# 1.3 GHz Microphonics Measurement and Mitigations

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MRCW18 - 2nd Topical Microphonics Workshop

October 25-26, 2018

# Microphonics Working Group

The material presented is on behalf of many people including but not limited to:

- B. Chase, C. Contreras, J. Einstein-Curtis, B. Hansen, E. Harms, J. Kaluzny, A. Klebaner, M. McGee, Yu. Orlov, Yu. Pischalnikov, T. Peterson, W. Schappert, R. Stanek, J. Theilacker, G. Wu
- Notice that this is a diverse list of skill sets, including mechanical engineers, cryogenics engineers, electrical engineers, operations/testing experts, project management, and scientific staff
- All of these were critical to the success of these efforts
- I will focus on work done at FNAL/FNAL staff, but this is not to minimize the testing and effort done at SLAC/JLab

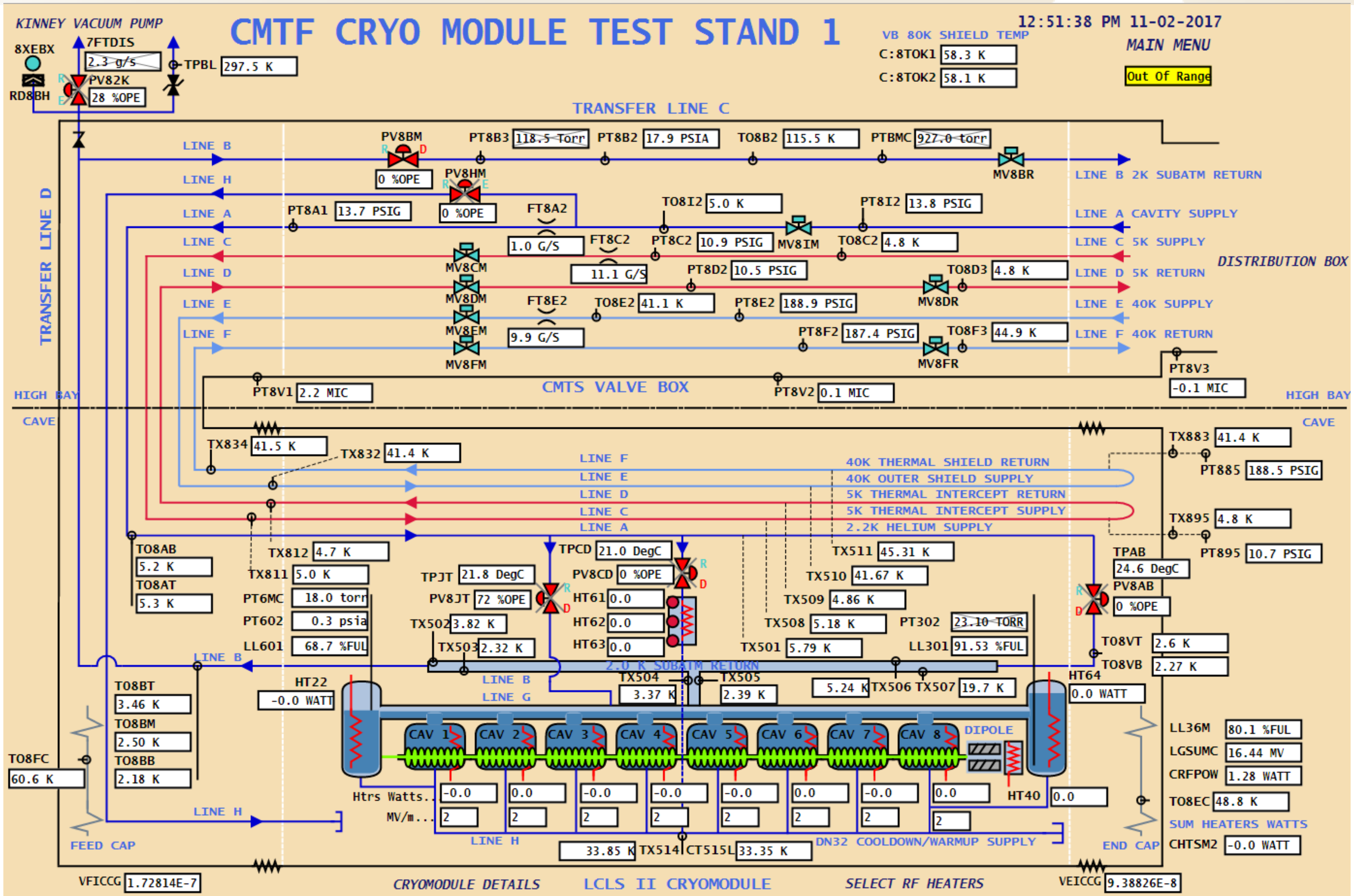
# Outline

- Background
- Diagnostic Efforts Overview
- Sources of Microphonics – Measurements/Mitigations
    - Cryogenic Valve Plumbing
        - Thermal Acoustic Oscillations in the Valve Stems
        - Helium Leakage into Cooldown Circuit
    - Cavity 1 Mechanical Support
        - Modification and Performance Improvement
- Summary

# Background – LCLS-II Cryomodule Design

- The initial conception of the LCLS-II cryomodule design was the XFEL cryomodule design
- The XFEL design was modified in several ways, but most importantly is the switch to CW operation with fast cooldown
  - Larger helium piping
  - Dual helium cooldown supply to each cavity
  - JT/CD valves added to each module to allow individual module cooldowns

# pCM (Prototype CM) Cryogenics Distribution System



# Background

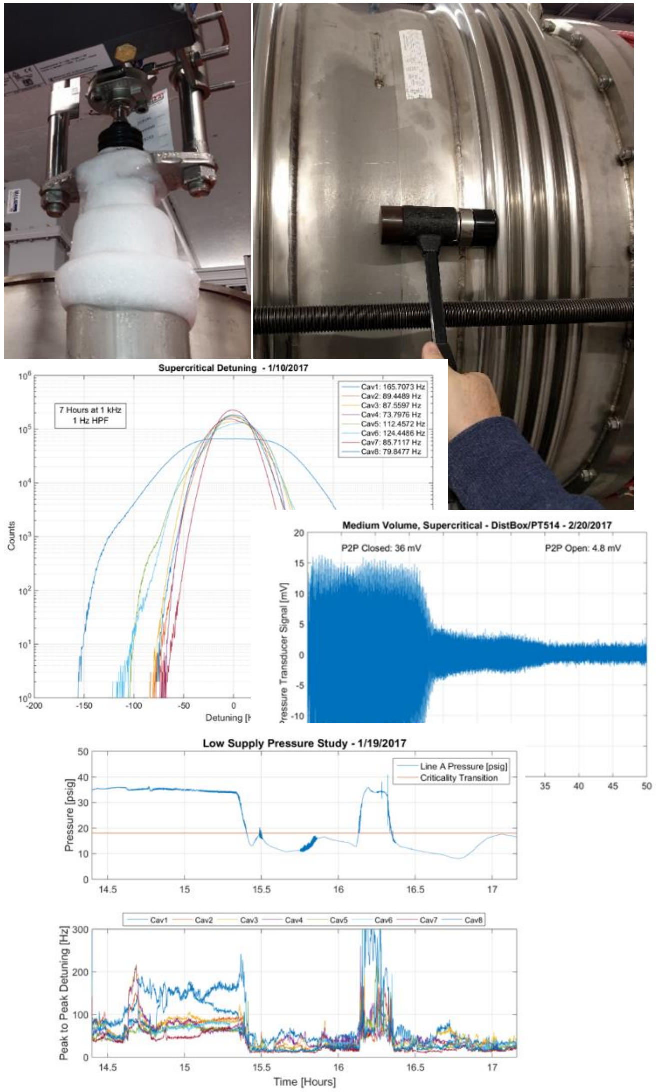
- 12+10 LCLS-II cryomodules have been tested at FNAL and JLab, in general with great success (especially most recent modules)
  - One notable exception was the resonance stability
  - Linac Specification: 10 Hz Peak Detuning (excursion from 1.3 GHz)
  - As first tested: up to 150 Hz Peak Detuning with a very complex, dynamic amplitude and spectrum
- This was not an unanticipated problem; significant changes had been made to the XFEL cryomodule design for LCLS-II
- The size and complexity of the microphonics (observed at both JLab and FNAL) required a significant response to mitigate
  - Working group formed to guide testing and determine solutions
  - Devoted extensive test time to microphonics studies
  - At the height of testing, group met 3x a week

# Background (2)

- Limiting cavity excursion from 1.3 GHz to 10 Hz is a very stringent parameter, driven by many machine design factors
  - Available RF power
  - Coupler RF capacity
  - Distribution losses
  - Control power overhead
  - Cavity bandwidth tolerances
  - …
- It is important, not only for machine operation but also for test stand operation, that the cavities are coherently locked (dark current measurement) in Generator Driven Mode (GDR)
- Microphonics testing goals:
  - Diagnose, design, and (with project approval) implement fixes with minimal schedule delay
  - Propose solutions that should help and do no harm

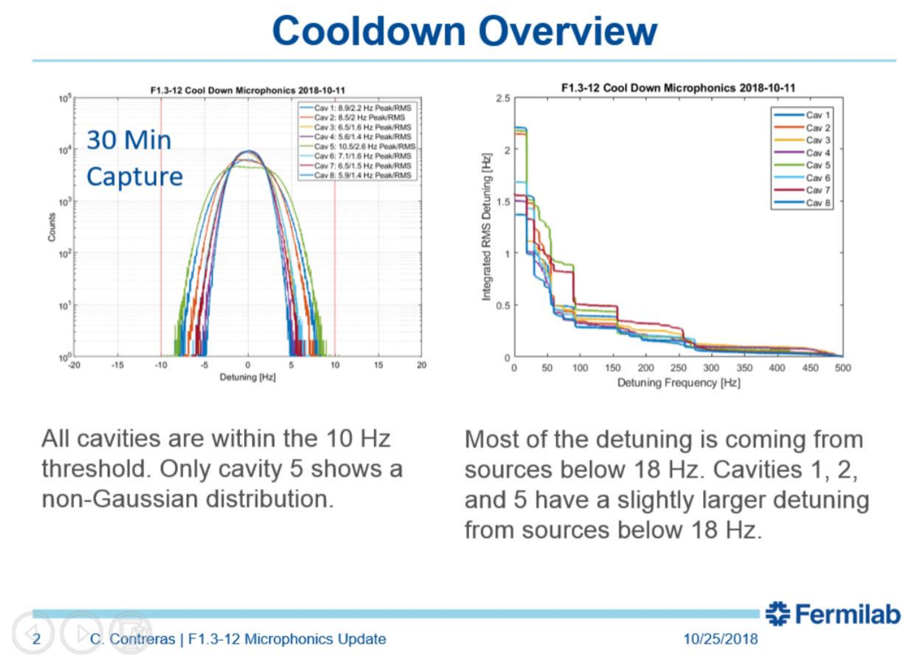
# Data from the Cryomodule Testing

- Significant testing effort was spent on microphonics mitigation
  - F1.3-01 Extended Testing (12 weeks)
  - Extensive Testing Program during further testing, including ongoing microphonics measurements
  - LLRF data capture system
    - >350 hours of cavity data recorded
  - Correlated many sources of data:
    - RF Data (On-line detuning capture)
    - Impact/Vibration Measurements
    - Temperatures, Pressures, etc. from instrumentation
  - Tested in many different cryogenics configurations
  - Leveraged significant work done at both labs on vibrational design and testing
- GDR (fixed frequency) operation achieved at both JLab and FNAL



# Testing Tools

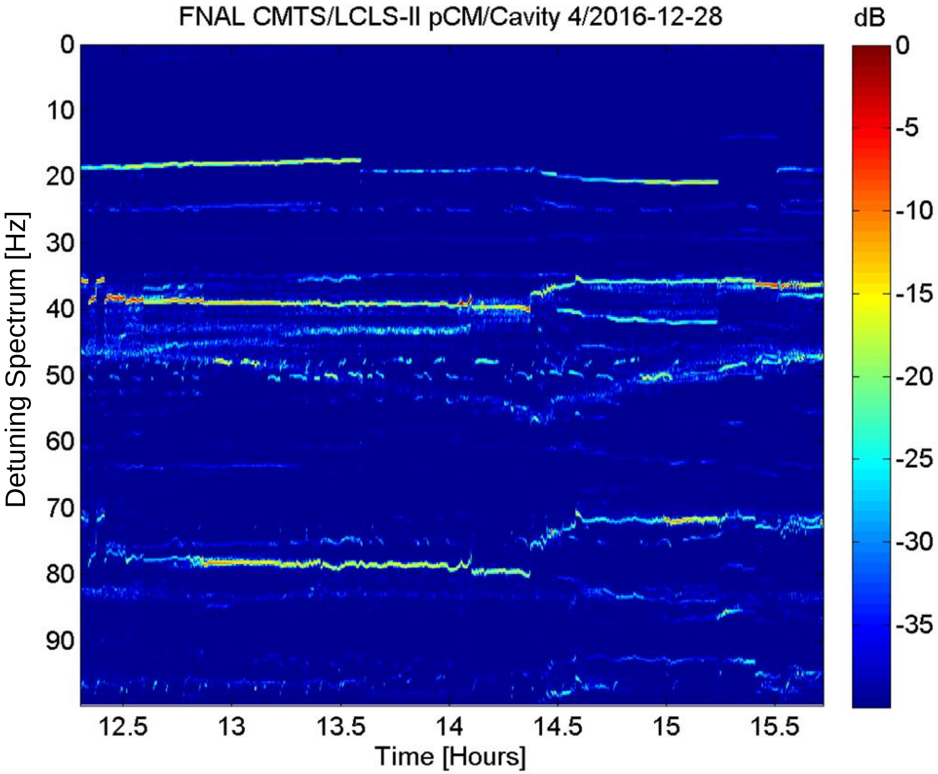
- Ground motion stations including seismometers and geophones at CMTF – FNAL
- Impact testing of cold string and cryomodule was used at both FNAL and JLab including string mode simulations done with JLab pCM
- LLRF system at FNAL captured all eight cavities detuning simultaneously and synchronously at 10 kHz
- ACNET data logging on all other cryomodule sensors (temperature, pressure, valve position, etc.etc.)
- Extensive scripting has been written to rapidly process and analyze these data sets



- **Sources of Microphonics – Measurements/Mitigations**
  **Cryogenic Valves**

# Cryogenic Valve Plumbing – Dynamic Detuning

- F1.3-01/J1.3-01 measured detuning was very dynamic
  - Vibration lines shift rapidly frequency and amplitude
  - Includes slow drifts, sharp jumps, and oscillations
  - Not mechanical resonances of the cryomodule
  - Narrow-band cryogenic source(s) exciting wide-band, low frequency mechanical response



# Cryogenic Valve Plumbing – TAOs (2)

- Cavity detuning was dominated by unstable, dynamic microphonics
- This unstable microphonics was clearly correlated with cryogenic sources (both internal and external to the cryomodule)
  - Testing revealed Thermal Acoustic Oscillations (TAO) in the supply valves *correlated with detuning* (normally only of concern for heat load). When TAO was reduced (valve wipers/valve reversal):
    - Icing on valves stopped/Heat load dropped significantly
    - Microphonics dropped by factor ~10
- TAOs also had destabilizing effect on cryogenic system
  - Changing heat load from changing TAO behavior drove cryogenic oscillations, further disturbing/detuning the cavities
  - Other instabilities were discovered/mitigated (e.g. JT injection, valve actuators)

# Brief Introduction to TAOs

Thermoacoustic oscillations generally occur in long gas-filled tubes with a large temperature gradient.

Acoustic modes couple to mass transport up and down column especially well when gas density is strongly tied to temperature.

- E.g. Warm gas from the top of a valve column moving to the cold bottom contracts, reducing pressure at warm region, driving the now cold gas back.

Long valves and very low speed of sound in cold helium can easily give lowest acoustic modes at dangerous frequencies.

- The quarter-wave mode in a 1 meter valve filled with 5K helium has a resonant frequency of 130 [m/s] / 4 [m] = 32 [Hz].

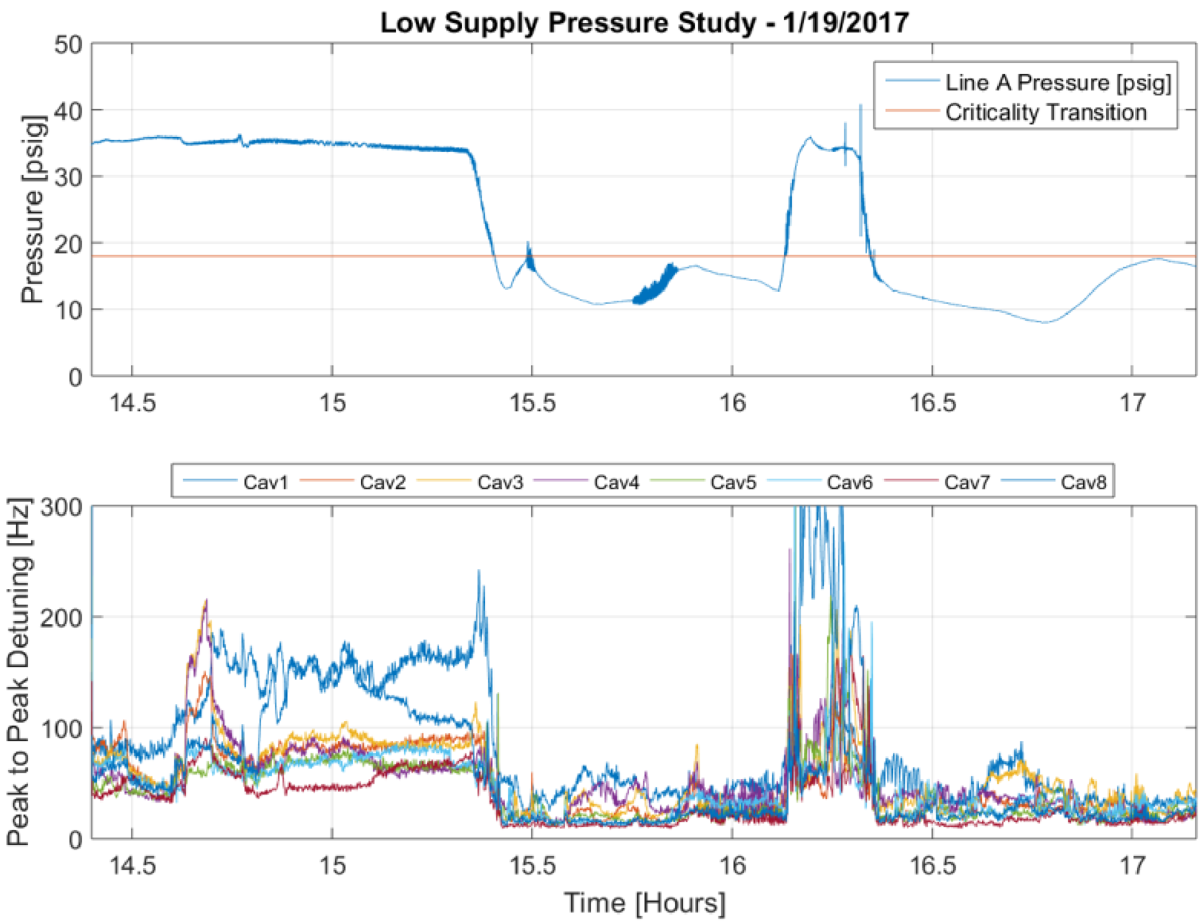
*These oscillations are generally important for the tremendous heat leaks they can represent, not microphonics.*

# Thermo Acoustic Oscillation

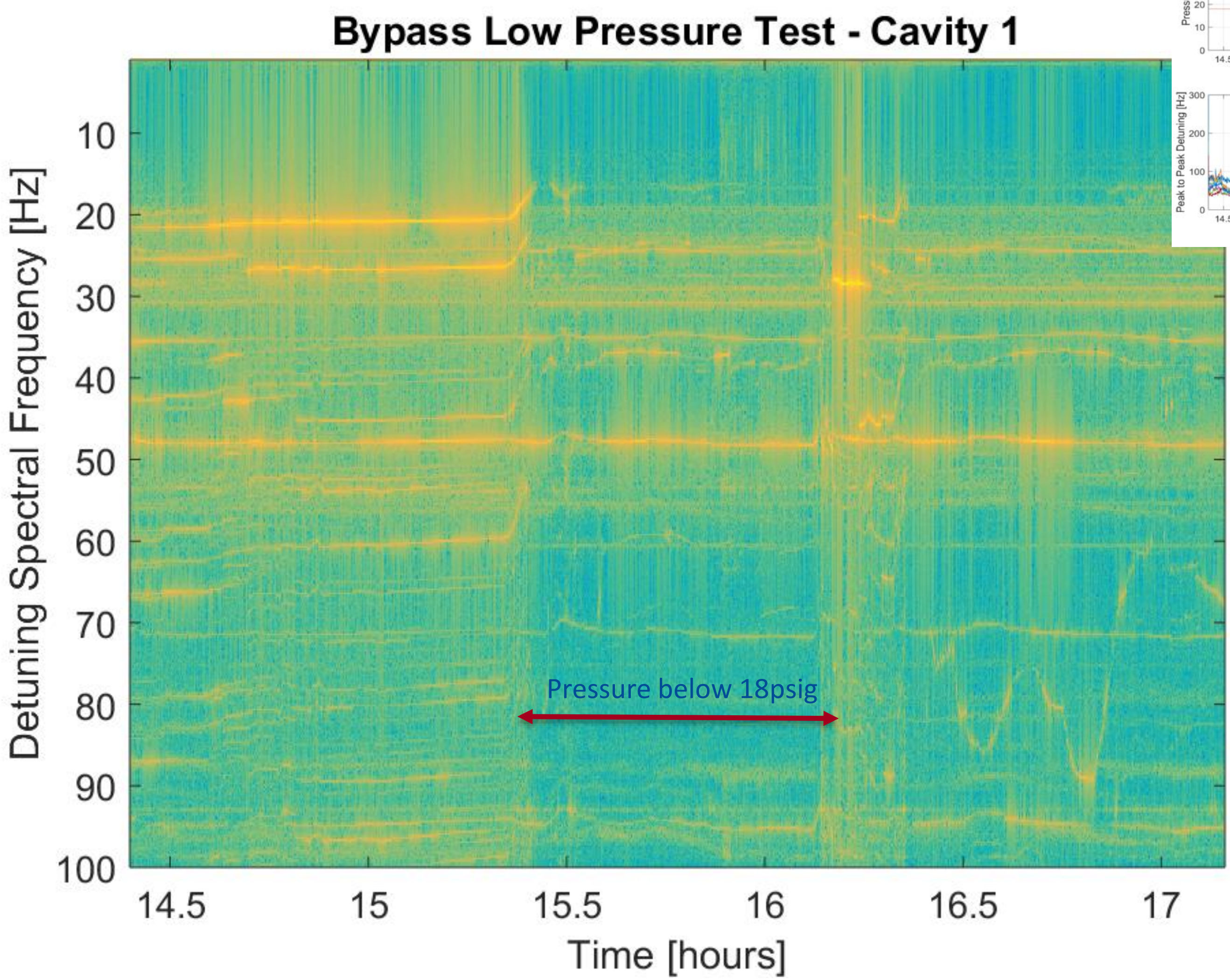
- Dropping the helium supply pressure to below the critical point (18 psig) significantly improved microphonics levels.
  - Although obviously not a realistic configuration, diagnostically, this was critical in our understanding of the detuning correlation with TAOs
  - Wipers were installed on the valve stems
    - JT first, but that alone was not enough
    - Even with no flow, the cooldown valve still exhibited a TAO that disturbed the cavities
    - Best performance was with wipers in all valve stems
    - Temperature sensors on the valve bonnets still showed some TAO behavior, and microphonics wasn't completely gone

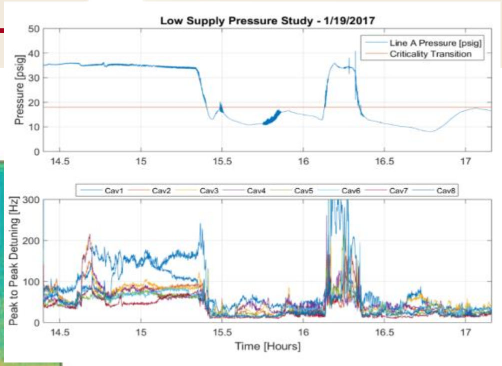
# Detuning During Low Pressure Operation

- Vibration levels fell consistently at subcritical pressures
- Different regime doesn't excite **<u>strong</u>** thermo-acoustic oscillations



# Critically Transition



# Valve Icing

Low pressure operation consistently eliminated icing on the supply valves (JT, bypass)

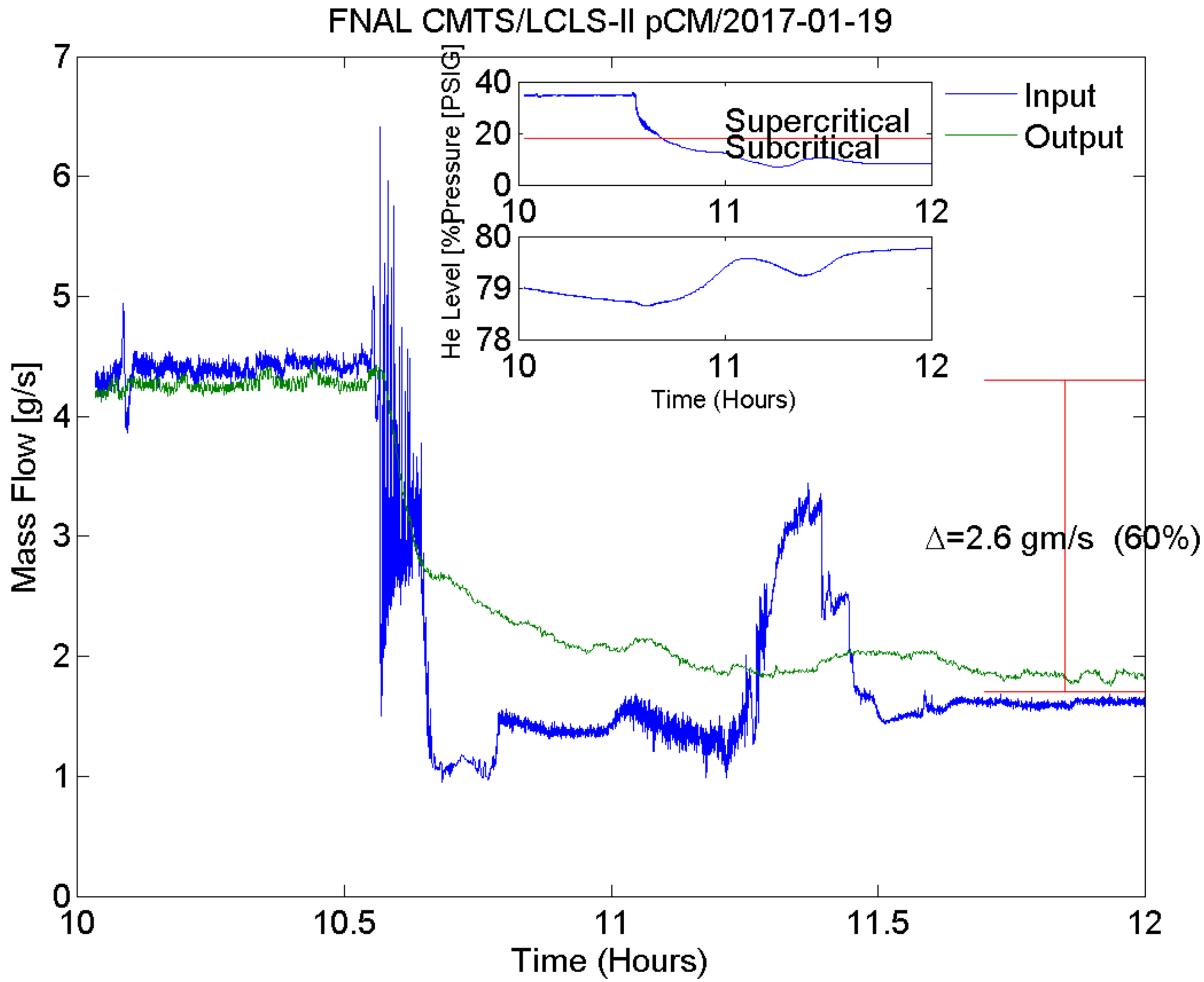
**Indicates *suppression* of thermo-acoustic oscillations**


# Helium Consumption

Static heat load significantly lower for lower JT inlet pressures

- Helium consumption falls by 60%

Supercritical operation after fixes maintain a lower heat load (although not quite as low).

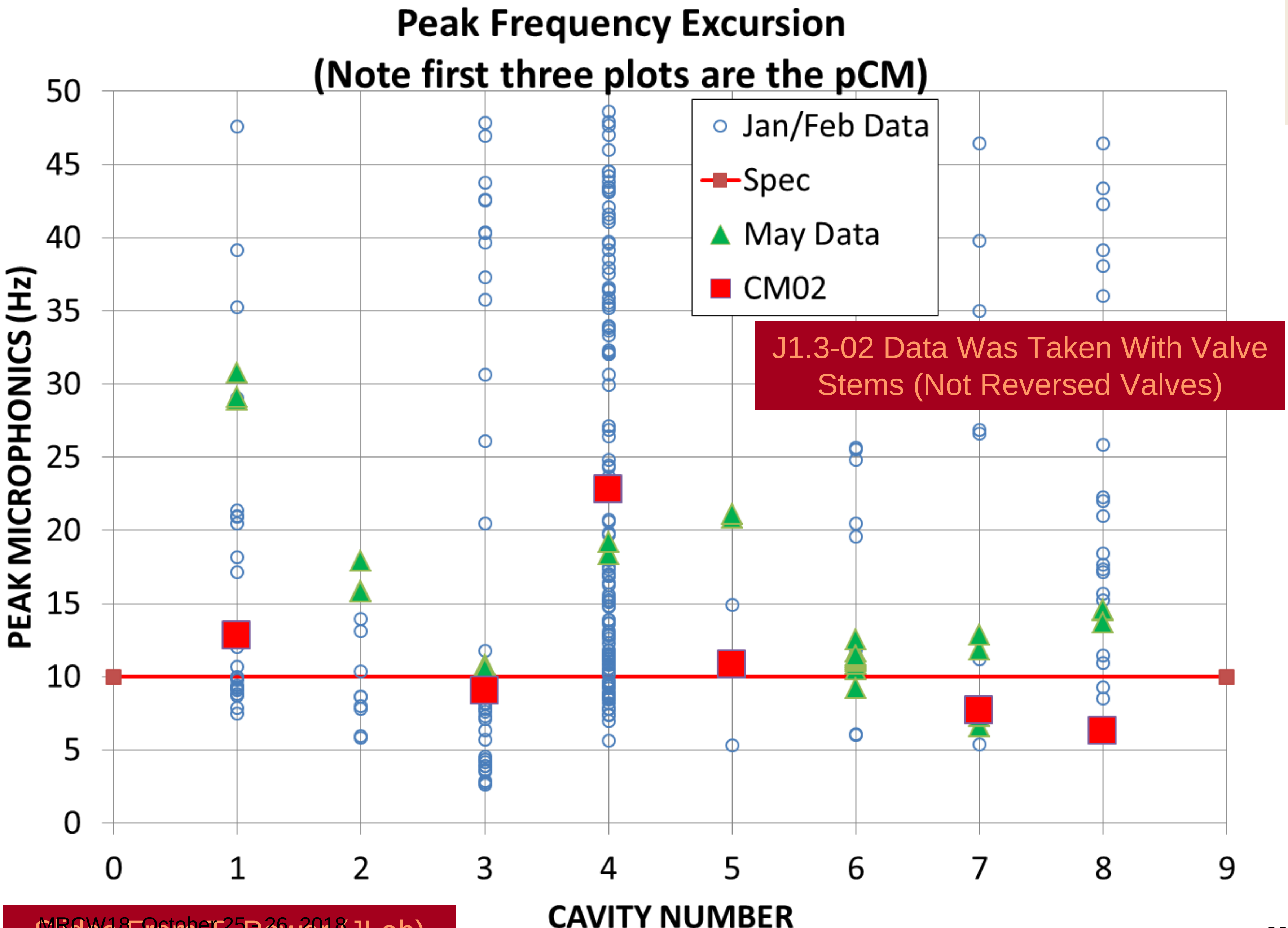


# Cryogenic Valve Plumbing – Improved Valve Stems

- TAOs are a pressure/temperature oscillation in cryogenic lines (in this case, valve stems)
  - During testing, wipers were added to close space in valve stem, acting as a damping term for the TAOs
  - Significant improvement in heat load and microphonics levels and stability for *both* F1.3-01 and J1.3-01
  - Optimized valve stems with wipers were used during F1.3-02 testing, *and will be used going forward for both labs*
    - 4-5 wipers, positioned to keep temperature ratio <4 as recommended by literature
    - Radiation hard material (PEEK)




Optimized wiper placement going forward

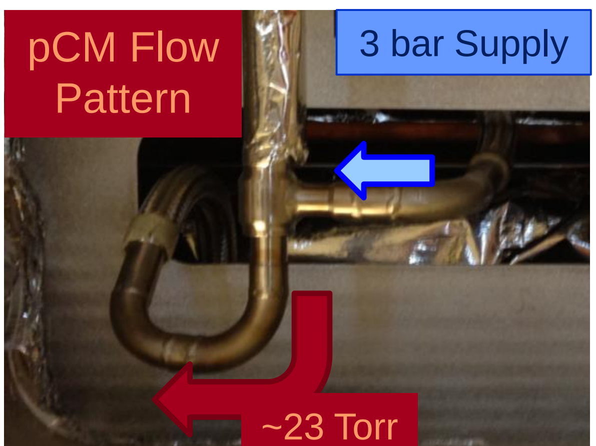


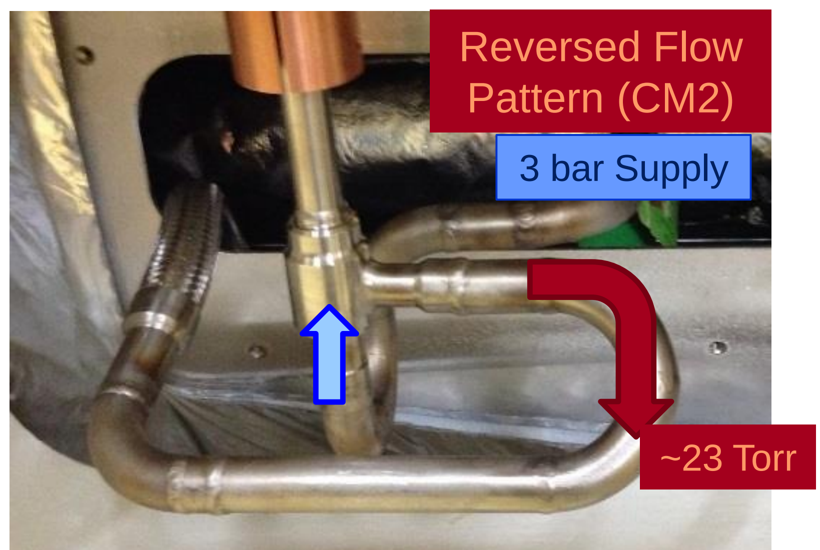

J1.3-02 Data Was Taken With Valve Stems (Not Reversed Valves)

Slides From T. Power (JLab)

# Cryogenic Valve Plumbing – Reverse Flow Path

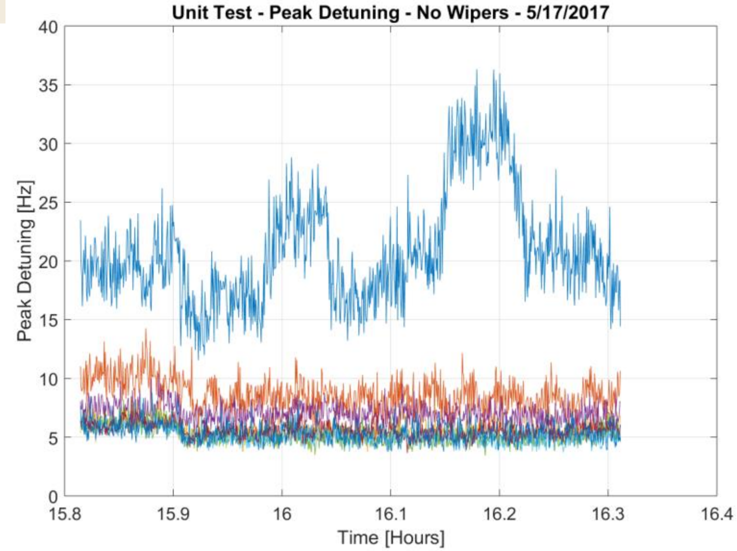
- Test results show valve reversal (lower press in stem) significantly reduces/eliminate TAOs there
  - F1.3-01 configuration has valve stem at supply pressure (~3 bar)
  - Reversing flow will lower this pressure to sub-atmospheric, requiring guard gas to prevent contamination
  - All cryomodules will have guard gas, reversed valves
- Additional effort to mitigate TAOs in cryogenic distribution system should improve inlet temperature at test stand
- Reversed additional valve on the FNAL test stand (bypass)

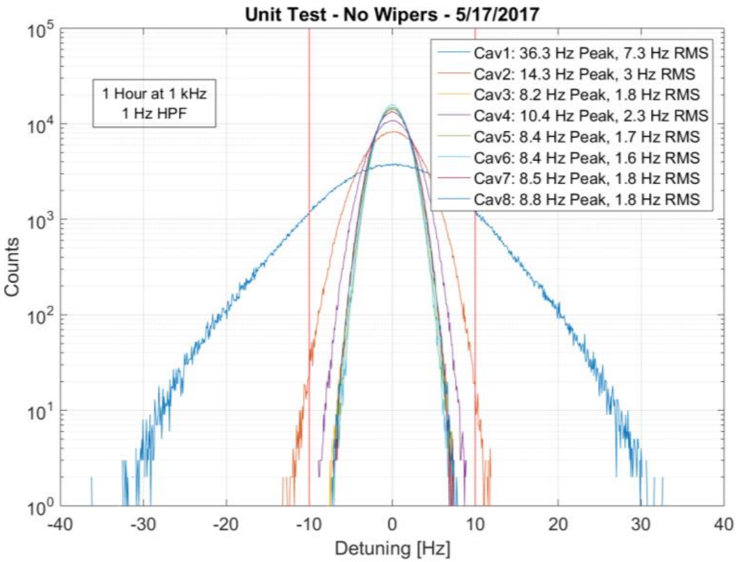



# Need for Wipers

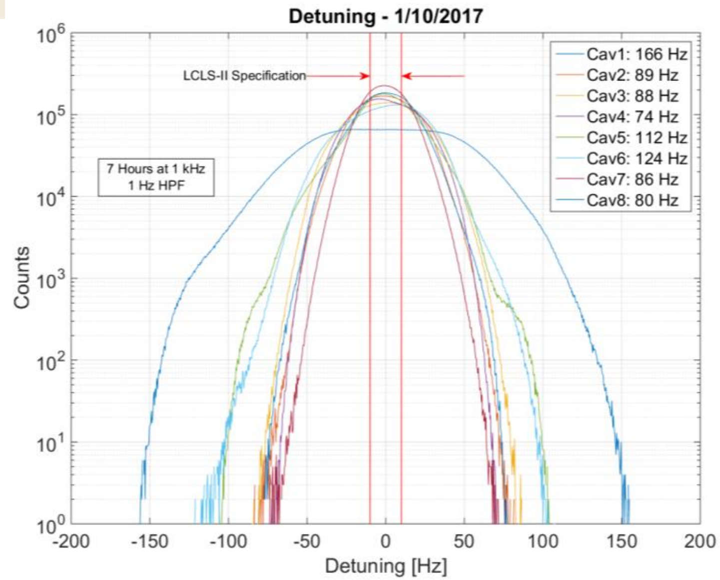
- F1.3-02 was tested with reversed valves but no wipers on JT and CD valve
  - Increased valve bonnet temperature drop during cooldown
  - Increase in unstable microphonics lines, to which Cavity 1 is especially sensitive
  - 4K mode will be sensitive to increased heat load without wipers



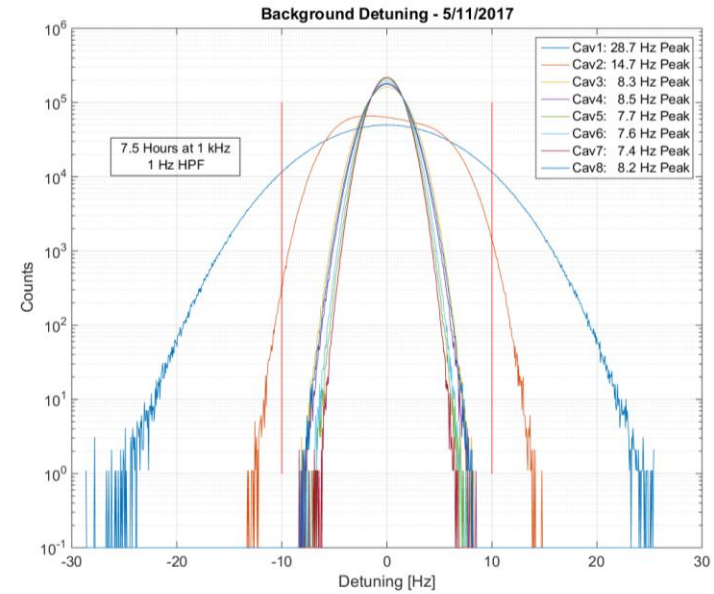



# Valve Modification Improvement

- Comparing performance of the standard cryogenics configuration, the microphonics environment in the F1.3-02/03/04 is a factor of ~10 improved
- Significant improvements in stability of the system, leading to a far more predictable detuning environment



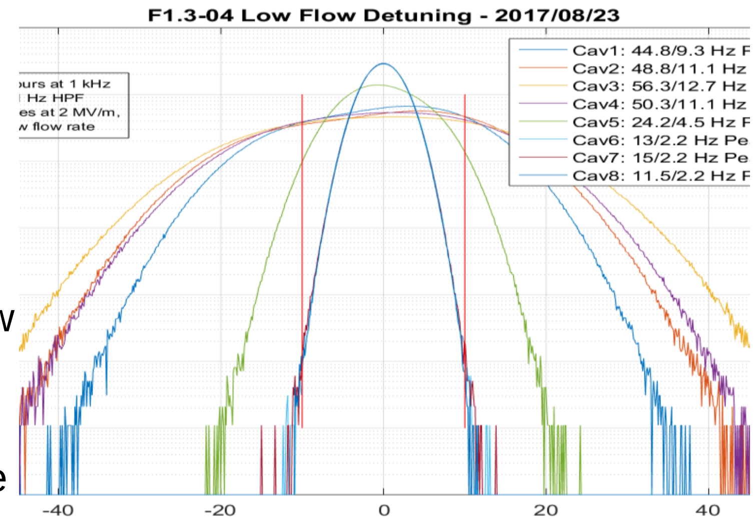

pCM As Cooled Down



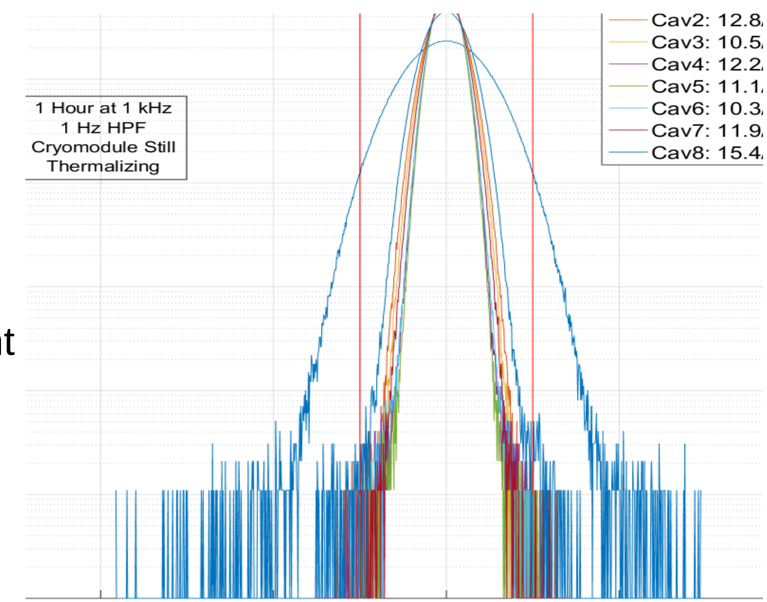

F1.3-02
After Improvements

# Cryogenic Valve Plumbing – Cooldown Valve Leakage

- F1.3-04 presented with higher than expected microphonics, worsening as the cryomodule thermalized
- F1.3-07 showed same noise after 3rd temperature bump
- Both characterized by solidly low temperature cooldown line (2 K vs ~25 K), indicating active flow
- Noise was narrowband and showed complex spatial and spectral distribution in cryomodule
- Testing showed noise to be coherent bubbling due to cooldown valve leakage, explains noise on upstream cavities
- Swapping valve stem returned expected performance in both cases
- Tails seen in ‘post-swap’ data are likely due to continued thermalization of cryomodule after cooldown
- Additional QA check step now included to prevent valve leakage in the future, although small leaks have been seen during other module tests




Thermalized Detuning

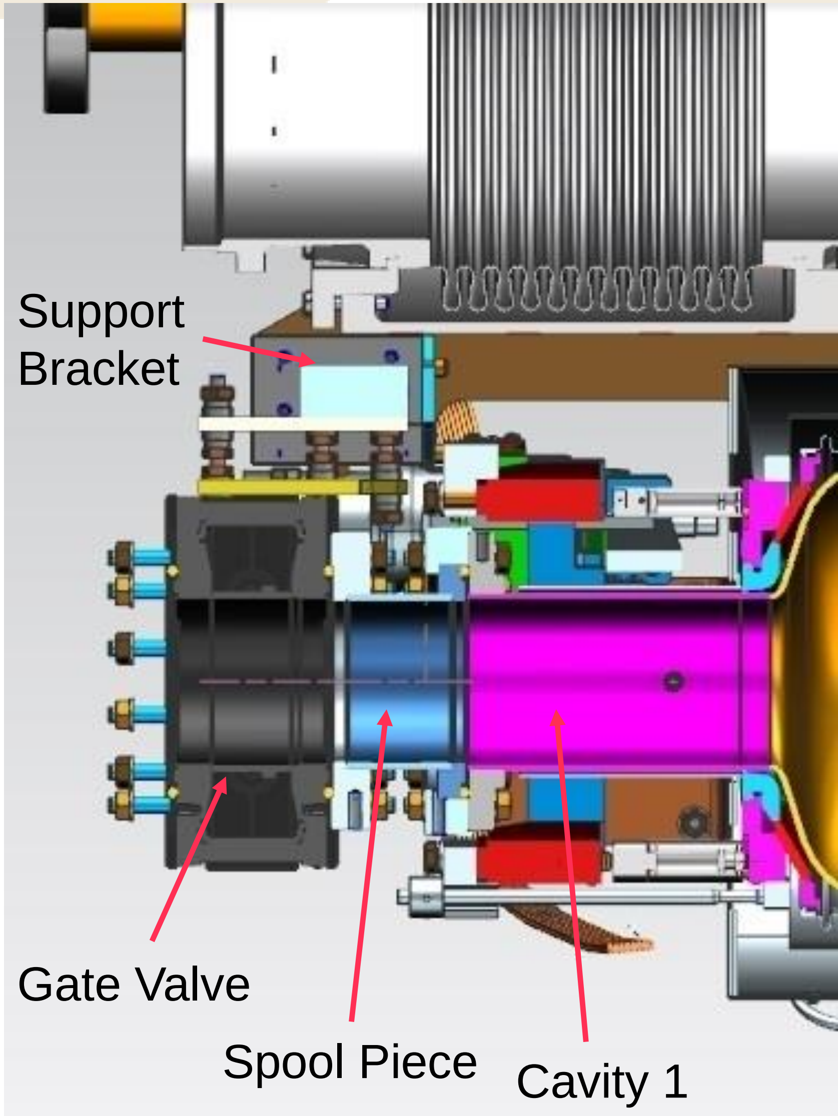



Post CD Stem Swap

- **Sources of Microphonics – Measurements/Mitigations**
  **Cavity 1 Mechanical Support**

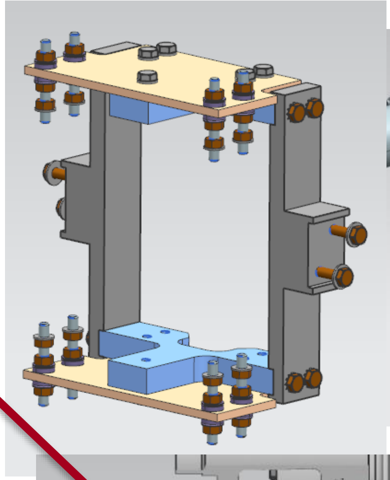
# Cavity 1 Mechanical Connections

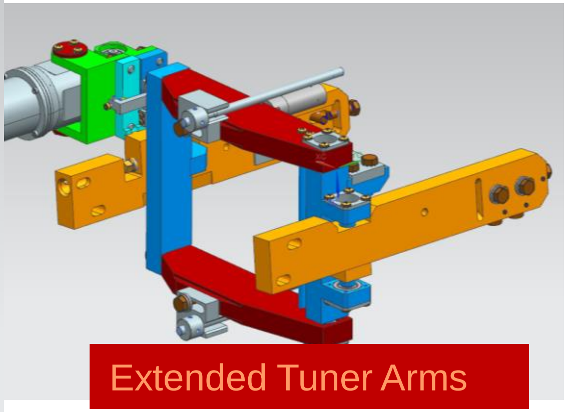
- Cavity 1 was consistently worse than other cavities by factor of ~2
  - *Cavity 1 and upstream gate valve are connected rigidly with no beamline bellows*
  - Gate valve supported vertically by bracket, but free to move in beam direction
  - Gate valve acts as large backing weight on tuner, lowering resonant frequency of longitudinal modes
  - In machine, will also have a beam line absorber, adding even more mass

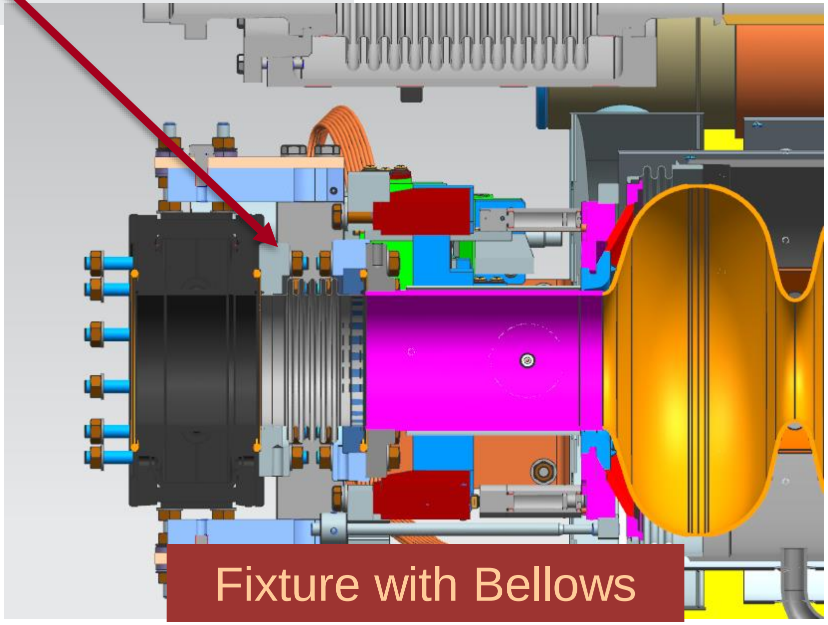


# Cavity 1 Mechanical Connections – Mitigation
## Beamline Gate Valve Bellows

- Replacing spool piece between cavity 1 and gate valve with a bellows is non-trivial
- Corrective fix includes extending tuner arms with fixture to connect to gate valve
  - When replacing spool piece with bellows, fixture fully supports gate valve
  - Current supports are long arms connected to the 300 mm pipe with needle bearing for the longitudinal motion
- With gate valve is supported by frame/helium vessel, the spool piece can be replaced with a bellows to separate mass from cavity/tuner system
- Many cryomodules with bellows have been tested at FNAL (F1.3-06-12)

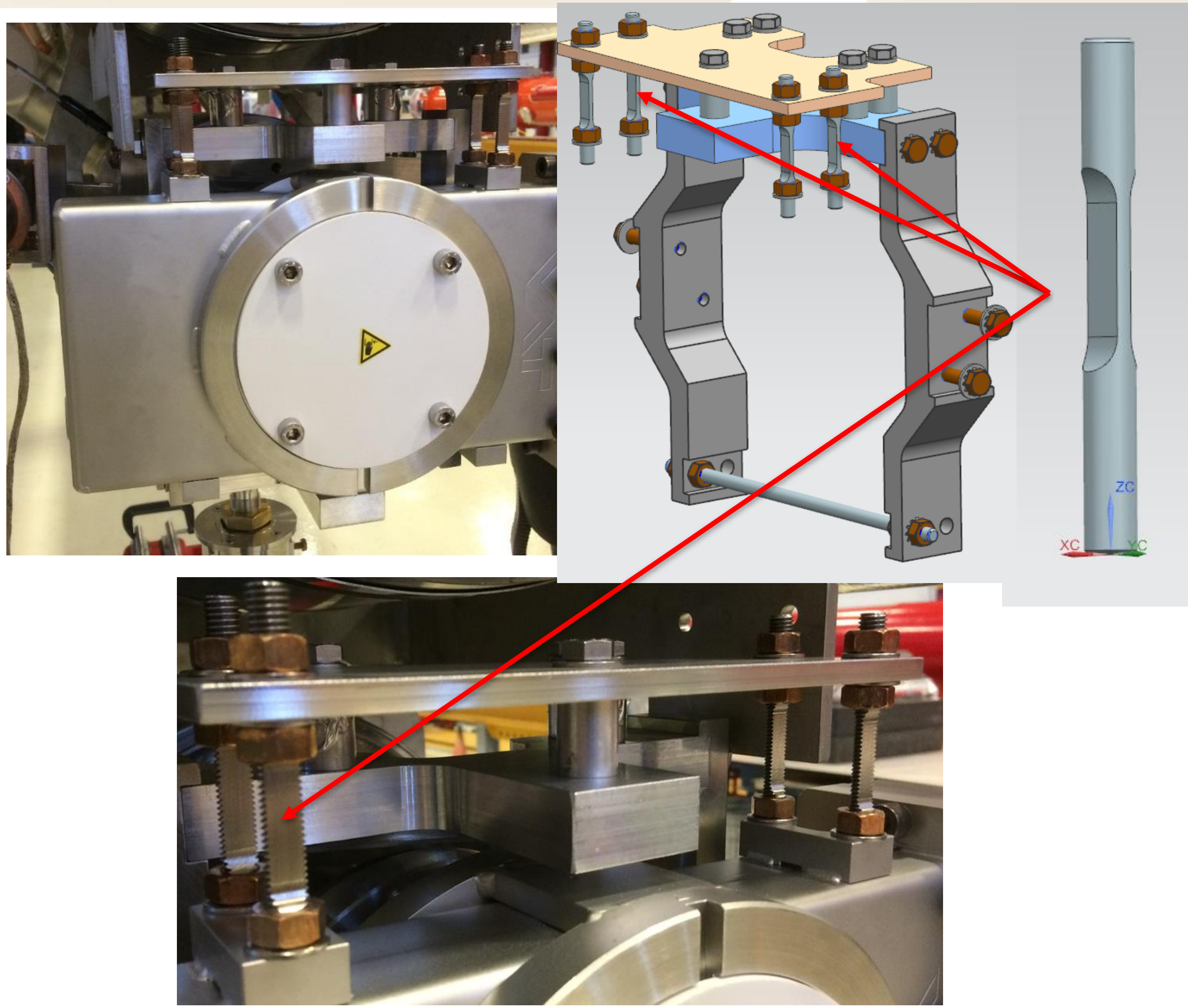




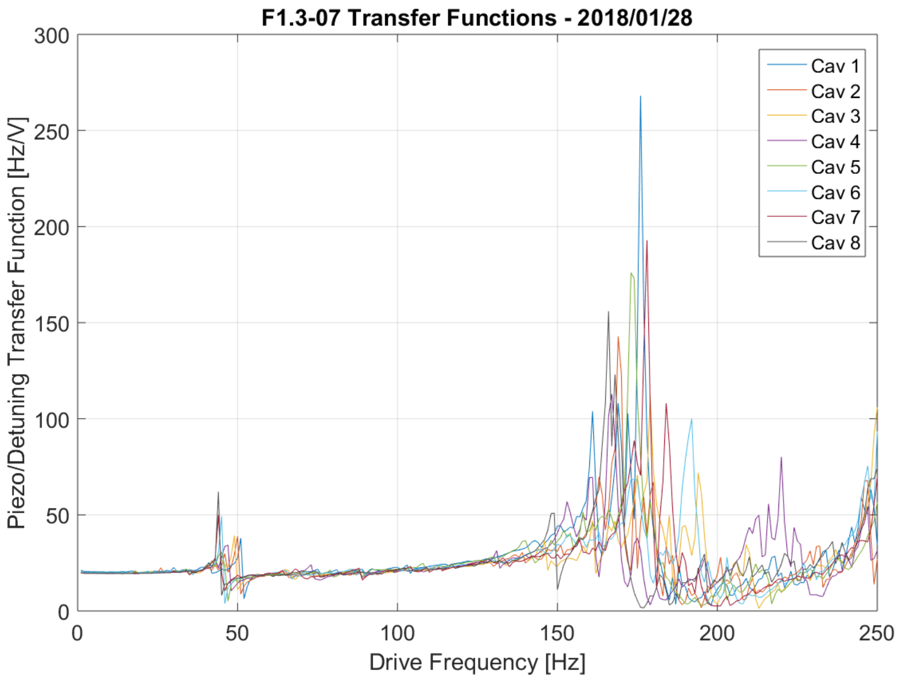



# Cavity 1 Mechanical Connections – Mitigation
## Beamline Gate Valve Flex Joint (no bellow)

- Assembled strings are impractical to retrofit with bellows
- Connection between helium vessel and tuner can be added with flex joints
    - Eliminates connection between gate valve and 300 mm pipe
    - Still uses long tuner arms and a fixture
    - Flexures spring constant can be adjusted if needed
- Installed on F1.3-04 and tested, *but without major improvement*



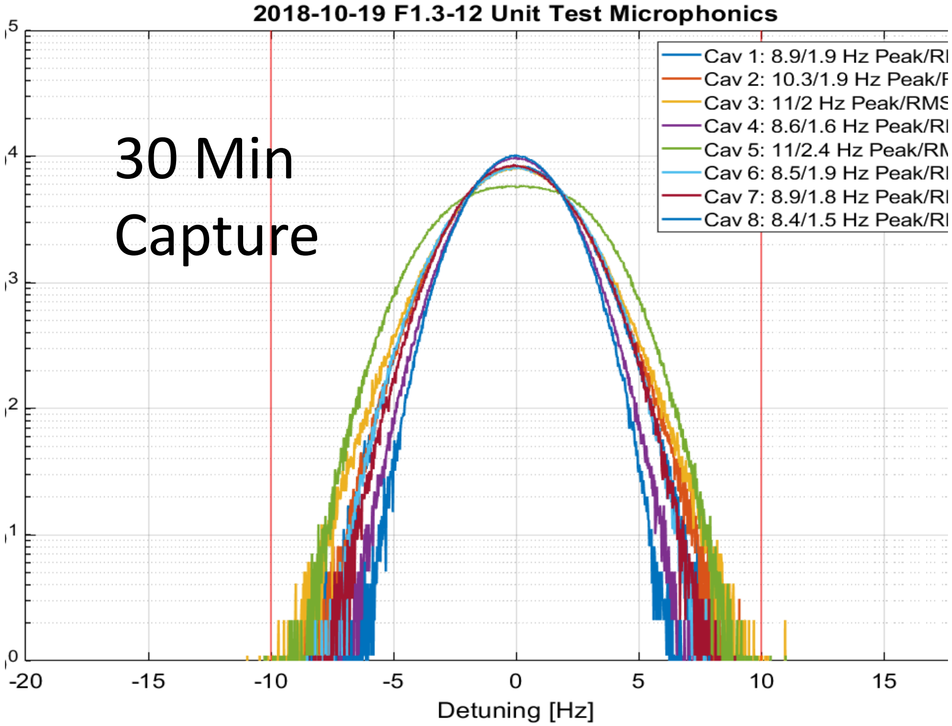
# Piezo/Detuning Transfer Function




- All eight cavities characterized by measuring piezo tuner transfer function to detuning
- Originally, cavity 1 had lower first resonance (~150 Hz compared to ~180 Hz)
- Bellows modification makes transfer function comparable to other cavities

# Cavity 1 Performance with Bellows

- Bellows gives significantly improved cavity 1 performance, relative to the other cavities
- The combination of cryogenic valve improvements and cavity 1 bellows has brought the microphonics levels to consistently at LCLS-II specification
- (Technically just above specification as very infrequent events exceed 10 Hz)
- GDR operation at CMTF has been maintained for >8 hours at gradient
  - Integrates all improvements on microphonics and LLRF control system



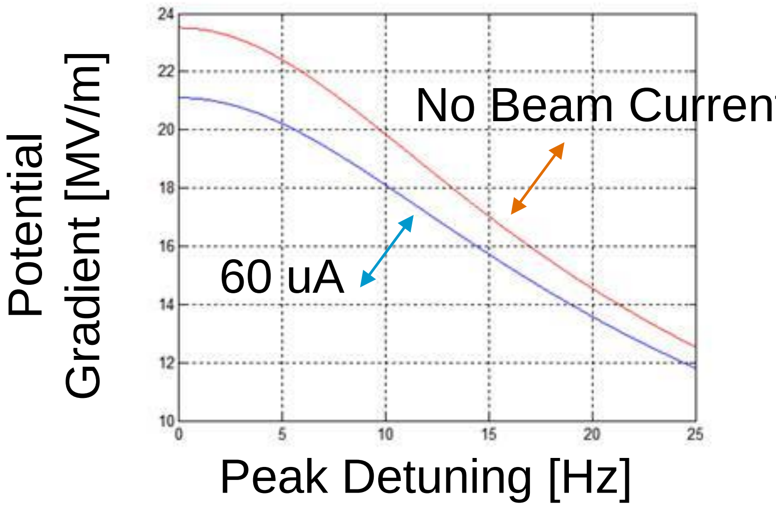
# Conclusions

# Other Mitigation Steps

- Other minor sources of detuning have been identified
  - 30 Hz line from Kinney Pump is significant contribution to detuning, but will not be present in the tunnel
  - Small lines are attributable to insulating vacuum pumping on test stand
  - Very small detuning correlated with supply pressure, flow rates, etc, but contribution is very small (<0.01 Hz RMS)
  - Cooldown effects are non-trivia, generally takes ~10 days before thermalization sources stop
- Other modifications were made in cryomodule assembly - the effects are unclear
  - Replaced JT injection line with injection tee to slow injection velocity and allow some initial phase separation
  - Audit of cryomodule and string resulted in many small restraints being added, tying relatively loose lines together to eliminate uncontrolled motion, putting spacers and shims to eliminate potential chattering
- Testing continues with good results
  - *Reversed valves, optimized stem wipers, cavity 1 bellow, and two-phase pipe baffles/vortex injection have been successful and will be used going forward*
- Results from JLab are in accord with FNAL results
- Continue to monitor microphonics with each test, but nothing new recently

# Machine Performance with Existing Detuning

- Estimates of machine performance given existing SSA power availability at 60 uA gives a tolerable RMS detuning value of 2.5 Hz (15 Hz / 6σ)
- Even including test stand effects (estimated at around 0.75 Hz RMS), enough RF overhead exists for 60 uA operation in recent test




| Cavity Number | Current RMS [Hz] |
|---|---|
| 1 | 1.9 |
| 2 | 1.9 |
| 3 | 2.0 |
| 4 | 1.6 |
| 5 | 2.4 |
| 6 | 1.9 |
| 7 | 1.8 |
| 8 | 1.5 |

Without Active Compensation

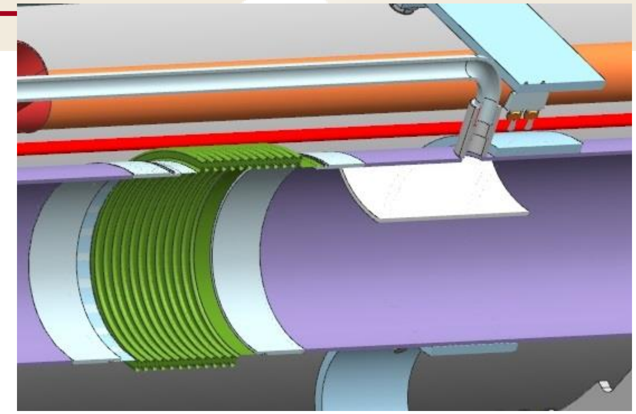
# Summary

- Early LCLS-II cryomodules showed significantly higher than expected microphonics
- A cross-disciplinary working group was formed to implement testing and mitigations
- Significant progress has been made diagnosing and mitigating microphonics issues
  - Testing shows factor of ~10-15 improvement in microphonics
  - Active compensation studies show good progress proceeding on remaining microphonics environment
- <u>The cryo-mechanical improvements and active resonance control system have demonstrated 10 Hz peak detuning</u>

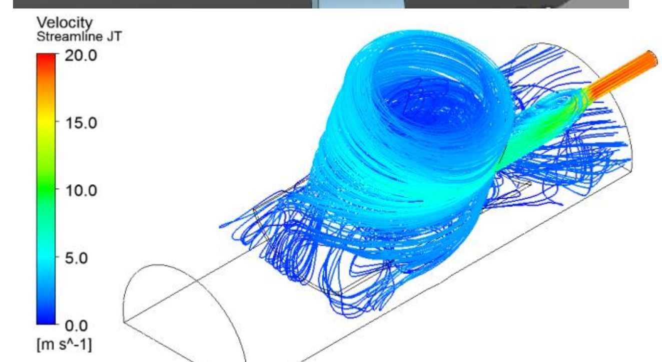
# Backup Slides

# Mitigation Steps in Cryomodule Design – 2 Phase Injection

- Liquid level control was coupled to input flow rate and the amount of flash gas generated across JT valve
  - Helium injection line impinged on liquid surface
  - Flash gas from JT caused liquid dragging
  - CM2 has baffles to protect liquid surface
  - CM3 has tangential injection into cap to reduce velocity and allow phase separation in addition to baffles
  - Should greatly reduce liquid dragging and improve liquid level stability, especially at high flow rates
  - Fluid simulation gives good confidence in improved injection behavior



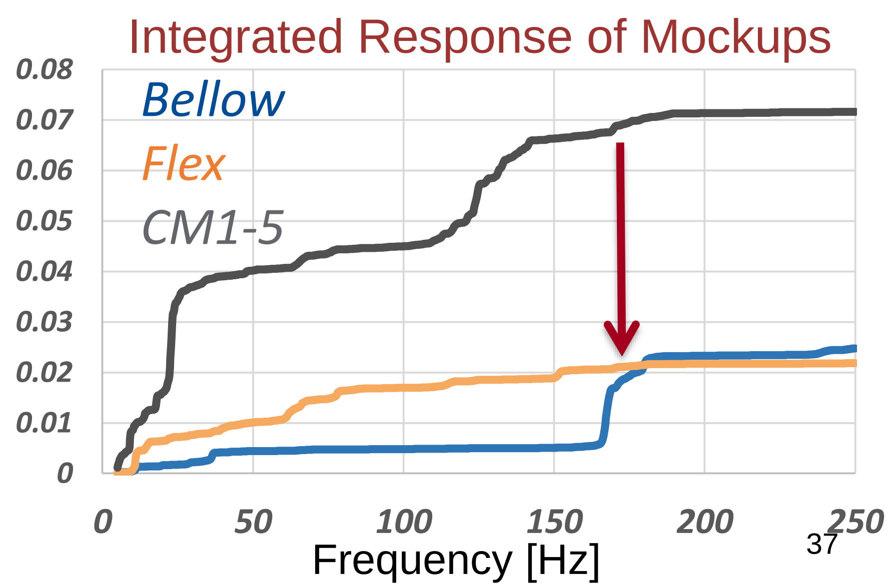
CM2




CM3

# Cavity 1 Mechanical Connections - Studies

- Mockup testing showed solid connection between upstream of Cavity 1 and beamline gate valve significantly increases Cavity 1 sensitivity
- Two mitigation options have been designed and tested in mock-up showing promising results
  - Replace spool piece with short bellows and support gate valve with helium vessel
  - Connect gate valve to helium vessel with controllable flexure (potential retrofit for assembled modules)

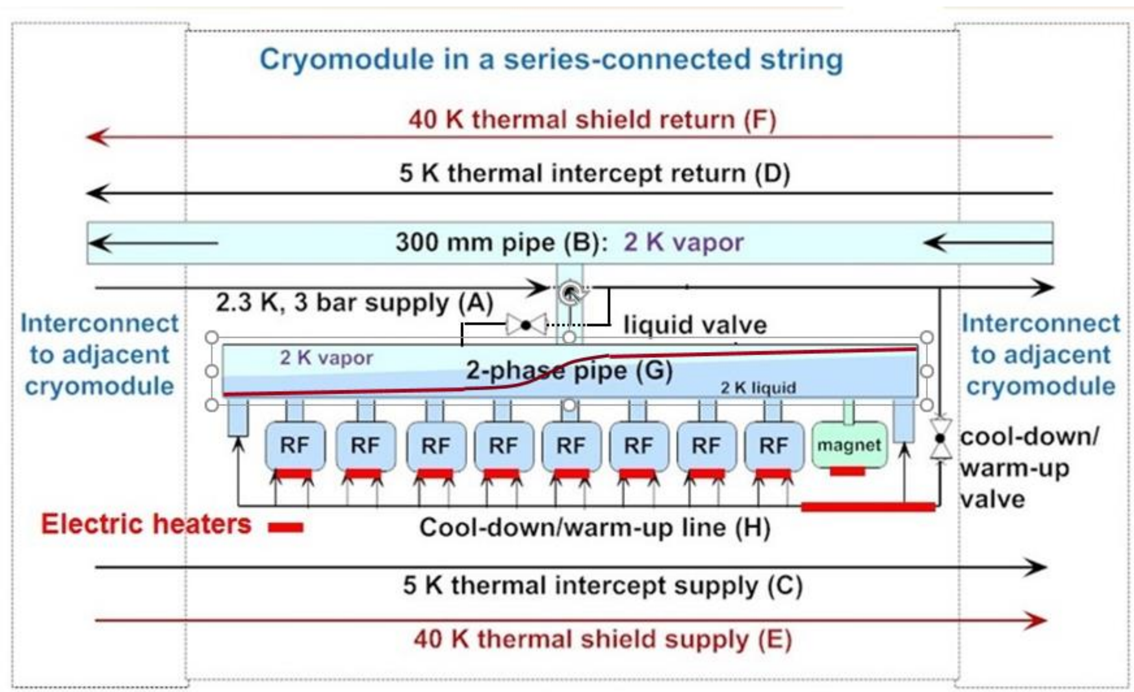
# High JT Flow Rates

High JT flow rates (high JT inlet temperature leads to lots of flash gas) gives large flow velocities (up to 70% of the speed of sound!).

JT injection hits directly on liquid surface (changed already in CM2).

The flash gas must escape to chimney, and this will push liquid downstream.

Remember that the upstream side is higher than the downstream side.

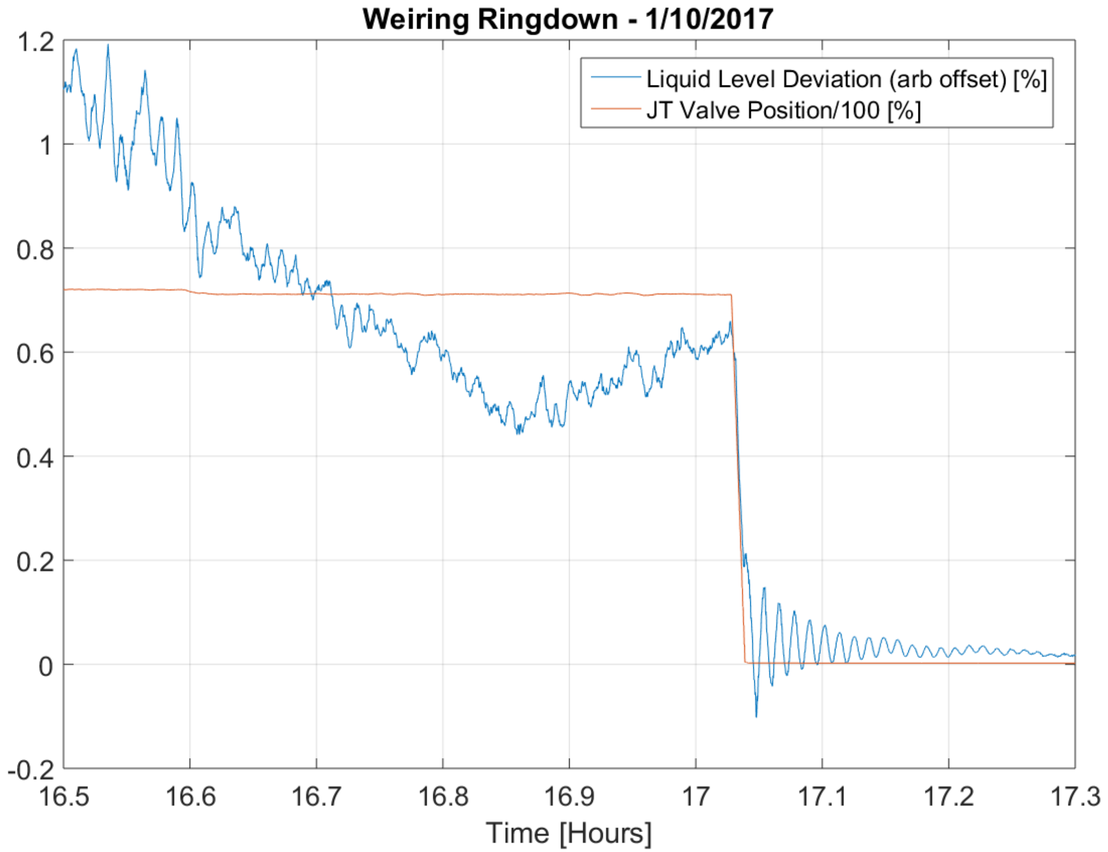


# Sloshing Mode in the 2-Phase Pipe

Changing the flow from JT to Bypass meant significantly reduced gas flow in the 2-Phase pipe.

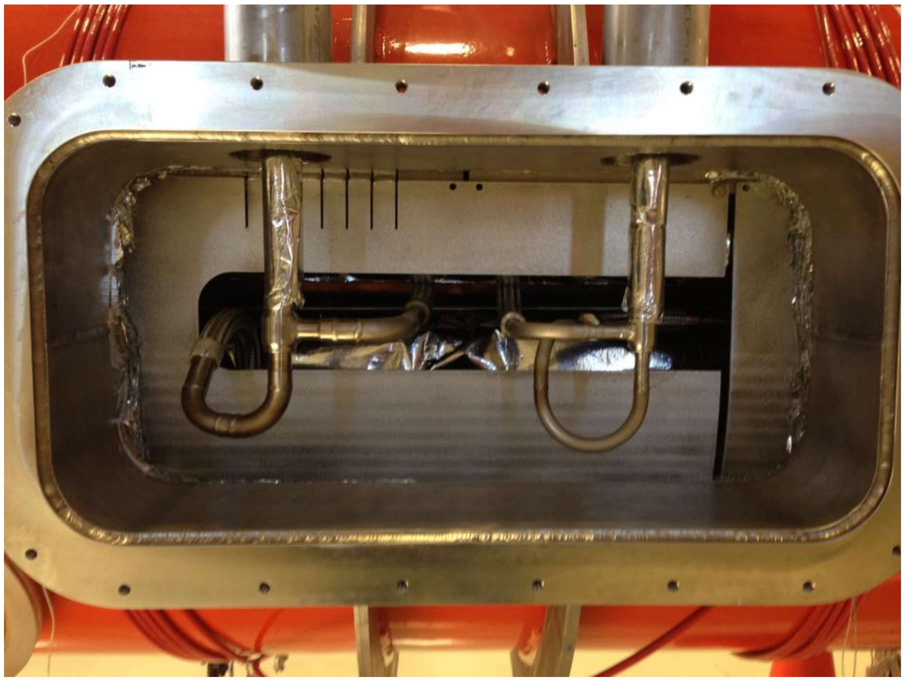
When the JT is closed, the difference between Upstream and Downstream liquid level suddenly changes, rings down to a stable (hopefully level) point (40 second period).

This couples liquid level and flow rate, complicating control.






Fermilab

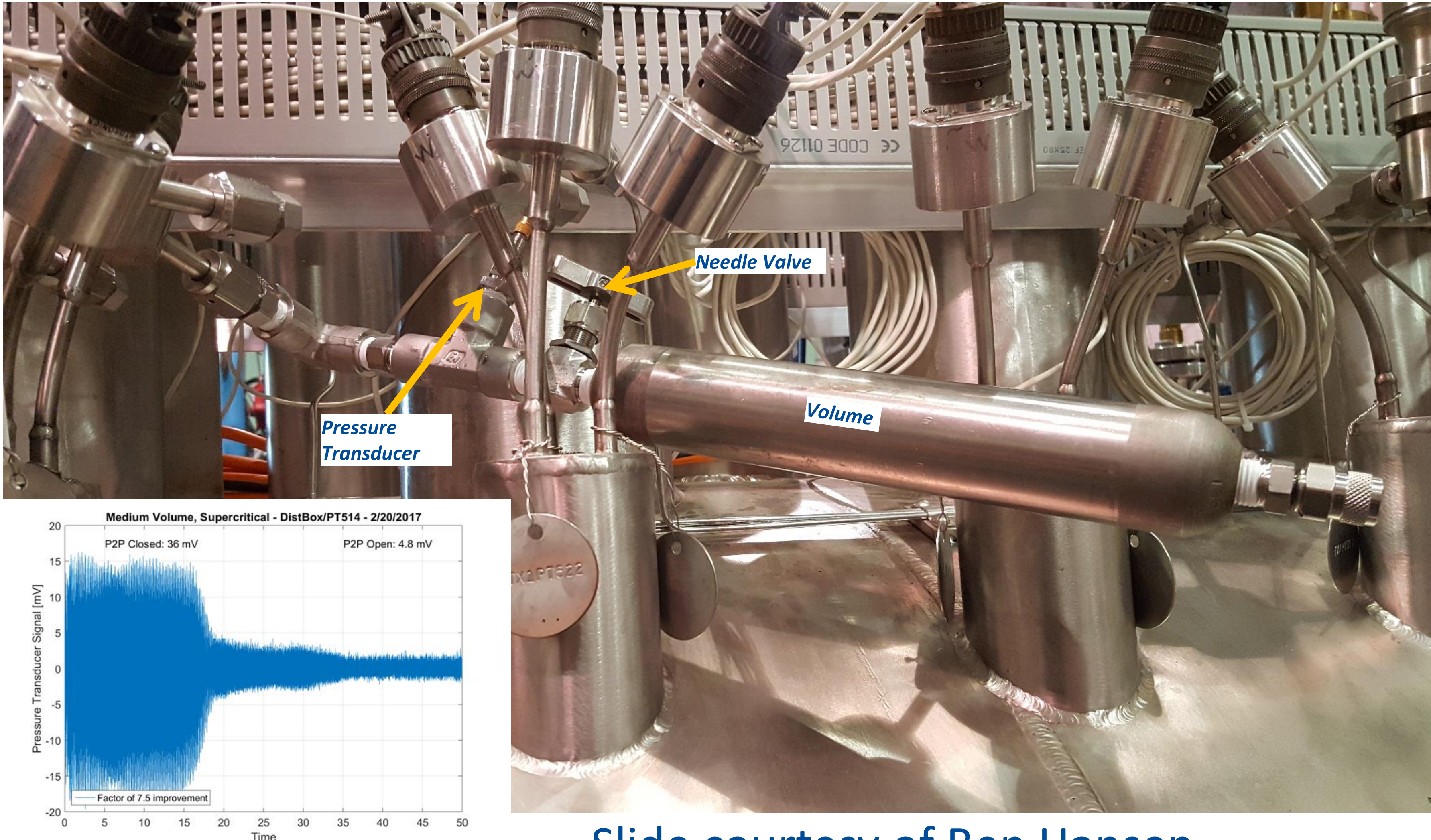


Normal Direction

Reverse Direction

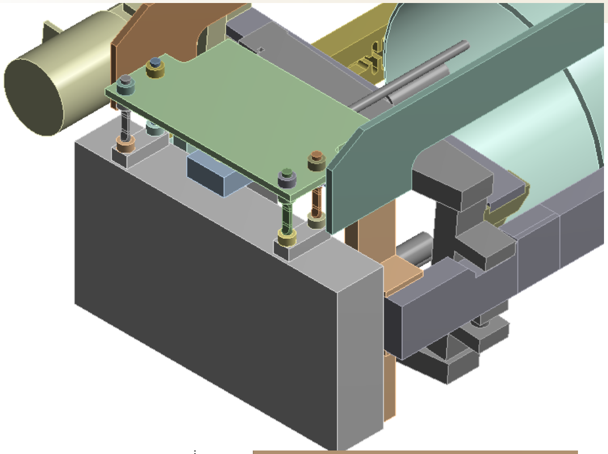
From Chuck Grimm

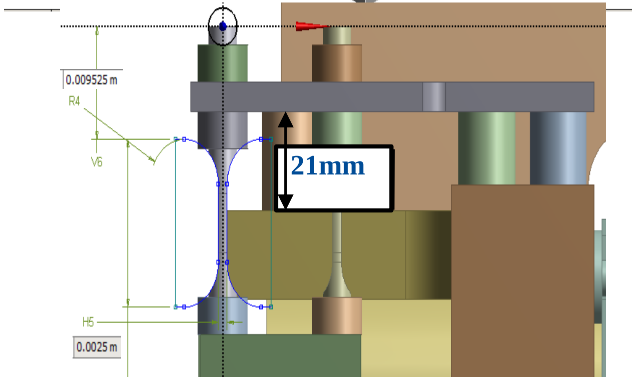
# Cryogenic Distribution Improvements




Slide courtesy of Ben Hansen

# Cavity#1 Tuner performance study (F1.3-04)






Estimated stiffness of the flex **~3kN/mm**
That is in addition to 3-4kN/mm (cavity+bellow)
Tuner installed on the cavity #1 will work against **7kN/mm** stiff system.

- Cavity #1 after cool-down to 2K landed at frequency F(2K)=1.300.149kHz

  Taking into account initial (during assembly) preload ~100kHz
  Cavity compressed on (149kHz+100kHz)/300KHz/mm~0.8mm.

- Cavity + flex loaded each piezo-capsule on 2.8kN (blocking forces 4kN)

  ~7kN/mm*0.8mm=5.6kN

- Measured at 2K piezo stroke for modified cavity#1 was **19.3Hz/V.**

  Average piezo stroke for cavities #2-#8 was **21.7Hz/V**

- Measured Cavity#1 Transfer Function confirmed that Flex GV support + extended tuner arms system did not introduced any low frequency (below 150Hz) mechanical resonances.

**Summary**
**New Flex GV support + extended tuner arms system did not compromise tuner performances.**

# Cooldown Leakage Theory

Leakage through the cooldown valve was verified by isolation of 2K supply upstream

Gas flow through cooldown circuit caused unexpectedly narrow frequency lines which has been identified as streams of bubbles

Gas flow as a cause was determined by large harmonics of these lines and complex spatial dependence upon perturbation as gas flow shifted around module