Experience in CBETA RF commissioning

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Overview

• Introduction

• Vibrations and Mitigation

• Active Suppression

• High Power RF

• Stability

• Energy Recovery
Introduction

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.
Vibration Sources

Vibrations of the cavity may arise from pressure waves in the cryogenic system or get coupled in from external sources.

**Needle Valves**

- Thermo-acoustic Oscillations (TAO)
  
  Caused large steady state oscillations with RMS ~15 Hz
  
  Insert sleeves to stop mass transport.

- Valve transients
  
  Caused peak detuning up to 200 Hz.
  
  Reduce valve actuation.

**Coupled Vibrations**

- Input Coupler
  
  Mostly coupled 60 Hz vibrations.
  
  Put damping material and bracing on waveguide supports.

- Cryogenic Pipes

After mitigating vibration sources, the peak detuning was 23 Hz among all cavities.
Mitigation of vibration sources is the preferred method of reducing peak microphonics detuning but having 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.

**Parameters:** Frequency, Learning Rate (gain) and Controller Phase

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**Equivalent to a set of Bandpass Filters**
Results

How to choose controller parameters? Match frequency, keep 3 dB gain margin. Use Least Mean Square (LMS) to determine optimum controller phase in-situ.

The modified narrowband ANC was tested on some cavities of the main linac.

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

We tested each of our RF sources separately to verify operation at full power.

Isolators suffered catastrophic failure due to manufacturing error. Later all isolators were repaired.

<table>
<thead>
<tr>
<th>Cavity #</th>
<th>Max $P_f$ (kW)</th>
<th>Max $P_r$ (W)</th>
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<tr>
<td>1</td>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
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<td>4</td>
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<tr>
<td>5</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
The goal of RF commissioning is to operate the accelerating cavities with stable fields i.e. the fluctuations of the voltage phasor around its steady state should be small compared to the operating voltage.

**Observations**
- Cavities 4 and 5 primarily show jitter oriented towards the Q axis, as expected from resonance detuning.
- Cavities 1 and 6 show a similar distribution with a tilt, which represents the phase error in field measurement.
- Cavities 2 and 3 show a lot more noise than others.
- Cavities 1, 4, 5 and 6 met specifications, while 2 and 3 didn’t.
Experience in CBETA RF commissioning, TTC 2021

Energy Recovery Efficiency

Net efficiency: $99.4 \pm 0.1\%$

Reached 70 μA!

Conclusion

Resonance Detuning
Primary Sources: Cryogenic needle valve, mechanical coupling through waveguides. After mitigation, maximum detuning is 23 Hz compared to the 54 Hz requirement.

Active Suppression
Stop-gap measure. Modified narrowband Active Noise Control (ANC) algorithm is effective and stable over hours of operation.

High Power RF
Lesson learnt: Do standalone tests early!

Stability
Mostly dominated by microphonics detuning on most cavities. Two cavities have lots of amplitude noise.

Energy Recovery
Measured an energy recovery efficiency of 99.4±0.1%. Reached 70 μA.
I would like to thank the entire CBETA team and the Cornell SRF group.

The work on CBETA was supported by New York State Energy Research and Development Authority and Brookhaven National Laboratory. The main linac cryomodule was designed and constructed using funds from the National Science Foundation.

Thank you!
Appendix 1: 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.
Appendix 2: ANC Stability

The ANC algorithm is a feedback controller.

The controller phase $\varphi_m$ and the gain $\mu_m$ determine the stability of the controller.

Tuner resonances also affect stability.

We use a FIR low pass filter to suppress resonances above 200 Hz.
Appendix 3: ANC Theoretical Performance

Graphs showing the relationship between attenuation and different parameters:

- **Graph a**: Attenuation vs. $\mu_m$ for fixed $Q_v$.
- **Graph b**: Optimal phase $\phi_m$ vs. $\mu_m$ for fixed $Q_v$.
- **Graph c**: Attenuation vs. $Q_v$ for fixed $\mu_m$.
- **Graph d**: Optimal phase $\phi_m$ vs. $Q_v$ for fixed $\mu_m$.

Parameters:
- $\mu_m$: Magnetic permeability
- $Q_v$: Voltage quality factor
- $\phi_m$: Phase angle

Legend: solid line represents theoretical prediction, dashed line represents experimental data.
Appendix 4: ANC Implementation

- The Cornell LLRF incorporates a FPGA for field control in Generator Driven Resonance (GDR) mode which operates on the 12.5 MHz IF signals.

- The field probe and forward power signals are used to calculate detuning.

- A DSP chip incorporates the modified ANC, proportional-integral and the LFD controller running at 10 kHz.