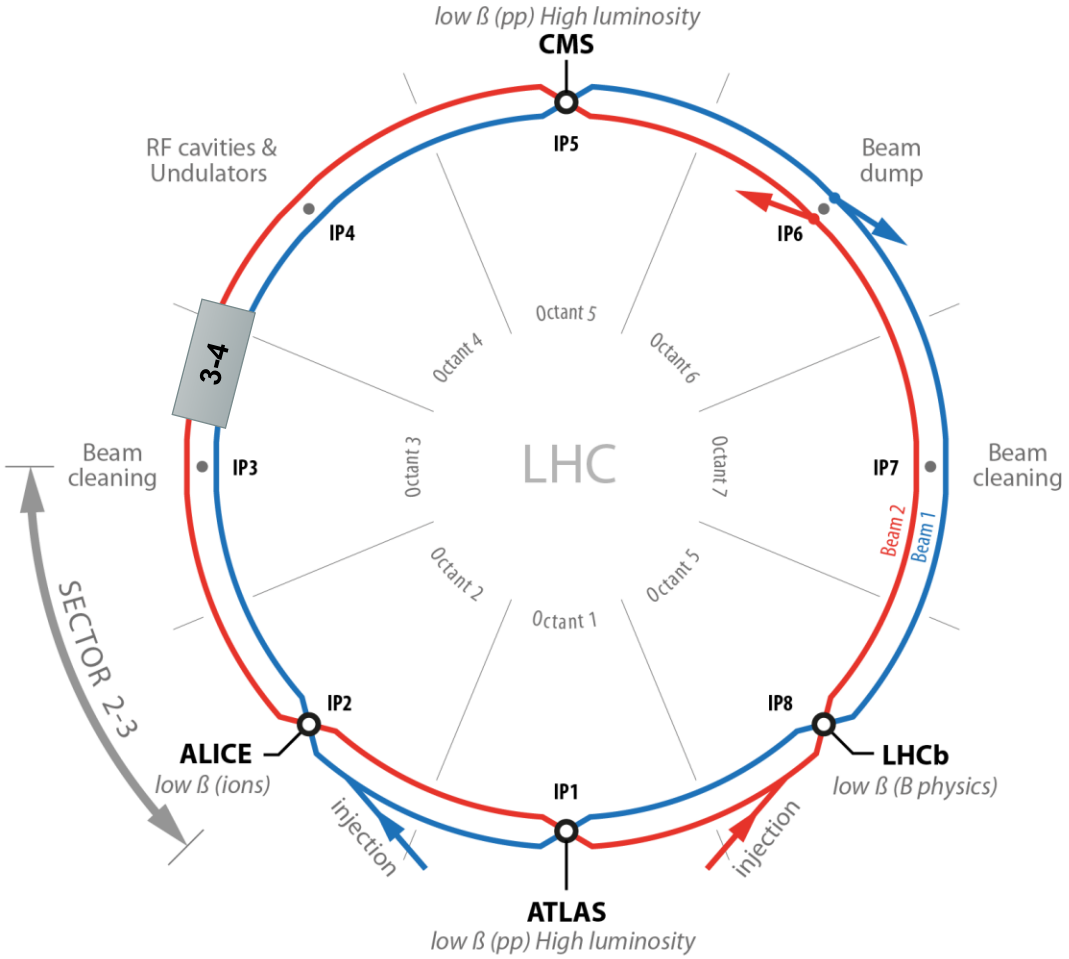
The LHC Main Magnet Electrical Interconnections:
the Subtle Size of Superconductivity

Lucio Rossi

CERN

Thanks to:
F. Bertinelli, P. Fessia, L. Lebrun, H. Prin, L. Tavian, JP Tock, D. Tommasini, A. Verweij, L. Williams

The two rings Large Hadron Collider



LHC SC Magnets in the tunnel

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LHC Tunnel
26.7 km
E_{beam}=7 TeV
I_{beam} = 1 A
E_{beam} = 350 MJ

1.9 K cryogenics
130 tonnes He
(100 t in LHC)

First massive use of **HTS CL**
1.5 MA $I_{power\ conv}$

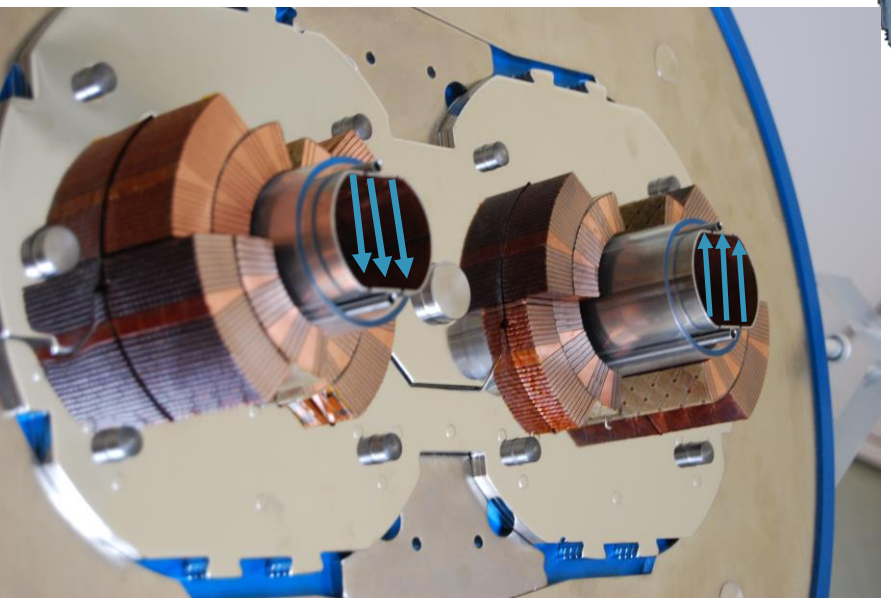
The cryostated part of LHC cover about 25 km of the ring

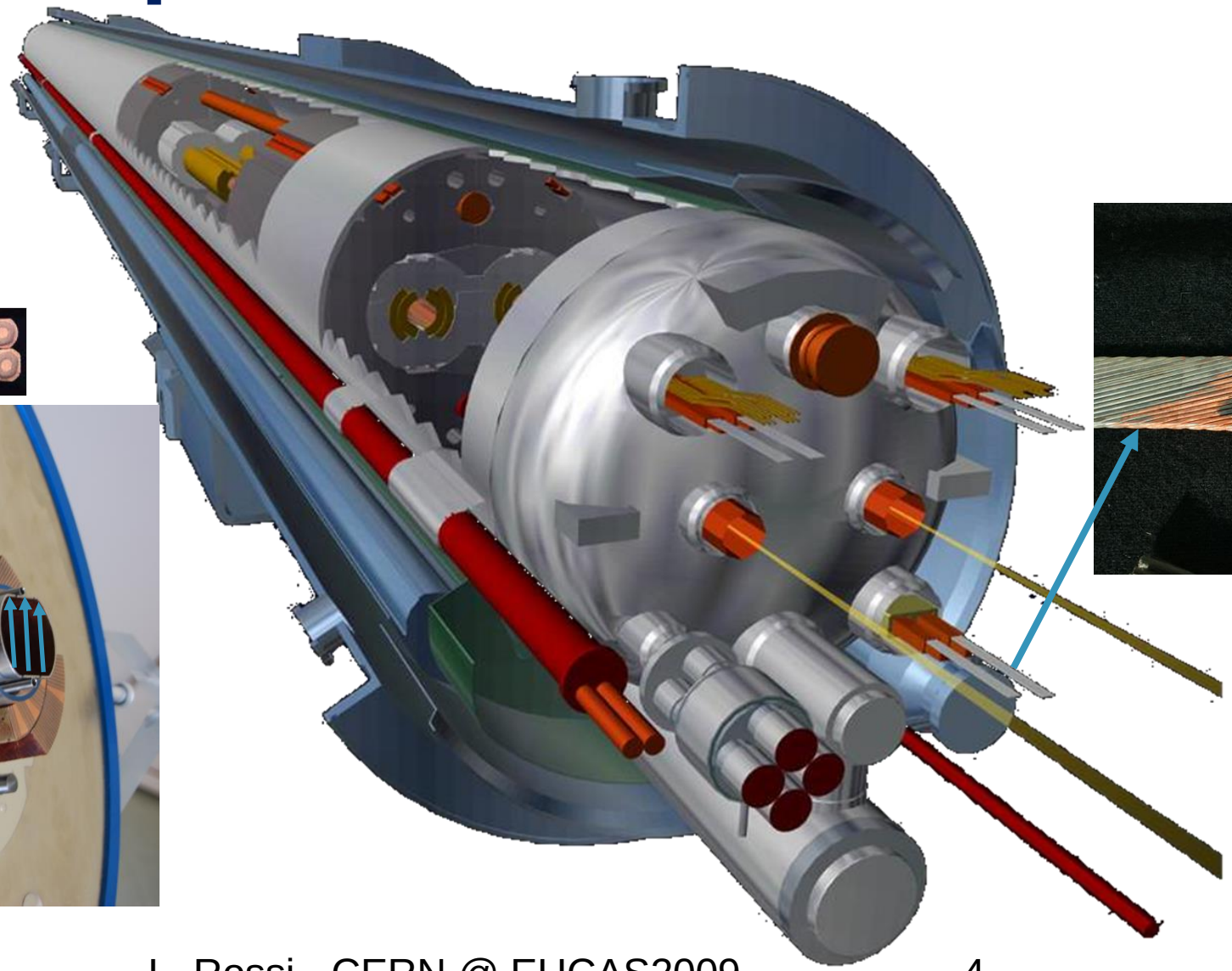
1232 Twin dipoles
2 x ∅56 mm
B_0 8.3 T – 15 m long
~ 30 ton cold mass
7 MJ energy each
154 series dipoles
~ **1100 MJ/circuit**

392 Main Quadrupoles
2 x ∅56 mm
B_{peak} 6.85
7 m long unit: SSS =
1 Quad + HO & corretors

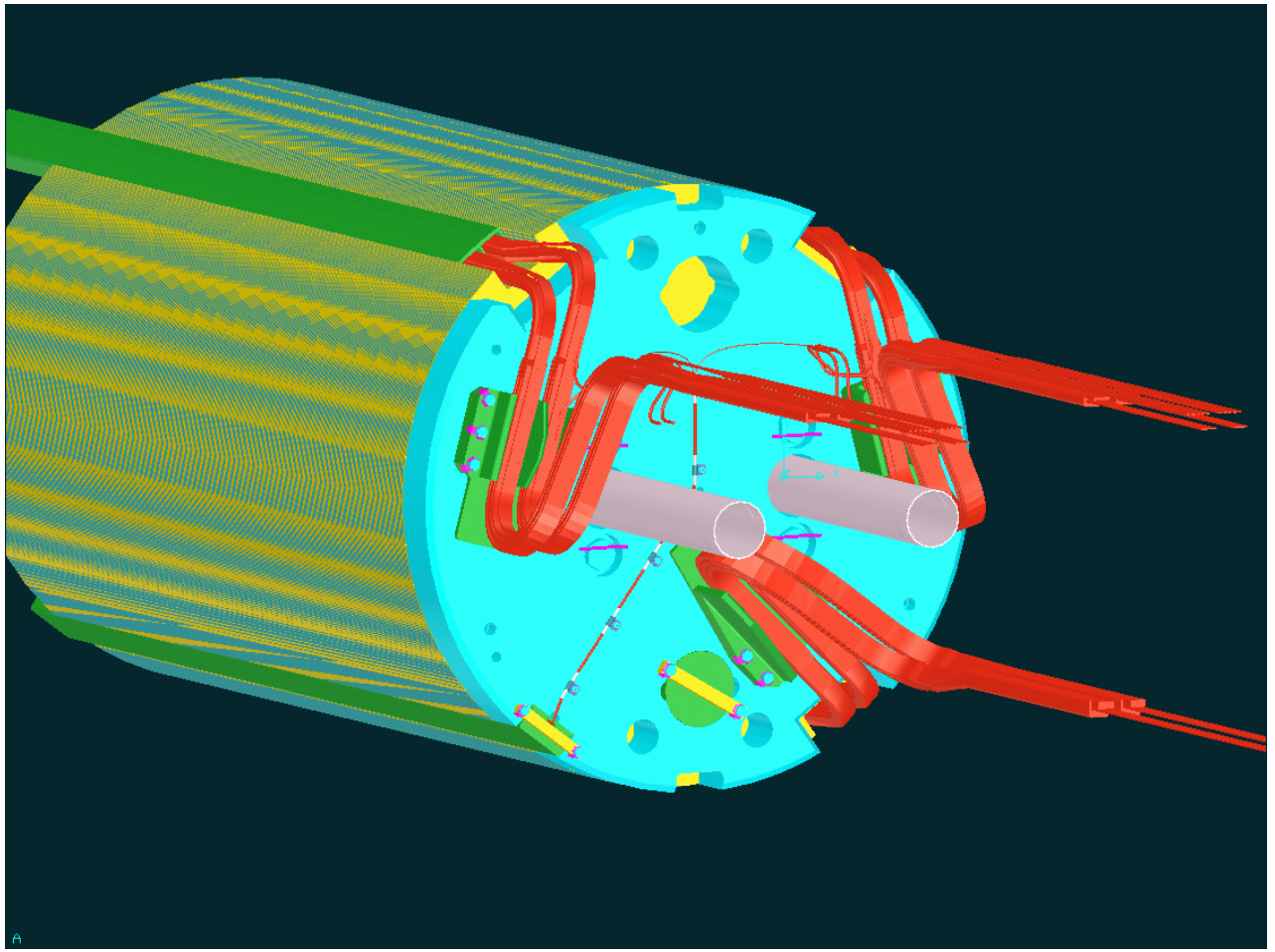
>100 special Quads
B ~ 6.5- 8 T
Also in long units with correctors

Cable, Dipole X-section and 3-D

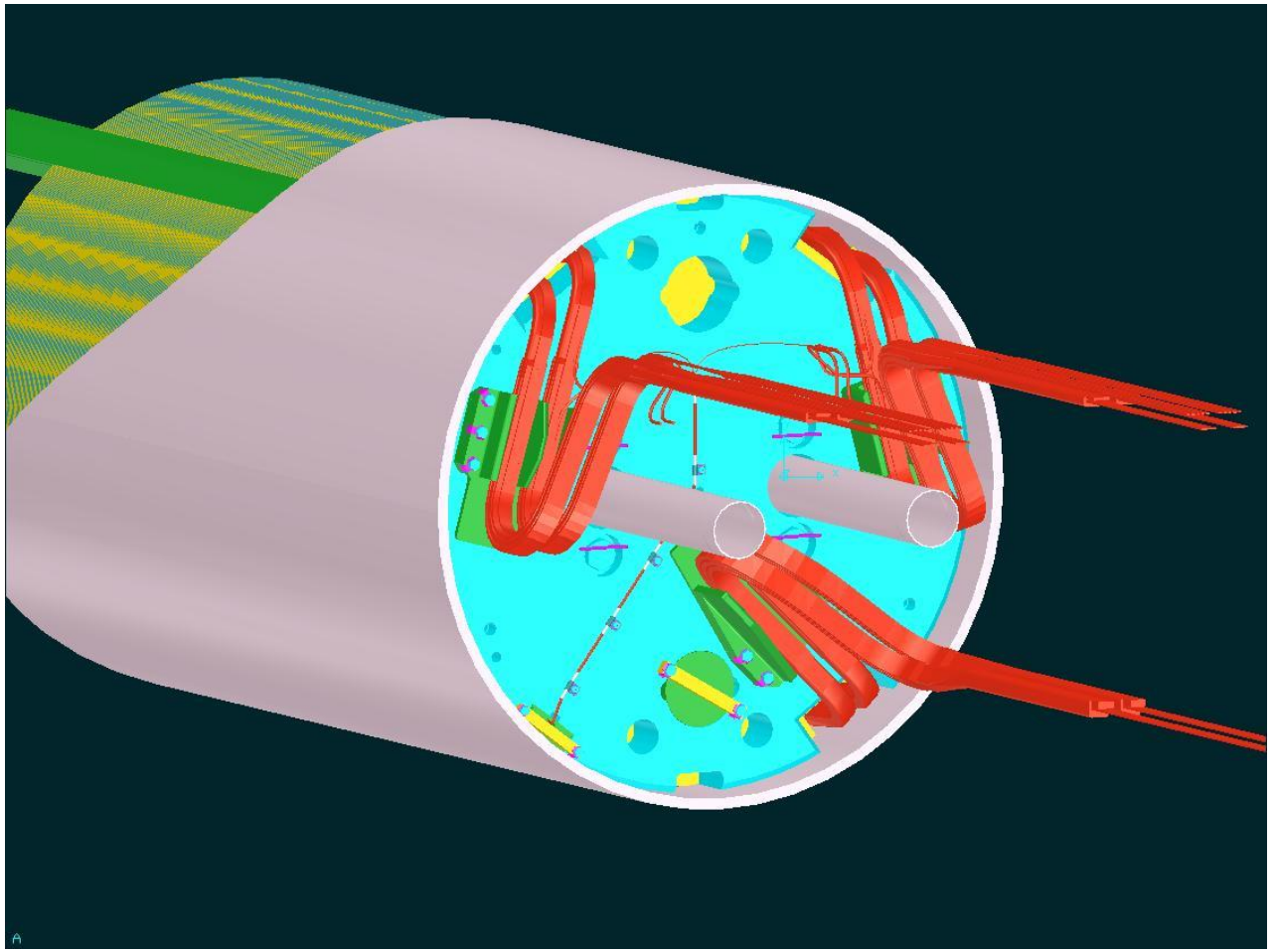




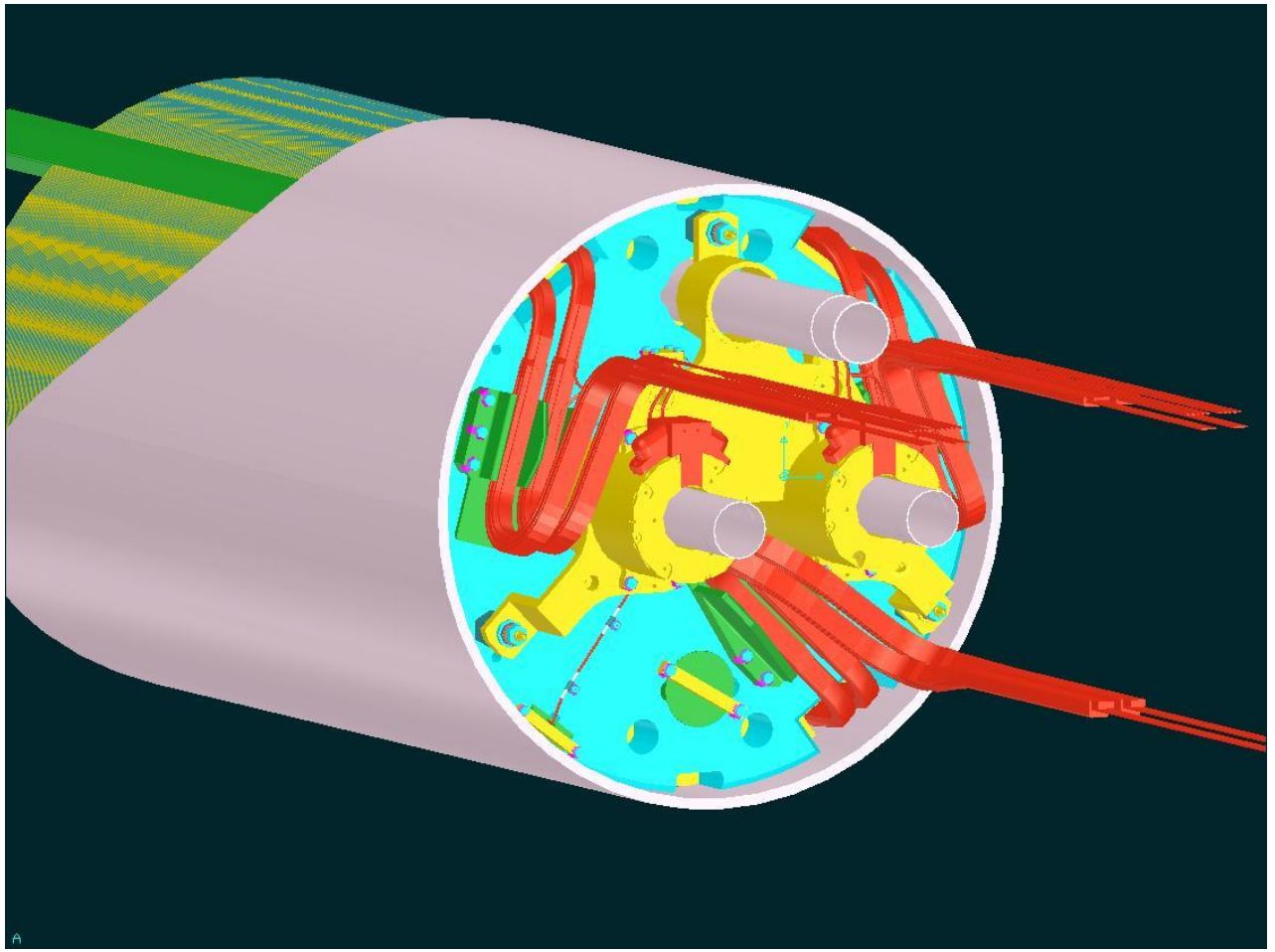
LHC Main Dipole



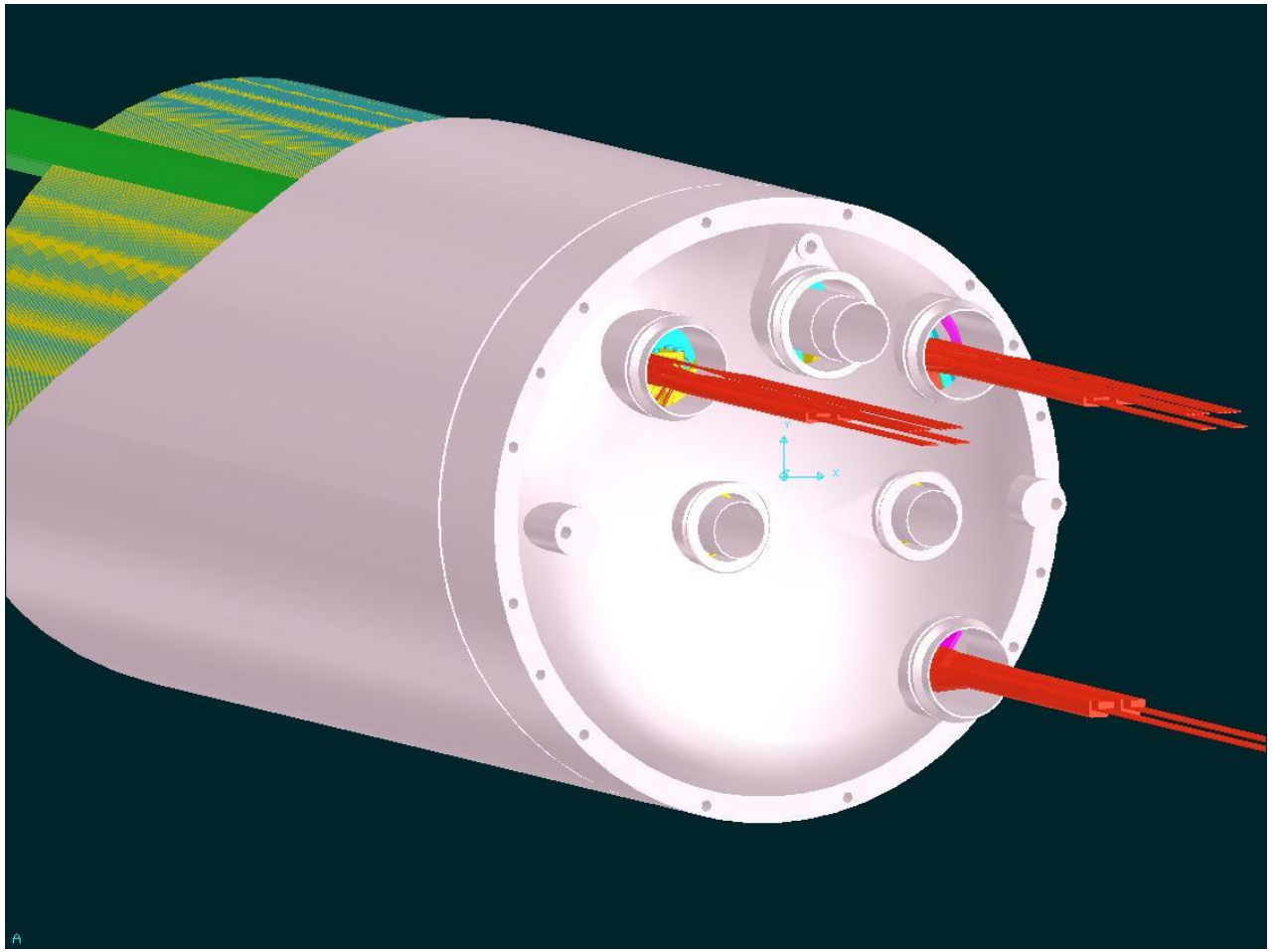
LHC Main Dipole



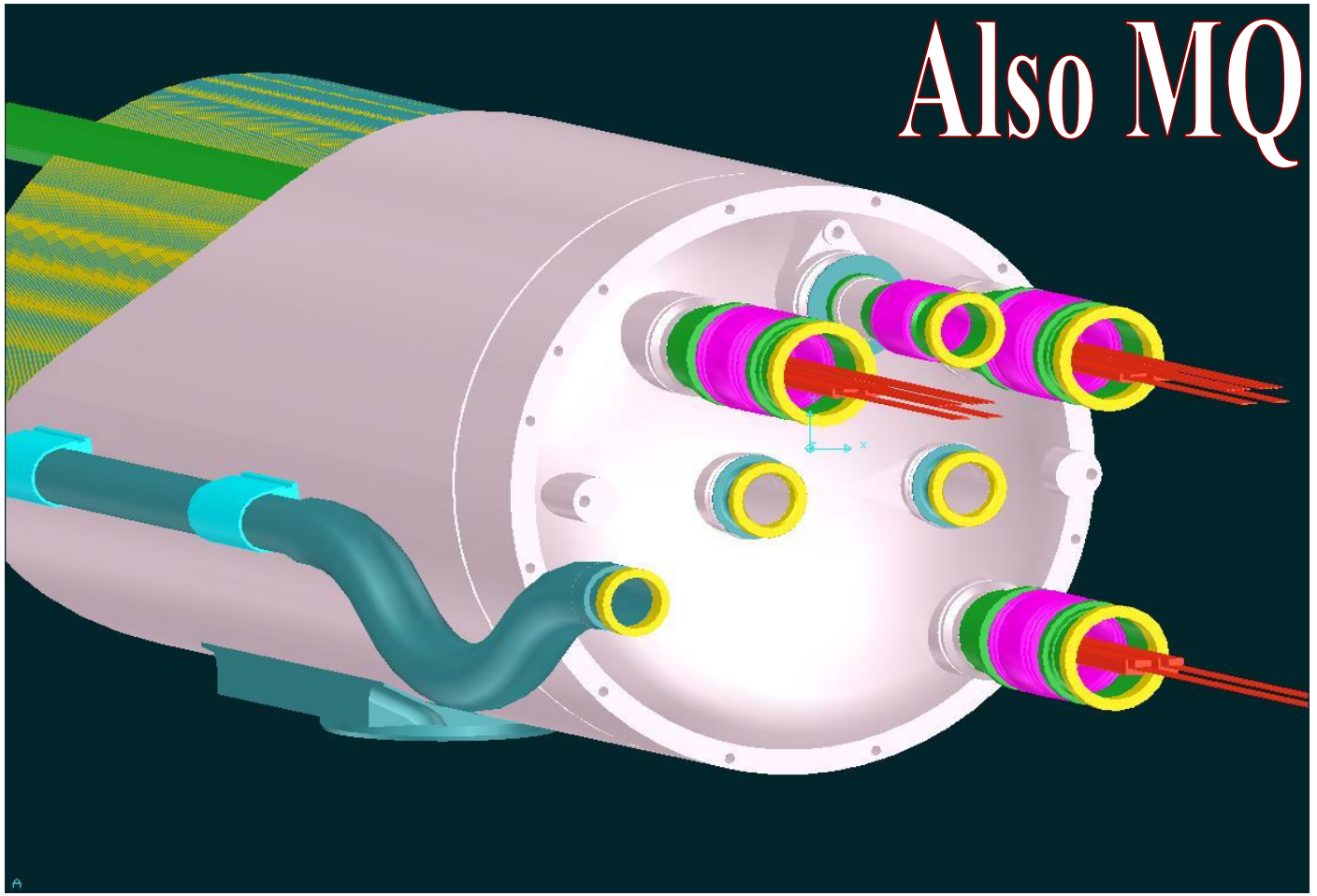
LHC Main Dipole



LHC Main Dipole



Dipole closed

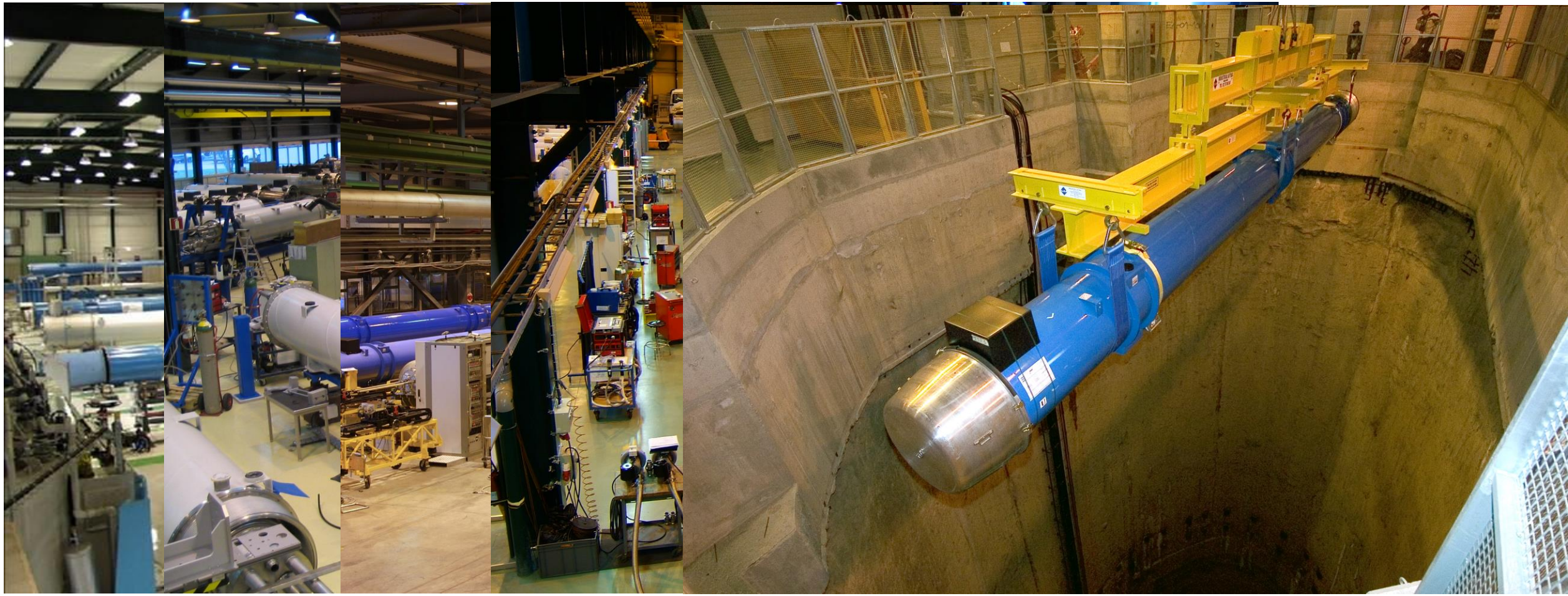


Construction and QA

- 3 companies made main quads
- 1 the main quads
- 4 companies the special quads
- The companies were charged to carry out
  - A full set of electrical tests in all conditions
  - To certify the conformity of operation to CERN design
- Each test reported on the electronic MTF (2 big paper folder/magnets)
- **Acceptance of a magnet upon extensive power test at CERN (release of the conformity certificate for payment).** Two year warranty

Cryostat, Magnet test, preparation, Installation by CERN (staff+temp.)

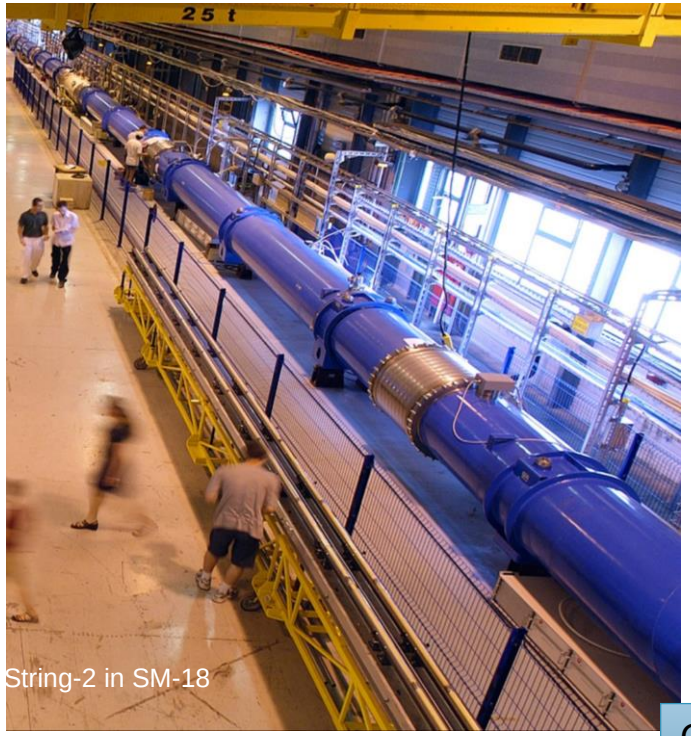
Foto SMI2 Paul



Experience and validation of system behavior: Magnet Strings

STRING-1 (1994-1998)

- One half LHC cell:
  - 3 MB (10 m) + 1 MQ
- Validation of:
  - Cryogenics (6 CD's)
  - Vacuum
  - Quench (172) and protection
  - Powering and energy extraction



String-2 in SM-18

STRING-2 (2000-2004)

- One full LHC cell
  - 6 MB (15 m) + 2 MQ + correctors
- Validation of:
  - Cryogenics,
  - Vacuum
  - Quench and protection
  - Powering
  - Accelerator relevant operation (e.g.tracking of MQ and MB)

Courtesy of Marta Bajko

LHC: approval end 1994 and end 1996 for commissioning 2005

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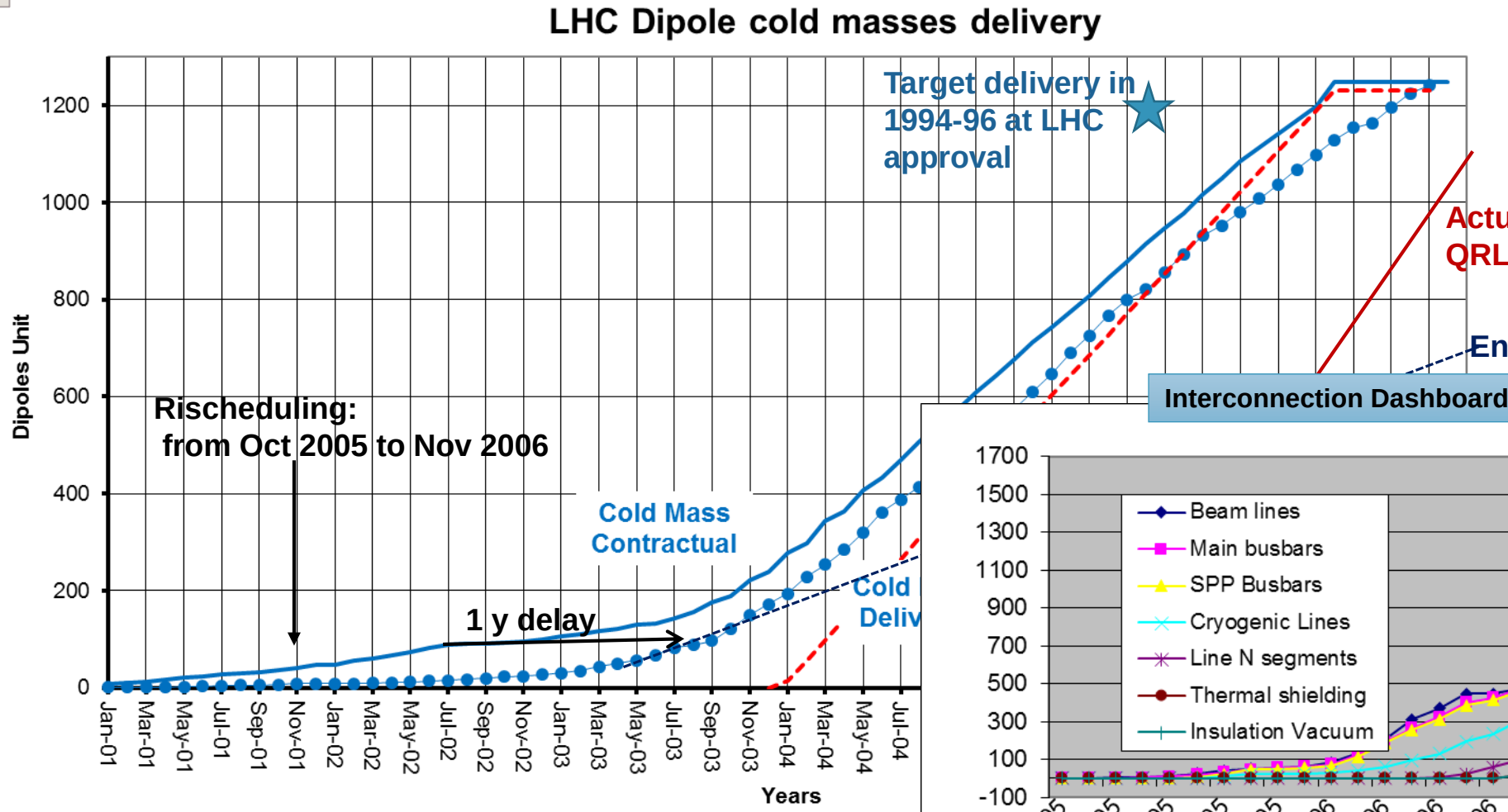
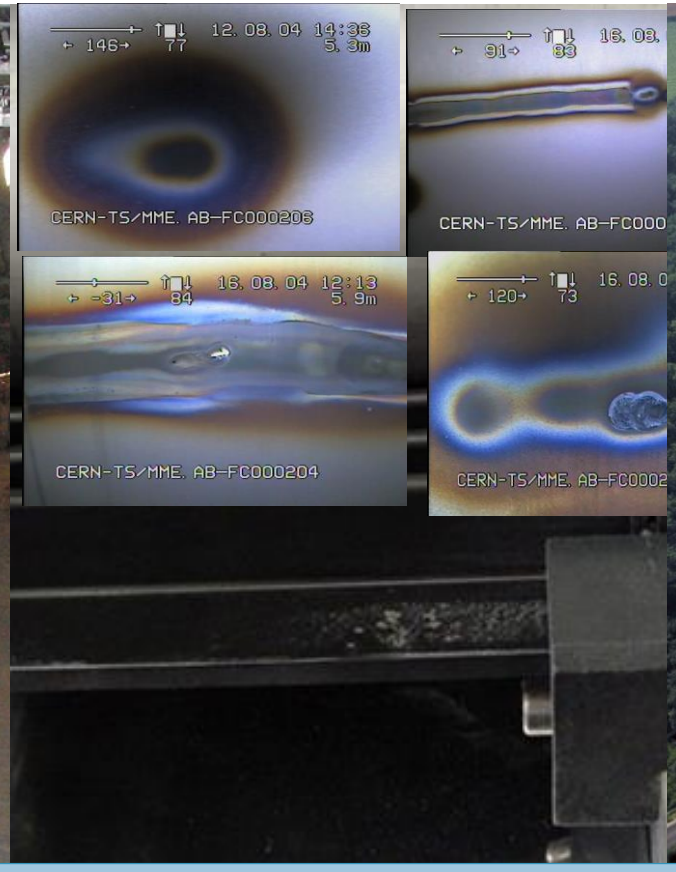
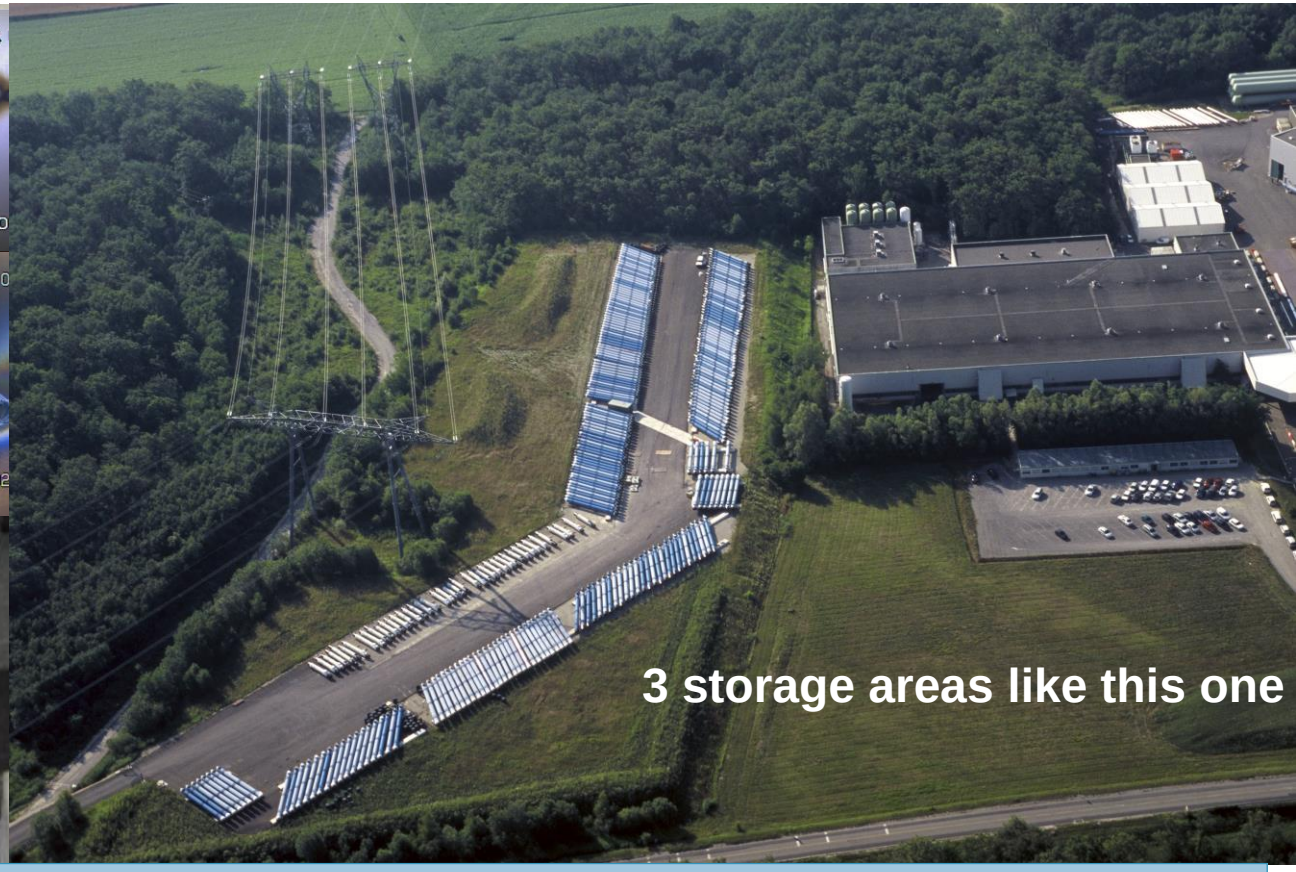


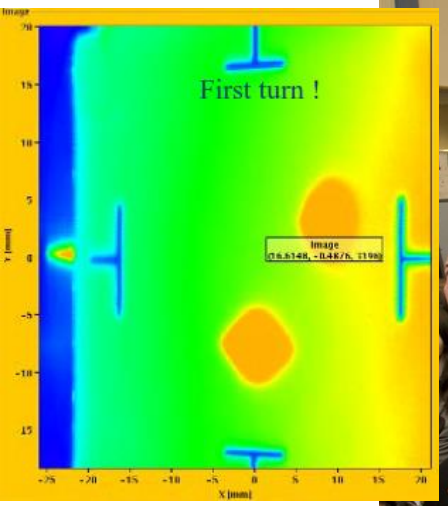
2004: problem of QRL (cryoline) (and : DFBs, IT Quads, Bus Bars…)





Large team of CERN to cope with QRL issues. Only 10 months delay at the end, but magnet installation started 18 month delayed. Good part of Interconnection team –and magnet and vacuum teams - were devoted to QRL issues

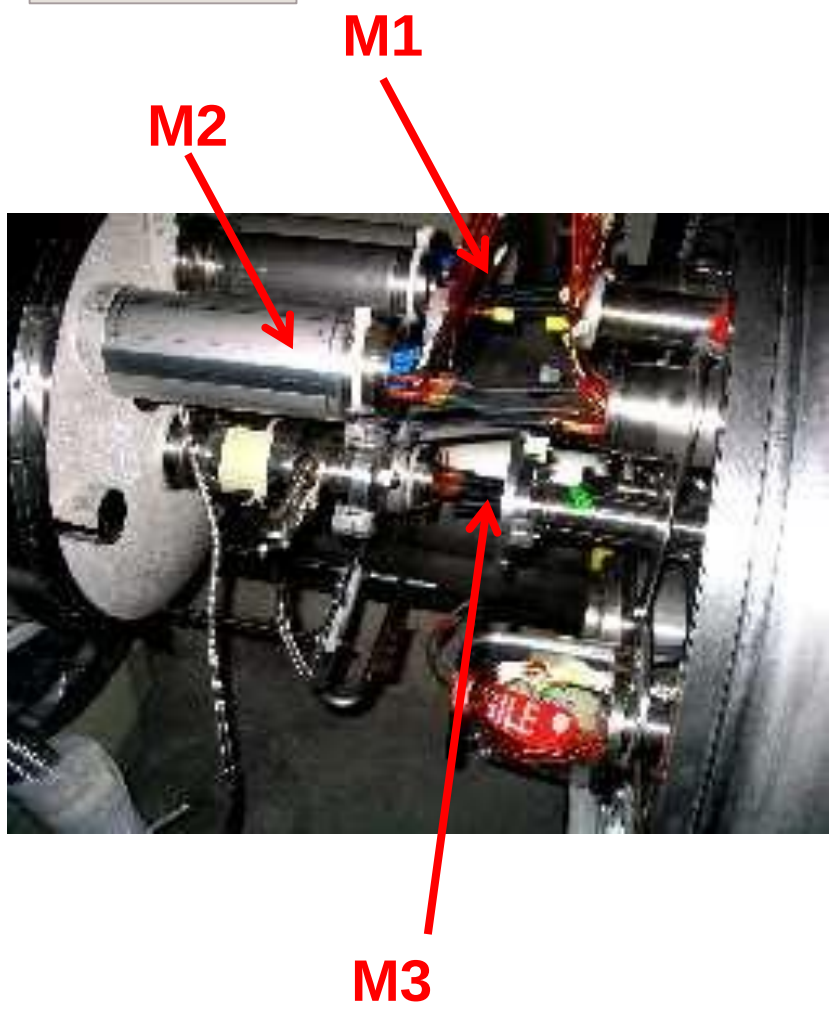
LHC start up fixed on 8 Sept 2008 (Inauguration 21 Oct.2008)



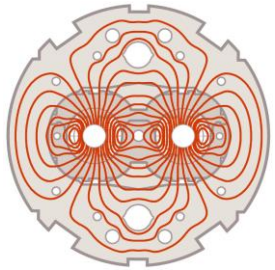
LHC first beam:
8 Sept 20008
Great success!!

However 2 out 8 sectors had been test only at injection energy (0.54 T). Hardware commissioning actually resumed a few day later.

The LHC interconnections



- **LHC has about 10,000 13 kA SC joints in the arc interconnects:** about 3.300 on the MB circuits and 6700 on MQ circuits.
  - 10,000 main junctions more are inside the main magnets
- These joints have been performed using soldering machine based on induction technology. **The soldering material is the Sn96Ag4.**
  Not mechanically clamped
- The interconnection activities started in May 2005 – 18 months late – and ended in November 2007. The last joint was soldered in July 2007.
- Max production rate of 250 joints/weeks. Only 0.1% re-worked.



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The LHC interconnection - cont.

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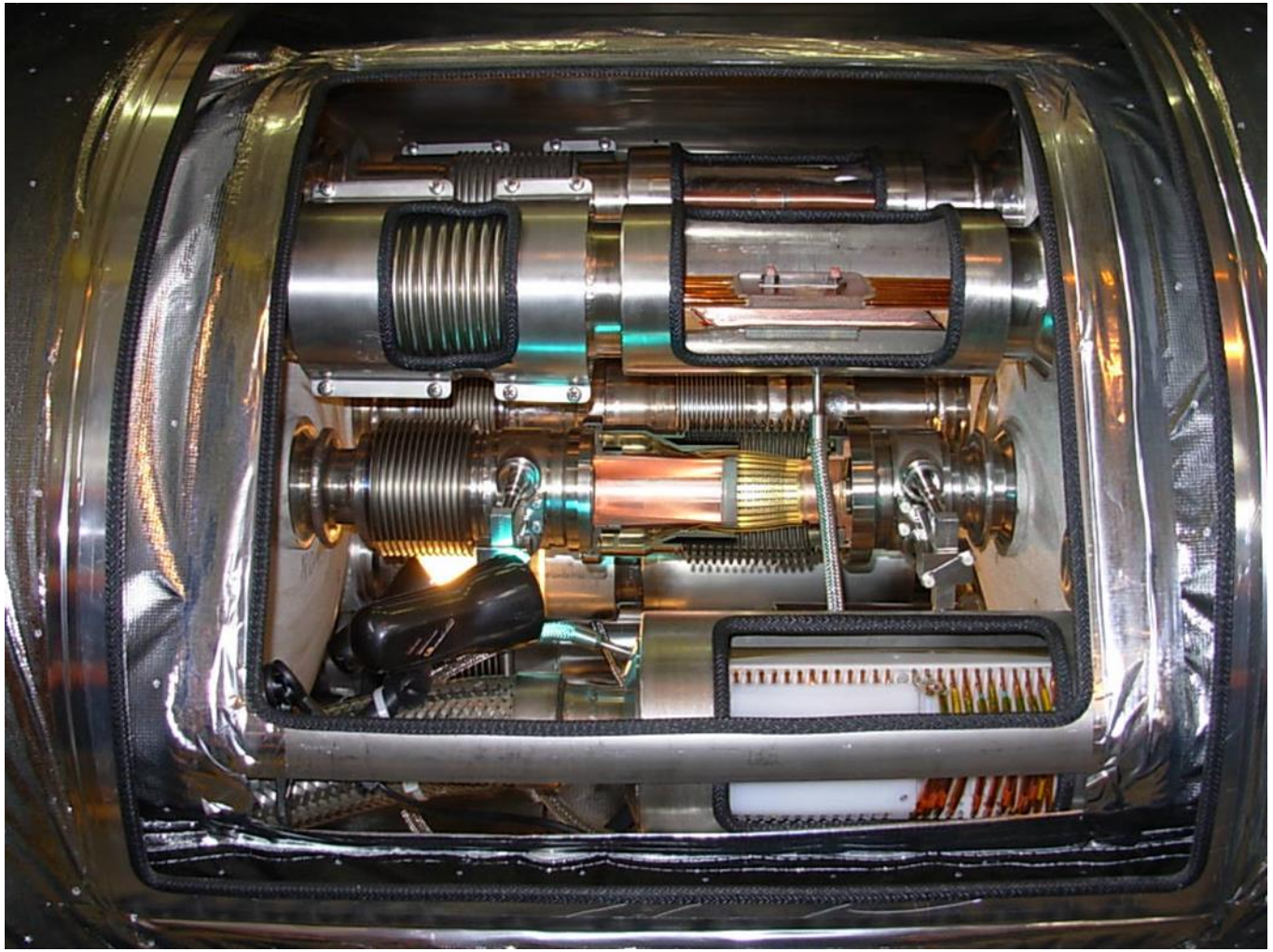
- 55,000 junction of 600 A done via u.s. welds
- A few hundreds 6 kA splices via soft soldering
- 40,000 orbital TIG welds for junctions
  - most for HEII vessel, other for beam UHV.
  - Only 0.4% leak rate; all repaired in a reasonable time (vacuum section: 100m)
- Observation about 3-4 sector (Oct06-Jul07):
  - the interconnection activity in this sector experienced among the worst working conditions in the whole project, with low temperature and high humidity in the tunnel
  - progress was particularly slow in January 2007 with low productivity of the industrial contractor's staff, as a consequence of uncertainties in the contracting policy of the company.
  - These effects could have detrimentally impacted on the overall quality of the work, but no direct evidence has been found of this.
- **e.m. interference was preventing data acquisition on induction soldering. All was left to machine interlocks.**



The 2008 LHC Cable Junction Box

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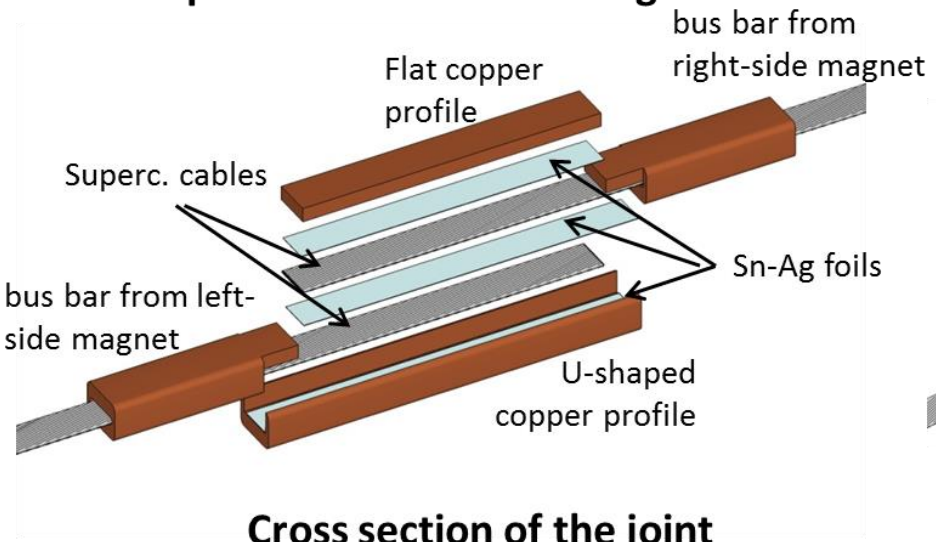
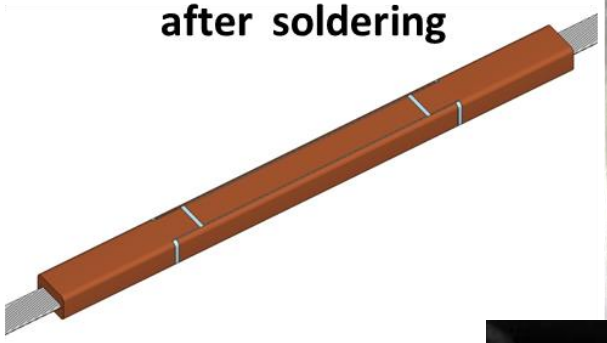
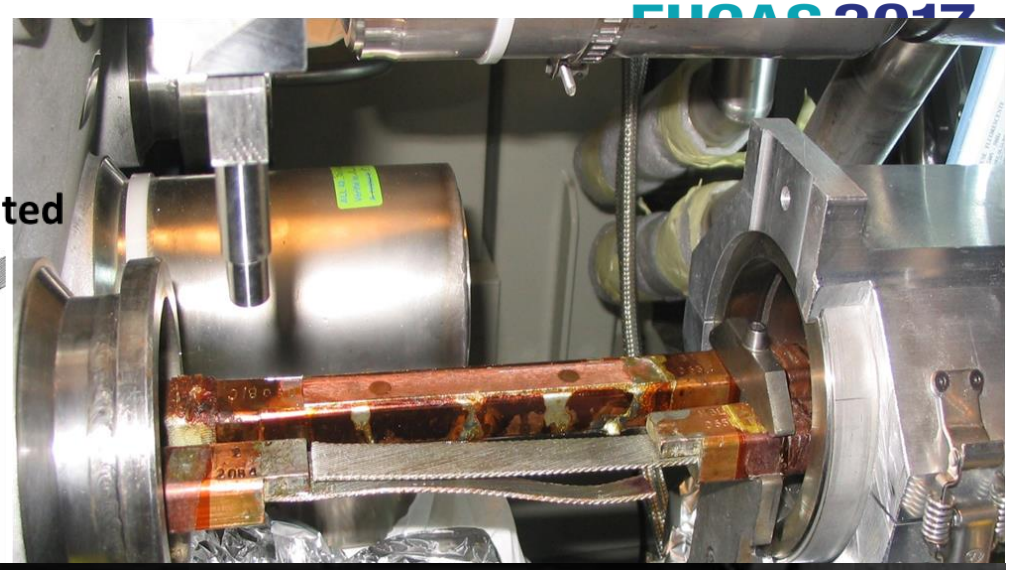
Joint components before soldering

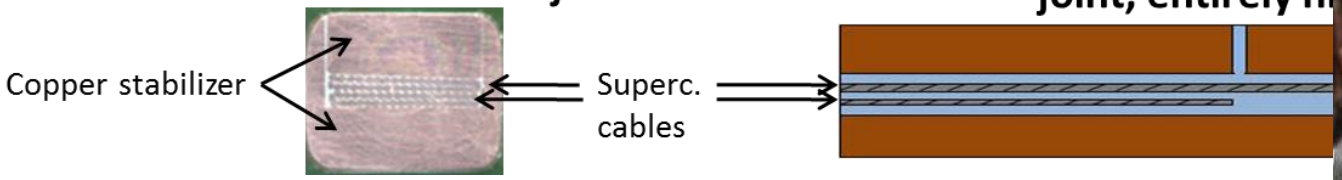


Bus bar well reconstituted after soldering

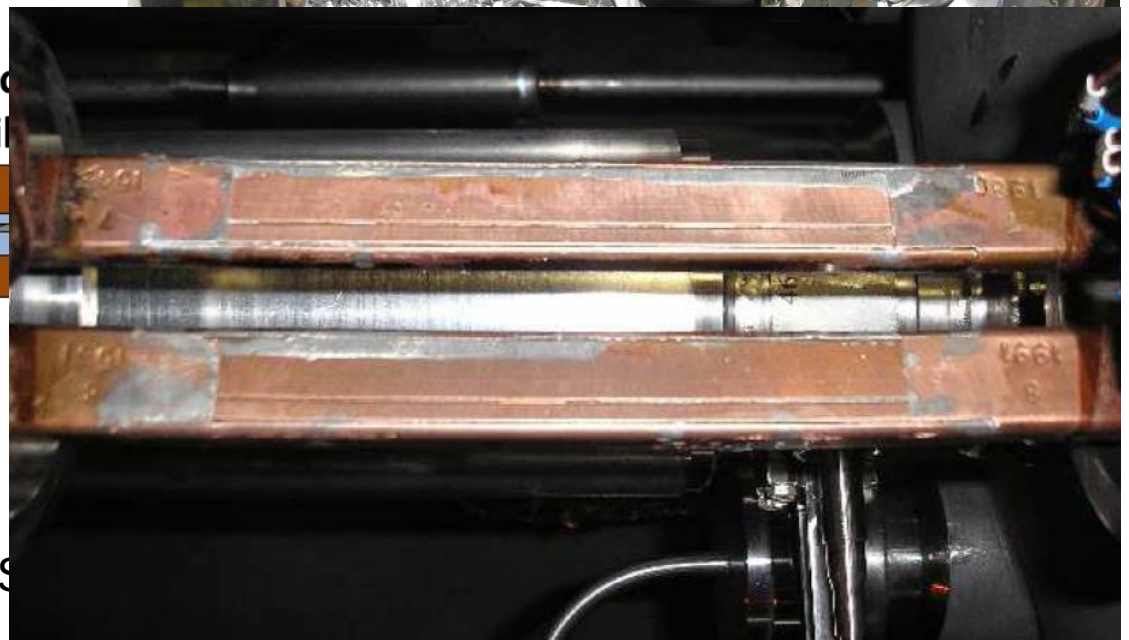




Cross section of the joint

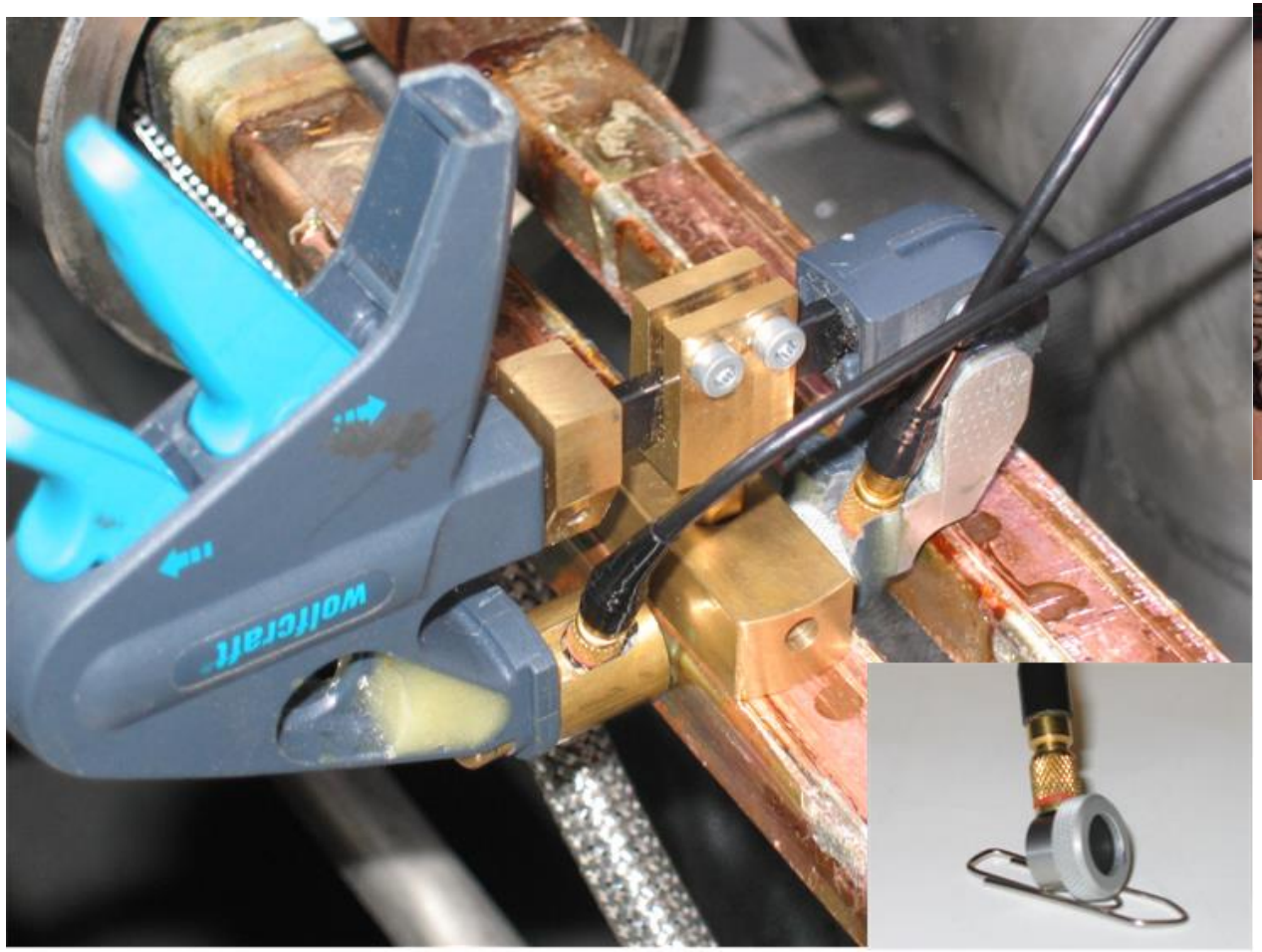


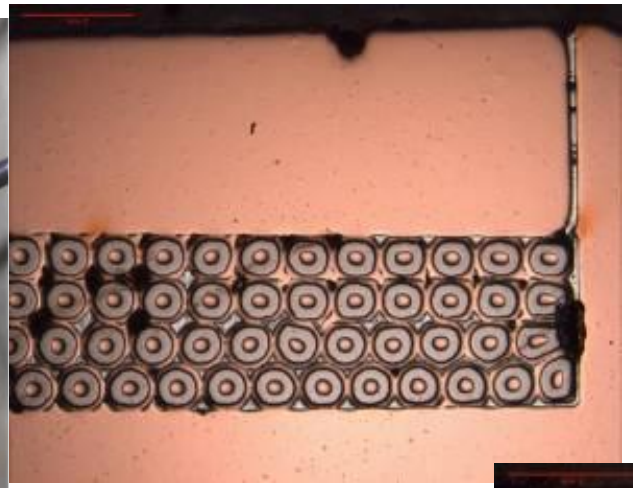
Longitudinal sec
joint, entirely fil



0.6 nΩ max specified
0.2-0.4 nΩ regularly achieved

LHC Main Dipole and Main Quads Bus-bar joint by induction technique

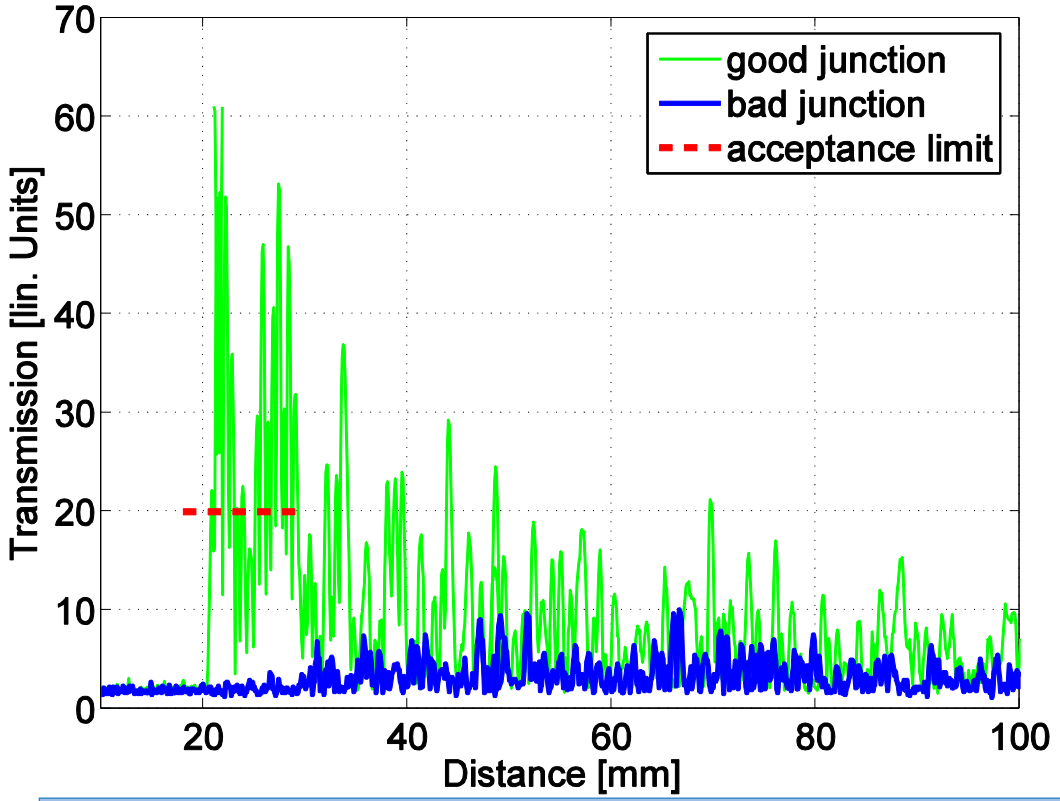


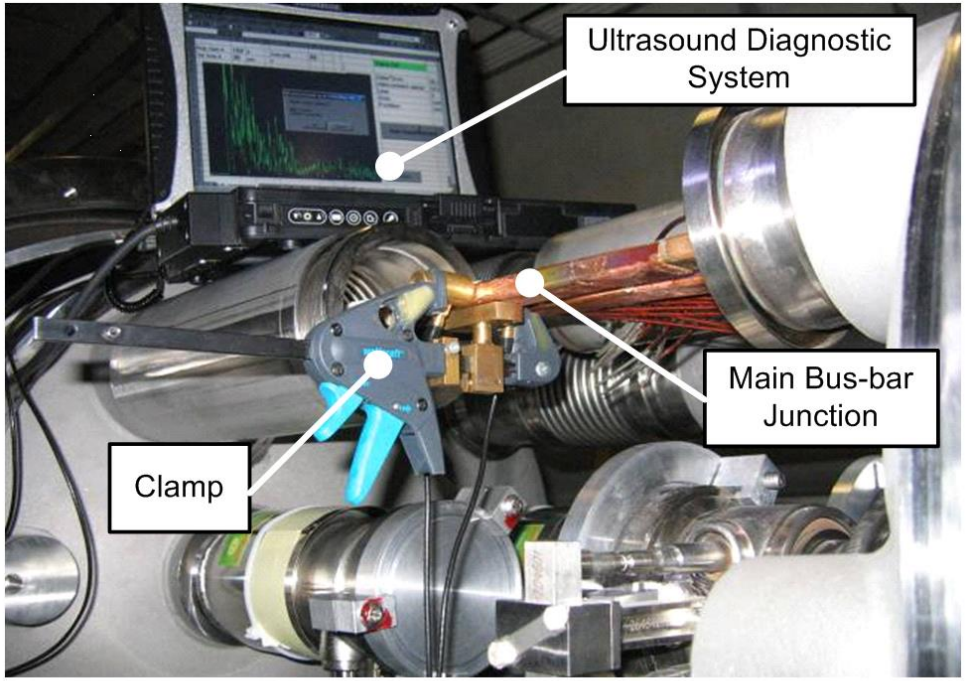


Good Junction

Bad Junction still with good electrical and mechanical properties: 3 tonnes

An on-line QA: U.S. introduced very late- results not always clear

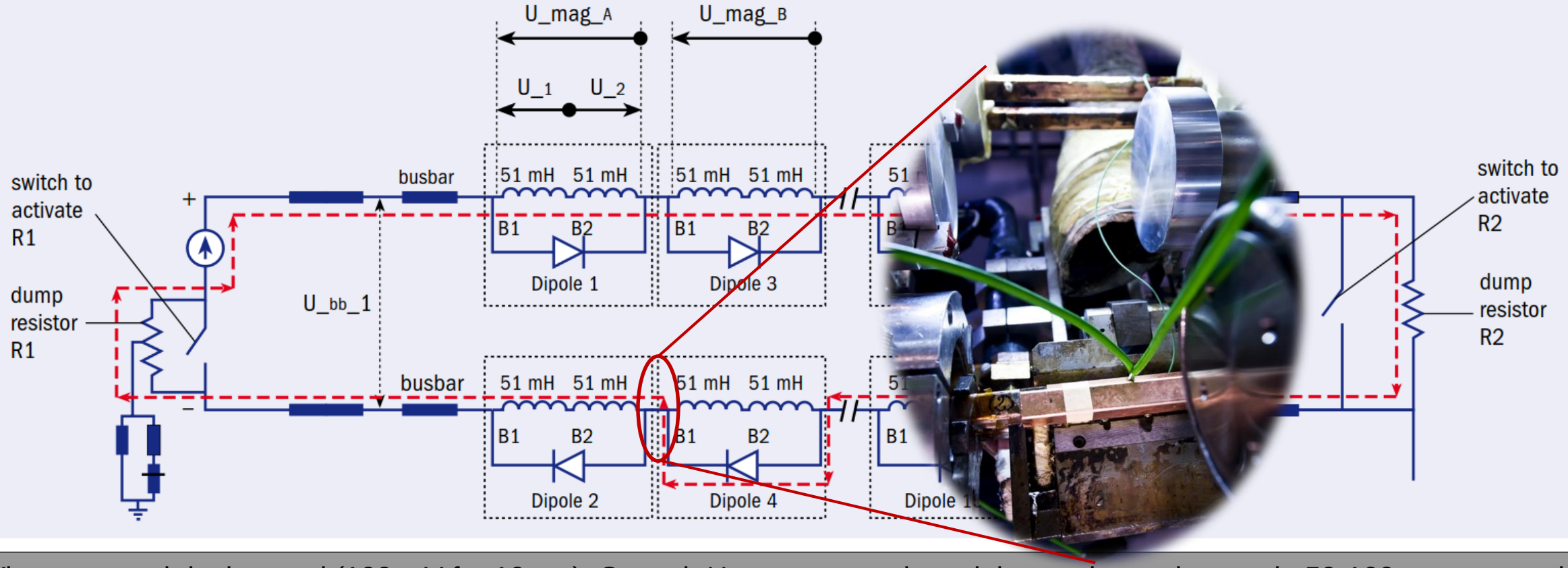




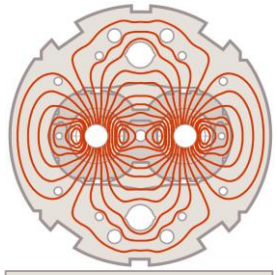
Courtesy: Lloyd Williams

Used extensively only in last sector; one defect intercepted.

Electrical Circuit and QP scheme of 8 x 154 dipoles in series (sector)



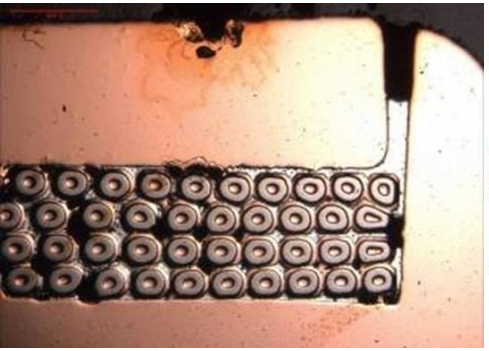
When a quench is detected (100 mV for 10 ms), Quench Heaters are activated, increasing resistance in 50-100 ms to pass the diode threshold voltage of 7 V. After 300 ms current is virtually zero in the magnet. But it flows in the bus bar, where current decrease with 105 s time constant (0.9 kV is the voltage limit). Bus Bar V_{thr} = 1 V.

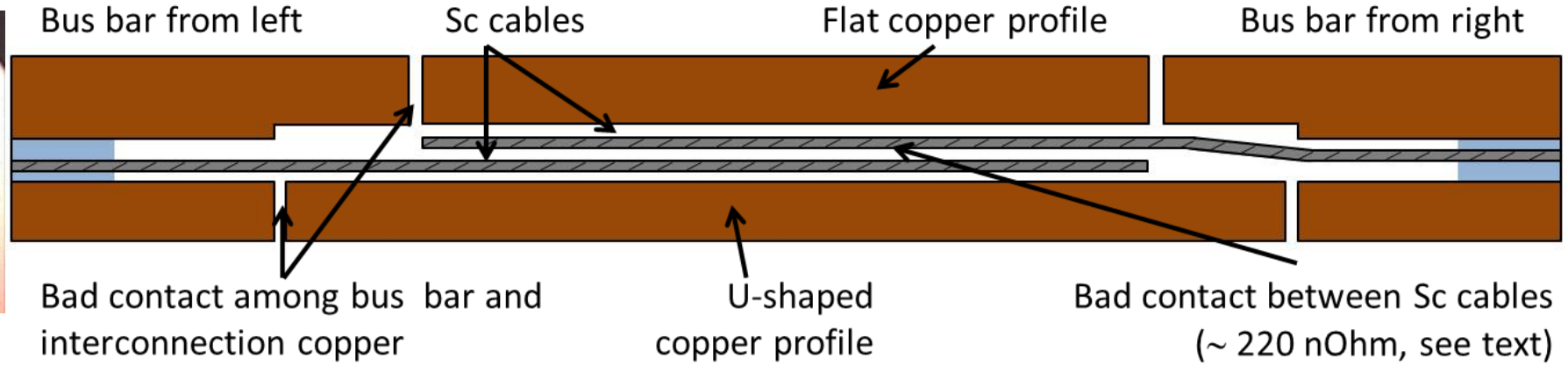


The 2008 incident: sequence of events of Friday 19th September

- Last ramp to 6.5 T in the dipoles of the last sector before giving the machine to operators. **The limit of 6.5 T (vs nominal 8.3 T) was due to "discovery" of symmetric quench during HWC**.
- A fast discharge on the dumping resistors was activated by a sudden resistance rise in the magnet line at about **8700 A (6.2 T).**
- Some 100 ms later a quench was detected on the bus bar (including interconnection joints).
- Almost immediately QDS detected many magnet quenches
- **The discharge was abnormally fast and the circuit sectioned in various two branches (shorts).**
- Very soon we lost control of the sectors and then the general power was lost in the sector.
- For one day we could do nothing. Oxygen deficiency signals triggered.
- Saturday afternoon firemen could go down with oxygen bottles and diving suite: oxygen level was coming back to almost normal everywhere.
- Sunday firemen went back with two our engineers (F. Bertinelli and V. Parma). Long line of magnet displaced, almost falling down or aside, opening of the cryostat, tunnel **frost on hundred meters**

A resistive joint of about 220 nΩ with no contacts with the stabilizer



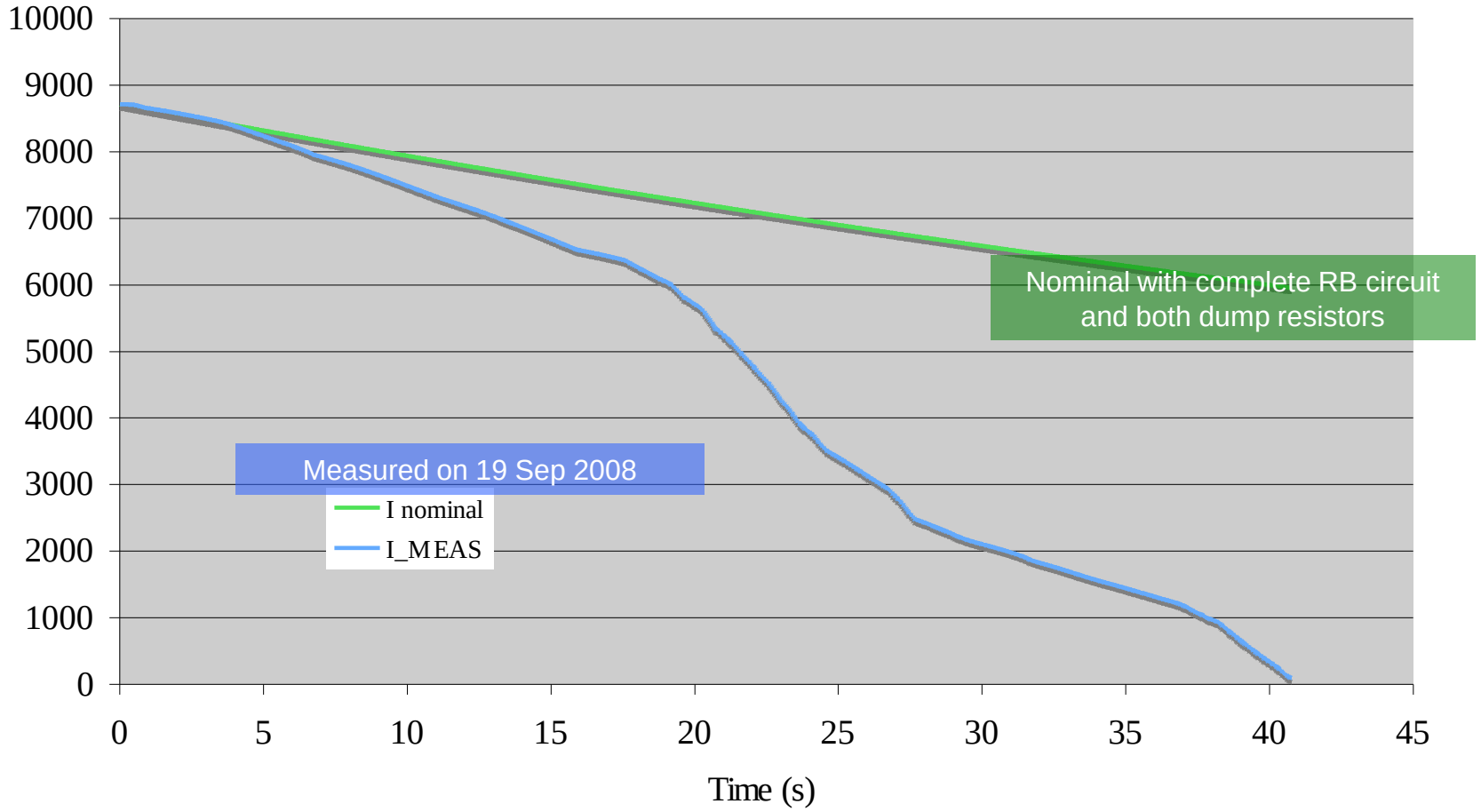


The value of 200 nΩ was find from electrical model (set up later) and independently confirmed by HeII calorimetry (see later)

Extensive measurements on various type of defects later on confirmed that a joint badly done is less than 10 nΩ (even without solder). **The faulty joint was not heated**. The joint melted away generating a low voltage high power arc fed by the magenta c energy stored in the magnets.

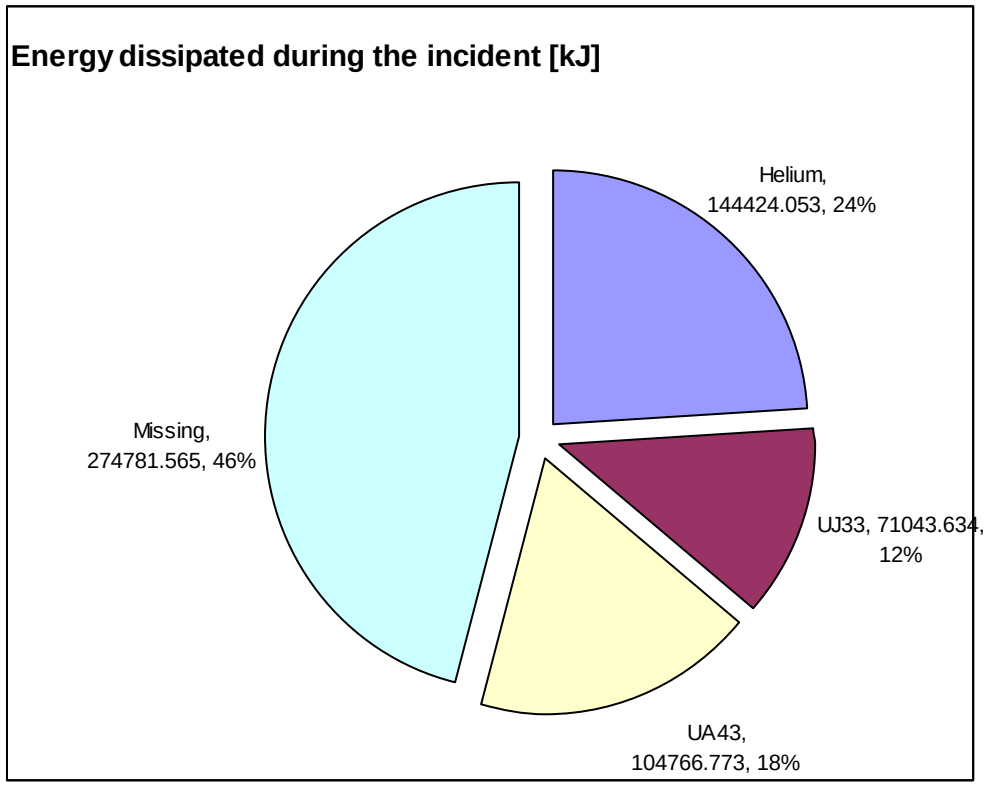
A worst joint, ~mΩ would have been easily detect at 1 kA.
The lack of continuity in the stabilizer of course **left the bad joint unprotected**: during IC works was noticed gaps between bus bar and flat copper profile 1-5 mm, filed when >1-2 mm; **however nobody thought of possible voids inside bus bar.**

Current decay in dipole circuit from 8.7 kA



Courtesy of M. Bajko, N. Catalan, G. de Rijk, G. Kirby, S. Le Naour

Energy balance in dipole circuit

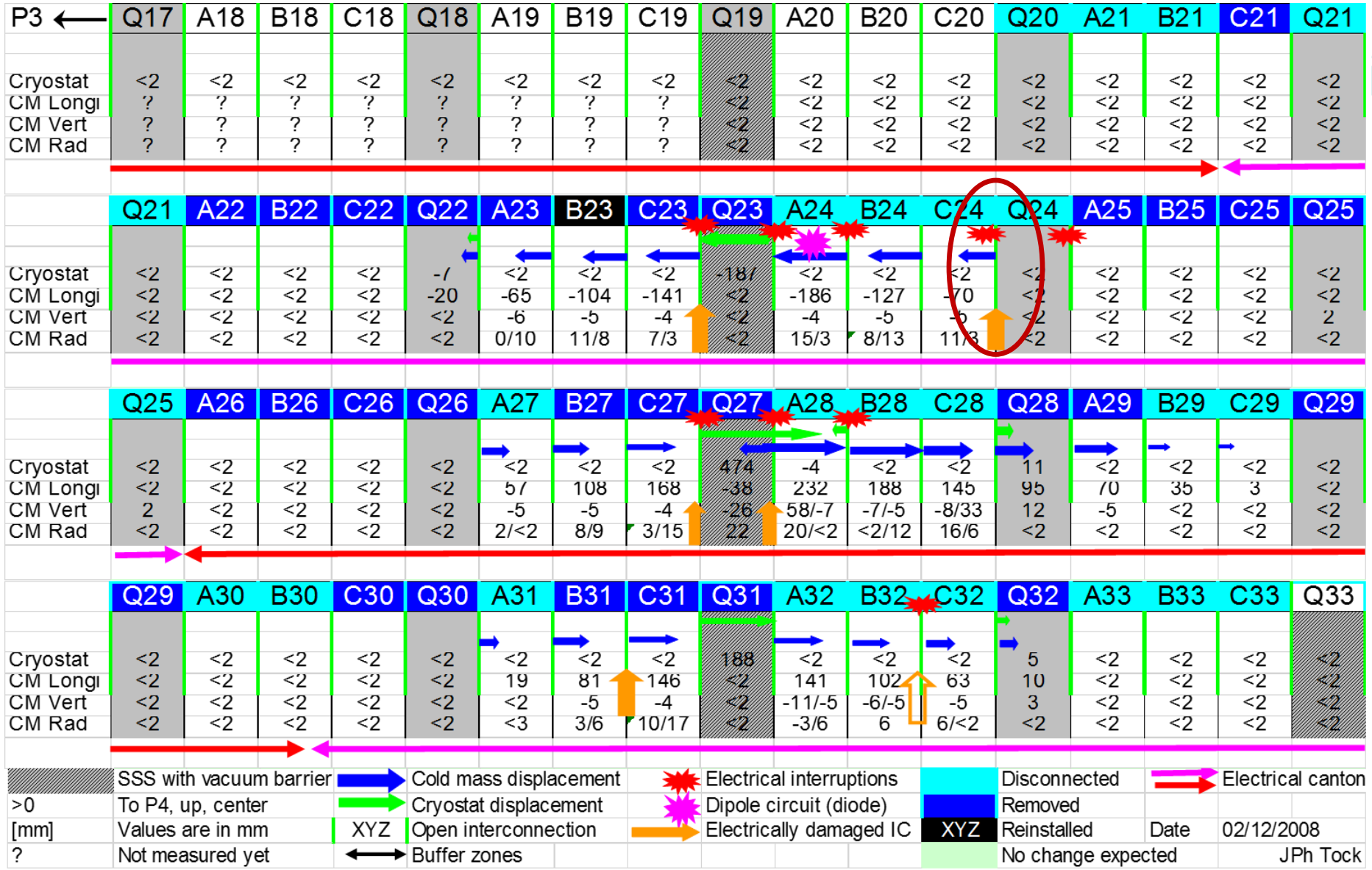


Energy	MJ	%
Stored in the magnets	595.0	100
Dissipated in UJ33	71.0	12
Dissipated in UA43	104.8	18
Dissipated in cold mass	144.4	24
Dissipated in electrical arcs	274.8	46

N. Catalan, S. Le Naour

A task force was set to analyze the event, to understand cause and propose remedies. Lead by Ph. Lebrun, Head of AT department

Heavily damaged zone extended over 3 subsectors



A, B, C = dipoles

Q = quadrupole

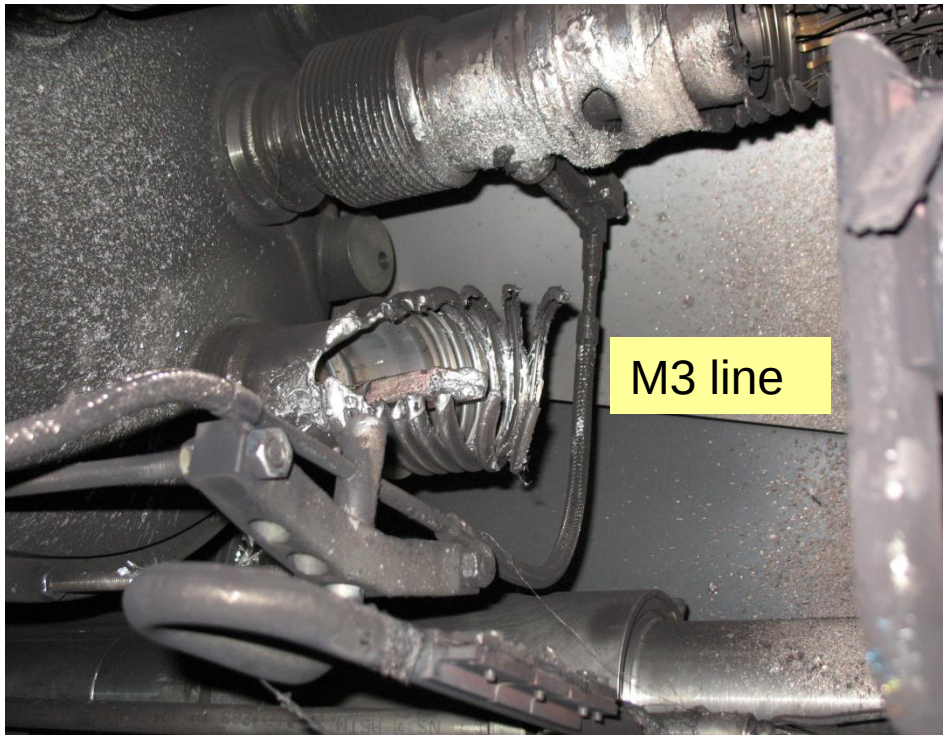
Overpressure in the cryostat with consequent cryo-magnet movement made the big damage

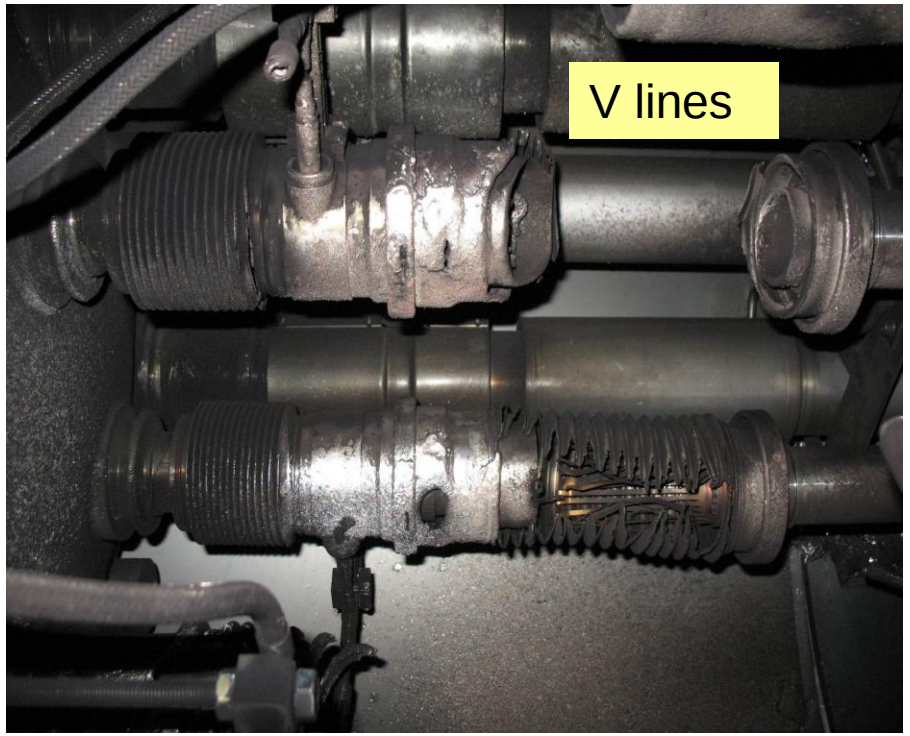
Through:

- Mechanics
- Secondary arcs

Picture reworked from: J.-Ph. Tock

Electrical arc between C24 and Q24

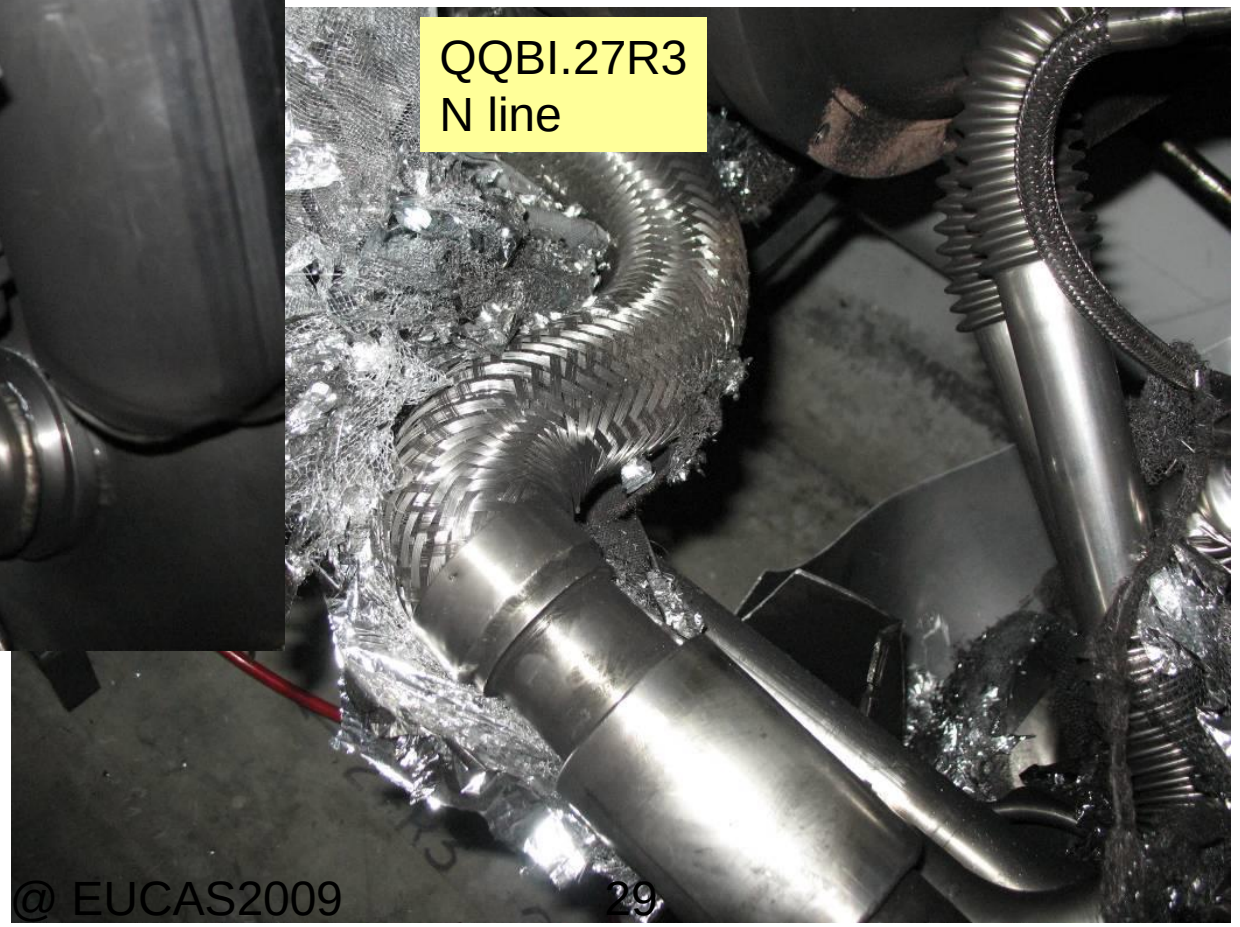




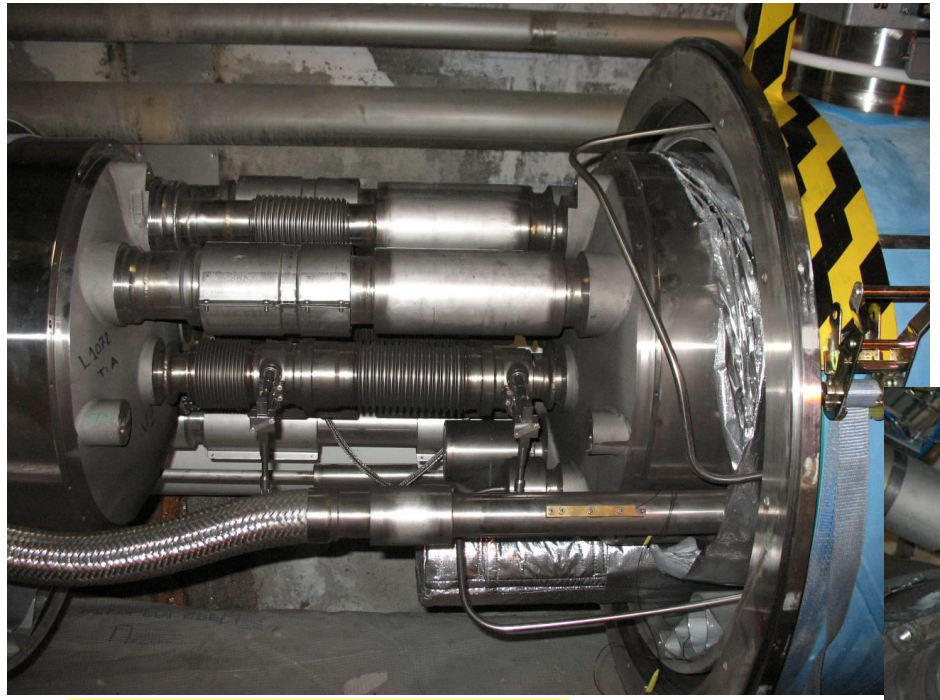
Collateral damage: magnet displacements with further arcs

QQBI.27R3

Collateral damage: magnet displacements and mechanical damage

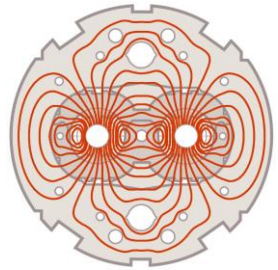


Collateral damage: magnet displacement



QBBI.B31R3
Extension by 73 mm

QBQI.27R3
Bellows torn open



Collateral damage: ground supports not enough robust

Beam vacuum pipe was perforated in a few points: contamination all along 3 km sector!!

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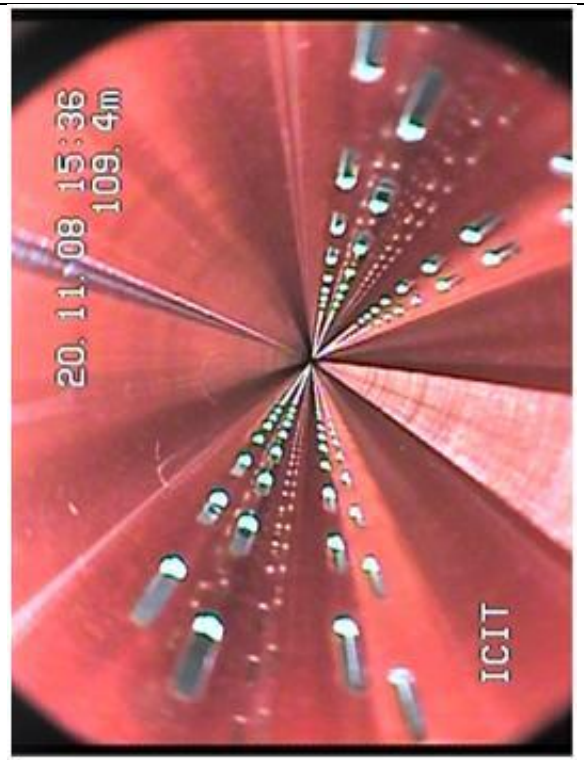
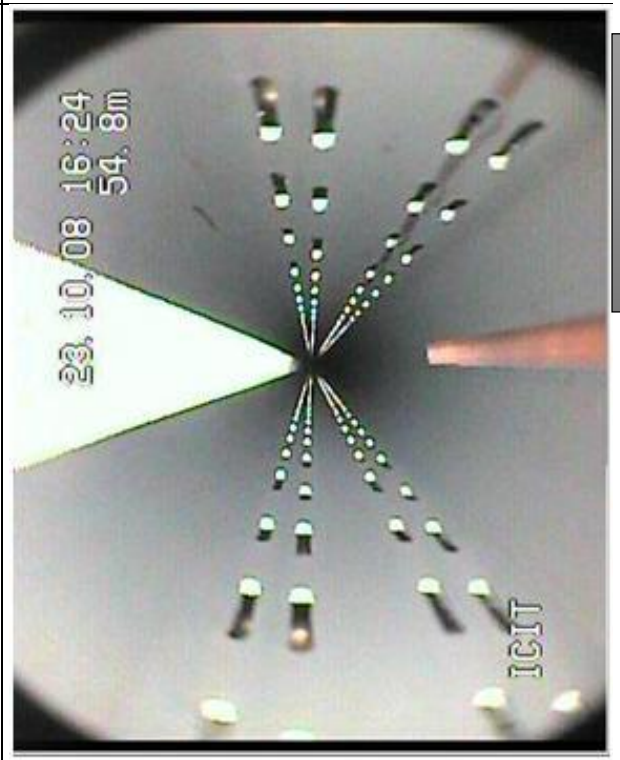
Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
		

Fortunately we were not near to Experiments

M. Jimenez

Bad electrical diagnostic : but we ignored cryogenic signals (installed for other scope…)

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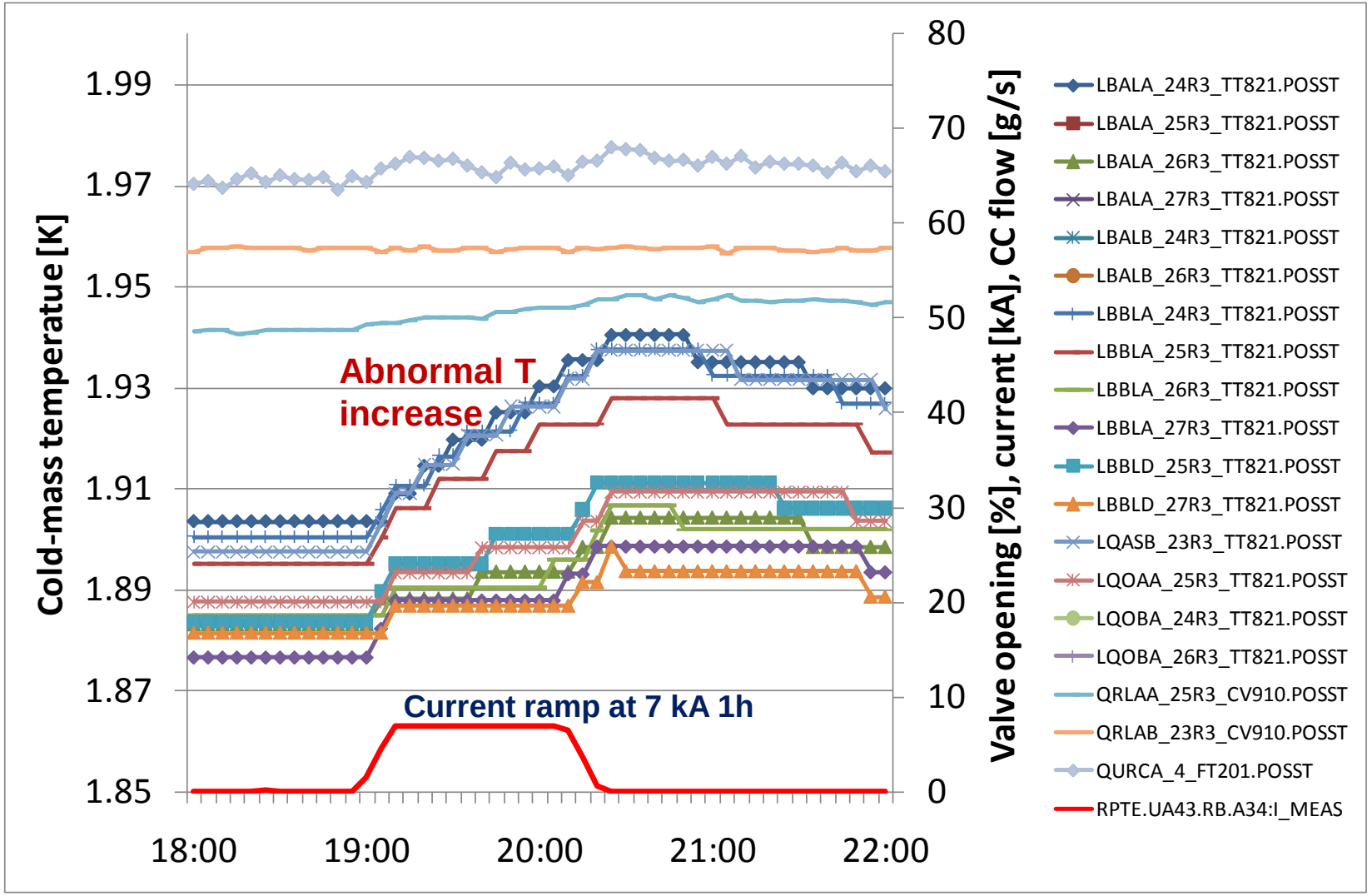
Electrical very difficult to see with the old system:
QPS on bus bar too weak:
V_{thr}= 1 V
V_{sens} = 0.1-0.3V

(**later sensitivity improved to 0.3 mV!**)

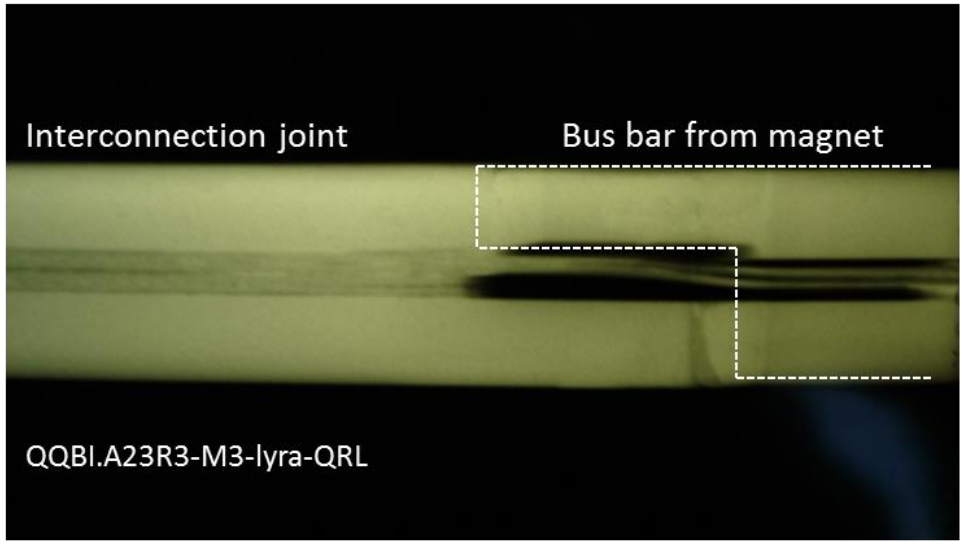


Precursor (a posteriori) : temperature drift @ 7 kA current flat top (15.09.08)
In the bad subsector the ΔT increase was 40 *m*K, double than normal

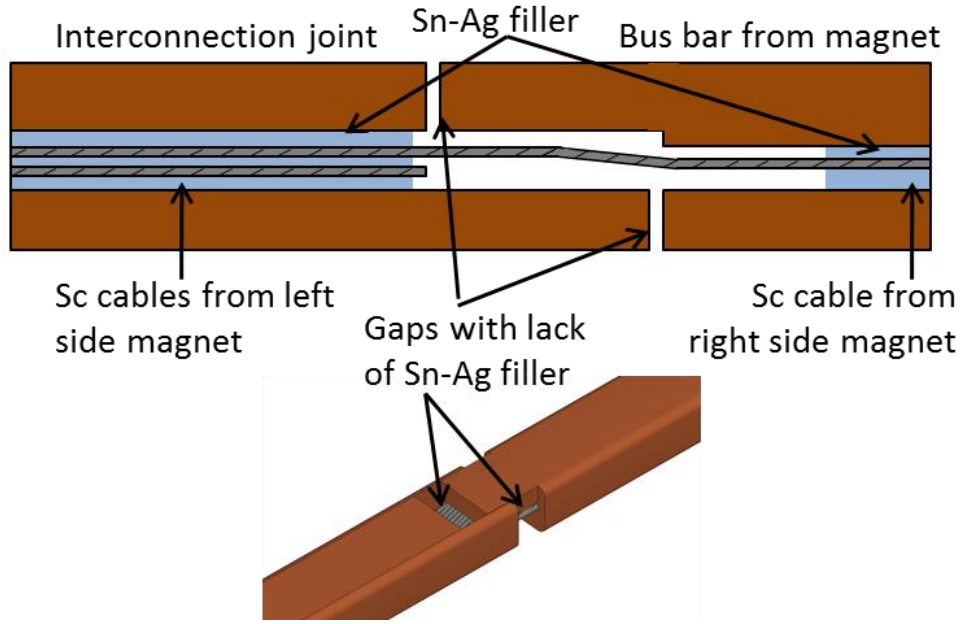
This technique led to discovery of very bad internal connections escaping the QA test of magnet test

But … later a more subtle joint failure mode was evidenced

- **Splice SC-SC can be good (or acceptable, < few nΩ), however the stabilizer may be not continous and not in contact with the cable.**
- **(Enhancing) Voiding bus bars solder due to excessive heating durign (good) joint**



Defective interconnetion-bus bar transition
γ-ray picture (left) and scheme (right)



This failure mode is more frequent for under- or overheating during melting

LHC PROJECT

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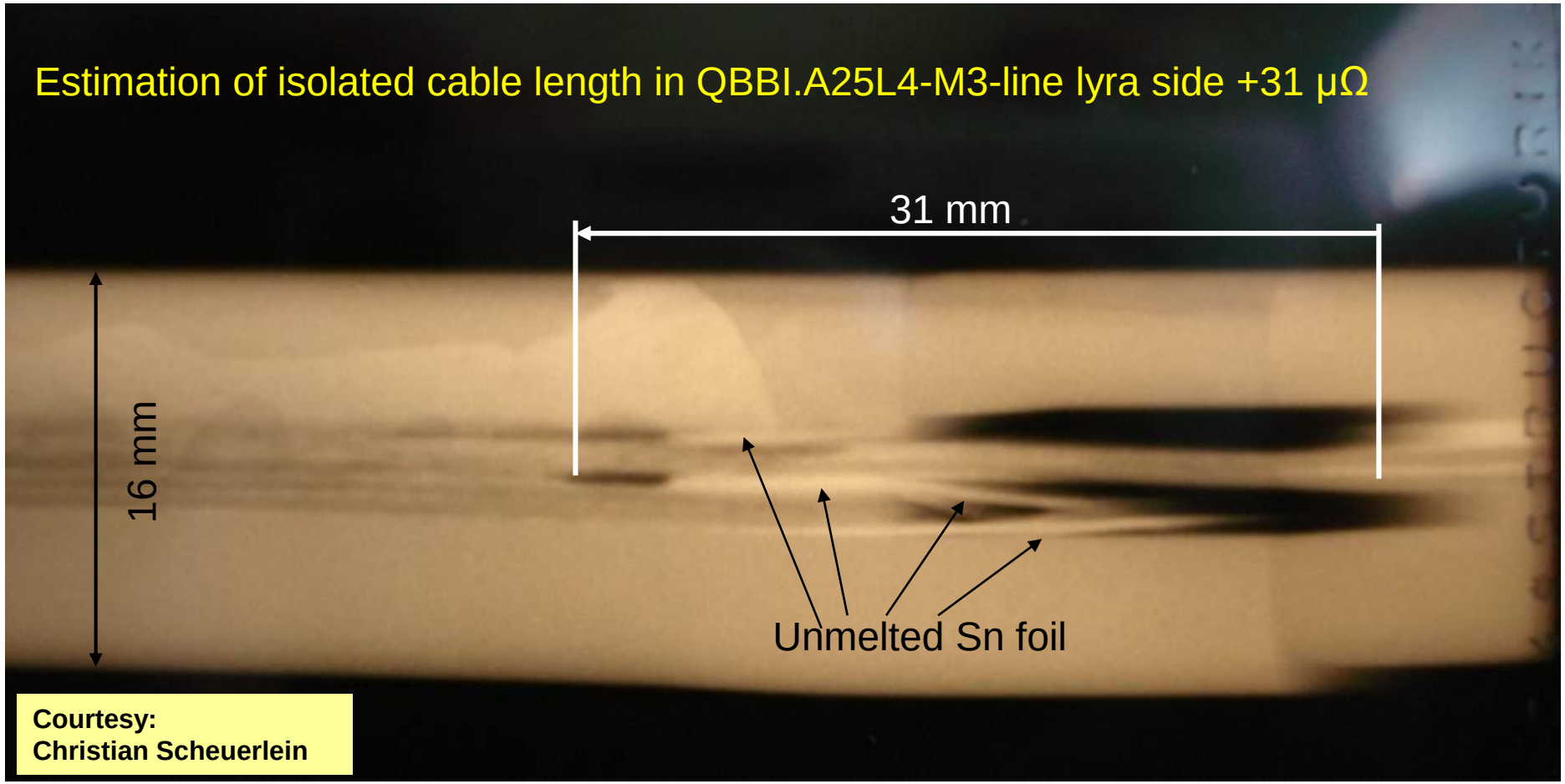
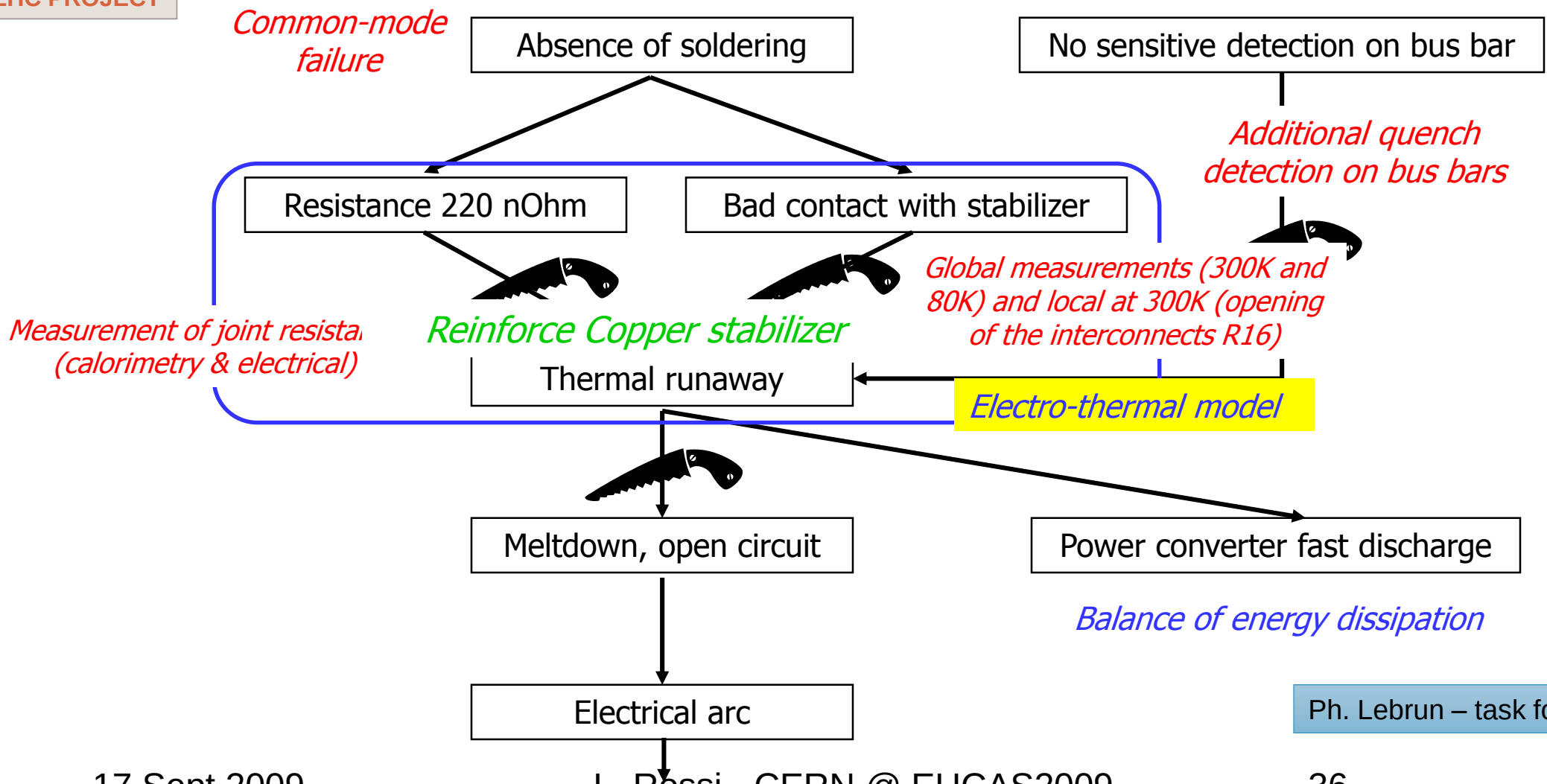
After the incident, simple Copper Stabilzing Resistance Measurement introduced: very effective. Most attention shifted from the nΩ of SC splice to Cu μΩ

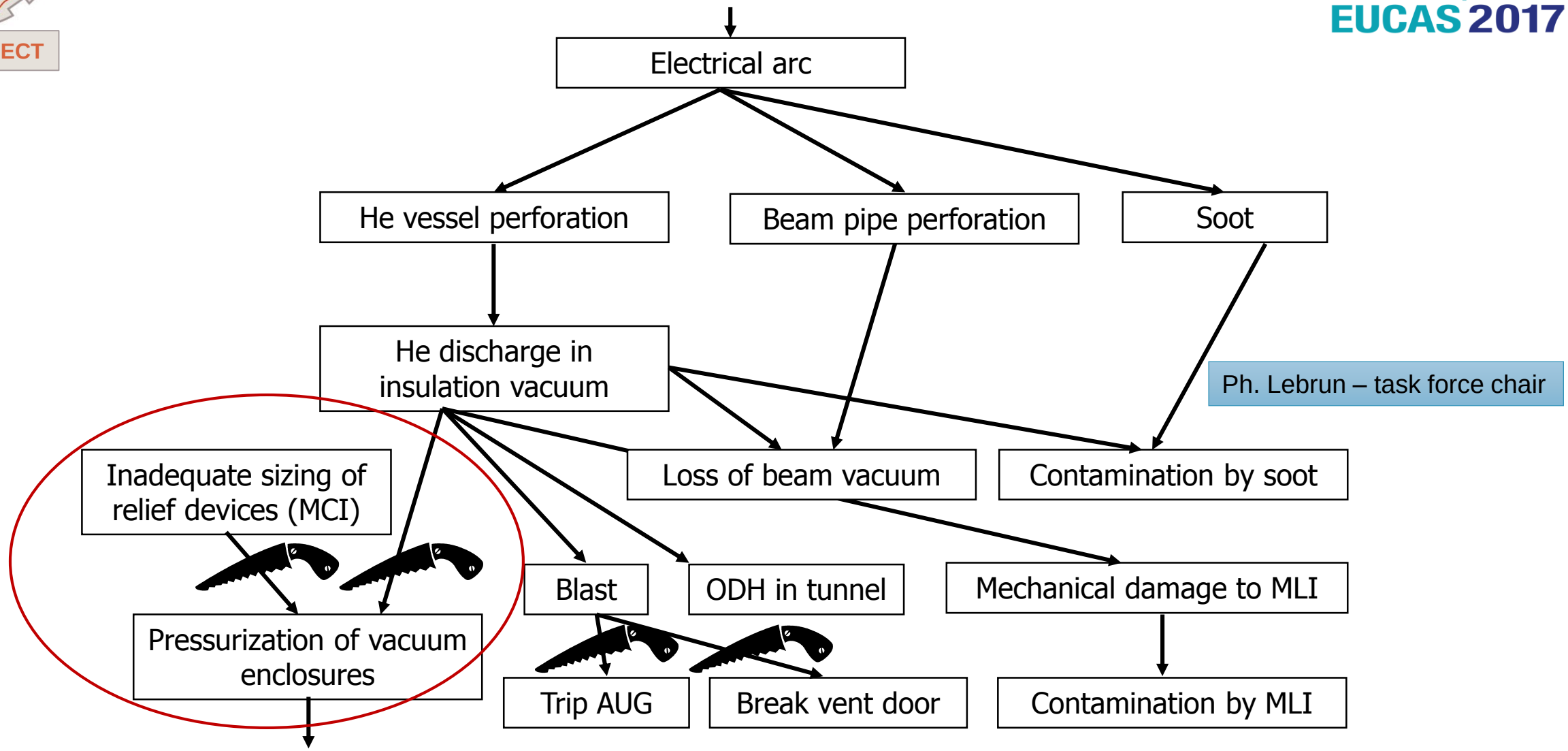


Fault tree of 19 September 2008 incident [1/3]



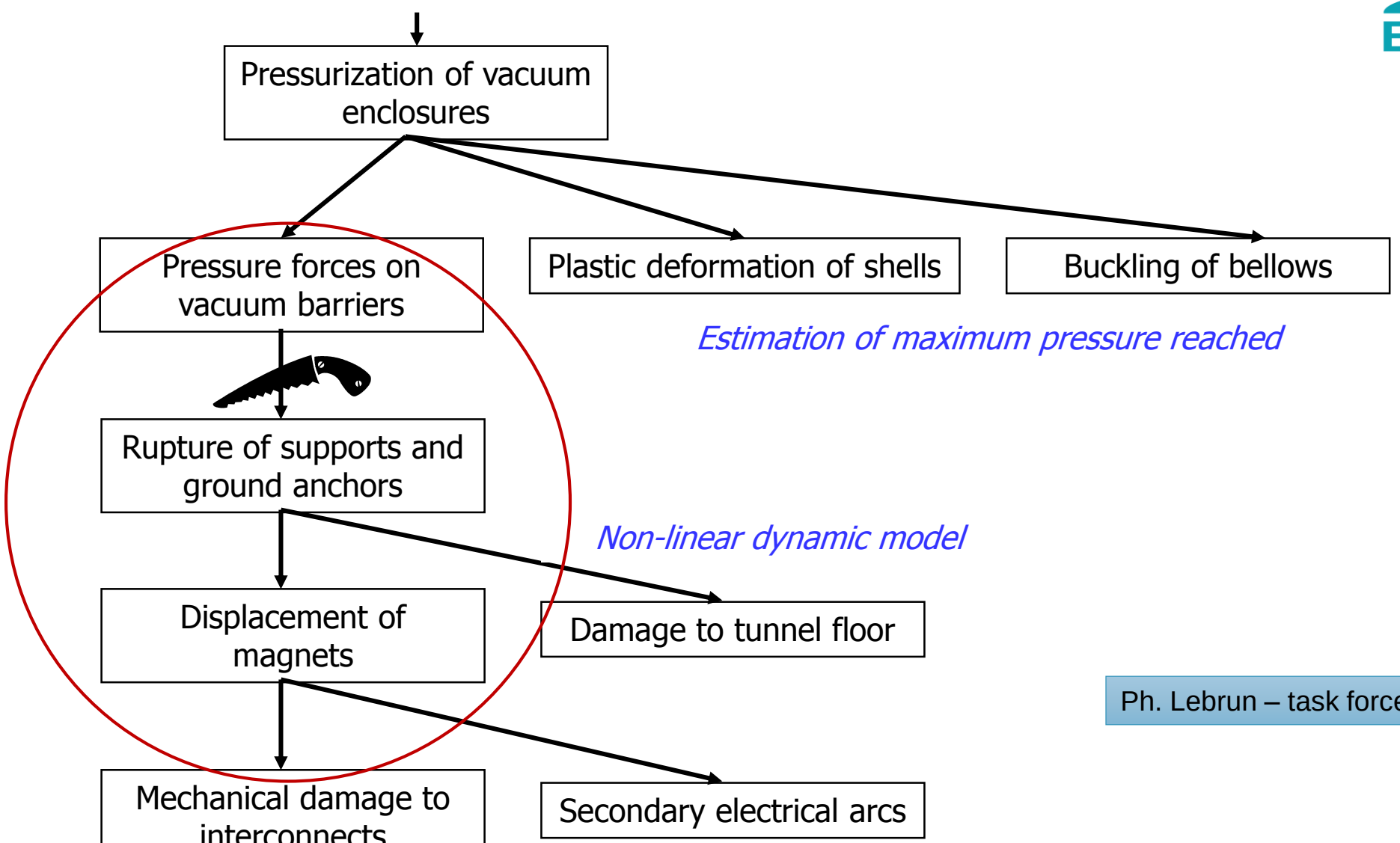
Ph. Lebrun – task force chair

Fault tree of 19 September 2008 incident [2/3]



Ph. Lebrun – task force chair

Fault tree of 19 September 2008 incident [3/3]

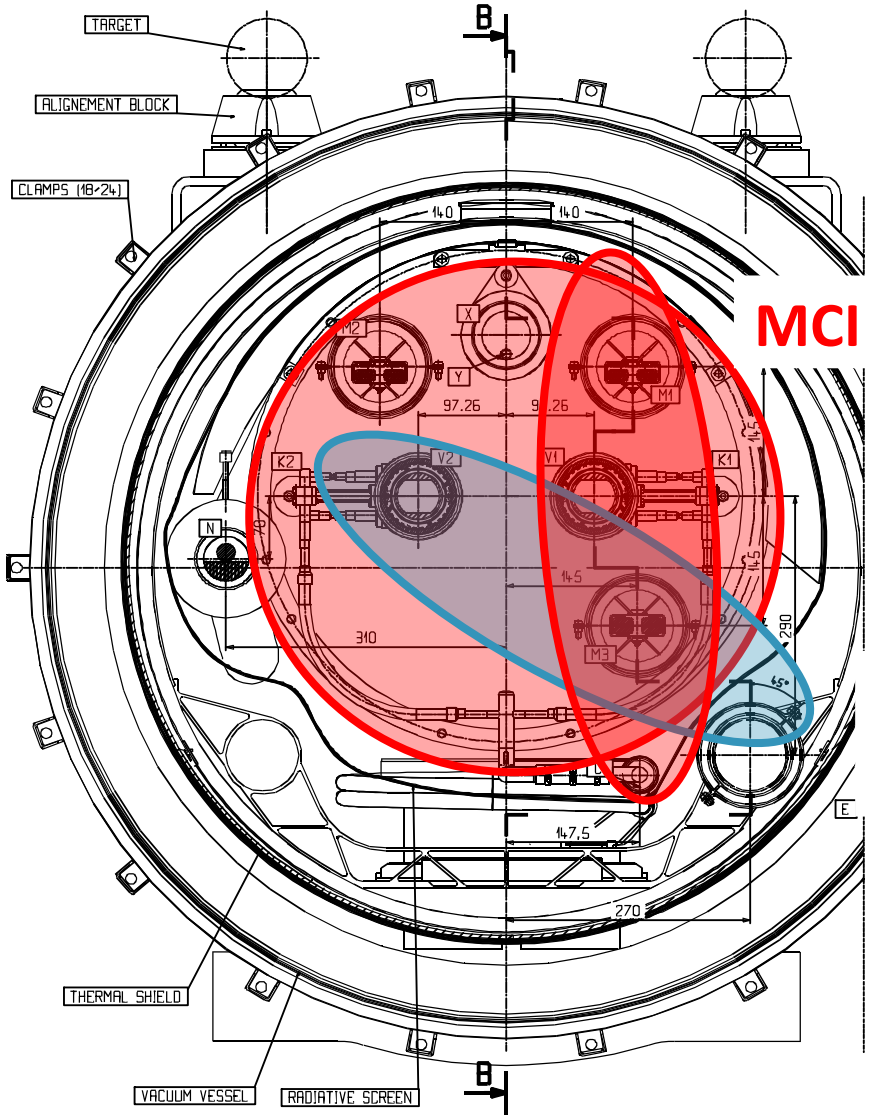


Ph. Lebrun – task force chair

Revision of MCI for electrical arc

Before the incident the MCI was set at 2kg/s of LH2 flowing into the vacuum vessel.

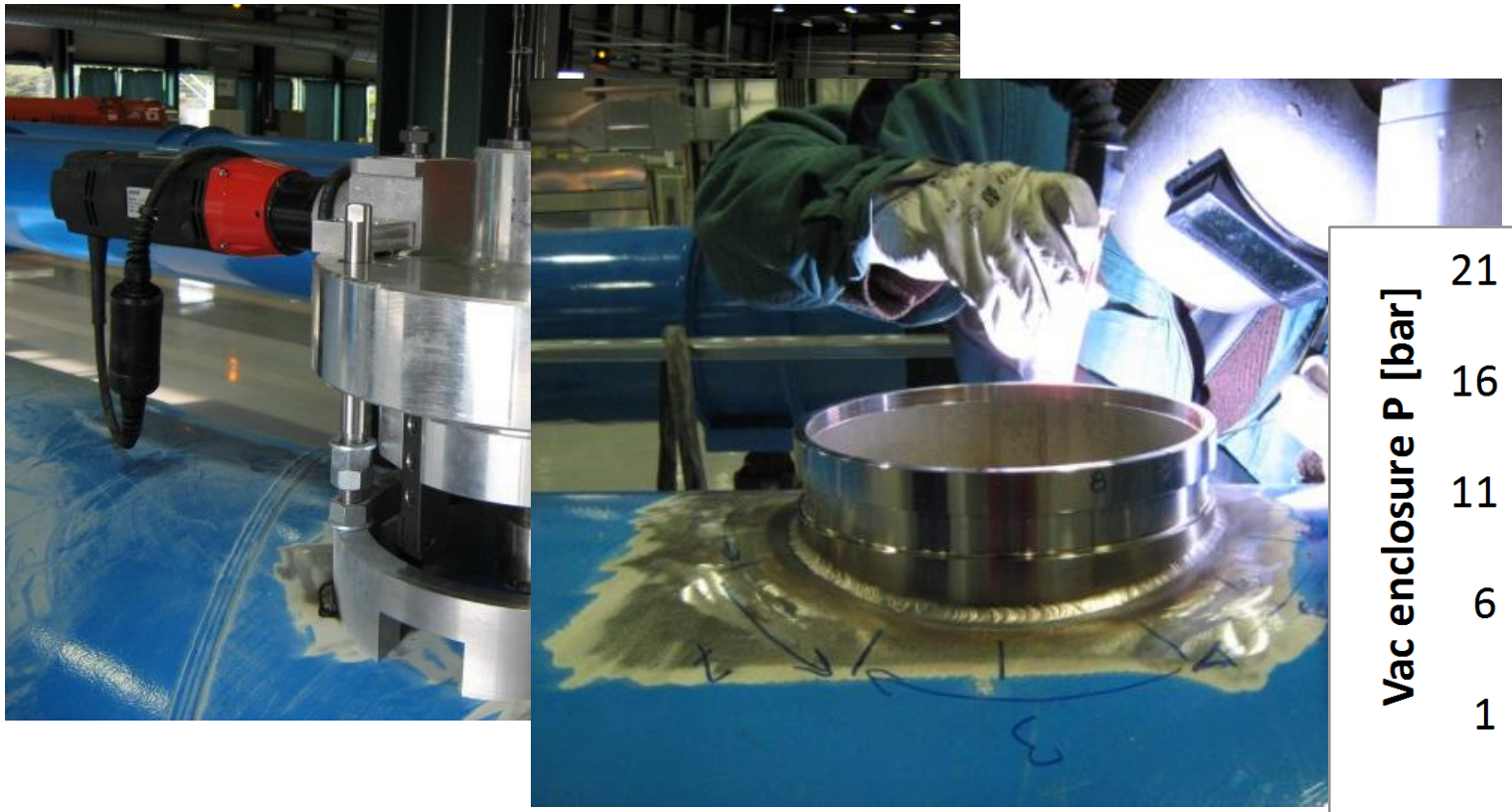
- Incident: peak at 20 kg/s
- New MCI: 40 kg/s



MCI = 40 kg/s

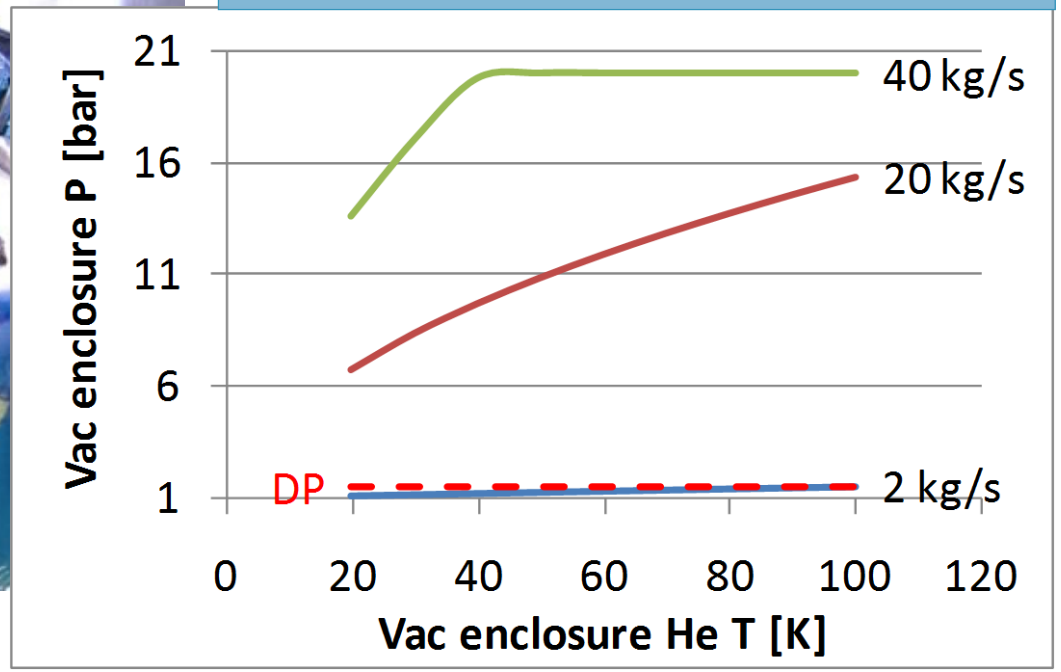
080919 incident
20 kg/s

Additional evacuation ports on dipole vacuum vessel



We had 1 DN50 to evacuate each 100 m.

Now we have >1 DN200 to evacuate each 15 m.



F. Bertinelli & L. Tavian

Reinforced anchoring of SSS (quads) with vacuum barrier

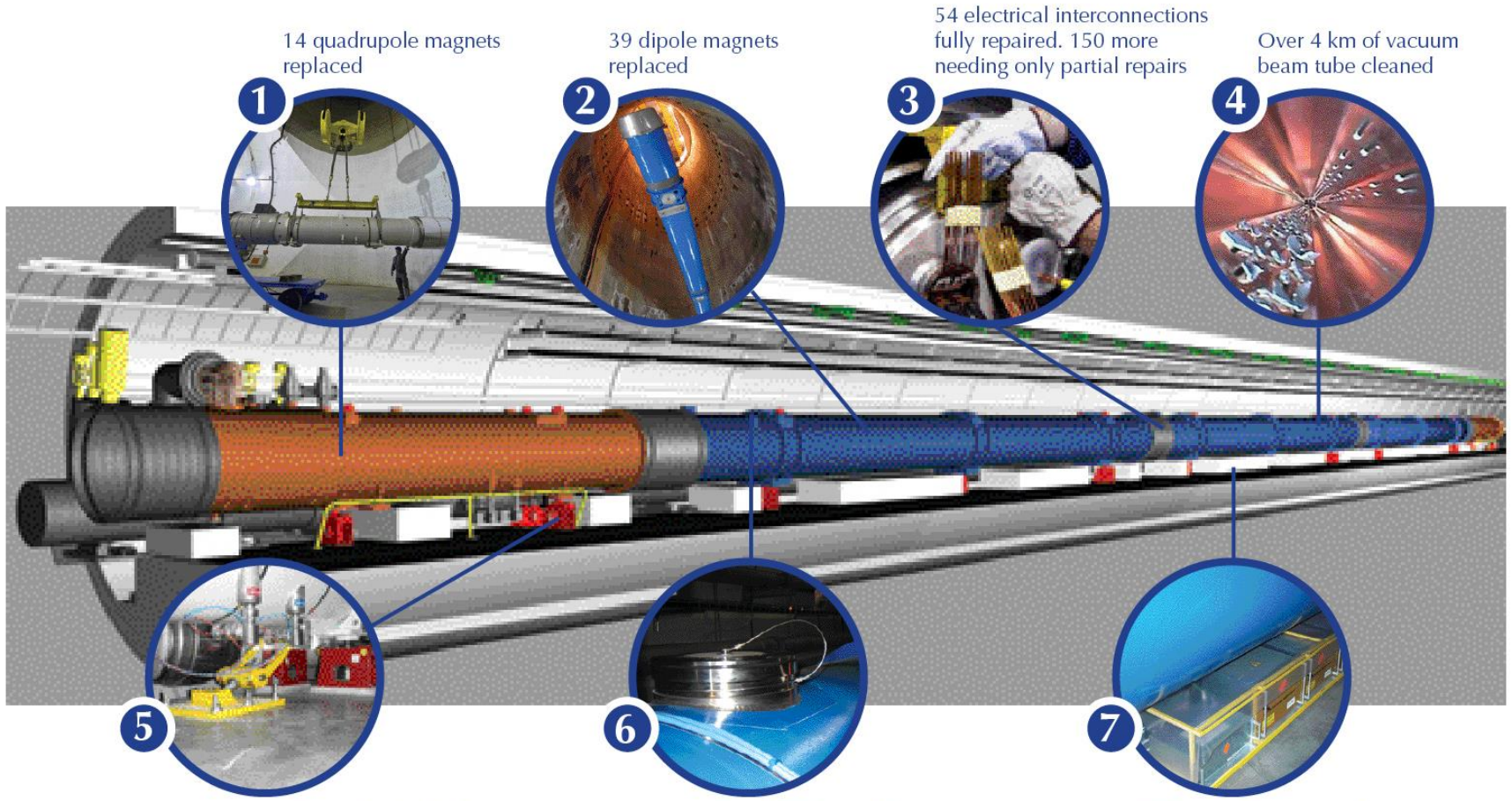
- Withstand longitudinal load of 240 kN (3 bar inner pressure)
- Implemented on 104 SSS with vacuum barriers in 8 sectors

Magnets preparation and replacement

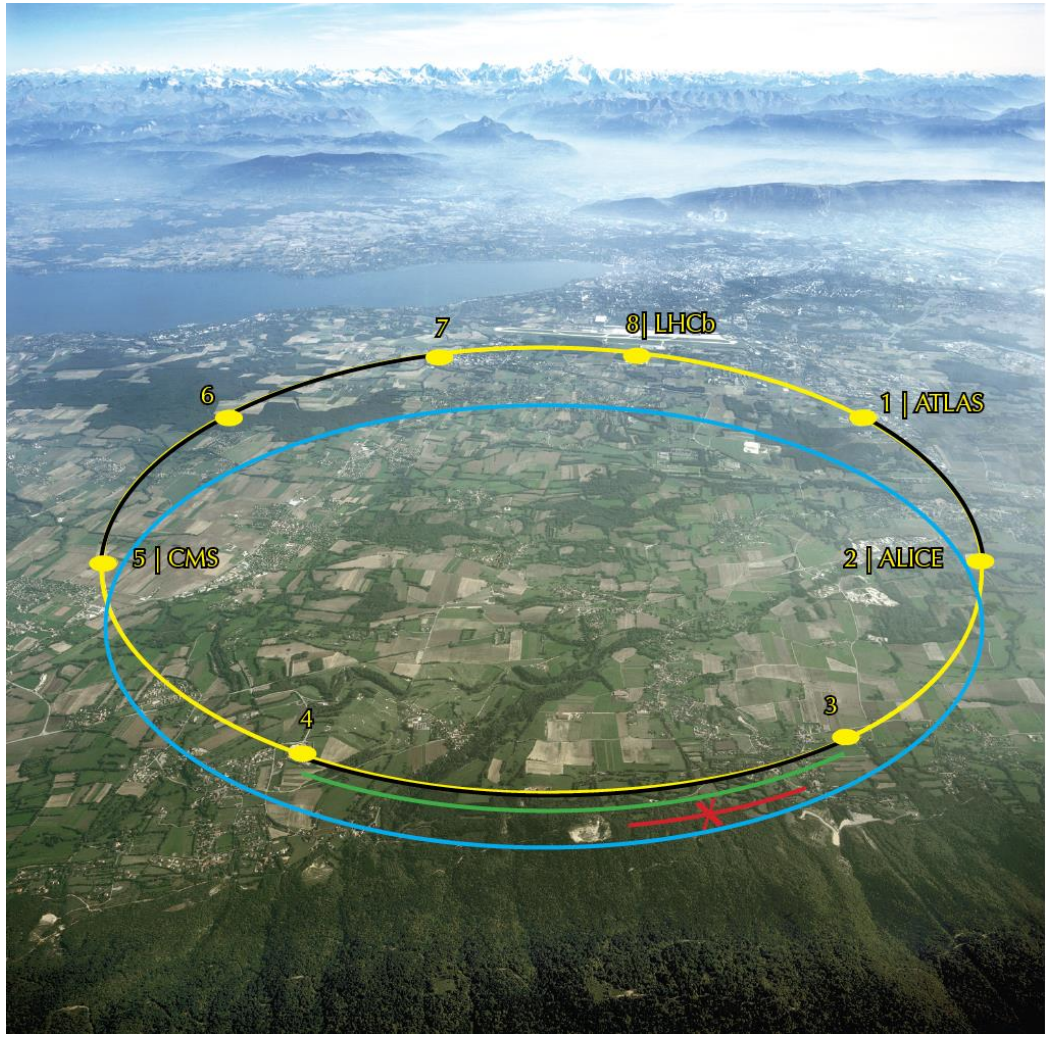
53 magnets replaced in sect.3-4:

- 39 dipoles:
  - 30 new spares
  - 9 recovered from sect.3-4 and refurbished
- 14 Short Straight Sections:
  - 7 new spares
  - 7 recovered from sect.3-4 and refurbished
- Spares were available, but just enough!

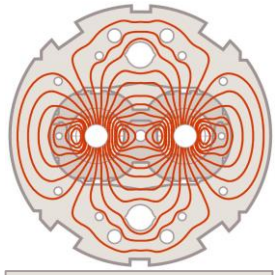
The LHC repairs in detail



Repairing all over the ring



- New pressure release ports fitted
- Upgrade of magnet protection system
- Cleaning ofvacuum beam tube
- Dipole and quadrupole magnets replaced and electrical interconnections
- LHC ring
- X Incident



Bad stabilization in joints: effect on running LHC

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- A **badly stabilized joint with a good SC-SC splice is dangerous: the splice** can quench because the nearby magnet has quenched (warm helium wave); or by beam irradiation…
- It takes 5-15 seconds, meanwhile current decays very little
- Computation of maximum acceptable defect as a function of current level and discharge time was set up via **th. – e.m. model** (**A. Verweij**)
- Running at lower current/field/beam energy: monitoring, acceptability for certain defects, reduced discharge time ⇒ reduced risk!
- Decision 2009 : not to open all machine. Measure as much as possible, repair what could be done to run **LHC at 50% field/beam energy** (25% magnet energy!) in 2010-11. In 2012 60% field (8 TeV c.o.m.)

LHC PROJECT

Machine restarted on 23 November 2009
on 13 December 2009 energy record:2x1.18 TeV
On 30 March 2010 we collided p-p at x3.5 TeV

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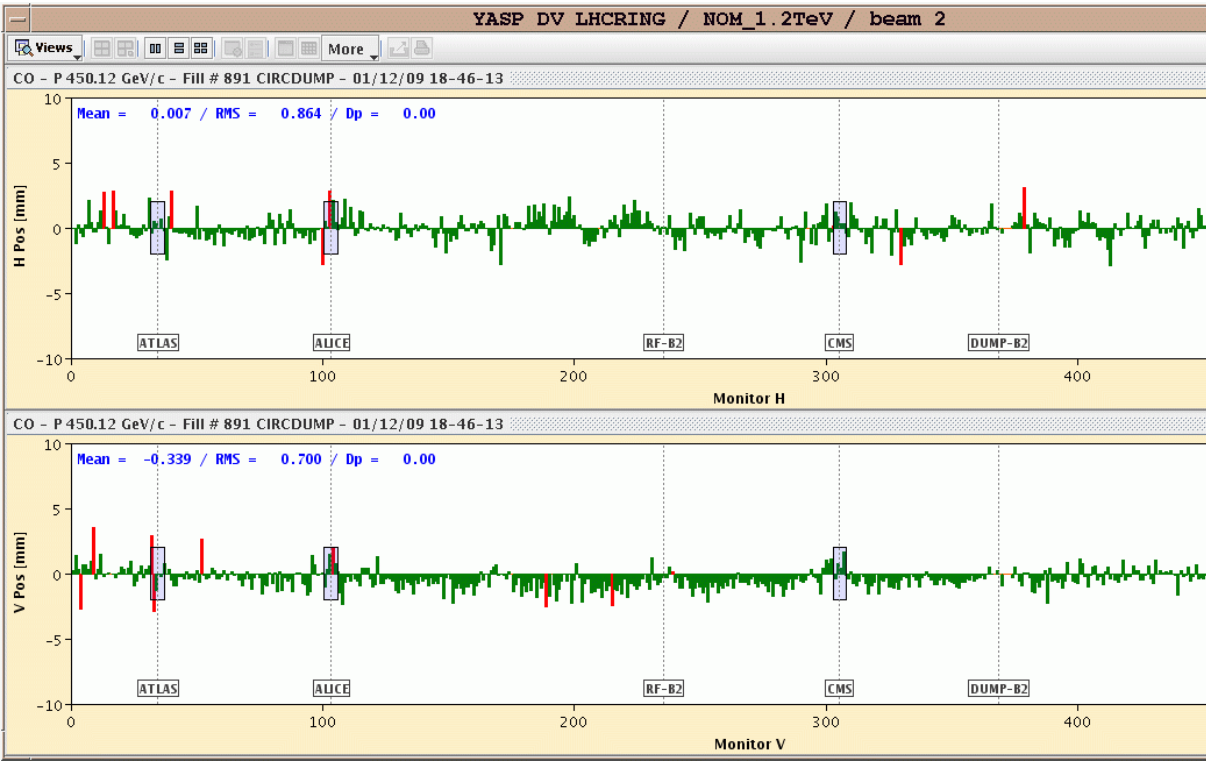
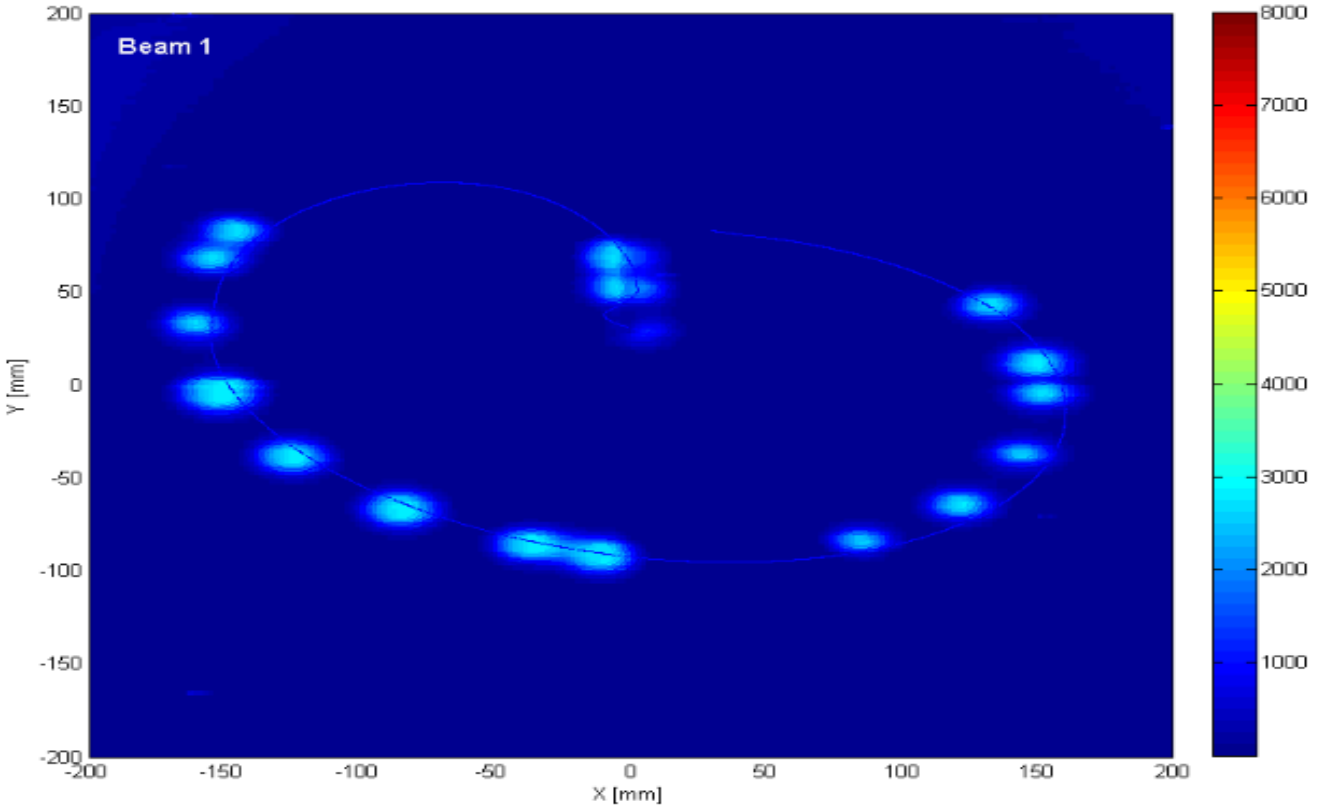
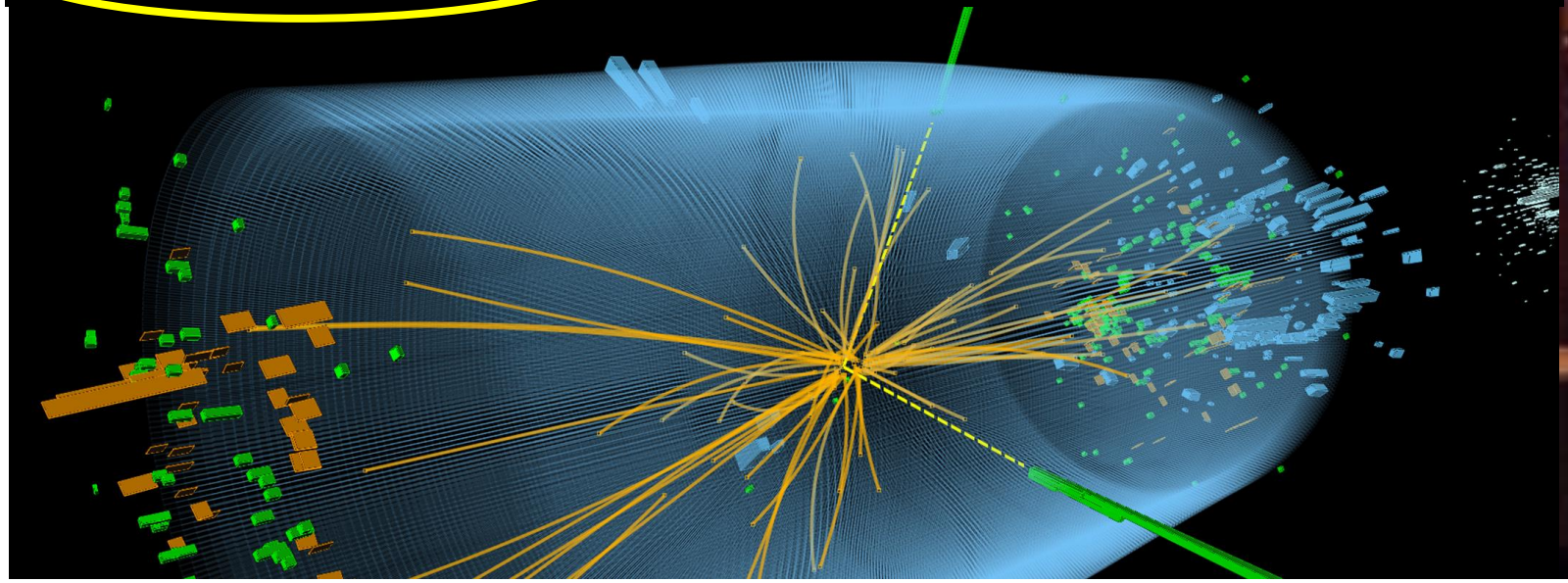




4 July 2012 : Higgs boson discovered! With 2x4 TeV p-p collisions

2013 Nobel Laureates

…for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.



Meanwhile LHC was running the final fix was studied and carefully implemented

LHC PROJECT

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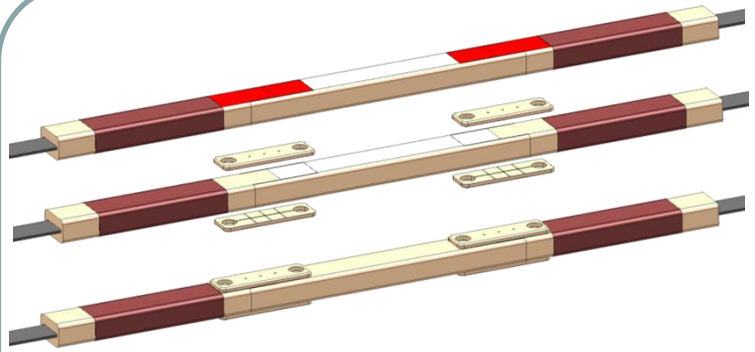
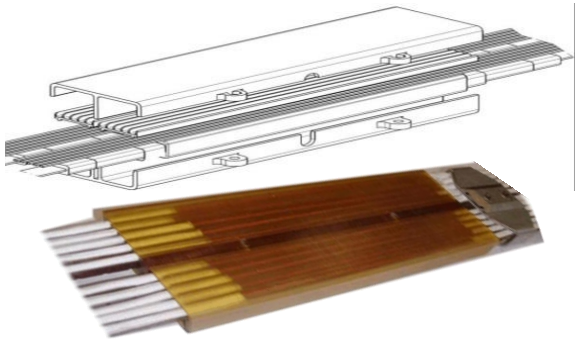


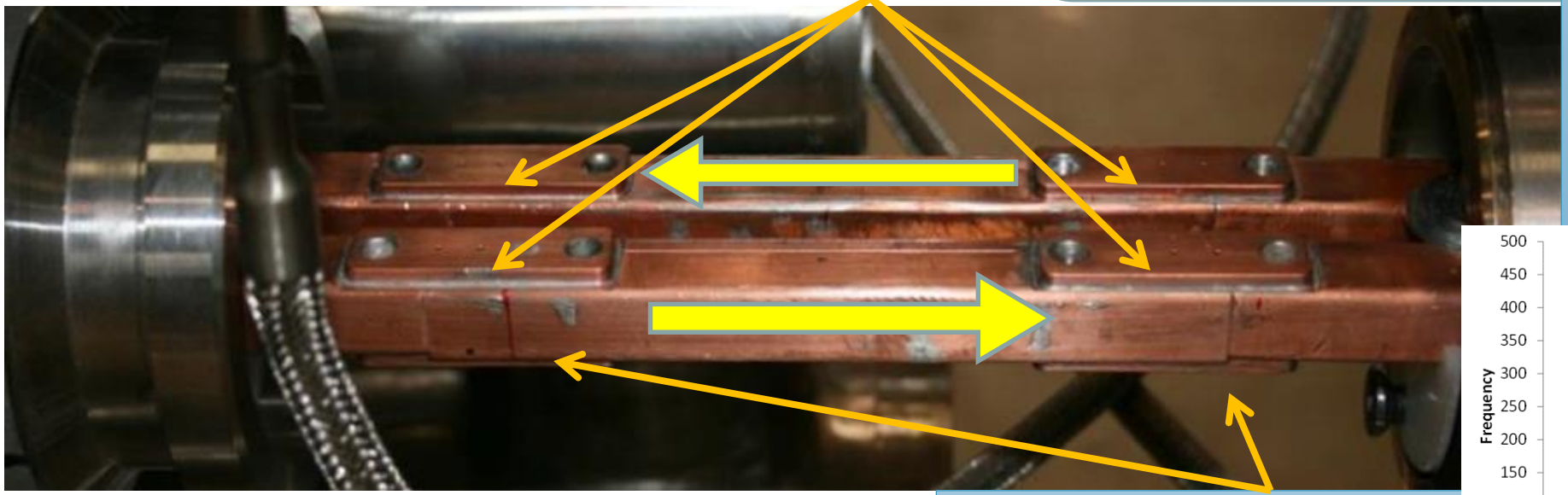
Consolidated dipole magnets bus splice



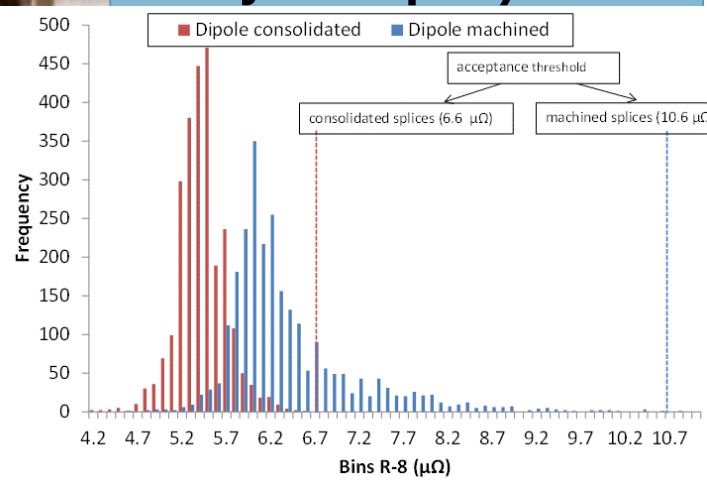
Consolidated electrical insulation system

Task Force to set the fix:
F. Bertinelli, P. Fessia, J.Ph. Tock
SMACC project to fix during a long shutdown of 2 years (led by J.Ph. Tock)
Splice quality improved dramatically! (not really clamped)

4 top shunts



4 bottom shunts (2 not v



LHC PROJECT

The main 2013-14 LHC consolidations

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1695 Openings and final reclosures of the interconnections

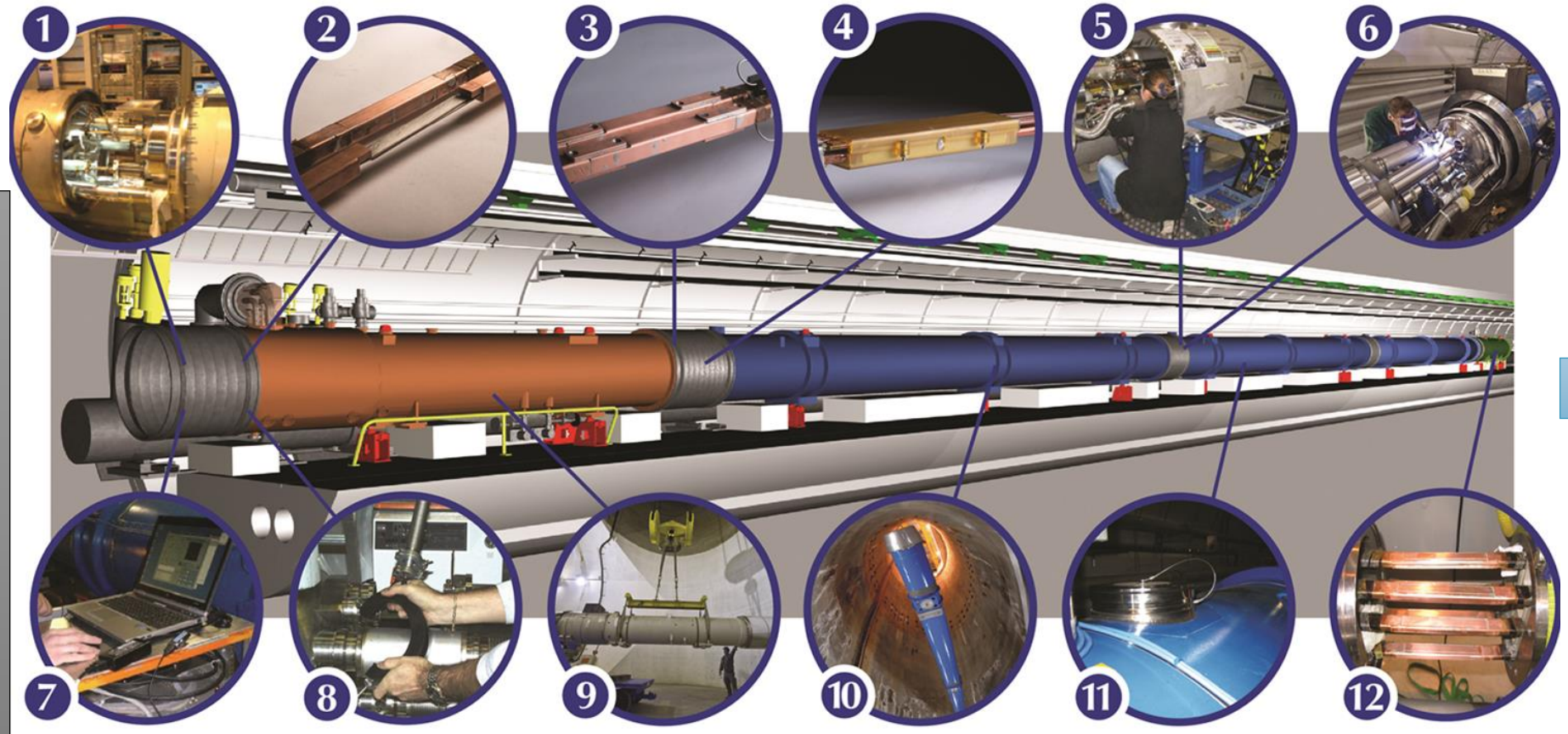
Complete reconstruction of 3000 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

3 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to

Consolidation of the 13 kA circuits in the 16 main electrical feed-

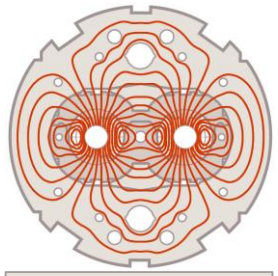
It took a huge campaign in 2013-14!

2010-12 preparation

But then we could run LHC nearly nominal energy

J.Ph. Tock

Improvement in QPS and we could measure all Continuity Copper Stabilizer at 20 K: elimination of silent killer!



Lesson learnt: observation

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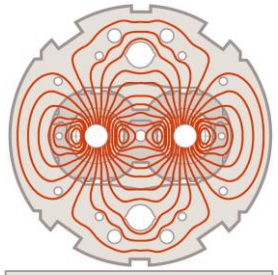
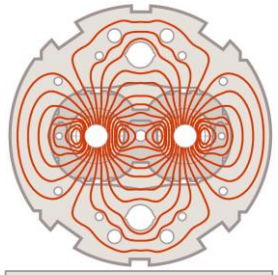
- LHC had a technical failure in a relatively low tech part
- All high tech parts
  - **SC cable with all properties constraints**
  - **SC Magnets**
  - **HTS current leads**
  - **1.9 HEll cryogenics**
  - **Collimation**
  - **Precision High Current Power Converters**
  - **…**
- Have worked successfully.
- **Especially the SC part went really on time and on budget which is a success of applied superconductivity and shows its industrial maturity.**

- The incident **itself** was primarily due to a single failure, a mistake.
- However **it has evidenced deficiencies in various areas**:
  - Basic design of IC splice
  - **Lack of robustness** of manufacturing process w.r.t. series production and vs. real situation (Cu terminals not perfect)
  - Not complete analysis of the process, especially induction heating (good but vulnerable to mishap)
  - Not careful, complete analysis of **the system: JOINT + BUS BAR**
  - Not a complete analysis of the consequence of an accident in the interconnections, betting on zero failure
  - Diagnostic was not adequate.
  - Even improbable the worst thing may happen: mitigation measurement were not appropriate.



Lesson: conclusions 1/2

- In SC devices, everything has to do with superconductivity! Inject more science (study) in the engineering.
- The electrical joints should have been treated like a SC Magnet. Any part in a SC device, especially with large energy must be regarded with “respect”. ICs weren’t “sexy”…
- Scientists should work more with system engineers. Lack of integration (and adequate risk analysis) may cause large damage to SC parts, unexpectedely.
- Do not underestimate mistakes and signals even in early stage: they reappear…
  - Magnet had problems in splice during construction and in the STRING2 (terminated by a burned splice incident of different nature and cause, still…).
- Safety is more important than schedule: everybody agrees but at the end of large projects (inevitable problem of budget and schedule) the pressure to take shortcuts is strong.
- Never spare on risk analysis (by competent people) and take mitigation measurements. Whatever might go wrong, it goes! What is important is to survive and limit damage (mitigation measurements).
- Diagnostics and measurements are key: but important is to select what really matters, to avoid to be overwhelmed by un-important Non-Conformities. QA effectiveness vs. paper QA. But what you measure look at it ! Data always say something – to non-biased mind.



Lessons: conclusion – 2/2

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- Test as much as can!!!! **But You cannot test whole system** before final commissioning. And risk zero is not an option (€€$$££…).
- But large stored energy requires prudence.
- ⇒ **Staged approach**: going by step, and taking the time to understand the SYSTEM (which is more than a just the sum of components: non-linear effect!)
  - In Commissioning
  - And in Operation (that is always more than commissioning)
- **No hunting for faulty people: team up and [illegible] people that had experience. Management is there [illegible] not to create panic.**
- **Learning from mistake: a[illegible] without prejudice.**
  - **Even mechanically clamped an un-stabilized joint would have caused the damage.**
  - **After appropriate analysis defects can be intercepted (Resistance vs. complex diagnostics)**
  - **Take the proper time to train people: as (more) important than QA. Take direct responsibility.**
  - **Superconductivity is a subtle system requiring GLOBAL APPROACH. A detail can be a killer.**

CERN has been - and is - good at this

LHC PROJECT

EUCAS 2017

SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)

LHC is now running near maximum energy, exploring new territories:
Superconductivity is working very smoothly: excellent repeatability
Thanks to the people that designed, built (Industry and laboratories), repaired and are running the LHC Magnet system

Any burning question?