Status of the LHC Machine

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Acknowledgements to R. Schmidt for some slides and many discussions.

Outline

Introduction

Commissioning 2008

Incident of September 19th

Repair and consolidation

2009/10 LHC run

Conclusions

LHC

7 years of construction to replace :

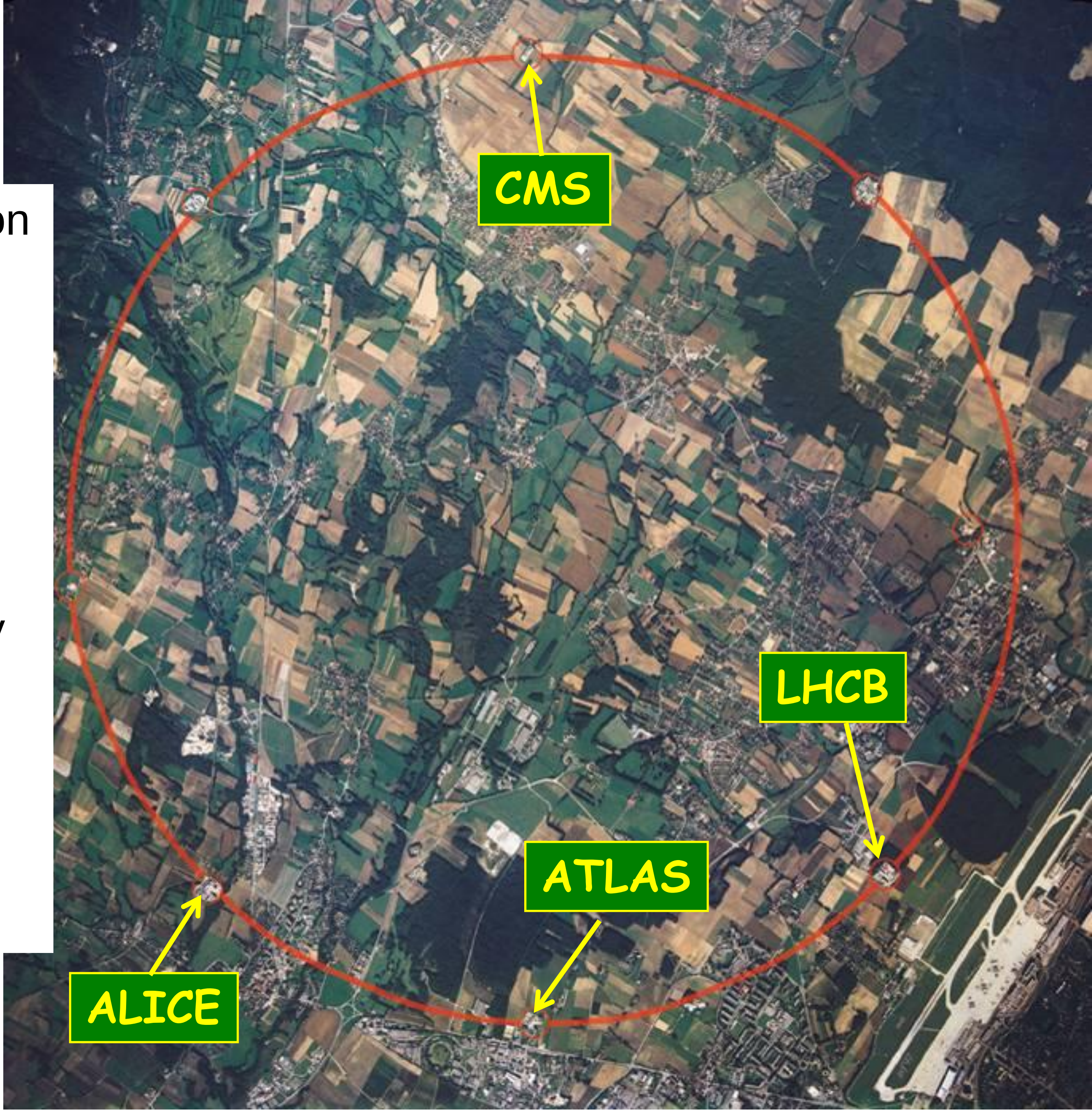
LEP: 1989-2000

- e+e- collider
- 4 experiments
- max. energy 104 GeV
- circumference 26.7 km

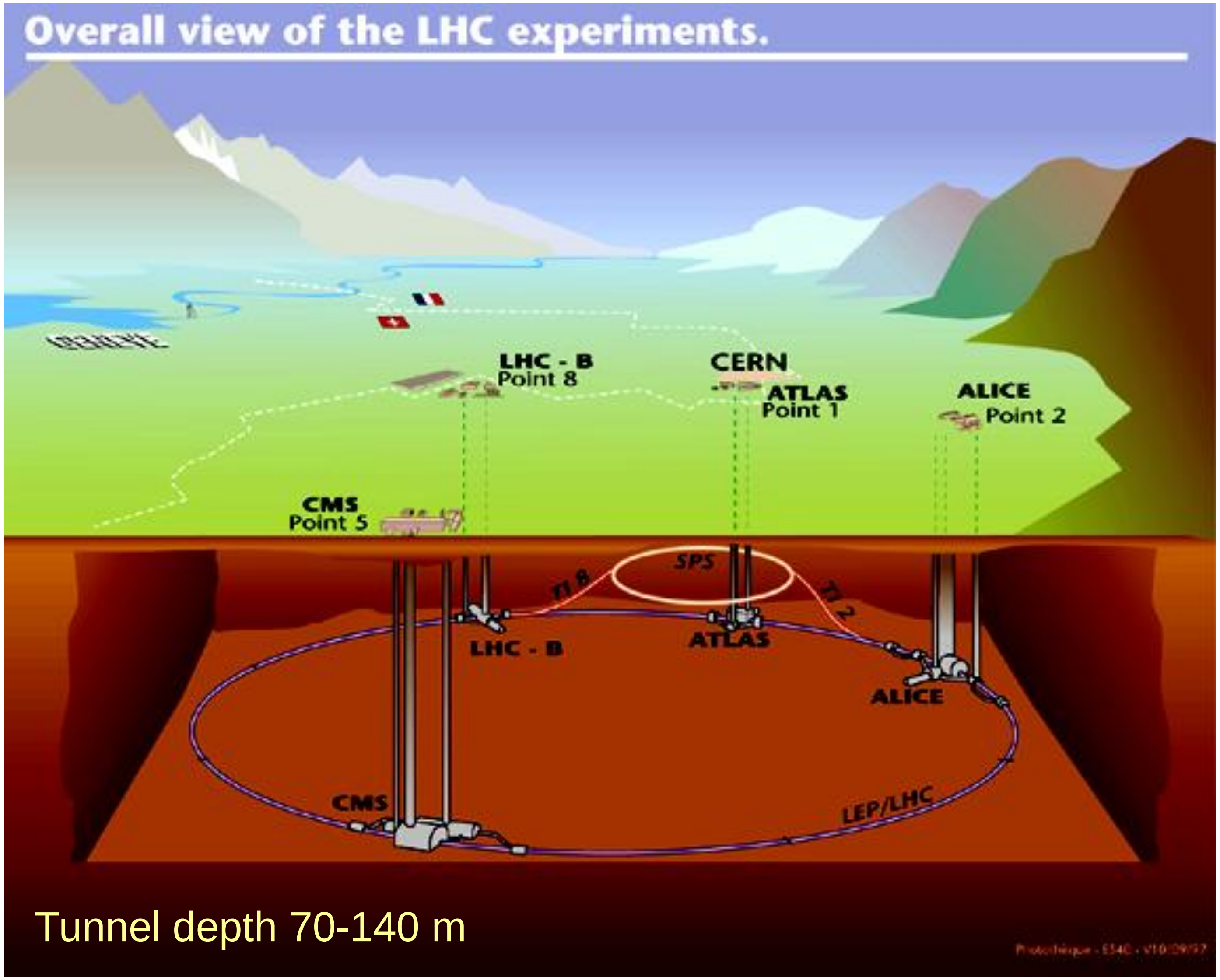
in the same tunnel by

LHC : 2008-2020+

- pp & ion-ion collider
- 4+ experiments
- energy 7 TeV



LHC overview

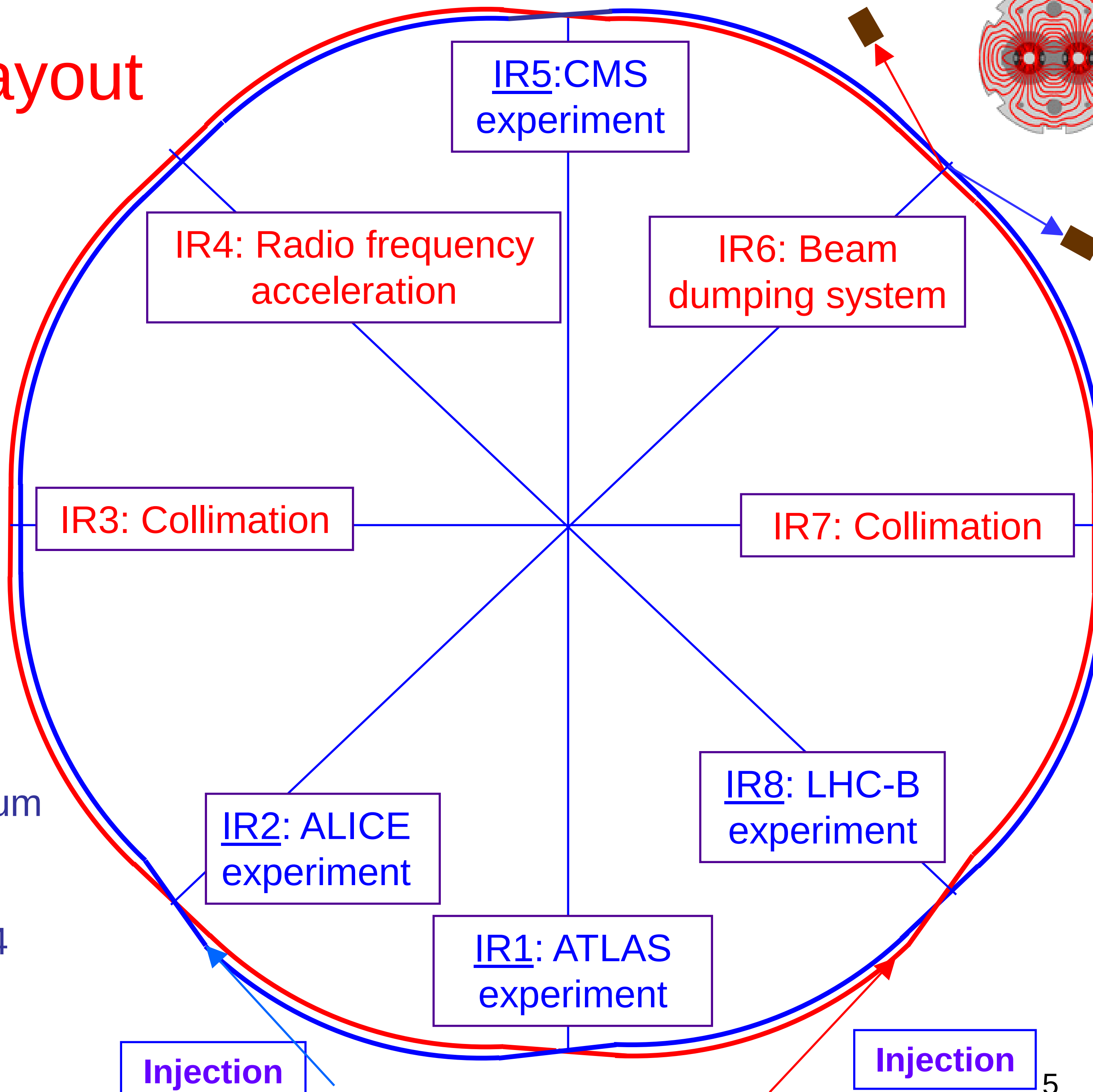


LHC Layout

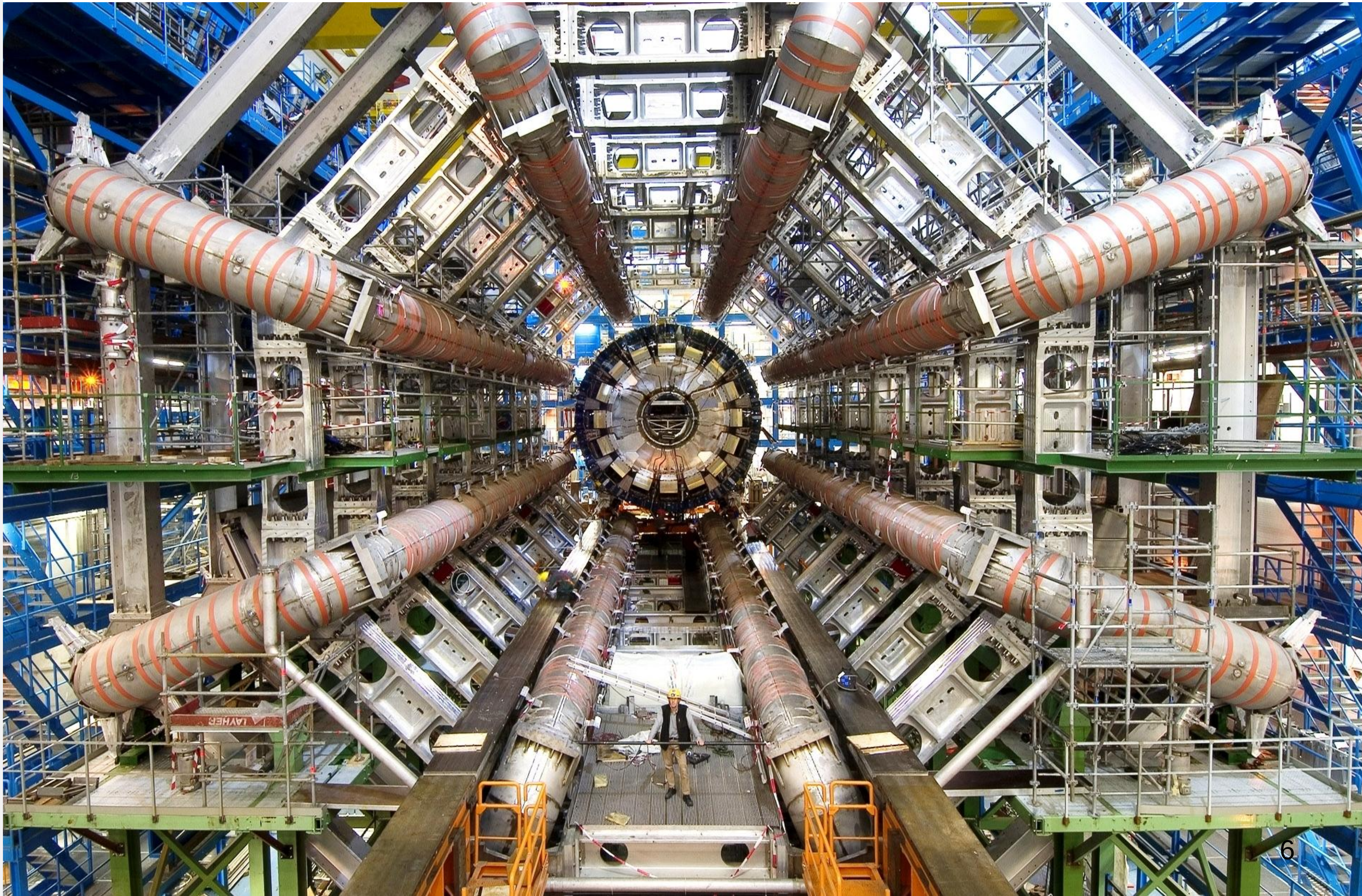
- 8 arcs (sectors)
- 8 long straight sections (700 m long):

  IR1 to IR8

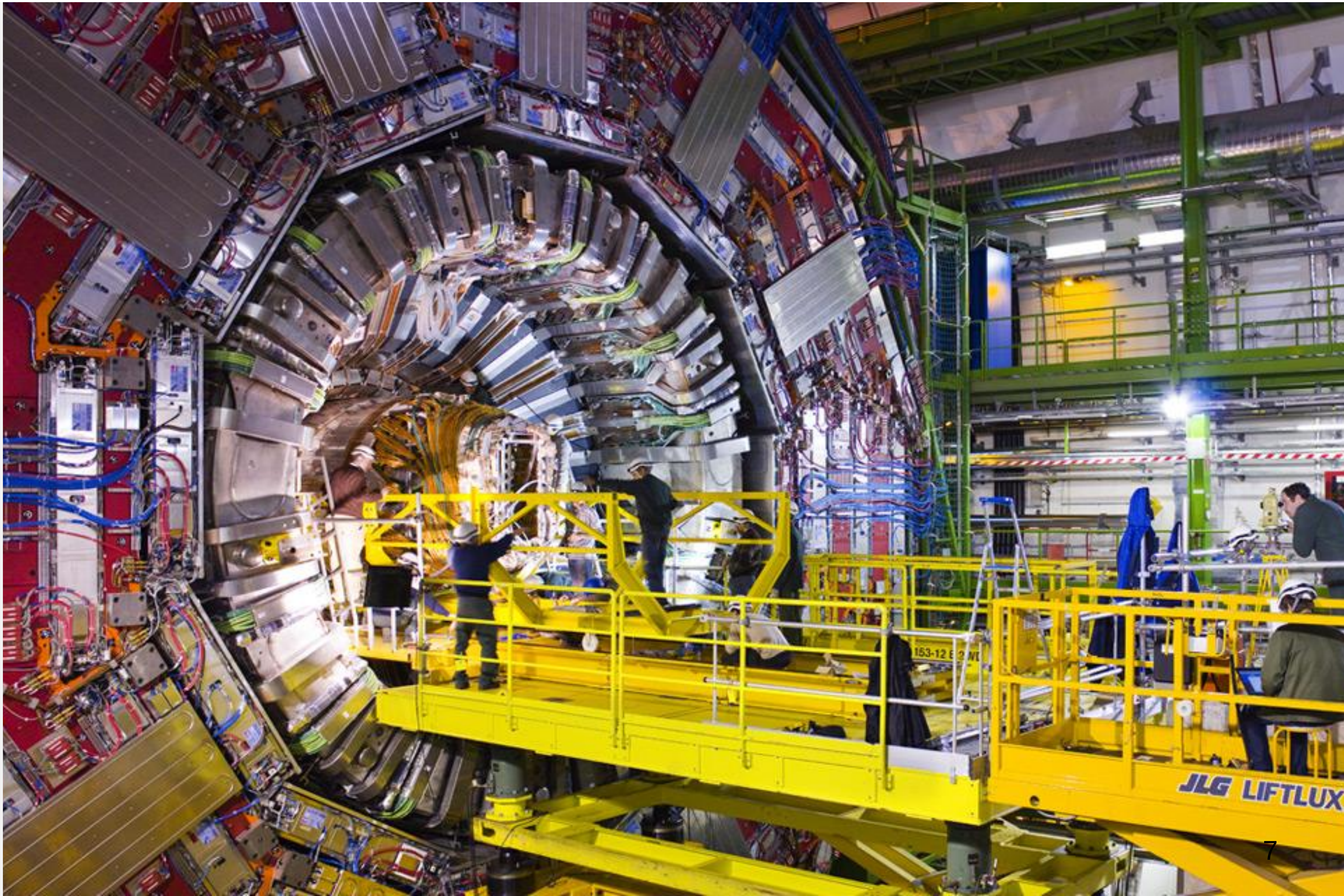
- 2 separate vaccum chambers
- beams cross in 4 points



ATLAS detector



CMS detector



The LHC challenge

The LHC surpasses existing accelerators/colliders in 2 aspects :

- The energy of the beam of 7 TeV that is achieved within the size constraints of the existing 26.7 km LEP tunnel.

LHC dipole field	8.3 T
HERA/Tevatron	~ 4 T

A factor <u>2</u> in field

A factor <u>4</u> in size

- The luminosity of the collider that will reach unprecedented values for a hadron machine:

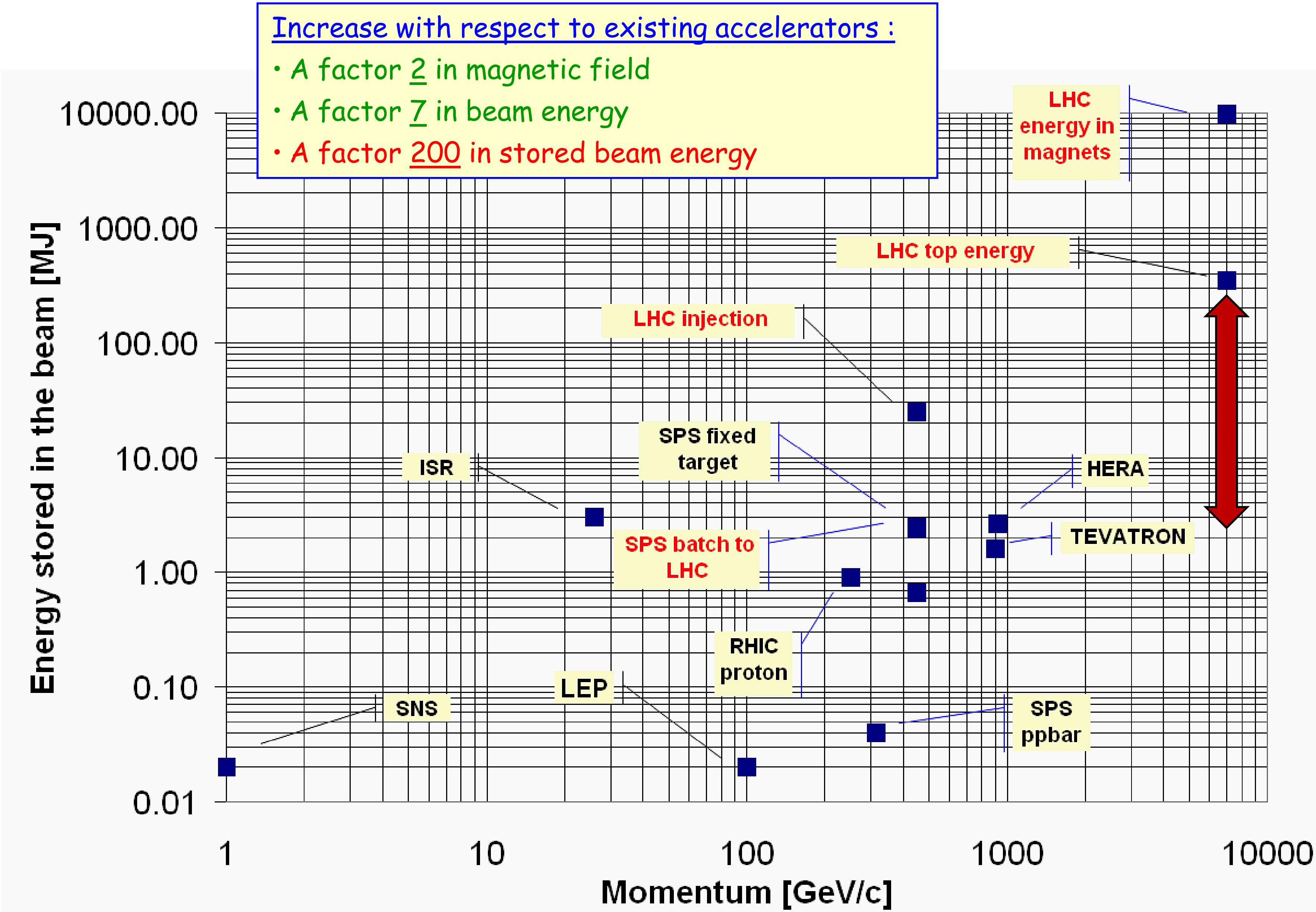
LHC	pp	~ 10^{34} cm^{-2} s^{-1}
Tevatron	pp	$3x10^{32}$ cm^{-2} s^{-1}
SppbarS	pp	$6x10^{30}$ cm^{-2} s^{-1}

A factor <u>30</u> in luminosity

Very high field magnets and very high beam intensities:

- Operating the LHC is a great challenge.
- There is a significant risk to the equipment and experiments.

LHC stored energy challenge



To set the scale

- The **11 GJ** of enery stored in the magnets are sufficient to heat and melt 15 tons of Copper (~1.7 m^3).
- The **350 MJ** stored in each beam correspond to ~90 kg of TNT.

  Plasma-hydrodynamic simulations indicate that the beam will drill a ~30 m long hole into Copper.

As an indication…

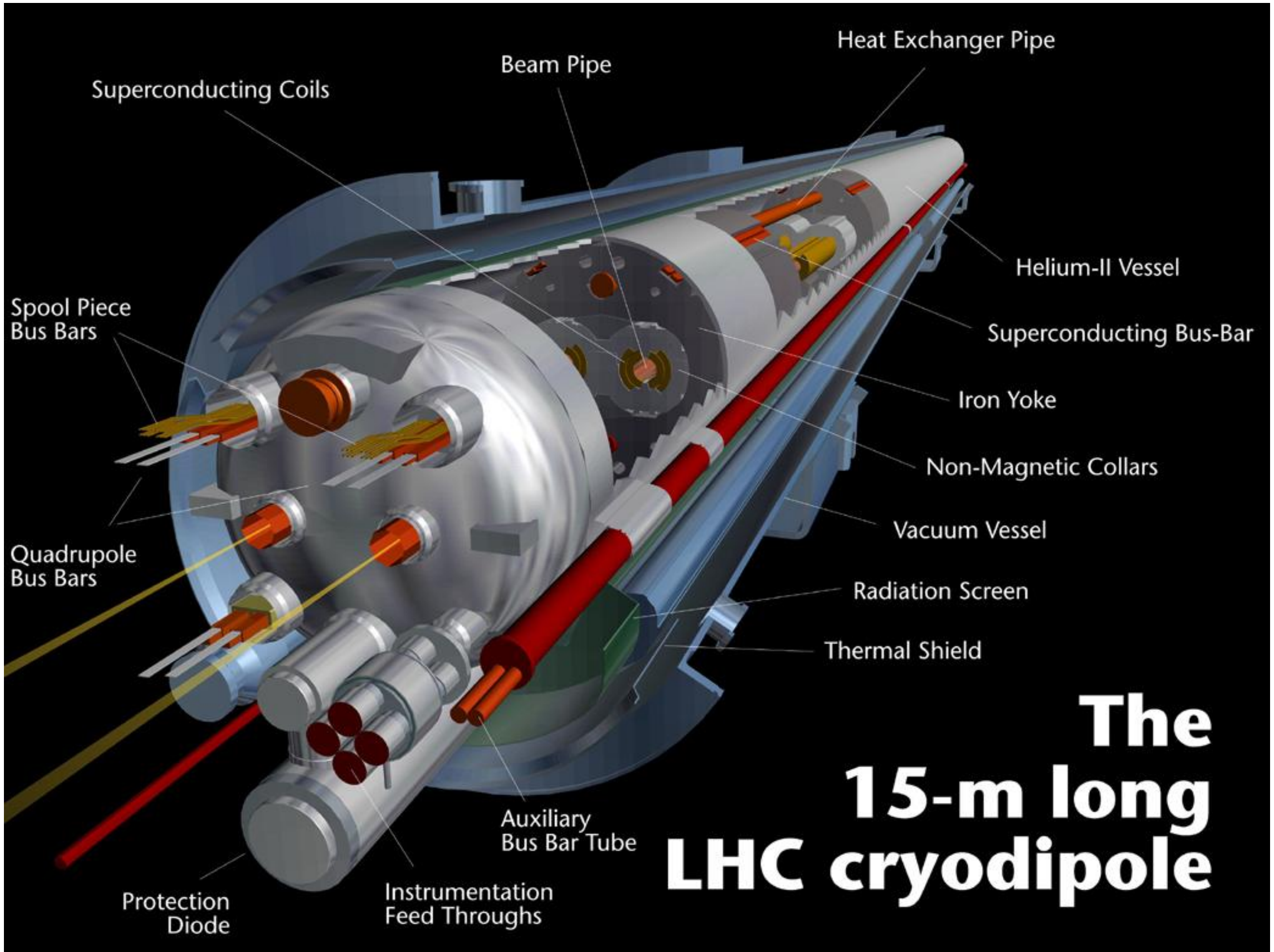
Few cm long groove on an SPS vacuum chamber from the impact of **~1% of a nominal LHC beam** during an incident:

- vacuum chamber ripped open.
- 3 day repair.

The same incident at the LHC implies a shutdown of > 3 months.

Dipole magnet challenge

- 1232 dipole magnets.
- 15 m long.
- Magnetic field 8.3 T @ 1.9 K.
- 2 magnets-in-one design : two beam tubes with an opening of 56 mm.



Super-conducting magnet quench

- A **‚quench‘** is the phase transition from the super-conducting to the normal conducting state.
- Quenches are initiated by an energy in the order of few mJ
  - movement of the superconductor (friction and heat dissipation),
  - beam losses,
  - cooling failures,
  - any other heat sources...
- When part of a magnet quenches, the conductor becomes resistive, which can lead to excessive local energy deposition due to the appearance of Ohmic losses. To protect the magnet:
  - the quench must be detected.
  - the energy in the magnet /electrical circuit must be extracted.
  - the magnet current has to be switched off within << 1 second.

An energy density of ~1 mJ/cm^3 is sufficient to destroy super-conductivity in a magnet (quench) : a local loss of 1 ppm of the beam is sufficient !

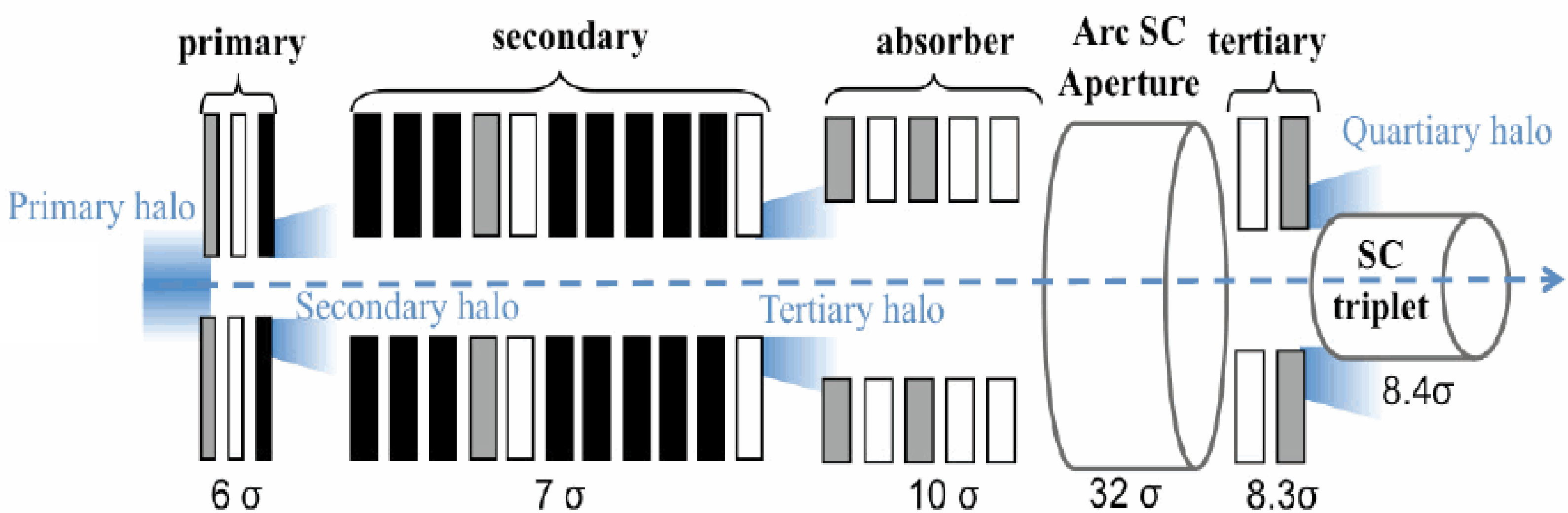
Collimation (1)

A <u>4-stage halo cleaning</u> (collimation) system is installed to protect the LHC magnets from beam induced quenches.

- A cascade of more than 100 collimators is required to prevent the high energy protons and their debris to reach the superconducting magnet coils.

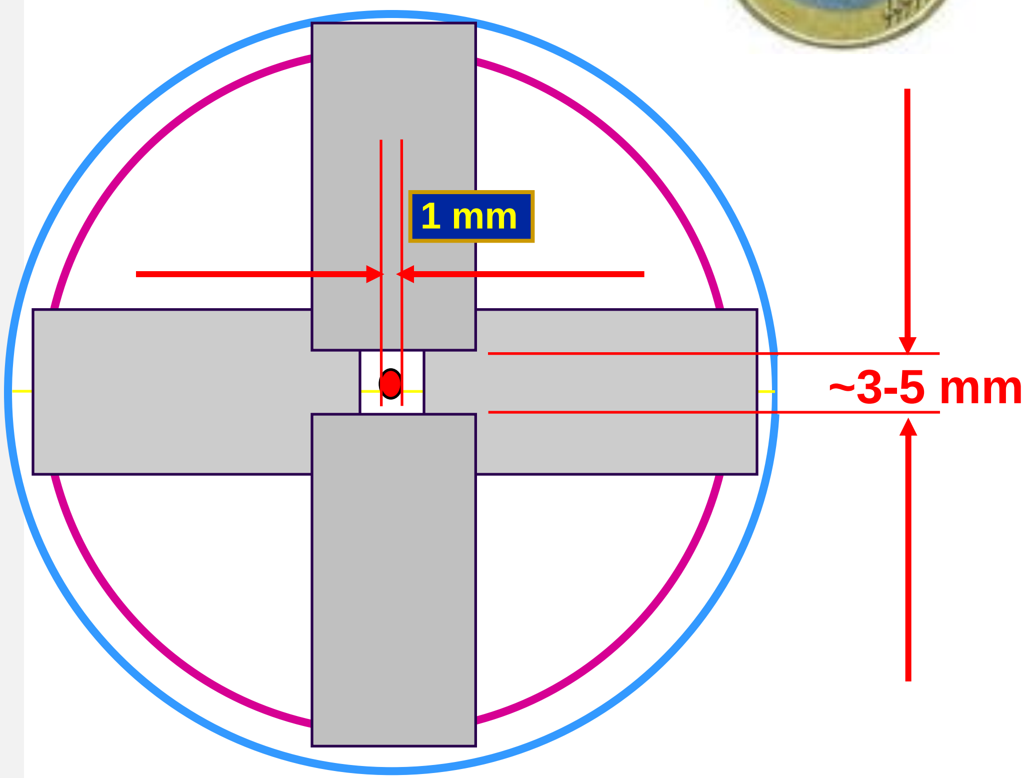
→ the collimators must reduce the energy load into the magnets due to particle lost from the beam to a level that does not quench the magnets.

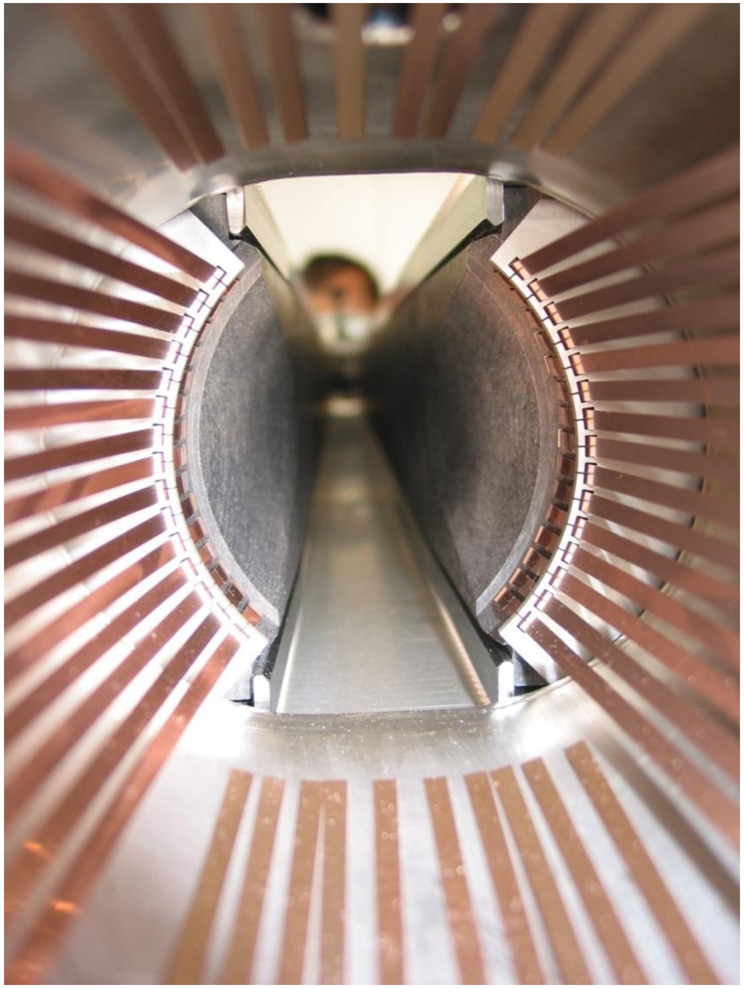
Operating the LHC beams is ~ 1000 more critical than TEVATRON.



Collimation (2)

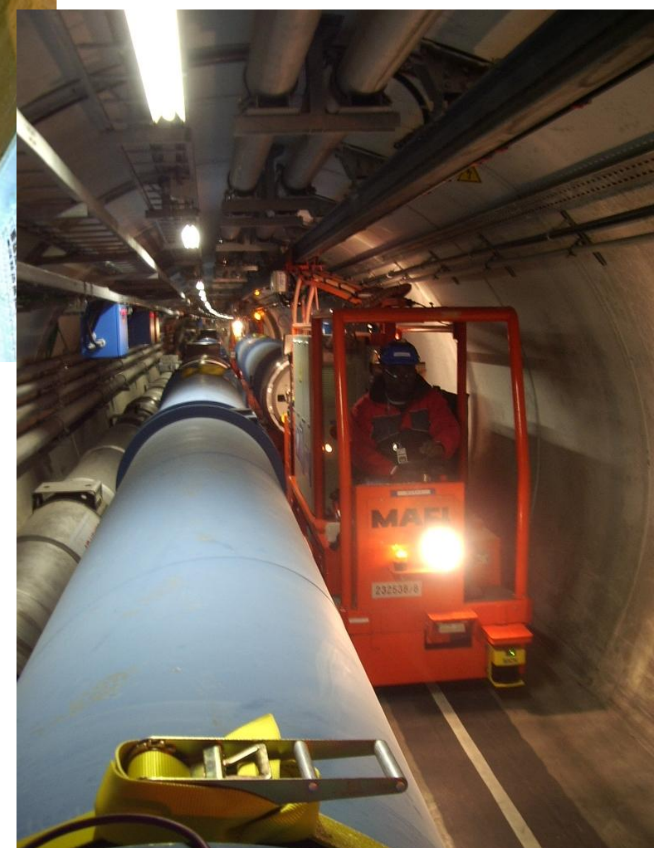
The collimator opening corresponds
roughly to the size of Spain !





LHC Commissioning

First dipole lowered 7th March 2005



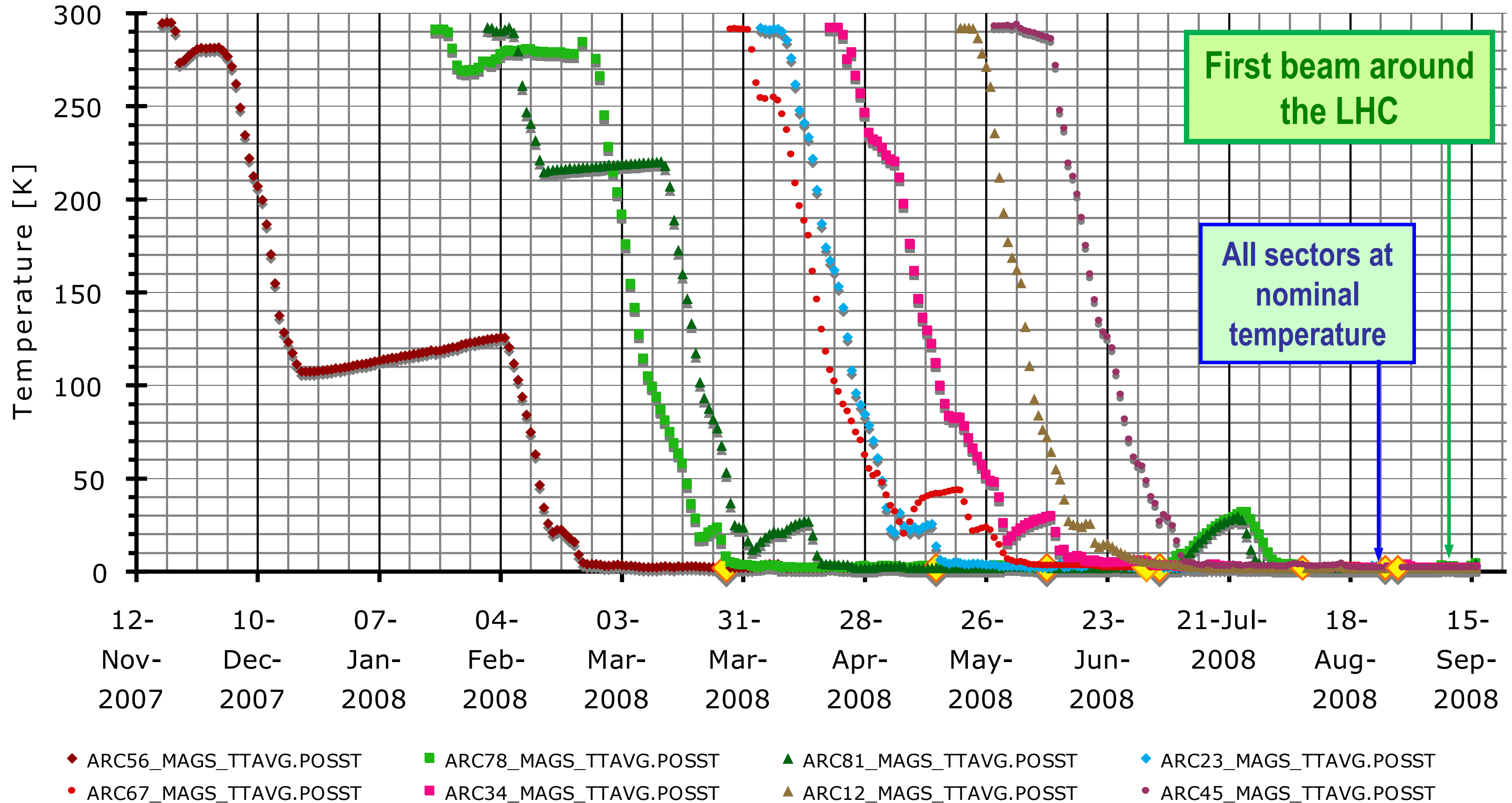
Transport in the tunnel with an optically guided vehicle

Approx. 1600 magnets to be transported over up to 20 km at 3 km/hour

3 km long cryostats

LHC cool-down in 2008

Cool-down time to 1.9 K ~ 4-6 weeks/sector
[sector = 1/8 LHC]



Magnet Commissioning

April to September 2008:

- Commissioning of the magnets & circuits (power converter, quench protection, interlocks..) following predefined test steps.

  1'700 circuits, 10'000 magnets

- The initial target energy of 7 TeV had to be reduced to **5 TeV** because of a large number of re-training quenches of the magnets from one of the three companies.

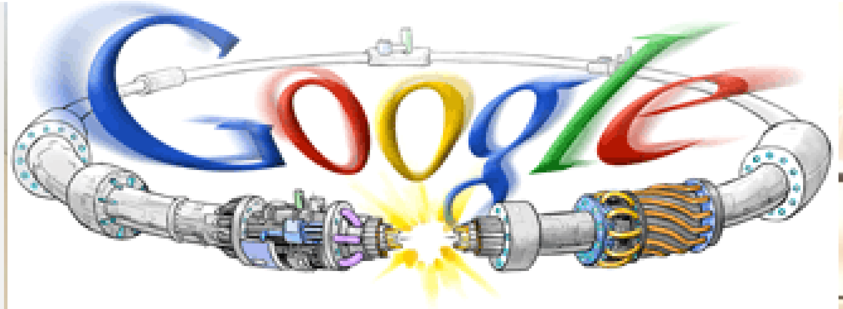
  All magnets were trained to 7+ TeV on test stands. This typically requires a few quenches until the coils settle.

  The magnets are then stored, moved to the tunnel and installed.

  Assumption is usually that the magnets come back to their test stand performance with no or few quenches. Turned out to be wrong for one company!

  Not understood !

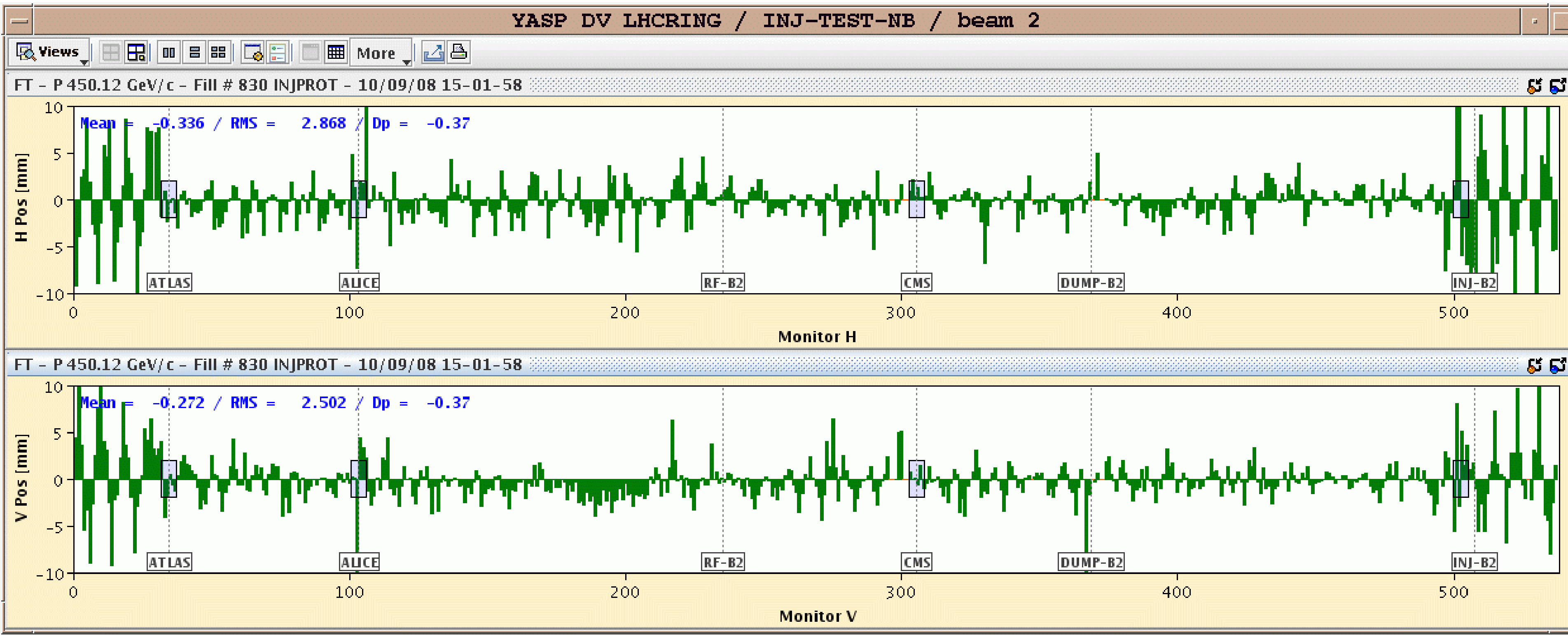
September 10th - control (show) room



Beam threading

- Unique feature of LHC: threading the beam around is a tricky exercise.
- After 3 days beam circulates with good lifetime, optics measured and most instrumentation operational.

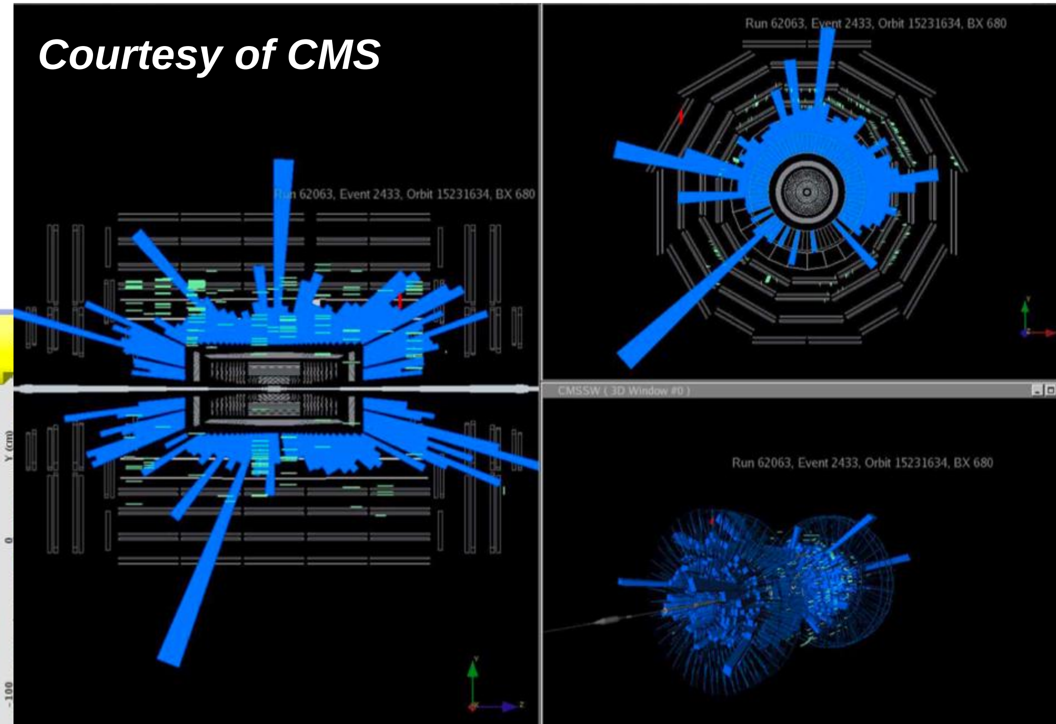
Beam 2

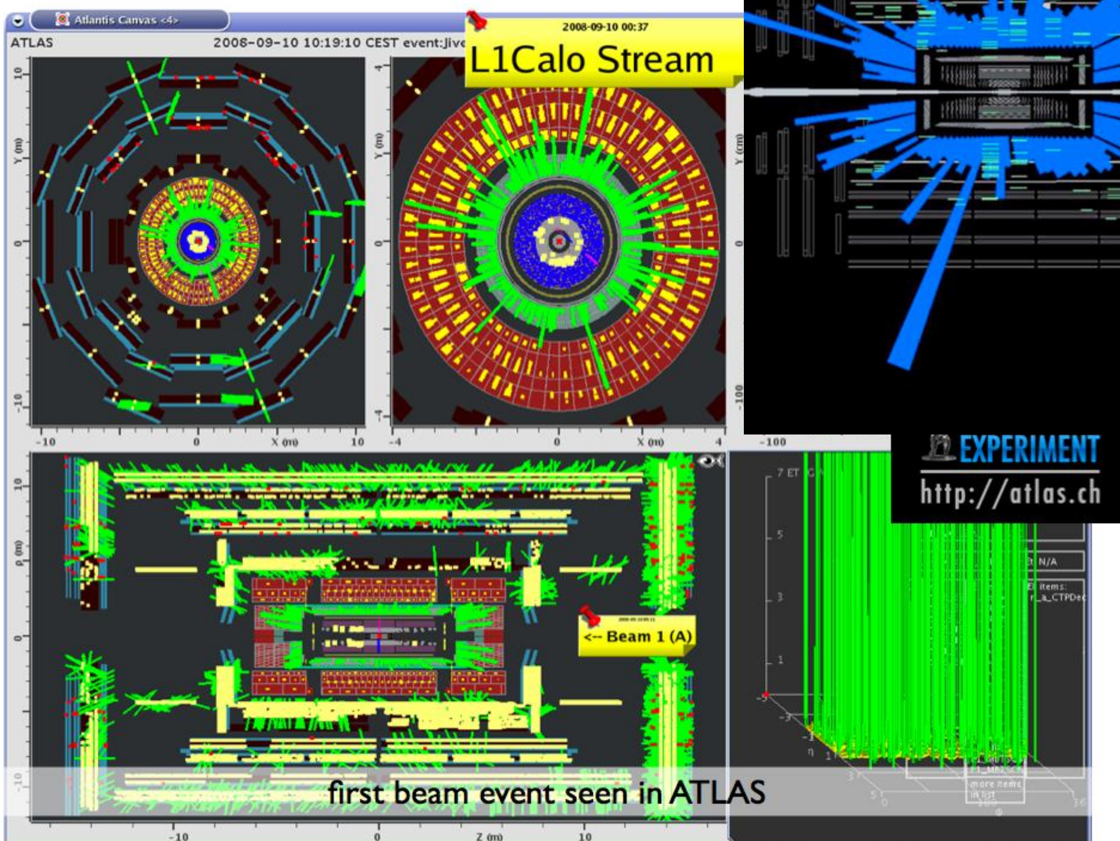


ATLAS & CMS ‘events’

‘Beam-on-collimator’ events

Synchronized to beam timing !





Courtesy of ATLAS

September 19th Incident

Event sequence on Sept. 19th

Introduction: on September 10th the LHC magnets had not been fully commissioned for 5 TeV.

A few magnets were missing their last commissioning steps.

The last steps were finished the week after Sept. 10th.

- Last commissioning step of the main dipole circuit in sector 34 : ramp to 9.3kA (5.5 TeV).
- At 8.7kA an electrical fault developed in the **dipole bus bar** (the bus bar is the cable carrying the current that connects all magnet of a circuit).
- An electrical arc developed which punctured the helium enclosure.

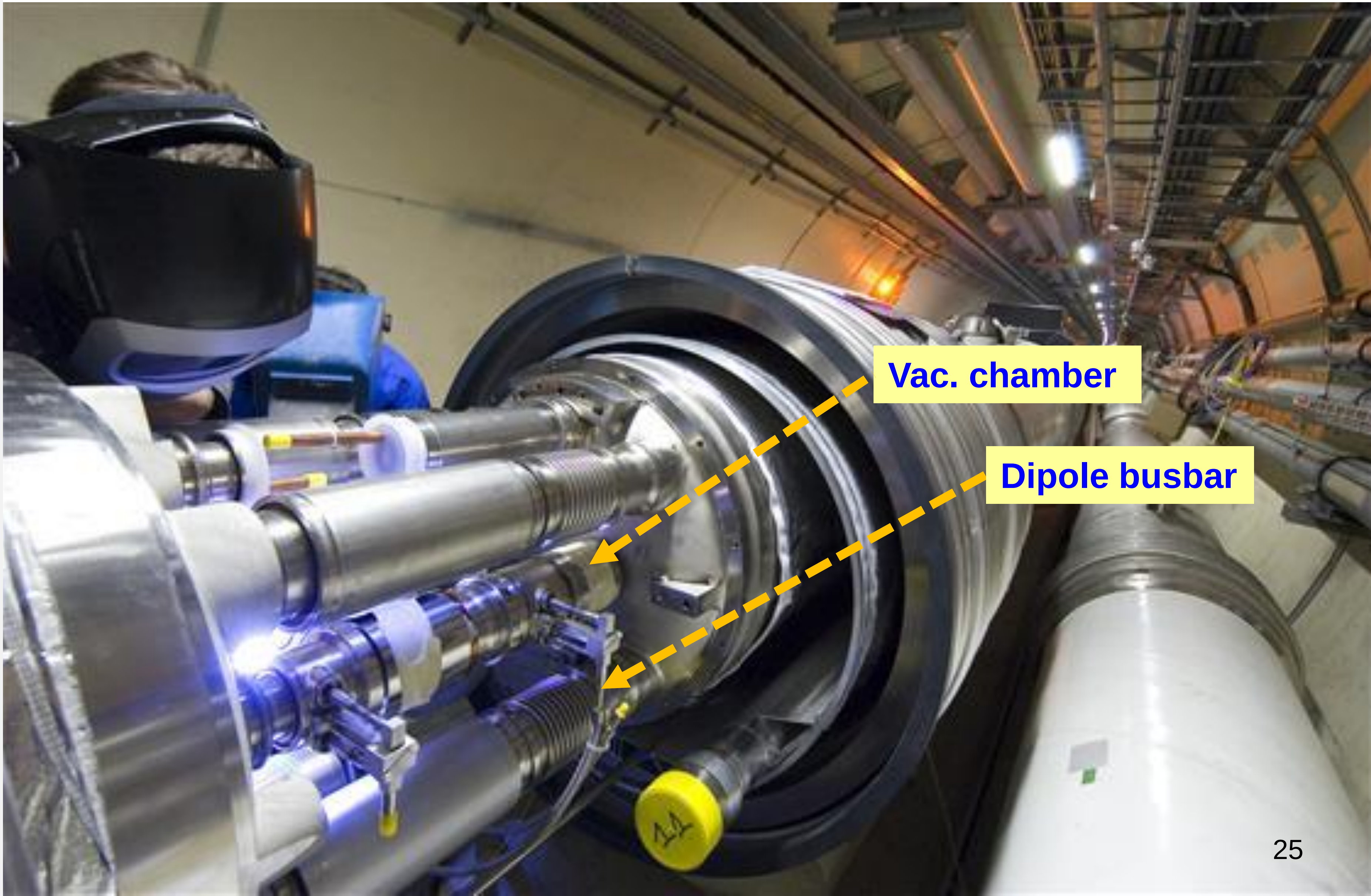
Secondary arcs developed along the arc.

Around 400 MJ were dissipated in the cold-mass and in electrical arcs.

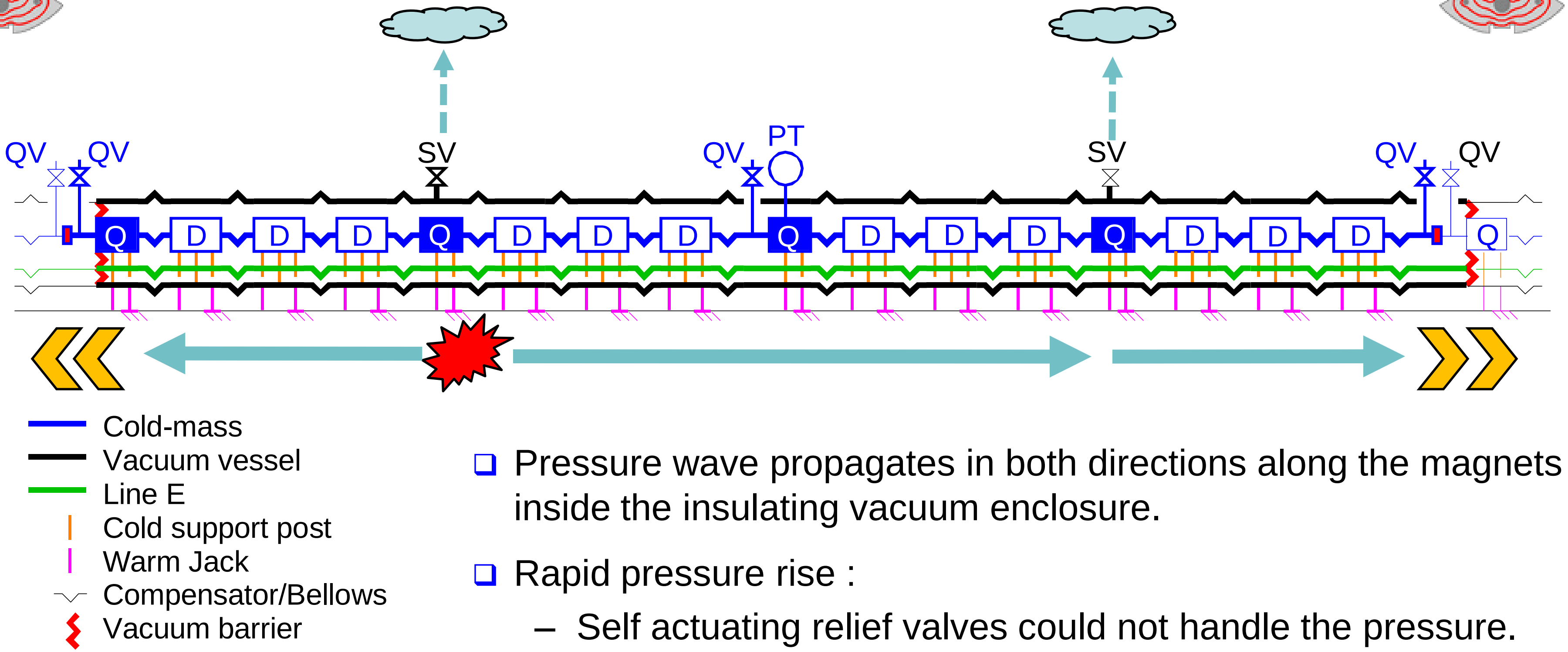
- Large amounts of Helium were released into the insulating vacuum.

In total 6 tons of He were released.

Inter-connection

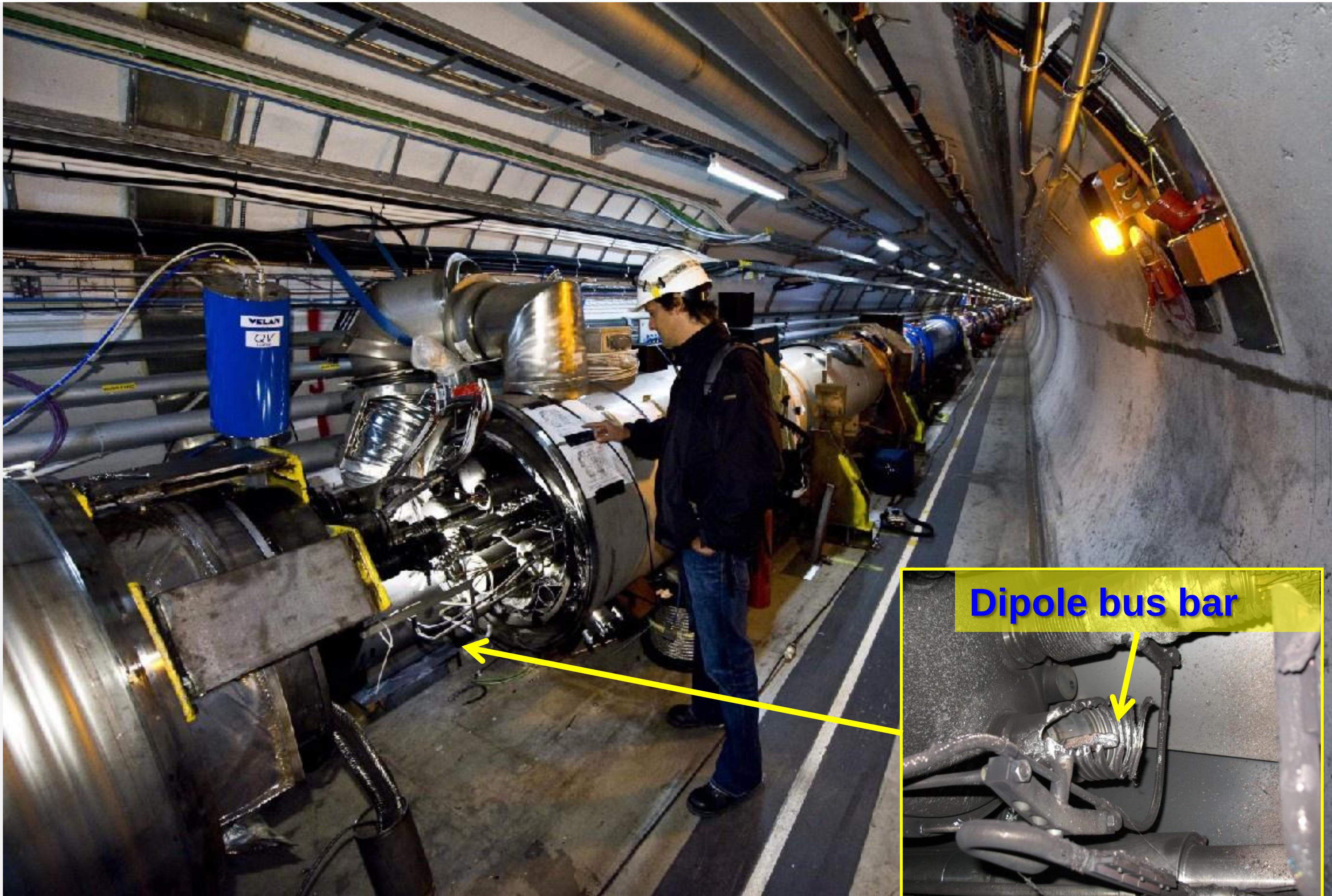


Pressure wave

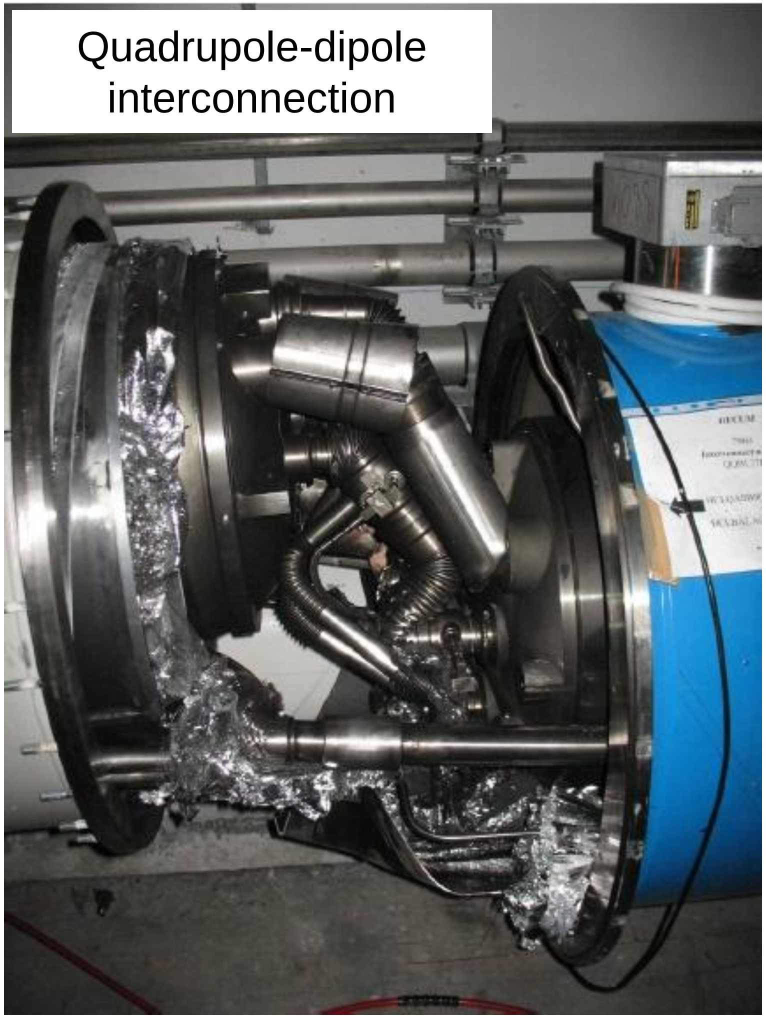


- Pressure wave propagates in both directions along the magnets inside the insulating vacuum enclosure.
- Rapid pressure rise :
  - Self actuating relief valves could not handle the pressure. *designed for 2 kg He/s, incident ~ 20 kg/s.*
  - Large forces exerted on the vacuum barriers (every 2 cells). *designed for a pressure of 1.5 bar, incident ~ 10 bar.*
  - Several quadrupoles displaced by up to ~50 cm.
  - Connections to the cryogenic line damaged in some places.
  - Beam vacuum to atmospheric pressure.

Incident location



Collateral damage : displacements



Quadrupole-dipole interconnection

Quadrupole support

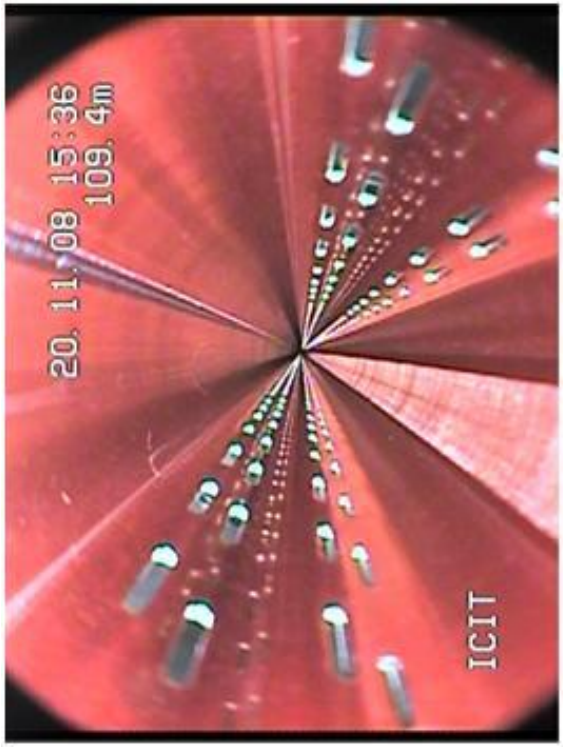
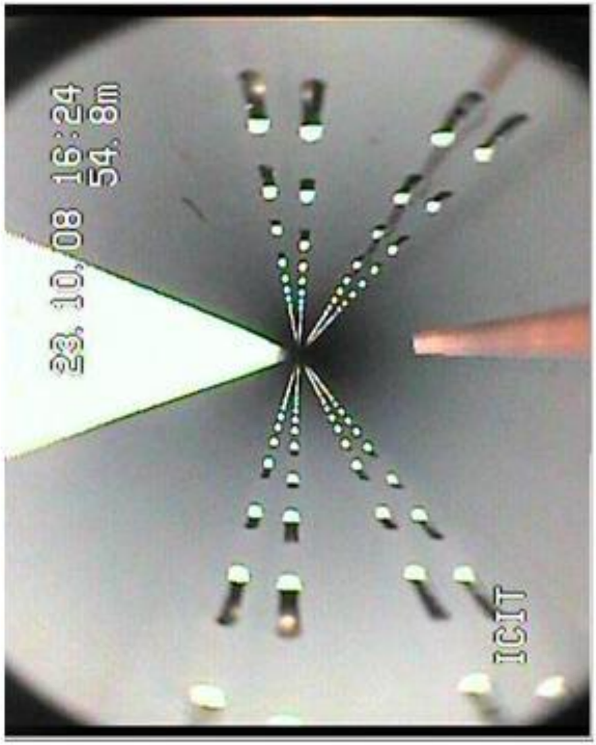
Main damage area ~ 700 metres.

- **39** out of 154 **dipoles**,
- **14** out of 47 **quadrupole** short straight sections (SSS)

from the sector had to be moved to the surface for repair (16) or replacement (37).

Collateral damage : beam vacuum

Beam vacuum was affected over entire 2.7 km length of the arc.

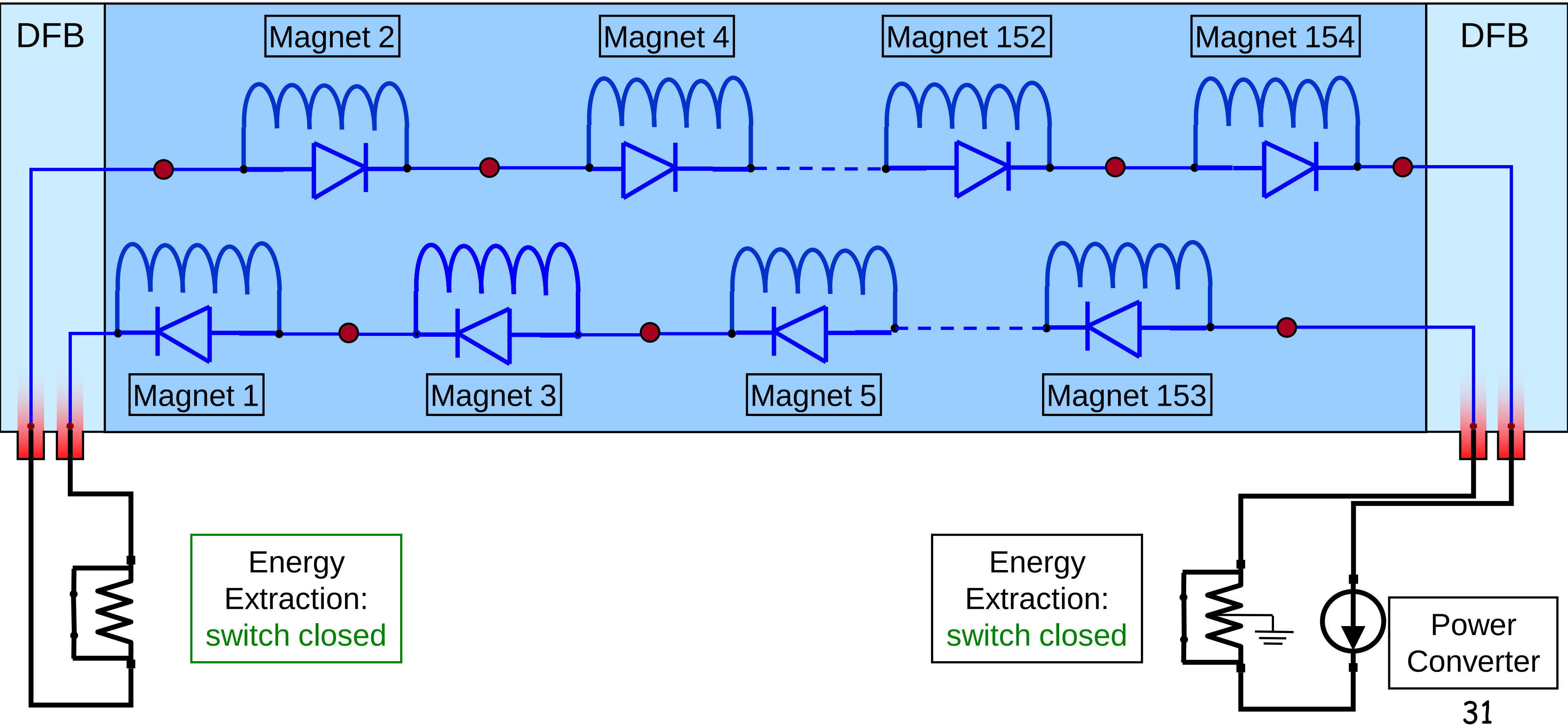
Clean Copper surface.	Contamination with multi-layer magnet insulation debris.	Contamination with sooth.
		

≈ 60% of the chambers **≈ 20% of the chambers**

Incident Trigger

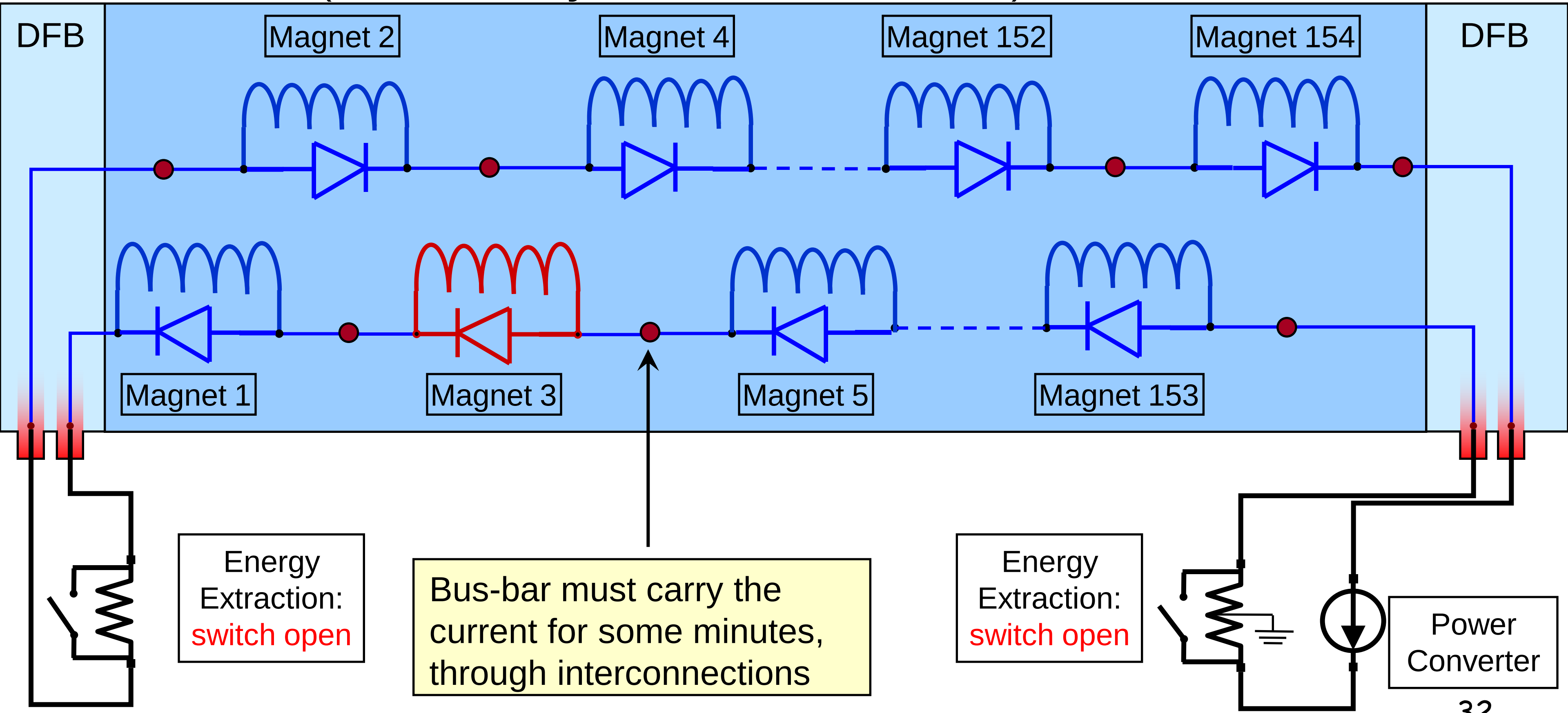
Dipole magnets in arc cryostat

- 154 dipole magnets are connected together as one circuit to the power converter.
- Time for the energy/field **ramp** is about **20-30 min** (energy from the grid)
- Time for regular discharge (ramp down) is about **the same** (energy to the grid)

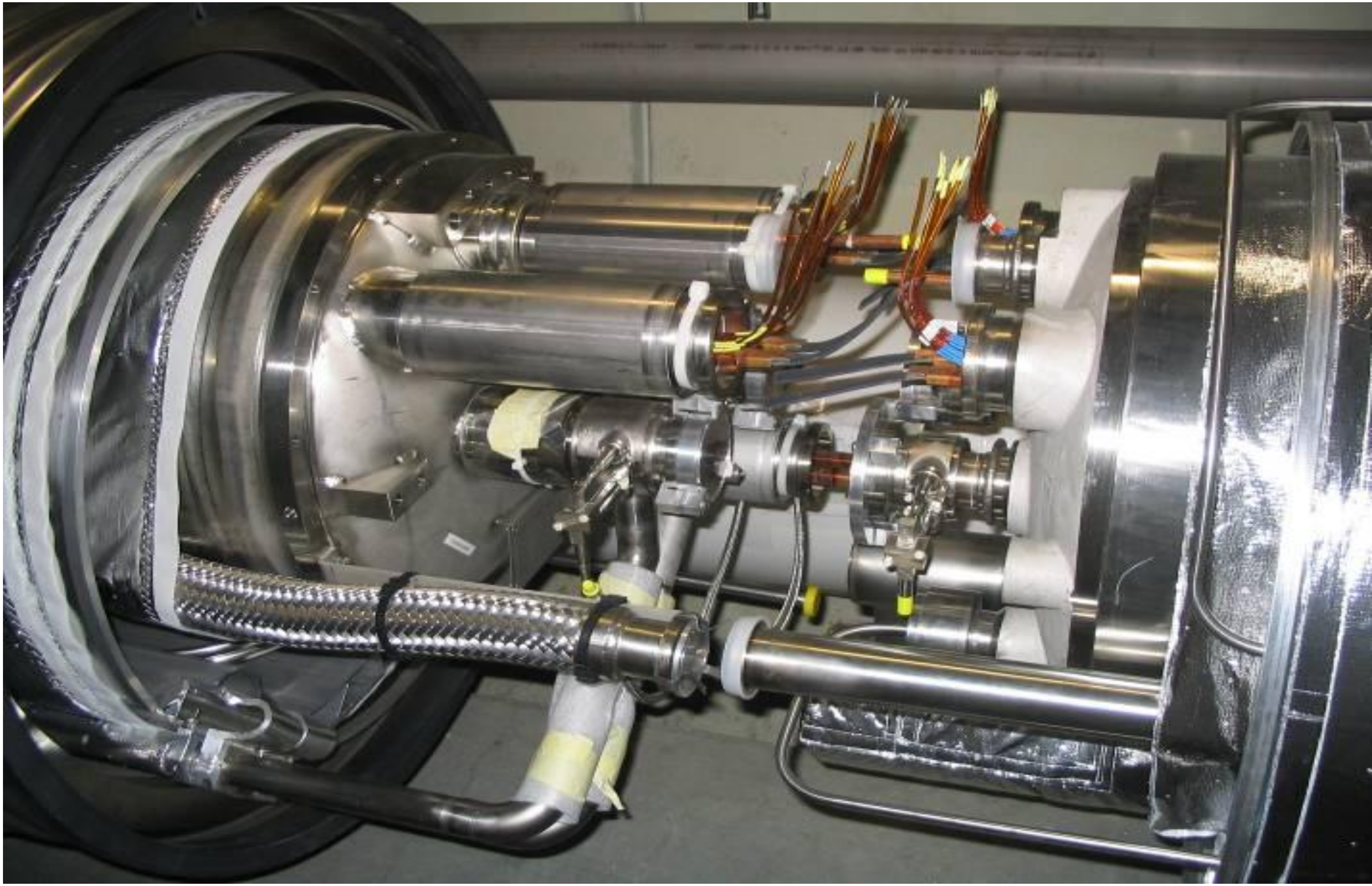


Dipole magnet protection

- Quench detected: energy stored in magnet dissipated inside the magnet (time constant of 200 ms).
- Parallel diode becomes conducting: current of other magnets through diode.
- Resistances are switched into the circuit: up to 1 GJ of energy is dissipated in the resistances (**current decay time constant of 100 s**).

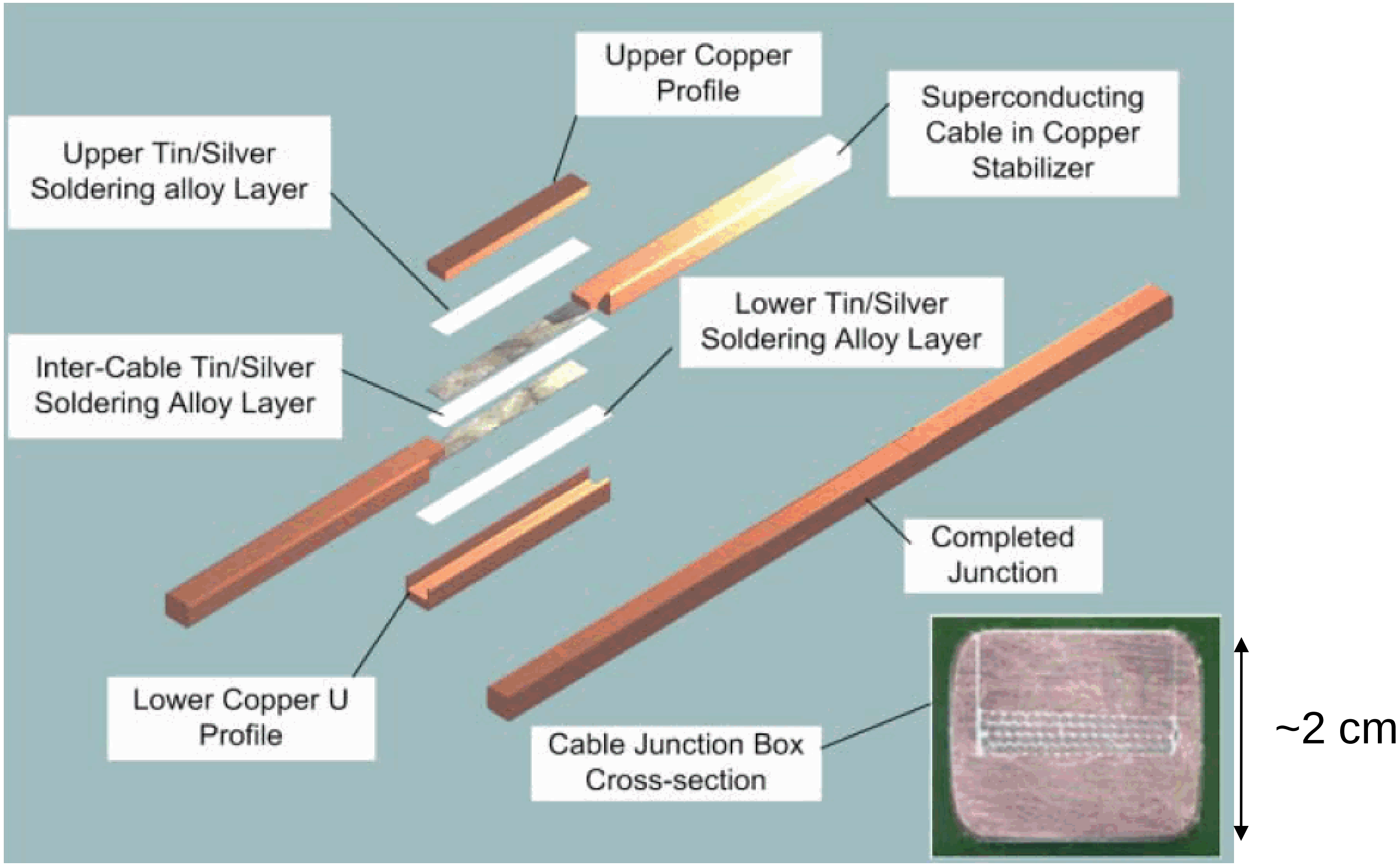


One of ~1700 bus-bar connections

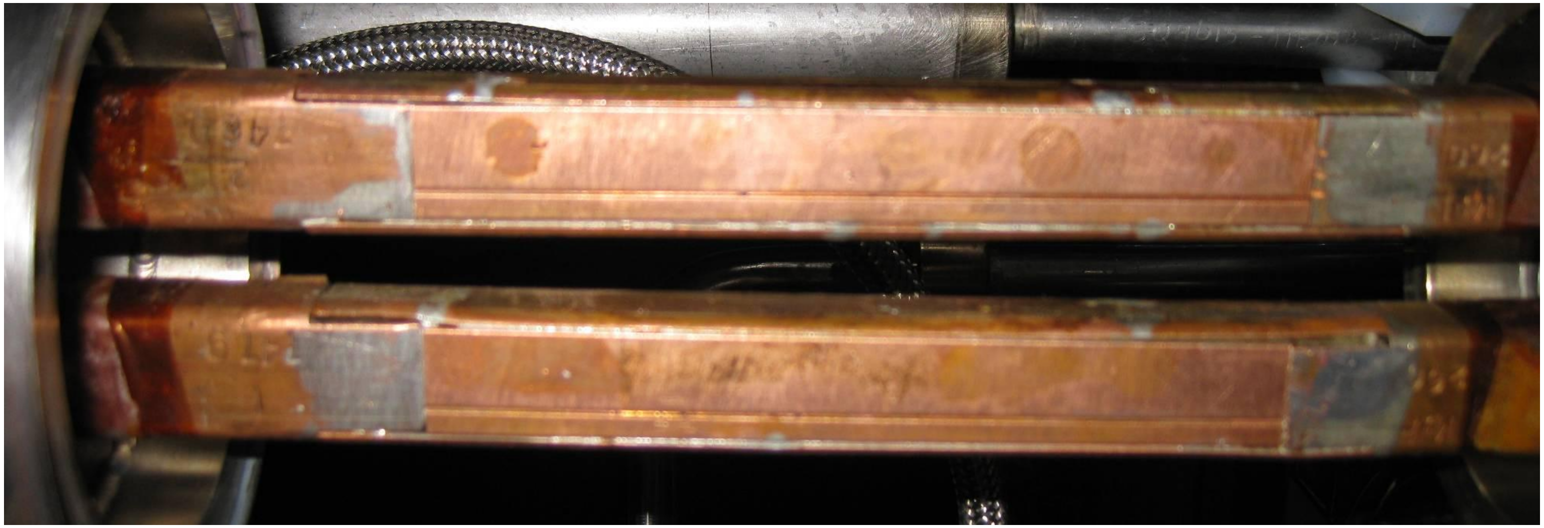


Bus-bar joint (1)

- Superconducting cable embedded in Copper stabilizer.
- Bus bar joint is soldered (not clamped).
- Joint resistance ~0.35 nΩ (@ 1.9 K).
- Protection of the joint during quench relies on *good joint quality.*



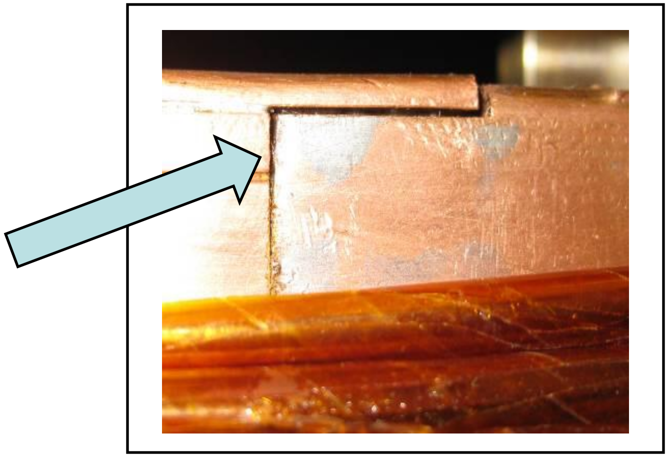
Bus-bar joint (2)



- A post-mortem analysis of the data from the sector with the incident revealed the presence of a 200 nΩ non-conform resistance in the cell of the primary electrical arc. This acted as a heat source that quenched the superconducting cable.

  >> Unfortunately the evidence is destroyed…

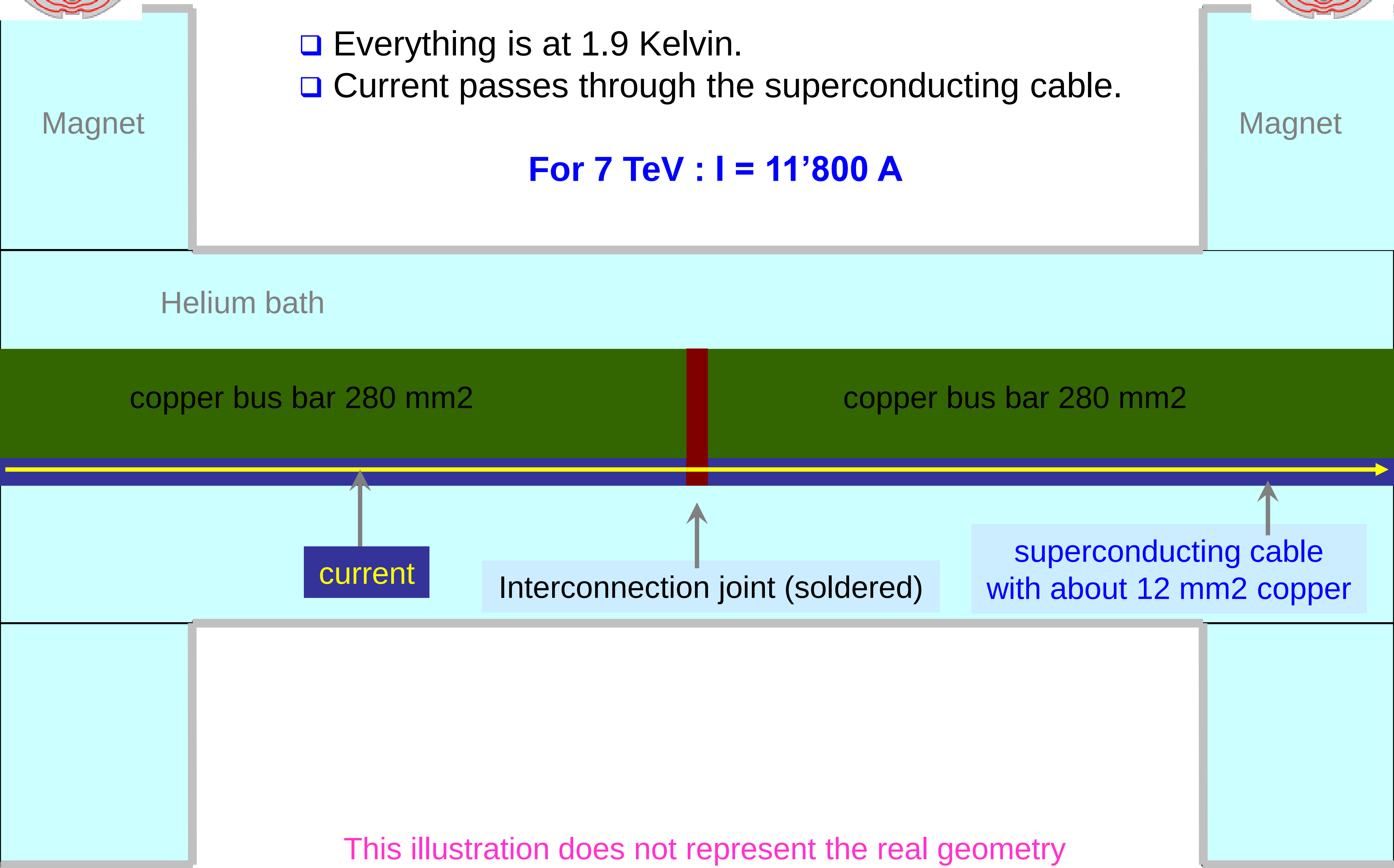
- A careful inspection of many other joints revealed non-conformities like bad soldering and.or reduced electrical contact as in the example to the right.



Normal interconnect, normal operation

- Everything is at 1.9 Kelvin.
- Current passes through the superconducting cable.

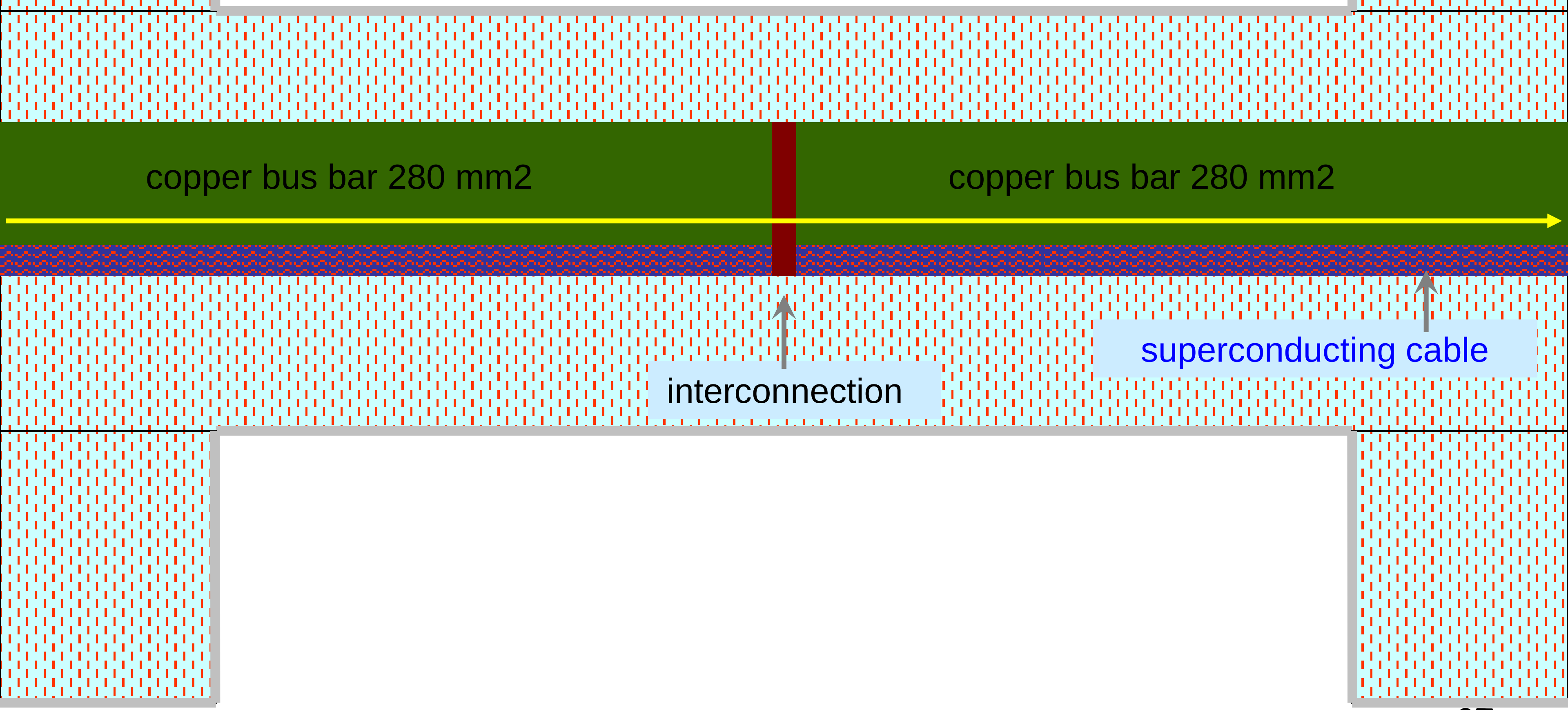
For 7 TeV : I = 11’800 A



This illustration does not represent the real geometry

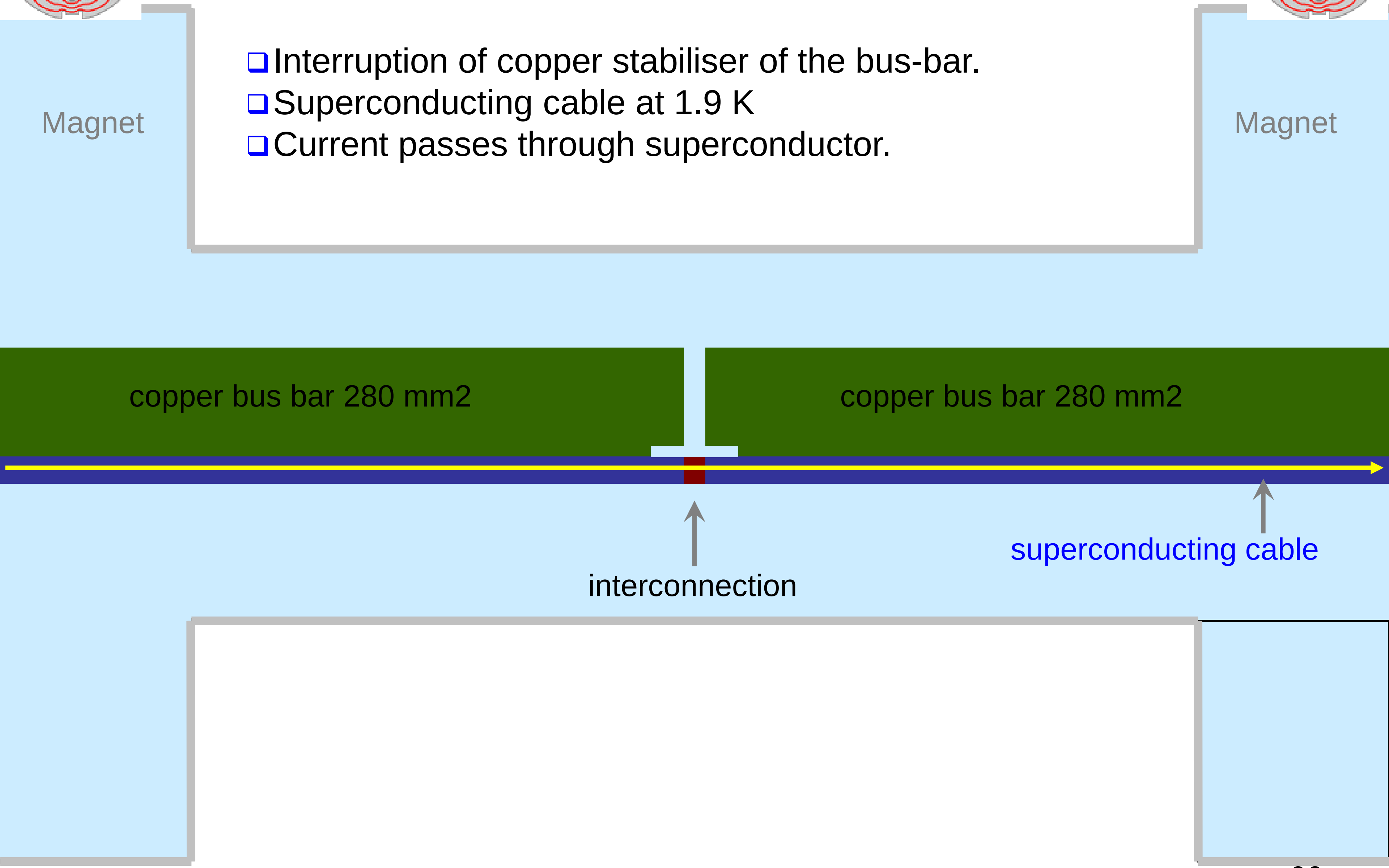
Normal interconnect, quench

- Quench in adjacent magnet or in the bus-bar.
- Temperature increase above ~ 9 K.
- The superconductor becomes resistive.
- During the energy discharge the current passes for few minutes through the copper bus-bar.



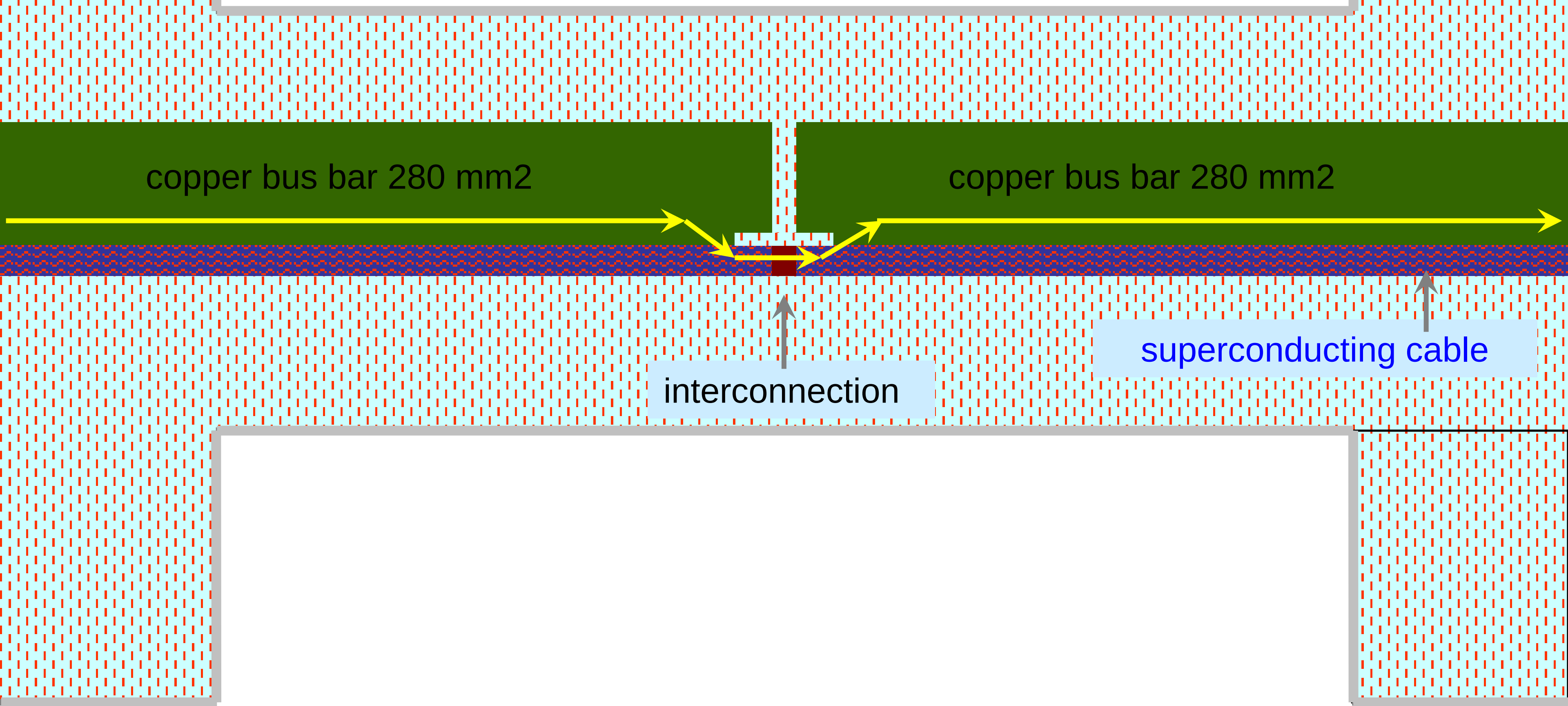
Non-conform interconnect, normal operation

- Interruption of copper stabiliser of the bus-bar.
- Superconducting cable at 1.9 K
- Current passes through superconductor.



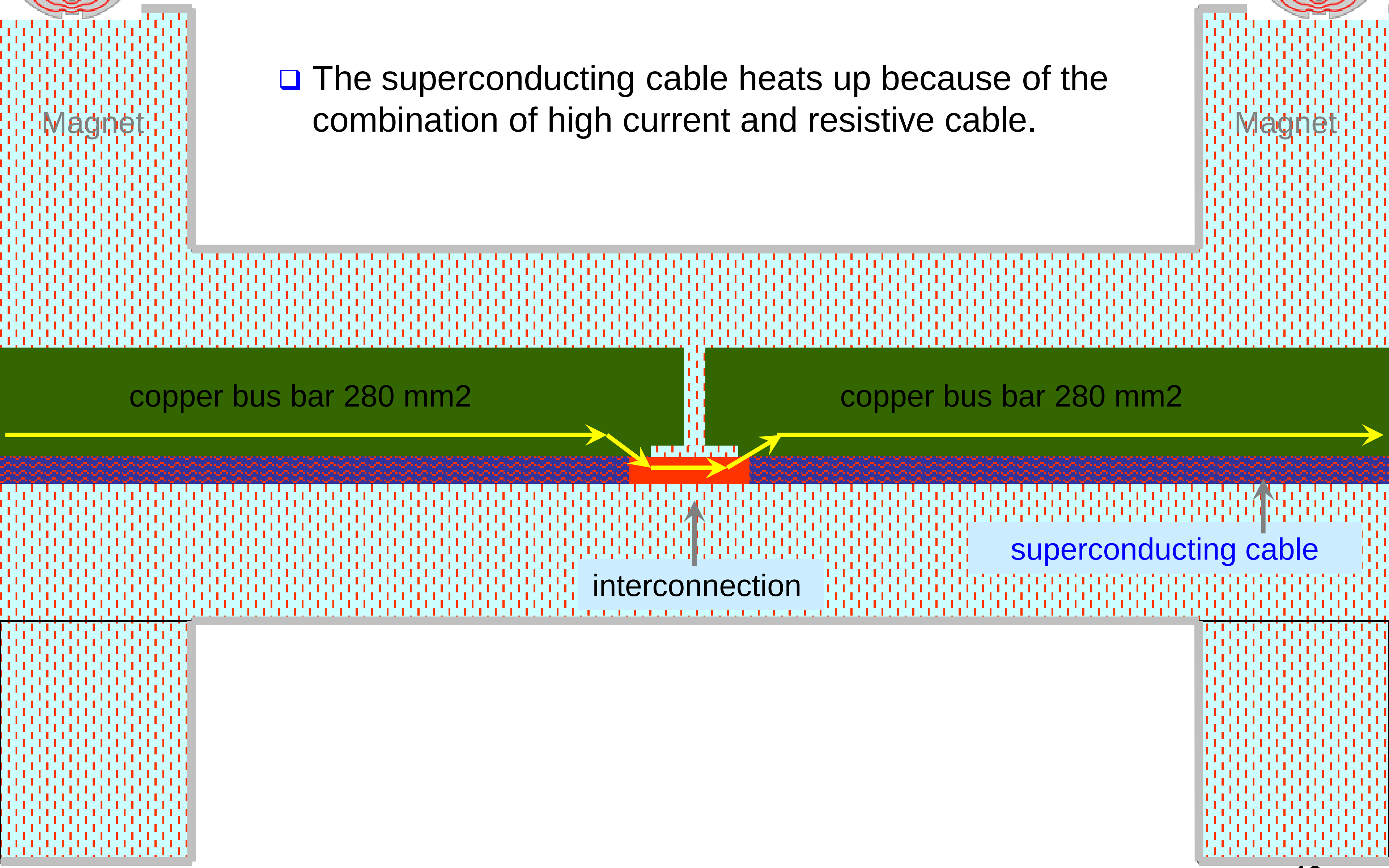
Non-conform interconnect, quench.

- Interruption of copper stabiliser.
- Superconducting cable temperature increase to above ~9 K and cable becomes resistive.
- Current cannot pass through copper and is forced to pass through superconductor during discharge.



Non-conform interconnect, quench.

- The superconducting cable heats up because of the combination of high current and resistive cable.

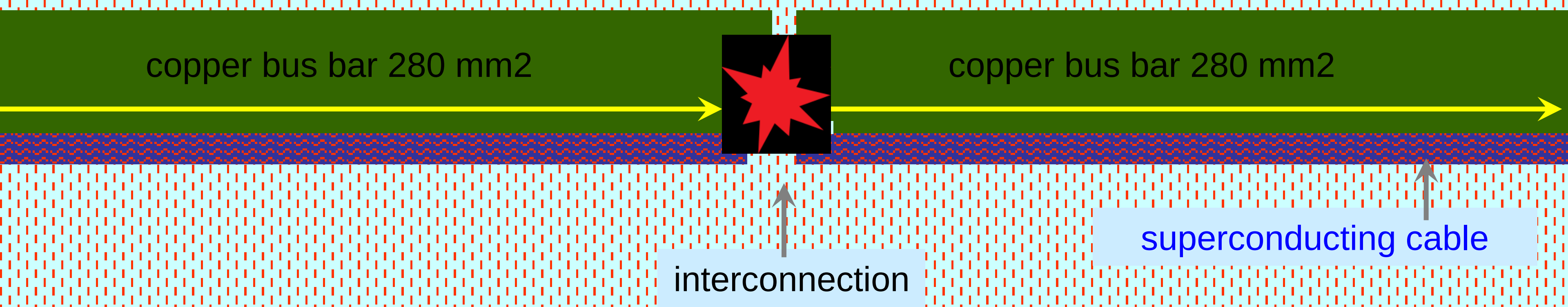


Non-conform interconnect, quench.

Magnet

Magnet

- Superconducting cable melts and breaks if the length of the superconductor not in contact with the bus bar exceeds a critical value and the current is high.
- Circuit is interrupted and an electrical arc is formed.



Depending on 'type' of non-conformity, problems appear :

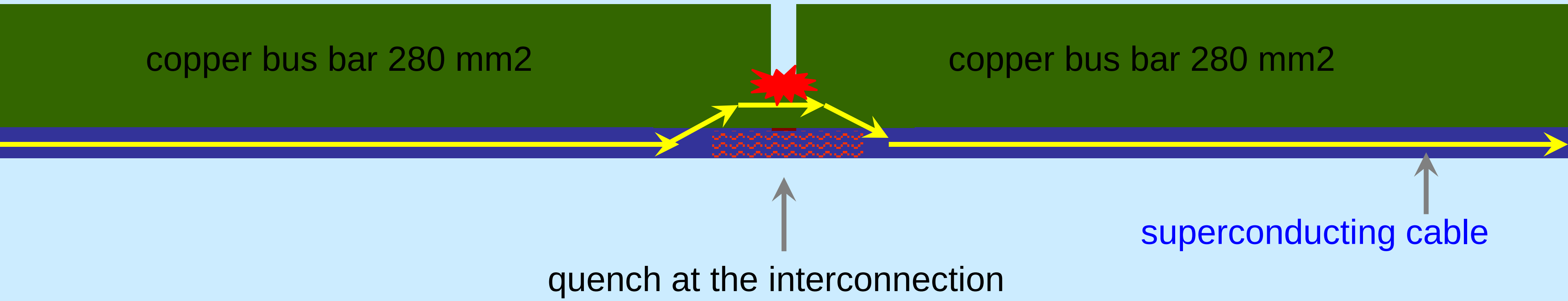
- at different current levels.
- under different conditions (magnet or bus bar quench..).

September 19th hypothesis

Magnet

- Anomalous resistance at the joint heats up and finally quenches the joint.
- Current sidesteps into Copper that eventually melts because the electrical contact is not good enough.

Magnet



>> New protection system will be installed to anticipate such incidents in the future,

Repair and consolidation

Repair (I)

- 39 dipoles and 14 quadrupoles short straight sections (SSS) brought to surface for repair (16: 9D + 7SSS) or replacement (37: 30D + 7SSS).

  All magnets are back in the tunnel. Interconnection work ongoing.

- A method to localize a bad quality joints by measuring the resistance of the copper cable (+joint) has revealed to be very powerful.
  - *Ongoing race to identify and repair faulty joints.*
  - *Unfortunately poor quality joints are localized in many places – likely to slow down progress with the machine re-commissioning.*
  - *½ LHC is still cold (<= 80 K)…*

- The vacuum chambers are cleaned in situ.

Repair (II) and consolidation (I)

- Major upgrade of the quench protection system.
  - *Protection of all main quadrupole and dipole joints.*
  - *High statistics measurement accuracy to < 1 nΩ.*
  - *Installation of > 200 km of cables, production of thousands of electronic boards.*

  >> protection against similar issues in the future.

- Reinforcement of the quadrupole supports.

- Improvement of the pressure relief system to eventually cope with a maximum He flow of **40 kg/s** in the arcs (maximum conceivable flow, 2 x incident).

LHC run 2009/20010

LHC Experiments Desiderata

- ✓ 50-100 pb^{-1} of *good* data at $\sqrt{s}$ = 10 TeV.

  Many new limits set on hypothetical particles.

- ✓ 200-300 pb^{-1} of *good* data at $\sqrt{s}$ = 10 TeV.

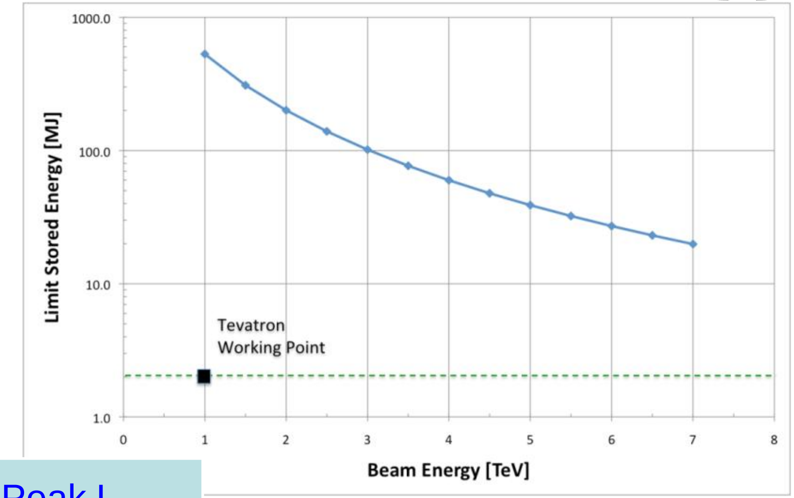
  Start competing with Tevatron on Higgs masses ~ 160 GeV/c^2.

- ✓ 1 fb^{-1} of *good* data at $\sqrt{s}$ = 10 TeV.

  Higgs discovery possible ~ 160 GeV/c^2.

Luminosity Targets 2009/10

- Present 4-stage collimation system limits the total intensity to ≈10% of the nominal intensity.



- Operation modes for 2009/10.

No. bunches/ beam	Protons/ bunch	% of nominal intensity	Peak L ($cm^{-2}\ s^{-1}$)
43	**5×10^{10}**	**0.7**	**6.9×10^{30}**
156	**5×10^{10}**	**2.4**	**5.0×10^{31}**
156	**1×10^{11}**	**4.8**	**2.0×10^{32}**
720 (50 ns)	**5×10^{10}**	**11.1**	**1.2×10^{32}**
2808	**1.15×10^{11}**	**100**	**1.0×10^{34}**

Int. luminosity target achievable with ~40% availability

← **Design**

- Short Pb ion run foreseen end 2010.

Ion setup should be ‘straight forward’ as little difference wrt protons.

Outlook (1)

- With beam the LHC is a wonderful machine (at injection).

  All key systems were operational, very efficient beam startup.

- The incident in sector 34 was due to a poor quality bus-bar joint.

  Good understanding of the incident mechanism.

  Quench protection system upgrade under way – largely improved protection for the future.

  Large quality control campaign on joint underway – is revealing localized issues in a number of places.

- Sector 34 repair is progressing well, re-commissioning will start soon.

Outlook (2)

- Cool-down of the first sectors has started.

  First magnet powering in June.

- Beam commissioning scheduled to resume in September or October 2009.

  Followed by a 12 months run over winter.

  Schedule is very tight.

  Physics energy target so far still 5 TeV.

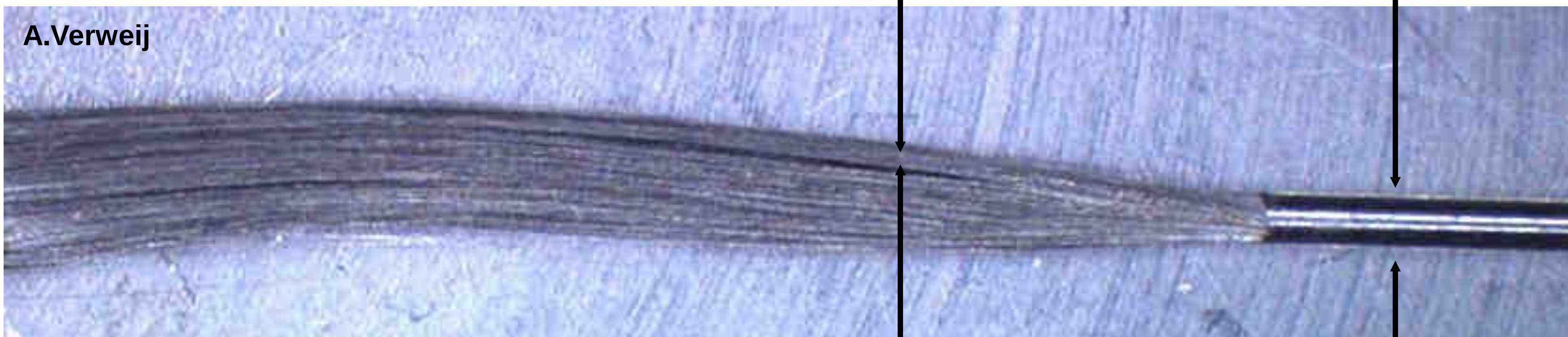
Reserve slides

Superconducting cable

NbTi filaments embedded in a
Copper matrix

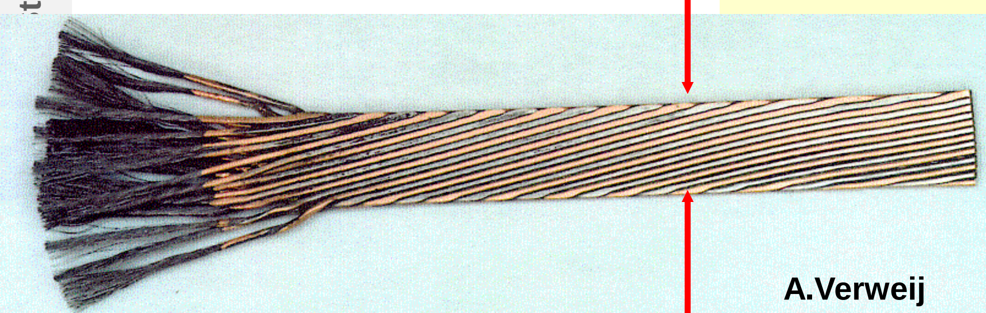
∅6 μm

∅1 mm



Typical value for operation at 8T and 1.9 K: 800 A

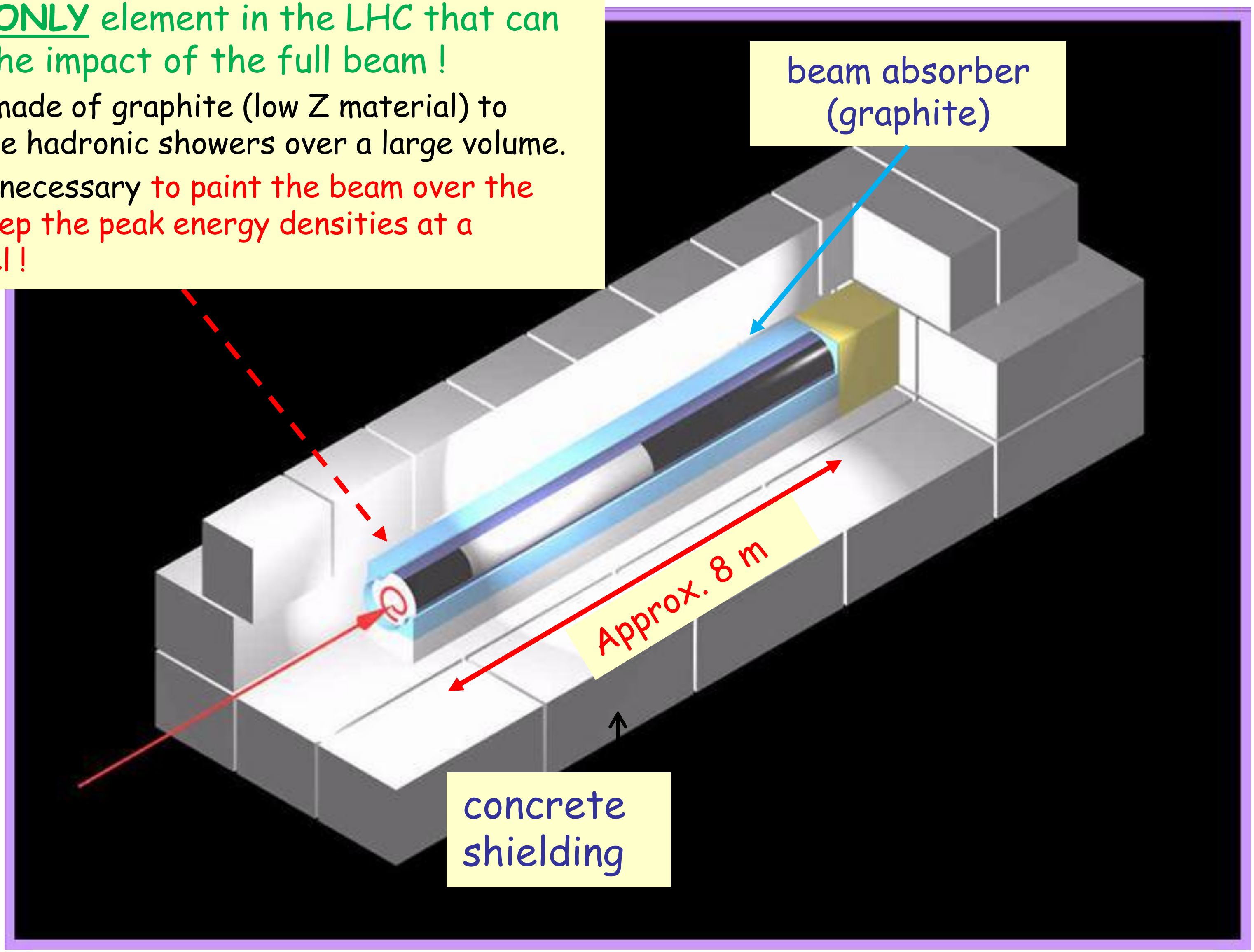
width 15 mm



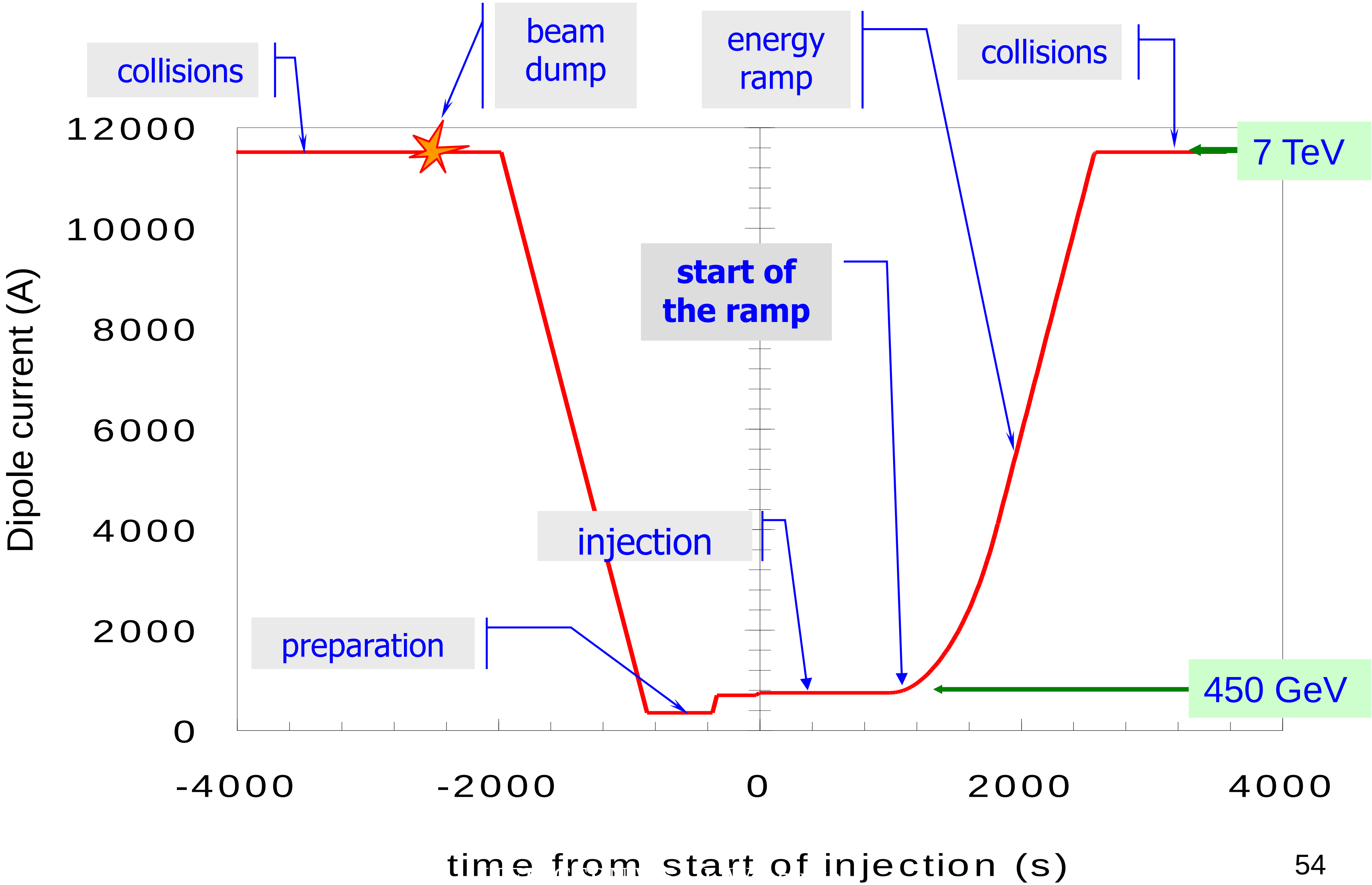
Rutherford cable

LHC dump block

- This is the <u>ONLY</u> element in the LHC that can withstand the impact of the full beam !
- The block is made of graphite (low Z material) to spread out the hadronic showers over a large volume.
- It is actually necessary to paint the beam over the surface to keep the peak energy densities at a tolerable level !



LHC cycle


collisions
beam dump
energy ramp
collisions
7 TeV
start of the ramp
injection
preparation
450 GeV
Dipole current (A)
12000
10000
8000
6000
4000
2000
0
-4000
-2000
0
2000
4000
time from start of injection (s)