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)
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### Introduction

**CERN accelerator chain (2/2)**

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<td>synchrotron</td>
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<tr>
<td>PS</td>
<td>decelerator</td>
<td>2004-09</td>
<td>100 MeV</td>
<td>partly</td>
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<td>300 m</td>
<td>pbar</td>
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<tr>
<td>CTF3 complex</td>
<td>linac/ing</td>
<td>1976</td>
<td>26 GeV</td>
<td>-</td>
<td>10^-6</td>
<td>~1.3 km</td>
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<tr>
<td>PS to SPS TL</td>
<td>Transfer line</td>
<td>1976</td>
<td>26 GeV</td>
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**SPS Complex**

<table>
<thead>
<tr>
<th>SPS Complex</th>
<th>SPS</th>
<th>synchrotron</th>
<th>1976</th>
<th>450 GeV</th>
<th>Extractions</th>
<th>10^7</th>
<th>7 km</th>
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<tbody>
<tr>
<td>SPS North Area</td>
<td>Transfer line</td>
<td>1976</td>
<td>2 x 4 TeV</td>
<td>-</td>
<td>10^-6 - 10^-7</td>
<td>~1.2 km</td>
<td>p, ions</td>
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<tr>
<td>SPS West Area</td>
<td>Transfer line</td>
<td>1976</td>
<td>2 x 1.4 TeV</td>
<td>-</td>
<td>10^-6 - 10^-7</td>
<td>~1.4 km</td>
<td>p, ions</td>
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<tr>
<td>SPS to LHC T12/8 Line</td>
<td>Transfer line</td>
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<td>2 x 12.2 TeV</td>
<td>-</td>
<td>10^-6 - 10^-7</td>
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<tr>
<td>CNGS Proton Line</td>
<td>Transfer line</td>
<td>2005</td>
<td>2 x 25 km</td>
<td>-</td>
<td>10^-6 - 10^-7</td>
<td>~730 m</td>
<td>p, ions</td>
</tr>
</tbody>
</table>

**LHC Accelerator**

<table>
<thead>
<tr>
<th>LHC Accelerator</th>
<th>LHC Arcs (Beam x2, Magnets &amp; QRL insul.)</th>
<th>collider</th>
<th>2007</th>
<th>2 x 7 TeV</th>
<th>&lt; 10^6</th>
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<tbody>
<tr>
<td>LSS RT separated beams</td>
<td>complete</td>
<td>2007</td>
<td>2 x 3.2 km</td>
<td>~570 m</td>
<td>p, ions</td>
<td></td>
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<tr>
<td>LSS RT recombination</td>
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<td></td>
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<table>
<thead>
<tr>
<th>Experimental areas</th>
<th>Beam Dump Lines TD62/68</th>
<th>Transfer line</th>
<th>2006</th>
<th>7 TeV</th>
<th>10^-6</th>
<th>2 x 720 m</th>
<th>~128 km</th>
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<tbody>
<tr>
<td>High Vacuum</td>
<td>~20 km</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>UHV w/o NEG</td>
<td>~57.5 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Insulation vacuum</td>
<td>~50 km</td>
<td></td>
<td></td>
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The CERN LHC – World’s Largest Vacuum Systems (WE4RA102)

J.M. JIMENEZ

PAC’09, Vancouver (CA), 06 May’09
# Introduction

**CERN accelerator chain (2/2)**

## Linac, Booster, ISOLDE, PS, n-TOF and AD Complex

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## Vacuum Systems

- **High Vacuum**: ~20 km
- **UHV w/wo NEG**: ~57.5 km
- **Insulation vacuum**: ~50 km

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The CERN LHC – World’s Largest Vacuum Systems (WE4RA102)

J.M. JIMENEZ

PAC’09, Vancouver (CA), 06 May’09
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
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

\[ \Rightarrow \text{Intercept most of the heat load, 1 W at 1.9 K requires 1 kW of electricity} \]
LHC Vacuum Systems
An Overview...
LHC Vacuum Systems
An Overview...

- 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

The CERN LHC – World’s Largest Vacuum
J.M. JIMENEZ
PAC’09, Vancouver (CA), 06 May’09
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

Saturated vapour pressure from Honig and Hook (1960)

Beam screen

Cryosorbers

100 h beam lifetime

1.9 K

4.5 K

Temperature (K)

Pressure (Torr, 300 K)

The CERN
J.M. JIMEI
PAC'09, Vancouver (CA), 06 May'09
LHC vacuum systems
RT Beam Vacuum in Long Straight Sections
LHC vacuum systems
RT Beam Vacuum in Long Straight Sections

- 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

- Pressure After 1 Month of Activation - 96 SVT gauges
- Pressure Before Beam Injection - 88 SVT gauges
- Pressure During Beam (10/09/08) - 86 SVT gauges

- Stainless Steel
  Temp = 250°C

- NEG Beam pipes
  Temp = 120°C

- NEG Beam pipes
  Temp = 230°C

- Stainless Steel
  Temp = 150°C

Standard NEG Coating Systems
LHC vacuum systems
An LSS Overview...

“Twin” sector
Beams circulate in different beam pipes

“Combined” sector
Both beams circulates in the same beam pipe

The CERN LHC – World’s Largest Vacuum Systems (WE4RA102)
J.M. JIMENEZ
PAC’09, Vancouver (CA), 06 May’09
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
Vacuum technician installing part of the beam pipe support system

ID 50 mm Beam pipe

φ22 m ATLAS detector

Posters MO6RFP009 & MO6RFP010
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 ($<10^{15} \text{H}_2 \text{m}^{-3}$), 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

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J.M. JIMENEZ
PAC'09, Vancouver (CA), 06 May'09
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

Combination of arcs and long straight sections in both horizontal and vertical planes...
LHC vacuum systems
Injection Transfer Lines Beam Vacuum

Tight injection into the LHC...

2 x 2.7 km

Combination of arcs and long straight sections in both horizontal and vertical planes...
LHC vacuum systems
Dump Transfer Lines Beam Vacuum
LHC vacuum systems
Dump Transfer Lines Beam Vacuum

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

Red Beam (Beam 2)

LSS1
LSS2
LSS3
LSS4
LSS5
LSS6
LSS7
LSS8
First operation with beams
Intrinsic limitations of the instrumentation

Red Beam (Beam 2)

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, $4 \times 10^9$ 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

<table>
<thead>
<tr>
<th>Status</th>
<th>V1 Magnet</th>
<th>V2 Magnet</th>
<th>V1 %</th>
<th>V2 %</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ok</td>
<td>54/49</td>
<td>39/30</td>
<td>26/31</td>
<td>18/19</td>
<td>22/25</td>
</tr>
<tr>
<td>MLI</td>
<td>124/111</td>
<td>129/124</td>
<td>58/69</td>
<td>61/78</td>
<td>59/73</td>
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<tr>
<td>Soot</td>
<td>35/0</td>
<td>45/6</td>
<td>16/0</td>
<td>21/4</td>
<td>19/2</td>
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<tr>
<td>Total</td>
<td>213/160</td>
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Beam vacuum recovery after sector 3-4 incident
Review of Damages to Beam Vacuum

Q8R3 V2: rupture disk blown
Q7R3
340 m
Q8R3 V2: rupture disk blown
Arcing position
130 m 390 m
D-zone (magnets removed)
1986 m
884 m
1260 m
1600 m
Q7L4

QSL4 V1/V2: rupture disk deformed but not perforated

Metallic debris
MLI
OK
Soot
Oxidized beam screen
Mark on surface

The CERN LHC – World’s Largest Vacuum Systems (WE4RA102)
J.M. JIMENEZ
PAC’09, Vancouver (CA), 06 May’09
# Beam vacuum recovery after sector 3-4 incident

**Review of Damages to Beam Vacuum**

<table>
<thead>
<tr>
<th>Beam Screen (BS): The red color is characteristic of a clean copper surface</th>
<th>BS with some contamination by super-isolation (MLI multi layer insulation)</th>
<th>BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.</th>
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<tr>
<td><img src="image1.jpg" alt="Image" /></td>
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J.M. Jimenez
PAC'09, Vancouver (CA), 06 May'09
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 |

The CERN LHC - World's Largest Vacuum Systems (WE4RA102)
J.M. JIMENEZ
PAC'09, Vancouver (CA), 06 May '09
**Beam vacuum recovery after sector 3-4 incident**

**Review of Damages to Beam Vacuum**

<table>
<thead>
<tr>
<th>Beam position monitor (BPM). The shiny red color is characteristic of the cleanliness of the copper surfaces</th>
<th>BPM with some contamination by super-isolation (MLI multi layer insulation) on the electrode at 8h.</th>
<th>BPM with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
<td><img src="image3.png" alt="Image 3" /></td>
</tr>
</tbody>
</table>

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

![Image 4](image4.png) | ![Image 5](image5.png) |
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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.

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- Both bellows are buckled: $P > 5$ bars
- None of the bellows has buckled: $P < 3.5$ bars
- Only the PIM bellows has buckled: $3.5 < P < 5$ bars
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Review of Constraints

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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 g
- 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 aspirated 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

Diagram:
- cold-bore tube with beam screen
- plug-in module
- cold-bore tube with beam screen
- Automatic venting
- nitrogen
- turbine
- filter
- camera
- nozzle
- airflow
Beam vacuum recovery after sector 3-4 incident

Beam Vacuum Cleaning: MLI & debris

- 3.2 g i.e 0.4 m²
- 1.2 g i.e 0.1 m²
- ~100 bits
- 10 cm x 15 cm

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

- 2 passages ~250 bits
- 5 passages 20 bits
- 9 passages 4 bits 2 per dipole!

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

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*AL43 Consortium