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Interdisciplinary Challenges of SRF Cryomodules

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FRIB-APES Seminar

November 18th, 2022

Outline

- What IS an SRF Cryomodule, and why is it so complicated?
- How does this complexity impact final delivery and performance?
- Examples:
  - Stability of LCLS-II cryomodules (microphonics)
  - Transportation for LCLS-II (failures and successes) and planning for PIP-II
- Successful strategies for facing challenges (organizational, strategic, technical).

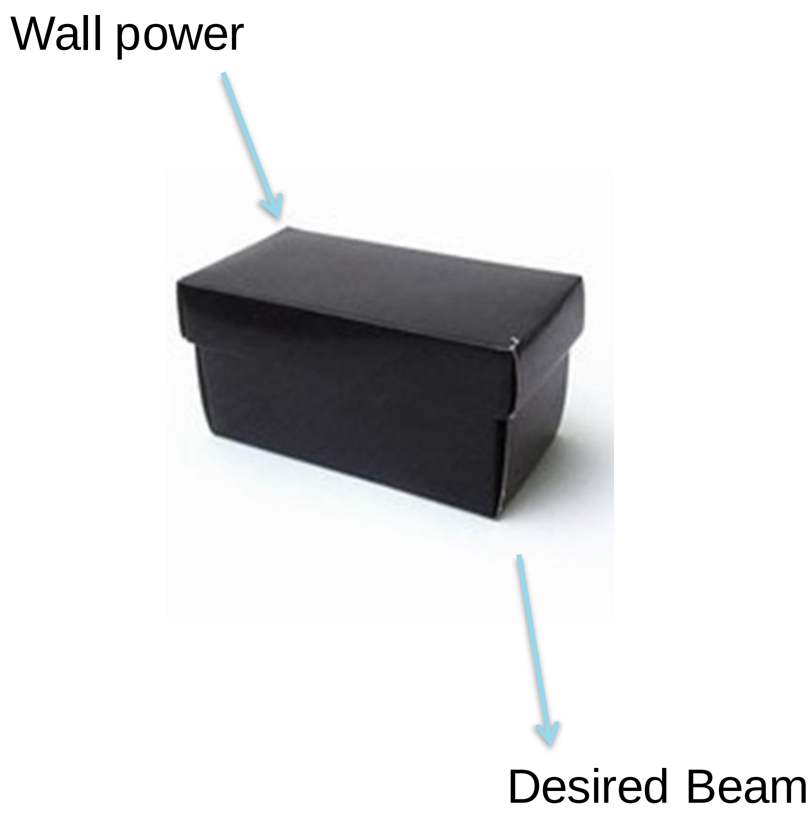
- Caveat: I'm focusing on Cryomodules, making a whole linac/accelerator is 10x more complicated. Also, I'm an RF guy; magnets are going to get short shrift, sorry.

What IS an SRF Cryomodule, and why is it so complicated?

High Energy Particles

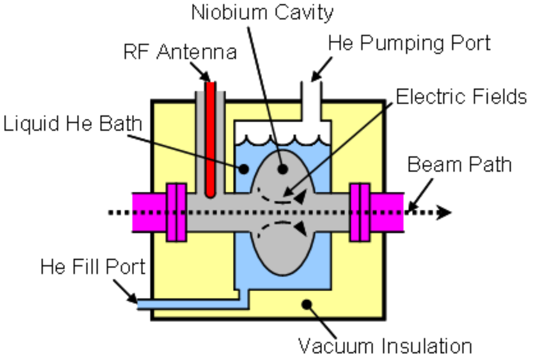
- What does the science want?
  - More Energy!
    - Different science available
  - Controllable/Tunable Energy!
    - Dynamic behavior studies
    - Fine structure investigations like resonances
  - More Intensity!
    - Take data faster
    - Study rare processes
      - Rare isotopes
      - Neutrinos
      - Rare particle decays
  - Variety of Particle Beams!
    - The ability to create and use beams of any element/isotopes

- What do they REALLY want?

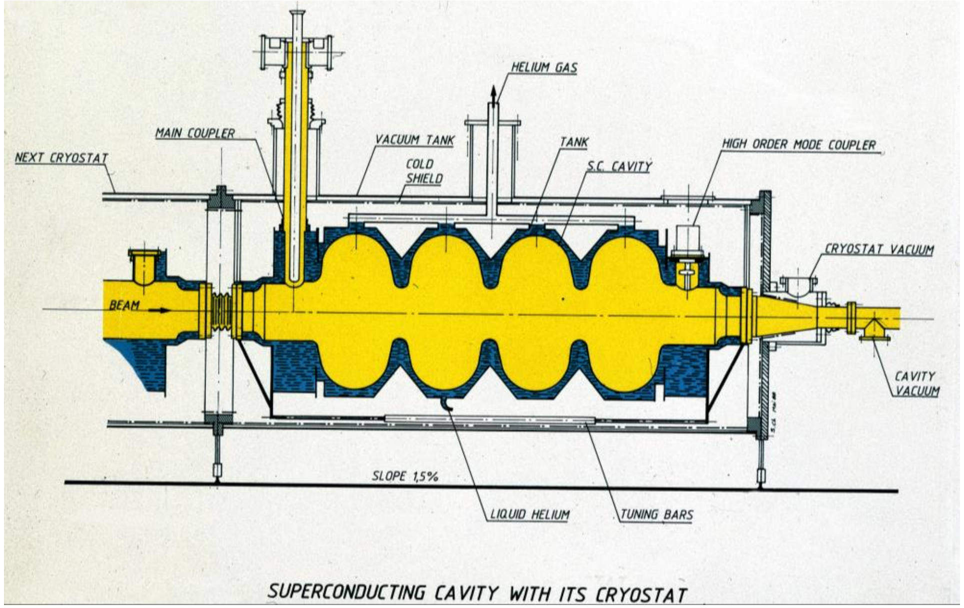


SRF Cryomodule (According to Wikipedia)

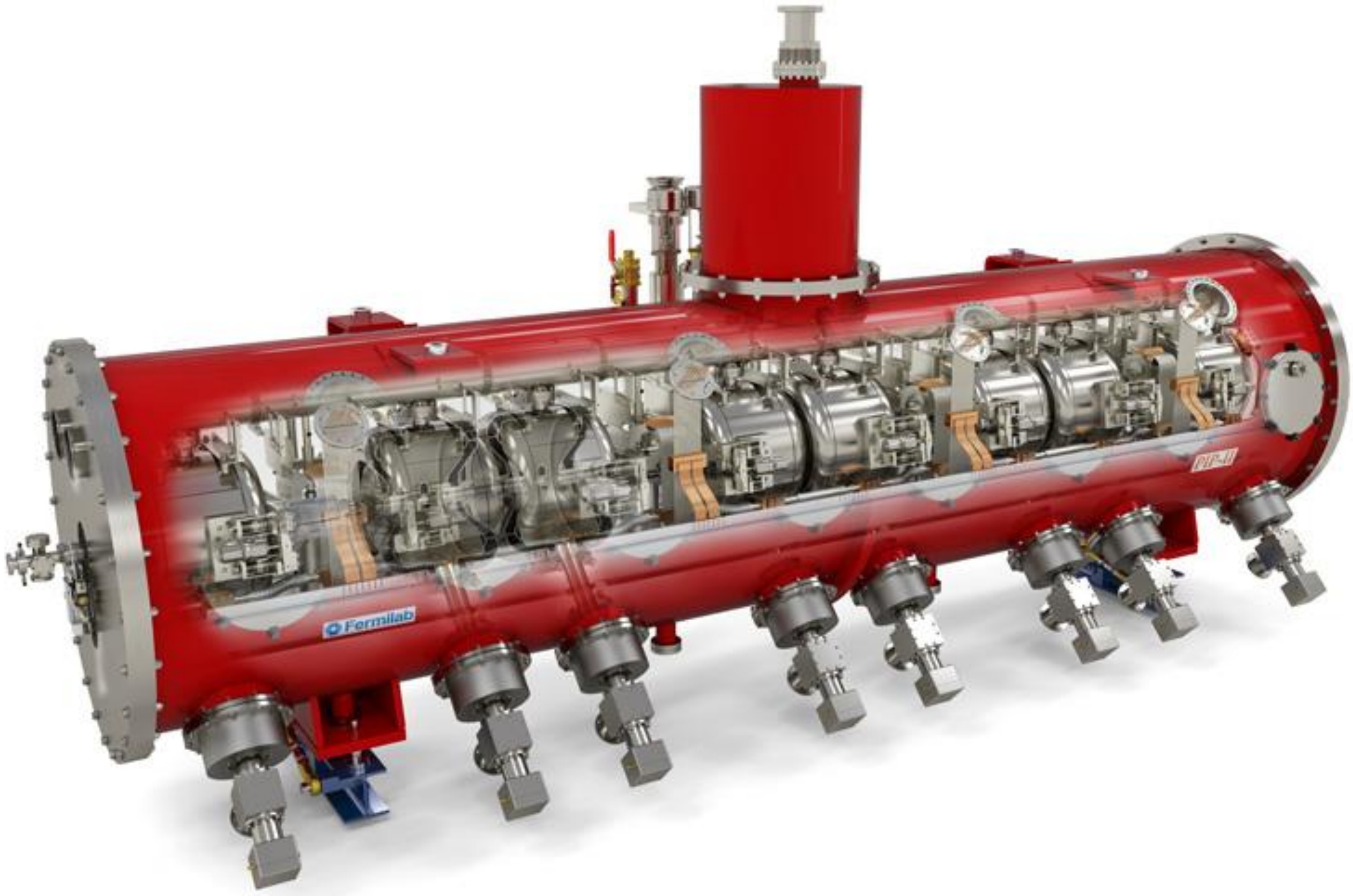
- The minimum criteria:
  - SRF Cavities (including coupler)
  - Cryogenic Vessel, insulation, fill and pumping
  - Beampipe
- Even in the broadest sense, what is needed to make build a particle accelerator? Electric and Magnetic fields.
- Many young scientists are trained this way (I do it myself), start from the RF cavity outward:
  - Maxwell leads to Helmholtz
  - Boundary conditions lead from waveguide to resonant structures
  - Coupled modes, tuning, bead pulls, coupling
  - Thermal breakdown, surface properties, material treatment, high pressure rinsing, etching, baking, doping
- All important, but not the whole picture



https://en.wikipedia.org/wiki/Cryomodule



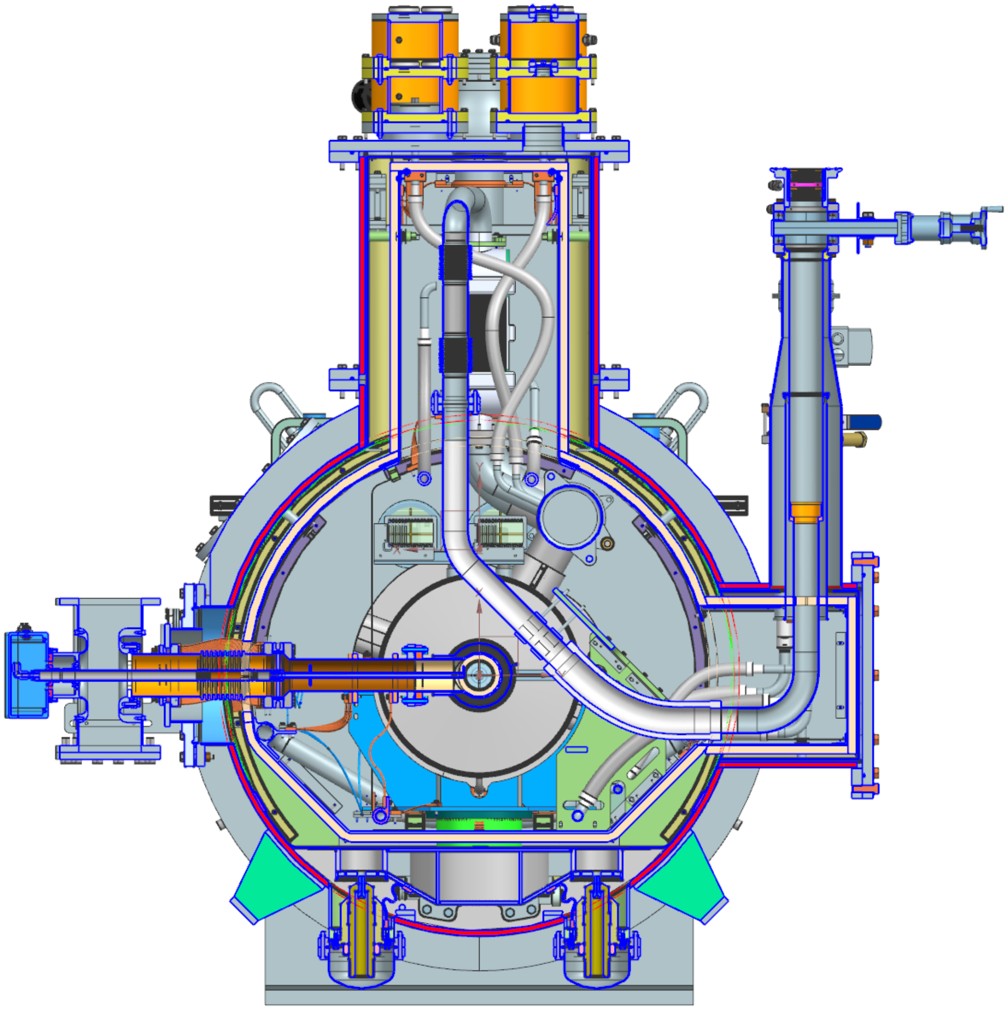
SSR1 Cryomodule (PIP-II)



HB650 Cryomodule Cross-Section (PIP-II)

High power RF couplers are a great example of the real complexity:

- 300K to 2K transition
- Clean Vacuum to Air
- High power RF (kW to MW)
- Thin-walled bellows and copper plating
- Ceramic Windows
- Thermal intercepts, static/dynamic heat loads
- Significant alignment, contraction, movement requirements
- Challenging assembly



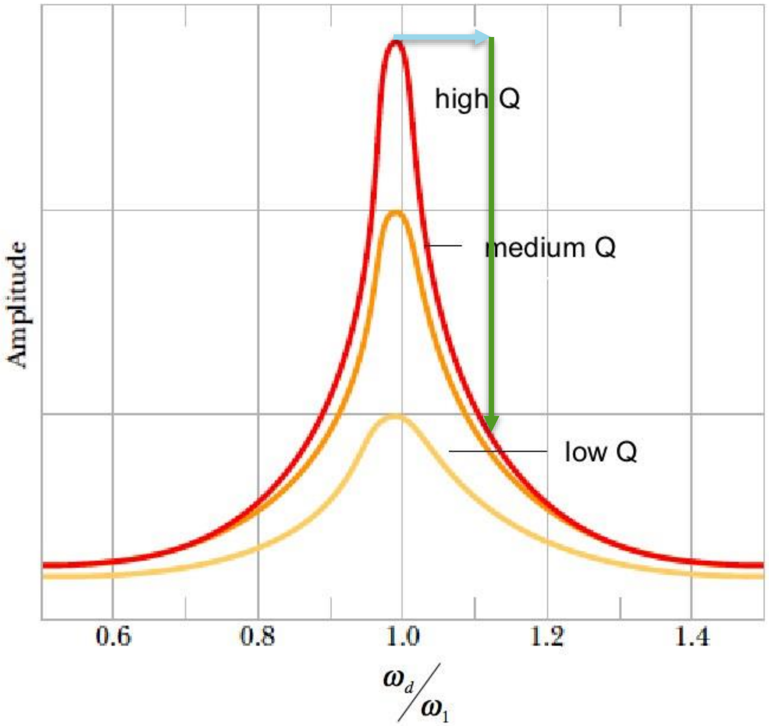
What is an SRF Cryomodule?

- A device that allows SRF cavities and superconducting magnets to accelerate/guide particle beams
- Why is it complicated:
  - Massive thermal challenges (minimize static heat leak, effectively manage dynamic heat load)
    - Ignoring complexity of Cryoplant and CDS!
  - Must preserve clean vacuum
  - Mechanical complexities (thermal contraction, alignment preservation, stability)
  - Enormously complex assembly process
  - Must integrate safety: pressure vessels, vacuum vessels, cryogenic circuit relieving, rigging and handling, transportation
  - Detailed instrumentation installation, wiring, and feedthroughs

How does this complexity impact delivery/performance?

Unintended Consequences: Vibration and Stability

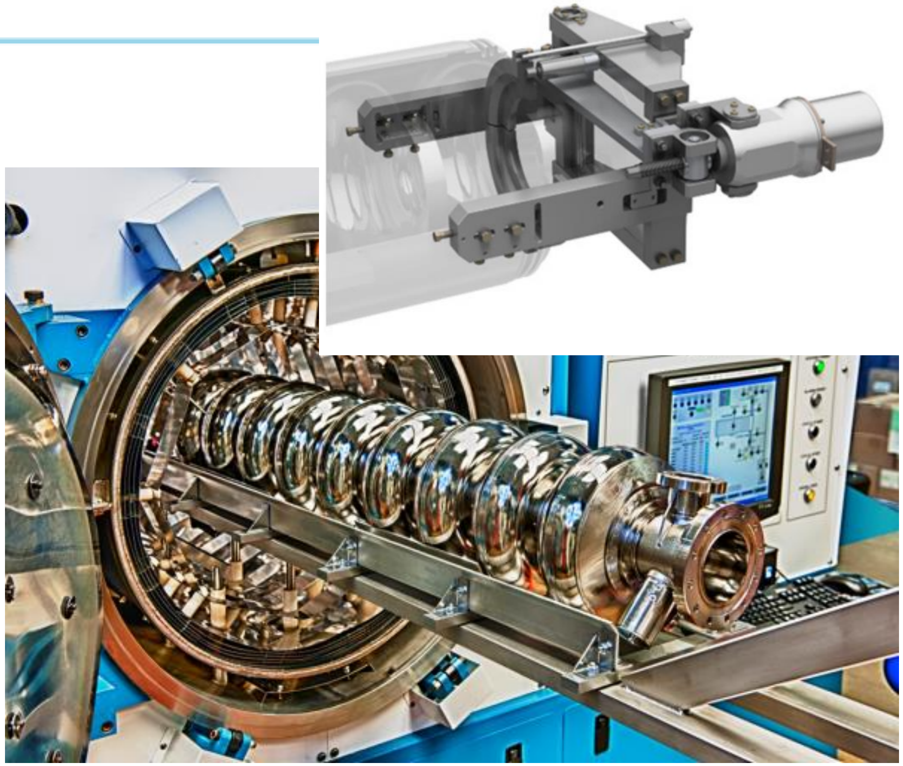
- SRF cavities are well modeled as coupled harmonic oscillators with extremely high quality factors/low damping coefficients
- Remember: Acceleration of particles requires tight timing synchronization of all components and amplitude regulation
- Thus, cavities are driven at design frequency and must be forced, with complex RF control systems, to stay at phase and amplitude required for acceleration
- RF power is limited (and expensive!)
- **Why would a cavity change frequency?**



If the cavity shifts frequency from design (blue arrow), the response drops (green arrow). The cavity must be driven harder to maintain field at the cost of RF power.

LCLS-II Cavity Microphonics

- Cavity frequency is proportional to length (in this case)
- Optimization for LCLS-II gives enough RF power to control only ~13 Hz of detuning of the cavity
- $\frac{\Delta \mathrm{f}}{\mathrm{f}} \approx \frac{\Delta L}{L}; \frac{13\ Hz}{1.3E9\ Hz} \cdot 1m \approx 10\ nm$
- At this level, many effects are very significant (*pressure*, temperature, dielectric constant, *resonant excitation*)
- Slow pressure control is generally quite good, *but fast pressure waves and mechanical vibration can have significant effects on cavity resonance*



Bare LCLS-II 1.3 GHz cavity after baking (lower), model of LCLS-II cavity end-level tuner (above)

LCLS-II pCM Testing at FNAL (~2017)

LCLS-II pCM Microphonics

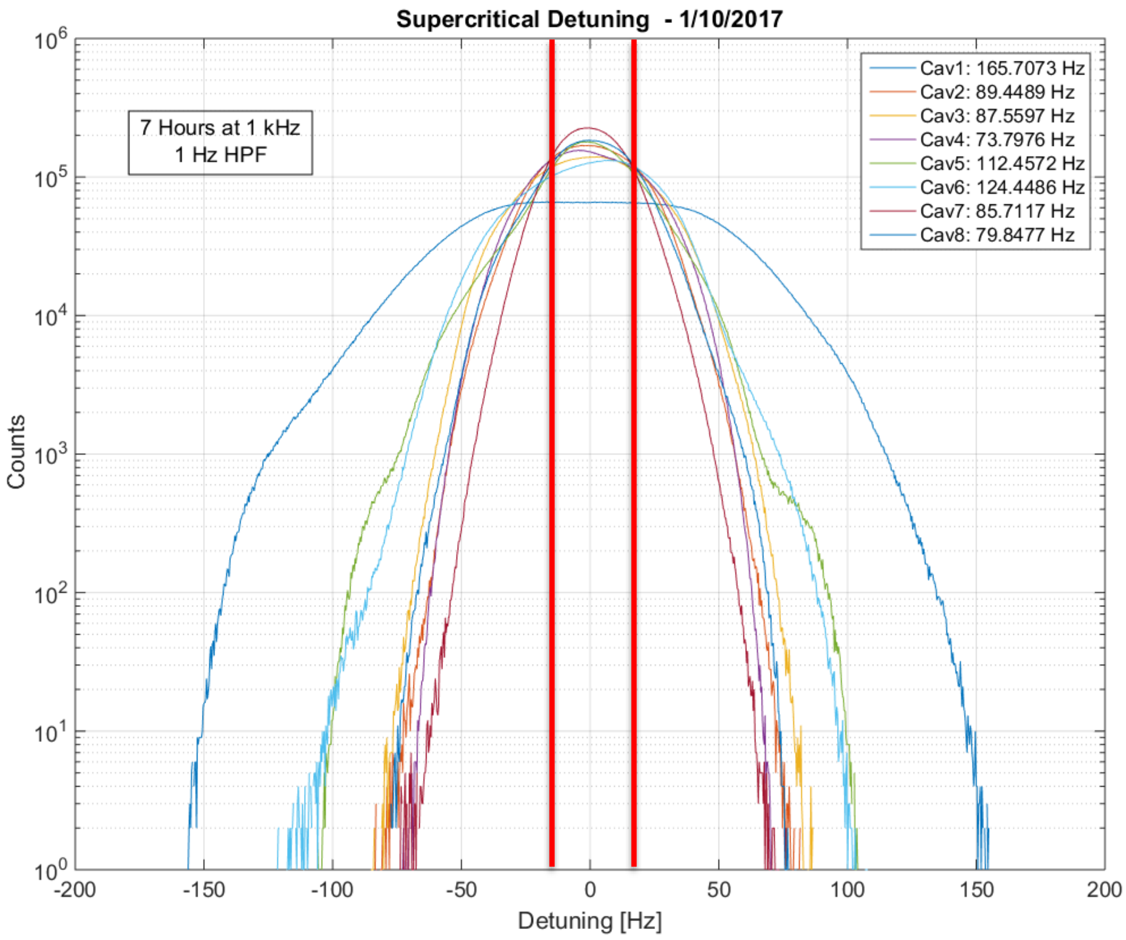
Capturing microphonics of all 8 cavities in SEL

Many acceptance criteria can be satisfied in this condition (gradient, Q0, coupler, heat loads), BUT:

This cryomodule ‘as is’ would be *non-functional* in the machine.

Working group formed, about a dozen people, all stakeholders included in a strongly collaborative effort.

-RF, Cryo, Mech, Vacuum, Controls, LLRF, HPRF, Instrumentation, etc.

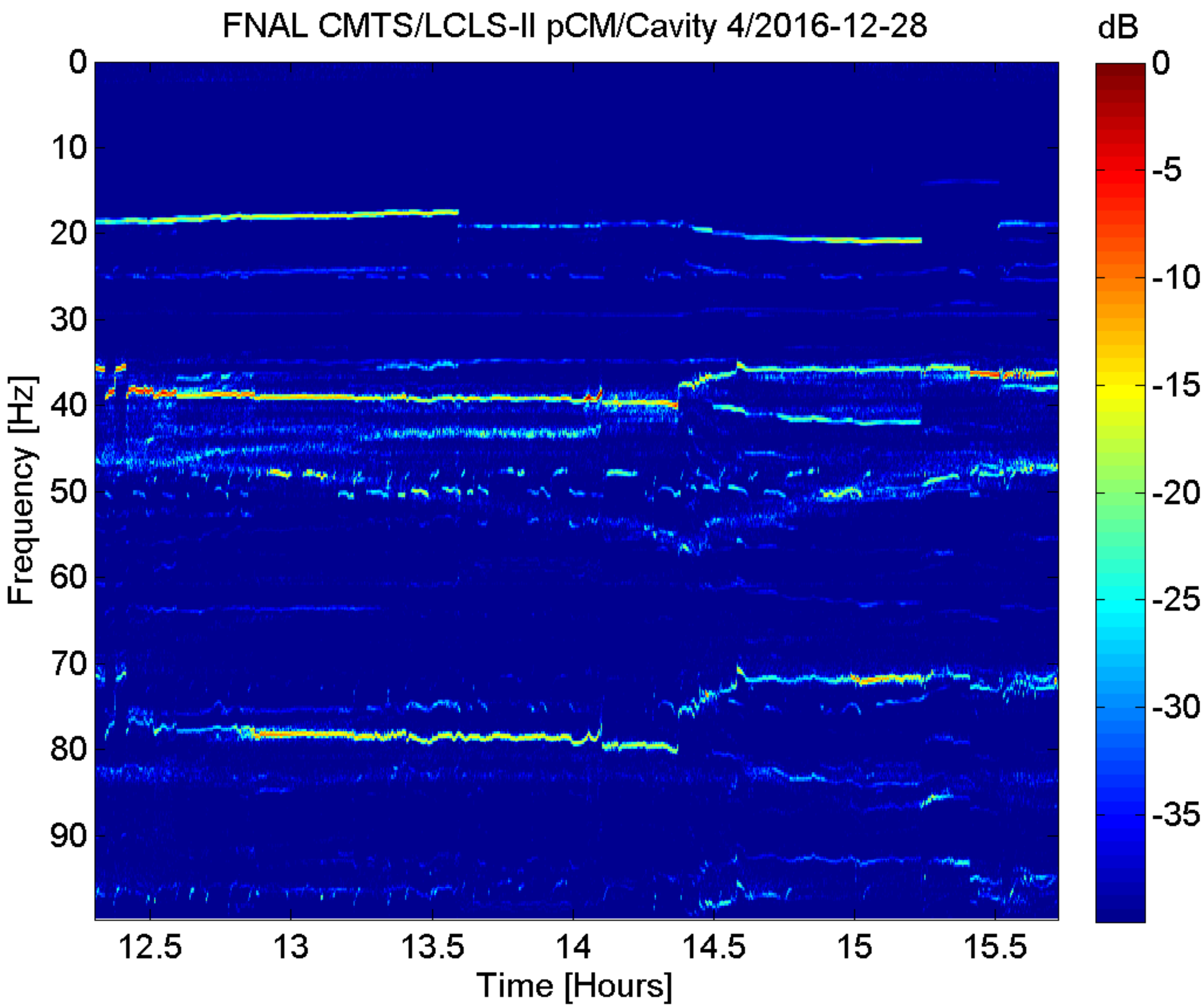


Many Avenues of Attack

- Cryogenic Concerns
  - Liquid quality/High gas velocities
  - **Thermo-Acoustic Oscillations**/Valve Icing
  - Weiring (liquid drag)
- Mechanical Concerns
  - Ground motion studies showed no sizable external vibrations.
  - Impulse testing could not be correlated with detuning
  - Why is cavity 1 worse?
- *TAOs are generally important for the tremendous heat leaks they can represent, not microphonics.*

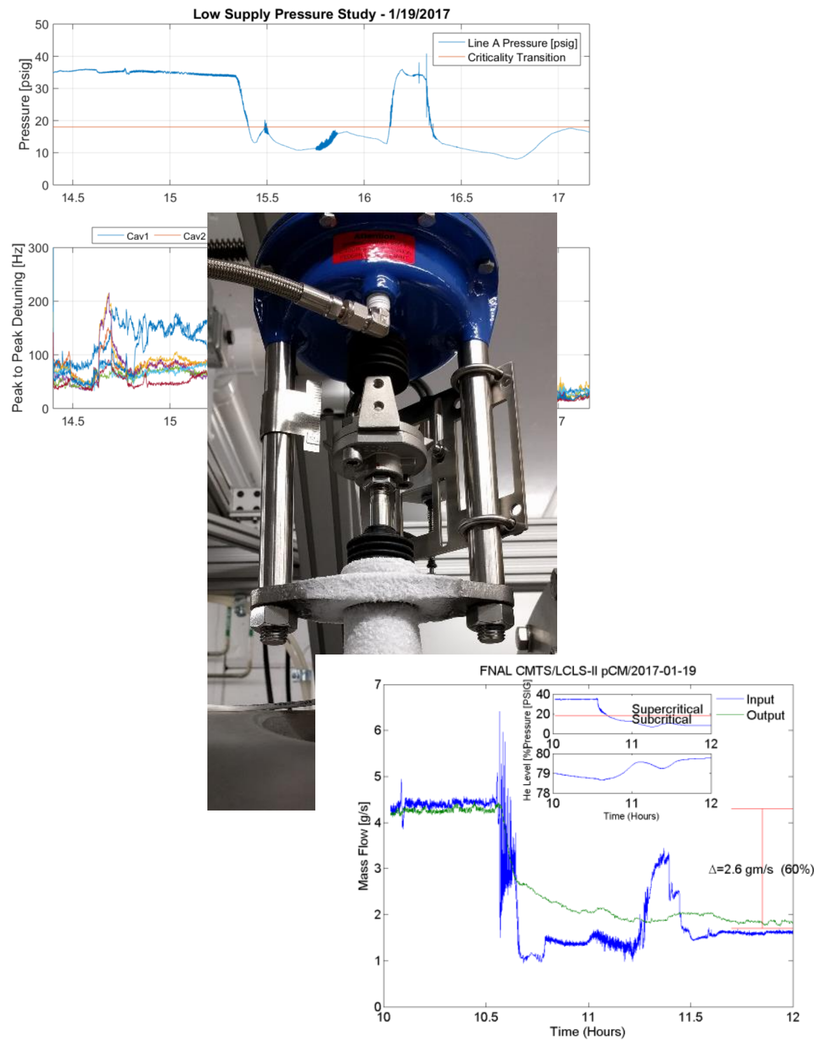
Dynamic Frequency Behavior

- Vibration lines shift rapidly frequency and amplitude
  - Not mechanical resonances
  - Narrow-band cryogenic source(s) exciting wide-band, low frequency mechanical response

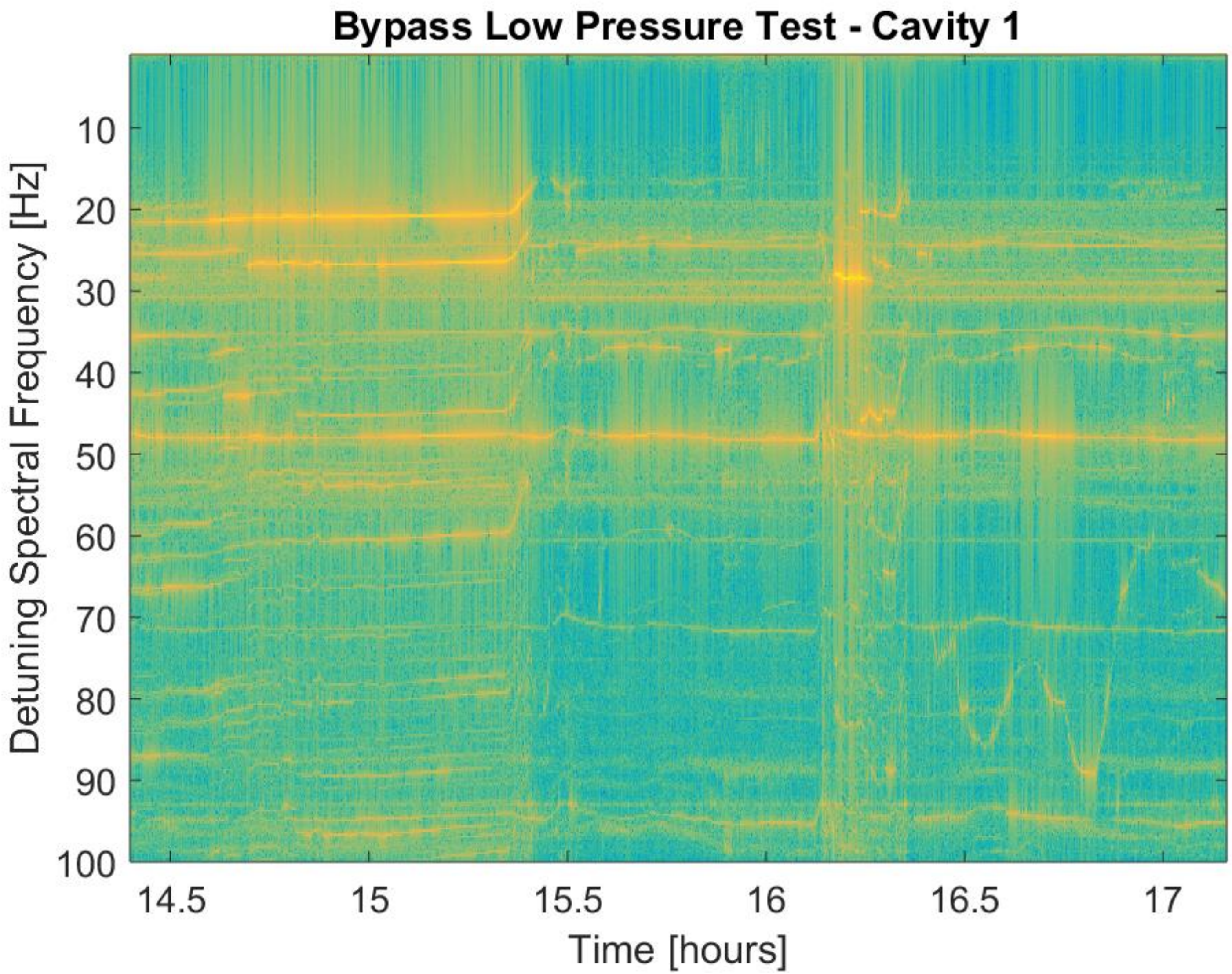


Low Pressure Tests

- Breakthrough occurred during a liquid level test (supplying via bypass valve), several minutes of ‘quiet’ were seen.
- Ben Hanson of AD-Cryo correlated this quiet with the transition to sub-critical supply pressure.
- Sub-critical via bypass and JT valves:
  - Vibration levels remained at low levels over a period of several hours
  - Ice on the head of the supply valve melted (both JT and bypass)
  - Helium consumption levels were lower than during comparable tests at super-critical injection pressures
- All three factors point to thermal-acoustic oscillations excited by the high pressure helium at the JT valve inlet



Critically Transition



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.*

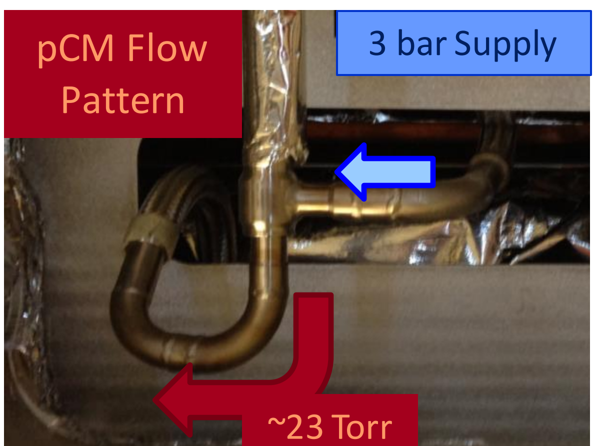
Cryogenic Valve Plumbing – Improved Valve Stems

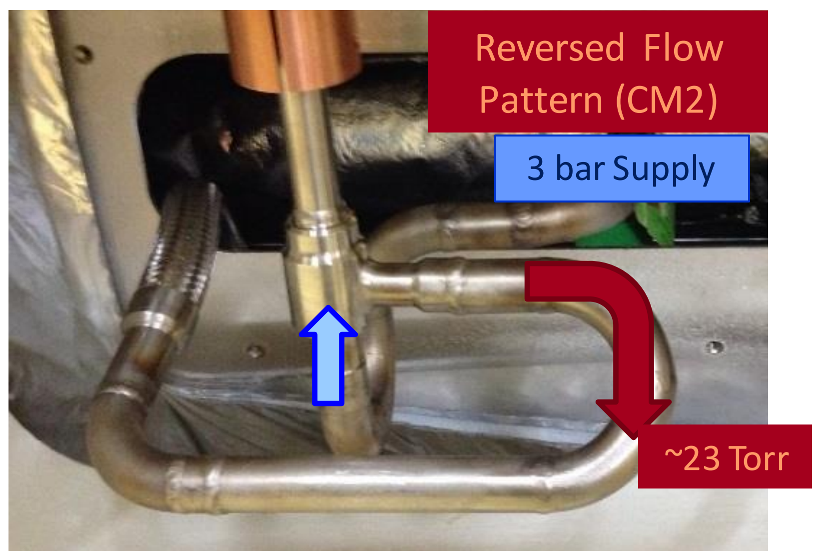
- TAOs are a pressure/temperature oscillation in cryogenic lines (in this case, valve stems)
  - During testing, wipers were added to close space in valve stem, acting as a damping term for the TAOs
  - Significant improvement in heat load and microphonics levels and stability
  - Optimized valve stems with wipers were used on all cryomodules
    - 4-5 wipers, positioned to keep temperature ratio <4 as recommended by literature
    - Radiation hard material (PEEK)

Optimized wiper placement going forward

Cryogenic Valve Plumbing – Reverse Flow Path

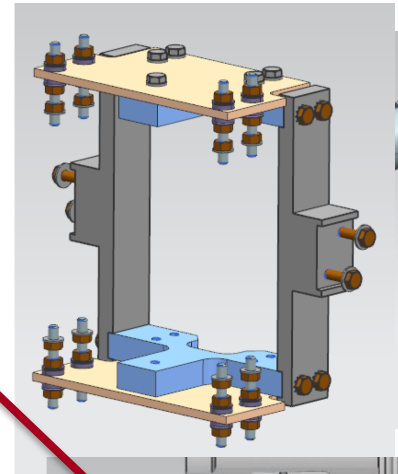
- Test results show valve reversal (lower press in stem) significantly reduces/eliminate TAOs there
  - F1.3-01 configuration has valve stem at supply pressure (~3 bar)
  - Reversing flow will lower this pressure to sub-atmospheric, requiring guard gas to prevent contamination
  - All cryomodules will 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) after latest test

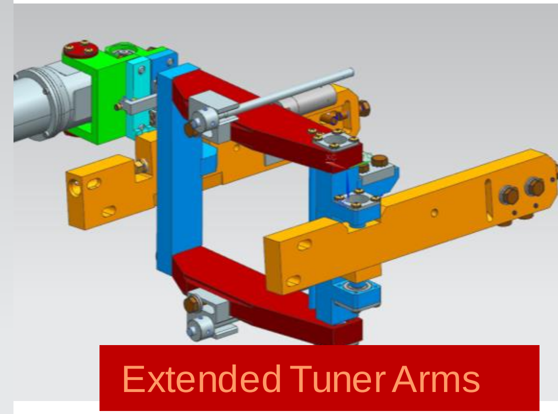


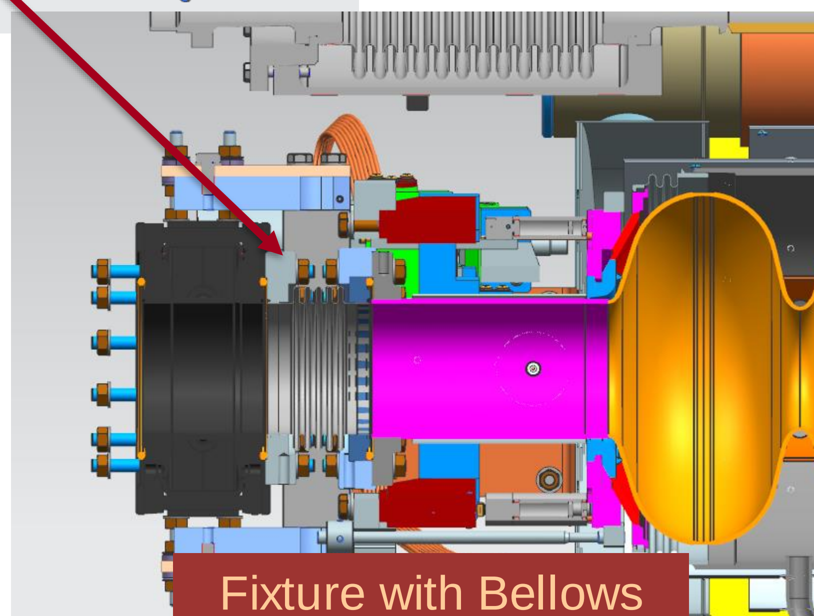


Cavity 1 Mechanical Connections – Mitigation
Beamline Gate Valve Bellows

- 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
- Two cryomodules with bellows have been tested at FNAL (F1.3-06/07)

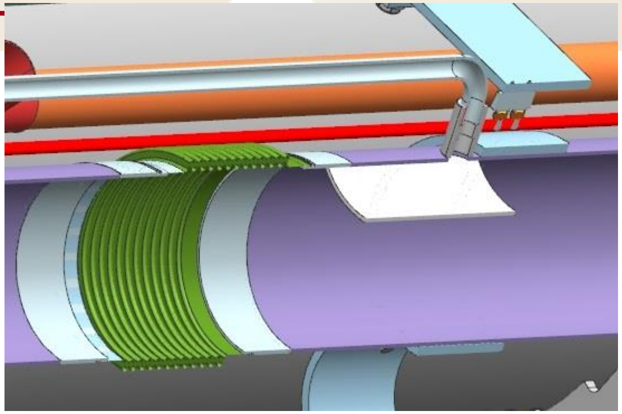




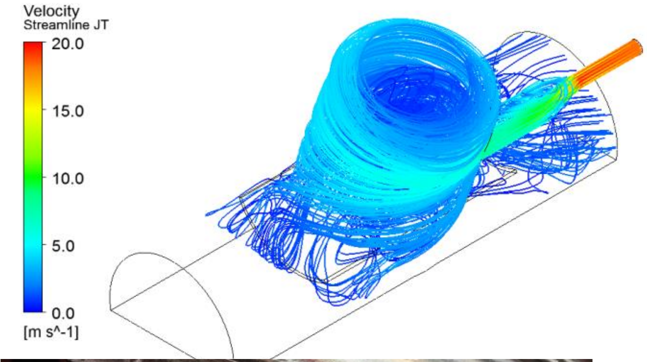


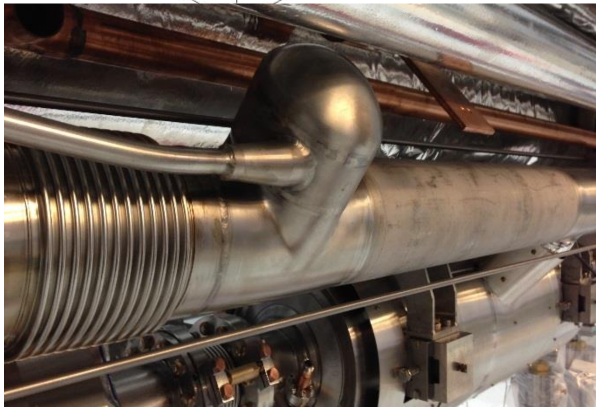
Mitigation Steps in Cryomodule Design – 2 Phase Injection

- 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

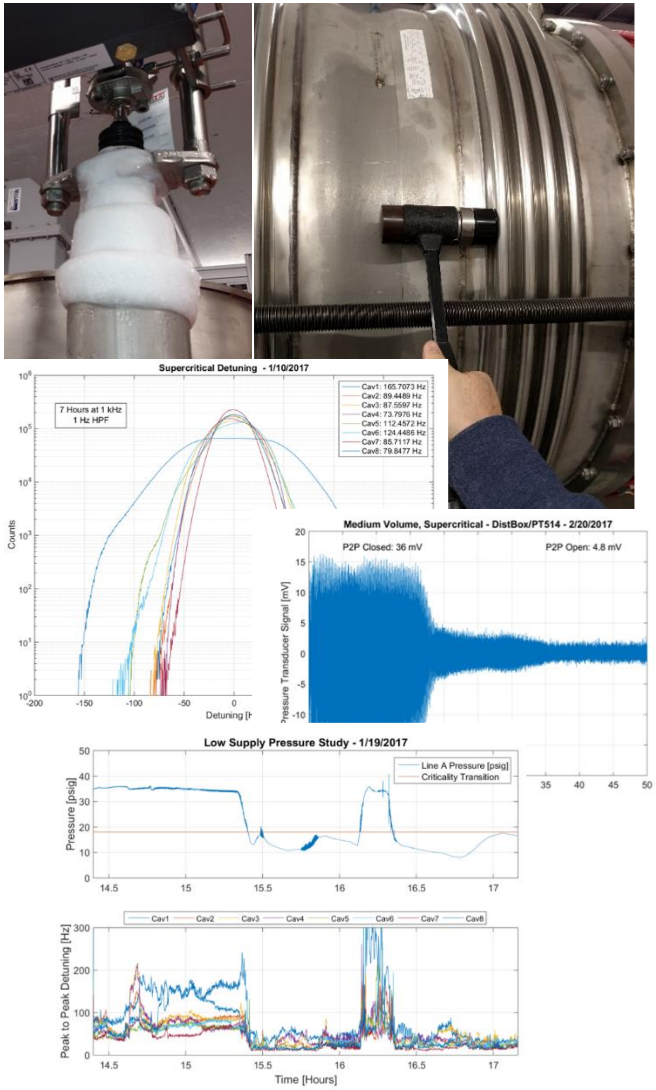




CM3

Mitigation Diagnostic Tools

- Significant testing effort was spent on microphonics mitigation
- This effort built up a sizable infrastructure of testing tools and techniques
  - LLRF data capture system allows capture of simultaneous detuning on all cavities for long times
  - Scripting has been built out significantly to process and analyze this data, and expertise has been spread to multiple people
  - Can be correlated many sources of data via ACNET:
    - Impact/Vibration Measurements
    - Temperatures, Pressures, etc. from instrumentation
  - On-site, expert cryogenics support and flexibility are powerful diagnostic tools, allows testing in different cryogenics configurations
  - Leveraged significant work done at both labs on vibrational design and testing as a baseline



Unintended Consequences: Superfluid Acoustics

For active compensation purposes, we took many piezo to detuning transfer function

Mysterious 45-55 Hz lines on all cavities resisted explanation

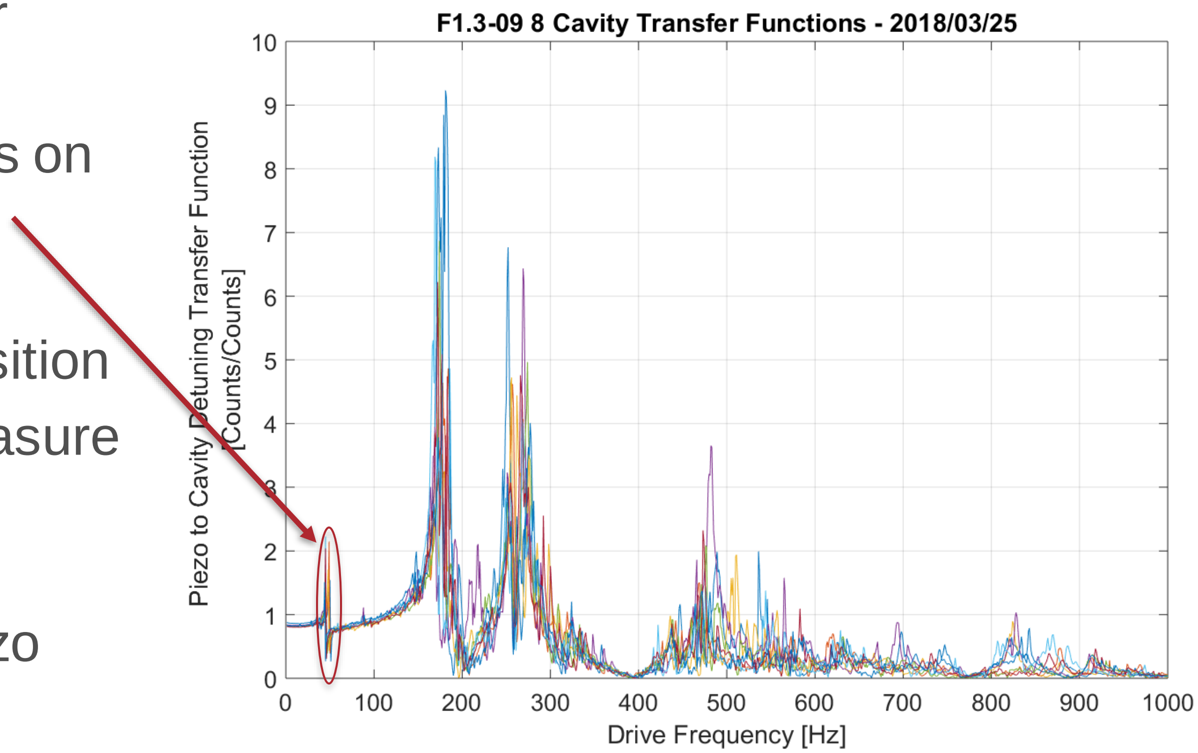
-Dependent on cavity position

-Very high Q, hard to measure exactly, and seemingly variable in frequency

-90 degrees out from piezo

-Varies with liquid level

-Severely suppressed at 4K



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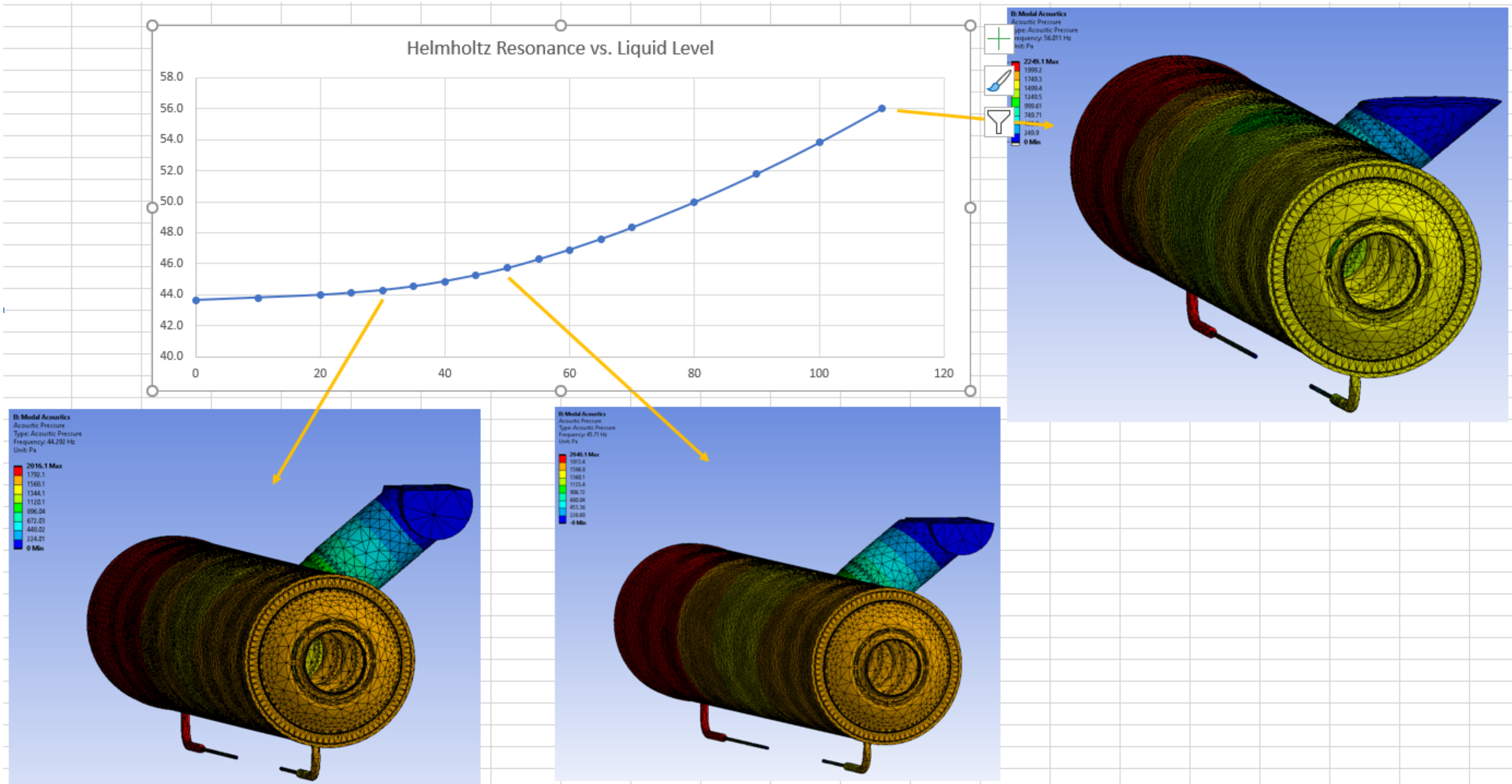
Helmholtz Resonance of 1.3 GHz Cavities



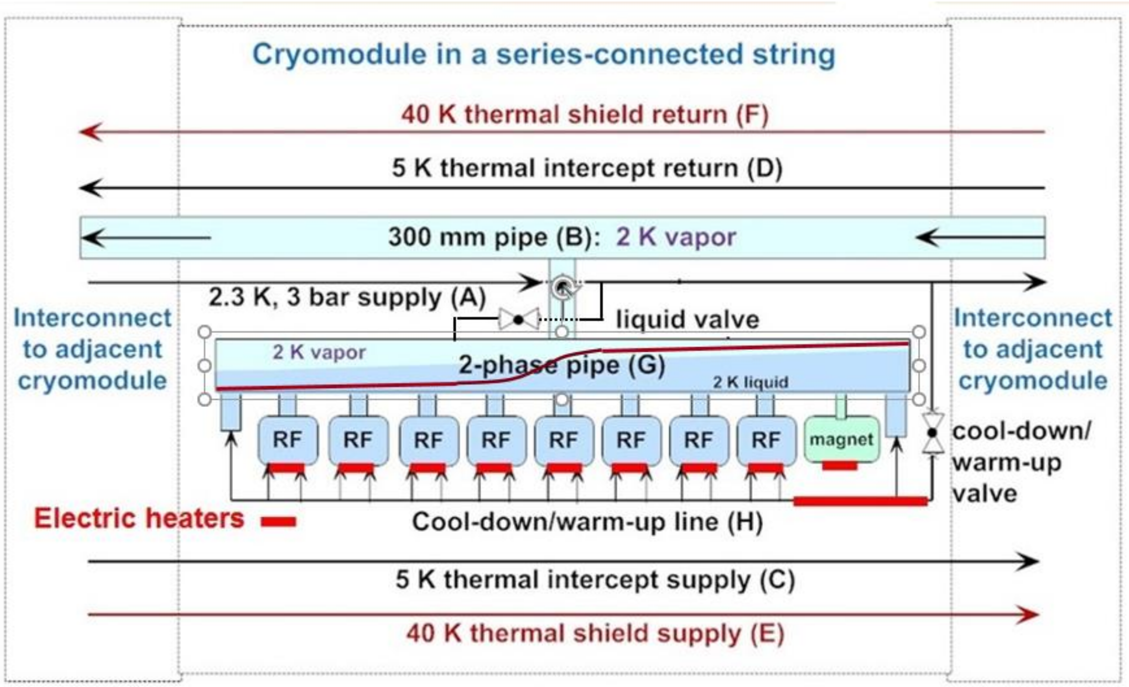
High JT Flow Rates and LCLS-II Module Tilt (0.5%)

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.



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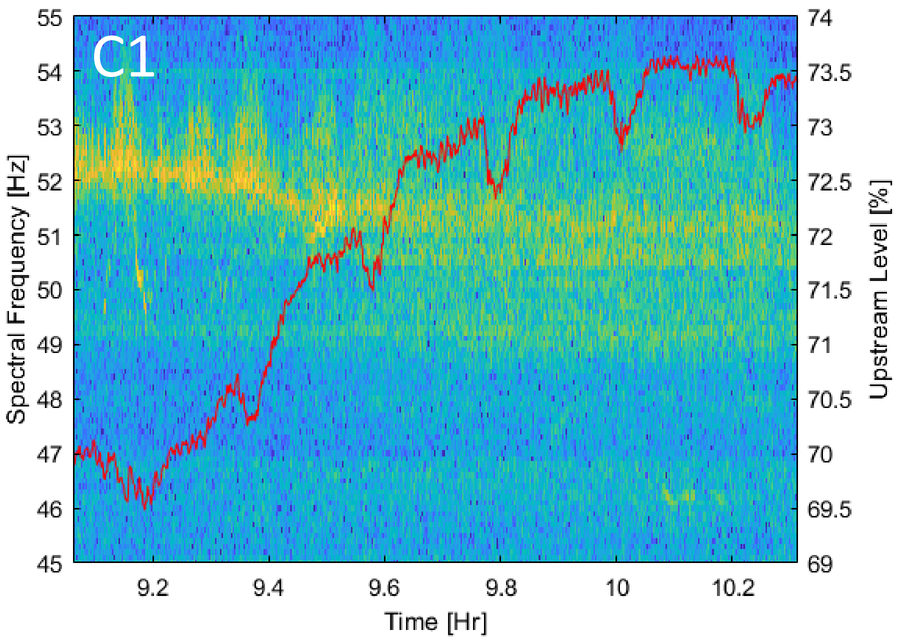
Bringing it all together

- Directly demonstrated correlation between:
  - Strong microphonics line amplitude and frequency
  - Liquid level
  - Cavity position
  - Resonance quality factor
- Done at Test Stand and in LCLS-II tunnel during commissioning
- Explained high piezo gain feedback microphonics during LCLS-II turn-on

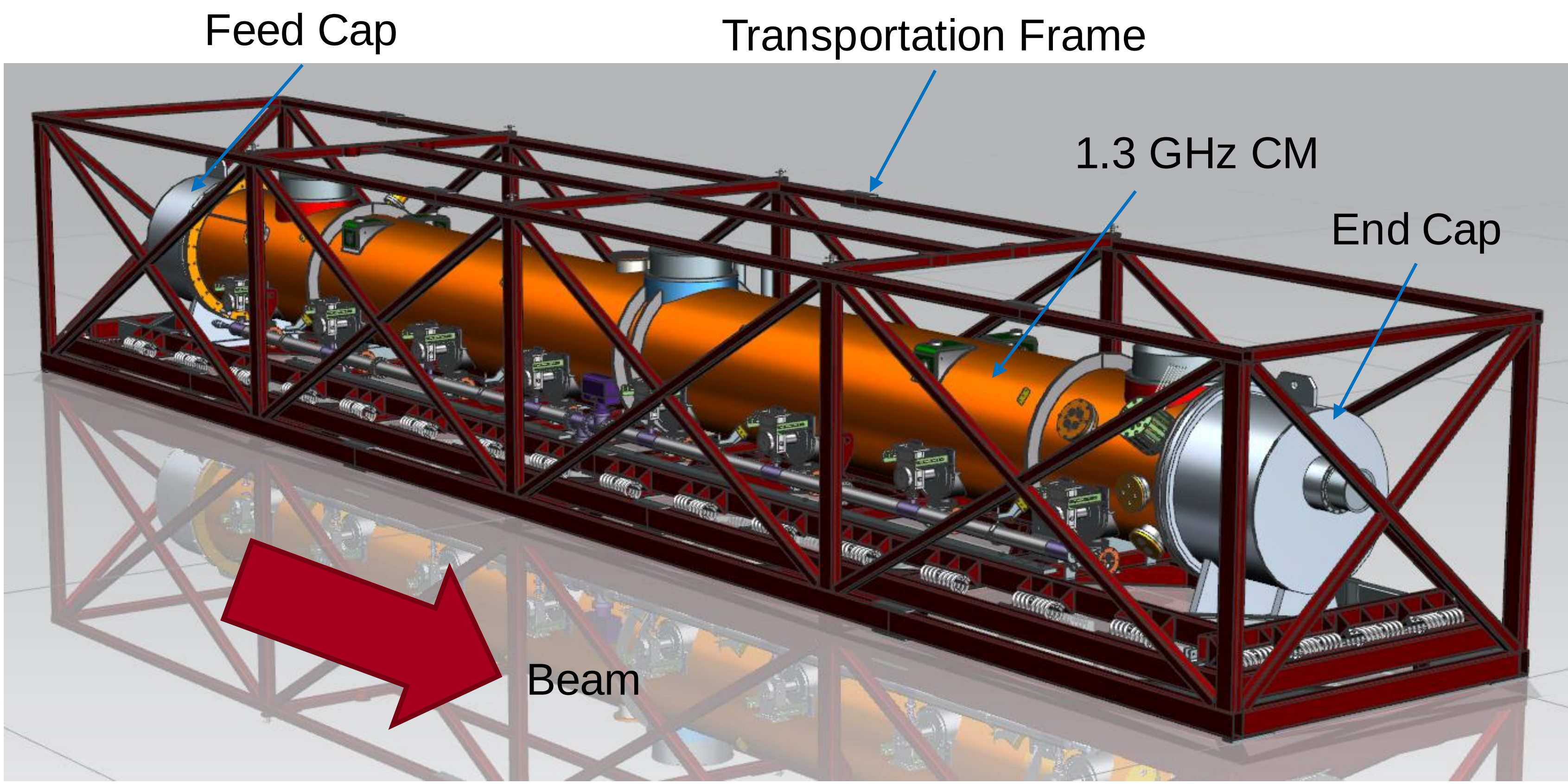


Cavity 1 has lowest liquid level, thus highest Helmholtz Q, strongest microphonics impact

Unintended Consequences: One-off Activities

- LCLS-II Transportation, or, how the lab director finally learned my name (not a great thing)
- LCLS-II needed to ship dozens of modules from JLab and FNAL to SLAC
  - LCLS-II Transport from FNAL on YouTube

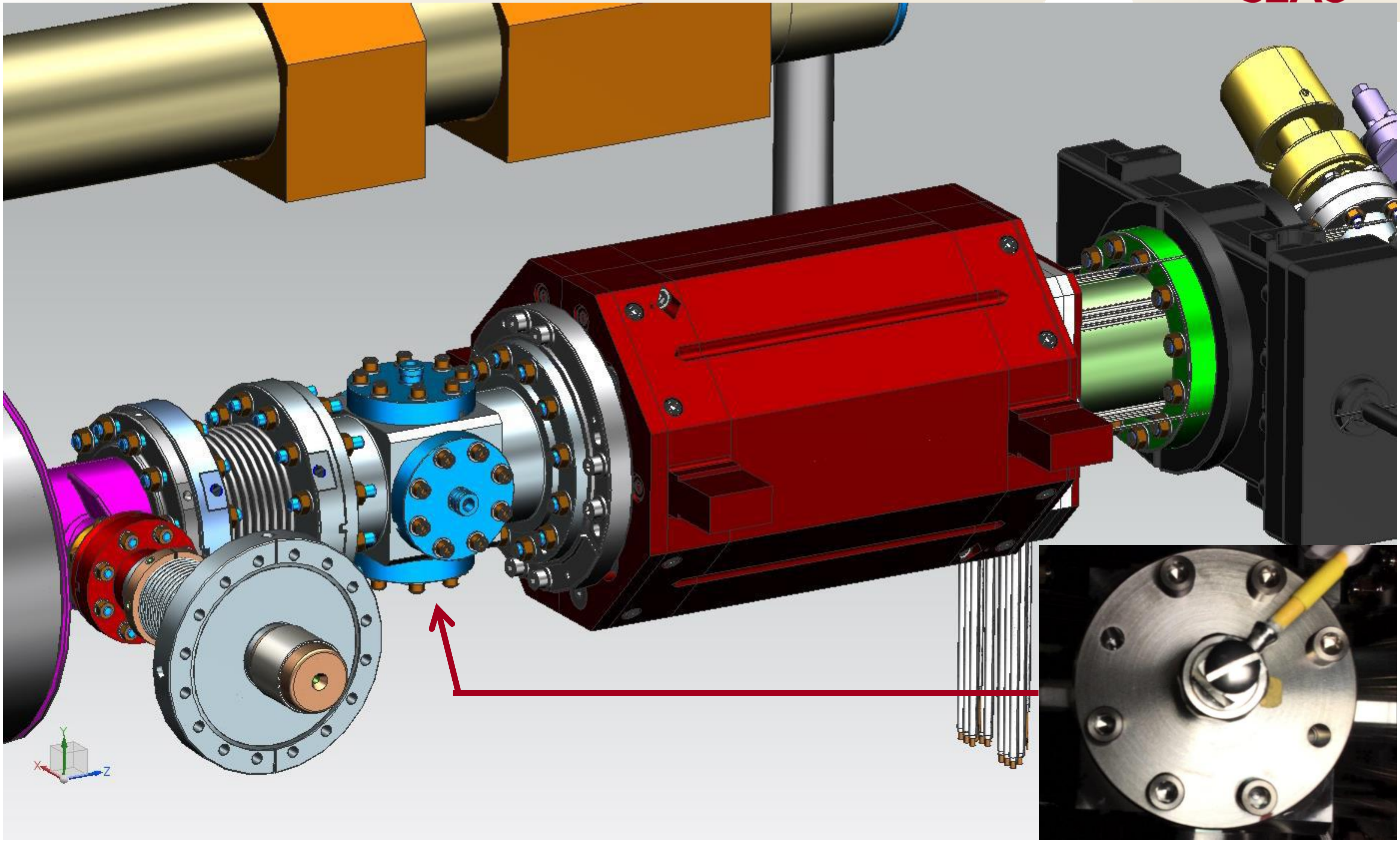
LCLS-II 1.3 CM Transport System



First Module at SLAC had Vented Clean String

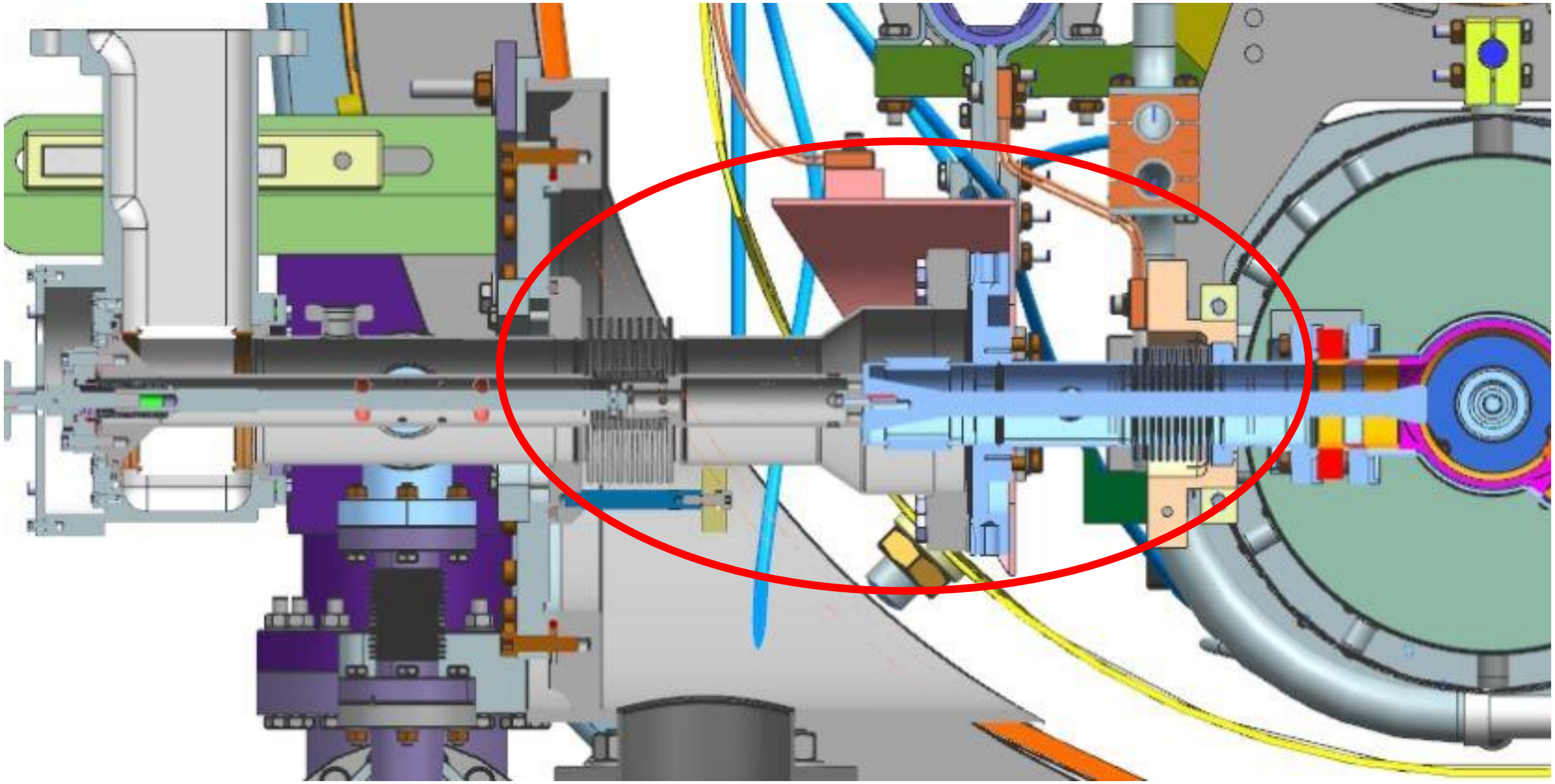
- Hardware at bottom of vessel
  - Systematically revisited and improved all fasteners: Loctite, lock washers, Bellville washers, torque specifications, etc.
- Beam Position Monitor Flange missing hardware
  - Wrong grade of titanium Bolts stretched at required torque
- Several RF Coupler bellows totally fatigued and torn
  - Much bigger issue
- Transport Frame was totally mis-designed
  - Far too stiff, no isolation, no validation of performance
- Transport instrumentation wildly inadequate
  - Needed to develop systems for high quality data capture including CW 3D acceleration, pressure, temperature, GPS, including active remote monitoring

LCLS-II-4.5-ES-0403, Cold Button Beam Position Monitor



CAD model cross section at RF power coupler

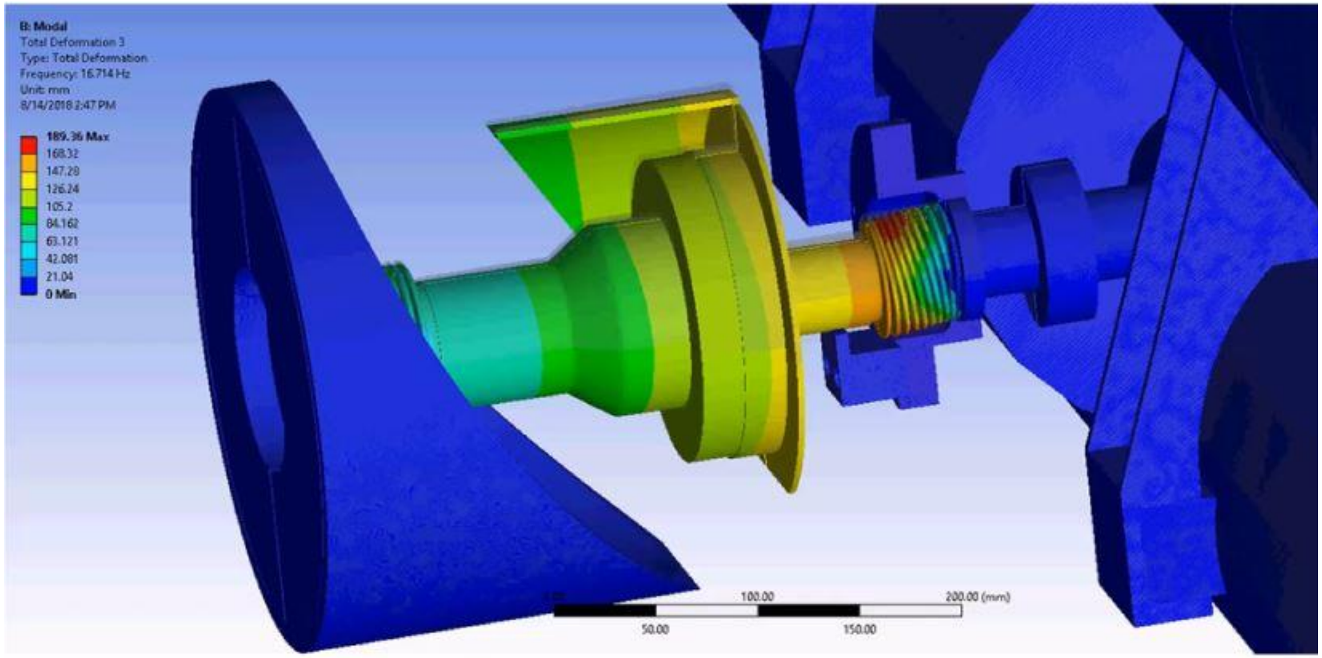
Center part of coupler between bellows is free to oscillate front to back in this image, cryomodule axis direction. Relative motion of cavity string and coupler in X (cavity string swinging side-to-side in this image) is also taken mostly via the inner coupler bellows.



Coupler internal motion during shipping

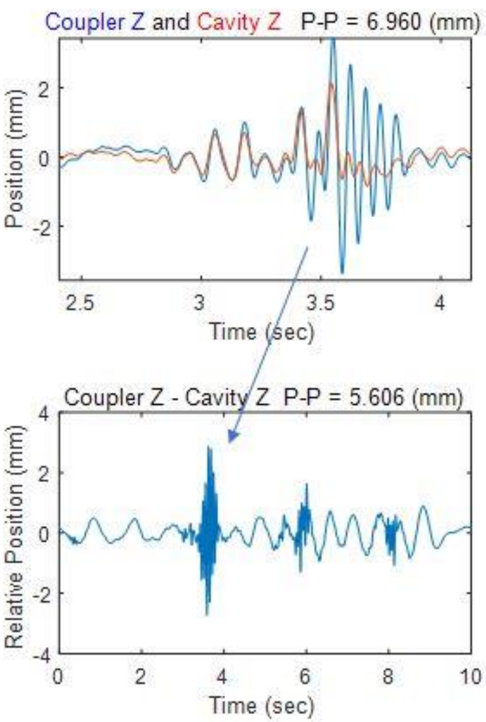
Analysis predicts 16 Hz. During last road test, we measured 15 Hz with amplitudes sufficient to damage the bellows.

F05 Cavity 4 Coupler Shroud appears to ring at 15 Hz

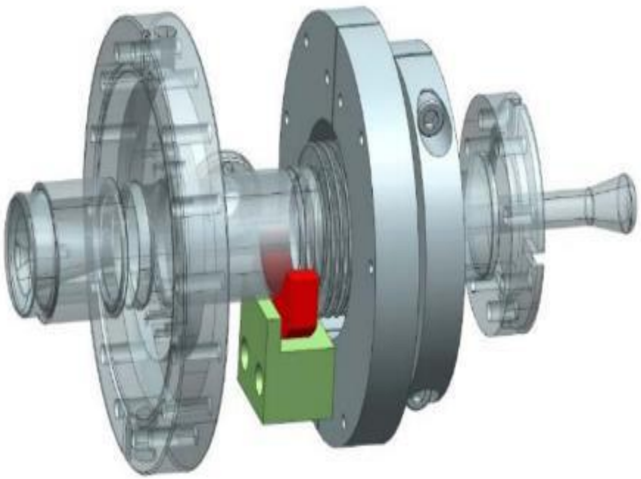


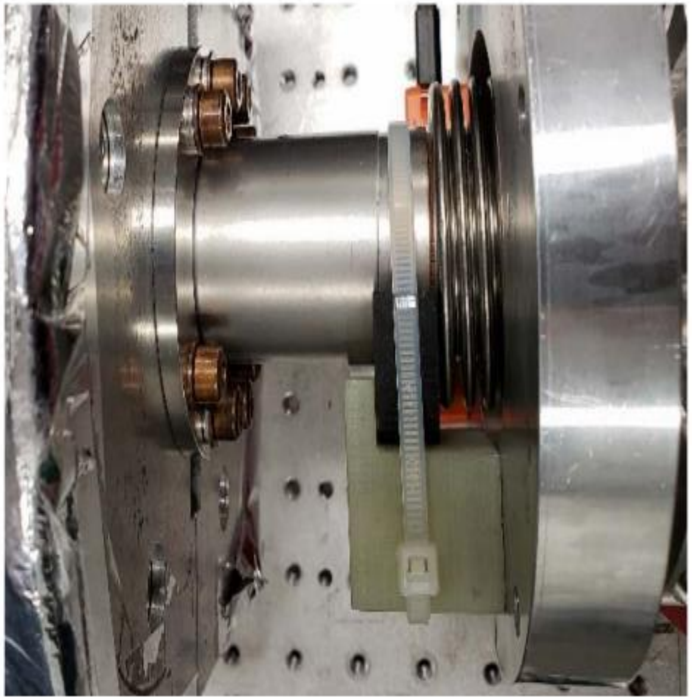
MODE 3 (16 Hz): Coupler Motion in Y Dir

F05 Example



"M-mount" constraint of assembled coupler

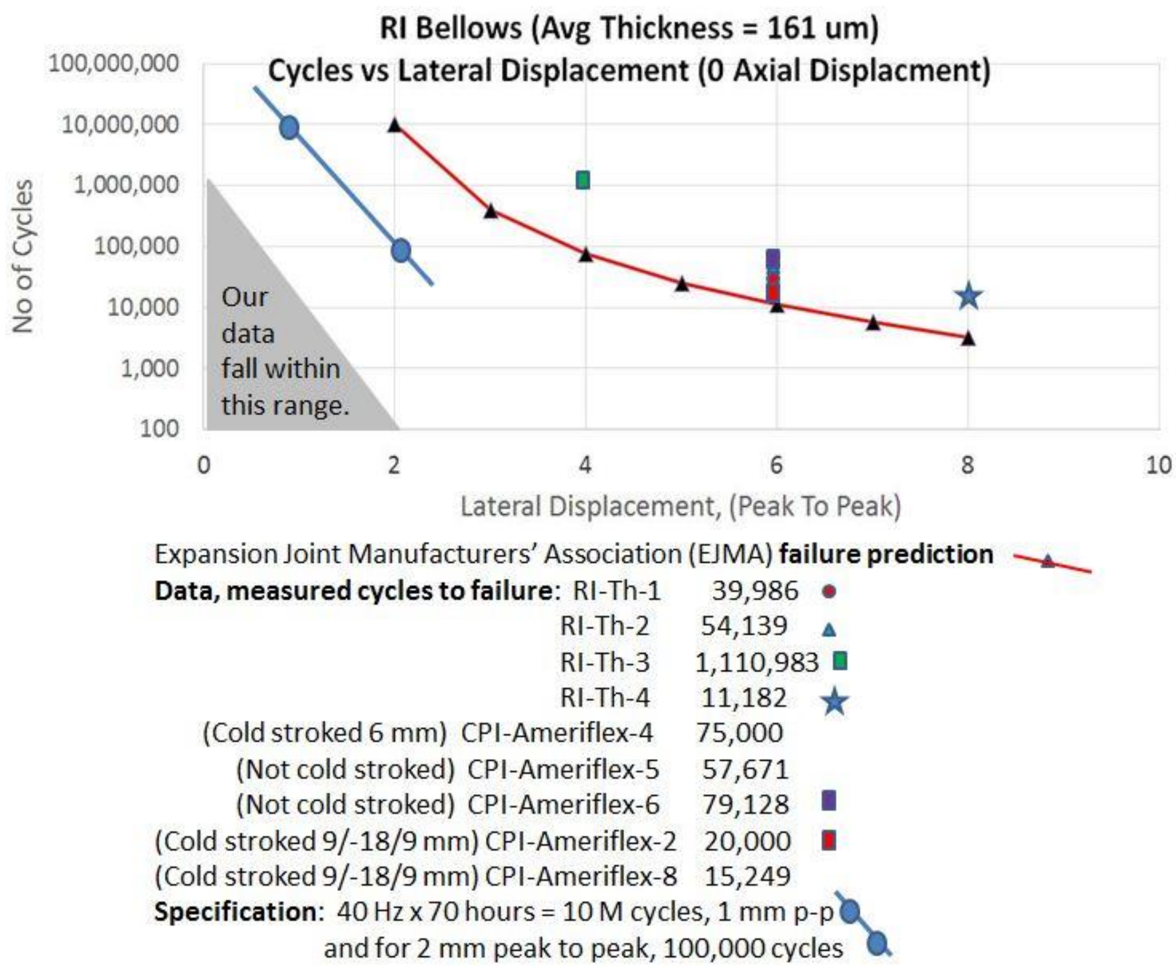




Neoprene constraint sits on G-10 block, held with tie-wrap.
Limits Z (coupler lateral) motion but permits axial movement.

Bellows prediction, data, and specification

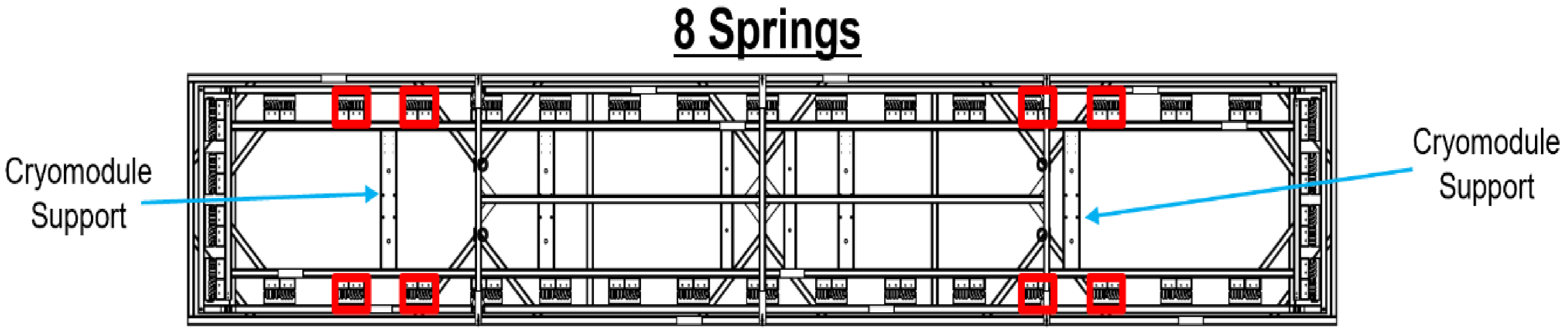
Note about the blue line specification:
Below 2 mm peak to peak lateral offset, bellows stress is below the fatigue limit for 316L stainless.
We selected a specification which sets the number of cycles at 2 mm peak to peak at no more than 100,000, two orders of magnitude below failure. We set the magnitude of high frequency cycles at 1 mm peak to peak, a factor of two below failure amplitude.



Key improvements in transportation system

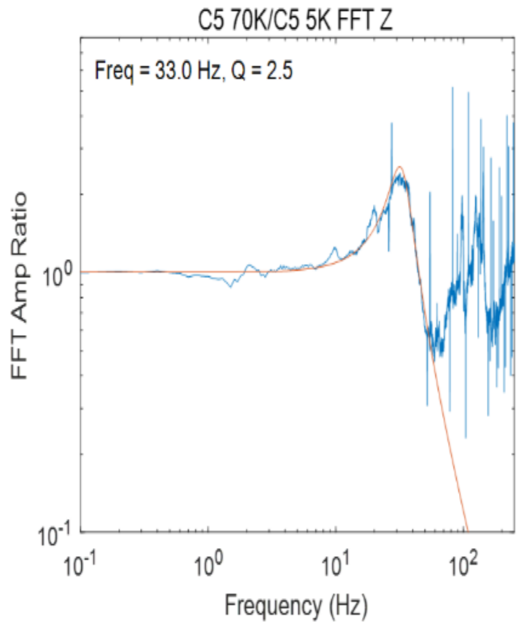
SLAC

Improved shipping frame spring configuration



Reconfigured CM isolation frame springs: lowered frame Z motion resonance from 13 Hz to 7 Hz

Constrained bellows motion: increased coupler Z motion resonance from 15 Hz to > 30 Hz



PIP-II Cryomodule Transport

The PIP-II Project is receiving over a dozen cryomodules from European partners as in-kind contributions

Overseas transport is identified as a high risk for the project, so significant resources are being spent to prepare

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Dummy Load Testing at STFC-UKRI

Departure from STFC-UKRI

Return of Load to FNAL (Logistics matter!)

FESHM 10210 – Equipment Transport

- Transport failures for LCLS-II led FNAL to evaluate how engineering was done at the lab
- Fundamentally, one-off activities like transport are still major design effort and sources of risk, but are not always treated as such
- FESHM 10210 is a new kind of engineering oversight at the lab, ensuring that realistic risk assessment and mitigation are done for all major transports

Fermilab	ES&H Manual	FESHM 10210 April 2022

FESHM 10210: EQUIPMENT TRANSPORT

Revision History

Author	Description of Change	Revision Date
Jeremiah Holzbauer	• Initial Release	April 28, 2022

Fermilab	ESH&H Manual	FESHM 10210 April 2022

FESHM 10210: TECHNICAL APPENDIX

Revision History

Author	Description of Change	Revision Date
Jeremiah Holzbauer	Initial Release	April 28, 2022

Systematic Risk Assessments and Mitigations

Process Failure Modes and Effects Analysis (PFMECA)

Process:	SBND Detector Transport	L2 WBS (or level first):		PFMEA Date (Orig):	
Author:	Core Team	L3 WBS:		Doc #:	
Core Team:	Shishir Shetty, Sai Kancharla, David Pushka, Min Jeong Kim, Steve Hentschel, Nicola McConkey, Monica Nunes, John Najdzian, Roberto Acciarri, Anne Schukraft, Peter			Rev:	

#	Process Step	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/Mechanism(s) of Failure	Probability	Current Controls (Prevention)	Current Controls (Detection)	Detection	Risk	Recommended Action(s)	Responsibility	Target Date	Action Results: Actions Taken	Severity	Probability	Detection	Risk
1	Assembly Transport Frame (atf) re-configuration	an installation step is missed in the re-configuration of the atf	decreased/failing structural integrity; injury to personnel; damage to the detector	high	human error	unlikely	Assembly documentation is in place; personnel has been instructed; lead technician (John) has previously led and completed this task in the practice for load test in 2019; supervision through engineering team	inspection of re-configured atf by engineering team prior to transport	almost certain	Minor	continue with current prevention and detection controls	Shishir Shetty	3 weeks prior to move date	-				
2	Moving out of DAB/into ND Building	Hillman roller fails	atf is no longer movable on tracks	low	material failure	rare	rollers fulfill spec; tested in 2019; mobile crane or building crane are in vicinity when moving on rollers	detector is not movable	almost certain	Negligible	have jacks available; mobile crane or building crane are in vicinity when moving on rollers; also have spare Hillman rollers	Shishir Shetty	Complete	Assuming all recommended actions taken	low	rare	almost certain	Negligible
3	Moving out of DAB	atf gets stuck on the ramp on the way out of DAB	atf is no longer movable on tracks	low	material failure	rare	steel plates, roller guides; procedure developed from practice in 2019	detector is not movable	low	Negligible	see preventive measures	Shishir Shetty	Complete	-				
4	Moving out of DAB	atf does not fit out the DAB door after ramp resurfacing	prevents transport	medium	design failure	rare	tested in 2019; ramp has been surveyed since resurfacing	will have people assigned to visually check the clearance during the transport from scissor lift (similar to 2019)	almost certain	Negligible	ensure this visual check is part of the work plan	Shishir Shetty	2 weeks prior to move date	Assume work plan includes visual checks	medium	rare	almost certain	Negligible
5	Moving out of DAB/into ND Building	Failure in securing ramp plate	steel plates loosen; no track available for atf	medium	material failure	unlikely	mount early; inspect prior to move day and on move day	visual	low	Minor	apply current controls	John Najdzian	3 days prior to move date	-				
6	Moving out of DAB/into ND Building	Mechanical failure of the tow sling that makes the connection between the pulling fork truck and the atf	loosing control of detector; injury/damage to detector & equipment	high	material failure	rare	Fork truck/wooden block brake following closely the atf in/out the building; Clear communication between operators in front and back will be ensured (work plan)	visual/braking fork truck will notice	low	Minor	see preventive measures	Shishir Shetty	Complete	-				
7	Trailer loading/unloading	Rigging failure	Damage to atf & detector; personnel injury	high	Mobile crane or rigging equipment failure; operational error	unlikely	Professional crane & rigging crew; required to present crane inspection certificate and operator license; all workers briefed on work plan and HA	visual	low	Moderate	see preventive measures	Shishir Shetty	On move day	-				
8	Trailer loading/unloading	Ground compression under mobile crane or trailer	Damage to atf & detector; damage lab infrastructure	high	unstable surface	rare	JULIE permits will be obtained; steel plating added where needed	visual	almost certain	Negligible	see preventive measures	Shishir Shetty	1 week prior to move day	-				
9	Trailer loading/unloading	Straps snap during fastening/unfastening	Shock to the detector; possible damage to delicate components such as electronics, PMTs	low	material failure	unlikely	inspection of material; operation by trained personnel; work plan adresses fastening procedure	visual; QC check post move (1 months after)	low	Minor	see preventive measures	Shishir Shetty	2 weeks prior to move day	-				
10	Transport	Movement of load on trailer	Shock to the detector; possible damage to delicate components such as electronics, PMTs	low	material failure/improper securing of load	unlikely	inspection of material; operation by trained personnel; work plan adresses fastening procedure; redundancy in securing chains & straps	visual; inspection if threshold inclination is reached	moderate	Minor	see preventive measures	Shishir Shetty	2 weeks prior to move day	-				
11	Transport	Light & elements exposure of the detector	Damage to the light sensitive components of the detector; detector cleanliness compromised	medium	external elements such as weather, branches, rocks, signs rip the plastic	possible	two layers of opaque plastic, and UV filtering plastic in place; route has been inspected several times and branches and signs will be addressed prior to move date; move will not take place at certain weather conditions	visual inspection	low	Moderate	test that the plastic layers are secured in place; install light sensors to monitor light exposure in real time during the transport	Monica Nunes & Nicola McConkey	2 weeks prior to move day	Assuming all recommended actions taken	medium	unlikely	moderate	Minor
12	Transport	Chains or fastener strips for securing atf on trailer break	Shock to the detector; possible damage to delicate components such as electronics, PMTs; load could shift on the truck	low	material failure/improper securing of load	possible	detailed plan for securing the load is in place, see work plan; experience from trial runs with loaded trailer; redundancy in securing chains & straps	visual inspection during the transport, as needed	low	Minor	Add redundancy in the chain & fastener straps when securing the load on the truck	Shishir Shetty	2 weeks prior to move day	Will use 12 vs required 6 points for load securing	low	rare	low	Minor
13	Transport	Damage caused by collision with obstacles	Damage to the protective plastic layers (most likely); less likely: damage to atf and/or trailer	medium	failure in preparing road appropriately for transport	rare	Prepare route ahead of move day; list of obstacles identified through trial runs; slow transport speed (< 5 mph)	visual	almost certain	Negligible	ensure route preparation is complete by SBND team	Sai Kancharla & Shishir Shetty	1 day prior to move day	Assuming all recommended actions taken	medium	rare	almost certain	Negligible
14	Transport	Large shock during transport	Shock to the detector; possible damage to delicate components such as electronics, PMTs	medium	Road conditions	unlikely	Trial runs; slow transport speed (< 5 mph); fix potholes ahead of move day; plate uneven surfaces	visual; shocklogger data	low	Minor	ensure route preparation is complete by SBND team	Sai Kancharla & Shishir Shetty	1 day prior to move day	Assuming all recommended actions taken	medium	rare	low	Minor
15	Transport	Truck/trailer or fork lifts get a flat tire	Delay; need to repair or move transport vehicles in challenging condition	low	material failure	unlikely	Trailer and truck undergo regular maintanance; tires will be inspected prior to move	visual	low	Minor	ensure inspection of truck & trailer including tires is complete	John Najdzian	morning of move day	Assuming all recommended actions taken	low	rare	low	Minor
16	Move into ND building	Hillman rollers fail to adjust for 90 deg rotation when moving in to the ND building	Delay; possible need for jacking up the atf for correction/repair; Note: this is after the detector is securely in the building so any remediation can be postponed to a later date	minimal	material failure	unlikely	The atf Hillman rollers have been specifically selected for this application and fulfill the requirements for this operation	atf will not move	low	Minor	none	Shishir Shetty	complete	-				

Conclusions

- Accelerators are wildly interdisciplinary devices, one of the great uses of Applied Physics
  - My undergrad degree with UW-Madison was Applied Math, Engineering, and Physics
- Integrated performance requires close collaboration between disciplines, cross-training, and significant effort
- Design efforts should be widely communicative and broadly reviewed, and operations teams should be similarly broadly skilled and collaborative
- Intensive diagnostic development can pay strong dividends