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Summary of Resonance Control and Microphonics Workshop at FNAL

J.P. Holzbauer on behalf of Resonance Control Group

PIP-II Weekly Meeting

Tuesday, October 13, 2015

Workshop Description

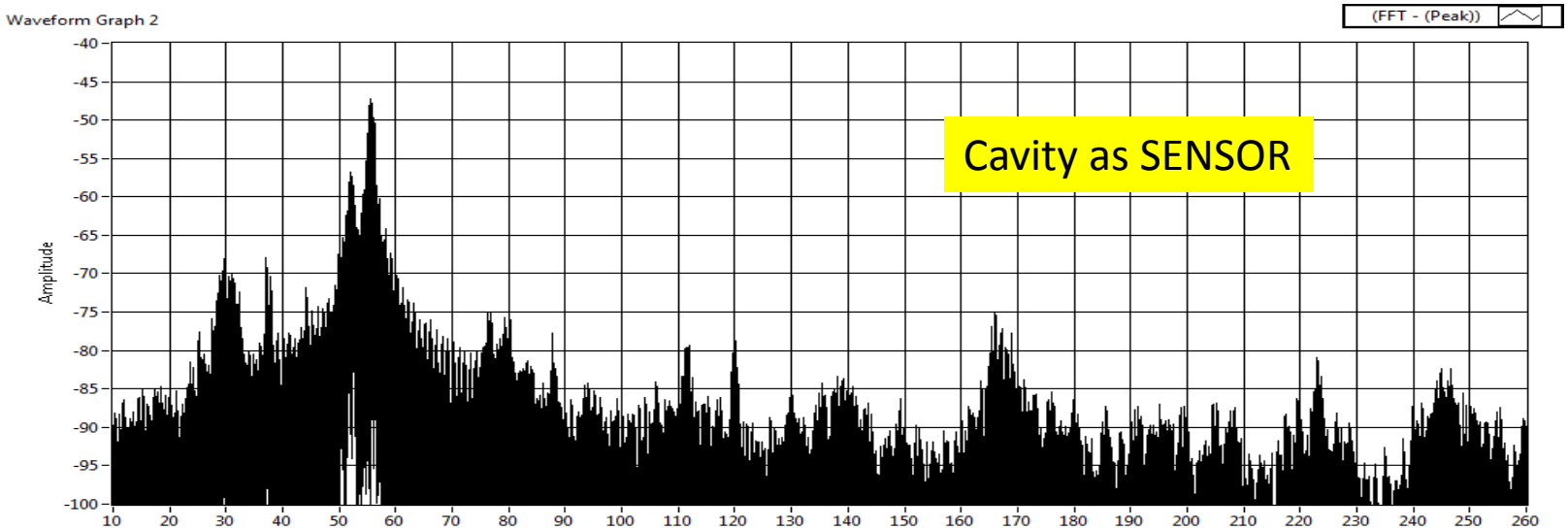
- Workshop Goal: “Simulate discussion of microphonics and vibration issues including experience from previous machines and discussion of requirements for future machines.”
- 1.5 Day workshop with 16 talks on day one, half day of round table discussion the second day.
- About 25 attendees in person, about 20 remote connections.
- Labs Represented: FNAL (AD, TD), LBL, SLAC, ANL-APS, FRIB, Cornell, JLab, RRCAT
- indico.fnal.gov/event/micro1
- References and supporting documents have been trickling in to the workshop indico page in response to questions/comments.

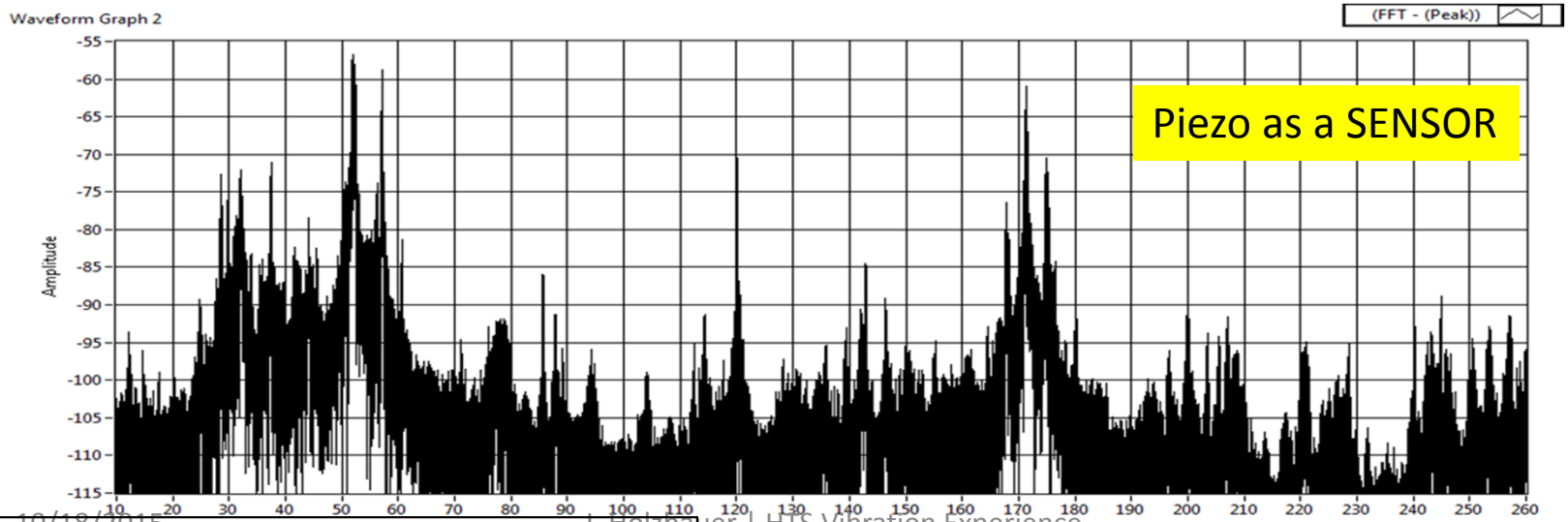
Topics Discussed

- Vibrational Environment
  - Measurement, improvement, isolation
- Cryomodule Characterization
  - Hardware characterization, design, prototype, production
  - Experience from CEBAF, FRIB, Cornell, FNAL
- Cavity/Tuner System
  - Initial mechanical design, prototyping, verification program
- LLRF/Active Control
  - Existing state of the art LLRF control systems being developed for LCLS-II
- Organizational Issues
  - All these problems are cross-disciplinary
  - How do we articulate the challenges/learn from the past?

Vibrational Environment

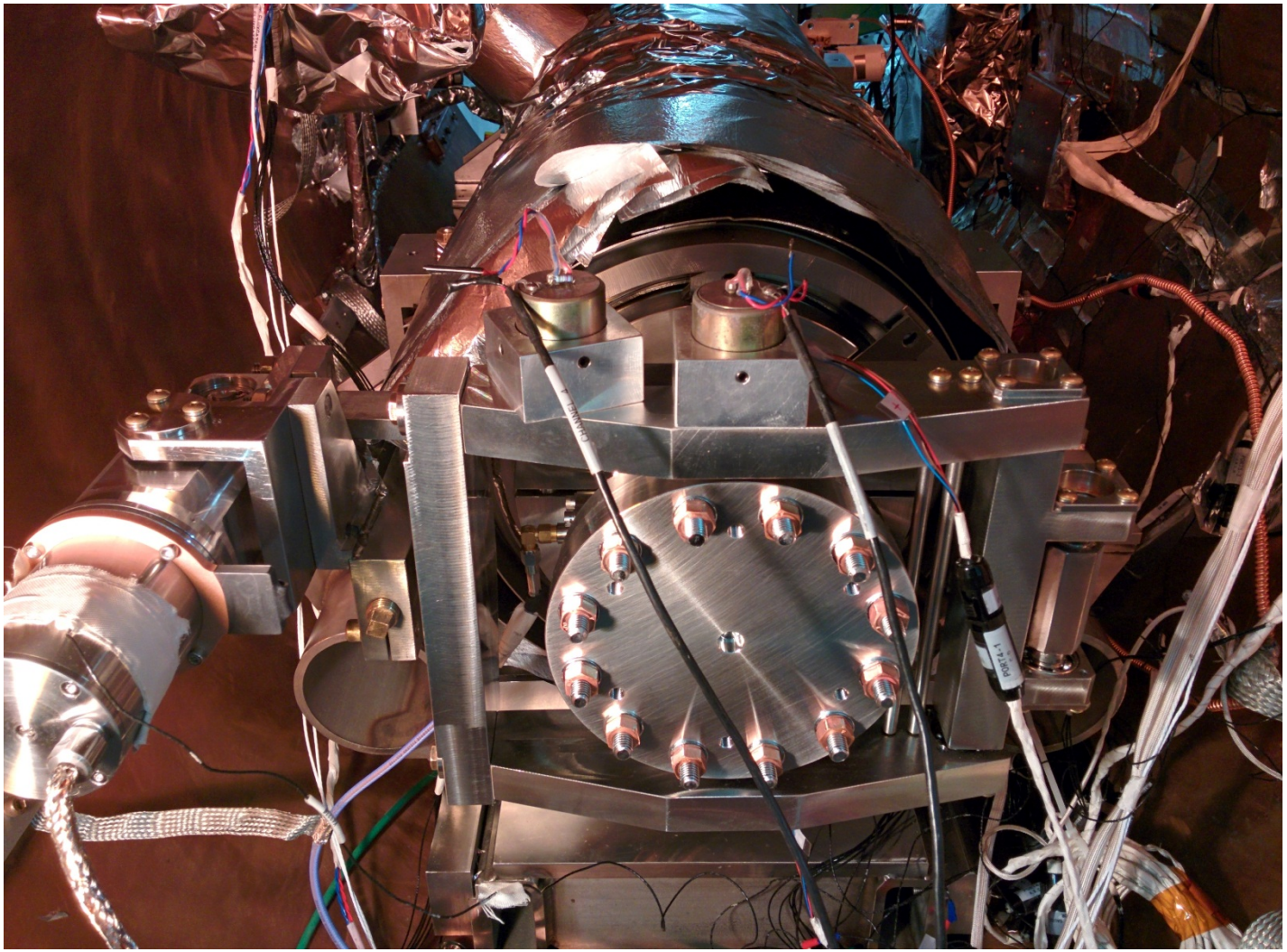
Measurements of cavity vibration (microphonics) using (1) RF signal from cavity & (2) piezo signal/piezo as a sensor





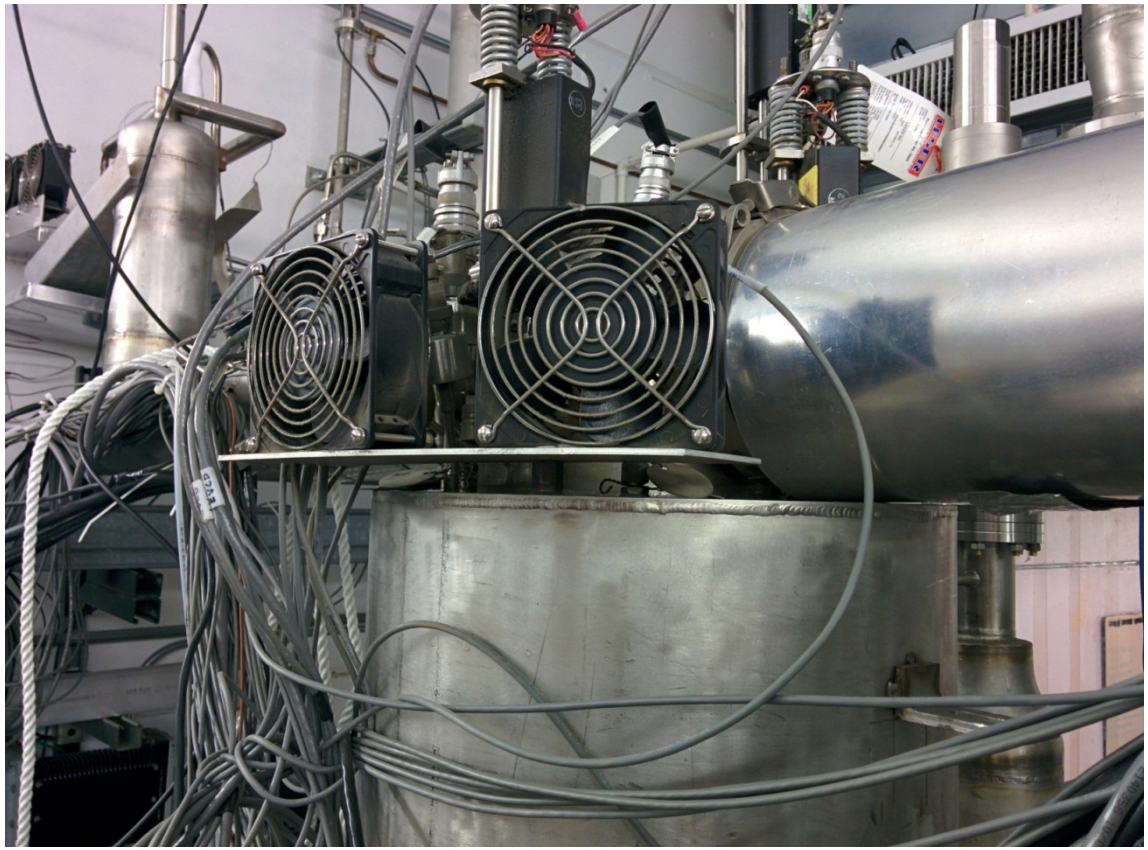
Credit to Yuriy for the Slide

Geophones on Tuner Bracket



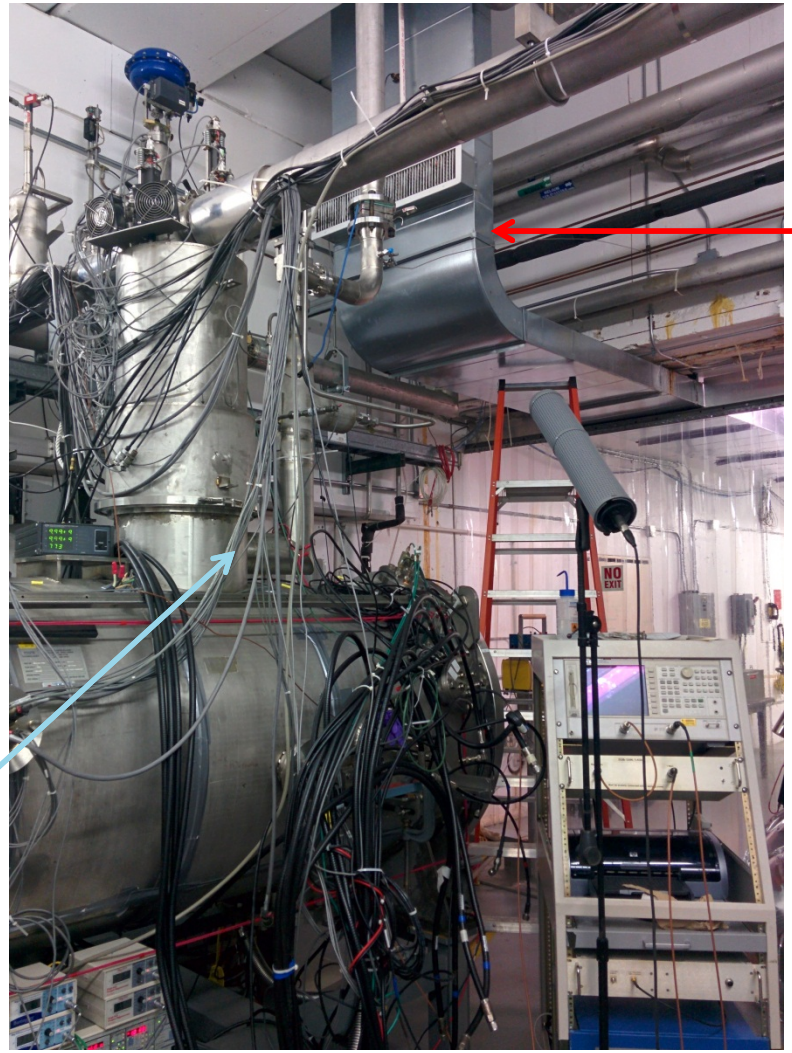
AD Cryo Box Fans

- Two box fans on a plate to mitigate valve heat leak, large vibration source
- Initially hard mounted, now soft mounted through grommets
- Heat leak is too large to have them off for more than a couple hours without significant icing
- AD cryo should be able to modify/replace with a non-vibrational heat source

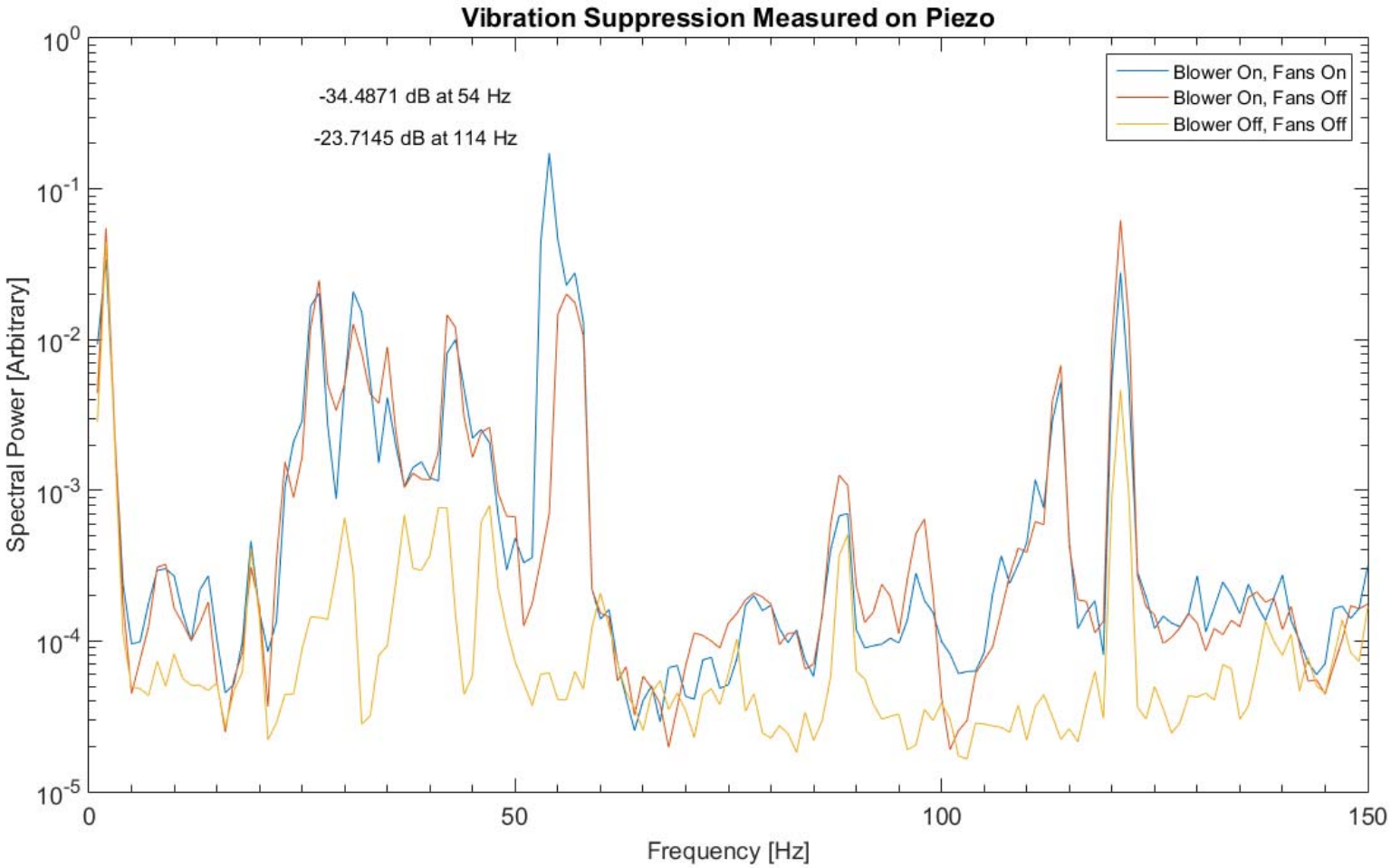


ODH Blowers/HVAC Duct

- Ventilation in the HTS cave is run by two systems in parallel
- HVAC is (theoretically) controlled by a thermostat outside the cave
- ODH ventilation blowers run 24/7 when the cave is unsecured
- ODH blowers should be off when cave is secured
- Primary vent blows directly onto a cryo relief stack which hard-connects to the HTS stack



HVAC/ODH Blower is a large noise source

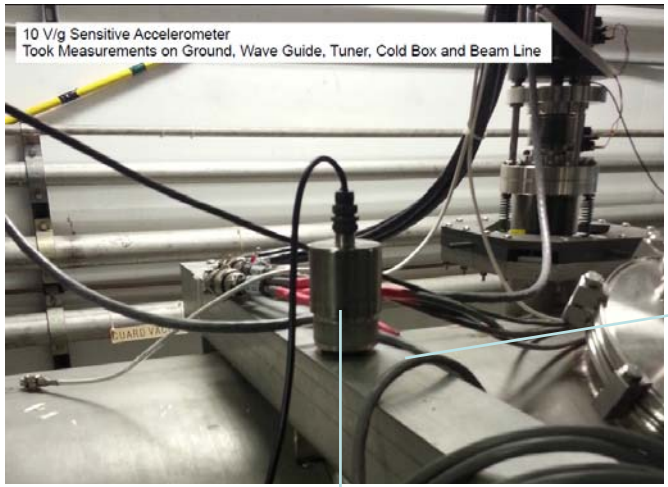


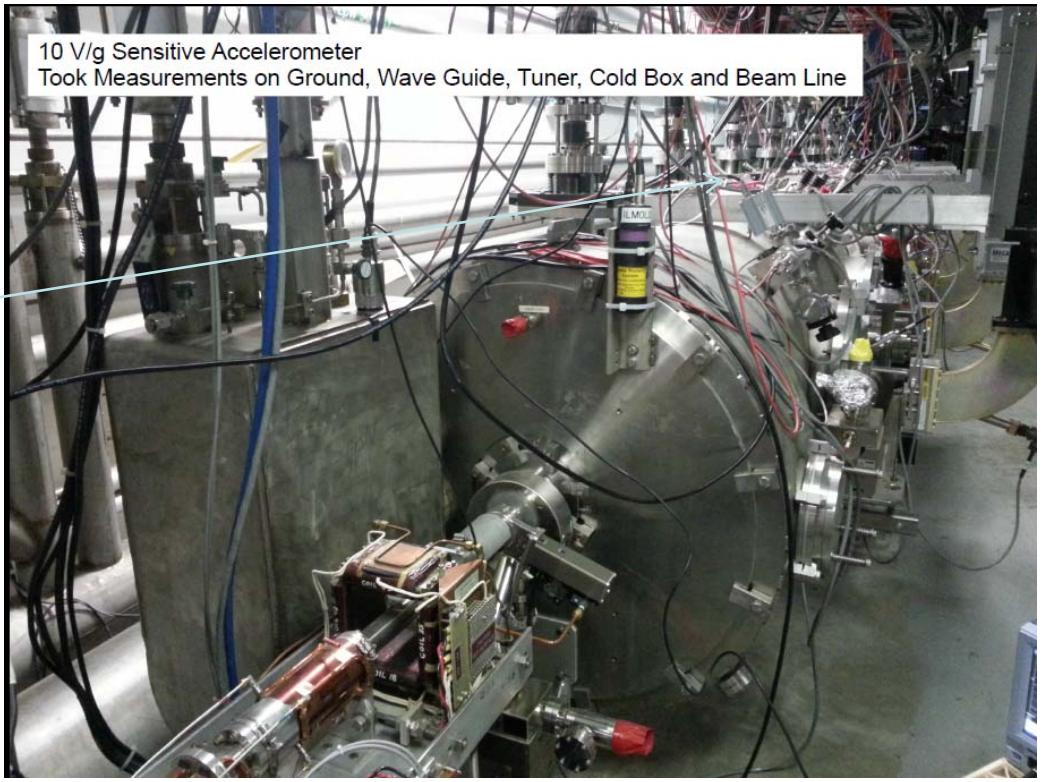
Vibrational Environment - Summary

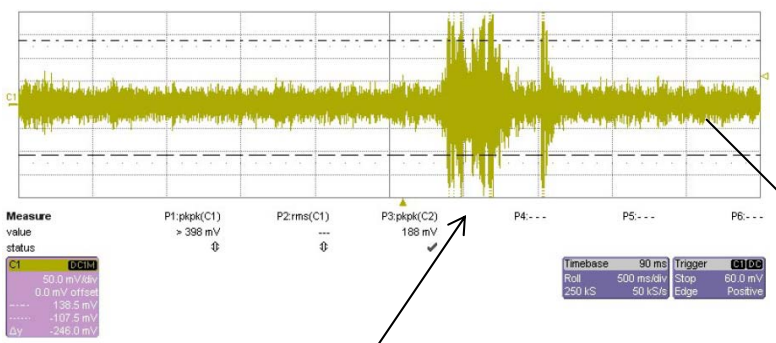
- General agreement that Environmental Sources are avoidable, if vigilance and education are good.
- Measurement techniques are generally well understood, but many reinventions of the wheel between labs
- Fluid noise especially is a source of concern
  - Mounting/isolation
  - Pipe sizing
  - Bend radius
  - Connection method (threaded vs. gasket)
- Mitigation is more likely after machine installation, but still costly in time and money

Cryomodule Characterization

Measurement Setup



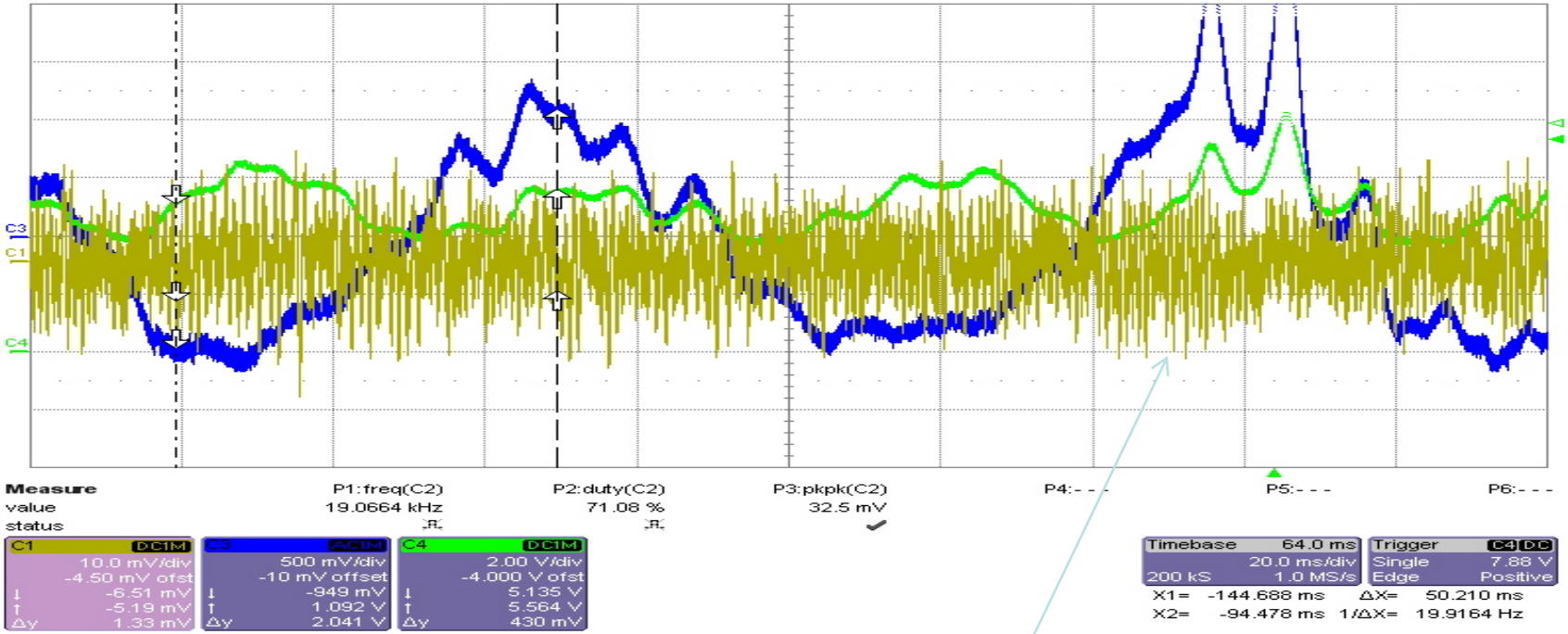




Mechanical vibration background – 0.004 g rms

Human voice in the tunnel 0.02 g rms

Mechanical Vibration vs Detuning



Signal from accelerometer

Detuning 18° /div

Forward power

Near Trip Event

frequency (mechanical modes) 11/21 Hz

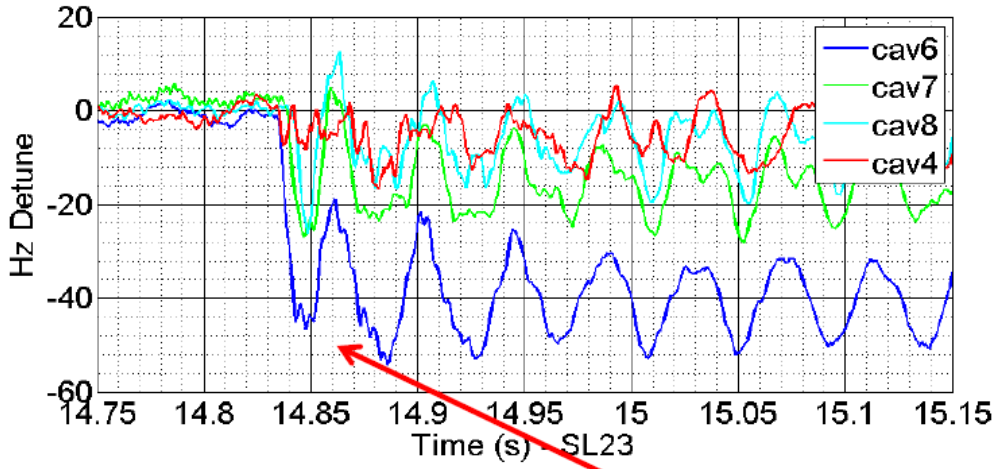
detuning ~ 47 deg,

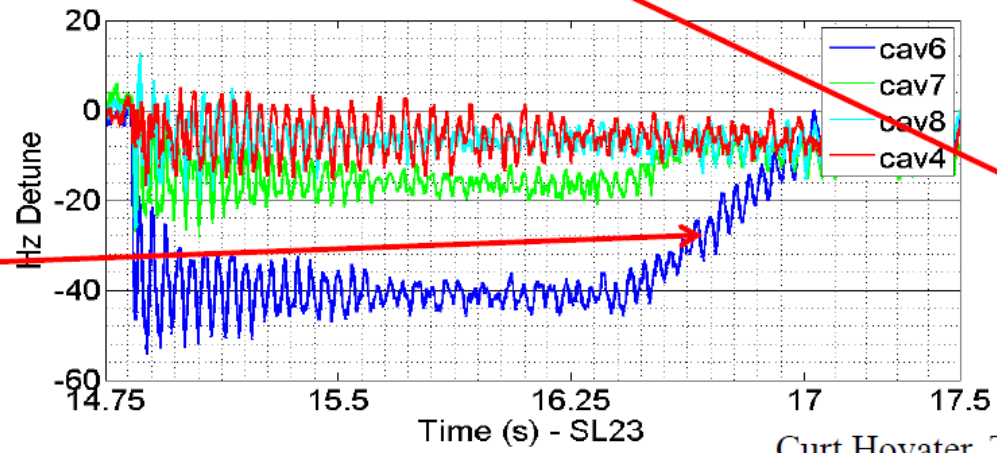
forward power rises >100 %

DYNAMIC COUPLING BETWEEN CAVITIES

C100-4 Cavities 4, 6, 7, 8 responding to an applied PZT step control voltage change from 52 to 39 volts (130 Volt range) in cavity 5

- Cavity 5 PZT moved 460 Hz.
- Locked in GDR Mode
- Because of 10 MV/m operating point, the klystron had the overhead to keep cavities locked
- Stepper Motor operated to tune the cavities



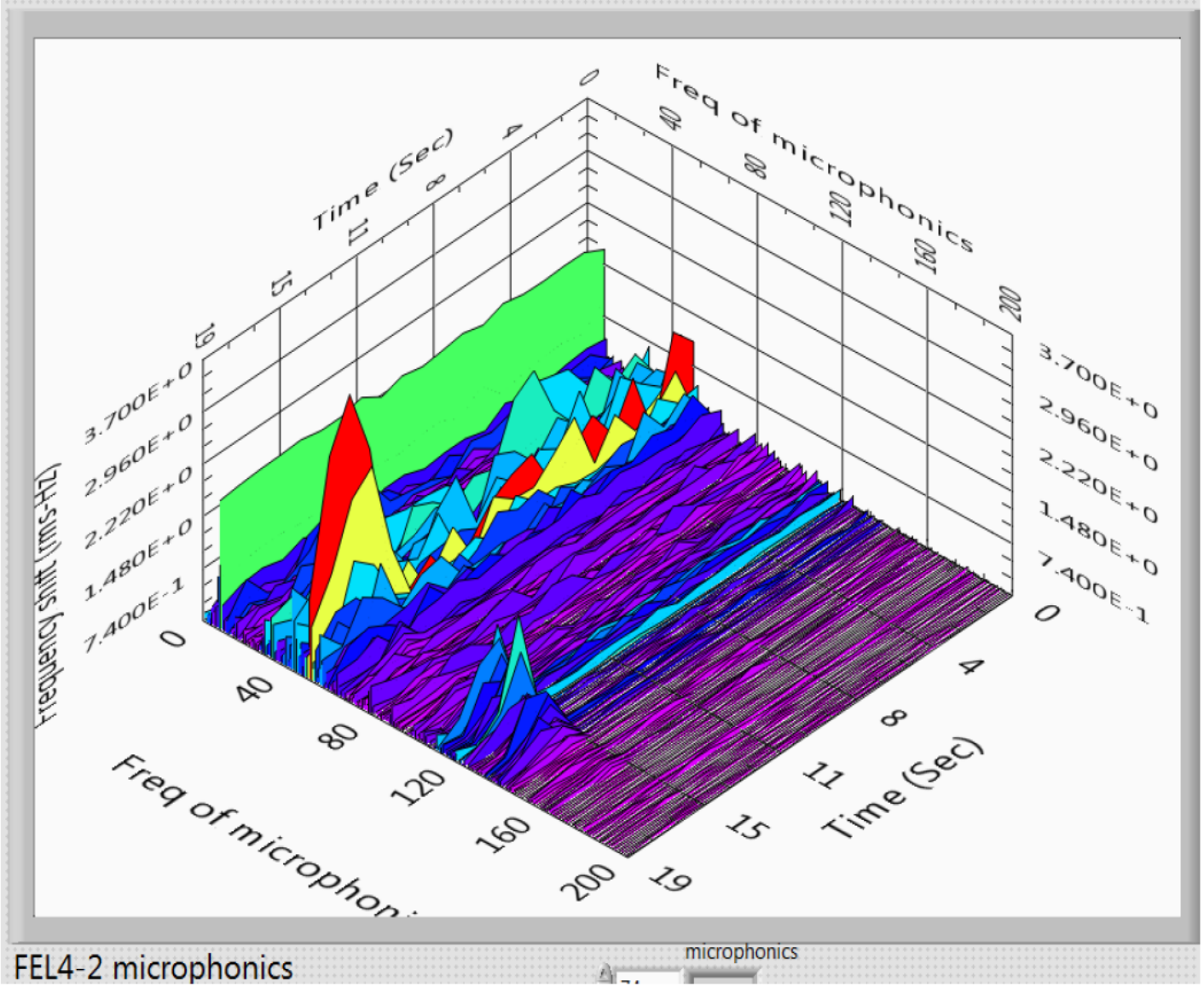


- Adjacent Cavity coupling is ~ 10% between 1-4 and 5-8 cavities
- Cavities 4 and 5 have a "quasi" mechanical support between them.
- Ringing is the 21 Hz mechanical Mode

Powers - JLab

Curt Hovater, Tomasz Plawski,, Michael Wilson, Rama Bachimanchi

FEL4-2 Frequency vs Time data



8 Hz perturbation due to poorly mounted beam line ion pump (over extended jack stand).

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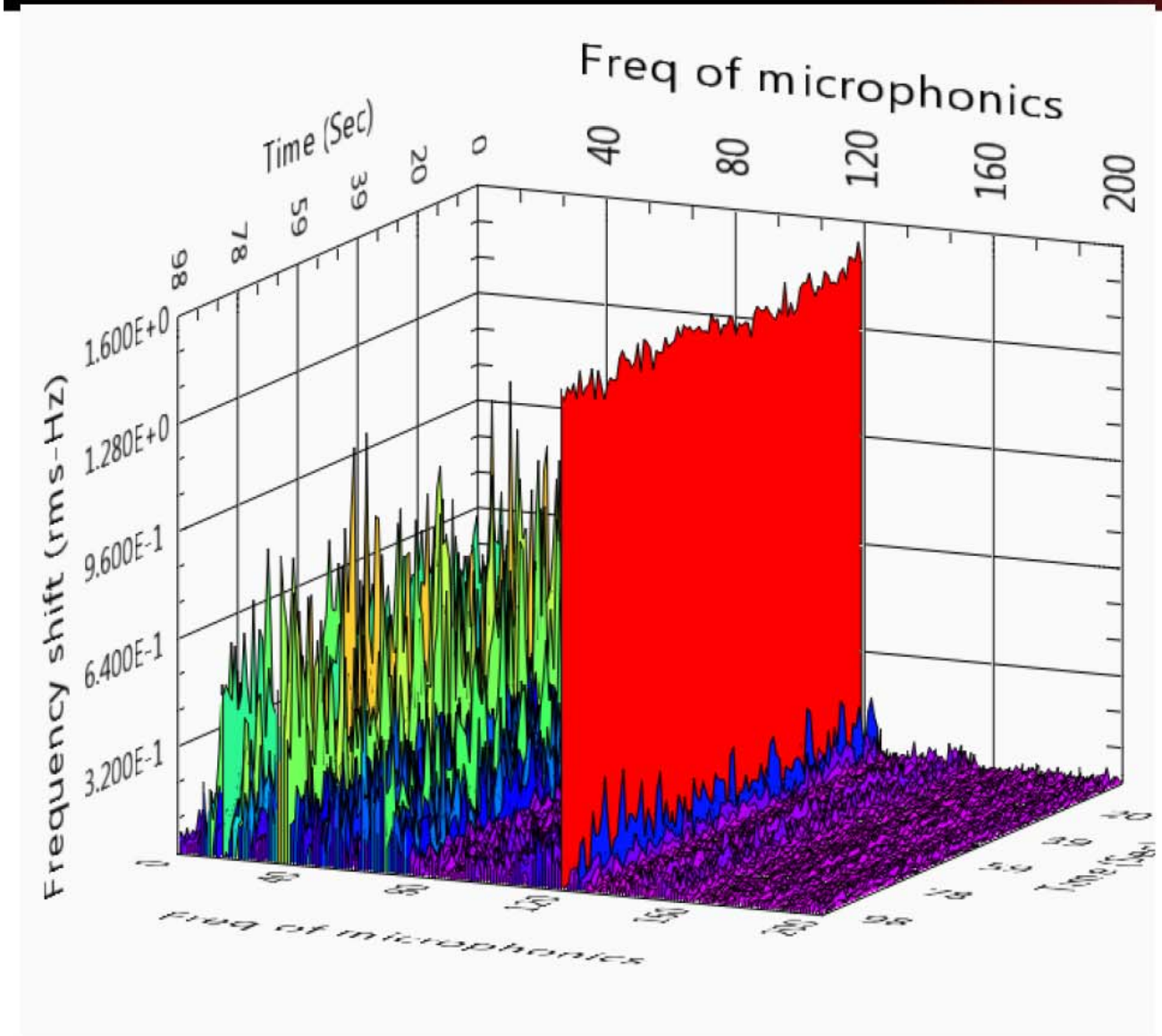
FEL3-6 Frequency vs Time Data



120 Hz noise due to insulating vacuum turbo pump backing pump coupled in through corrugated hose.

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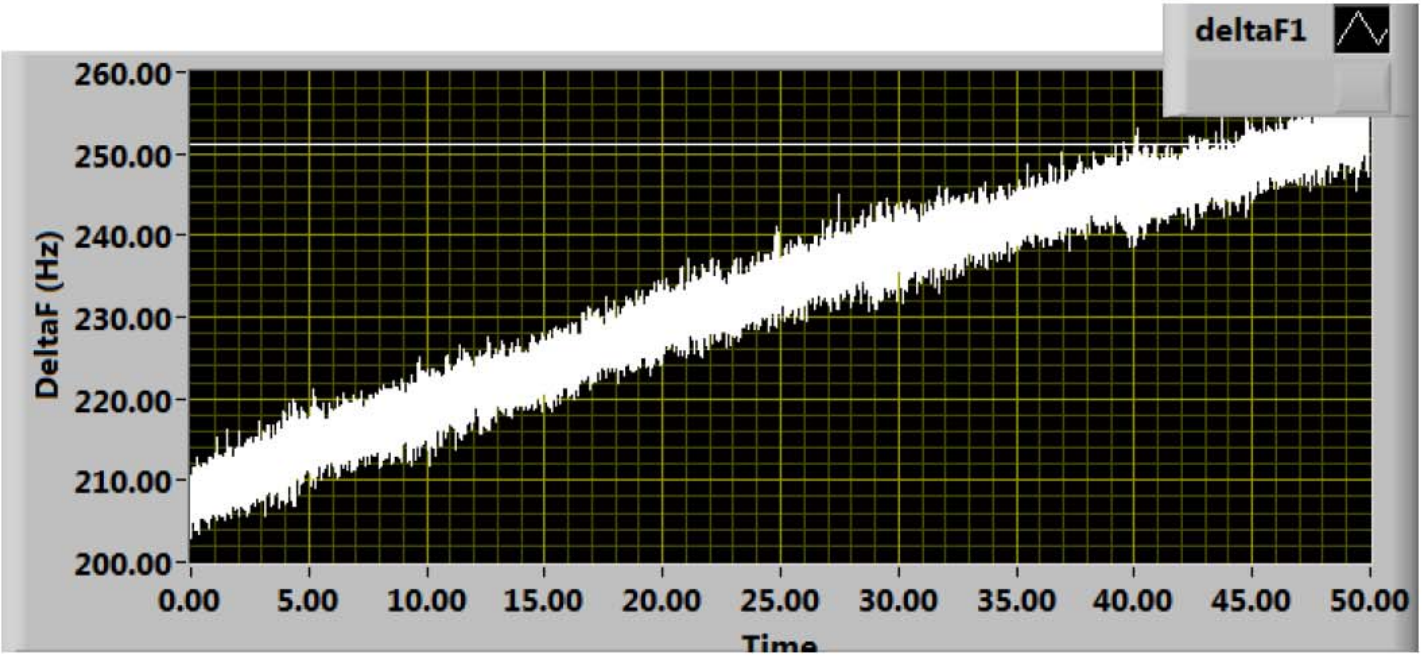
FEL3-6 with fan blowing on beam line



Time (seconds)

- Fan blowing on inner cryomodule girder caused slow temperature shift of about 200 Hz. Removal of the fan caused the frequency to restore to the previous value.

- Similar continuous (hours and hours) detuning has been seen in cryomodules operated at constant gradient overnight.

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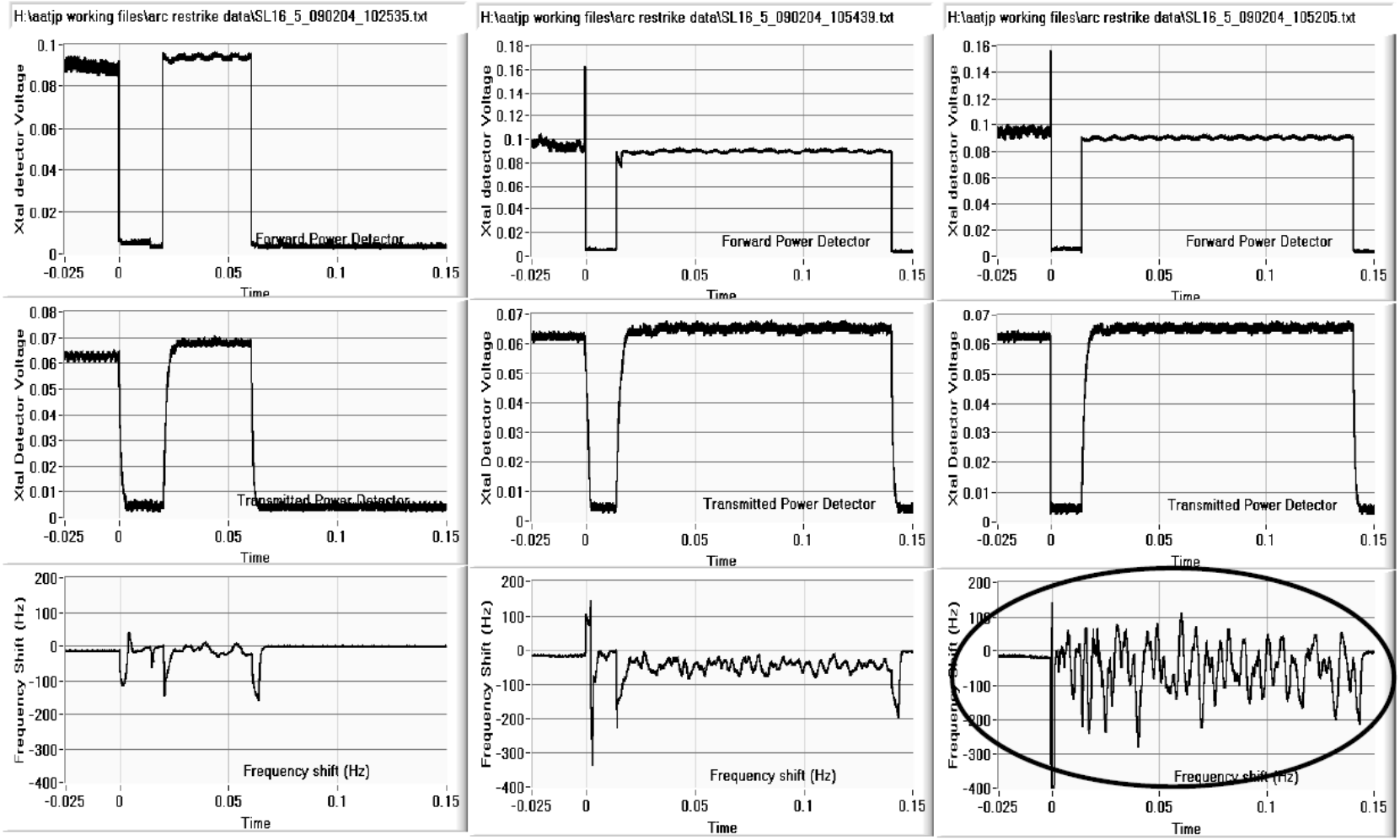
Frequency Shift Measurements at 7.7 MV/m

Forward Power

Transmitted Power (Gradient)

Frequency Shift



Normal Pulse (no event)

Pulse following Waveguide Arc

Pulse following "Electronic Quench"

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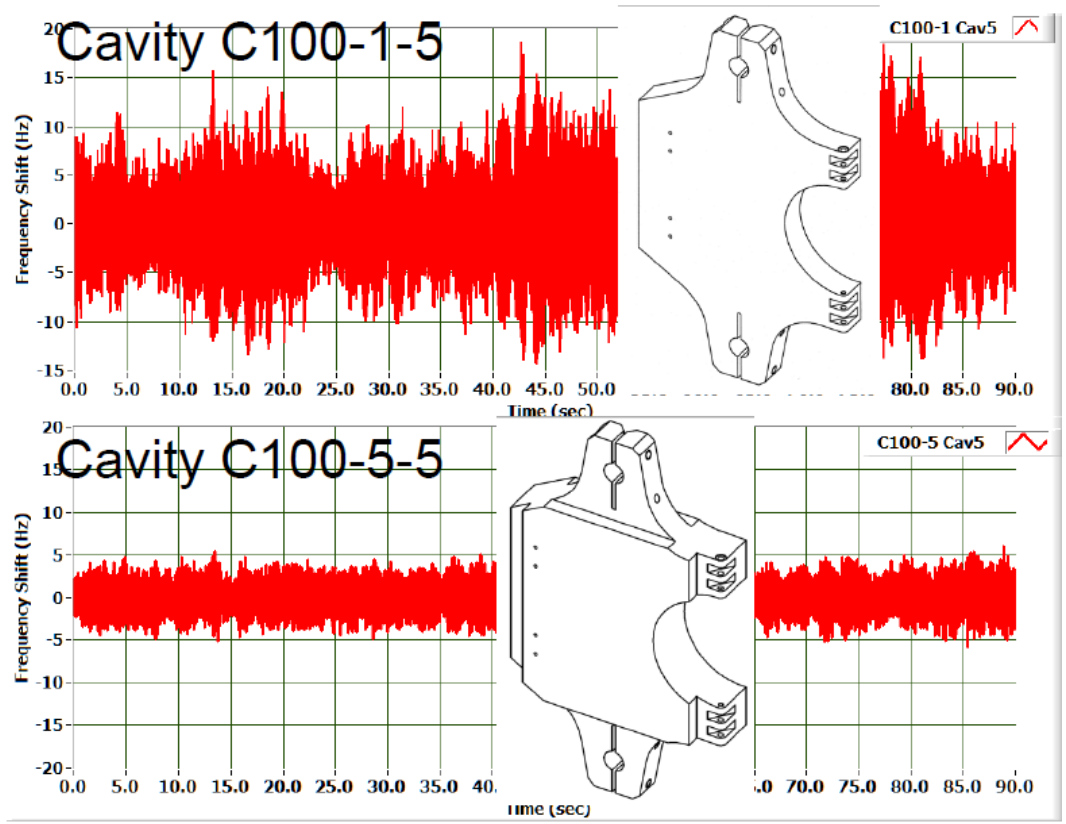
C100 Cryomodule Fix

- Design allows for 25 Hz Peak Detuning
- Actual peak detuning **(21 Hz)** was higher than expected in first cryomodules
- A detailed vibration study was initiating which led to the following design change.
- A minor change to the **tuner pivot** plate substantially improved the microphonics for the CEBAF C100 Cryomodules.
- While both designs meet the overall system requirements the improved design has a larger RF power margin

Microphonic Detuning*	C100-1	C100-4
RMS (Hz)	2.985	1.524
6σ(Hz)	17.91	9.14



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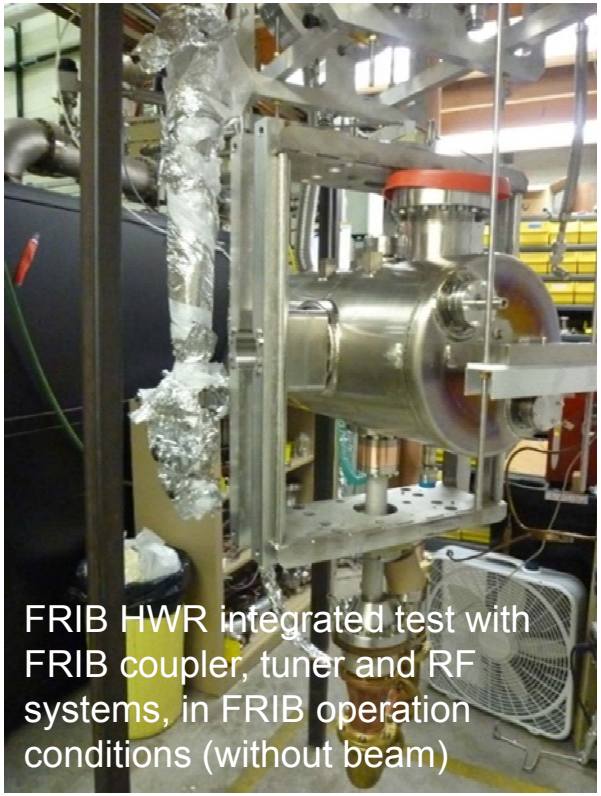
β = 0.29 HWR + Coupler + Tuner System Operation Validated in VTA Integrated Tests

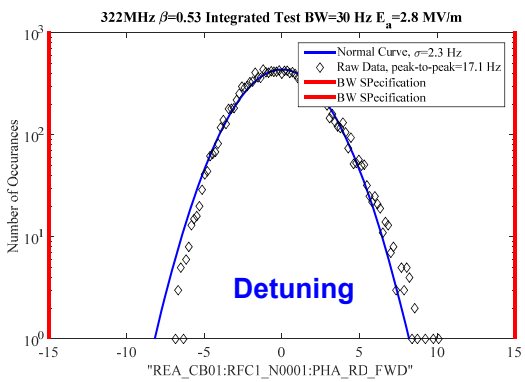
- FRIB HWR + Coupler + tuner + LLRF system successfully tested in β = 0.29 cavity
- 2 Test sessions performed at 4.3 K with 20 W RF load and He pressure fluctuations of several mbars
- MP and FE easily conditioned, validated FRIB HWR coupler cleaning/assembly procedure
- ANL type pneumatic tuner: smooth and precise in locked conditions during cold test
- Cavity locked at 4.3 K for long periods at E_a = 7.7 MV/m (FRIB gradient at 2 K)
  - Stable and reliable phase and amplitude lock reached (no unlocks in 24 h run)
  - Phase errors at 4.3 K still slightly above 2 K specifications, LLRF parameters still under optimization
  - Amplitude error within 2 K specifications

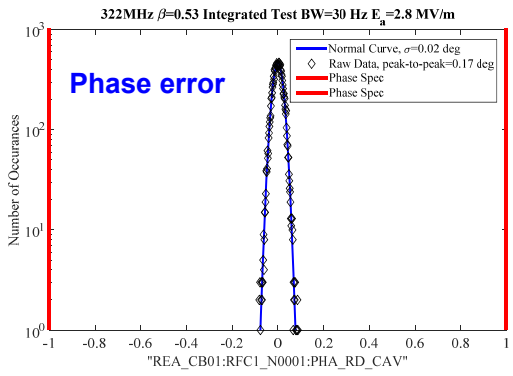


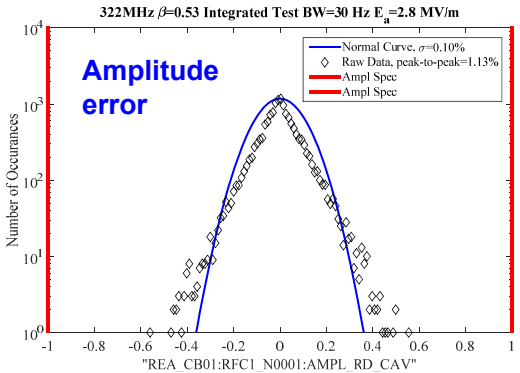
FRIB HWR integrated test with FRIB coupler, tuner and RF systems, in FRIB operation conditions (without beam)

β = 0.53 HWR Integrated Test Ongoing; Significant Progress with LLRF Firmware Improvements

- March: 24 h run at 4.3 K and low field (2.7 MV/m) and 74 Hz BW with no unlocks
  - Detuning from microphonics and phase/amplitude errors: σ fitting FRIB specifications, but long tails were still present
- Tuner control and LLRF parameters optimized after lessons learned in ReA6 testing: Meeting spec at 4 K with 30 Hz but still 2.8 MV/m, in 4 h run

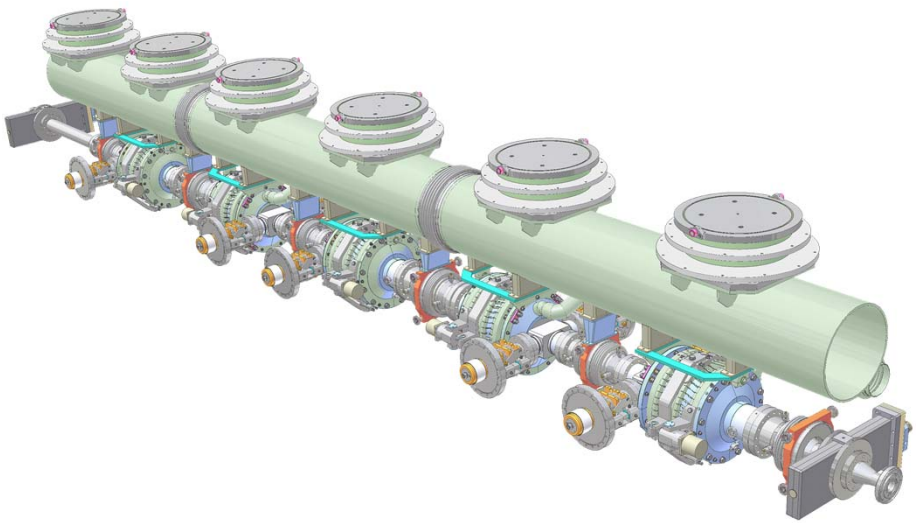


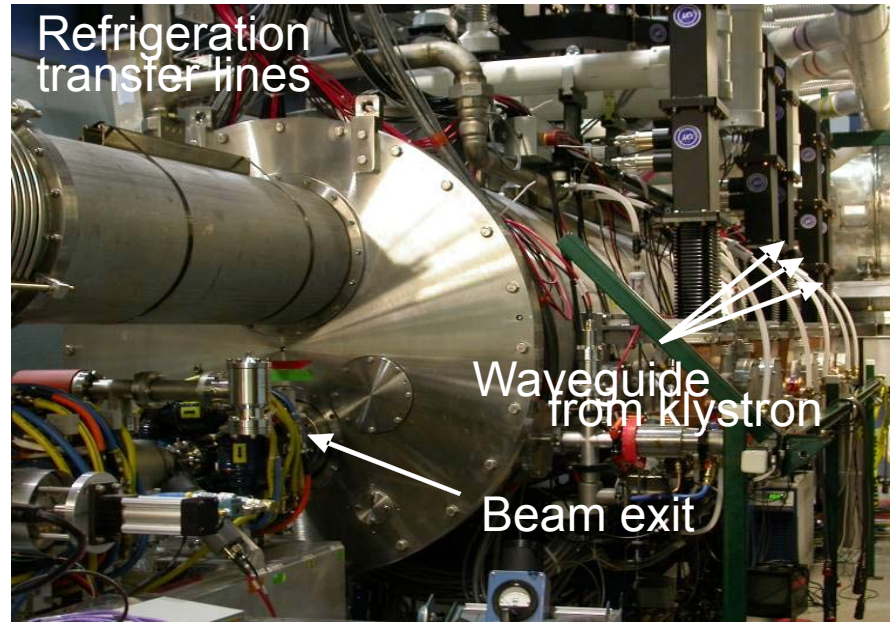




	Field	RF BW	Detuning distr.		Phase err.		Ampl. Err.	
	E_a (MV/m)	Hz	σ (Hz)	p-p (Hz)	σ (deg)	pk-pk (deg)	σ (%)	p-p (%)
Measured Test 1 (24 h, 4.3 K)	2.7	74	1.5	**78**	0.1	**3.3**	0.1	**3.7**
Measured Test 2 (4 h, 4.3 K)	2.8	30	2.3	17.1	0.02	0.17	0.1	1.13
FRIB goal 2 K	7.8	30	<1.25	<15	<0.25	<2	<0.25	<2

1.3 GHz ERL Injector Cryomodule

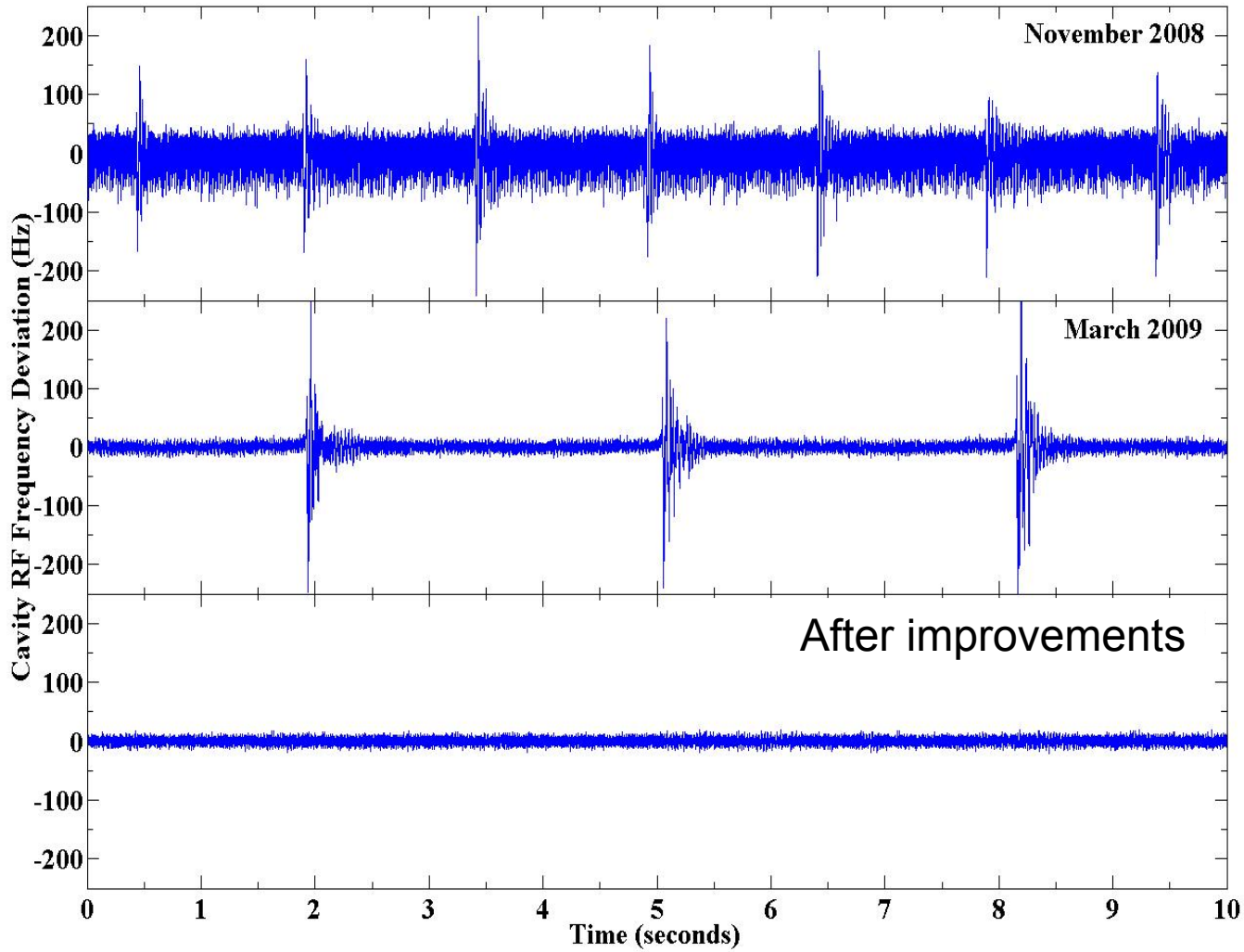




- Number of 2-cell cavities 5
- Acceleration per cavity 1 – 3 MeV
- Accelerating gradient 4.3 – 13.0 MV/m
- R/Q (linac definition) 222 Ohm
- Q_{ext} 4.6×10^4 – 4.1×10^5
- Total 2K / 5K / 80K loads: 30W / 60W / 700W

- Number of HOM loads 6
- HOM power per cavity 40 W
- Couplers per cavity 2
- RF power per cavity 120 kW
- Amplitude/phase stability 10^{-4} / 0.1° (rms)
- ICM length 5 m

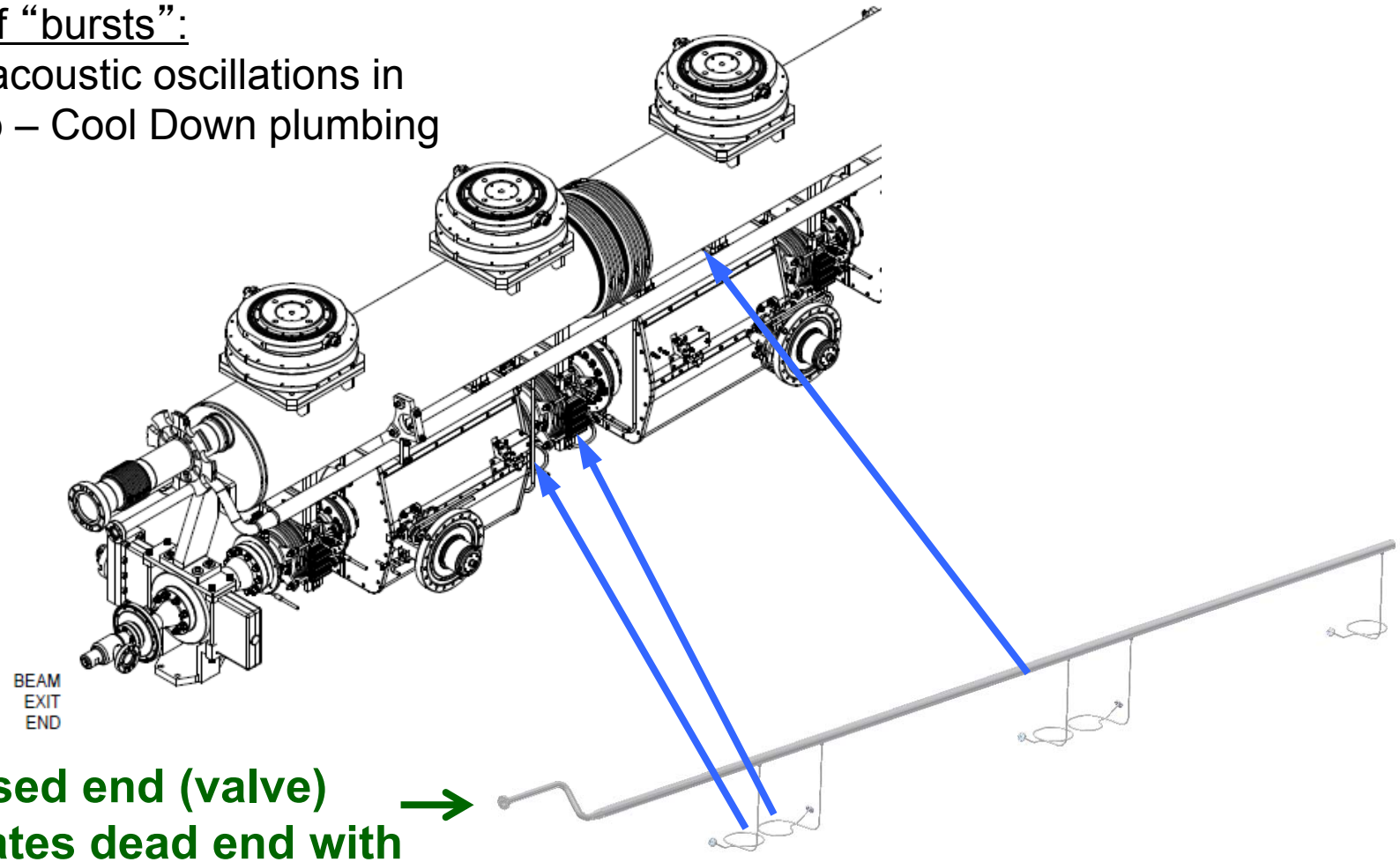
ERL Injector: Microphonics Bursts



- **Significant changes over time**
- **Step impulses at ~second rep-rate!?**

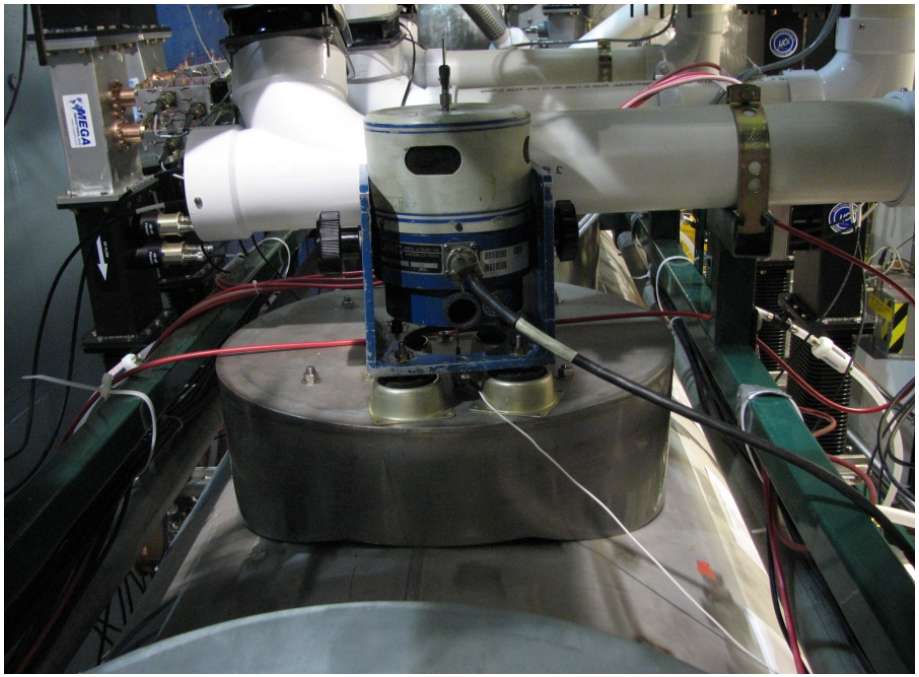
ERL Injector: Source of Microphonics Bursts

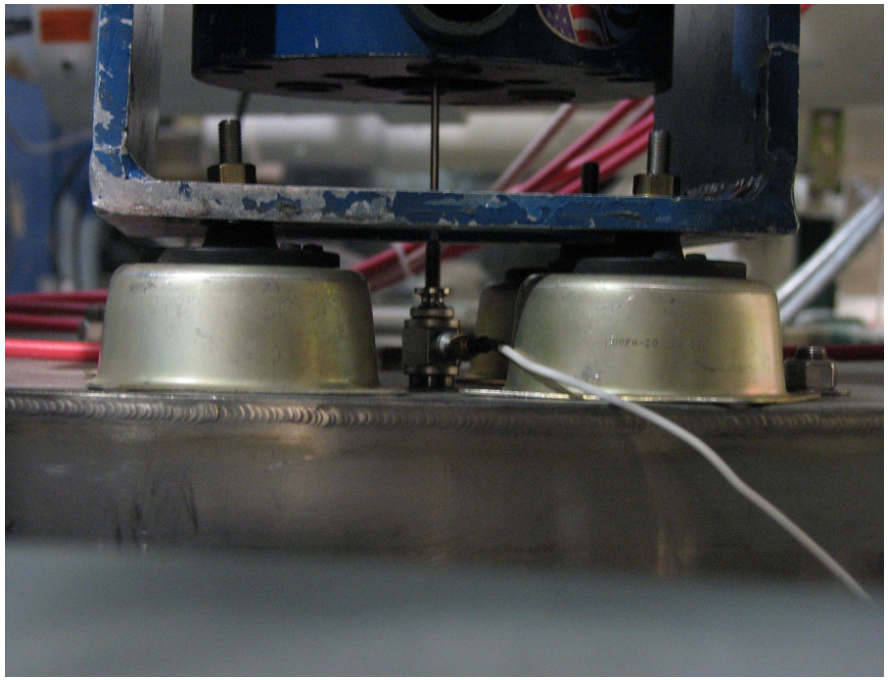
Source of "bursts":
Thermo-acoustic oscillations in
Warm Up – Cool Down plumbing



Closed end (valve) creates dead end with trapped gas

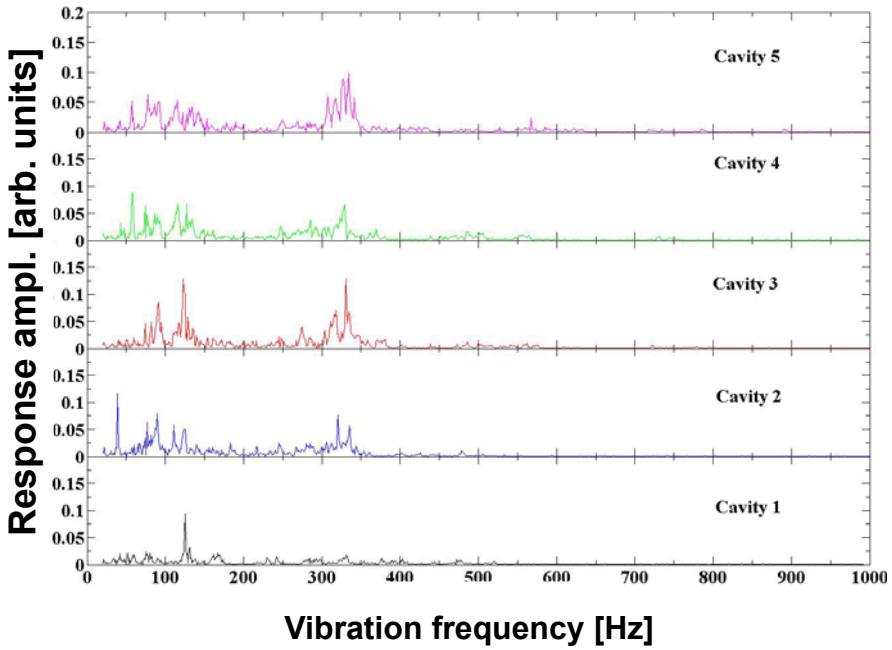
Mechanical Coupling Characterization Measurements with a Modal Shaker



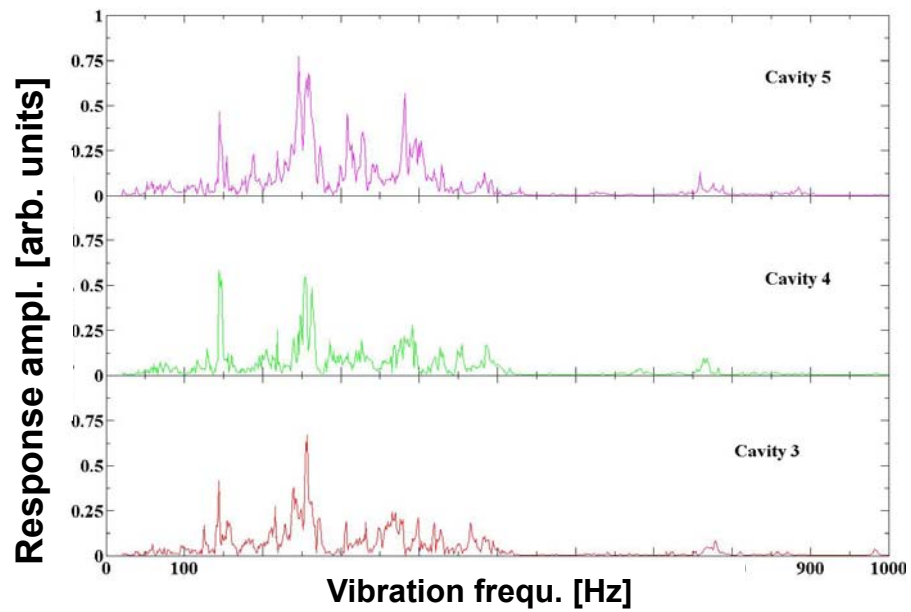


Measurements with a Modal Shaker

Shaker on module support



Shaker on module top (HGRP support)



Mechanical Coupling Characterization

Excitation Point	Excitation Force	Detectable With Cavity Accelerometer	Detectable On Cavity RF Frequency (>0.1Hz modul.)
Coupler Waveguide	110 N (25 lbs)	No	No
Coupler	110 N (25 lbs)	No	No
Cryomodule Saw-Horse Support	110 N (25 lbs)	Yes	No
Helium Gas Return Pipe Support	110 N (25 lbs)	Yes	Yes
Beam Line	10 N (2 lbs)	No	No
Helium Supply/Return	110 N (25 lbs)	No	No

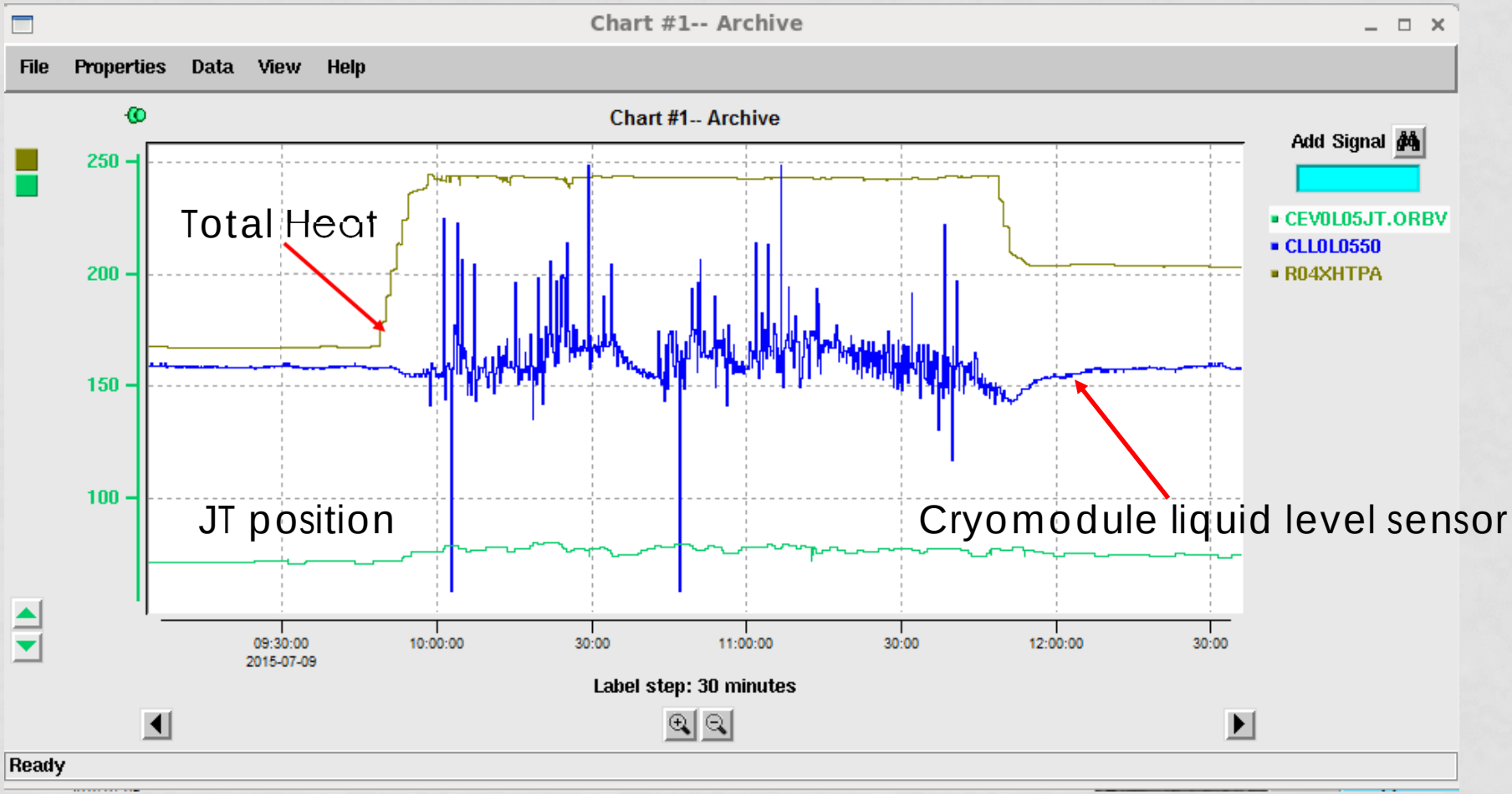
- Ground vibrations and other mechanical vibrations do **not** strongly couple to the SRF cavities!
- Main contribution to cavity microphonics comes from fast fluctuations in the He-pressure and vibrations in the cryogenic system

THE PROBLEM

- R100 cryomodule, situated last in the injector to provide necessary energy gain to facilitate the re-injection match, proved to be a “sensitive” child…
  - Multiple trips **(Microphonic induced Detuning)** – especially during normal workday times that abated during evening hours and weekends.
  - Difficult and lengthy recovery from zone trips once they occurred
  - The trips all correlated to large transient cavity detuning
  - Multiple causes for trips, evolving solutions
  - Focus on helium pressure and transient effects on cryomodule performance

C. Mounts - JLab

CLUES



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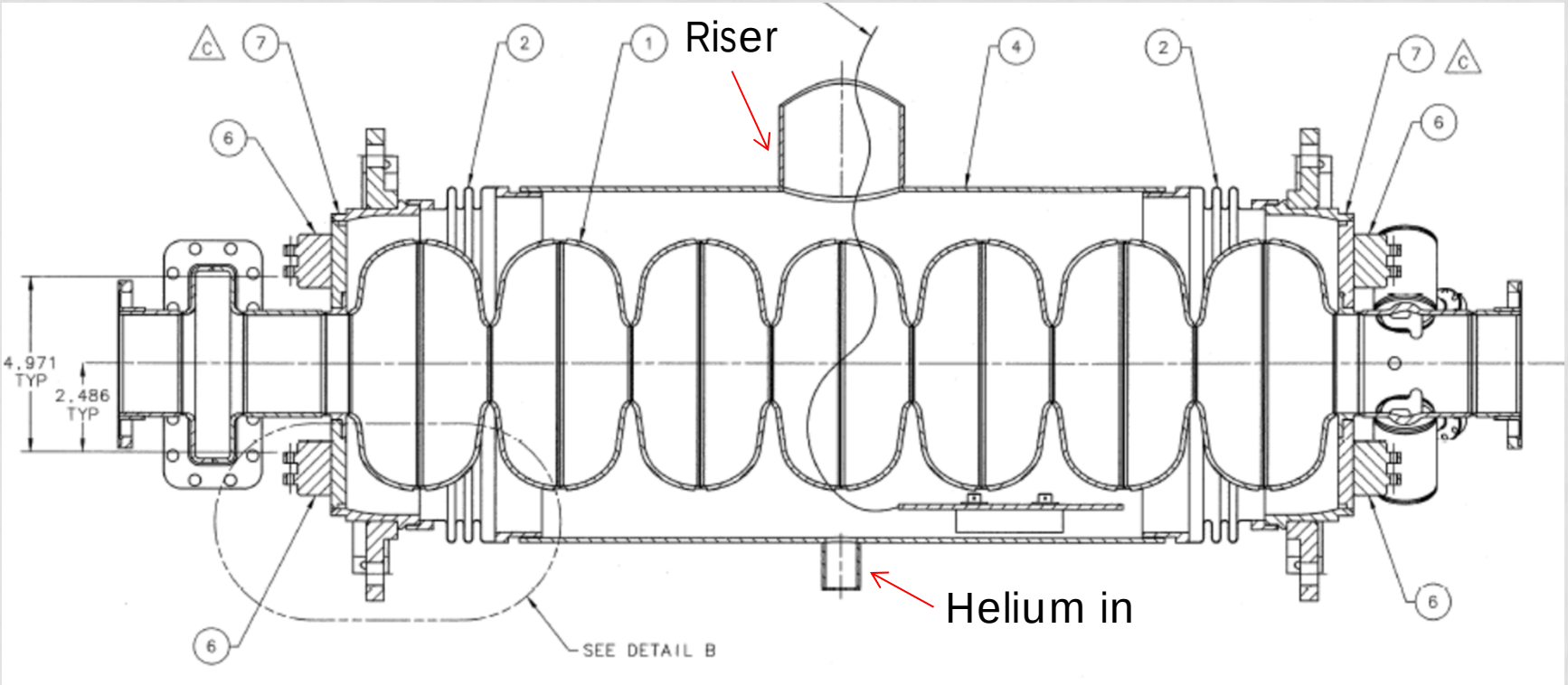
C100 CAVITY IN HELIUM VESSEL



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CONCLUSIONS

- For the C100 cavities, helium return pressure and stability is critical for maintaining maximum cryomodule performance
- There is a detectable pressure rise at the ends of the helium transfer lines that require offsets to the measured pressure at the "T" for the cryogenic plant to account for the pressure differential at the cryomodules at the far ends of the lines
- Still work to do – Why was detune angle affected at heat levels well below CHF limits, prior to observable liquid boiling?
- From the tech note:
  - It appears that regardless of the source, when heat in the module is increased the tuning becomes increasingly unstable. This is possibly due to bubbles created as the critical heat flow is exceeded in the risers. It is expected that at reduced pressures, this instability would be reduced or eliminated.

C. Mounts - JLab

Cryomodule Characterization - Summary

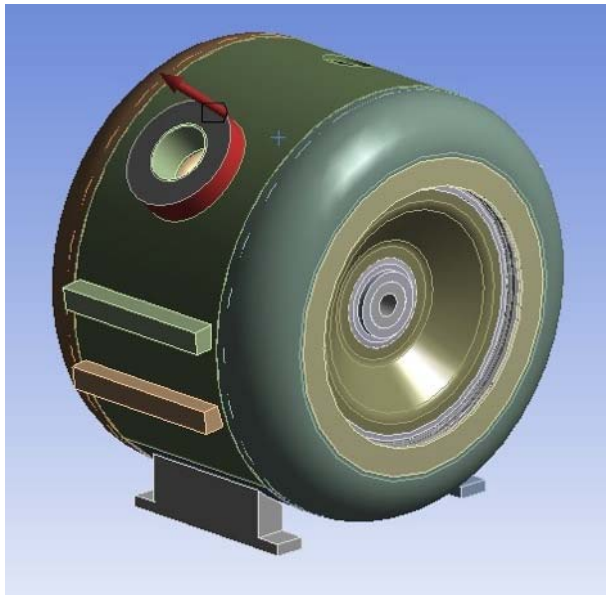
- Full system integration and testing is critical for diagnosis and mitigation of issues.
- Most issues are multi-disciplinary, vibration can be caused by any sub-system (cryo, vacuum, alignment fixtures, etc.)
- Detailed testing and measurement should be done at every point in cryomodule design/prototyping: bare cavity, dressed cavity, string assembly, cryomodule. These measurements should be complimented by mechanical simulations.
- These measurements can be done by direct measurement and with RF detuning, all tools should be used to attack the problem.
- Any ONE issue missed can be devastating to machine performance.

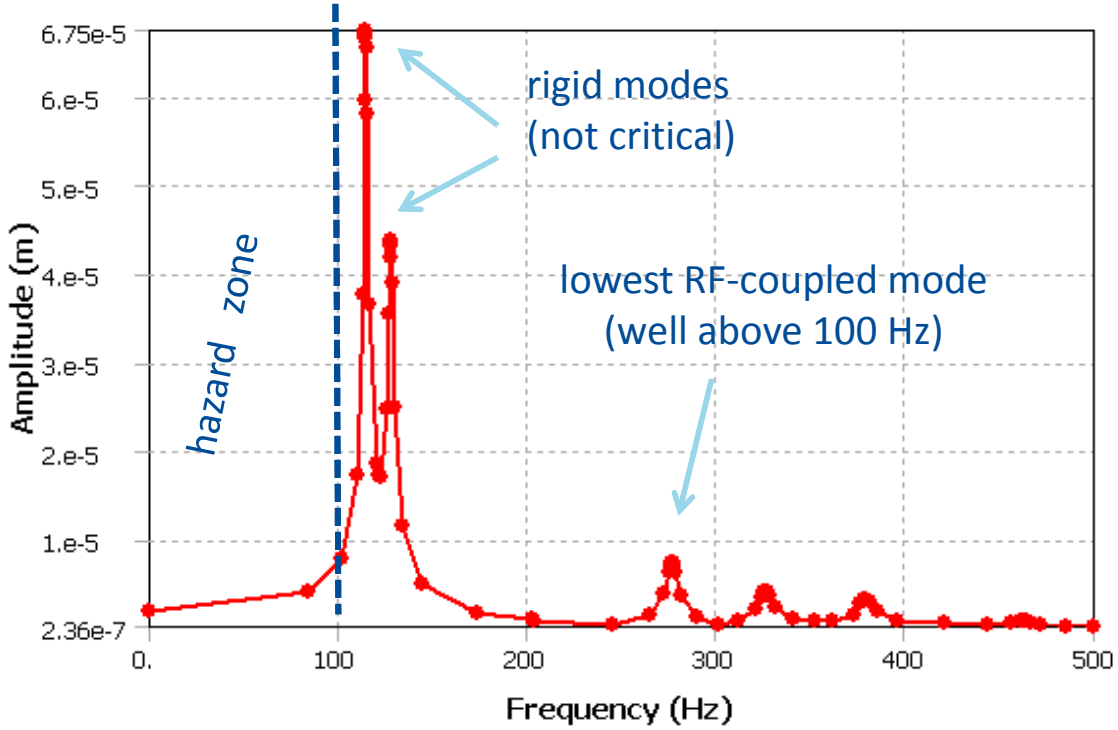
Cavity/Tuner System

Passive Control: Mechanical Resonances

L. Ristori

Oscillating force f (x,y,z)





Results					
Minimum	0. m				
Maximum	0.14647 m	0.16846 m	0.29507 m	0.41893 m	0.41125 m
Minimum Occurs On	Part 33				
Maximum Occurs On	Part 25	Bellows	ssr1_rf	Bellows	
Information					
Frequency	114.77 Hz	127.92 Hz	276.87 Hz	326.31 Hz	378.96 Hz

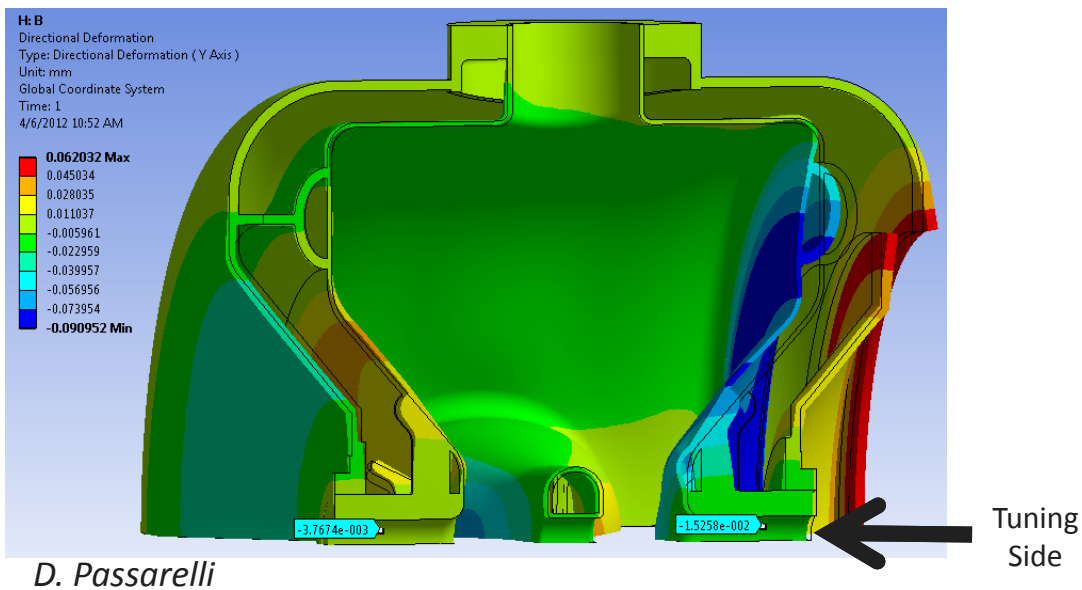
PIP-II SSR1 325 MHz, β=0.2

A self-compensating design was developed allowing low sensitivity

Despite non-negligible deformations (30-90 μm), net shift is very low thanks to Slater's Theorem

- Bare cavity ~ -650 Hz/Torr,
- Prediction with He vessel **-2 Hz/Torr** (no tuner), with infinitely rigid tuner **6 Hz/Torr**

Ease of tuning 39 N/kHz (bare), 40 N/kHz (with He vessel)



D. Passarelli

Methods used to balance deformations:

1. Diameter of bellows optimized to counteract Helium pressure on cavity end-wall.
2. Opposite end-wall coupled with vessel

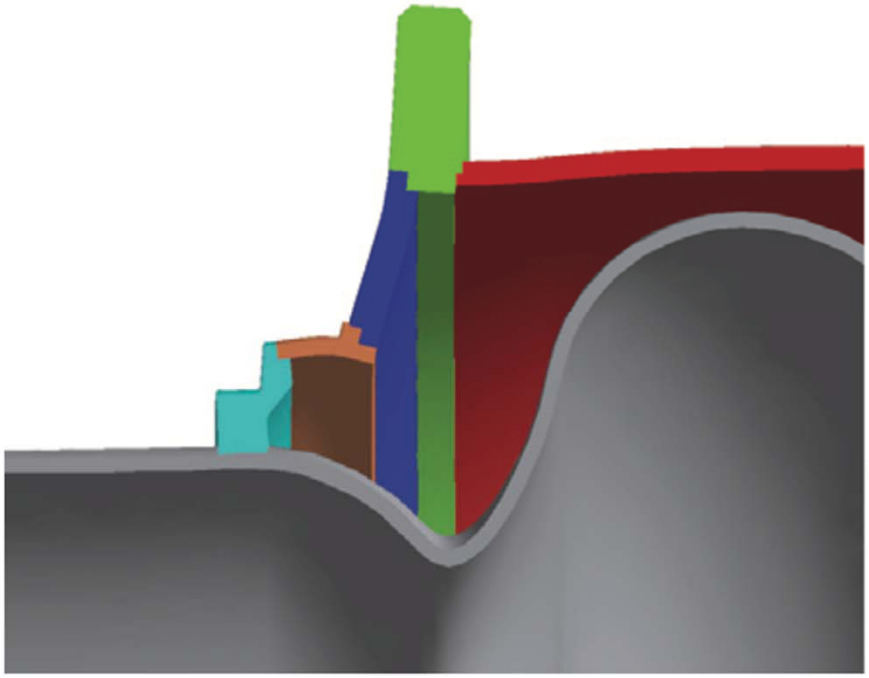
End-wall sensitivity 540 Hz/μm
When shooting for 5 Hz = 1 nm !

Manufacturing variation of df/dP

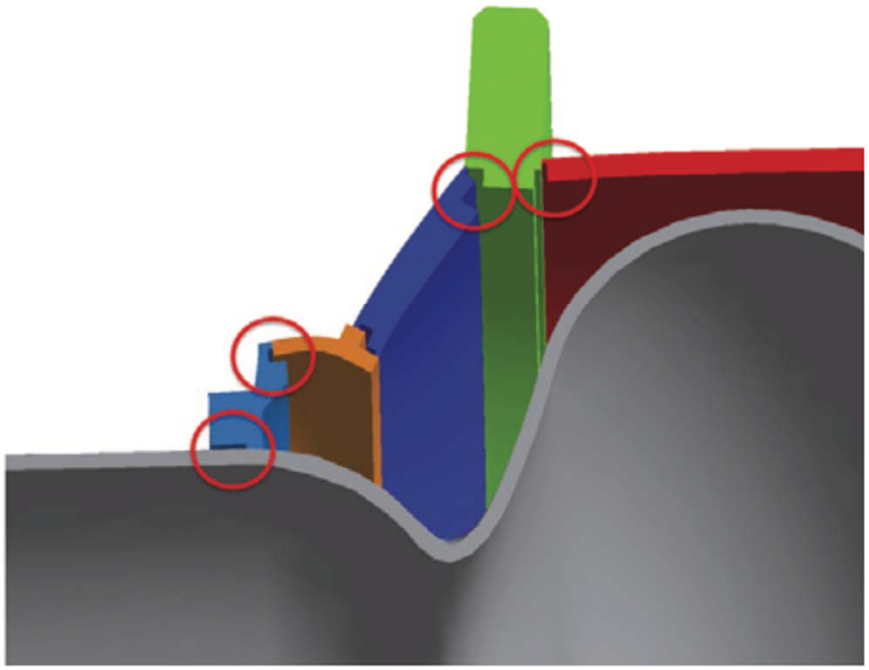
Room temperature measurements on bare and jacketed SSR1 resonators showing the influence of manufacturing variations on the value of df/dP.
An ~8% variation for bare cavities transforms into a much higher variation (in %) when aiming for very low numbers.
A value of 4 ± 5 Hz/Torr was achieved on a sample of 6 cavities

Hz/Torr	S108	S109	S110	S111	S112	S113
Bare cavity	-553.5	-555.1	-568.8	-525.8	-524.6	-544.7
With He Vessel	-1.2	5.4	7.9	2.7	9.0	6.3

Main Linac Cavity: Detuning Pressure Sensitivity



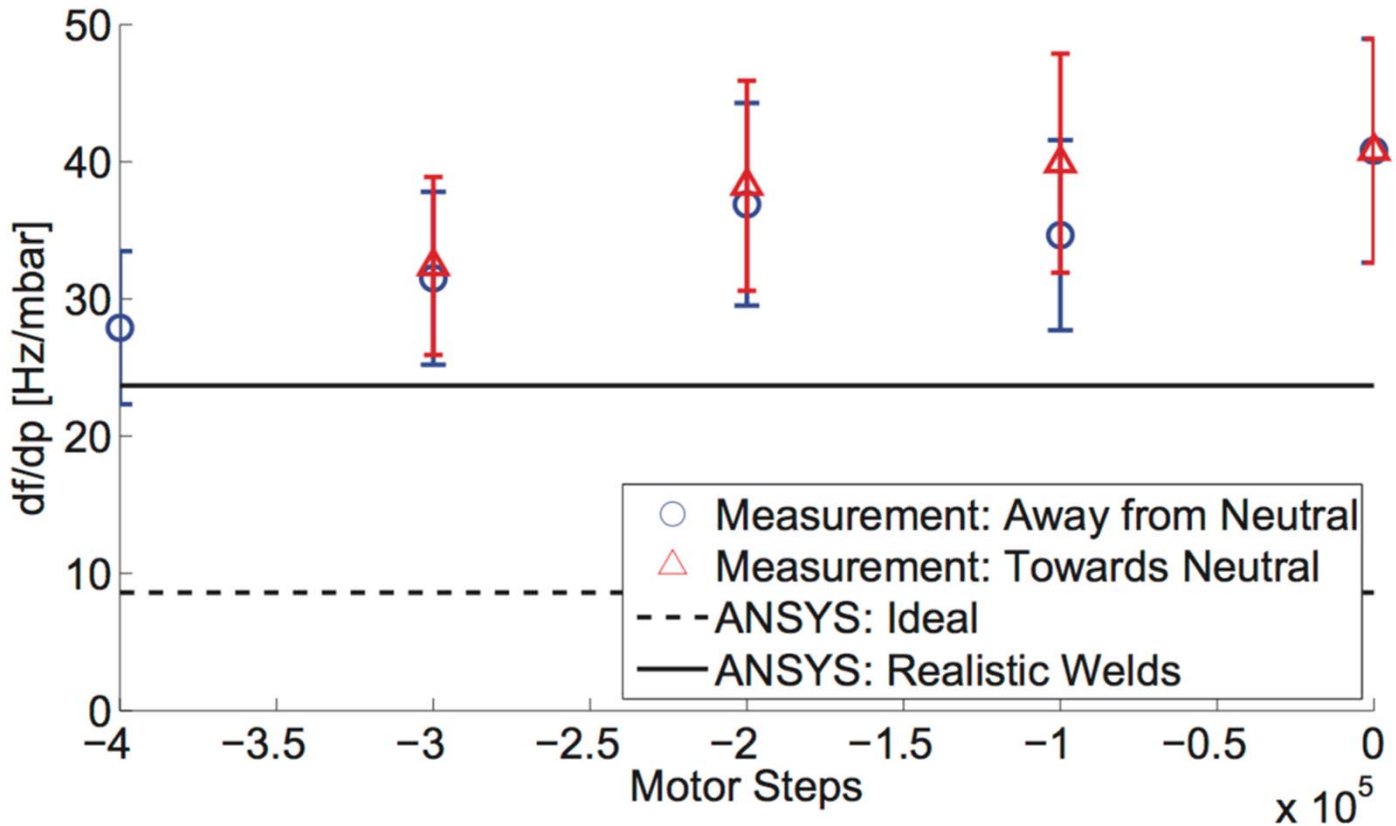
Original model for production cavity, deformed by helium pressure



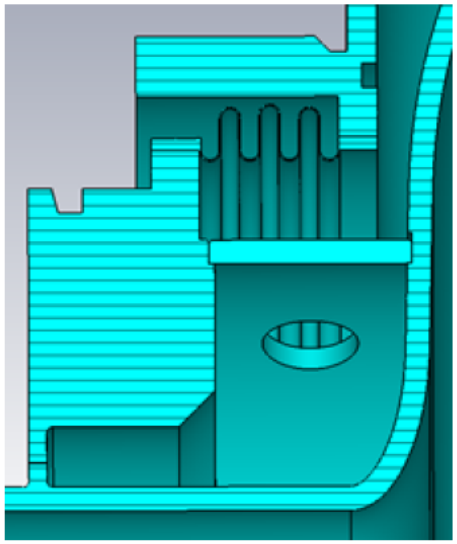
Model in which the welds are modelled more realistically

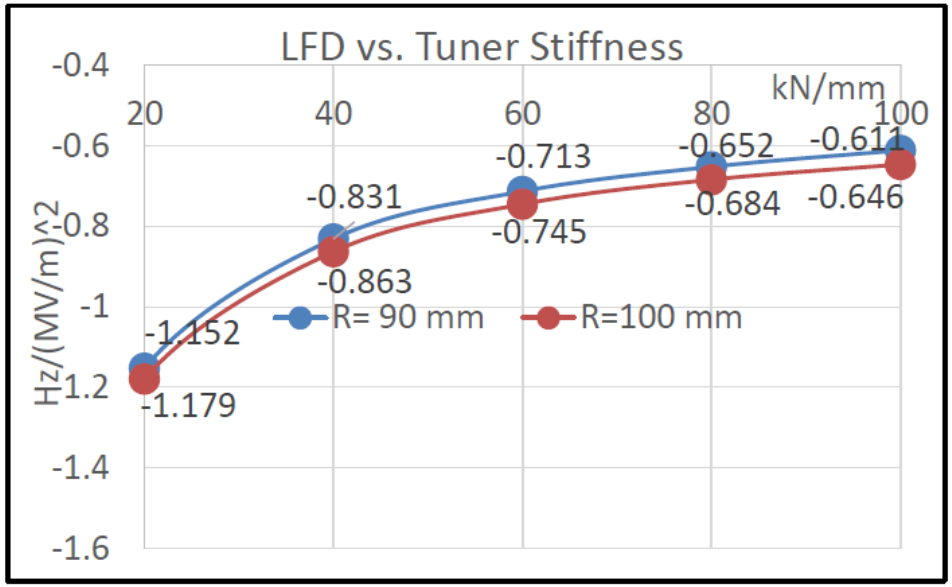
Main Linac Cavity: Measured Detuning Pressure Sensitivity

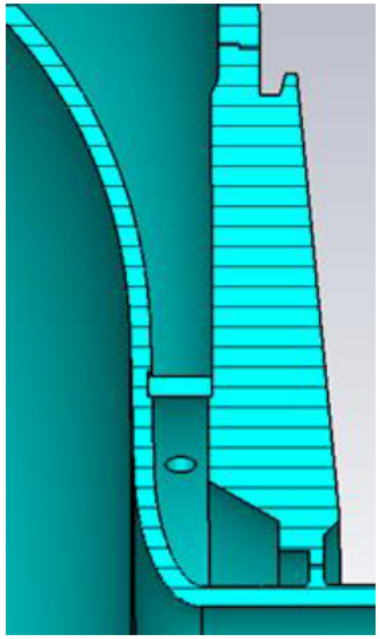
***df/dp* as a function of tuner motor steps**



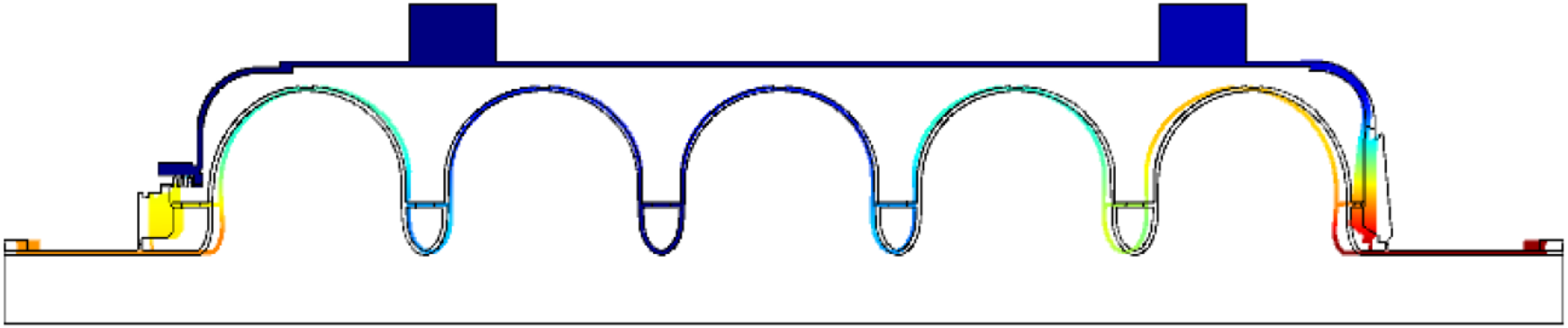
LFD for HB650 MHz dressed cavity





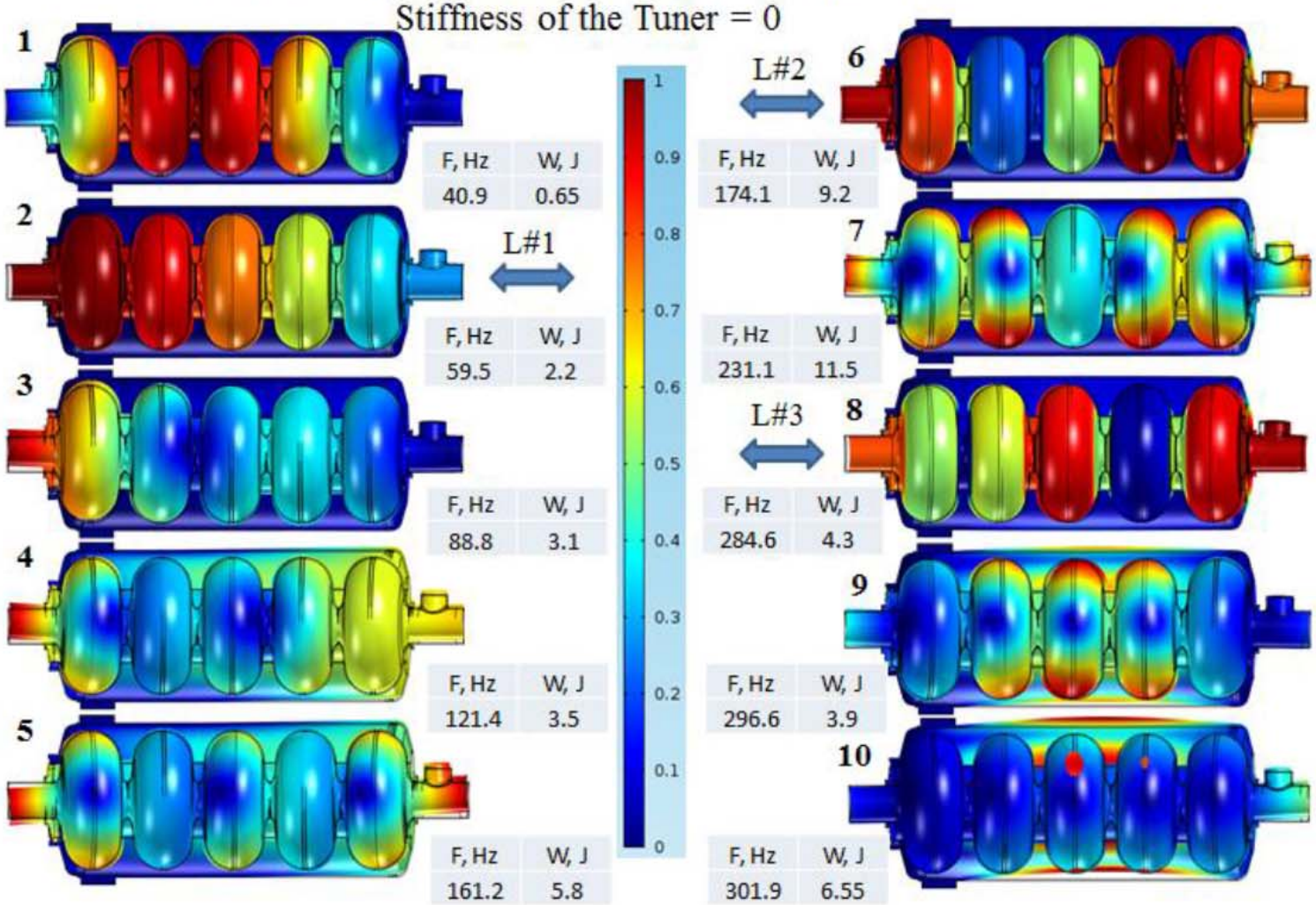


LFD 90 mmm vs. 100 mm for dressed cavity

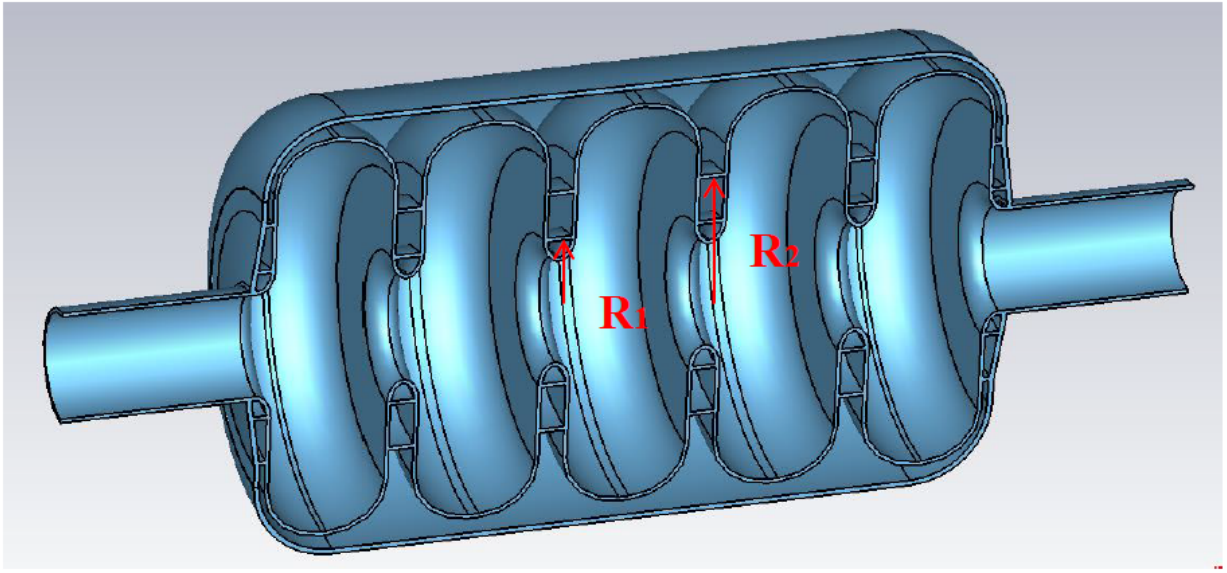


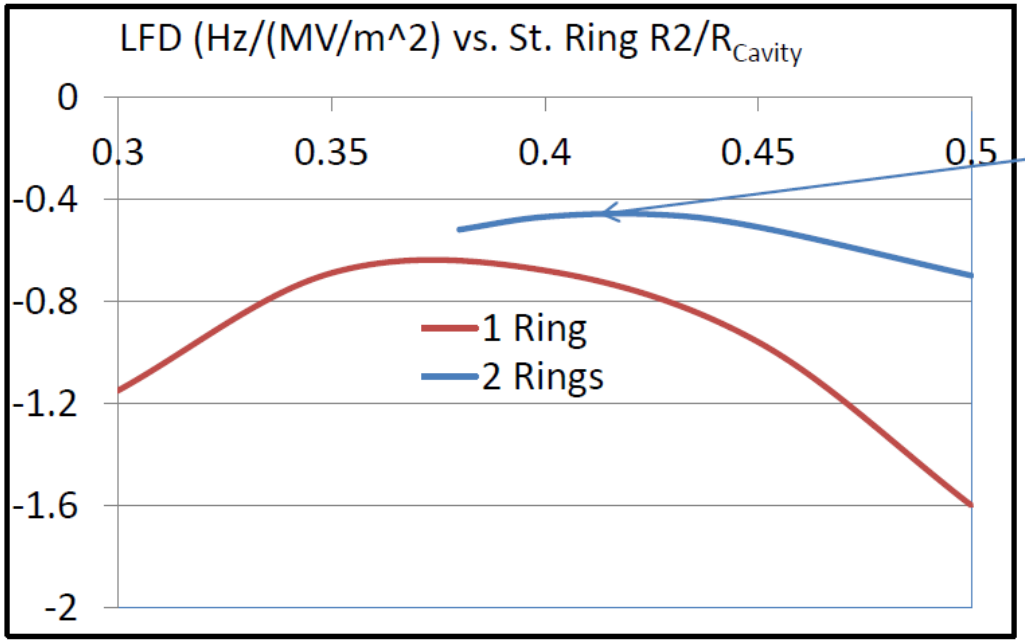
HB650 MHz cavity

10 Lowest Mechanical Resonance
Total Energy normalized on 1mm max-displacement
Stiffness of the Tuner = 0



LFD in LB650 cavity for PIP II



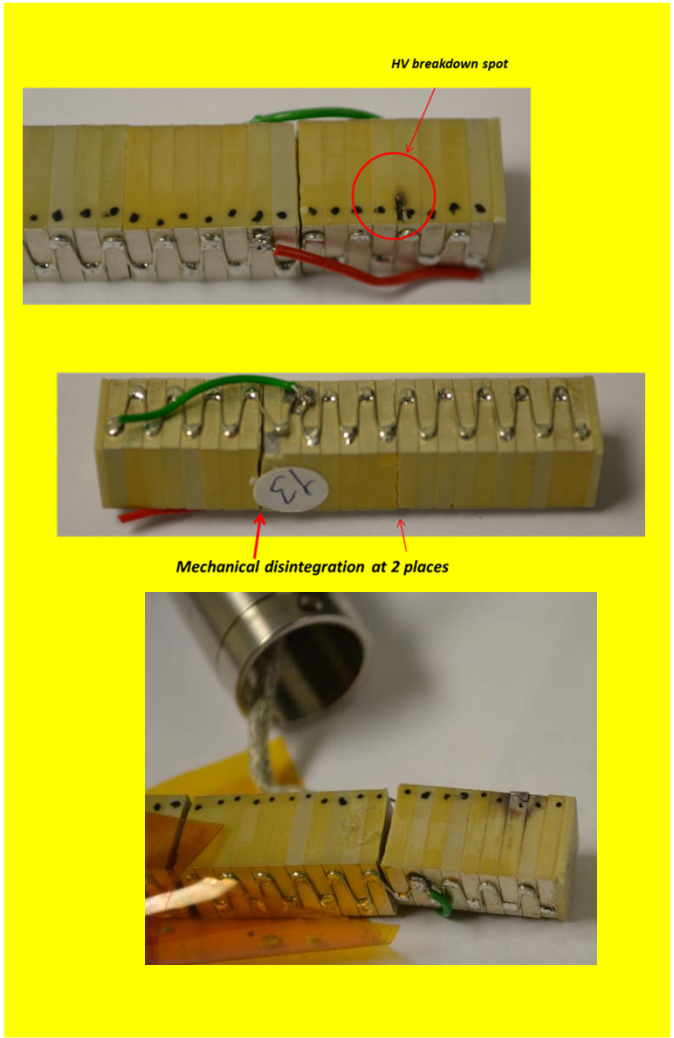


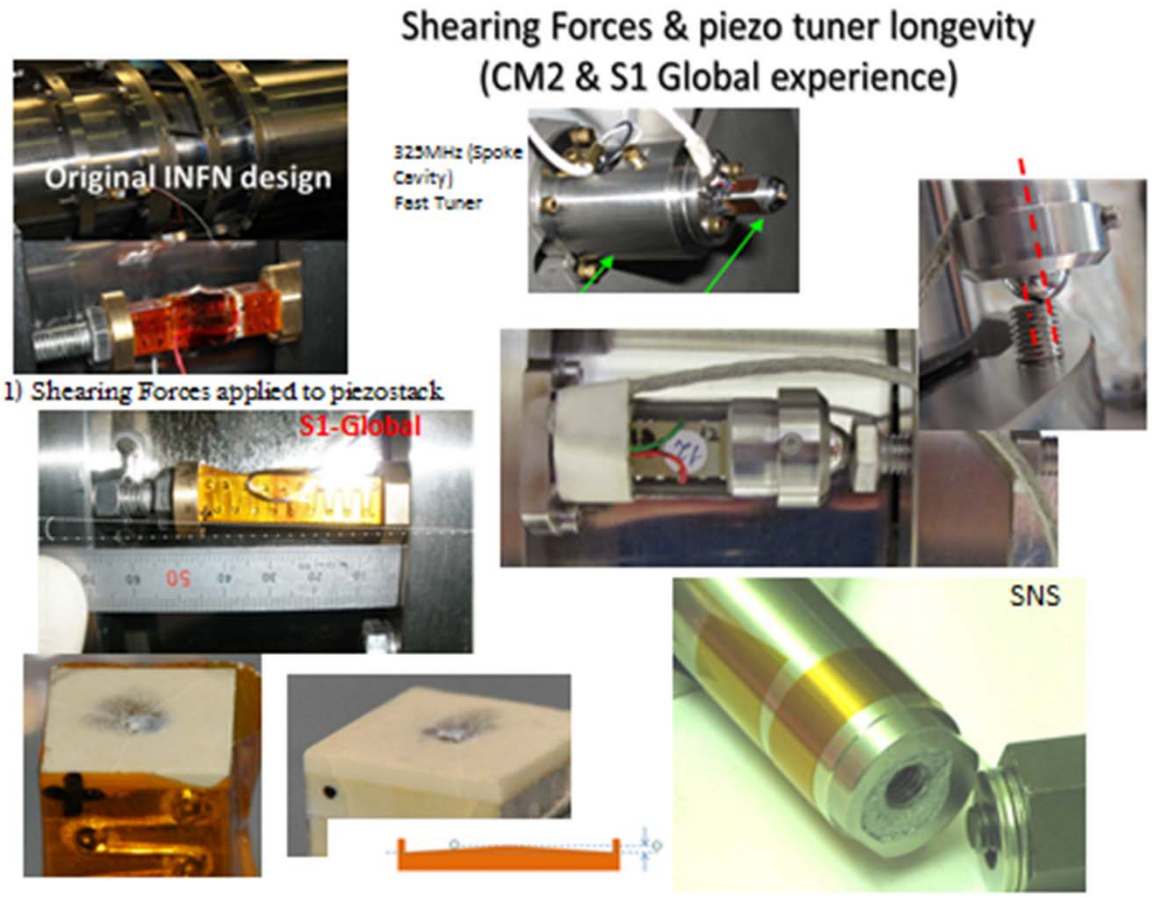
Cavity Stiffens ~2.7 kN/mm

Stiffness of the LB650 cavity is even lower compared to stiffness of the HB650 cavity

LCLS II Piezo Tuner

Shearing Forces on the piezo
Piezo-stack caplsulation





Y. Pischalnikov

Piezo-reliability: slew rate

	XFEL	LCLS II	FNAL-test-stand *(2month)*
Operation	10 pulses/sec	CW	CW
stimulus pulse, Hz	200 *(2 sinewave per pulse)*	40	5000
Vpp, V	120	2	2
piezo stroke,[um]	5	0.2	0.2
number pulses for 20 years	1E+10	2E+10	2E+10
total stroke of piezo for 20years, [km]	60	5	5
Piezo-stack motion speed (rms) (mm/s)	4.5	0.02	2.2
Piezo-stack motion acceleration (rms)(g)	0.6	0.0004	7
Heat dissipation, [mW]	90	0.05	6
Piezo ΔT raised	20K	0.1K	2K

Fast slew rate → large acceleration of the ends of the piezo-stack → cracks inside thin piezo-ceramics layer → HV break down → failure of whole Piezo

Limiting slew rate… design of Piezo amplifier per project requirements

Y. Pischalnikov

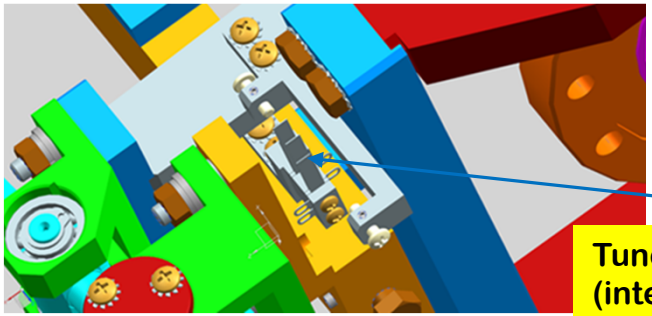
High reliability of tuner components (electromechanical actuator)

1. Phytron electromechanical Actuator (stepper motor/planetary gear/Ti spindle)

(designed per FNAL specs in the frame of the Project X.)

Joint test (JLAB/FNAL) of production unit is underway at JLAB

Picture	Name	Motor	Gear Box	Spindle/Nut	Forces	Longevity tested
	LCLS II	Phytron 1.2A	planetary gear (ration 1:50)	Titanium & SS M12*1	+/-1300N	tested in ins. vacuum at HTS for 5000 turns **(5 XFEL lifetimes).** In the force range +/- 1500N. Motor run with current 0.7A

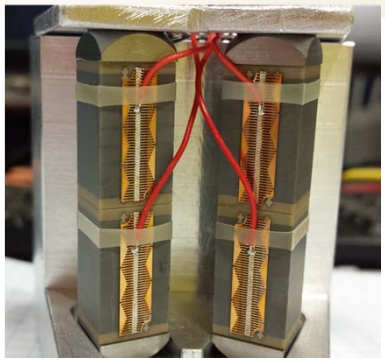


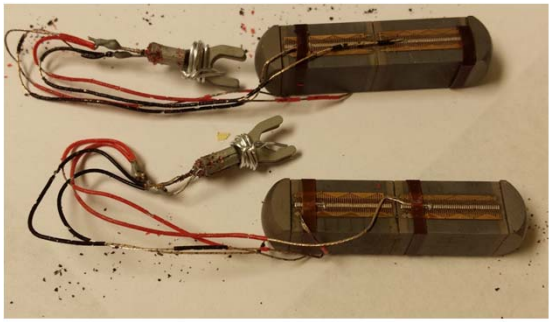
Slow Tuner/ electromechanical actuator lifetime (20 years)	1,000 spindle rotations

Tuner will have stepper motor limit switches (interlocks) to prevent hitting "hard stops".. Running motor to "hard stop " will create excessive forces on the spindle/traveling nut components

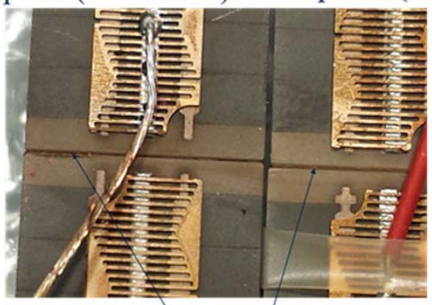
Y. Pischalnikov

Irradiation of the Piezo-stacks up to 10^9Rad (gamma)

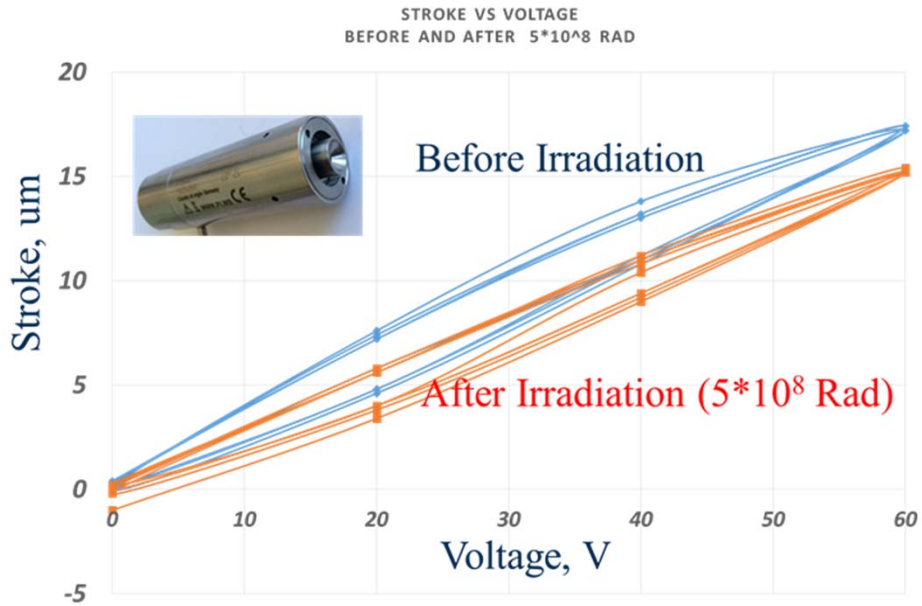




Sample A($5*10^8$ Rad) Sample C (0 Rad)



Discoloration of the thing layer of Epoxy



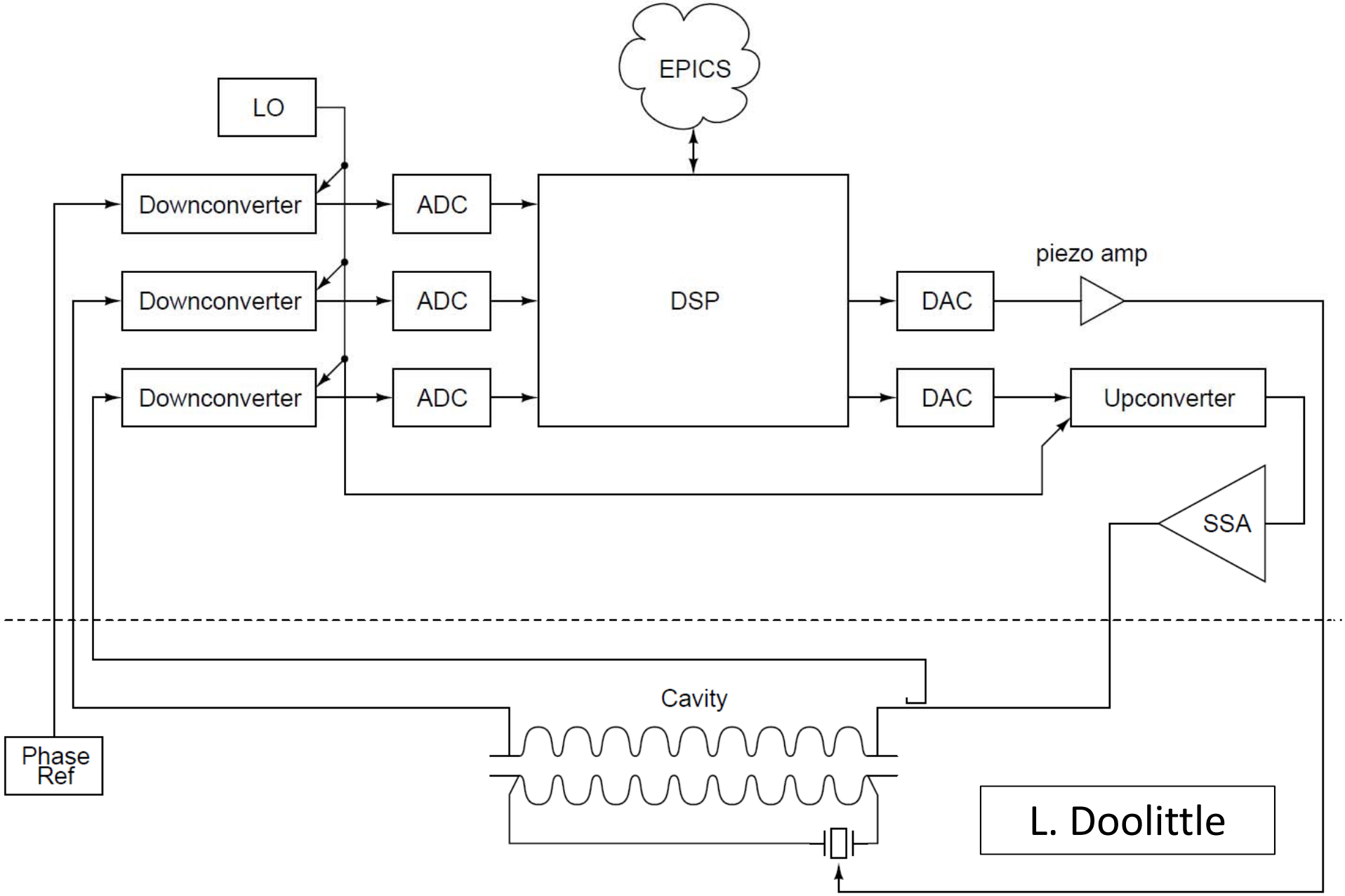
Stroke of the piezo-stack decreased only on 10% after irradiation up to 10^9 Rad

Y. Pischalnikov

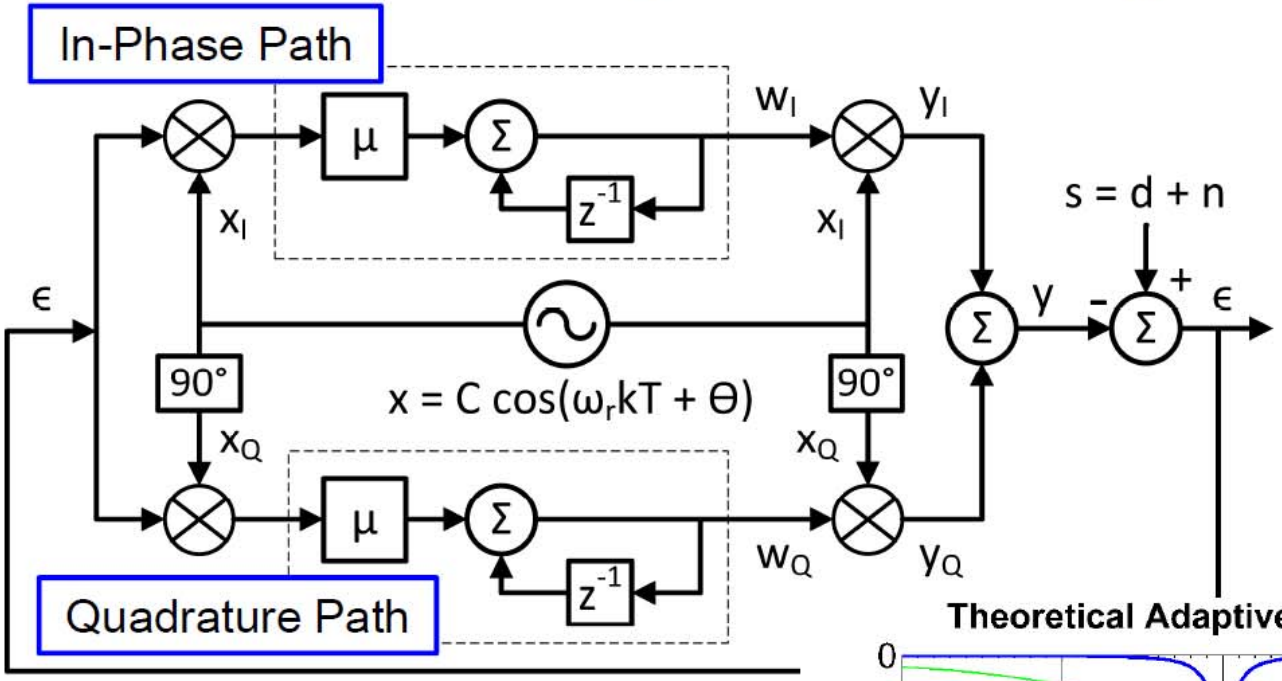
Cavity/Tuner System Summary

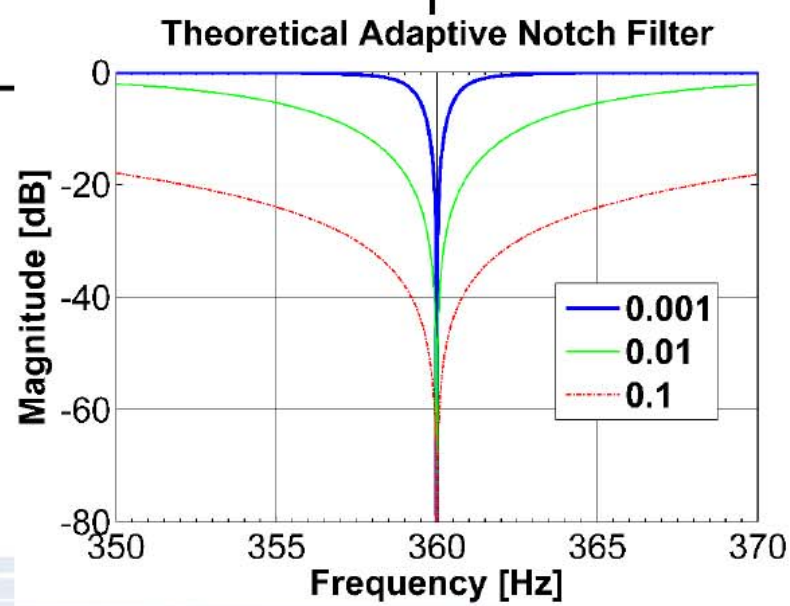
- A significant amount of design effort is required for due diligence in a cavity/helium vessel/tuner system.
- Coupled electromagnetic/mechanical simulations must be coupled with detailed prototyping and optimization of production procedures to have a good-performing and reliable system.
- These components are expected to live and operate reliably in a very challenging environment for years, if not decades. Extensive engineering/testing must be done to demonstrate reliability under these conditions.
- SSR1 is an excellent, successful example of cavity design with frequency stability in mind.

LLRF/Active Resonance Control Techniques

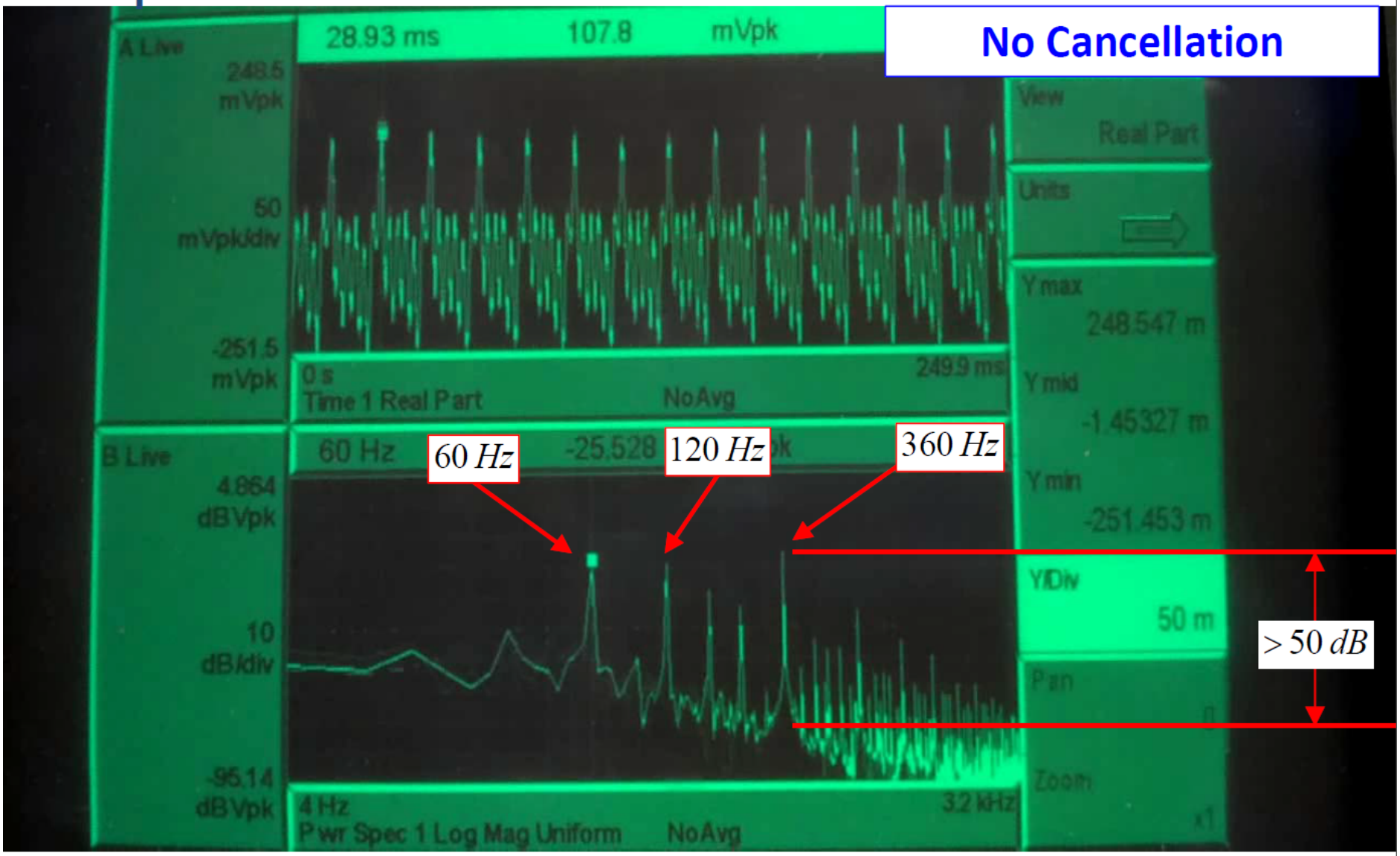

EPICS
LO
Downconverter
Downconverter
Downconverter
ADC
ADC
ADC
DSP
DAC
DAC
piezo amp
Upconverter
SSA
Cavity
Phase Ref
L. Doolittle

2-Weight Filter = Tracking Notch Filter
= LLRF system with Integral Gain

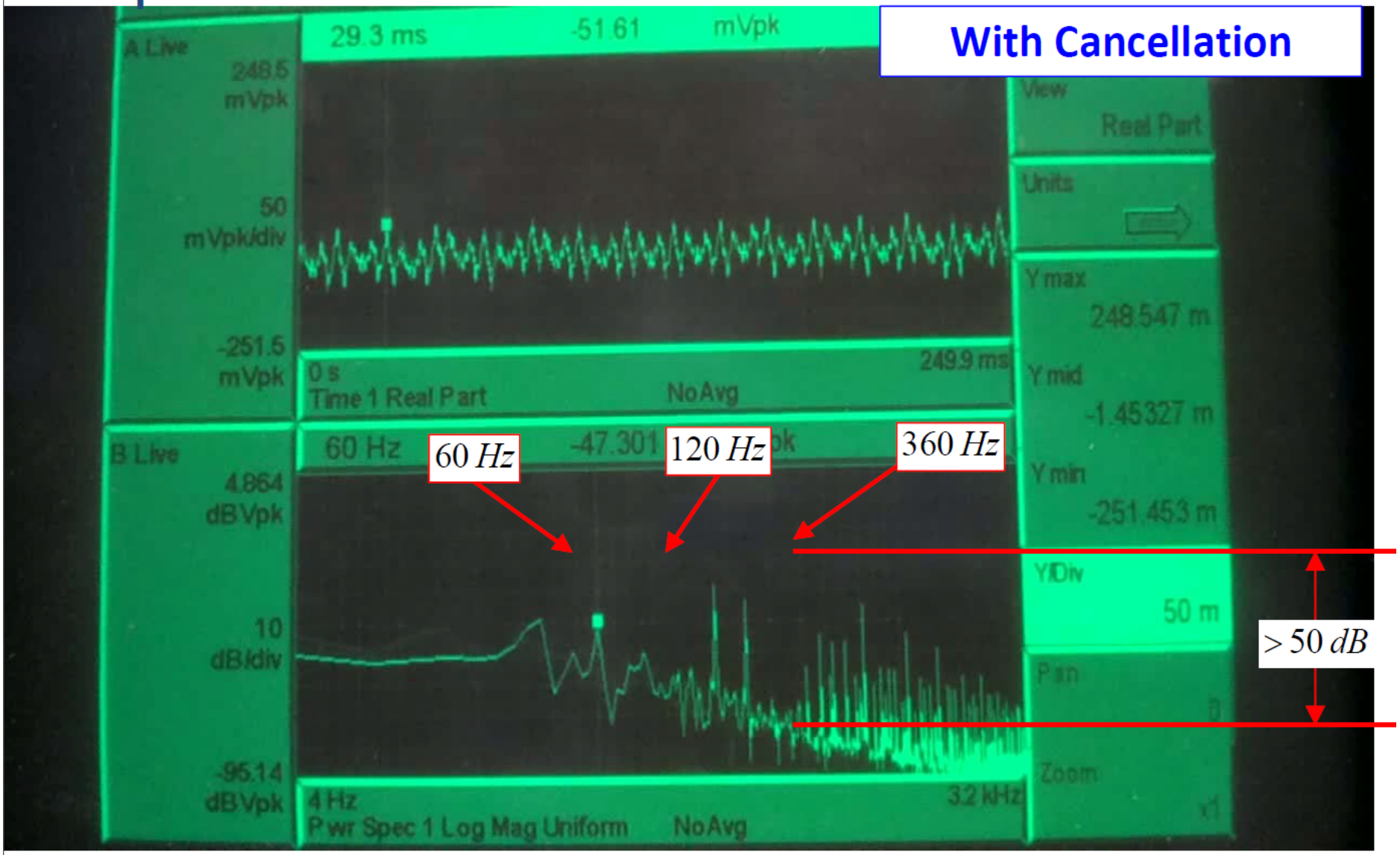




Adaptive Noise Cancellation - Demo at RF Test Stand



Adaptive Noise Cancellation - Demo at RF Test Stand



Controlling Detuning in the PIP-II Cavities

- PIP-II design calls for narrow bandwidth ($f_{1/2} \cong 30$ Hz) cavities operating in pulsed mode
  - Narrow bandwidth makes cavities susceptible to vibration induced detuning
  - Pulsed mode LFD can excite vibrations
- PEAK detuning of PIP-II cavities must be limited to 20 Hz or less
  - PIP-II cavities will require active detuning compensation of both LFD and microphonics during routine operation
    - Will require combination of
      - best LFD compensation achieved to date
      - AND best active microphonics compensation achieved to date
      - AND 24/7 operation over hundreds of cavities for several tens of years
- **No examples of large machines that require active detuning control during routine operation currently exist**

	N	f	Q_0	r/Q	E	$L_{Effective}$	Voltage	Current	Control	Losses	P_{Beam}
		MHz	10^9	Ω	MV/m	m	MV	mA	%	%	kW
HWR	8	162.5	5.0	275	9.7	0.21	2.01	2	20	10	4.02
SSR1	16	325	6.0	242	10.0	0.21	2.05	2	20	10	4.10
SSR2	35	325	8.0	296	11.4	0.44	4.99	2	20	10	9.99
LB650	33	650	15.0	375	15.9	0.75	11.86	2	20	10	23.72
HB650	24	650	20.0	609	17.8	1.12	19.92	2	20	10	39.84

Some LCLS-II LLRF Challenges:

"Why don't you follow the XFEL design?"

Finding the resonance: 20 Hz wide, at least in the initial turn-on it could be anywhere in a 200 kHz band.

Resonance shifts by many bandwidths when you run the gradient up to its design value.

Unknown microphonic spectrum, vs. tight requirements (0.01° and 0.01%) on cavity field stability. 82 dBA measured in gallery (with LCLS-I modulators turned off). A bridge carries I280 over the linac.

Scale to 280 cavities: strung along 700 m of linac. Need to include a drift-compensating Phase Reference Line.

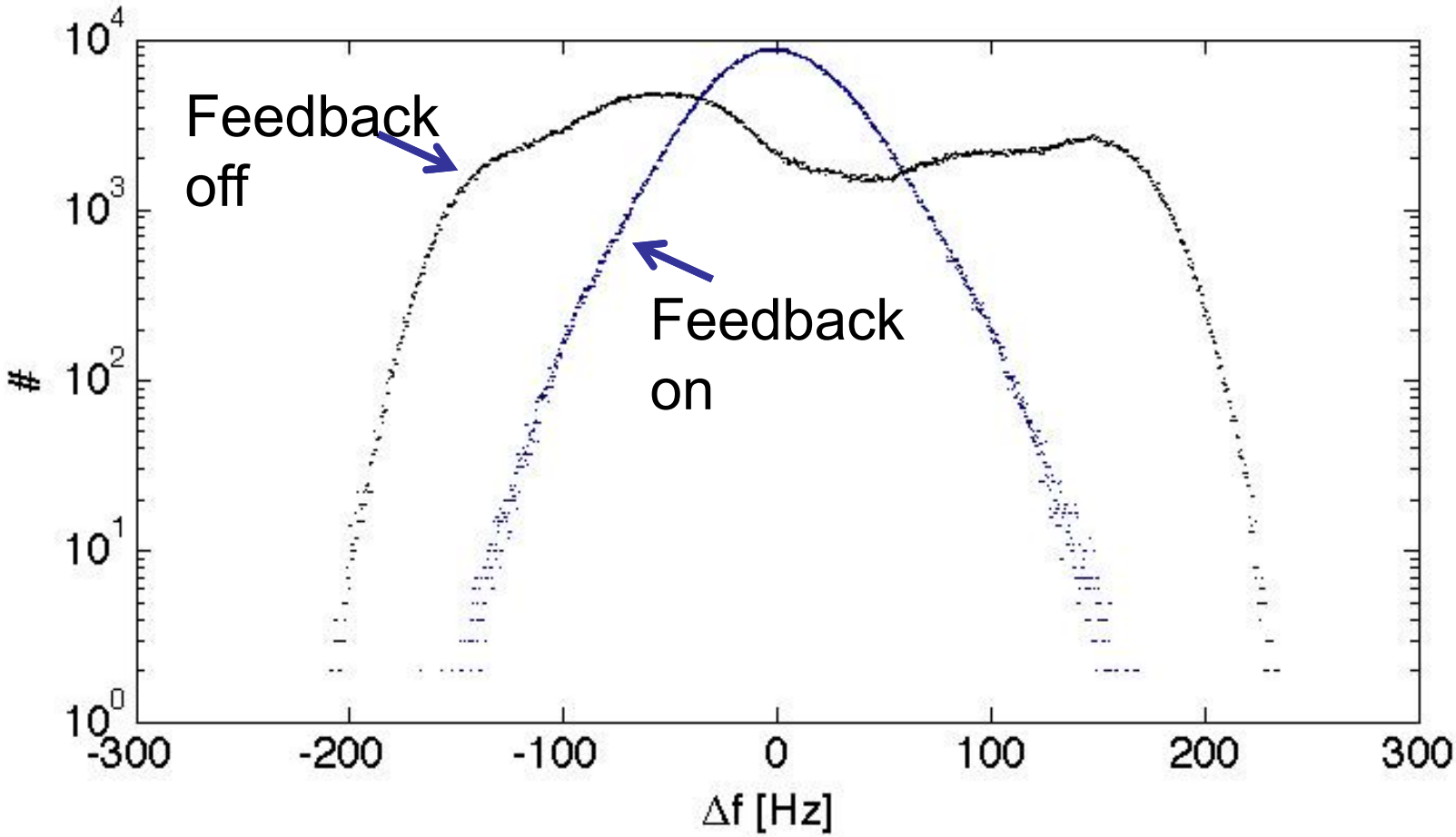
Interact with other SLAC subsystems and mandates, some of which are moving targets, culture clash between software and gateware paradigms, ...

Software Project Management/Estimation, our parochial component of an industry-wide problem. Usual estimates are that 50% to 80% of large projects fail.

L. Doolittle

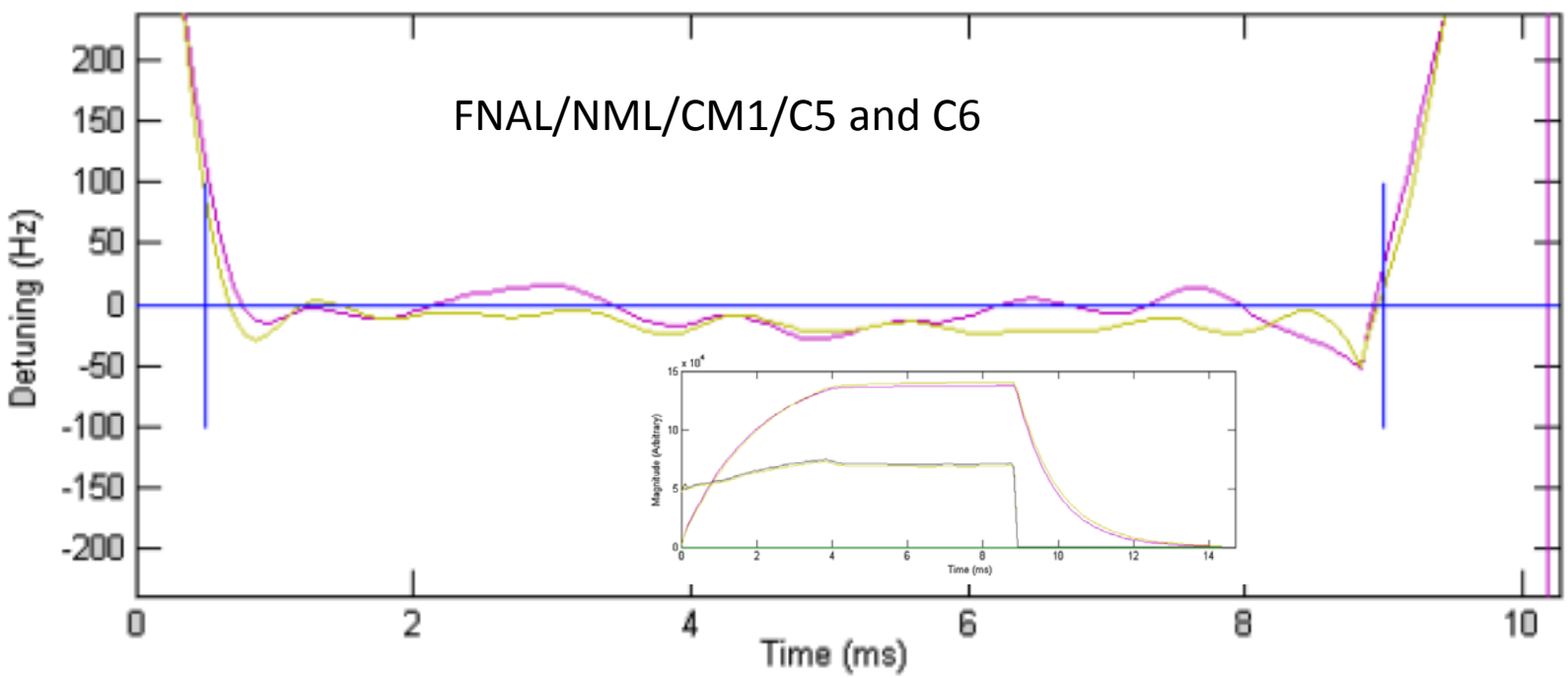
Active Microphonics Compensation

Detuning Histogram: ~30% reduction in peak detuning



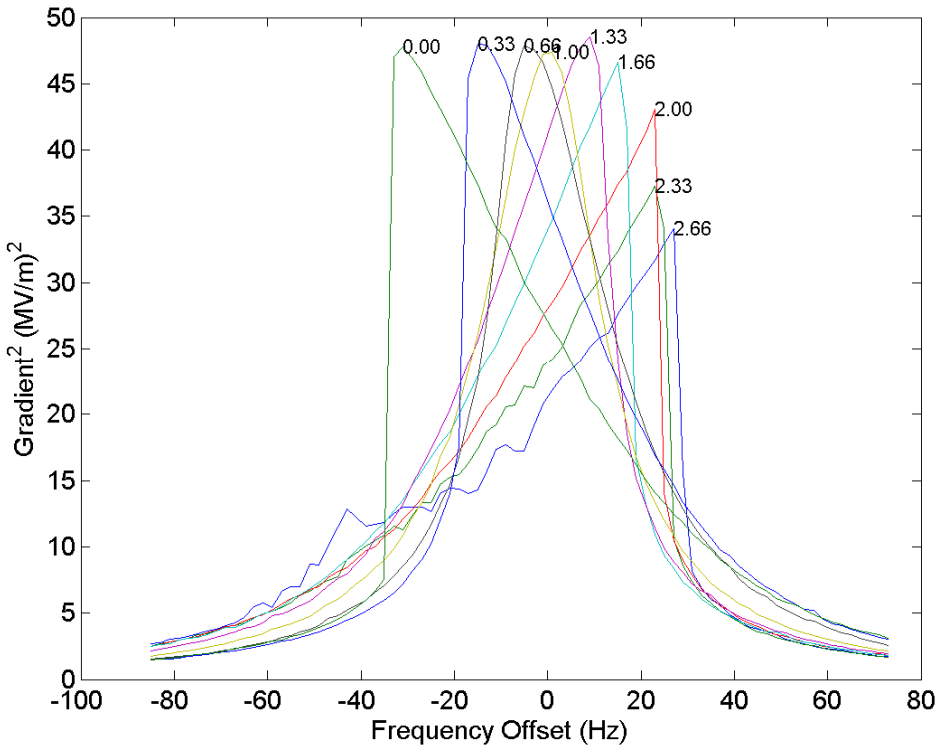
Narrow Bandwidths and Long Pulses

- For some applications longer pulses and narrower bandwidths may be useful
  - 2011 Test using 9ms pulses in FNAL/NML/CM1/C5 and C6 for Project X
    - Q_L ranged between $3x10^6$ and $3x10^7$
  - Adaptive LFD control able to limit detuning to better than 50 Hz across the flattop and most of the fill



Feed-Forward LFD Compensation

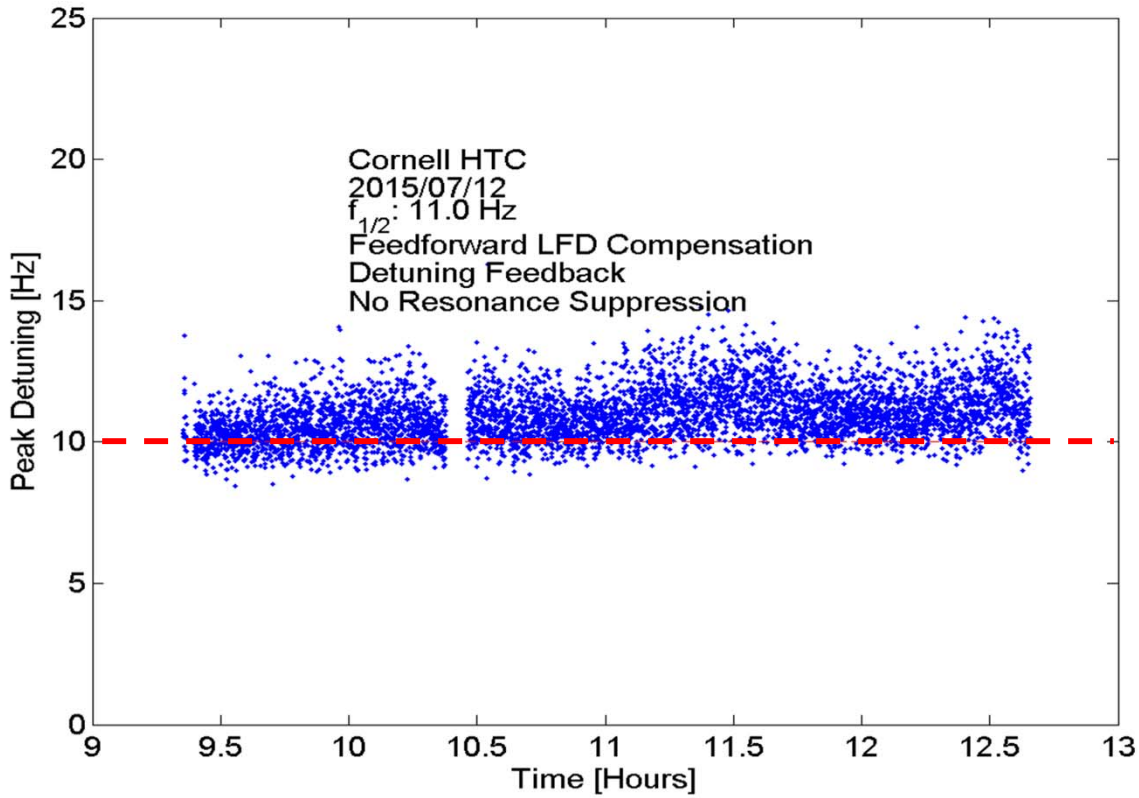
- Possible to remove the instability using piezo feed-forward tied to cavity square of gradient
  - Previously shown for SSR1 spoke resonator
  - Now demonstrated for multi-cell elliptical cavities



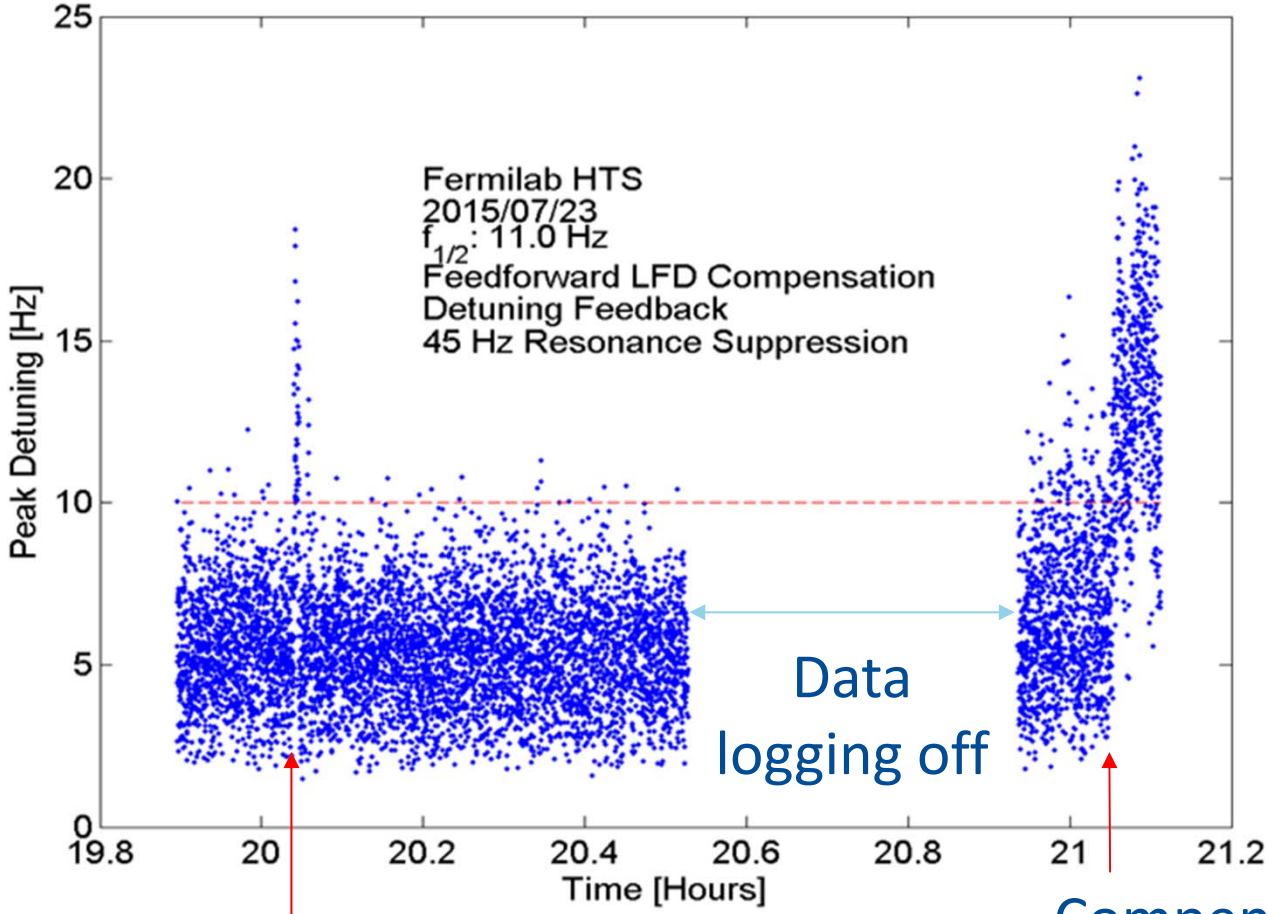
LCLS II 1.3GHz 9-cell elliptical cavity CW-mode operation

f1/2=12Hz ; Eacc=7.5MV/m; T=2K

LFD Feedforward Compensation and Detuning feedback



Added 45Hz Cavity Vibration Suppression



Data logging off

Compensation OFF

Compensation OFF

Active Control - Summary

- Active control is a measure of last resort, and is easily the most speculative aspect of resonance control
- Previous work at Cornell, BESSY, and other places has made strides in damping detuning with fast, piezo tuners
- Pondermotive instability has been demonstrated correctable with piezo feed-forward
- Cavity characterization has progressed to the point where it's achievable to construct a complete cavity electromechancial model
- Best accomplishments to date have been close to LCLS-II specifications, but for short periods of time on R&D systems
- While encouraging, *significant* effort will be required to translate these developments to a production LLRF system

(Technical)

Conclusions

- **Microphonics levels vary significantly from cavity to cavity**
- **Microphonics spectra are often complex with many lines, making active compensation more challenging**
- **Ground vibrations might not be the main driving source, but the He-system might be**
- **Passive compensation/mechanical design for low microphonics can be powerful, but not always possible**
- **Active compensation feasible within limits, but challenging. Success strongly depends on actual microphonics spectrum**
  - **Easier to reduce RMS then peak detuning value!**
- **Best Cornell results are ~20 Hz peak detuning for long periods of time (hours)**
- **Much more work needed to understand dominant sources of microphonics, how to reduce them, and to improve active compensation**

Background

- It is challenging to write good requirements for vibration control that are
  - Understandable to non-experts
  - Analyzable
  - Enforceable

- PIP-II's current approach
  - Develop rigorous requirements that apply to systems that "touch" SRF cavities (see J. Holzbauer)
  - Disseminate best practices for passive vibration control in other systems (this talk)
  - We are piloting this approach in the ongoing construction of the PXIE test bed

Best Practices Document

- Available in Teamcenter – ED0002931
  - For external access, the document will be filed with this talk http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=30
- Outline of document
  - List of common vibration sources
  - Guidelines for passive isolation of vibration-causing equipment
    - Administrative controls for “environmental” sources
    - Compliant mounting of rotating equipment
  - Guidelines for passive measures in beamline structural design
    - Avoidance natural frequencies <~10Hz or near 60Hz
    - Consideration of load paths to vibration sources
  - Known good component list

How do we police this?

- **Design reviews**
  - Vibration needs to be considered in the review of anything that *could* be a problem
- Training
  - Sensitize engineers and techs to the issues
- Measures specific to PXIE
  - Facility walk-thrus
  - In-situ measurements to identify changes

Logistical Problems - Summary

- Many stories of technical failures/successes shared
- Common frustration with organizational issues and lack of direct support for this sort of work from projects
- *I will personally add, with the exception of PIP-II*
- Vibration/microphonics is a complex cross-disciplinary topic, with machine-wide issues, can seem frustrating and nebulous
- There was general acclaim that Baffes' environmental vibration system should be extended to all vibration issues
- Some person/group should, with the same model, be involved in cryomodule/cavity design/testing, then follow into machine commissioning and operations
- 'We' must do better at both communicating the seriousness of the topic and presenting effective strategies