Experience with Microphonics in the CBETA Main Linac Cryomodule

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Overview

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The **Cornell-BNL ERL Test Accelerator** is a 4-turn energy recovery Linac with a FFA return loop.

The peak detuning of the cavity must be less than **54 Hz** in order to sustain a cavity voltage of 6 MV using a power amplifier capable of delivering **5 kW**.
We relax the peak detuning limit by using 10 kW power amplifiers for unstiffened cavities. We can further relax the limit by changing the loaded quality factor to $Q_L \sim 2 \times 10^7$ using a 3 stub tuner.
Vibration Sources

Vibrations can couple into the cryomodule from outside sources.

Water Pumps
(6 m away)
No contribution

Blower Pumps
(4 m away)
No direct contribution

Klystron Platform
59 Hz vibrations coupled in through waveguide suspended from platform.

Vibrations can also come from inside the cryomodule.

Turbomolecular Pump with Backing Pump
Weak source

5 K Helium System
Turning off gas flow changes vibration spectrum quite a bit!
1. Valve Actuation
- Actuation of the JT valve correlates with peak detuning events of as much as 280 Hz in cavity 3.
- Valves made static and the Helium level control done using 2 K 2 Phase heater.

2. Excited Structural Resonances
- The gas flow due to pump skid excites 8 Hz. The amplitude of this line increases when heat load is high.
- Impulse response testing will be done to ascertain this effect and steps will be taken to damp it.

3. Thermo-acoustic Oscillations[1]
- Thermo-acoustic oscillations in the needle valve produce 40 Hz and 80 Hz.
- Fit PEEK plastic sleeves on the 5K adjust valve stem to reduce the gas flow and damp the instability.

[1] LCLS – II cryomodule commissioning in FermiLab

Addressed!
Mitigation Results

Valve modification was highly successful! Exceeded design energy gain by 50%!

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Stiffened</th>
<th>Old Peak Detuning (Hz)</th>
<th>New Peak Detuning (Hz)</th>
<th>Field (MV)</th>
<th>Nominal Amplitude Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>78</td>
<td>30</td>
<td>6 (9.5)</td>
<td>4.0 x 10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>18</td>
<td>25</td>
<td>6 (10)</td>
<td>3.9 x 10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>280</td>
<td>50</td>
<td>6 (8)</td>
<td>4.0 x 10^{-4}</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>18</td>
<td>20</td>
<td>6 (10)</td>
<td>4.1 x 10^{-4}</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>163</td>
<td>41</td>
<td>6 (8.5)</td>
<td>3.1 x 10^{-4}</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>33</td>
<td>18</td>
<td>6 (11.3)</td>
<td>2.9 x 10^{-4}</td>
</tr>
</tbody>
</table>
Besides mitigation of vibration sources, an active control system is also necessary! We can compensate for narrowband microphonics detuning by applying a sum of sine waves on the actuator. (Narrowband Active Noise Control (ANC))

Problem: Adjust $I_m$ and $Q_m$ to modulate the carriers at frequencies $\omega_m$ to reduce detuning.

Fixed Parameters: Learning Rate (gain) $\mu_m$ and Controller Phase $\phi_m$

Stability:
1. There is a range of controller phase $\phi_m$ within which the system is stable. As the gain increases this span decreases.
2. There is an upper limit to gain $\mu_m$ inversely proportional to group delay and tuner transfer function amplitude.
3. Tuner resonances also affect stability. We use a FIR low pass filter to suppress resonances above 200 Hz.
Phase Adaptation

How to choose controller parameters?

Instead of depending on transfer function measurements, use Least Mean Square (LMS) to determine optimum controller phase in-situ and introduce $\eta_m$

The modified ANC algorithm estimates the phases and keeps them in the stable region even if the transfer function changes.
The modified narrowband ANC was tested on some cavities of the main linac.

<table>
<thead>
<tr>
<th>Run Description</th>
<th>Peak Detuning (Hz)</th>
<th>RMS Detuning (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANC Off</td>
<td>ANC On</td>
</tr>
<tr>
<td>Cavity 1 with JT and precool static</td>
<td>78</td>
<td>45</td>
</tr>
<tr>
<td>Cavity 3 with JT and precool static</td>
<td>100</td>
<td>57</td>
</tr>
<tr>
<td>Cavity 3 with JT and precool static and 5 K valve modified</td>
<td>50</td>
<td>22</td>
</tr>
<tr>
<td>Cavity 4 with JT and precool static</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>Cavity 6 in original configuration</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>

The algorithm is effective and stable over hours of operation! No mechanical coupling with neighboring cavities because of bellows in our cryomodule.
Conclusions

• Initial Measurements
  The peak detuning for un-stiffened cavities were more than 100 Hz compared to the 54 Hz maximum which a 5 kW system can tolerate while maintaining the CBETA design energy gain of 6 MeV. Microphonics was mainly dominated by 40 Hz and 80 Hz vibrations along with sudden impulses of large amplitude.

• Cryogenic System Modifications
  We made the JT and precool valves static to prevent large impulsive detuning. We fit the 5 K adjust valve stem with plastic sleeves to damp thermo-acoustic oscillations at 40 Hz and 80 Hz. After the modifications, maximum peak detuning was 50 Hz on cavity 3 primarily caused by 59 Hz vibrations coupled in through the waveguide. **We exceeded our required energy gain by 50% during beam operations.**

• Active Resonance Control
  We developed a modified narrowband Active Noise Control algorithm which optimizes the controller phase parameter online and requires three parameters frequency $\omega_m$, gain $\mu_m$ and adaptation rate $\eta_m$. These parameters along with the mechanical eigenmodes determine the stability and we used additional filtering to attenuate the eigenmodes.

• Results
  We demonstrated stable and effective operation of the algorithm with beam over multiple hours with almost a factor of 2 reduction in the peak detuning on both stiffened and un-stiffened cavities.
Acknowledgements

Peter Quigley, Vadim Vescherevich, Adam Bartnik, John Dobbins, Fumio Furuta, Colwyn Gulliford, Georg Hoffstaetter, Roger Kaplan, Matthias Liepe, Dan Sabol, James Sears, Colby Shore, Eric Smith

We would also like to thank Warren Schappert and Ben Hansen for discussing their experience with LCLS-II cryomodule commissioning at FNAL, prompting us to look for it in our Main Linac.

Thank you!
Cryogenic System

Three subsystems:
1. **40 K / 80 K**
   Thermal shield, input couplers, HOM loads.
2. **4.5 K / 6.5 K**
   Input couplers, beam pipe.
3. **2 K / 1.8 K**
   Cavities.

**2 K liquid Helium system controlled by:**
1. Pneumatic Joule-Thomson (JT) and precool valve.
   Controls amount of LHe entering the 2 K 2 phase pipe.
2. 2 K 2 Phase heater
   Adds heat load if necessary.
3. Pump Skid
   Controls vapor pressure in 2 K 2 phase pipe supplying to the Helium vessels thus controlling bath temperature.
Mitigation of vibration sources is the preferred method of reducing peak microphonics detuning, but having an active control system is also necessary!

The Main Linac 7 cell cavities are attached to a tuner based on the Saclay I design with added fast actuators.

**Observations:**

1. Phase response is almost 0° up to 30 Hz, this makes it ideal for proportional integral feedback control.
2. For higher frequencies of the phase response is very noisy, especially for un-stiffened cavities.
3. The mechanical eigenmodes of stiffened cavity starts at a higher frequency and in general has a smaller response amplitude.
Idea: Treat this as a real time least squares optimization problem.

**Actuator Signal:**

\[
\begin{aligned}
    u_{pz}(t_n) &= \sum_m I_{mn} \cos \omega_m t_n + Q_{mn} \sin \omega_m t_n \\
\end{aligned}
\]

Assuming that the tuner is a LTI system the detuning can be written as:

\[
\begin{aligned}
    \delta f_{comp}(t_n) &= \delta f_{ext}(t_n) + \sum_m \alpha_m \{ I_{mn} \cos(\omega_m t_n - \phi_m) + Q_{mn} \sin(\omega_m t_n - \phi_m) \} \\
\end{aligned}
\]

Where, \( \alpha_m \) and \( \phi_m \) describe the transfer function from actuator to detuning at the frequency \( \omega_m \).

**Mean Square Detuning:**

\[
F_n = E[\{\delta f_{comp}(t_n)\}^2] \sim \{\delta f_{comp}(t_n)\}^2
\]

Minimize the mean square detuning using a gradient descent algorithm.

\[
\begin{aligned}
    I_{m,n+1} &= I_{m,n} - \mu_m \delta f_{comp}(t_n) \cos(\omega_m t_n - \phi_m) \\
    Q_{m,n+1} &= Q_{m,n} - \mu_m \delta f_{comp}(t_n) \sin(\omega_m t_n - \phi_m) \\
\end{aligned}
\]

\( \omega_m, \mu_m \) and \( \phi_m \) are fixed by the operator.

\[
\begin{aligned}
    \phi_{m,n+1} &= \phi_{m,n} - \eta_m \delta f_{comp}(t_n) \{ I_{m,n+1} \sin(\omega_m t_n - \phi_m) - Q_{m,n+1} \cos(\omega_m t_n - \phi_m) \} \\
\end{aligned}
\]
Experience with Microphonics in the CBETA Main Linac Cryomodule, MRCW2018