Status of splices in 6 kA circuits [Progress report]

- Inventory of 6 kA splices
- Currents expected in function of energy level
- Example of Q7L2
- Measurement of splice electrical resistance at cold (SC)
- QPS characteristics for IPQs/IPDs
- Praying hand splices
    - Design
    - Production method
    - Tests performed
    - MCI
    - Proposed actions for the future
- Further work
- Conclusions

Inventory of 6 kA circuits (1/2)

TOTAL : 94 circuits
78 IPQs + 16 IPDs

Individually Powered Quadrupoles and Dipoles (IPQ/IPD):

- In the continuous cryostat:
  - DS : Q8, Q9, Q10 @ P1,2,4,5,6,8 Left & Right: # 36
  - MS : Q7 @ P1,2,4,5,8 (Not P6) Left & Right: # 10
- In Stand-Alone cryostats:
  - Q6 @ P1,2,4,5,8 (Not P6) Left & Right: # 10
  - Q5 @ P1,2,5,6,8 Left & Right: # 10
  - Q4 @ P6 Left & Right: # 2
- In Semi Stand-Alone cryostats:
  - Q5 @ P4 Left & Right: # 2
  - Q4 @ P1,2,5,8 Left & Right: # 8
  - D4 @ P4 Left & Right: # 2
  - D3 @ P4 Left & Right: # 2
  - D2 @ P1,2,5,8 Left & Right: # 8
- In triplets
  - D1 @ P 2&8 Left & Right: (In Nuria's talk) # 4

Technology Department

Inventory of 6 kA circuits (2/2)

Sector	#
1-2	17
2-3	9
3-4	8
4-5	16
5-6	13
6-7	5
7-8	9
8-1	17
TOTAL	94

Powered by	#	
DFBA	49	Q7 to Q10 + some Q6
DFBM	25	D3, D4 + some D2, Q4, Q5, Q6
DFBL	16	D2, Q4,5,6 @ P1 & P5
DFBX	4	D1 @ P2 & P8

TOTAL : 94 circuits
* 5 to 17 per sector (12 in average)
* 4 different powering units

Many different types & specificities

Currents in “6kA” circuits

Technology

Sector		12					23					34					45					56					67					78					81				
Energy		3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]	3.5	5	7	7.6	L [H]
D1	R						3000	4500	5800	6100	0.026																										3000	4500	5800	6100	0.026
D2	R	2300	3500	6000	6500	0.052	3100	4600	6000	6500	0.052											2300	3500	6000	6500	0.052											3100	4600	6000	6500	0.052
D3	R																[illegible]	[illegible]	[illegible]	[illegible]	[illegible]																				
D4	R																																								
Q4	R	1																				1900	2800	3610	3900	0.074	1900	2800	3610	3900	0.074						1900	2800	3610	3900	0.148
Q5	R	2																				2300	3500	4310	4650	0.021	1900	2800	3610	3900	0.074						1900	2800	3610	3900	0.148
Q6	R	2																				2300	3500	4310	4650	0.021											2300	3500	4310	4650	0.036
Q7	R	3100	4000	5390	5820	0.03	2800	4000	5390	5820	0.03						2800	4000	5390	5820	0.015	2800	4000	5390	5820	0.03											2800	4000	5390	5820	0.03
Q8	R	3100	4000	5390	5820	0.021	2800	4000	5390	5820	0.021						2800	4000	5390	5820	0.021	2800	4000	5390	5820	0.021	2800	4000	5390	5820	0.021						2800	4000	5390	5820	0.021
Q9	R	3100	4000	5390	5820	0.026	2800	4000	5390																															820	0.026
Q10	R	3100	4000	5390	5820	0.021	2800	4000	5390																															820	0.021
Q10	L	3100	4000	5390	5820	0.021																																		820	0.021
Q9	L	3100	4000	5390	5820	0.026																																		820	0.026
Q8	L	3100	4000	5390	5820	0.021																																		820	0.021
Q7	L	3100	4000	5390	5820	0.03																																		820	0.03
Q6	L	2100	3500	4310	4650	0.036																																		650	0.021
Q5	L	1900	2800	3610	3900	0.148																																		650	0.021
Q4	L	1900	2800	3610	3900	0.148											1900	2800	3610	3900	0.074	1900	2800									1900	2800	3610	3900	0.148	1900	2800	3610	3900	0.074
D4	L											3100	4020	5520	6000	0.052																									
																					2											3100	4600	6000	6500	0.052	2300	3500	6000	6500	0.052
																																3000	4500	5800	6100	0.026					

94 circuits:
- Current at 3.5, 5, 7, 7.6 TeV equivalent
- Magnet inductance

[A]	3.5 TeV	5 TeV	7 TeV	7.6 TeV
Q7, Q8, Q9, Q10	3100	4000	5390	5820
Q4, Q5, Q6	2100	3500	4310	4650
D1, D2, D3, D4	3200	4600	6000	6500

In 2010

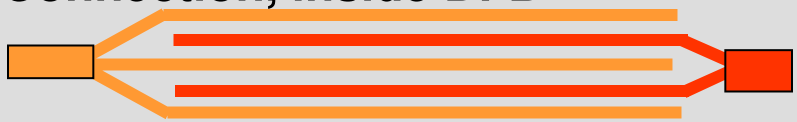
References:
- Layout database
-Powering specificities (EDMS):
1-2 1009658, 2-3 883231, 3-4 883247, 4-5 883273
5-6 883295, 6-7 883317, 7-8 883182, 8-1 883200

Technology

Different types of joints: Example of Q7L2

Cable to Pigtail Connection, inside DFB

Round Cable « Flattened »
HTS Side



Round Cable « Flattened »
HCM Side

At least 5 different types

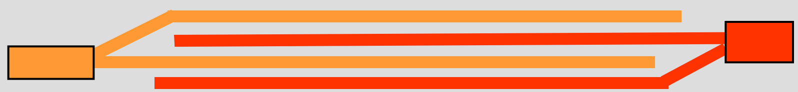
Shake-hands Connection, inside SSS

Flat Cable
SSS Side

Round Cable « Flattened »
Interconnection side

Shake-hands Connection, Interconnections HCM-SM & DFB-Q7

Round Cable « Flattened »



Round Cable « Flattened »

Pray-hands Connection, inside cold masses

Round Cable « Flattened »
Flat Cable

Pray-hands Connection, in Line N

Round Cable « Flattened » from SSS

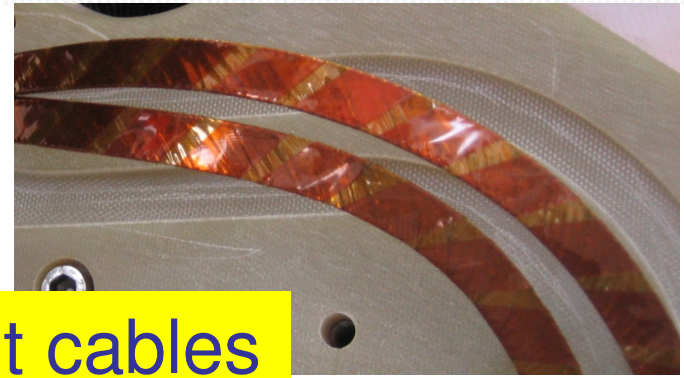
Round Cable « Flattened » from Line N

From A Jacquemod @ Splices TF

Different types of cables: Example of Q7L2

Two types of cables:

Rutherford flat type inside magnets



At least 2 different cables

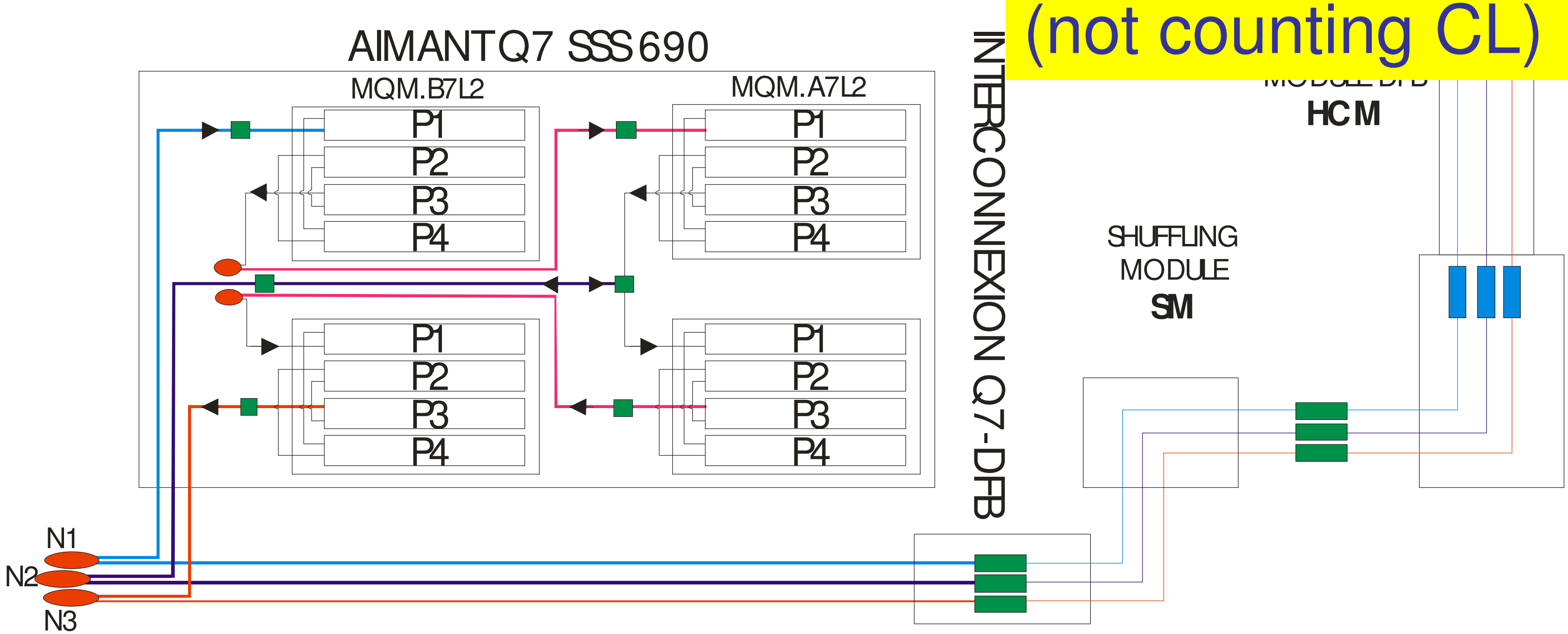
Circular type in the powering lines and DFB's

Many different configurations ; inventory to be continued

Technology Department

Electrical circuit : Example of Q7L2

TOTAL : 20 splices (not counting CL)

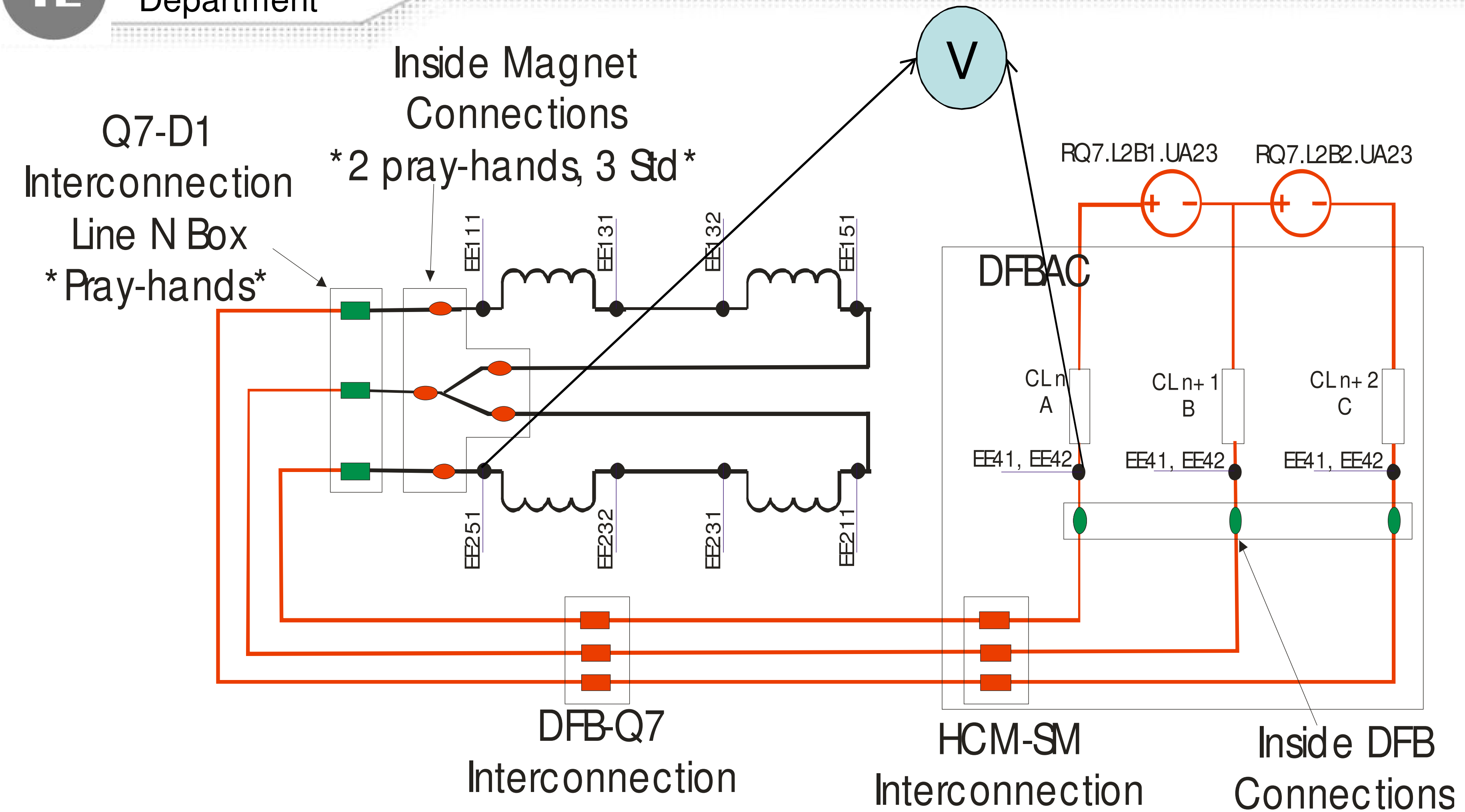


= Cable to Pigtail Connection, inside DFB
= Shake-hand Connection, inside SSS
= Shake-hand Connection, interconnectio
= Pray-hand Connection, inside SSS
= Pray-hand Connection, in line N Box

Black Wire = Flat Cable
Color Wire = Round Cable

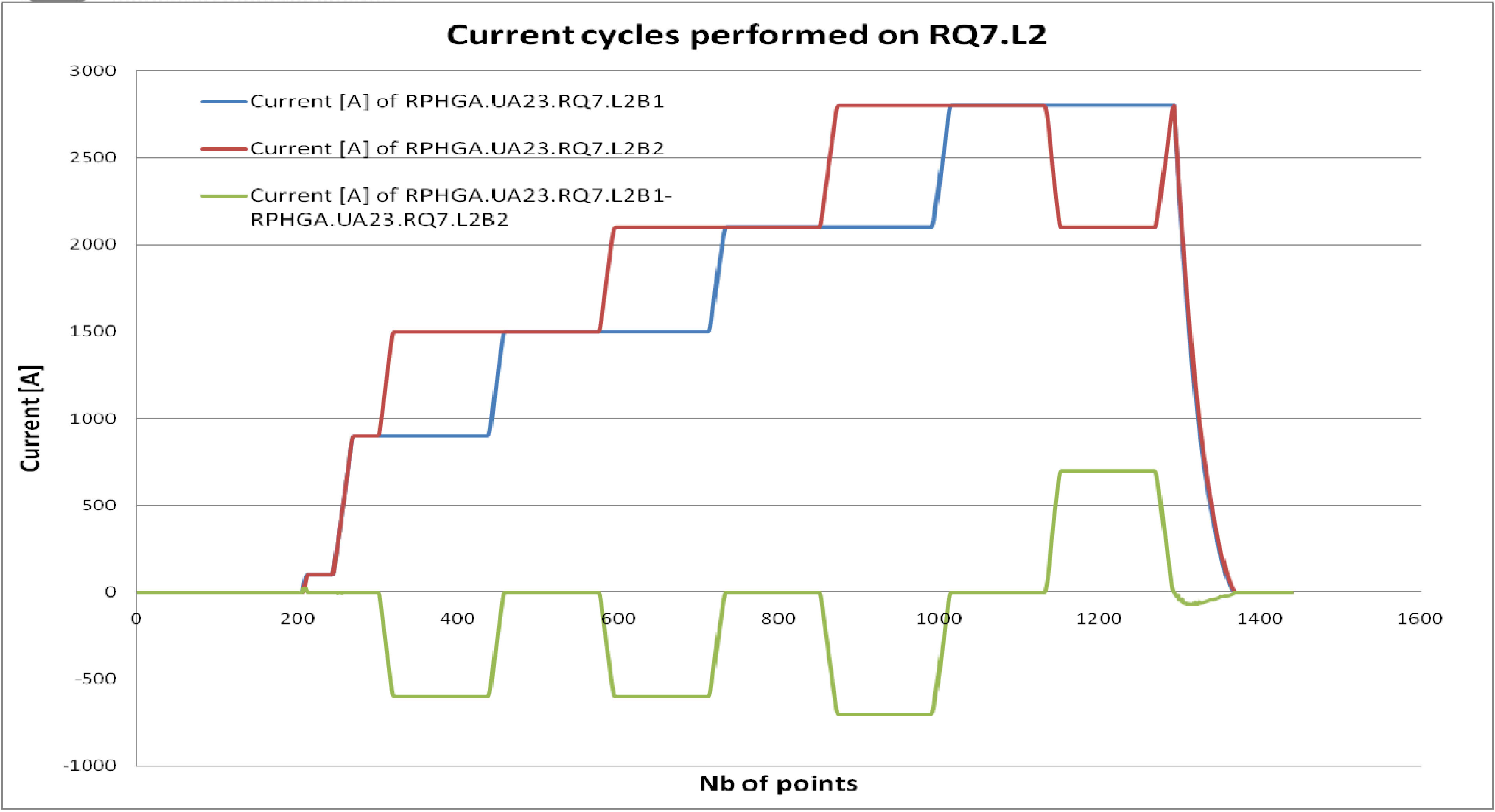
Other praying-hand splices in cold masses, held in a box

Measurement of electrical splice resistance at cold



From R Mompo @ MP3

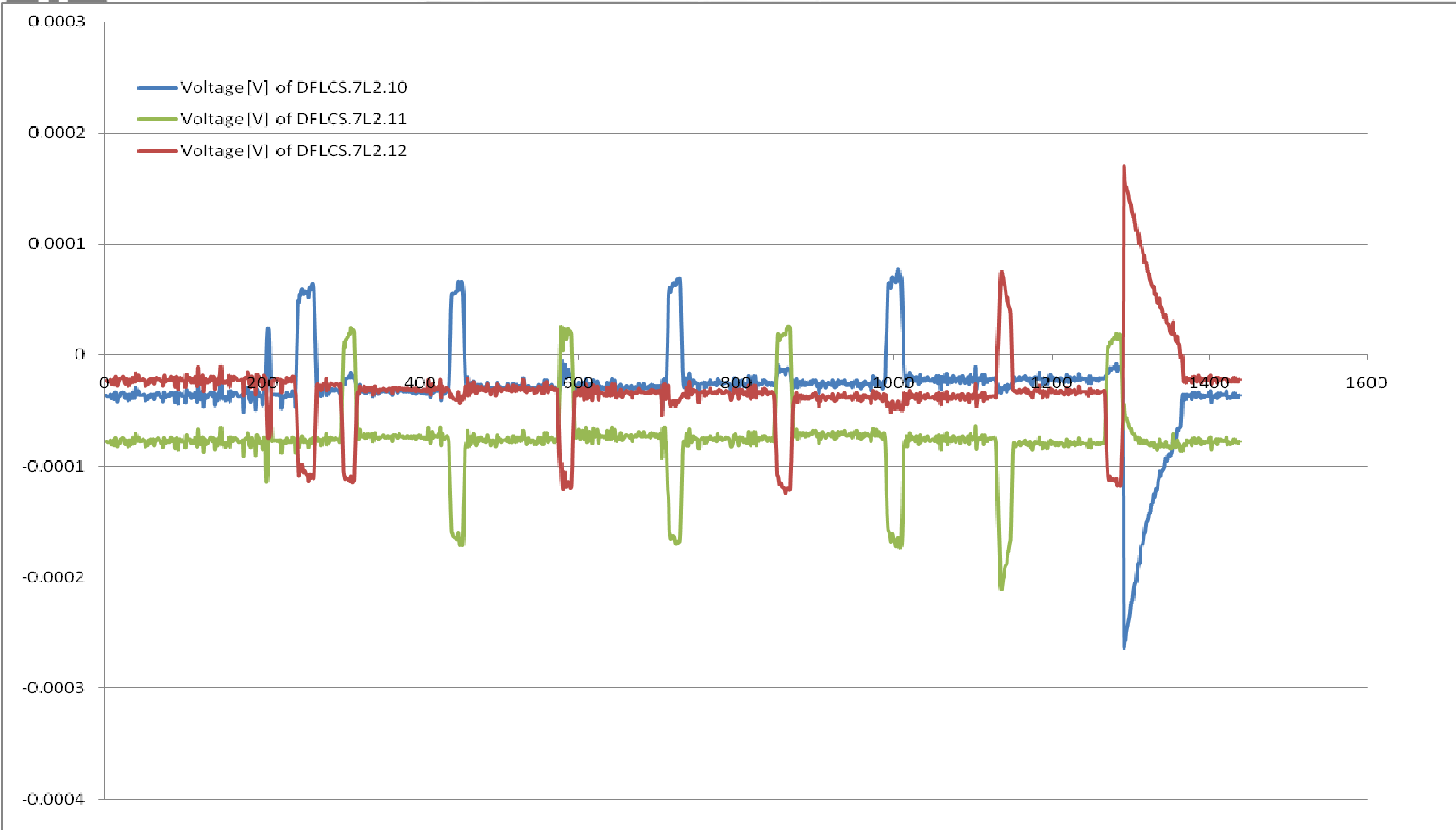
Measurement of electrical splice resistance at cold



From R Mompo @ MP3

Technology

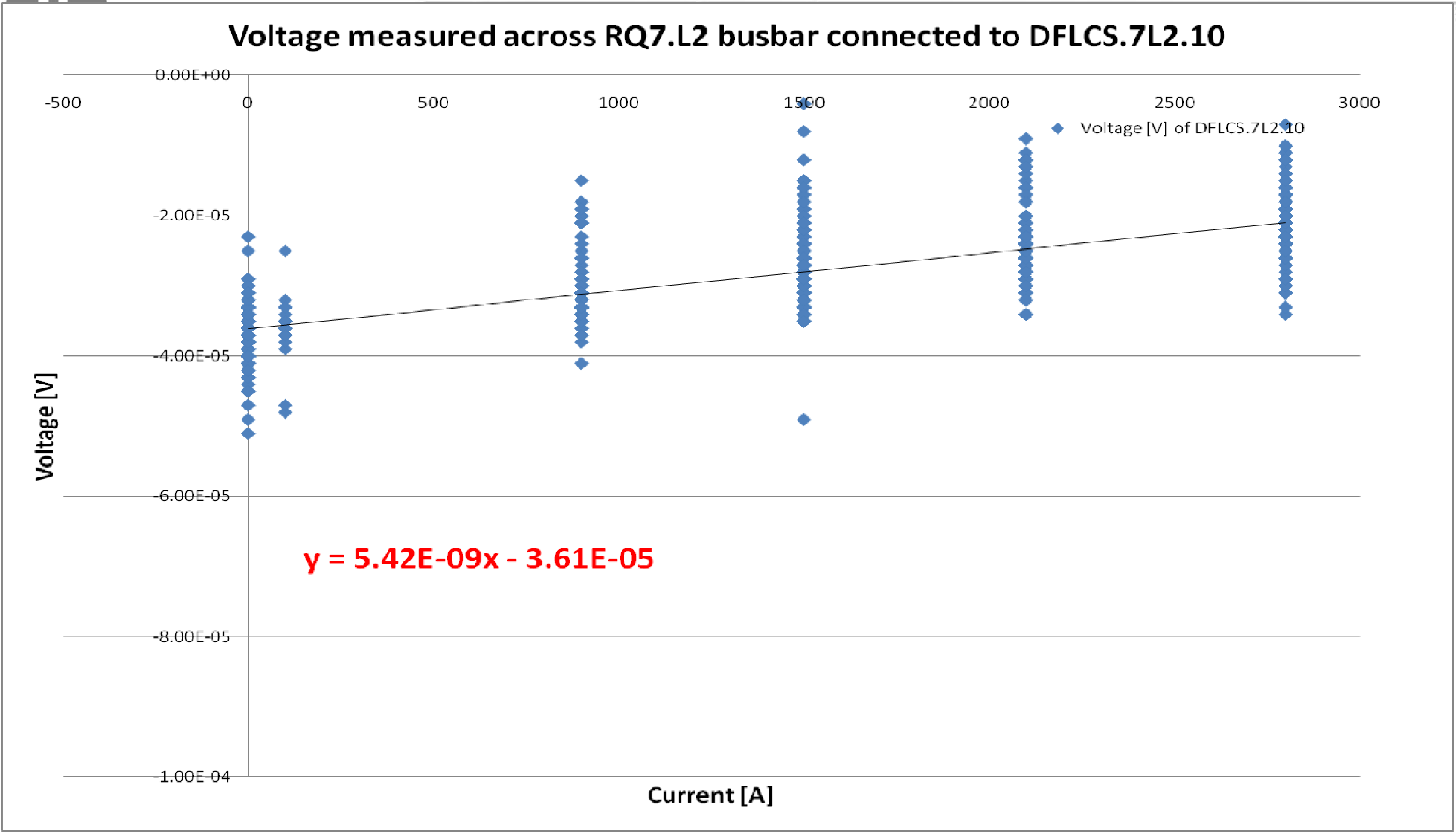
Measurement of electrical splice resistance at cold



From R Mompo @ MP3

J.Ph. Tock

Measurement of electrical splice resistance at cold



From R Mompo @ MP3

Measurement of electrical splice resistance at cold

Magnet	Bus-bar of lead	Resistance [?]	Uncertainty (1σ) [?]	Offset [V]
Q10	DFLCS.7L2.1	5.3E-09	1.E-09	-6.1E-05
Q10	DFLCS.7L2.2	5.4E-09	**3.E-09**	1.3E-05
Q10	DFLCS.7L2.3	5.3E-09	1.E-09	2.4E-05
Q9	DFLCS.7L2.4	5.7E-09	1.E-09	9.4E-06
Q9	DFLCS.7L2.5	5.9E-09	2.E-09	1.0E-05
Q9	DFLCS.7L2.6	6.1E-09	1.E-09	1.8E-05
Q8	DFLCS.7L2.7	5.3E-09	7.E-10	2.9E-05
Q8	DFLCS.7L2.8	**6.1E-09**	2.E-09	1.7E-05
Q8	DFLCS.7L2.9	5.4E-09	7.E-10	5.6E-06
Q7	DFLCS.7L2.10	5.4E-09	1.E-10	-3.6E-05
Q7	DFLCS.7L2.11	5.7E-09	3.E-10	-7.7E-05
Q7	DFLCS.7L2.12	5.3E-09	1.E-10	-2.4E-05

4 SSS tested (12 segments with 5 splices per segment):
- Max is 6.1 nOhm
- Average splice resistance is 1.1 nOhm
- Expected: 1 nOhm / Specified < 1.5 nOhm

From R Mompo @ MP3

Measurement of electrical splice resistance at cold

Sequence of events :

- Method was not available at the beginning of the commissioning
- Proposal / Recommendation to commission the circuits to reduced currents to 3.5 TeV level (MP3 on 30/09/2009 & TEMB on 05/10/2009), so not requiring splice mapping
- In parallel, the system and the method have been developed by TE-MPE

Proposal :

To measure all splices before increasing energy higher than 3.5 TeV

This will require time and access

QPS for IPQs/IPDs

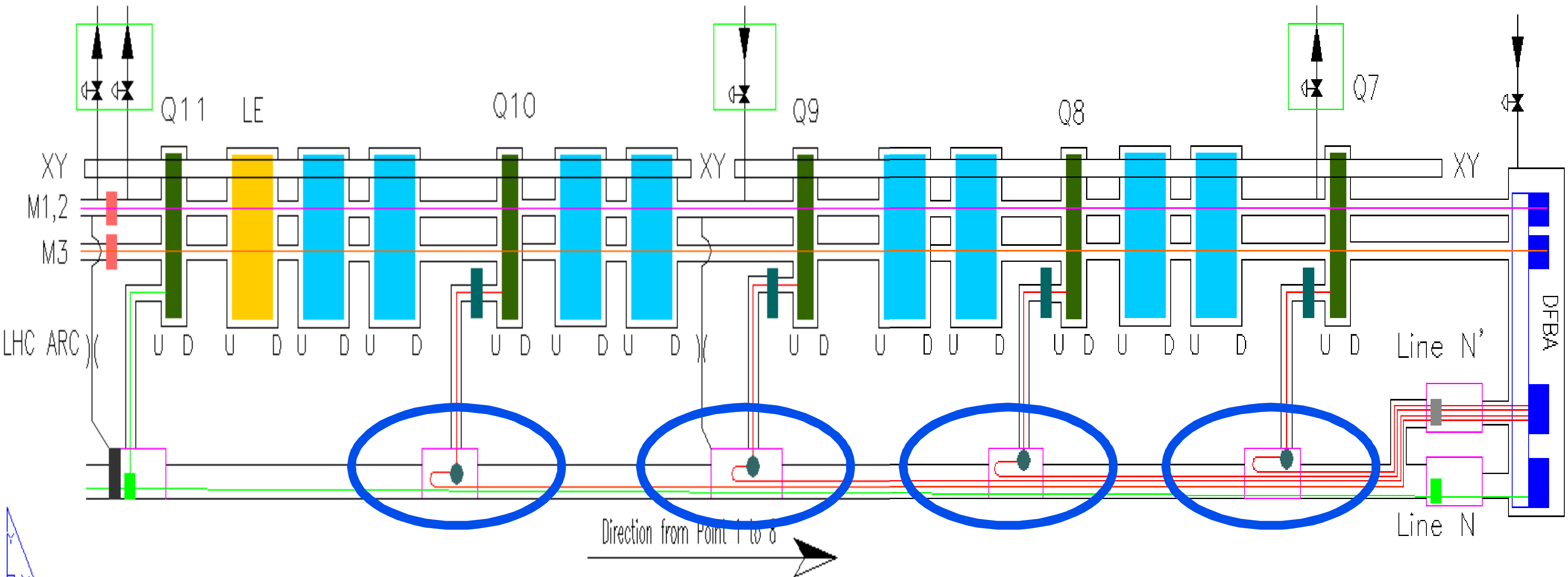
Characteristic	IPQ/IPD (pres)	Dipole (nQPS)
Detection time	10 msec	10 sec
Detection threshold	100 mV	0.3 mV
Figure of Merit	1 mV sec	3 mV sec
Discharge time	< 1 sec	50 / 100 sec
Supply	2 UPSs	2 UPSs

Present QPS for IPQs/IPDs is already "better" than nQPS for dipoles
Upgrade of QPS could be done for end of 2010 to protect magnet and busbars separately. This would allow to reduce the threshold and make diagnostics / monitoring measurements of splices

Infos from R Deinz

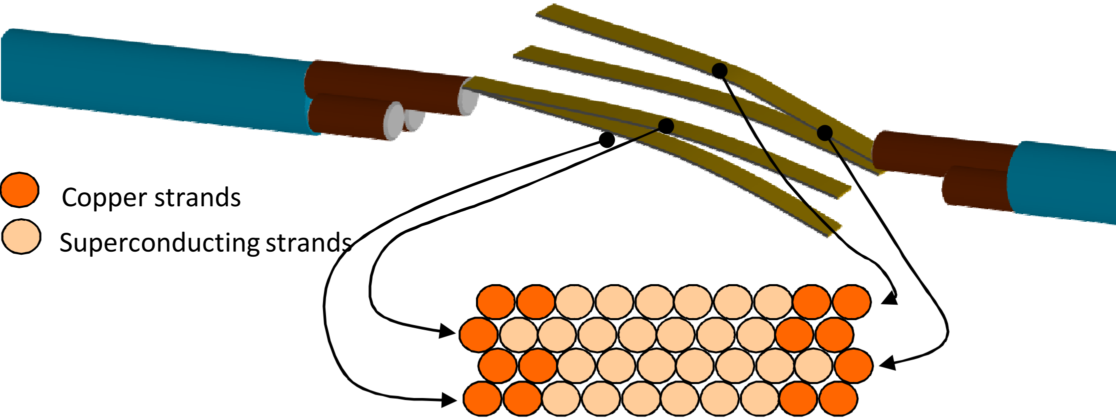
Interconnection praying hand splices

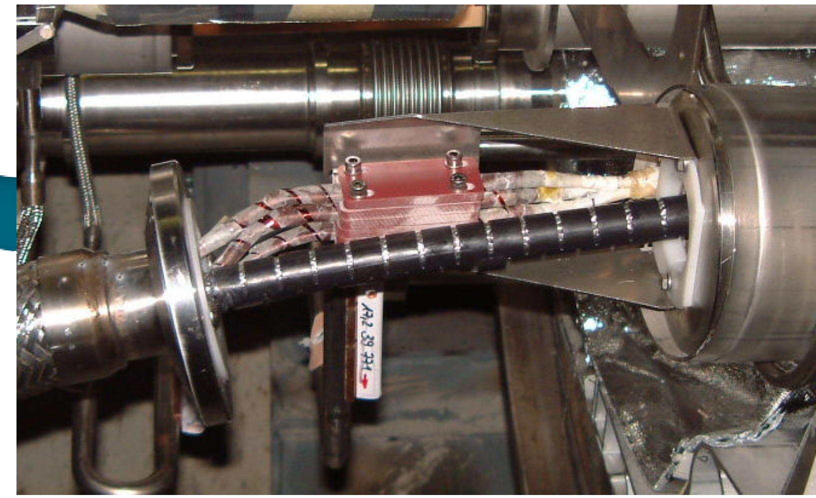
- In DS zones for IPQs (Q7 to Q10) @ P1,2,4,5,6,8 :
  - 23 quadrupoles (No Q7 @ P6)
  - 69 splices

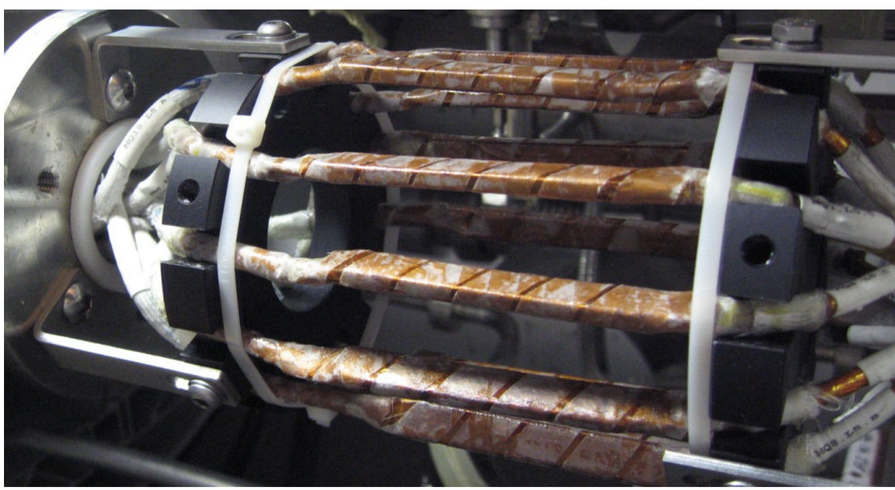


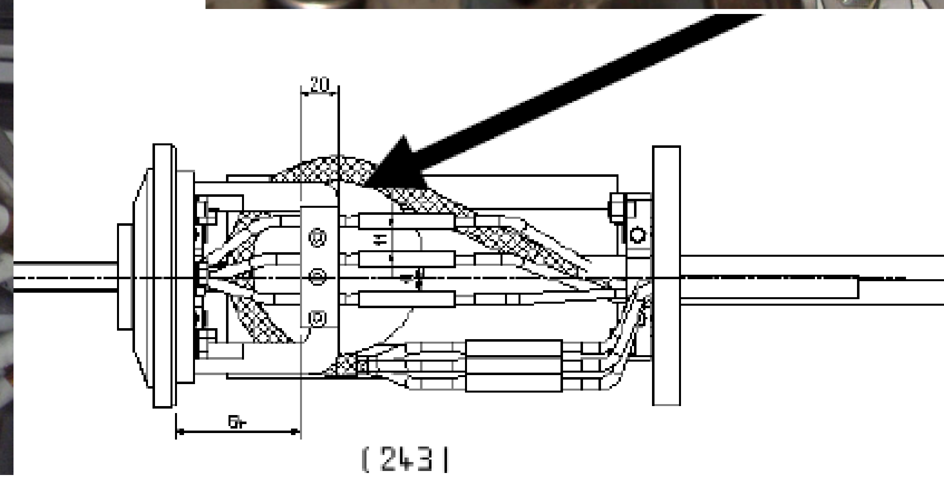
Interconnection praying hand splices

- Initial design was in-line ; as applied at the right of IP and between DFBA and Q7



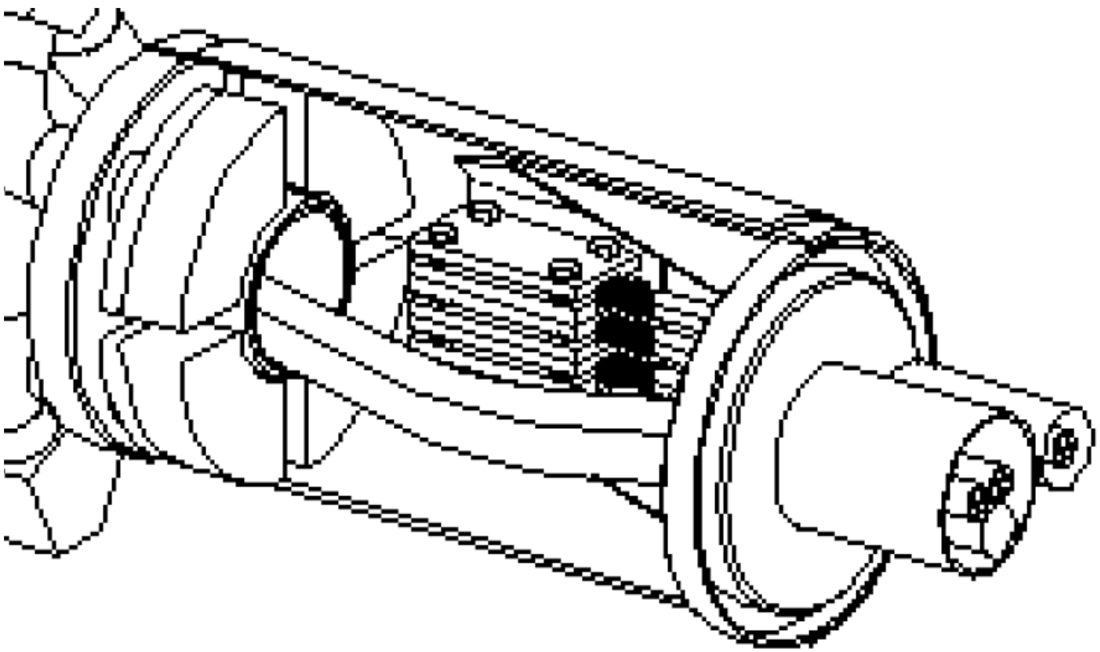


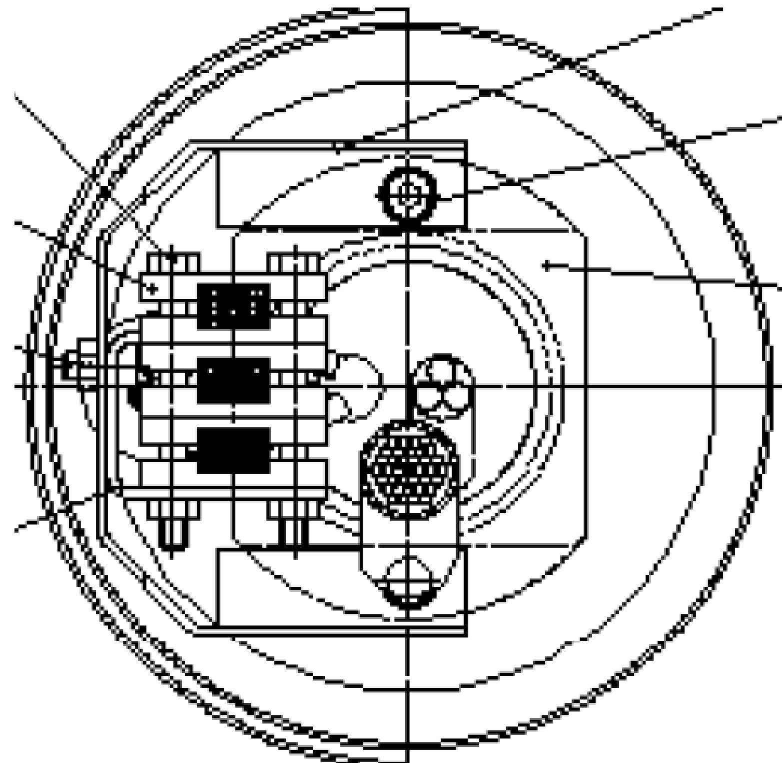




Interconnection praying hand splices

- Not possible have a “U” turn for space limitation reasons
- A too small radius of curvature would have broken superconducting filaments
  - **So design changed to “hair pin” or “praying hand” splices**

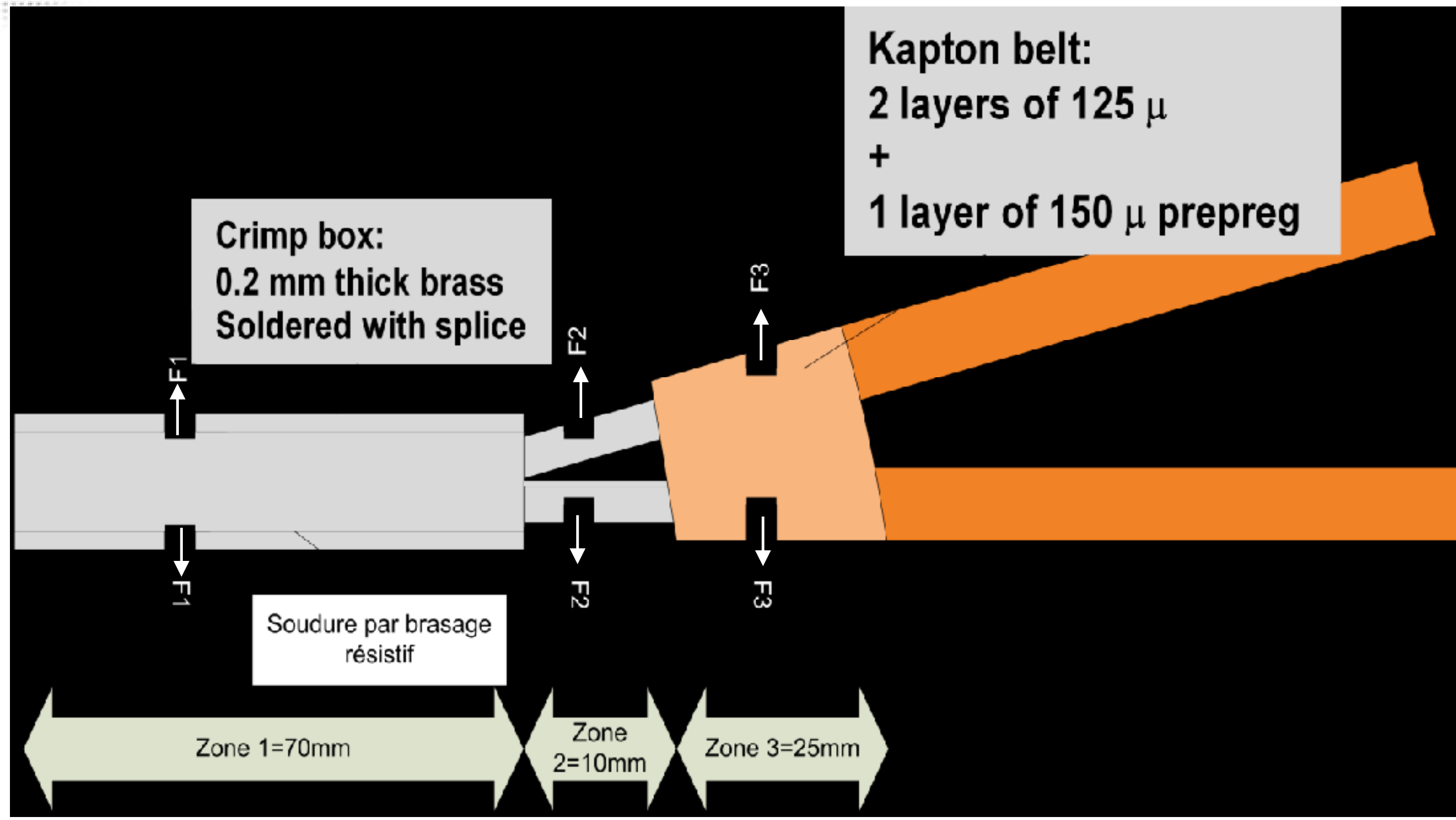




Interconnection praying hand splices: Mechanical design

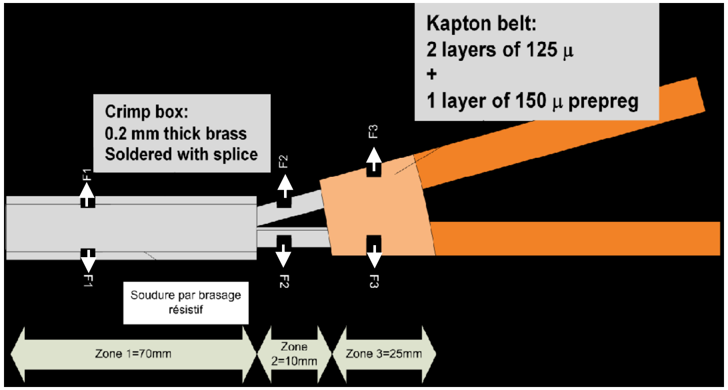
Divided in 3 zones :

- ❖The box
- ❖Free zone
- ❖Kapton belt



Interconnection praying hand splices: Mechanical design

Zone	1	2	3
Name	Box	Free	Belt
Force [N]	138	2	12
σ [MPa]	5	25	1.2
Deflection [mm]		0.008	< 0.1
Yield strength @ 4K [MPa]	Brass>270		333
Infinite lifetime @ RT [MPa]	80 to 100	80 to 100	



Ample margin in all zones

Ref: EDMS 990048

Interconnection praying hand splices: Tests performed : Electrical resistance

ANNEX B

Résultats des mesures de résistances de busbars supraconducteurs de type 6 kA-6 kA

Inductance bus bars L = 161 nH

Mesures du 02/09/04 **Ech 7**-6 kA-6 kA

Courant primaire d'alimentation 10 A :

Ech 7-10a	τ = 233.76 s	R = 0.689 nΩ
Ech 7-10b	τ = 244.17 s	R = 0.659 nΩ
Ech 7-10c	τ = 244.11 s	R = 0.659 nΩ
Moyenne		**R = 0.669 nΩ**

Courant primaire d'alimentation 20 A :

Ech 7-20a	τ = 220.12 s	R = 0.731 nΩ
Ech 7-20b	τ = 233.60 s	R = 0.689 nΩ
Ech 7-20c	τ = 235.52 s	R = 0.684 nΩ
Moyenne		**R = 0.701 nΩ**

Mesures du 09/06/04 **Ech 6**-6 kA-6 kA

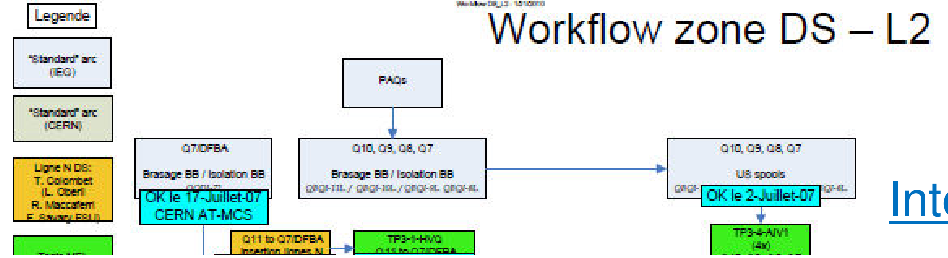
Observation : l'échantillon comporte une soudure non entrelacée.
Niveau initial d'hélium = 587 mm Niveau final d'hélium = 578 mm.

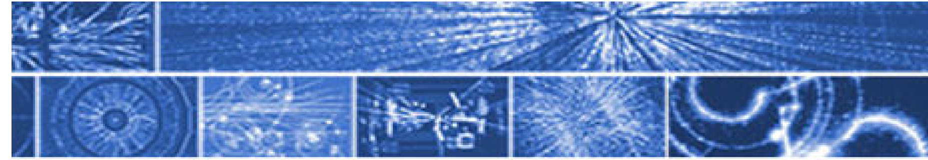
Ech 6-20a	τ = 142.867 s	R = 1.127 nΩ
Ech 6-20b	τ = 142.456 s	R = 1.130 nΩ
Ech 6-20c	τ = 142.778 s	R = 1.128 nΩ
Moyenne		**R = 1.128 nΩ**

Loops tested at CRYOLAB

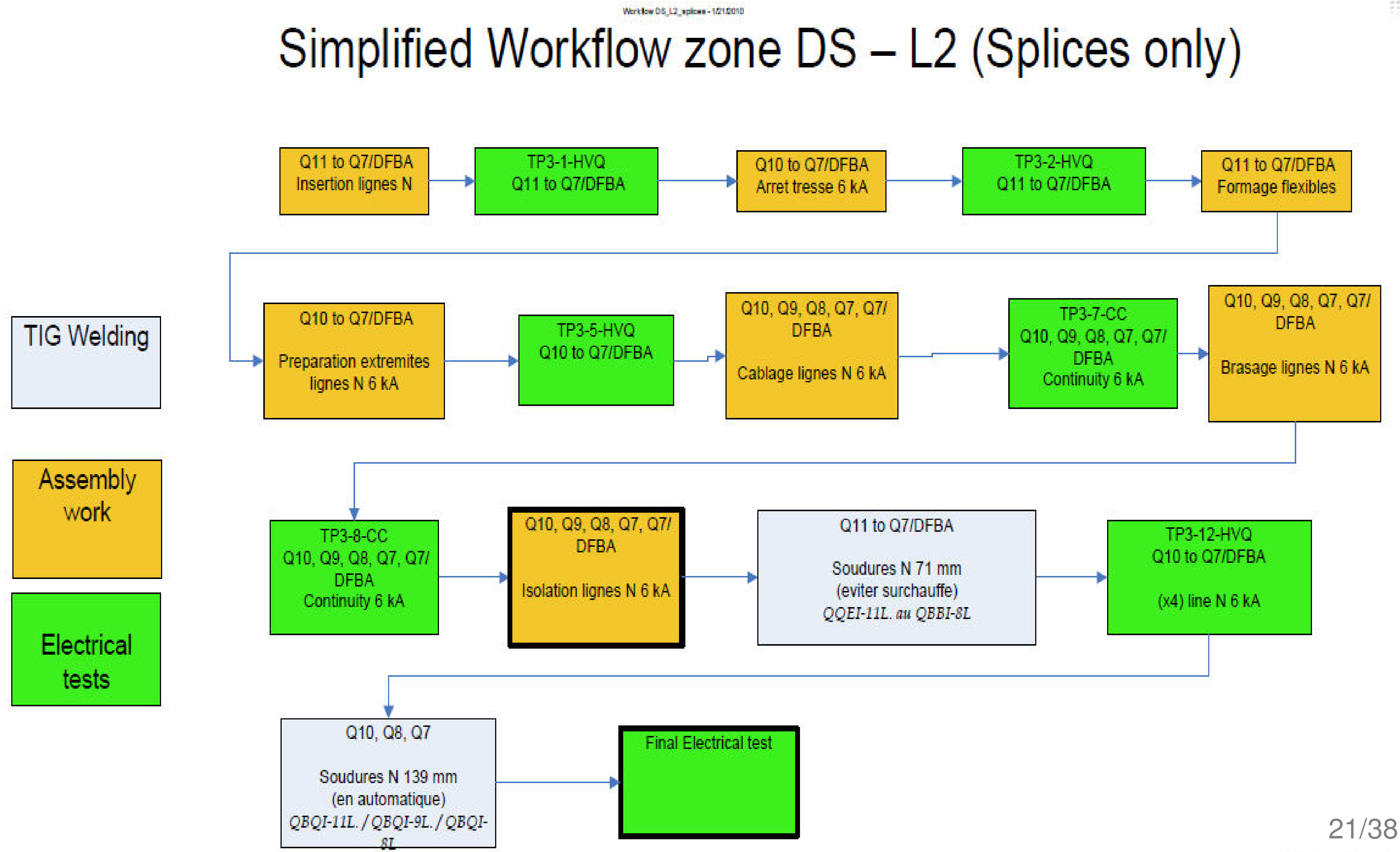
Ref: EDMS 533260

R < 1.5 nOhm
(Average : 1 nOhm)



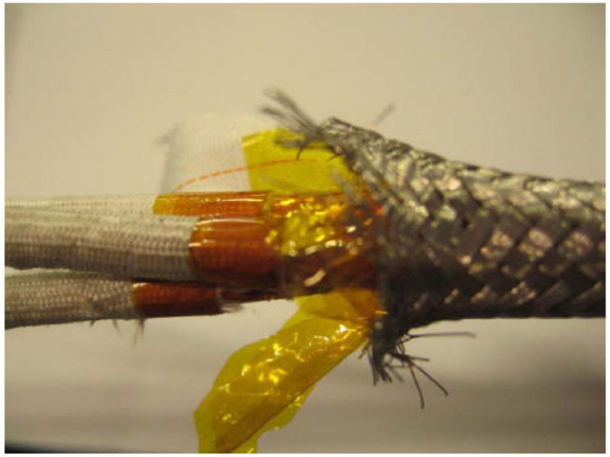


Interconnection praying hand splices: Workflow

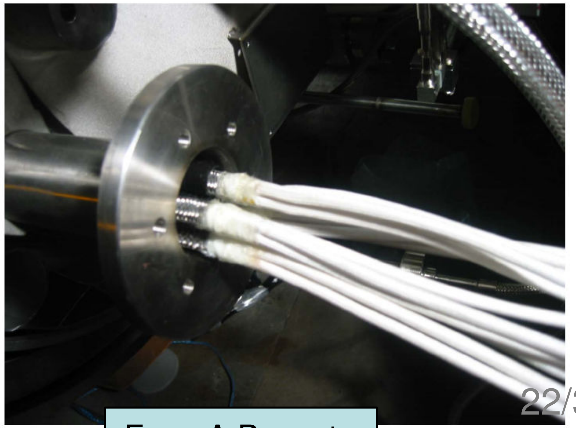


Interconnection praying hand splices: Assembly procedure

1. Preparation of cable extremities : A : Braid stopping



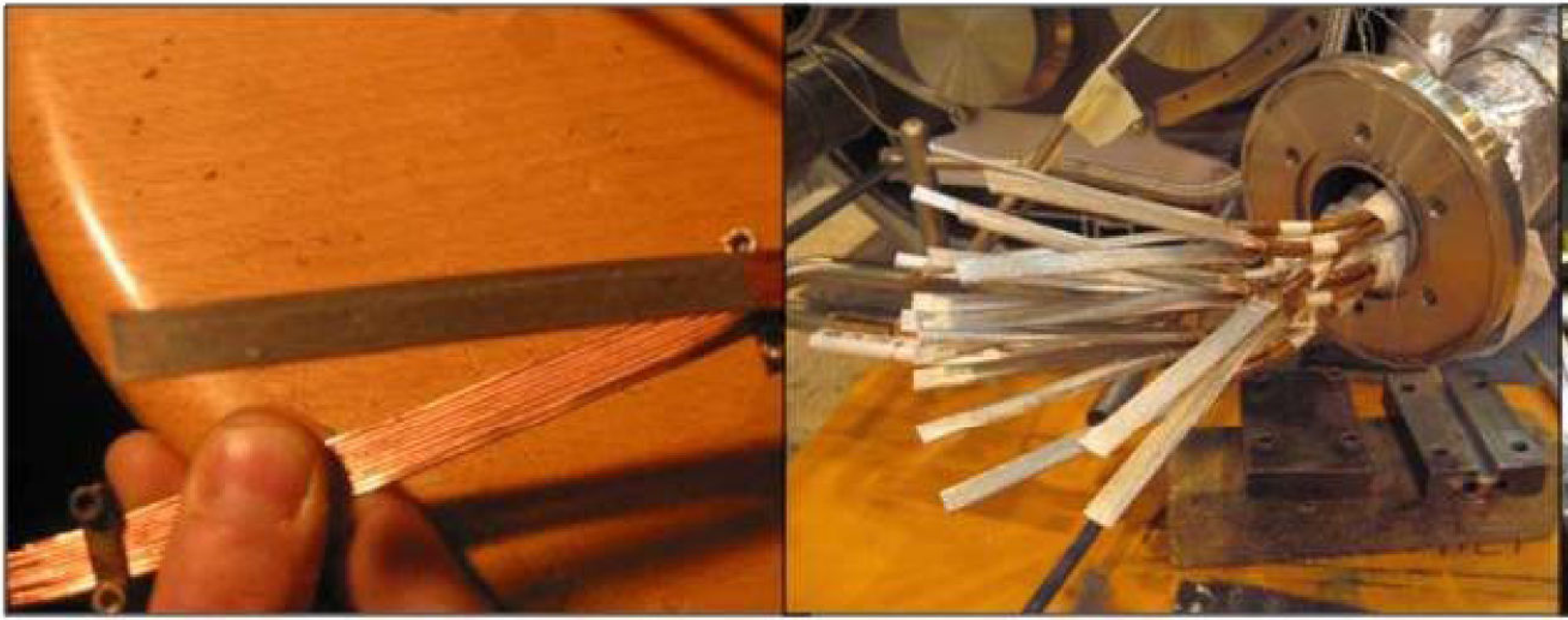
Arrêt de tresse (L1- Q7-DFB)



From A Poncet

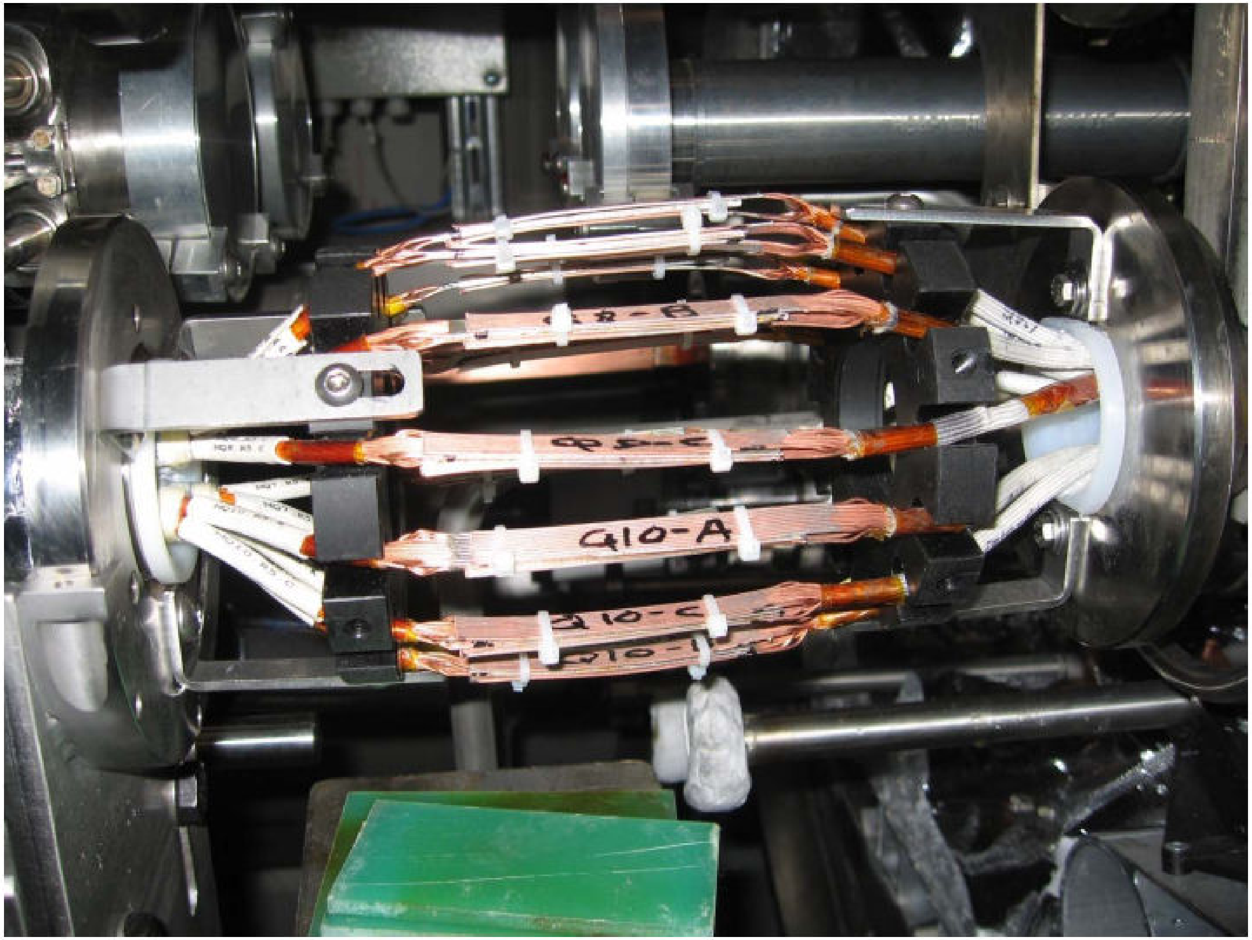
Interconnection praying hand splices: Assembly procedure

2. Preparation of cable extremities (Flattening and stabilisation)



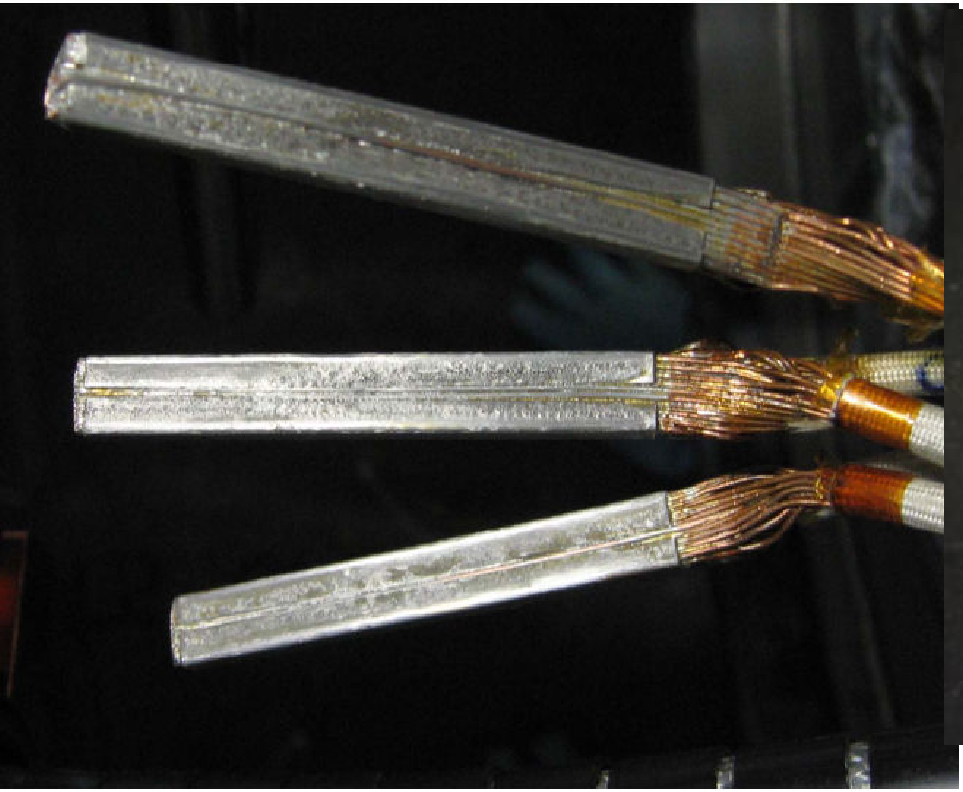
Interconnection praying hand splices: Assembly procedure

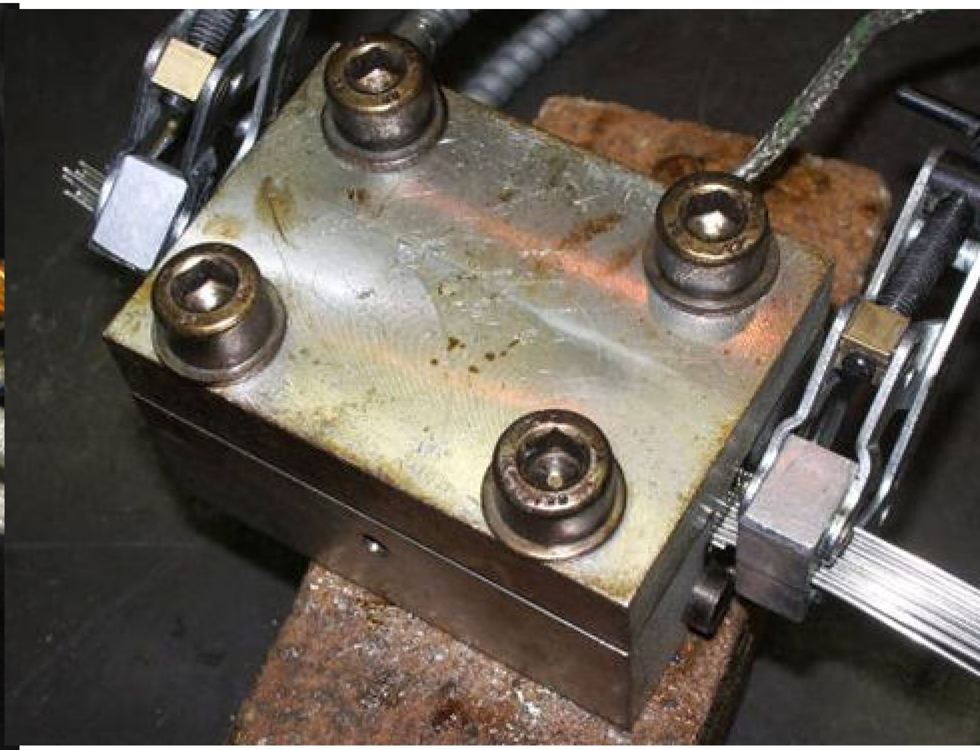
3. Cabling without soldering for electrical test



Interconnection praying hand splices: Assembly procedure

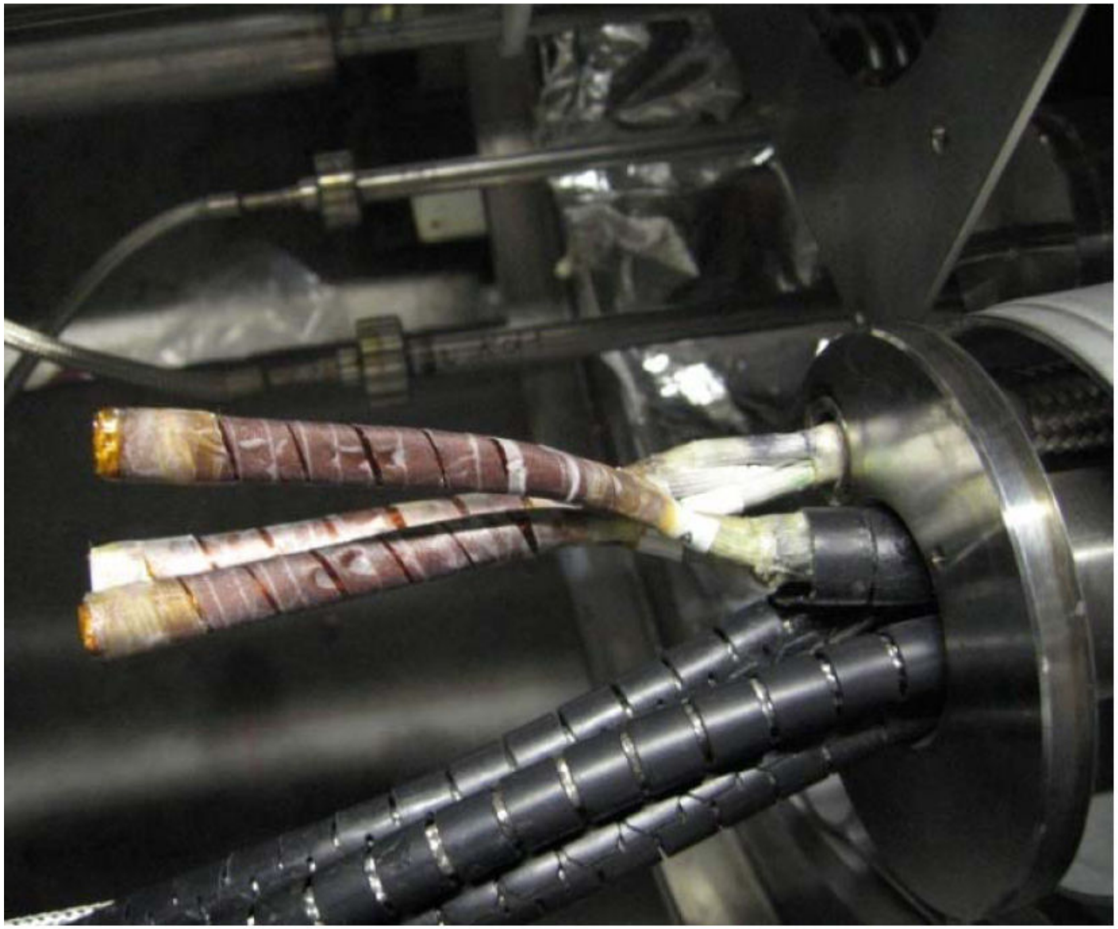
4. Soldering





Interconnection praying hand splices: Assembly procedure

4. Electrical insulation

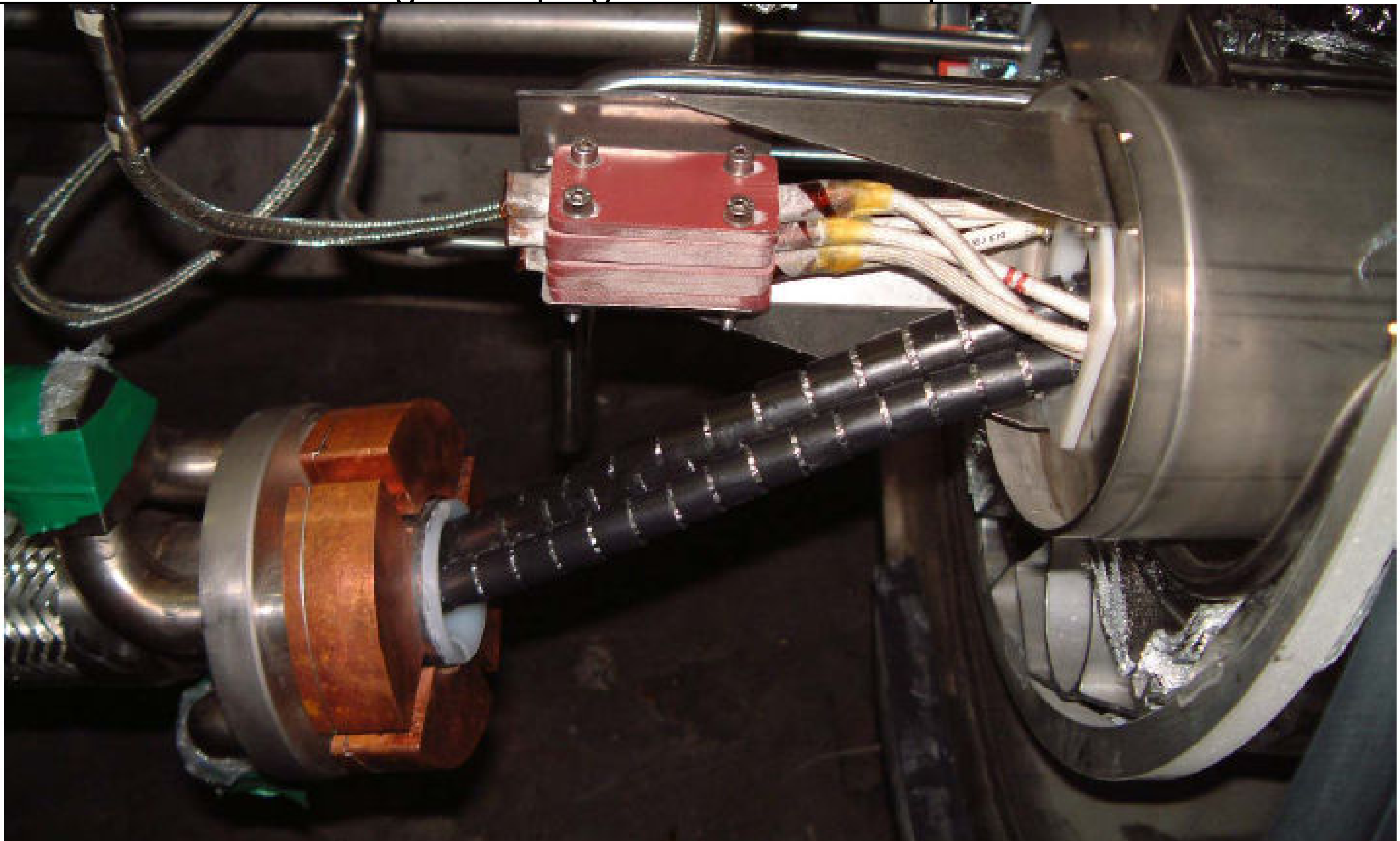


- Wrap 4 layers of polyimide film (overlapping 50 %)
- Wrap self adhesive glass cloth tape at both extremities
- External layer of prepreg

From A Poncet

Interconnection praying hand splices: Assembly procedure

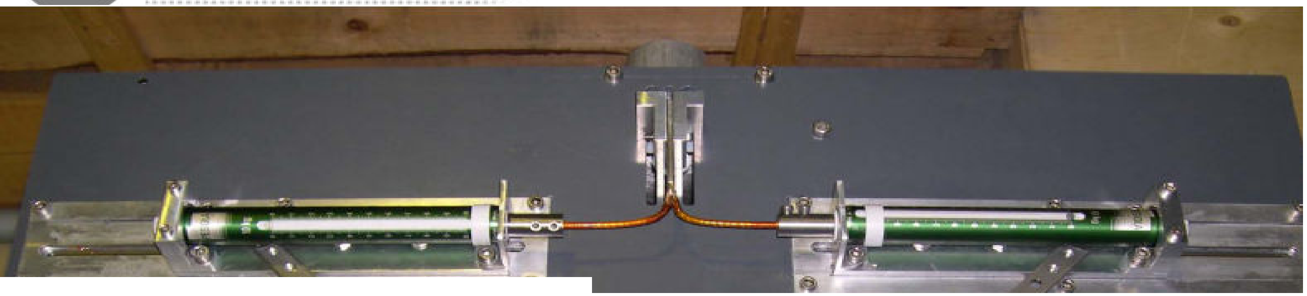
5. Install and fix an insulating / clamping box around the splices



From A Poncet

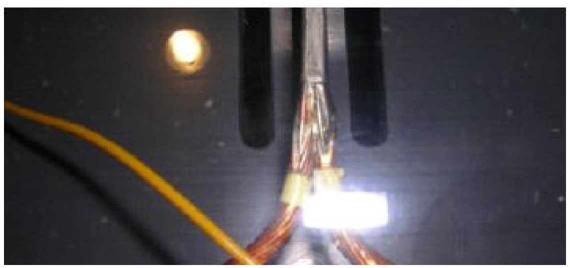
Interconnection praying hand splices: Tests performed : Fatigue testing at room temperature

By A Ballarino, A Jacob



Ref: EDMS 993835

Test configuration much more severe than actual conditions
So tested in FRESCA



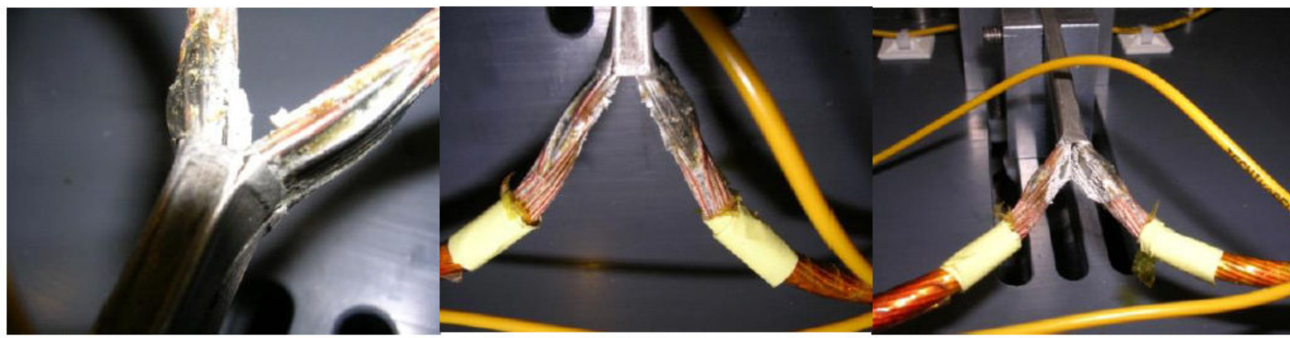
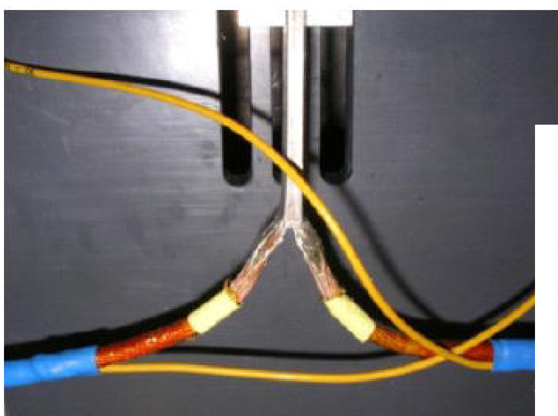


Fig.4 Electrical connection after 11000 cycles



Electrical connection after 2200 c

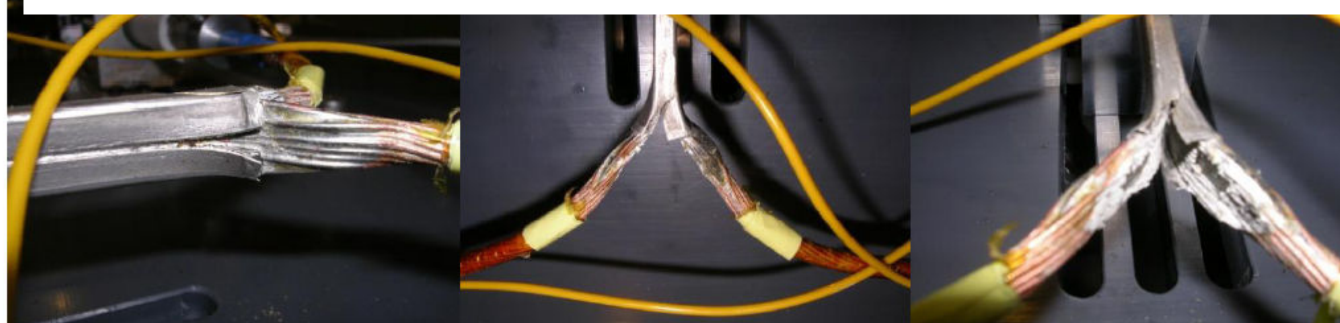
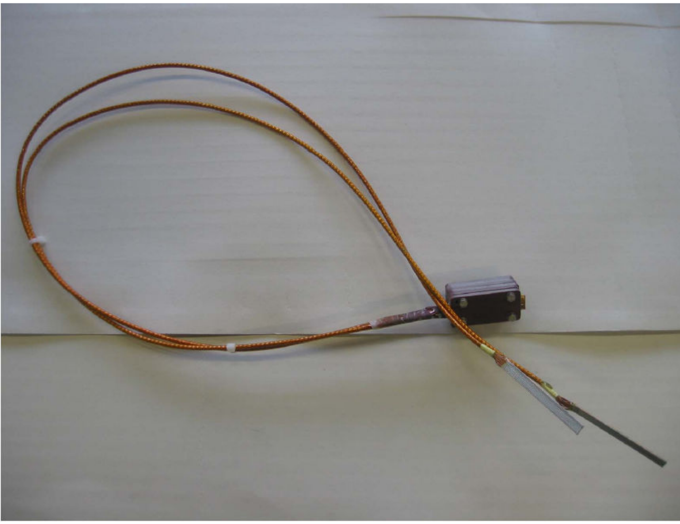


Fig.5 Electrical connection after 17190 cycles

Fresca test – 6 kA



Interconnection praying hand splices: Tests performed : Fatigue testing at cold in FRESCA

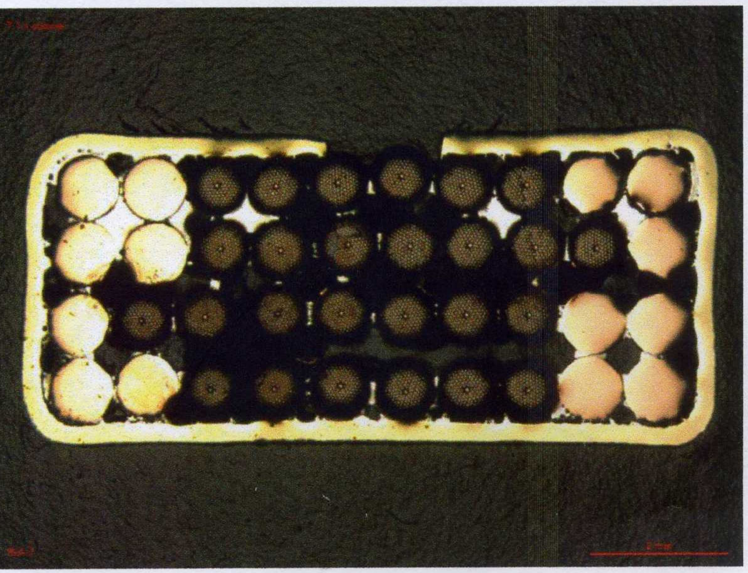
From A Poncet

Junction tested in FRESCA:

- 2 tests conducted
- Constant splice resistance monitoring
- 1328 cycles @ 6 kA ; no resistance increase
- 1416 cycles @ 9 kA
  - 2.25 mechanical loads
  - lifetime reduction of a factor 10
  - no resistance increase
- Oxygen free atmosphere/ few MPa so lifetime * > 10
- Visual inspection : No sign of damage
- Micrographic examination done (see next slide)

Interconnection praying hand splices: Tests performed : Fatigue testing at cold in FRESCA

- Micrographic examinations
  - Conclusions ?



Sample Id:
6 kA hairpin connection

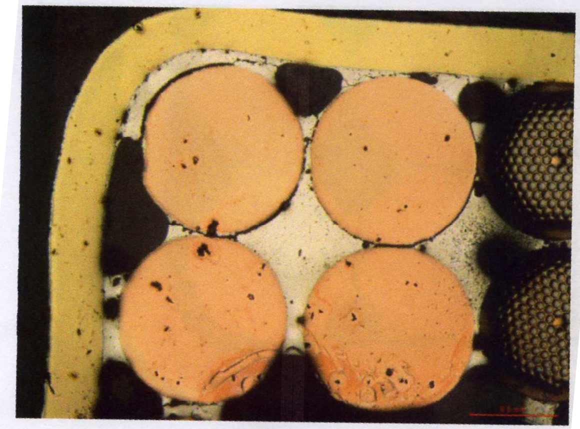
Magnification:
7.1 x coaxial

Date:
03.04.2009

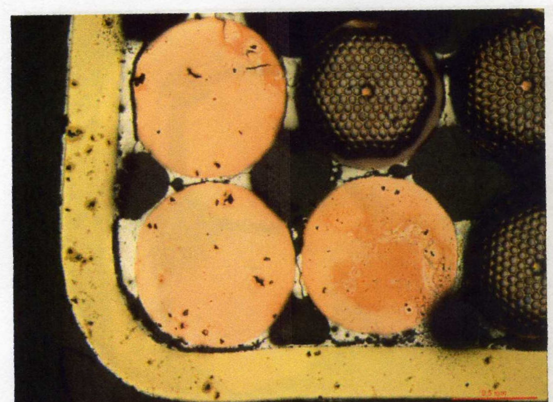
Description:
Cross-section, at crimp, sligh
presence of brazing

epartment

CERN-EN/MME/MM – Metallurgy and Met



Sample Id: 6 kA hairpin connection
Description: Cross-section corner 3, at crimp, lack of wetting
al magnification: 25.0 x coaxial

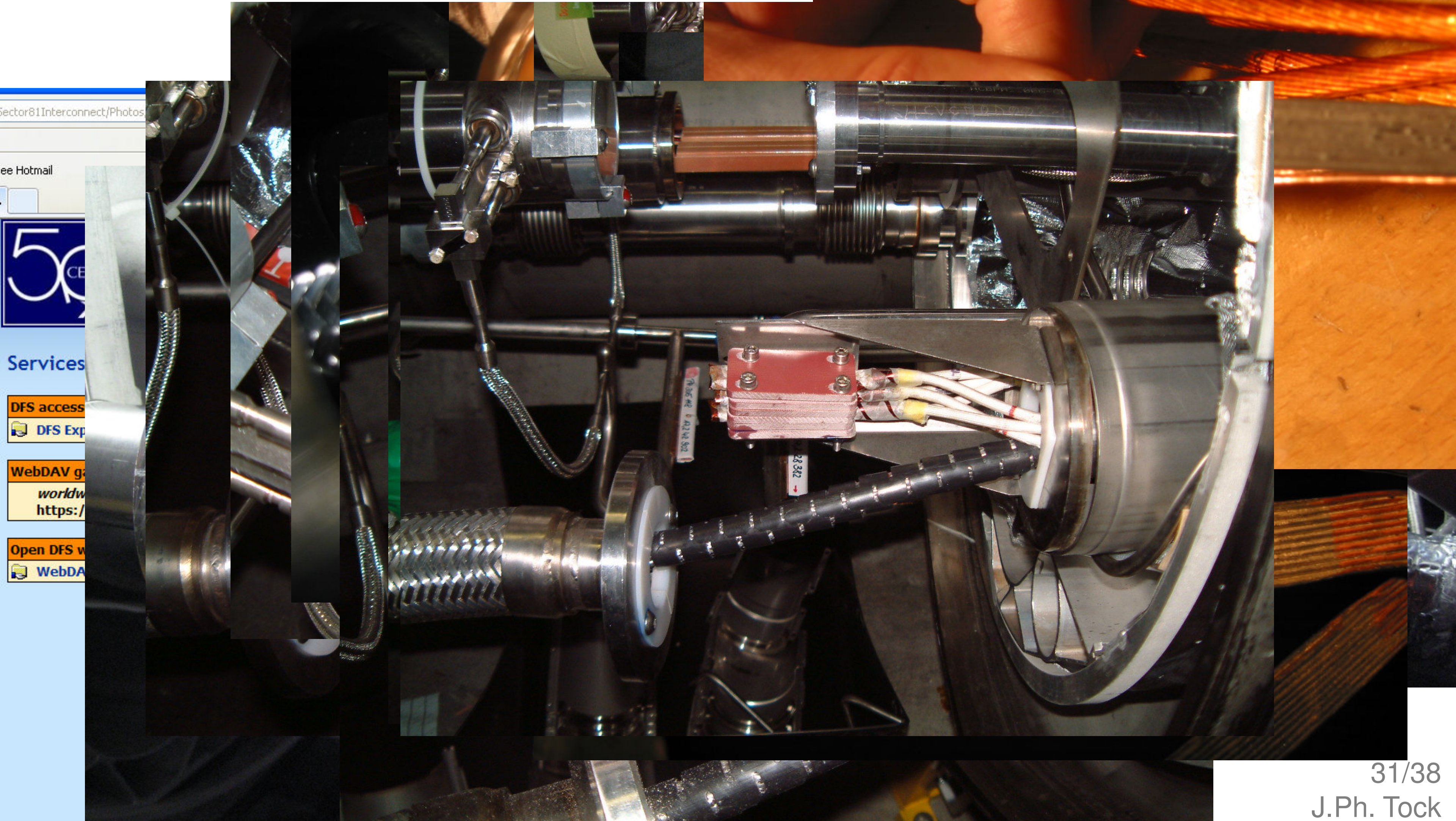


Sample Id: 6 kA hairpin connection
Description: Cross-section corner 4, at crimp, lack of wetting
+ presence of cracks in the brazing
Original magnification: 25.0 x coaxial

From A Poncet

Interconnectio

- No info on L8 (the first sector)
- A lot of pictures for the other points (Not 100 %)

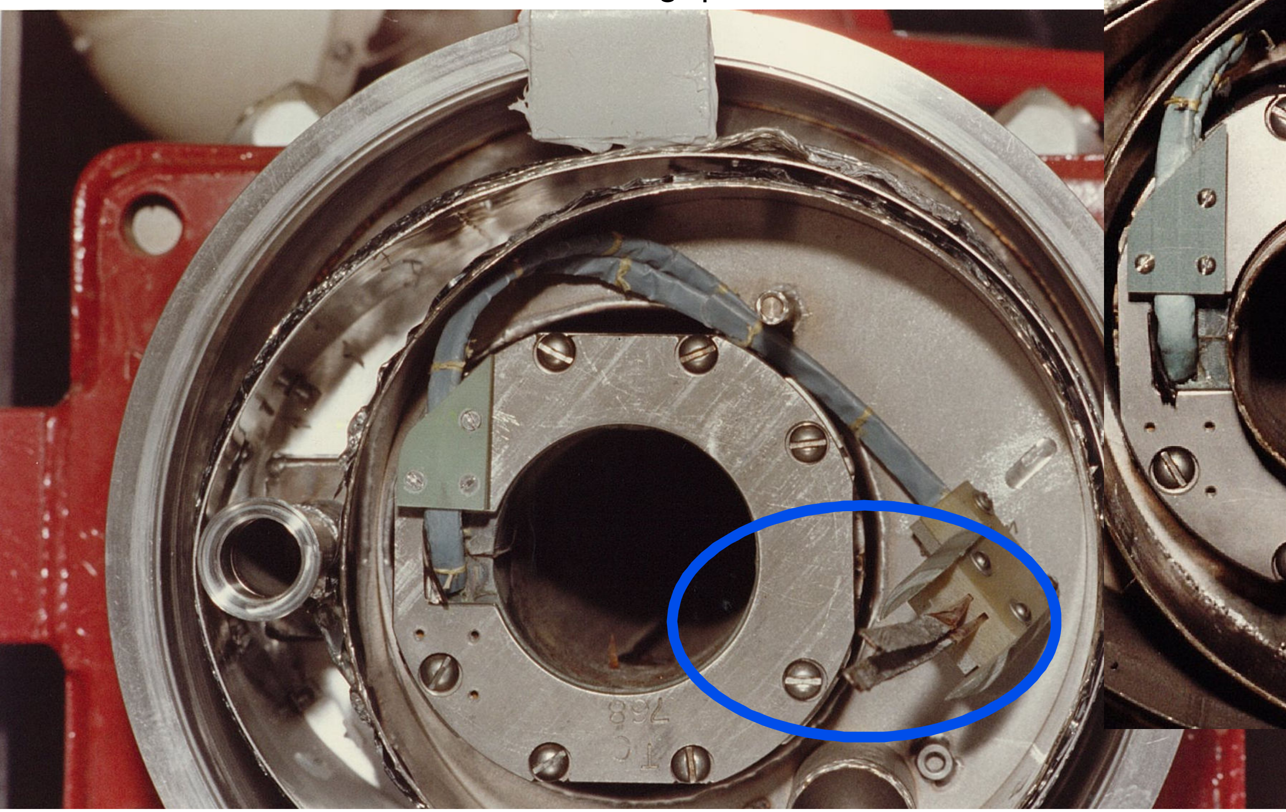


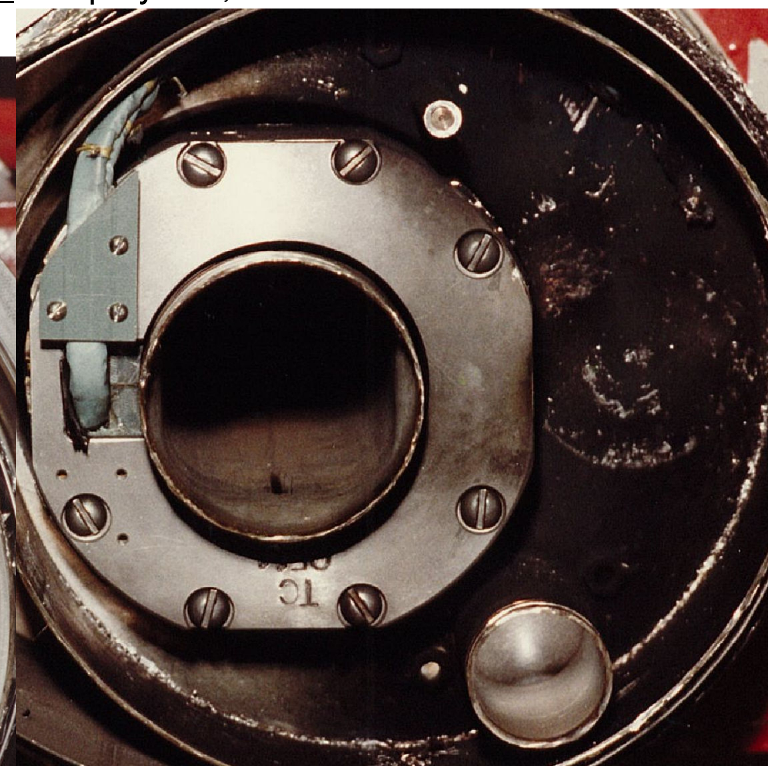
Hand praying splices : A reason to be prudent ?

Experience from Tevatron (P Limon @ splices Task force) 20/01/2010

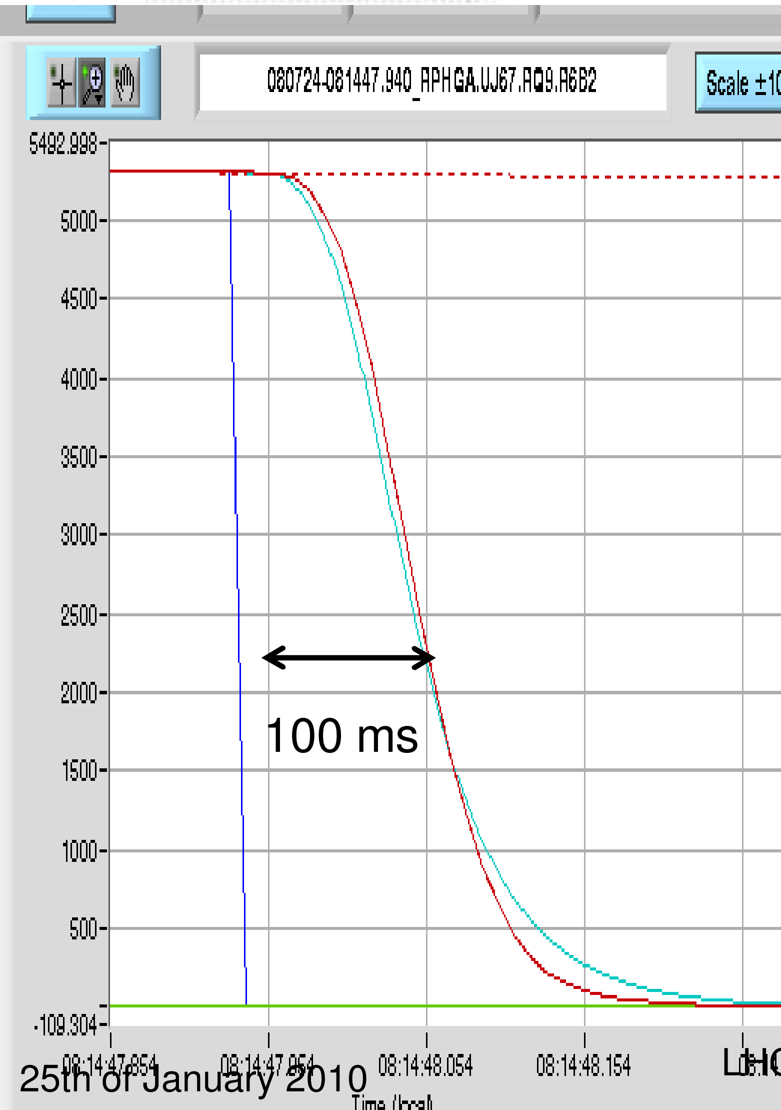
The TC magnet leads problem

- Leads on one end of TC magnets not properly tied together
- Flexing resulted in broken strands after about <u>100,000</u> ramp cycles, motion of a few cms
- Broken strands arced during quenches





Interconnection praying hand splices: MCI



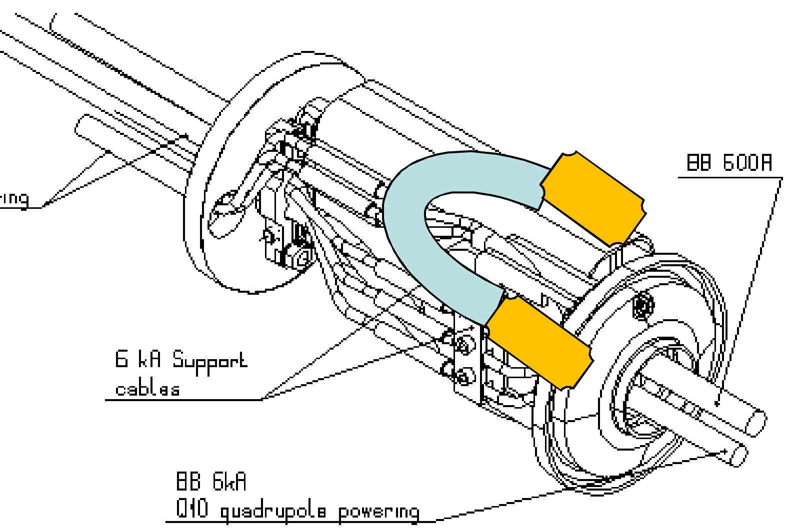
- Current decay is very fast (I/2 in < 100 msec)
- Detection time is < 10 msec

At ultimate current (5820 A),
Assuming an arc (20 V): dissipated energy < 12 kJ

Limit phase I/II is 100 kJ
If hole is done, He flow < < 1 kg/s
assuming 0.33 kg/s cm^2 (34 task force report)
OK without extra pressure relief devices

Hand praying splices : Future work (1/2)

+ Revalidate the design with an extra set of samples in representative configuration (FRESCA)
+ Perform extra mechanical studies (FEM)
+ Make a new design with only in-line splices, test it and qualify it
  Another cable accepting smaller radius of curvature,
  2 splices, … Considerable amount of work. Priority ?
+ Tomograph images in parallel with powering to check displacement
  TBC : Feasibility and safety



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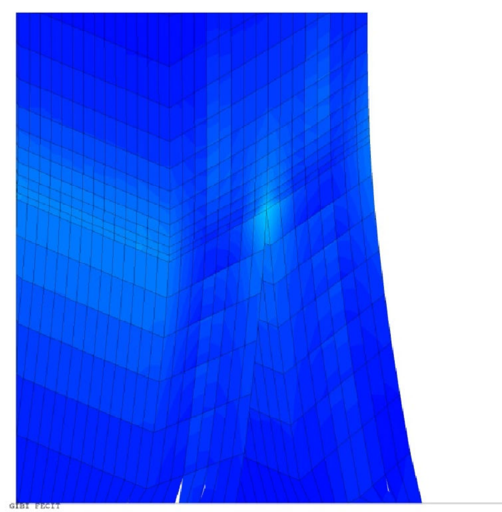
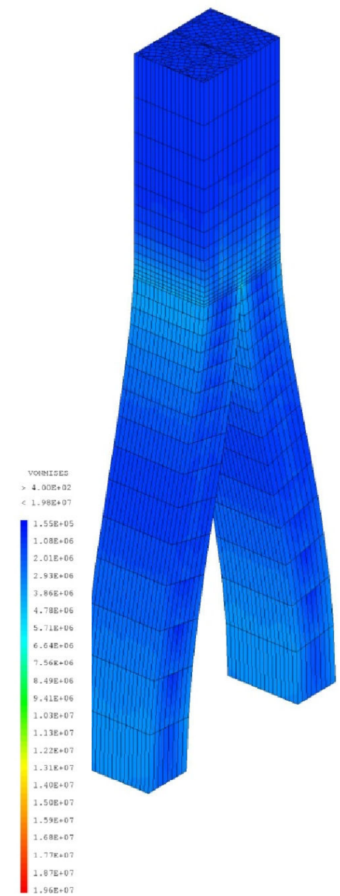




Hand praying splices : Future work (2/2)

Intervention in the tunnel : 3 scenarios

- Open all 23 IC (8 sectors), inspect, consolidate splices if necessary or implement new design

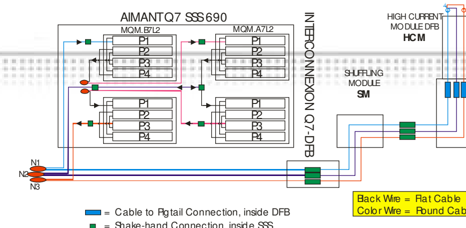
- Open only 8L (4 IC in sect 78), inspect and reinforce if necessary (present design)

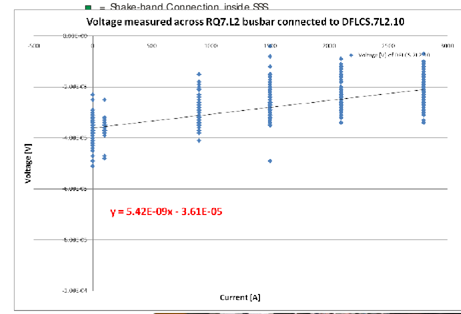
- No intervention

Proposal : Intermediate scenario (Worst case: 1st one and no documentation)
Massive intervention not required shortly as current levels are reduced (<5 TeV)
To update after next shutdown

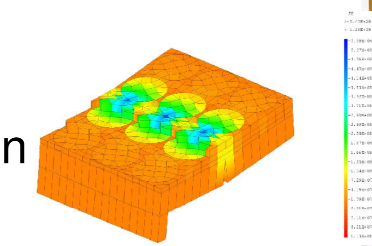
Technology
Department

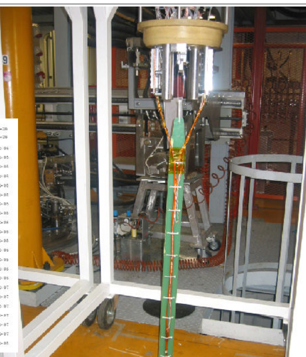
Further work on 6 kA splices





- Complete inventory and schemes of all 6 kA circuits/families
- Map all 6 kA splices at cold, prior to powering at E > 3.5 TeV
  Time window to be allocated
- Upgrade the QPS for IPQ/IPDs during next shutdown
- Praying hand splices :
  - New samples to definitively validate the present design
  - FEM mechanical verification of the present design
  - Develop an alternative design and qualify it
  - Refine MCI scenario
  - Tomograph investigation with current (if confirmed)
  - Inspect and possibly reinforce splices in 8 L
  - Then review the situation





Conclusions

- The present status of the 6 kA splices has been presented (progress report)
- No show-stopper has been identified so far
- Approach is proposed for the praying hand splices
- Work is still required to carefully scrutinized all 6kA splices
- Priority wrt other projects will need to be defined

Thank you for your attention