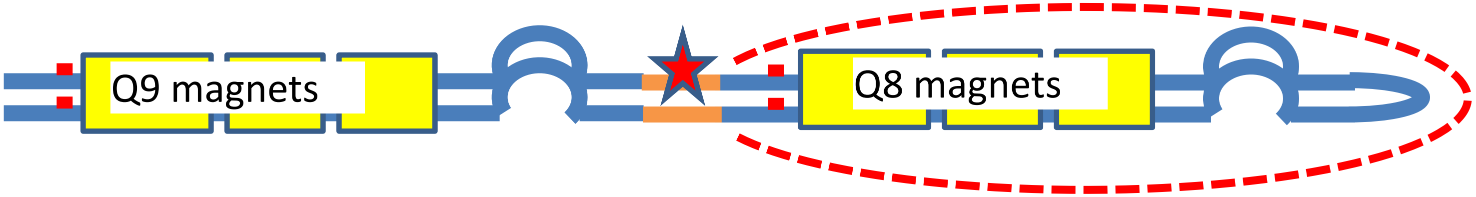
Instrumentation overview

290 Wires :

- 64 Vtaps (6 from end of Q9 routed using 600A spool cables)
- 16 for heaters
- 12 for Temperature
- 168 for Protection & Acquisition
- 34 for RRR measurements

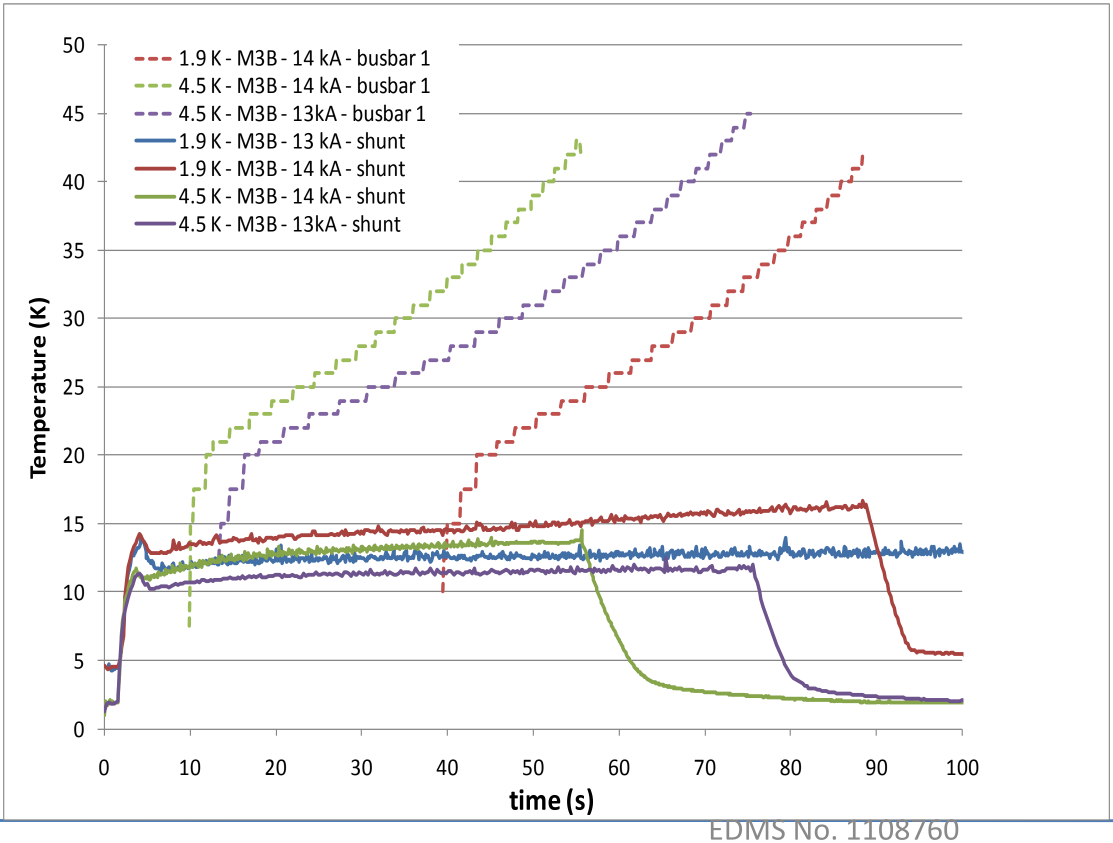


Thermal runaways in the interconnections



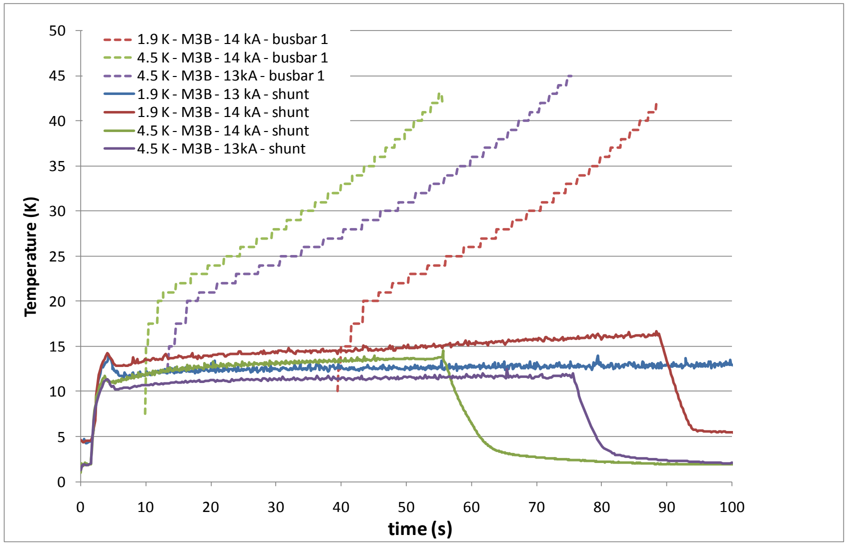
busbar temperature calculated from voltage (dashed lines)

Thermocouple measures the temperature of the shunt (solid line)



Busbar is less stable than the interconnection, while the interconnection has a defect

Thermal runaways in the interconnections



Busbar is less stable than the interconnection, while the interconnection has a defect.

Reason: Difference in helium volume available for cooling the busbar in the straight part and in the interconnection.

Very little helium available in the straight part.