HL LHC: impedance considerations for the new triplet layout in IR1 & 5

N. Mounet, A. Mostacci, B. Salvant, C. Zannini and E. Métral

Possible layout changes around the triplets

Changes in each impedance contribution & possible options:
- resistive-wall,
- weld,
- tapers,
- pumping holes,
- BPMs,
- beta functions.

Summing all the contributions:
→ final comparison between LHC & HL-LHC triplets

Conclusions
Current layout in the triplets (IR1 & 5)
Current layout in the triplets (IR1 & 5)

IR5 right (from LHC drawing LHCLSXG_0003 + N. Kos for beam screens info)
Current layout in the triplets (IR1 & 5)

IR5 right (from LHC drawing LHCLSXG_0003 + N. Kos for beam screens info)

BS 53V 7.9 m  BS 63V 23.7 m  BS 74 2.7 m

Q1 Q2 Q3 D1
MQXA MQXB MQXADF3X MBXW

Beam screen

Model (elliptic cylinder, 50µm Cu + inf. stainless steel)

<table>
<thead>
<tr>
<th>BS type</th>
<th>53V</th>
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Current layout in the triplets (IR1 & 5)

IR5 right (from LHC drawing LHCLSEXG_0003 + N. Kos for beam screens info)

Model: 1.5 µm NEG ($\rho = 10^{-6} \Omega \cdot m$) + 2 mm Cu ($\rho = 1.7 \times 10^{-8} \Omega \cdot m$) + vacuum

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</table>
Possible HL LHC triplet layout (IR1 & 5)

New beam screen (BS), radius $r = 59$mm

New BS, $9.5$m, $r = 49$mm

Taper

Assume same total length as currently, i.e. $L = 61.7$m.

Model: circular cylinder, 2mm-thick s. steel
- with or w/o $0.5\mu$m amorphous carbon "aC" ($\rho = 10^{-2}\ \Omega.m$ – from M. Taborelli, pessimistic),
- with or w/o $50\mu$m Cu.

2 options
Resistive-wall transverse impedance of beam screens and warm pipe in the triplets

- Comparison between current and new (=HL-LHC) resistive-wall (RW) impedance of each kind of device around the triplets:
Resistive-wall transverse impedance of beam screens and warm pipe in the triplets

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Comparison between current and new (=HL-LHC) resistive-wall (RW) impedance of each kind of device around the triplets:

- Resistive-wall transverse impedance of beam screens and warm pipe in the triplets.

### Graph

- Most critical new BS ($r = 49$ mm, aC coating)
- Current warm pipe around D1
- Current BS type 74
Comparison between current and new (=HL-LHC) resistive-wall (RW) impedance of each kind of device around the triplets:

- Most critical new BS \((r = 49\, \text{mm}, \text{aC coating})\)
- Current warm pipe around D1
- Current BS type 74
- New BS \((r = 49\, \text{mm}, 0.5\, \mu\text{m} \text{aC} + 50\, \mu\text{m} \text{Cu})\)
Comparison between current and new (=HL-LHC) resistive-wall (RW) impedance of each kind of device around the triplets:

- Most critical new BS ($r = 49$ mm, aC coating)
- Most favourable new BS ($r = 59$ mm, 50 µm Cu)
- Current warm pipe around D1
- Current BS type 74

Impact of aC coating (mostly on imag. part)
Resistive-wall transverse impedance of beam screens and warm pipe in the triplets

- Comparison between current and new (=HL-LHC) resistive-wall (RW) impedance of each kind of device around the triplets:

```plaintext
Resistive-wall transverse impedance of beam screens and warm pipe in the triplets

<table>
<thead>
<tr>
<th>Device</th>
<th>Impedance (per unit length)</th>
<th>Impact of aC coating (mostly on imag. part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New BS (r = 49 mm, 0.5 µm aC + 50 µm Cu)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most critical new BS (r = 49 mm, aC coating)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current warm pipe around D1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current BS type 74</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

⇒ RW impedance of each device (per unit length) heavily depends on coating and can be much better or much worse than now.
```
Currently: weld on the flat parts of the beam screen

HL-LHC: 3 different positions tested from center to corner, with either 1mm or 2mm height:

- Pos. 1
- Pos. 2
- Pos. 3

Resistive-wall impedance of beam screens: impact of the weld

Weld (2 mm height)

Courtesy of N. Kos

C. Zannini
Current beam screens: weld modeled by a frequency dependent factor which can be more than 2 (dipolar horizontal): from 3D CST simulations

Obtained with 50µm Cu + stainless steel, 2mm-high weld

Very weakly dependent on beam screen size (BS 53, 63 or 74)

C. Zannini – PhD thesis
HL-LHC beam screens: high frequency constant values of the factors obtained from CST simulations:

- Resistive-wall impedance of beam screens:
  - Impact of the weld
    - Much smaller impact of the weld: down to < 6% increase for a 1mm weld on the corner.
    - Probably due to:
      - shape (more symmetric),
      - larger radius.

Obtained with 50µm Cu + stainless steel

Very weakly dependent on beam screen radius (49 or 59mm)

From C. Zannini
Resistive-wall power loss in the triplets

- Comparison between current and HL-LHC resistive-wall power loss (gaussian bunches) of each kind of device in the triplets, including BS weld factor:

**Current (2012):** 6.5 TeV, \(N_b = 1.5 \times 10^{11}\), \(M=2*1404\) bunches, \(\sigma_z = 9.4\)cm

<table>
<thead>
<tr>
<th>Device type</th>
<th>BS 53</th>
<th>BS 63</th>
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<tr>
<td>(b [\text{mm}])</td>
<td>20.2</td>
<td>25.2</td>
<td>30.5</td>
<td>40</td>
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<tr>
<td>(P_{\text{loss}}/L [\text{W/m}])</td>
<td>0.13</td>
<td>0.11</td>
<td>0.09</td>
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**HL-LHC:** 7 TeV, \(N_b = 3.5 \times 10^{11}\), \(M=2*1404\) bunches, \(\sigma_z = 7.5\)cm, 2mm weld in a corner

<table>
<thead>
<tr>
<th>BS type</th>
<th>small, aC coating, no Cu</th>
<th>small, aC + Cu coating</th>
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<tr>
<td>(b [\text{mm}])</td>
<td>49</td>
<td>49</td>
<td>59</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>(P_{\text{loss}}/L [\text{W/m}])</td>
<td>9.7</td>
<td>0.38</td>
<td>8.1</td>
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<tr>
<th>BS type</th>
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</tr>
</tbody>
</table>

⇒ Power loss of each device (per unit length) heavily depends on Cu coating (but not much on size & not at all on aC coating) and is worse than now (intensity much higher).
Geometric impedance of the tapers

- **Broad-band (BB) impedance of taper** evaluated with Yokoya’s formula [CERN SL/90-88] for cylindrical geometry, valid under the conditions $b\theta/\sigma_z << 1$ and either $a/\sigma_z >> 1$ or $(b-a)/a << 1$:

$$Z^T = \frac{jZ_0 \theta}{\pi} \left(\frac{1}{a} - \frac{1}{b}\right), \quad Z^L = \frac{j\mu_0 \theta f_0}{2} (b - a)$$

with $a$ the smallest radius, $b$ the largest radius, $\theta$ the taper slope, $\sigma_z$ the RMS bunch length and $f_0$ (~11.2 kHz) the revolution frequency.

- **Currently** (parameters from N. Kos + LHC drawings) (4 tapers of each kind of the whole):

<table>
<thead>
<tr>
<th>Taper parameters</th>
<th>BS53 → BS63</th>
<th>BS63 → BS74</th>
<th>BS74 → warm pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$ [mm]</td>
<td>20.2</td>
<td>25.2</td>
<td>30.5</td>
</tr>
<tr>
<td>$b$ [mm]</td>
<td>25.2</td>
<td>30.5</td>
<td>40</td>
</tr>
<tr>
<td>angle</td>
<td>9.5°</td>
<td>3.9°</td>
<td>15.2°</td>
</tr>
<tr>
<td>$\text{Im}(Z^T)$ [Ω/m]</td>
<td>98</td>
<td>28.5</td>
<td>127</td>
</tr>
<tr>
<td>$\text{Im}(Z^L/n)$ [µΩ]</td>
<td>5.9</td>
<td>2.6</td>
<td>18</td>
</tr>
</tbody>
</table>

- **New BS**: possible taper between Q1 and Q2 (4 tapers on the whole):

<table>
<thead>
<tr>
<th>Taper parameters</th>
<th>BSQ1 → BSQ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$ [mm]</td>
<td>49</td>
</tr>
<tr>
<td>$b$ [mm]</td>
<td>59</td>
</tr>
<tr>
<td>$\tan(\text{angle})$</td>
<td>$\theta$</td>
</tr>
<tr>
<td>$\text{Im}(Z^T)$ [Ω/m]</td>
<td>56 \cdot (θ / 0.27)</td>
</tr>
<tr>
<td>$\text{Im}(Z^L/n)$ [µΩ]</td>
<td>19 \cdot (θ / 0.27)</td>
</tr>
</tbody>
</table>

⇒ new taper better in transverse than most of the old, with typical 15° angle (because it is further away).

But higher beta functions (see later)...

HL LHC: impedance considerations in IR1 & 5 - N. Mounet et al - 01/07/2013
**Geometric impedance of pumping holes in the beam screens**

- **Broad-band** impedance contribution evaluated with Kurennoy's formulas (small holes vs. wavelength, circular pipe) [Part. Acc., vol. 50, pp. 167-175, 1995]:

\[
Z^T = j \frac{2 Z_0 \eta L (\alpha_m + \alpha_e)}{\pi b^3 A}
\]

\[
Z^L = \frac{j Z_0 \eta L (\alpha_m + \alpha_e)}{2 \pi R b A}
\]

\(\eta\) → fraction of surface covered by holes. Now: \(\eta = 2.6\%\) max in straight sections [E. Métral et al, “Answers to N. Kos”, 20/01/2010], \(R\) → machine total radius (4242.9m here)

\(L\) → total length covered by holes, \(b\) → pipe radius (or smallest dimension), \(Z_0\) → 120\(\pi\) \(\Omega\),

\(A\) → area of each hole. For rounded rectangular holes (length \(L_h\), width \(W_h\)):

\[
\alpha_e = -\frac{\pi}{16} L_h W_h^2 \left(1 - 0.765 \frac{W_h}{L_h} + 0.1894 \frac{W_h^2}{L_h^2}\right),
\]

\[
\alpha_m = \frac{\pi}{16} L_h W_h^2 \left(1 - 0.0857 \frac{W_h}{L_h} - 0.0654 \frac{W_h^2}{L_h^2}\right),
\]

⇒ With \(W_h = 1\)mm, \(L_h = 8\)mm and \(\eta = 2.6\%\) (as now – pessimistic for HL-LHC), we get:

<table>
<thead>
<tr>
<th>BS type</th>
<th>Current 53</th>
<th>Current 63</th>
<th>Current 74</th>
<th>New (6mm tung.)</th>
<th>New (16mm tung.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b) [mm]</td>
<td>20.2</td>
<td>25.2</td>
<td>30.5</td>
<td>49</td>
<td>59</td>
</tr>
<tr>
<td>(\text{Im}(Z^T/L)) [(\Omega/m^2)]</td>
<td>12.4</td>
<td>6.4</td>
<td>3.6</td>
<td>0.87</td>
<td>0.5</td>
</tr>
<tr>
<td>(\text{Im}(Z^L/(n*L))) [(\mu\Omega/m)]</td>
<td>0.7</td>
<td>0.24</td>
<td>0.2</td>
<td>0.12</td>
<td>0.1</td>
</tr>
</tbody>
</table>

⇒ Much better for new BS (due to larger radius).

But higher beta functions...
Thanks to A. Mostacci mathematica notebook, PhD thesis and help:

- power loss due the TEM (coaxial) wave propagating between beam screen & cold bore,
- pessimistic approach adopted: assume holes are uniformly distributed (actually they are random in size and position), and all area outside BS is filled with TEM wave,

⇒ result: power loss (per unit length) is negligible compared to the resistive-wall power loss: less than 0.1 mW/m both for LHC and HL-LHC, taking a small beam screen thickness for HL-LHC (0.5mm)

⇒ even much smaller in new BS with larger stainless steel thickness (2 mm).
From R. Jones, HL-LHC PLC meeting (18/01/2013):

Could think of Duplicating in these regions for more redundancy

→ what is the impedance of all these BPMs?
BPMs: geometric impedance

- All stripline BPMs ($l=0.12m$ for the strip length), except one combined BPM (buttons / stripline) in front of Q1.
- Diameter $D$ between electrodes:
  - $D=60\text{mm}$ for the current ones (except the one at 70m from the IP → 80mm),
  - $D=140\text{mm}$ for the HL-LHC ones (scaling by the same factor the transverse dimension of the strip-lines).
- Two approaches:
  - analytic formula for stripline BPM by K. Y. Ng [Handbook of Acc. Phys. & Eng., Sec. 3.2] + values obtained for button BPM by B. Spataro [LHC Project Note 284],
  - CST simulations made by B. Salvant

→ agreement within a factor ~2.
BPMs: geometric transverse impedance

- Evaluated as a **broad-band model** → pessimistic: stripline BPM impedance actually decreases above a few hundreds of MHz:

![Impedance Graph]

\[ Z_y^{\text{dip}} \, [\Omega] \]
(with beam offset of 10mm)

Note: with **tungsten shielding inserts**, geometric impedance seems to **decrease** (to be confirmed).

→ **Final broad-band impedances** (including buttons before Q1): better with HL-LHC (due to higher radius)

<table>
<thead>
<tr>
<th>BPM type</th>
<th>Current combined (before Q1)</th>
<th>Current (after Q1)</th>
<th>Current (after Q3)</th>
<th>New combined (before Q1)</th>
<th>New (after Q1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D [mm]</td>
<td>60</td>
<td>60</td>
<td>80</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>(\text{Im}(Z^T)) [\Omega/m]</td>
<td>880</td>
<td>800</td>
<td>300</td>
<td>130</td>
<td>100</td>
</tr>
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Beta functions in IR1 & 5: current vs HL LHC

- IR5: $\beta^*=55\text{cm}$ in current layout / $\beta^*=10\text{cm}$ in HL-LHC (most critical option up to now)

$\Rightarrow$ in this region $\beta$ can be up to a factor 11 higher with HL-LHC optics.

Note: similar in the other plane and in IR1.
- **Longitudinal impedance**: total triplet relatively small (<1%) compared to full model → we do not look at it here.
- Dipolar horizontal and vertical quite close → here restrict to vertical dipolar.
- Preliminary: current LHC triplets impedance contributions:

\[
\Rightarrow \text{resistive-wall dominant up to a few } 100 \text{ MHz (less for imag. part), then BPMs & pumping holes become dominant.}
\]
Most favourable HL-LHC scenario (no reduced beam pipe in Q1, Cu coating, no amorphous carbon) vs current LHC: triplets impedance

⇒ HL-LHC triplets impedance significantly higher than current one, especially above 100 MHz.
Most favourable HL-LHC scenario (no reduced beam pipe in Q1, Cu coating, no amorphous carbon) vs current LHC: ratio vs. total 2012 impedance:

⇒ For HL-LHC, the percentage of the triplets impedance vs. the total 2012 impedance is up to ~10% at 1GHz, which is very high.
Most favourable HL-LHC scenario (no reduced beam pipe in Q1, Cu coating, no amorphous carbon): impedance contributions

⇒ HL-LHC triplets impedance dominated by:
  - Resistive-wall at low frequency → not really a concern (smaller than now),
  - BPMs & pumping holes at high frequency
    → decrease nb of BPMs ?
    → decrease pumping surface ? (here pessimistic assumption: 2.6%)
Impact of smaller radius in Q1, amorphous carbon coating and copper coating

- Ratio between HL-LHC triplet impedance (Zydip) and current LHC triplet impedance in 4 different configurations:

  1. Most favourable case (see previous slides)
  2. Add reduced BS in Q1 → no change
  3. Add amorphous carbon → no big change
  4. Take out copper → large increase

⇒ Only copper coating matters (a lot).
Conclusions on impedance of individual elements

- **Still very preliminary study!**

- On the HL-LHC resistive-wall impedance in the triplets:
  - copper coating crucial to reduce impedance and power loss,
  - amorphous carbon coating can increase significantly imaginary part of impedance,
  - weld (if 1mm and put in a corner) has almost no impact → better than now.

- Power loss:
  - Resistive-wall: HL-LHC much higher than now (due to beam parameters), copper coating crucial parameter (otherwise factor 30 on power loss),
  - Pumping holes: negligible in both cases, even smaller in HL-LHC with 2mm-thick BS,
  - BPMs and tapers: not evaluated yet (resistive-wall).

- Geometric impedances from tapers and BPMs better in HL-LHC layout for individual elements.

- But **beta functions** up to 11 times higher largely compensate...
Conclusions on total impedance

- Even in the best case scenario (up to now), the triplets impedance is increased by a factor 2 – 3, and can become as high as **10% of the total impedance budget** of 2012.

- What matters a lot for the total impedance:
  - Number (and beta functions) of the BPMs,
  - Copper coating,
  - Surface covered by holes.

- What matters less:
  - amorphous carbon coating,
  - reduced beam screen in Q1 and taper between Q1 and Q2.