Splices in 13 kA circuits
status of an ongoing work just started

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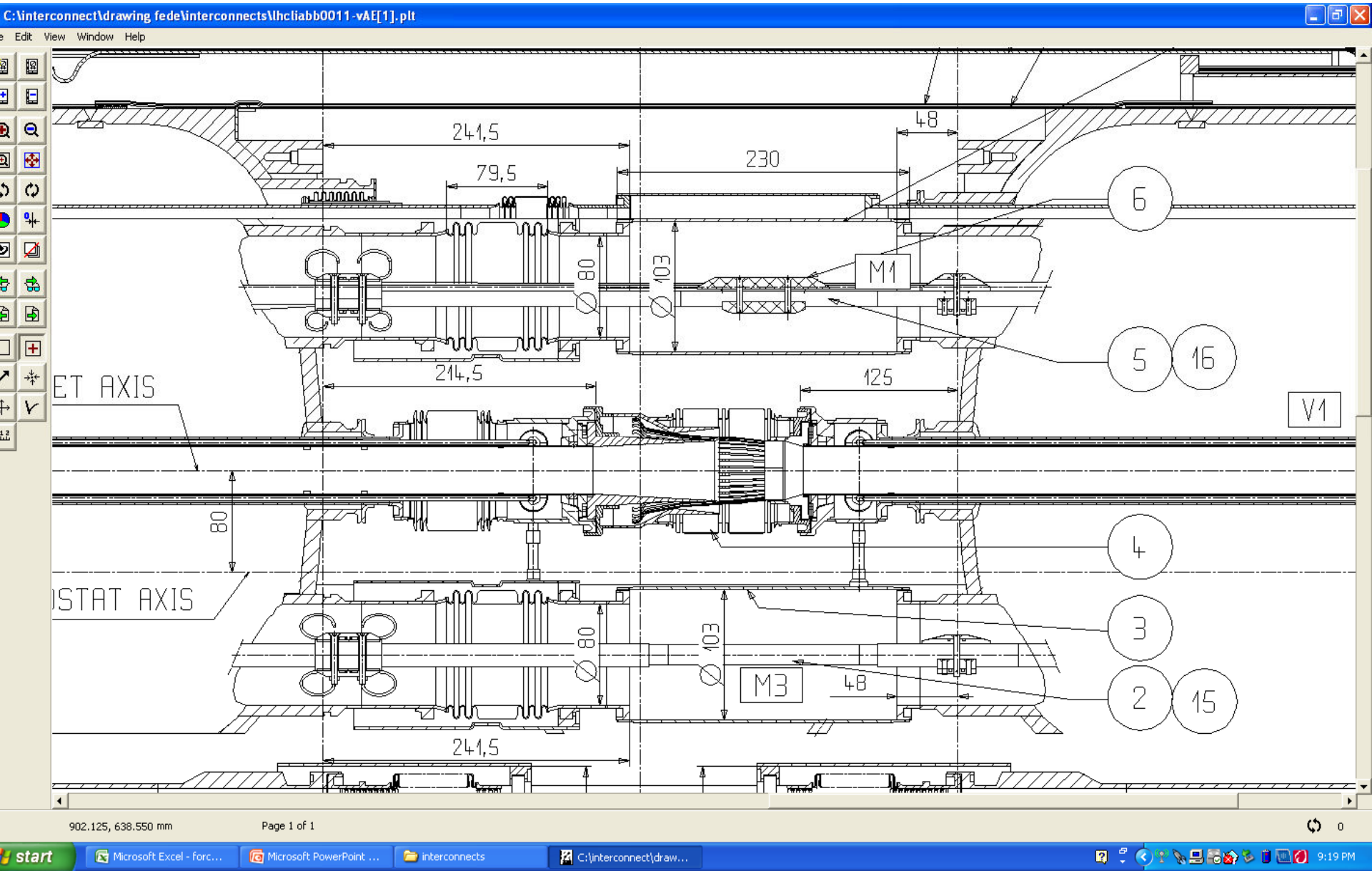
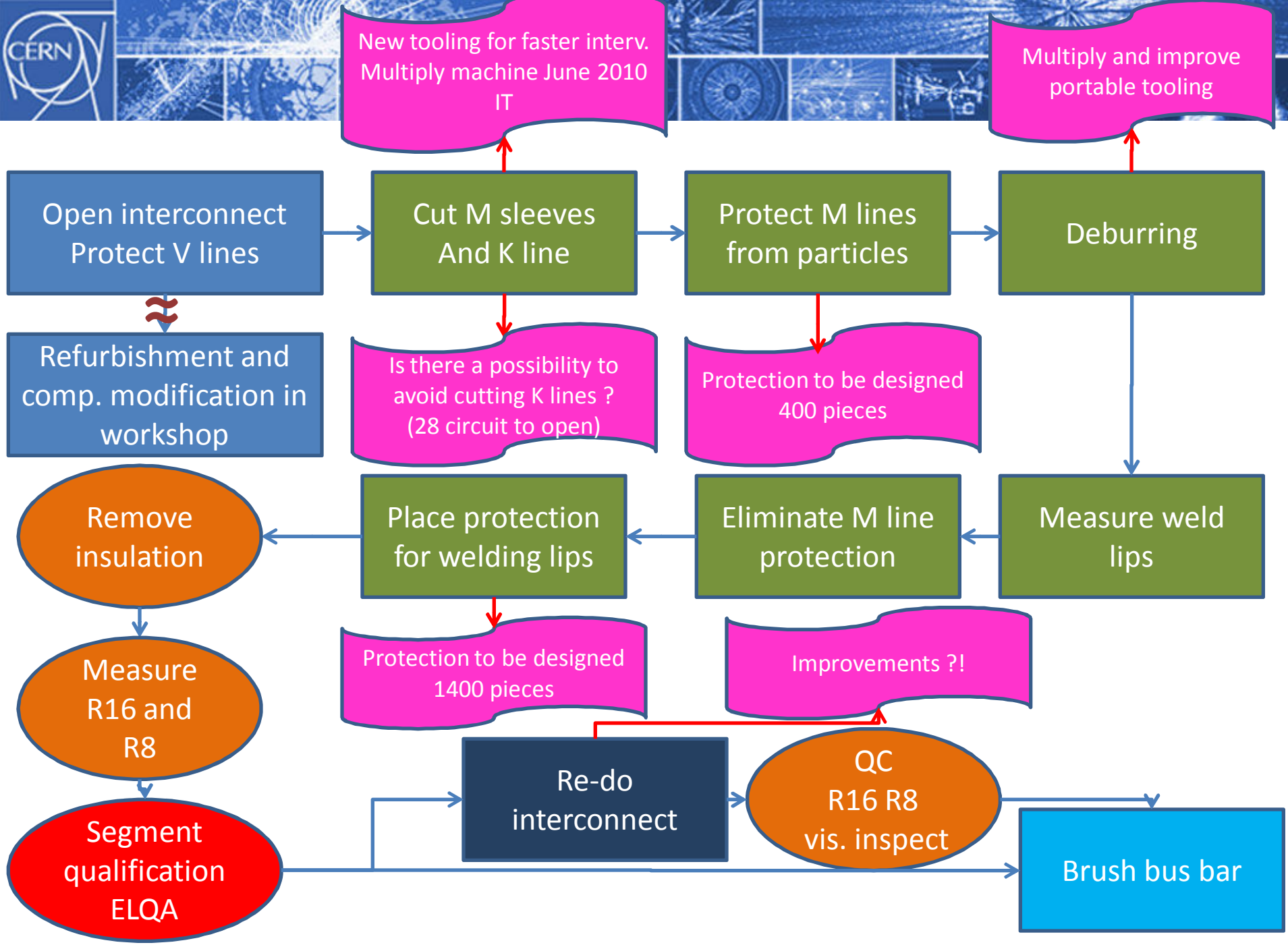
Co-authors and Acknowledgments

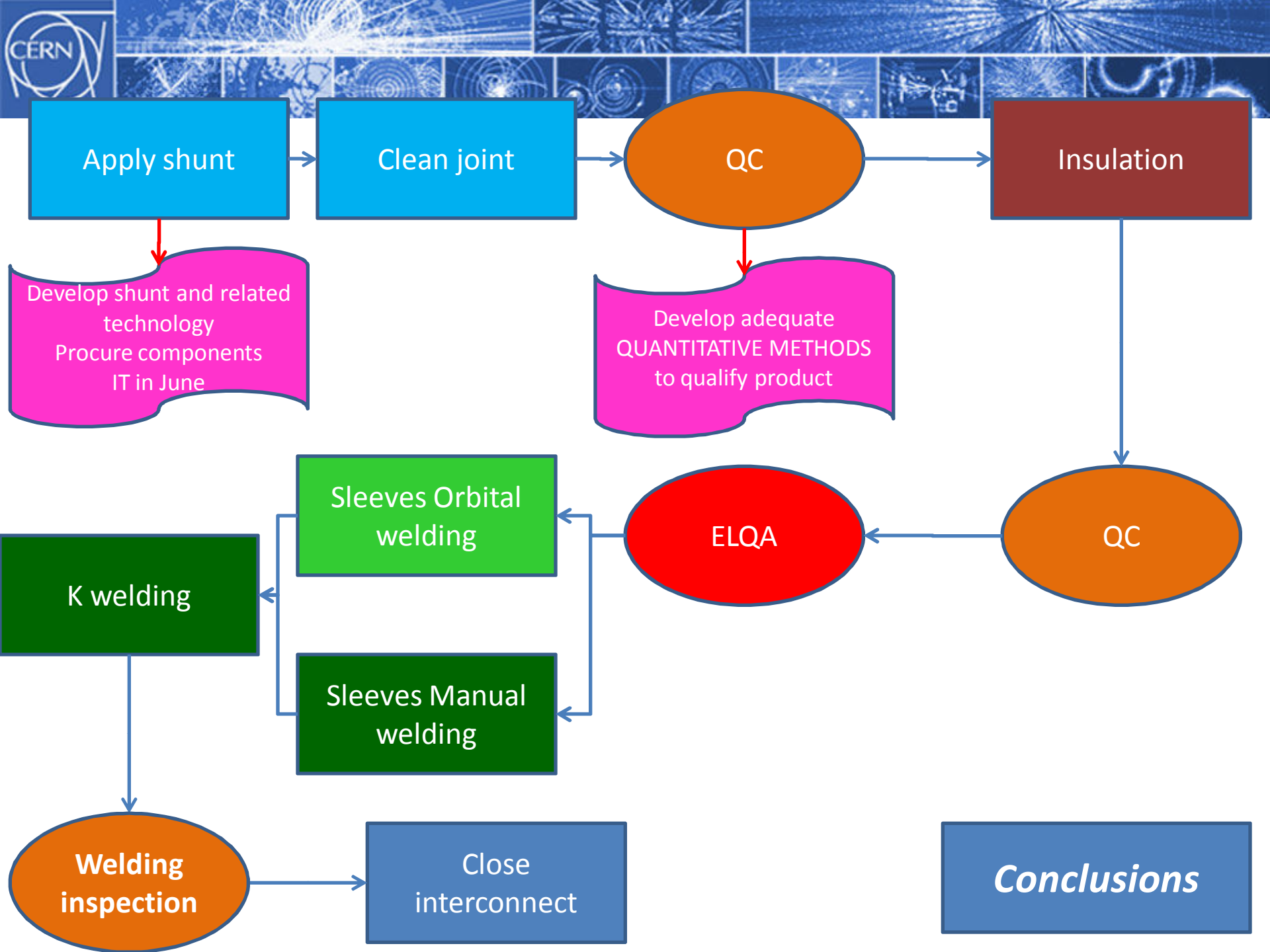
- 3-4 production data collection: Christian Scheuerlein
- Shunt thickness evaluation: Arjan Verweij
- Sample assembly and practical development: S. Triquet, M. Pozzobon
- Inductor Analysis: Federico Regis
- Insulation Concept and gamma-ray analysis: Herve Prin
- Soldering material discussion and process development: Stefano Sgobba, Serge Mathot, Christian Scheuerlein
- Fruitful discussions: Herman Ten Kate, Alexey Dudarev
- Thanks to the **Task Force LHC Splices Consolidation** brain storming

POSSIBLE ACTIVITY SEQUENCE

Interconnect partial schematic view




New tooling for faster interv. Multiply machine June 2010 IT
Multiply and improve portable tooling
Open interconnect Protect V lines
Cut M sleeves And K line
Protect M lines from particles
Deburring
Refurbishment and comp. modification in workshop
Is there a possibility to avoid cutting K lines ? (28 circuit to open)
Protection to be designed 400 pieces
Remove insulation
Place protection for welding lips
Eliminate M line protection
Measure weld lips
Measure R16 and R8
Protection to be designed 1400 pieces
Improvements ?!
Re-do interconnect
QC R16 R8 vis. inspect
Segment qualification ELQA
Brush bus bar

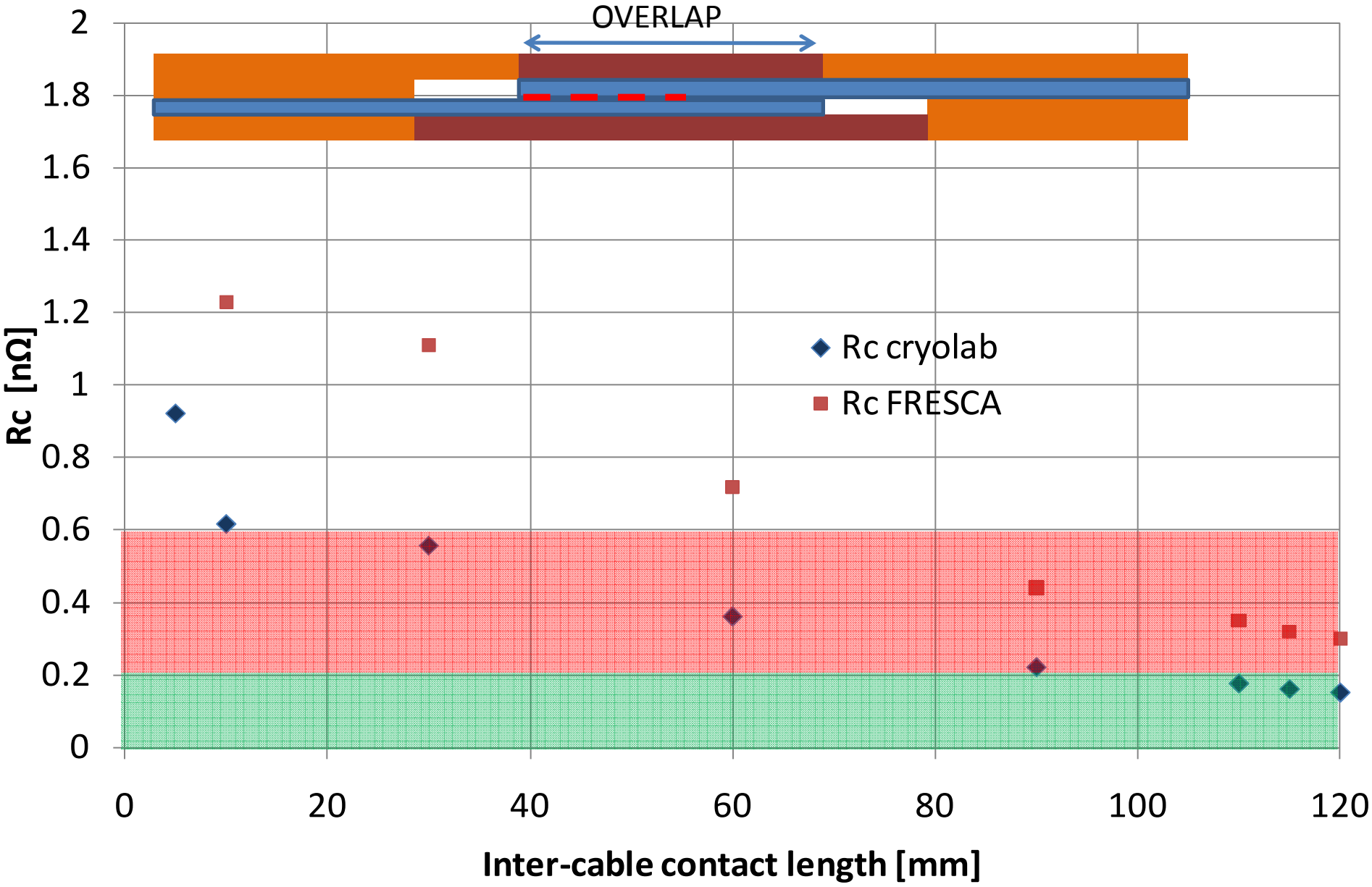

Apply shunt
Clean joint
QC
Insulation
Develop shunt and related technology
Procure components
IT in June
Develop adequate QUANTITATIVE METHODS to qualify product
Sleeves Orbital welding
ELQA
QC
K welding
Sleeves Manual welding
Welding inspection
Close interconnect
Conclusions

RE-DOING INTERCONNECTS WHY ?
CAN WE DO THEM BETTER ?

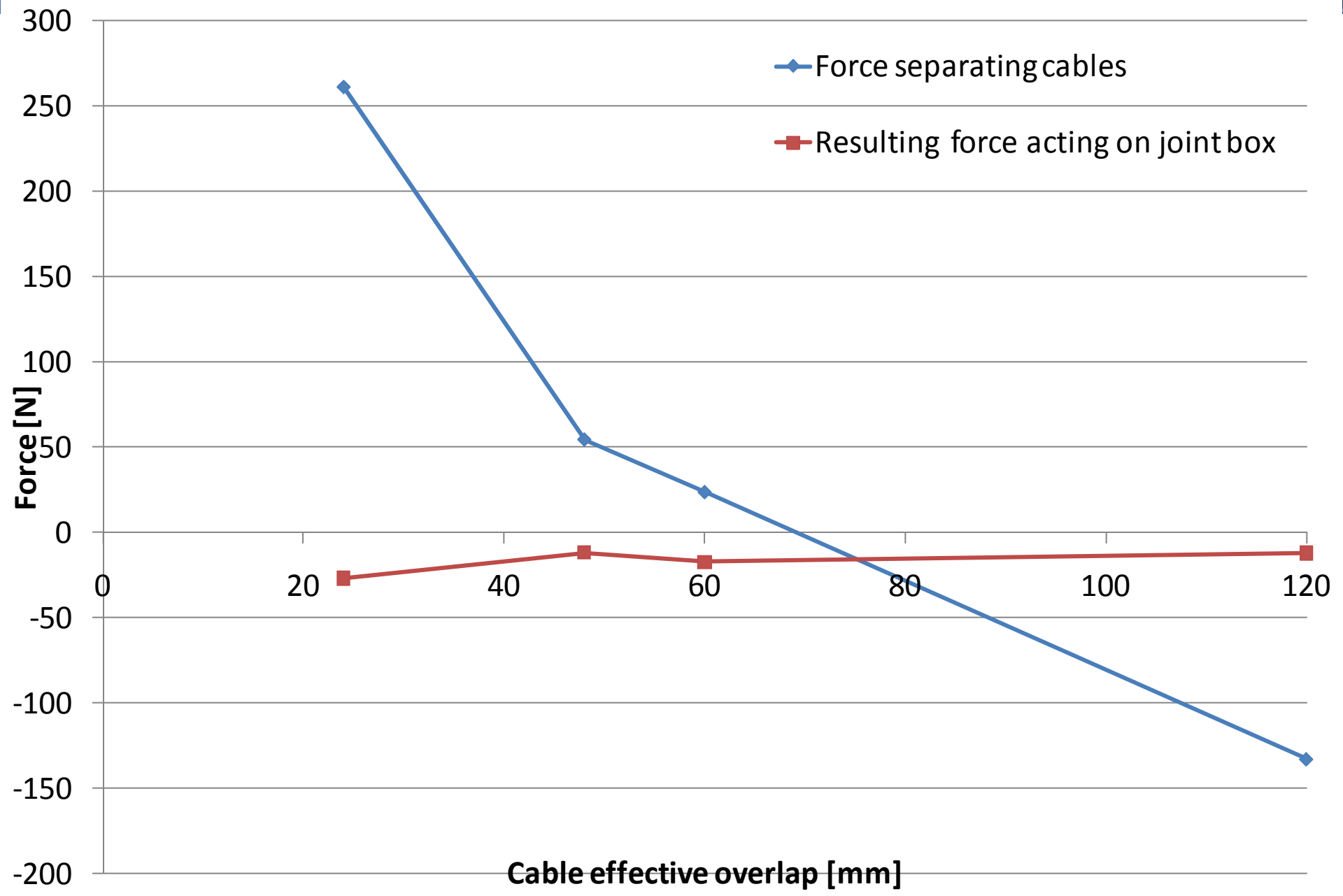
Re-do interconnect why

1) If there is a resistive component in the SC to SC joint larger than ***0.8 nΩ***
2) If the $R8_{add}$ on one of the 2 sides is larger than ***10-15 μΩ***
3) If there is a strong misalignment and/or deformation of the bus bar and/or interconnect extremity that would be detrimental for the interconnect consolidation

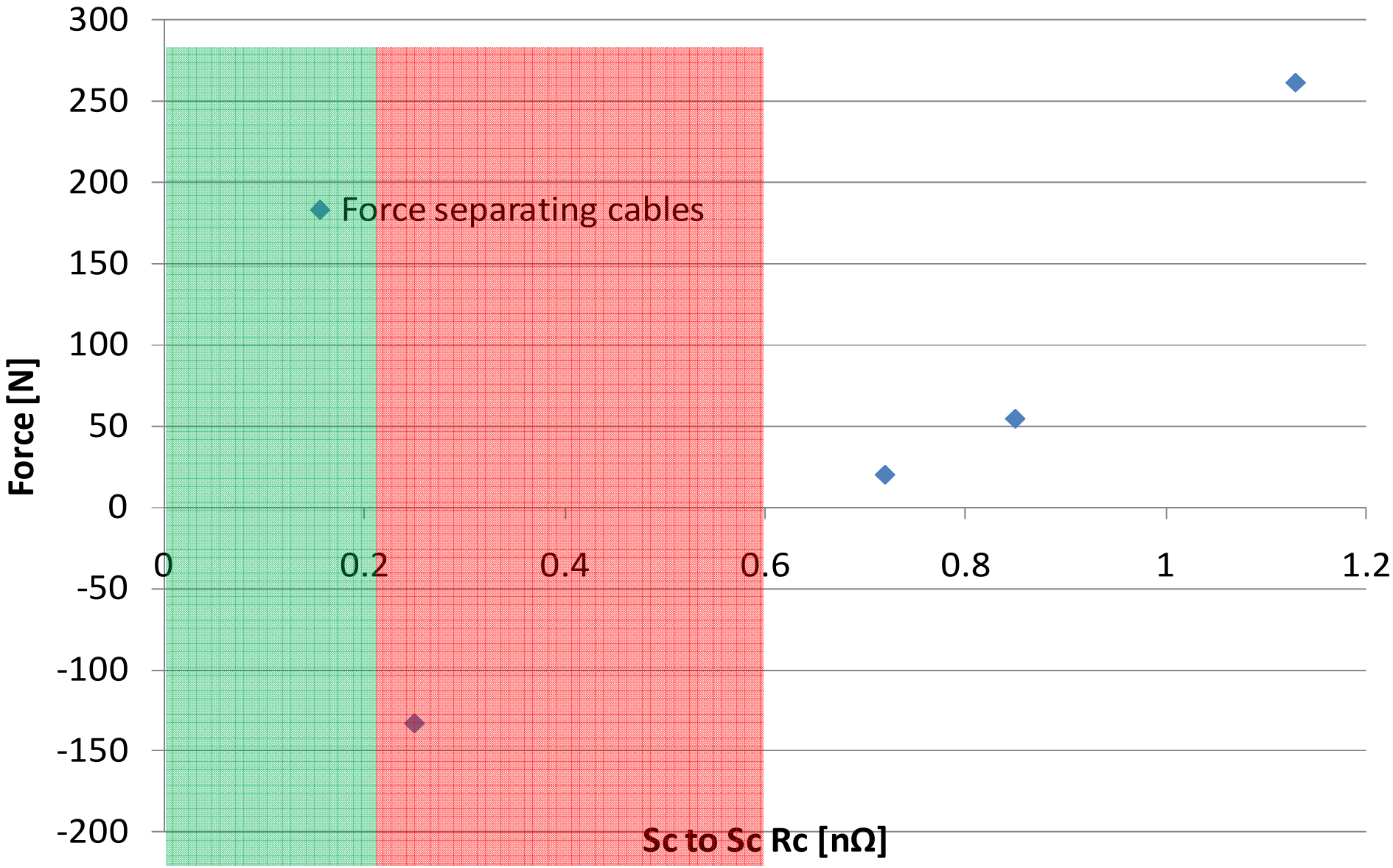
Resistive component of SC to SC joint vs. effective joint length



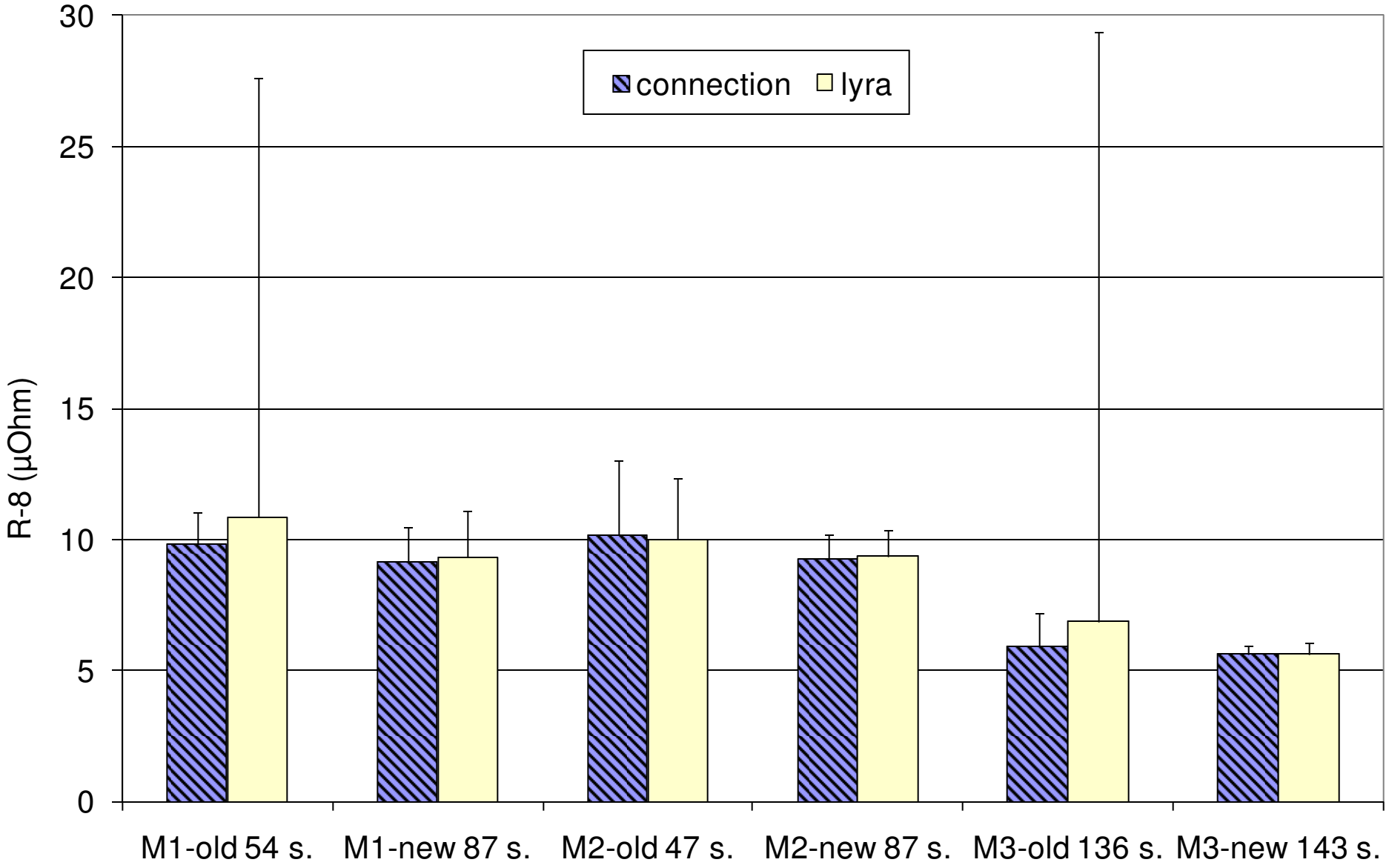
Magnetic forces vs. effective joint length



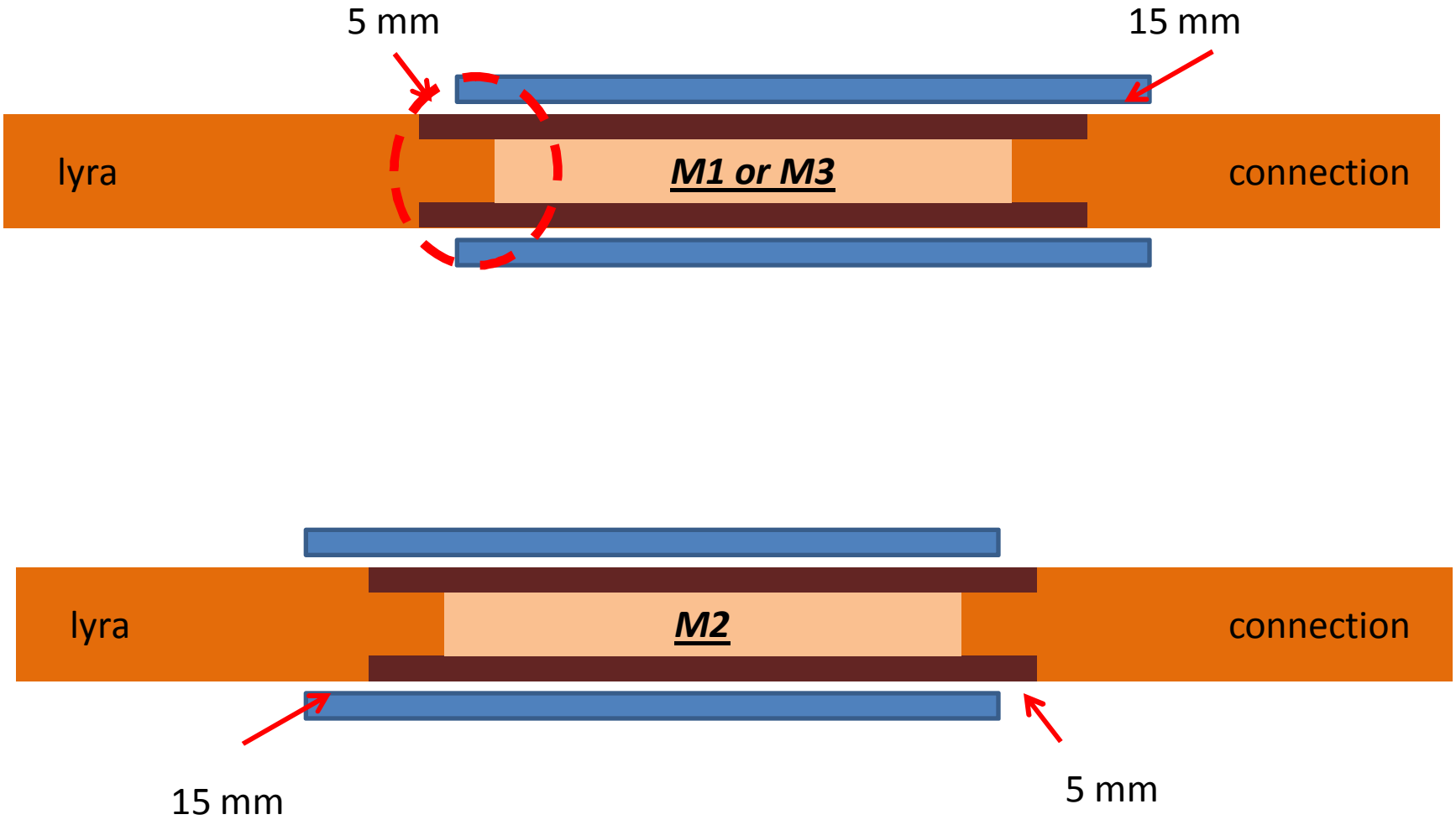
Magnetic forces vs. resistive component of SC to SC joint



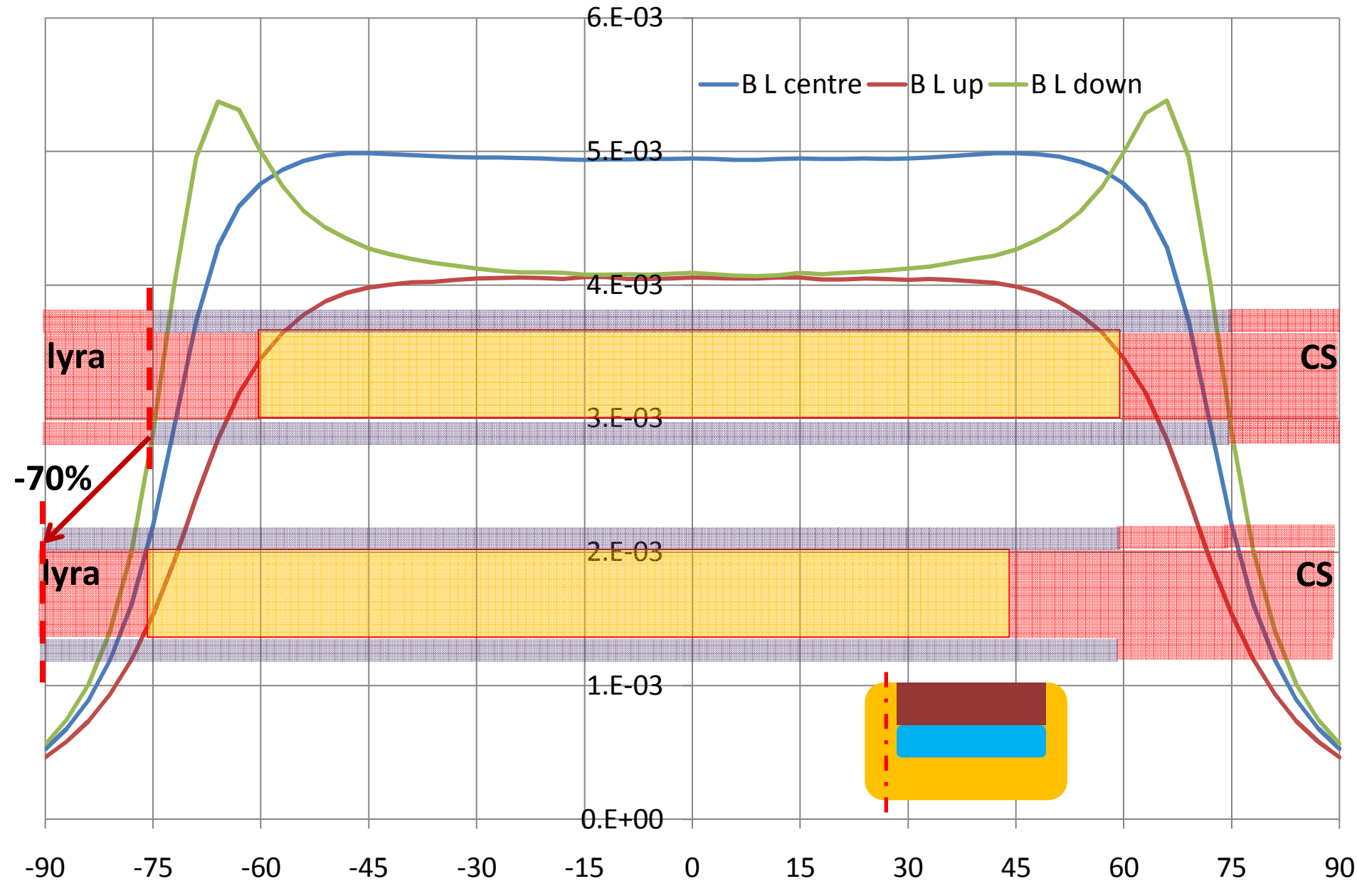
Old production vs. new production: a quality index



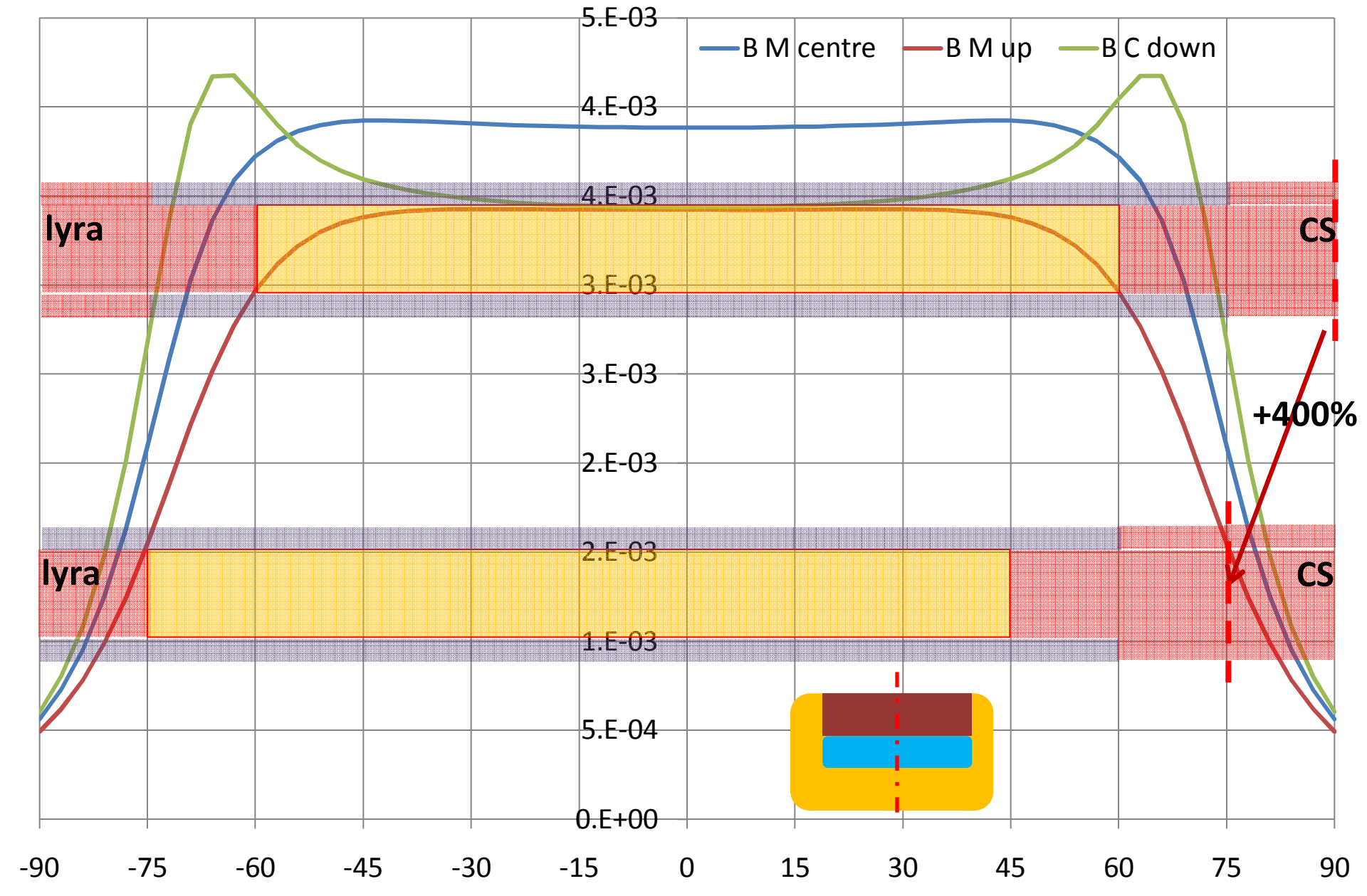
Series production inductor positioning

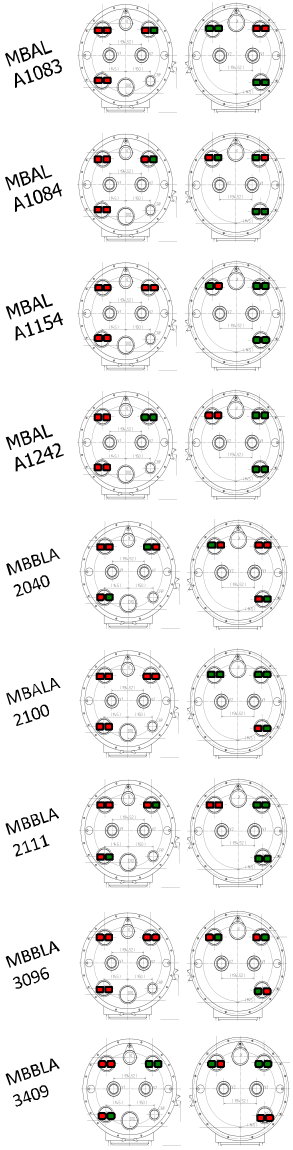


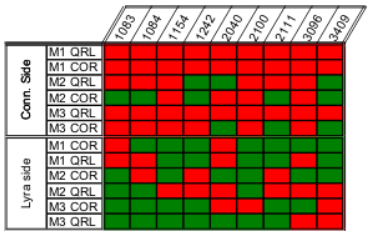
Profile of induced field in the assembly

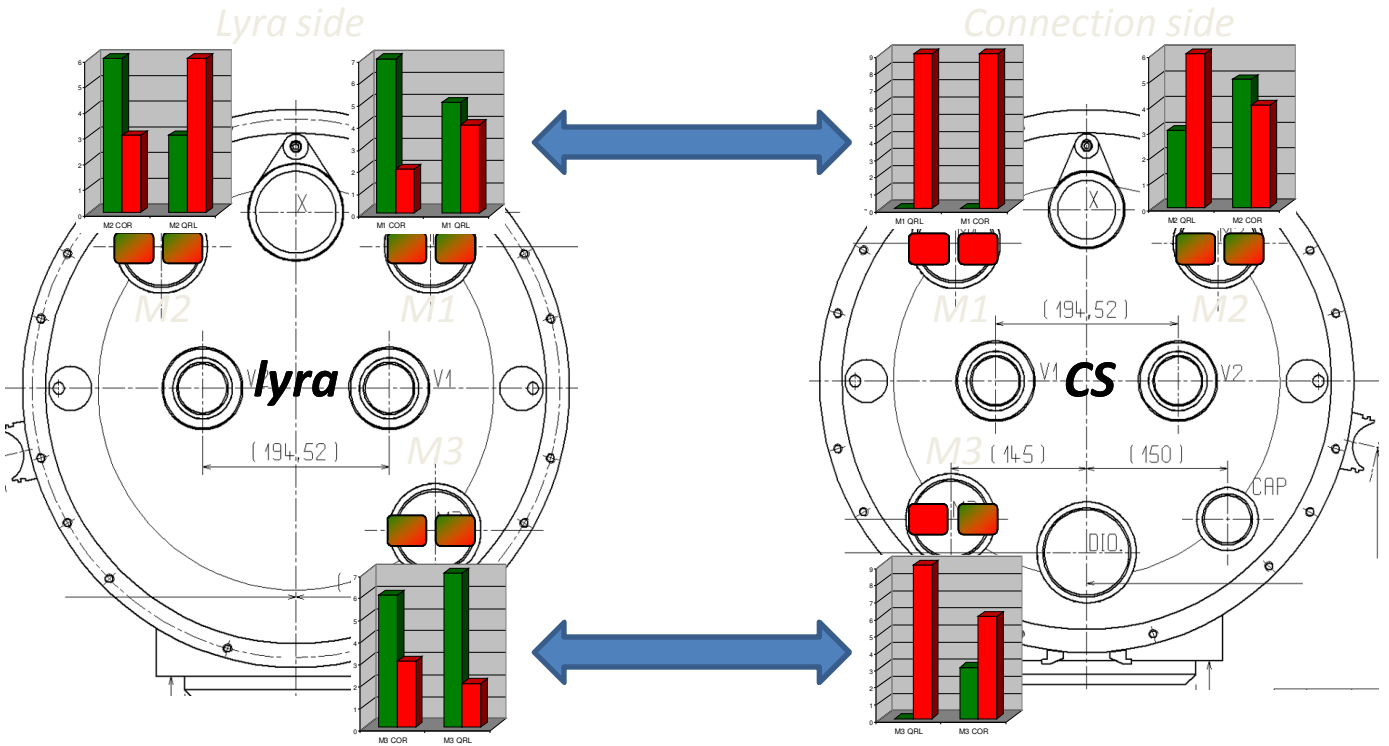


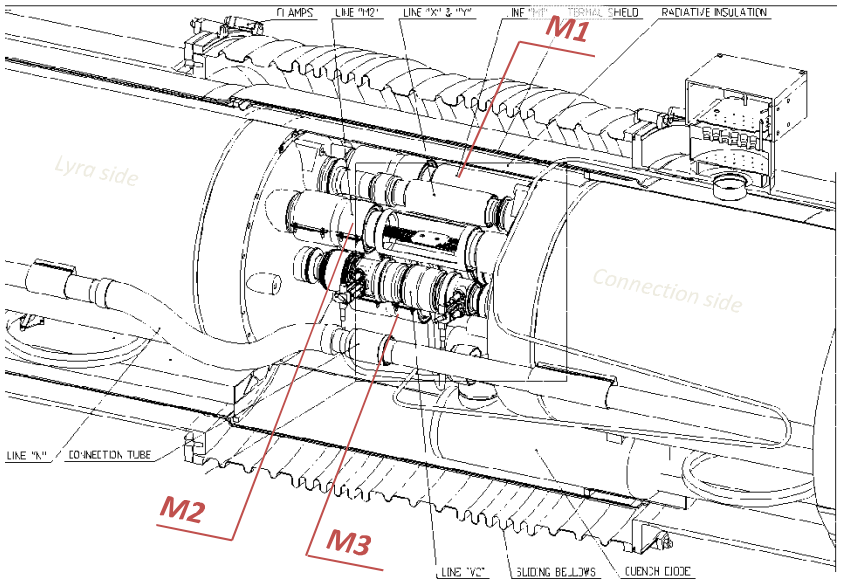
Profile of induced field in the assembly

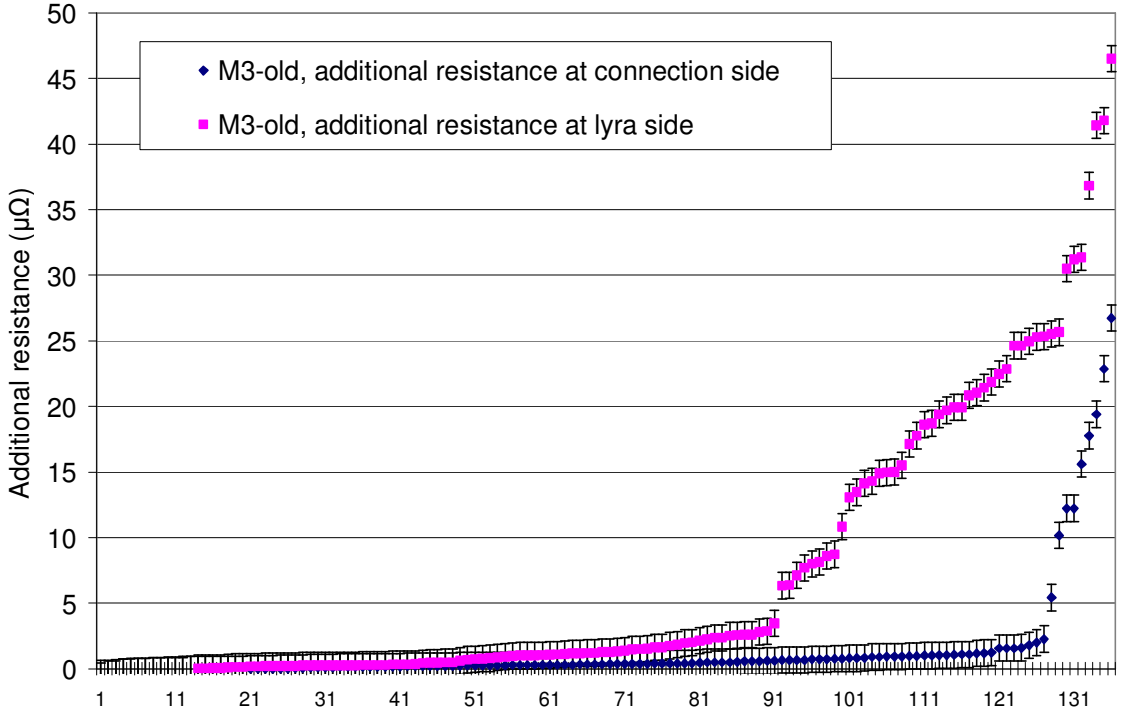


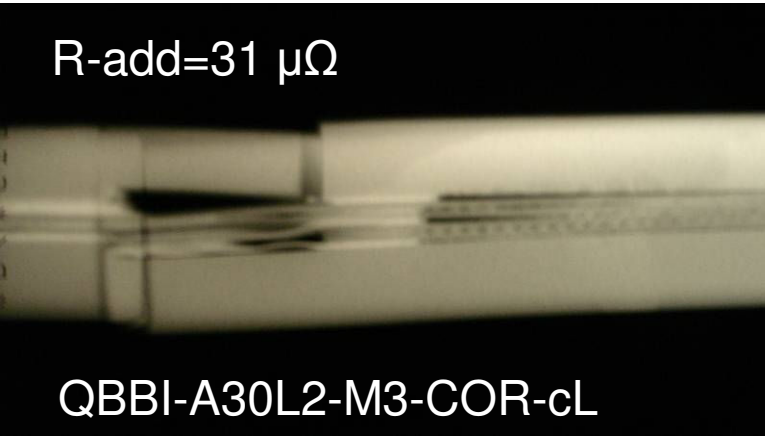

MBAL A1083
MBAL A1084
MBAL A1154
MBAL A1242
MBBLA 2040
MBALA 2100
MBBLA 2111
MBBLA 3096
MBBLA 3409

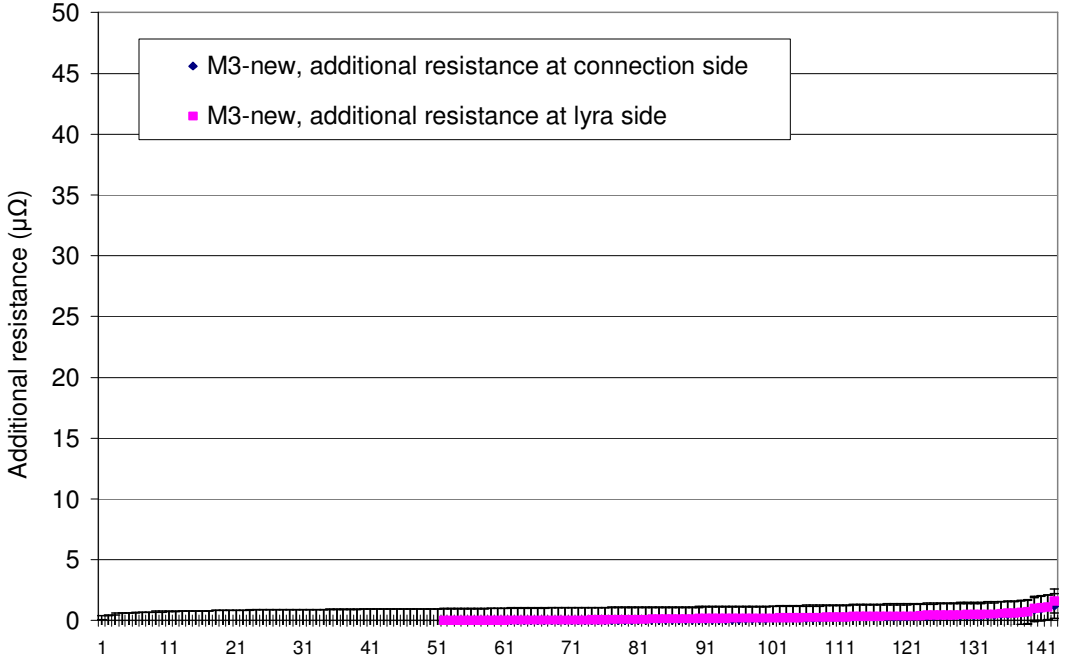

1083
1084
1154
1242
2040
2100
2111
3096
3409
Conn. Side
M1 QRL
M1 COR
M2 QRL
M2 COR
M3 QRL
M3 COR
Lyra side
M1 COR
M1 QRL
M2 COR
M2 QRL
M3 COR
M3 QRL


Lyra side
Connection side
M2 COR
M2 QRL
M1 COR
M1 QRL
lyra
(194,52)
M3 COR
M3 QRL
M1 QRL
M1 COR
M2 QRL
M2 COR
CS
(194,52)
(145)
(150)
CAP
DIO.


M1
M2
M3
Lyra side
Connection side
LINE "X" / CONNECTION TUBE
LINE "V"
SLIDING BELLOWS
QUENCH DIODE
RADIATIVE INSULATION


M3-old, additional resistance at connection side
M3-old, additional resistance at lyra side
Additional resistance (µΩ)
0
5
10
15
20
25
30
35
40
45
50
1
11
21
31
41
51
61
71
81
91
101
111
121
131


R-add=31 µΩ
QBBI-A30L2-M3-COR-cL


M3-new, additional resistance at connection side
M3-new, additional resistance at lyra side
Additional resistance (µΩ)
0
5
10
15
20
25
30
35
40
45
50
1
11
21
31
41
51
61
71
81
91
101
111
121
131
141

Further improvements ?!

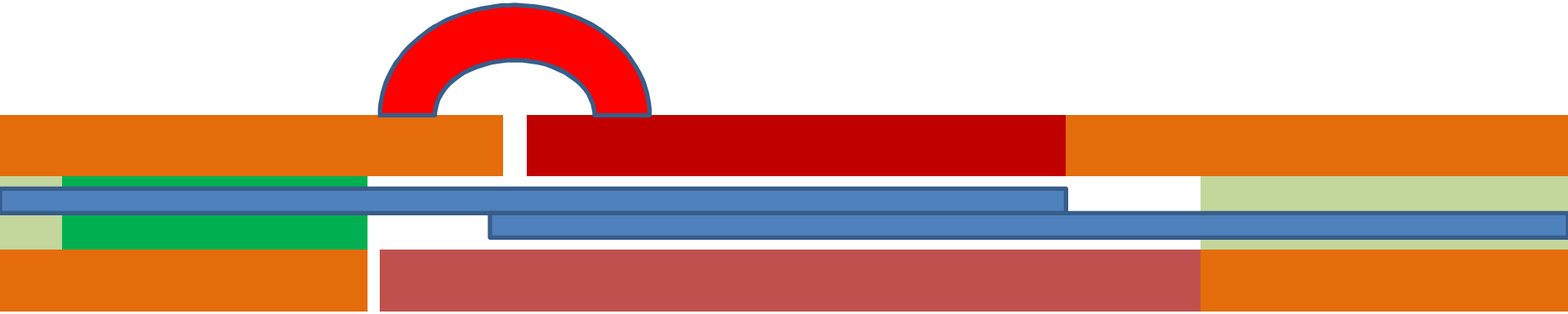
1) Improve SC to Copper contact in the joint

2) Improve, if feasible, heat distribution in order to limit loss of Sn in the bus bar. It needs re-design the inductor

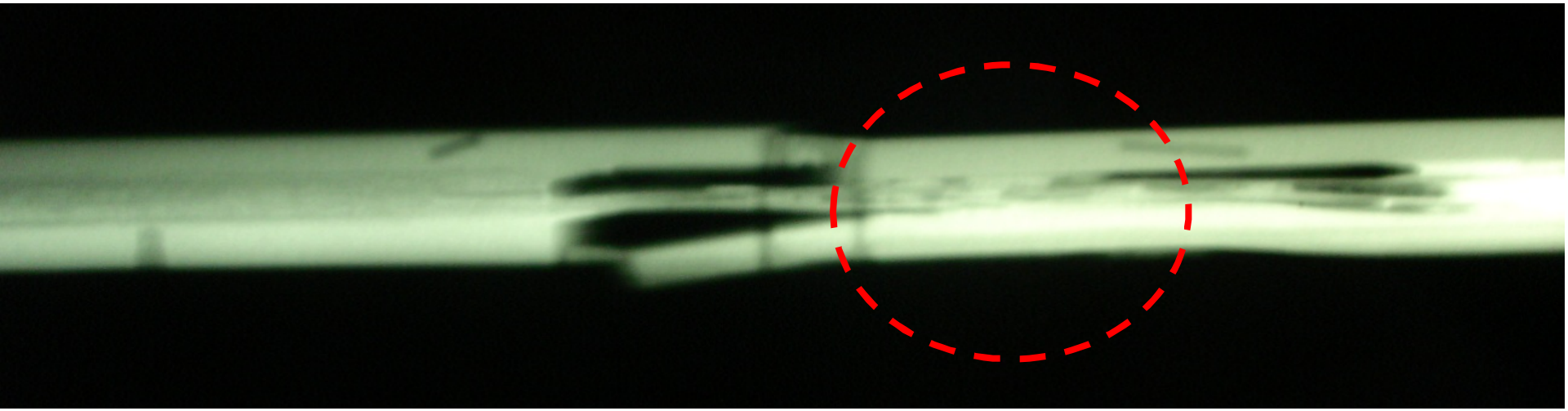
back

SHUNT: REQUIREMENTS, OPTIONS, POSSIBLE TECHNOLOGICAL CHOICES

Where we can act



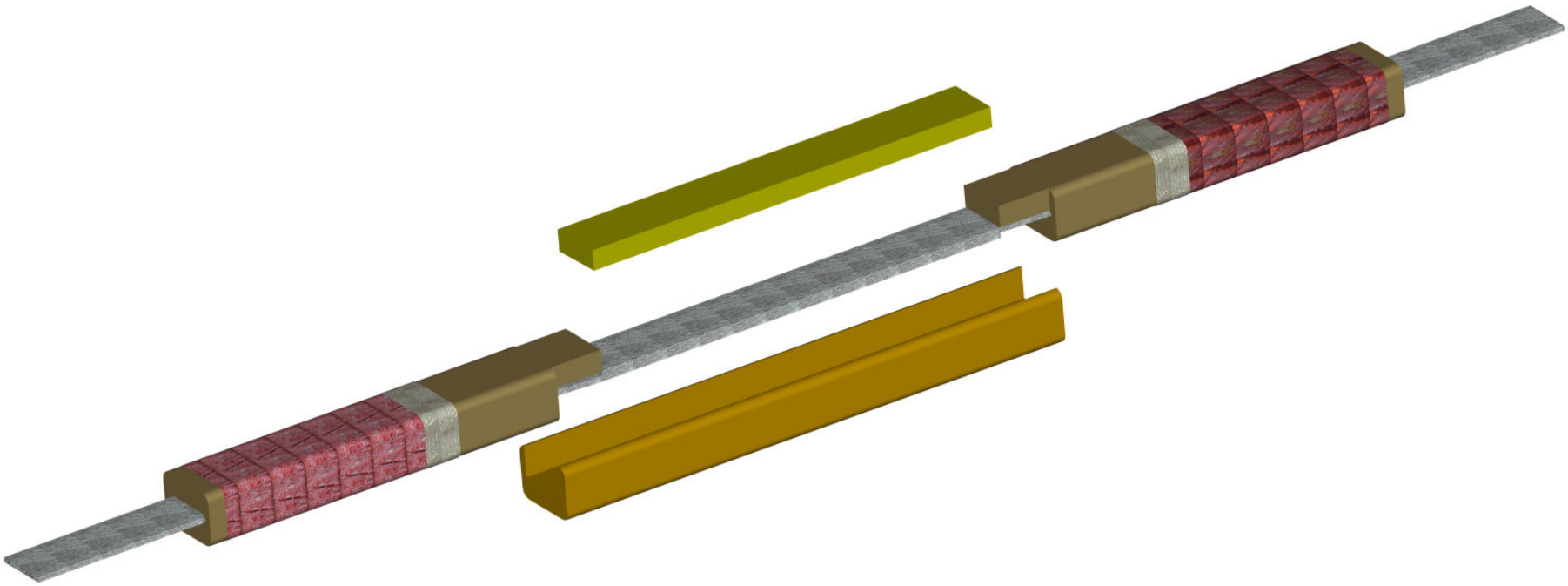
From 53 μΩ to 21 μΩ

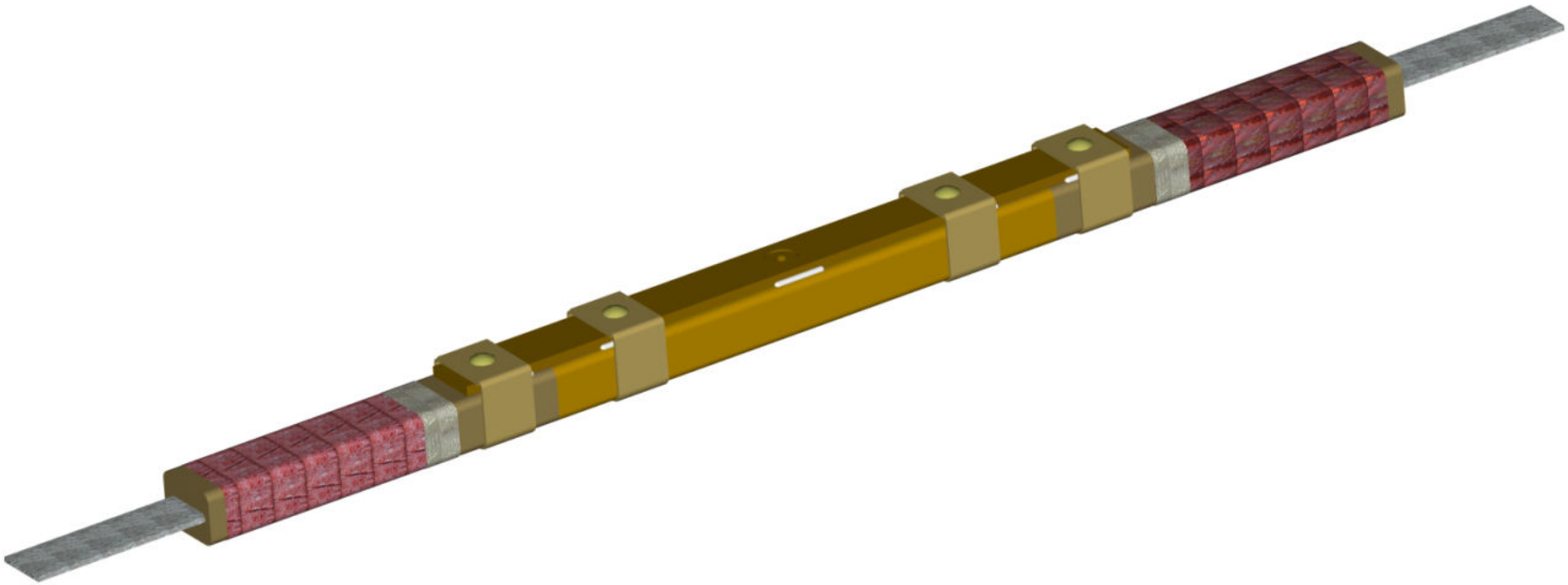


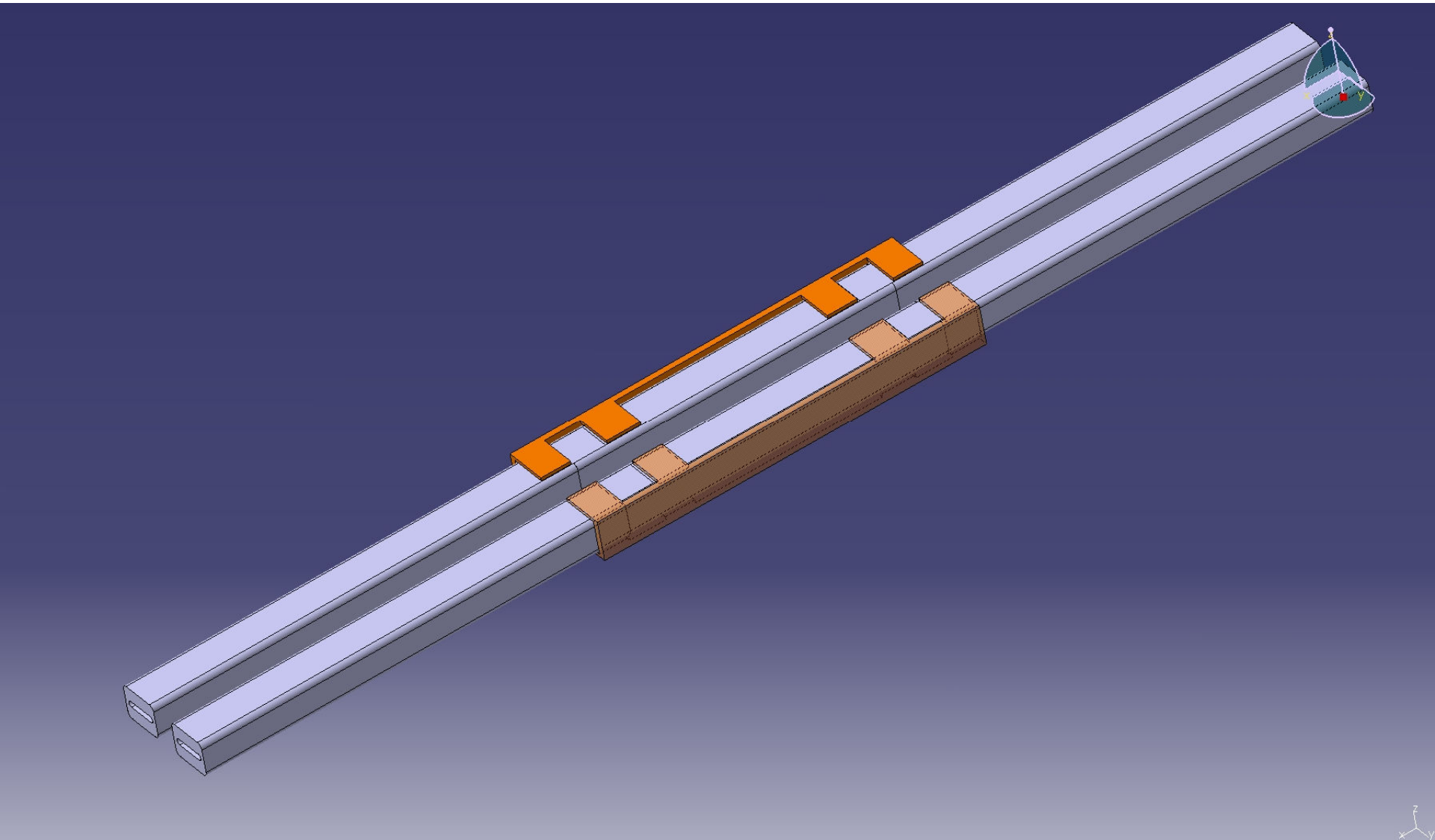
A 1st list of technical requirements

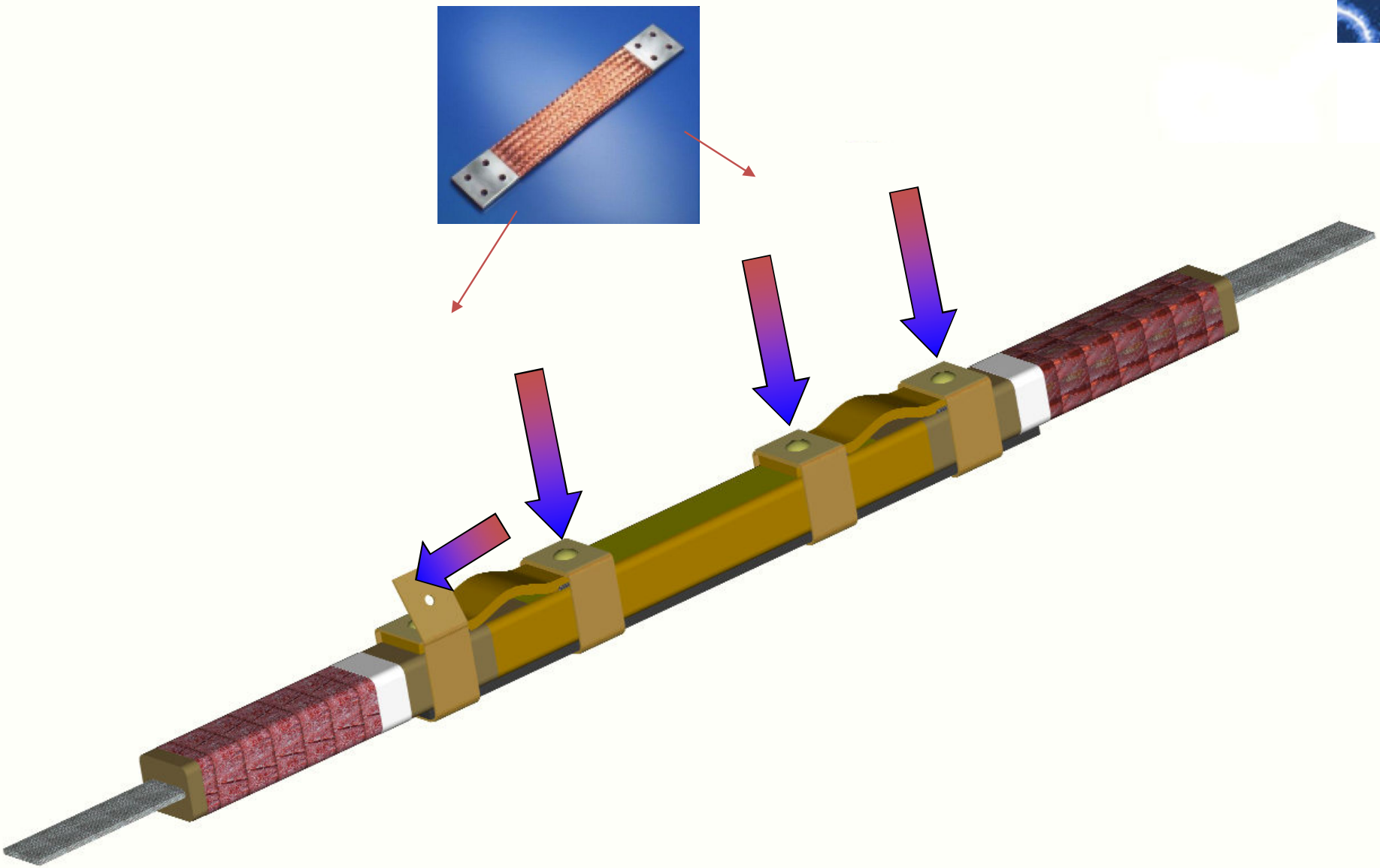
Apply a copper section ***(2X15 mm section)*** connected in parallel to the copper to copper junction complying with the following requirements:

1) Do not melt or interfere with the existing junction
2) Apply it without cutting the spools on the top of the quadrupole bus bar
3) Accommodate the shape defect of an existing interconnection
4) Being redundant by design
5) To be easily inspected and declared acceptable by QC
6) Be of rapid installation and minimize the risk of error dy design
7) Use “small” tooling allowing co-activity
8) Use of tooling easy to multiply
9) Possibly industrially based tooling









Possible 1st approach for installation of shunt

- Solder using Sn-Pb in order to have lower melting temperature than the base soldering (183^{o}C vs. 221 ^{o}C)
- Using a fast machine delivering high power in order to
  - Heat locally and do not rise the temperature in the bus bar core
  - Have a fast process

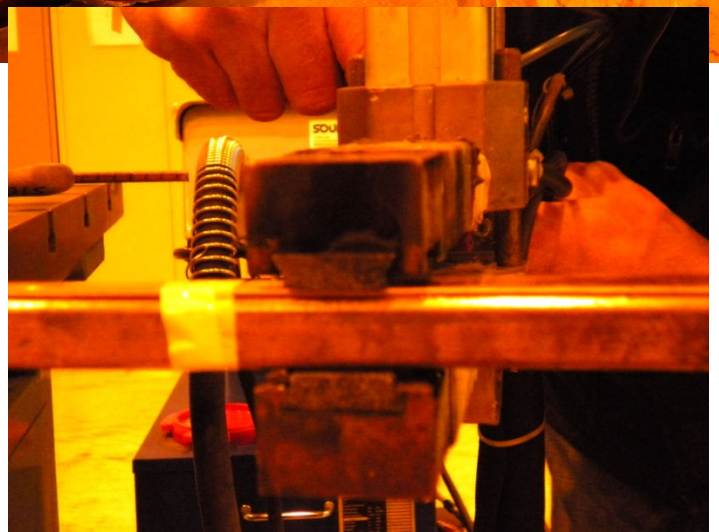
Heating technologies

- Resistive heating:
  - Very well known technology
  - Easy to control
  - Quite long heating cycles
  - Long assembly of the tooling around the bus bar
  - Difficult to fit all mechanical defects
- Inductive heating
  - Design of new inductor needed
  - Very large tooling difficult to handle in an almost completed interconnect
  - Problems of coactivity due to tooling dimensions
  - Control to be redeveloped
- “Spot welding” type machine
  - Very fast cycles and fast assembly around the bus bar
  - Small tooling easily adapting to bus bar geometry defects
  - Medium size tool
  - Is the quality of the soldering good (very fast process, too fast ?)
  - Control to be developed

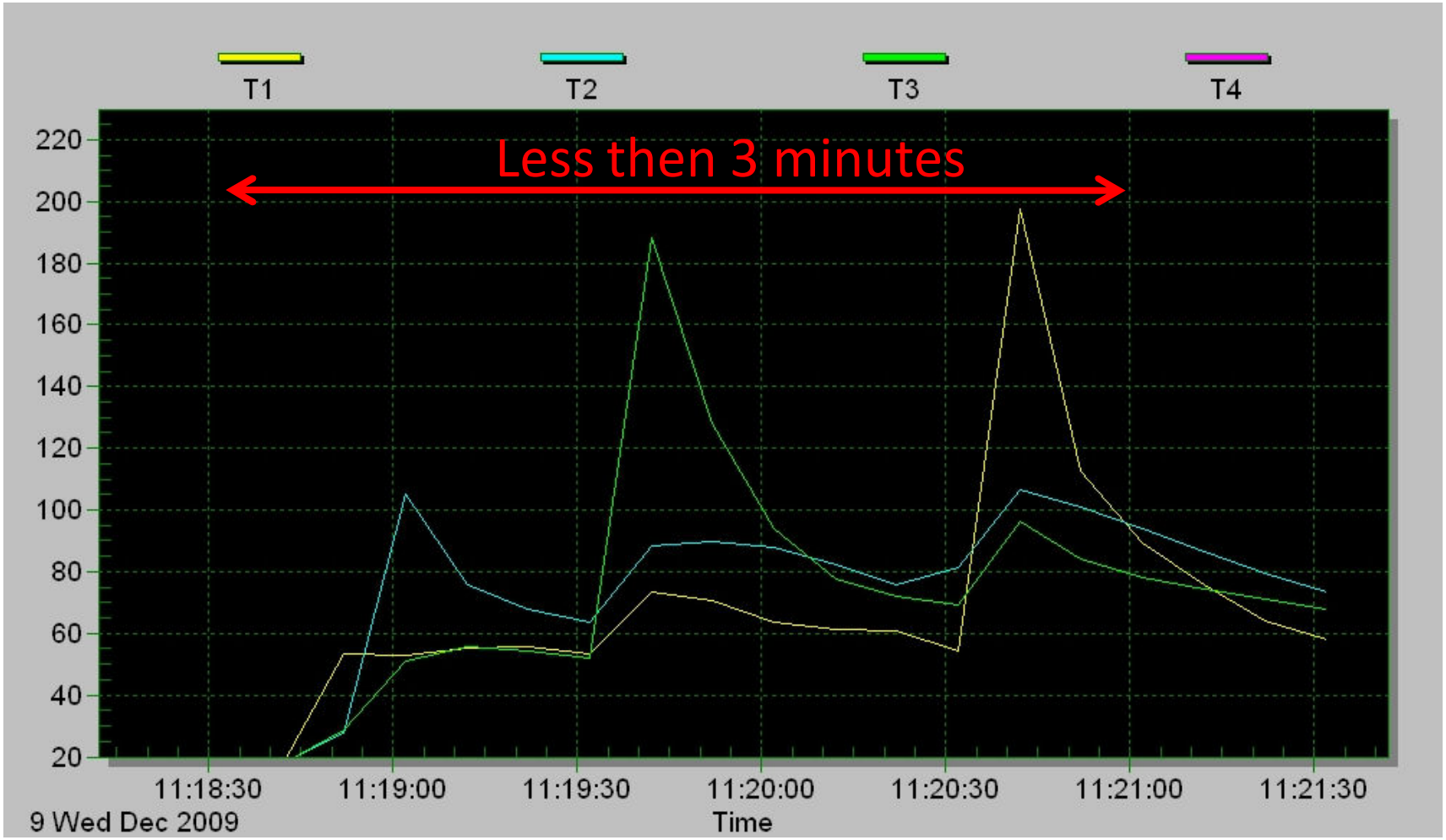
Spot welding machine

from an original use by C. Urpin and undergoing development by S. Triquet http://www.pei-point.com/pdf/catalogo_carrozeria_2005.pdf

http://www.soudax.com/index_dyn-page-is-recherche-and-rubid-is-10-and-feuille-is-1.html



Test on BB quad, shunt 2mmx15mmx200mm



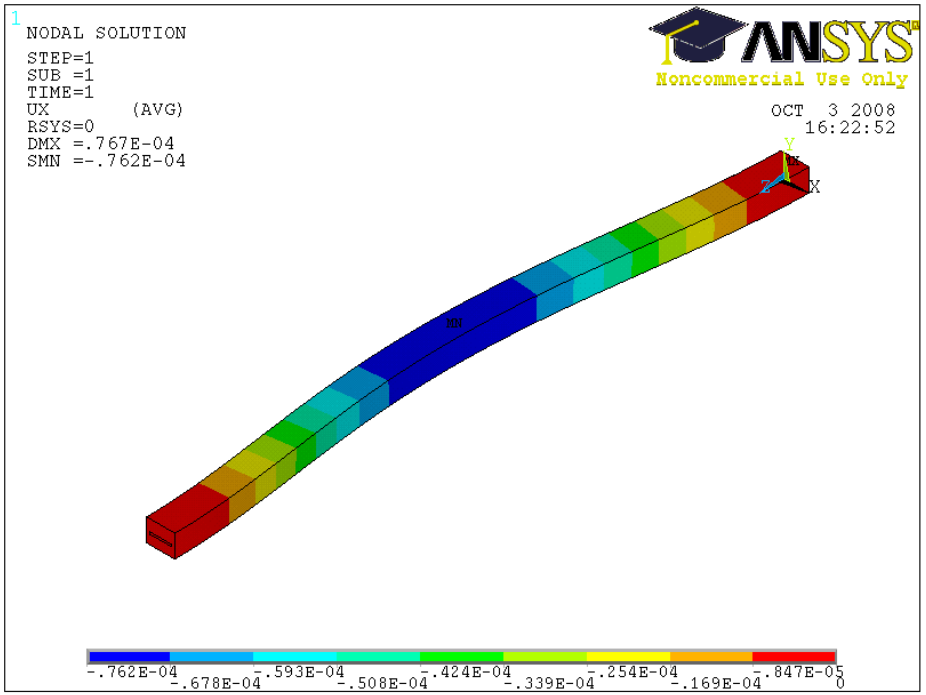
back

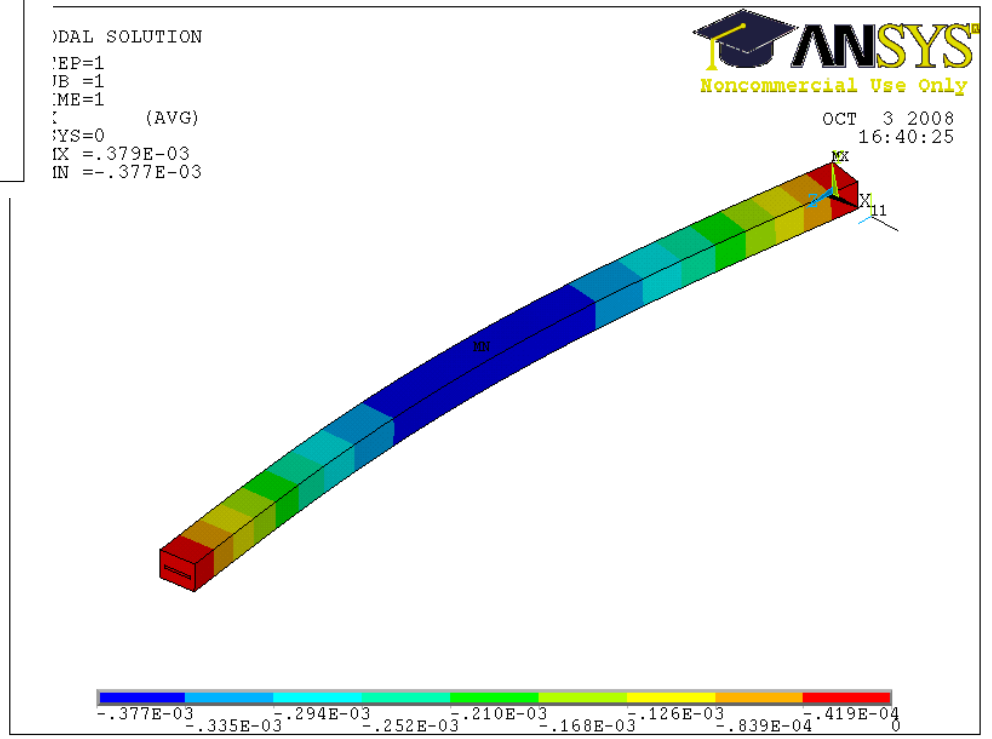
INSULATION: PROVIDING ALSO MECHANICAL SUPPORTS …

A 1st list of technical requirements

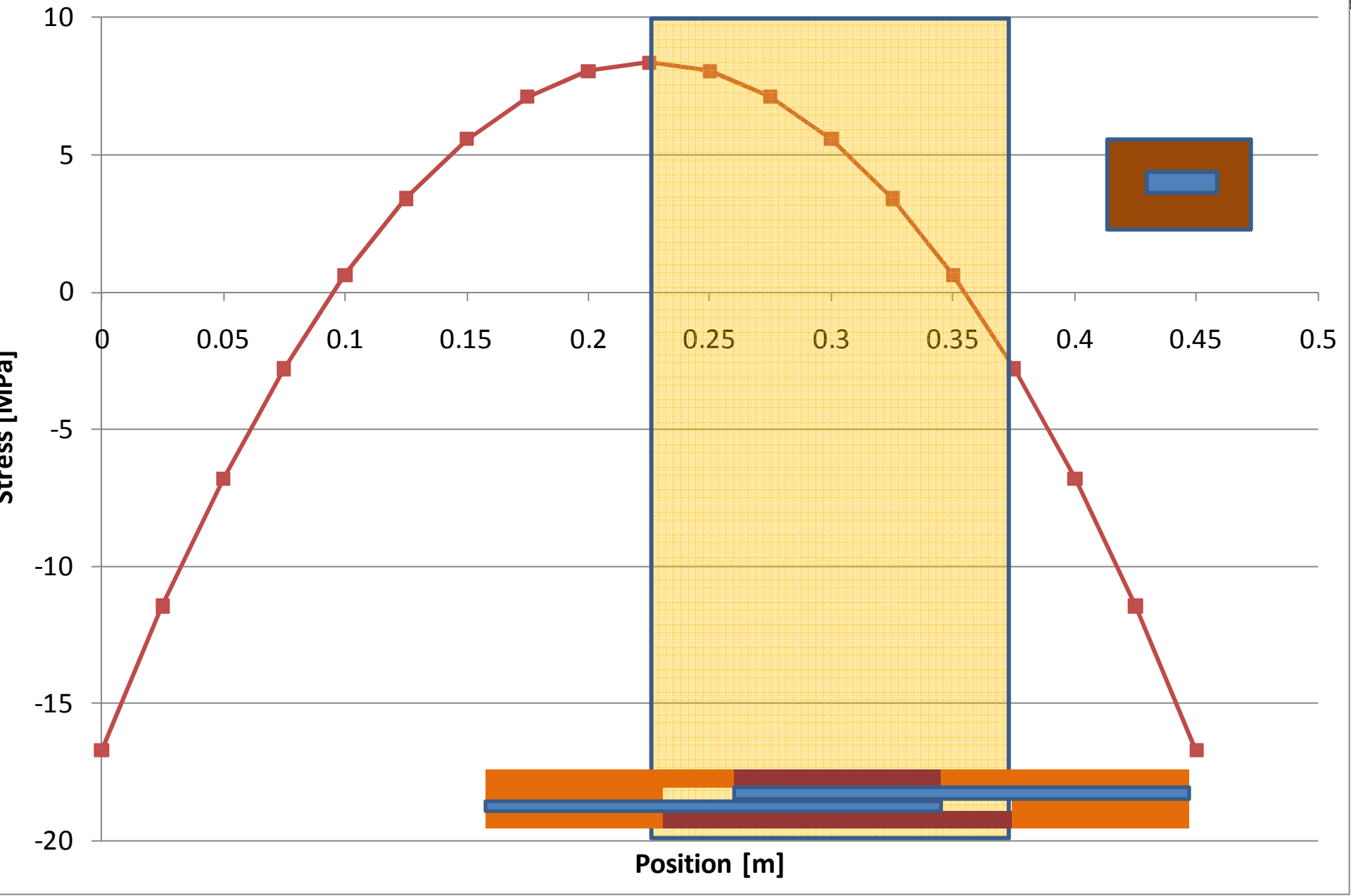
- Provide electrical insulation. Bus bars are protected with polyimide 15 mm wide, 50% overlapped and they are separated by 12 mm of He. Total distance for electrical path 27 mm. This is equivalent to 4 KV at 1 bar.
- Accommodate the new shunt
- Accommodate the differences in bus bar geometry due to shape defects
- Provide enhanced cooling
- Block lateral movement during the ramp up in current

Bus bar horizontal displacement.





Stress in the bus bar copper profile

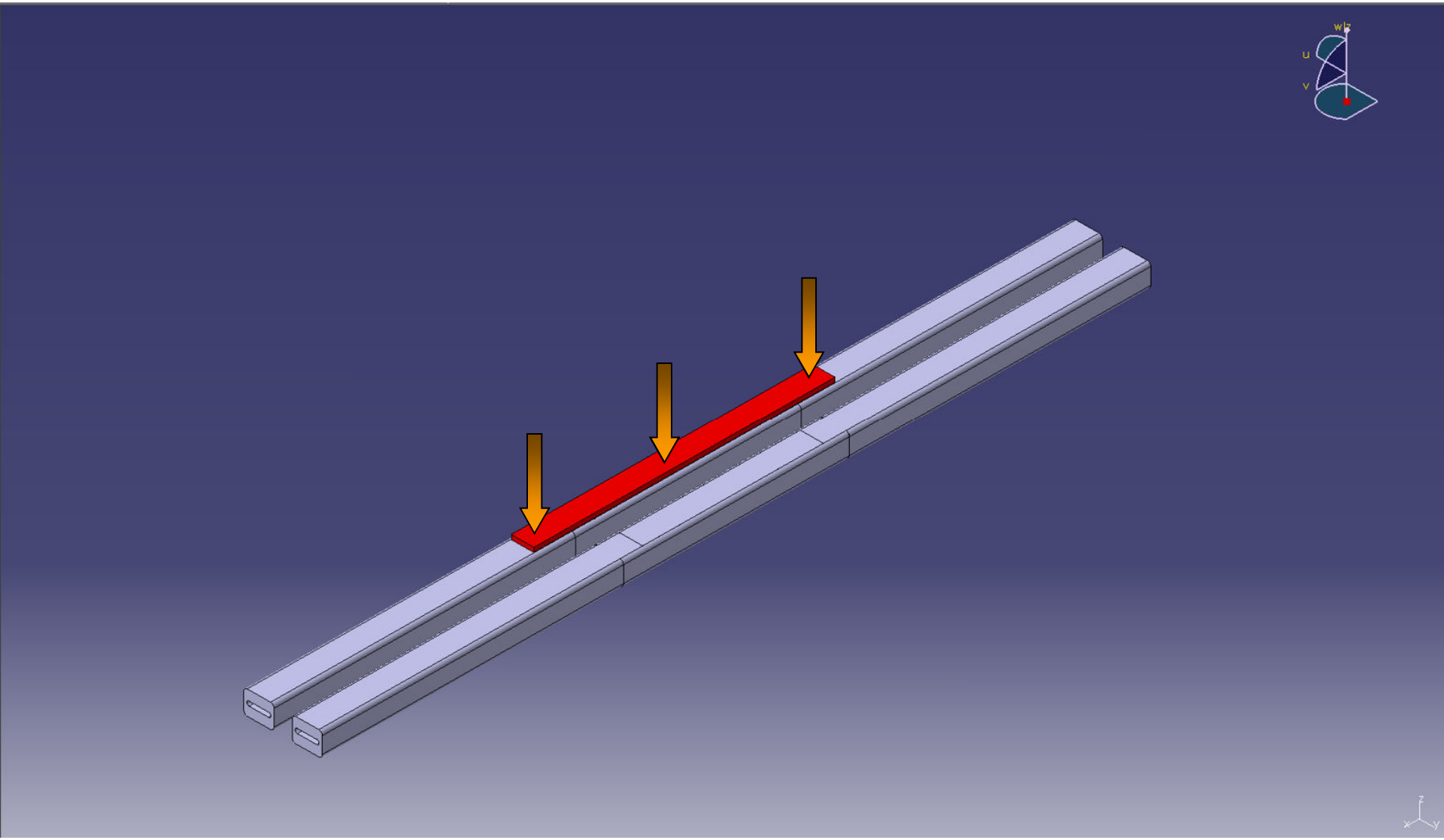


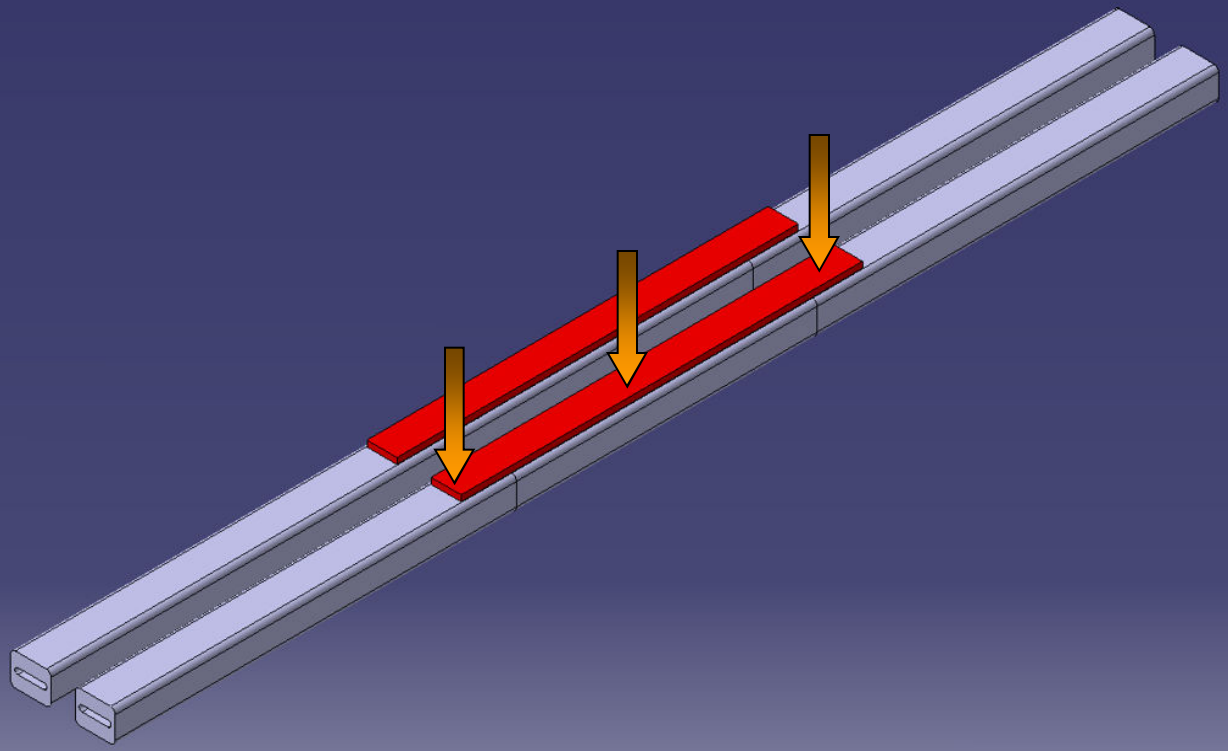
Deformation and induced stresses

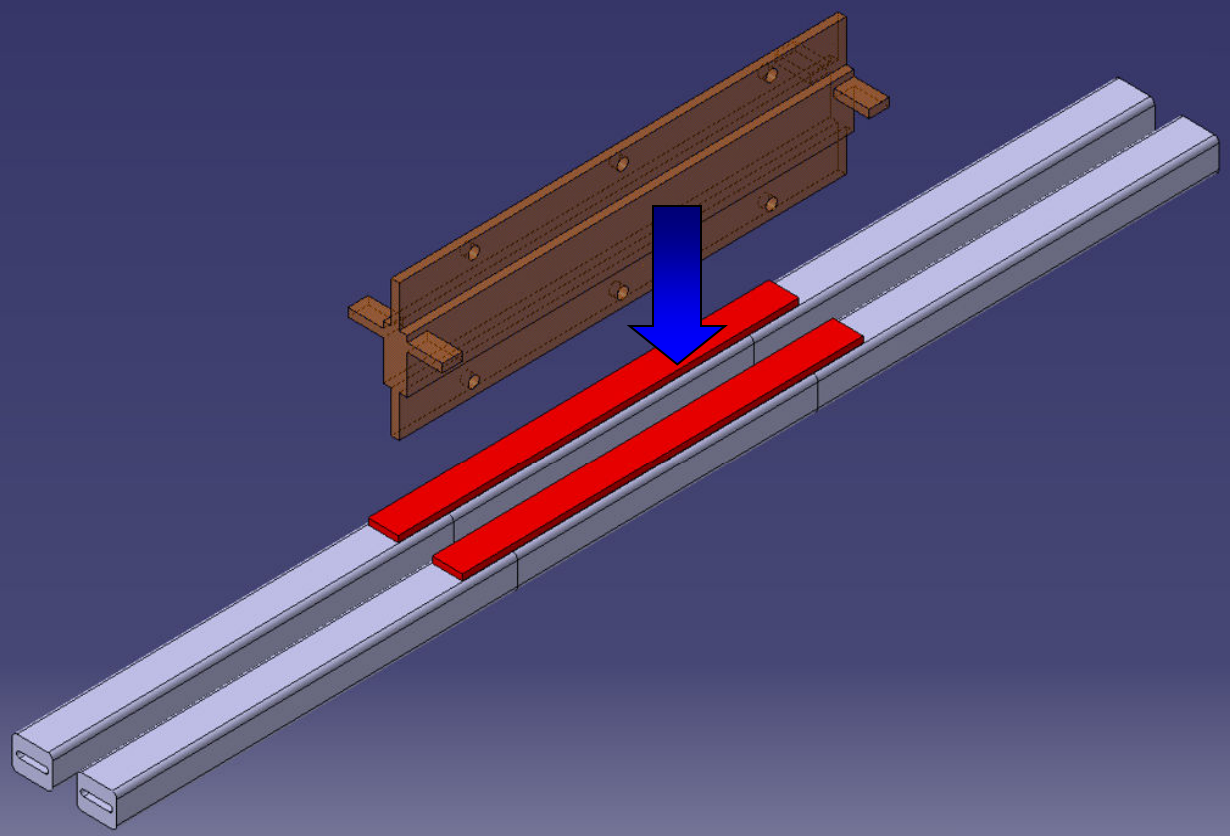
	Restrained	Supported
Max displacement	$-\frac{w \times l^4}{384 \times E \times I}$	$-5 \times \frac{w \times l^4}{384 \times E \times I}$
Max induced tensile stress	$-\frac{w \times l^2}{24 \times \frac{I}{c}}$	$-\frac{w \times l^2}{8 \times \frac{I}{c}}$

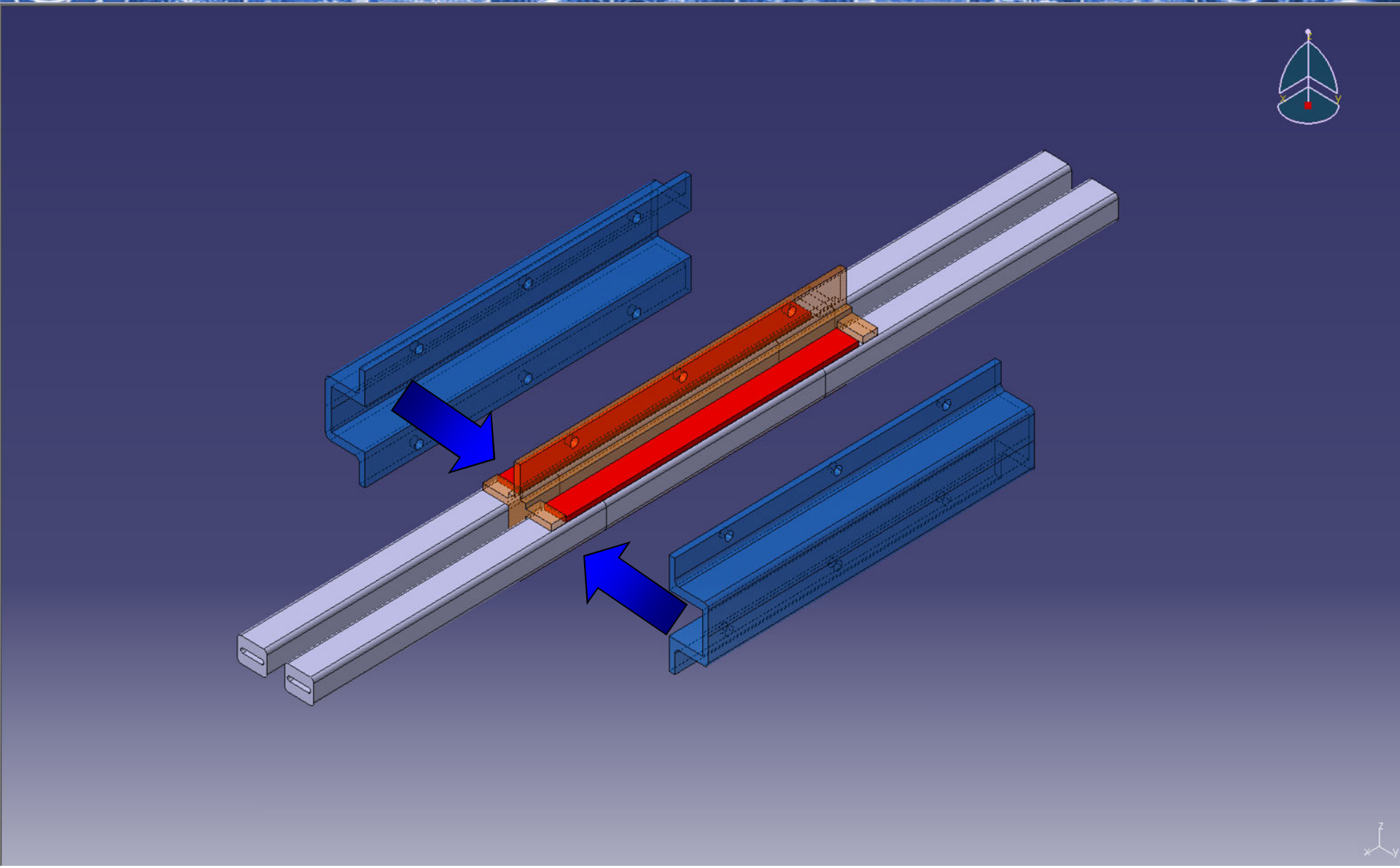
Deformation and induced stresses

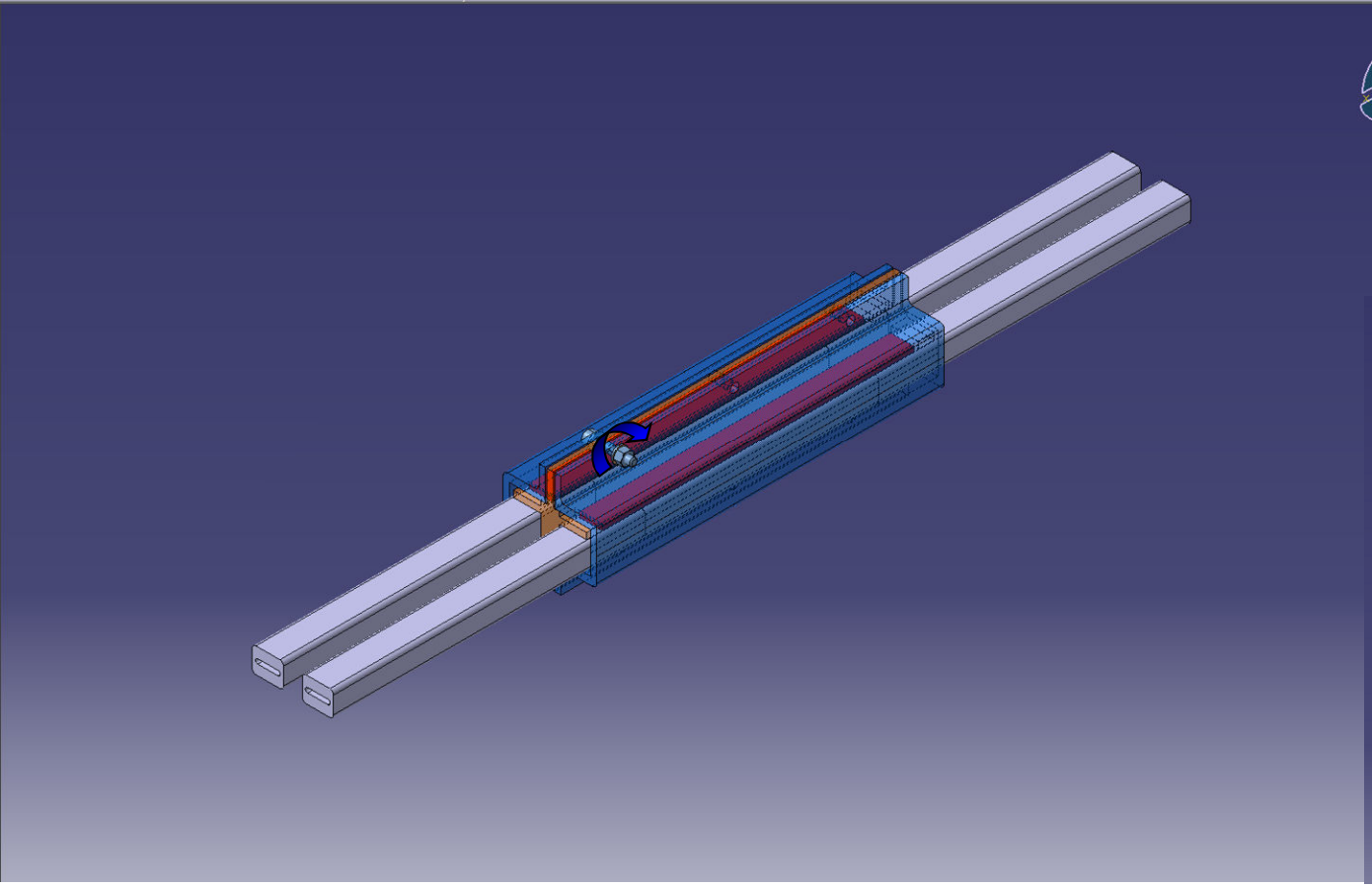
	Restrained		Supported	
Inter-Spider distance	***0.45 m***	***0.6 m***	***0.45 m***	***0. 6m***
Max. displacement	0.08 mm	0.25 mm	0.4 mm	1.25 mm
Max. induced tensile stress	9 MPa	17 MPa	28 MPa	50 MPa

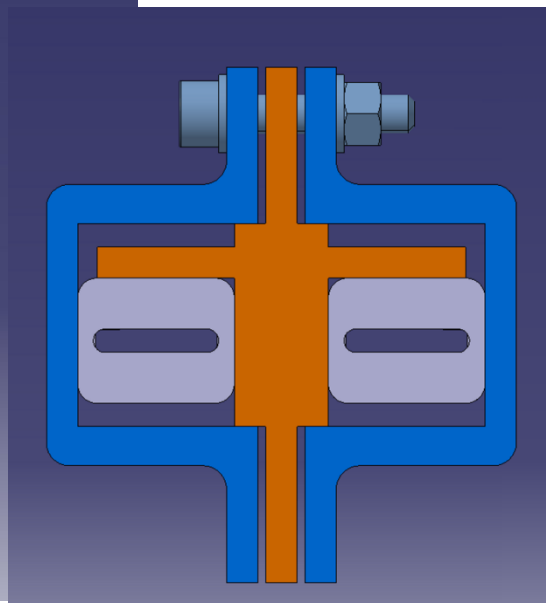

w
u
v











Screw will be closed at fixed torque, distance between the bus bar and the screw is 19 mm (3 KV). Total distance between bus bar 38 mm (5 KV)

We intend to insulate the screw or to make them of Vetresit

The insulating pieces would be produced by injection molding in IXEF 1022 (polyarylamide) or RYTON (PPS) or VERTON

back

Shunt Road-map

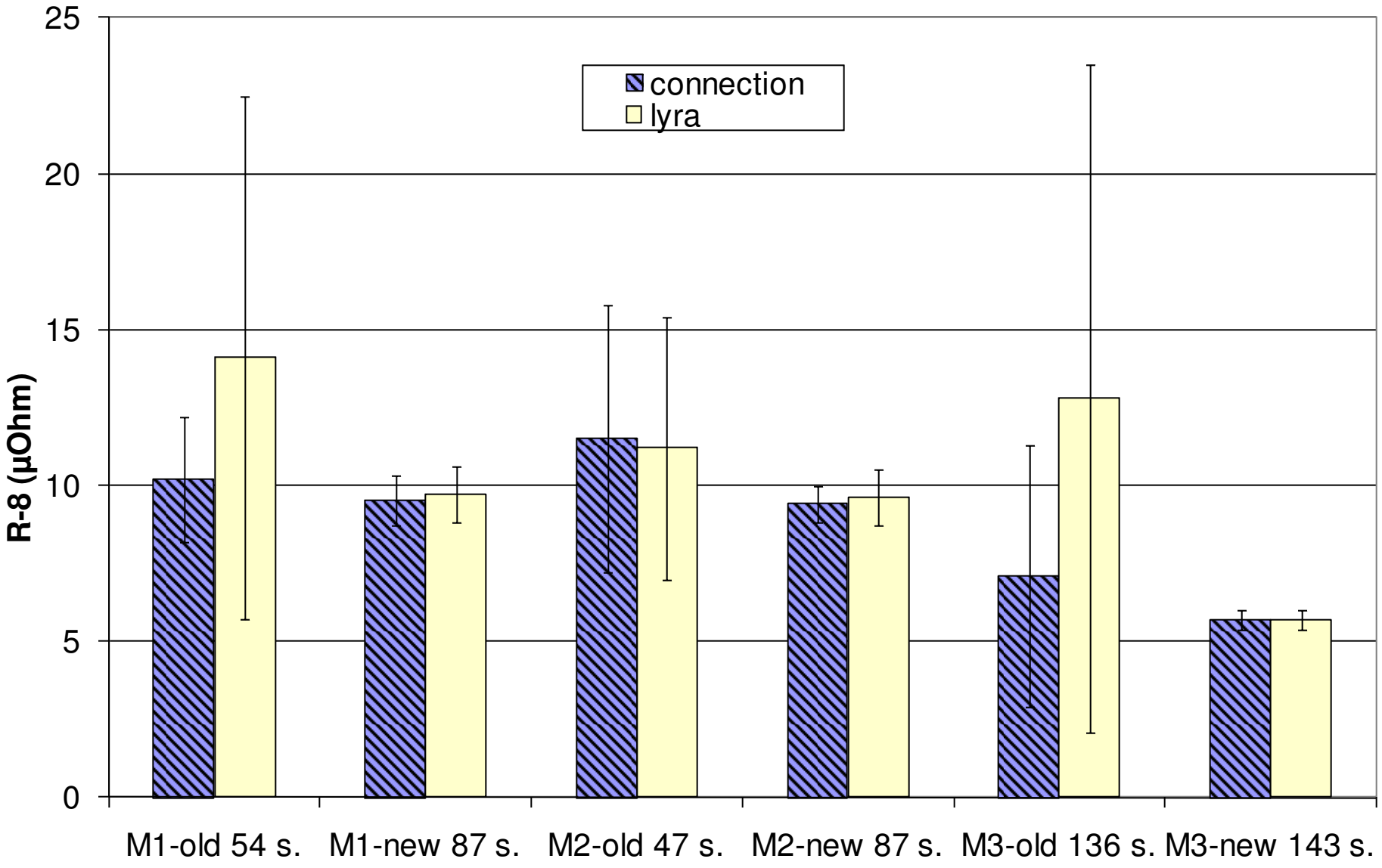
1) *Define technological parameters to obtain good soldering in shortest time: ongoing*
2) *Procure ad hoc flexible shunt: ongoing*
3) *Investigate possible tooling solutions: ongoing*
4) Perform test to get to an acceptable quality of the shunt assembly
5) Proof of concept: apply shunt on FRESCA 2 samples and re-test
6) Full functional prototype with proto components
7) Finalise tooling
8) Start I.T. phase in June

Conclusions

- A possible consolidation activity sequence has been proposed putting in evidence the main issues to be solved in the next months
- Parameters on which triggering the decisions of re-doing an interconnect have been proposed
- New interconnect procedure provides a better result and the possibility for further improvement shall be pursued
- A road map to fix a shunt design has been proposed and ongoing work resumed
- The shunt shall be coupled to lateral mechanical restrain to prevent mechanical fatigue of the joint

SUPPORT SLIDES

Old production vs. new production: a quality index

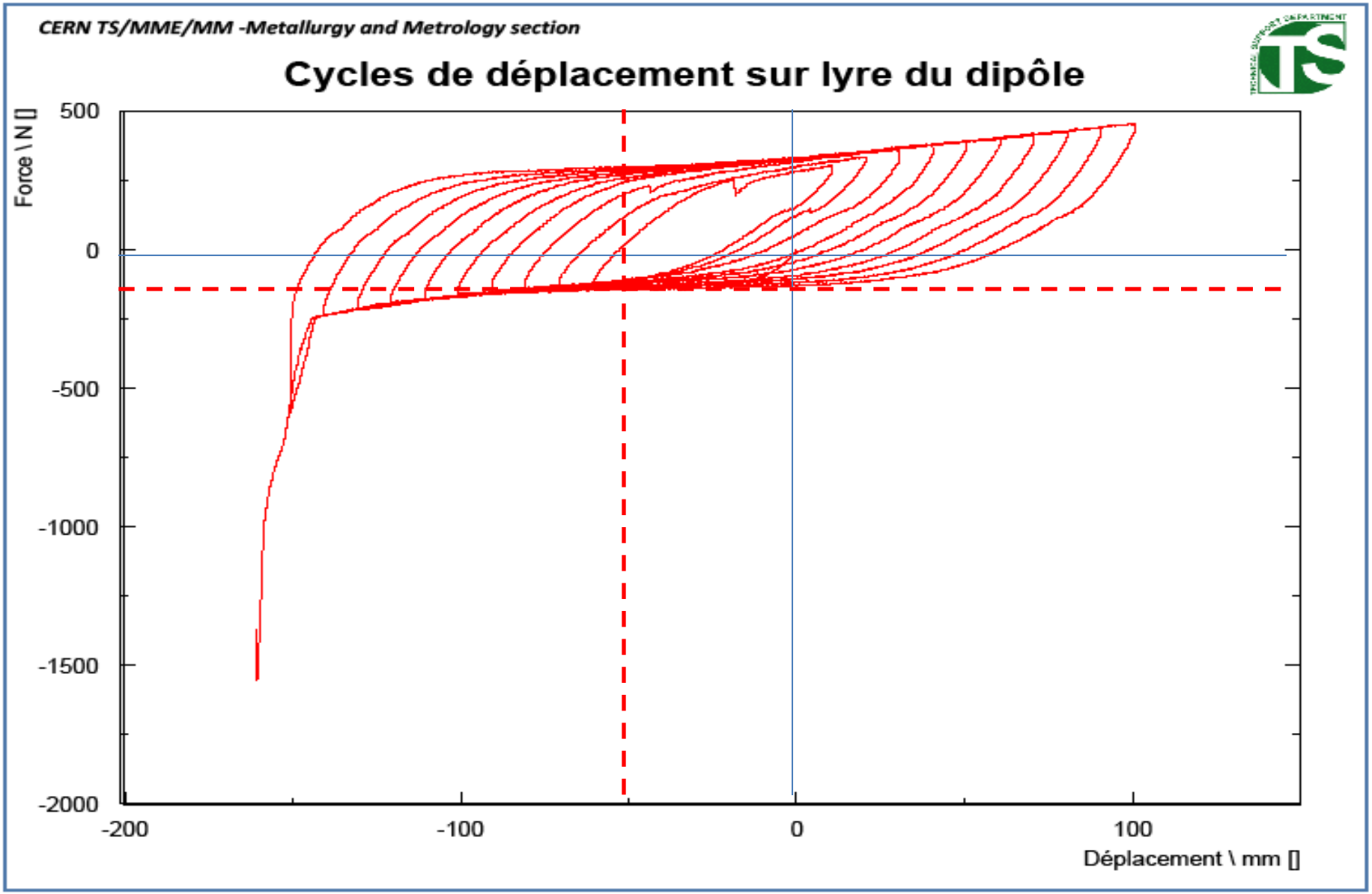


MECHANICAL LOADS

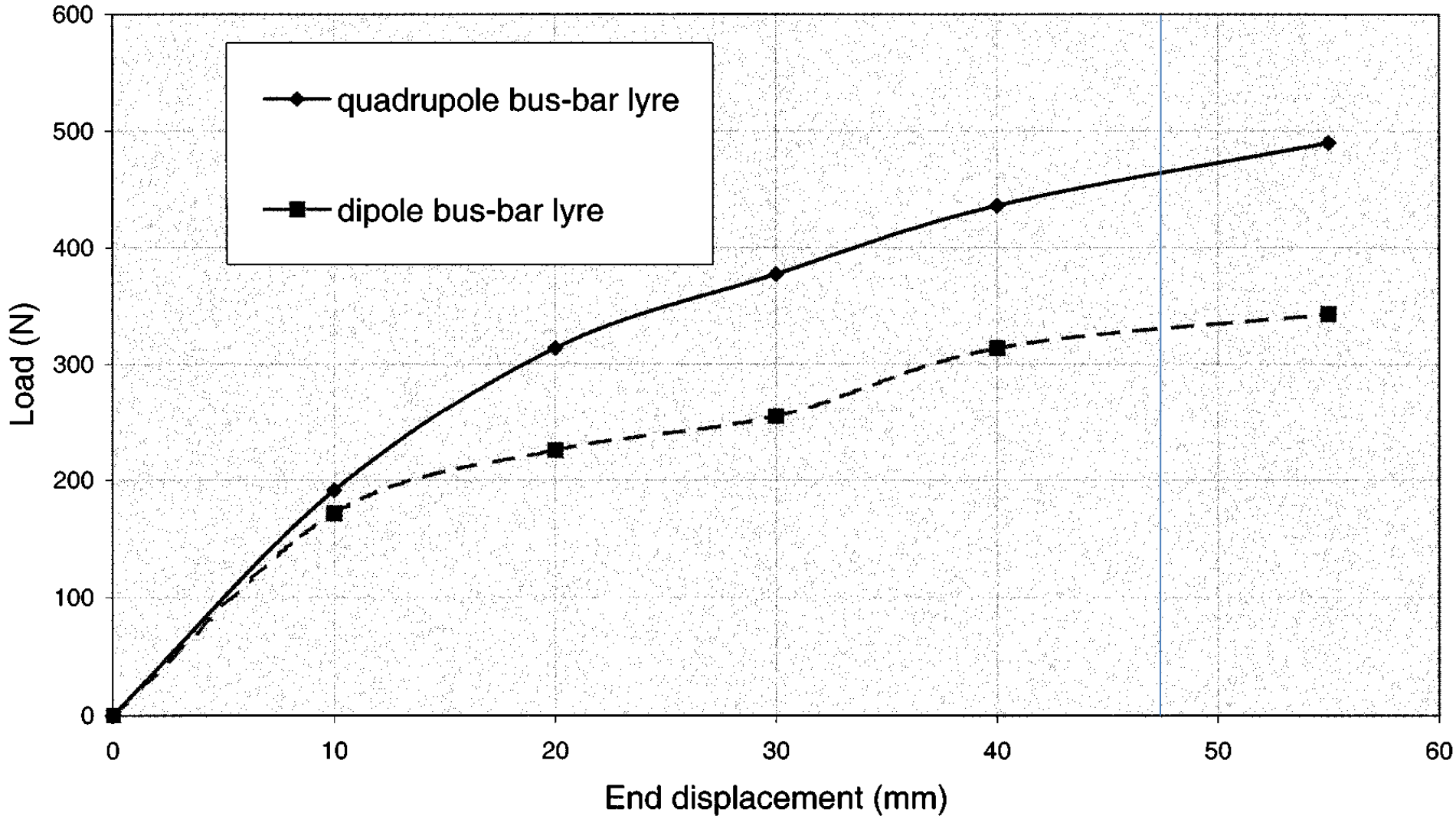
Mechanical forces on the splice

- Room temperature: compressive longitudinal force due the compression of the lyre for about **47 mm=450 N**
- With current and with perfect current re-distribution :
  - Vertical direction (y). Total force on each joint is null but the 2 cables are submitted to a force towards the joint plane
  - Horizontal direction (x). The 2 joints are submitted to force rejecting the 2 bus bars

Longitudinal force restrain



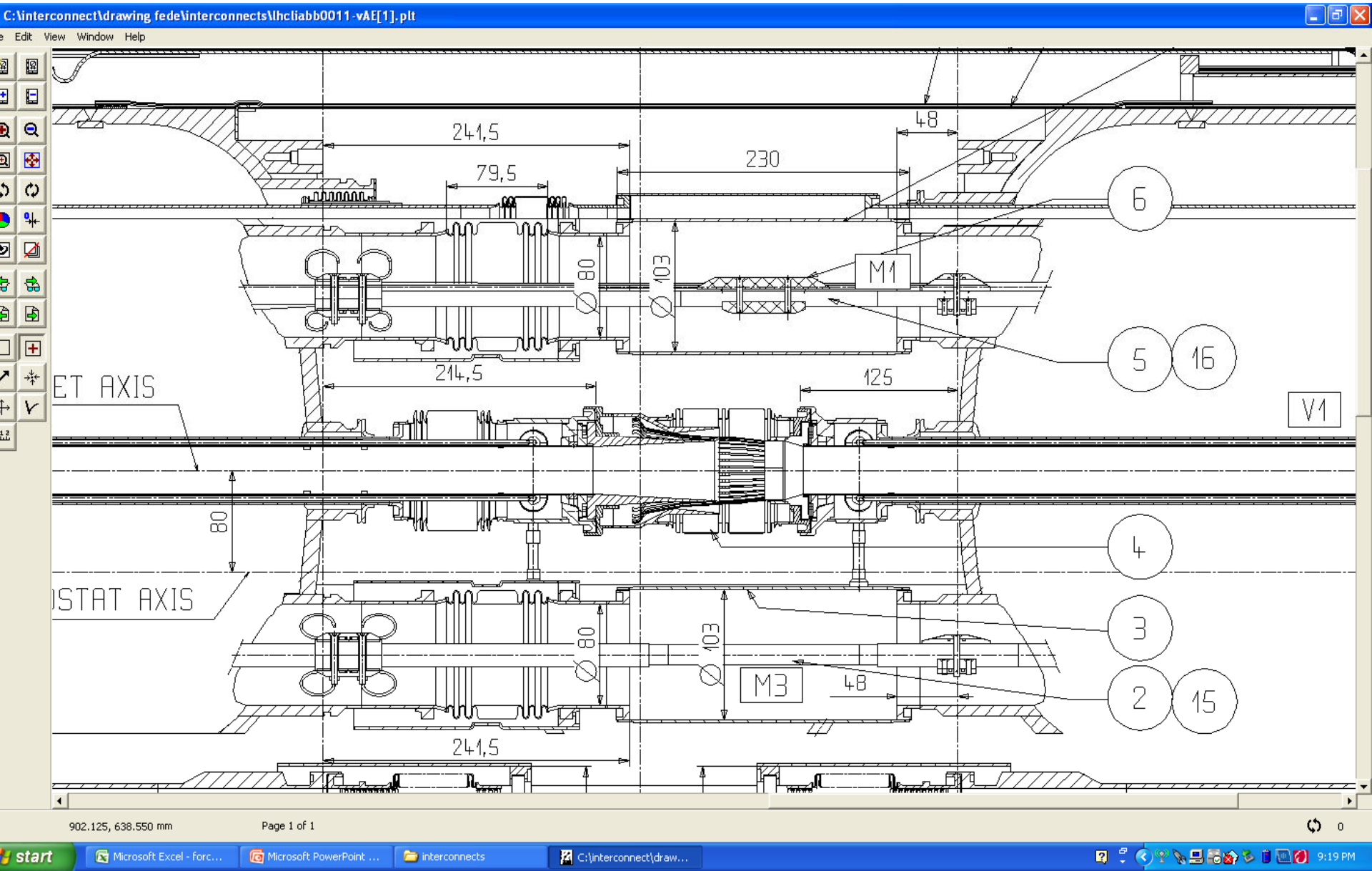
Compressive force on lyre at RT vs. displacements



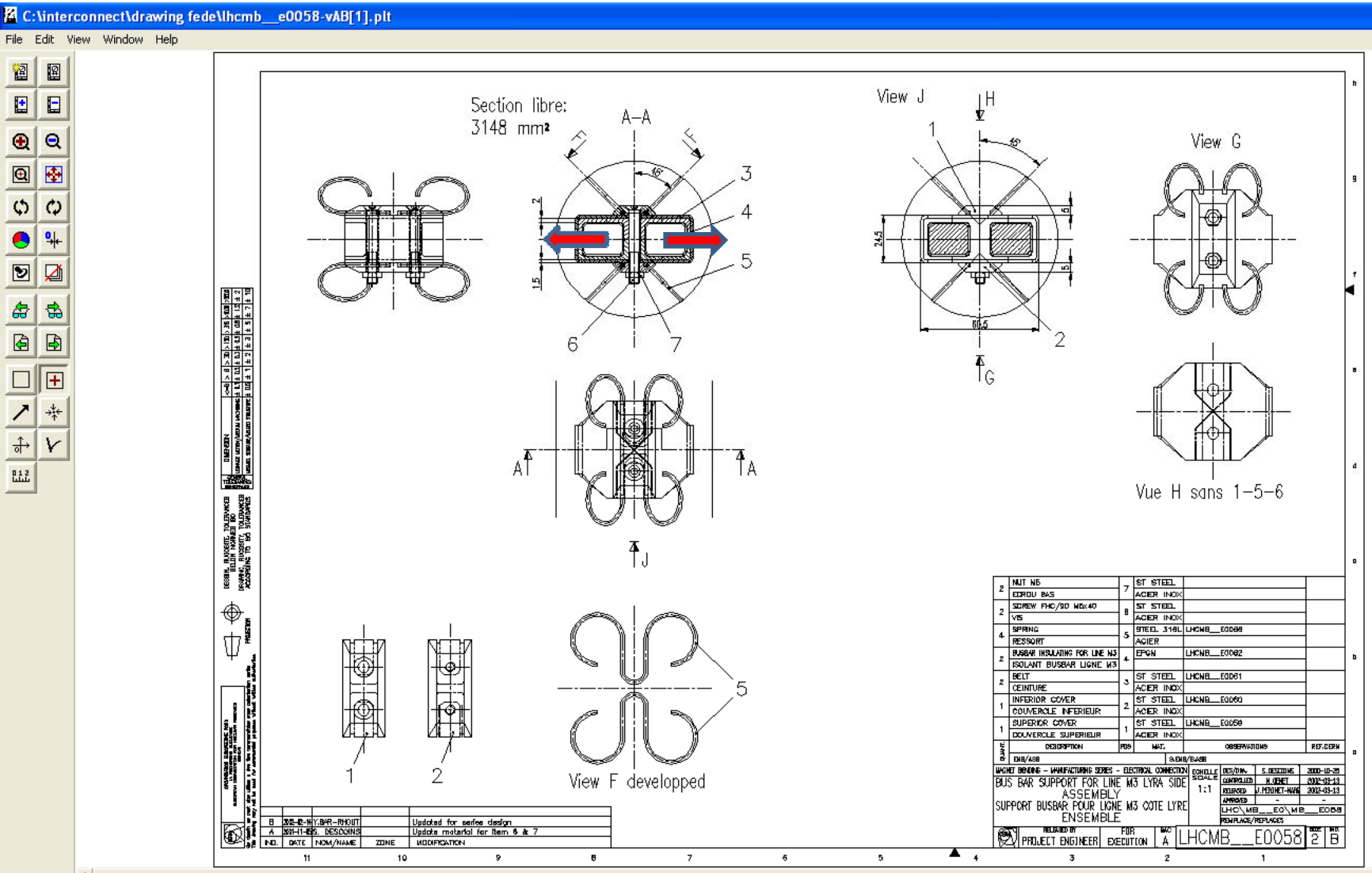
A fatigue test on a good Cu-Cu connection for tensile efforts

step	R8 A [μΩ]	R8 B [μΩ]
Initial values	9.6	10.7
After LN shock	9.6	11
After compression 500 N 40 cycles	9.8	10.7
After tension 500 N 40 cycles	9.9	10.7
500 N	9.9	11.6
2000 N	9.9	11.6
4000 N	10	12
6000 N	11	12
8000 N	11	12
13000 N	11.6	12.9
13800 N	breakage	

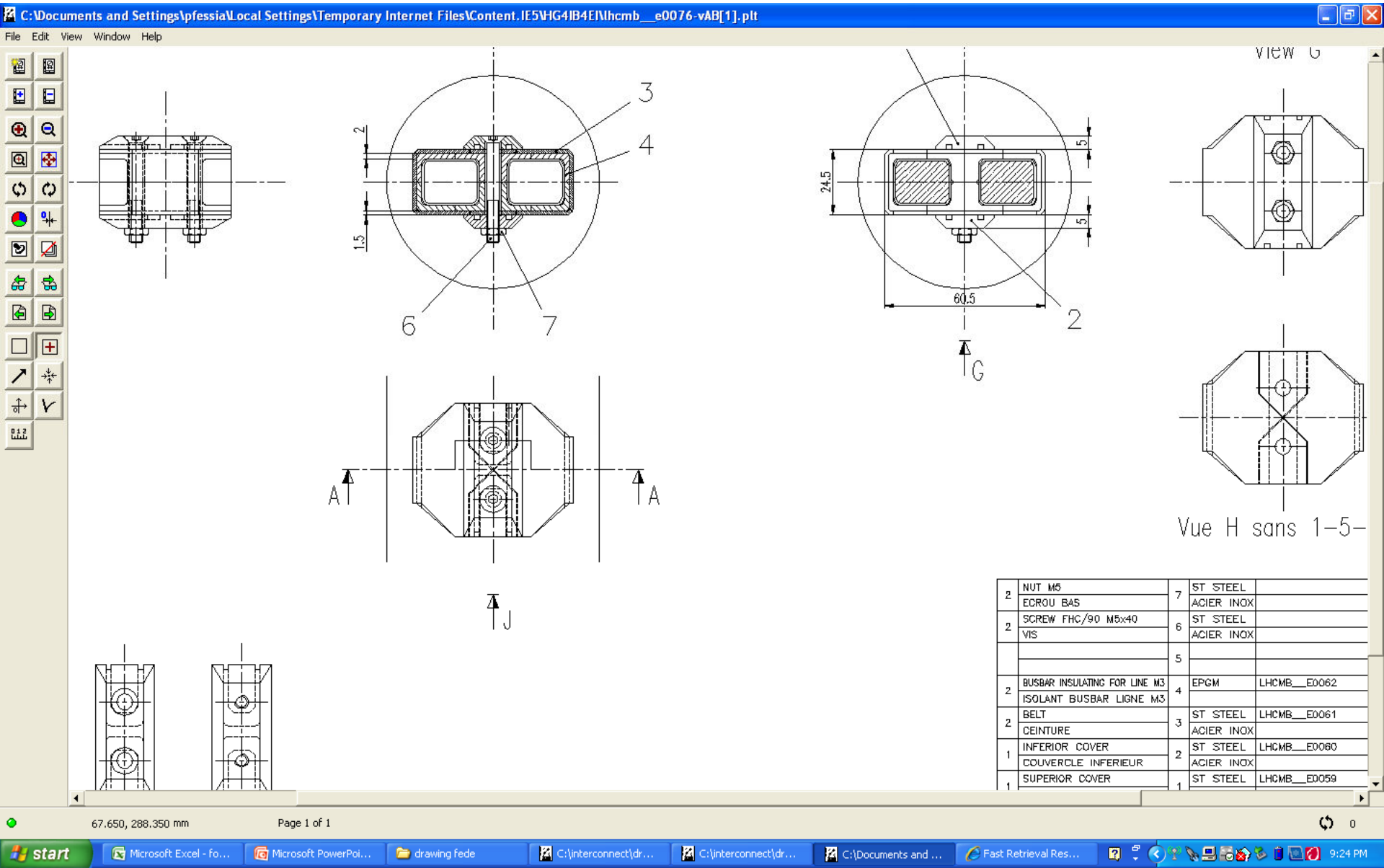
Bus bar loading case



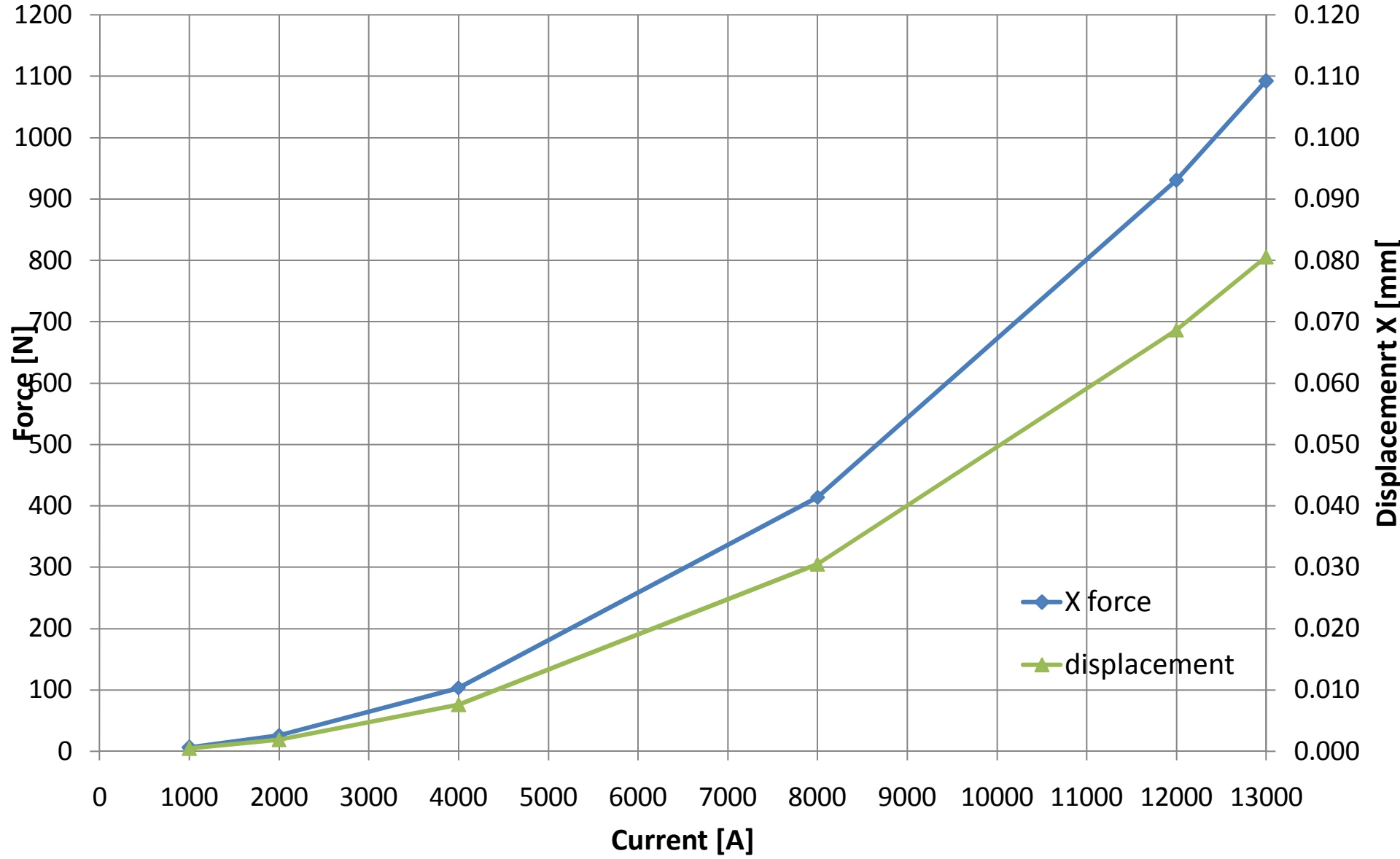
M3 spider lyra side



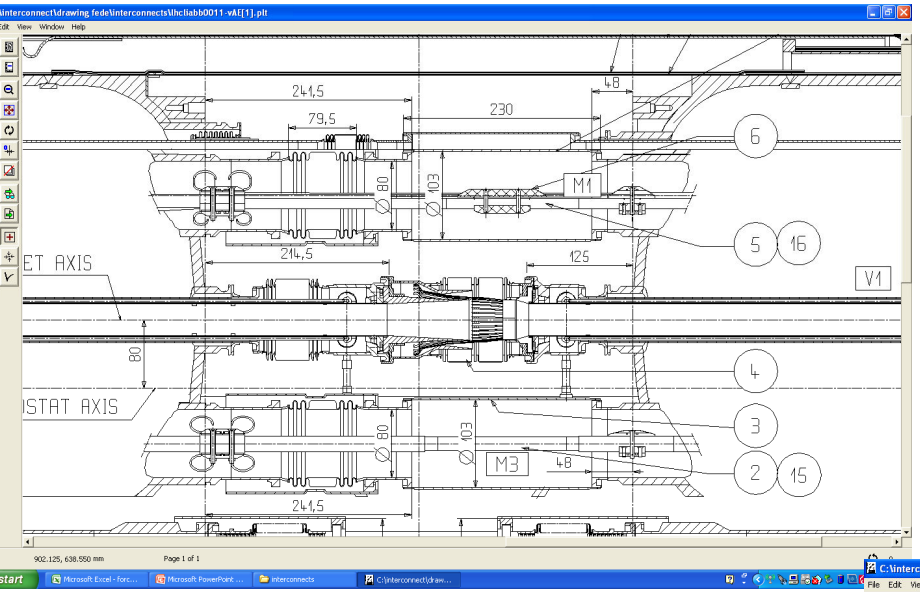
Bus bar support connection side

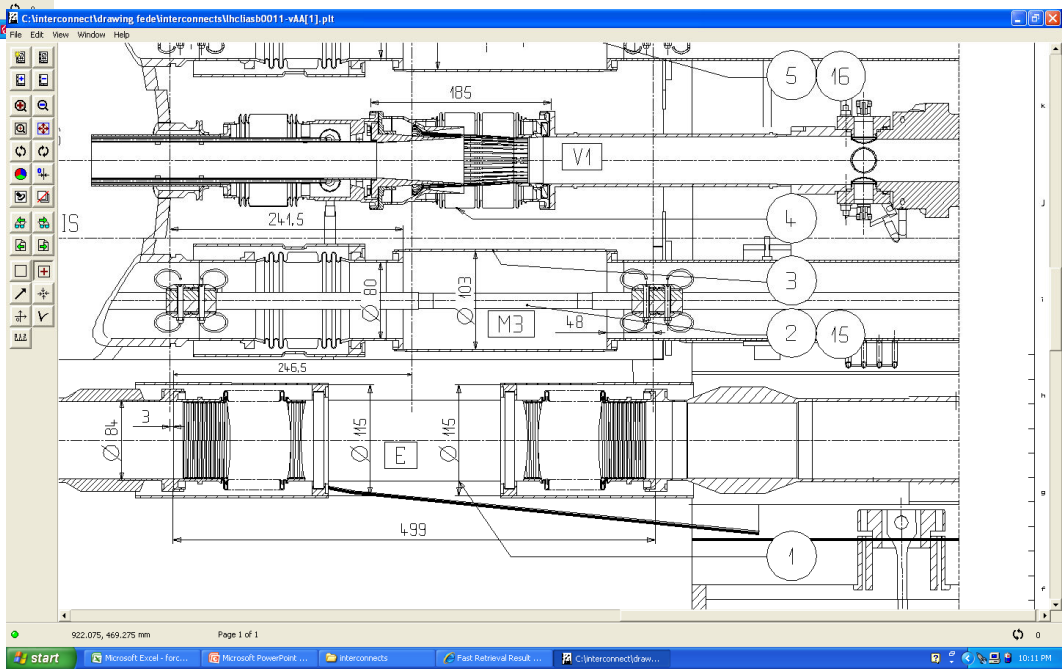


Forces and displacements at cold (bus bar fully restrained by the spiders)

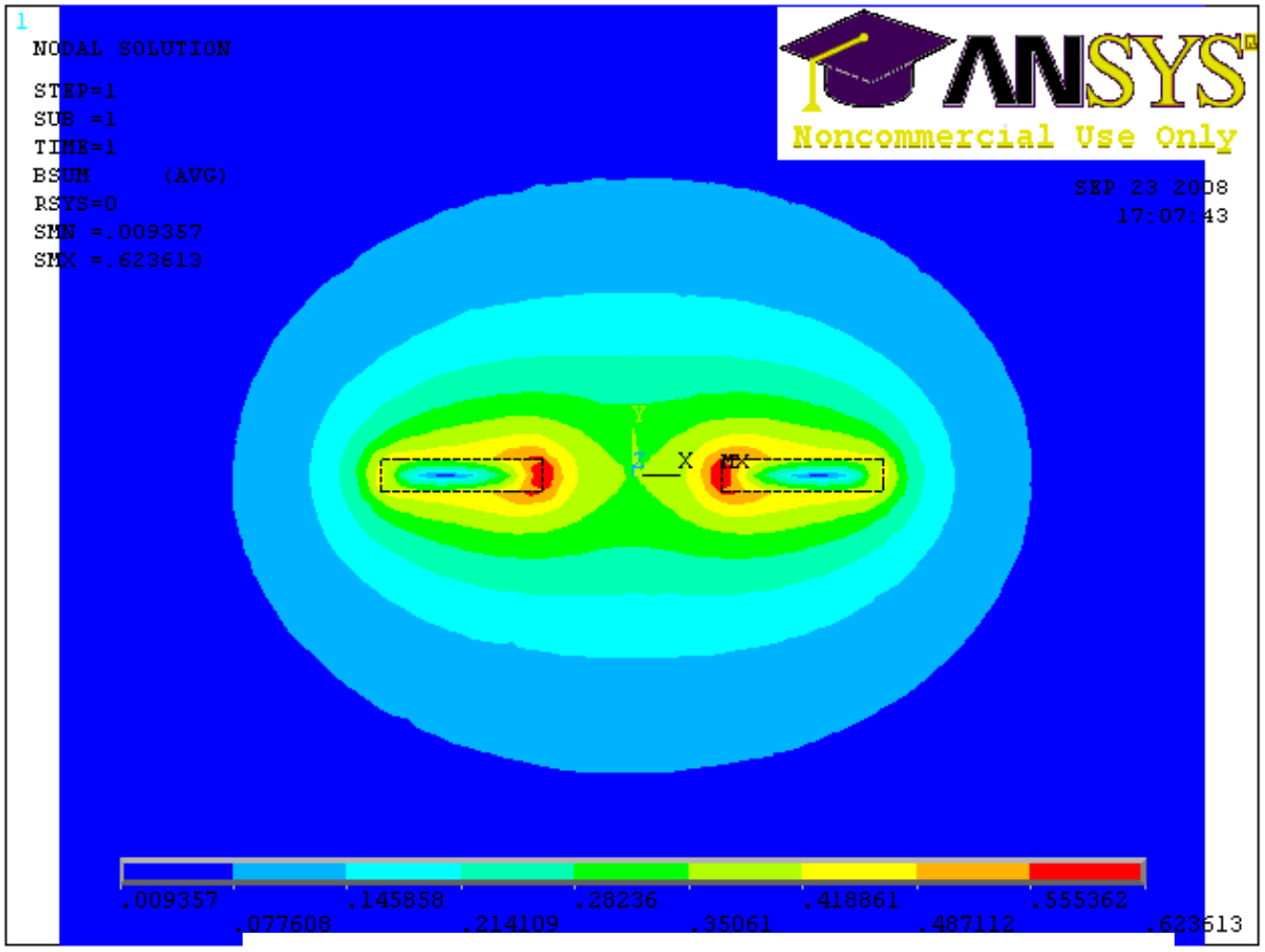


Spiders displacements

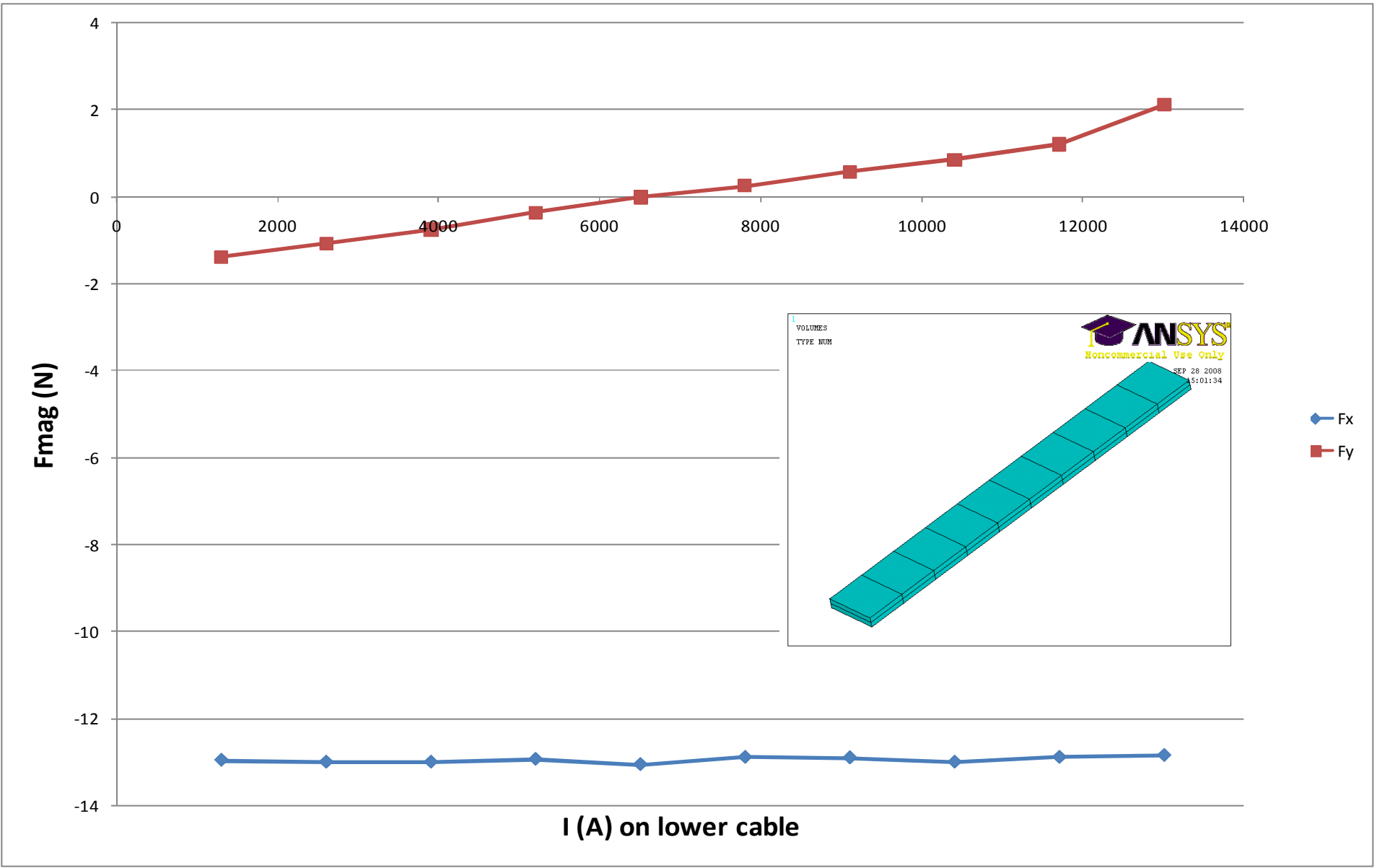




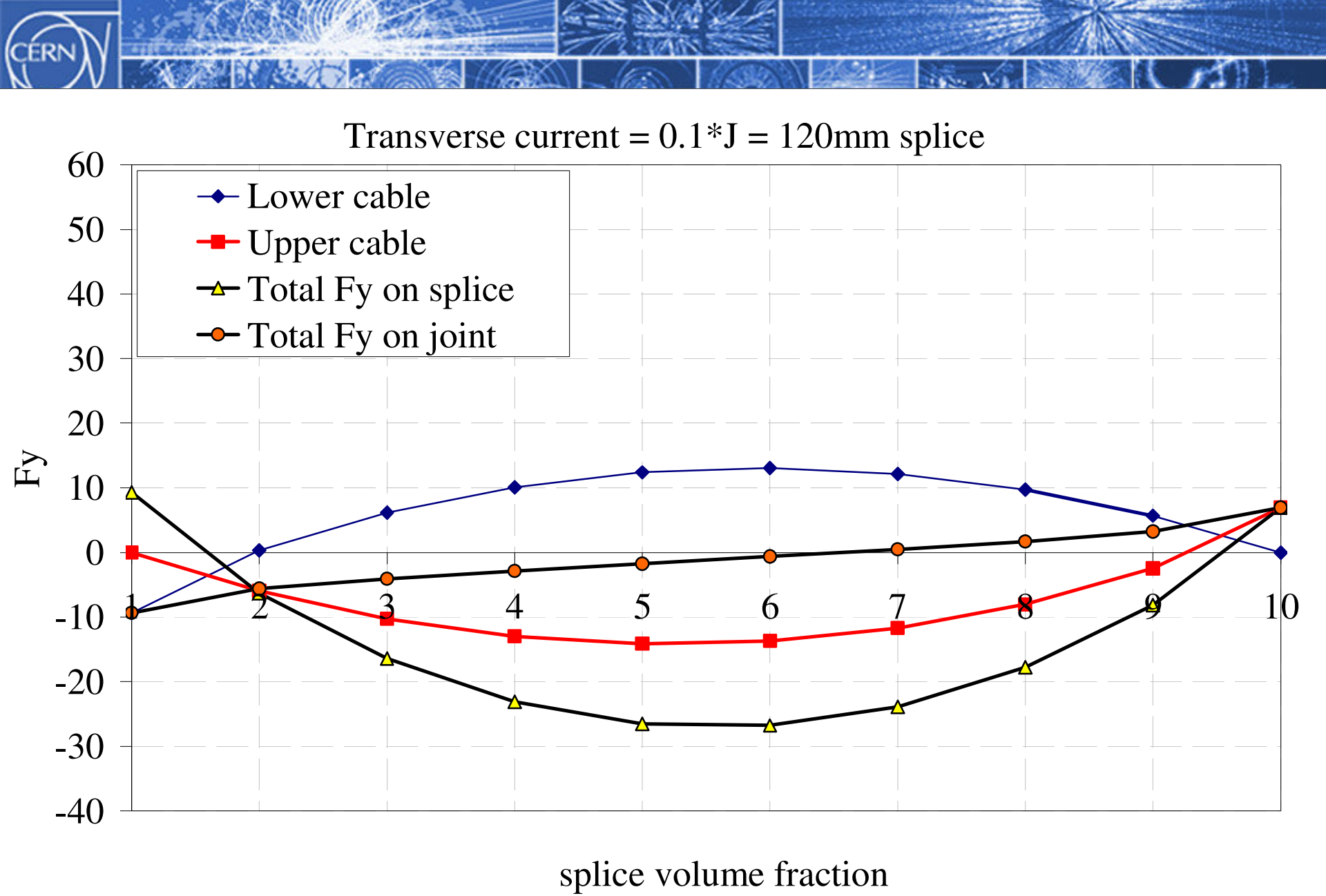
Electromagnetic forces

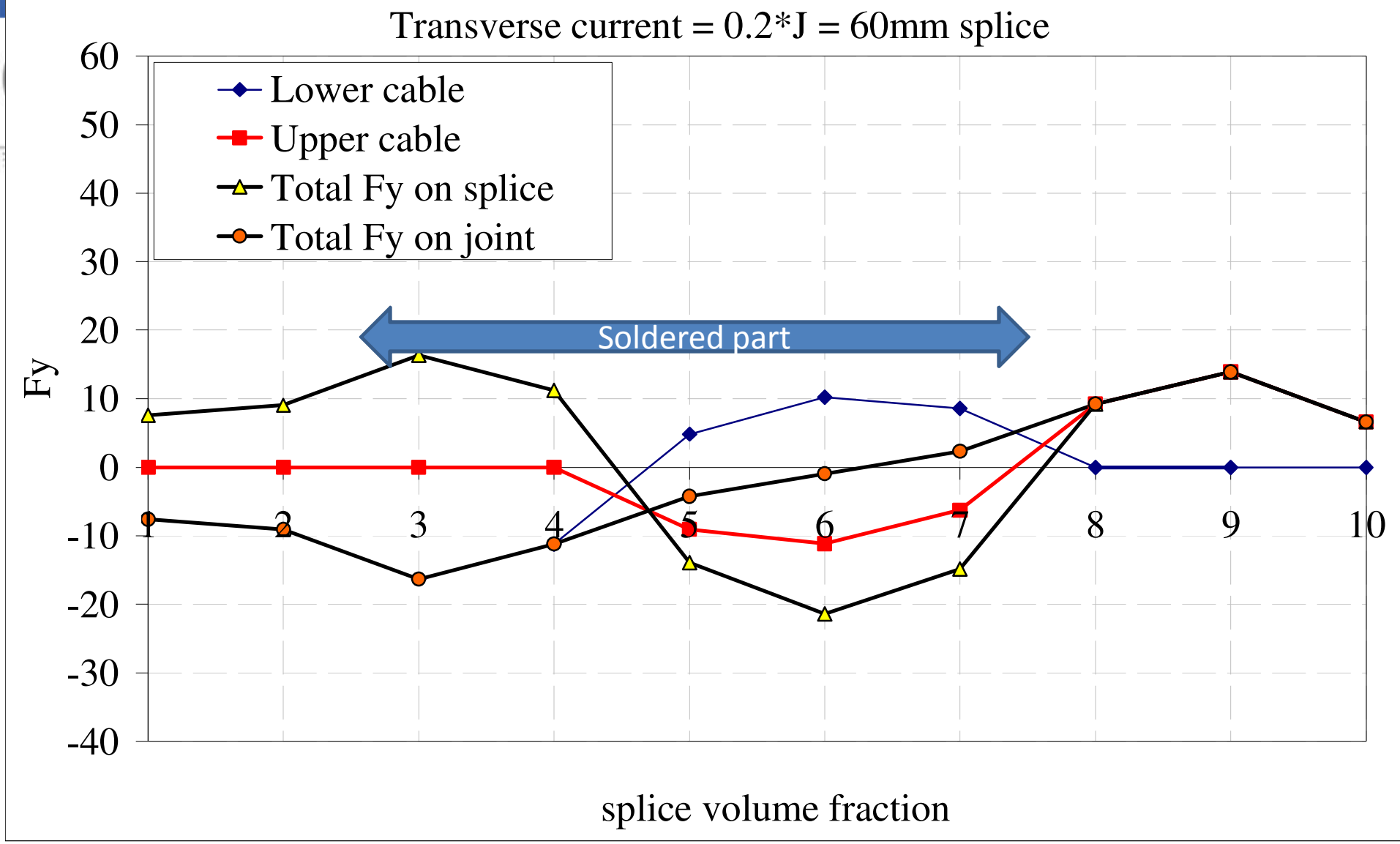


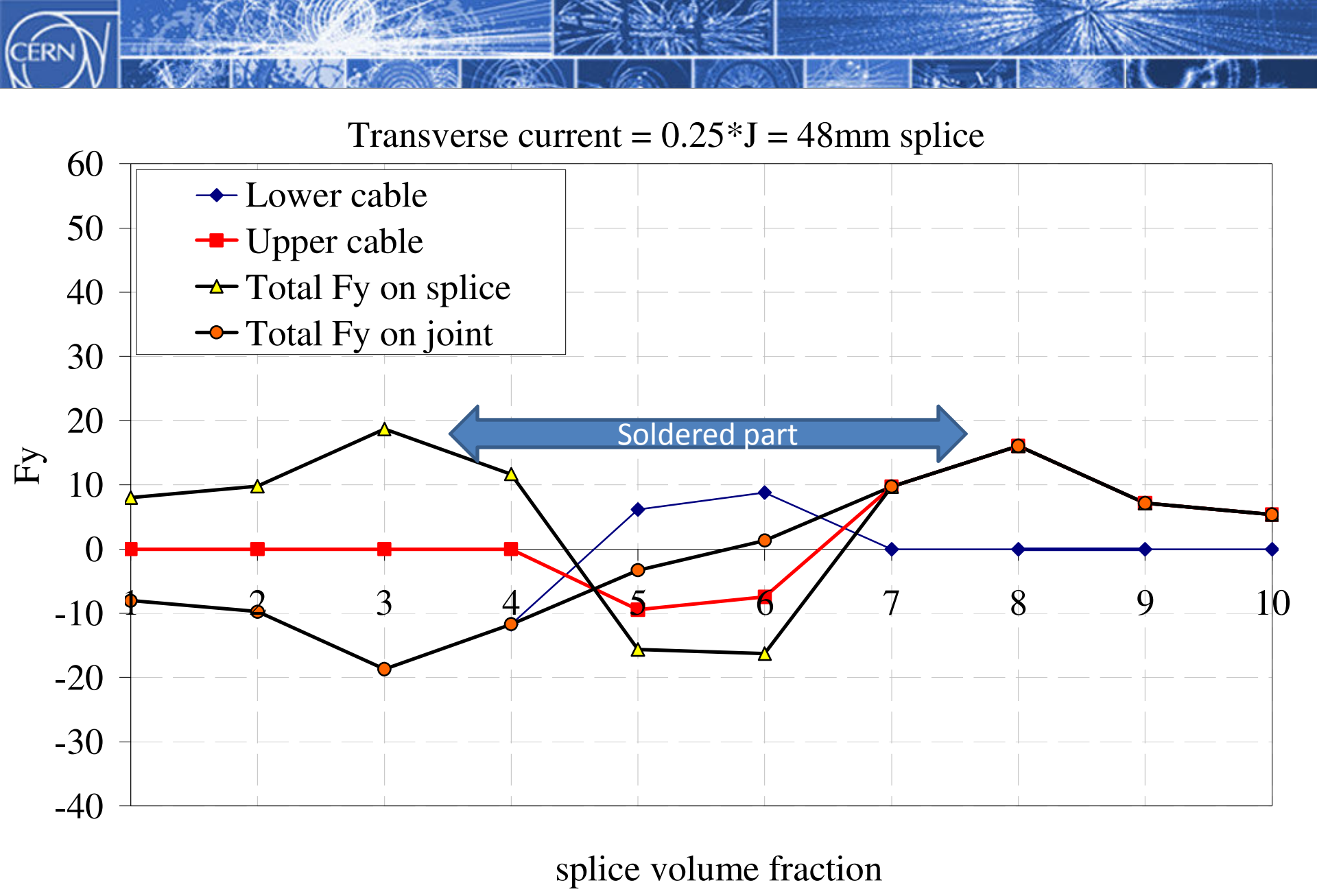
Magnetic forces distribution due to current profile

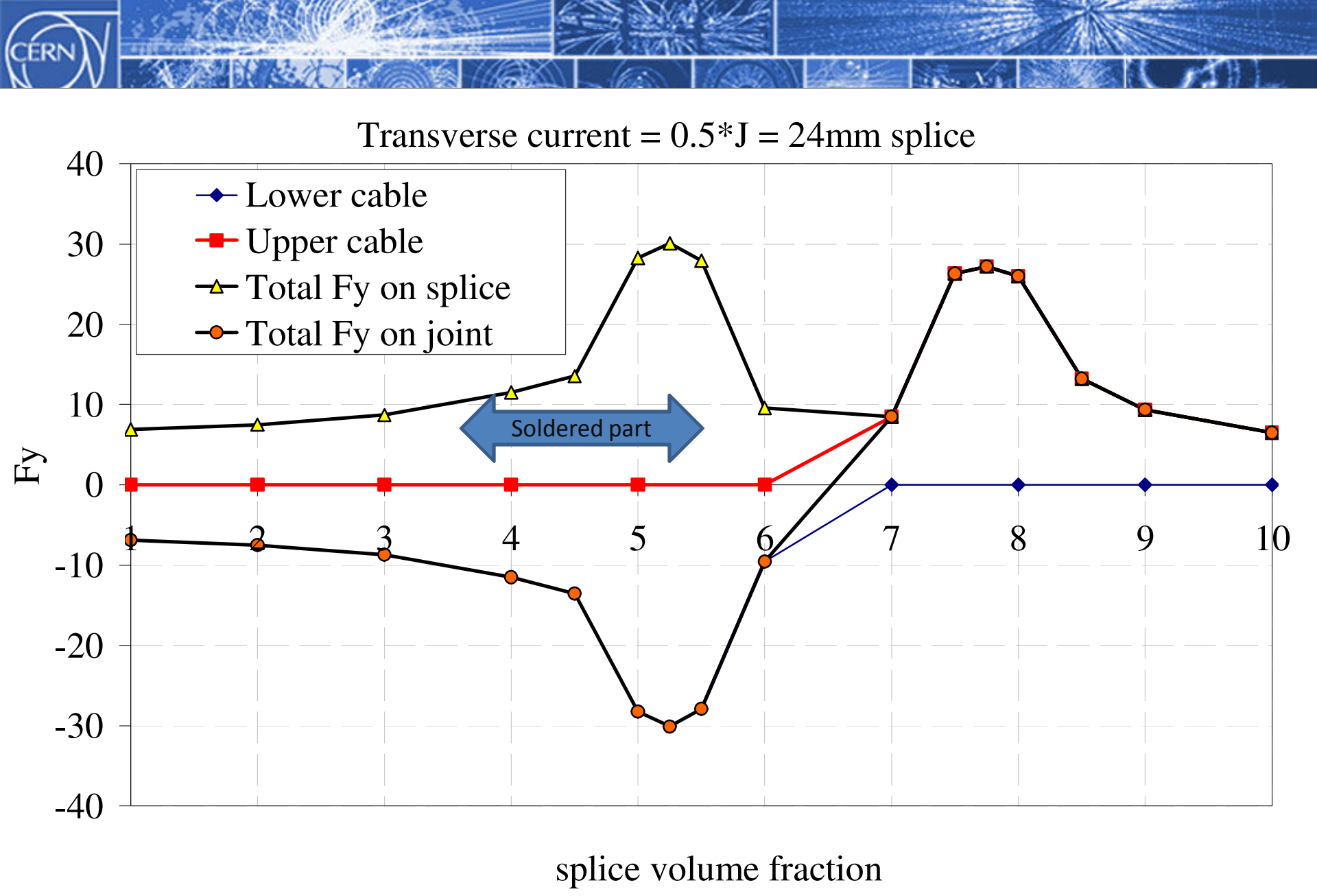


Re-evaluation of the junction forces in function of the junction length

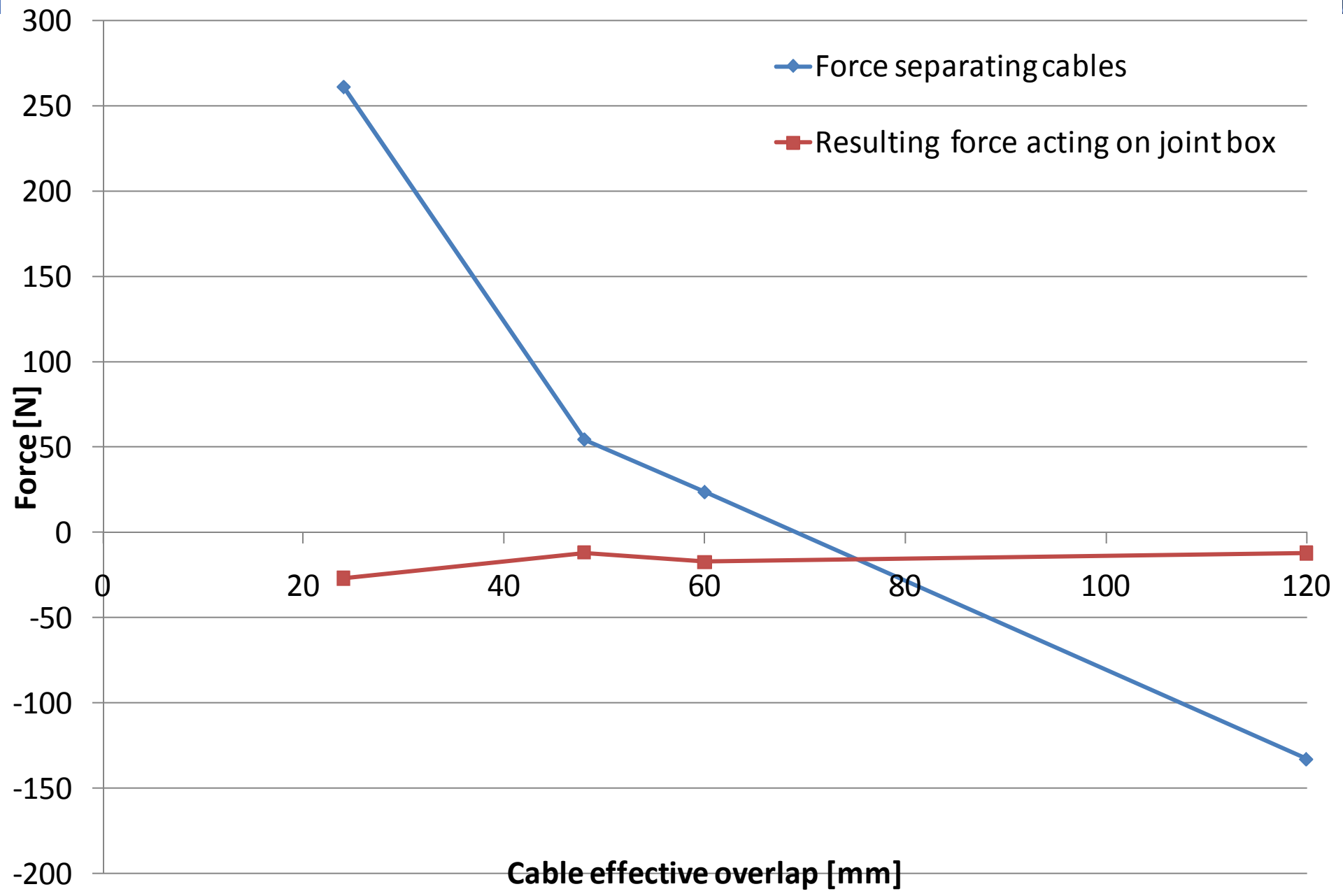

Transverse current = 0.1*J = 120mm splice
Lower cable
Upper cable
Total Fy on splice
Total Fy on joint
Fy
60
50
40
30
20
10
0
-10
-20
-30
-40
1
2
3
4
5
6
7
8
9
10
splice volume fraction


Transverse current = 0.2*J = 60mm splice
Lower cable
Upper cable
Total Fy on splice
Total Fy on joint
Soldered part
Fy
60
50
40
30
20
10
0
-10
-20
-30
-40
1
2
3
4
5
6
7
8
9
10
splice volume fraction

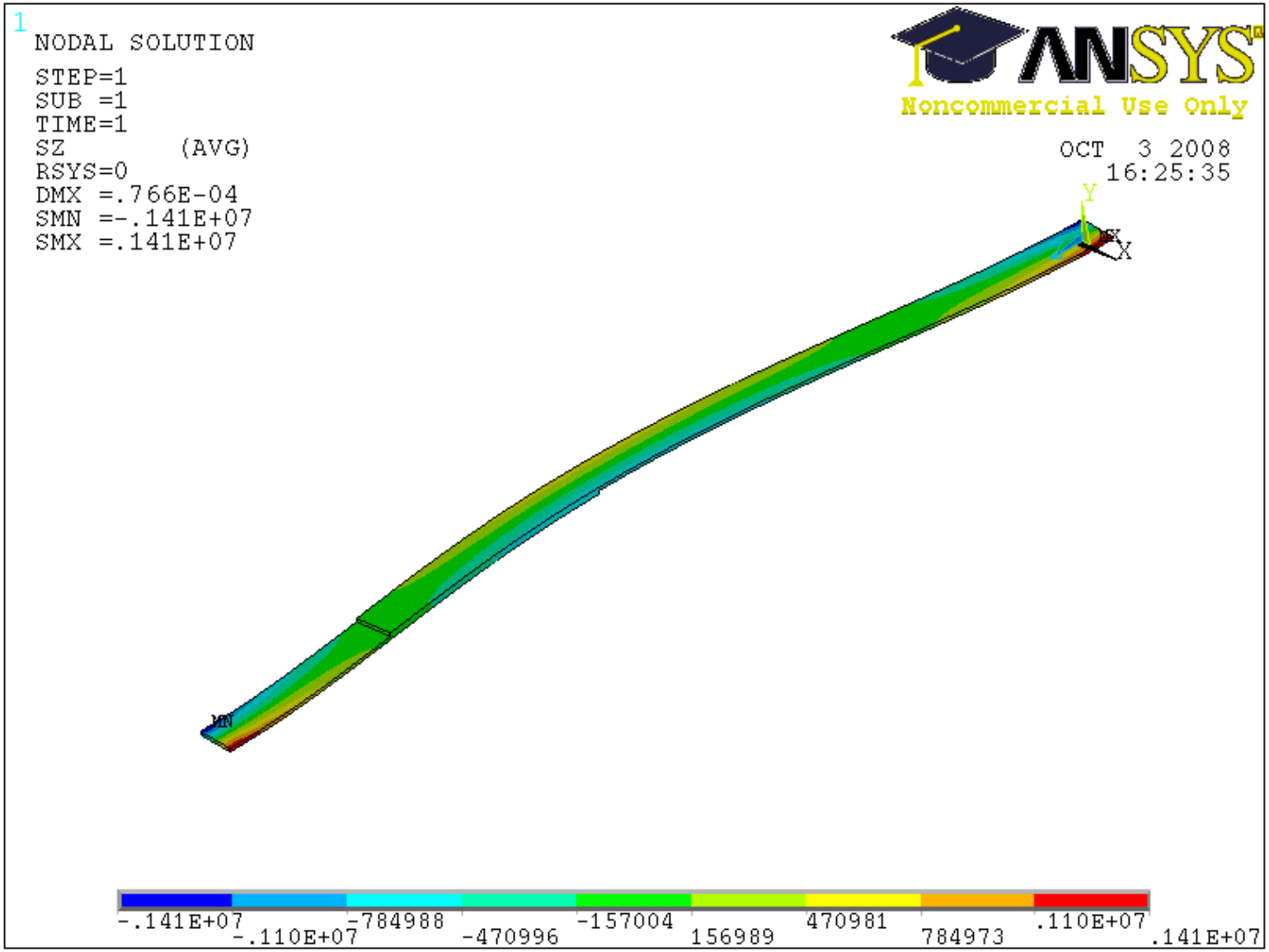

Transverse current = 0.25*J = 48mm splice
Lower cable
Upper cable
Total Fy on splice
Total Fy on joint
Soldered part
Fy
splice volume fraction
60
50
40
30
20
10
0
-10
-20
-30
-40
1
2
3
4
5
6
7
8
9
10


Transverse current = 0.5*J = 24mm splice
Lower cable
Upper cable
Total Fy on splice
Total Fy on joint
Soldered part
Fy
40
30
20
10
0
-10
-20
-30
-40
1
2
3
4
5
6
7
8
9
10
splice volume fraction

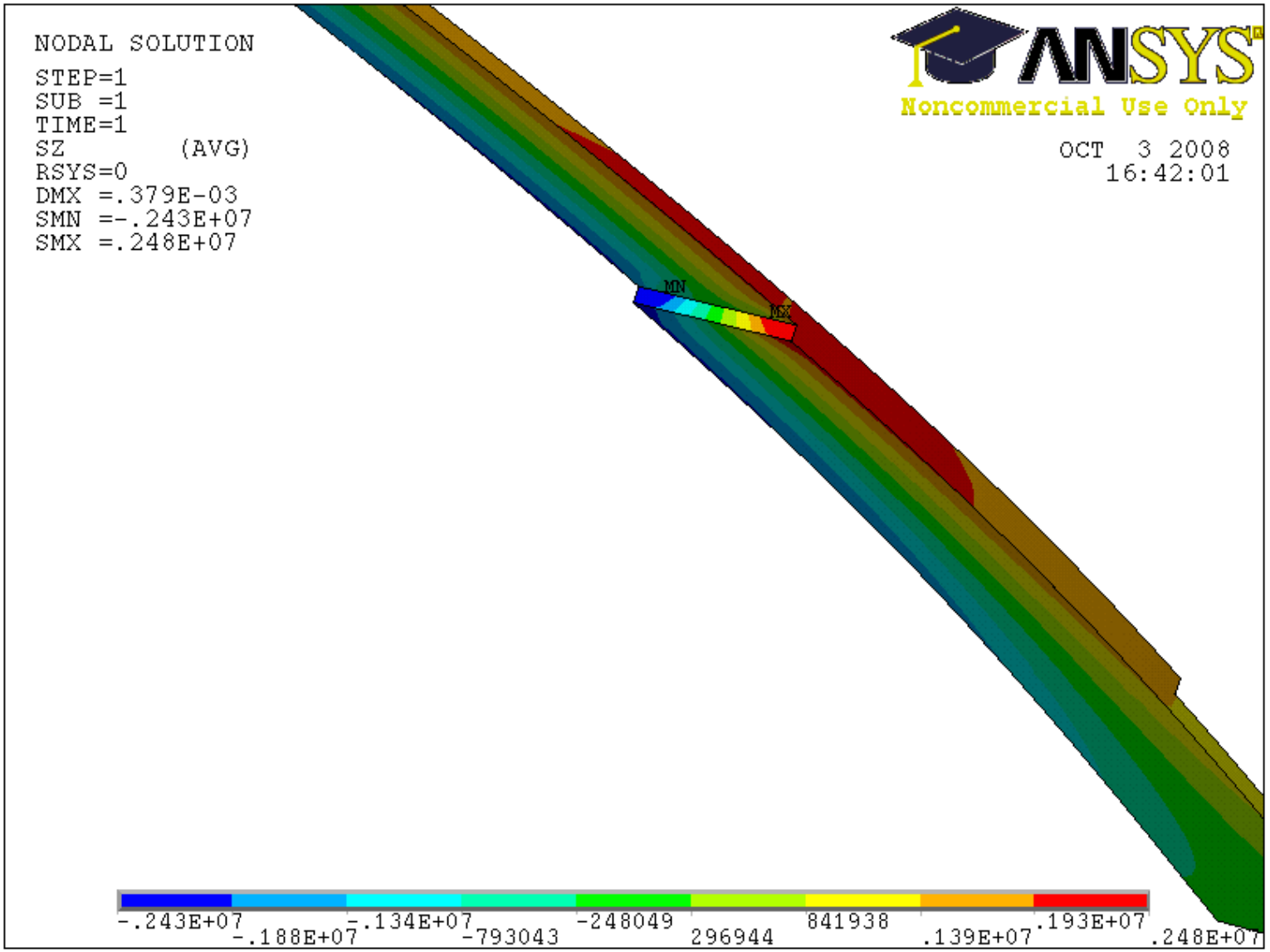
Magnetic forces vs. effective joint length



Stresses along the bus bar. Restrained extremities



Stresses along the bus bar. Supported extremities

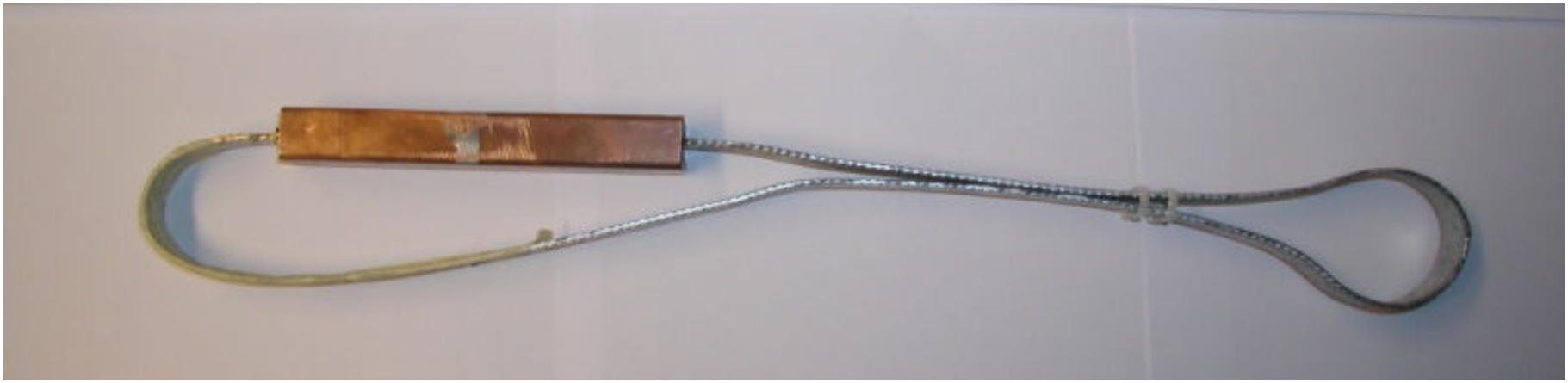


MECHANICAL TESTS

Mechanical test procedure and acceptance limits

- At room temperature
  - Fatigue life cycle: 5000 cycles from 20 N to 240 N
  - Tensile test: minimum force for joint breakage 900 N
- At 4.2 K
  - Fatigue life cycle: 5000 cycles from 40 N to 510 N
  - Tensile test: minimum force for joint breakage 1000 N
- Total number of tests performed: 34 R.T., 46 4.2 K

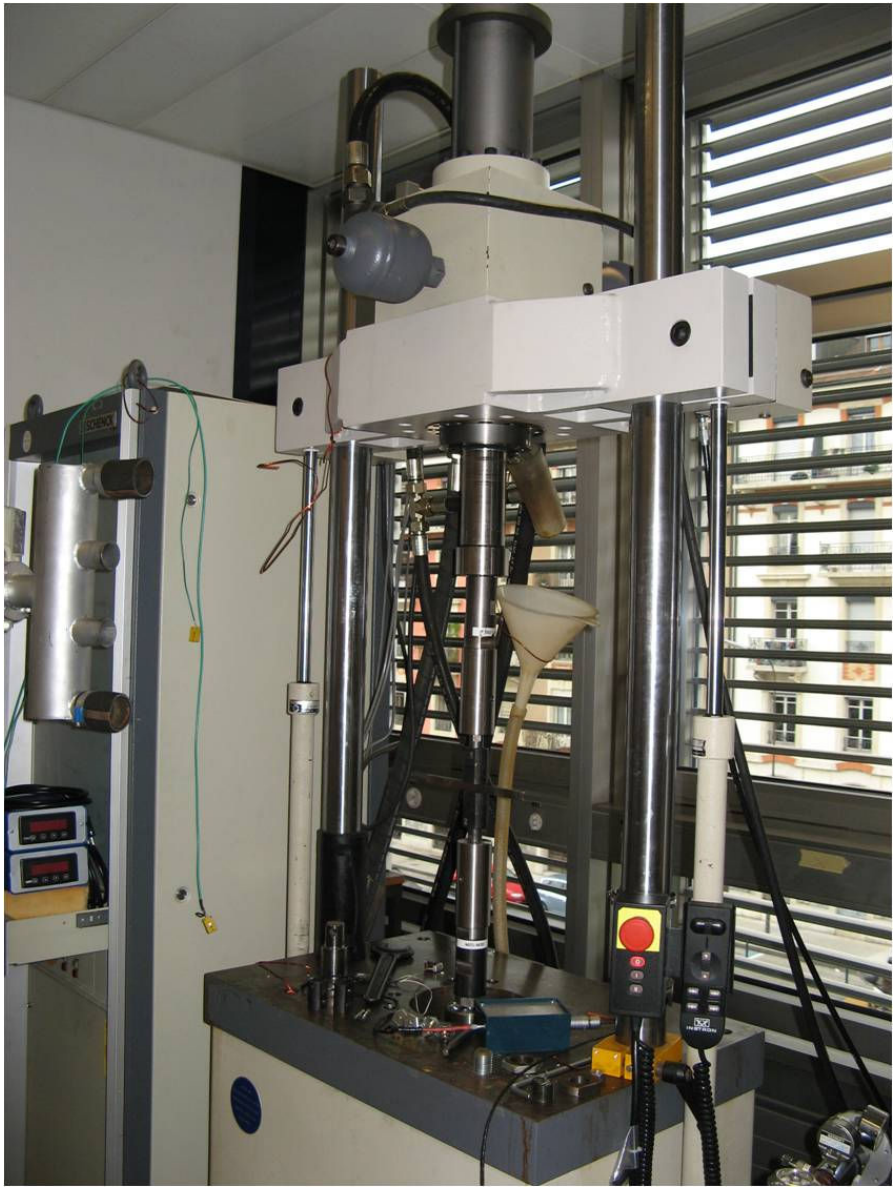
Production samples



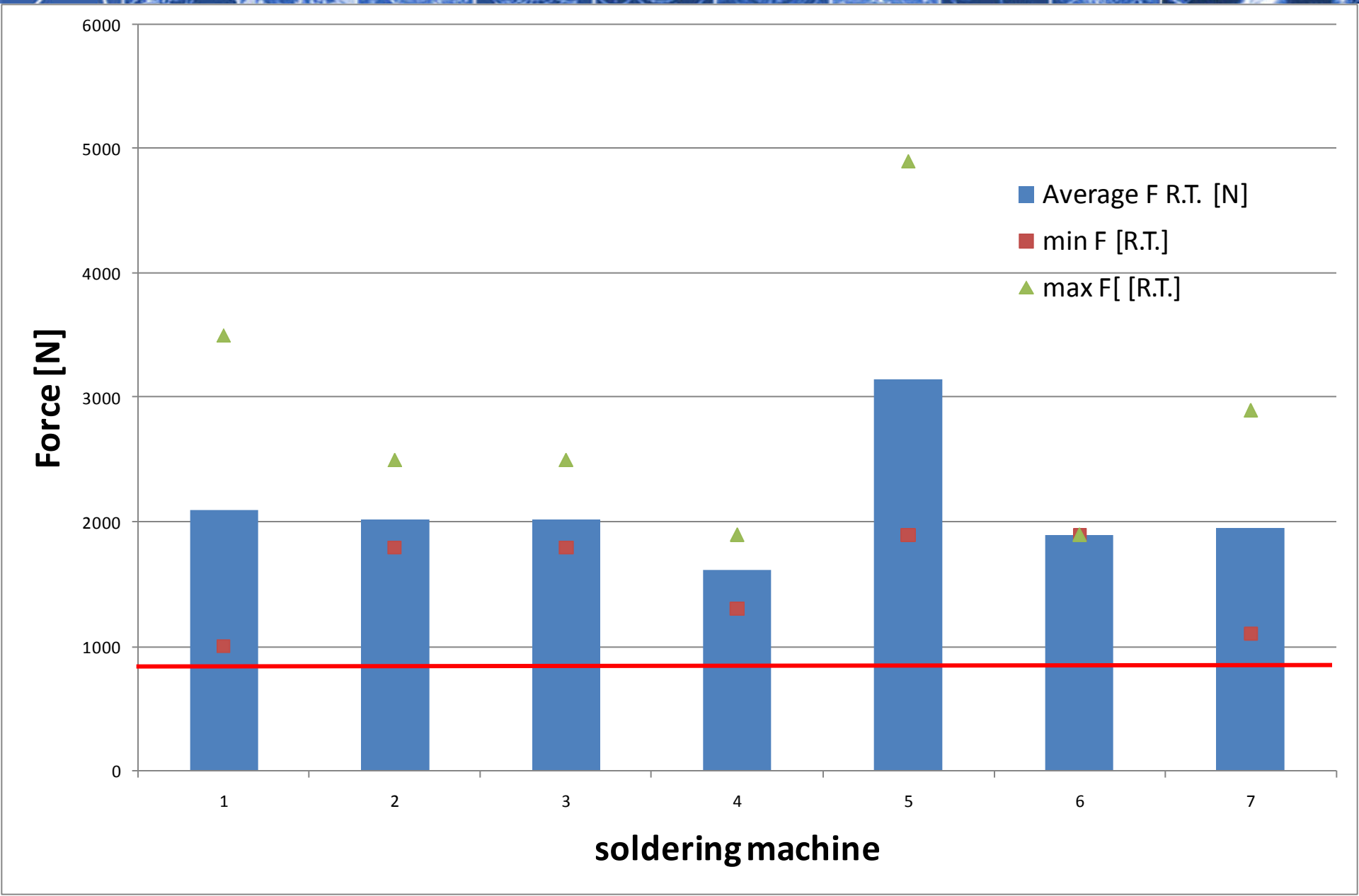
The check was performed by the execution, by the same operators using that specific machine, of two production samples.
After a visual inspection, the samples were tested electrically at the CERN cryolab and thereafter mechanically at the EIG (Ecole d'Ingénieurs de Genève).

Important: no one of the joints tested was broken during the tests.
A test was stopped because
1) An upper test limit due to the test set up was reached (typically 2 KN for the 4.2 K and 5 KN for the R.T. tests)
2) A discontinuity on the loading curve was observed (see case I and case II) and that value was declared the limit of the joint

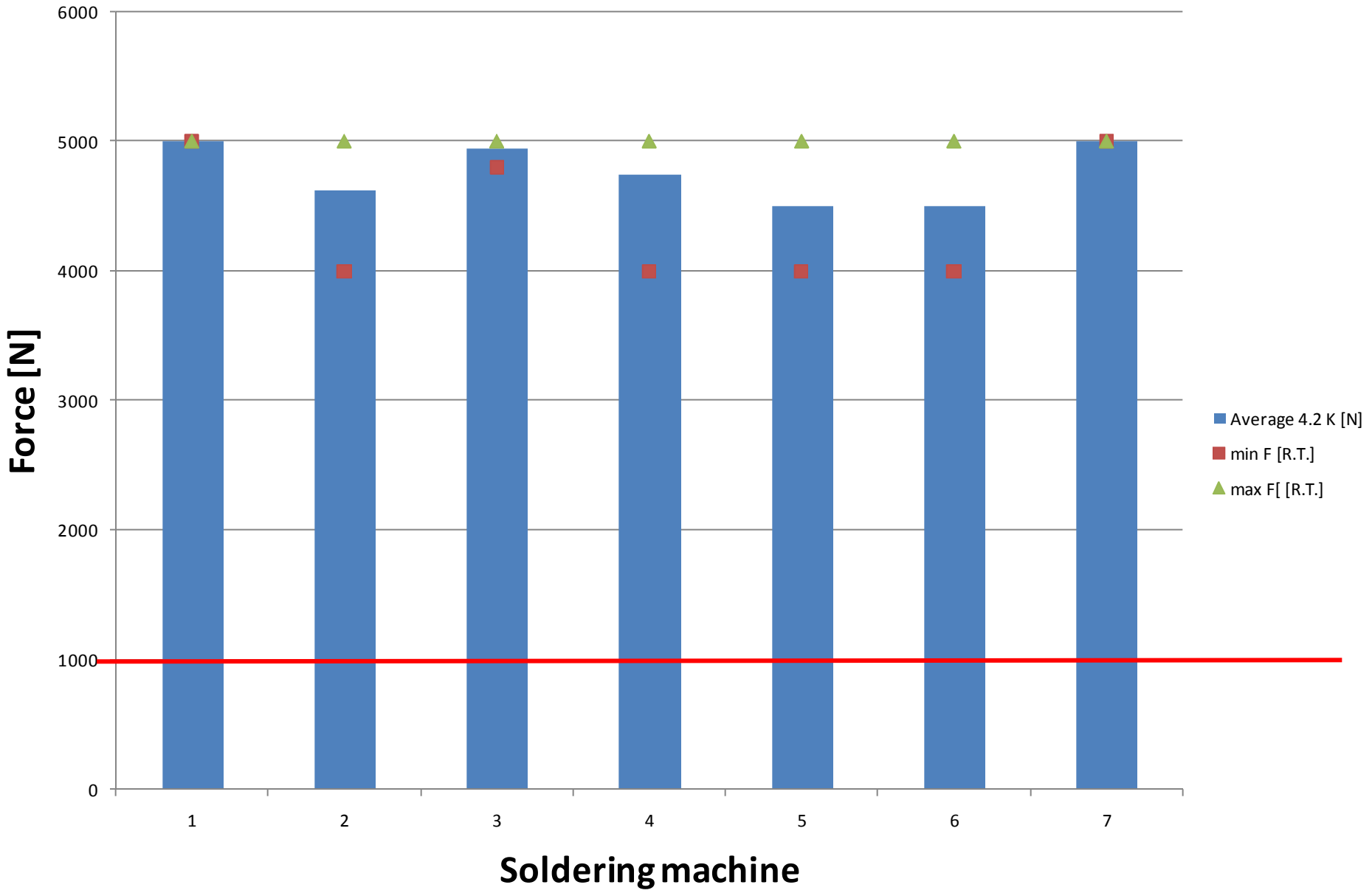
Test equipment EIG



Tensile test R.T.

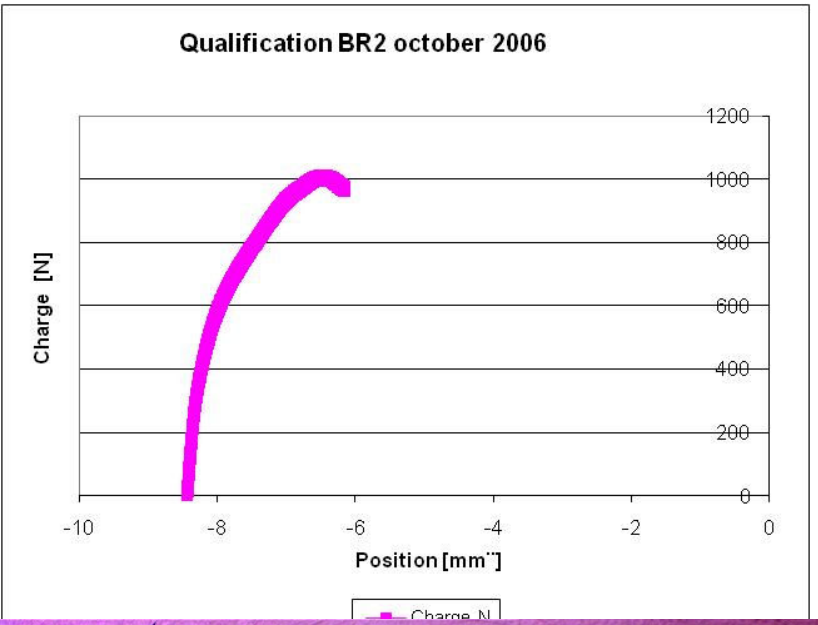


Tensile test 4.2 K

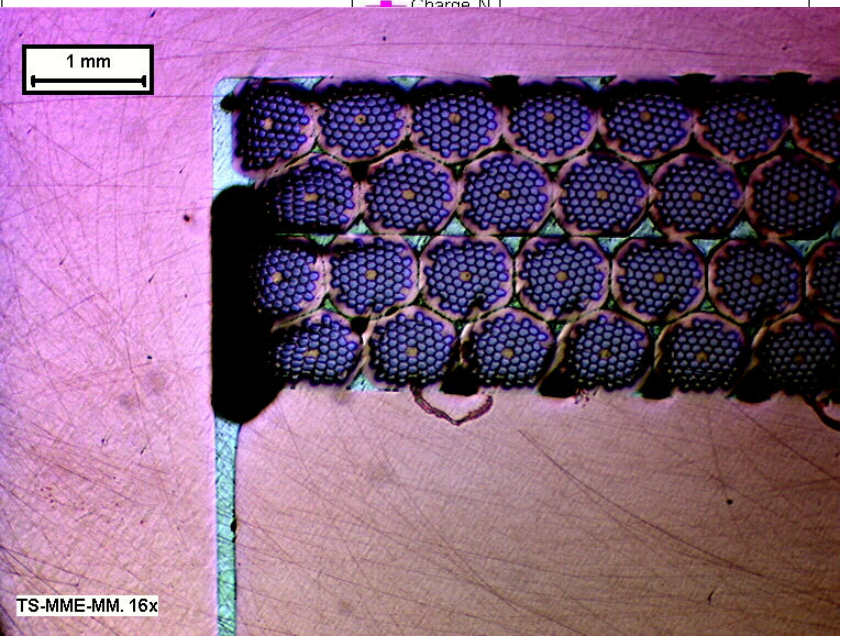


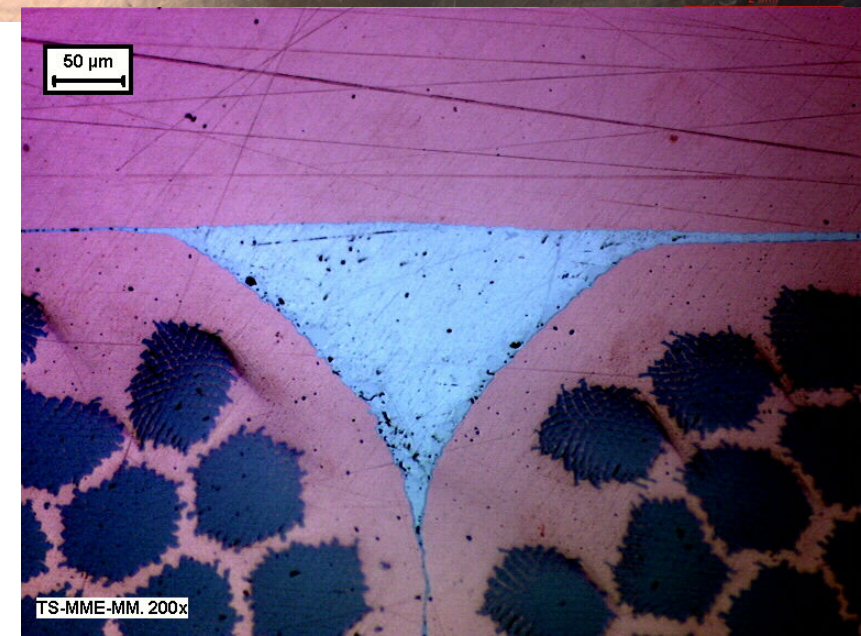
3 cases studied in detail

Case I R.T.

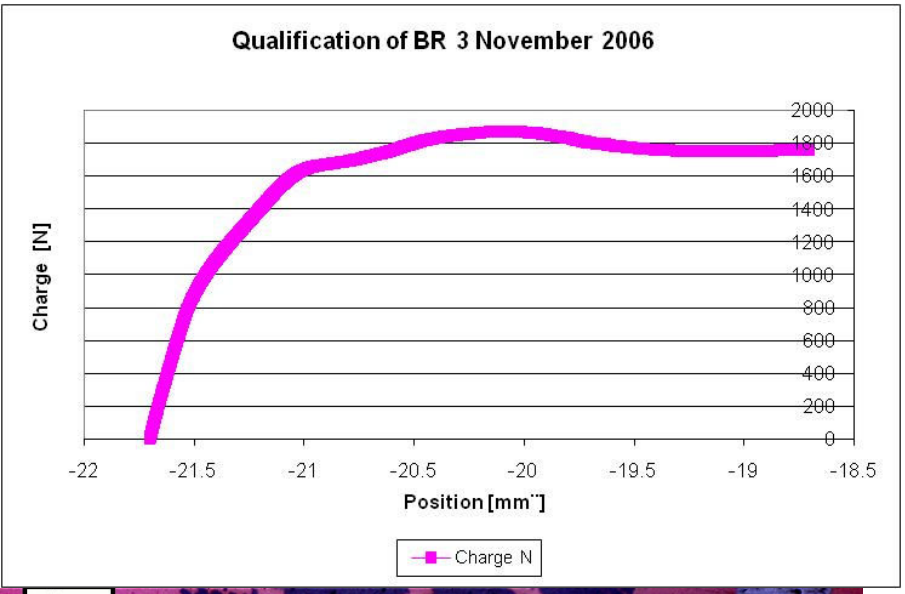

Qualification BR2 october 2006
Charge [N]
1200
1000
800
600
400
200
0
-10
-8
-6
-4
-2
0
Position [mm¨]

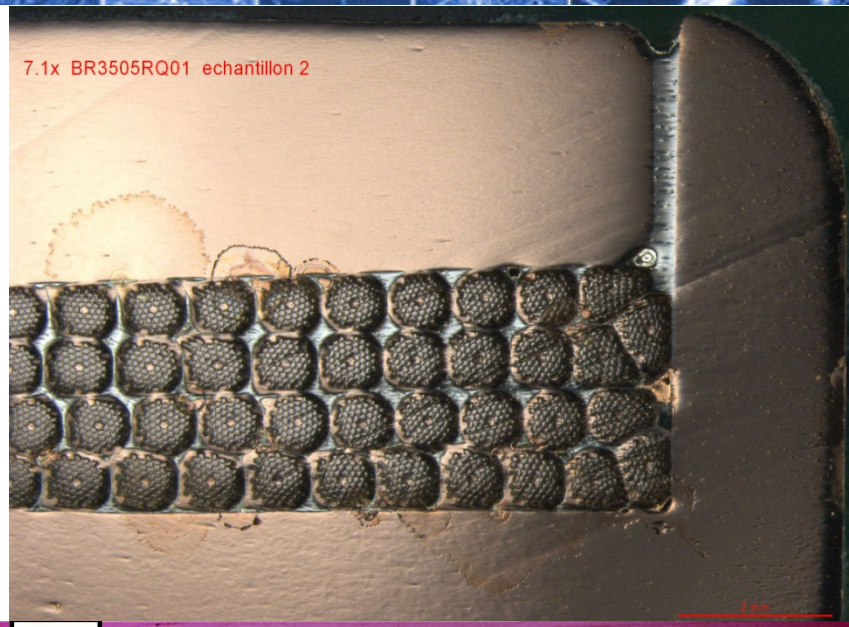

7.1x BR2505RQ02 echantillon 2
2 mm

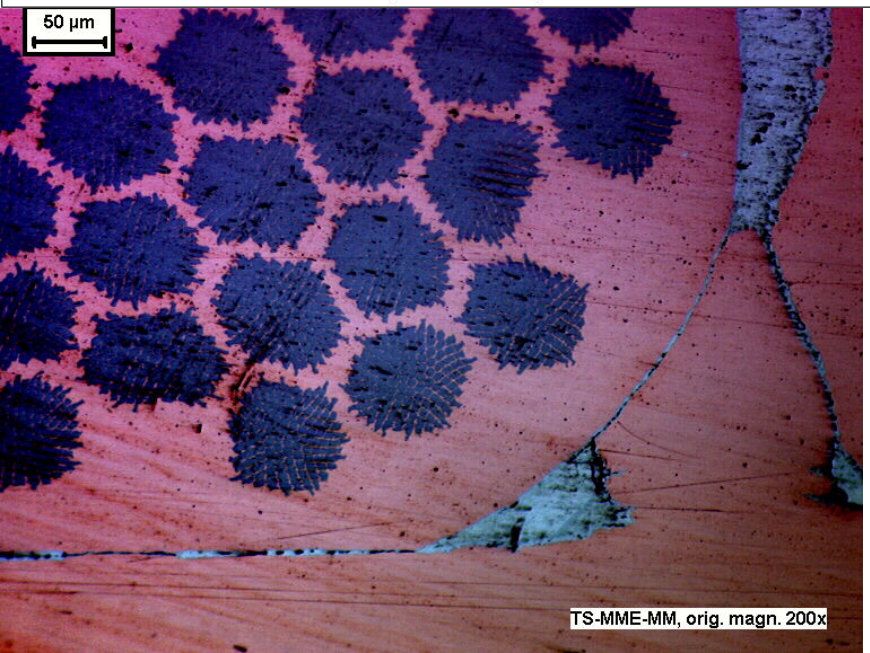

1 mm
TS-MME-MM. 16x

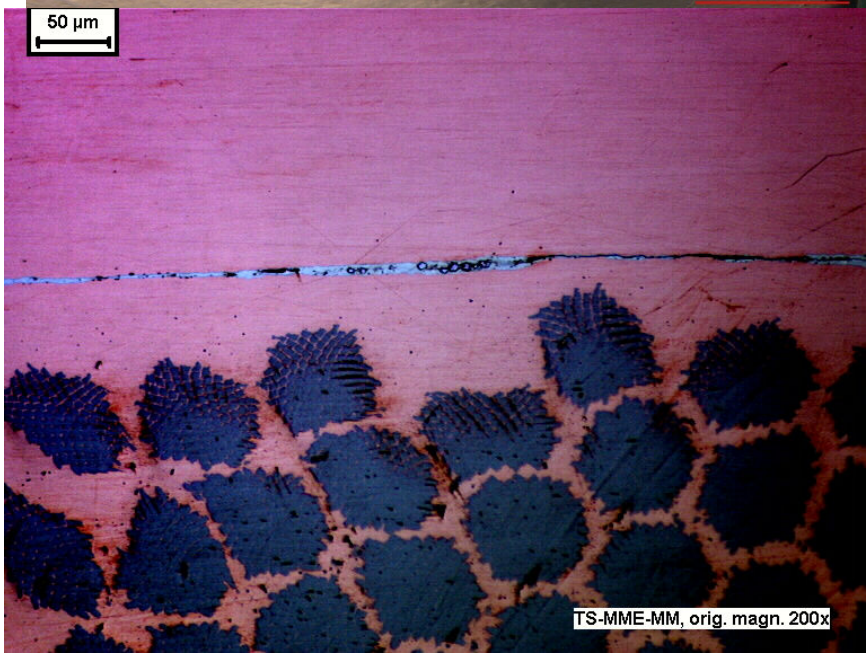

50 µm
TS-MME-MM. 200x

Case II R.T.


Qualification of BR 3 November 2006
Charge [N]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-22
-21.5
-21
-20.5
-20
-19.5
-19
-18.5
Position [mm¨]
Charge N

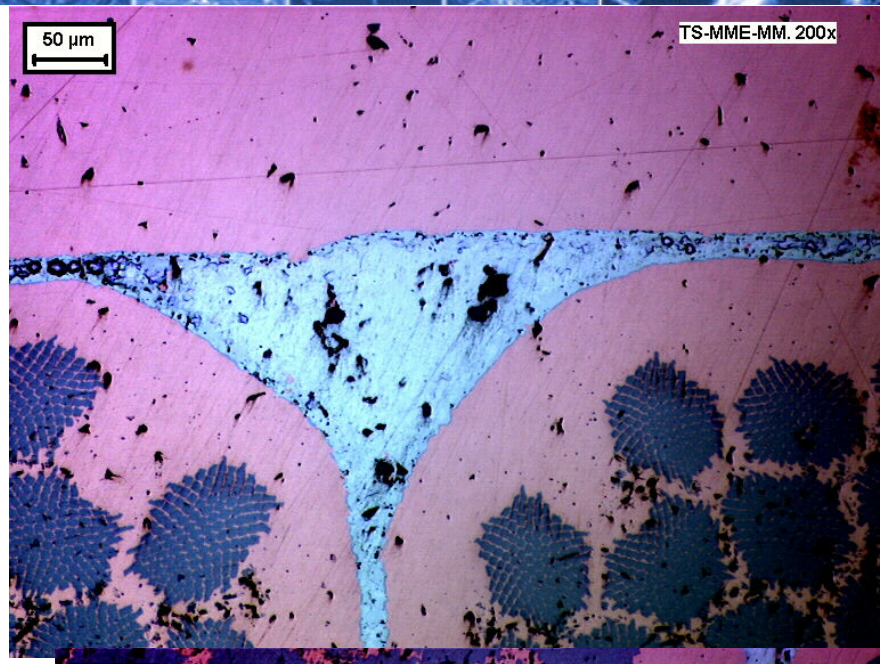

7.1x BR3505RQ01 echantillon 2


50 µm
TS-MME-MM, orig. magn. 200x

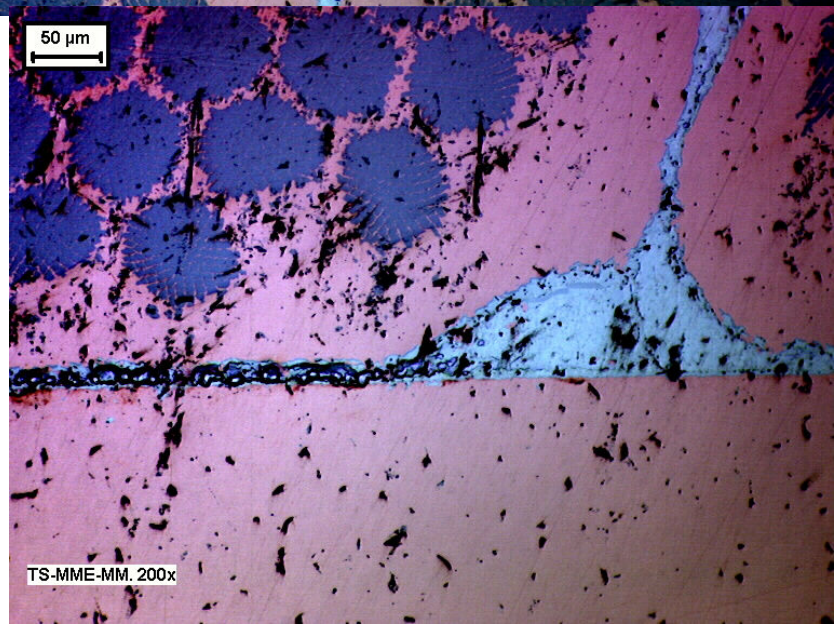

50 µm
TS-MME-MM, orig. magn. 200x

Case III 4.2 K


Qualification BR2 June 2007
6000
5000
4000
3000
2000
1000
0
-1000
Charge [N]
29.3
29.4
29.5
29.6
29.7
29.8
29.9
30
30.1
Position [mm¨]
Charge N

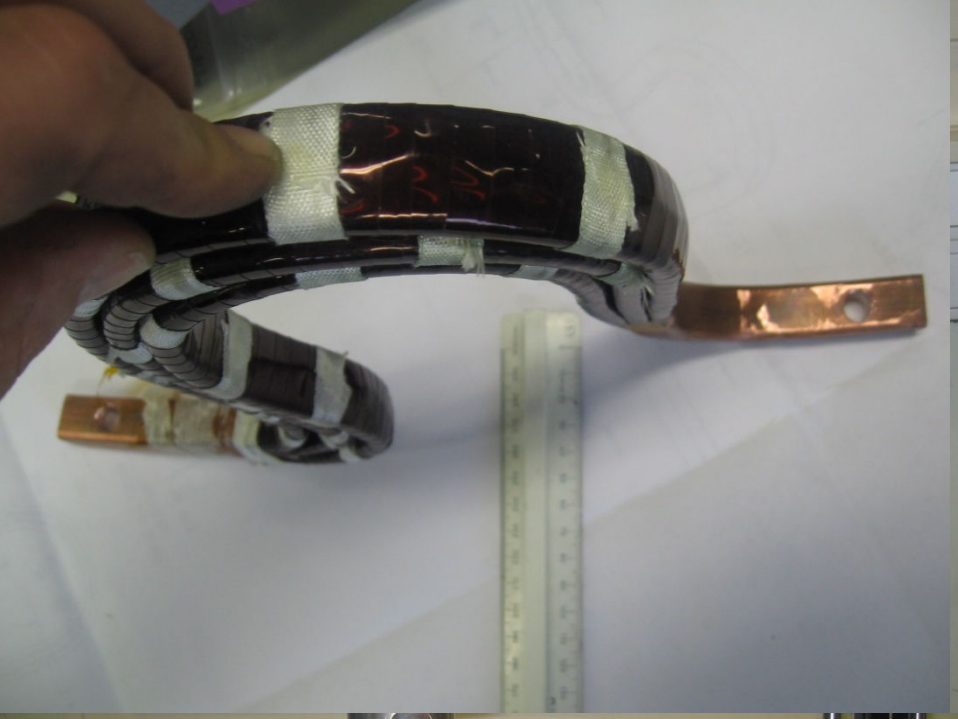

50 µm
TS-MME-MM. 200x

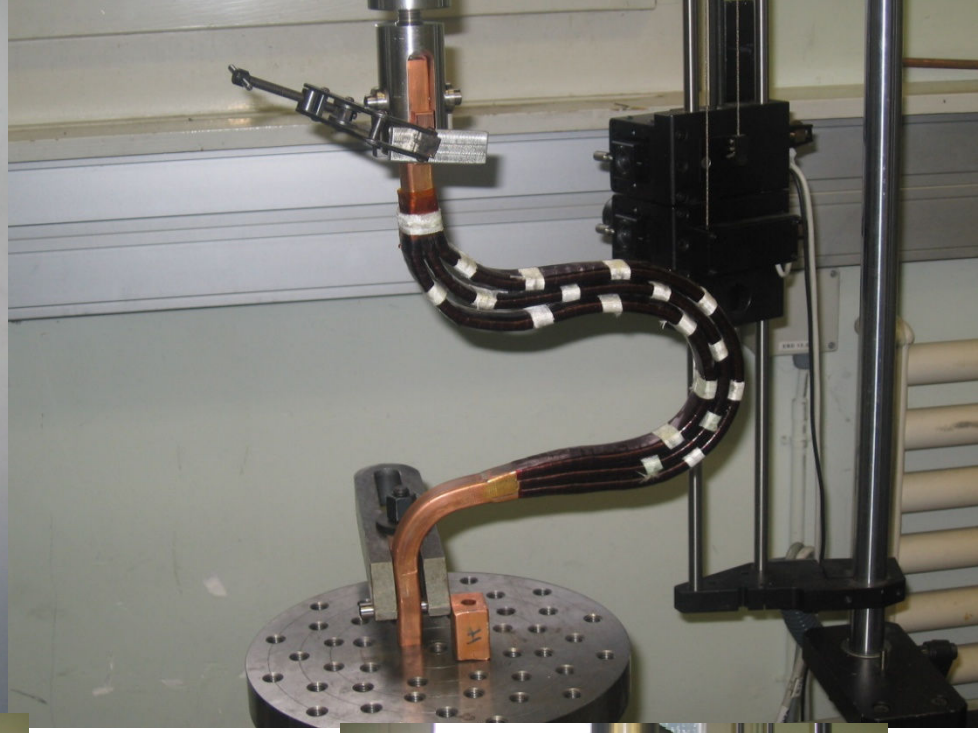

BR2510RB01 echantillon 1
7.1x

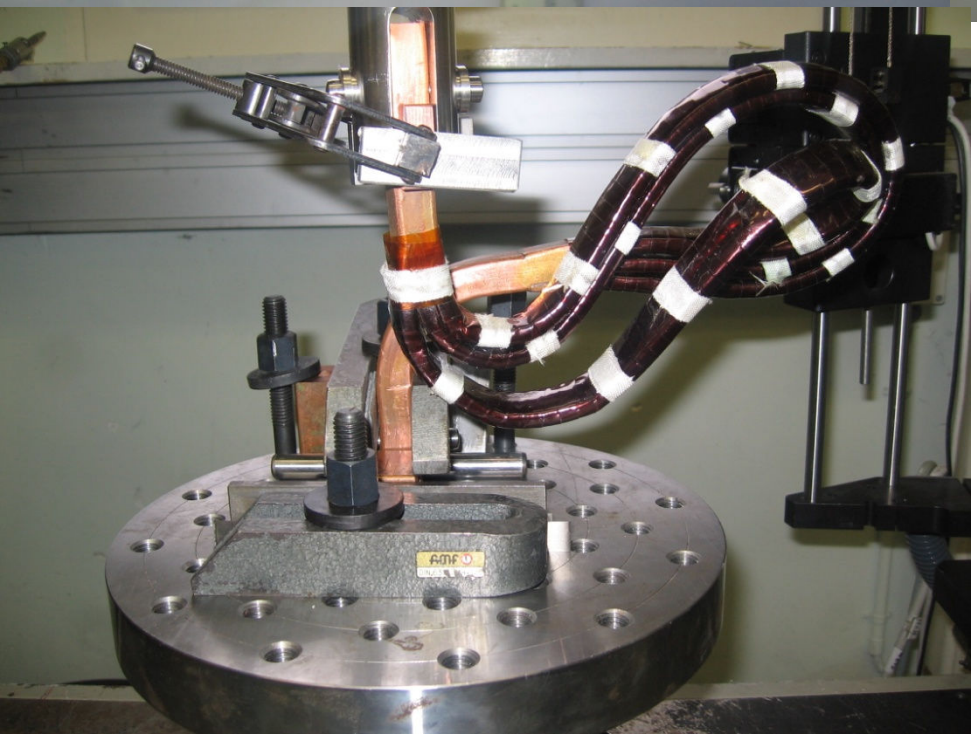

50 µm
TS-MME-MM. 200x

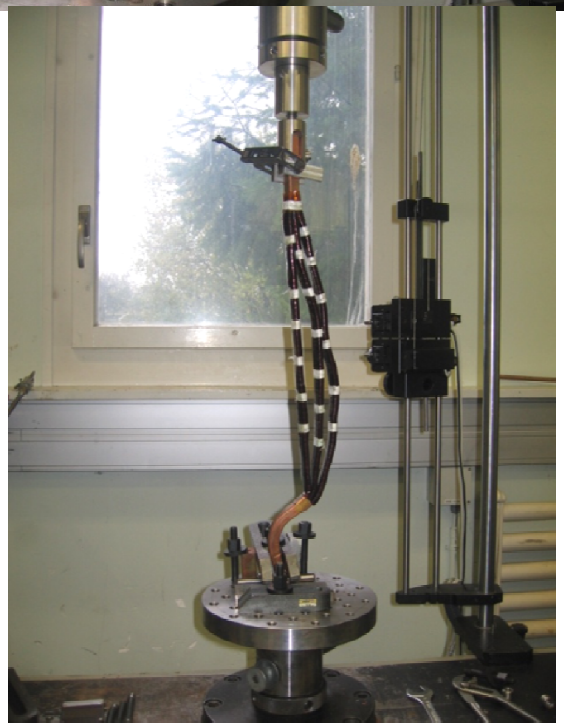
Test on dipole bus bar lyra

- Aim
  - Identify the failure modes
  - Measure the force vs. displacement curve outside the standard working window
  - Derive the force that would be applied on a joint when the interconnect is moved
- Performed
  - At 293 K
  - On a interconnection cryostat dipole bus bar lyra
  - On a dipole cold mass dipole bus bar lyra



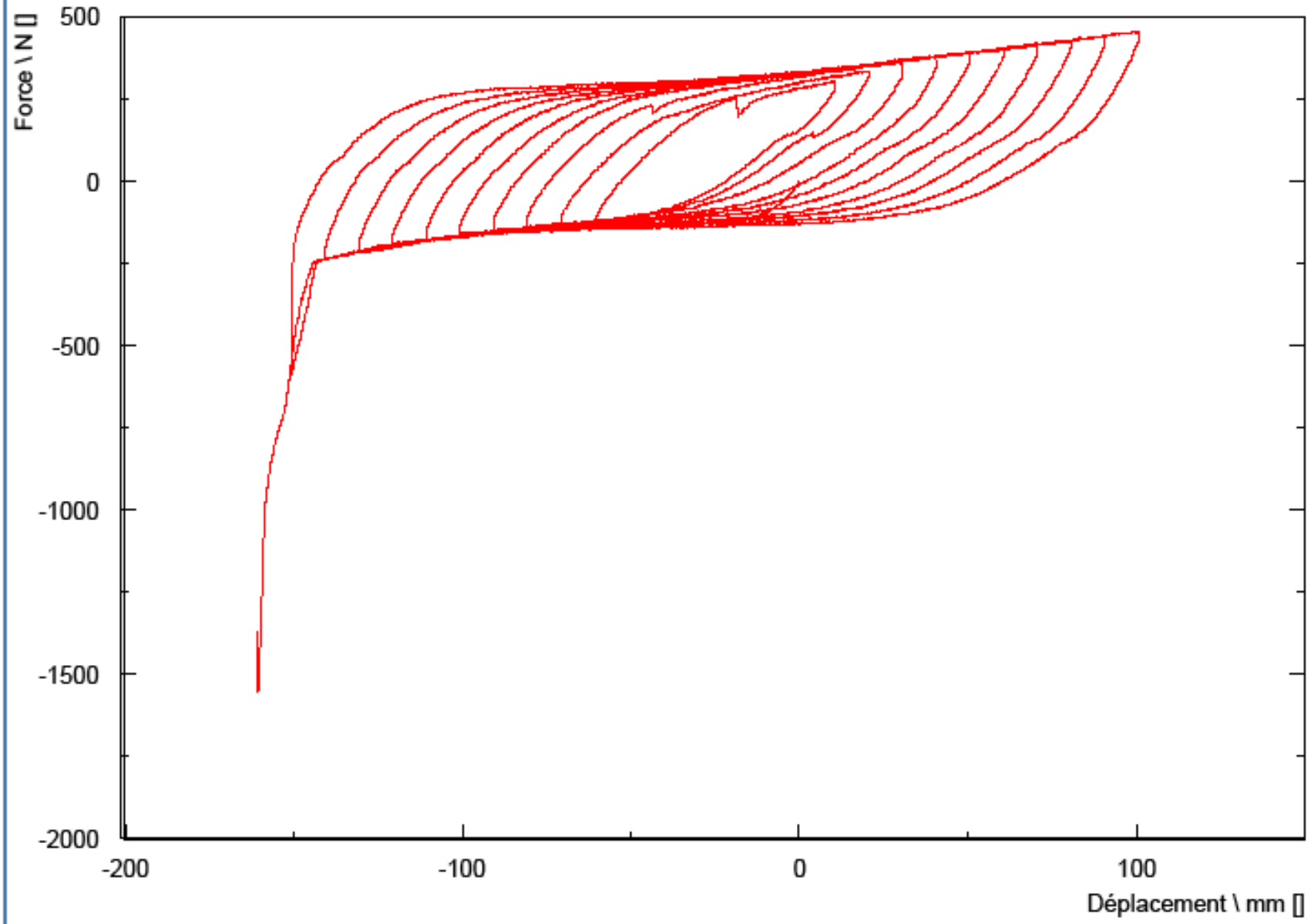






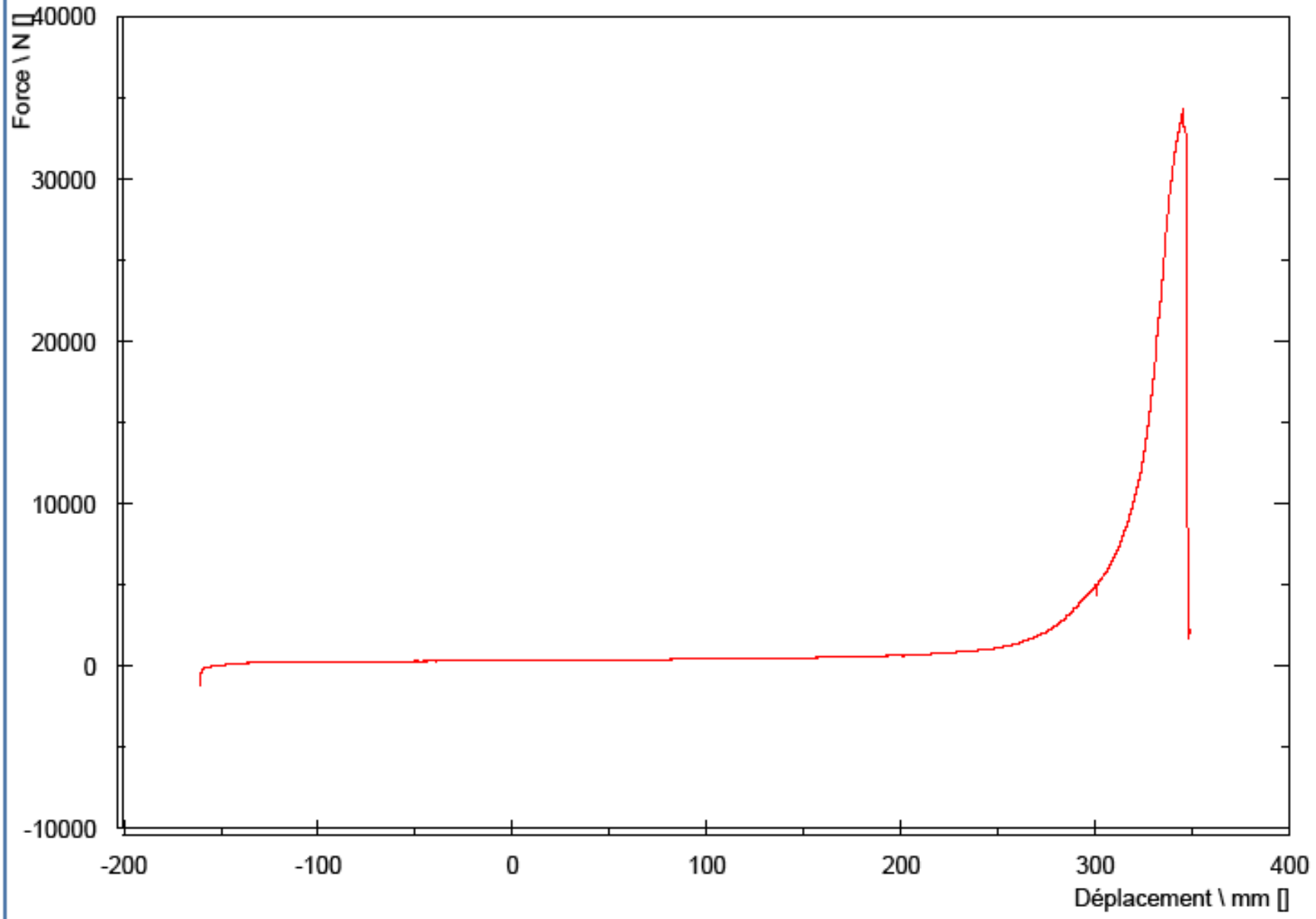
CERN TS/MME/MM -Metallurgy and Metrology section

Cycles de déplacement sur lyre du dipôle



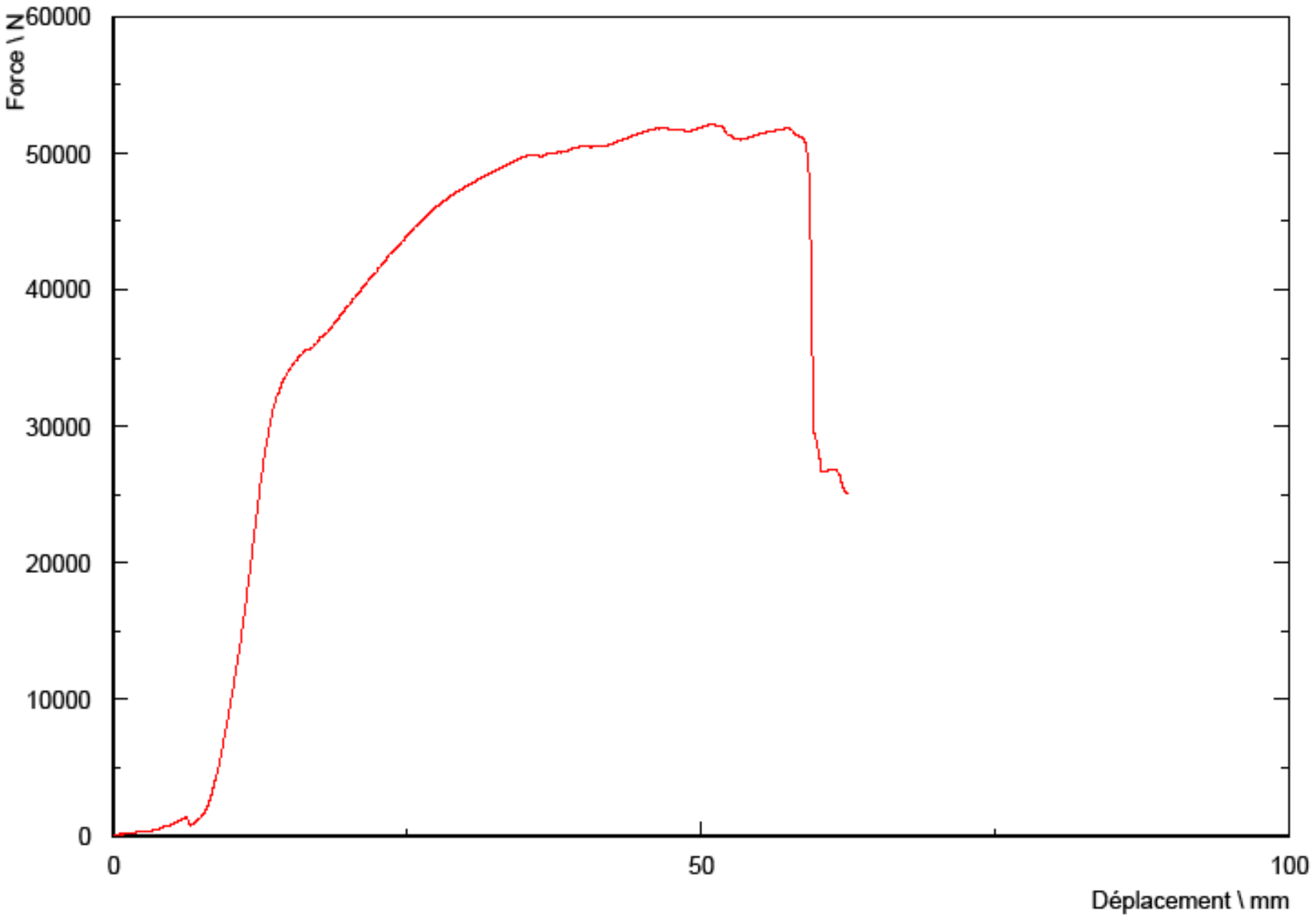
CERN TS/MME/MM -Metallurgy and Metrology section

Traction sur lyre du dipôle



CERN TS/MME/MM -Metallurgy and Metrology section

Traction sur lyre redressée du dipôle



Results summary

	Dipole cold mass lyra	Interconnection cryostat lyra
Force top of plateau	250 N – 450 N	250 N – 750 N
Force bottom plateau	250 N – 300 N	500 N
Max compression mov. before force runaway	-150 mm	-210 mm
Max traction mov. before force runaway	300 mm	300 mm
Breakage force	52000 N	58000 N
Displacement at breakage	350 mm	270 mm

The insulation did not show any relevant damage

The 1st elements to break were the thin copper sheet

The final break on the SC-copper element

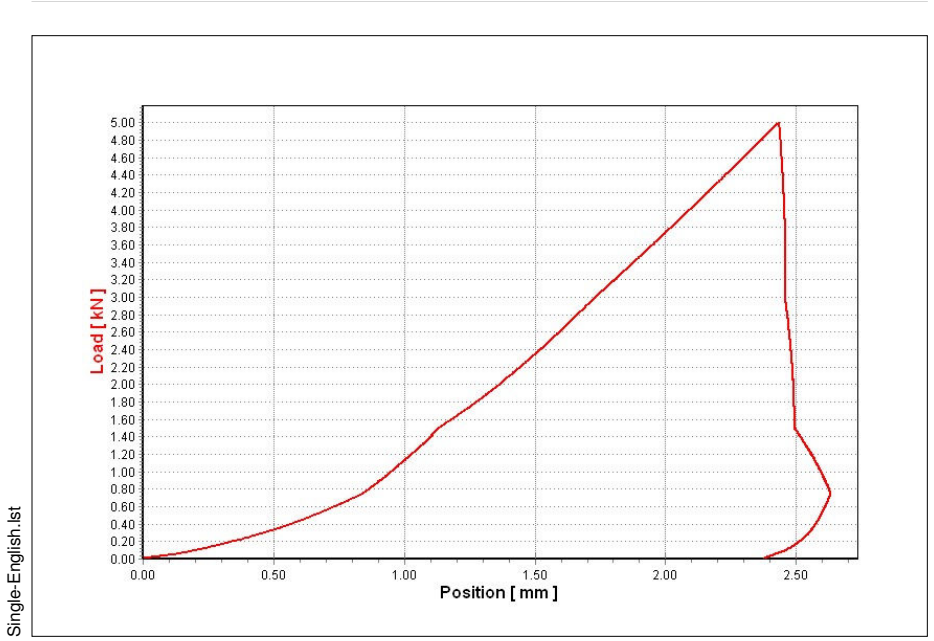
The lyra has a large deflection window for very low forces

The blockage would happen before because of interference with the other bus bar (compression -75 mm) or with the end cover

The interconnection joint could see a force between 350 N and 600 N at cold in case of large displacement

SC joint: combined electrical and mechanical tests

- Aim
  - Evaluate possible deterioration of the electrical quality of the joint because of the mechanical efforts
- How
  - Measure the resistance of standard joint
  - Submit the same joints to tensile load (500 N, 1000 N, 5000 N)
  - Re-measure the resistance



Results

Joint type	R before mechanical test	R after mechanical test *500 N*
Quadrupole	0.1 nΩ	0.1 nΩ
Dipole	0.09 nΩ	0.09 nΩ

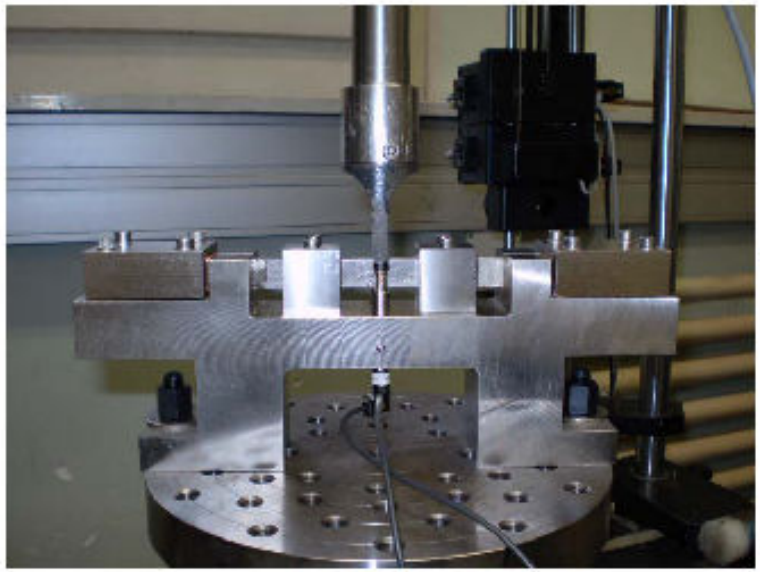
Joint type	R before mechanical test	R after mechanical test *1000 N*
Quadrupole	0.13 nΩ	0.13 nΩ
Dipole	0.12 nΩ	0.10 nΩ

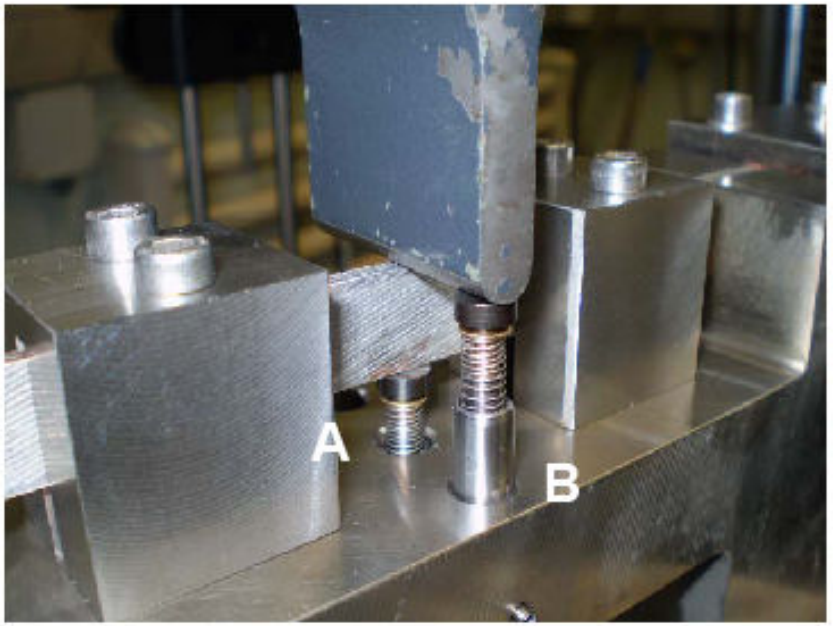
Joint type	R before mechanical test	R after mechanical test *5000 N*
Quadrupole	0.1 5nΩ	0.14 nΩ
Dipole	0.11 nΩ	0.11 nΩ

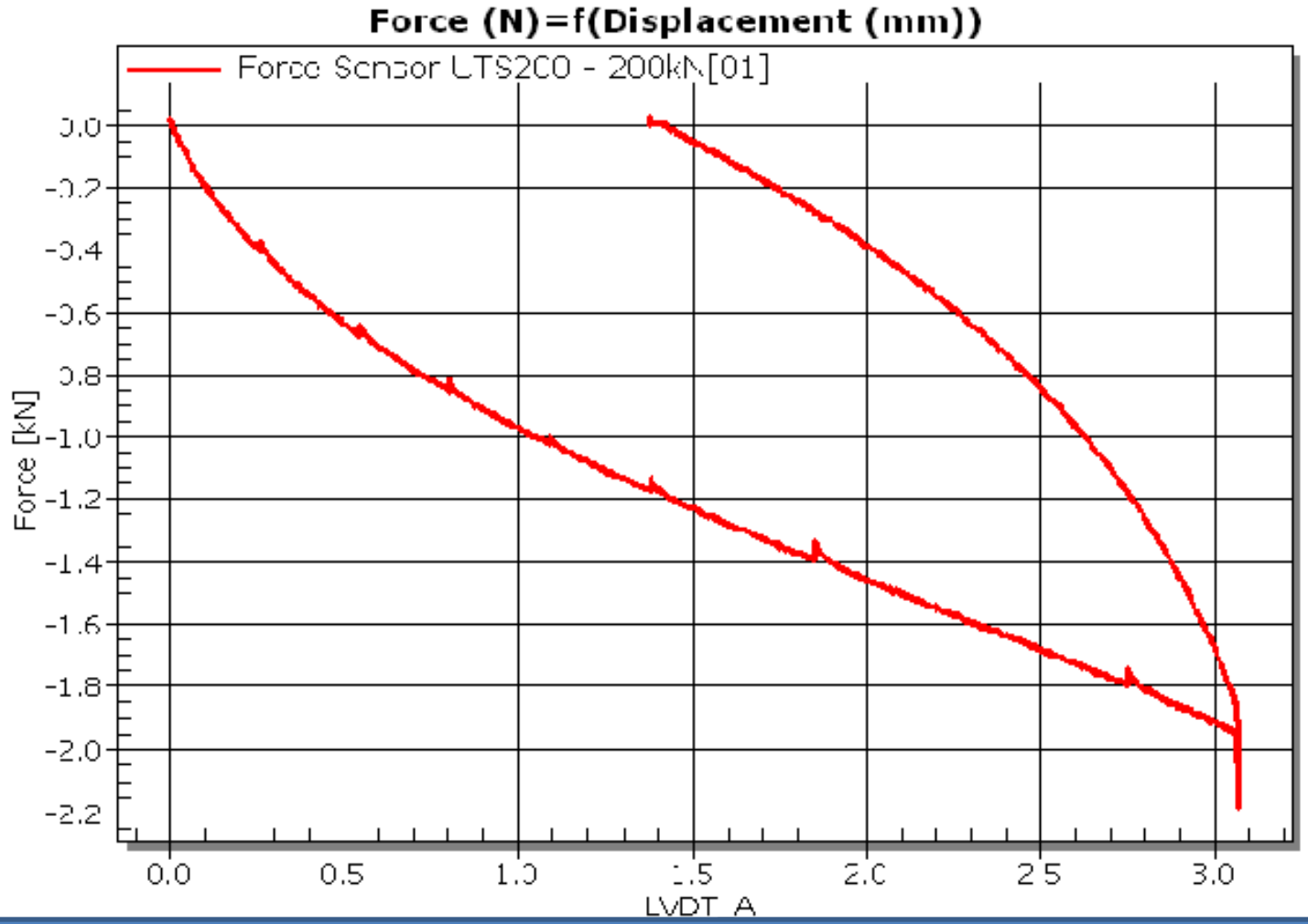
Flexural measurement

- Aim:
  - Evaluate the strength of a splice under flexion and the flexural modulus for extra data for previous analitical and Ansys computation
- How
  - Produce a splice with low tin content (the layer of tin between the SC cables has been forgotten only the 2 outer one are present)
  - Remove the copper
  - Measure the force vs displacement curve under flexion

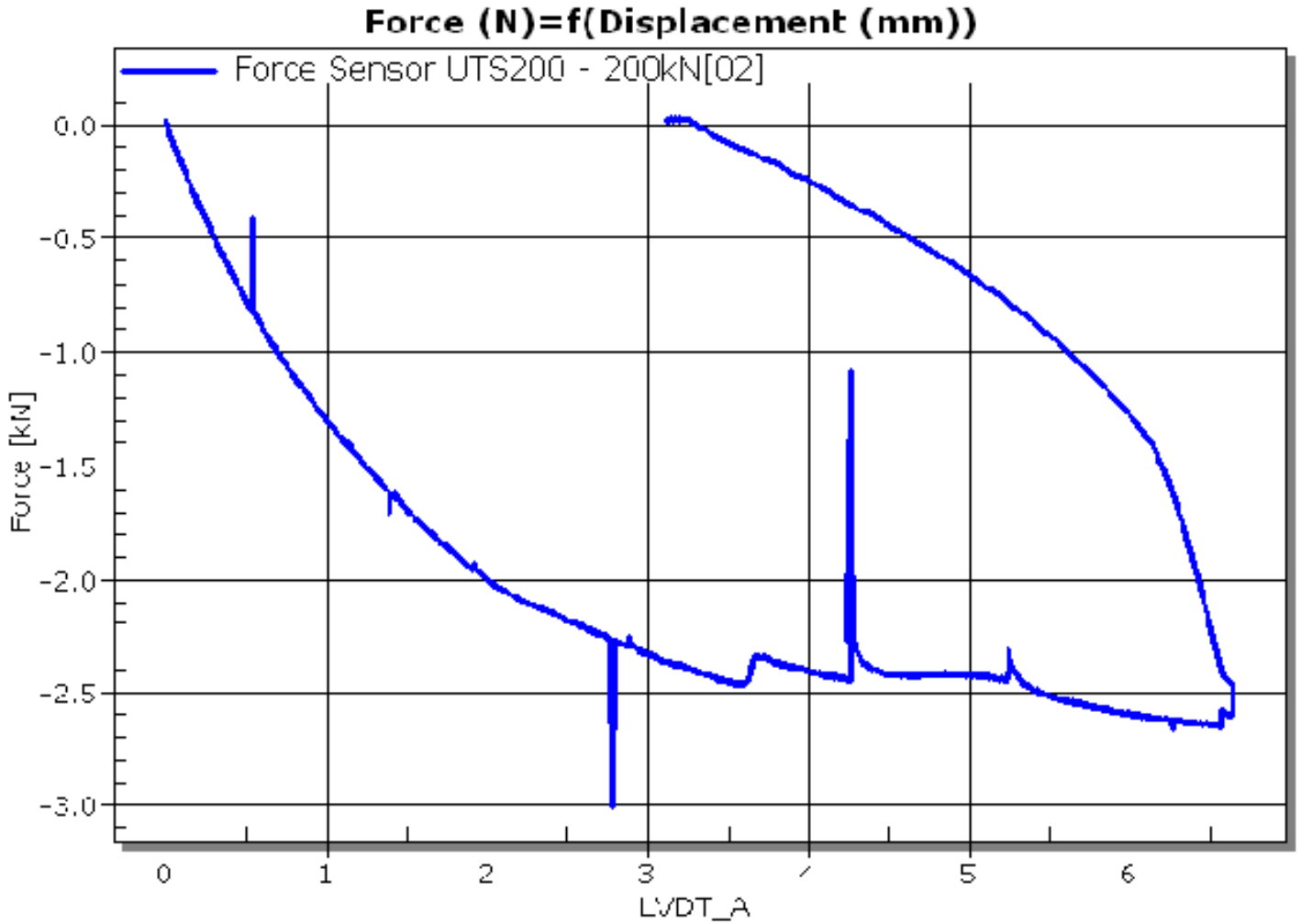
TEST 1







No evidence of rupture (optically and graph). Limit at 3.1 mm due to the tooling dimension
1KN 1 mm of deformation

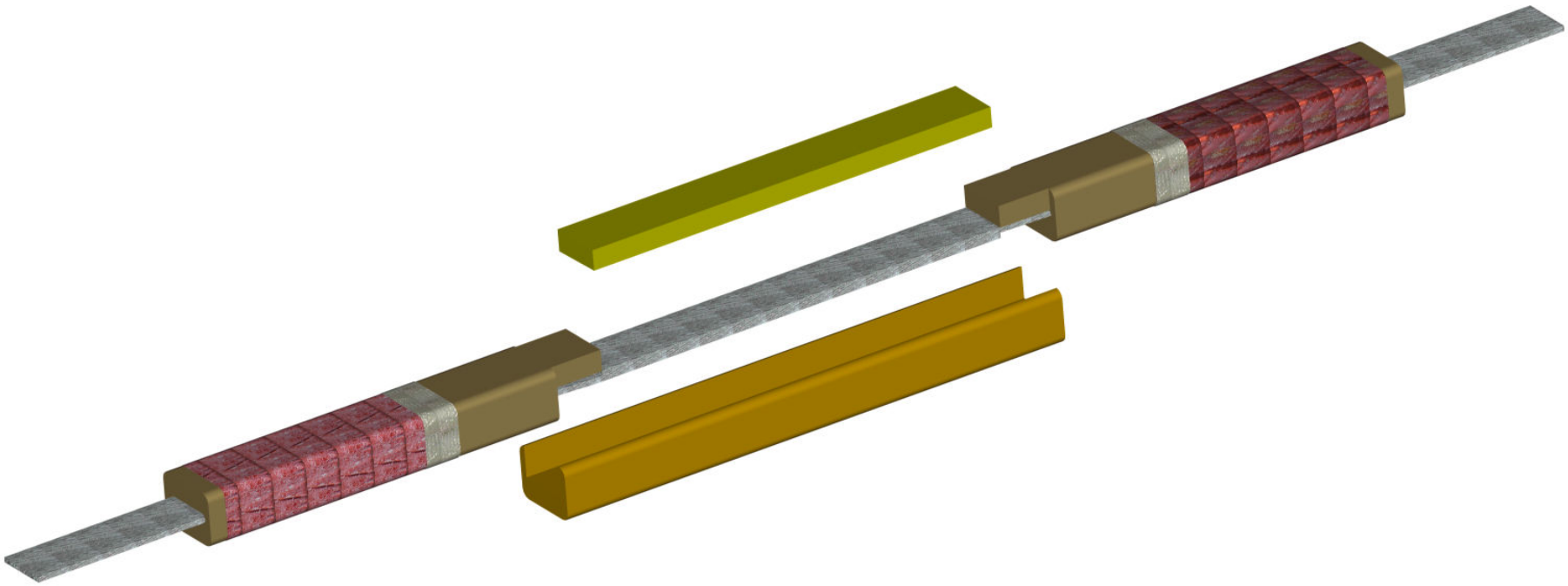


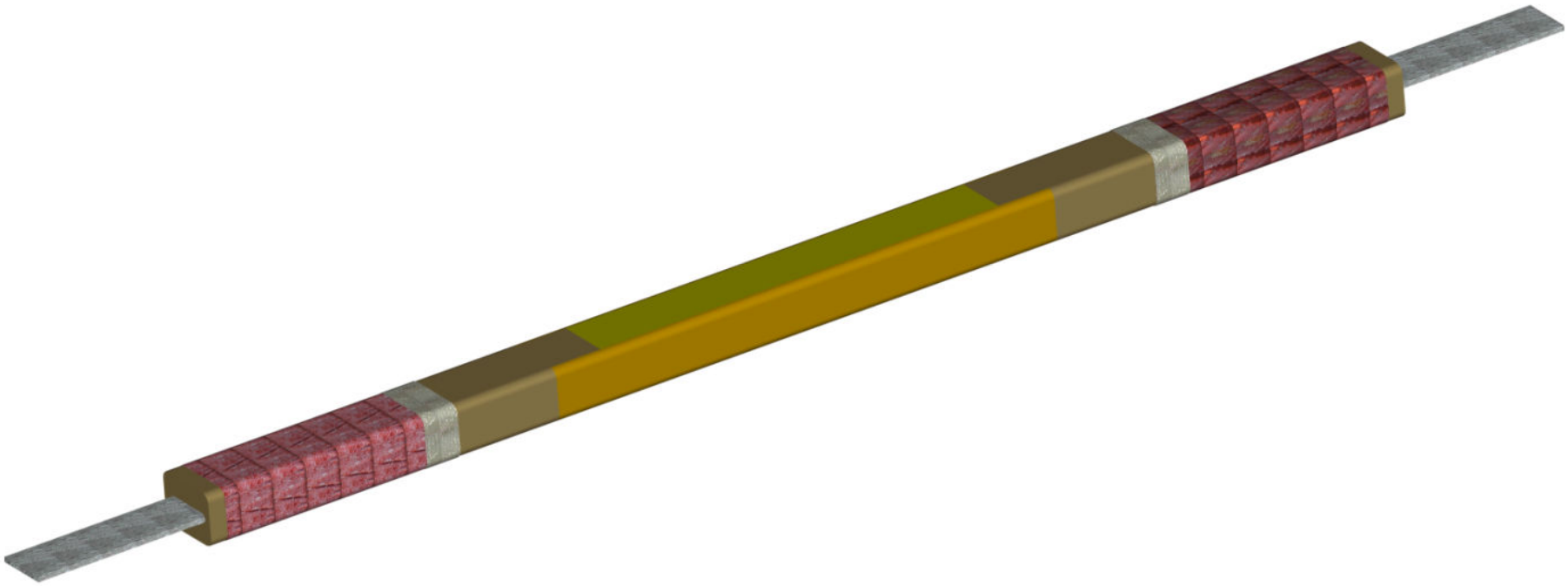
No evidence of rupture till 3.3 mm.
1KN 0.8 mm of deformation

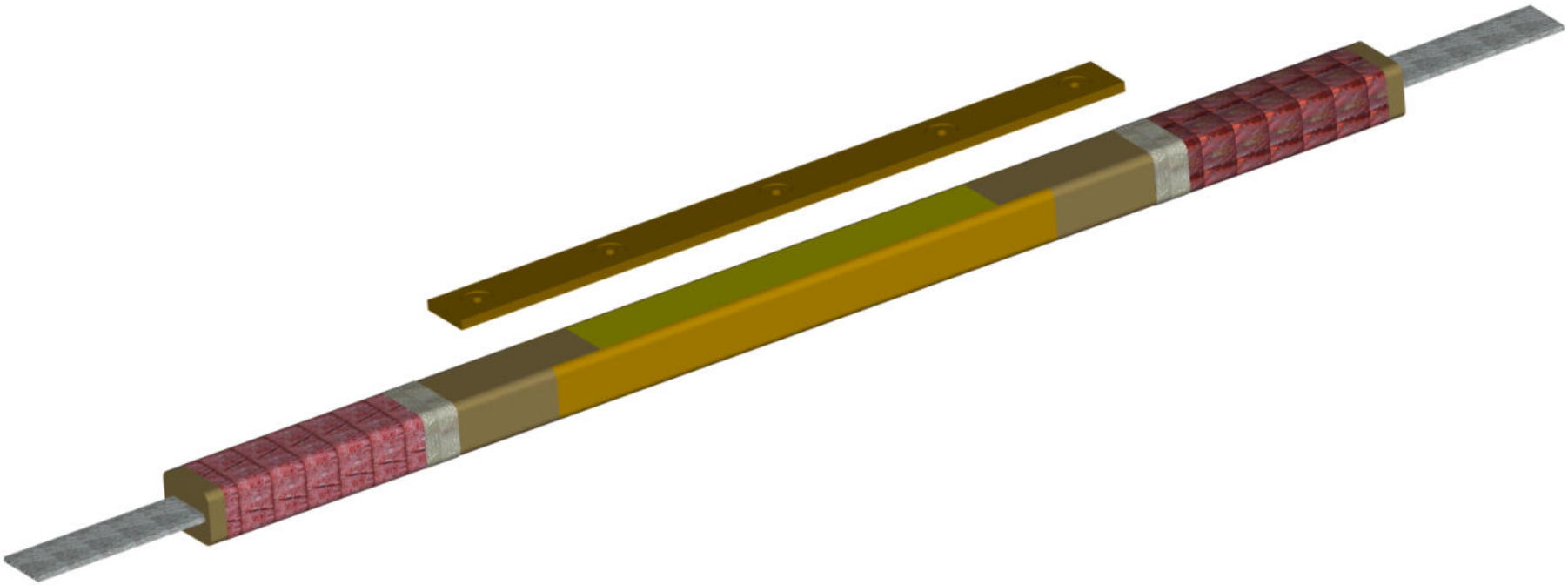
Conclusion

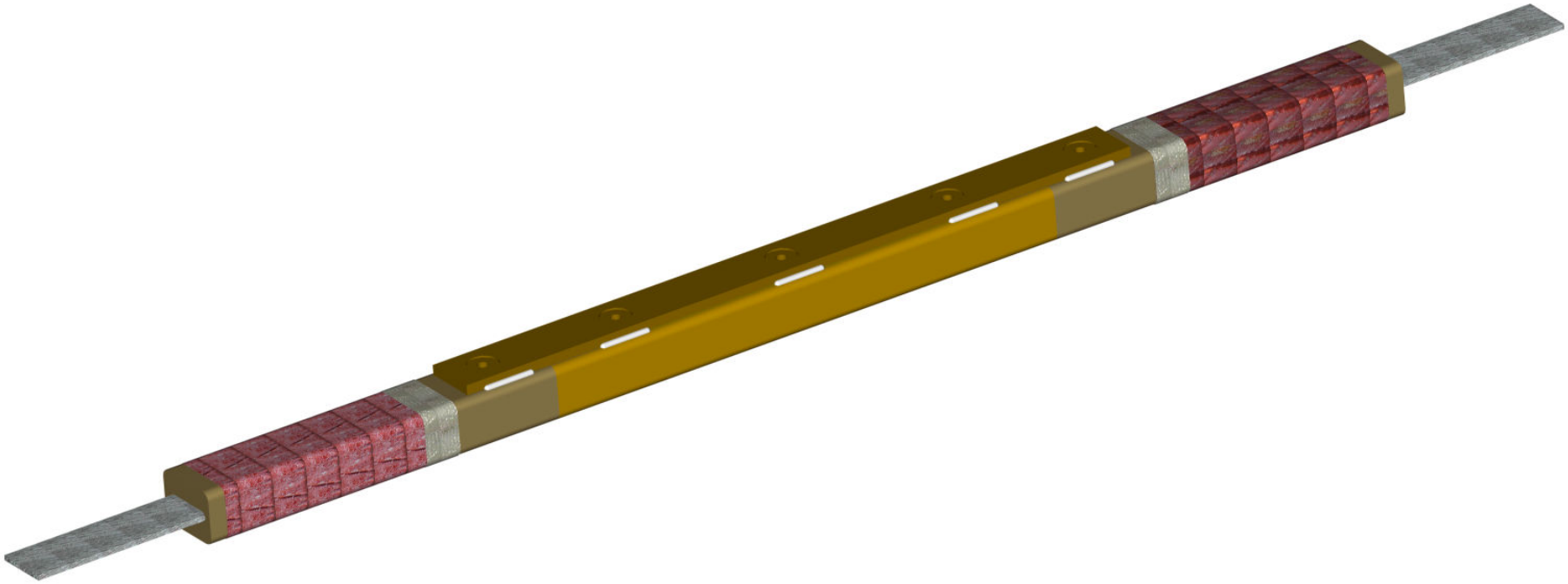
- No evident damage (a part from tool indent) with an imposed deformation of 3 mm on a length of 170 mm
- The module is 19500 MPa . In previous computation we assumed 15000 MPa. The previous computations are valid

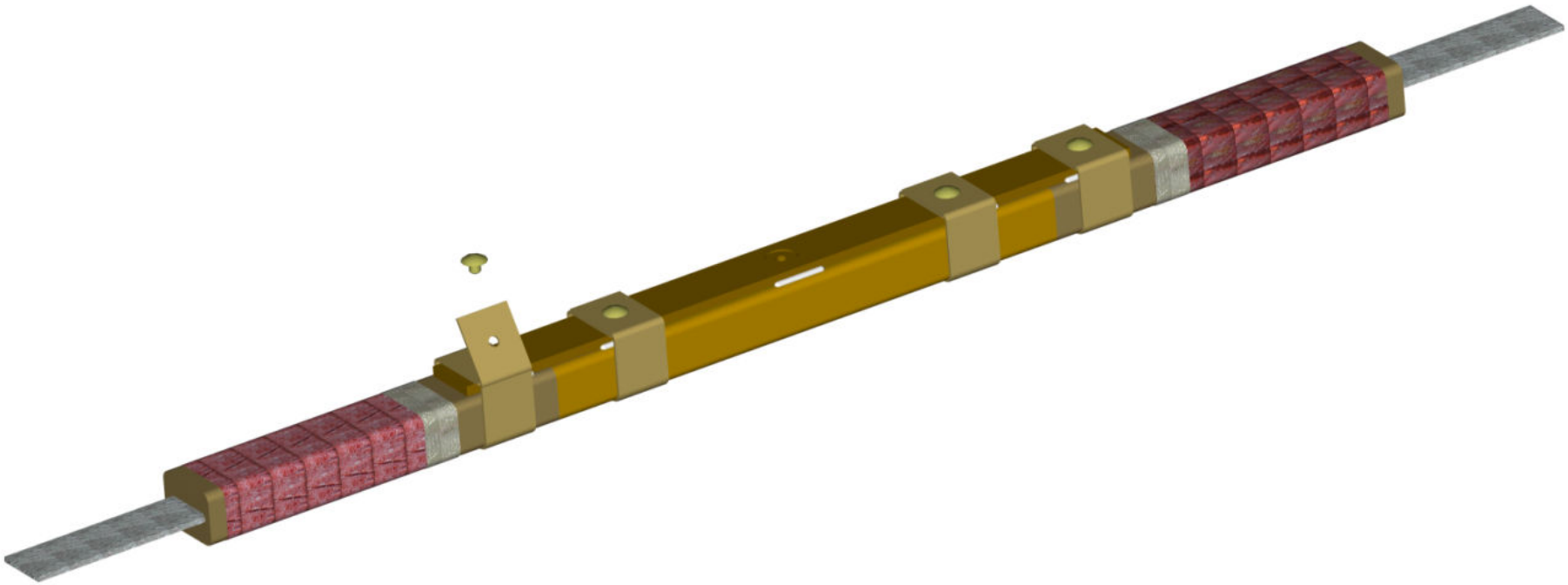
SHUNTING DESIGN OPTION A

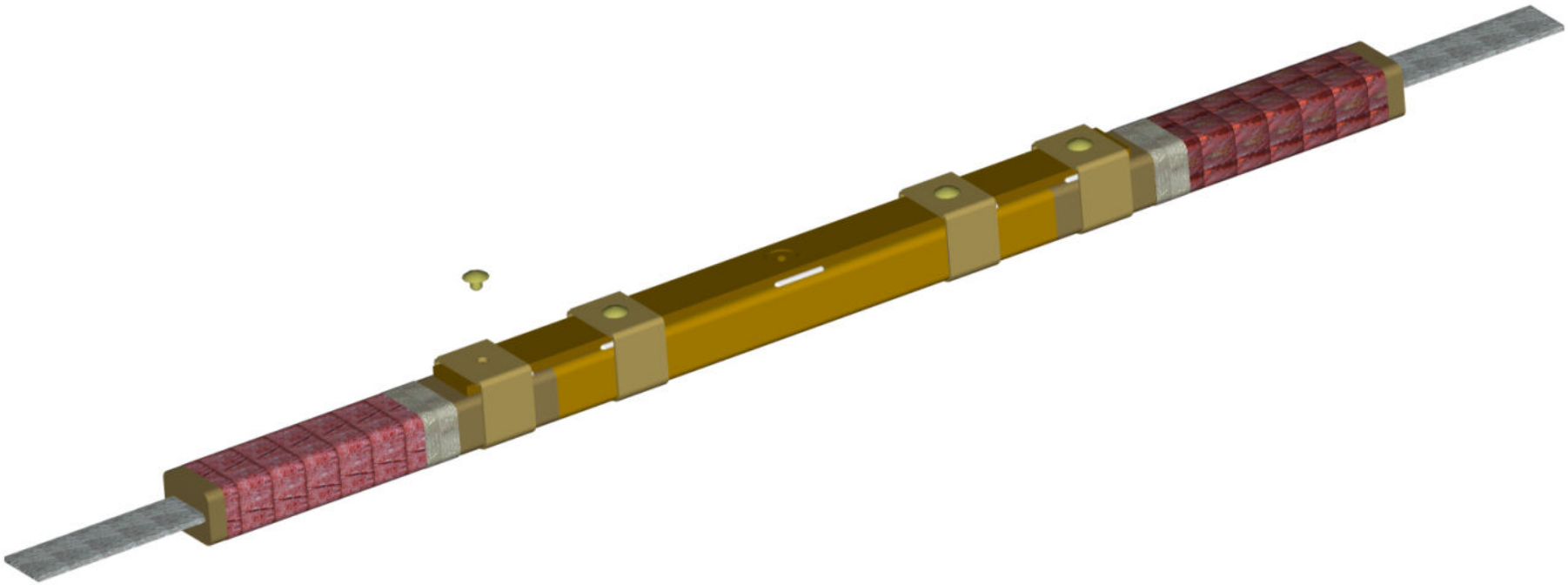


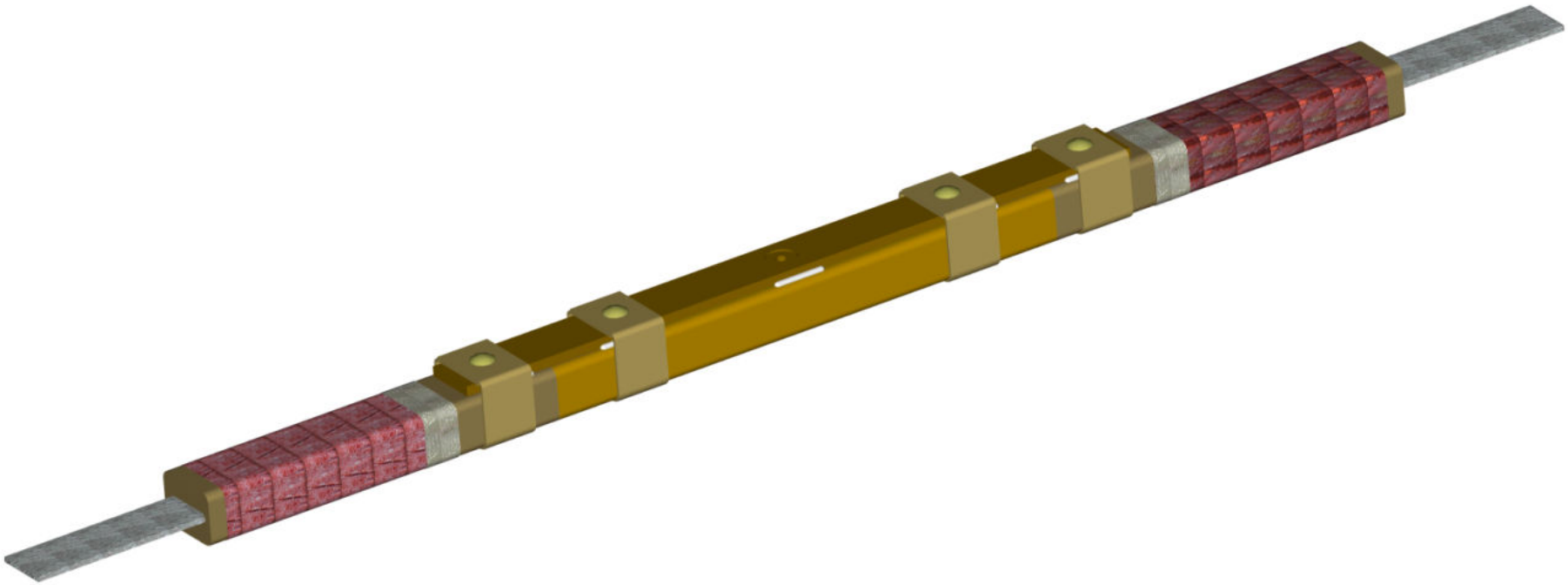












Observations

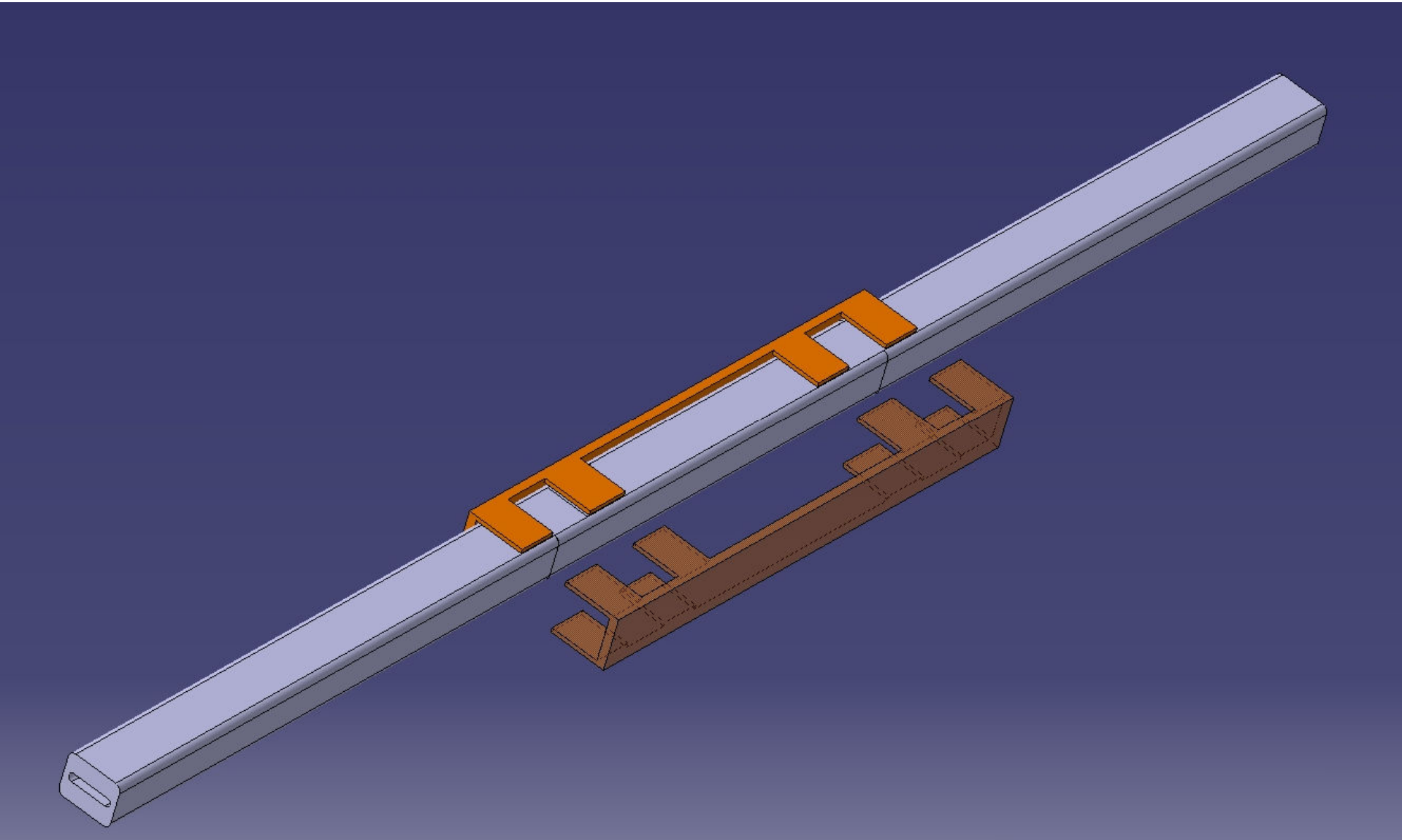
Pros.

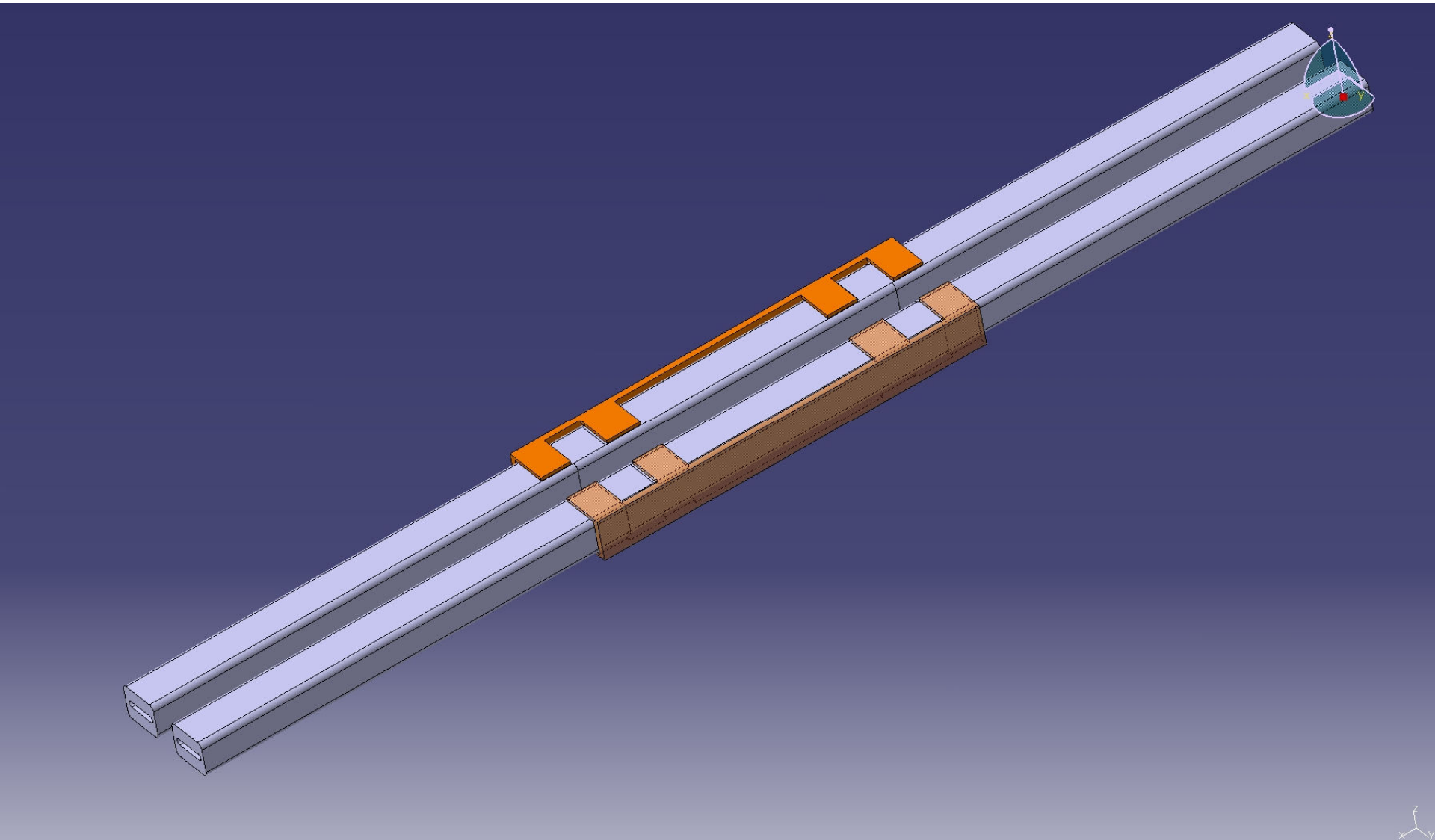
1) Easy to apply
2) Can integrate mechanical restrain
3) Copper shunt it is very easy to produce

Cons.

1) There is only one continuous piece connecting the left and right side of the copper junction, we have to verify if it can accept the different defects of a real junction
2) There is no redundancy on the new soldering

SHUNTING DESIGN OPTION B





Observations

Pros

1) The two side of the copper junction are partially decoupled
2) The largest piece is lateral and not on the top
3) There is redundancy for the new soldering spots

Cons

1) Piece more complicate to produce, but in any case easy
2) To be seen if we can integrate the mechanical restrain
3) There are more soldering to be done
4) The current path from left to right of the connection is slightly longer

Flexible shunt