RF CONSIDERATIONS FOR THE LHC TOTEM RPs

- Reminder on impedances
- LHC impedances and guidelines
- Impedances of the TOTEM RPs
- Conclusion
Wake fields = Electromagnetic fields generated by the beam interacting with its surroundings (vacuum pipe, etc.)

- Energy loss
- Beam instabilities
- Excessive heating
Impedance = Fourier transform of the wake field

Origin of the impedance in the previous case is coming from a (abrupt) change of geometry (cavity, trapping some EM fields) => Usually computed using EM simulation codes

Can come also from a smooth pipe due its finite conductivity (considering also permittivity and permeability) => Available theories

=> Usually the geometric and resistive parts are treated separately but both contributions should be added

An impedance is a complex function of frequency => Interesting frequency range for the LHC: few kHz to few GHz
(At least) 5 impedances are needed to describe the beam dynamics

- Longitudinal
- Horizontal => Dipolar and quadrupolar
- Vertical => Dipolar and quadrupolar

Dipolar => Linear part vs. transverse displacement of $q_1$ (source particle)

Quadrupolar => Linear part vs. transverse displacement of $q_2$ (test particle)
Consider now the case of a longitudinal narrow resonance (trapped mode due to geometry) => 3 parameters:

- Resonance frequency => Assumed to be here \( f_r = 1 \text{ GHz} \)
- Shunt impedance => Assumed to be here \( R_i = 10 \Omega \)
- Quality factor \( Q \) => Scanned below

\[
\text{HWHH = Half Width at Half Height} = \frac{f_r}{2Q}
\]
REMINDER ON IMPEDANCES (5/7)

\[ W_t \text{ [V/nC]} \]

- For different values of \( Q \):
  - \( Q = 10000 \)
  - \( Q = 1000 \)
  - \( Q = 100 \)
  - \( Q = 20 \)

- Waveforms for 1st and 2nd bunches.
Power loss formula for the case of a (sharp) resonance (i.e. with only 1 line), i.e. for

\[ P_{\text{loss}} = I_{\text{total}}^2 \times 2 R_l \times 10^{P_{\text{dB}}(f_r)/10} \]

\[ Q >> \frac{f_r}{2f_b} \]

Bunch frequency

Total beam current (1 beam)
REMEMBER ON IMPEDANCES (7/7)

- Consider the hypothetical case of a sharp resonance of 5 kΩ at 1.4 GHz => Effect of a bunch length change from 9 cm to 4.5 cm

Theoretical beam power spectrum

\[ P_{db}(f) = 10^{\frac{10}{10}} = 10^{-4} \]

\[ \frac{P_{loss}[\sigma_b = 4.5 \text{ cm}]}{P_{loss}[\sigma_b = 9.0 \text{ cm}]} \]

Assuming the same shape of the profile

5 kΩ gave 1 W at 1.4 GHz for 9 cm => Becomes ~ 2 kW for 4.5 cm

1 A assumed here
LHC IMPEDANCES AND GUIDELINES (1/7)

- **2 major concerns in 2011-2012**
  - Beam-induced RF heating!

  => This is why the rms bunch length was ~ 9 cm in 2011 and ~ 10 cm in 2012

---

**Diagram:**
- **Axes:**
  - Y-axis: Lumi reduction from crossing angle
  - X-axis: $\sigma_s$ [cm]
- **Graph:**
  - Red curve indicating the relationship between Lumi reduction and $\sigma_s$.
  - Marked point: LHC nominal: 7.5 cm

---

Elias Métral, TOTEM collaboration week, CERN, 11/06/2013
LHC IMPEDANCES AND GUIDELINES (2/7)

- Many instabilities and 1 instability remained at the end of 2012 (at the end of the $\beta^*$ squeeze) without a clear understanding => It is therefore a worry for the future...

Fill 3238 (Monday 29/10 evening)
However, overall the machine worked very well

- Peak luminosity record: 77% of design luminosity with
  - 57% of design energy
  - ½ number of bunches

- Bunch brightness: \( \sim (1.6/1.15) \times (3.75/2.2) \sim 2.4 \text{ times larger than nominal} \)
  - \( \sim 1.6 \times 10^{11} \text{ p/b} \Rightarrow 39\% \text{ more particles than nominal} \)
  - \( \sim 2.2 \mu\text{m} \Rightarrow 70\% \text{ smaller transverse emittance (and there was blow-up in the LHC…)} \)

=> Thanks to the people who designed the LHC and the past impedance police!
LHC IMPEDANCES AND GUIDELINES (4/7)

◆ Past recommendations => General guidelines
  ▪ Tapering angle => Famous 15 deg (this is a general recommendation / trade-off but ideally should be re-evaluated carefully for each design)
  ▪ Copper coatings
    • Beam-induced RF heating => Usually only few µm enough (high-frequency mechanism)
    • Transverse coupled-bunch instability => Could be larger (can also be a low-frequency mechanism)
  ▪ Ferrite to damp some trapped modes (reducing the Q factor while keeping $R_l/Q$ almost constant)
  ▪ Shielding of bellows, Etc.

◆ Recommendations for the future
  ▪ Similar + we try and do all the simulations + we should try and decrease the impedances of new / replaced equipments…
LHC IMPEDANCES AND GUIDELINES (5/7)

- Guidelines mentioned by Benoit Salvant in some of his talks

General view on what can be accepted from the impedance team point of view for a change to the LHC impedance (for the low frequency part which impacts beam stability)

These are orders of magnitude, and are drafts still subject to discussions

<table>
<thead>
<tr>
<th>Ratio device change/total LHC impedance</th>
<th>Impedance team opinion</th>
<th>Management decision required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 0</td>
<td>Very happy!</td>
<td>no</td>
</tr>
<tr>
<td>Less than 0.1%</td>
<td>Should be OK if valid arguments</td>
<td>no</td>
</tr>
<tr>
<td>Between 0.1% and 1%</td>
<td>Can be discussed if strong arguments</td>
<td>no</td>
</tr>
<tr>
<td>Between 1% and 10%</td>
<td>Does not agree</td>
<td>yes</td>
</tr>
<tr>
<td>Above 10%</td>
<td>Strongly objects</td>
<td>yes</td>
</tr>
</tbody>
</table>
LHC IMPEDANCES AND GUIDELINES (6/7)

- Need for efficient cooling of near-beam equipment to avoid what happened to TDI, BSRT and ALFA

- Maximize evacuation of heat (optimize emissivity, thermal conduction)

- Need to ensure good RF contact to avoid what happened to VMTSA

- Use high Curie temperature ferrites whenever possible (e.g. Transtech TT2-111R => To be treated at high temperature to be compatible with UHV)

- Need for more monitoring of temperature inside critical equipment (e.g.: TDI, BSRT, etc.)
Comparison between predictions and measurements

- Longitudinal imaginary effective impedance:
  - PREDICTION
    - Injection and 7 TeV: ~ 90 mΩ
  - MEASUREMENT
    - From loss of LD: ~ 90 mΩ

- Transverse imaginary effective impedance (dip + quad):
  - PREDICTION
    - 7 TeV: ~ 25-30 MΩ/m
  - MEASUREMENT
    - ?

Meas. at 3.5 and 4 TeV revealed a factor ~ 2 higher than predicted
IMPEDEANCES OF THE TOTEM RPs (1/3)

- New RP with timing detector, too big for current RP
  - Rotate current RP
  - Make a new cylindrical RP

- # of RPs in 2012
  - 2 stations at 147 m and 2 stations at 220 m
  - 2 V + 1 H / station

- # of RPs > LS1
  - 4 stations at 220 m: 8 V + 4 H
  - + 1 or 2 new H ones (cylindrical)

- # of RPs for high-intensity runs: 3 or 4 max
# IMPEDANCES OF THE TOTEM RPs (2/3)

<table>
<thead>
<tr>
<th></th>
<th>$Z^e_{\parallel}/n$ (mΩ)</th>
<th>% to total LHC current impedance (90 mΩ)</th>
<th>$\tilde{Z}^e_{\perp}$ (KΩ/m)</th>
<th>% to total LHC current impedance (25 MΩ/m)</th>
<th>Heating (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present RP ¹)</td>
<td>1.7</td>
<td>1.9%</td>
<td>80</td>
<td>&lt; 0.3%</td>
<td>62</td>
</tr>
<tr>
<td>Rotated RP ²)</td>
<td>2.6</td>
<td>2.9%</td>
<td>20</td>
<td>&lt; 0.1%</td>
<td>241</td>
</tr>
<tr>
<td>Cylindrical RP ³)</td>
<td>1.1</td>
<td>1.1%</td>
<td>50</td>
<td>&lt; 0.2%</td>
<td>13</td>
</tr>
<tr>
<td>Cu shielded RP ⁴)</td>
<td>1.2</td>
<td>1.3%</td>
<td>70</td>
<td>&lt; 0.3%</td>
<td>10</td>
</tr>
</tbody>
</table>

- Present RP ¹) and 2) $\Pi / 2 \text{ rot.}$
- Cylindrical RP ³) ~ 35% better
- Cu shielded RP ⁴) ~ 30% better
- Rotated RP ²) ~ 5x better
- Rotated RP ²) ~ 6x better
**IMPEDANCES OF THE TOTEM RPs (3/3)**

- Studies of Cu coating thickness for the Resistive-Wall part
  - 3 layers (NEG 1.5 µm + Copper + infinite stainless steel)
  - Only 1 RP on one side (horizontal) at 1 mm distance to the beam
  - Computations for nominal Gaussian beam (25 ns and 1.15E11 p/b)

\[ \Rightarrow > \sim 5 \, \text{µm is OK (10 \, \text{µm recommended if possible)} \]

---

**Power loss as a function of Copper coating thickness (TOTEM single pot d=1mm)**

- **5 µm**

**RW transverse impedance of the TOTEM pot vs. LHC budget**

- **5 µm**

---

**Benoît Salvant**
CONCLUSION

◆ 3 or max 4 H RPs for high-intensity runs => Should be OK but depends also on all the other impedance contributors => Imagine 10 impedance contributors each increasing by 5%... The other equipments linked to the RPs need to be also considered (collimators, etc.)

◆ Detailed heat transfer studies to be done with the ferrite

◆ Recommended Cu coating for the Resistive-Wall impedance: > ~ 5 µm is OK (10 µm if possible)

◆ EM simulations based on several assumptions => Measurements on a prototype should be performed as a final check / validation!

ACKNOWLEDGEMENTS

◆ Many thanks to Nicola Minafra for all his nice studies over the past few months with Benoit Salvant and the impedance team

◆ A lot of collaboration with ALFA which was very positive and useful