



# LHC Commissioning

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CERN

WAO 2010

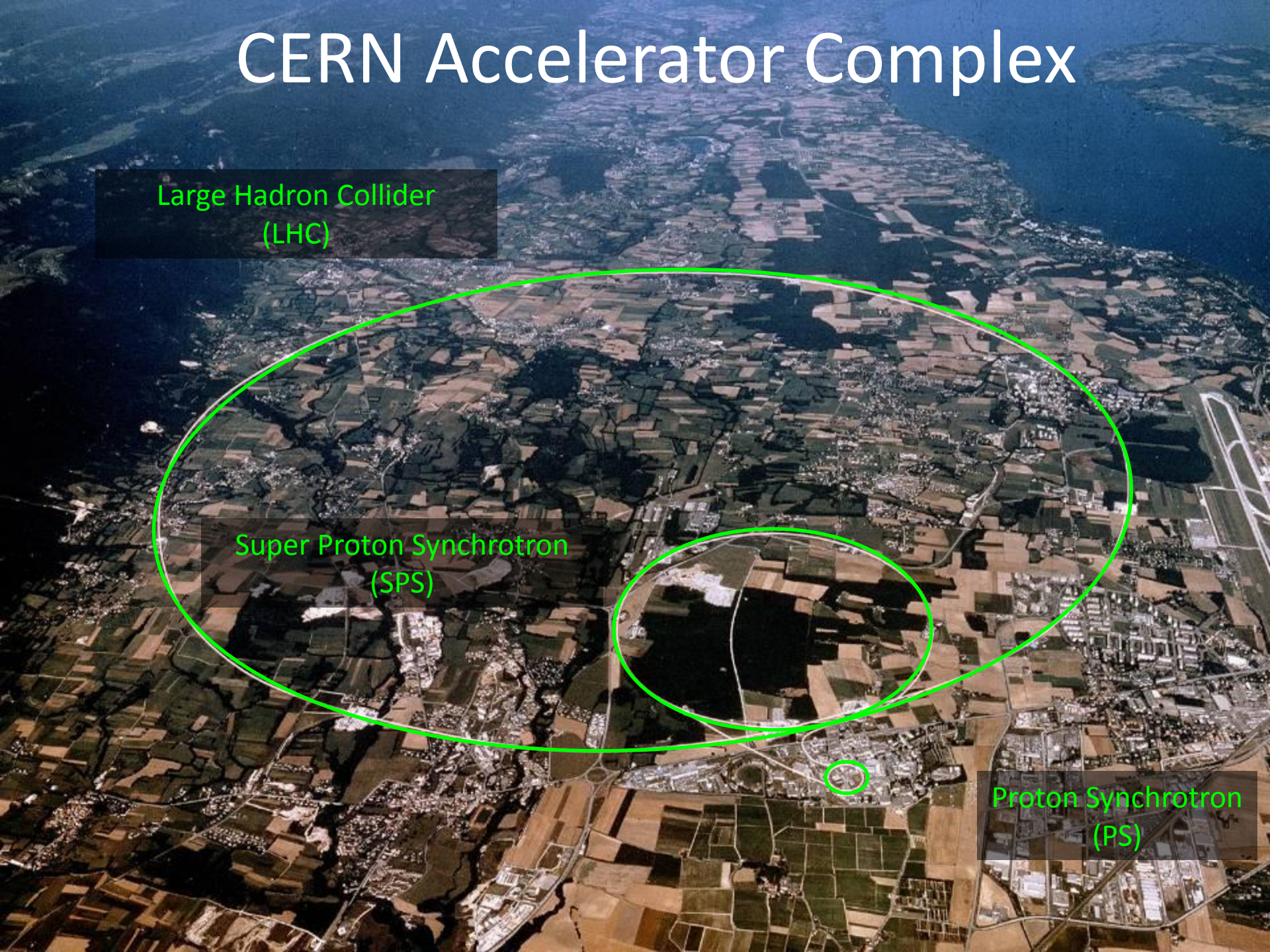
1. Introduction
2. Starting the LHC
3. Sector 3-4 Incident & Repair
4. LHC Beam Operation
5. Conclusions

# CERN Accelerator Complex

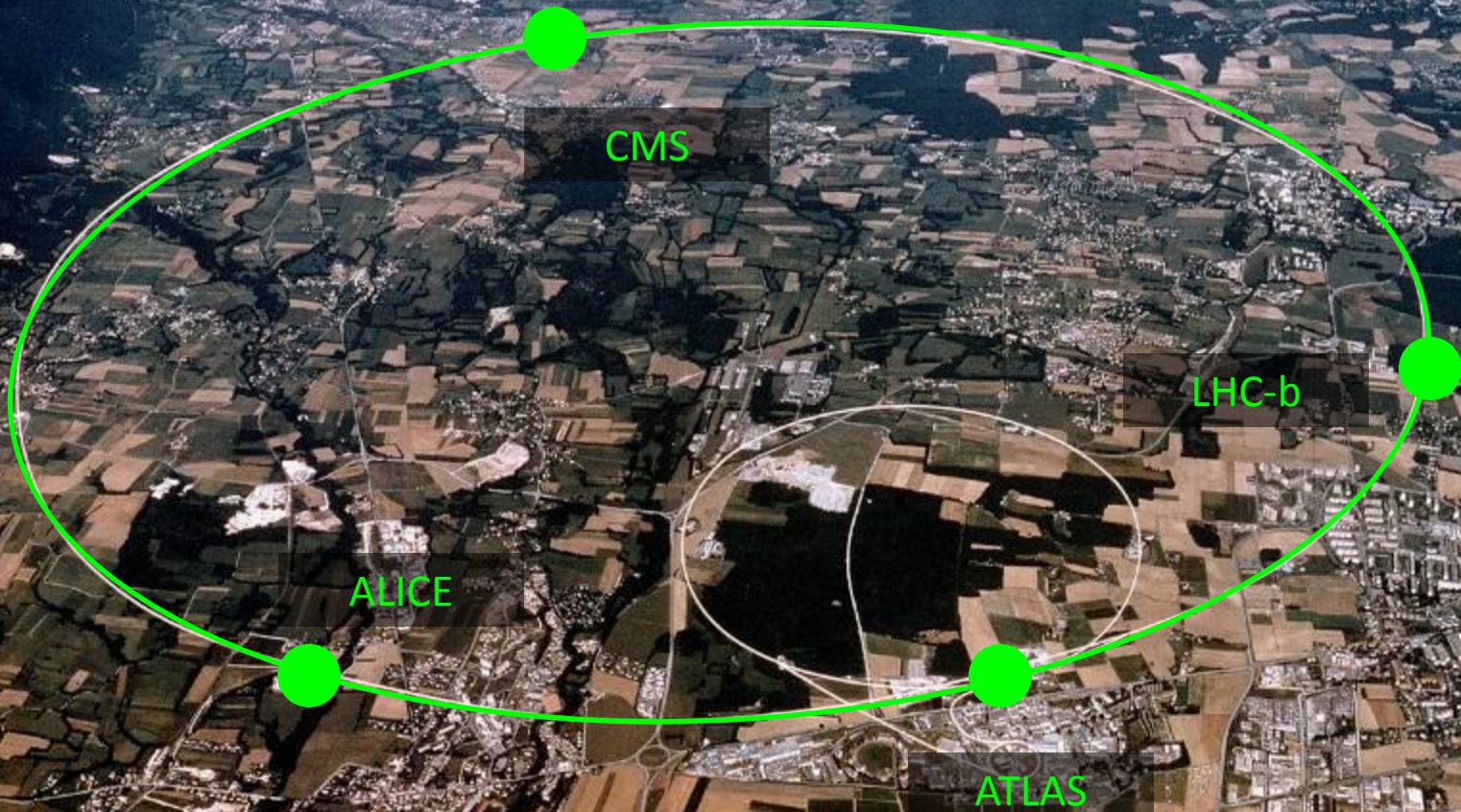
Large Hadron Collider  
(LHC)

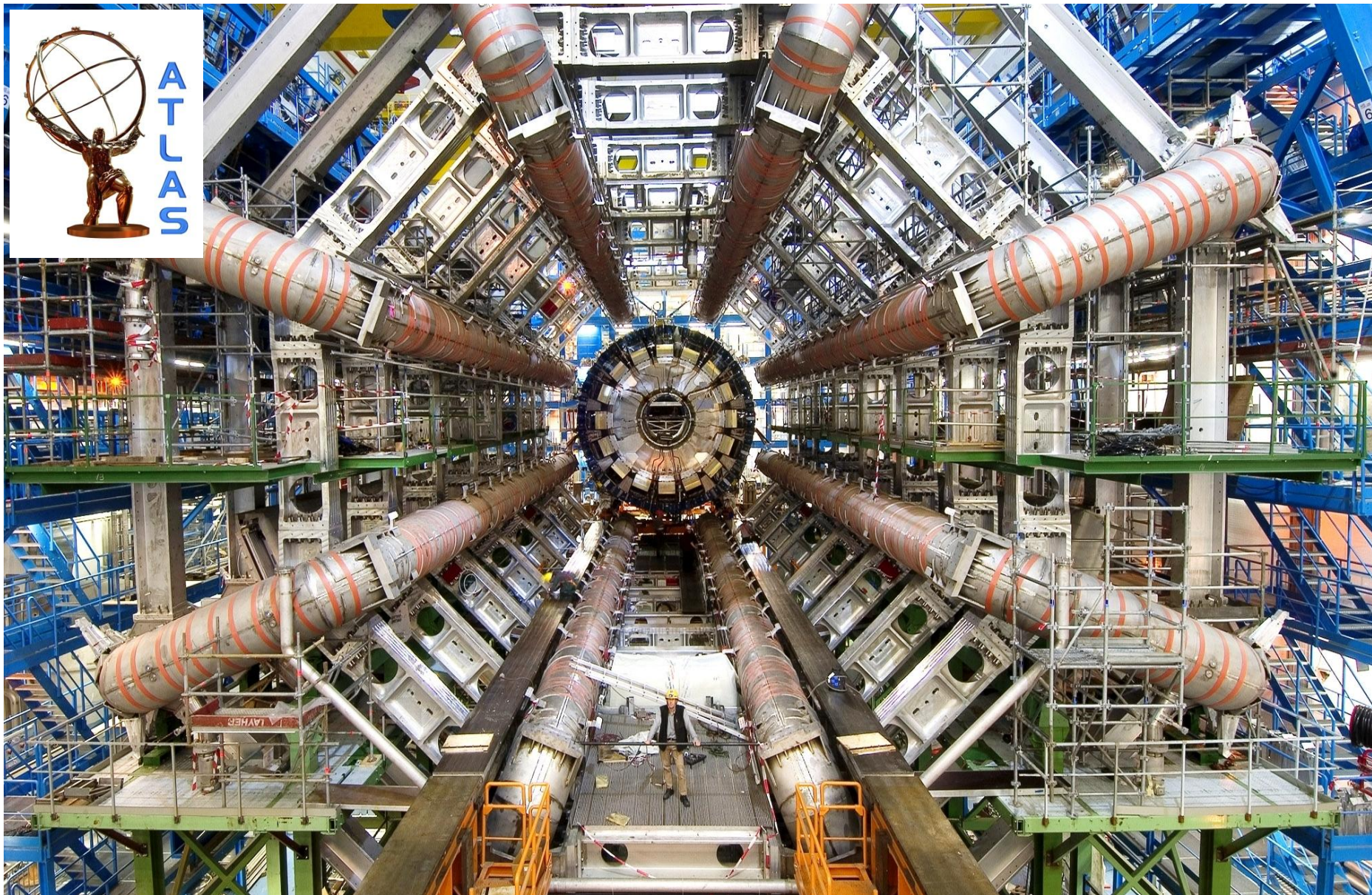
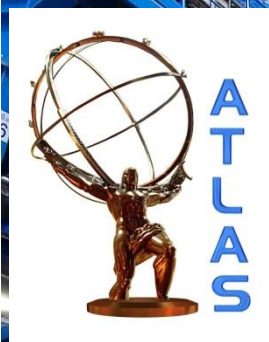
Super Proton Synchrotron  
(SPS)

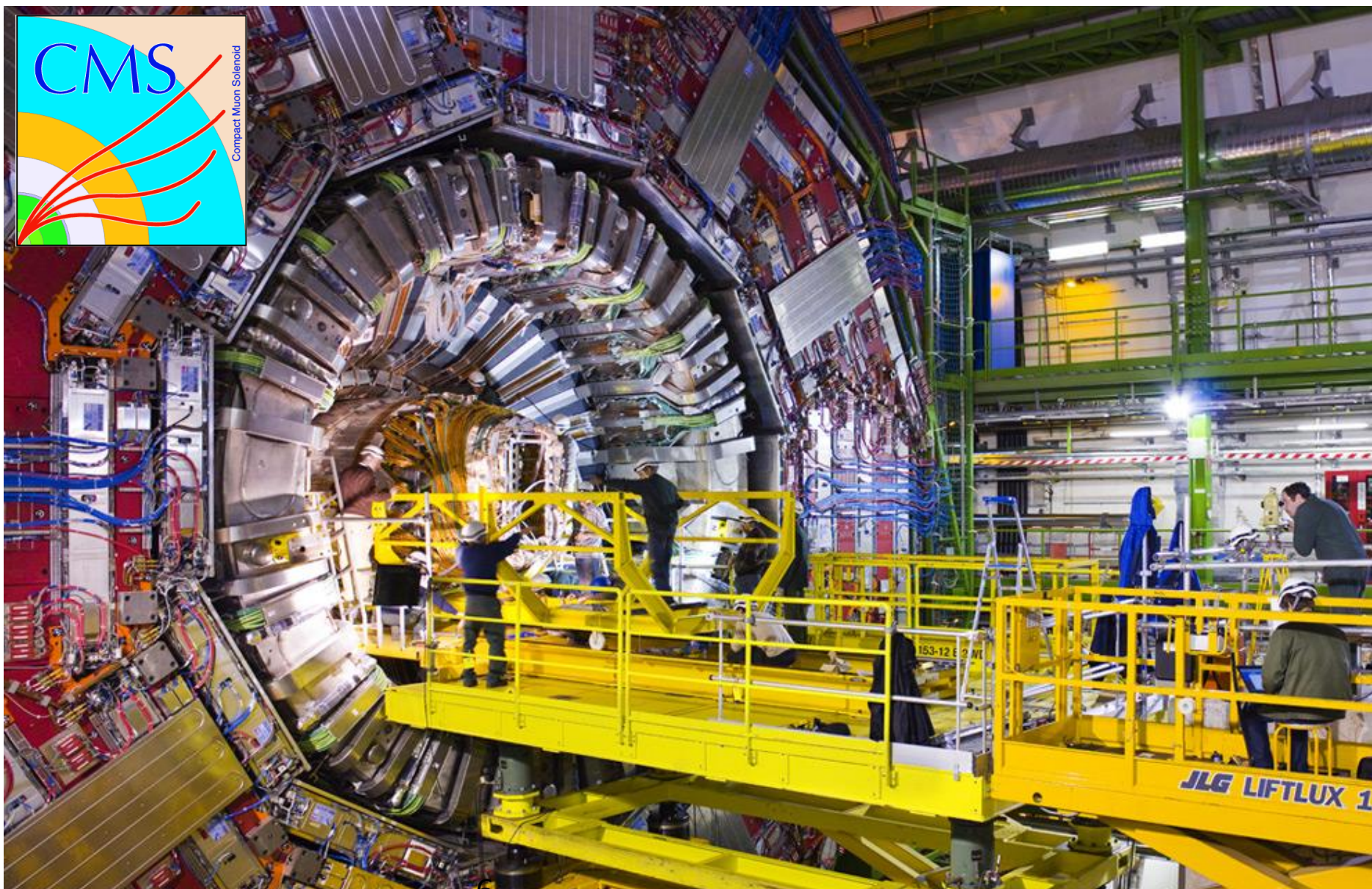
Proton Synchrotron  
(PS)



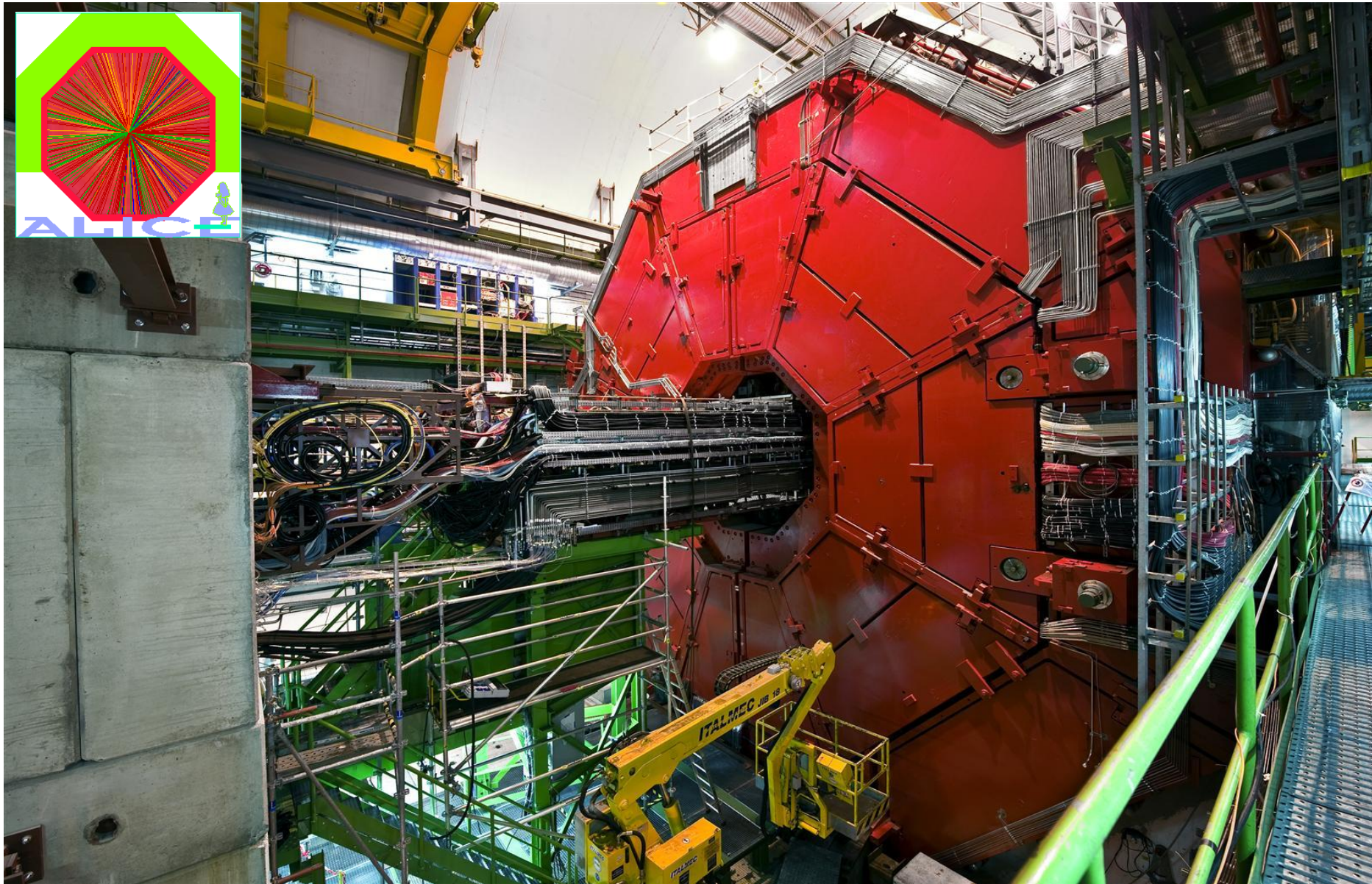
# CERN Accelerator Complex





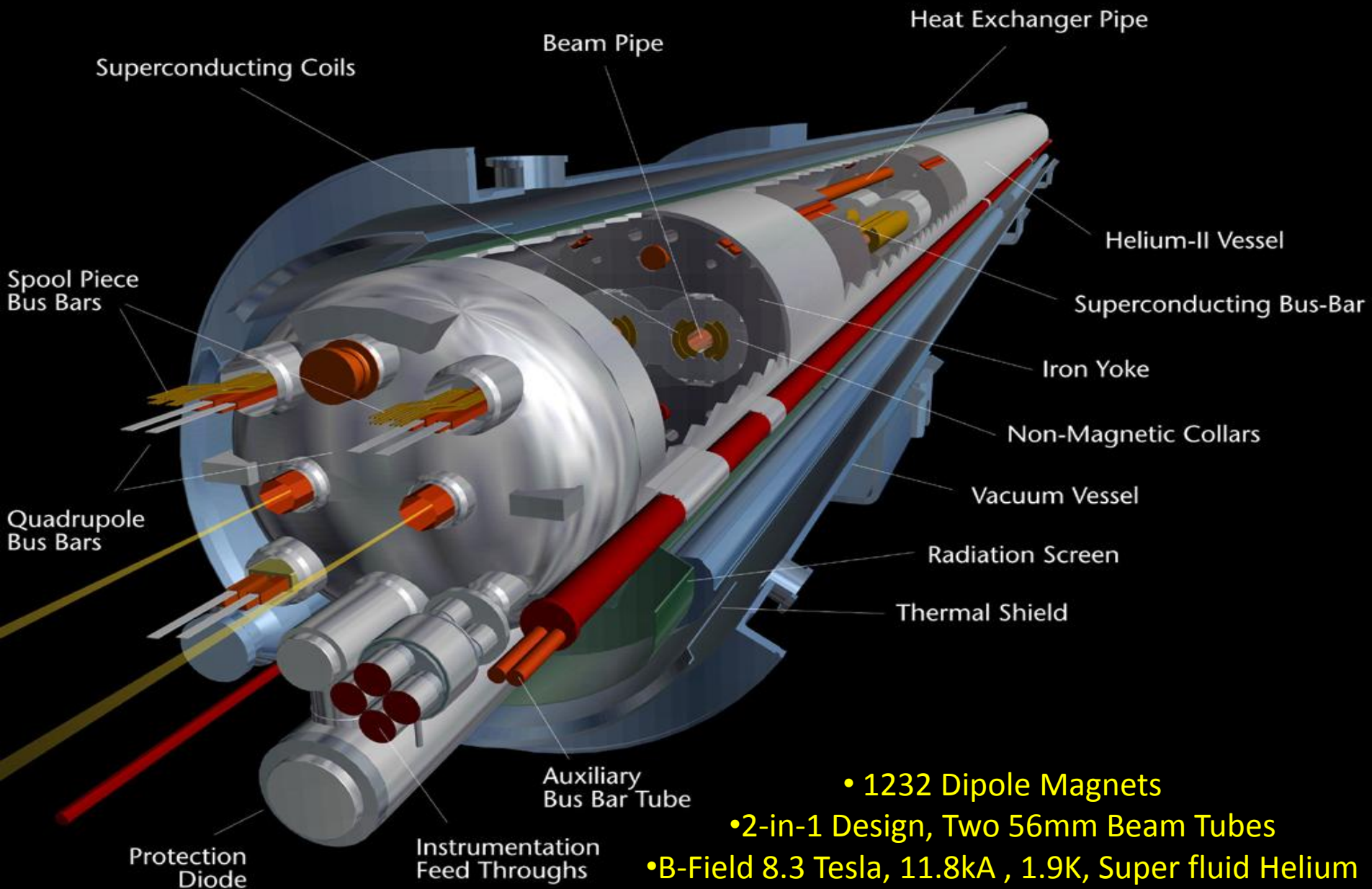




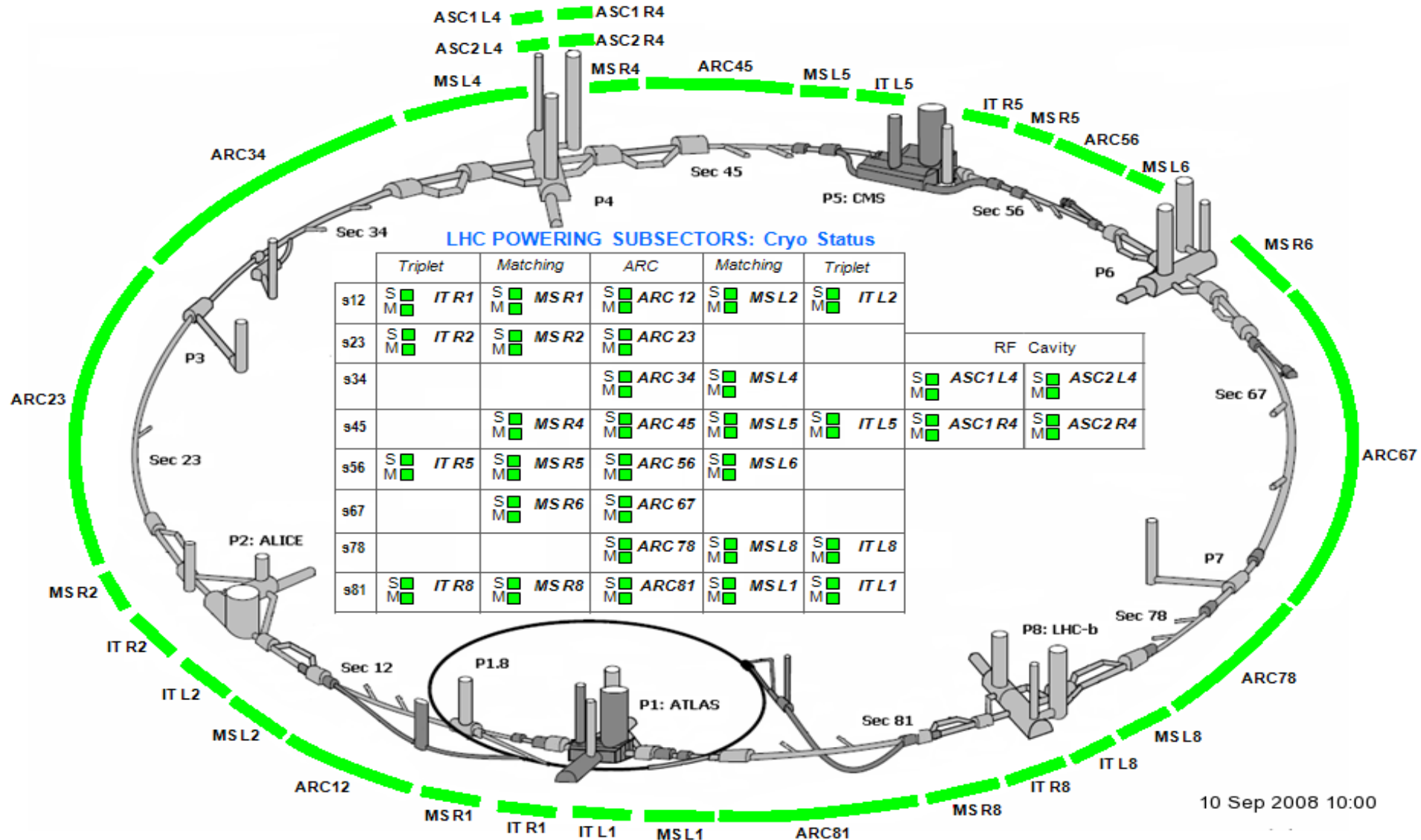




# The 15m LHC Cryodipole



“Cryo Maintain” – Allowing Circulating Beams 90.4% Available



10 Sep 2008 10:00



# Day One – September 10<sup>th</sup> 2008



Single bunch of protons  $3 \times 10^9$

## Beam 1

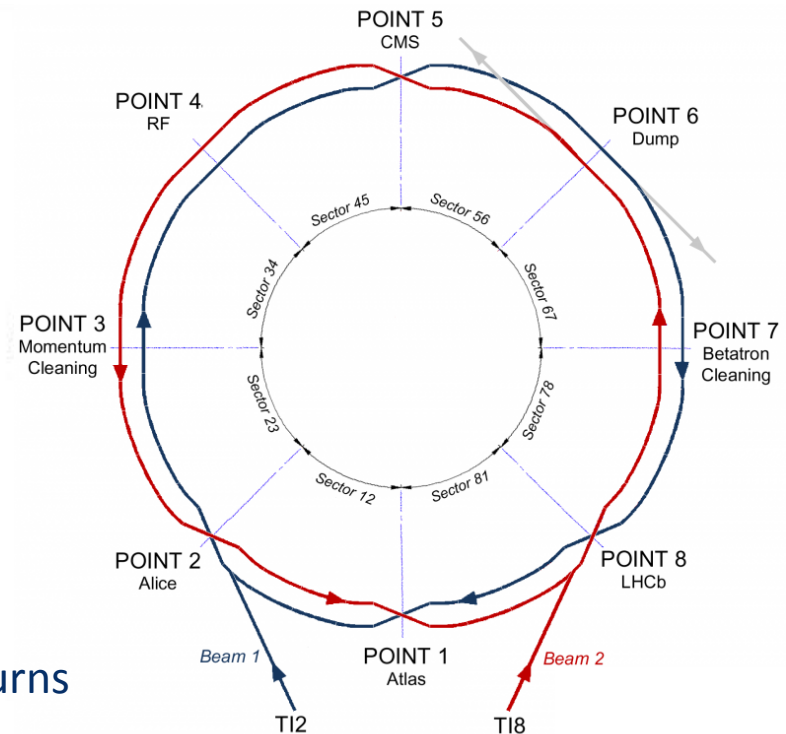
1. Injected Point 2
2. Threaded around machine in 1 hour
3. Trajectory steering gave 2 or 3 turns

## Beam 2

1. Injected Point 8
2. Threaded around machine in 1.5 hours
3. Trajectory steering gave 2 or 3 turns
4. Q and Q' tuning gave several hundred turns

No Major Magnetic Problem

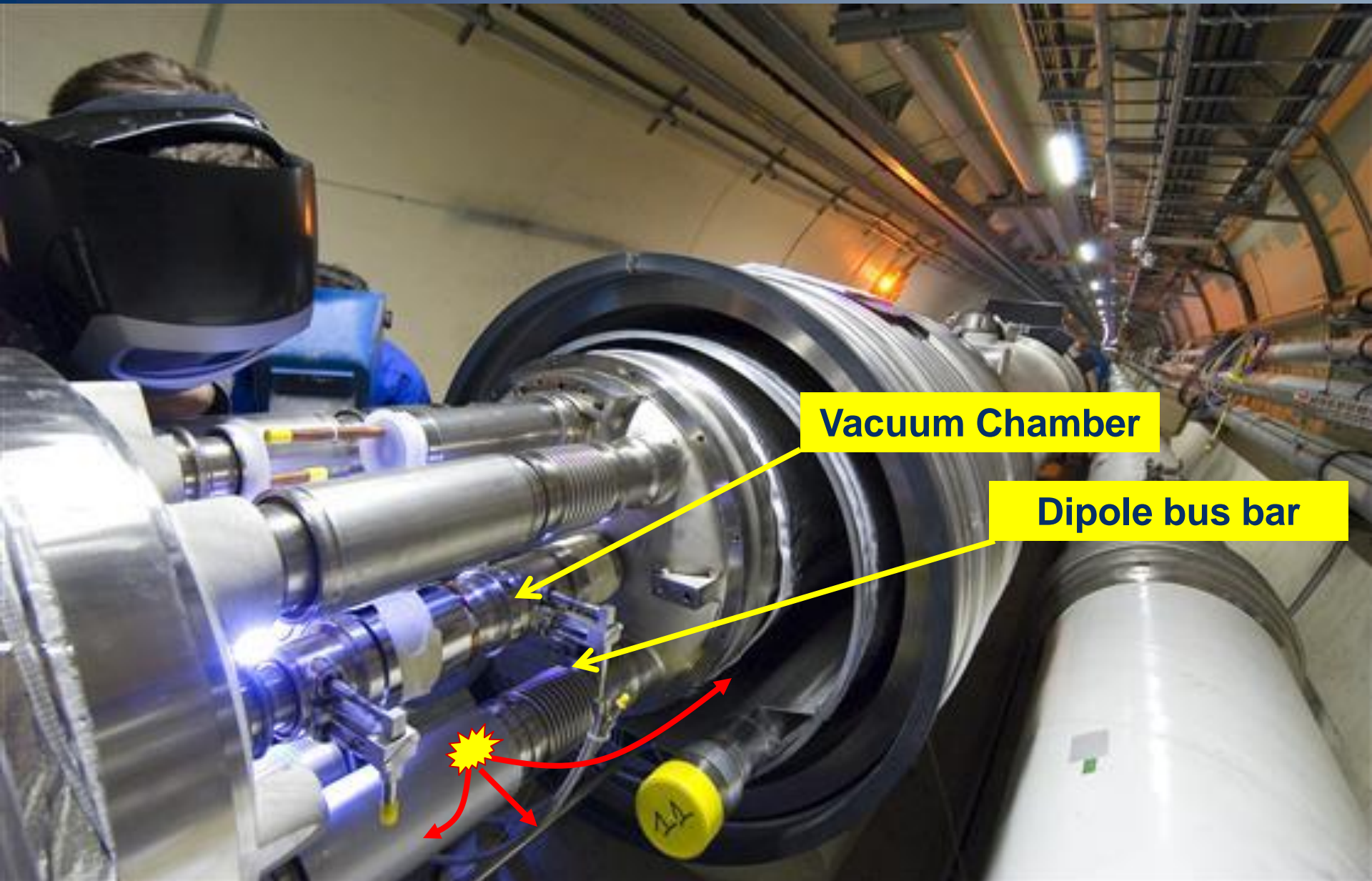
No Major Obstacle



On Day One not all circuits **had been commissioned**

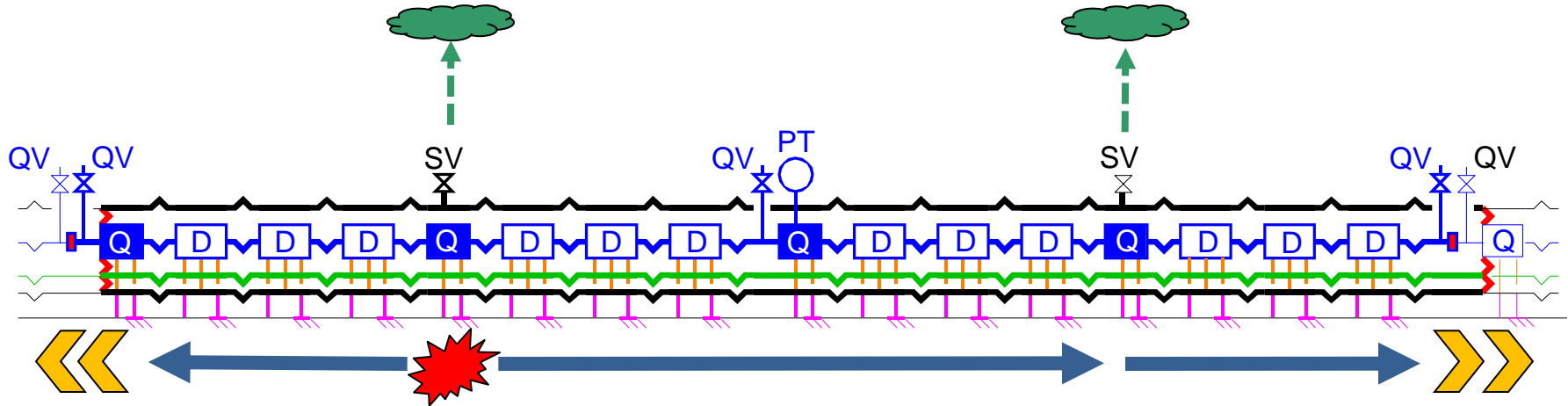
## Final Commissioning Main Dipole Circuit 34

- Electrical Fault at 5.2 TeV in dipole bus bar, between quadrupole and dipole  
Post-Analysis:  $R = 220 \text{ n}\Omega$ , nominal =  $0.35 \text{ n}\Omega$
- Electrical Arc developed and punctured helium enclosure  
Post-Analysis: 400 MJ dissipated in cold-mass and arcing
- Helium Release into the insulating vacuum  
Post-Analysis: Pressure wave caused most damage



**Vacuum Chamber**

**Dipole bus bar**



- Cold-mass
- Vacuum vessel
- Line E
- | Cold support post
- | Warm Jack
- ~ Compensator/Bellows
- ⚡ Vacuum barrier

1. Pressure Wave propagates inside insulation Vacuum enclosure

2. Rapid Pressure Rise

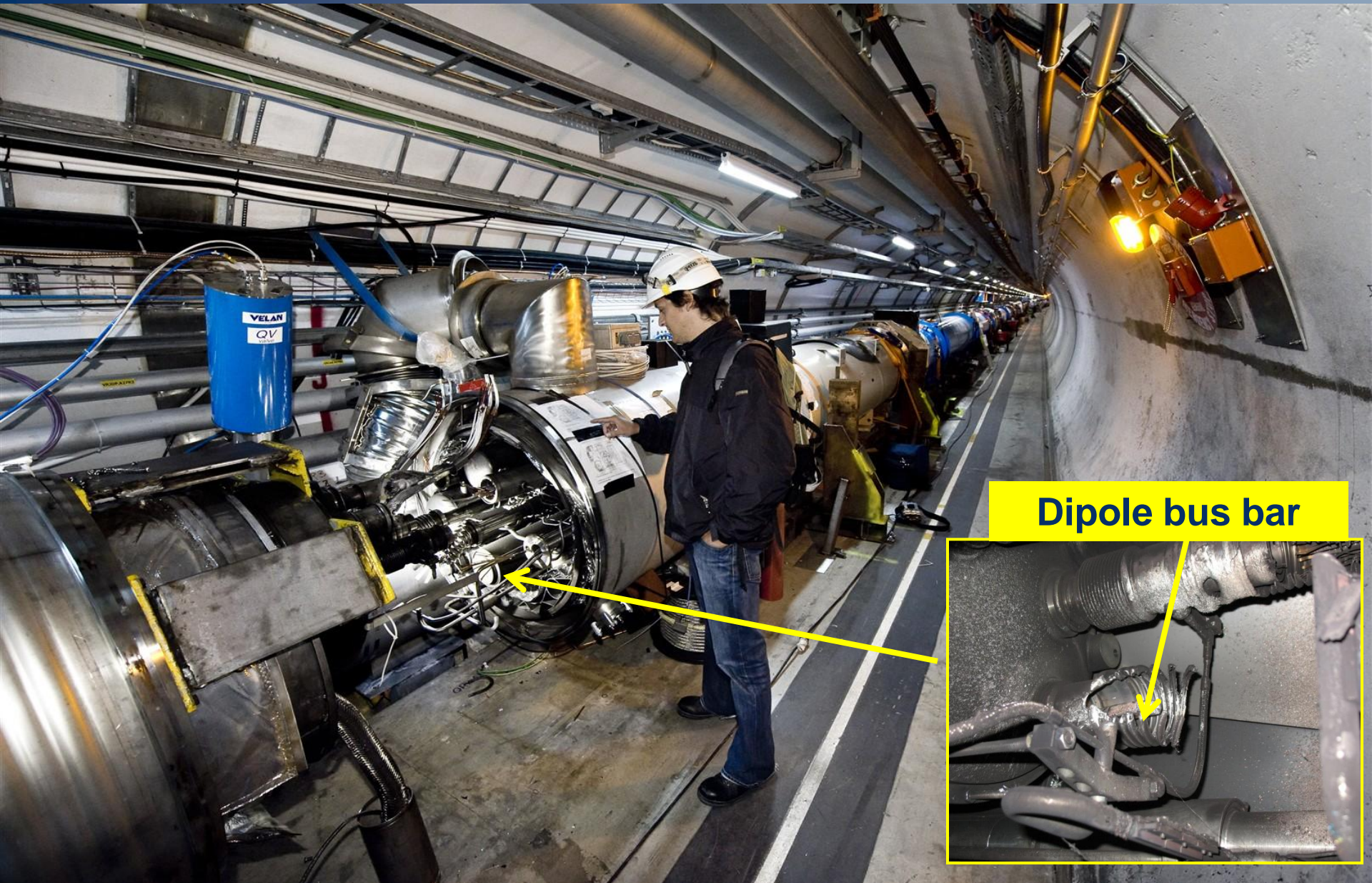
Self actuating relief valves could not handle pressure

Design: 2Kg He/s Incident: ~20 kg He/s

3. Forces on the vacuum barriers (every second cell)

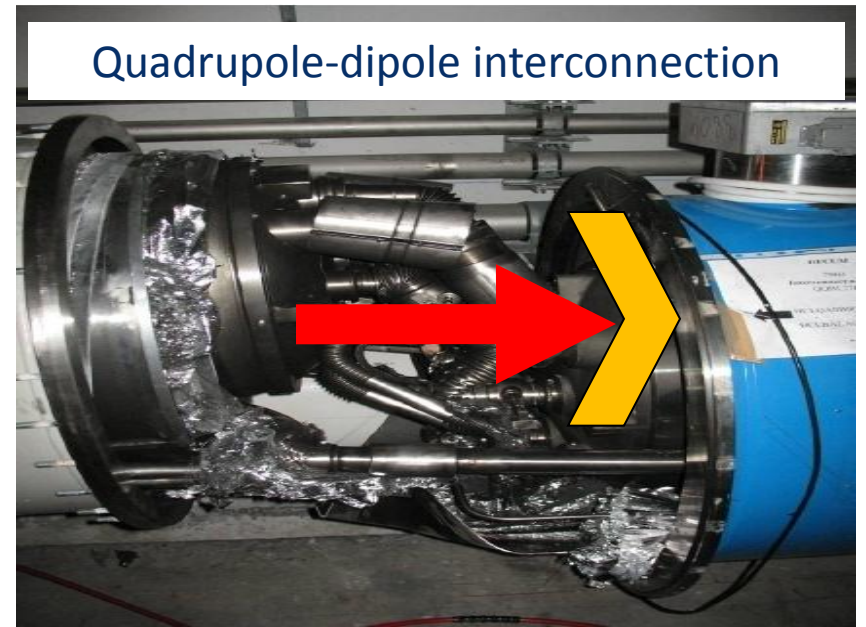
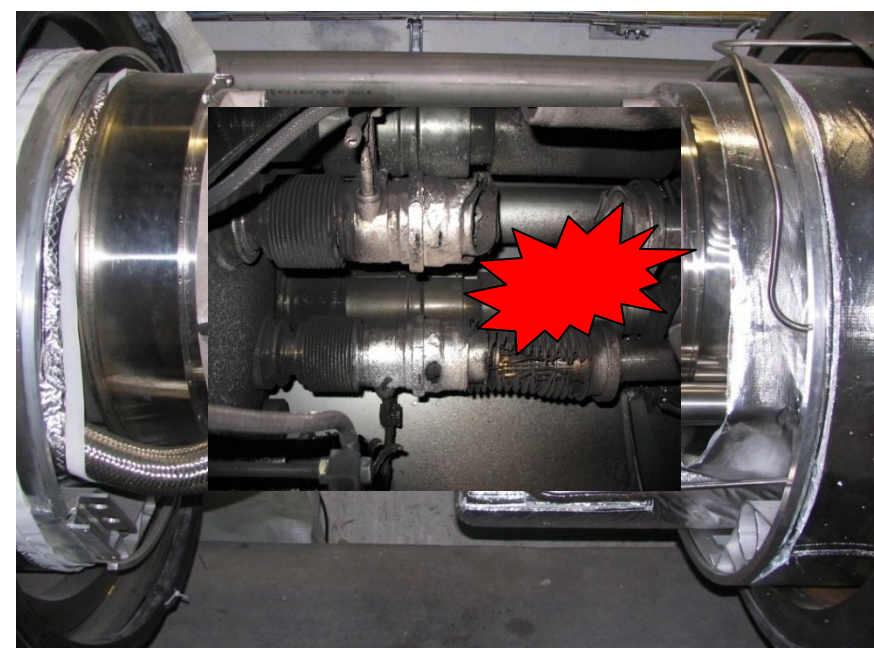
Design: 1.5 bar Incident: ~8 bar

- Several Quadrupoles Displaced by ~50 cm
- Cryogenic line connections damaged
- Vacuum to atmospheric pressure





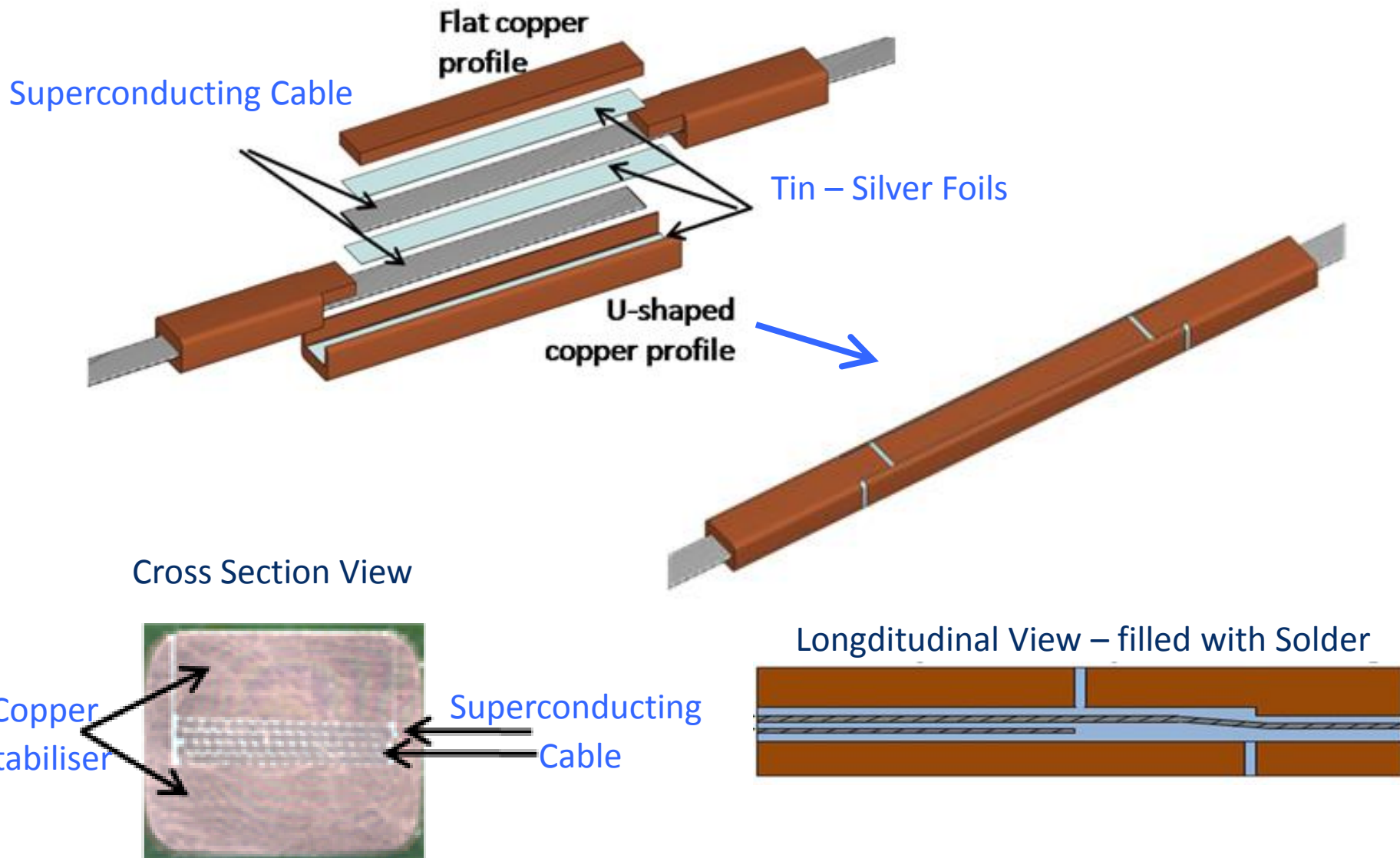
# Collateral Damage

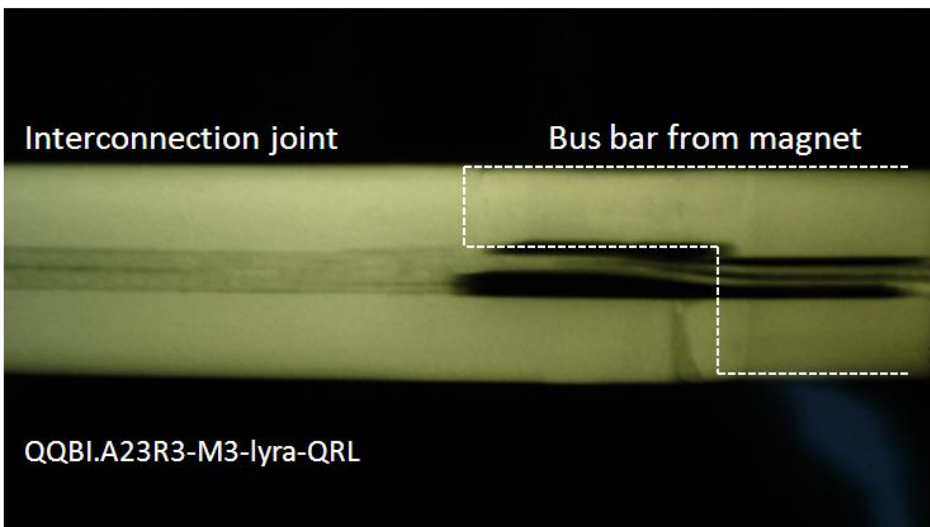


Main Damage Area: 700m

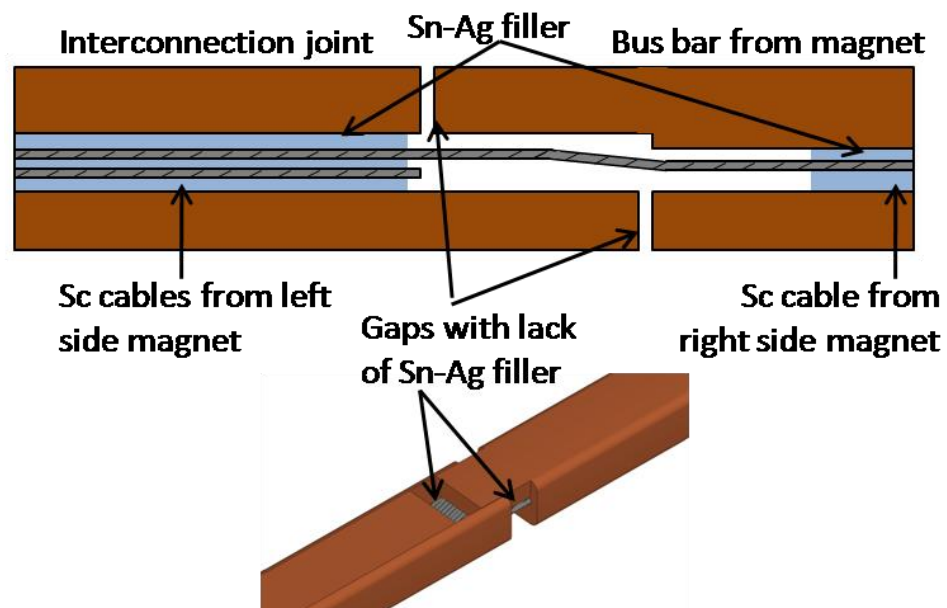
- 39 dipoles and 14 quadrupoles effected
- moved to surface:
- 37 replaced and 16 repaired

# Ideal 13 kA Connection Scheme





## Defective interconnection-bus bar transition $\gamma$ -ray picture (left) and scheme (right)



# LHC repair and consolidation

14 quadrupole magnets replaced



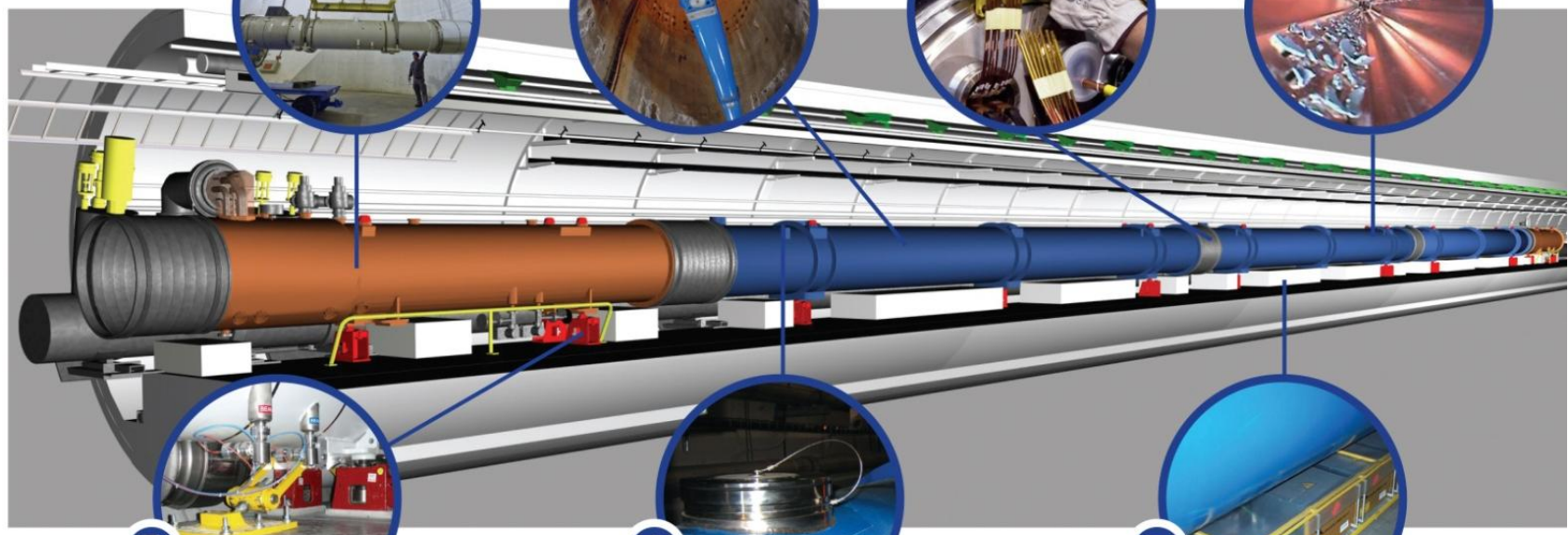
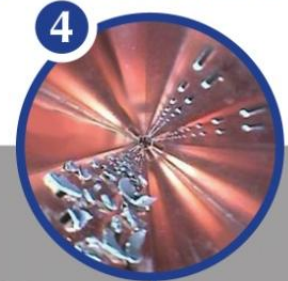
39 dipole magnets replaced



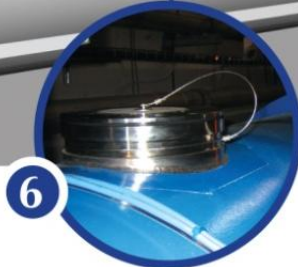
204 electrical inter-connections repaired



Over 4km of vacuum beam tube cleaned



New longitudinal restraining system for 50 quadrupoles



Almost 900 new helium pressure release ports

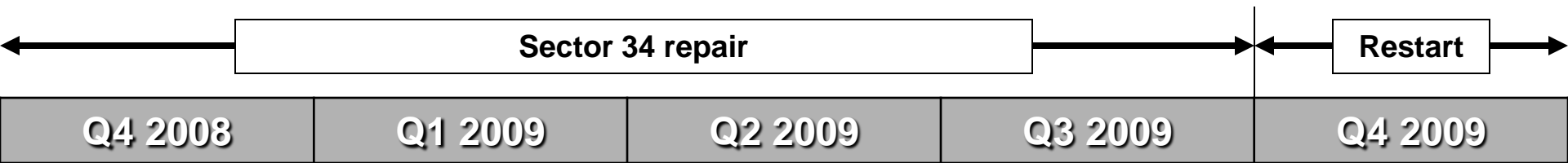


6500 new detectors and 250km cables for new Quench Protection System to protect from busbar quenches

Collateral damage mitigation



# Machine wide activities 2008/9



- Calorimetric & electrical splice measurements at cold (measuring  $n\Omega$ ) Q4 2008
  - Had to warm up sectors 1-2 6-7 to exchange magnets (and 5-6 for other reasons)
- Electrical stabilizer measurements at warm or 80K (measuring  $\mu\Omega$ ) Q1 - Q3 2009
- Major new protection system based on electrical measurements Q1 – Q4 2009 (nQPS)
- Pressure relief valves installed where possible Q1 – Q3 2009 (dipoles have to be warm)
- floor anchors reinforced Q1 – Q3 2009

	Q4 2008	Q1 2009	Q2 2009	Q3 2009	Q4 2009
12	Cold	Cold → Warm	Warm	Warm → Cold	Cold
23	< 100K	< 100K	< 100K → Cold	Cold → 80K → Cold	Cold
34	Warm	Warm	Warm	Warm → Cold	Cold
45	< 100K	< 100K	80K → Warm	Warm → Cold	Cold
56	Cold	Cold → Warm	Warm	Warm → Cold	Cold
67	Cold	Cold → Warm	Warm	Warm → Cold	Cold
78	Cold	< 100K	< 100K → 80K	80K → Cold	Cold
81	Cold	< 100K	< 100K → 80K	80K → Cold	Cold

# 20<sup>th</sup> November 2009 LHC was back

14 months to repair, consolidate and re-commission all elements

- Energy Limit 1.2 TeV in 2009 – bringing bus-bar quench protection system online

20<sup>th</sup> November – Circulating beams again!

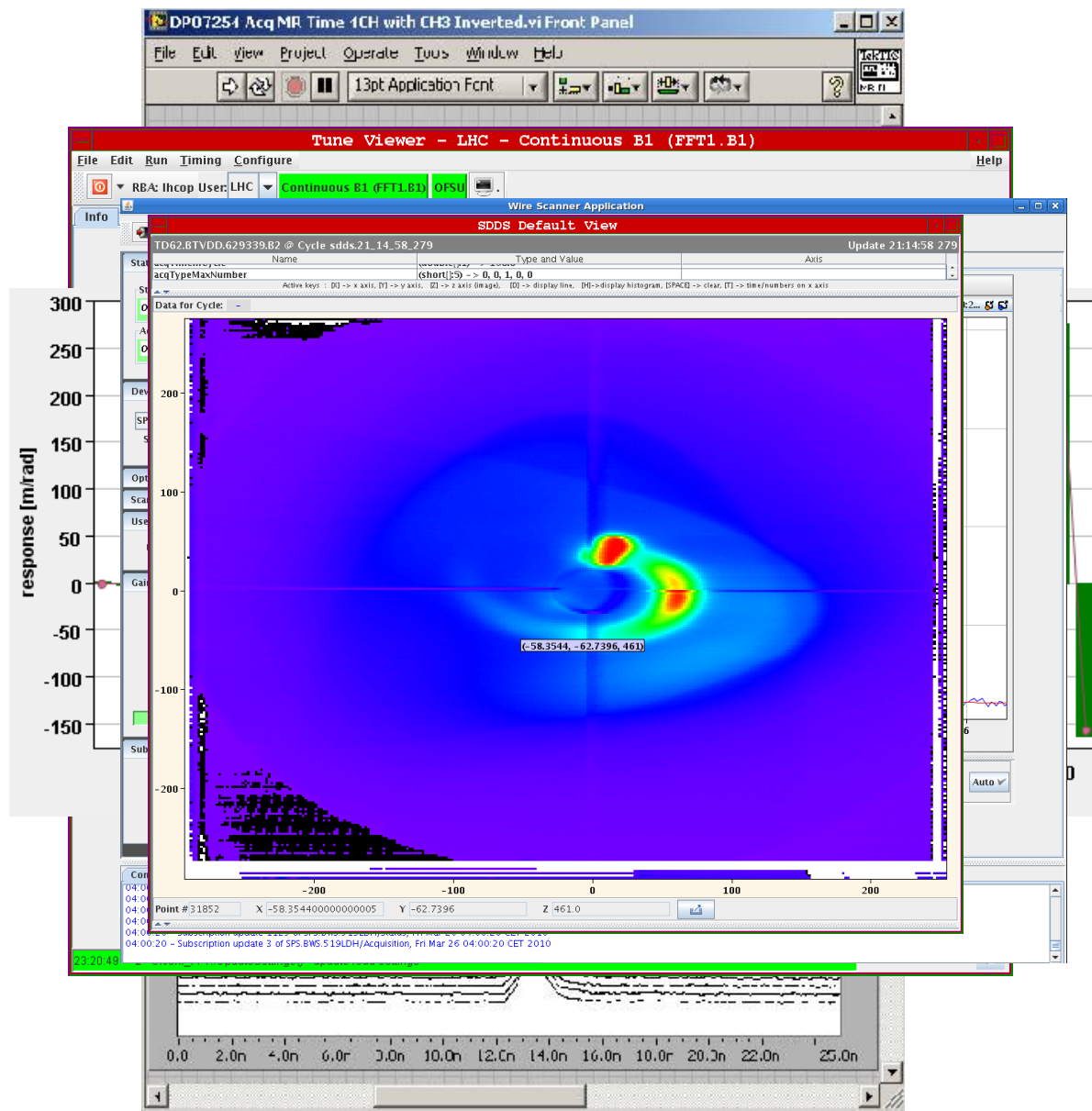


# Diagnostics Available on Day Zero

Some examples...

- RF / Capture
- Tune Measurements
- Orbit Measurements
- Wire Scanners
- Machine Protection

And more...





# 2009 Beam Operation Milestones

20 <sup>th</sup> November	Day 0	Both Beams Circulating after 6 hours
23 <sup>rd</sup> November	Day 3	First pilot collisions at 450 GeV
29 <sup>th</sup> November	Day 9	Beams ramped to 1.18 TeV
6 <sup>th</sup> December	Day 16	Stable Collisions at 450 GeV for experiments
8 <sup>th</sup> December	Day 18	First collisions at 1.18 TeV

- Commissioned at a forced pace – aim to check as much as possible
- Uptime 60% - Very good at this stage
- Most optimistic dreams came true
- A touch of modesty

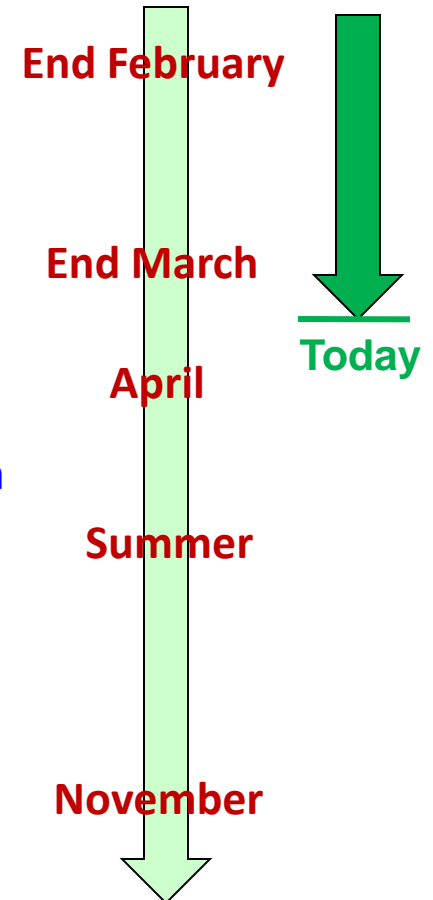
Stored energy did not exceed 30 kJ – 0.01% of nominal



Jan-Feb 2010: commissioning of LHC circuits for 3.5 TeV operation.

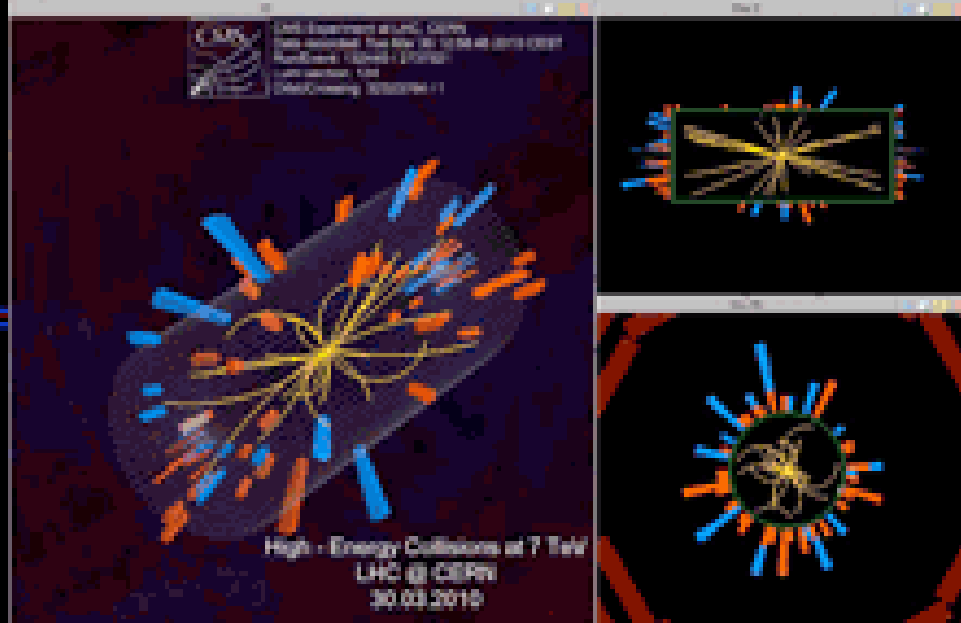
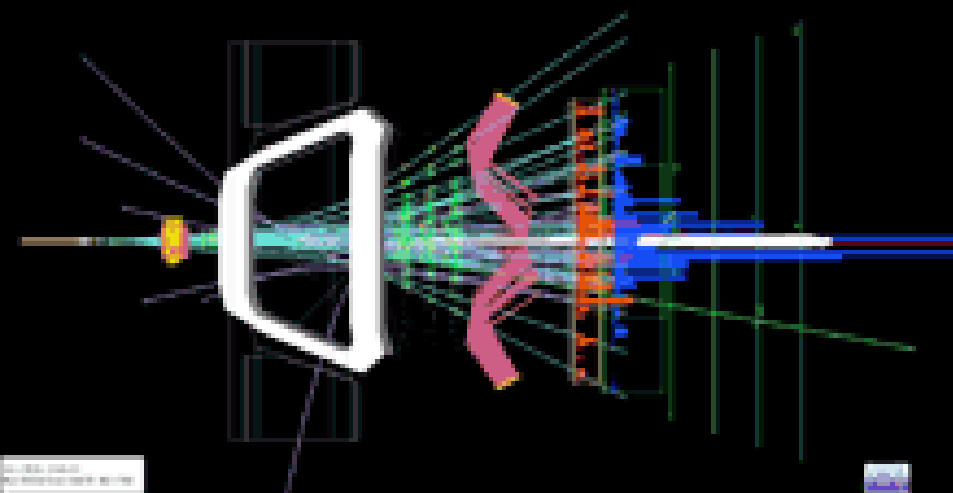
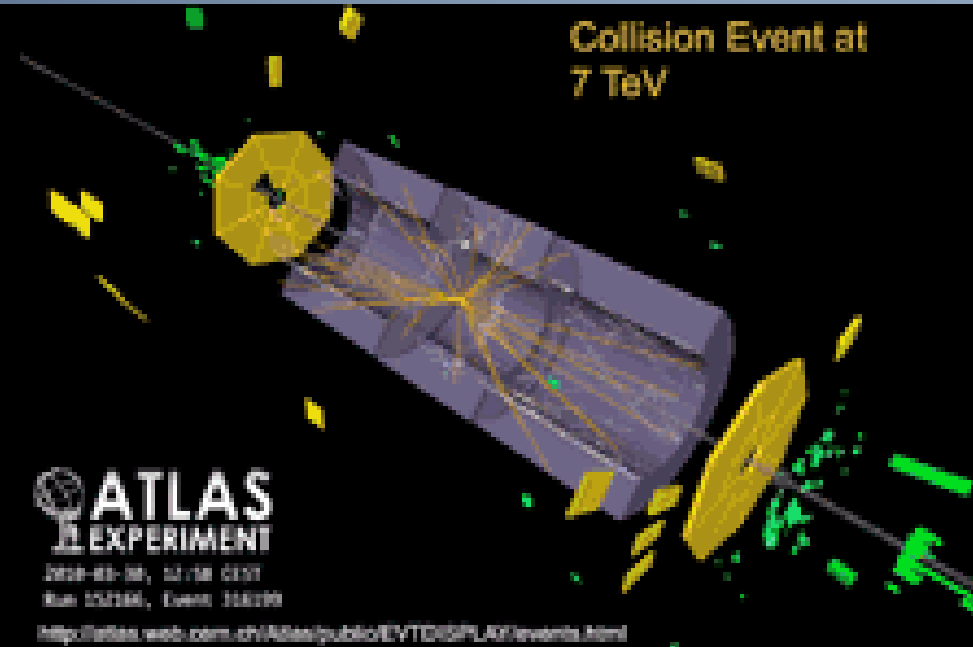
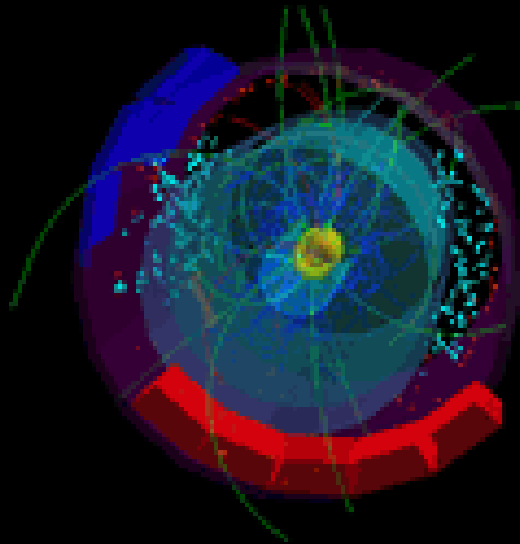
## Beam operation 2010:

- Start-up with beam.
- Consolidation at 450 GeV (optics...).
- Ramp to 3.5 TeV.
- **Low intensity collisions at 3.5 TeV.**
- Interaction spot size squeezing.
- Low intensity collisions at 3.5 TeV squeezed.
- Stepwise (factor 2-4) increase of intensity to 1-2 MJ/ beam
- Switch from individual bunches to bunch train (50 ns).
- ...
- Lead ion run





# 3.5 TeV collisions



The electrical incident revealed quality issues of the bus-bar joints.

14 months of repair and re-commissioning.

New diagnostics for online monitoring and protection of all joints.

Eradication of joint issues requires a complete warm-up and long shutdown.

The LHC beam energy will be limited to 3.5 TeV in 2010/2011.

Long shutdown in 2012 to prepare LHC for 7 TeV / beam.

**Very successful beam commissioning to 1.2 & 3.5 TeV.**

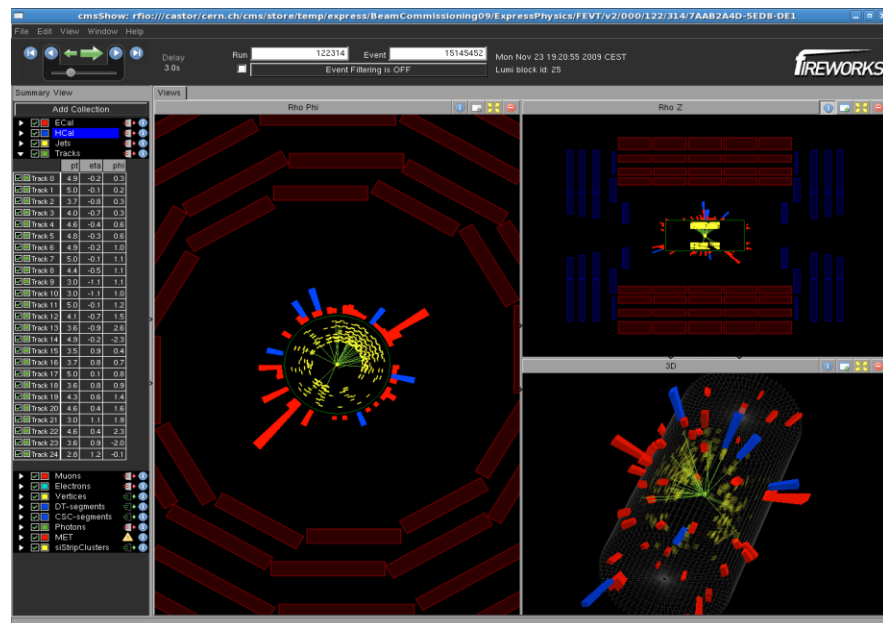
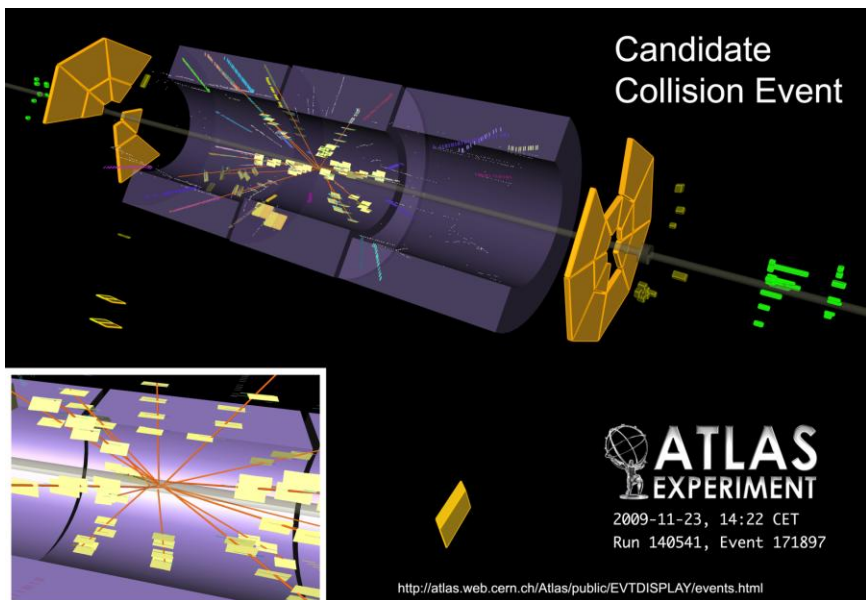
LHC is reproducible.

Collisions at 3.5 TeV established.

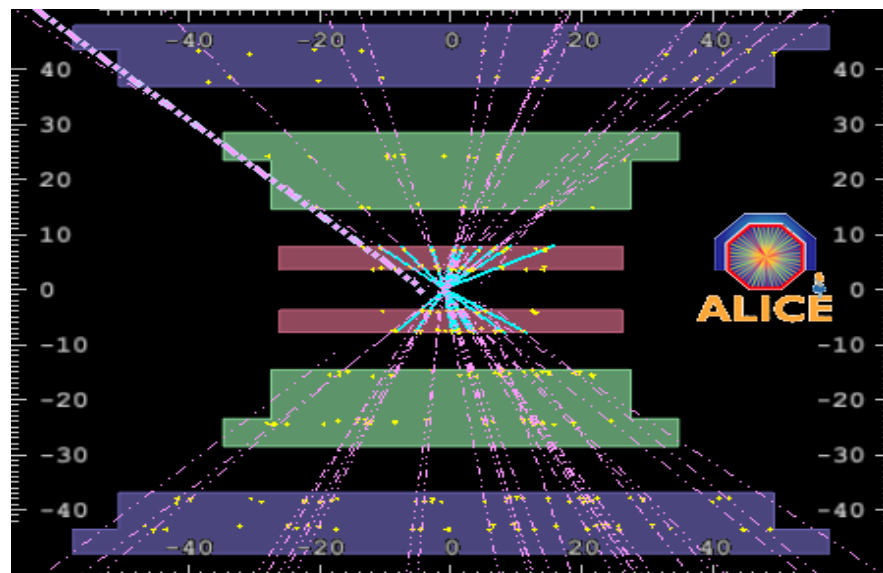
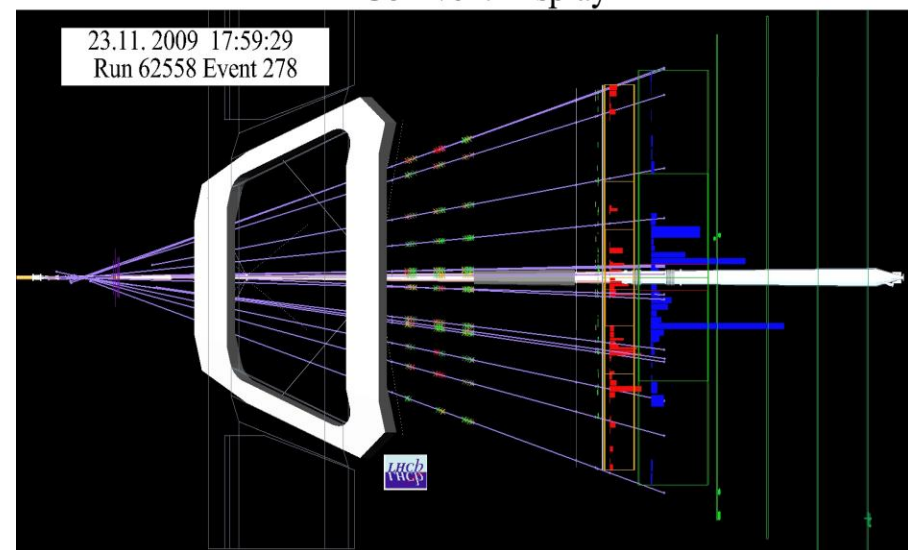
Increase stepwise intensity through the year.

Ready to operate 18 months at 3.5 TeV

**But the real beam challenges are ahead of us !**



LHCb Event Display



# Food for thought – Tune Spectra

