Review of Expected Crab Cavity Heat Loads Due to Impedance

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13.06.17
Some HOMs close to a multiple of the bunch spacing frequency might cause massive heat load

Example: DQW design (update of 10.2016)

<table>
<thead>
<tr>
<th>Shunt impedance (Ω)</th>
<th>Quality factor</th>
<th>HOM Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.34E+07</td>
<td>2.17E+10</td>
<td>4E+08</td>
</tr>
<tr>
<td>2.13E+04</td>
<td>1.60E+03</td>
<td>5.64E+08</td>
</tr>
<tr>
<td>0.005098</td>
<td>1.05E+03</td>
<td>5.69E+08</td>
</tr>
<tr>
<td>5.401713</td>
<td>1.04E+03</td>
<td>5.69E+08</td>
</tr>
<tr>
<td>1.15E+05</td>
<td>2.63E+03</td>
<td>5.86E+08</td>
</tr>
<tr>
<td>0.206092</td>
<td>6.71E+03</td>
<td>6.81E+08</td>
</tr>
<tr>
<td>417.1959</td>
<td>2.34E+03</td>
<td>6.82E+08</td>
</tr>
<tr>
<td>6.313443</td>
<td>1.06E+03</td>
<td>6.83E+08</td>
</tr>
<tr>
<td>0.205469</td>
<td>5.37E+00</td>
<td>8.53E+08</td>
</tr>
<tr>
<td>0.662133</td>
<td>5.39E+00</td>
<td>8.54E+08</td>
</tr>
<tr>
<td>3.30E-07</td>
<td>7.95E-01</td>
<td>8.6E+08</td>
</tr>
<tr>
<td>0.002906</td>
<td>6.09E+02</td>
<td>9.28E+08</td>
</tr>
<tr>
<td>1.14E+04</td>
<td>1.17E+03</td>
<td>9.6E+08</td>
</tr>
<tr>
<td>2209.216</td>
<td>2.62E+05</td>
<td>1.04E+09</td>
</tr>
<tr>
<td>55.08195</td>
<td>7.83E+02</td>
<td>1.07E+09</td>
</tr>
</tbody>
</table>

High R + close to a beam harmonic
Why is this not an issue in normal RF cavities?

The main mode is transverse, not longitudinal

- The HOMs are lower in frequency

The crab cavities sit in the places with high $\beta$

- Low Q of the HOMs is needed to ensure transverse stability

See also:

- N. Biancacci et al., Effect of tail cut and tail population on octupole stability threshold in the HL-LHC, HSC Meeting, 05.10.15
- E. Metral, Impedance update (other components than Crab Cavities), Joint LARP CM26/Hi-Lumi Meeting, SLAC, 19.05.16
- E. Metral et al., CC: Impedance status, International Review of the Crab Cavity Performance for Hi-Lumi, CERN, 05.04.17
Simulation procedure

1. Take the actual beam spectrum

2. Sum the contributions of all the HOMs

\[ P = 2\left(q_e N_b M f_0\right)^2 Z_{\parallel,\text{eff}} \]

\( p \) per bunch \hspace{1cm} \text{No. bunches}

3. N. Biancacci’s code:
   1. Adding an extra ±3 MHz spread to the HOM frequencies to account for manufacturing uncertainties
   2. Equidistant Gaussian bunches

4. B. Salvant’s code:
   1. Actual filling pattern
   2. Gaussian or \( \cos^2 \) distribution
Double Quarter Wave: Total heat load has increased

In reality, not all the buckets are filled. The power loss will be lower.

2.2 \times 10^{11} \text{ ppb}

25 \text{ ns spacing}
The sidebands of the beam spectrum significantly affect the power loss. It is quadratic with the number of bunches only if only the main line contributes.

From [1] we know that:
- Broad Band impedance $\rightarrow$ The sum can be replaced with an integral $\Rightarrow P_{\text{loss}} \propto M$
- Very narrow band impedance (1 term in the sum) $\Rightarrow P_{\text{loss}} \propto M^2$

In the meeting of the 10/04/2017 we have assumed that in the middle case we have:

$$P_{\text{loss}} \propto c \cdot M^{\alpha}$$

And for an ideal Gaussian filling scheme we have obtained

If $P_{\text{loss}} \propto c \cdot M^{\alpha}$ is true, in the LHC $\alpha$ is almost never equal to 2.

F. Giordano, B. Salvant, *Update on power loss for resonator impedance with various filling schemes*, APB HSC Meeting, 08.05.17
Going to 9 cm rms bunch length decreases the peak power loss

The effect is more prominent at 1 GHz and higher

8.1 cm rms bunch length

9.0 cm rms bunch length
The most dangerous modes

3564 gaussian bunches of $\sigma_z = 9\text{cm}$

Power loss $\times$ HOM $\times$ 1 crab cavity [W]

- 760 MHz
- 560 MHz
- 960 MHz

The recipe of high loss:
- High R 28 kΩ
- Low Q 300
- Close f 761 MHz

We need the HOMs to have low Q to ensure the transverse stability
Intersection of the mode line with the peak in beam spectrum leads to kW-scale power losses.

For a more realistic $\cos^2$ spectrum the losses are lower. Up to a factor of 2 for a 1 GHz mode in DQW.
Need to look at all potentially dangerous modes

The modes may shift significantly during the tuning
- As far as 50 MHz
- No way of controlling the individual frequencies

To be safe, one might need to take into account all potentially dangerous modes
- Not only the ones that are close to beam harmonics at the moment

Adding a ±25 MHz spread to HOM frequencies

The modes with peak power loss > 100 W are highlighted
DQW: Stay at least 2 MHz away from the critical HOMs

<table>
<thead>
<tr>
<th>Intensity</th>
<th>$2.2 \times 10^{11}$ ppb</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. bunches</td>
<td>2748</td>
</tr>
<tr>
<td>Bunch distribution</td>
<td>$\cos^2$</td>
</tr>
<tr>
<td>Mode frequencies</td>
<td>586 MHz</td>
</tr>
<tr>
<td>Q-factor</td>
<td>2600</td>
</tr>
<tr>
<td>Shunt imp.</td>
<td>115 kΩ</td>
</tr>
</tbody>
</table>

![Graph showing power loss from main DQW mode at 586 MHz](image)
DQW: Stay at least 2 MHz away from the critical HOMs

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<td>2748</td>
</tr>
<tr>
<td>Bunch distribution</td>
<td>$\cos^2$</td>
</tr>
<tr>
<td>Mode frequencies</td>
<td>960 MHz</td>
</tr>
<tr>
<td>Q-factor</td>
<td>1100</td>
</tr>
<tr>
<td>Shunt imp.</td>
<td>11 kΩ</td>
</tr>
</tbody>
</table>

Can significantly reduce the losses from the 2nd potentially dangerous mode
RFD: Stay at least 5 MHz away from the critical HOM

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</tr>
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<tr>
<td>No. bunches</td>
<td>2748</td>
</tr>
<tr>
<td>Bunch distribution</td>
<td>$\cos^2$</td>
</tr>
<tr>
<td>Mode frequency</td>
<td>760 MHz</td>
</tr>
<tr>
<td>Q-factor</td>
<td>290</td>
</tr>
<tr>
<td>Shunt imp.</td>
<td>28.7 k$\Omega$</td>
</tr>
</tbody>
</table>

![Power loss from main RFD mode at 760.9 MHz](image)

500 W level

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What can be measured at SPS?

- **Intensity**: $1.35 \times 10^{11}$ ppb
- **No. bunches**: 288
- **Bunch length, extraction**: 1.65 ns
- **Bunch length, injection**: 4.0 ns
RFD: up to 50 W at extraction

INJECTION, 4.0 NS BUNCH LENGTH

EXTRACTION, 1.6 NS BUNCH LENGTH
DQW: up to 2 kW, very narrow peak
DQW: HOM damping system is designed to take up to 1 kW

DQW has several HOM couples

The coaxial line can transport up to 1 kW of HOM power load out of the cavity

Thermal breakdown might be an issue

A dedicated breakdown test is foreseen
Summary

If a high-impedance HOM is close to a beam spectrum line, it may lead to a high power loss
◦ kW-scale losses!

HOM lines can be quite broad (low-Q), making it challenging to avoid

Would like to have at least 2-5 MHz from the harmonics of 40.08 MHz to keep the beam induced heating below 500 W
◦ How feasible it actually is?

As measurement in SPS might reveal some information
◦ Substantial power loss
◦ Tens of Watts can be achieved at extraction
◦ May be hard to tune on certain lines