Resonance HOM excitation in LCLS-II

A. Sukhanov, A. Vostrikov, A. Lunin, T. Khabiboulline, N. Solyak and V. Yakovlev
Motivation

• SRF cavities are very good resonance systems with multiple eigenmodes (HOMs) with very low losses (high Q-factors)

• Beam of charged particles interacts with HOMs in SRF cavities
  ‣ Single bunch interaction
    - incoherent losses and wake fields
  ‣ CW beam may have beam harmonics close to HOM frequencies
    - resonance excitation of HOMs
    - at exact resonance beam power loss may be high
  • for monopole modes:
    \[ P_{\text{loss}} = I_n^2 (R/Q)_m Q_L \]

  ‣ For a single cavity analysis of non-propagating modes is sufficient
  ‣ For SRF CW linac of multiple cavities conditions may be realized when propagating modes become trapped

**Analysis of resonance excitation of HOMs is important for design of CW SRF linacs**
Introduction and outline

• Developed method for analysis of resonance HOM excitation in CW SRF proton (H⁻) linac of PIP-II (Project X)
  ‣ presented by V.Yakovlev at HOMSC12 in Daresbury

• Applied for HOM analysis in LCLS-II
  ‣ monopole HOM excitation (this presentation)
    - heat load to cryomodule systems
  ‣ dipole HOM excitation (A.Vostrikov poster presentation)
    - effects on beam dynamics, BBU, transition effects

• Outline:
  ‣ Model
  ‣ Properties of monopole modes in 1.3 GHz and 3.9 GHz 9-cell cavities
  ‣ Results
  ‣ Conclusion
• **CW SRF electron linac**
  - 35 TESLA-style cryomodules (each CM contain 8 1.3 GHz 9-cell TESLA-type cavities, 280 cavities in linac)
  - 1-2 CM of 3.9 GHz 9-cell cavities
  - bunch size from 2 mm to 25 um along the linac
    - THz range in beam spectrum, flat beam spectrum up to few hundred GHz
  - bunch charge 0.1-0.3 nC, bunch rep. rate up to 1 MHz, average beam current up to 0.3 mA
Model of resonance HOM excitation in LCLS-II

- TESLA 9-cell structure 1.3 GHz cavity and 9-cell 3.9 GHz cavity
- Use RF simulation code (SuperLANS) to calculate cavity spectrum, \((R/Q)\), EM fields etc
  - 400 monopole modes (up to 11 GHz) in 1.3 GHz cavity
    - cut-off frequency of propagating modes: 2.94 GHz
  - 120 monopole modes (up to 16 GHz) in 3.9 GHz cavity
    - cut-off frequency of propagating modes: 5.74 GHz
- Find worst trapping conditions (highest \((R/Q)\)) for propagating monopole HOMs by varying distance between cavities \(L_{BP}\), then use maximum value of \((R/Q)\)
  - In real linac only very few (if any) of propagating modes may become trapped
Model of resonance HOM excitation in LCLS-II

- For each mode calculate losses in cavity walls ($Q_0$) and bellows ($Q_b$):
- Surface resistance of SC Nb (H. Padamsee, J. Knobloch, and T. Hays, RF Superconductivity for Accelerators):

\[
R_s = R_{\text{res}} + R_{\text{BCS}}, \text{ where } R_{\text{res}} = 1\Omega, \\
R_{\text{BCS}}[\Omega] = 2 \cdot 10^{-4} \frac{1}{T[K]} \left( \frac{f_n[GHz]}{1.5} \right)^2 \exp \left( -\frac{17.67}{T[K]} \right)
\]

- Use simplified bellow geometry:
  - Cylinder with the radius of beam pipe and the length of the bellow
  - Small surface field variation at the length of single bellow convolution
  - Take into account increased surface of bellow by multiplying results by a factor 2-3 (depends on specifics of bellow geometry)
- Normal skin effect in SS bellow, $\sigma = 2$ MSi, $R_s \sim \omega^{1/2}$
- Anomalous skin effect in Cu bellow at 4.5 K in GHz range, $R_s = A\omega^{2/3}$, $A = 3.3 \times 10^{-10}$ Ohm s$^{2/3}$ (Reuter and Sondheimer, Proc. R. Soc. A195, 336 (1948), Podobedov, Phys. Rev. STAB, 12, 044401 (2009))
Model of resonance HOM excitation in LCLS-II

• Power removal through HOM couplers and power coupler ($Q_h$)
  • Measurements of $Q_h$ for non-propagating modes at DESY (J. Sekutowicz) and Fermilab (T. Khabiboulline): $Q_h < 2 \times 10^5$. May vary due to small variations in cavity geometry because of manufacturing tolerances. Trapped modes may have higher value of $Q_h$
  • Use the following values in our analysis: $Q_h = 2 \times 10^5, 10^6, 10^7$.
• Total mode losses (loaded $Q$):
  \[
  \frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_h} + \frac{1}{Q_b}
  \]
• Assume random variations of HOM frequencies from cavity to cavity along linac
  ‣ $\sigma_f \approx 1$ MHz
    ‣ Cornell model: $\sigma_f \approx 10.9 \times 10^{-4}$ ($f_{HOM} - f_0$)
    ‣ SNS model: $\sigma_f \approx (9.6 \times 10^{-4} - 13.4 \times 10^{-4})$ ($f_{HOM} - f_0$)
    ‣ Data on HOM frequency spread in TESLA cavities at Fermilab (T. Khabiboulline)
• Idealized beam current spectrum
  ‣ No time/charge jitter
Cavity geometry

- TESLA 9-cell 1.3 GHz elliptical cavity

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Left cell</th>
<th>Regular cell</th>
<th>Right cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>r, mm</td>
<td>39</td>
<td>35</td>
<td>39</td>
</tr>
<tr>
<td>R, mm</td>
<td>103.3</td>
<td>103.3</td>
<td>103.3</td>
</tr>
<tr>
<td>L, mm</td>
<td>55.7</td>
<td>57.692</td>
<td>56.84</td>
</tr>
<tr>
<td>A, mm</td>
<td>40.34</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>B, mm</td>
<td>40.34</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>a, mm</td>
<td>10</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>b, mm</td>
<td>13.5</td>
<td>19</td>
<td>12.8</td>
</tr>
<tr>
<td>α</td>
<td>16.0</td>
<td>13.3</td>
<td>17.4</td>
</tr>
</tbody>
</table>
Cavity geometry

- 9-cell 3.9 GHz elliptical cavity

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Left cell</th>
<th>Regular cell</th>
<th>Right cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>r, mm</td>
<td>20</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>R, mm</td>
<td>35.79</td>
<td>35.79</td>
<td>35.79</td>
</tr>
<tr>
<td>L, mm</td>
<td>19.22</td>
<td>19.22</td>
<td>19.22</td>
</tr>
<tr>
<td>A, mm</td>
<td>14.4</td>
<td>13.6</td>
<td>14.4</td>
</tr>
<tr>
<td>B, mm</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>a, mm</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>b, mm</td>
<td>6.0</td>
<td>6.0</td>
<td>6</td>
</tr>
<tr>
<td>α</td>
<td>28.1</td>
<td>17.5</td>
<td>28.1</td>
</tr>
</tbody>
</table>
(R/Q) vs distance between cavities

Mode: 20; f= 2.692 GHz
Mode: 171; f= 7.294 GHz
Mode: 322; f= 9.975 GHz

L_{BP} in LCLS-II CM
Spectrum of monopole HOMs

- $\frac{R}{Q}$ approximated by exponential function (can be used to extrapolate to higher HOM frequencies)

![Figure showing the spectrum of monopole HOMs with graphs and data points.]

- Maximum $\frac{R}{Q}$
  - Fit: $\frac{R}{Q} = 47.3 \, \Omega \exp(-f/4.8 \, [GHz])$
  - $\frac{R}{Q}$ at $L_{\text{BP}} = 35 \, \text{cm}$

- Threshold of propagating modes

Graphs showing frequency vs. $\frac{R}{Q}$, with data points and fitted line.
Density of monopole HOMs

• Approximated by linear function
  ▶ Can be used to extrapolate to higher HOM frequencies

\[
\text{Fit: \text{#modes/0.5 GHz} = -3.5 + 3.6 \times f [GHz]}
\]
Losses in cavity walls and bellows

- $Q_0 \sim (5-10) \times 10^9$, $Q_{b} \sim 10^6$ (Cu), $Q_{b} \sim 5 \times 10^4$ (SS).
Power loss calculation

- Magnetic field on the surface of cavity induced by the \(n\)th component of the beam spectrum is equal to the sum of all exited modes:

\[
H_n = \sum_p H_{pn}(z), \quad \text{where} \quad H_{pn} = \frac{-i\omega_p^2}{\omega_n^2 - \omega_p^2 - i\frac{\omega_n\omega_p}{Q_p}} \frac{I_n}{2} \sqrt{\frac{(R/Q)_p}{\omega_p W_p}} H_p^{\text{sim}}(z)
\]

- Here:
  - \(H_p^{\text{sim}}(z)\) is the field calculated by RF simulation code for mode \(p\)
  - \(\omega_p\) is the mode frequency
  - \(W_p\) is the mode stored energy normalized by LANS to 1 mJ
  - \(Q_p\) and \((R/Q)_p\) are the mode (loaded) quality factor and impedance
  - \(I_n\) and \(\omega_n\) are the amplitude and frequency of beam harmonic

- Total power loss in the cavity walls is calculated as sum of losses by individual beam harmonics
  - in expression for \(|H_n|^2\) cross-terms \(H_{pn} H_{qn}^*\) have extremely small contribution and can be neglected

- Total power loss:

\[
P_{(0,h,b)} = \sum_p \sum_n \frac{\omega_p^4}{\left(\omega_n^2 - \omega_p^2\right)^2 + \left(\frac{\omega_n\omega_p}{Q_p}\right)^2} \frac{I_n^2}{4} \frac{R}{Q} \frac{1}{Q_{(0,h,b)}}
\]
Power loss in cavity walls

- Median (0.5 probability) values < 1 mW. Probability < $5 \times 10^{-4}$ for losses > 100 mW

Heat load at 2K due to resonance HOM excitation is not a problem
Power removed by HOM couplers

- Median $P < 5$ W; Prob.$10^{-3}$ (in 1/1000 cavities) to have $P > 50$ W

- Use HOM spectra manipulation (T. Khabiboulline): detune cavity and tune back
Power removed by HOM couplers: HOM spectra manipulation

- Detune cavity and tune back: HOM frequencies shift by few 100 Hz

![Graph showing probability vs. power loss with different Q values and frequency shifts.](image)

Median power < 5 W. HOM spectra manipulation: P < 10 W with prob. < 10^{-3}
Power loss in bellows

- Median losses < 5 W (\(Q_h=10^7\)). Probability of higher losses can be reduced by HOM spectra manipulation.

\[
\begin{align*}
Q_{\text{hom}} &= 2 \times 10^5, \text{ SS bellows} \\
Q_{\text{hom}} &= 2 \times 10^5, \text{ Cu bellows} \\
Q_{\text{hom}} &= 10^6, \text{ SS bellows} \\
Q_{\text{hom}} &= 10^6, \text{ Cu bellows} \\
Q_{\text{hom}} &= 10^7, \text{ SS bellows} \\
Q_{\text{hom}} &= 10^7, \text{ Cu bellows}
\end{align*}
\]
Power loss in bellows: HOM spectra manipulation

- Worst case ($Q_{\text{hom}}=10^7$, SS bellows), losses reduced < 6 W with prob. $10^{-3}$

Median power < 5 W. HOM spectra manipulation: $P < 6$ W with prob. $< 10^{-3}$
3.9 GHz: spectrum of monopole HOMs

- $(R/Q)$ approximated by exponential function (can be used to extrapolate to higher HOM frequencies)

$$\text{Fit: } (R/Q) = 222.6 \, [\Omega] \cdot \exp(-f/4.9 [\text{GHz}])$$
3.9 GHz: density of monopole HOMs

- Approximated by linear function
  - Can be used to extrapolate to higher HOM frequencies

![Graph showing the relationship between frequency (GHz) and number of modes per 0.5 GHz, with a linear fit equation: #modes/0.5 GHz = -0.0 + 0.4 × f [GHz].]
Losses in cavity walls and bellows

- $Q_0 \sim (1-2) \times 10^9$, $Q_b \sim 2 \times 10^5$ (Cu), $Q_b \sim 10^4$ (SS).
3.9 GHz: Power removed by HOM couplers

- Median $P < 5$ W
- Prob. $10^{-3}$ (in 1/1000 cavities) to have $P > 20$ W
  - Can be controlled by HOM spectrum manipulation

![Graph showing probability distribution of $P_{\text{loss}}$ with different $Q_{\text{hom}}$ values for SS and Cu bellows. Median values (probability 0.5) are marked.]
3.9 GHz: power loss in bellows

- Median losses $< 3\, \text{W}$ ($Q_h=10^7$). Probability of higher losses can be reduced by HOM spectra manipulation.
Summary

- Analyzed resonance excitation of monopole HOMs in LCLS-II linac
- Median heat load at 2 K < 1 mW
  - heat load > 100 mW has prob. < 5x10^{-4}
- Median power removed by HOM couplers (2 HOM couplers + 1 power coupler per cavity) < 5 W
- Median power dissipated in bellows < 5 W
  - higher power levels can be remedied by HOM spectrum manipulation (detuning cavity and tuning it back, which shifts HOM frequencies by 100s Hz)