

ENVIRONMENTAL NOISE AND DISTURBANCE EFFECTS FOR HIGH-Q SRF SYSTEMS.

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Deutsches Elektronen-Synchrotron DESY

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HELMHOLTZ



Funding Acknowledgements

This work was funded in the context of the R&D program of the European XFEL. This project has received funding from the European Unions Horizon Europe research and innovation program under grant agreement N. 101131435.



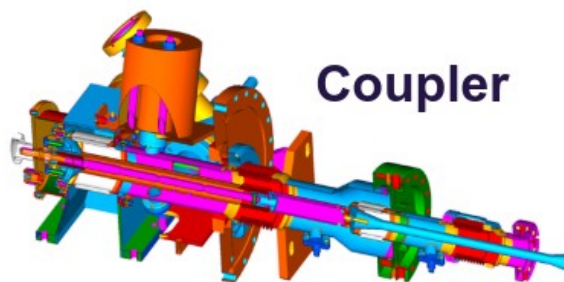
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 - Current Operation
 - Proposed High Duty Cycle (HDC) upgrade
- What is the problem?
- What we see right now.
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- The Wrap Up

The European XFEL

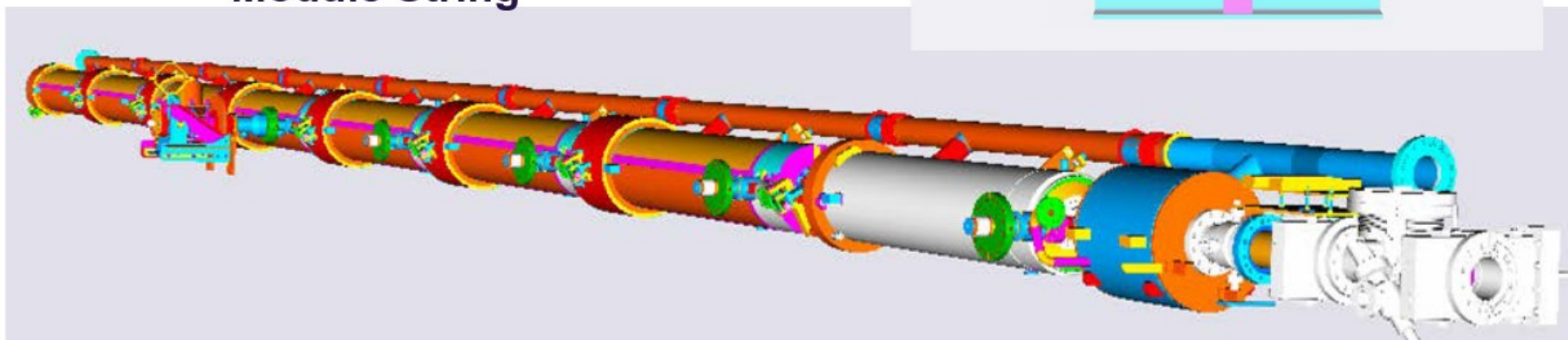
Parameter	Value
RF Pulse Rate	10 Hz
Flattop Length	600 us to 800 us
QL	>3.5e6
Bunch Repetition Rate	4,5 MHz
Max Cavities per Amplifier	32

Cavity made of niobium, operated at 2K,
gradient $>23\text{MV/m}$ $Q=10^{10}$ at 1.3GHz

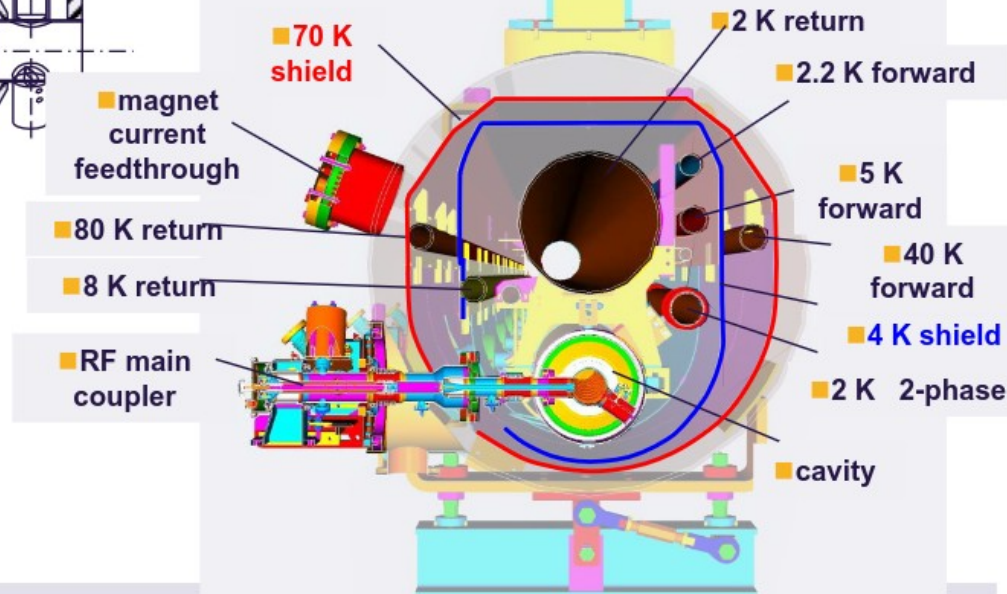


Coupler

Module String



Cryomodule



The European XFEL

Accelerator Information.

- XFEL is a high energy (>16 GeV electrons), pulsed (> 1 ms RF pulse) machine
- > 4 MHz electron bunches of up to 1 nc per bunch within RF pulse
- Cavities operate at a QI of $3.5e6$ at 1.3 GHz (**371 Hz** half power BW)
- The current system **uses vector sum stations of 32 cavities** with >5 MW of RF power per station
- Cryogenic Layout:
 - Up to **12 cryomodules in each cryogenic section** (per JT valve)
 - 32 cavities per RF station
 - **Up to 3 RF stations per cryostrung**
- See poster on **"Resonant filling for long pulse operation of EuXFEL using iterative learning based feed forward"** (Wed 1630, Bozo Richter) or talk to me for details on operational modes
- The accelerator uses a normal conducting gun with a photocathode
 - **See talk in a few minutes: "Performance Comparison of Linear vs. Unscented Kalman Filter-Based Gun Detuning Estimation with a Focus on Parameter Identification"** (Max Herrmann).

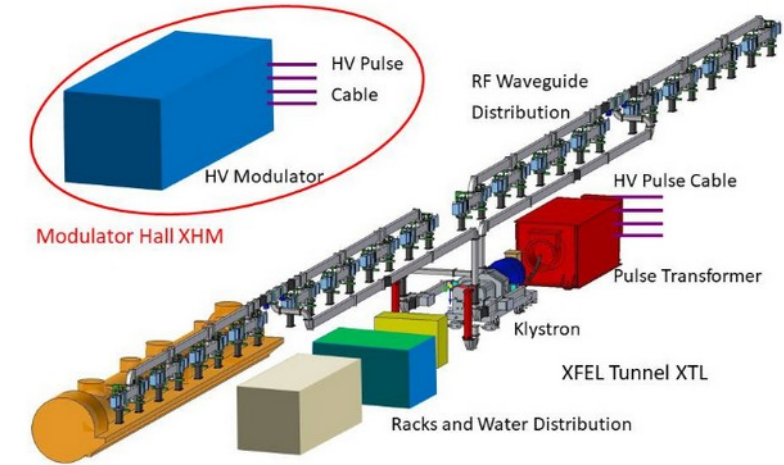


Figure 2: RF station layout.



Figure 3: RF station in the E-XFEL tunnel.

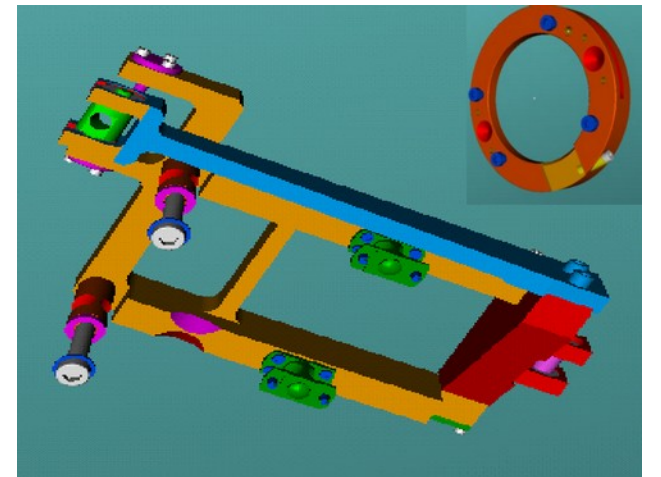
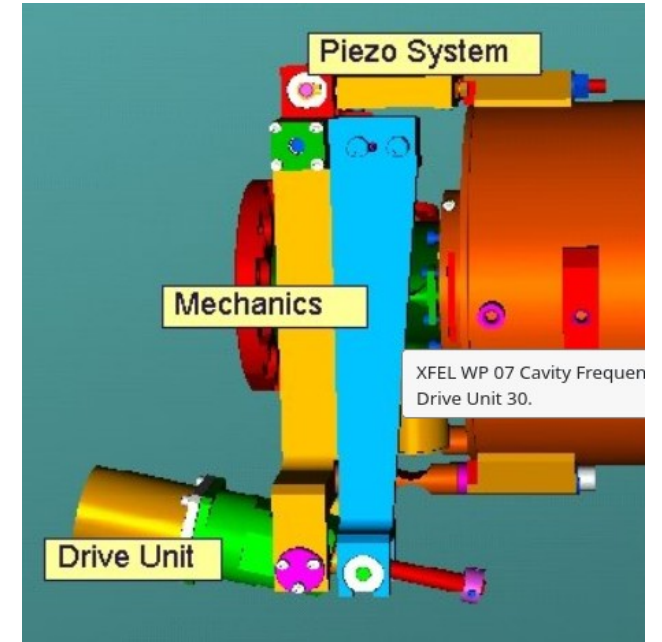
Cavity Tuning System

System Information.

- TTC cavities have a design **df/dL of 315 kHz / mm, or ~ 3 nm/Hz.**¹
- Tuner arm is attached to end of each cavity
- One of the direct physical interfaces between vacuum vessel and cryostrapping
- Sees both direct cryostrapping excitations as well as support structure
- Piezos are in parallel in-line with one of the mounts to the vacuum vessel

Automated Tuning System.

- Piezos adjust their DC offset based on a calculated detuning measured by the LLRF system
- Mechanical modes and LFD excitations are suppressed using a "pre-pulse" on the piezo drive for each cavity



¹ Paparella, <https://repository.cern/records/8dt42-jzh17>

Images from https://agenda.linearcollider.org/event/5840/contributions/26318/attachments/21754/34099/20130529_XFEL_Tuner_Lutz_Lilje.pdf

Proposed Upgrade

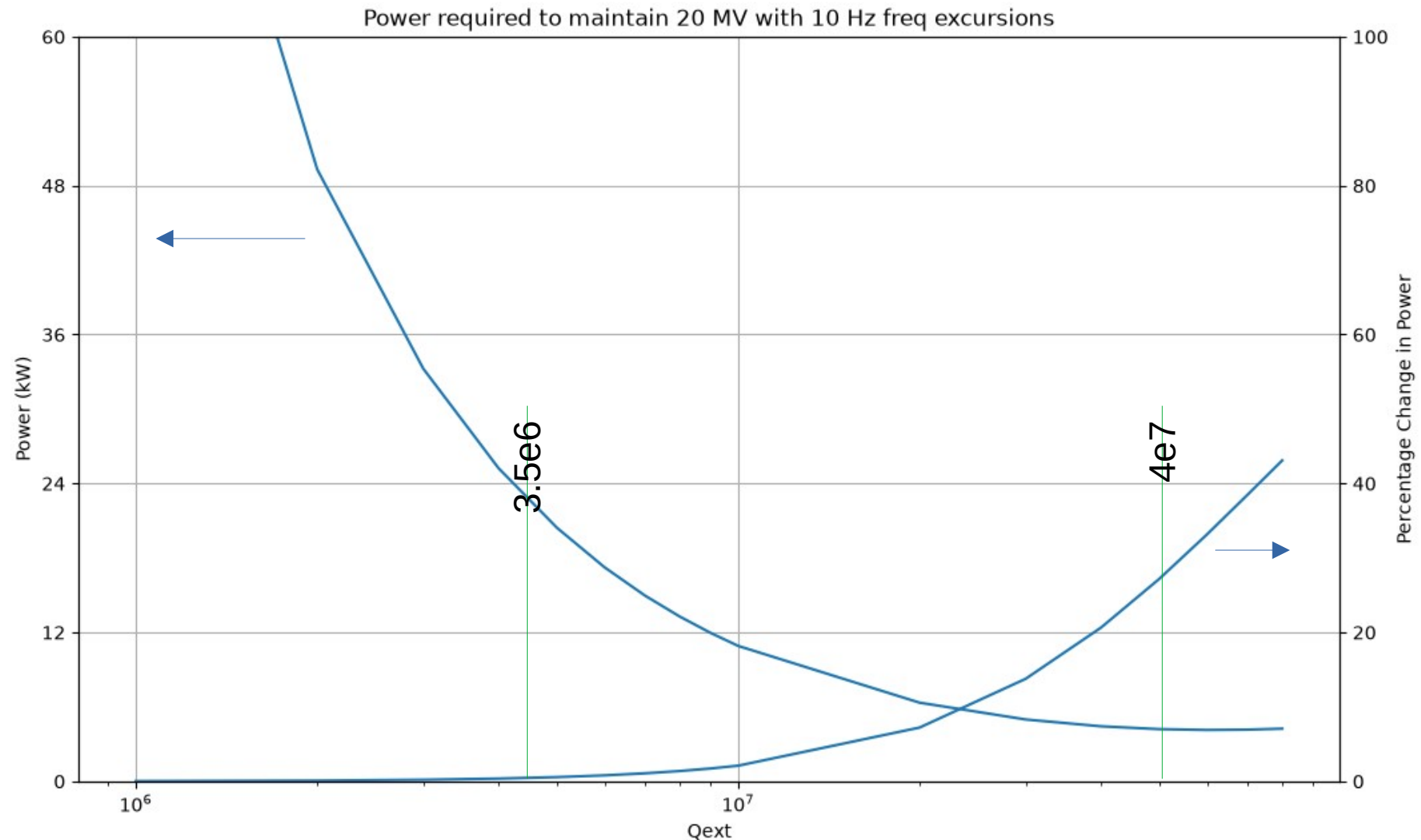
Accelerator Information.

- CW/Long-pulse (High Duty Cycle, HDC) RF operation with configurable machine energy, ~1 MHz bunch repetition rate
- Increase QI to $> 4e7$ (**32.5 Hz** half power BW)
- Single cavity per amplifier control for critical regions, eight cavities per amplifier in less critical regions
- Addition of a JT valve per cryomodule and additional cryo plant
- **Significant helium flow rates** expected for HDC operation
- Significant controls and analysis upgrades required to handle non- and long-pulse operation and alternative timings

Parameter	Value
RF Base Pulse Rate	10 Hz
Flattop Length	600 us to CW
QL	$>4e7$
Bunch Repetition Rate	1 MHz
Max Cavities per Amplifier	8

What is the problem?

The Important Plot – RF Power

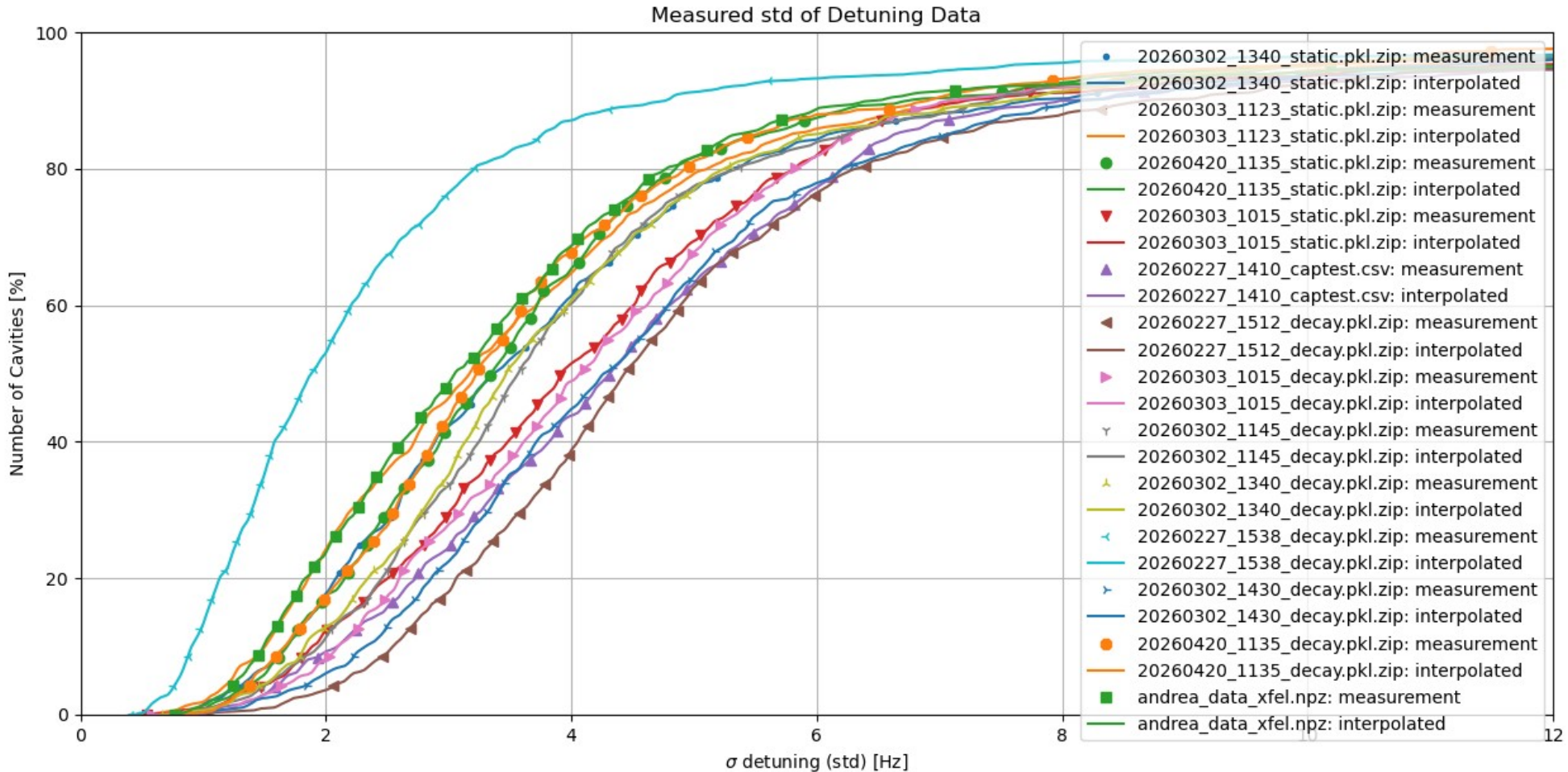


Upgrade Challenges

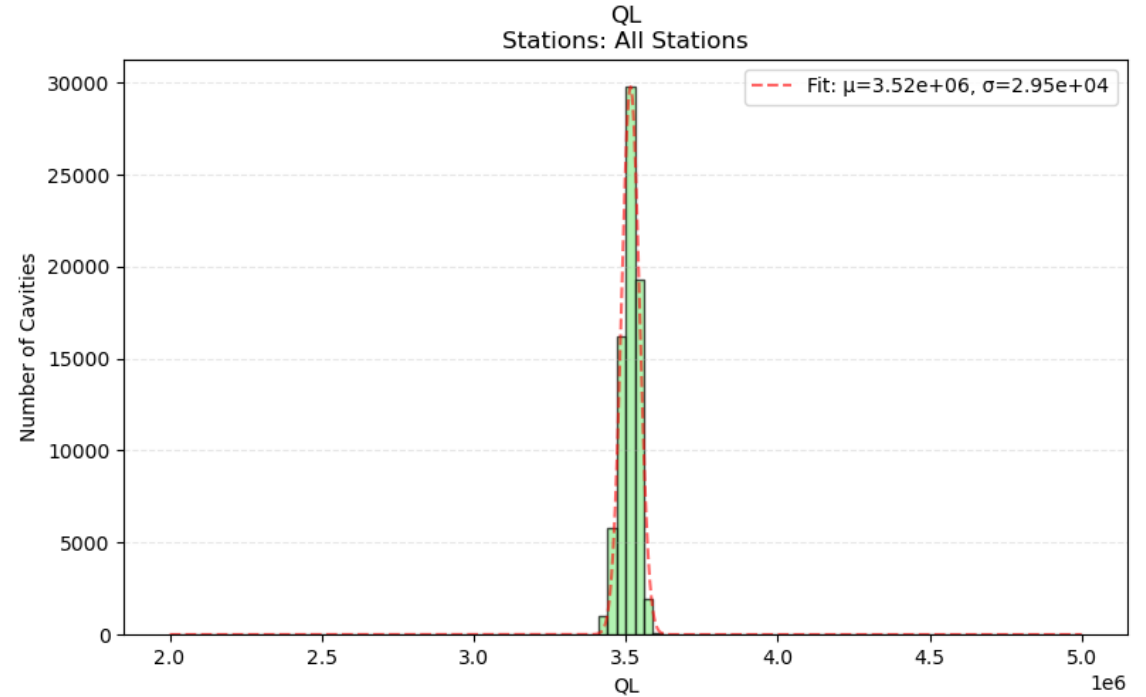
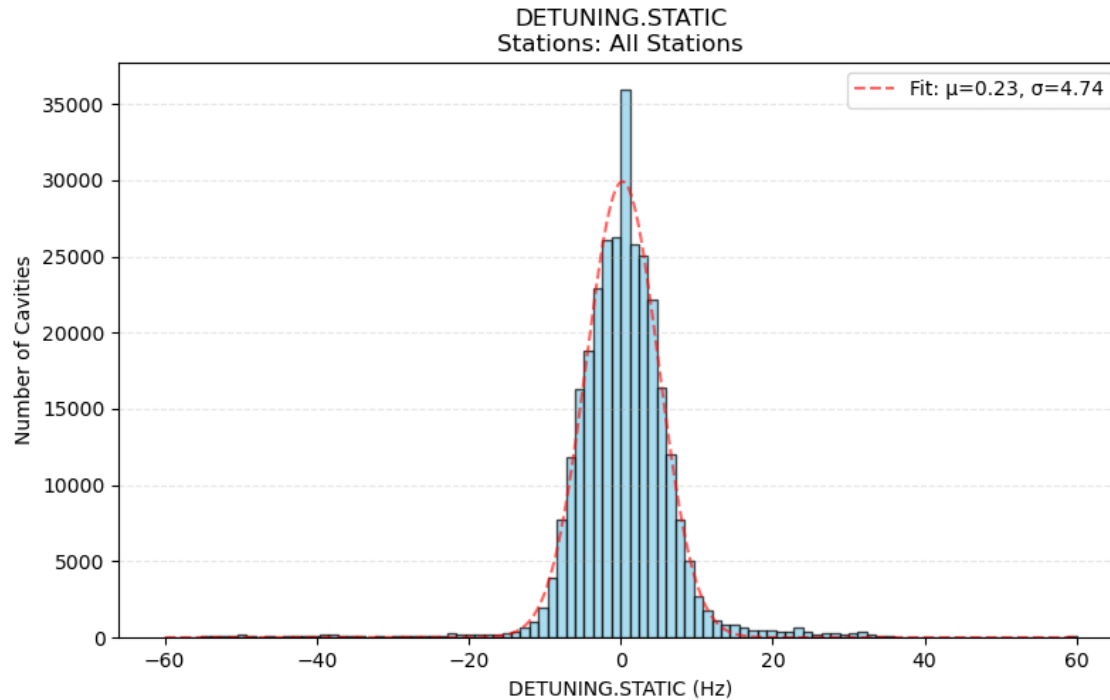
Background

- Several control (and monitoring) problems arise:
 - **Microphonics:**
 - How to measure during operation on a pulsed RF machine?
 - Are the sources seen in operation the same as in quiet periods?
 - **Inter-pulse variations/detuning:**
 - Do these directly map to microphonics?
 - Can we determine these from current monitoring? (e.g., modulator voltage fluctuations)
 - **LFD and pulse control:**
 - High-Q, pulsed operation **in vector sum** has significant challenges (limitations to SEL)
 - See poster on **resonant filling**
 - **Monitoring:**
 - Can we see the regions of interest?

Cavity Detunings Seen in Operation

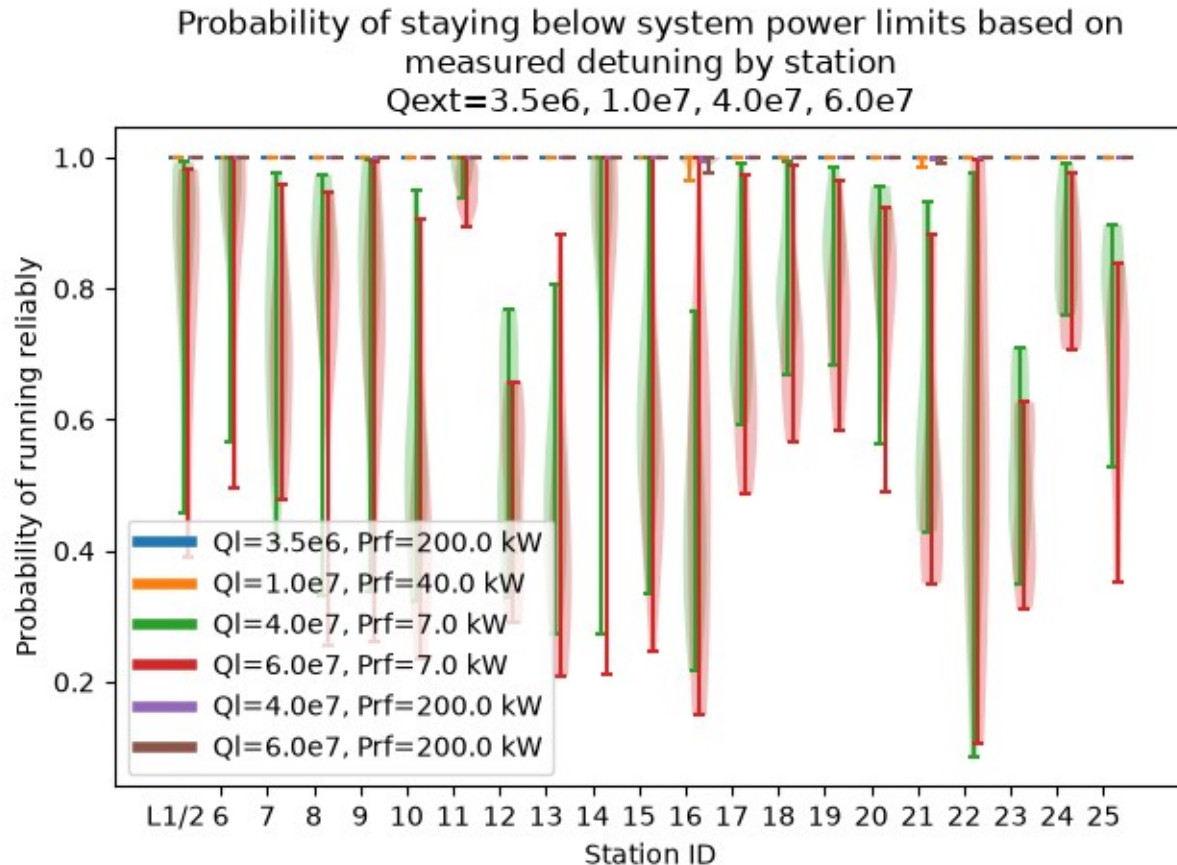


Detunings in Another Form



- The DESY LLRF system provides several measures of detuning across a pulse.
- This plot shows STATIC – a sample calculated at a single point of flat top
- 100 captures, 20261007, ~1500 Uhr, plot courtesy Mona Eberenz

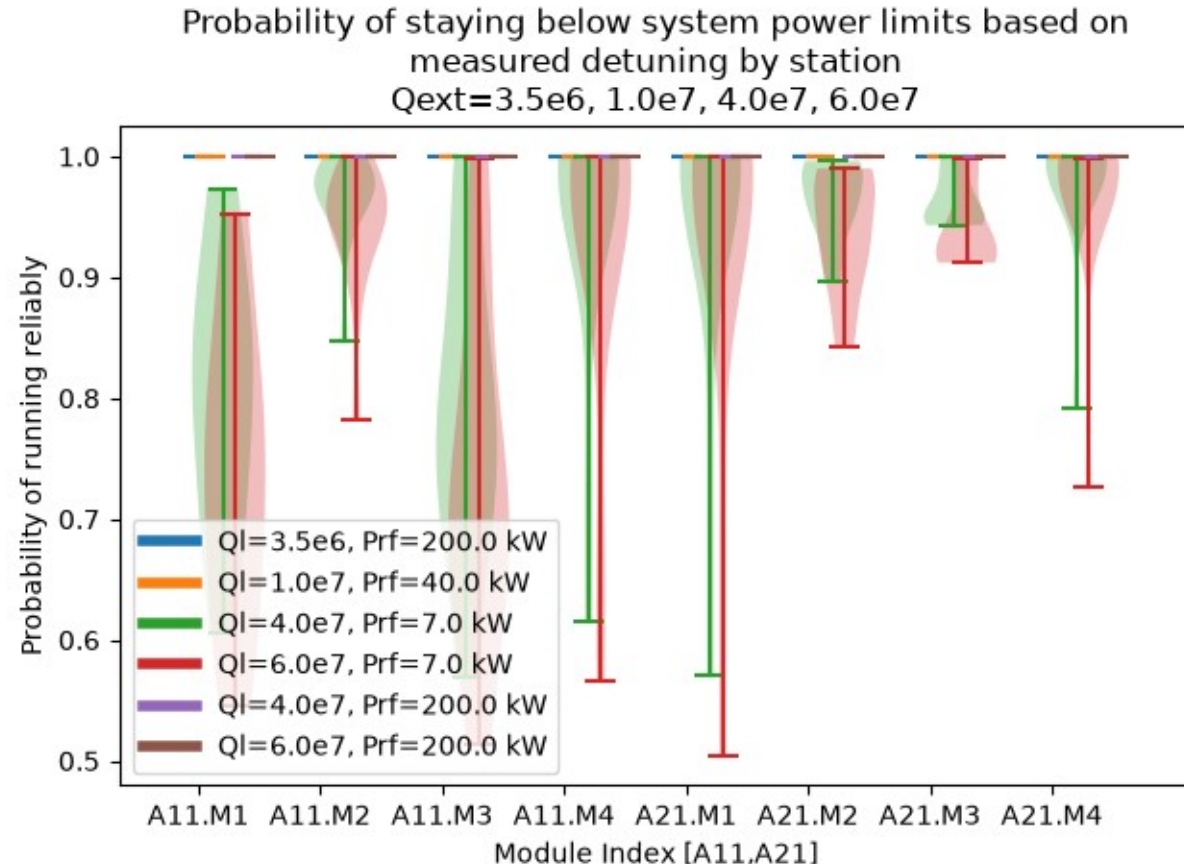
All Comes Down to Reliability



Violin Plot Visualization.

- Mean and extremes readily seen, with distribution as thickness of plot
- Station reliability in vector sum is **all cavities that are not detuned operating**
- Calculation based on **if there is enough power** to correct for detuning for all cavities in series
- Notes on plot:
 - No calculation for true “hot spares”
 - Different QIs, power per cavity
 - Bad data removal and guesswork required
 - For example, numbers are for high gradient operation
 - CW for upgrade would be at lower gradient

All Comes Down to Reliability



But the Math is not Straightforward.

- The captured datasets show different behavior at the module level, thus measuring long-term reliability needs a different method to visualize it

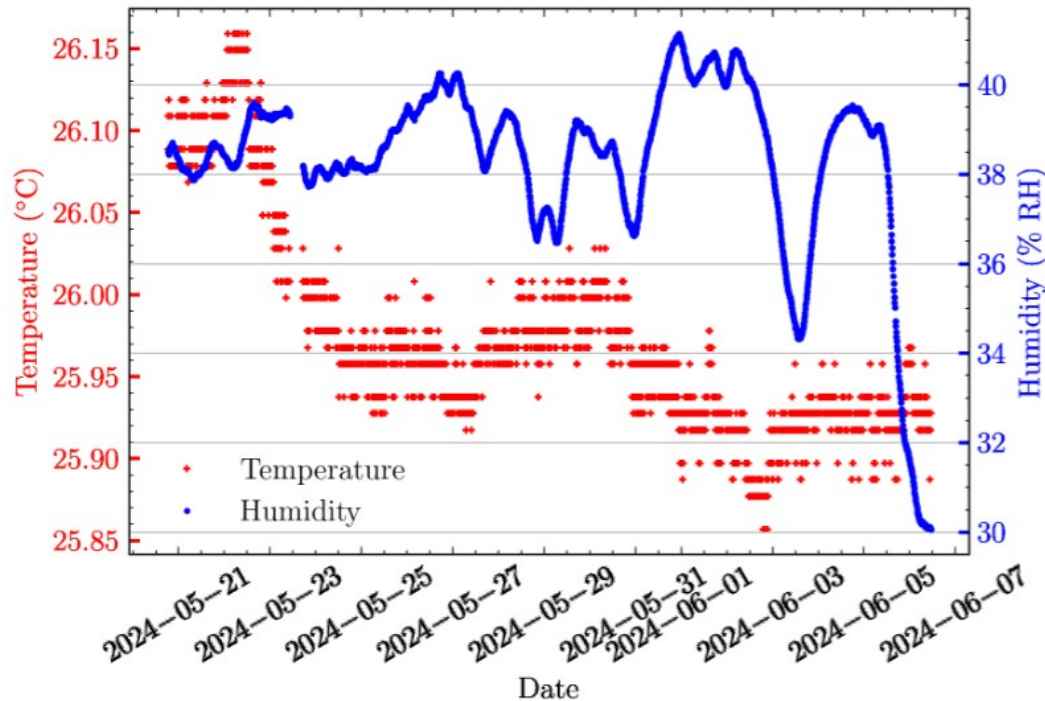
What We See Right Now.

Recent XFEL shutdown (LIMP) provided opportunity to monitor environment without pulsed RF

Very different timescales in the disturbances that we see

Local Climate Effects

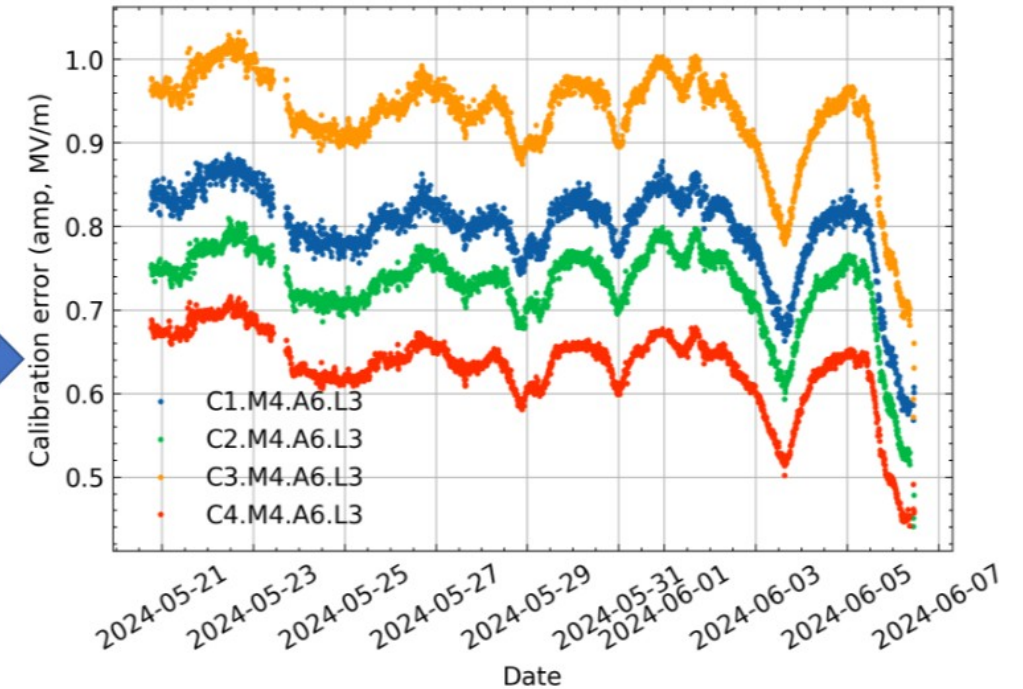
Humidity and temperature fluctuations



Temperature is more stable than humidity, which is not actively controlled.



Long-term calibration drift (E_A)

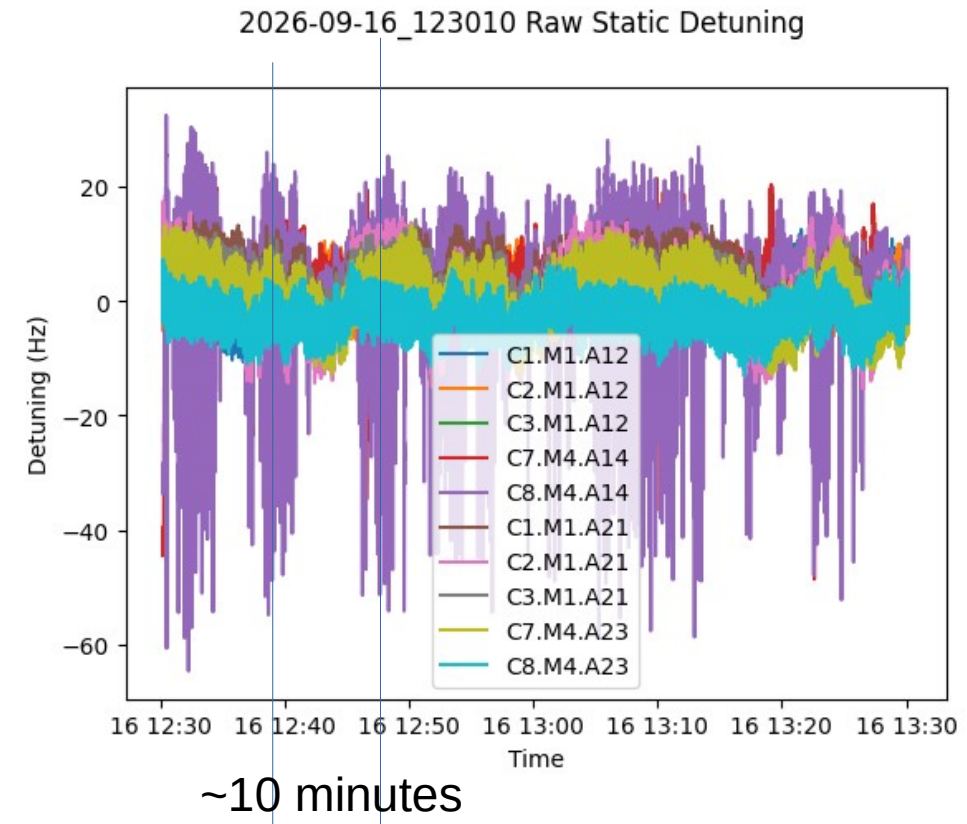
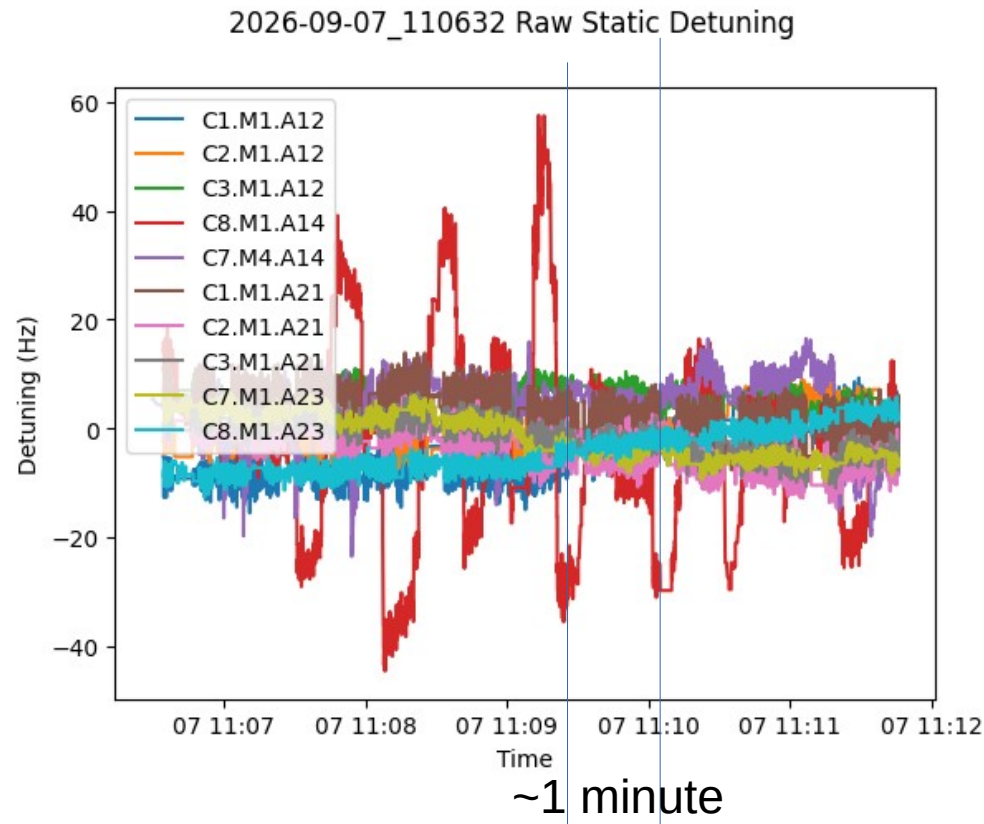


The amplitude of the calibration errors E_A fluctuate with environmental factors.

Previous work on calibration drifts (sampled every 10 minutes), effect seen on daily basis

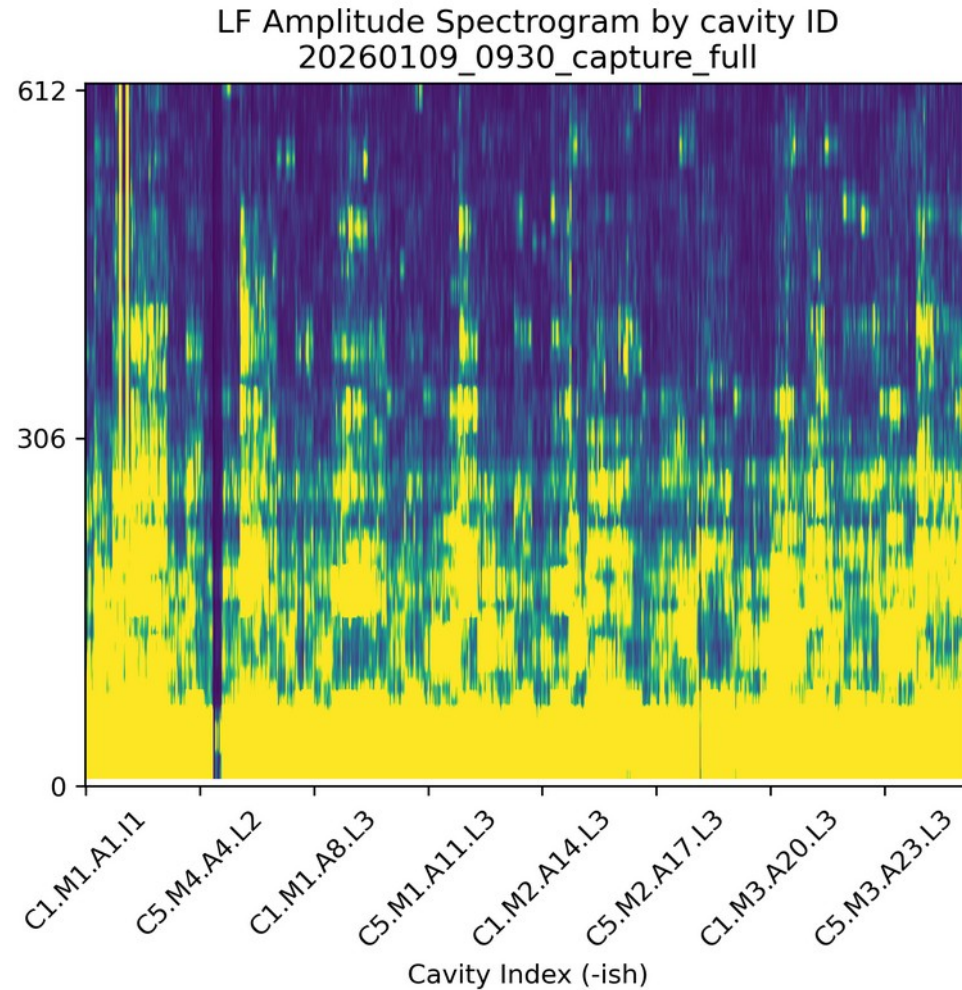
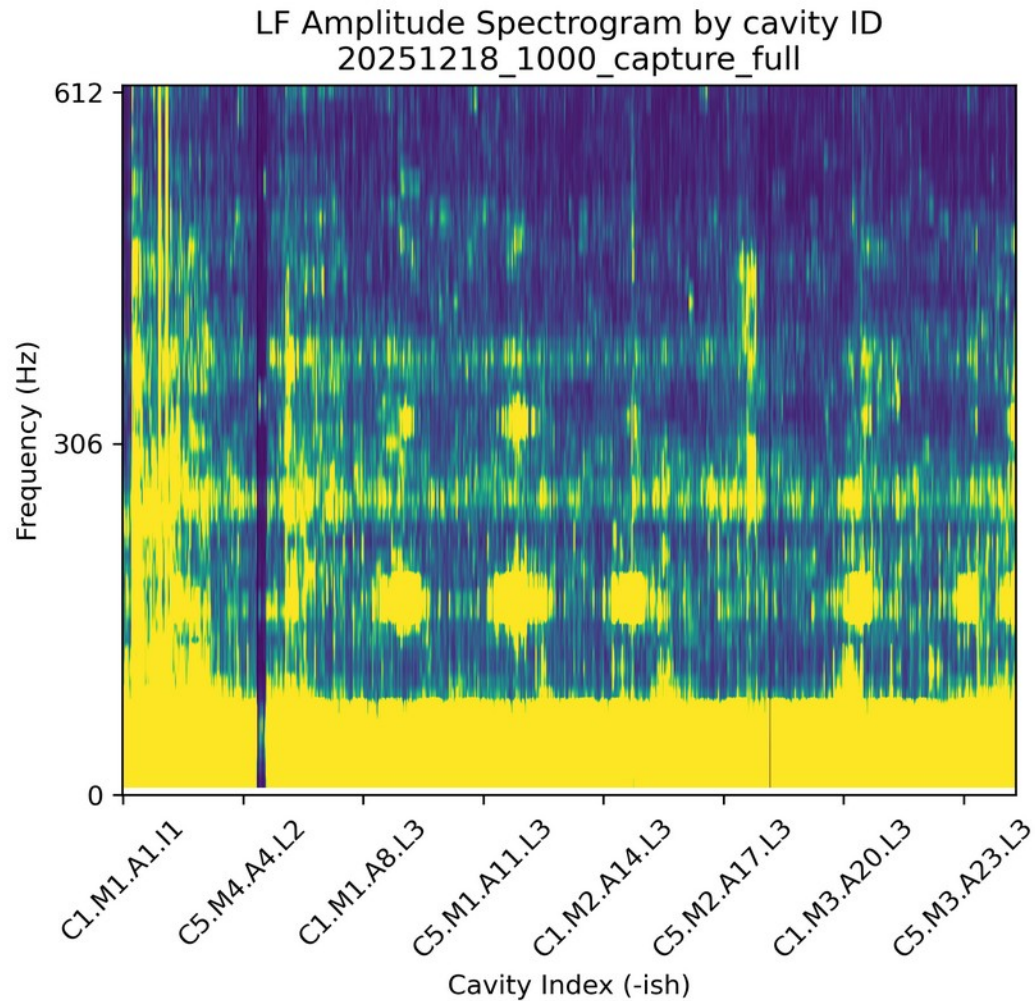
Sun, Y., A. Bellandi, J. Branlard, et al. Influence of Environmental Parameters on Calibration Drift in Superconducting RF Cavities. n.d.

Detuning Excursions



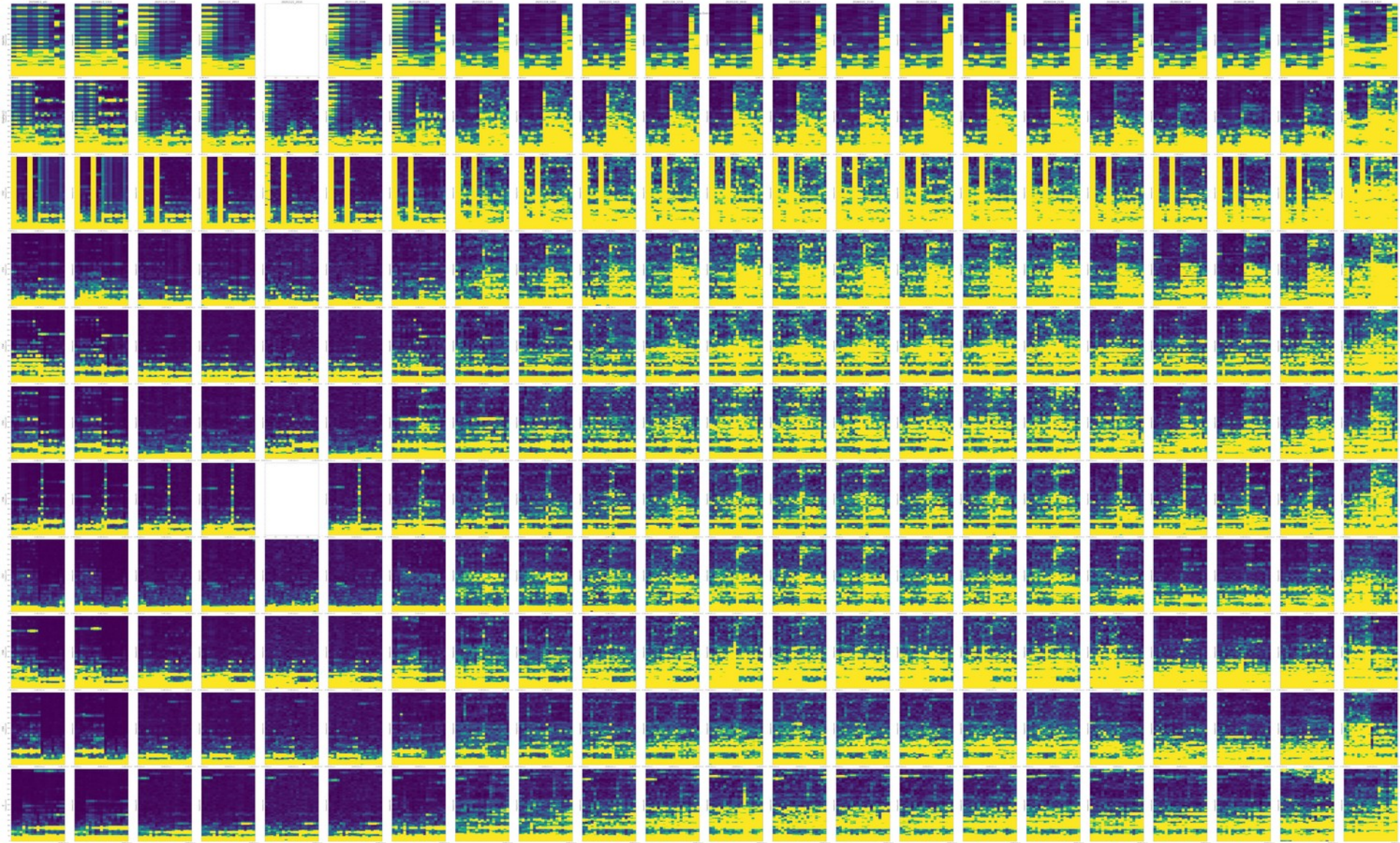
Detuning is calculated per-pulse (10 Hz) from 9 MHz RF data

Piezos as Environment Sensors

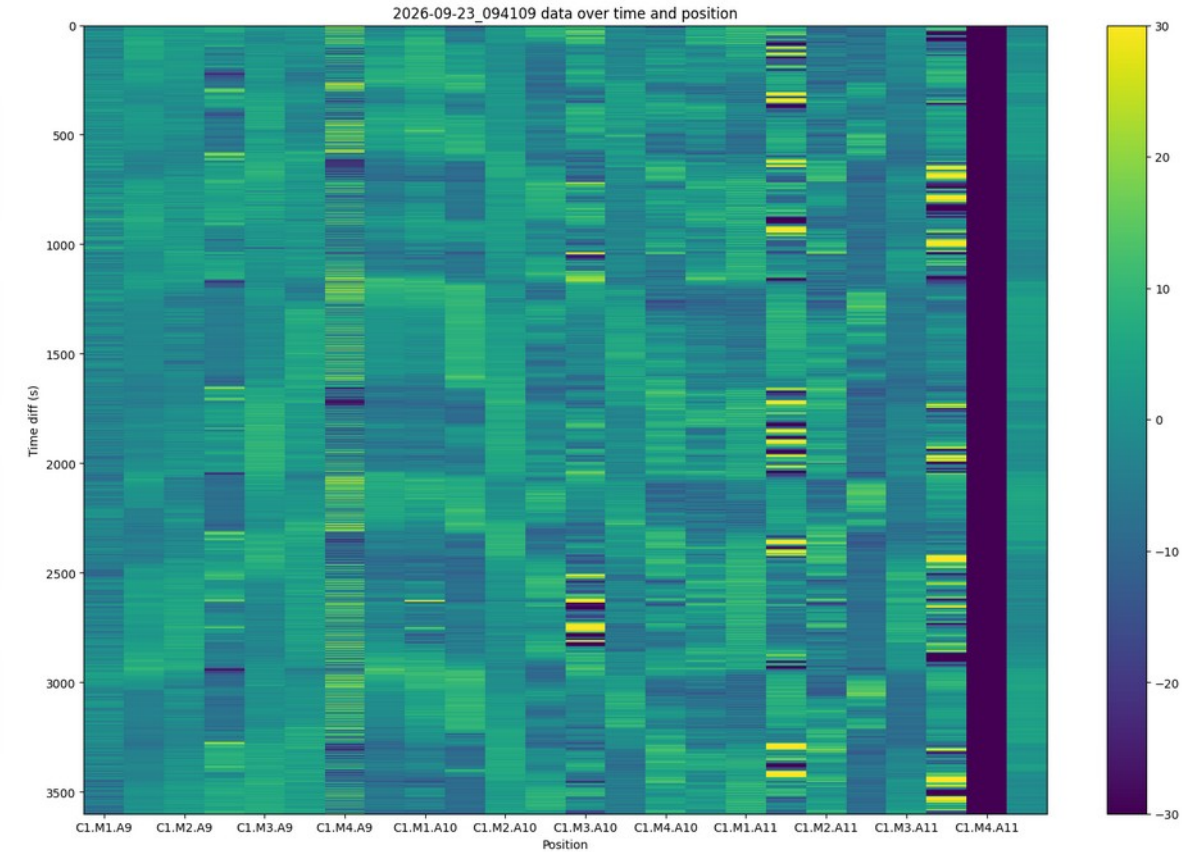


Piezo waveforms are gathered per-pulse (25 kHz) and
processed/averaged between pulses. ~80 ms/pulse, 10 Hz/waveform

Piezos as Environment Sensors



Bad Cavities and Detuning Spikes



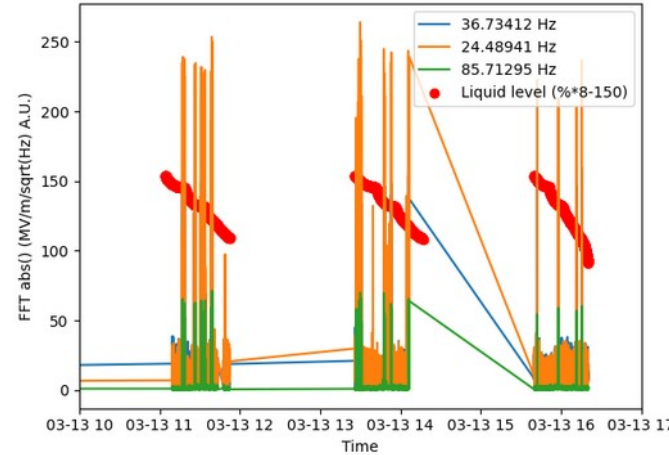
10 Hz sampling of static detuning over time for cryostring 4
Singular cavities showing the worst performance

What About at a Test Stand?

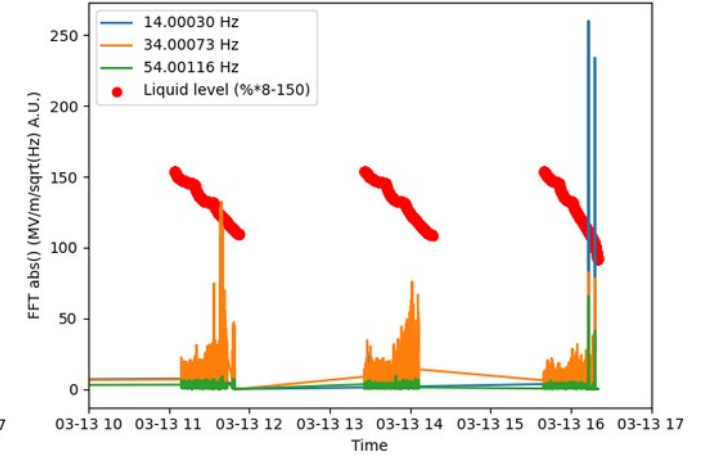
Background

- Dynamic heat load measurements with parasitic capture of piezo and RF data
- Detuning data based on RF probe amplitude (1 MHz, 16k samples, near CW capture length)
- Piezo capture waveforms (~80 ms, 2.5 kHz)

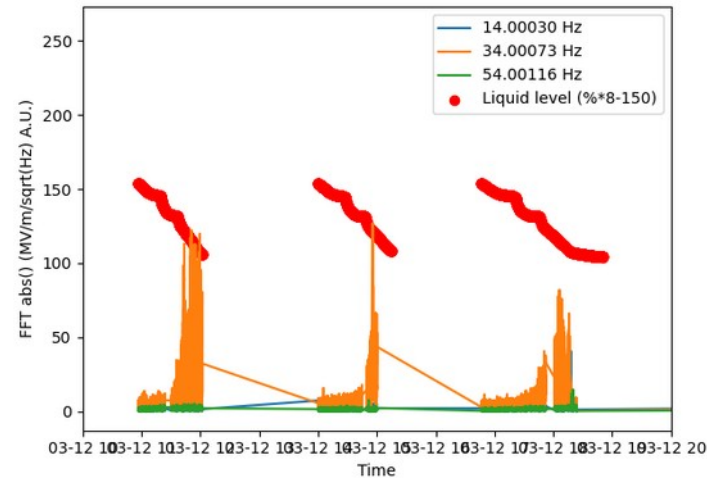
C5.M1.MCAV.CMTB.PIEZO_SENSE.h5 and Liquid Level for DHL



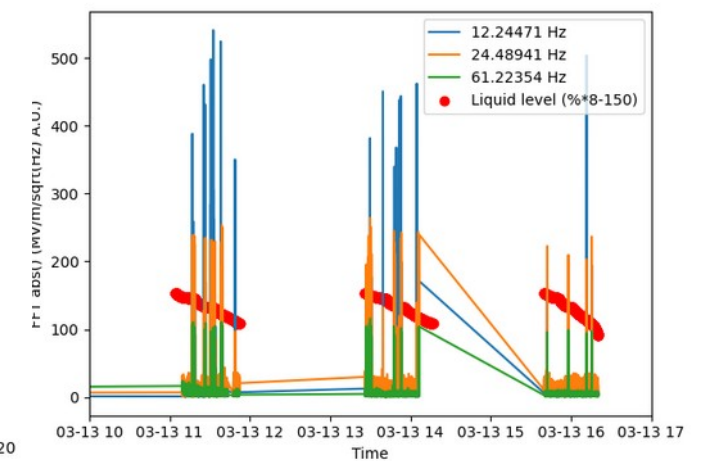
C5.M1.MCAV.CMTB.PROBE.AMPL.h5 and Liquid Level for DHL



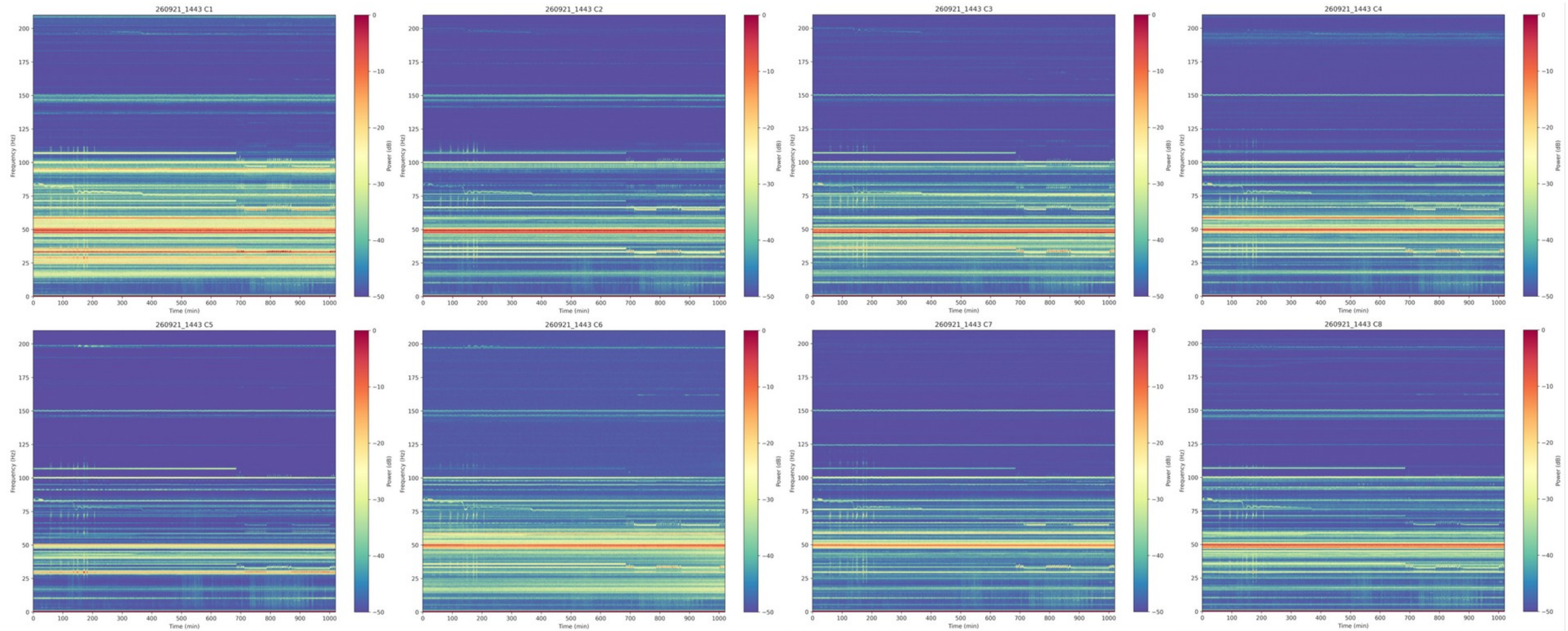
C5.M1.MCAV.CMTB.PROBE.AMPL.h5 and Liquid Level for DHL



C5.M1.MCAV.CMTB.PIEZO_SENSE.h5 and Liquid Level for DHL

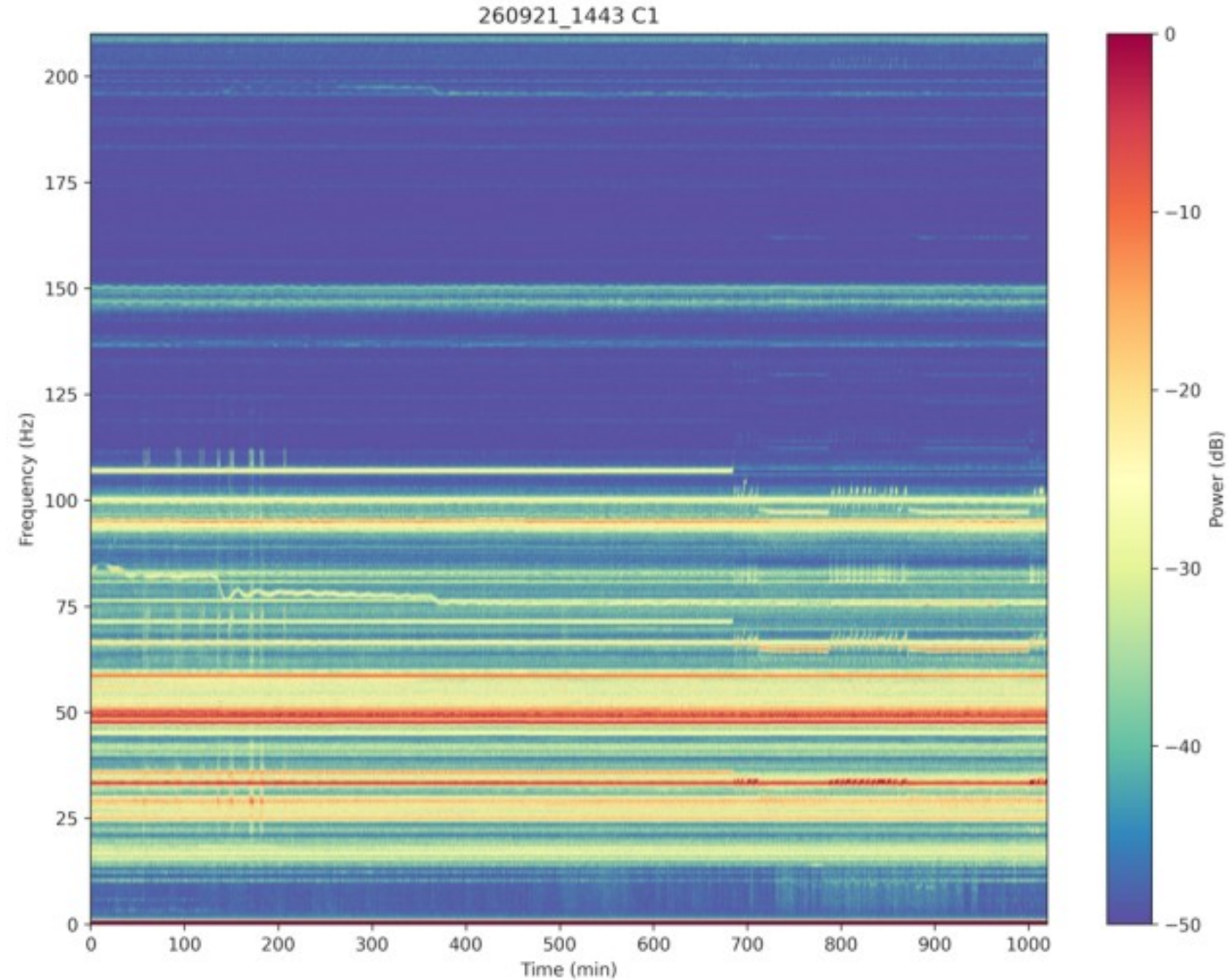


What About at a Test Stand?

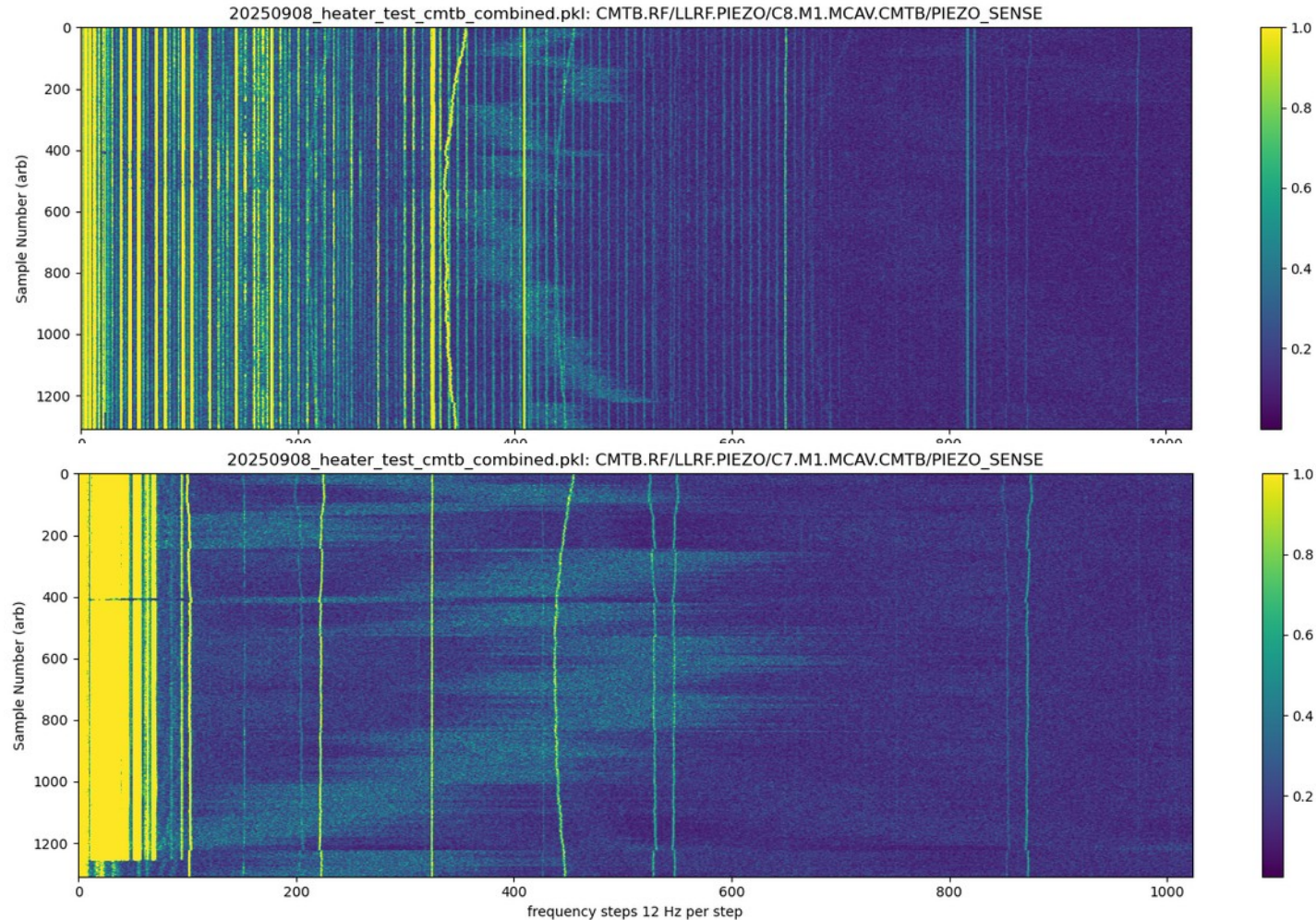


Long-term stability test in closed loop operation at CMTB test stand
Courtesy Bozo Richter

What About at a Test Stand?



The Simple Technical Challenges (Bad Wiring)



The Search for Meaning.

What effect **will** these disturbances have for control?
What **types** of control techniques and mitigations do we need?

Visual Inspection

Signal Correlations

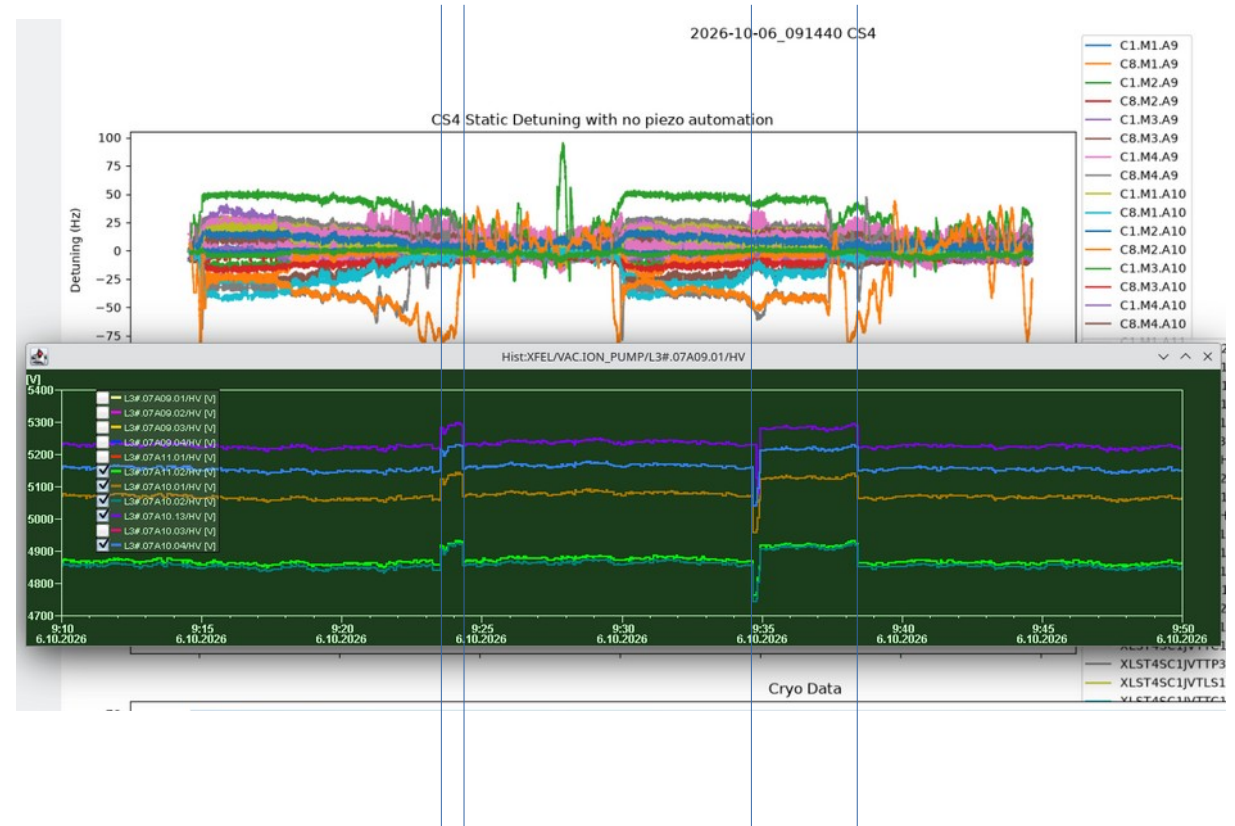
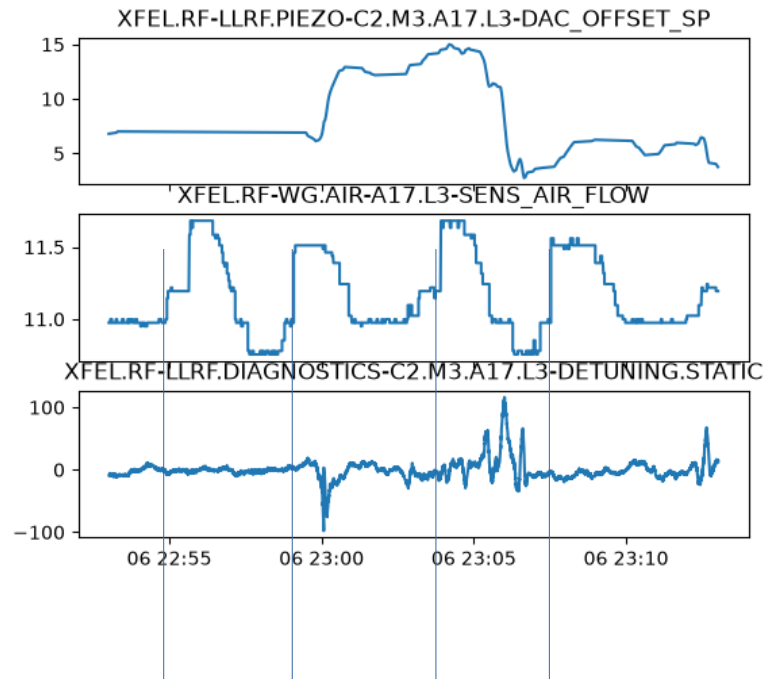
FFTs/Wavelets and frequency stability

The Tools We Have Available

Background

- Visual Inspection
 - Quick determination of time-dependent behaviors
 - Relies on display tools on appropriate archival data resolution
- Signal Correlations
 - Relies on interpolations and what relationships exist (linear, nonlinear, Pearson, distance correlation)
 - Significant processing time if looking for correlations in frequency-space
- FFTs/Wavelets and frequency stability
 - Determination of narrow- vs wide-band noise sources
 - Frequency stability can help determine external/internal and mechanical device/resonances

Visual Inspection – Does Anything Line Up?

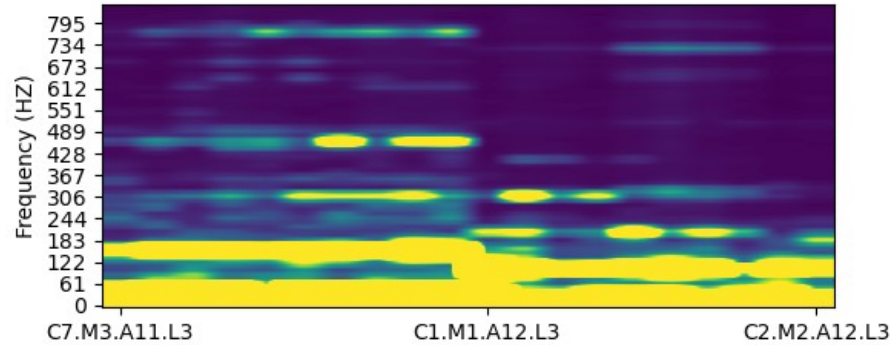


C2.M3.A17.L3 is a troublesome cavity; are the large disturbances caused by the piezo moving, or is the piezo moving because of large disturbances?
Does anything line up?

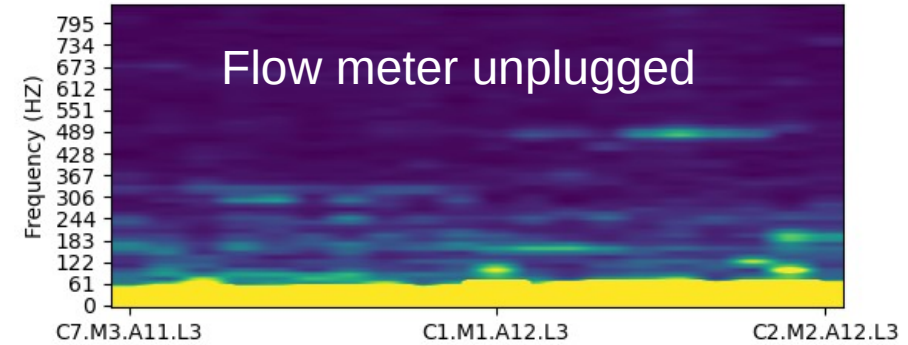
No detuning correction enabled; disturbances align with ion pump HV fluctuations

Working with Other Departments: Cryogenics

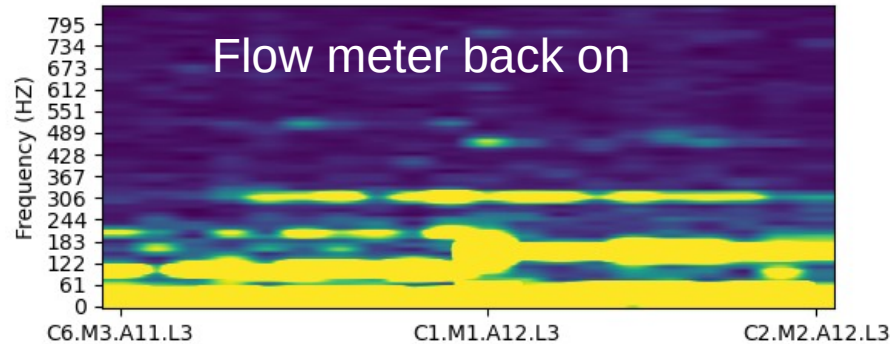
LF Amplitude for CSC CS5
20250811_allcav_noAH1_noA7_noA24.pkl



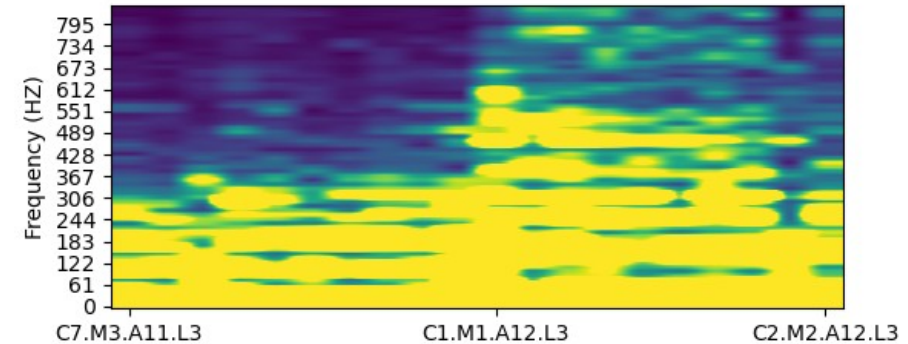
LF Amplitude for CSC CS5
20251121_0953_capture_full.pkl



LF Amplitude for CSC CS5
20251121_2010_capture_full.pkl

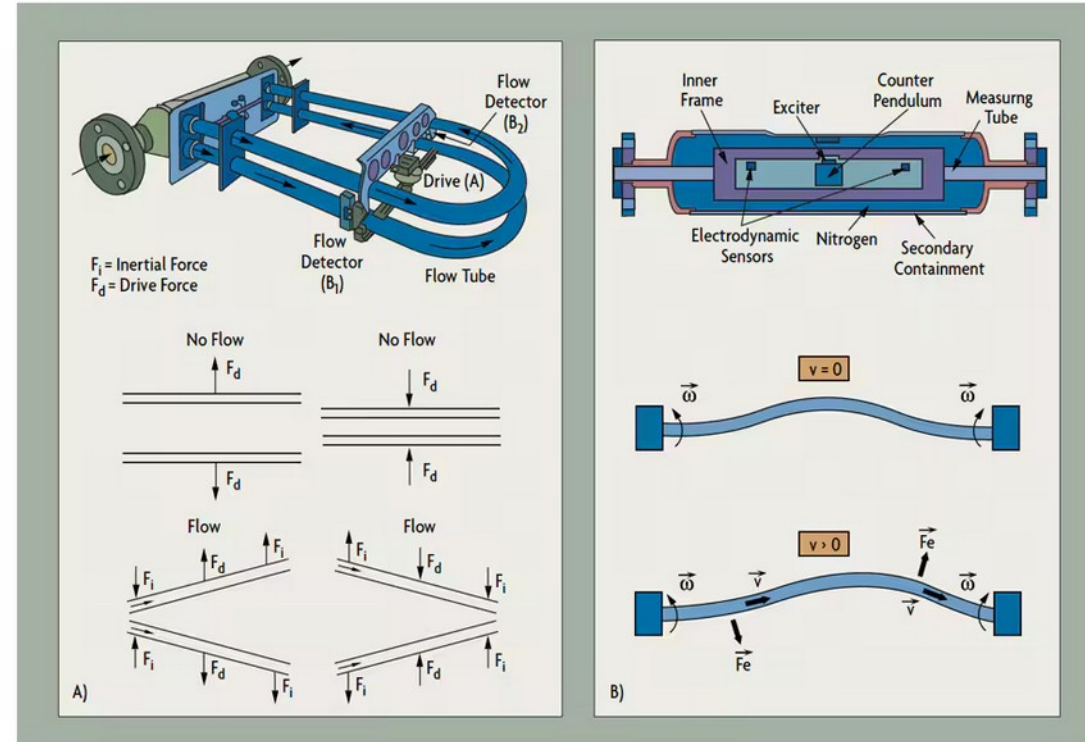


LF Amplitude for CSC CS5
20260114_1313_capture_full.pkl



Coriolis Flow Meter

“Coriolis mass flow meters measure mass through inertia. A liquid or gas flows through a tube which is being vibrated by a small actuator. This artificially introduces a Coriolis acceleration into the flowing stream, which produces a measurable twisting force on the tube resulting in a phase shift. This twisting force is proportional to the mass – and the meter measures mass flow by detecting the resulting angular momentum. Coriolis flow meters are capable of measuring flow through the tube in either the forward or the reverse directions.”

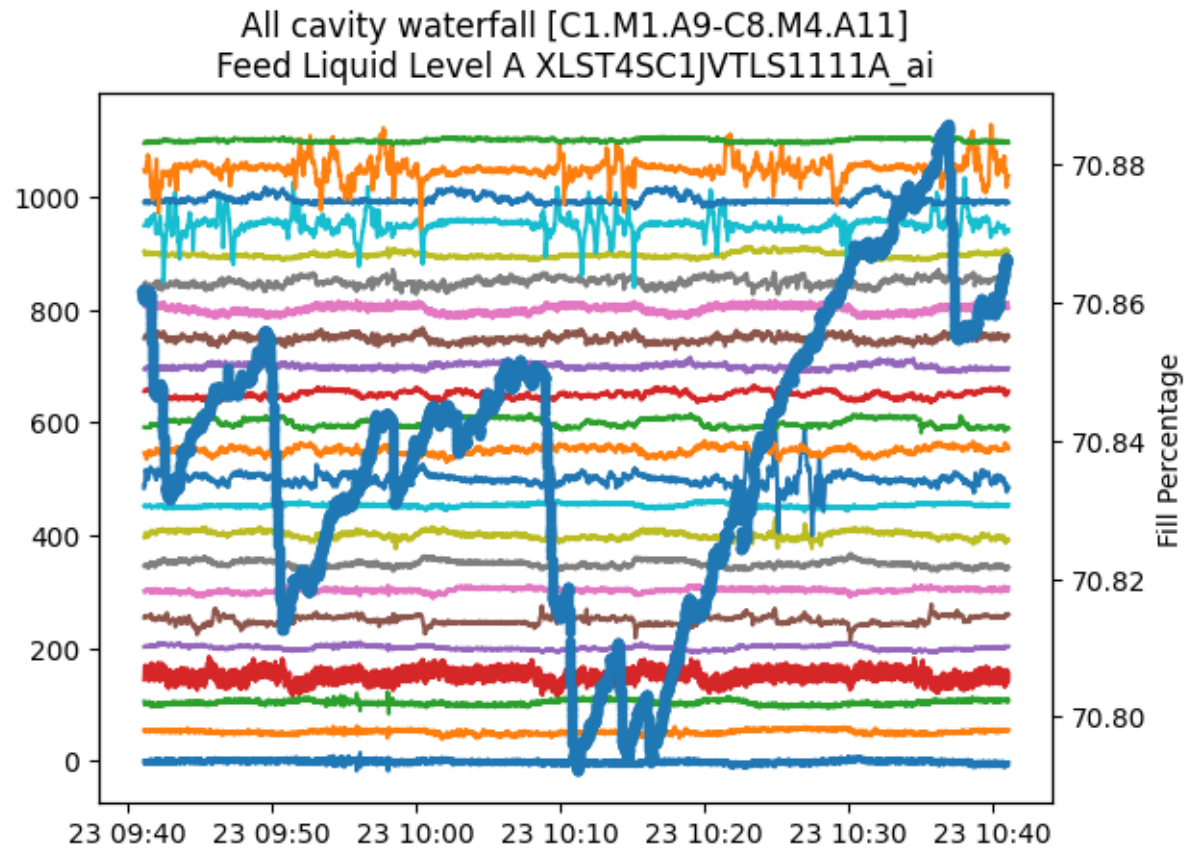


<https://www.dwyeromega.com/en-us/resources/what-is-a-coriolis-flow-meter>

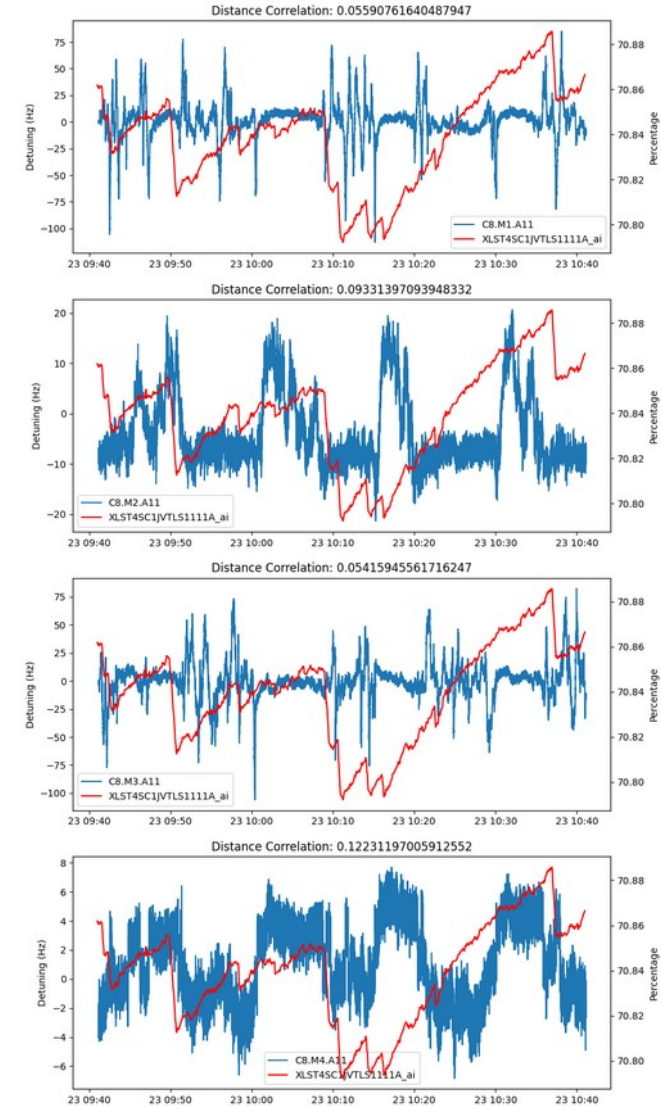
The device frequency is currently **not available in any control system**

The operating frequency is being added, such that if it changes we can track it

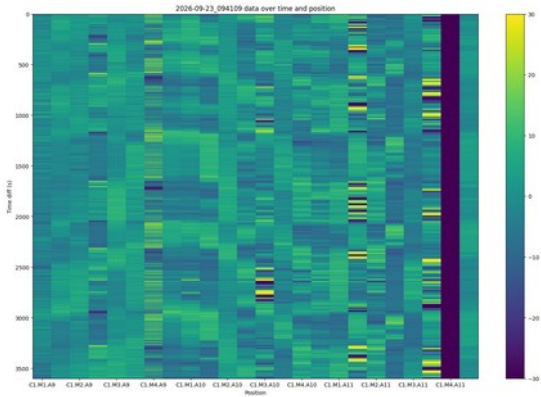
So, Cryogenics?



- Across a cryostrung, can we correlate any process variables with our detuning?
- Liquid level sensor readbacks?
- Can we use this to **predict** any future behavior?



So, Cryogenics?

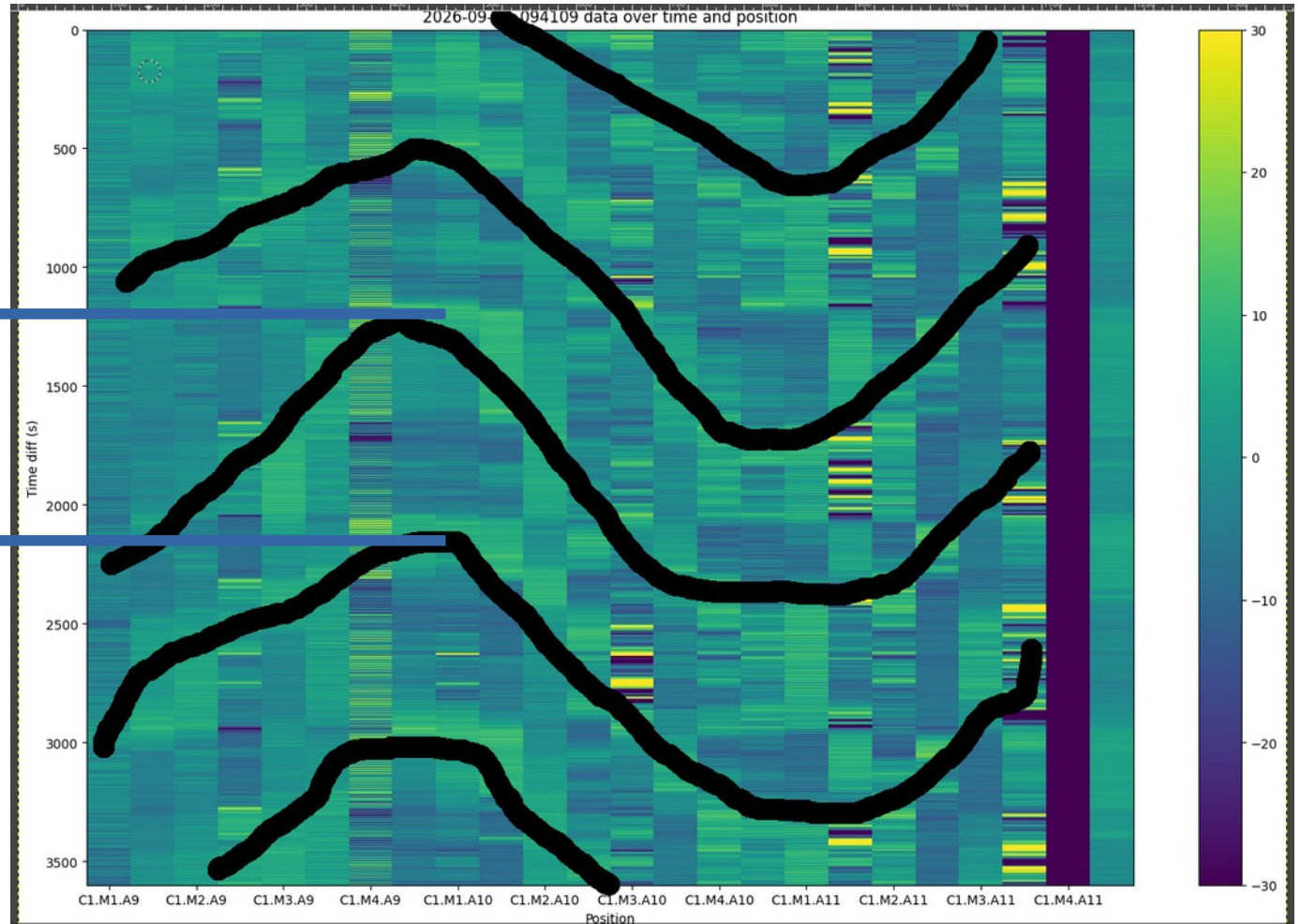


~900 seconds
15 minutes

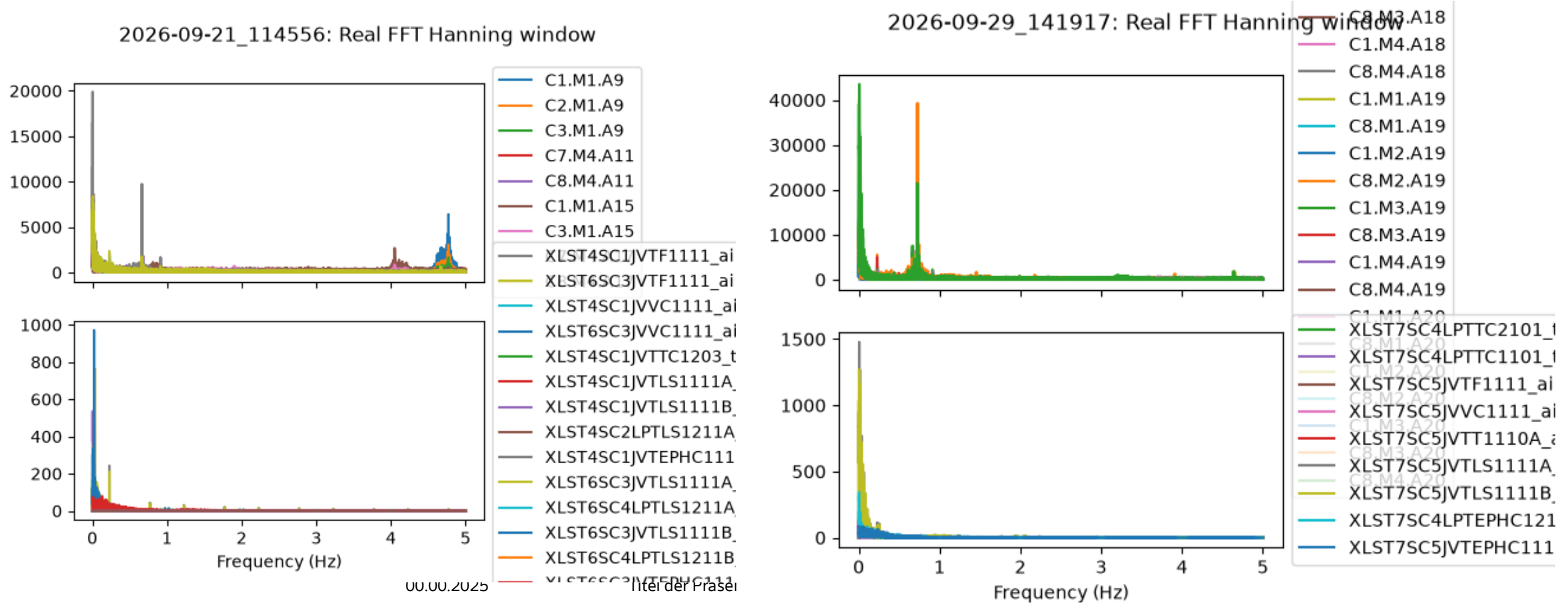
Viewing image as a thumbnail showed a distinct pattern

In automated analysis, would have required a check for regular periods between peaks

Slow control should be able to take care of this, **if it is only a slow process**



FFT of Detuning Captures



- We also see a peak in the FFT at ~0.7 Hz in multiple cryostrings.
- Poor correlation with other data, but maybe seen in small liquid level variations

What About at a Test Stand?

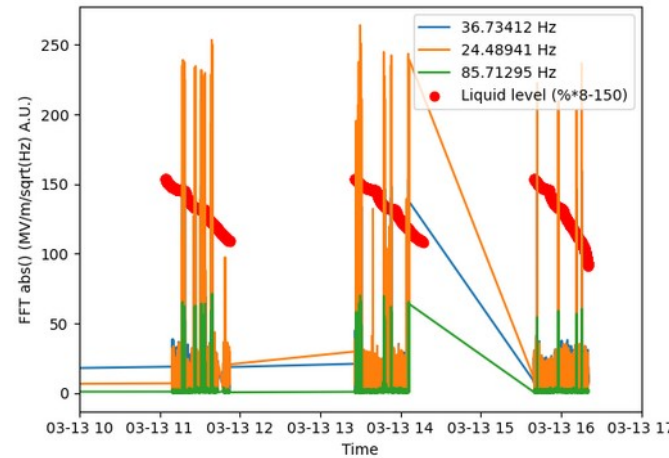
Background

- Dynamic heat load measurements with parasitic capture of piezo and RF data
 - Open Loop
- Detuning data based on RF probe amplitude (1 MHz, 16k samples, near CW capture length)
- Piezo capture waveforms (~80 ms, 25 kHz)

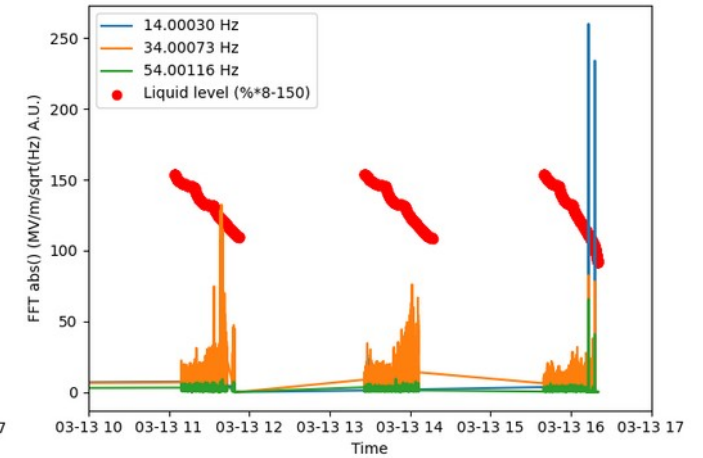
Analysis

- High correlation (>0.6) for ~34 Hz broadband noise disturbance with liquid level
- Correlations tested across large number of cryogenic variables and every captured cavity signal (PROBE_AMPL and PIEZO_SENSE)

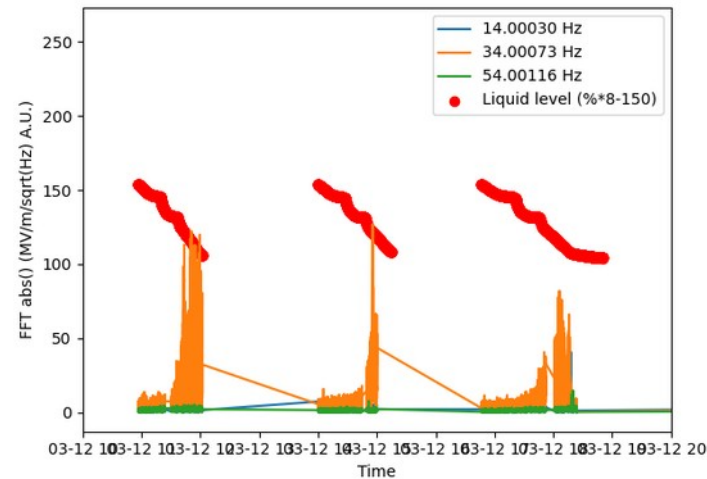
C5.M1.MCAV.CMTB.PIEZO_SENSE.h5 and Liquid Level for DHL



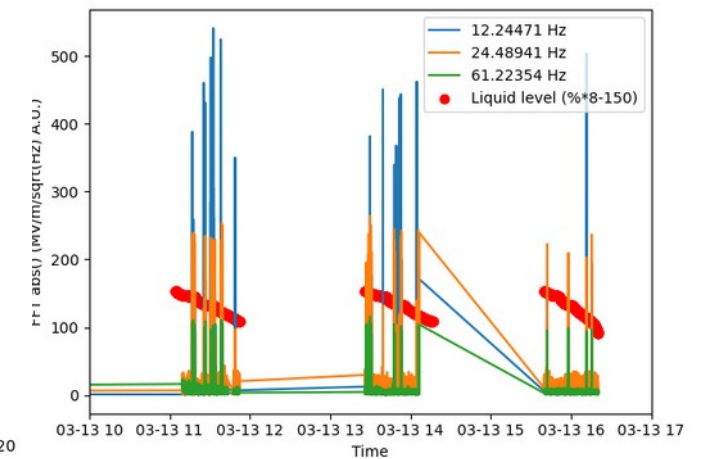
C5.M1.MCAV.CMTB.PROBE_AMPL.h5 and Liquid Level for DHL



C5.M1.MCAV.CMTB.PROBE_AMPL.h5 and Liquid Level for DHL



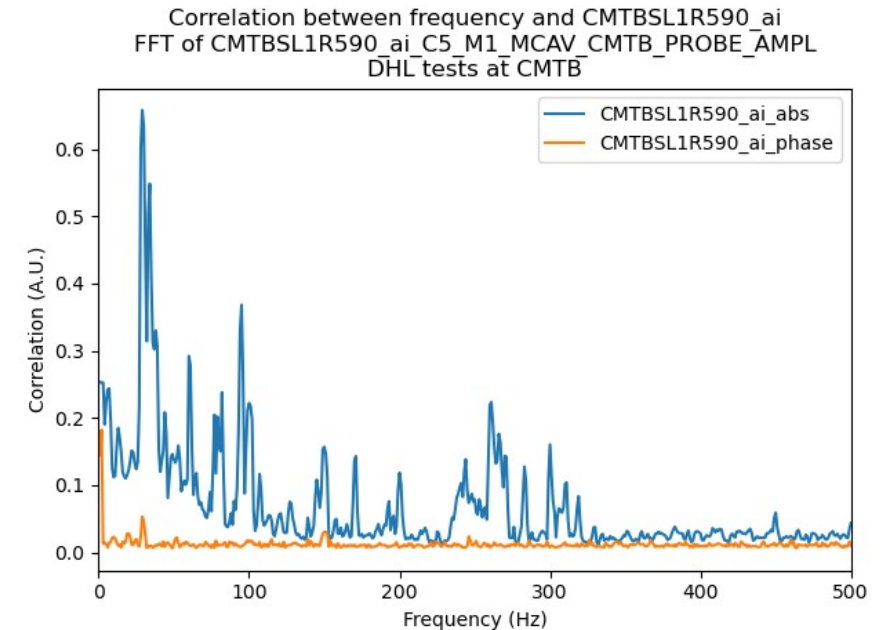
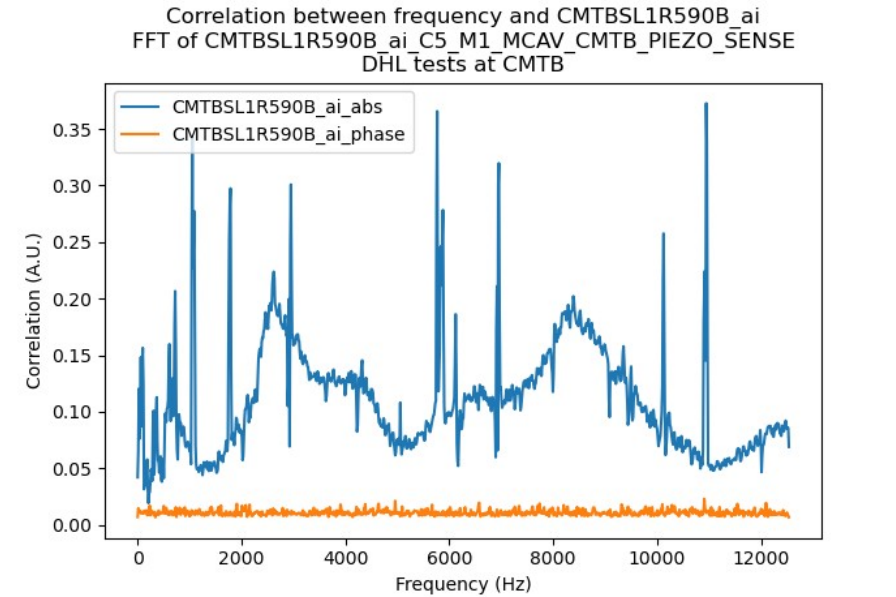
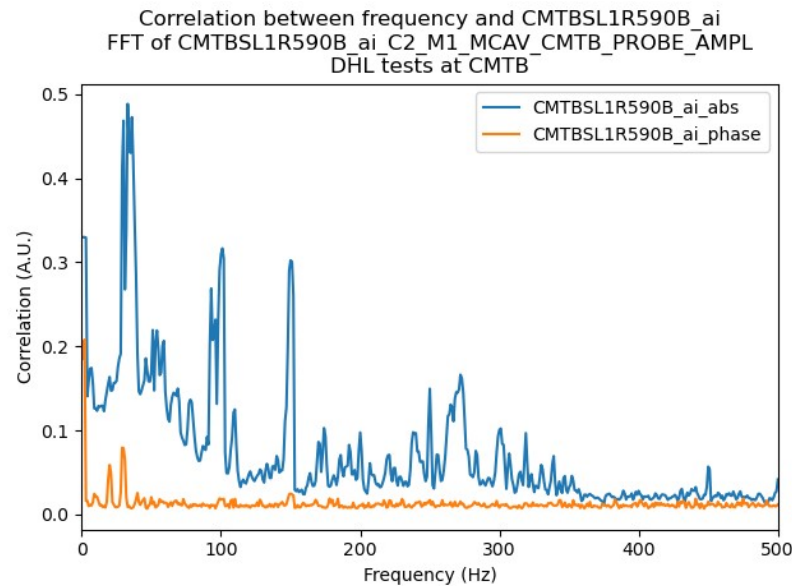
C5.M1.MCAV.CMTB.PIEZO_SENSE.h5 and Liquid Level for DHL



What About at a Test Stand?

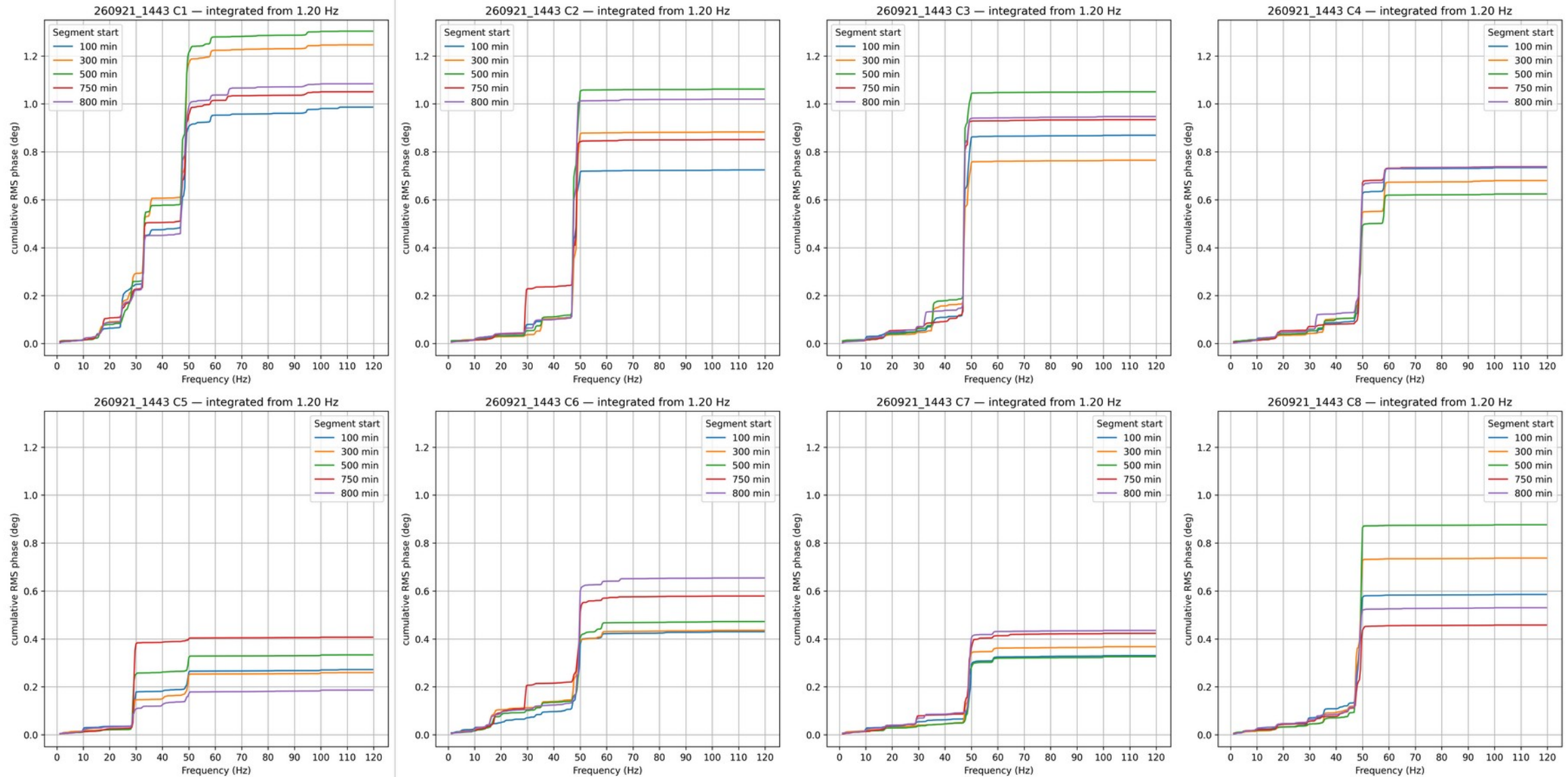
Correlations

- Statistically significant (p-value) and measure of relationship at frequency
- Not a measure of strength of signal or response



CMTB Teststand Time Evolution

49 Hz is known source; vacuum pump



CMTB Teststand Heaters



So to Wrap it All Up.

Conclusion

- Accelerator reliability and recovery time should be quantified for vector sum operation
 - With noise suppression, resonant filling, and wider-spaced beam, can we provide users with more beamtime?
- How **complicated** an analysis pipeline is needed? Can we catch everything?
 - And can we fix what we see?
- We have some methods in development to suppress **narrow band** noise sources
 - Broadband disturbances, possibly from cryomodule subsystems, are a concern
- Understanding the operating environment needs the development of better online monitoring tools with **continuous data**, whether for CW or pulsed RF
 - Online FFTs with anomaly monitoring, for example

Thank you

Contact

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ORCID: 0000-0003-3579-7024

Deutsches Elektronen-Synchrotron DESY

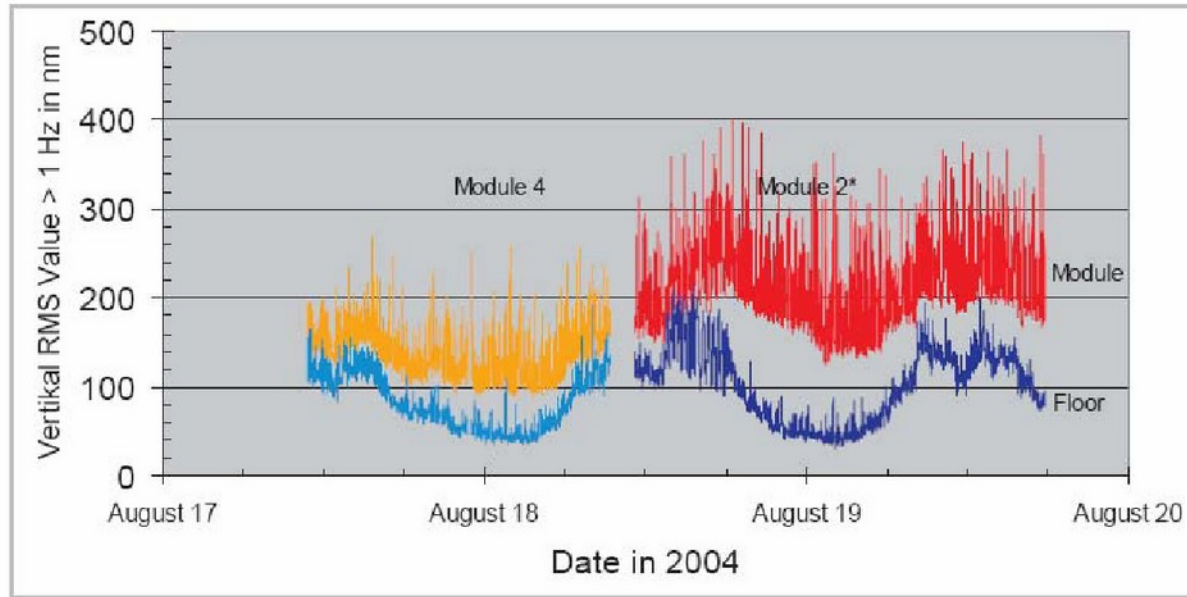
MSK.LLRF OPS

Notkestraße 85
22607 Hamburg
www.desy.de



So to Wrap it All Up.

What has been done before?

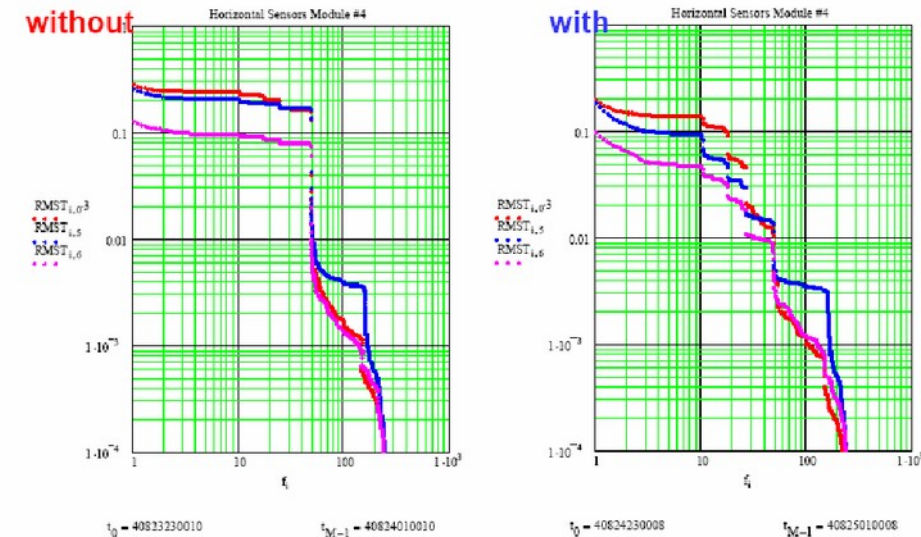


Comparison between the vertical vibration on the floor and on the module 4 and 2*.

XFEL Linac Module Meeting · DESY · September 2, 2004

Pump stand **without/with** modifications Horizontal Sensors (2 different days)

RMS average, midnight $\pm$ 1 hour



XFEL Module Meeting DESY, Sep. 2, 2004

H. Brueck, DESY MKS

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https://agenda.linearcollider.org/event/7128/contributions/35490/attachments/28913/43453/XFEL_module_evolution_LL.pdf

What has been done before?

31st Int. Linear Accel. Conf.
ISBN: 978-3-95450-215-8

LINAC2022, Liverpool, UK
ISSN: 2226-0366

JACoW Publishing
doi:10.18429/JACoW-LINAC2022-MOPOPA02

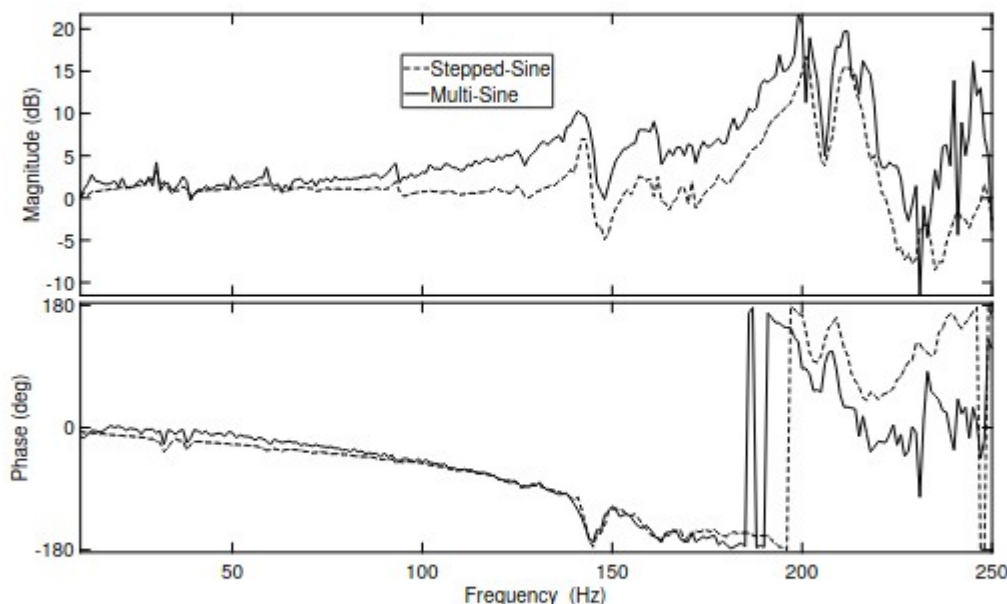


Figure 2: Comparison of transfer functions from piezo voltage to detuning for multi-sine and stepped-sine.

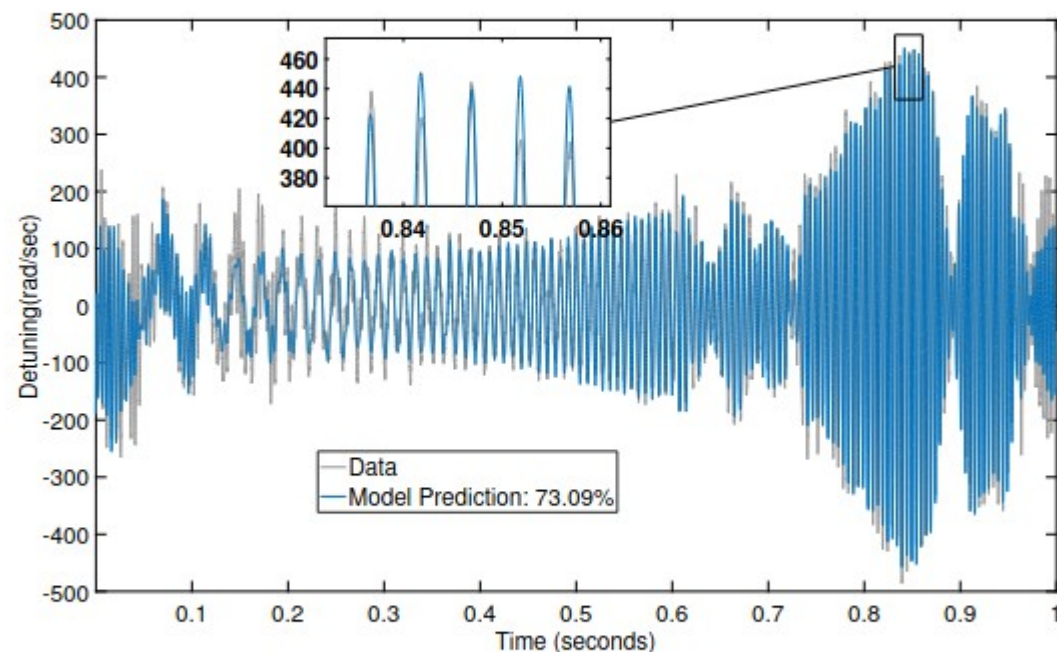


Figure 3: Time-domain validation of model identified using multi-sine data set.

Syed, Wasif, Andrea Bellandi, Julien Branelard, and Annika Eichler. "Identification of the Mechanical Dynamics of the Superconducting Radio-Frequency Cavities for the European XFEL CW Upgrade." Proceedings of the 31st International Linear Accelerator Conference LINAC2022 (2022): 4 pages, 0.549 MB. PDF, 4 pages, 0.549 MB.
<https://doi.org/10.18429/JACoW-LINAC2022-MOPOPA02>.