LHC Risk Review
- Beam Tube Cleaning -

J.M. Jimenez

On behalf of the Vacuum, Surface and Coatings Group
Main topics

- Introduction
- Evaluation of damages
- Sorting the magnets
- Cleaning strategy
- Follow-up of Chamonix’09 recommendations
Introduction
LHC dipole magnet cross-section

- **Insulation vacuum** is a high vacuum between:
  - Cryomagnet and its cryostat
  - Inner cold cryogenic lines and the outer envelope of the liquid helium transfer lines
  *Both are wrapped with super insulation layers*

- **Beam vacuum fulfils the ultra-high vacuum specifications**
### Evaluation of damages

#### Types of contamination (BS)

<table>
<thead>
<tr>
<th>Beam Screen (BS)</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>
</tr>
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<td>The red color is characteristic of a clean copper surface</td>
<td>BS with some contamination by super-isolation (MLI multi layer insulation)</td>
<td>BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.</td>
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05 March’09
Evaluation of damages
Types of contamination (BS)

| 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 | The magnets in which both soot and debris were expected, were not checked to preserve the head of the endoscope |

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Evaluation of damages
Beam Screens of 3-4 Declared Cleaned
Evaluation of damages
Types of contamination (PIMs)

| 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 |

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**Evaluation of damages**

**Types of contamination (BPM)**

<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" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>

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**Evaluation of damages**  
**Types of contamination (BPM)**

| 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 | None of this type of component has been found contaminated by soot, only available in the 4L side of sector 3-4 |

![Image 1](image1.png)  
![Image 2](image2.png)
Beam screen (BS) removed 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 (CB) tube are also contaminated by soot.

Cleaning the CB and BS without removing the BS from the magnet from the tunnel is impossible.
Evaluation of damages
Beam Screen (BS) / Cold Bore (CB) configuration (1)
Evaluation of damages
Beam Screen (BS) / Cold Bore (CB) configuration (2)

• No access to the volume between the BS and the CB
  – Pumping slots are too small
  – Taps are installed at each extremities
  – Nested bellows are the « ideal » trap

• Cooling capillaries are bended and welded to the cooling tube exit pieces
  – Once cut, these components can no longer be reused
    • Re-bending of the capillaries could lead to helium leaks
    • No weld is allowed (LHC Design Report) between the liquid helium circuits and the beam vacuum

An helium leak in the beam vacuum will stop the LHC for 6 months!
Evaluation of damages
PIM configuration (1)
Evaluation of damages
PIM configuration (2)

- Pieces are welded to the magnet extremities
  - Can be reused only 3 or 4 times

- Trap volume for soot and dusts

- Sliding requirements are critical for the operation of the PIM RF fingers
  - Gold and Rhodium coatings
    - No soot is allowed

- Bellows can be damaged (buckled) by an internal over pressure
Evaluation of damages
Soot impact on performances...

- **BS and CB show soot contamination**
  - Both are contaminated in the “D” zone
    - Soot is magnetic
      - Total removal in situ is excluded
        » Magnet need to be removed from the tunnel
- **Contamination of the BS, PIMs and nested bellows**
  - Spare components will be used instead
- **Contamination of BPMs**
  - All contaminated BPMs will be replaced at the surface
  
  Soot particles can lead to beam blow up if captured by the beams
Evaluation of damages
LHC vacuum sectorisation: arcs and LSS (1)

- 8 arcs and 8 straight sections
- Separation of cold and RT vacuum systems
- Create vacuum sectors in long/fragile RT zones
- Equipment which need and ex-situ conditioning
- At the experimental areas

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Evaluation of damages
Impact on the adjacent LSS RT sectors (IR3R and IR4L)

6.10^{-11} \text{ mbar} \text{ reached after 3 days of pumping confirming the venting with dry helium ONLY}

Beam pipes vented and inspected: no soot or MLI were found!

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Evaluation of damages
Impact on the 3-4 Sector

Q8R3 V1: rupture disk deformed but not perforated

Q8R3 V2: rupture disk blown

Q8L4 V1/V2: rupture disk deformed but not perforated

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### Evaluation of damages

**7L3/20R3**

**21R3/33R3**

**34R3/22L4**

**21L4/7L4**

- **Metal debris** removal made in-situ

- **Soot on magnets** identified for removal from the tunnel

- Additional PIMs need to be opened

- **Magnets removed from the tunnel**

- **Soot contamination recovery** is independent from MLI contamination

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Evaluation of damages  
Results from the endoscopic inspections

- All beam lines in the tunnel have been inspected
- All visual and endoscopic inspections of the beam tubes and interconnects are documented

<table>
<thead>
<tr>
<th></th>
<th>V1</th>
<th>V2</th>
<th>V1</th>
<th>V2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ok</td>
<td>54</td>
<td>39</td>
<td>26 %</td>
<td>18</td>
<td>22 %</td>
</tr>
<tr>
<td>MLI</td>
<td>124</td>
<td>129</td>
<td>58 %</td>
<td>61</td>
<td>59 %</td>
</tr>
<tr>
<td>Soot</td>
<td>35</td>
<td>45</td>
<td>16 %</td>
<td>21</td>
<td>19 %</td>
</tr>
<tr>
<td>To be done</td>
<td>0</td>
<td>0</td>
<td>0 %</td>
<td>0</td>
<td>0 %</td>
</tr>
<tr>
<td>Total</td>
<td>213</td>
<td>213</td>
<td>100 %</td>
<td>100</td>
<td>100 %</td>
</tr>
</tbody>
</table>
• 53 cold masses are back to the surface from Q20R3 to Q33R3 (14 MQ, 39 MB)

• V2 line : 6 cold masses with soot (B19R3 -> C20R3)

…to be cleaned in the tunnel.

<table>
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<tr>
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<th>V1</th>
<th>V2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ok</td>
<td>49</td>
<td>30</td>
<td>31 %</td>
<td>19 %</td>
<td>25 %</td>
</tr>
<tr>
<td>MLI</td>
<td>111</td>
<td>124</td>
<td>69 %</td>
<td>78 %</td>
<td>73 %</td>
</tr>
<tr>
<td>Soot</td>
<td>0</td>
<td>6</td>
<td>0 %</td>
<td>4 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Total</td>
<td>160</td>
<td>160</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
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</table>
**Evaluation of damages**

**Available documentation (1)**

**Report from the inter-connexion inspections**

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Evaluation of damages
Available documentation (2)

Report from the endoscopic inspections
Evaluation of damages
Available documentation (3)

Others...

- Pictures
- Videos

...of all magnets... both beams.
Sorting the magnets

Tunnel

- Magnets stays in the tunnel
- MLI and debris
- MLI, debris and soot
- Aspirat. aspirat.+ local blowing + mec. cleaning
- Endoscopic inspection

Surface

- Magnets removed from the tunnel
- Endoscopic inspection
- Magnet is reused
- BS stays in place
- Aspirat. aspirat.+ local blowing + mec. cleaning
- Endoscopic inspection

- BS is removed
- Installation of a new BS
- Endoscopic inspection

- Magnet not reused
- Will be treated after the 3-4 repair
- In-situ wet cleaning tests will be carried on
- Temporary storage
- Evaluation
- Endoscopic inspection

Machining

PIMs cut

Traceability

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Cleaning Strategy
Soot on magnets not removed from the tunnel (1)

- Two plugs: one for horizontal and one for vertical parts of the beam screen
- Use of a foam-plug wet with alcohol
- Use of a dry foam-plug
- Up to 50 passages in each direction with wet foam-plug
- Up to 15 passages with dry plug
Cleaning Strategy

Soot on magnets not removed from the tunnel (2)

C19R3.V2 before cleaning

After cleaning

entrance  centre  end
Cleaning Strategy
Soot on magnets not removed from the tunnel (3)

Q19R3.V2 before cleaning

After cleaning

entrance  centre  end

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Cleaning Strategy
Soot on magnets not removed from the tunnel (4)

C20R3.V2 before cleaning

After cleaning

entrance | centre | end

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• Four vacuum systems have been mechanically cleaned to validate the cleaning process at the surface

• Cleaning completed on the 6 magnets
  – B19R3, C19R3, Q19R3, A20R3, B20R3 and C20R3 have been swept
  – Interconnections already re-closed
  – Two vacuum systems are oxidized (C19R3 & Q19R3). The oxide layer cannot be removed by the mechanical process. However, it is expected to have negligible impact on the vacuum performance since the outgassing rate scales like $\sim \exp(1/T)$
Cleaning Strategy
MLI removal in the tunnel: Procedure

- **1st step: pumping/venting process**
  - 45 minutes, tempo of 20 seconds, pumping of the beam pipe only
  - 15 minutes, tempo of 20 seconds, pumping of both the beam pipe and the pumping hose

- **2nd step: local blowing with a nozzle + aspiration**
  - 10 passages with the nozzle, 6 seconds temporization, 10 bar nitrogen pressure
  - First 3 passages with 10 min / PIM, then 5 min / PIM
  - Speed in the beam screen 3-4 cm/min
    - Stop if an event is found to allow for local aspiration
  - Opening of the nozzle to:
    - 60 microns for passage 1-2, 5-6 and 9-10
    - Closed to the minimum for passages 3-4 and 7-8
  - Pumping of:
    - The beam line only for passages 1 to 4 and 9-10
    - Both beam line and pumping hose for passages 5 to 8
  - Debris are collected in a plastic bag after each passage
  - Closure of the beam lines and pumping hose with a cap at cleaning completion and identification with a sticker
Cleaning Strategy
MLI removal in the tunnel: 1st step (1)

• Based on automatic pumping/venting of a half-cell (~50 m)

• A cycle: 20 s pumping, 18 s plateau, 2 second vent

• The pressure in the beam tube is reduced from 1 atm to 0.8 atm in 2 s
  • To be compared to the arc pump down of 200 mbar/h

• Air speed of 20 m/s
Cleaning Strategy
MLI removal in the tunnel: 1st step (2)

This procedure give good results i.e no more MLI are observable by endoscopy inside the beam screen, Case of the area between Q8L4 till Q13L4 line V1 (~ 250 m)

3.2 g i.e 0.4 m²
1.2 g i.e 0.1 m²
~ 100 bits
Cleaning Strategy
MLI removal in the tunnel: 2nd step (1)

- Based on aspiration with local perturbation controlled by endoscope
- A nozzle blows filtered air, the MLI residues left behind the beam screen and the RF fingers are directed towards the beam aperture where they are aspired away.

N₂

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Cleaning Strategy
MLI removal in the tunnel: 2\textsuperscript{nd} step (2)

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

First MLI cleaning with gas nozzle in sector 3-4
P1a: only beam screen V2-B8L4
P1b: only PIM V2-B8L4
P1c: only beam screen V2-A8L4
P1d: only beam screen V2-B8L4
P1e: only beam screen V2-B8L4
P2-P10: full passages

5 passages: 97 \% 
9 passages: 99.8 \%

Measurements made in the tunnel 3-4 sector

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Cleaning Strategy
MLI removal in the tunnel: 2\textsuperscript{nd} step (3)

2 passages
\(~ 250 \text{ bits}~

5 passages
\(20 \text{ bits}\)

9 passages
\(4 \text{ bits}~

\(2 \text{ per dipole}!\)
• **Started with two fronts**
  – Soot removal is completed
  – Removal of MLI on going

• **Two teams**
  – A third team by next week
  
  • Complete the cleaning by mid-April

• **Cleaning activities started beginning of January**
  – Procedure for MLI removal has taken two months to be qualified

• **All QQBI (~50 m) interconnects have been open to allow MLI removal and perform PIM’s consolidation in the meantime**
Follow-up of Chamonix’09 recommendations
Collateral damages to beam vacuum: Origin of the incident

- **Electrical arc**
  - In bus bars
    - The beam vacuum can be affected if:
      - The arc destroys the beam vacuum interconnection
      - The over pressure in the insulation vacuum buckles the bellows and induces a mechanical failure
      - A physical displacement of the magnet or cold mass damages the bellows
  - In the magnet coil
    - The arcing burns a hole on the magnet cold bore

- **Beam lost**
  - The lost beam makes a hole in the cold bore (it has to burn a hole on the beam screen first but rather easy taking into account the SPS experience)
Follow-up of Chamonix’09 recommendations
Collateral damages to beam vacuum: Expected consequences

• Beam vacuum contamination
  – By soot
    • Only light contamination can be cleaned in situ
    • Interconnection upstream and downstream of the contaminated magnets need to be cut
  – By dusts (MLI, PI, metallic pieces…)
    • Cleaning is feasible but need a warming up and time…
    • On RT temperature system, bake out is required to recover the vacuum performances if a venting is made to clean the beam pipes
  – By helium
    • Dry helium does not contaminate the beam vacuum
    • In 3-4, it was observed that the NEG was not saturated
    • Reactivation is needed in case of venting to air
Follow-up of Chamonix’09 recommendations
Collateral damages to beam vacuum: Expected consequences

- **Sudden lost of vacuum integrity**
  - Over pressure in the beam line resulting on the buckling of the bellows
    - PIM ⇒ can be exchanged in situ, need warming up of the entire arc
    - Nested bellows ⇒ magnet shall be removed from the tunnel to exchange the beam screen

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Follow-up of Chamonix’09 recommendations
Collateral damages to beam vacuum: Expected consequences

- Sudden lost of vacuum integrity
  - Induced lateral forces which were not taken into consideration during the design of the supports
  - Supports can fail leading to mechanical damages and “domino” effect
    - More collateral damages, even far away (hundreds meters) from the incident area
  - Buckling of the beam pipes

In all cases, expected downtime shall be counted in months.
Follow-up of Chamonix’09 recommendations
Collateral damages to beam vacuum: Expected consequences

- Sudden lost of vacuum integrity

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

![Graph showing pressure vs. position for different states of bellows buckling.](QBQ1.24R3)

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Follow-up of Chamonix’09 recommendations
Collateral damages to beam vacuum: Expected consequences

• Sudden lost of vacuum integrity

![Graph showing pressure loss over distance](image)

- 1 rupture disk at each extremity
- 1 SSS sur 3
- Aperture of the rupture disk does not change significantly the results
• **Systematic inspections revealed debris of soot and MLI all along the arc**
  - Soot was removed by a mechanical action with a foam-plug in the tunnel (6 magnets)
  - No traces of debris have been found outside the arc
  - Room temperature vacuum sectors are under vacuum with NEG activated

• **MLI is being removed by a combination of pumping/venting mechanism and a local blow-up using a nozzle together with a pumping mechanism**
  - Still a lot of work to do in the tunnel
  - The objective of the coming weeks is to release sectors for PIMs interconnection

• **Traceability**
  - All cleaning activities are documented

• **Recovery of the store magnets has not started yet**
  - Experience with quadrupole magnets give us confidence on these estimations
• The sudden loss of the beam vacuum integrity can lead to two types of consequences:
  – Contamination of the beam pipes
  – Mechanical damage of vacuum components

• The existing design and layout can not limit this impact
  – Consolidation is being studied and solutions will be submitted to the management approval next Wednesday 12th March
  – The case of the LSS and experimental areas will also be adressed

• Some hypothesis regarding the resistance of all vacuum components to buckling above 0.5 bar relative are being investigated
Many peoples have been involved in the endoscopies, the cleaning, the tooling preparation, etc. It will be a challenge to set a list, I would like to thank all of them...