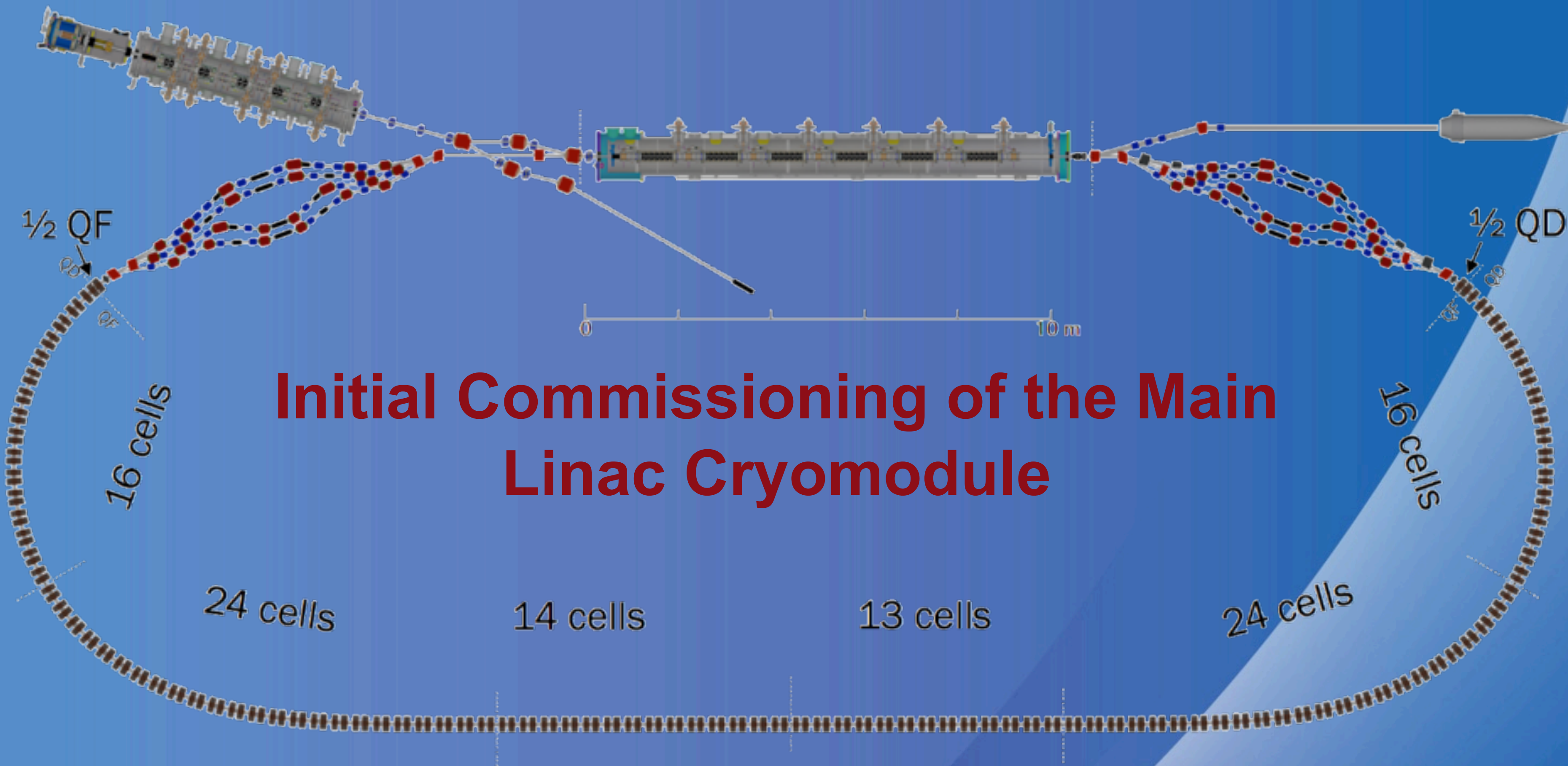

Initial Commissioning of the Main Linac Cryomodule

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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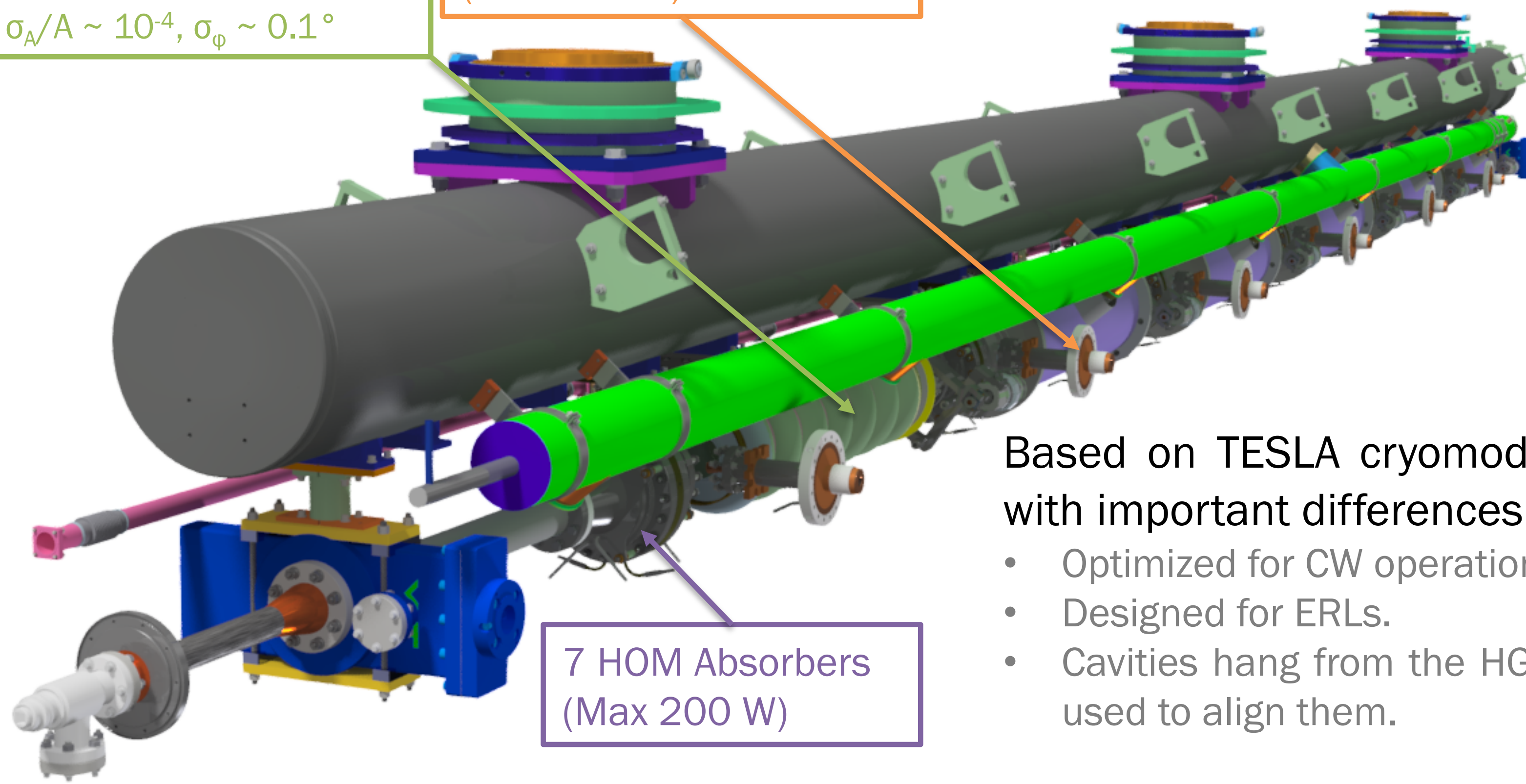


Based on TESLA cryomodule design with important differences:

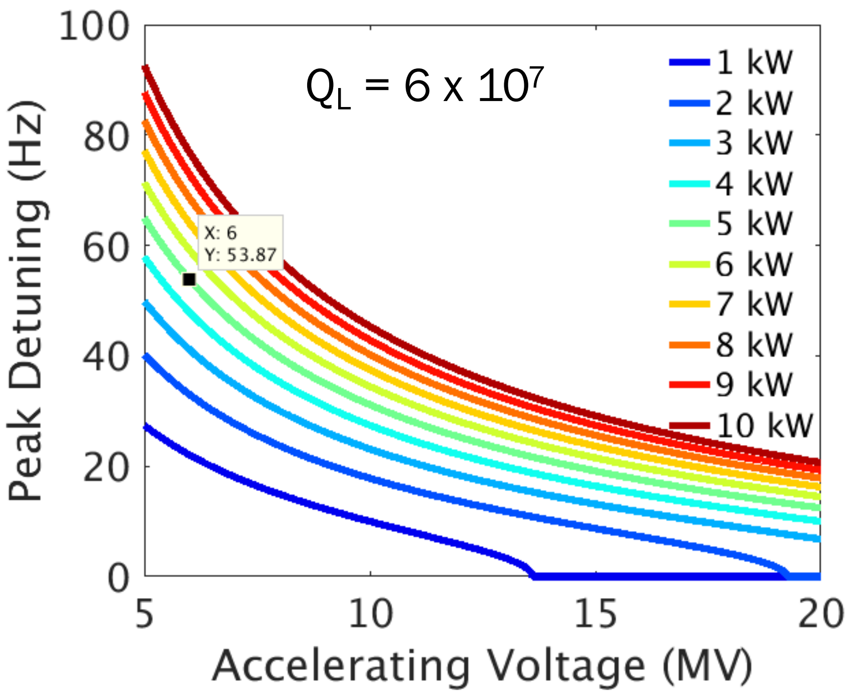
- Optimized for CW operation.
- Designed for ERLs.
- Cavities hang from the HGRP which is used to align them.

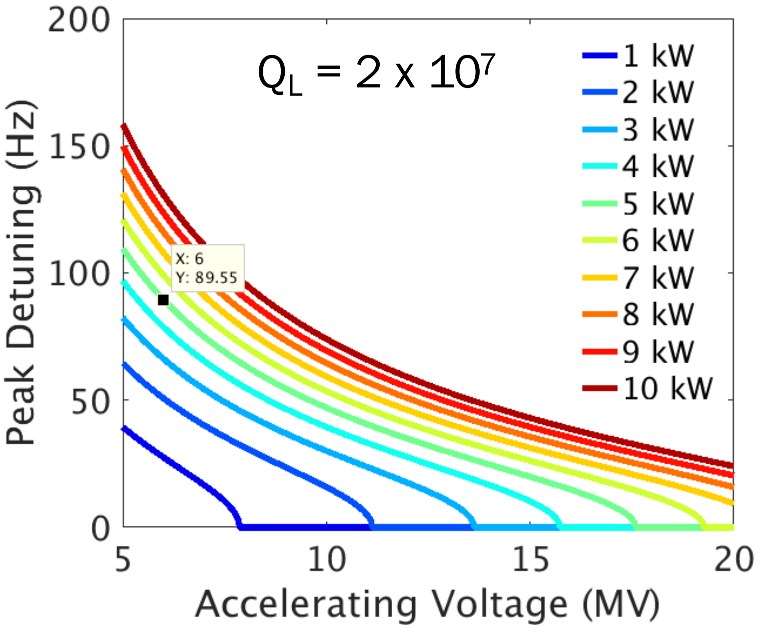
Critical Questions

1. Can all cavities be tuned to 1.3 GHz?
2. Can we stably maintain 6MeV energy gain/loss per cavity using a 5kW amplifier?
3. Can the cryogenic system handle the total dynamic heat load?
4. Can we minimize beam loading on all cavities due to the 8 beams?

The Main Linac cavities were designed to be powered by solid state amplifiers capable of delivering a forward power of 5kW.

The peak detuning of the cavity must be less than 54 Hz in order to sustain a cavity voltage of 6MV using a power amplifier capable of delivering 5kW.

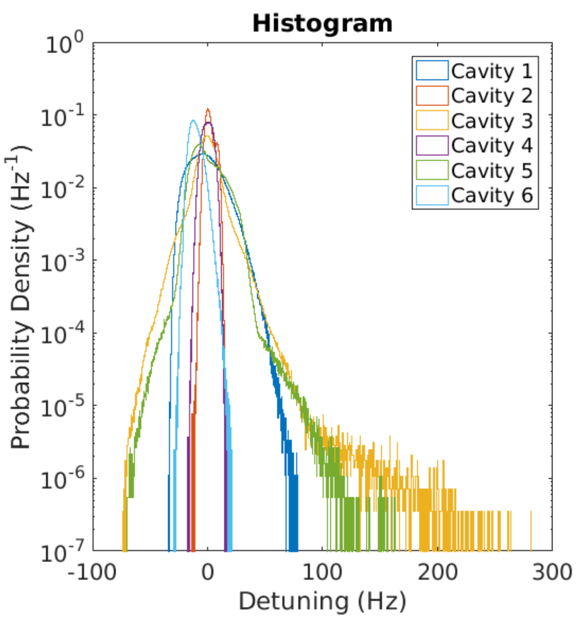


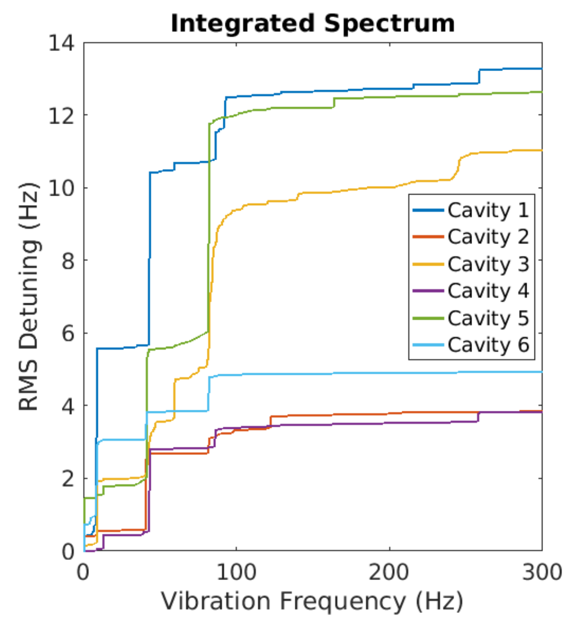


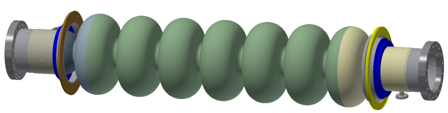
Changing the loaded quality factor to $Q_L \sim 2 \times 10^7$ increases the peak detuning limit to 90 Hz.

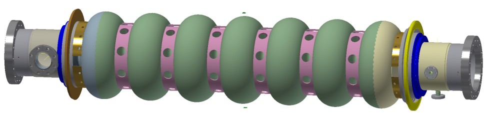
Microphonics Measurements

Cavity detuning was observed at various field levels for durations of 800 seconds.







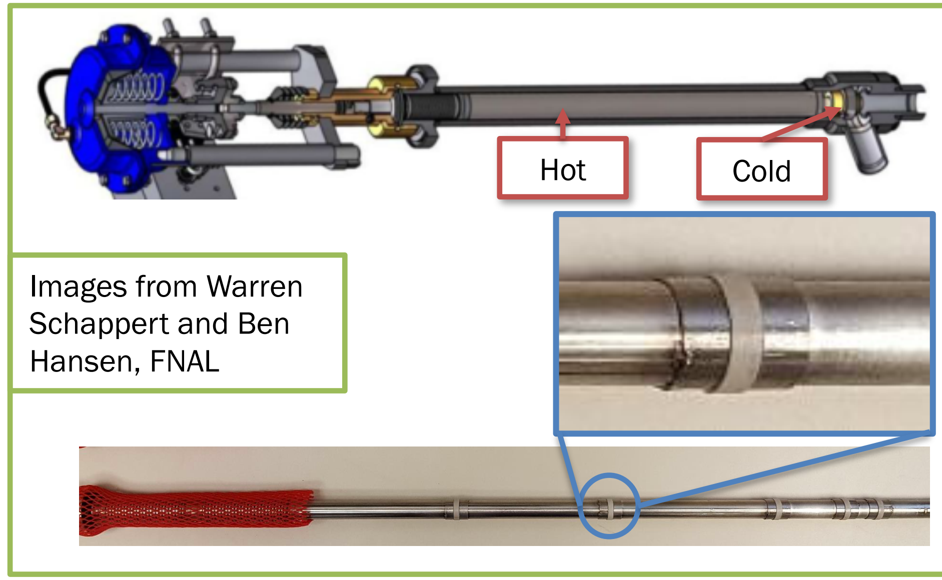


Cavity Number	1	3	5	2	4	6
Peak Detuning (Hz)	78	280	163	18	18	33
Major Vibration Frequencies (Hz)	8, 40, 80	8, 40, 80	40, 80	40, 80	40, 80	8, 40, 80

Vibration Sources

1. Thermo-acoustic Oscillations

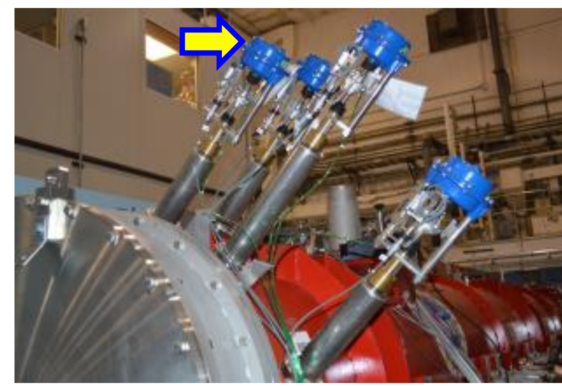
- Observations indicate that Thermo-acoustic oscillations in the needle valve produce 40 Hz and 80 Hz.
- Valves on the LCLS-II cryomodules at FNAL had the same problem and fitting vipers on the valve greatly damped the TAOs.



Images from Warren Schappert and Ben Hansen, FNAL

2. Excited Structural Resonances

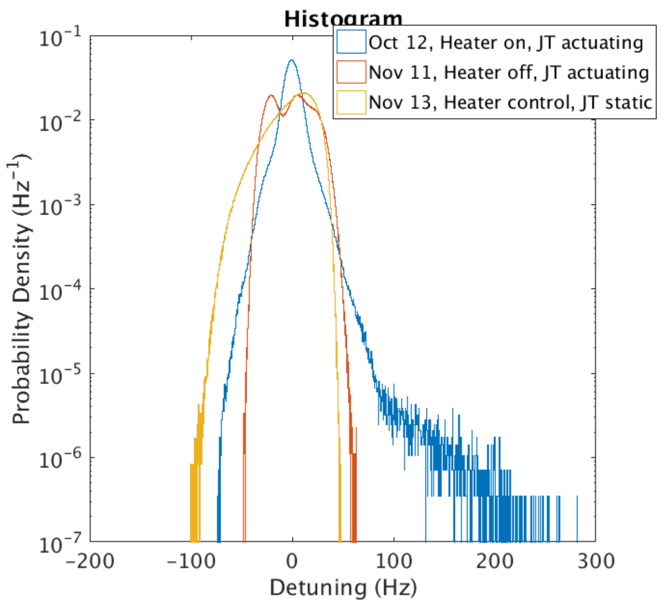
- The gas flow due to pump skid excites 8 Hz. The amplitude of this line increases when heat load is high.
- Impulse response testing will be done to ascertain this effect and steps will be taken to damp it.

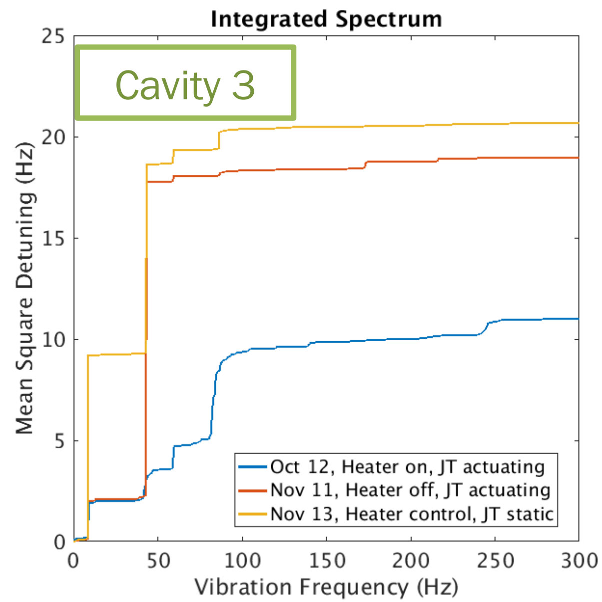


3. Valve Actuation

- Actuation of the JT valve correlates with peak detuning events of as much as 280 Hz.
- Valves can be made static and the Helium level control can be done differently.

Microphonics Suppression

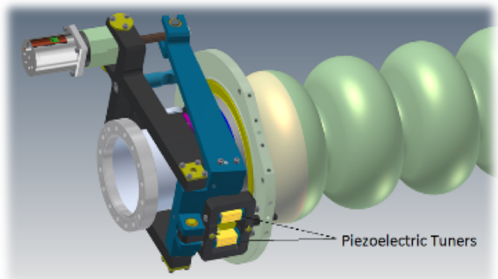


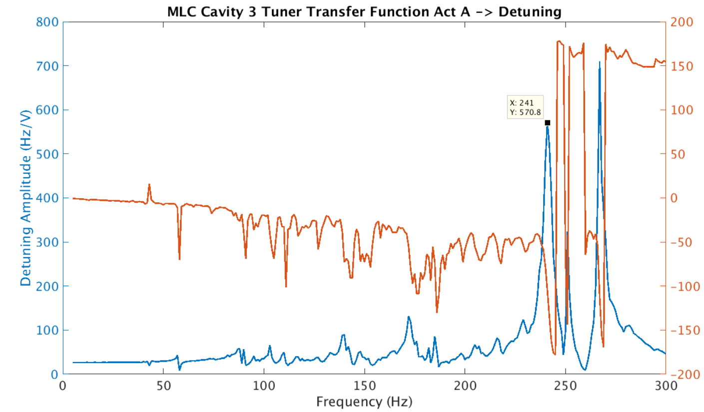


Valve Operation	Peak Detuning (Hz)
Both JT and pre-cool valves on automatic control loop to control Helium level in 2K-2 phase pipe.	280
Both JT and pre-cool valves made static. No active control on Helium level.	50
Both JT and pre-cool valves made static to overfill the 2K-2 phase pipe. Helium level control using heater.	100

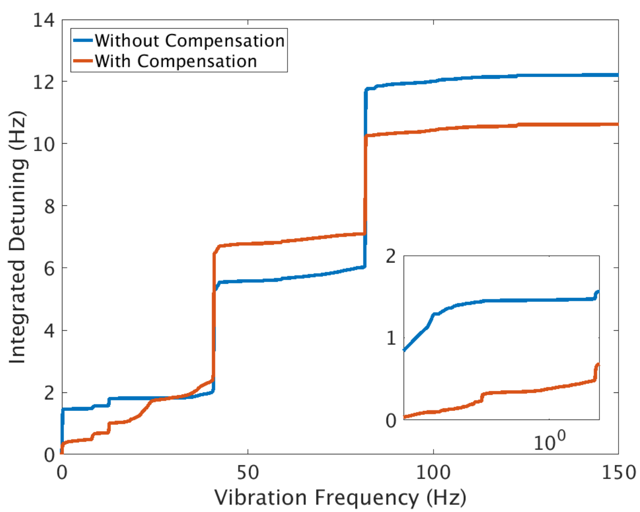
Active Compensation

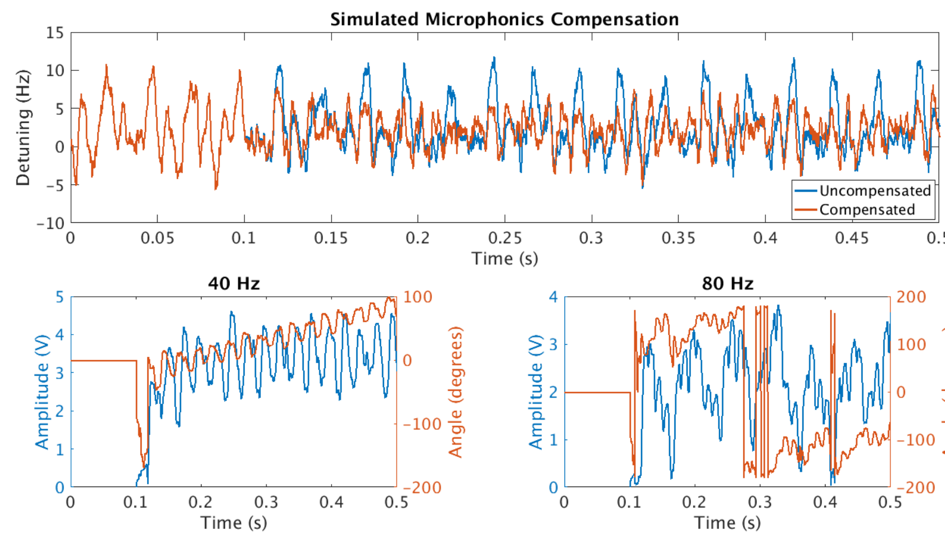
A piezo-electric actuator based fast tuner is used actively compensate for remaining vibrations.





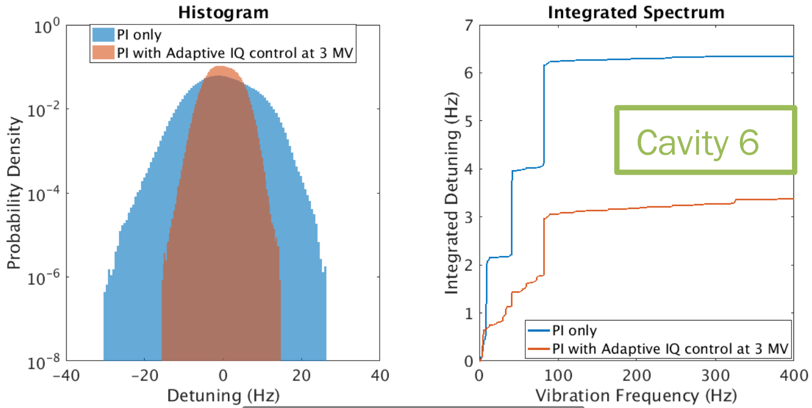
Vibrations arising from TAOs of the needle valves and slow pressure fluctuations have to be actively compensated using a fast tuner.



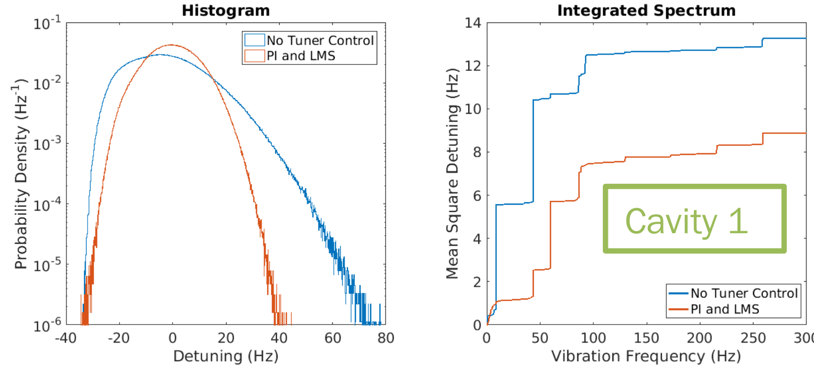


- A proportional-integral control loop compensates for slow pressure fluctuations.
- A Least Mean Square (LMS) algorithm is used to compensate for 8 Hz, 40 Hz and 80 Hz.

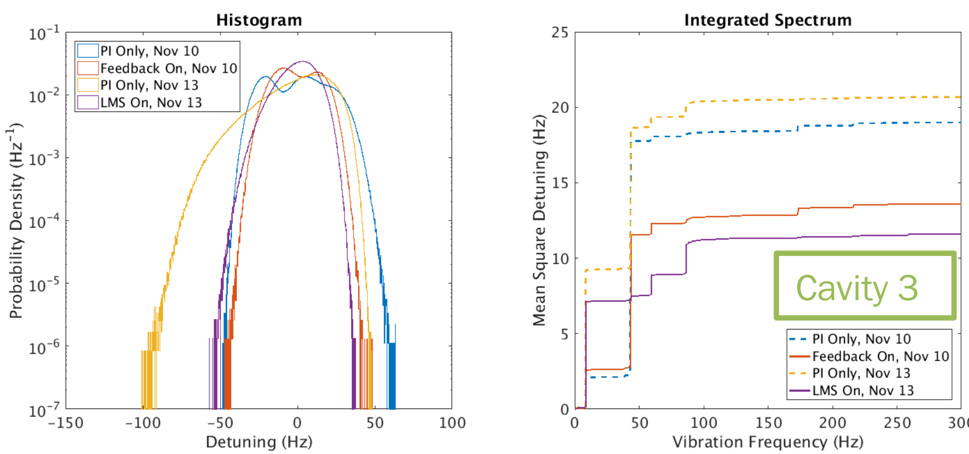
The algorithm works well for both stiffened and un-stiffened cavities.



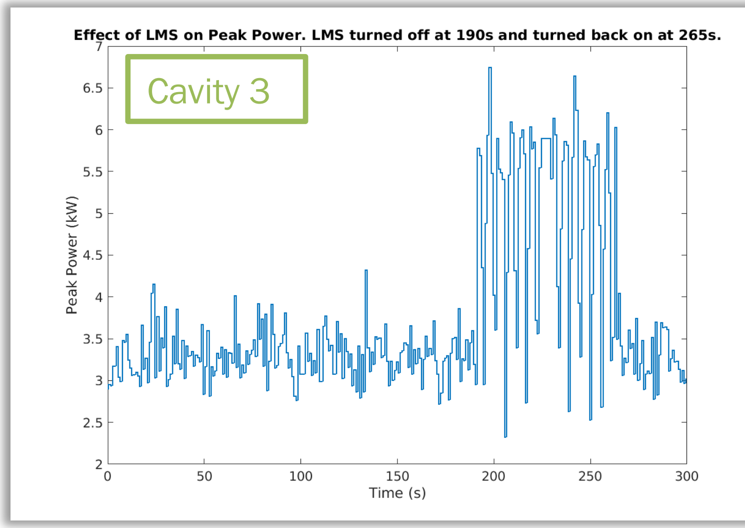
30 Hz -> 15 Hz



78 Hz -> 45 Hz



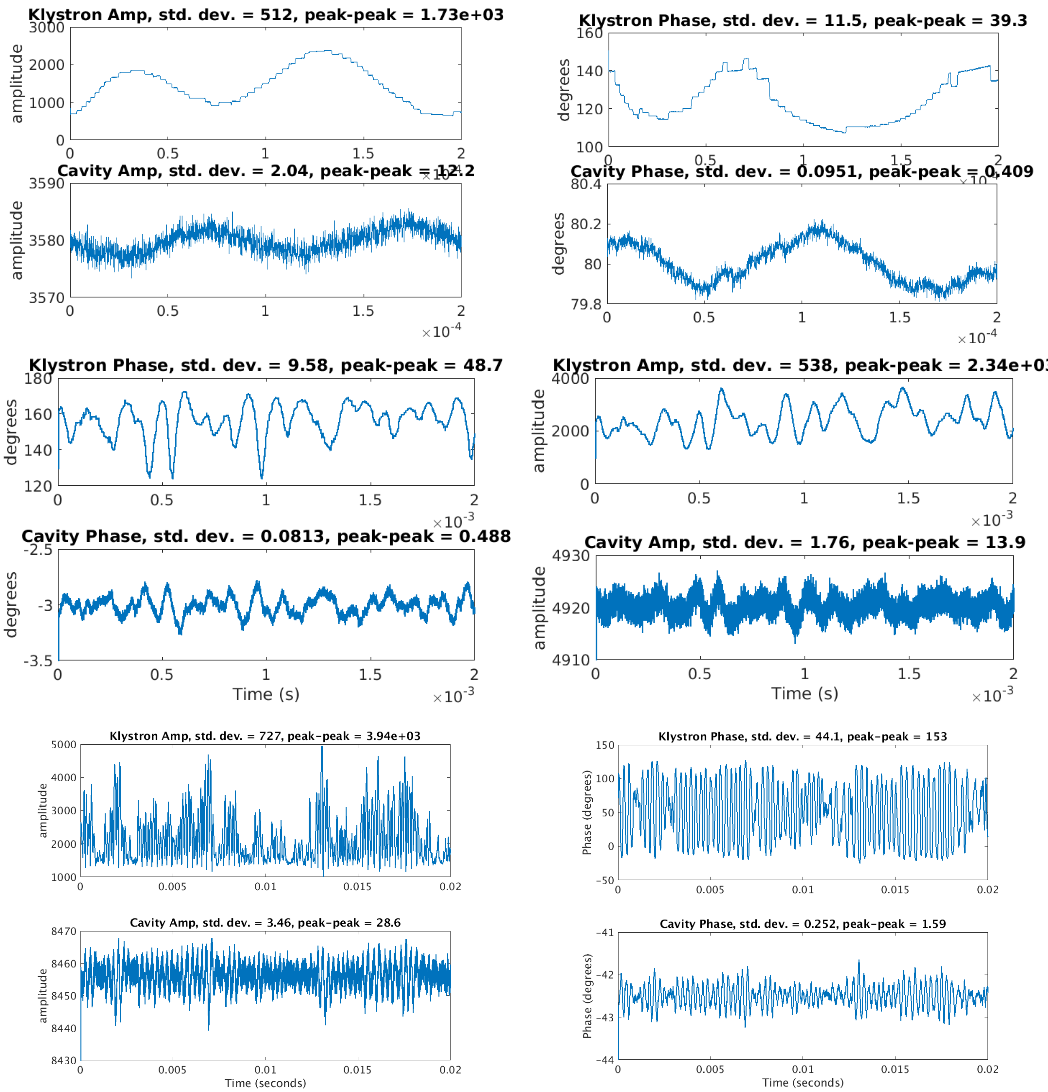
100 Hz -> 57 Hz



Peak RF power consumption almost reduces by a factor of 2 in cavity 3!

Field Stability

Goal: RMS amplitude stability of 1e-4 and a RMS phase stability of 0.1 degrees.



Cavity	Voltage (MV)	RMS Amp Stability	RMS Phase Stability (degrees)
1	4	5.7e-4	0.1
3	5.5	3.6e-4	0.1
4	8.5	4.1e-4	0.2

The gain settings have to be optimized for better numbers. Also, these are likely to decrease with the new amplifiers, and a clean rack.

Quantitative effects of field stability in CBETA have not yet been simulated.

Performance Parameters

Current performance parameters based on testing at Q^L ~ 6 x 10^7 and 5kW RF peak power:

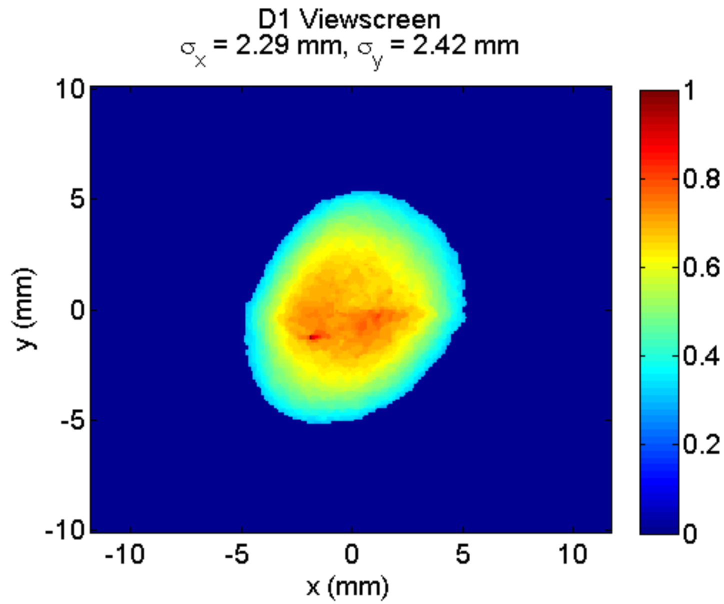
Cavity	Stiffened?	Peak Detuning (Hz)	Maximum Voltage Tested (MV)	RMS Amplitude Stability	RMS Phase Stability (°)
1	No	50 (78)	4	5.7e-4	0.1
2	Yes	20	6	2.3e-4	0.5
3	No	60 (280)	5.5	3.6e-4	0.1
4	Yes	20	8.5	4.1e-4	0.2
5	No	* (160)	1	NA	NA
6	Yes	20 (33)	7.5	7e-4	1.0

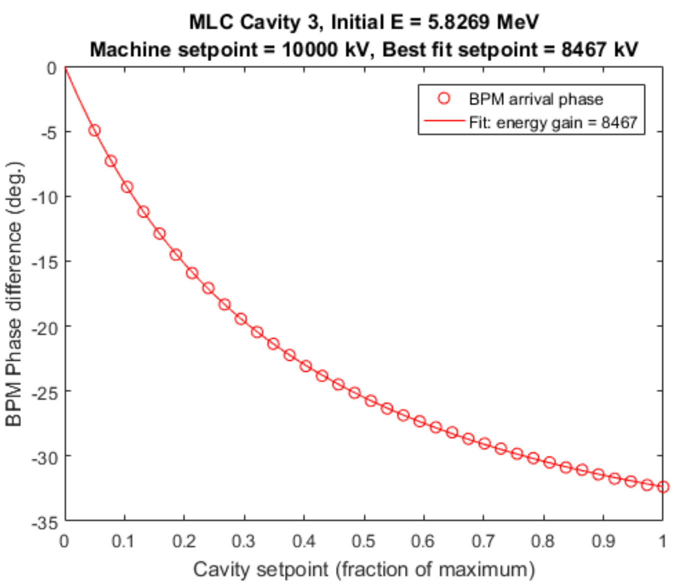
* We don't have data on how the new operating point of the cryogenic system affects this cavity.

10 kW power amplifiers will be used to power the un-stiffened cavities.

Beam Tests

- Acceleration tested using cavities 2, 4 and 6.
- Energy gain calibrated using time of flight data from BPMs.





We are preparing for the Fractional Arc Test in March 2018. This will be the first time we will operate all cavities together.

Commissioning

1. **Tuning**
   Tuning up all cavities to the finally decided frequency. Also checking available range on cavity 6.

2. **Cryogenics**
   Setting up the cryogenic system control parameters, to maintain a quiet yet stable working point.

3. **LLRF**
   Measuring microphonics, Lorentz Force detuning and configuring active compensation. Carrying out gain scans to optimize field stability.

4. **Beam**
   Calibrating the field probes of all cavities. This requires beam running.

Summary

- The Main Linac Cryomodule (MLC) used in the CBETA project is a modification of the TESLA design, being optimized for CW ERL operation.
- Microphonics is a limiting factor with respect to sustaining stable field with limited power available. A peak detuning of 54 Hz can be tolerated in order to sustain 6MV using a peak power of 5 kW.
- While all the stiffened cavities have detuning below 54 Hz, the un-stiffened cavities show large peak microphonics detuning, as high as 280 Hz in cavity 3.
- The large peak microphonics has been traced to cryogenic valve actuation which has been made static leading to reducing peak detuning of 280 Hz to 100 Hz.
- Active compensation has been successfully demonstrated which attenuates the remaining microphonics effectively. Peak power consumption has been shown to be reduced by almost a factor of 2 in cavity 3.
- In the next phase of commissioning, we will optimize the operation of the cryomodule with all cavities running simultaneously and prepare for the Fractional Arc Test.