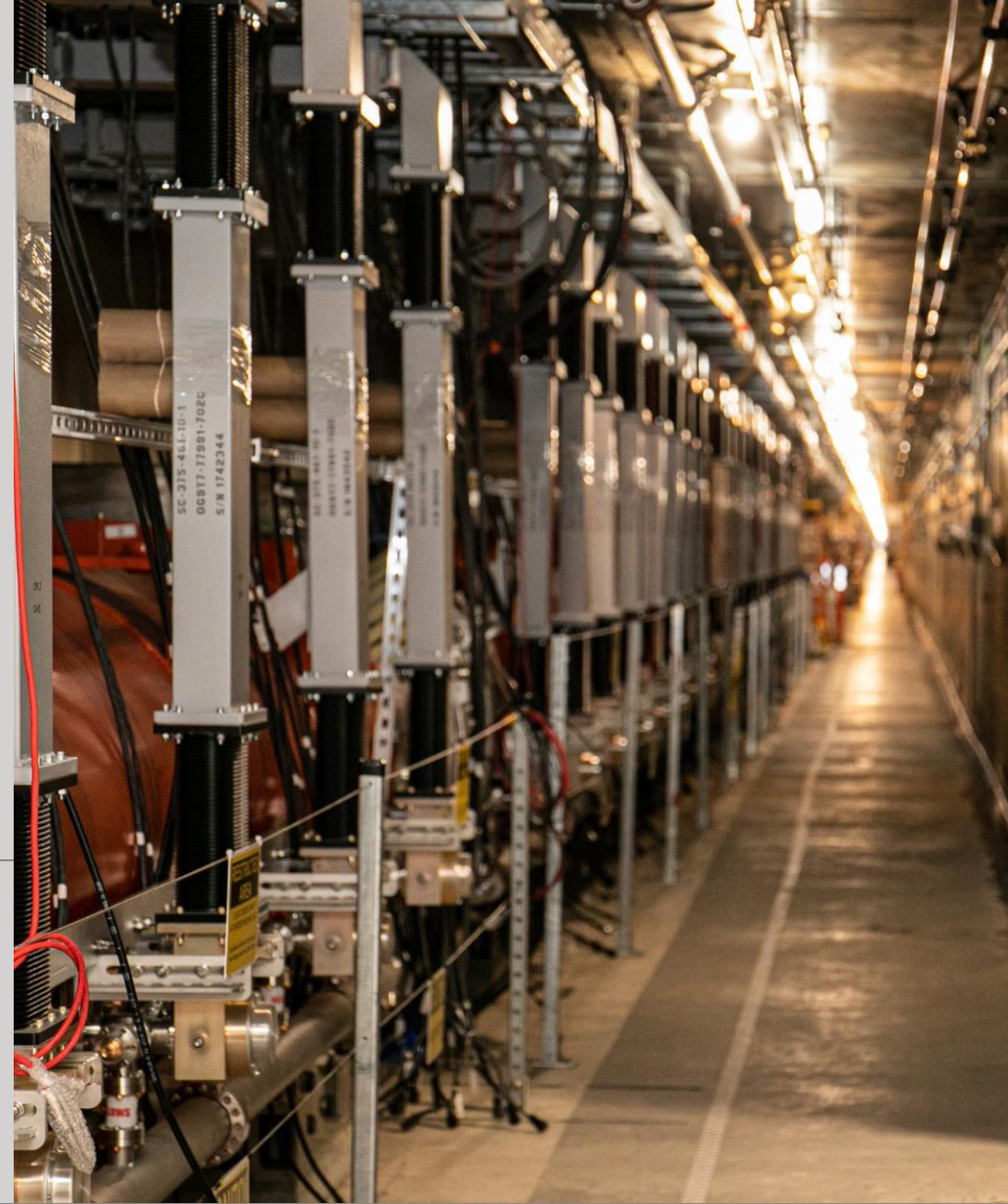


Active Noise Cancellation Measurements on LCLS-II SRF Cavities

Operational experience with Narrowband Active Noise Cancellation (NANC)

Andy Benwell, SLAC on behalf of many contributors
10/14/26 - LLRF Topical Workshop on Advanced Feedback Control



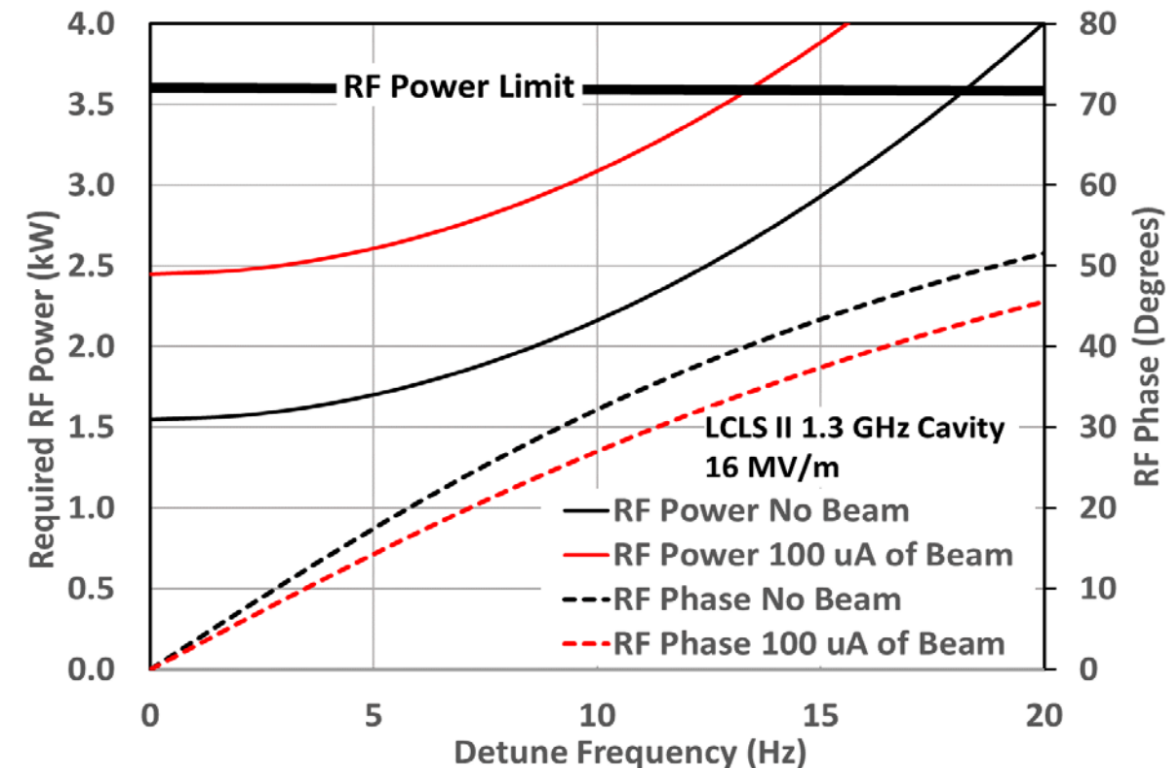
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- LCLS-II LLRF System
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 - LCLS-II LLRF SEL Regulation and "clipping"
 - LCLS-II Resonance Control System
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 - Theory
 - User Interface
 - Test results... Proof of Concept
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 - Test results. Full Cryomodule
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Motivation

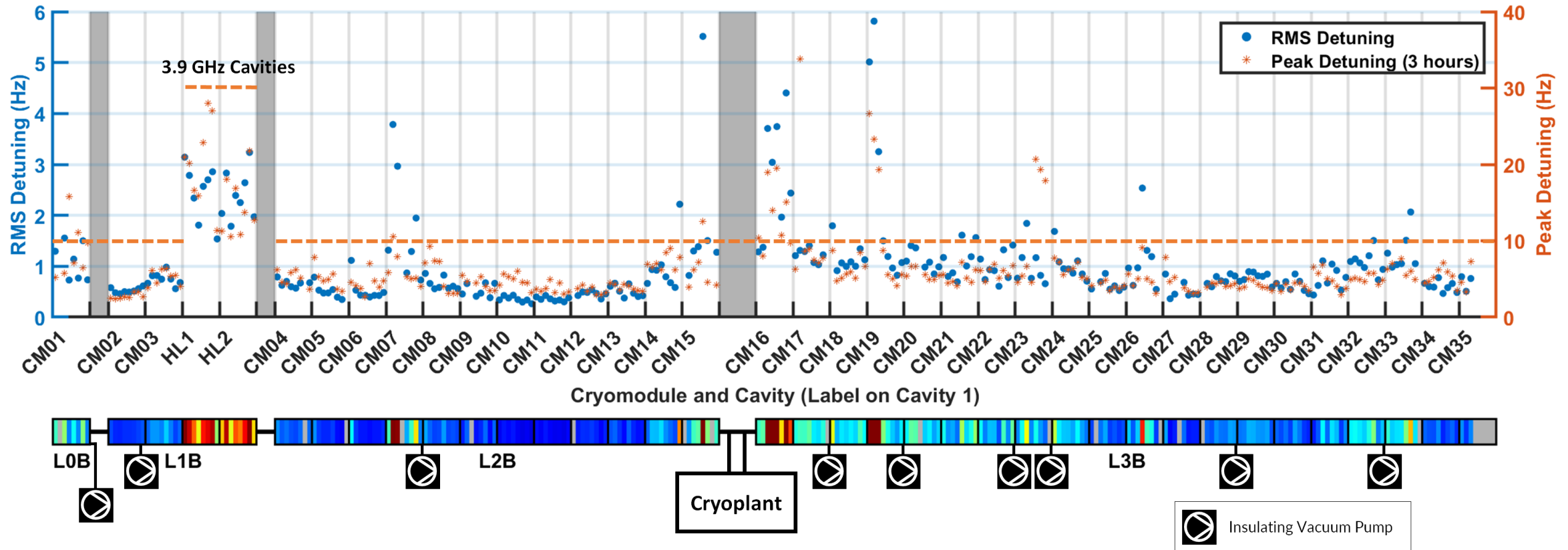
Microphonics are the main motivation!

- Microphonics induced detuning can adversely affect high-Q SRF cavities
- The LCLS-II peak detuning limits are < 10 Hz
 - Yet we regularly observe that SRF cavities can have detuning of tens of Hertz
- The assumption that we have full SSA power to compensate detuning, is not quite valid (I'll explain why later)
- To mitigate severe detuning, various forms of active resonance control (ARC) have been implemented with successful, yet varied, results.
- To operate within its RF Power limits, LCLS-II and its High Energy upgrade, will benefit from a proven and mature ARC system.



Microphonics in LCLS-II

- Some cavities in LCLS-II are gradient-limited due to microphonics.
 - The main source of microphonics are liquid helium valves, vacuum pumps, and cool-down valve leaks.
- Similar effects can be expected in LCLS-II-HE
 - Yet even higher gradient operation will be expected from those cavities.



LCLS-II LLRF System Details

Hardware/Firmware

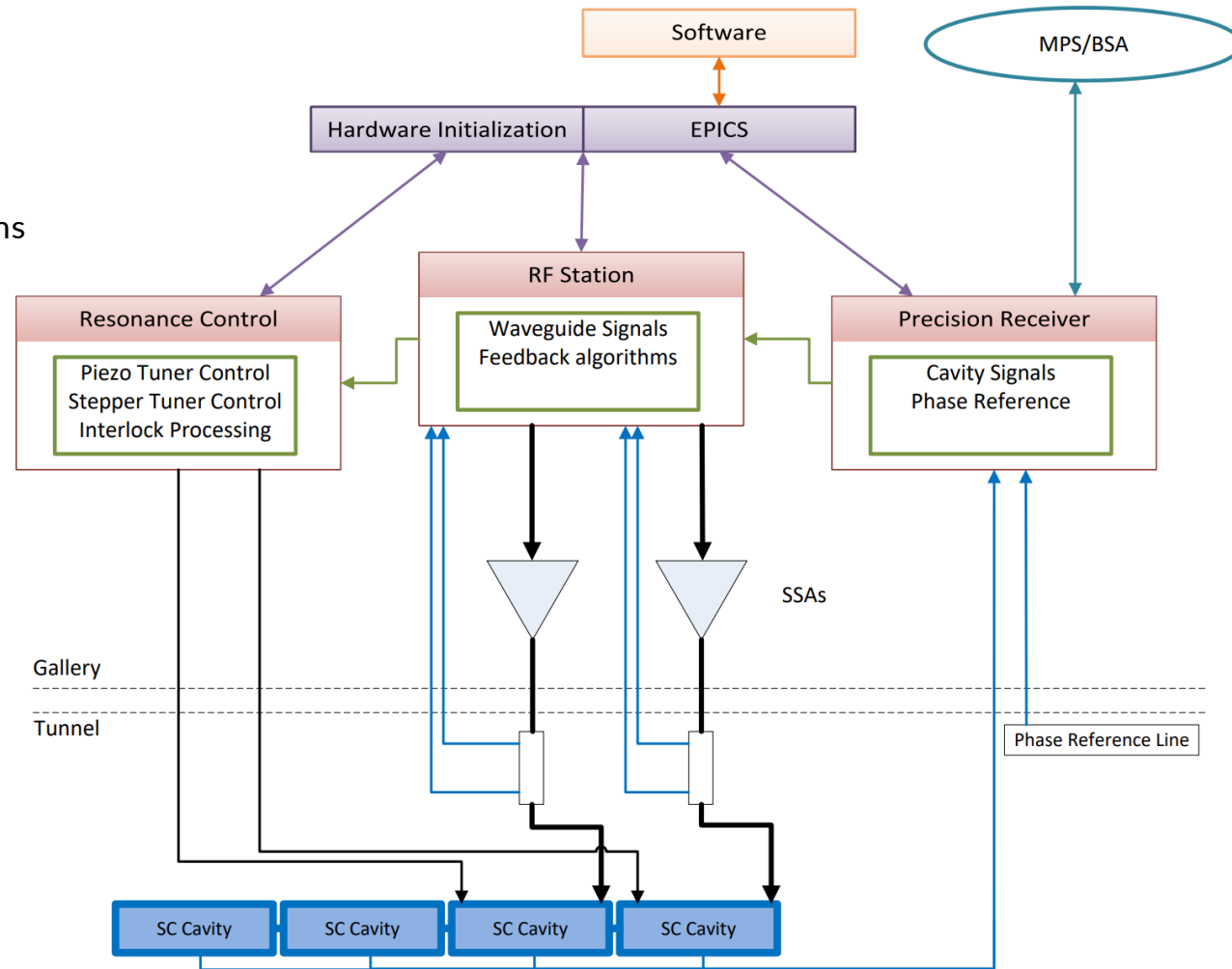
- Precision Receiver Chassis (PRC)
 - Exclusively for cavity signals
 - Fiber communication for high Isolation necessary for $0.01^\circ/0.01\%$
- RF Station (RFS)
 - Generates independent RF signal for 2 cavities
 - Forward, Reverse and SSA Drive signals
 - Detune frequency calculation, PI loop control
- Resonance Control
 - Piezo Tuner Control
 - Stepper Motor Control
 - Temperature Monitoring
 - Interlock processing

Software

- Automated Scripting
 - Cavity and SSA characterization
 - Piezo transfer-functions
- Smooth transition between modes
- Channel Access

EPICS

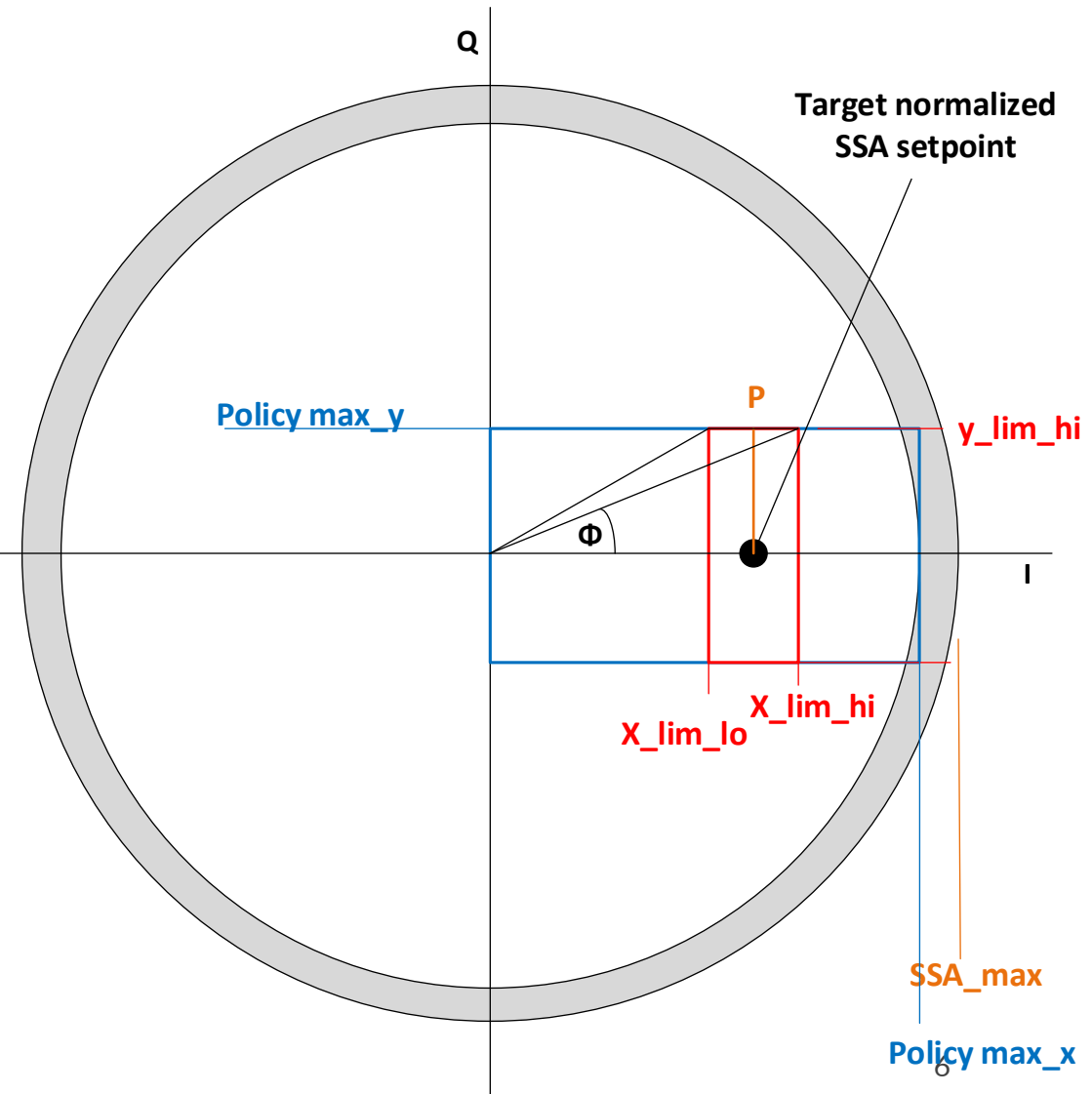
- All control displays and waveform readouts
- Cavity control interface
- Modes of Operation
- Hardware health



LLRF System Clipping

For SELAP operation a series of limits are applied to the available RF amplitude to prevent oscillations and instabilities from high gain feedback

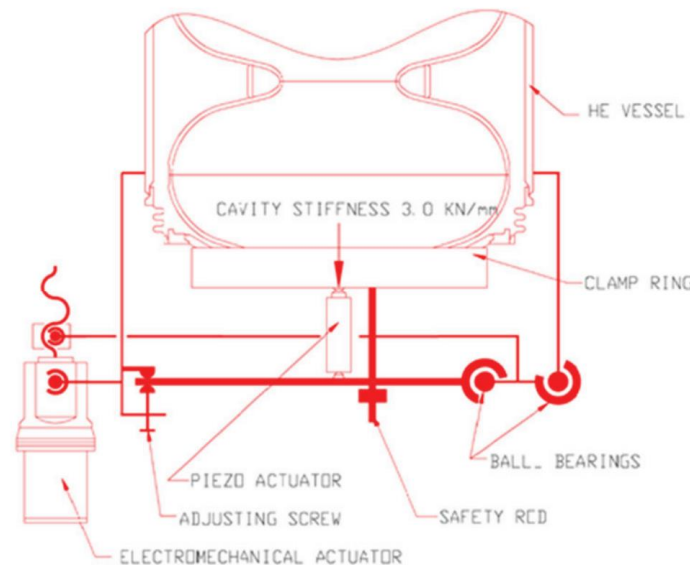
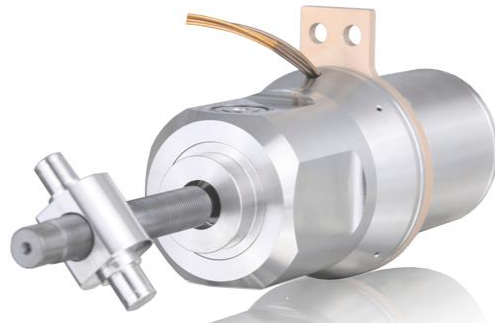
- The gradient "Target" is calculated from the desired amplitude and is based on cavity and system scaling parameters.
- The RF "Target" is the nominal setpoint for the RF FWD Power
- Policy maximum X and maximum Y are estimated to form the basic frame for total drive and I & Q in SEL mode
- X and Y limits (lo and hi) form the upper and lower bounds for SELAP operation the "clip limits" for SELAP operation
 - Note that x_lim_hi is NOT the same as the SSA_max !!
- If the cavity goes beyond the y limits, it will exit SELAP and enter SELA in order to preserve cavity amplitude and prevent Lorentz force induced faults.
 - We refer to this effect as "Clipping"



LCLS-II Resonance Control System

The LCLS-II LLRF system makes use of two mechanical tuners for cavity control

- Coarse tuning over hundreds of kHz is performed by a stepper motor tuner: Phytron LVA-52
 - Manual tuning mode only
 - Turned off with no holding current when the cavity is tuned
- Fine tuning is performed by a piezoelectric tuner assembly: Physik Instrumente P-844K075
 - Nominally runs with low bandwidth feedback enabled ($<5\text{Hz}$)
 - Higher frequency feedback modes are avoided to prevent driving mechanical eigenmodes leading to instabilities



LCLS-II Piezo Tuner System

The piezo tuner system provides continuous fine control of the cavity natural frequency

The tuner is driven by a PDU150 amplifier with output voltage limits set at 50 V_{pp}

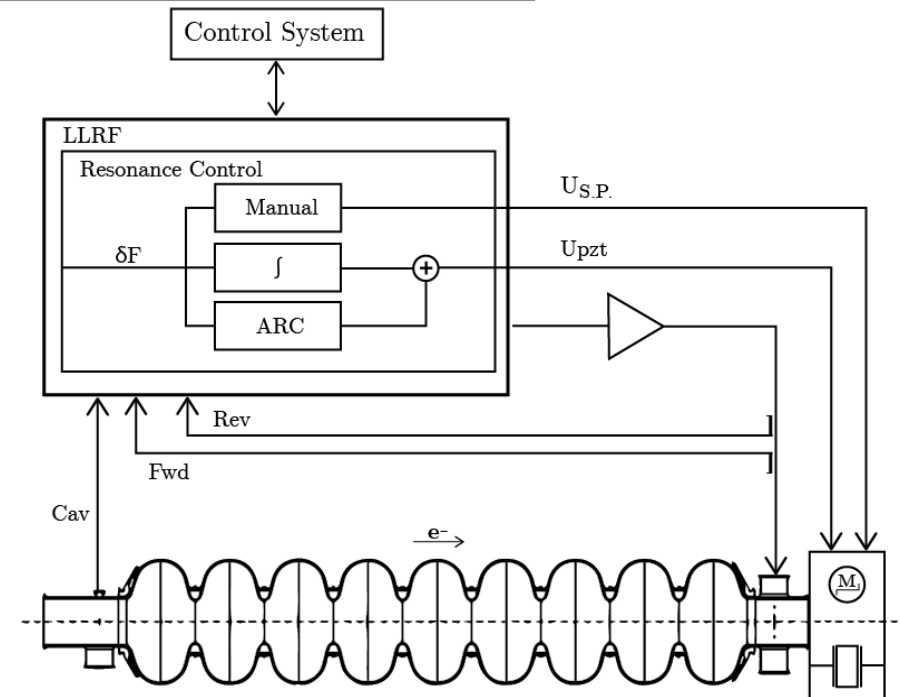
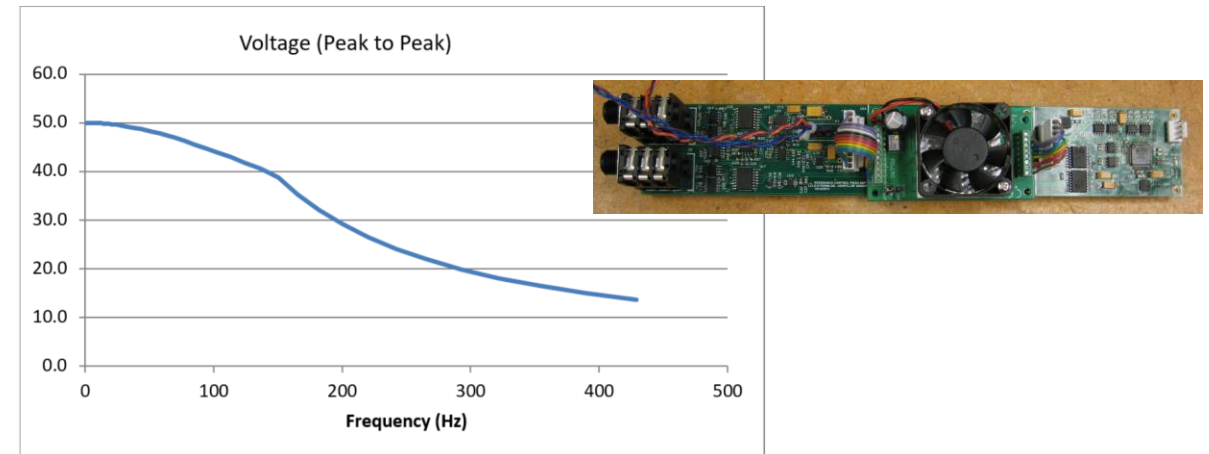
Two modes of operation are normally used

- Manual, including a DC bias to center the useable range of the piezo controller
- Integrator feedback for low frequency detuning correction

Both "normal" modes of operation can take advantage of the full piezo tuner range

In LCLS-II firmware *Active Resonance Control* is control is summed with the standard integrator feedback mode compensates for detuning in at higher frequencies, up to 200 Hz

Of concern, some power bandwidth limitations exist in the PDU150, but not too much over frequencies of interest for detuning

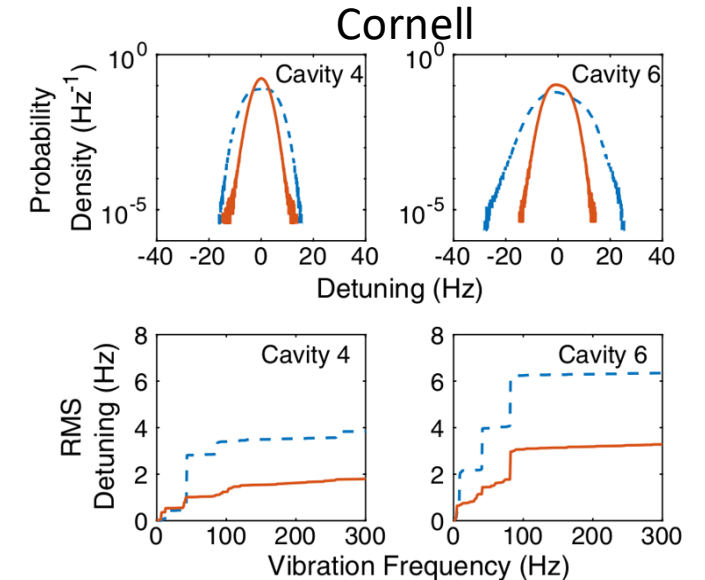
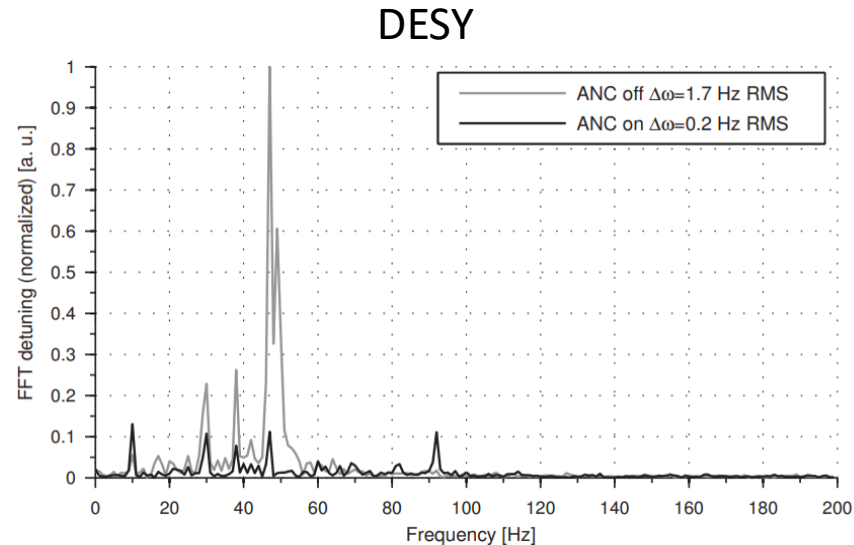
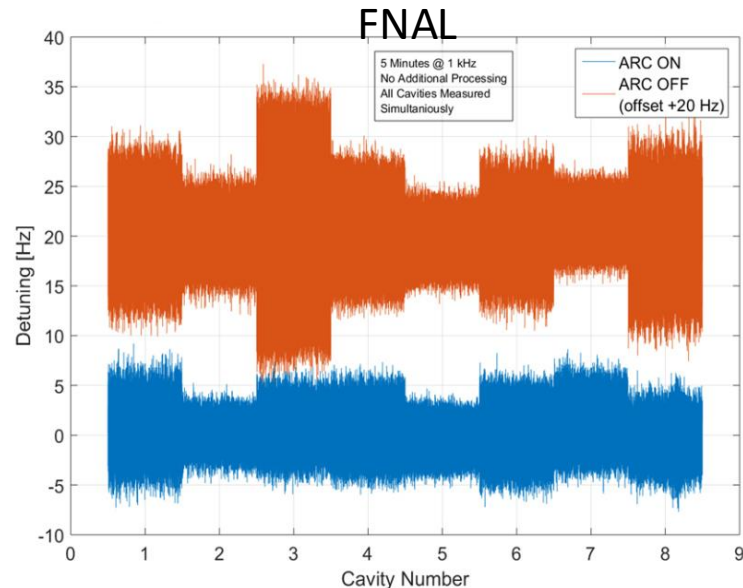


Narrowband Active Noise Cancellation (NANC)

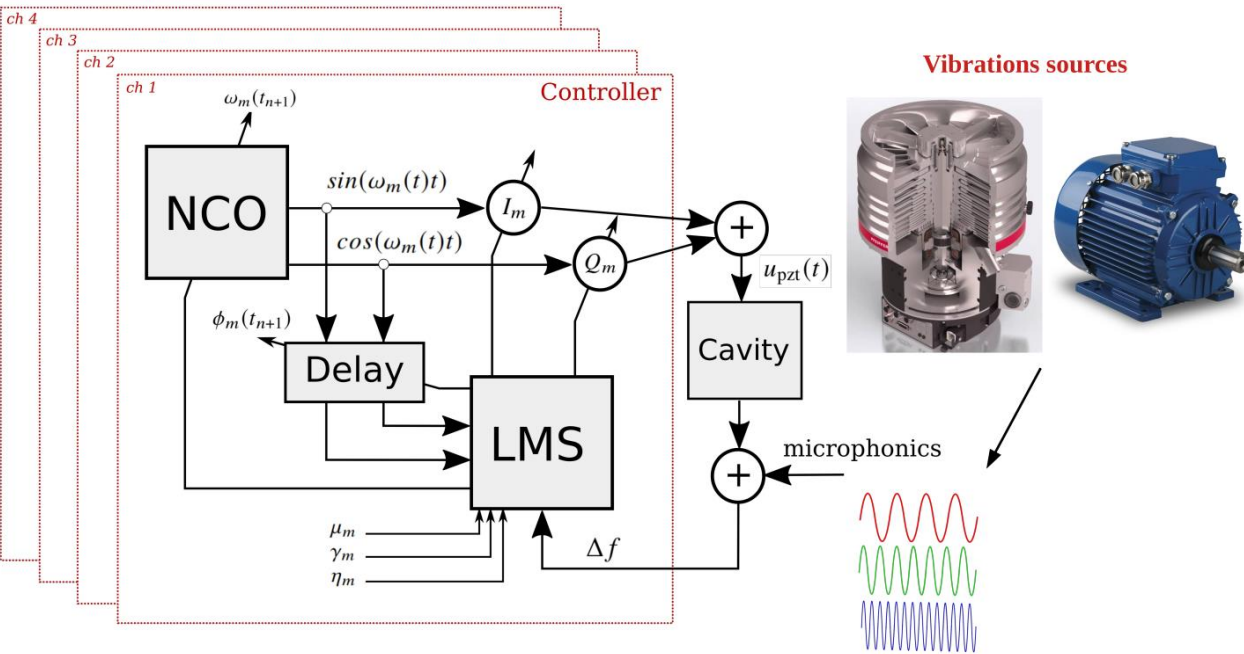
Over the years, and external to LCLS-II, Active Resonance Control efforts have yielded positive outcomes

- FNAL effort reduced detuning by x2 with a comb filter
- DESY / Cornell reduced detuning by as much as 20 dB with a NANC style approach
- In 2020, SLAC used the DESY approach with the direct help of Andrea Bellandi, and began development of a real time adaptable - Narrowband Active Noise Cancellation algorithm
- In 2025, the system was generalized for the LCLS-II LLRF platform with open-source code

Our ongoing goal has been to adapt this proven system for LCLS-II LLRF and make it widely deployable for use in LCLS-II operations and for LCLS-II HE commissioning



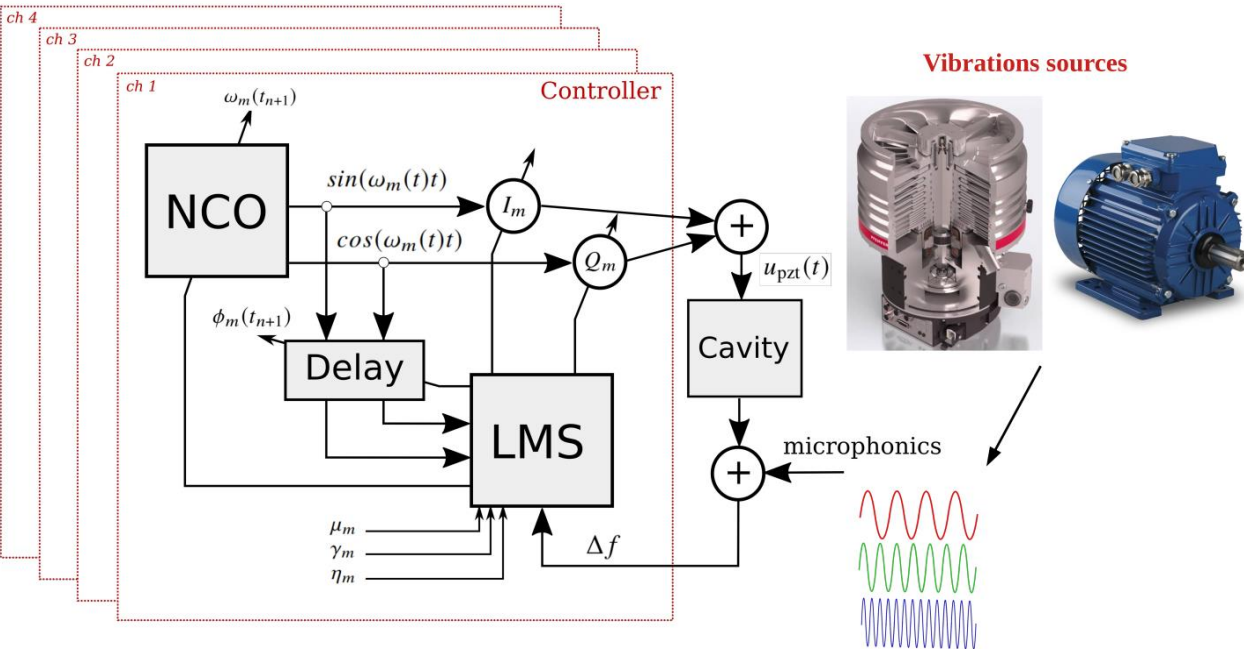
Theory – Noise Cancellation



Shown here: 4 parallel noise cancelling signals being generated by the NANC controller, each minimizing a microphonic frequency peak of concern

- NANC focuses on canceling specific narrow band detuning oscillations that can shift in frequency (and amplitude)
- External microphonic disturbances are assumed to be sources of superimposed sinusoidal signals of unknown phase, amplitude and frequency
- A Numerically Controlled Oscillator (NCO) in the piezo tuner controller is used to generate a sinusoidal signal.
- The signal is modulated by an I&Q vector to change frequency, phase and amplitude.
- To match (or cancel) the detuning disturbance, a Least Mean Square (LMS) algorithm adapts the I&Q.
- To estimate the I&Q correctly, the actuator delay has to be calculated as well

Theory - Adaptation



*We found no need to use delay adaption rate in this system.
It is folded into I&Q adaptation*

I&Q Adaptation

$$I_m(t_{n+1}) = I_m(t_n) - \mu_m \Delta f(t_n) \times \cos(\omega_m(t)t_n - \phi_m(t_n))$$

$$Q_m(t_{n+1}) = Q_m(t_n) - \mu_m \Delta f(t_n) \times \sin(\omega_m(t)t_n - \phi_m(t_n))$$

Frequency Adaptation

$$\omega_m(t_{n+1}) = \omega_m(t_n) + \gamma_m \frac{I_m(t_n)Q_m(t_{n+1}) - Q_m(t_n)I_m(t_{n+1})}{I_m(t_n)^2 + Q_m(t_n)^2}$$

Chain Delay Adaptation

$$\phi_m(t_{n+1}) = \phi_m(t_n) - \eta_m \Delta f(t_n) \times \{I_m(t_n)\sin(\omega_m(t)t_n - \phi_m(t_n)) - Q_m(t_n)\cos(\omega_m(t)t_n - \phi_m(t_n))\}$$

μ_m : I&Q adaptation rate

γ_m : frequency adaptation rate

η_m : delay adaptation rate

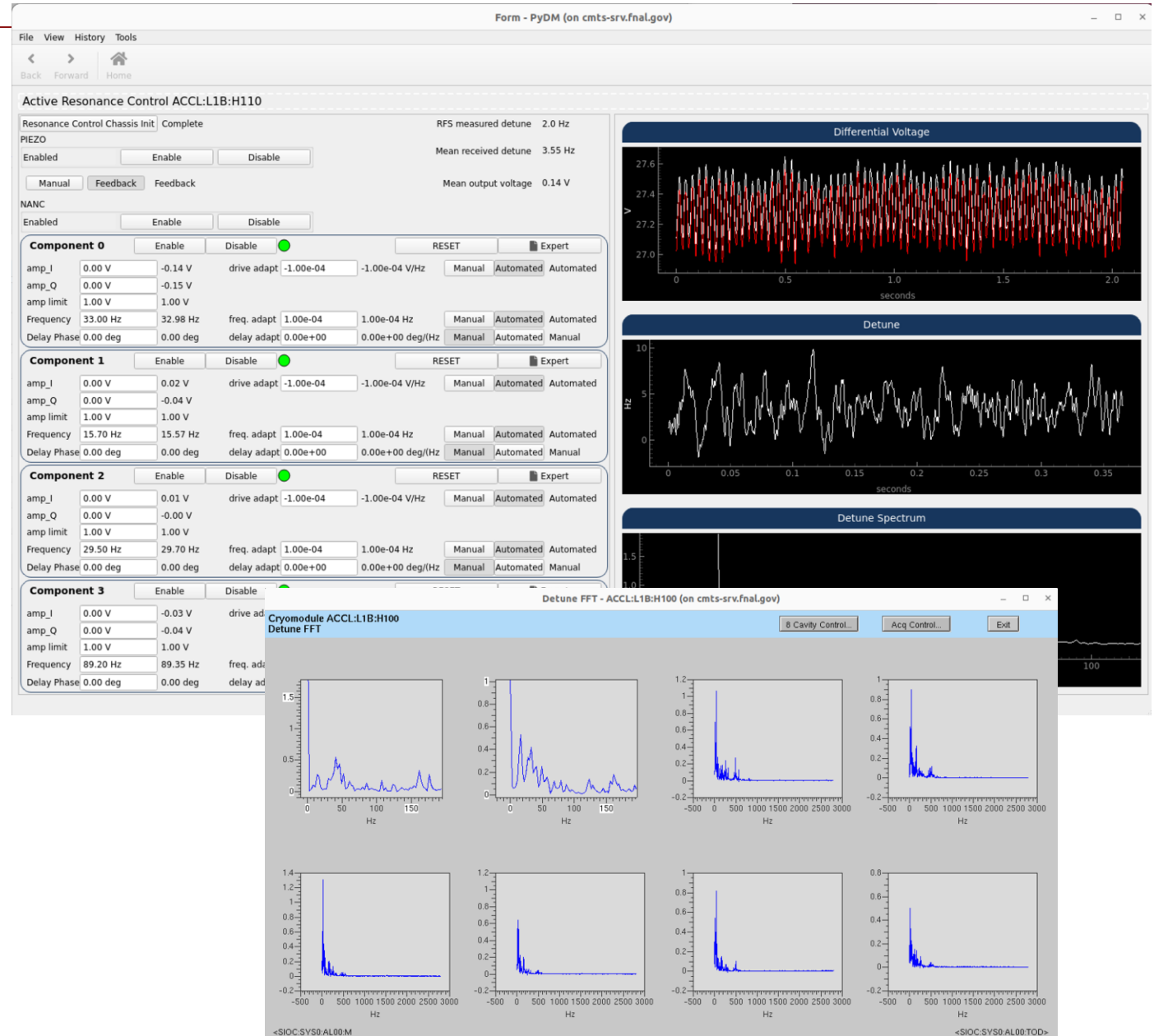
User Interface for Individual Cavities

The expert level User Interface enables individual control of every cavity while observing detuning of all cavities

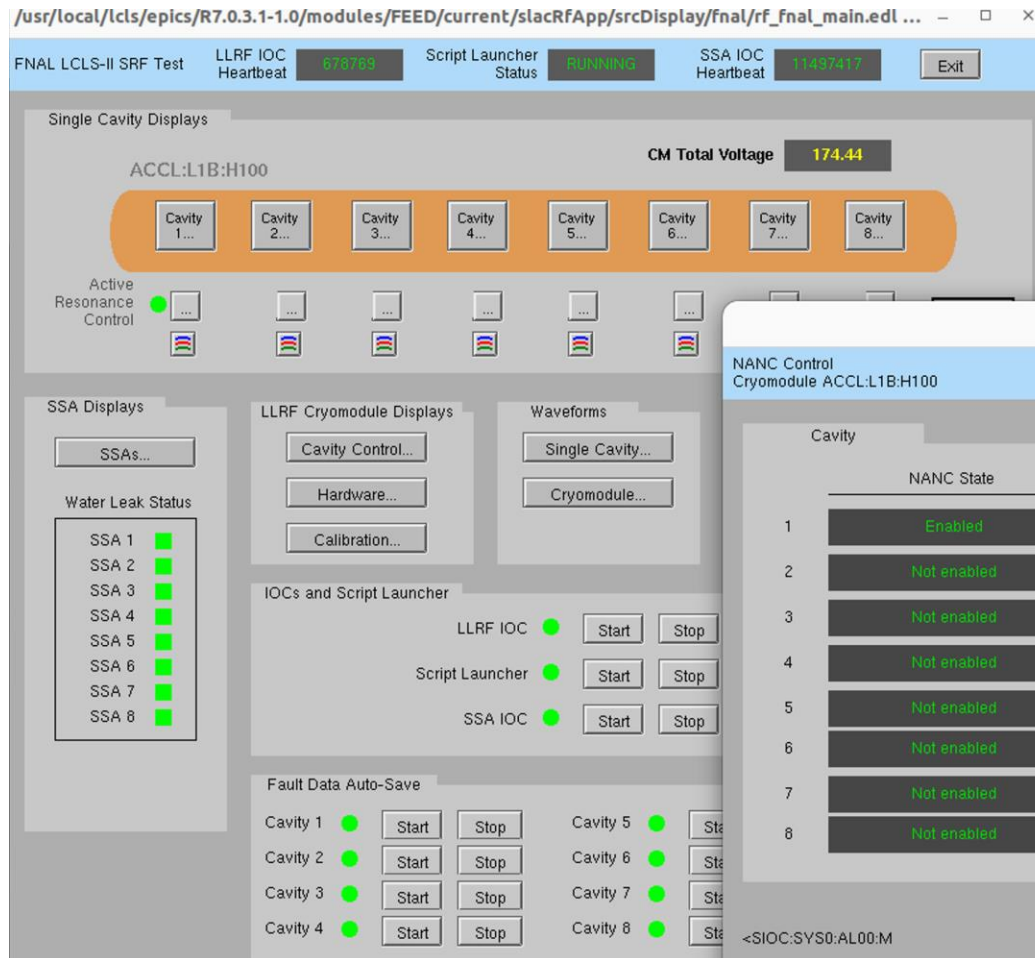
Up to 4 frequencies per cavity can be acted upon by NANC (32 "components" for the entire 8 cavity cryomodule)

Each component has independently settable attributes

- Enable/disable
- Amplitude limits
- Amplitude adaptation speed
- Frequency search range
- Frequency adaptation speed
- Manual / Automatic
- Delay phase
- Delay adaptation rate

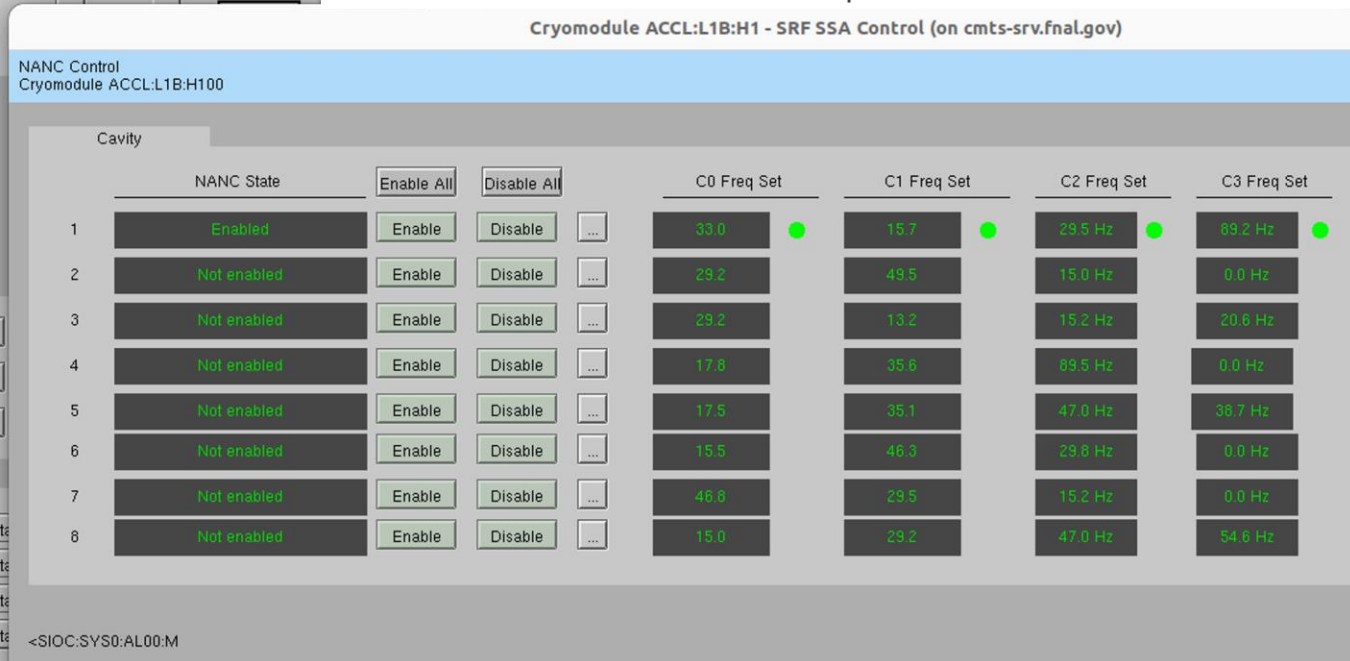


User Interface for Full CryoModule



Global control of NANC for a full crymodule is being developed to simplify use at scale.

- Enable/Disable full CM control
- Enable/Disable full cavity control
- Enable/Disable individual components



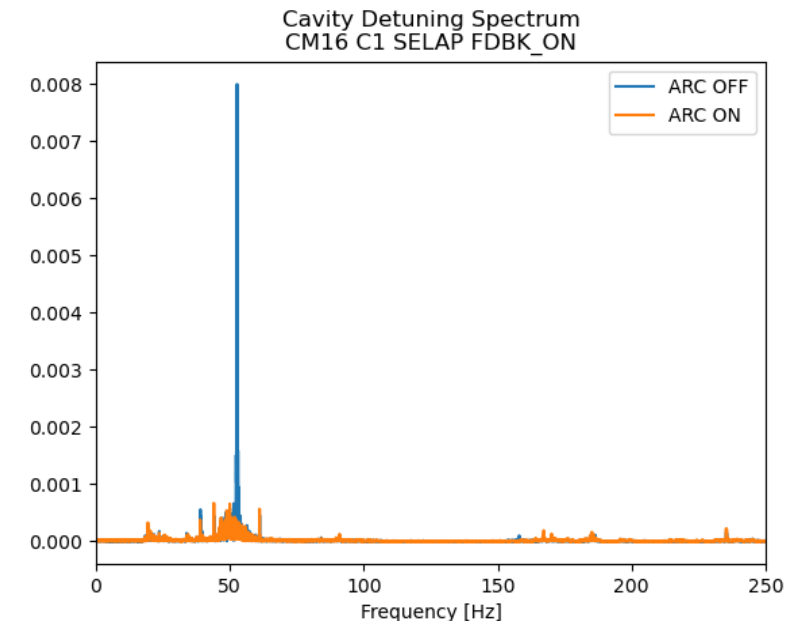
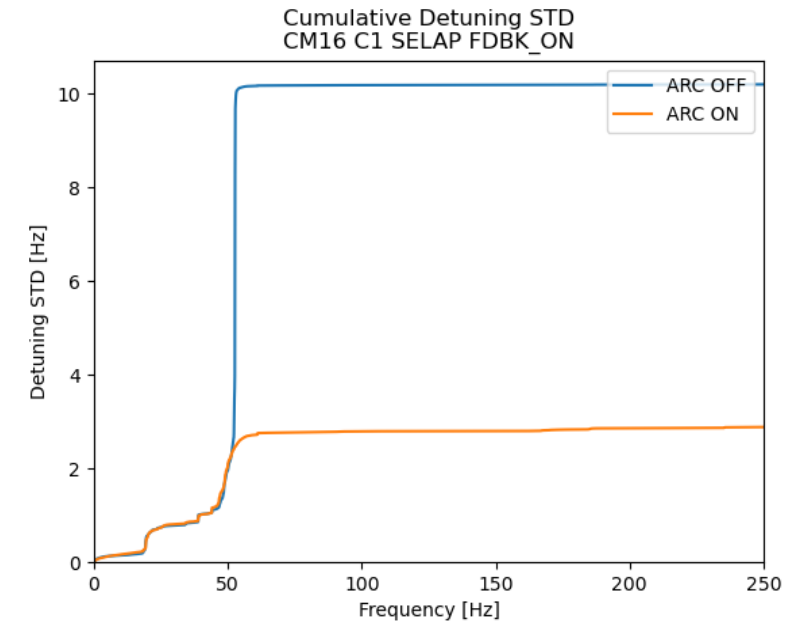
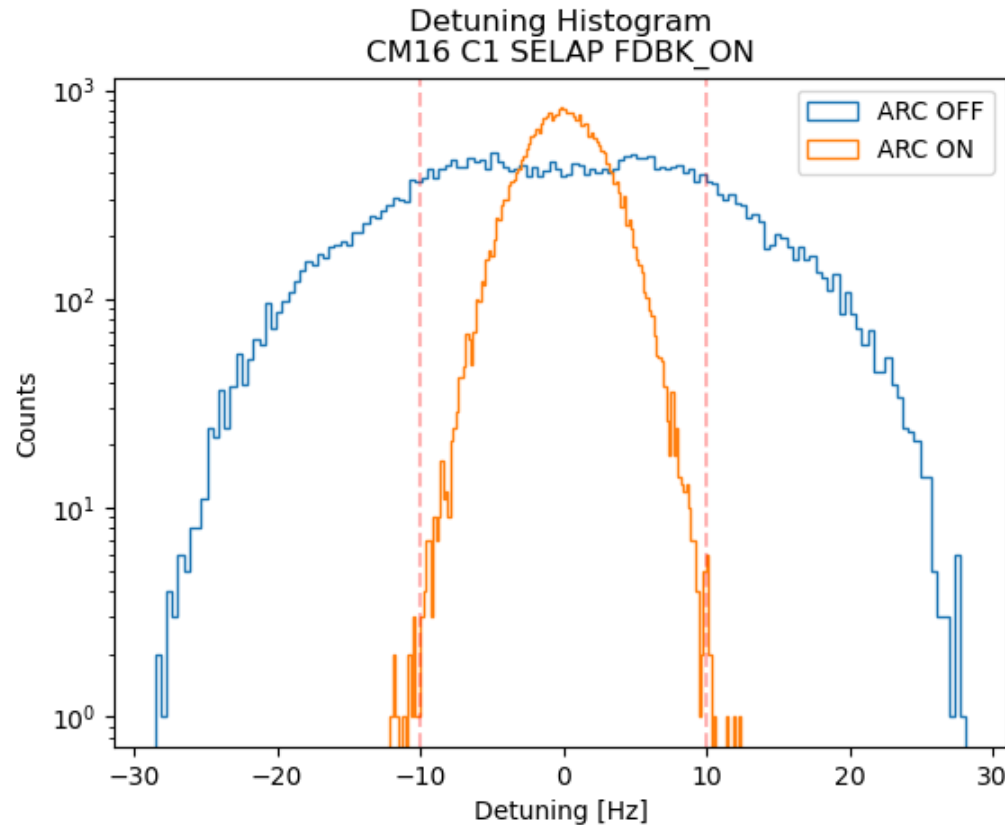
Testing so far

SRF tests on the NANC system have occurred over several rounds as opportunities

1. 2020 @ LCLS-II proof of concept with a single frequency and single cavity operation
2. 2020 @ LCLS-II proof of concept with multiple frequencies on a single cavity
3. 2025 @ LCLS-II over several hours while observing a cyclical pressure driven disturbance
4. 2025 @ LCLS-II increasing gradient to beyond microphonics limited operation
5. 2026 @ FNAL HE Cryomodule Test Facility (CMTF) controlling multiple frequencies and multiple cavities
6. 2026 @ FNAL HE CMTF with artificially induced sources of detuning
7. 2026 @ FNAL HE CMTF during an 8-hour full Cryomodule unit test

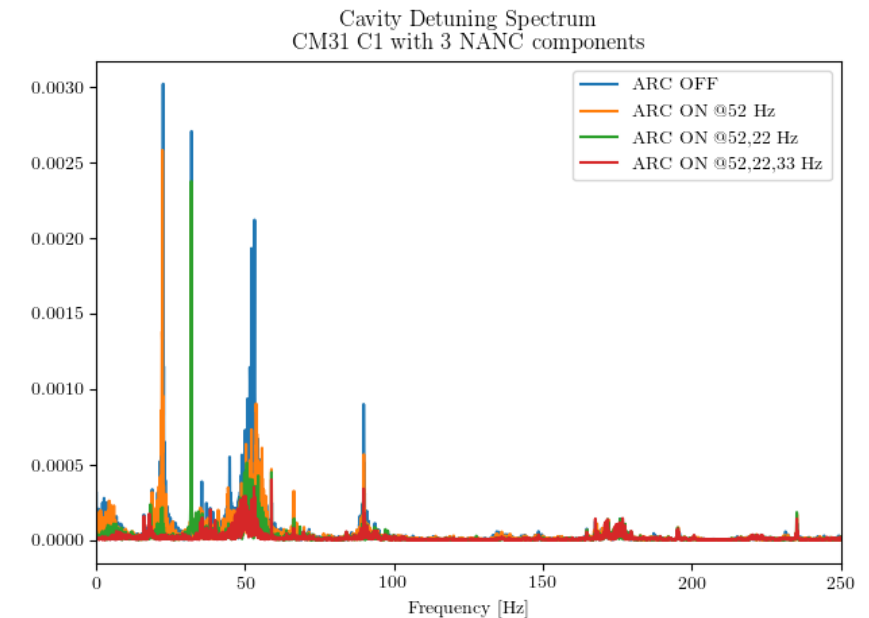
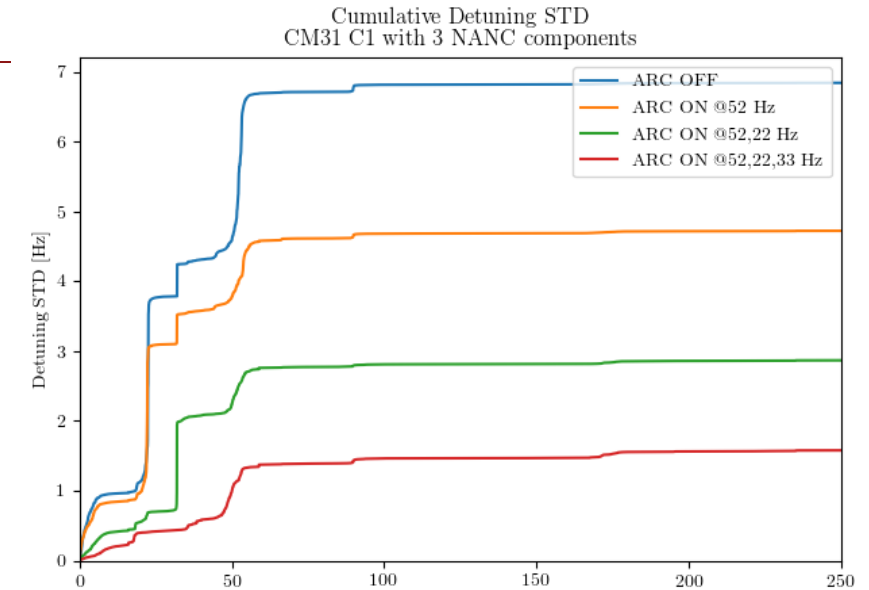
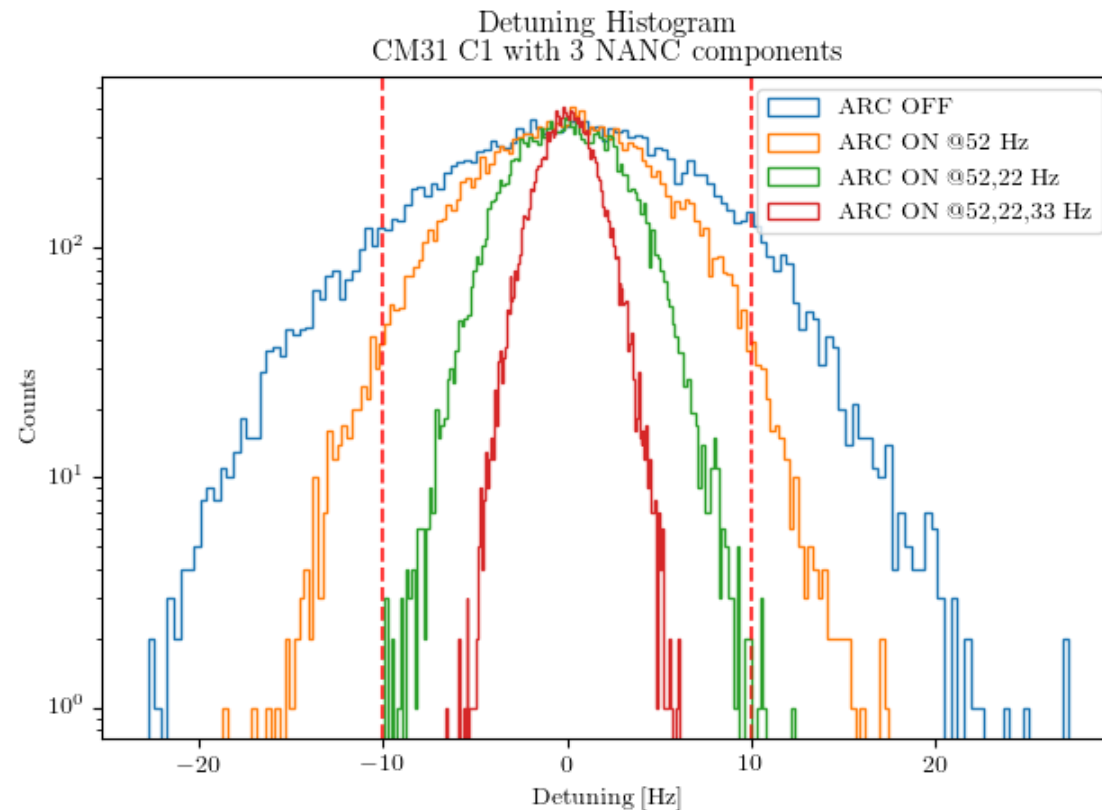
Single Cavity, Single Frequency

- Performed during a proof of concept test on a single particularly noisy cavity
- Other cavities in the cryomodule were off
- Gradient was set to a low value due to microphonics



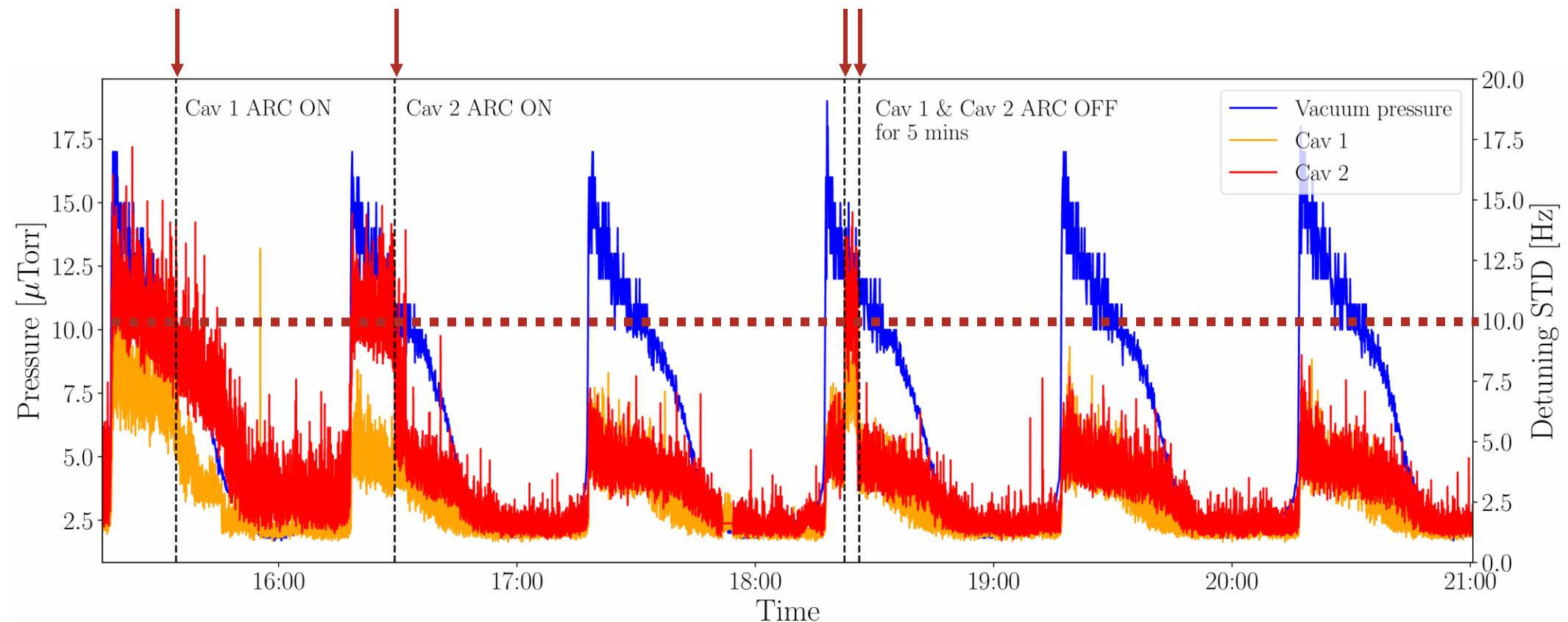
Single Cavity, Multiple Frequencies

- Compensation for 3 sources of detuning
- Other cavities in the cryomodule were off
- Gradient was set to a low value due to microphonics



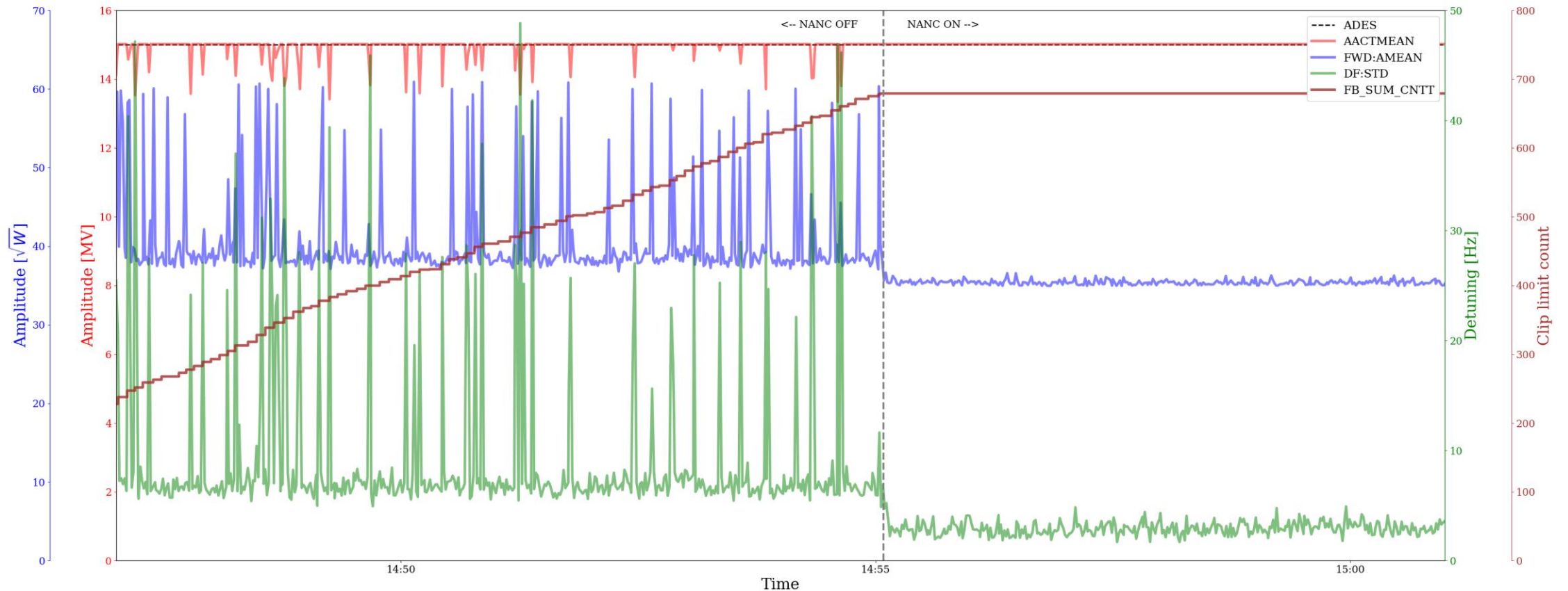
Adapting to changing conditions

- First test for improving a true, well understood source of instability in the LCLS-II Linac
- A small cryogenic distribution leak during the LCLS-II initial run resulted in *periodic* vacuum spikes with correlated microphonic disturbances in the downstream linac cavities
- This condition encouraged us to test NANC under changing conditions to observe the effect of system adaptability
- Under NANC, cavities were within the LCLS-II detune specifications at the target gradient



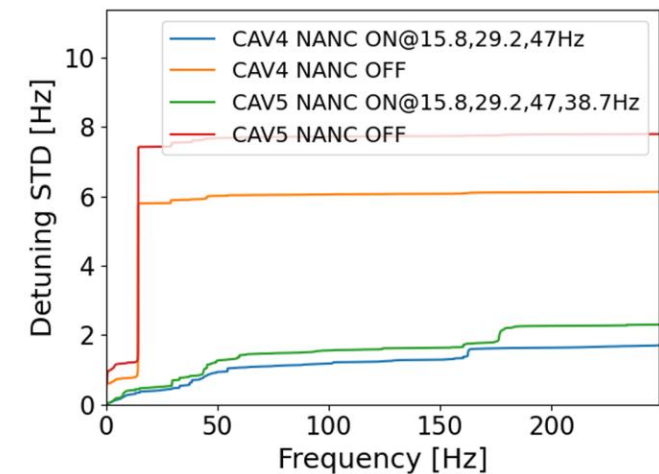
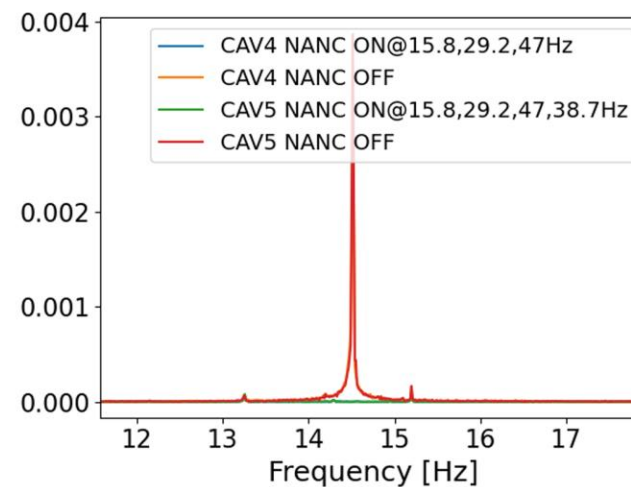
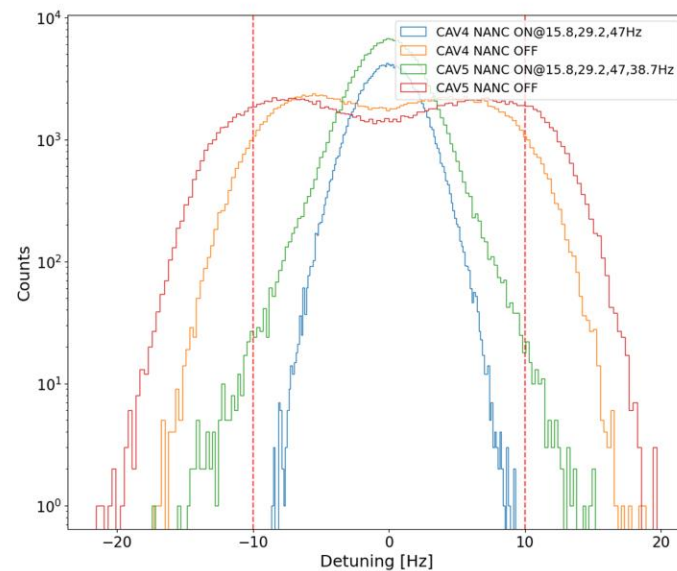
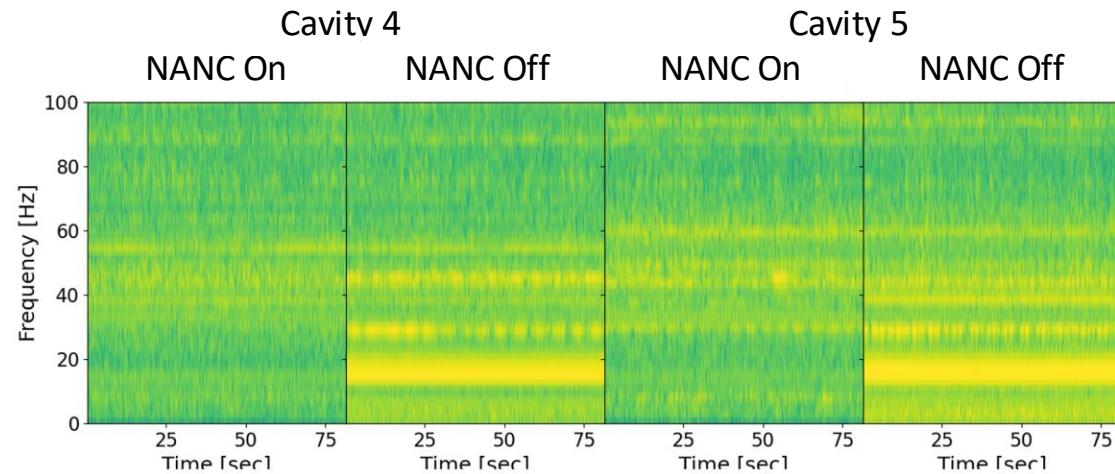
Improving High Gradient Stability

- Gradient of CM19 Cavity 2 normally limited to 9MV due to microphonics induced instability
- At 15 MV operation the cavity exhibits frequent clipping
- With NANC enabled, cavity gradient was stable at 15MV for the duration of the test



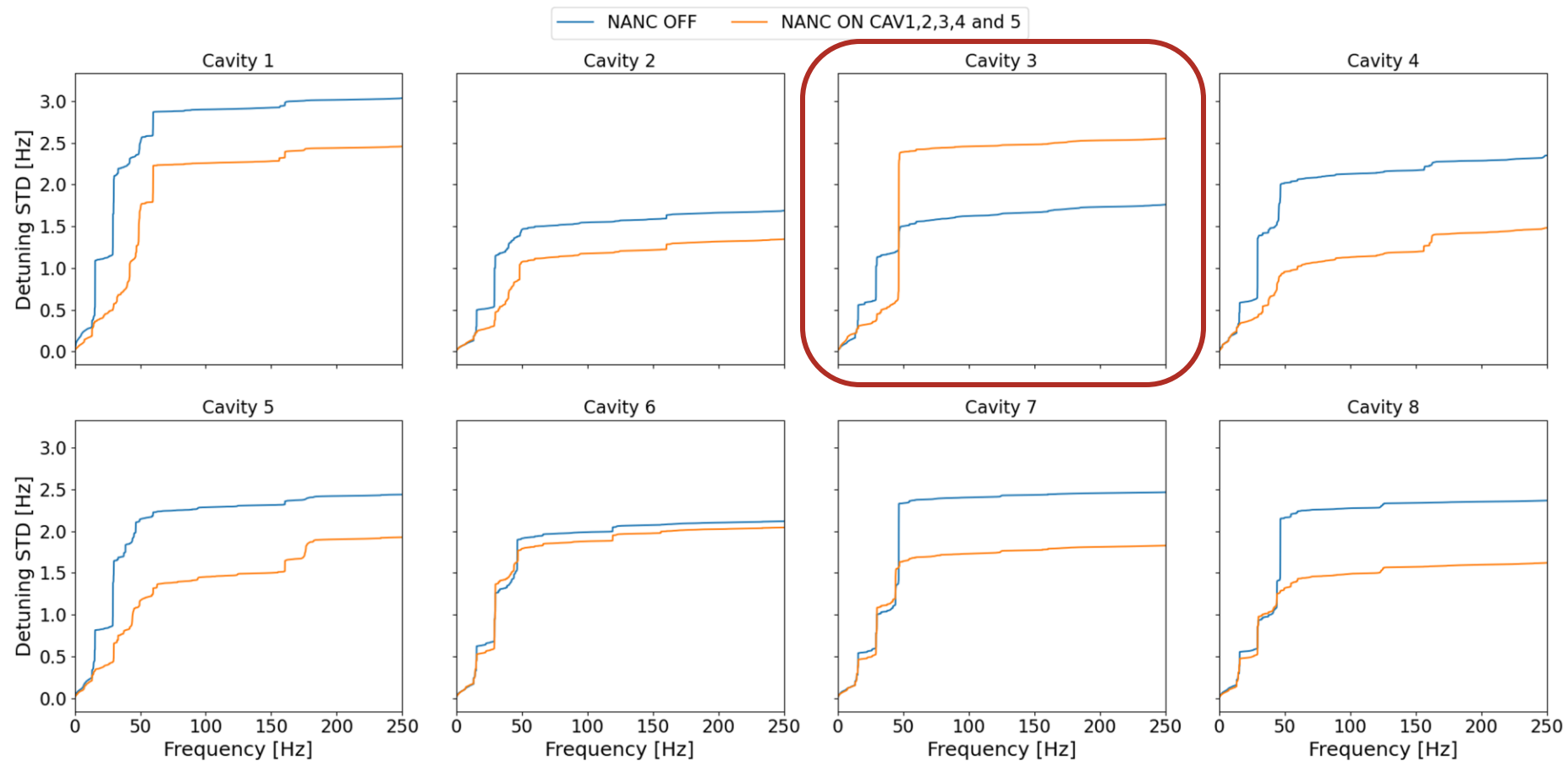
Multiple Cavities Simultaneously Controlled

Two neighboring cavities, simultaneously configured for multiple frequencies



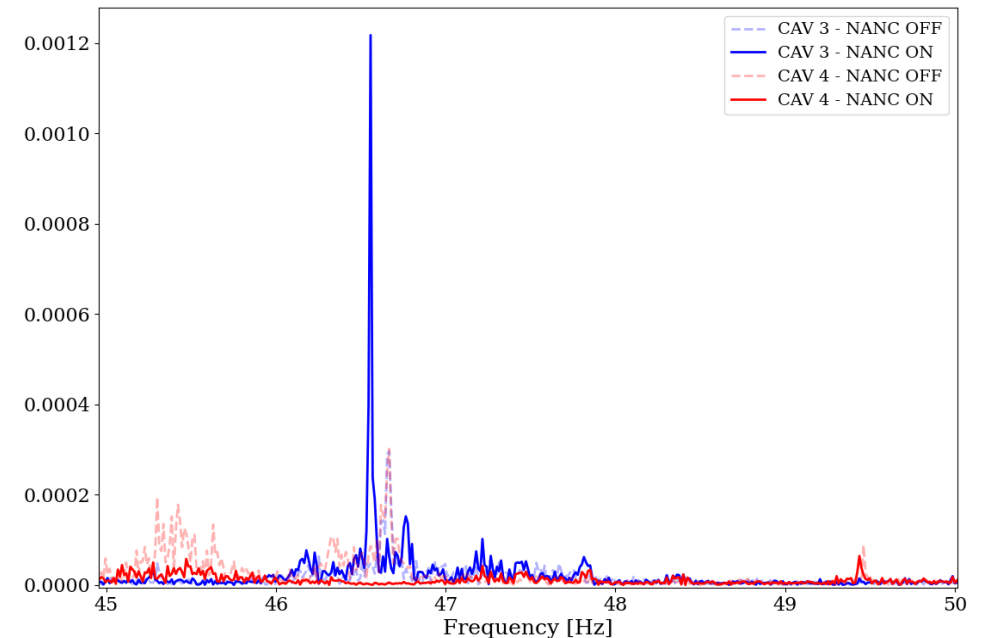
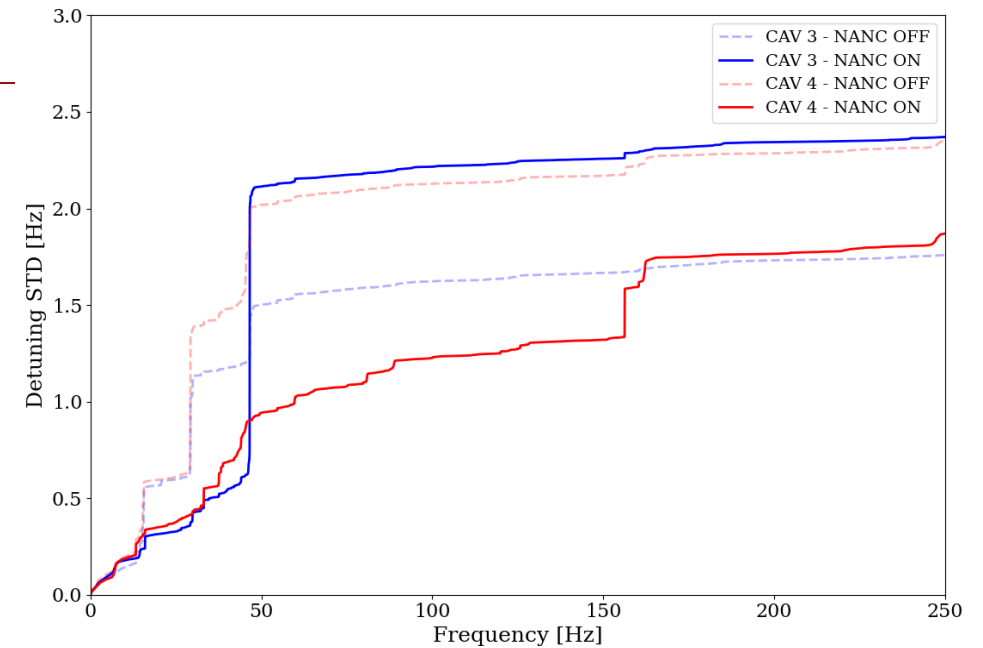
NANC exciting modes other cavities

- When 5 of 8 cavities were controlled for multiple frequencies, we noticed some instances of mechanical "crosstalk"
- Cavity 3 exhibited greater detuning when certain frequencies from cavity 4 were dampened



Mechanical Eigenmodes

- A natural mechanical mode of cavity 3 was excited when a cavity 4 microphonic source was being dampened
- This became more apparent when trying to operate cavity 3 with NANC enabled to suppress the eigenmode
- Clearly some frequencies must be avoided by NANC to prevent exciting them which results in severe detuning
- And in some cases, NANC can excite mechanical modes in neighboring cavities
- These modes should be measured and catalogued prior to broad deployment of NANC



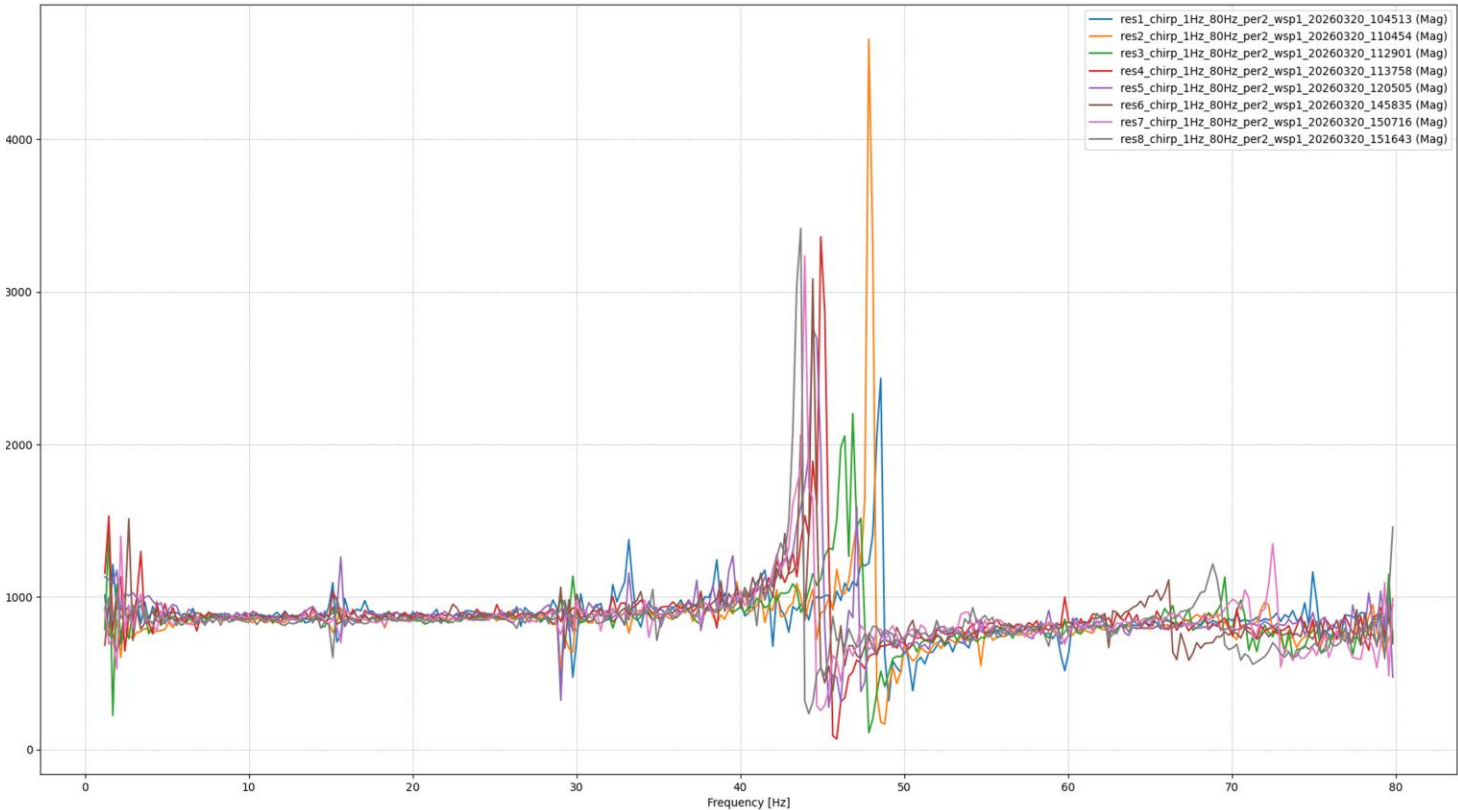
Measuring and Cataloging Eigenmodes

Performing piezo tuner "chirps" enable the characterization of mechanical eigenmodes

- Piezo tuners are driven with a small sinusoidal wave at low frequency with RF enabled
- Natural cavity modes are observed in the transfer function waveform
- These modes are then catalogued so that they can be avoided by the NANC controller

These modes were already known and well understood by the cryomodule experts we tested with!

NANC will not dampen out natural modes of the cavity and they should be avoided.



Cavity	1	2	3	4	5	6	7	8
Dominant Mode (Hz)	47.5	47	45.5-46	45	44.5	44.5	44	43.5

Summing up

NANC has become a powerful tool for suppressing external sources of mechanical detuning of SRF cavities.

Even though its promise was apparent from early testing, system maturity took many years of incremental development.

Integration into the LCLS-II and LCLS-II HE control system is now under way.

- The LCLS-II HE commissioning effort may benefit immediately with the use of NANC to mitigate any currently unknown sources of microphonic instability.
- The system is ready to drop in "as needed" for mitigating local microphonic problems and help prevent hasty repairs,
- Or the system could simply be broadly used to minimize cavity detuning.

While NANC is ready for use, there are some improvements already underway

- The NANC system is implemented with an open-source RISC-V softcore processor on an FPGA
 - Adaptation toward a pure firmware-based approach will increase the bandwidth of the system, and possibly reduce FPGA resource consumption
- Other broadband approaches are being considered and tested by team members at LBNL, SLAC and FNAL – please take the time to look up their efforts if you are interested in this work

A Long-Term Team Effort

Development of this system from concept and through several rounds of development to its current mature form has been a long-term effort

This work has been a true team effort. THANK YOU:

- to **DESY** and **Andrea Bellandi** for kicking off the effort at SLAC in 2000
- to **Sebastian Aderhold**, **Lauren Alsberg**, and the entire SRF team at SLAC for providing occasional opportunities to test NANC on LCLS-II, and support for travel to CMTS
- to **Jorge Diaz** and **Sonya Hoobler** for the many rounds of incremental improvement in the system
- to **Bozo Richter** (again at **DESY**) for adapting the system to an open-source platform enabling it to be broadly supported by the LCLS-II LLRF system
- to the **Shree Murthy** and **Du Qiang** and the entire **LBNL** LLRF team for assisting firmware development and all the tools and scripts for making this system work properly
- to our partners at **FNAL**, particularly the team at the Cryomodule Test Facility led by **Andrew Cravatta** for the many hours of SRF testing time, and for your expertise and suggestions