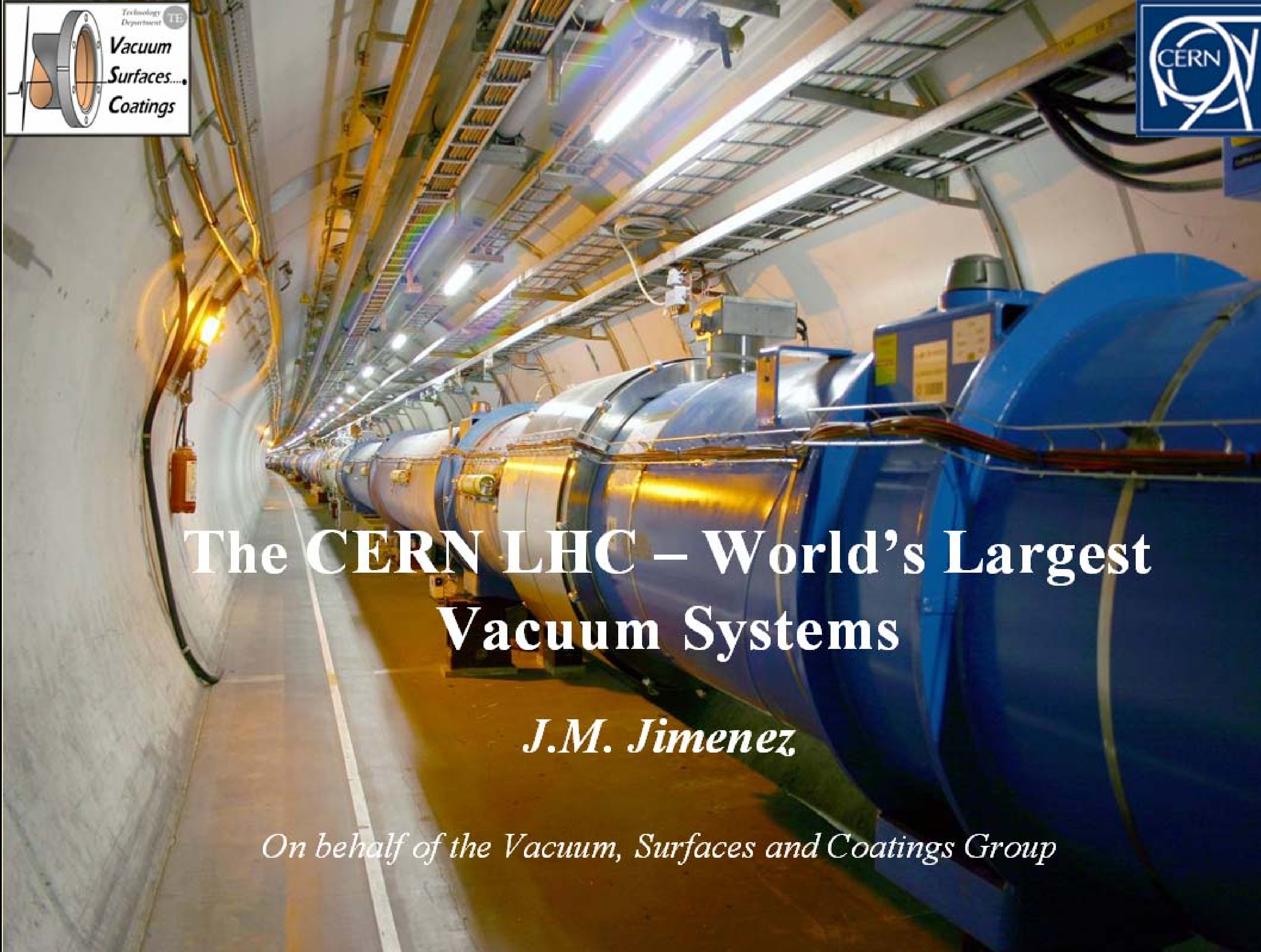


# The CERN LHC – World's Largest Vacuum Systems

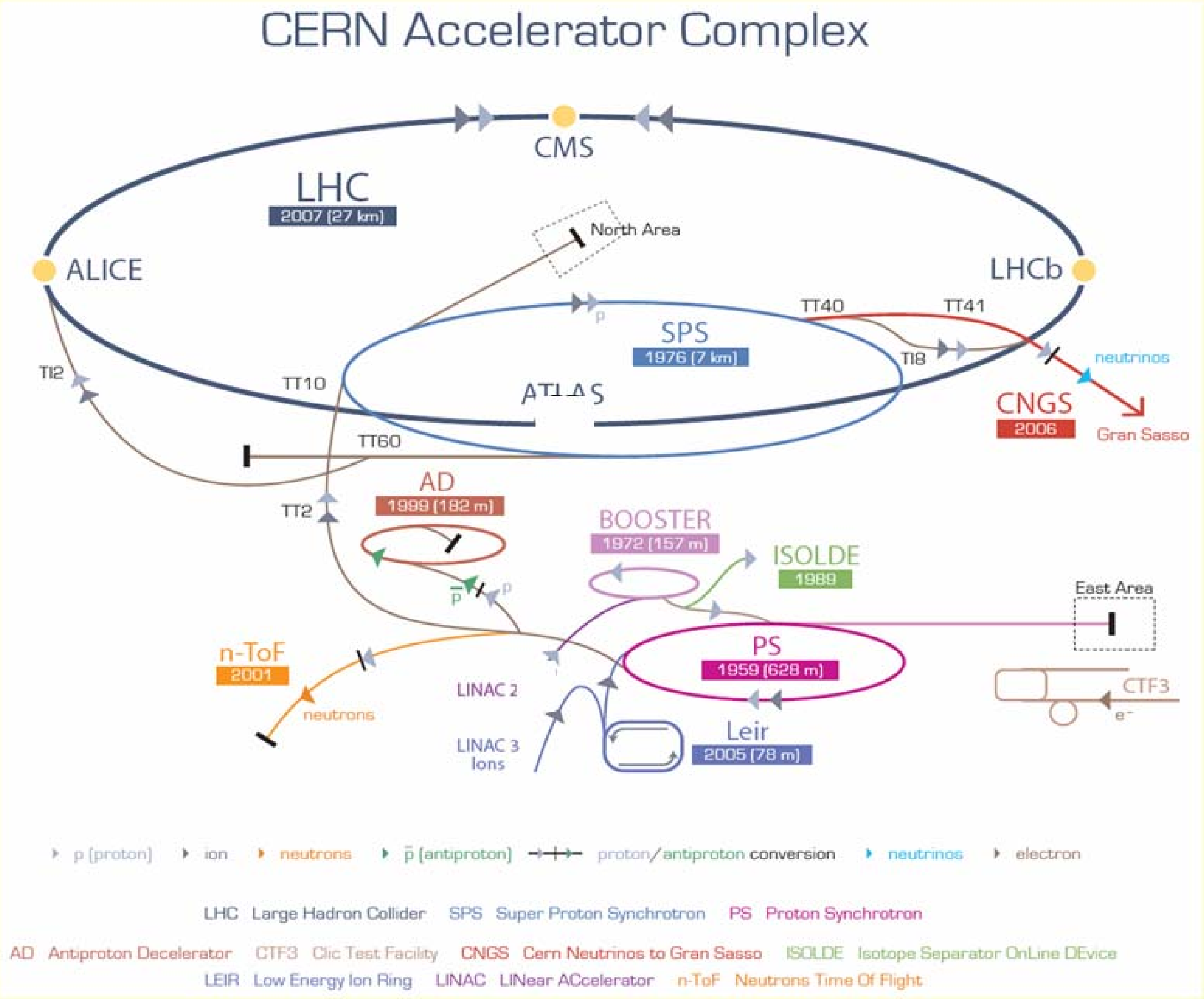

*J.M. Jimenez*

*On behalf of the Vacuum, Surfaces and Coatings Group*

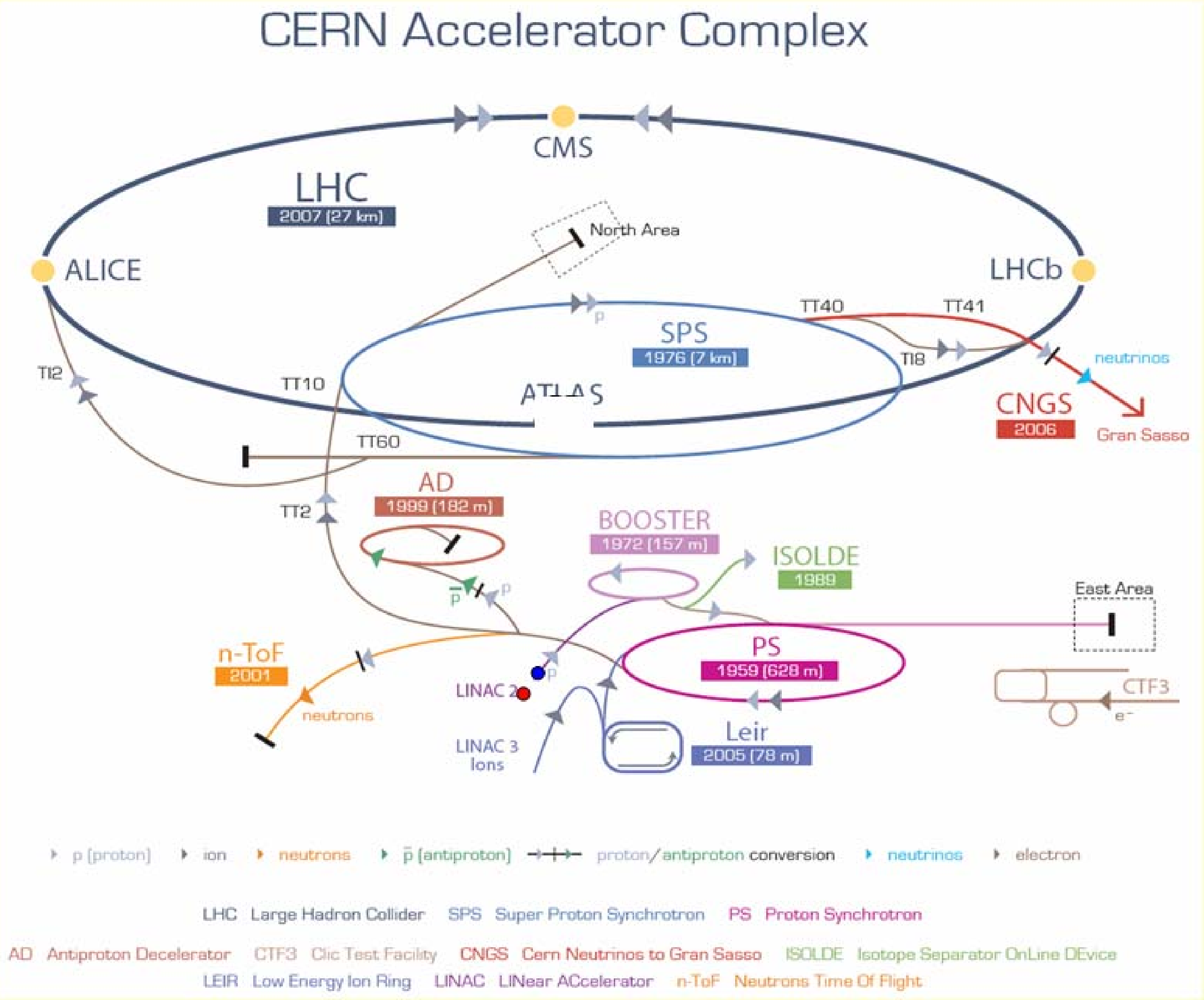
# Main topics

- **Introduction to CERN accelerator chain**
- **LHC vacuum systems**
- **First operation with beams**
- **Beam vacuum recovery after sector 3-4 incident**
- **Closing remarks**

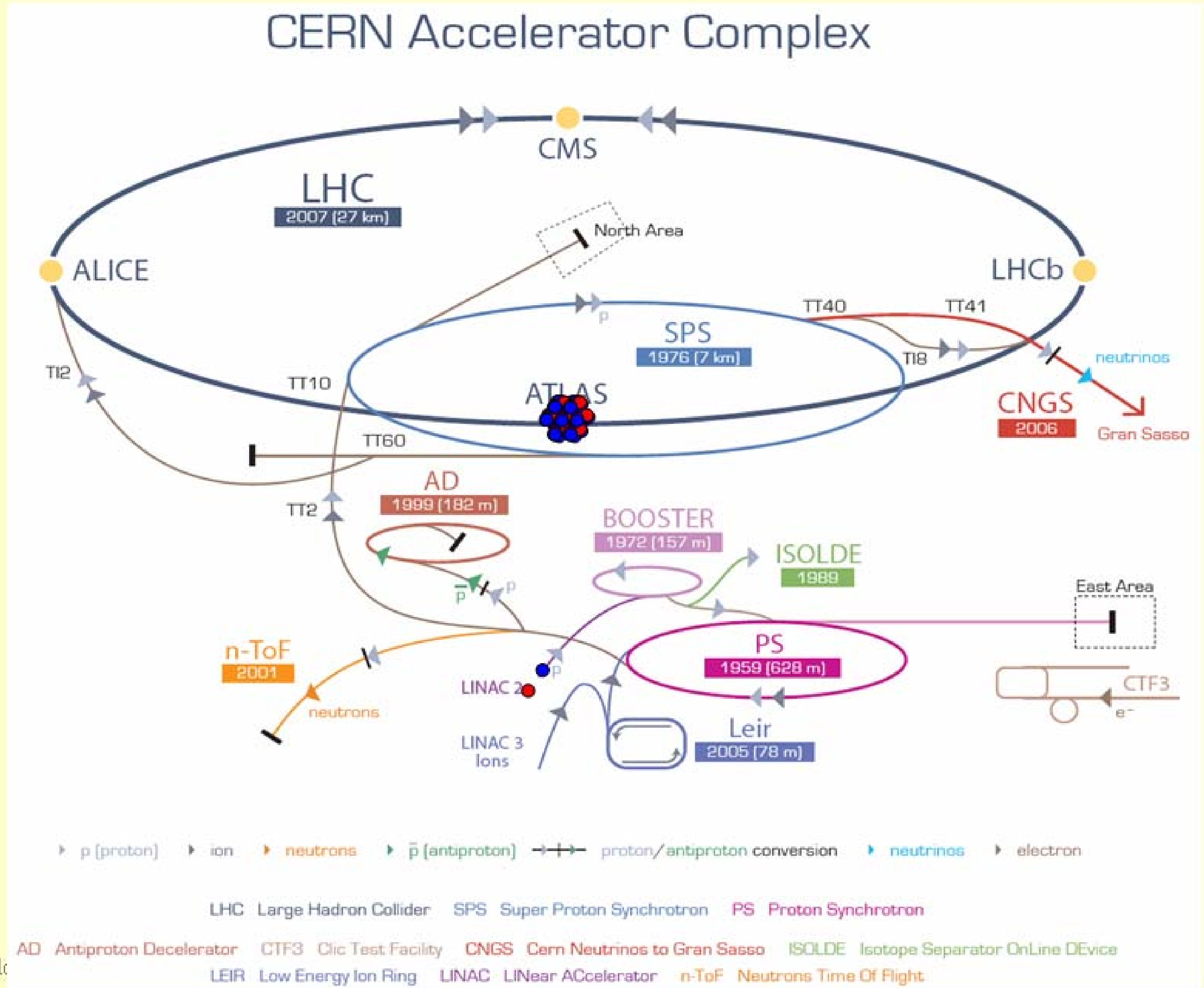
# Introduction
## CERN accelerator chain (1/2)



# Introduction
## CERN accelerator chain (1/2)



# Introduction
## CERN accelerator chain (1/2)



# Introduction
## CERN accelerator chain (2/2)

| Machine | Type | Year | Energy | Bakeout | Pressure (Pa) | Length | Particles |
|---|---|---|---|---|---|---|---|
| **Linac, Booster, ISOLDE, PS, n-TOF and AD Complex** | | | | | | **2.6 km !** | |
| LINAC 2 | linac | 1978 | 50 MeV | Ion pumps | $10^{-7}$ | 40 m | p |
| ISOLDE | electrostatic | 1992 | 60 keV | - | $10^{-4}$ | 150 m | ions: 700 isotopes and 70 (92) elements |
| REX-ISOLDE | linac | 2001 | 3 Mev/u | partly | $10^{-5}$ - $10^{-10}$ | 20 m | |
| LINAC 3 | linac | 1994 | 4.2 MeV/u | Ion pumps | $10^{-7}$ | 30 m | ions |
| LEIR | accumulator | 1982/2005 | 72 MeV/u | complete | $10^{-10}$ | 78 m | pbar, ions |
| PSB | synchrotron | 1972 | 1-1.4 GeV | Ion pumps | $10^{-7}$ | 157 m | P, ions |
| PS | synchrotron | 1959 | 28 GeV | Ion pumps | $10^{-7}$ | 628 m | P, ions |
| AD | decelerator | ? | 100 MeV | complete | $10^{-8}$ | 188 m | pbar |
| CTF3 complex | linac/ring | 2004-09 | | partly | $10^{-8}$ | 300 m | e |
| PS to SPS TL | Transfer line | 1976 | 26 GeV | - | $10^{-6}$ | ~1.3 km | P, ions |
| **SPS Complex** | | | | | | **15.7 km !** | |
| SPS | synchrotron | 1976 | 450 GeV | Extractions | $10^{-7}$ | 7 km | p, ions |
| SPS North Area | Transfer line | 1976 | | - | $10^{-6}$ - $10^{-7}$ | ~1.2 km | |
| SPS West Area | Transfer line | 1976 | | | | ~ 1.4 km | |
| SPS to LHC TI2/8 Line | Transfer line | 2004/2006 | | | | 2 x 2.7 km | |
| CNGS Proton Line | Transfer line | 2005 | | | | ~730 m | |
| ***LHC Accelerator*** | | | | | | ***~109 km !*** | |
| LHC Arcs (Beam x2, Magnets & QRL insul.) | collider | 2007 | 2 × 7 TeV | - | < $10^{-8}$ | 2 x (2 x 25 km) | p, ions |
| LSS RT separated beams | | | | complete | | 2 × 3.2 km | |
| LSS RT recombination | | | | | | ~ 570 m | |
| Experimental areas | | | | | | ~ 180 m | |
| Beam Dump Lines TD62/68 | Transfer line | 2006 | 7 TeV | - | $10^{-6}$ | 2 × 720 m | |
| | | | | **High Vacuum** | | ~20 km | **~128 km !** |
| | | | | **UHV w/wo NEG** | | ~ 57.5 km | |
| | | | | **Insulation vacuum** | | ~ 50 km | |

# Introduction
## CERN accelerator chain (2/2)

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| | | |
|---|---|---|
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| **UHV w/wo NEG** | ~ 57.5 km | |
| **Insulation vacuum** | ~ 50 km | |

# Introduction
## Vacuum requirements (1/2)

**Vacuum aims to reduce beam-gas interaction which is responsible for:**

- **Machine performance limitations**
  - Reduction of beam lifetime (nuclear scattering)
  - Reduction of machine luminosity (multiple coulomb scattering)
  - Intensity limitation by pressure instabilities (ionization)
  - Electron (ionization) induced instabilities (beam blow up )
  - Magnet quench i.e. transition from the superconducting to the normal state
    - ⇨ Heavy gases are the most dangerous
- **Background to the experiments**
  - Non-captured particles which interact with the detectors
  - Nuclear cascade generated by the lost particles upstream the detectors

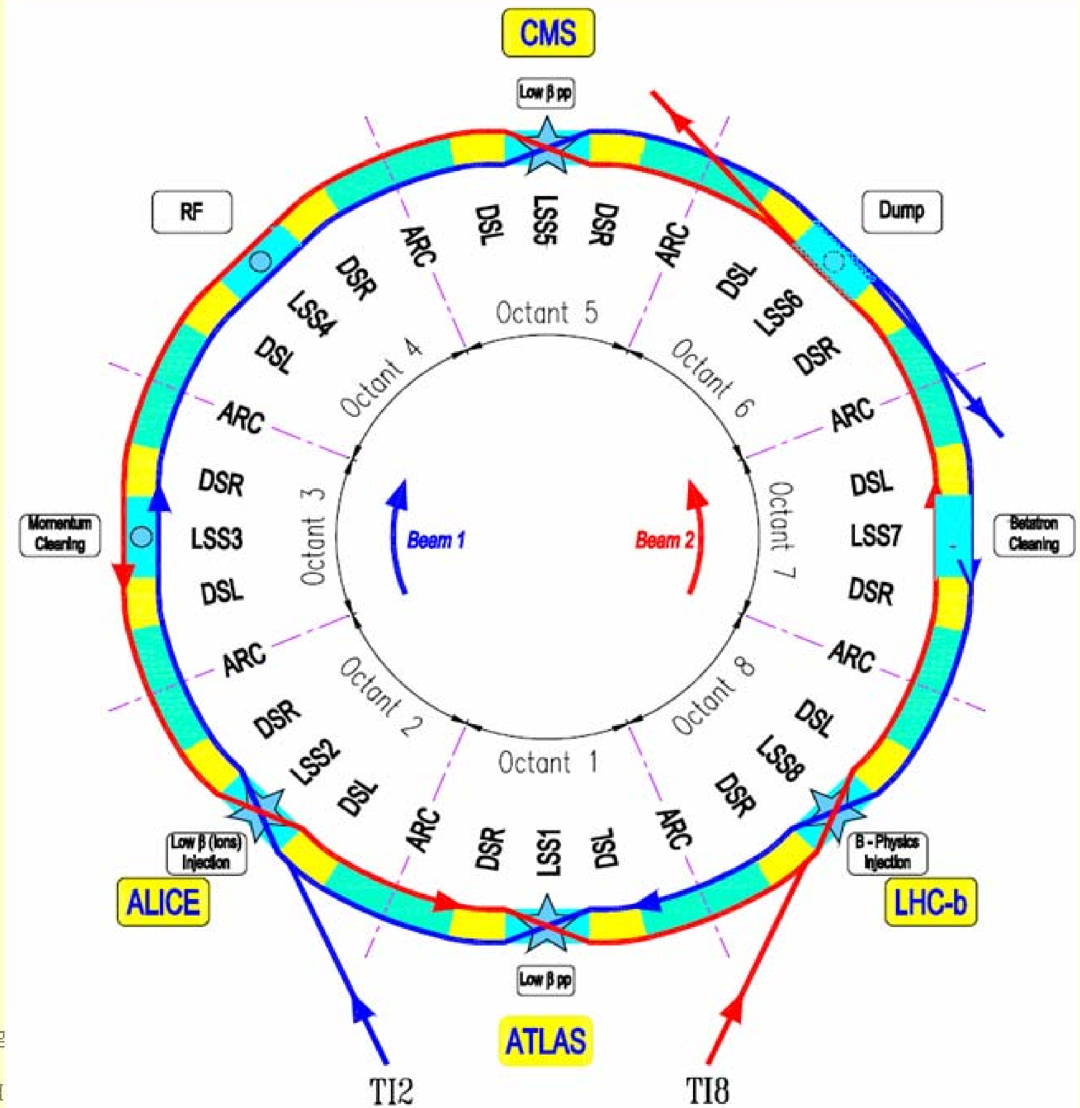
# Introduction
## Vacuum requirements (2/2)

**Beam vacuum pipes are designed to:**

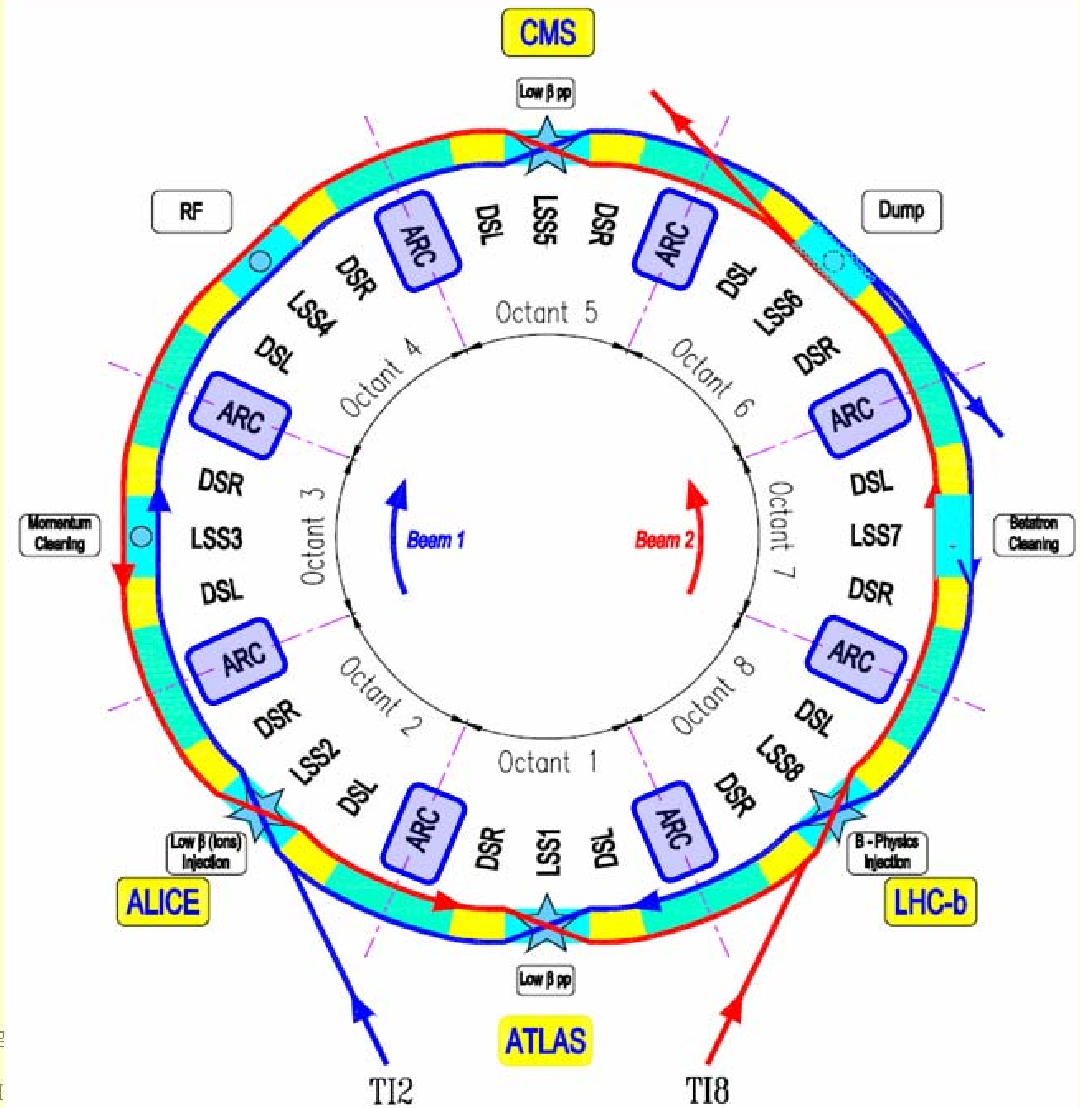
- **Minimise beam impedance and HOM generation**
- **Optimise beam aperture**
- **Intercept heat loads (cryogenic machines)**
  - Synchrotron radiation ($0.2\ W.m^{-1}$ per beam)
  - Energy loss by nuclear scattering ($30\ mW.m^{-1}$ per beam)
  - Image currents ($0.2\ W.m^{-1}$ per beam)
  - Energy dissipated during the development of electron clouds

⇨ **Intercept most of the heat load, 1 W at 1.9 K requires 1 kW of electricity**

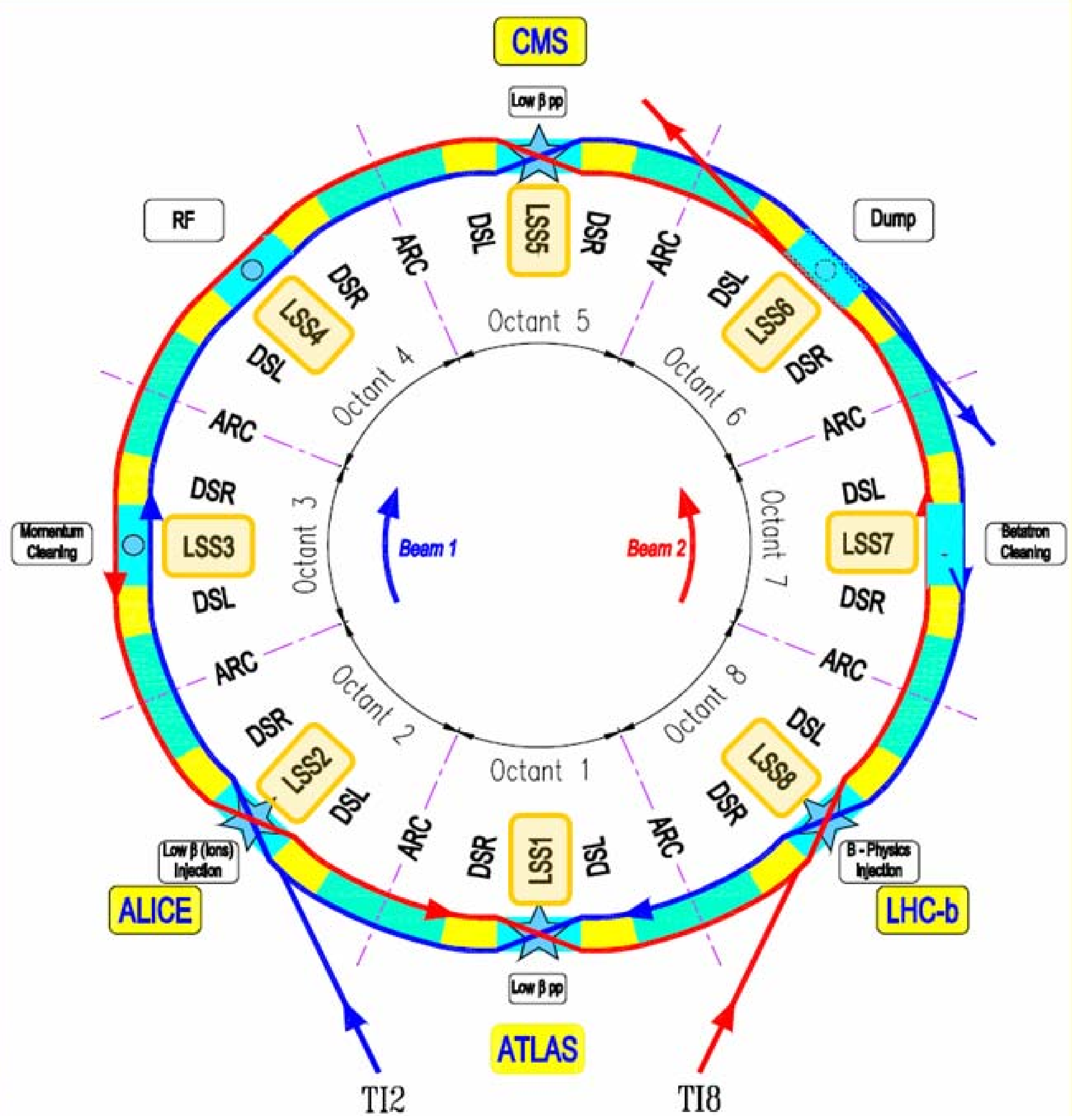
# LHC Vacuum Systems
## An Overview...



# LHC Vacuum Systems
## An Overview...

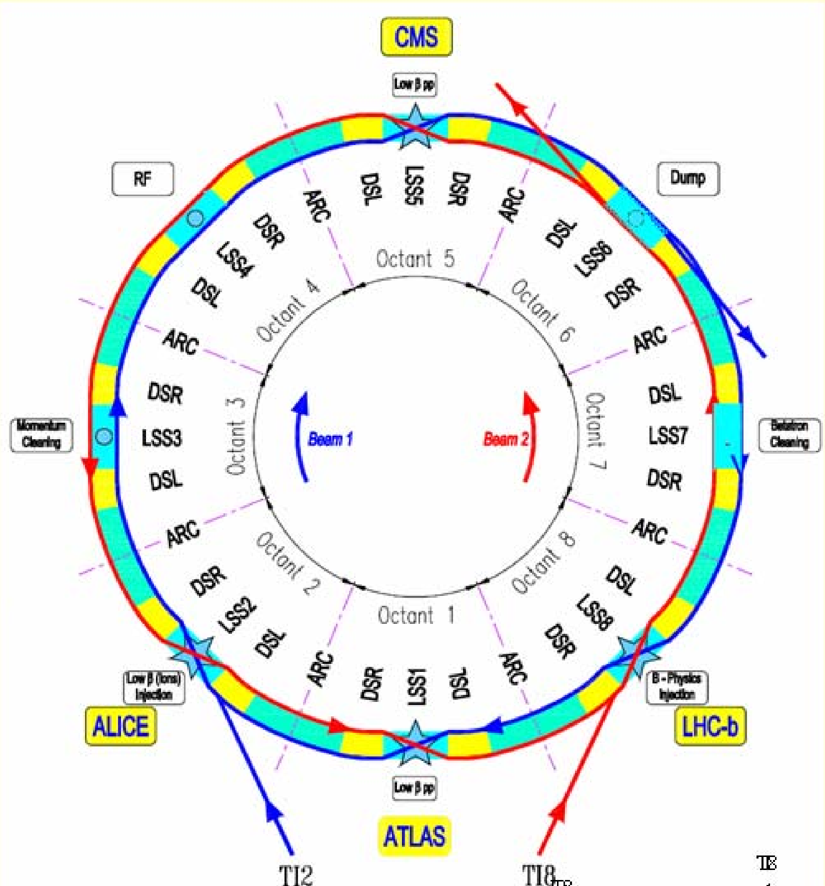


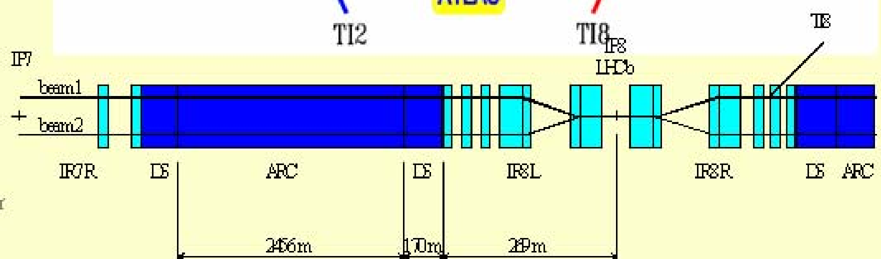
# LHC Vacuum Systems
## An Overview...



# LHC Vacuum Systems
## An Overview...

- 8 bending sections
  *2.4 km each*
- 2 independent beam pipes per arc and in LSS Standalone
- 1.9 K operating temperature
  *Standalones at 4.5 K*
  *Triplets @ 1.9 K*
- Non-baked beam vacuum
  2-3 weeks pumping time
  *$10^{-4}$ Pa before cool down*
- P $<10^{-10}$ Pa after cooling @ 1.9 K
  *Temperature dependant*



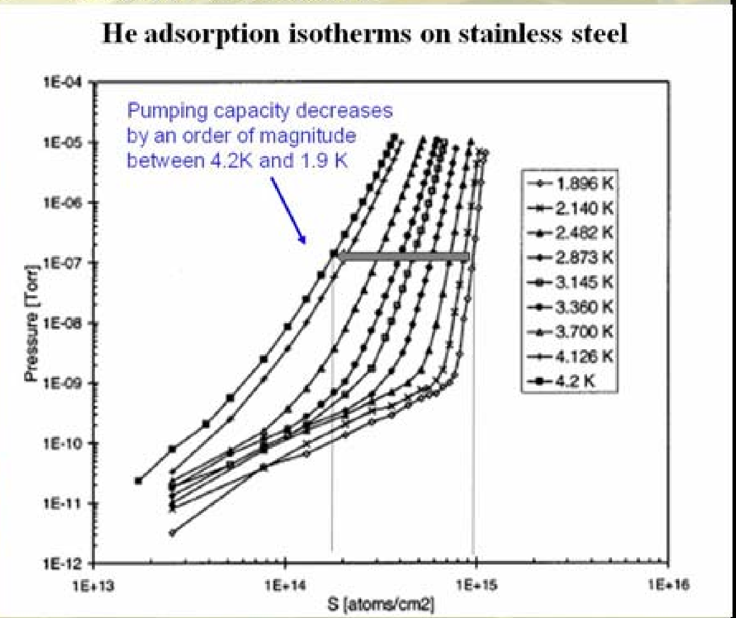



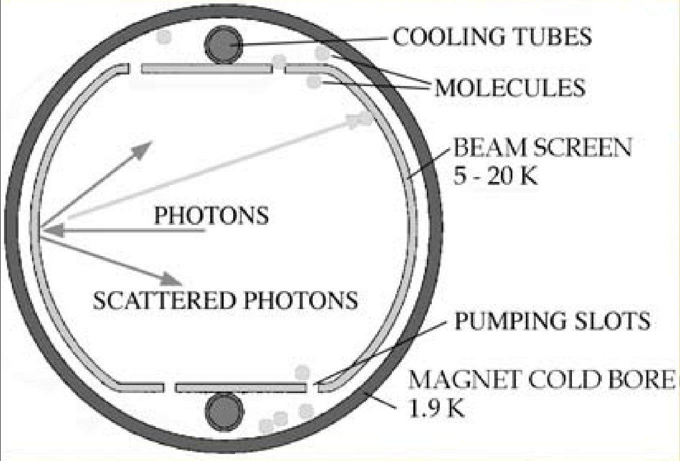

- 8 Long Straight Sections (LSS)
  *0.6 km each housing collimators, beam instrumentation, injections, dumps, etc.*
- 2 independent beam pipes (twin sectors) except close to experiments (combined sector)
- Operating at RT
- UHV systems with NEG coatings and bake out at 250°C
  *(Standalones at 4.5 K)*
- P< $10^{-9}$ Pa after NEG activation

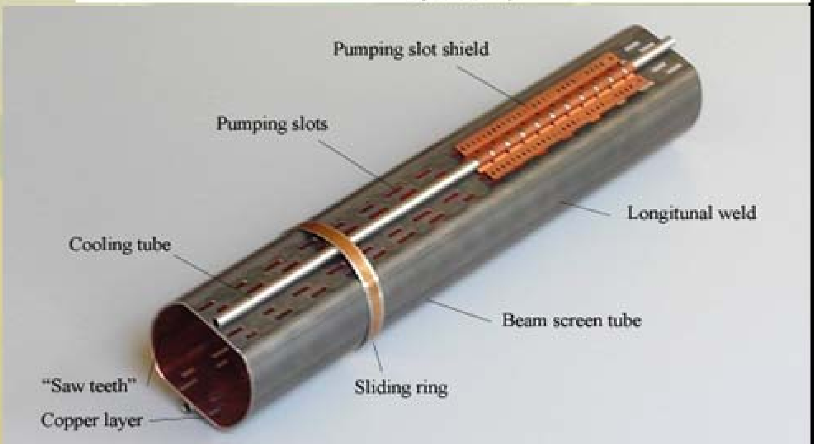
# LHC vacuum systems
## Cryogenic Beam Vacuum in Bending Sections

# LHC vacuum systems
## Cryogenic Beam Vacuum in Bending Sections

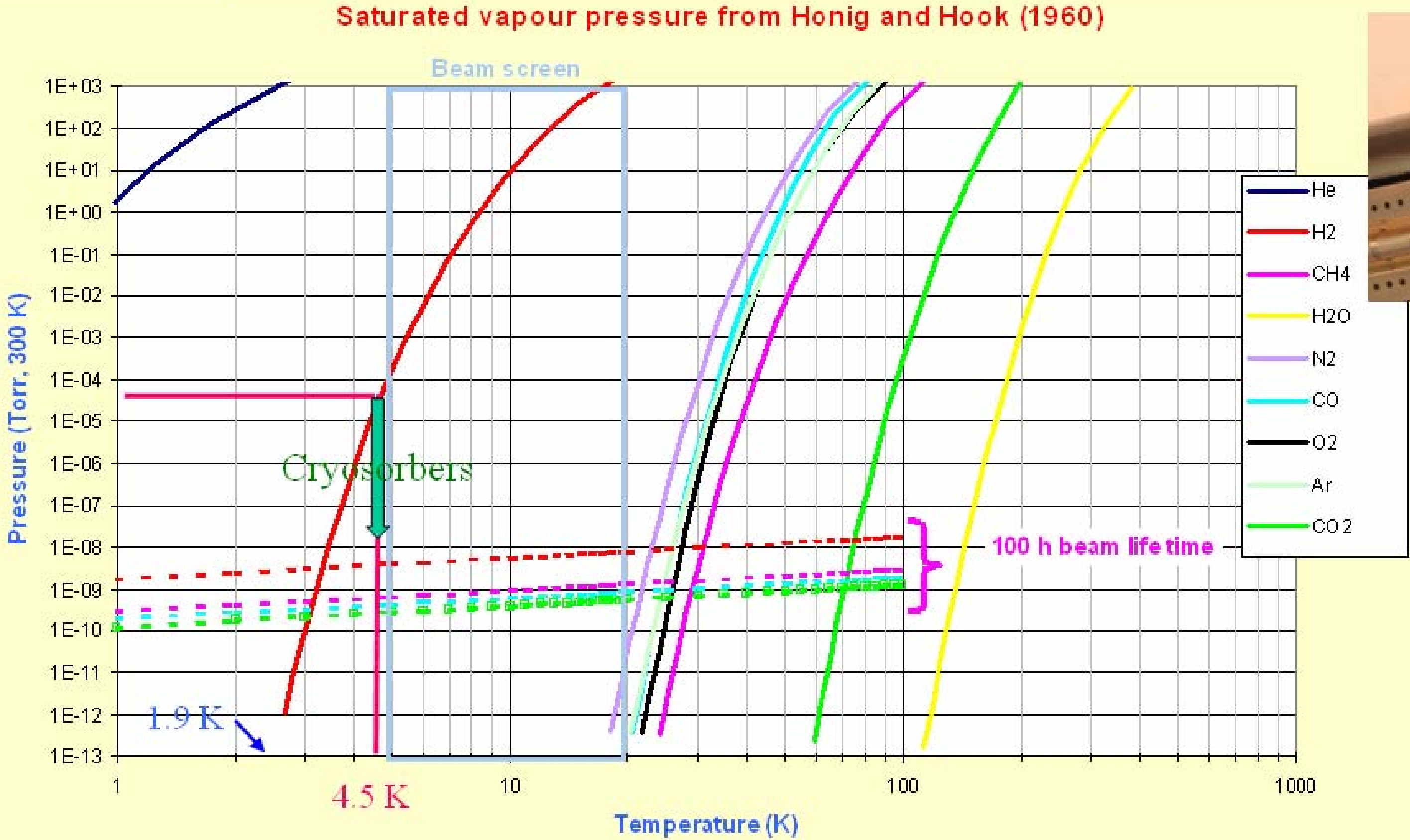
- **Innovating conceptual design with a “beam screen”**
  - Beam screen inserted inside cryomagnet cold bore @ 1.9 K
  - Operated between 5 and 20 K
    - Most of the heat load is intercepted
    - Cryopumping ensures the beam lifetime
    - Desorbed molecules transferred to the magnet cold bore
    - HOM trapping is reduced
  - Standalone @ 4.5 K need cryosorbers

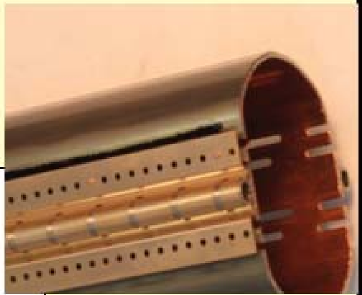


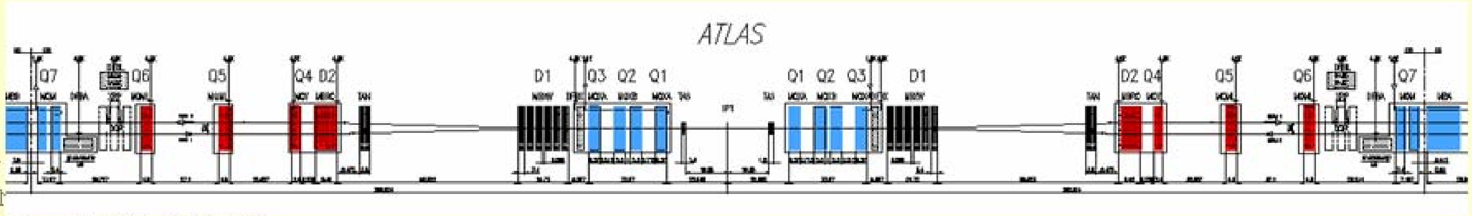



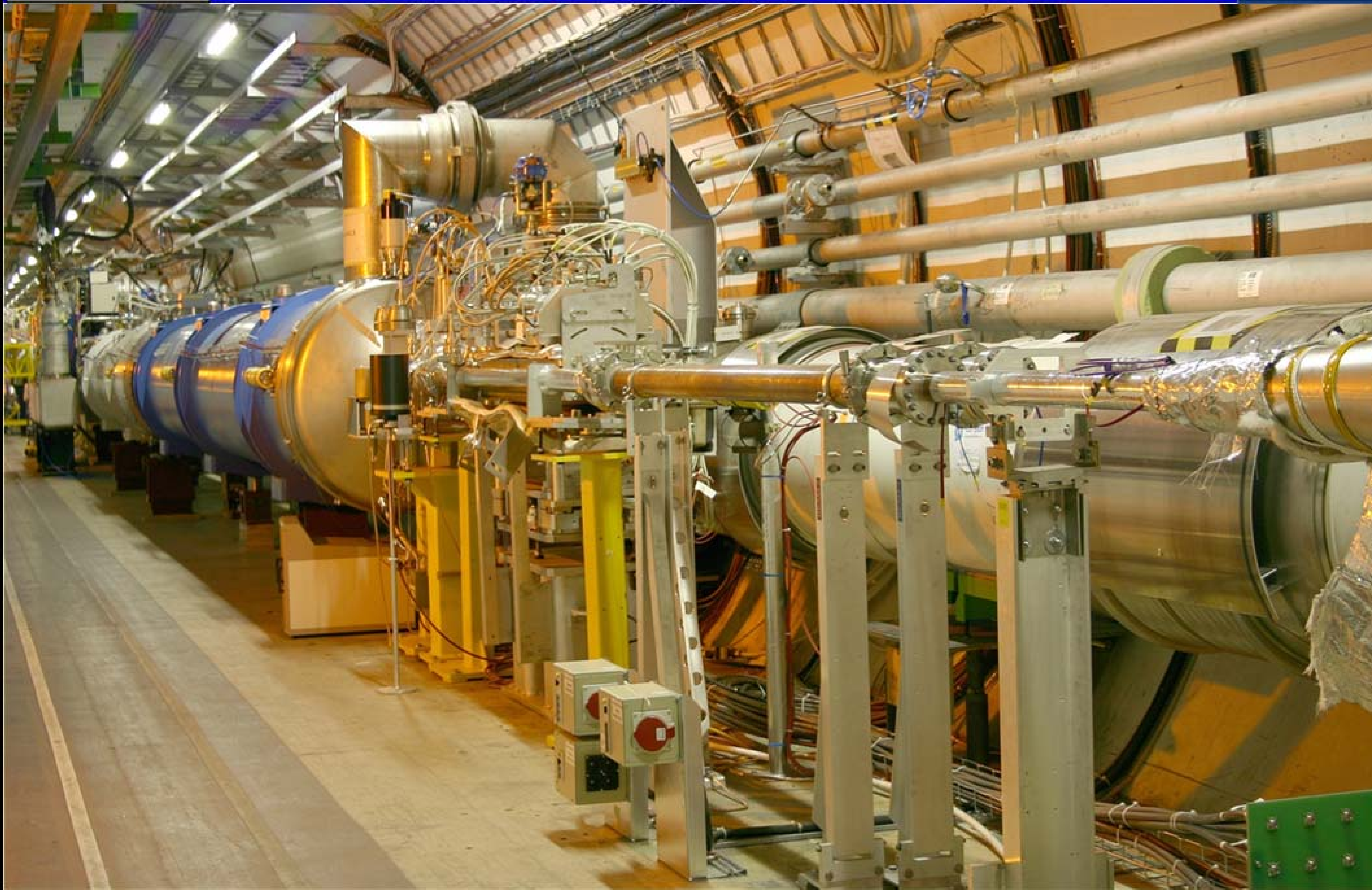
# LHC vacuum systems
## Cryogenic Beam Vacuum in Bending Sections





# LHC vacuum systems
## RT Beam Vacuum in Long Straight Sections



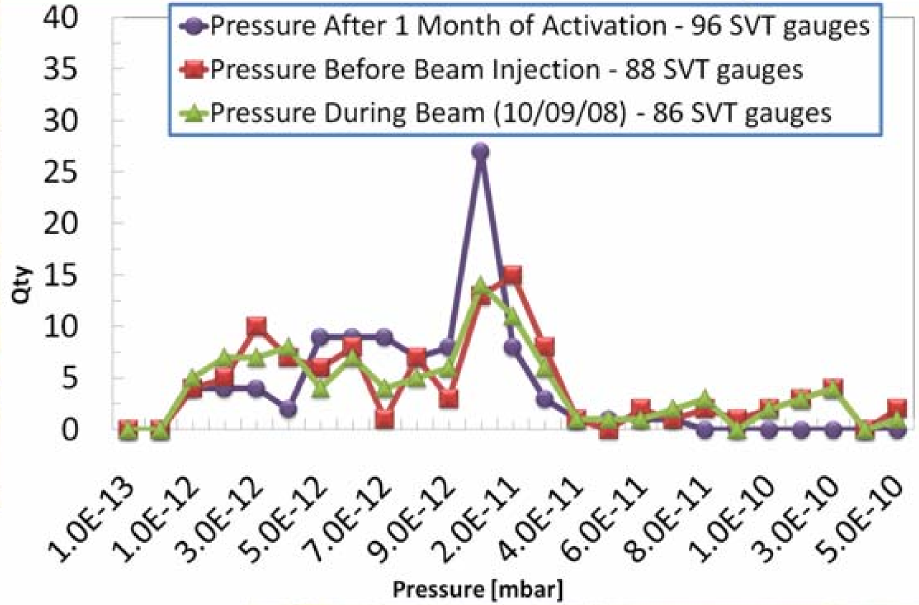
# LHC vacuum systems
## RT Beam Vacuum in Long Straight Sections

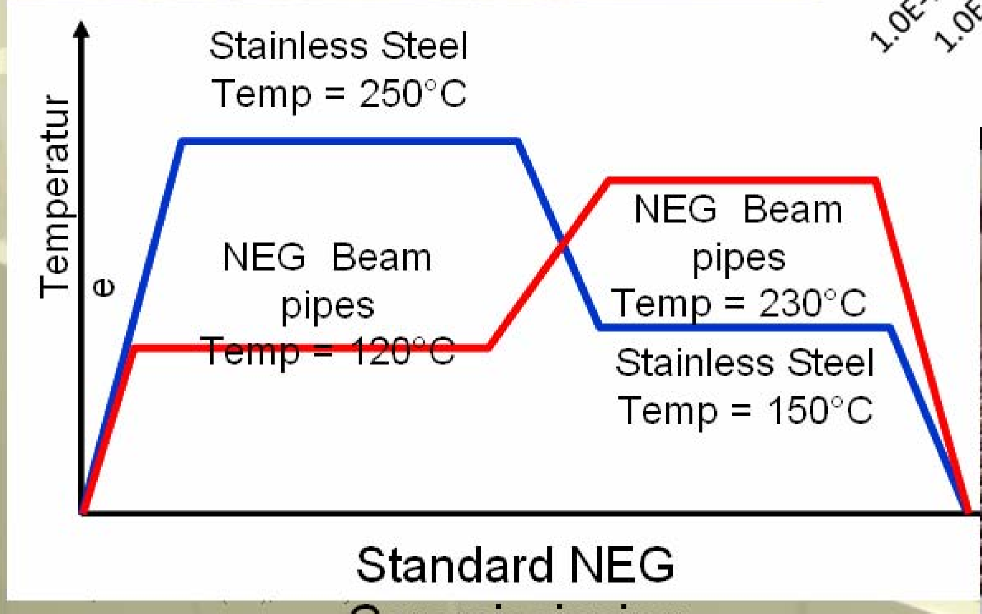
Poster MO6RFP006 & WE6RFP048

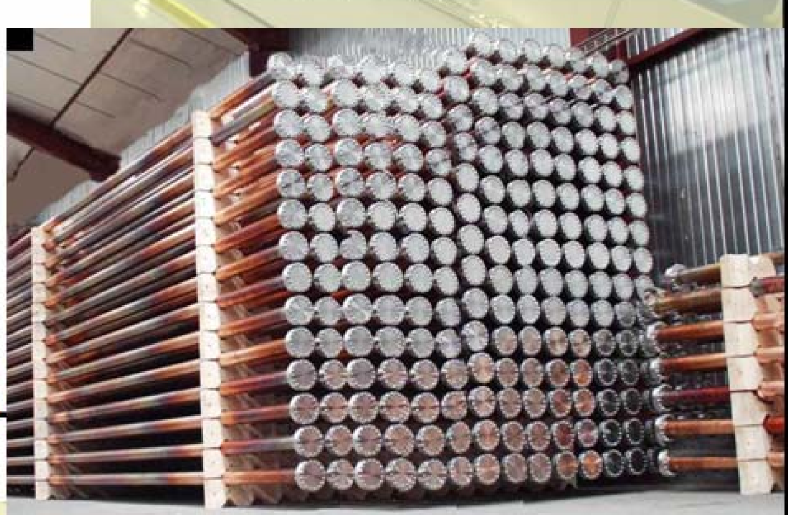
- **6.8 km of RT beam vacuum in the LSS**
  - Except in standalone cryomagnets
- **303 sector valves as vacuum protection**
  - Prevents saturation of the NEG coating during warming up
- **Extensive use of NEG coatings**
  - All beam pipes are NEG coated
    - Baked-out allows the activation of NEG coatings
- **780 ion pumps to avoid ion instability**
  - Provide pressure indications
    - In complement to the 1084 Pirani and Penning gauges and 170 Bayard-Alpert
      - Are used as sector valve interlocks

# LHC vacuum systems
## Extensive use of NEG coatings in LSS

# LHC vacuum systems
## Extensive use of NEG coatings in LSS

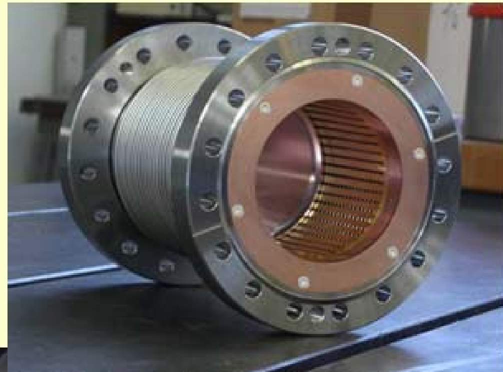


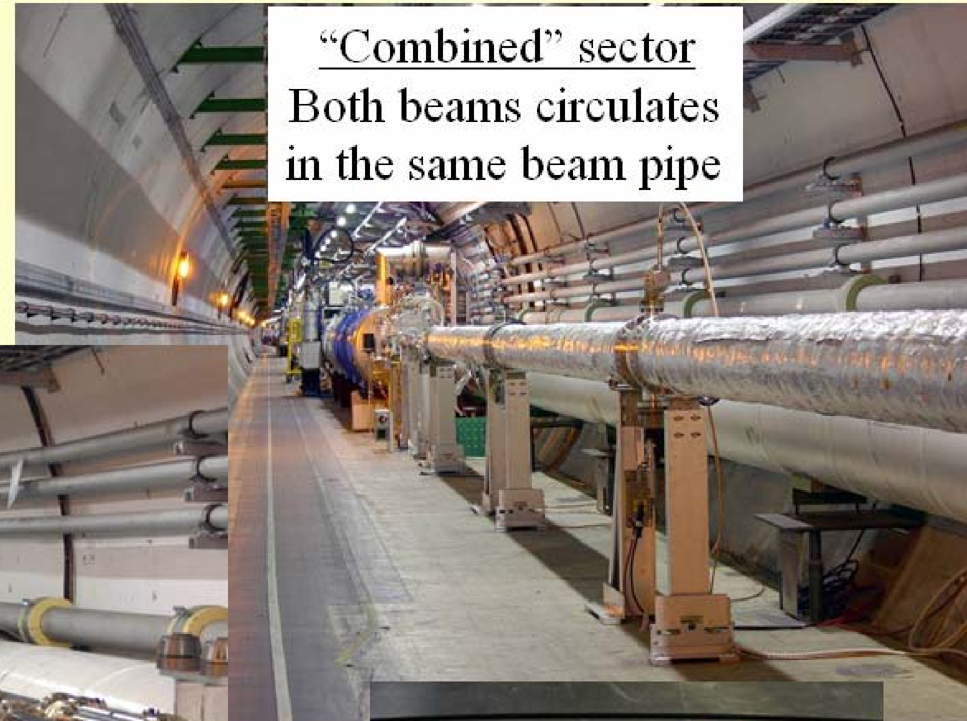



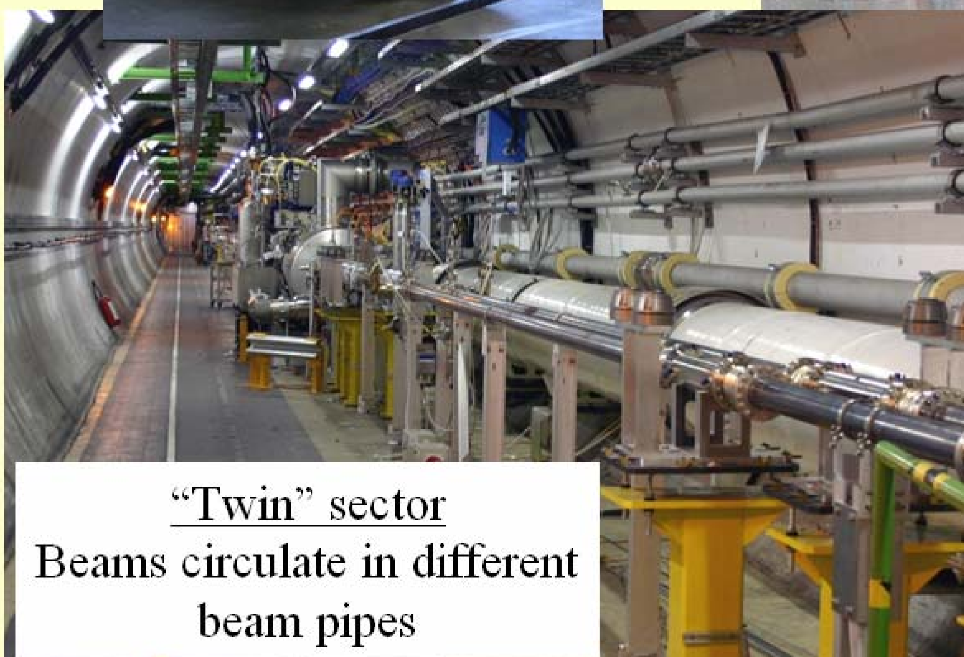



# LHC vacuum systems

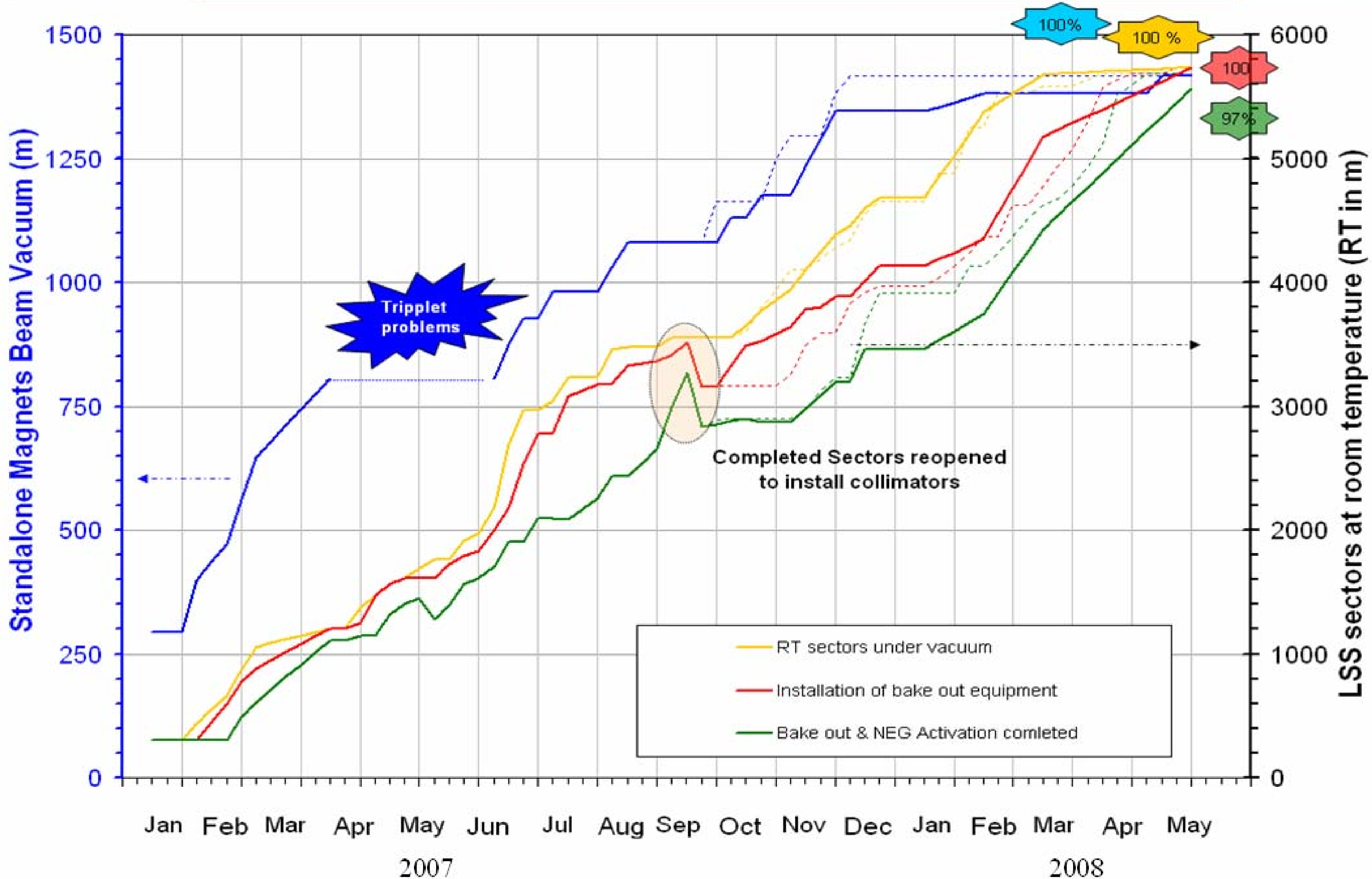
## An LSS Overview…






# LHC vacuum systems
## LSS Installation Overview



# LHC vacuum systems
## LSS Installation Overview

- **Resource management**
  - Installation sequence and speed were fixed by the available slots
  - Parallelism had to be started to cope with delays
  - Co-activities with the hardware commissioning were solved

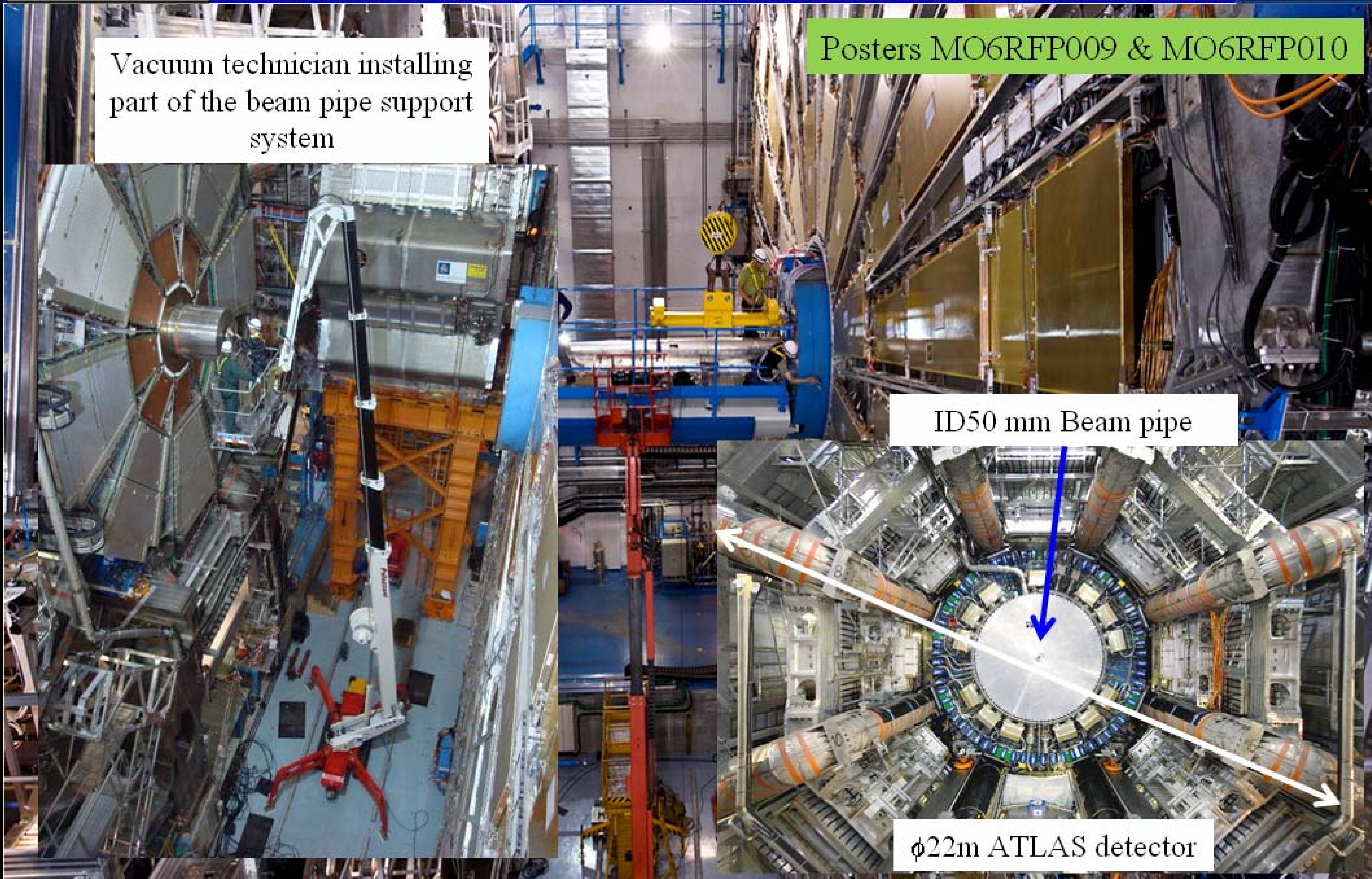
- **Material management & handling**
  - Components tested at the surface and transported into the tunnel right on time (Limited underground storage)
    - At the right place
    - With the appropriate orientation

- **Independent handling of the non-conformities**

☞ **Average speed for LSS installation: ~100 m/week !**

# LHC vacuum systems
## RT Beam Vacuum in Experimental Areas

# LHC vacuum systems
## RT Beam Vacuum in Experimental Areas



# LHC vacuum systems
## RT Beam Vacuum in Experimental Areas

- **Integration: Vacuum installation follows detector closure**
  - "Bad surprises" are not acceptable
  - Temporary supports and protections required at each stage of the installation
- **Reliability**
  - Leak detection and bake-out testing compulsory at each step of the installation
    - Vacuum pipes get encapsulated in the detector
- **Availability**
  - Detector installation imposes the "speed" and sequence of the installation
- **Performances**
  - Vacuum ($<10^{15}$ $H_2.m^{-3}$), HOM, impedance and alignment requirements
    - Must be fulfilled
- **Engineering**
  - Beryllium and aluminum material used since "transparent" to the particles escaping from the collision point
  - Innovative bake-out solutions to fit with the limited space available between vacuum pipes and the detector

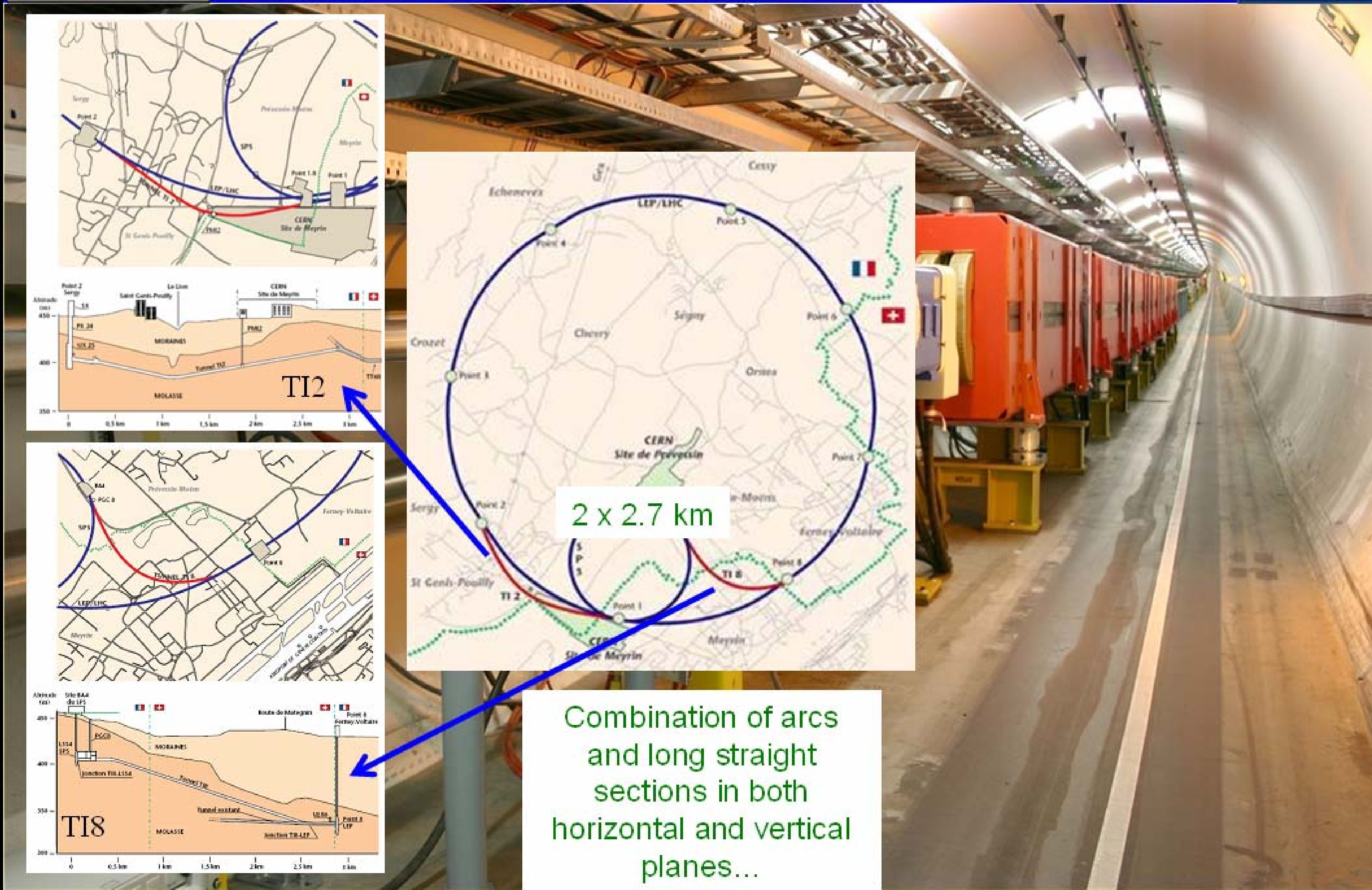
# LHC vacuum systems
## Insulation Vacuum in Bending Sections

# LHC vacuum systems
## Insulation Vacuum in Bending Sections

- **Size and volume: 50 km and 15'000 m³**
  - 2-3 weeks pumping required – mobile turbomolecular pumps
- **$10^{-1}$ Pa enough to allow for the cool down**
  - Cryopumping by cold surfaces maintains a static vacuum in the $10^{-5}$ Pa range
    - Low helium cryo-pumping
  - Leak tightness is a key issue
    - 250'000 welds, 90'000 made in-situ, 100 km integrated length
    - 18'000 elastomer joints, 22 km integrated length
    - 178 turbo-molecular pumps to remove small helium leaks
- **9 million square metres of multi-layer thermal insulation**
  - Huge outgassing after venting to atmosphere
    - Huge amount of water partly trapped by these multi-layers.

# LHC vacuum systems
## Injection Transfer Lines Beam Vacuum

# LHC vacuum systems
## Injection Transfer Lines Beam Vacuum

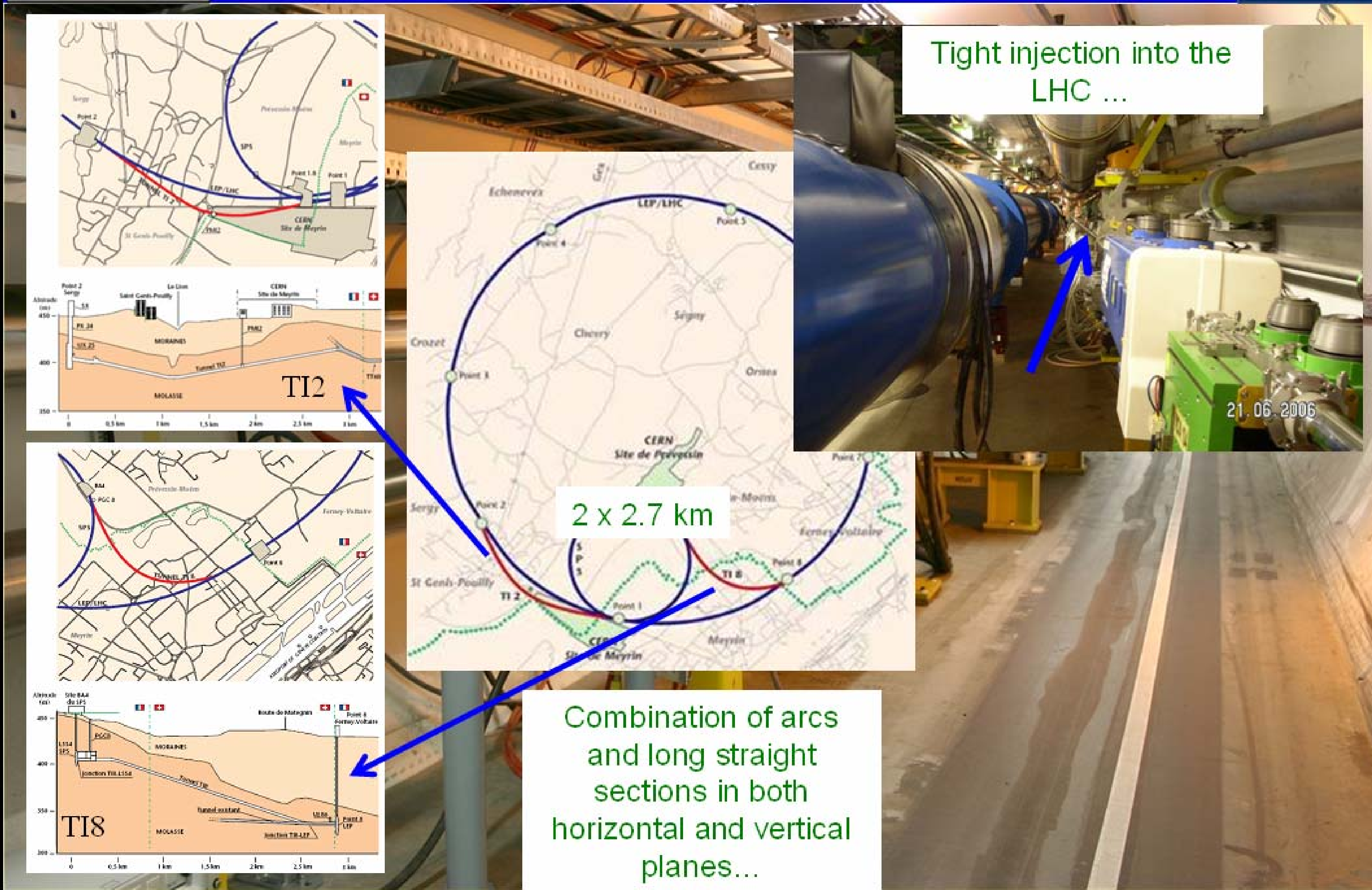



Combination of arcs and long straight sections in both horizontal and vertical planes...

Technology Department TE
Vacuum
Surfaces....
Coatings

# LHC vacuum systems
## Injection Transfer Lines Beam Vacuum

CERN



# LHC vacuum systems
## Dump Transfer Lines Beam Vacuum

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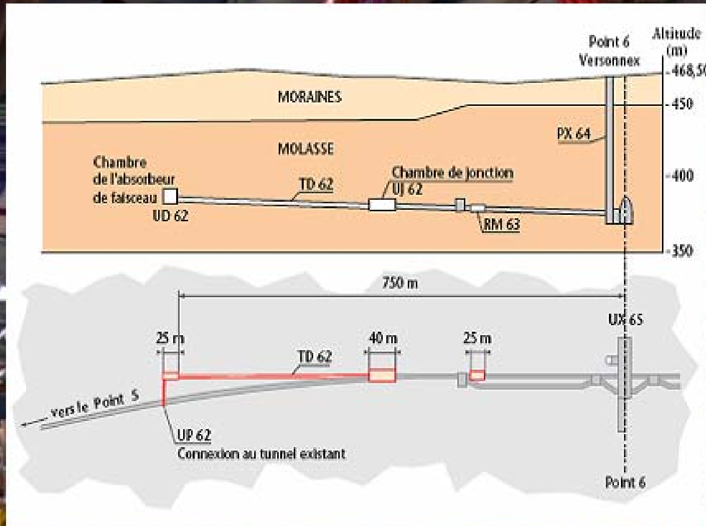
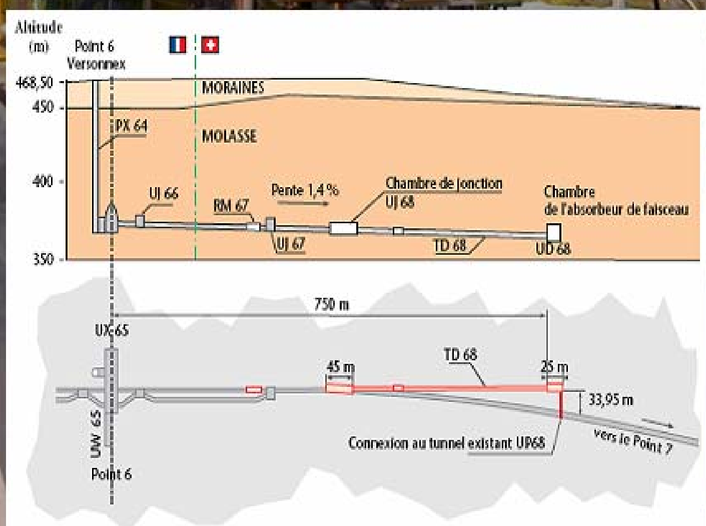
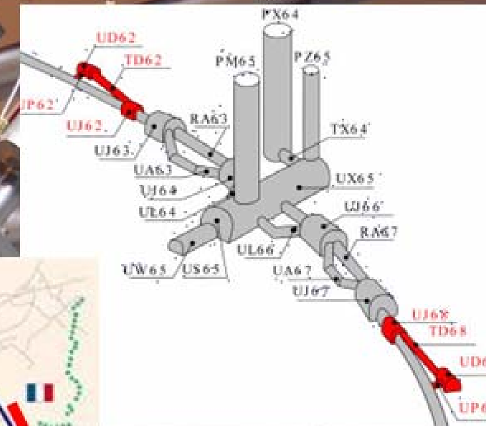
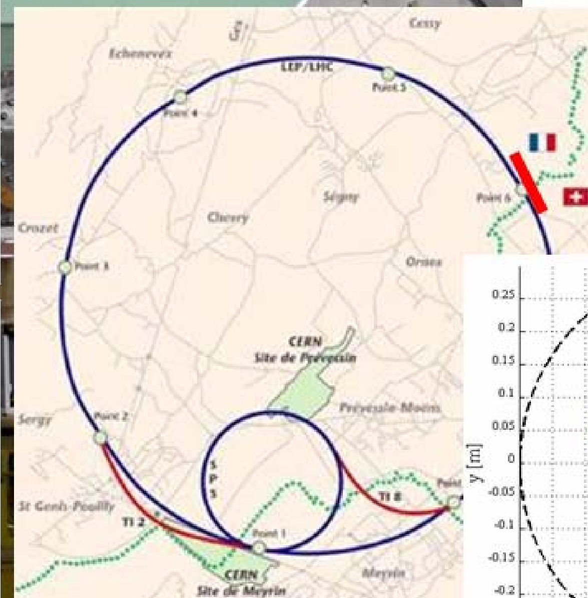
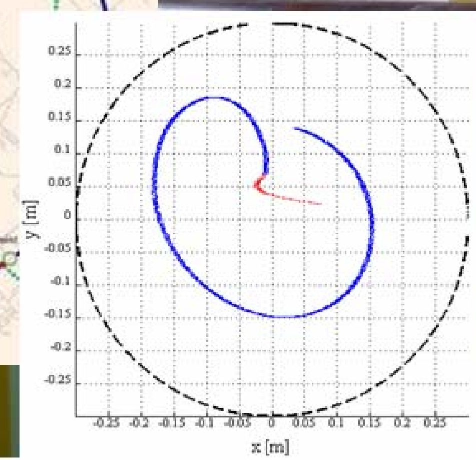


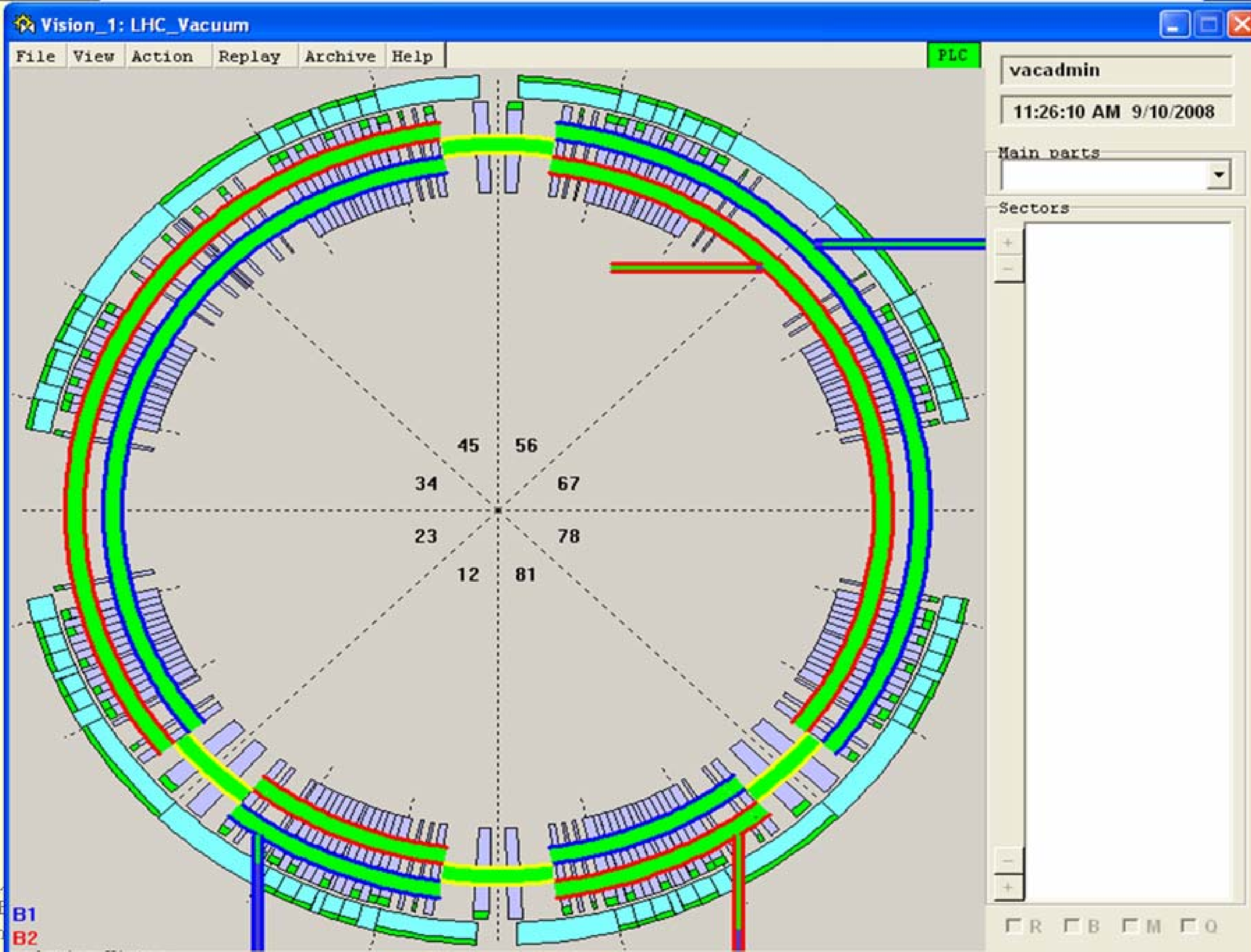



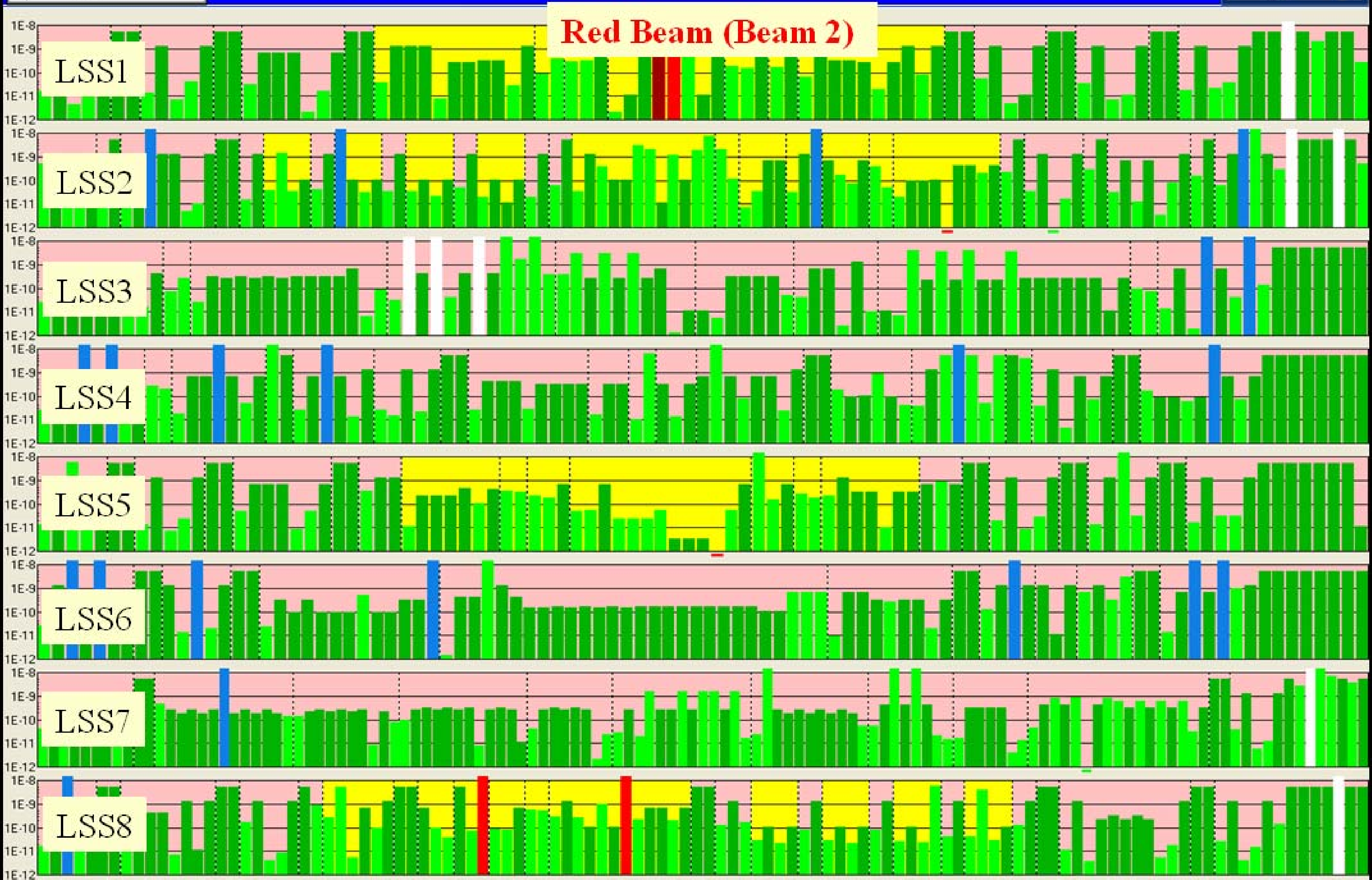

Expected sweep form on beam monitor (2808 bunches @ 7 TeV)

*Courtesy B. Goddard*

# First operation with beams
## Synoptic of LHC Vacuum Systems



# First operation with beams
## Intrinsic limitations of the instrumentation



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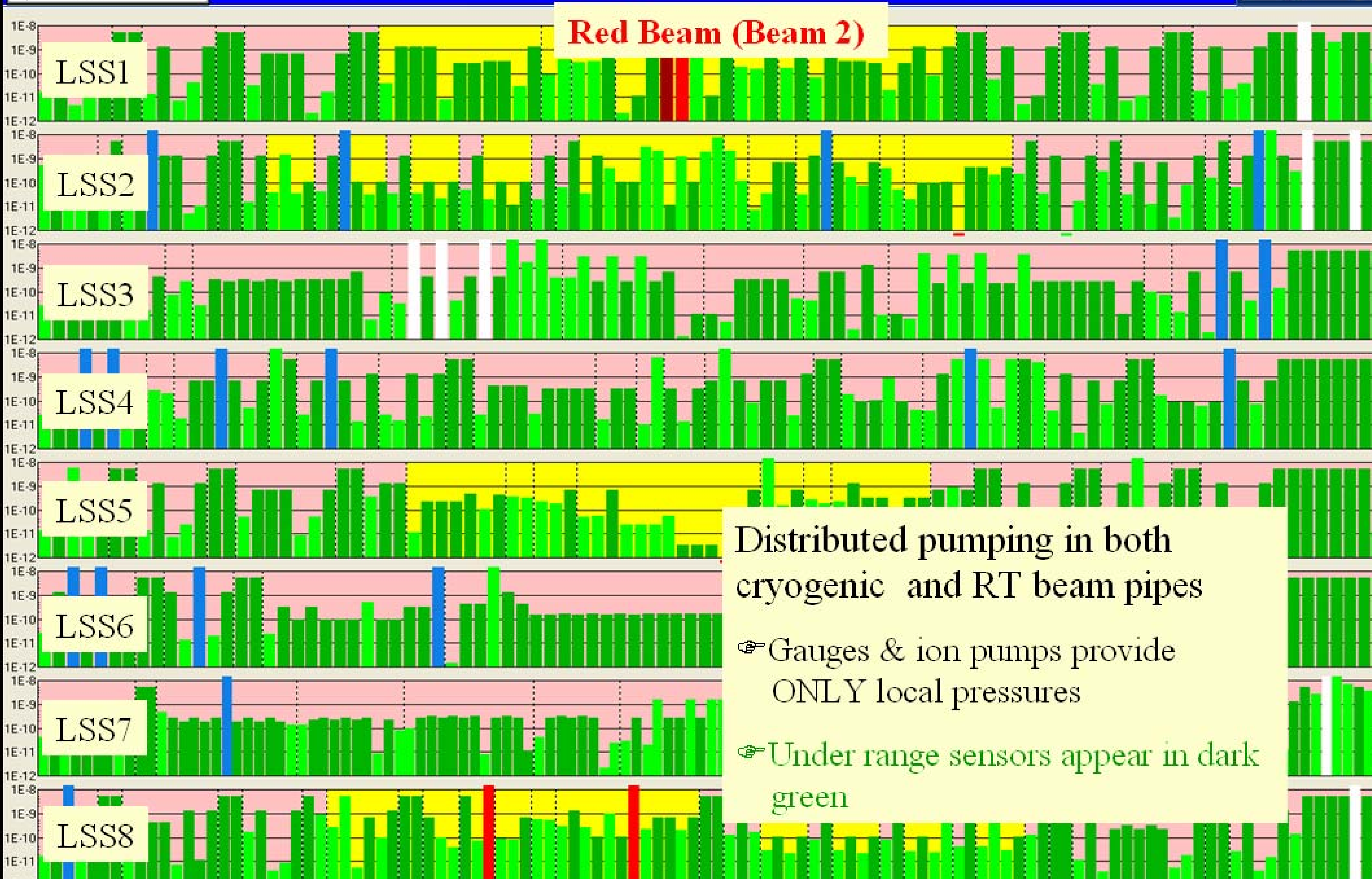
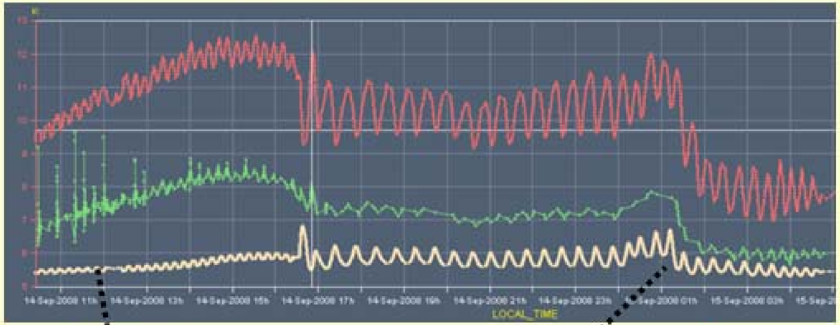
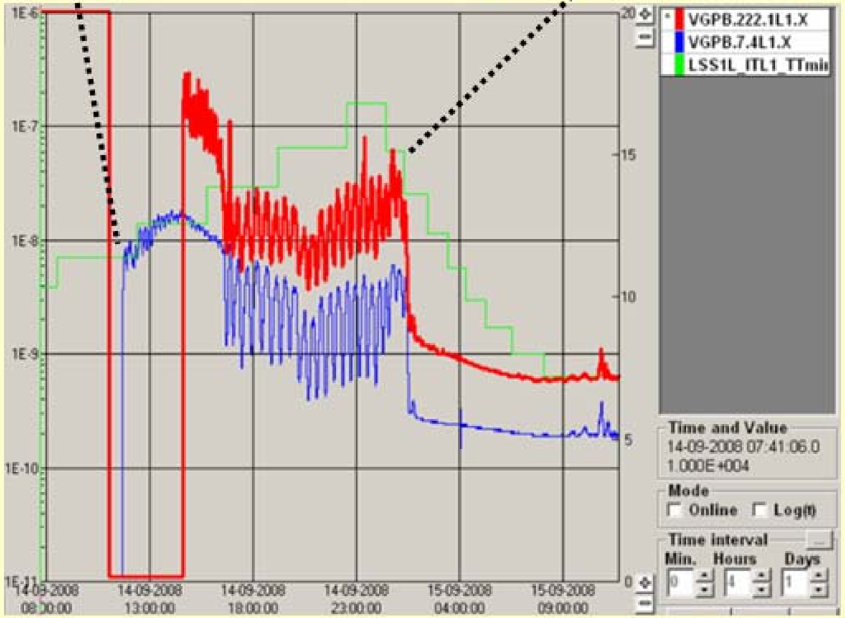



Distributed pumping in both cryogenic and RT beam pipes

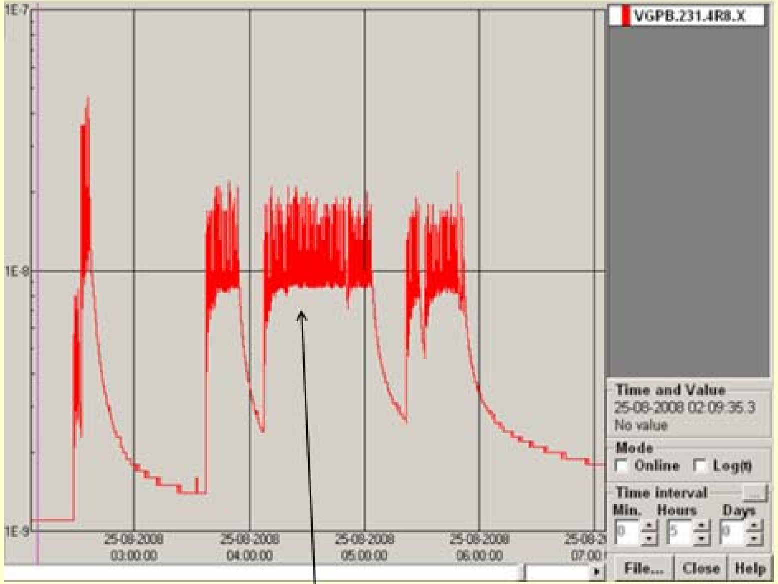
- Gauges & ion pumps provide ONLY local pressures
- Under range sensors appear in dark green

# First operation with beams
## Beam induced Dynamic Effects




Hydrogen oscillations induced by temperature variations




Multiple shots

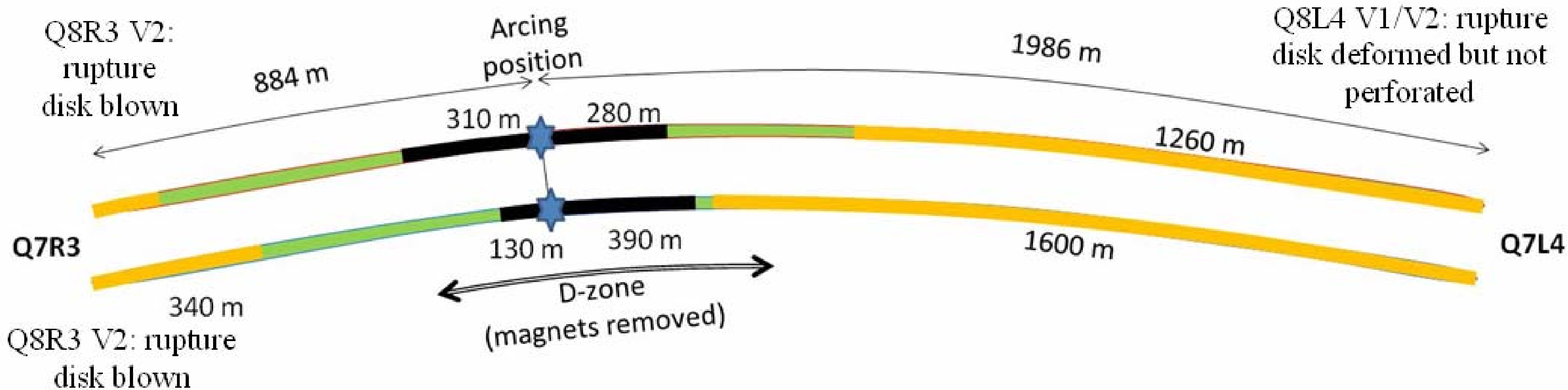
Pressure rise induced by the beam (1 bunch @ 450 GeV, $4.10^9$ protons) impacting on the injection collimator

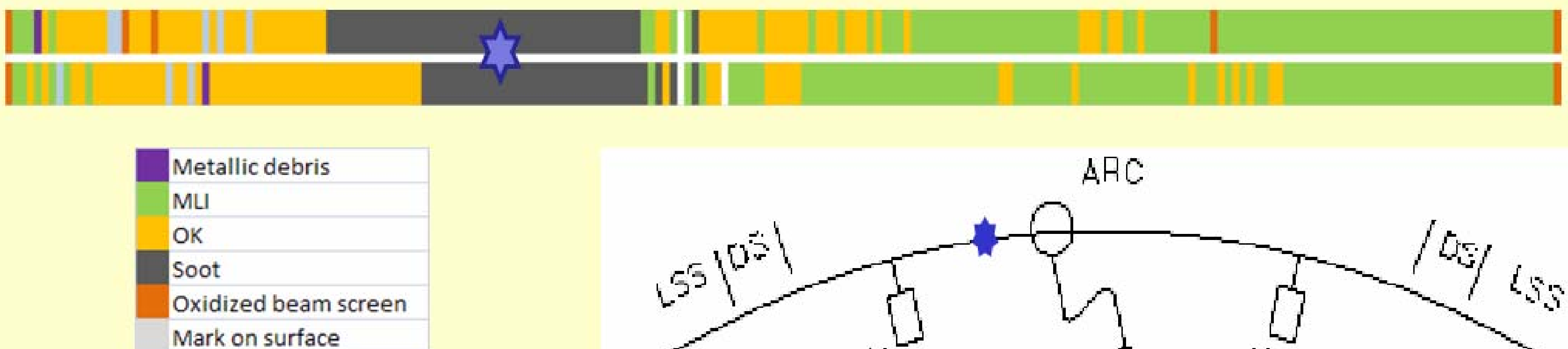
# Beam vacuum recovery after sector 3-4 incident
## Sequence of Events

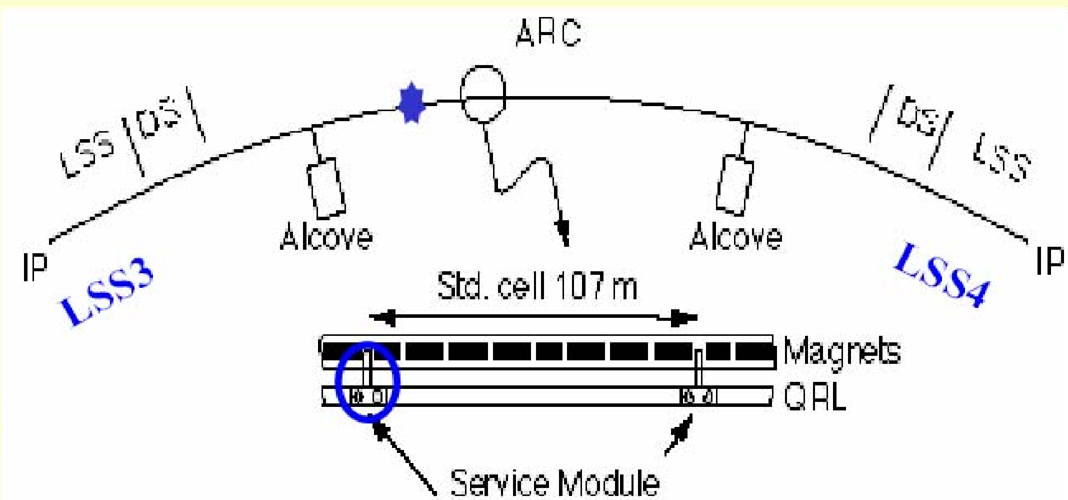
- **19 September 2008: during the powering test of the main dipole circuit in sector 3-4, an electrical fault occurred producing an electrical arc and resulting in:**
  - Mechanical and electrical damages
  - Release of helium from the magnet cold mass
  - Venting and contamination of the insulation and beam vacuum enclosures
- **Contamination by MLI or soot as observed in the tunnel after the incident. The second number refers to the situation in the tunnel after removing the 53 magnets of the D-zone**

| | V1 | V2 | V1 | V2 | Total |
|---|---|---|---|---|---|
| **Status** | **Magnet** | **Magnet** | **%** | **%** | **%** |
| **Ok** | 54/49 | 39/30 | 26/31 | 18/19 | 22/25 |
| **MLI** | 124/111 | 129/124 | 58/69 | 61/78 | 59/73 |
| **Soot** | 35/0 | 45/6 | 16/0 | 21/4 | 19/2 |
| **Total** | 213/160 | 213/160 | 100 | 100 | 100 |

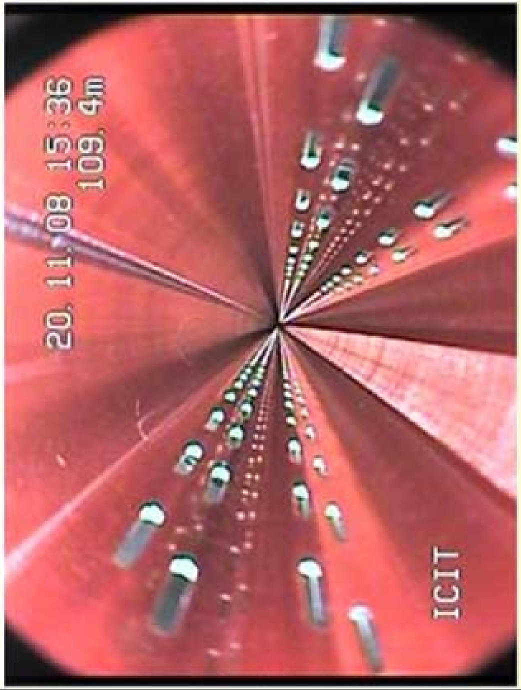
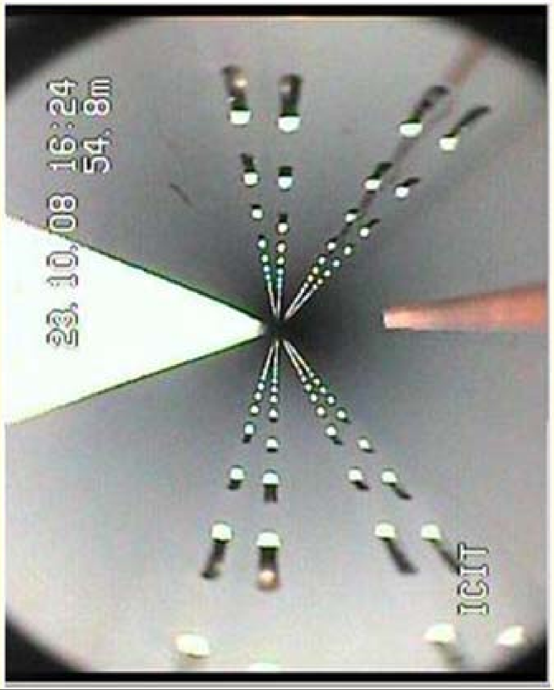
# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum



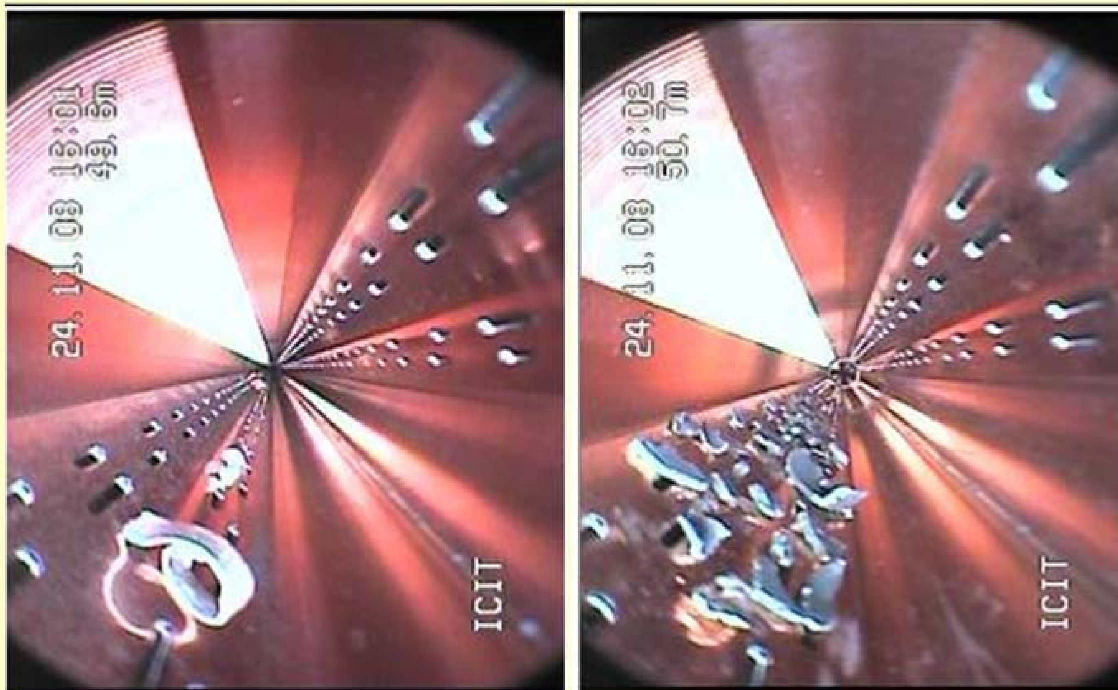
# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum

| 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. |
|---|---|---|
|  |  |  |

# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum



Beam Screen (BS) with debris of metal coming from melted RF fingers or Cold Bore (CB) pipes. The red color is characteristic of a clean copper surface



# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum

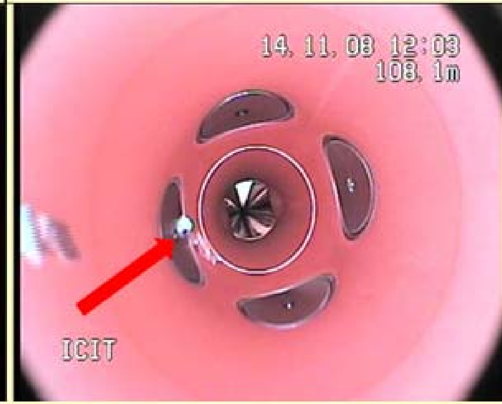
| Interconnecting bellows (PIM) with its RF screen to minimize the beam impedance. The shiny red color is characteristic of the cleanliness of the copper surfaces | PIM with some contamination by super-isolation (MLI multi layer insulation) | BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark |
| --- | --- | --- |


Vacuum Surfaces.... Coatings

# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum

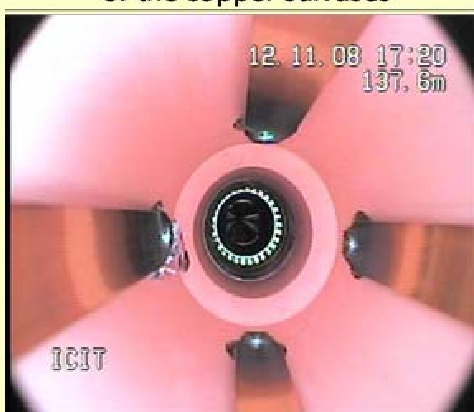
Beam position monitor (BPM). The shiny red color is characteristic of the cleanliness of the copper surfaces


BPM with some contamination by super-isolation (MLI multi layer insulation) on the electrode at 8h.




BPM with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark


Another variant of beam position monitor (BPM). The shiny red color is characteristic of the cleanliness of the copper surfaces




BPM with some contamination by super-isolation (MLI multi layer insulation) on the electrode at 9h

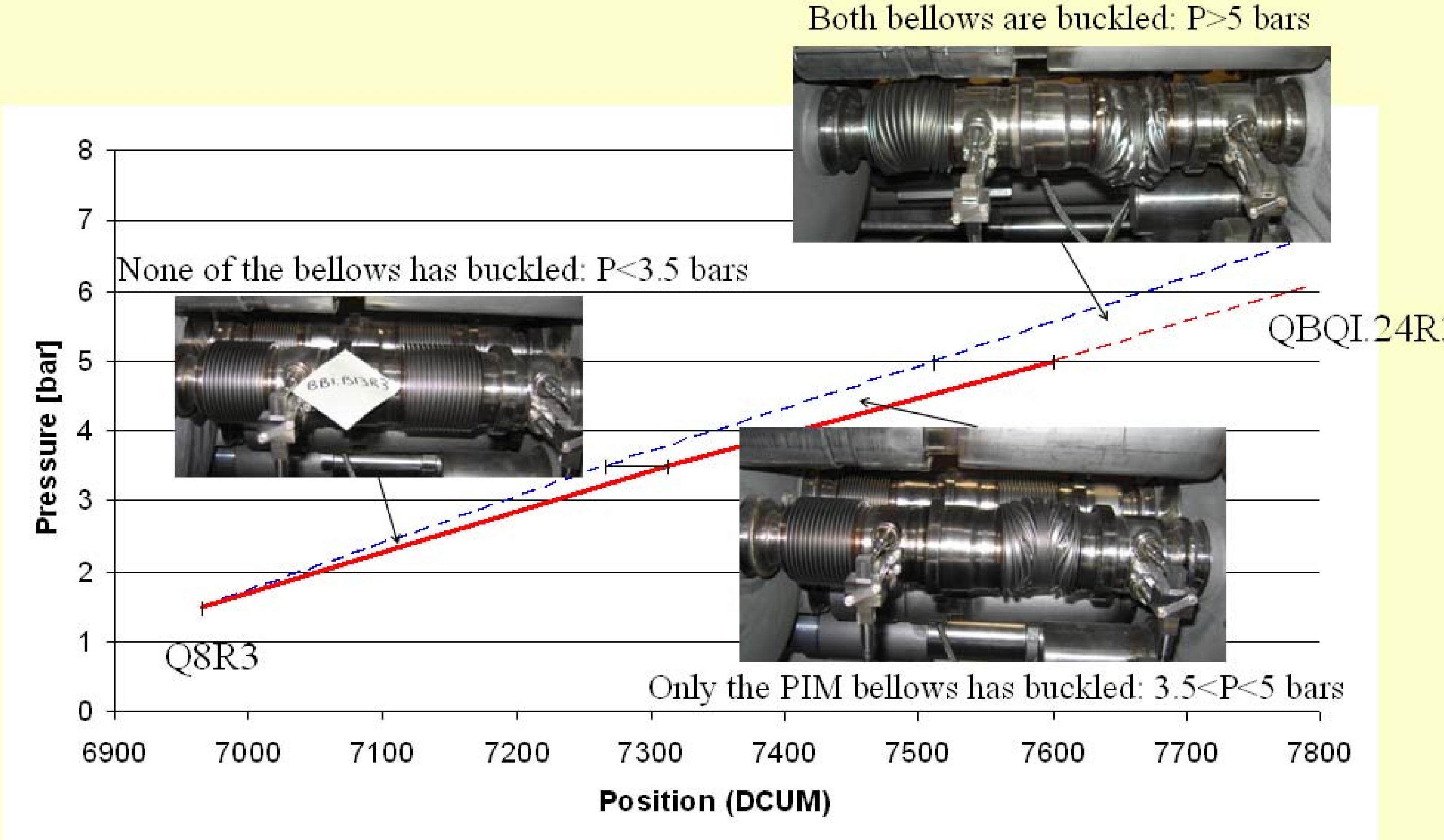
# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum

Beam Screens removed at the surface from a heavily soot contaminated magnet

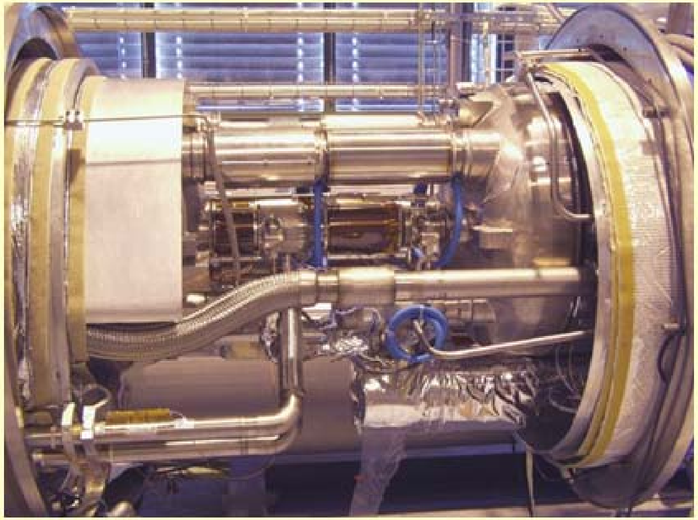
The pictures show that the external surface of the beam screen (cold bore side) and the inner surface of the cold bore tube are also contaminated by soot.

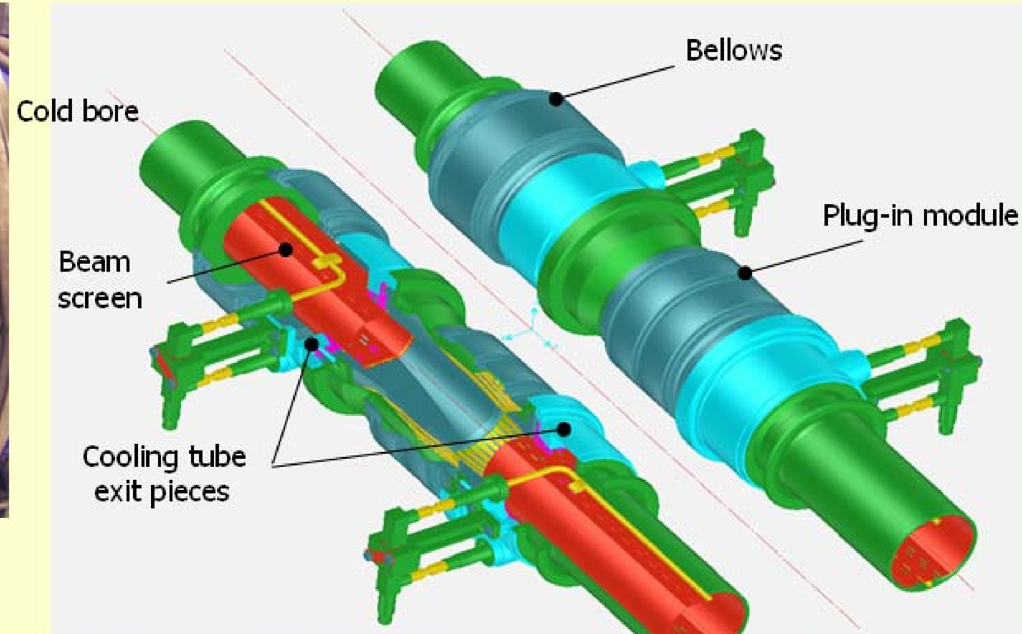
Cleaning the cold bore without removing the beam screen from the magnet is being studied but can only be made at the surface.

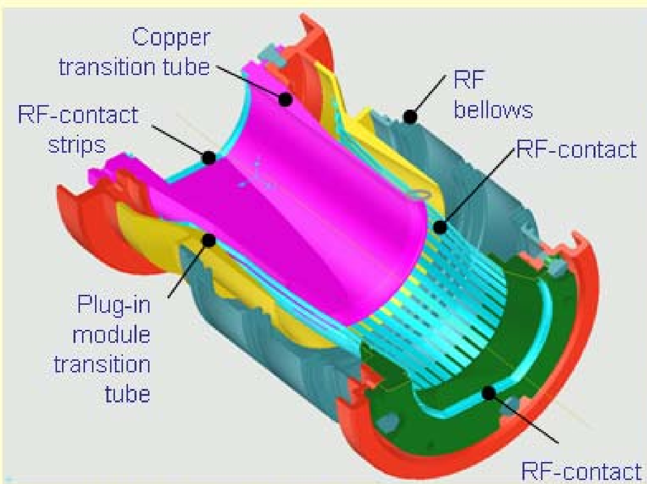
# Beam vacuum recovery after sector 3-4 incident
# Review of Damages to Beam Vacuum



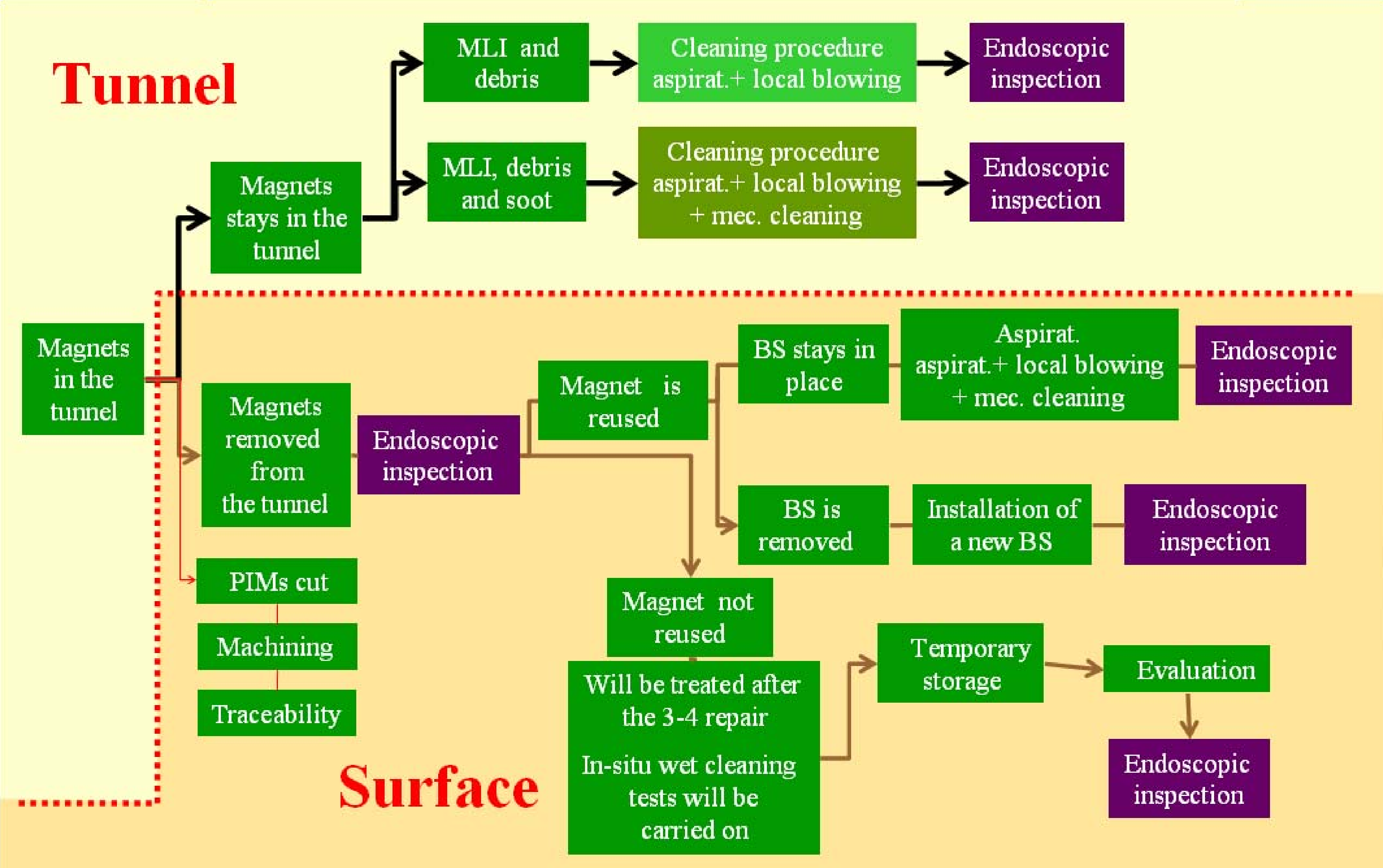
# Beam vacuum recovery after sector 3-4 incident
# Review of Constraints





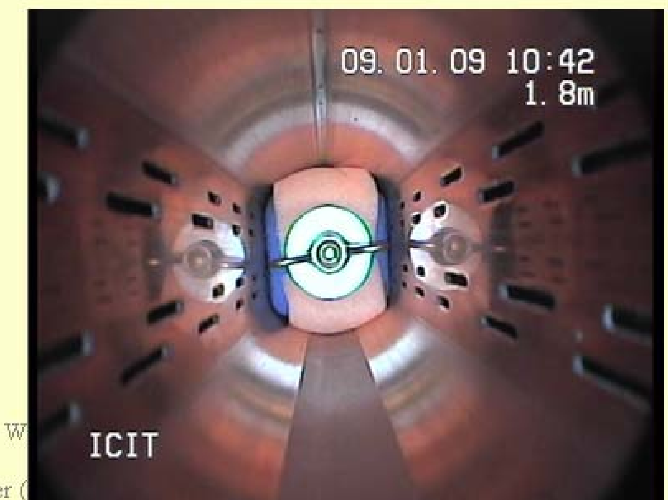



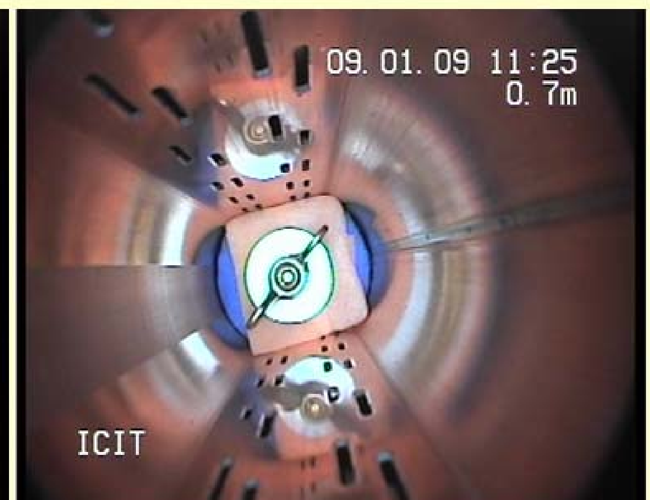

# Beam vacuum recovery after sector 3-4 incident
# Beam Vacuum Cleaning



# Beam vacuum recovery after sector 3-4 incident
# Beam Vacuum Cleaning: Soot

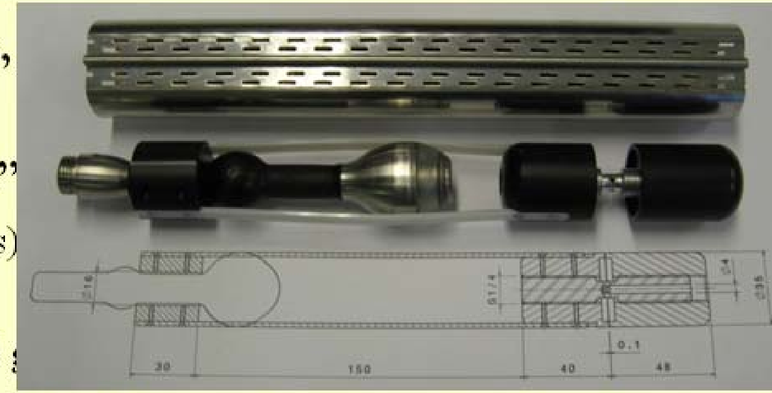
- **59 magnets with beam pipes contaminated by soot**
  - 53 (14 MQ and 39 MB) within the D-zone were removed
    - 37 (7 MQ and 30 MB) replaced by spare magnets
    - 16 (7 MQ and 9 MB) recovered requiring the exchange of 13 beam screens and a cleaning of the cold bore (wet process, detergent circulation)
  - 6 magnets (half-cells 19R3-20R3) left in the tunnel
    - Only one aperture contaminated by soot
    - Cleaned in-situ mechanically
    - 50 passages per aperture alternating wet (alcohol) and dry foams



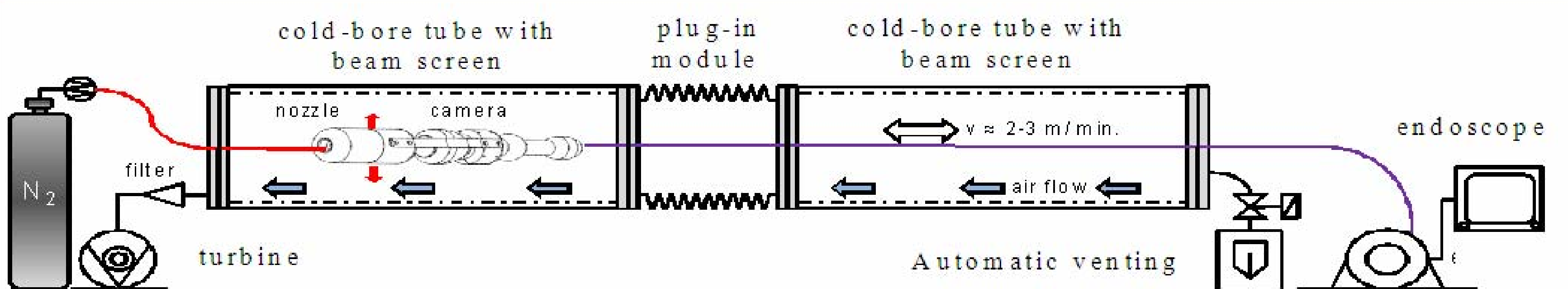



# Beam vacuum recovery after sector 3-4 incident
# Beam Vacuum Cleaning: MLI & debris

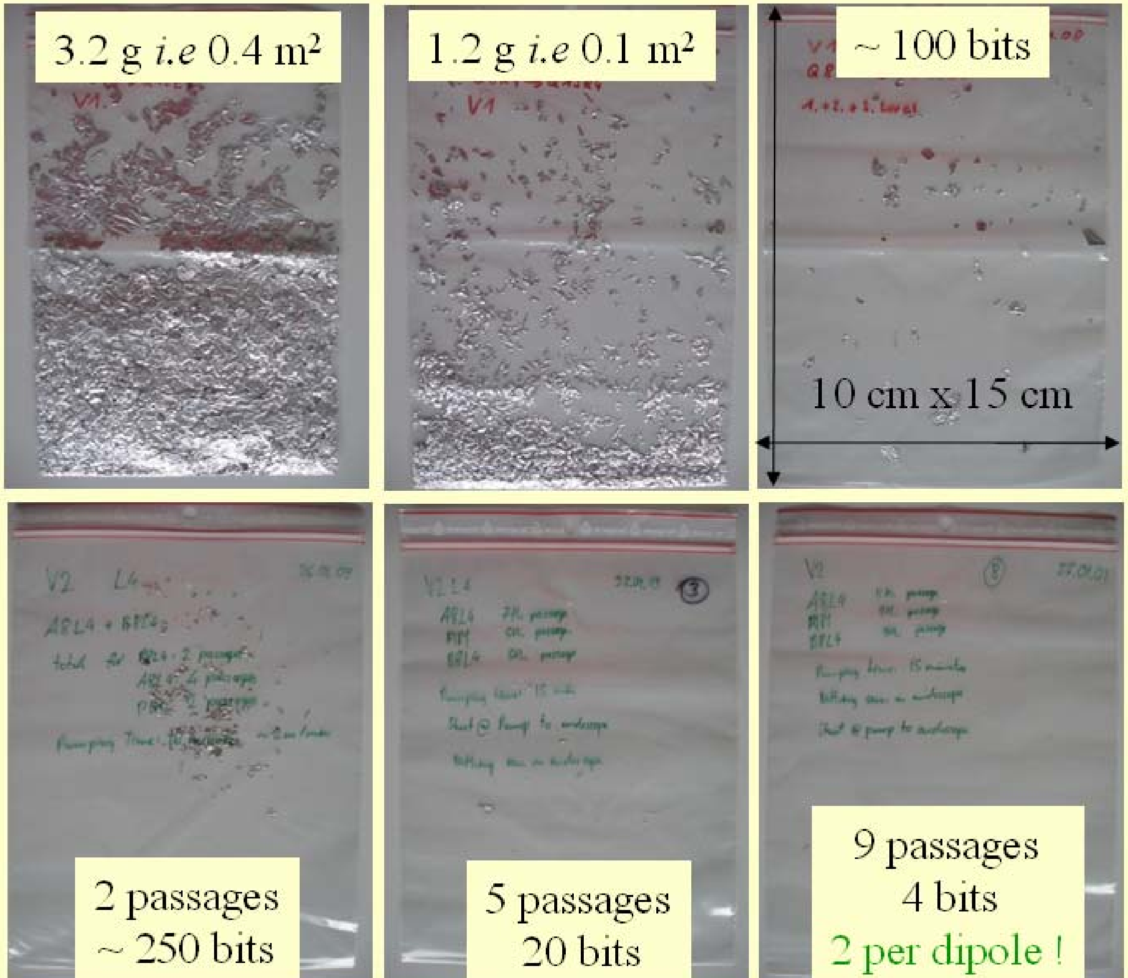
- **Systematic endoscopy of both apertures,**
  - 4.8 km in total for the two apertures
- **Pumping/venting cycle: 20” pumping, 8”**
  - During at least 1 h (120 pumping/venting cycles)
  - Pressure variations: atm - $8.10^4$ Pa (800 mbar)
  - Air speed is about 20 m/s corresponding to a 70

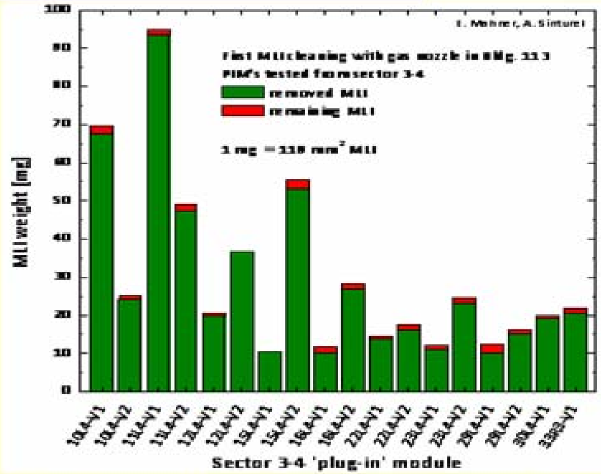


- **Aspiration with local perturbation controlled by endoscope (monitoring of position and efficiency)**
  - A nozzle blows filtered air (2 bar.l/s), the MLI residues left behind the beam screen and the RF fingers are directed towards the beam aperture where they are aspired away
  - 10 passages at 3.2 m/min and 5-10 minutes on top of the RF fingers (PIMs/nested bellows)
  - Specified cleaning efficiency: two dust (<1 $mm^2$)/magnet and 1 fibre (<3 mm)/half-cell
  - Final endoscopy made by an independent team gives the final green light

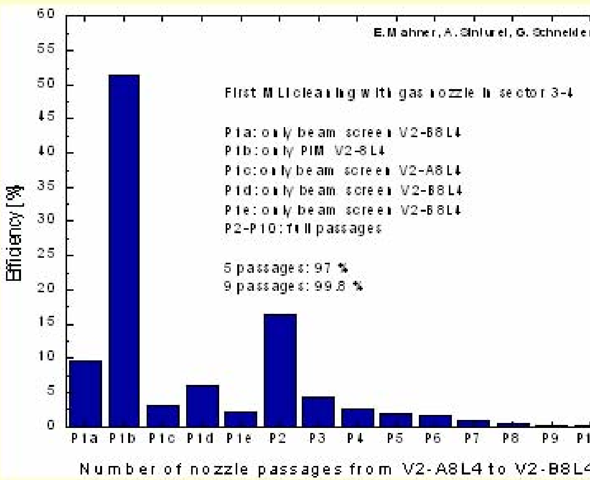


# Beam vacuum recovery after sector 3-4 incident
# Beam Vacuum Cleaning: MLI & debris




Measurements made at the surface on PIMs removed from 3-4 sector




Measurements made in the tunnel 3-4 sector

# Closing remarks

- **Vacuum systems were operational to their nominal for the beam injections on the 10th September'08**
- **The incident of sector 3-4 spoiled all the beam tubes in the arc**
  - After removing the D-zone, ¾ of them were polluted with super insulation debris
  - In-situ cleaning was mandatory as well as the evaluation of the cleaning efficiency and consequences of the remaining dust for the future operation
- **Today, beam vacuum cleaning in sector 3-4 is completed, closure and leak detections ongoing**
  - Equivalent to 58 km CLEANED and INSPECTED cm-by-cm !
- **Other vacuum sectors (beam and insulation) are being completed after the safety relief valves consolidations**
- **Surely, the operation of the LHC will be challenging due to the variety of technologies, performances, expected behaviour in presence of beams and collateral damages in case of incidents.**

# Acknowledgements

The author would like to acknowledge years of efforts of colleagues at CERN and in the world through collaborations; the vacuum systems availability for the first operation with beams is the result of their efforts.

The author would like also to gratefully acknowledge the commitment of many people at CERN (CERN staff or staffs of the industrial support companies) for their devotion to repair and recover the LHC vacuum systems after the September 19th incident and more specifically, V. Baglin, F. Bertinelli, P. Chiggiato, P. Cruikshank, C. Garion, A. Grimaud* and R. Veness as representatives of their teams.

*AL43 Consortium