CERN

European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Recovering and lessons learned from LHC *(Large Hadron Collider)* incident (Sept. 2008)

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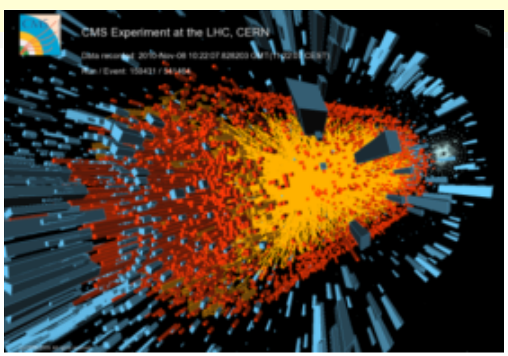
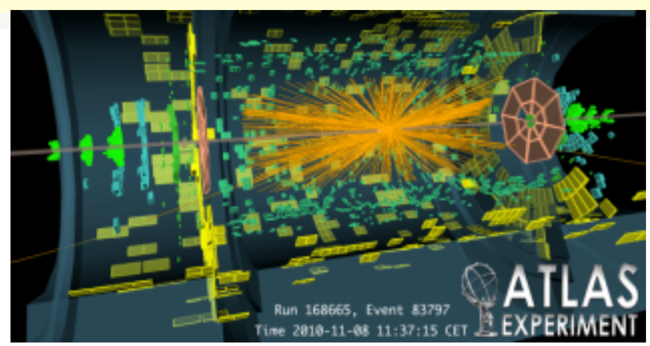
ICOPS 2011 SOFE

Menu

- **LHC machine recap and main challenges**
- **Magnet interconnection activity**
- **10^{th} and 19^{th} September 2008**
- **LHC repair and restart in 2009**
- **Last results and future**
- **Lessons learnt & Conclusions**





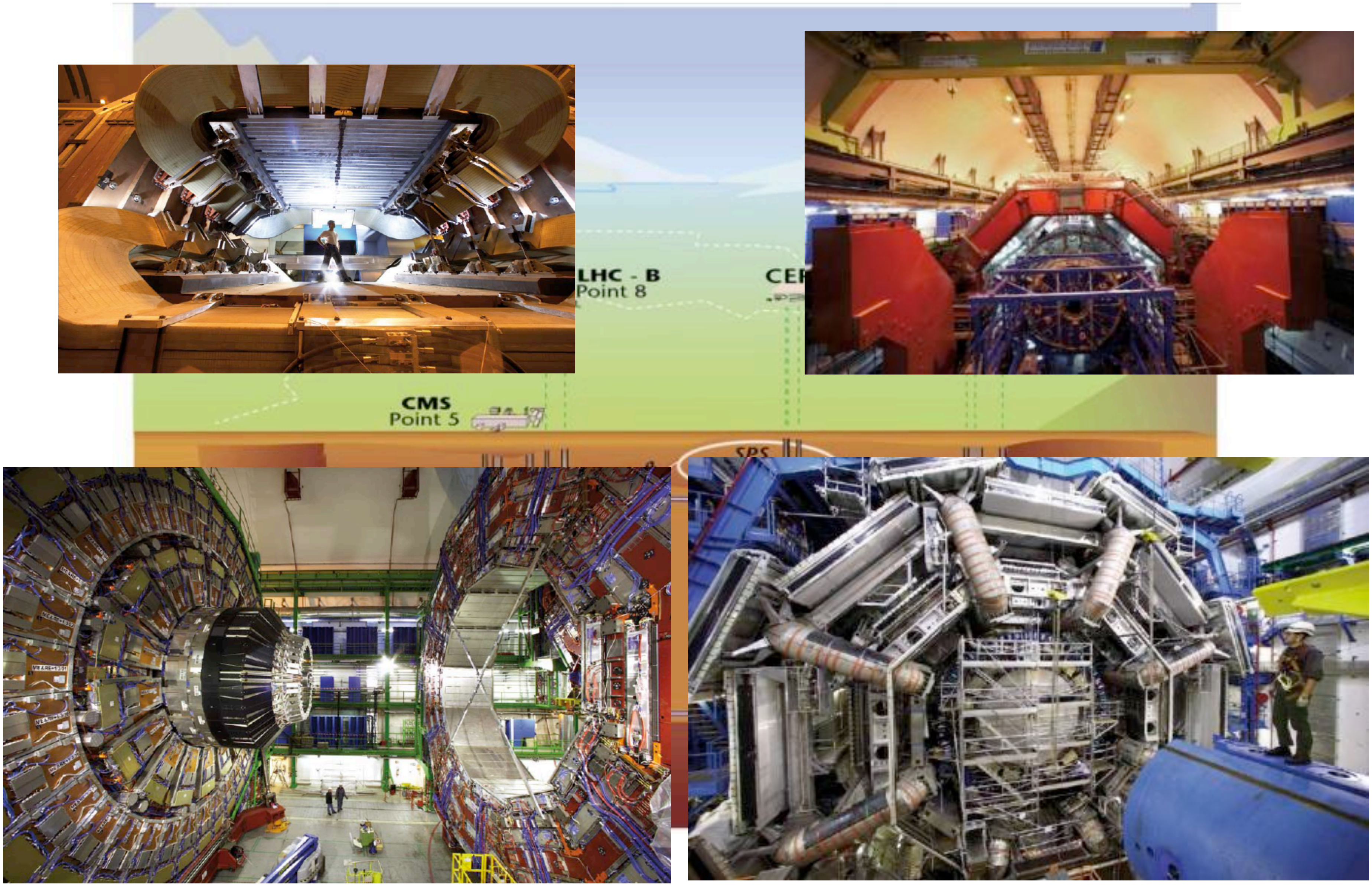
What is LHC (Large Hadron Collider) ?

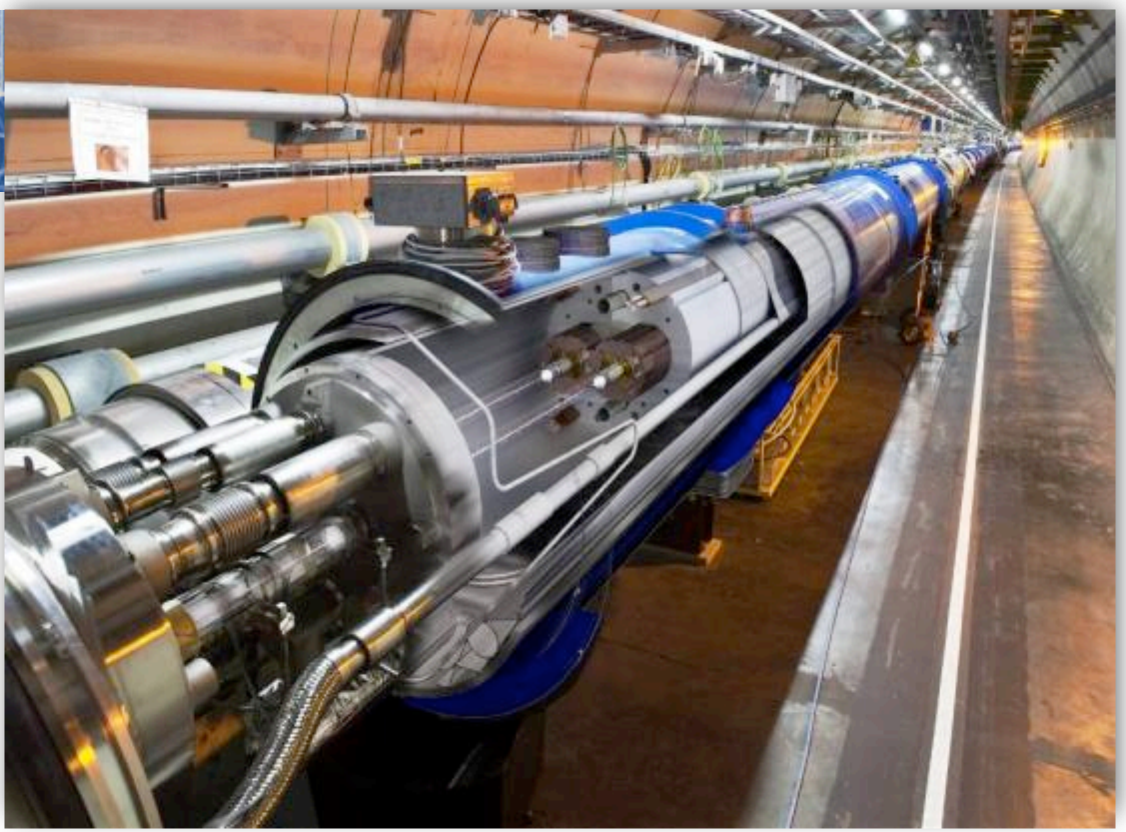
7 TeV
proton-proton
accelerator-collider
built in the LEP
tunnel

1982 : First studies for the LHC project
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction
2004 : Start of the LHC installation
2006 : Start of hardware commissioning
2008 : End of hardware commissioning and start of commissioning with beam
2009-2030: physics operation

Beams of LEAD nuclei will be also accelerated, smashing together with a collision energy of 1150 TeV

Four large experiments
Overall layout of LHC





What is special with LHC ?

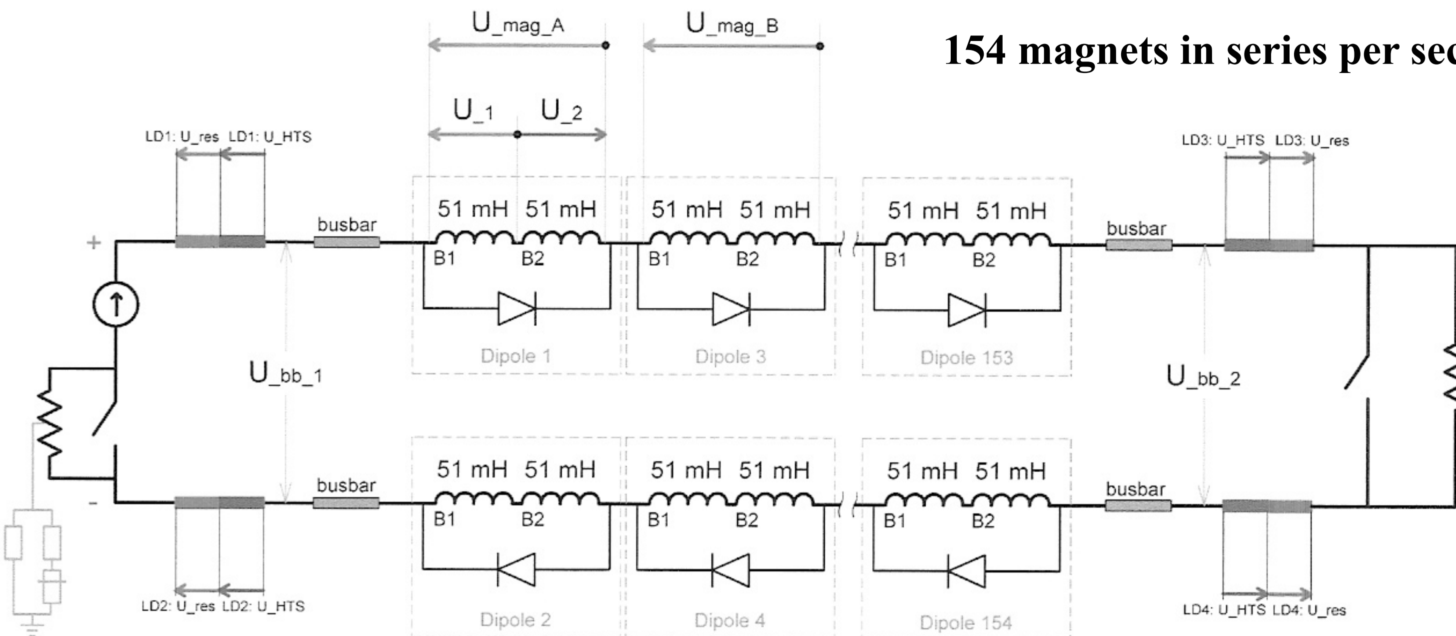
- The highest field accelerator magnets: 8.3 T (ultimate: 9 T)
- Proton-Proton machine : Twin-aperture main magnets
- The largest superconducting magnet system (~8000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium)
- The highest currents controlled with high precision (up to 13 kA)
- The highest precision ever demanded from the power converters, a few ppm
- A sophisticated and ultra-reliable magnet quench protection system

Energy management challenges

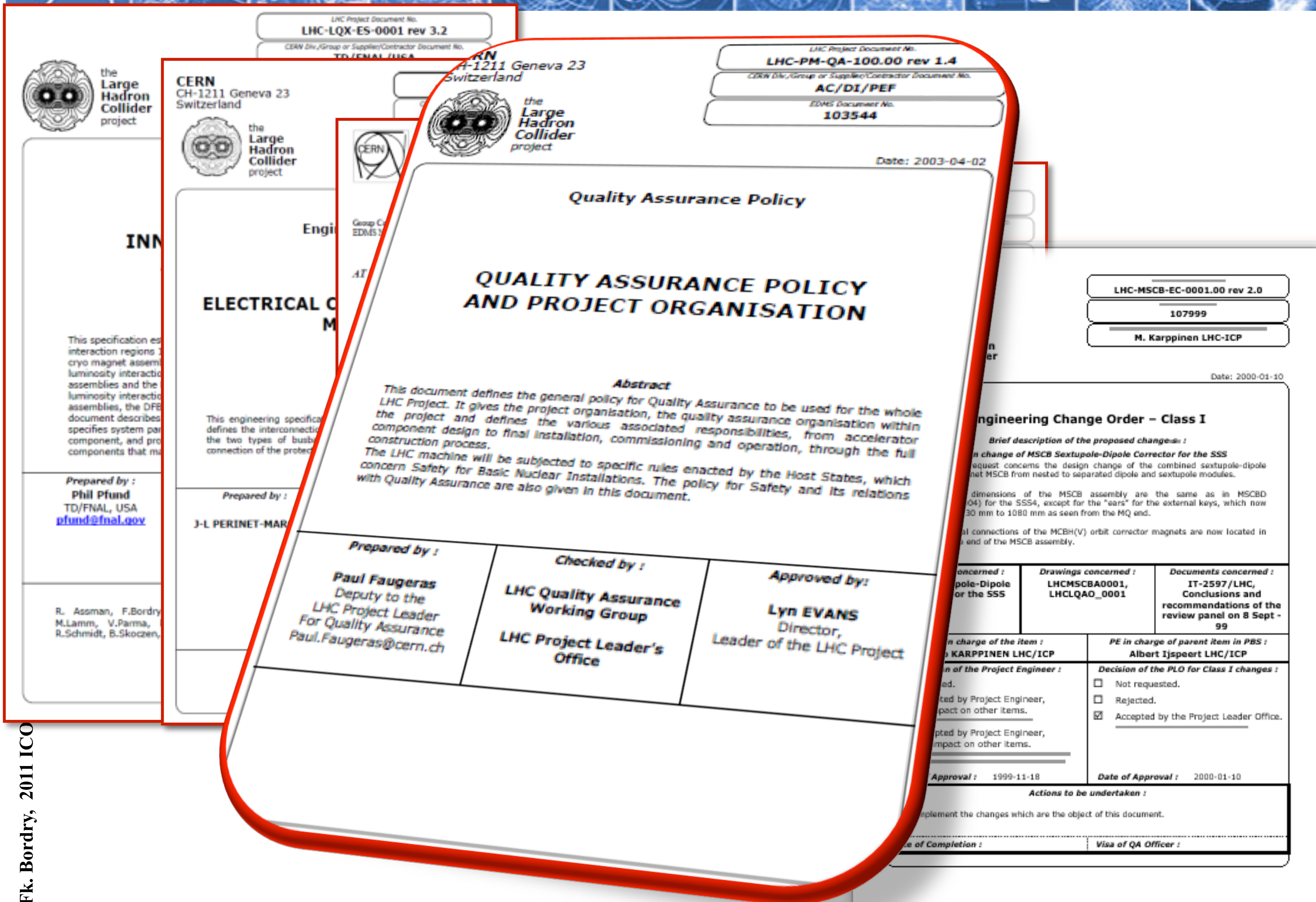
Energy stored in the magnet system: 11.3 GJoule

Ener

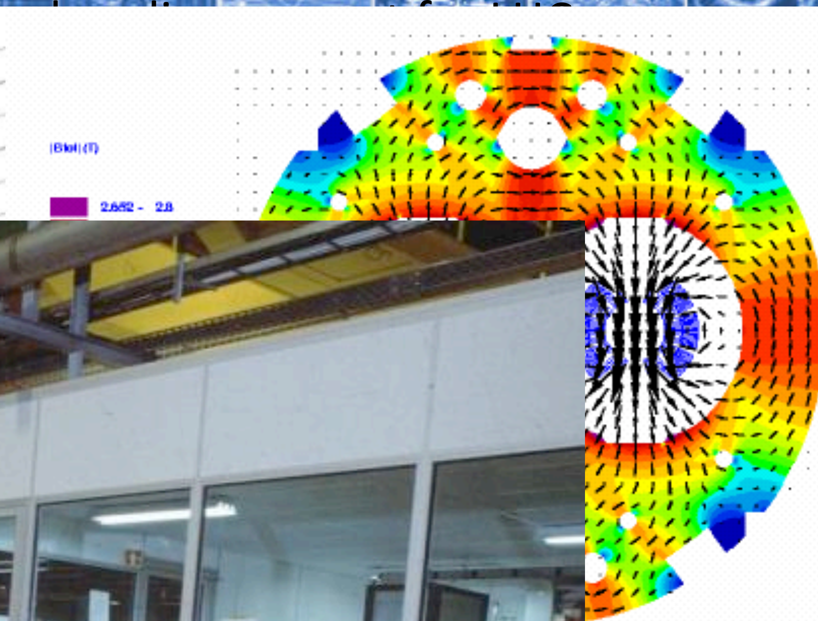
154 magnets in series per sector (x8)

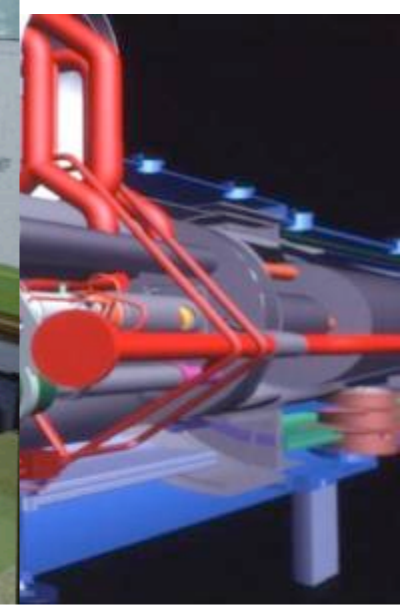


QAP : Very formal process



Conception, simulation and prototypes





100% cold tests at CERN (up to ultimate field)

Contracts by 4.7cm during cool-down

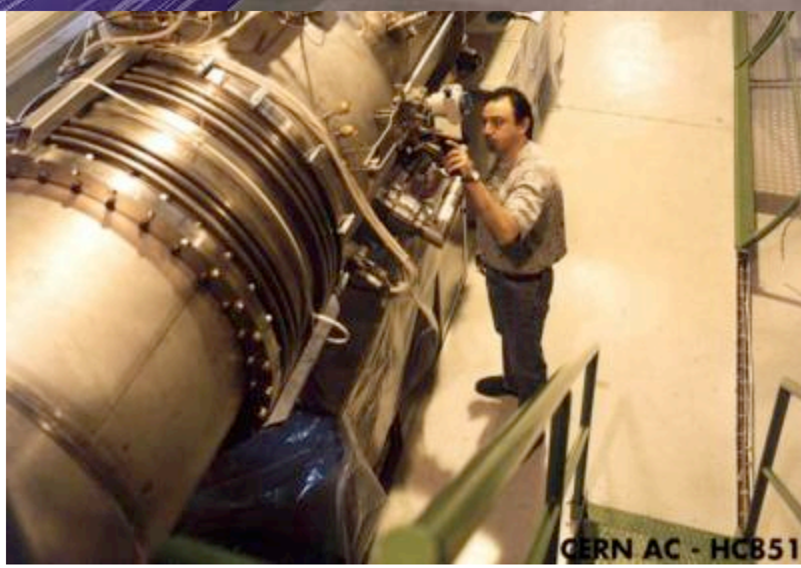
1232 dipoles and 400 quadrupoles

Cold magnetic performance measured on 20% of the magnets
(correlation between warm and cold measurements)

String test :

Full 3D integration

Four years after its start-up, the first test string of the LHC comes to the end of its operation. Composed of prototypes, it made it possible to test and validate the various components and systems of the LHC.



one complete cell (100m)

Interconnections : giant work (QA)

Interconnections the superconducting magnets of LHC means:

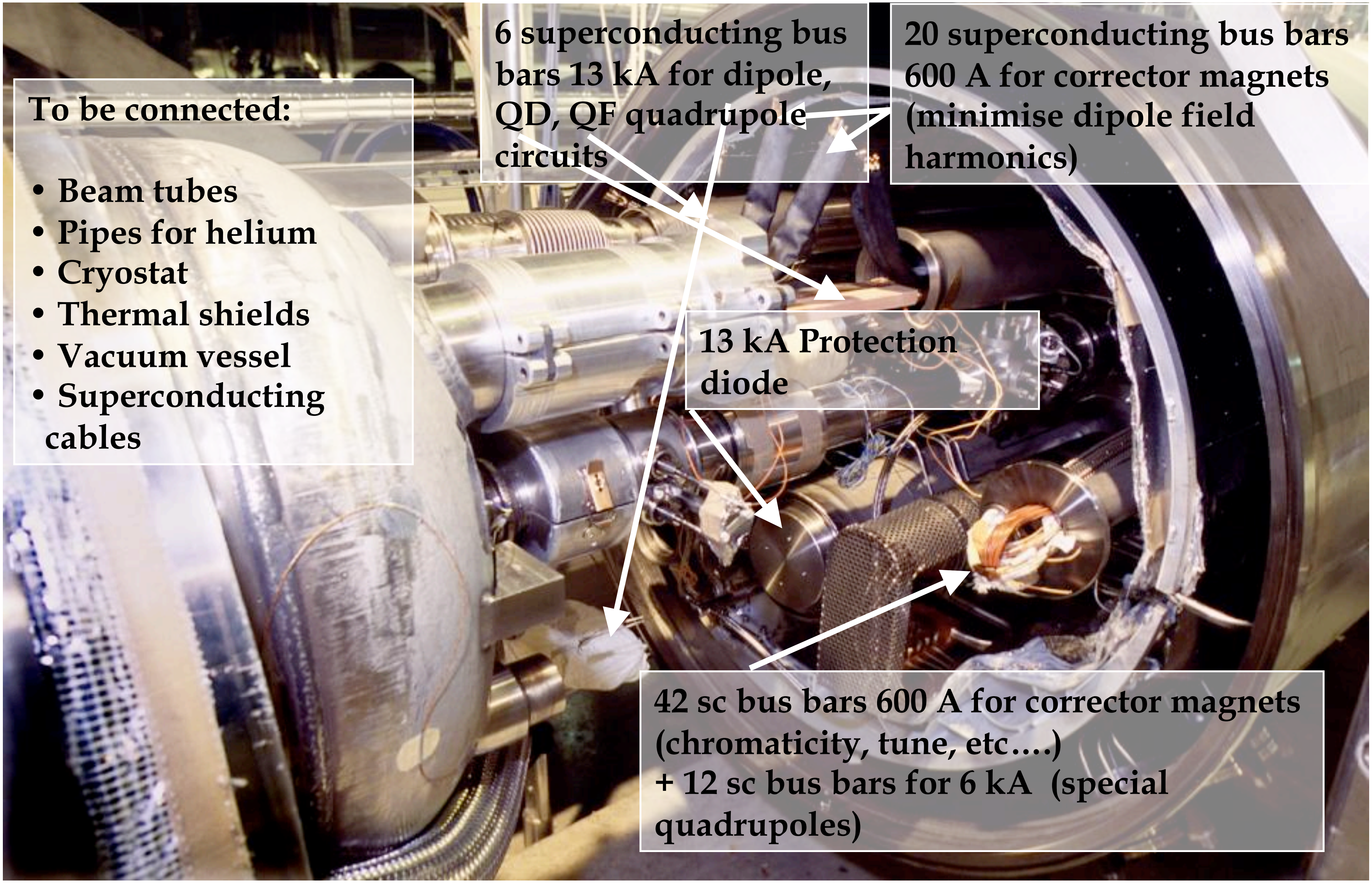
- **1695 magnet-to-magnet interconnects**
- **224 magnet to QRL interconnects**

Each magnet to magnet interconnect consists of:

- ✓ **18 assembly actions divided in 9 interventions**
- ✓ **5 leak tightness check**
- ✓ **5 electrical tests**
- ✓ **1 RF test**

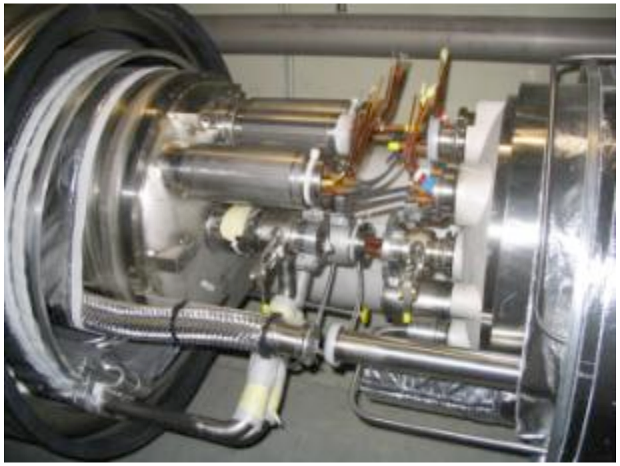
For each sector *(8 sectors*) this is:
1964 assembly interventions
226 electrical tests on sub-assemblies
70 vacuum tests on sub-assemblies
14 RF test on sub-assemblies

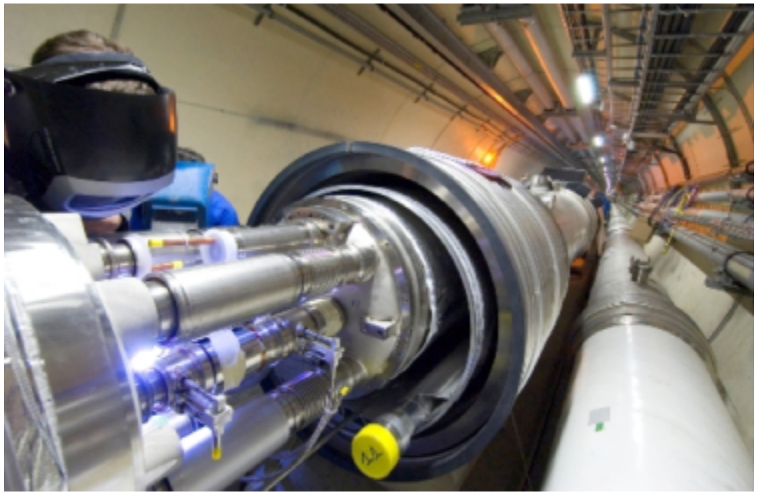
Interconnections : giant work (QA)



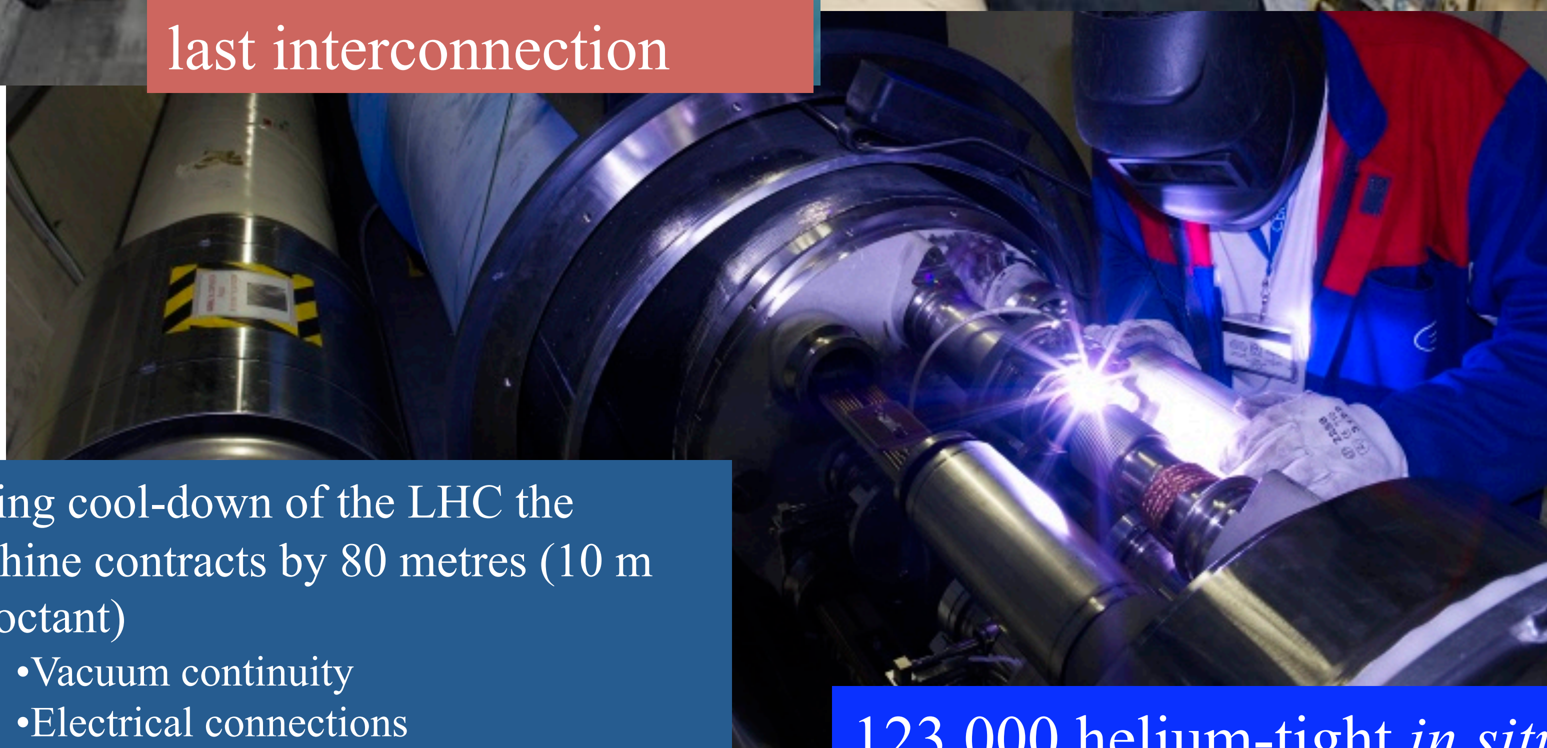
Interconnection (many technical domains): integration and quality are crucial !

- Late start, for cryo-line problems: accelerated rate
- 200 people in the tunnel at peak
  - 100 contractors
  - 100 CERN + associated for managing, QA, repair, in-sourcing of special WPs
- 30 people on surface





7th November 2007
last interconnection



During cool-down of the LHC the machine contracts by 80 metres (10 m per octant)

- Vacuum continuity
- Electrical connections

123 000 helium-tight *in situ* welds

10th September 2008…

The Sector 3-4 incident (just before the 1st ramp with beam)

19th Septembe

last test of the last circuit of the las

Electrical arc betwe

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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken — *Voting Procedure*

For Recommendation to Council	**SCIENTIFIC POLICY COMMITTEE** 255th Meeting 15-16 September 2008	-
For Approval	**CLOSED COUNCIL** 148th Session of Council 18 September 2008	Two-Thirds Majority of All the Member States

One day before the incident

MANAGEMENT STRUCTURE OF CERN
AND LEADERSHIP POSITIONS
for the years 2009 to 2013

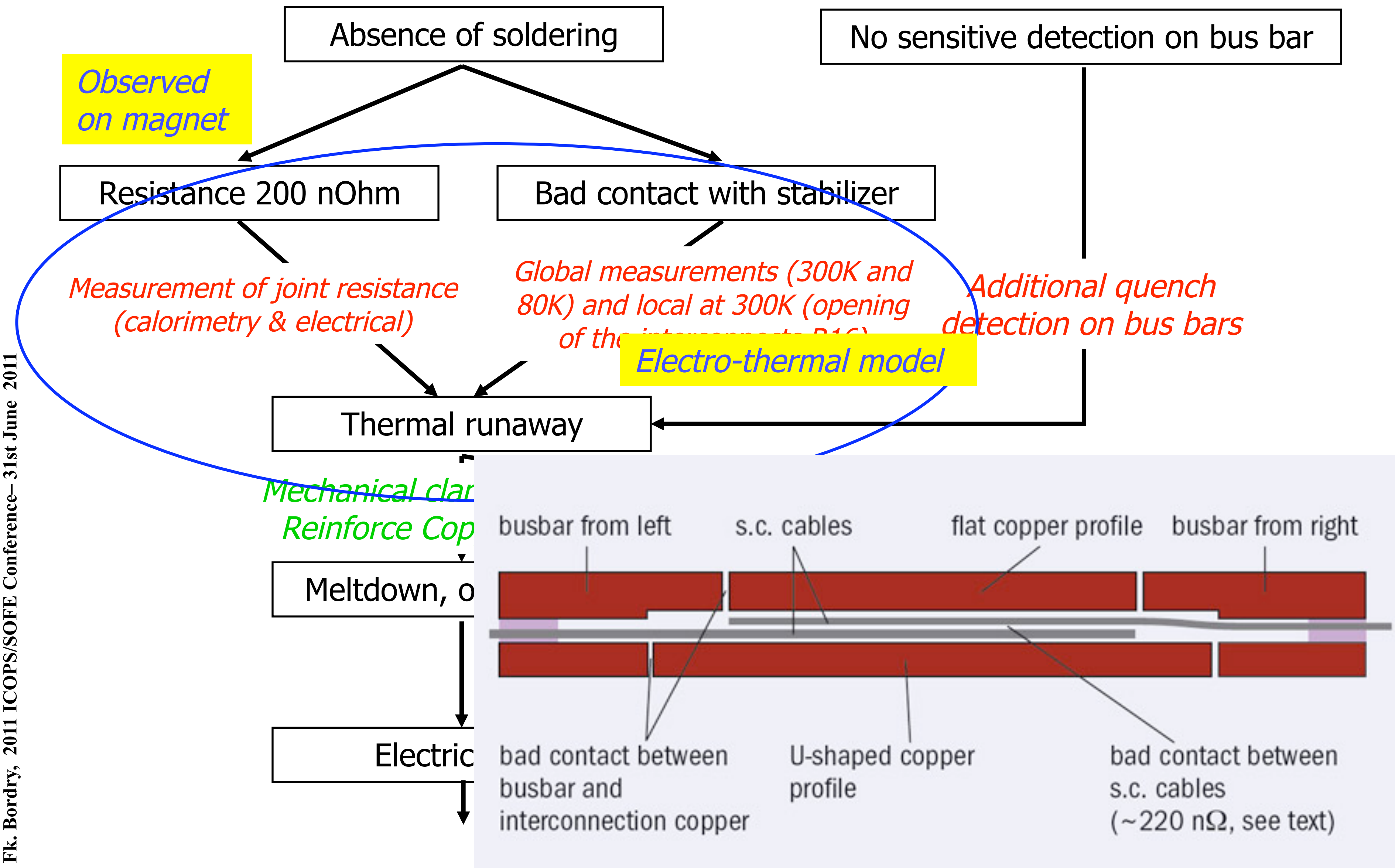
by
Director-General Designate

Consequences

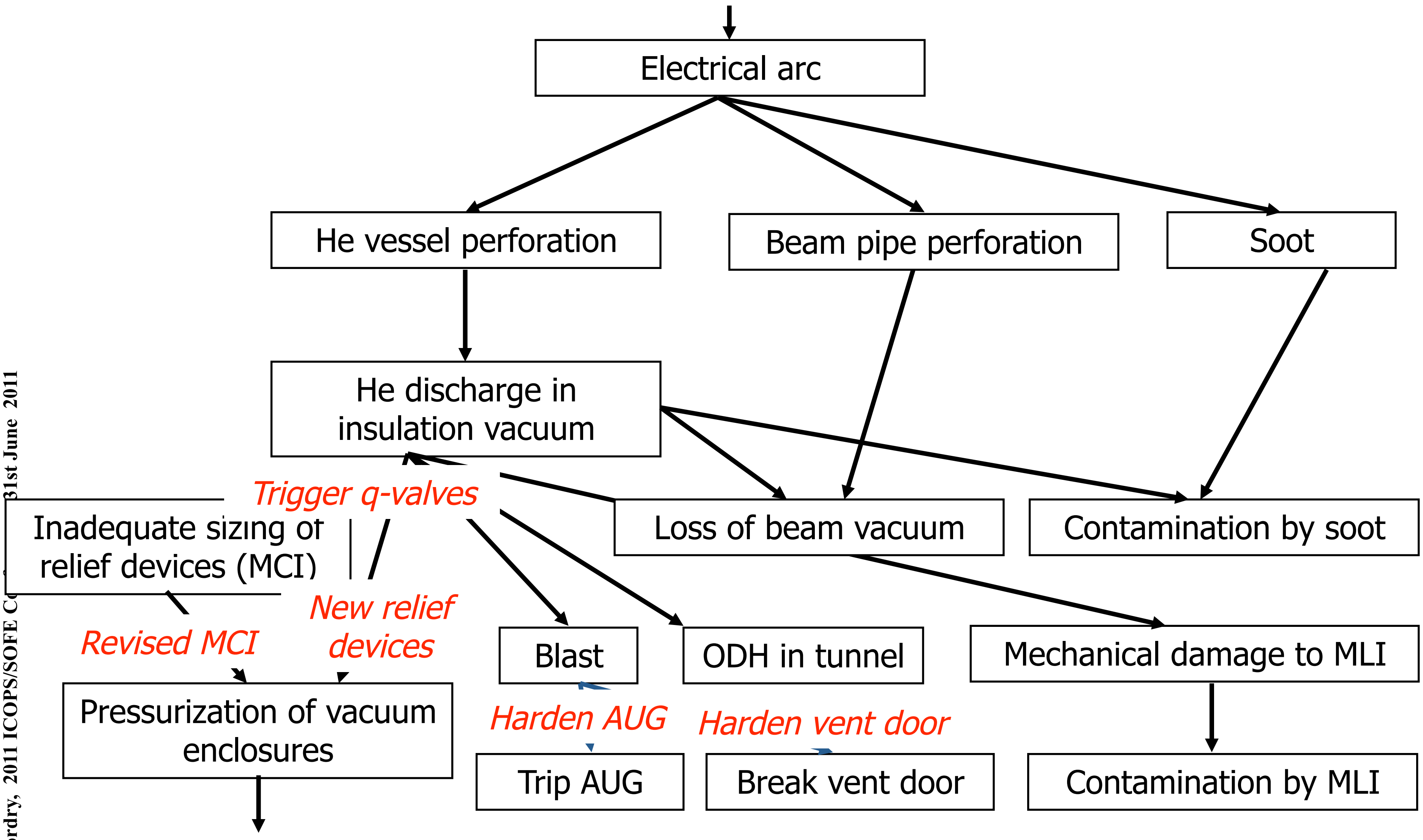
This was NOT a good time for us!!

Collateral damage

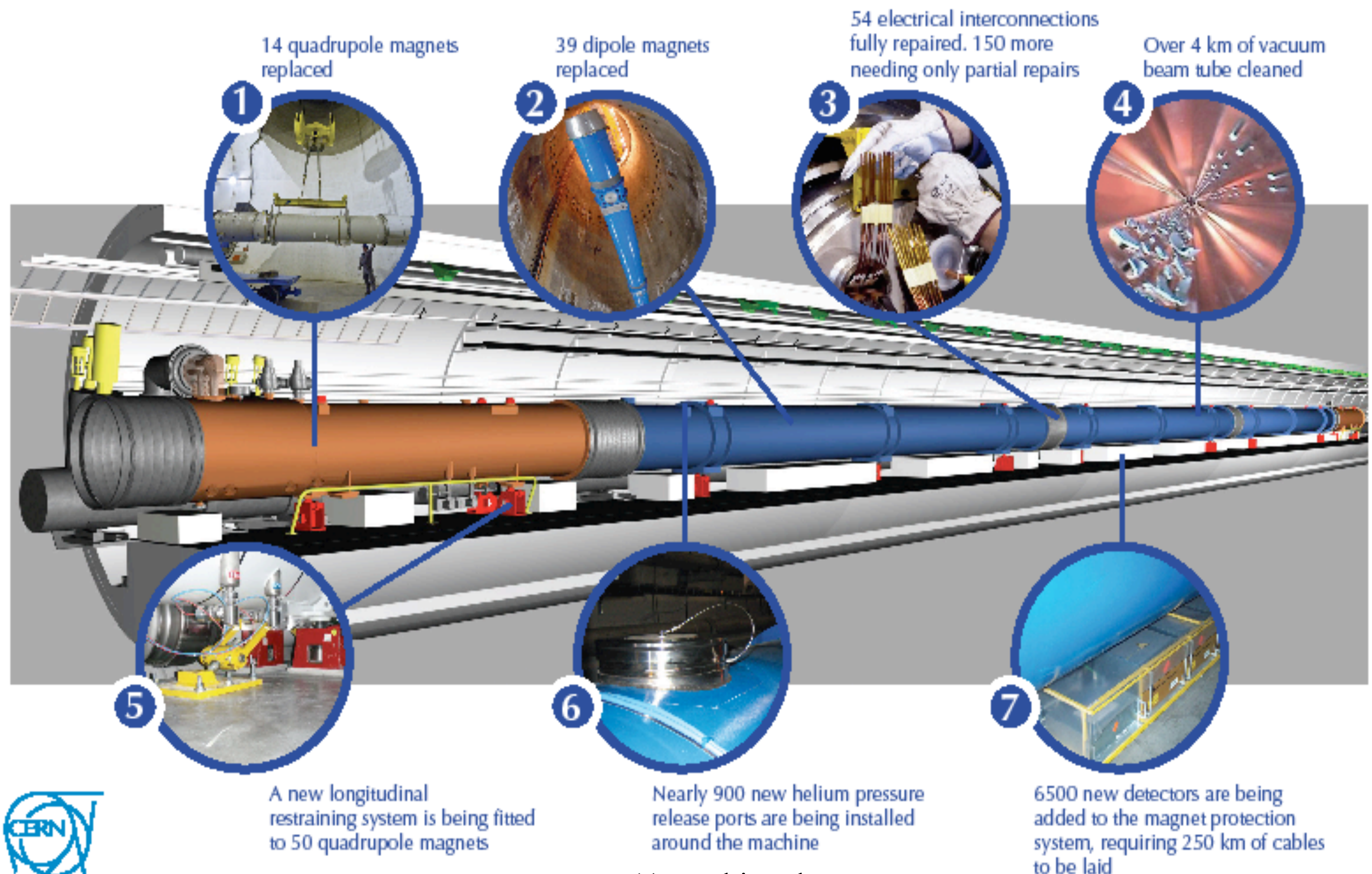
Fault tree and Corrective measures [1/2]



Fault tree and Corrective measures [2/2]



The LHC repairs in detail



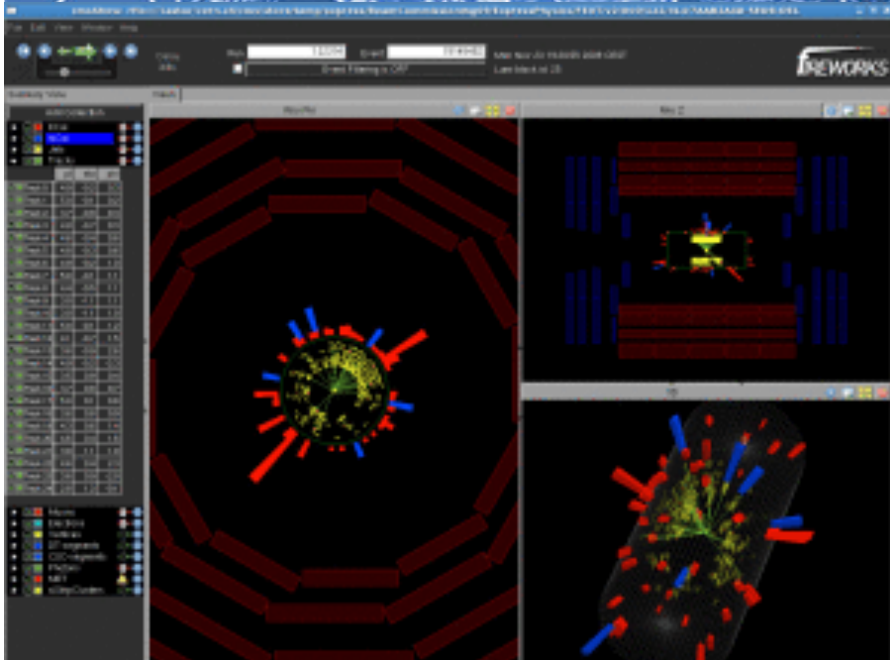
½ machine done

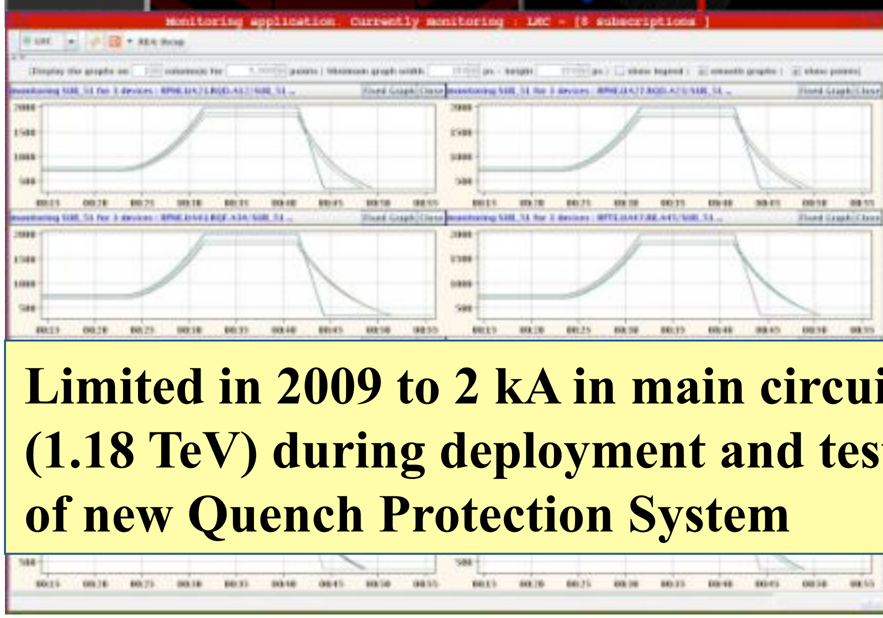
Magnet repair strategy

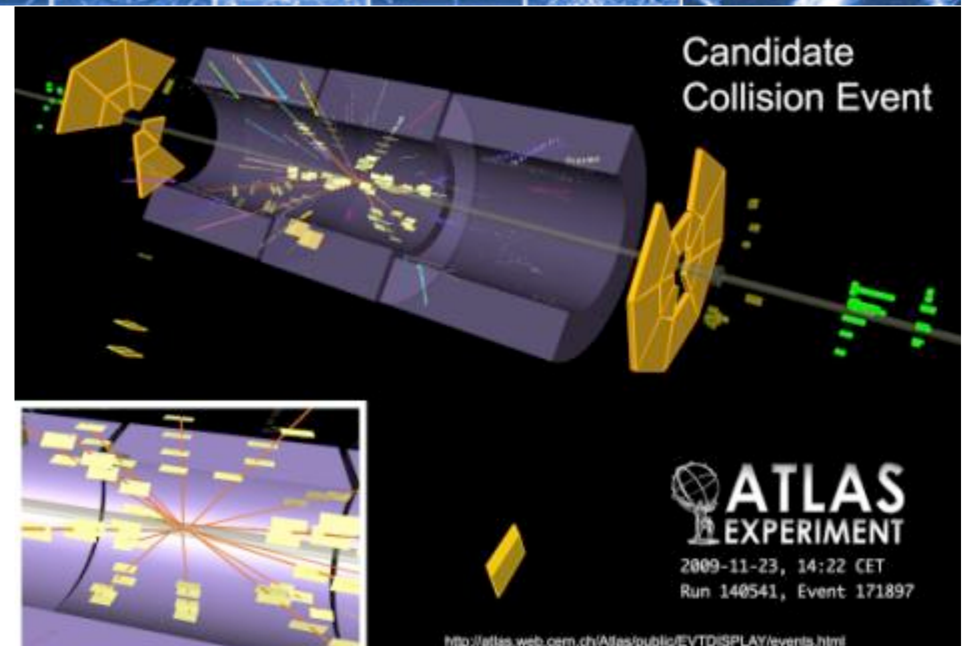
53 magnets replaced in sector 3-4:

- 39 dipoles:
  - 30 new spares
  - 9 recovered from sector 3-4 and refurbished
- 14 Short Straight Sections:
  - 7 new spares
  - 7 recovered from sector 3-4 and refurbished
- All cold tested (or re-tested)
- Spares available, but just enough!

Beam back on 20th November 2009

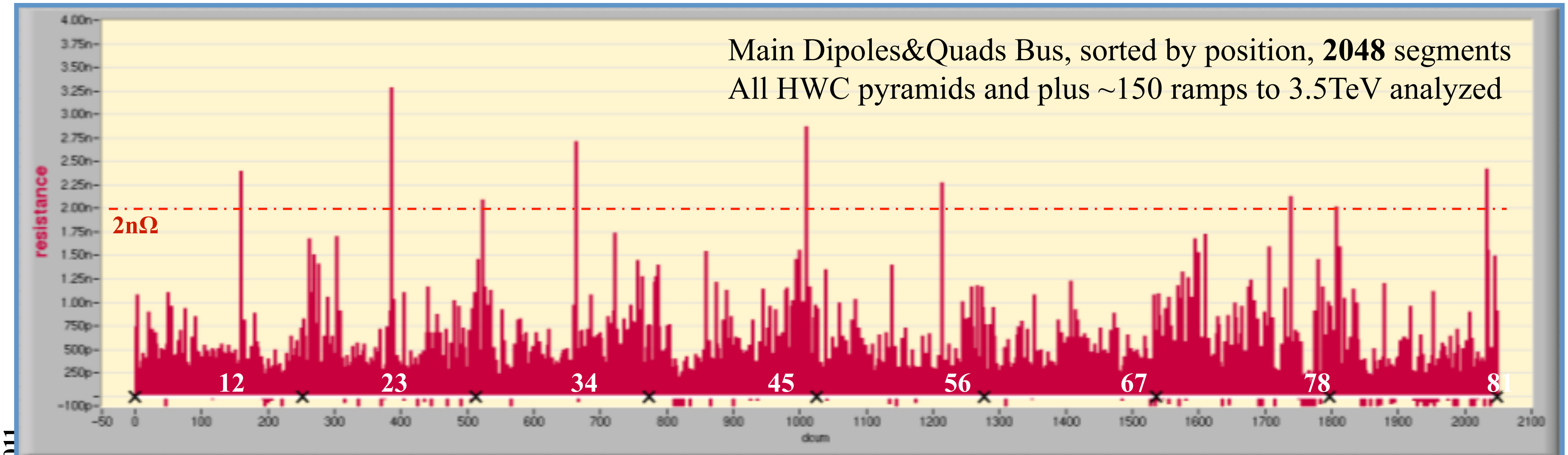


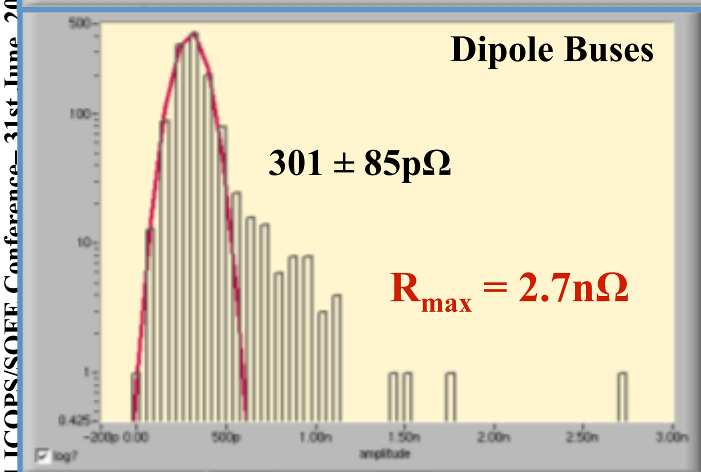


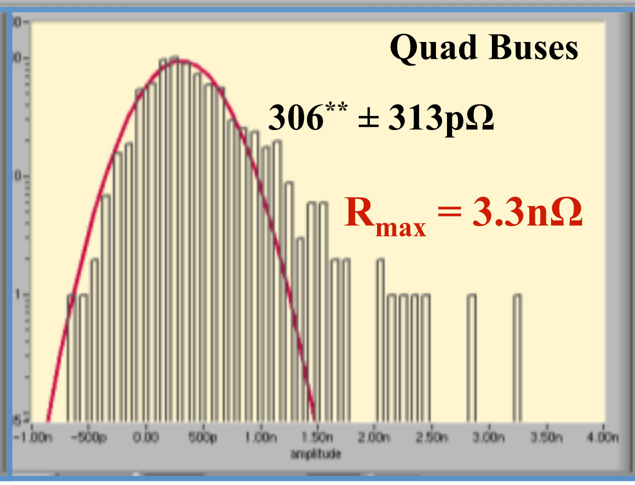


Limited in 2009 to 2 kA in main circuits (1.18 TeV) during deployment and testing of new Quench Protection System

LHC main splices today: busbars SC







<u>Top 10 Splice Resistances</u>

MQ.A23	MQ.33L3.B2	<->	MQ.33R2.B2	3.28E-09
MQ.A45	MQ.12L5.B2	<->	MQ.11L5.B1	2.87E-09
MB.A34	MB.A31L4	<->	MB.C31L4	2.71E-09
MQ.A81	MQ.12L1.B2	<->	MQ.11L1.B1	2.42E-09
MQ.A12	MQ.27L2.B2	<->	MQ.25L2.B2	2.40E-09
MQ.A56	MQ.21L6.B2	<->	MQ.19L6.B2	2.27E-09
MQ.A78	MQ.20L8.B1	<->	MQ.22L8.B1	2.13E-09
MQ.A34	MQ.9R3.B2	<->	MQ.11R3.B2	2.09E-09
MQ.A81	MQ.11R8.B2	<->	DFLAS.7R8.4	2.02E-09
MB.A34	MB.C19L4	<->	MB.B20L4	1.74E-09

(**) number of splices in the quads segments corrected, 1.3 added

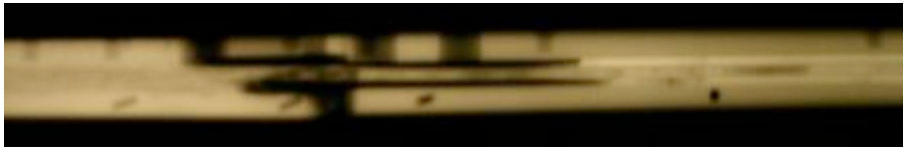
From Z. Charifoulline

All the work done since November 2008 makes certain that a repeat of September 19th 2008 can NEVER happen.

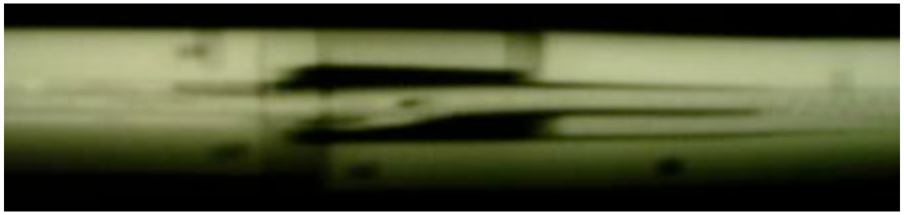
The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.7nΩ for dipole busbars and 3.3nΩ for dipole busbars

BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the "copper stabilizers" of the magnet interconnects

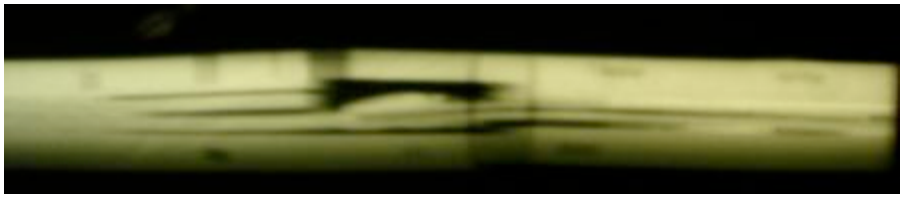
Sample pictures



Sample 1 (61 μΩ)

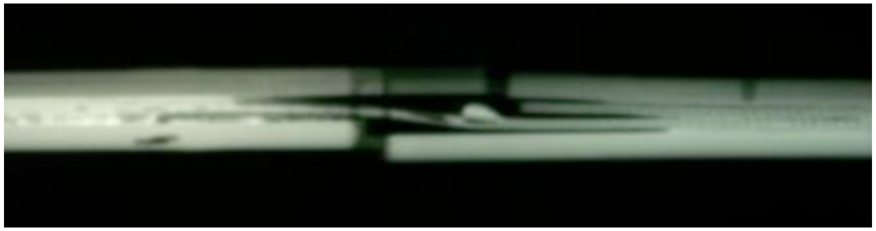


Sample 2A left (32 μΩ)

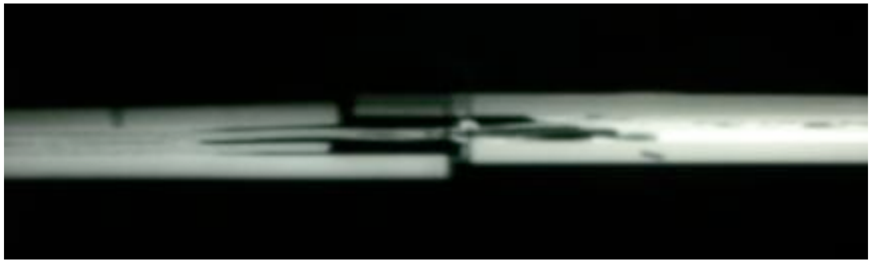


Sample 2A right (43 μΩ)

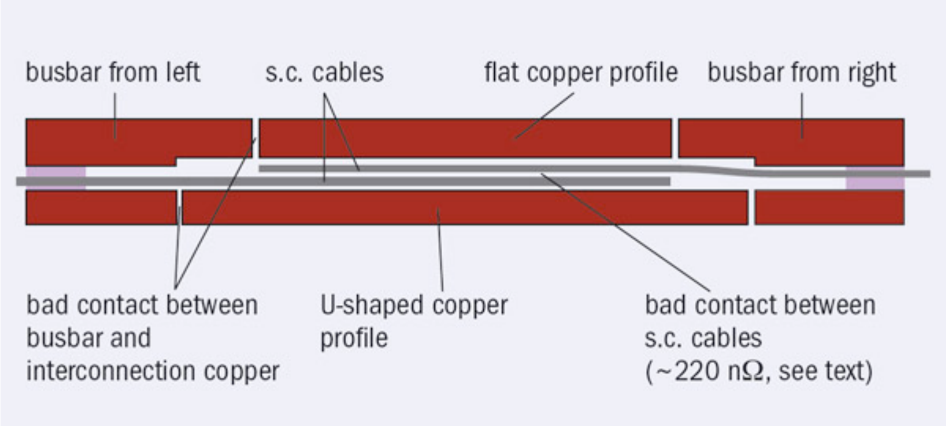
Sample 2B (42 μΩ)



Sample 3A left (26 μΩ)



Sample 3A right (43 μΩ)

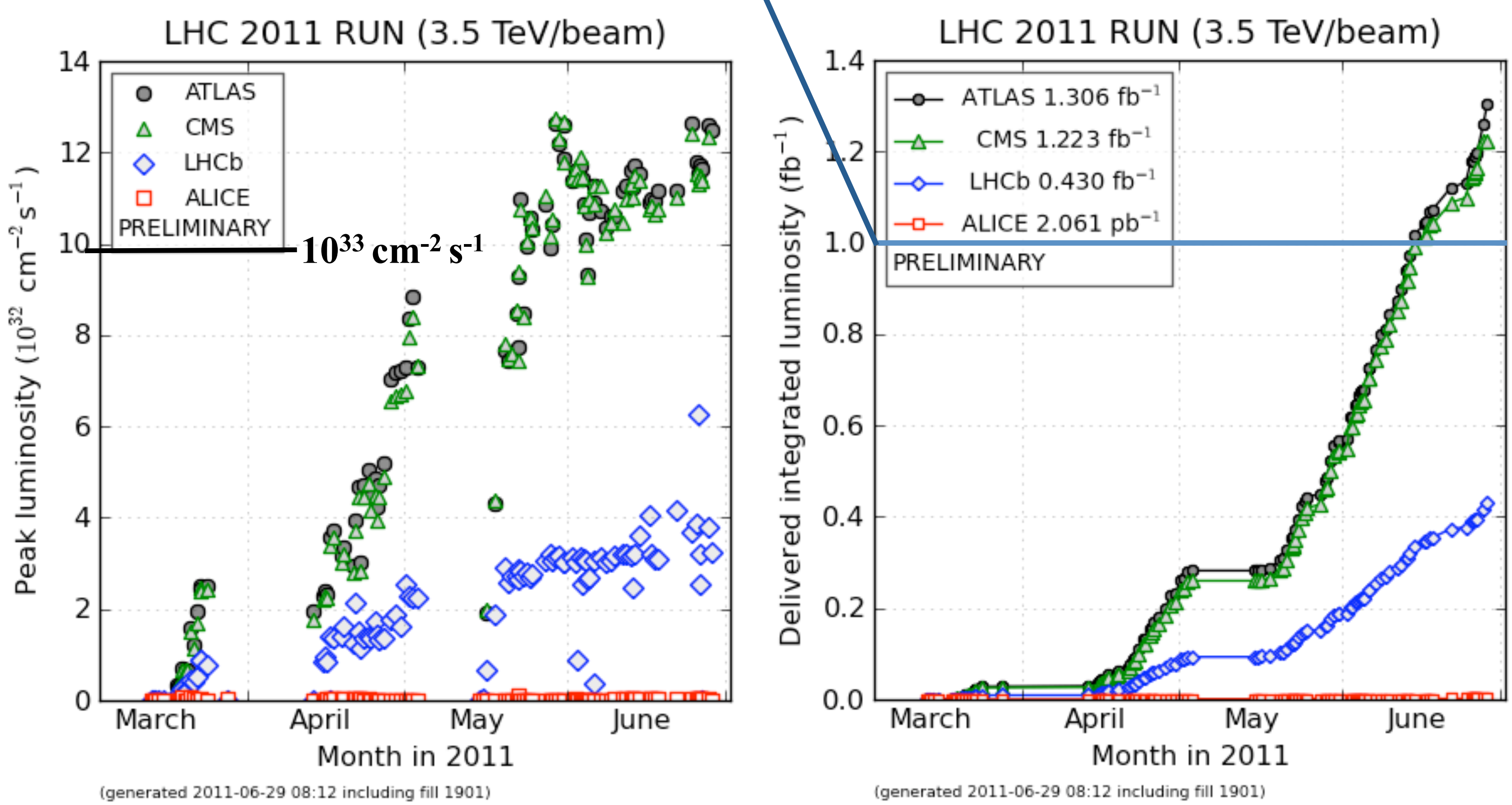


30th March 2010: first collisions at 7 TeV (2 x 3.5 TeV)

Luminosity evolution 2011 (proton)

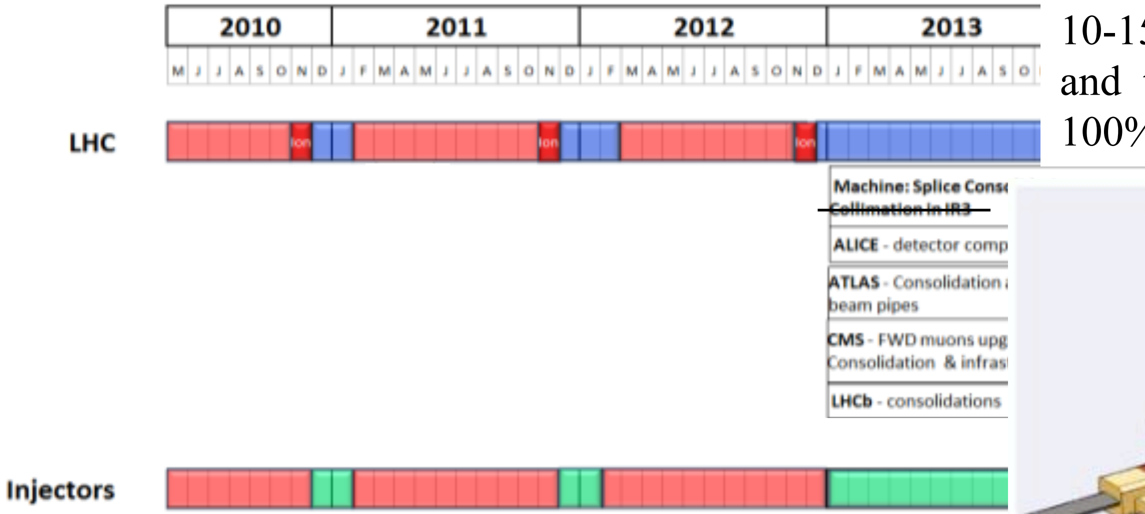
Initial goal for 2011: 1 fb^{-1}

~50 pb^{-1} delivered in 2010
Already above 1.3 fb^{-1} in 2011

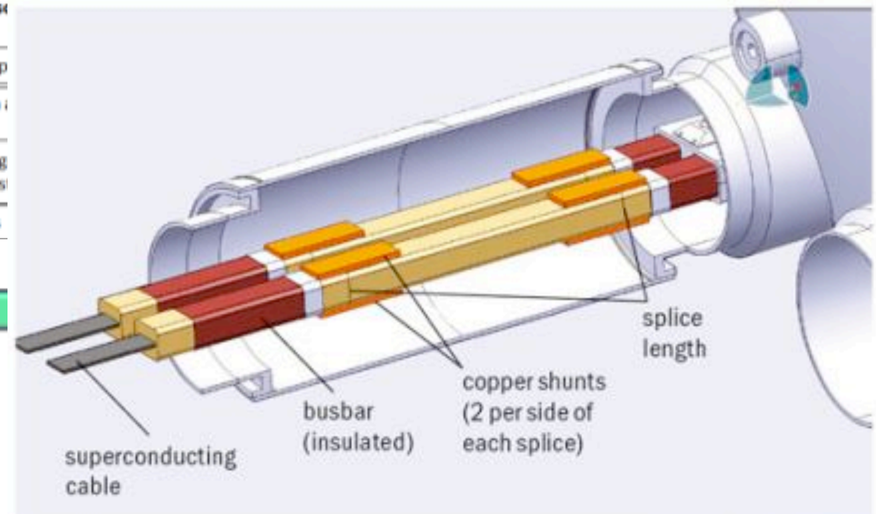


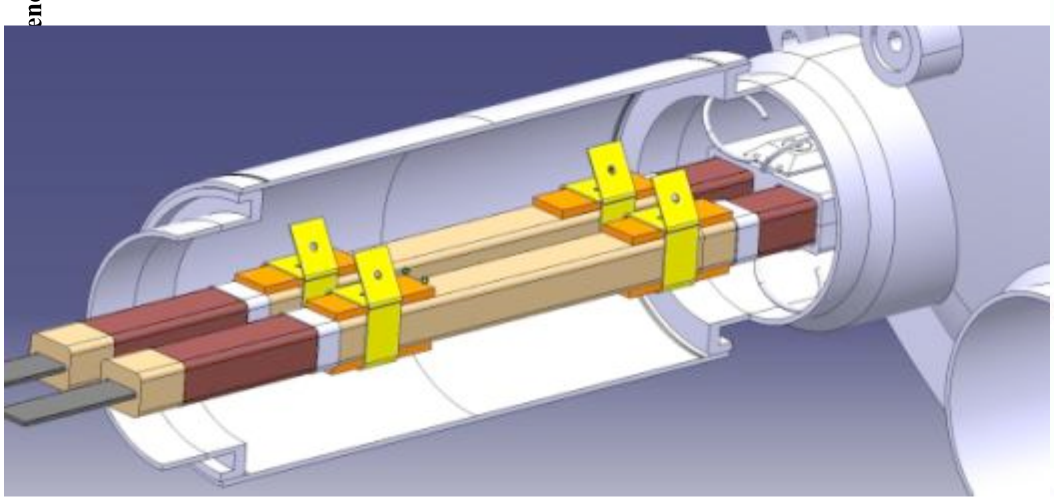
29th June 2011

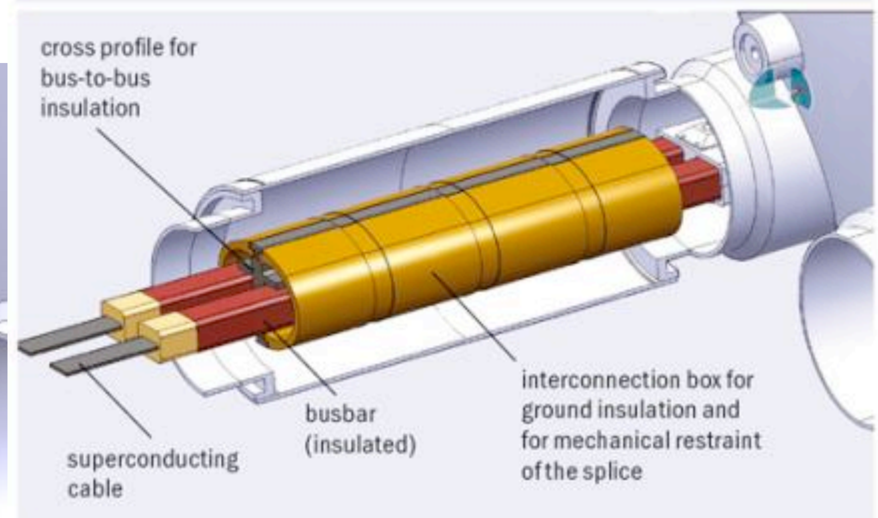
2013-2014 long shutdown



10-15 % of interconnections to be opened and to be re-welded
100% (10’000) to be consolidated







ence– 31st June

ween 6.5

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Fk. Bo

LHC experience

The LHC is its own prototype!

Limit in all technologies: field 9T, 1.9K, 1 ppm precision demanded from the power converters, high vacuum, protection, energy storage, ...

Complexity of the project.

In an accelerator (accelerator chain): the components are all in series!

Experience in the field of accelerators and large projects.
Continuity of projects since 1954 (PS, SPS, ISR, LEP, LHC).
Project based on the competence of specialists (design, construction, operation, maintenance)

Systematization of prototypes and when possible sub-systems (String 1 and String 2)
Individual component tests, e.g. electrical testing of 100% cold magnets and magnetic measurements of 20% (after verification of the measurement transfer between warm to cold conditions).

Long Hardware Commissioning of equipments (debugging)

LHC experience (cont'd)

- **LHC QAP: introduction of EDMS** ***(data available on-line worldwide, functional specification, technical specification, Engineering Change Request, ...)***
- **Complete integration (3D)**
- **EVM (Earned Value Management)**
- **Competitive production contracts,** **when possible n+1 strategy**
- **LHC Technical committee involving every group leader of the systems**

- **Reviews: systematic, independent, international**
- **Machine Advisory Committee**

Final Design – Quality - Cost (M +P) – Planning - Pressure

In a project as large and innovative as LHC it is not realistic to expect that everything goes smooth without problems. The incident in Sept.2008 is one of the problems that we had, there were others with similar consequences, but less noticed by the public. Example are the QRL (Cryogenics Line) (probably more expensive that the 2008 accident), ...

Large projects of the size of the LHC are never riskless.
Excluding any risk would be out of reach (P+M)
Risks are to be evaluated and accepted

Problems are not to be hidden.
Create a structure allowing problems to surface (open atmosphere), especially under heavy pressure.

QA IS VITAL but it takes time !

Tests are to be performed by independent teams (especially if outsourcing)

Lessons learned

Don't minimize the interfaces : interface specifications shall be systematic
Don't under consider systems : often considered as low-technology

Think system and global protection from the design (forum, committees, fight against group territory).
Electro-mechanical systems are complex: specialists of both are rare and close cooperation is crucial

Avoid overconfidence during the commissioning

Difficult period after the incident: depression, fear,…
Fact findings and then strategy plan by stages and crash programs
Take the personnel's fatigue into account
Rebuild the motivation of the teams.

Have on site enough competent staff with the know-how
Have a strong support of many institutes (and industries) that collaborate

Lessons learned

Staged approach : ½ energy 3.5 TeV (1/4 of power) is very important to learn how to operate the machine and to cure teething problems

14 month-delay: short repair (~ 4 months) thanks to spare equipments.
Consolidation and completion of many other systems.
Experiments needed more time to be completed.

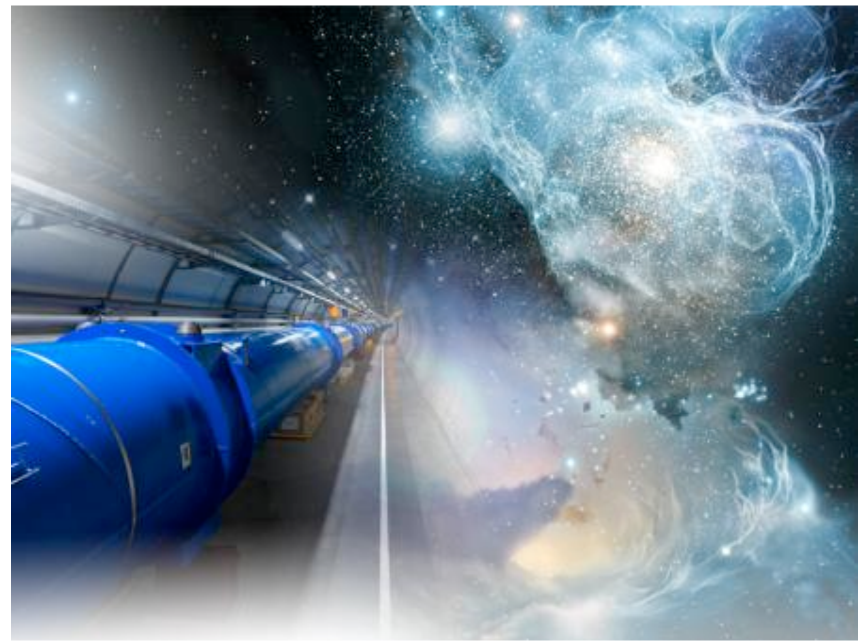
This allowed to commission LHC in shorter time (many weaknesses were corrected: important for the LHC long operation).

We caught up !

There is light at the end of the tunnel !

Robert Aymar:
The machine is well designed.
Be proud of it.
I'm confident ,you'll correct the problem
Be strong and courageous.
Do not be terrified; do not be discouraged

The last 3 years were absorbing, captivating and finally successful for the LHC



As any large and complex project, LHC was not all plain sailing project but CERN and collaborations have shown an impressive reactive force to overcome the obstacles, to put into operation the machine ***(with intensity, peak and integrated luminosity going up very rapidly)*** **and continue progressing towards the nominal performance.**

Thanks for your attention