Update on 915 MHz HOM

M. Schwarz

Acknowledgements:
A. Farricker, I. Karpov, P. Kramer, E. Shaposhnikova,
BLonD dev team
Motivation 915 MHz HOM

- The 915 MHz HOMs have high Q and large R/Q → long range wake field couples batches
- Exact values for 915 MHz HOM are not known at present \((R_{sh}, f_r, Q)\) and are difficult to measure and simulate
- CST simulations of 915 MHz HOM assuming open boundary conditions (P. Kramer, 19/10/24 LIU-SPS BD WG meeting) give twice larger \(R_{sh}\) than what is in present longitudinal impedance model
- What is the impact of this ‘higher \(R_{sh}\) case’ on multi-batch stability?
- How does the threshold change when HOM resonance frequency is at exact multiples of the revolution frequency?
**Simulation Parameters**

- Flat top, double RF $V_{200}=10\text{MV}$, $Q_{20}$
- 4x72 bunches with 1 Million macro-particles per bunch
- $V_{800}/V_{200}=0.16$, including voltage limitation due to beam loading (relevant above 2.5e11 p/b)
- Multi-batch simulation possible thanks to BLonD-MPI (K. Iliakis, LIU-SPS BD WG meeting, 21/02/2019)
- Bunch spacing 5 RF buckets (25ns), batch spacing 40 RF buckets (200ns)
- Using full SPS impedance model, in particular
  - 200 & 800 MHz TWC feedbacks modeled by reducing $R_{sh}$ by 26dB
  - different models for 915 MHz HOM (see next slide)
  - no phase loop
- BLonD simulation parameters: frequency resolution exactly $f_{\text{rev}}$
- Initial bunches were matched including intensity effects!
- Simulate 100 000k turns of flat top (2.3s)
- Beam considered unstable if maximum relative bunch length spread exceeds 0.07:
  $$\frac{\max \Delta \tau}{\tau_{av,\text{inj}}} > 0.07$$
Models for 915MHz HOMs

- **lower $R_{sh}$**: $R_{sh} \sim 2\,\text{M}\Omega$, $Q \sim 5\,\text{k}$ (in current longitudinal SPS impedance model)
- **higher $R_{sh}$** (open boundary conditions): $R_{sh} \sim 5\,\text{M}\Omega$, $Q \sim 18\,\text{k}$ (see appendix for exact values)
- **worst case**: higher $R_{sh}$ model, where $f_r$ of the two modes at (nearly) integer multiples of $f_{rev}$ (next slide)
- **random**: each cavity HOM (4 3-sections, 2 4-sections) has $f_r$ randomly shifted by $\pm 50\,\text{kHz}$

- ‘higher $R_{sh}$ model’ has larger $R_{sh}$, but reduced $R/Q$ compared to ‘lower $R_{sh}$’ model
- 3MΩ estimate from fixed target beam (I. Karpov, LIU-SPS BD WG meeting)
Effect of 915 MHz HOM frequency shift ($V_{800}/V_{200} = 0.10$)

- 915 HOMs at $f_r = (n_0 + n + df) f_{rev}$; nominal resonance frequency $f_{r0}$
  - $n_0$ closest integer such that $f_{r0} \approx n_0 f_{rev}; n = -2, ..., 2; df = 0, 0.1, 0.5, 0.8$
  - $\Delta f = f_r - f_{r0}$; dashed lines are at multiples of $f_{rev}$
- Shifting by $\Delta f \sim 15$kHz ($n=0$, $df=0.1$) yields ‘worst case’ model with lowest threshold

lower $R_{sh}$ model: $R_{sh} \sim 2M\Omega$, $Q\sim 5k$

higher $R_{sh}$ model: $R_{sh} \sim 5M\Omega$, $Q\sim 18k$
Thresholds, different 915 MHz HOM models
Thresholds

- 4x72 bunches; $V_{800}/V_{200}=0.16$, including voltage limitation due to beam loading
Summary

• Different models of 915 MHz HOM yield similar multi-batch threshold
• Beam HL-LHC design values (2.4e11 p/b and 1.65 ns bunch length) is stable, but no margin for shorter bunches
• Power limitation mainly due to 200 MHz TWC, and $V_{800}/V_{200}$ was kept at 16%
  → ratio $V_{800}/V_{200}$ could be increased to gain larger stability margin

Next steps

• On-going CST simulations of 200 MHz TWCs including terminations (load and Y-chamber) and correct lengths of feeder lines
  → simulate threshold once new ‘realistic’(?) model of 915 MHz HOM becomes available

Thank you for your attention!
## Values for 915MHz HOMs

<table>
<thead>
<tr>
<th></th>
<th>4 section*</th>
<th>higher $R_{sh}$</th>
<th>lower $R_{sh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>fr / GHz</td>
<td>913.7; 914.8</td>
<td>914.0; 914.8</td>
<td></td>
</tr>
<tr>
<td>R / kΩ</td>
<td>1064; 791</td>
<td>385.0, 386.0</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>18586; 15290</td>
<td>5000; 5000</td>
<td></td>
</tr>
<tr>
<td>R/Q / Ω</td>
<td>57; 52</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>τ / μs</td>
<td>6.5; 5.3</td>
<td>1.7; 1.7</td>
<td></td>
</tr>
<tr>
<td>BW / kHz</td>
<td>155; 192</td>
<td>574; 575</td>
<td></td>
</tr>
</tbody>
</table>

*scaled

<table>
<thead>
<tr>
<th></th>
<th>3 section</th>
<th>higher $R_{sh}$</th>
<th>lower $R_{sh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>fr / GHz</td>
<td>913.7; 914.8</td>
<td>914.0; 914.8</td>
<td></td>
</tr>
<tr>
<td>R / kΩ</td>
<td>798; 593</td>
<td>231.0, 231.6</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>18586; 15290</td>
<td>3000; 3000</td>
<td></td>
</tr>
<tr>
<td>R/Q / Ω</td>
<td>43; 39</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>τ / μs</td>
<td>6.5; 5.3</td>
<td>1.0; 1.0</td>
<td></td>
</tr>
<tr>
<td>BW / kHz</td>
<td>155; 192</td>
<td>957; 958</td>
<td></td>
</tr>
</tbody>
</table>
Power limitation

- Total voltage $V$ in a TWC (interaction length $L$, series impedance $R_2$, zero phase slip) for given power $P$ and beam current $I$:
  \[ V(n_b, \sigma)^2 = \left( P - \frac{R_2 L^2}{64} I^2 - \frac{|V|}{4} \sin \phi_s \right) R_2 L^2 \]  
  [G. Dôme, CERN-SPS/ARF/77-11, 1977]

- Beam current at frequency $f$:
  \[ I = 2I_0 F(f), I_0 = n_b e / \tau_{bb}, n_b : \text{p/b, bunch spacing } \tau_{bb} = 25\text{ns} \]

- Use binomial-μ distribution with bunch length $\tau_L$ and bunch spectrum $F(f)$
  - Spectrum close to 1 at 200MHz and only mild dependence on bunch length
  - Strong bunch length-dependence at 800MHz

- Available power:
  - 4-section cavity: 1.6MW
  - 3-section cavity: 1.05MW
  - 800MHz TWC: 216kW (peak), 144kW (average)
Power limitation, 200 MHz TWC

- Total voltage $V$ (plot capped at 10MV)
- Mild dependence on bunch length
- 10 MV can be obtained below $2.5\times10^{11}$ p/b
- Voltage drops quickly above $2.5\times10^{11}$ p/b
Power limitation, 800 MHz TWC

- Total voltage $V$ for peak power (left) and average power (right)
- Use $I \rightarrow I/\sqrt{2}$ when computing voltage from average power
- Voltage primarily limited by limited average power
Power limitation, voltage ratio

- Plot ratio: \( \min(V_{800}) / \min(10\text{MV}, V_{200}) \)
- Voltage ratio \( V_{800} / V_{200} \geq 0.16 \) can be satisfied everywhere
- \( V_{800} / V_{200} \geq 0.2 \) cannot be fulfilled for small bunch length and intensities between 1.5 and 2.7e11 p/b
- A ratio \( V_{800} / V_{200} \geq 0.25 \) can only be fulfilled above 3.0e11 p/b, where \( V_{200} \) is power-limited