

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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CERN – Head of Technology Department

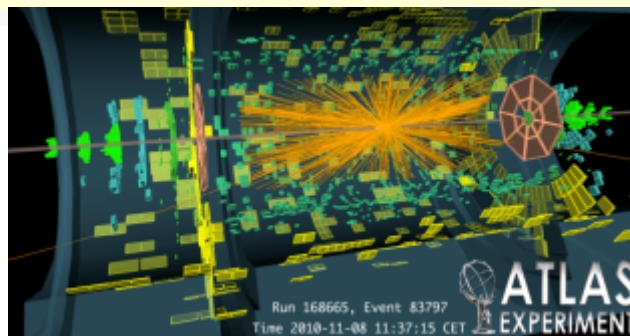
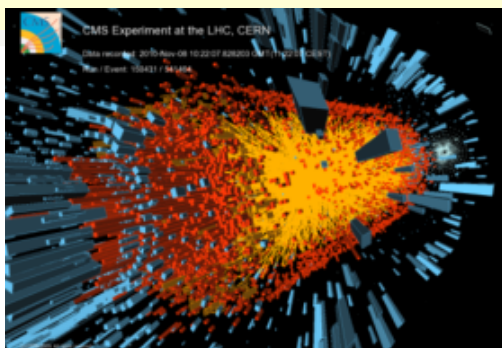
ICOPS 2011 SOFE





Menu

- LHC machine recap and main challenges
- Magnet interconnection activity
- 10th and 19th 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**



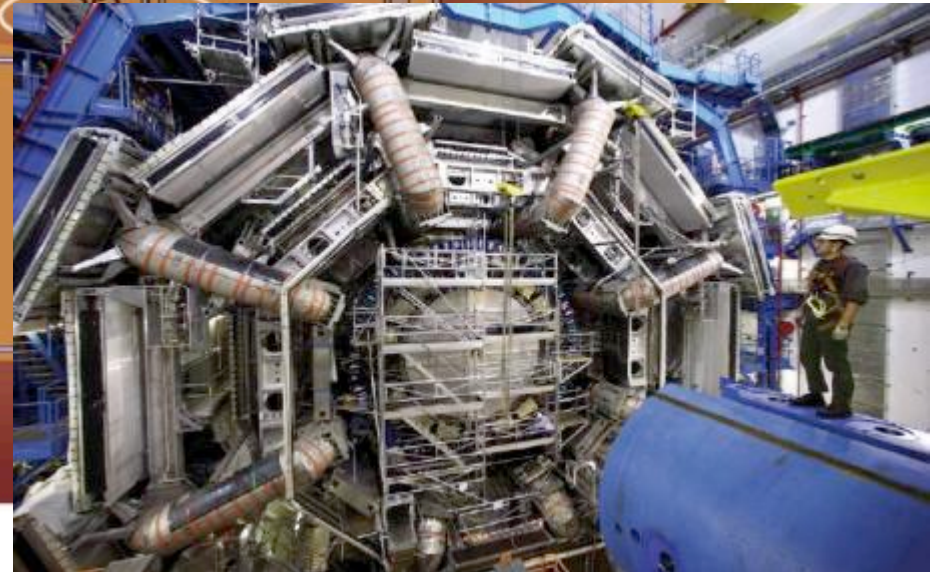
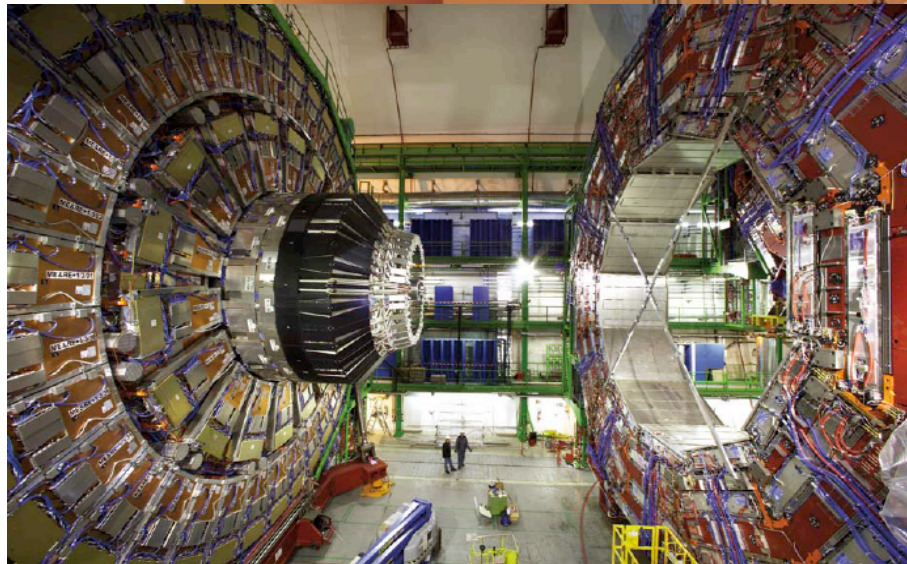
- 1982 : First studies for the LHC project**
- 1994 : Approval of the LHC by the CERN Council**
- 1996 : Final decision to start the LHC construction**
- 2004 : Start of the LHC installation**
- 2006 : Start of hardware commissioning**
- 2008 : End of hardware commissioning and start of commissioning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

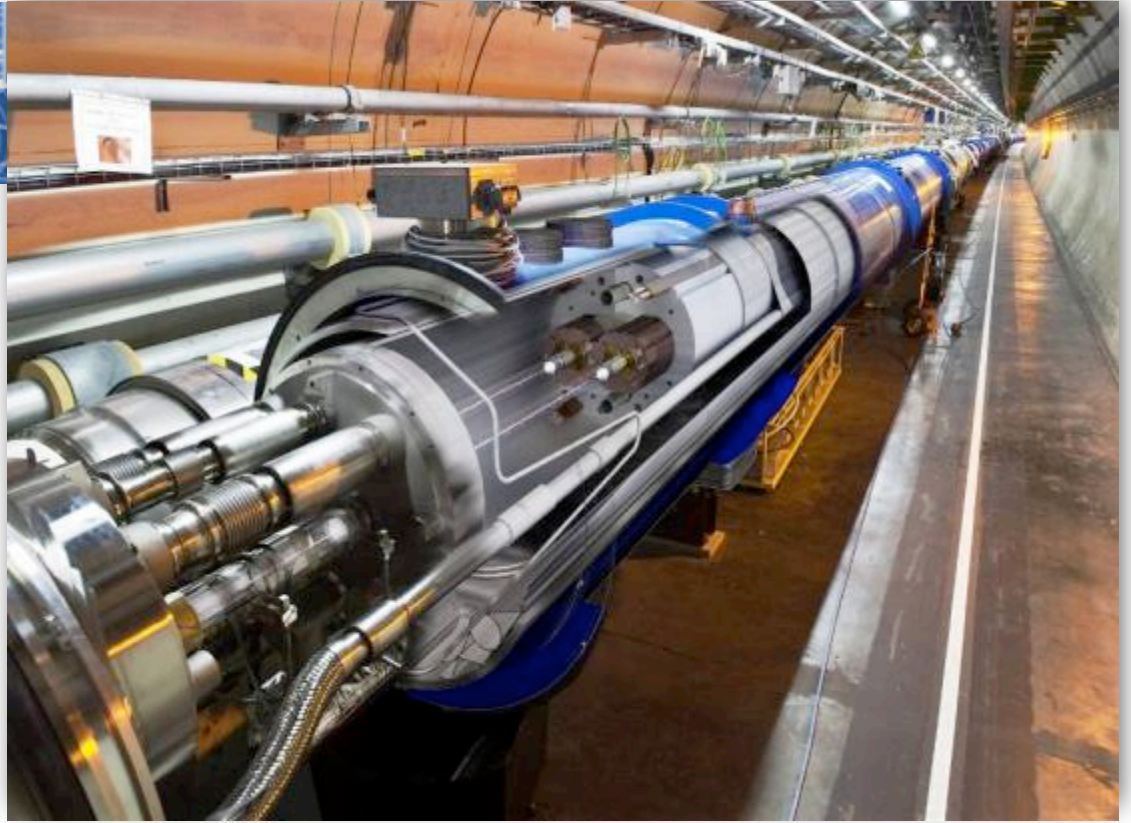
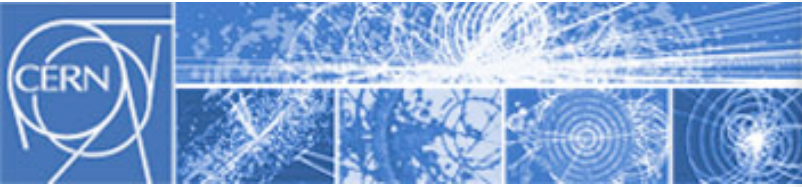
Beams of LEAD nuclei will be also accelerated, smashing together with a collision energy of 1150 TeV

Overview of the project of LHCs



CMS Point 5





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**

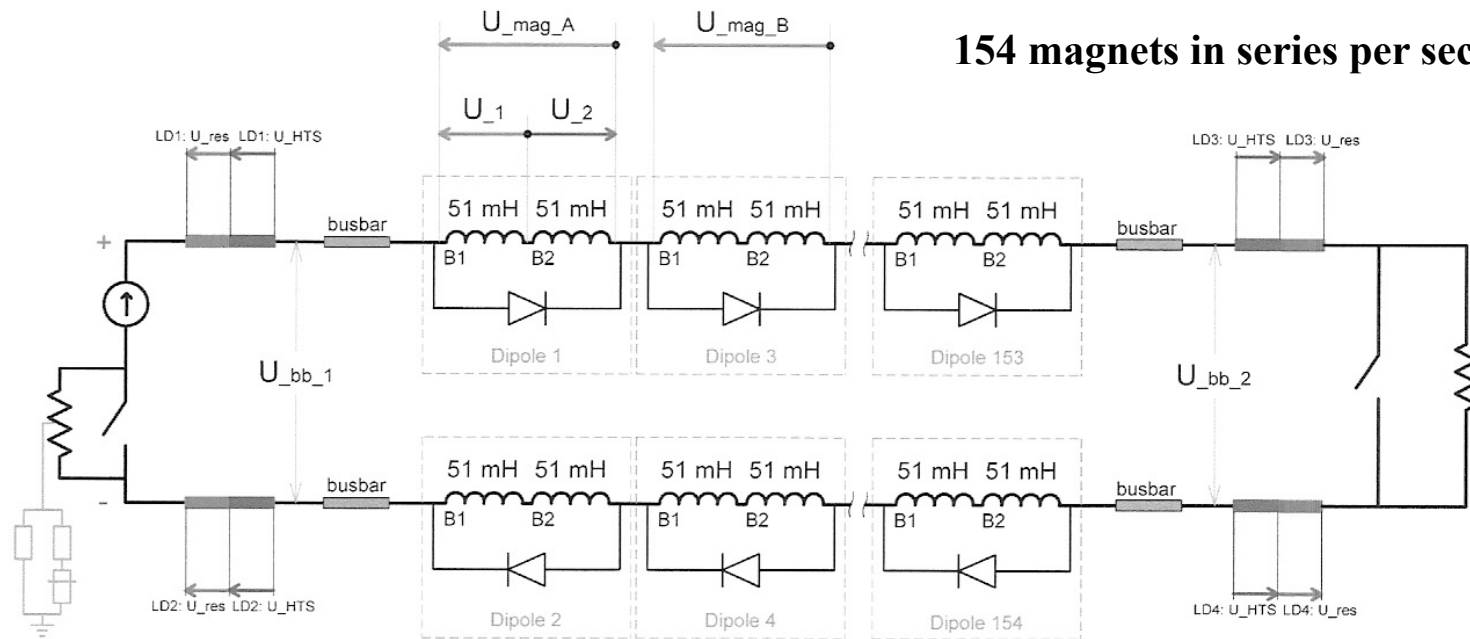


Energy management challenges

Energy stored in the magnet system: **11.3 GJoule**



Ener





QAP : Very formal process

LHC Project Document No. LHC-LQX-ES-0001 rev 3.2
 CERN Div./Group or Supplier/Contractor Document No. TD/FNAL/USA

LHC Project Document No. LHC-PM-QA-100.00 rev 1.4
 CERN Div./Group or Supplier/Contractor Document No. AC/DI/PEF
 EDMS Document No. 103544

Quality Assurance Policy

QUALITY ASSURANCE POLICY AND PROJECT ORGANISATION

Abstract
 This document defines the general policy for Quality Assurance to be used for the whole LHC Project. It gives the project organisation, the quality assurance organisation within the project and defines the various associated responsibilities, from accelerator component design to final installation, commissioning and operation, through the full construction process. The LHC machine will be subjected to specific rules enacted by the Host States, which concern Safety for Basic Nuclear Installations. The policy for Safety and its relations with Quality Assurance are also given in this document.

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LHC Project Document No. LHC-MSCB-EC-0001.00 rev 2.0
 107999
 M. Karppinen LHC-ICP

Engineering Change Order - Class I

Brief description of the proposed change:
 In change of MSCB Sextupole-Dipole Corrector for the SSS request concerns the design change of the combined sextupole-dipole magnet MSCB from nested to separated dipole and sextupole modules. The dimensions of the MSCB assembly are the same as in MSCBD (V4) for the SSS4, except for the "ears" for the external keys, which now are 30 mm to 1080 mm as seen from the MQ end. The electrical connections of the MCBH(V) orbit corrector magnets are now located in the end of the MSCB assembly.

Documents concerned :
 Sextupole-Dipole Corrector for the SSS

Drawings concerned :
 LHCMSCB0001, LHCLQAO_0001

Documents concerned :
 IT-2597/LHC, Conclusions and recommendations of the review panel on 8 Sept - 99

In charge of the item :
 M. KARPPINEN LHC/ICP

PE in charge of parent item in PBS :
 Albert Jaspers LHC/ICP

Decision of the PLO for Class I changes :
 Not requested.
 Rejected.
 Accepted by the Project Leader Office.

Approval : 1999-11-18
Date of Approval : 2000-01-10

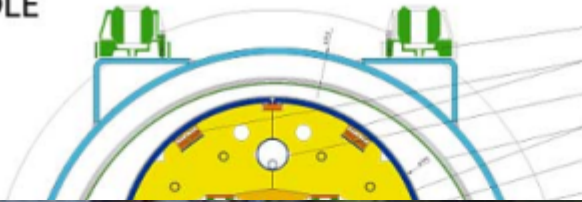
Actions to be undertaken :
 Implement the changes which are the object of this document.

Date of Completion : _____
Visa of QA Officer : _____



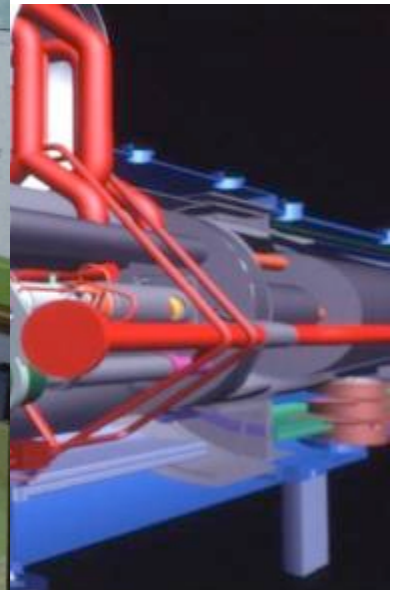
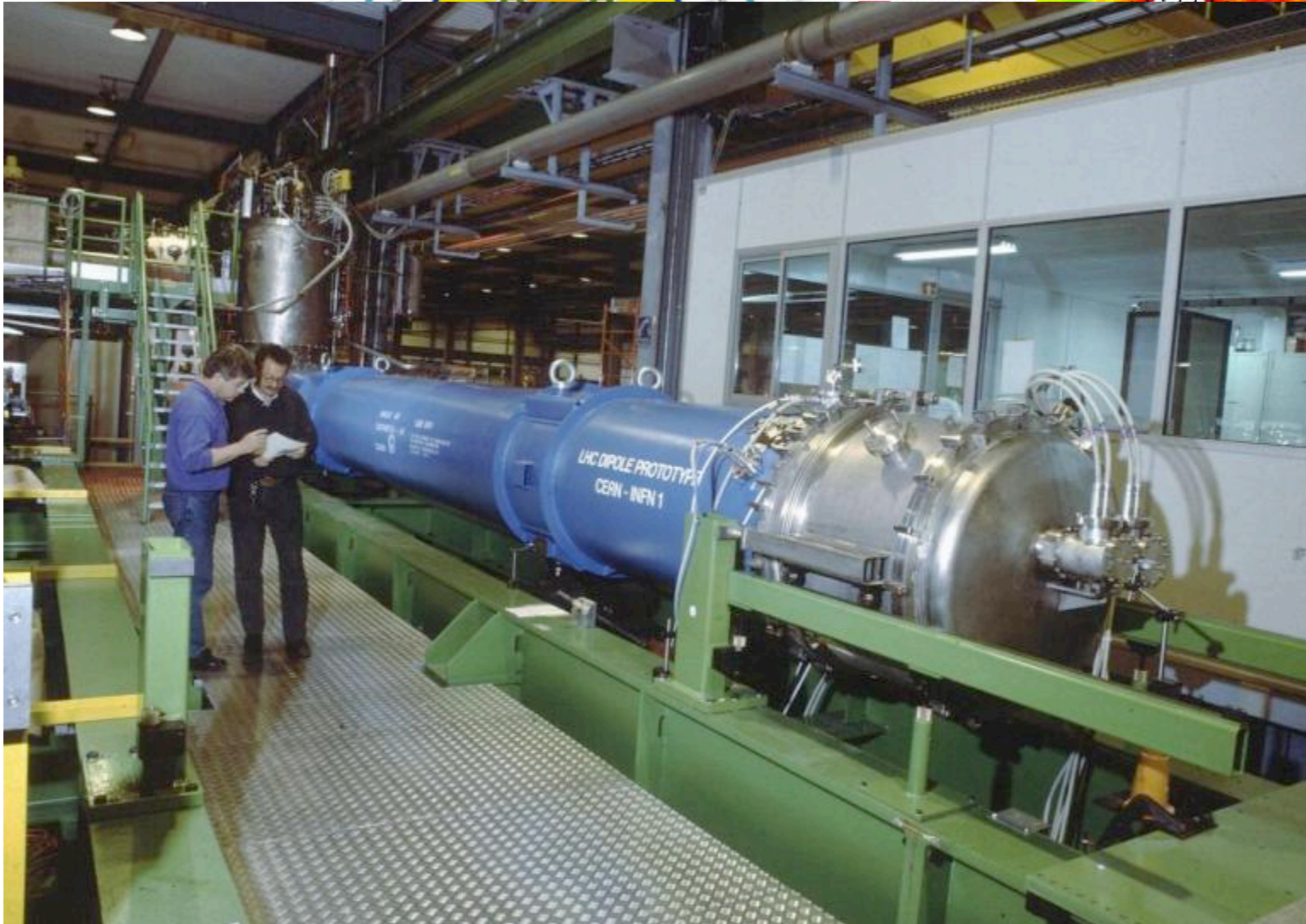
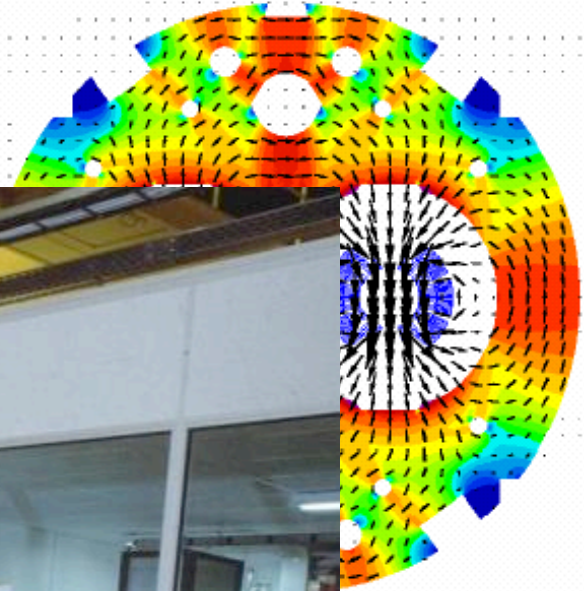
Conception, simulation and prototypes

LHC DIPOLE
CROSS SECTION



|B_{net}(T)

2.652 - 2.8





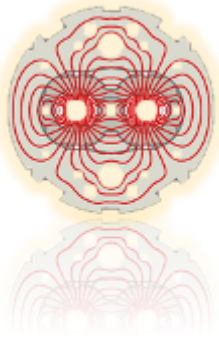
100% cold tests at CERN (up to ultimate field)



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)

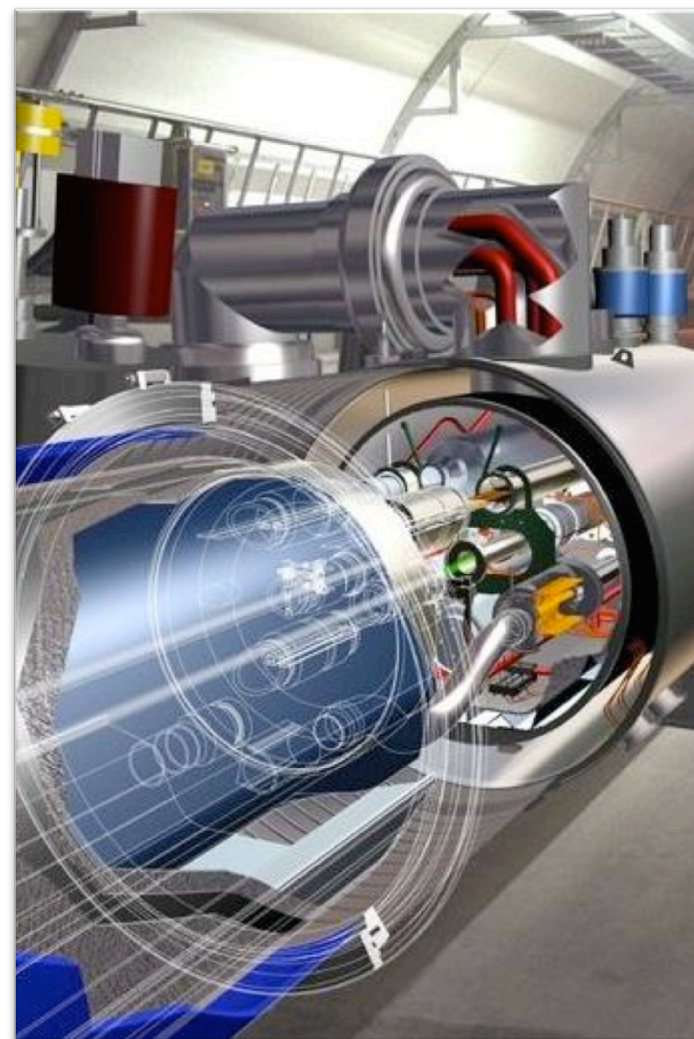
Interconnections the superconducting magnets of LHC means:

- **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)

To be connected:

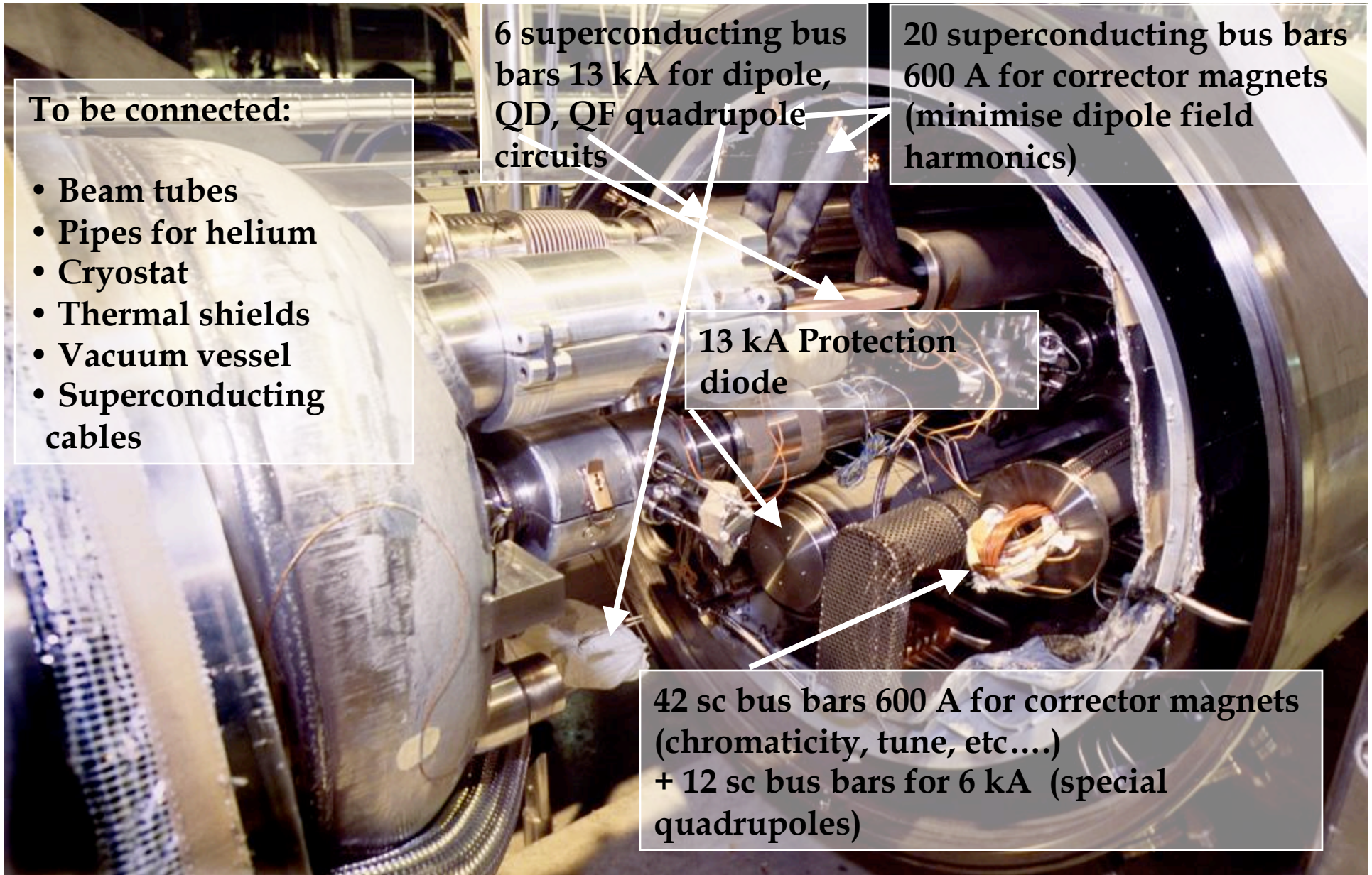
- Beam tubes
- Pipes for helium
- Cryostat
- Thermal shields
- Vacuum vessel
- Superconducting cables

6 superconducting bus bars 13 kA for dipole, QD, QF quadrupole circuits

20 superconducting bus bars 600 A for corrector magnets (minimise dipole field harmonics)

13 kA Protection diode

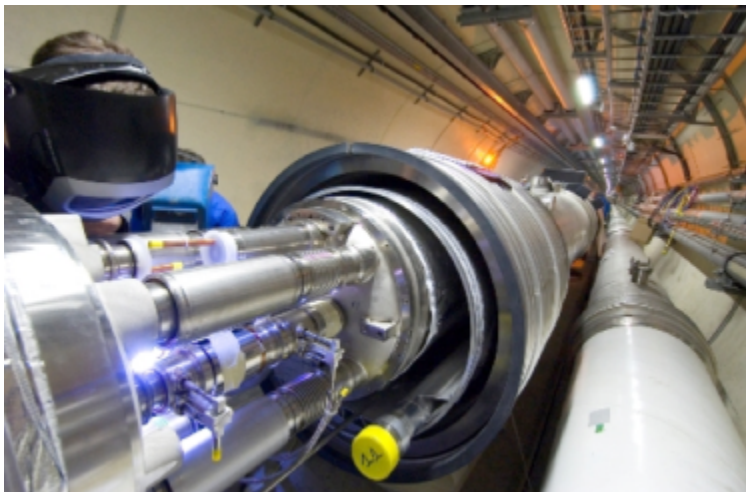
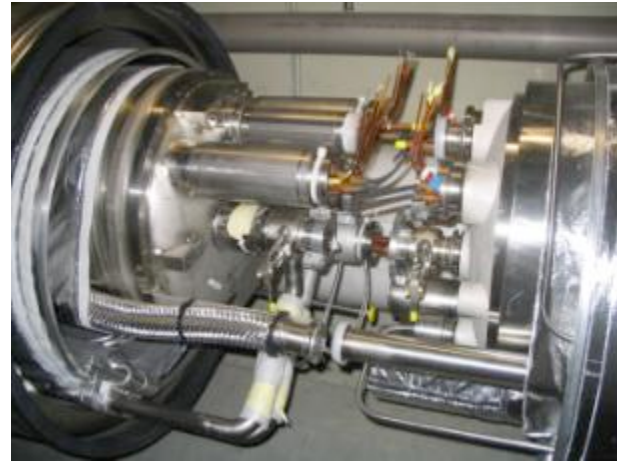
42 sc bus bars 600 A for corrector magnets (chromaticity, tune, etc....)
+ 12 sc bus bars for 6 kA (special quadrupoles)





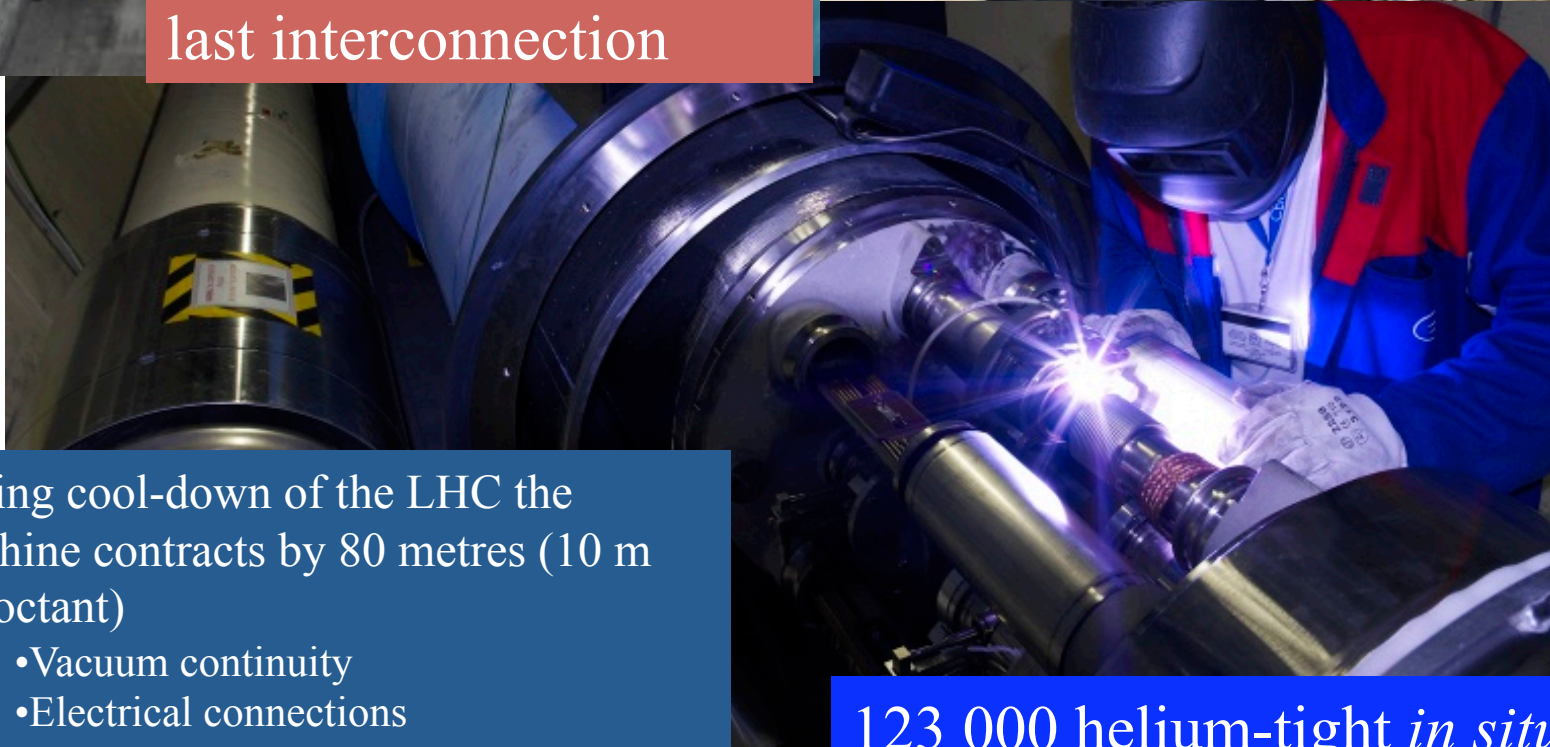
Interconnection (many technical domains): integration and quality are crucial !

- 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

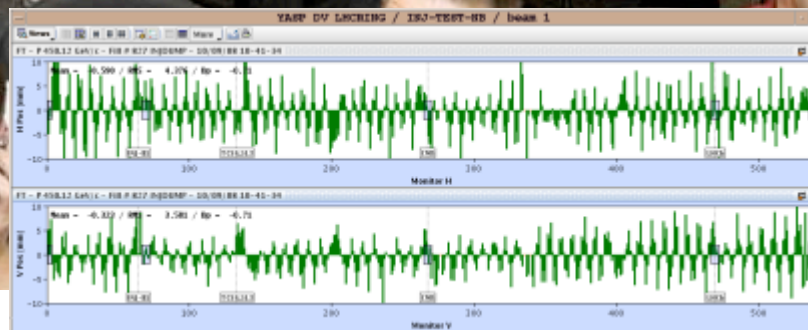
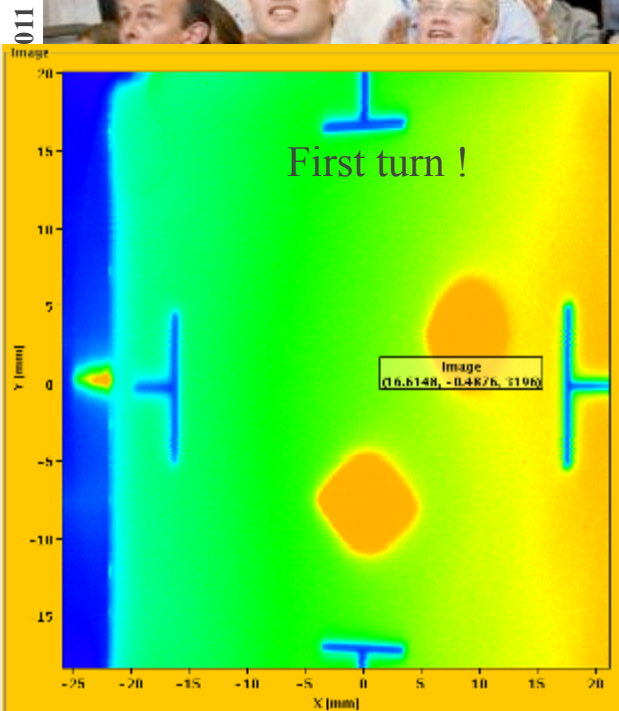


During cool-down of the LHC the machine contracts by 80 metres (10 m per octant)

- Vacuum continuity
- Electrical connections

123 000 helium-tight *in situ* welds

10th September 2008...



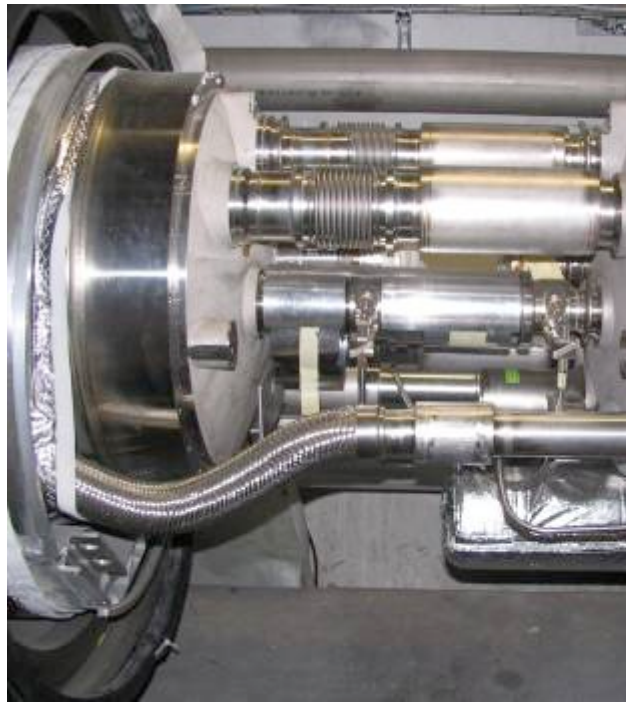


The Sector 3-4 incident (just before the 1st ramp with beam)

19th September

last test of the last circuit of the last

Electrical arc between



ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken

Voting Procedure

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

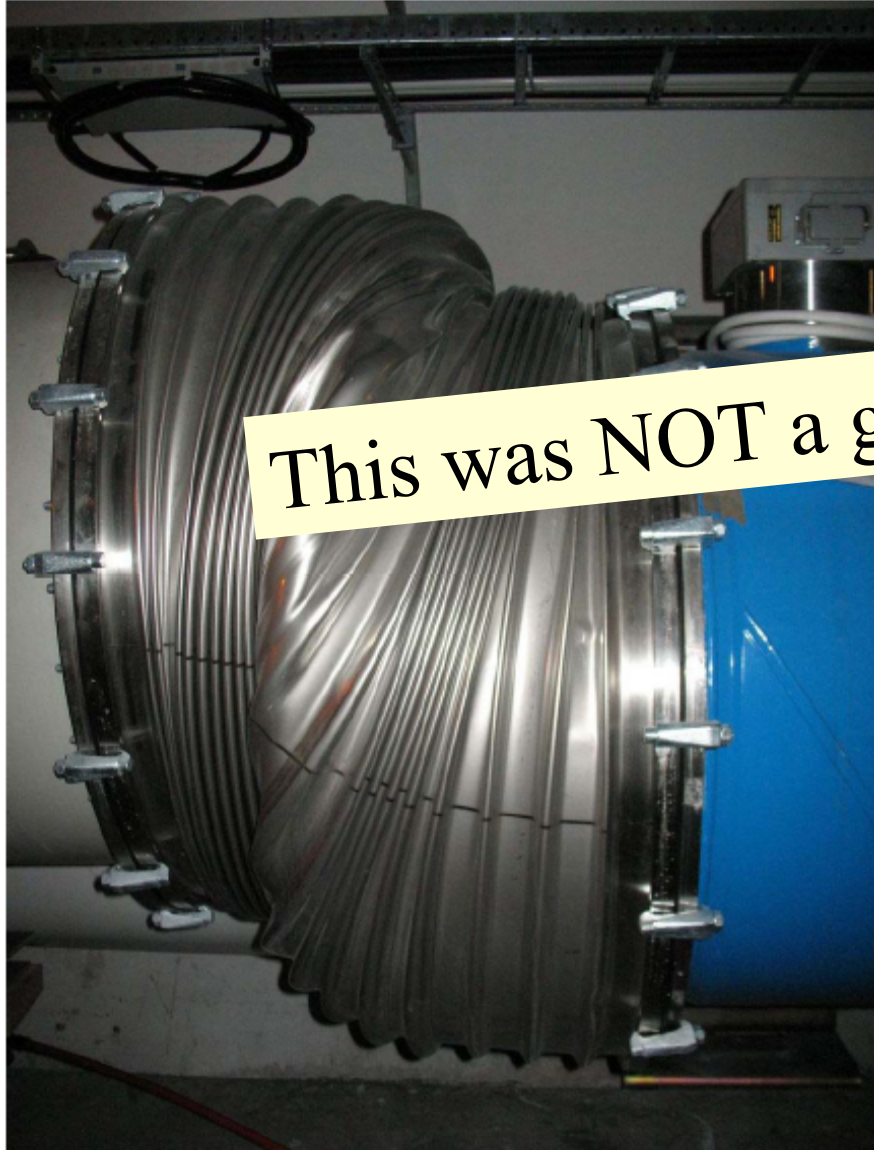
One day before the incident

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

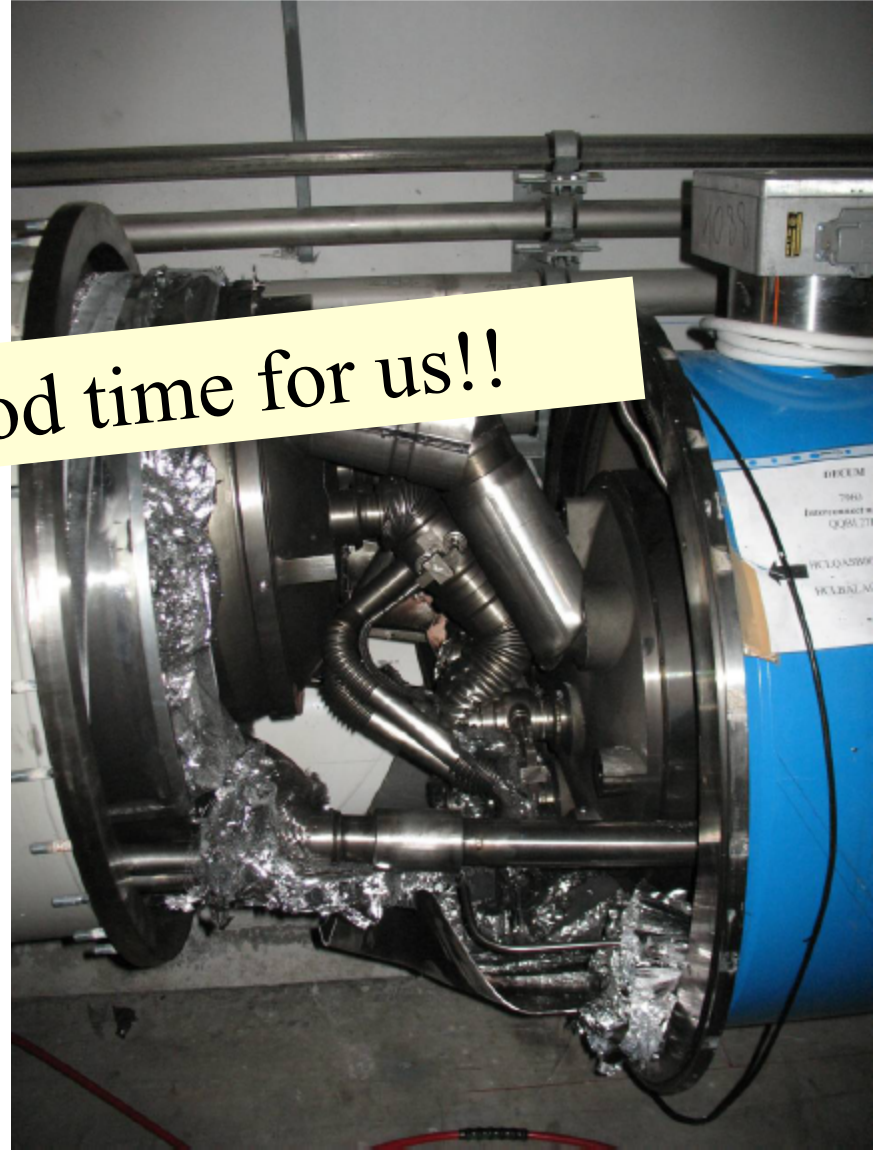
by
Director-General Designate



Consequences



This was NOT a good time for us!!



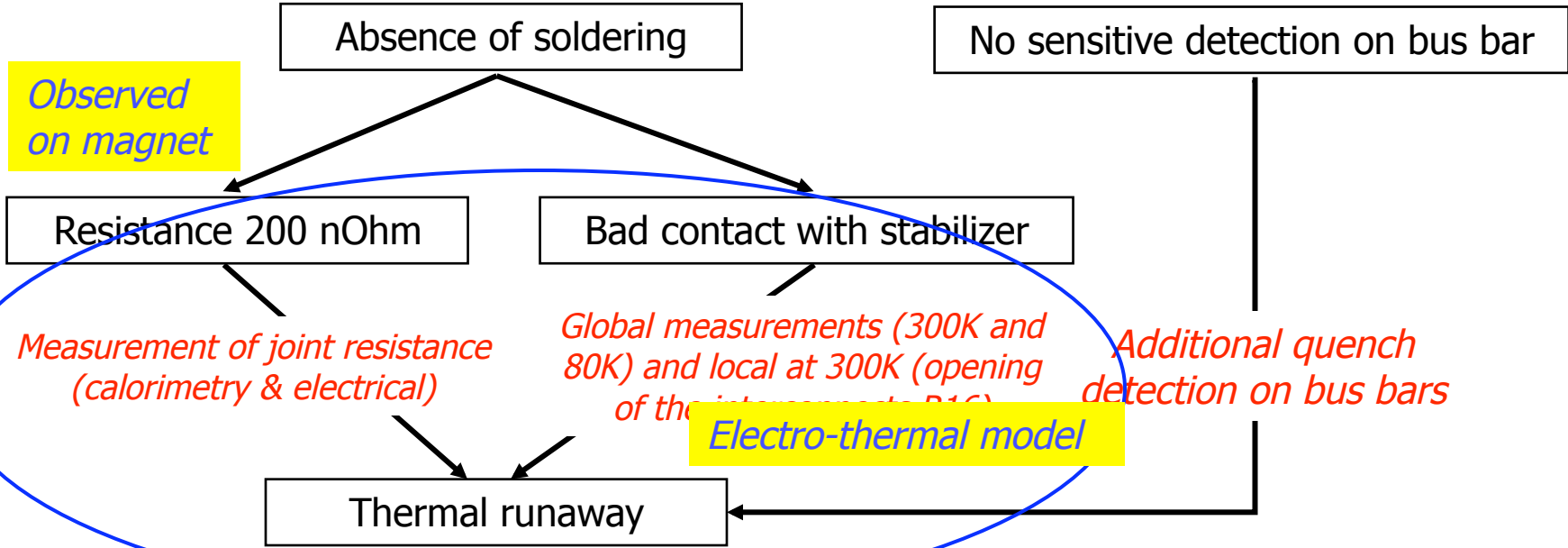


Collateral damage





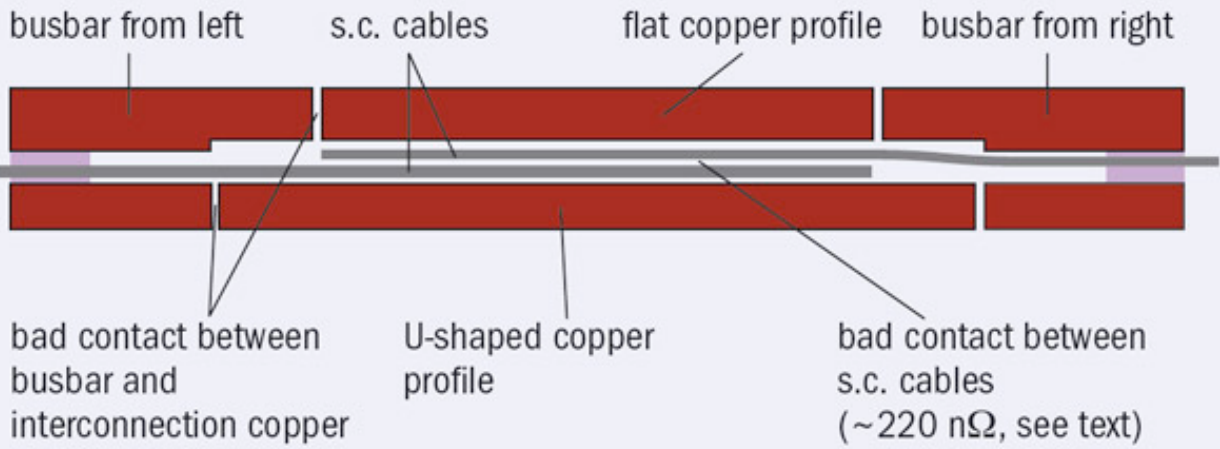
Fault tree and Corrective measures [1/2]



*Mechanical clarification
Reinforce Copper*

Meltdown, o

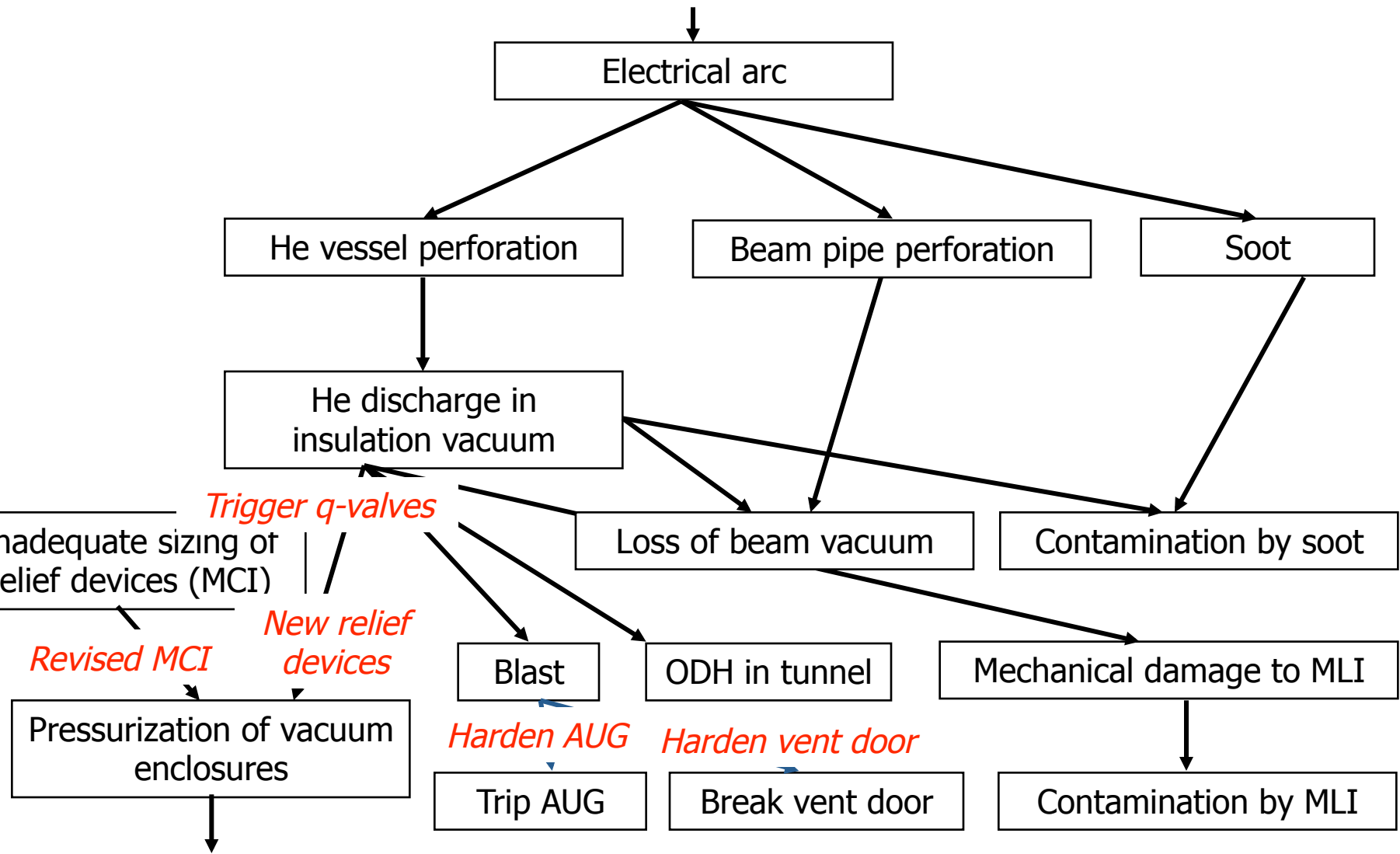
Electric



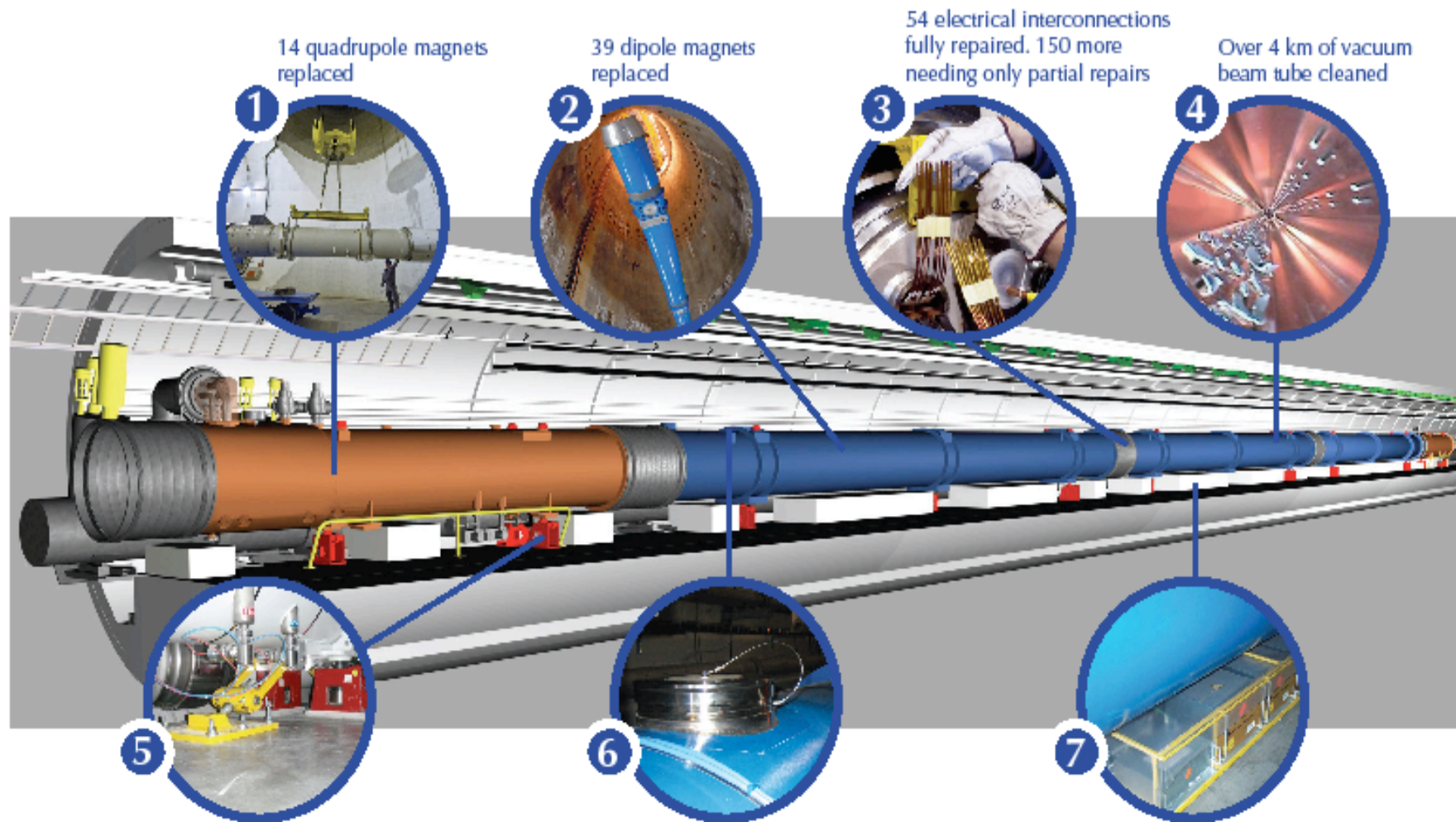


Fault tree and Corrective measures [2/2]

Fk. Bordry, 2011 ICOPS/SOFE C 31st June 2011



The LHC repairs in detail



14 quadrupole magnets replaced

39 dipole magnets replaced

54 electrical interconnections fully repaired. 150 more needing only partial repairs

Over 4 km of vacuum beam tube cleaned

5 A new longitudinal restraining system is being fitted to 50 quadrupole magnets

6 Nearly 900 new helium pressure release ports are being installed around the machine

7 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

½ machine done

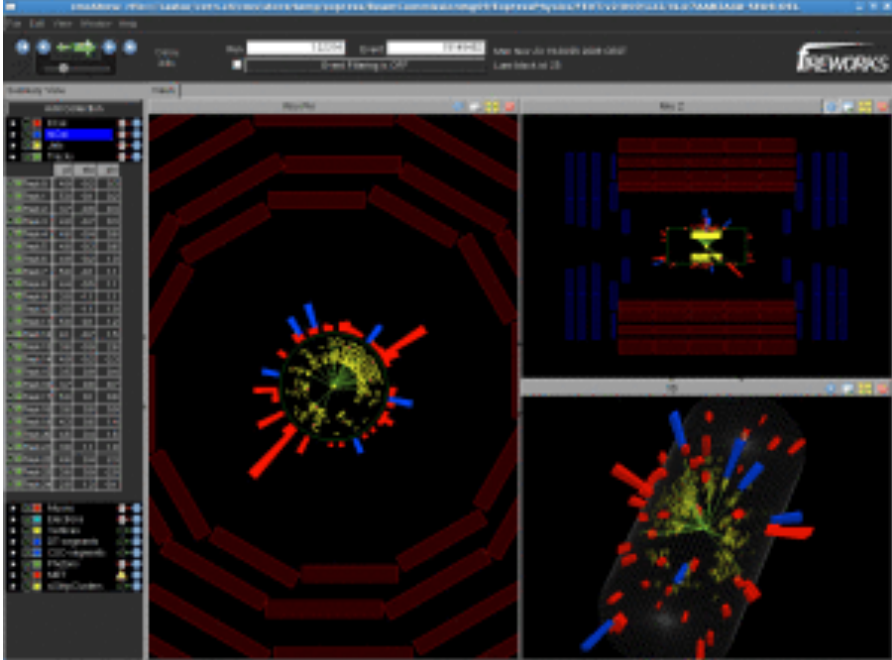


Magnet repair strategy

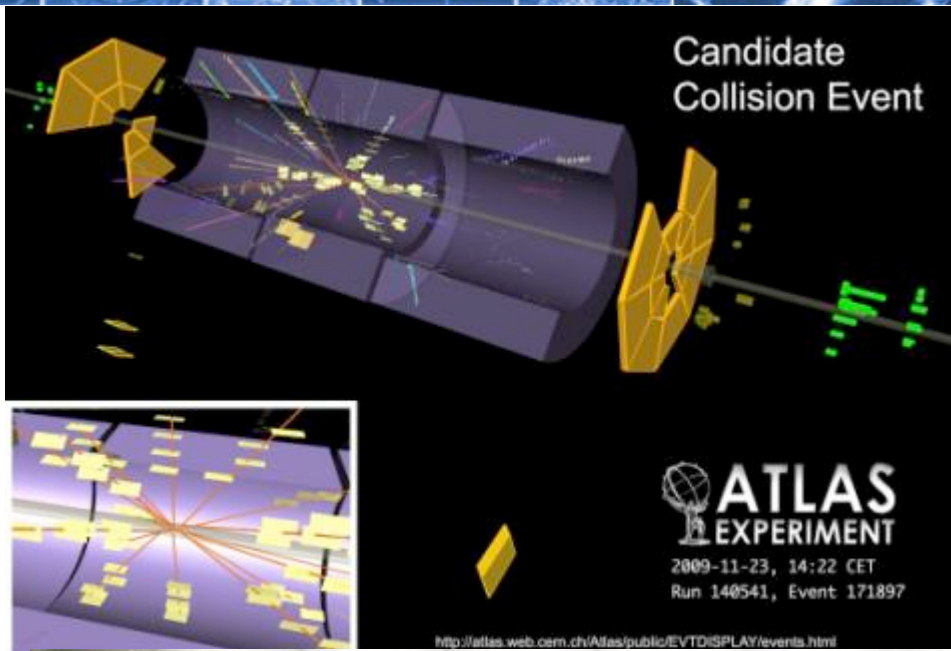
- 53 magnets replaced in sector 3-4:
 - 39 dipoles:
 - 30 new spares
 - 9 recovered from sector 3-4 and refurbished
 - 14 Short Straight Sections:
 - 7 new spares
 - 7 recovered from sector 3-4 and refurbished
 - All cold tested (or re-tested)
 - Spares available, but just enough!



Beam back on 20th November 2009

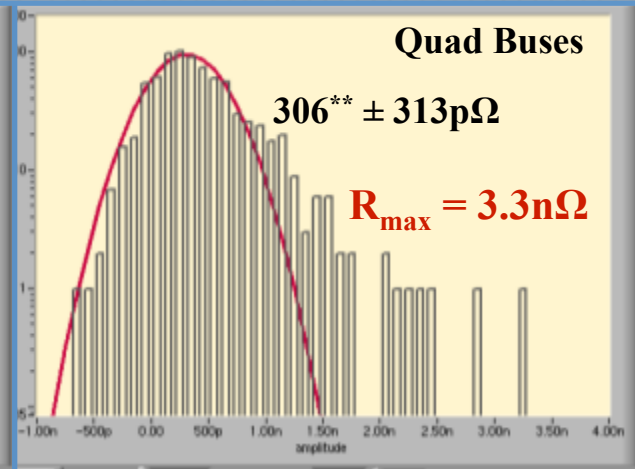
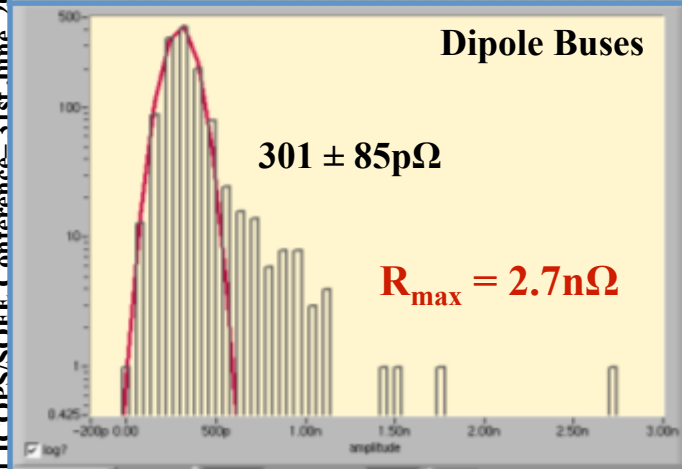
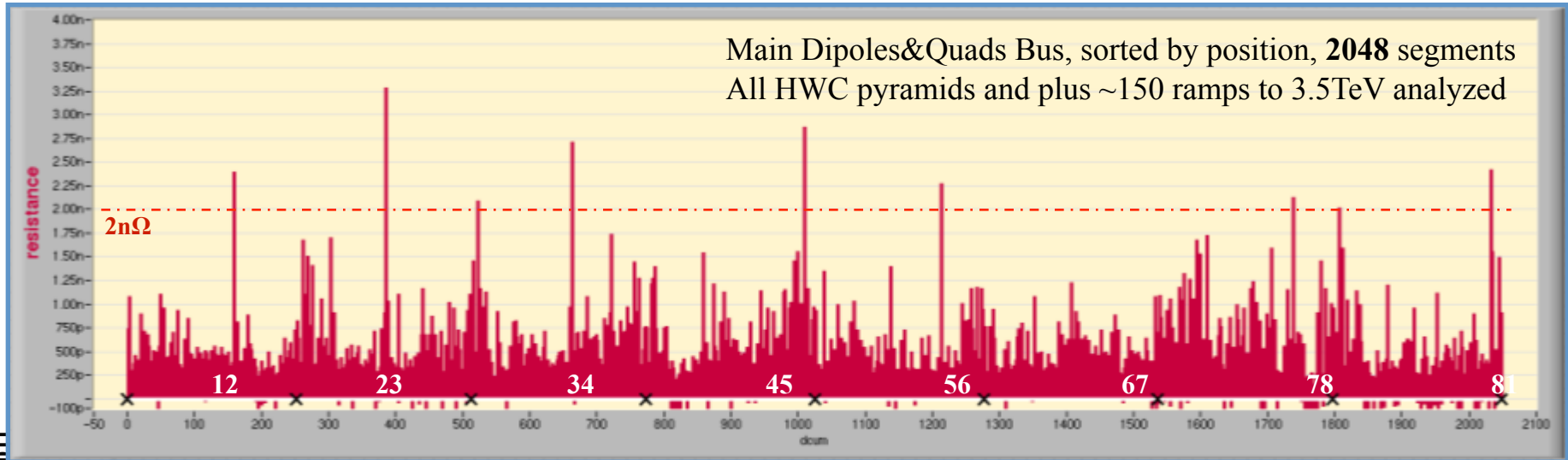


Limited in 2009 to 2 kA in main circuits (1.18 TeV) during deployment and testing of new Quench Protection System





LHC main splices today: busbars SC



Top 10 Splice Resistances

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

Fk. Bordry, 2011 ICOPS/SOEF Conference - 31st June 2011

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

From Z. Charifouline



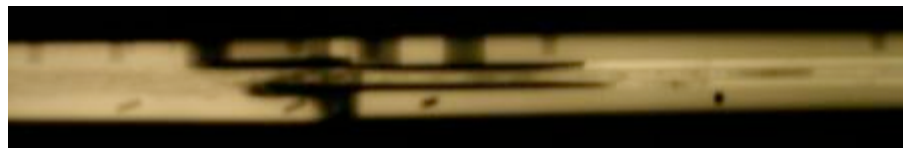
Why do we limit the beam energy to 3.5TeV in 2010-2012?

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

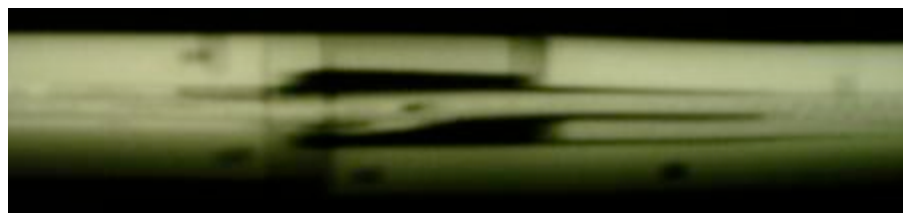
The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.7nΩ for dipole busbars and 3.3nΩ for dipole busbars

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

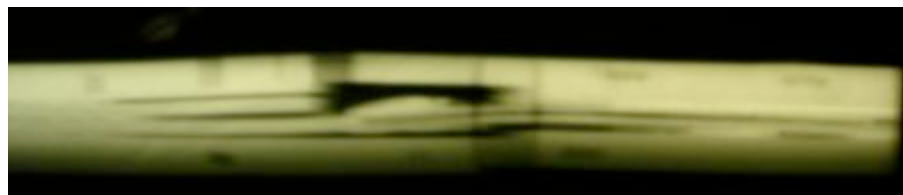
Sample pictures



Sample 1 (61 $\mu\Omega$)



Sample 2A left (32 $\mu\Omega$)



Sample 2A right (43 $\mu\Omega$)



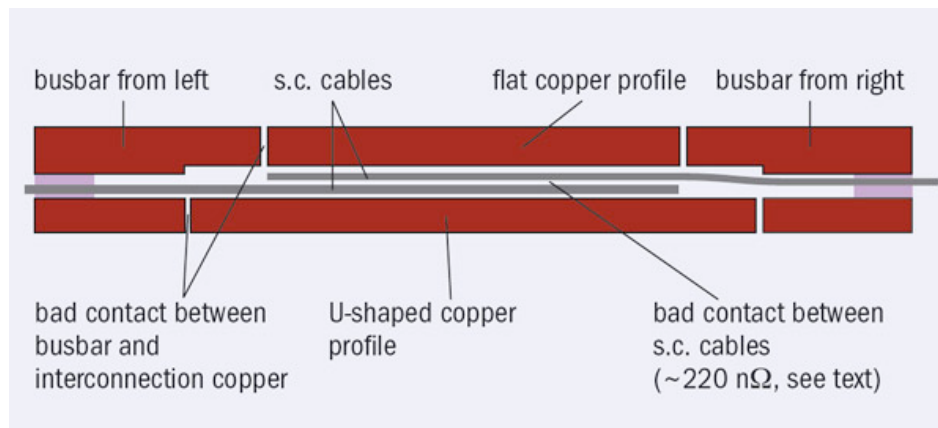
Sample 2B (42 $\mu\Omega$)



Sample 3A left (26 $\mu\Omega$)



Sample 3A right (43 $\mu\Omega$)





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

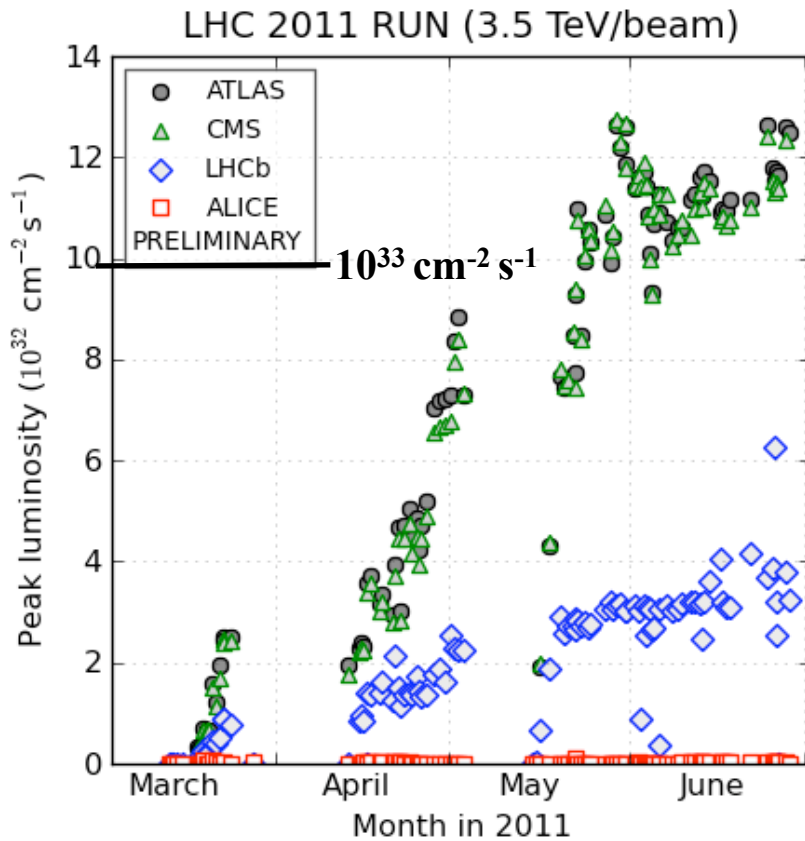




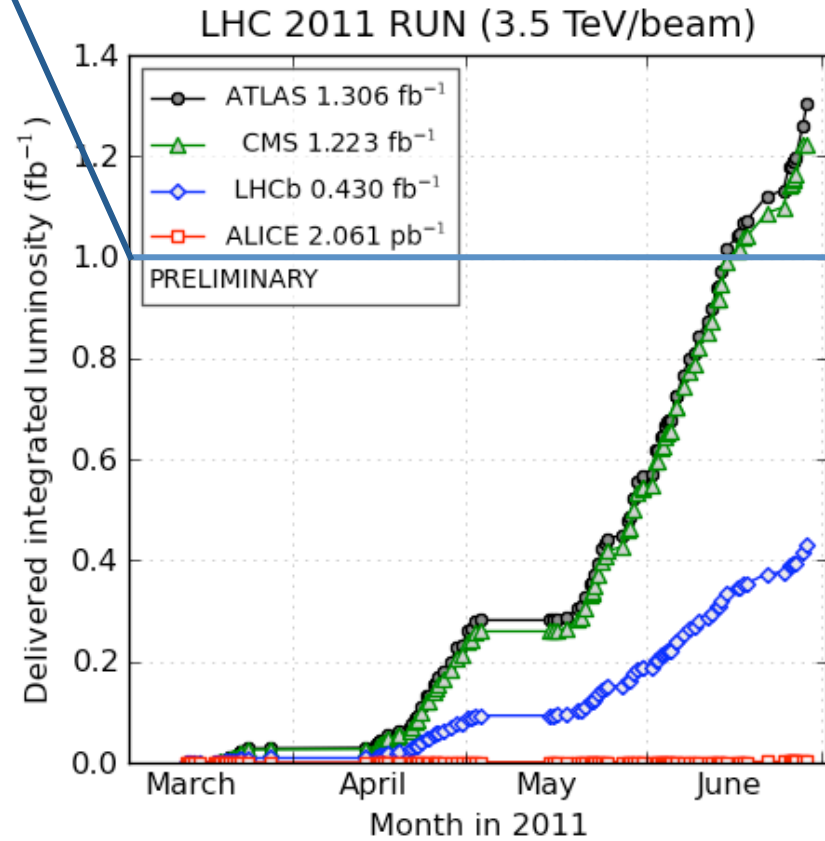
Luminosity evolution 2011 (proton)

Initial goal for 2011: 1 fb⁻¹

**~50 pb⁻¹ delivered in 2010
Already above 1.3 fb⁻¹ in 2011**



(generated 2011-06-29 08:12 including fill 1901)



(generated 2011-06-29 08:12 including fill 1901)

29th June 2011



2013-2014 long shutdown

2010	2011	2012	2013
M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D			

LHC

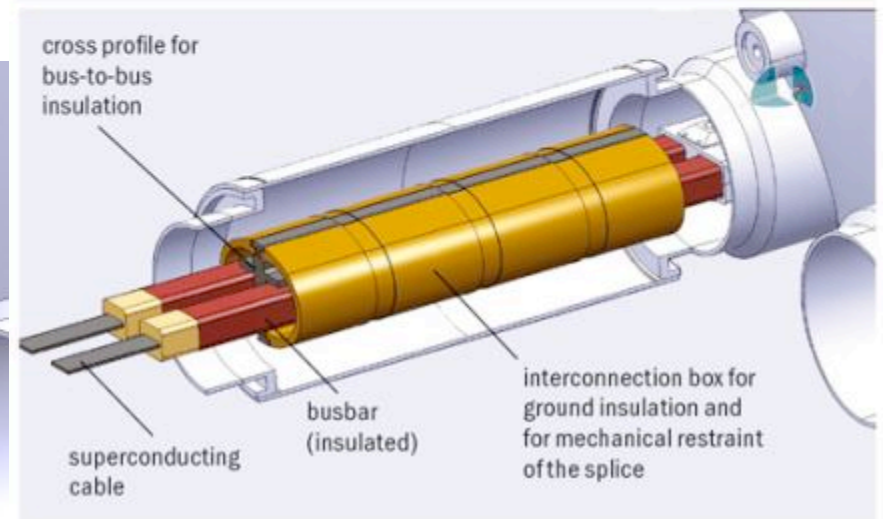
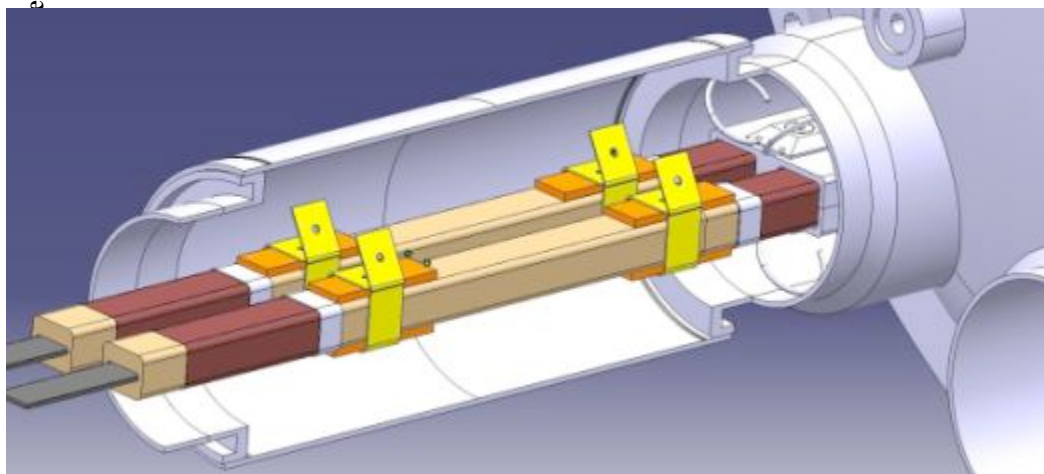
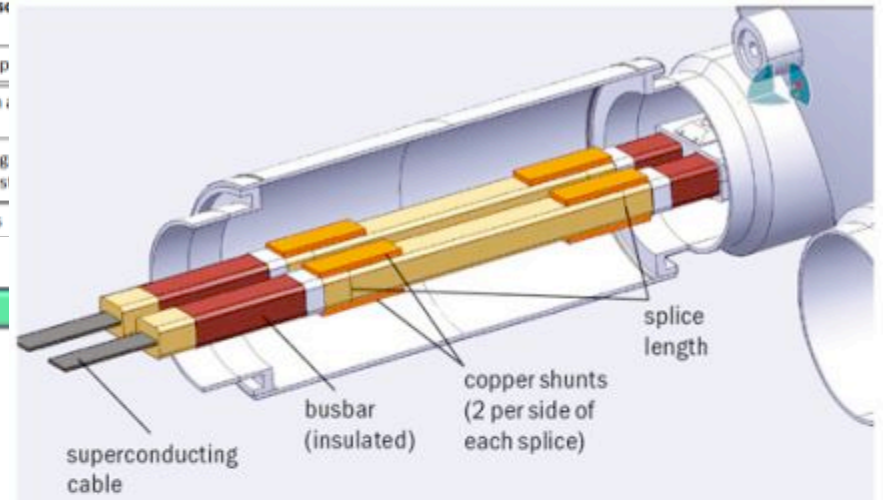


- Machine: Splice Cons
- ~~Collimation in IR3~~
- ALICE - detector comp
- ATLAS - Consolidation; beam pipes
- CMS - FWD muons upg Consolidation & infras
- LHCb - consolidations

Injectors



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





2010					2011					2012					2013					2014					2015					2016																									
M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D

LHC



- Machine: Splice Consolidation
- ~~Collimation in IR3~~
- ALICE - detector completion
- ATLAS - Consolidation and new forward beam pipes
- CMS - FWD muons upgrade + Consolidation & infrastructure
- LHCb - consolidations

Injectors



2017					2018					2019					2020					2021																												
D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D

LHC



- Machine: Collimation & prepare for crab cavities & RF cryo system
- ATLAS: nw pixel detect. - detect. for ultimate luminosity.
- ALICE - Inner vertex system
- CMS - New Pixel. New HCAL Photodetectors. Completion of FWD muons upgrade
- LHCb - full trigger upgrade, new vertex detector etc.

X-mas maintenance

- Machine - maintenance &
- ATLAS - New inner detector
- ALICE - Second vertex detector upgrade
- CMS - New Tracker

Injectors



ween 6.5
ording to



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 than 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 : $\frac{1}{2}$ 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