Introduction to SRF

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LLRF – USPAS 2023

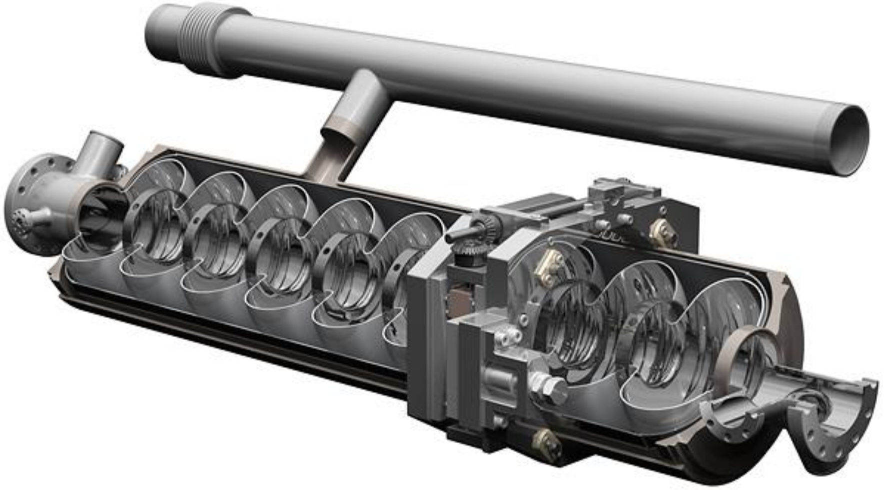
A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

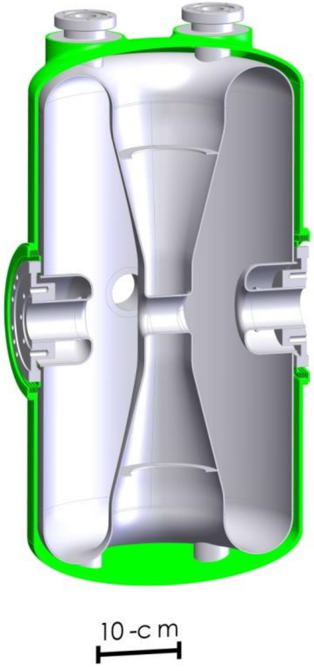
Questions to Answer

- What is an SRF Cavity, and why is it different from a normal conducting cavity?
- What is required to test a single cavity?
- What more do you need to test an integrated cryomodule?
- What more would you need to commission and run an SRF machine?

What is an SRF Cavity?

- Electromagnetic resonator, meant to store RF energy, and shaped for effective particle acceleration
- Constructed with superconducting material so that it can store the RF energy extremely efficiently
- Must be cold to be in the superconducting state
- ~1e6 more efficient than copper, but costs 1e3 more to cool

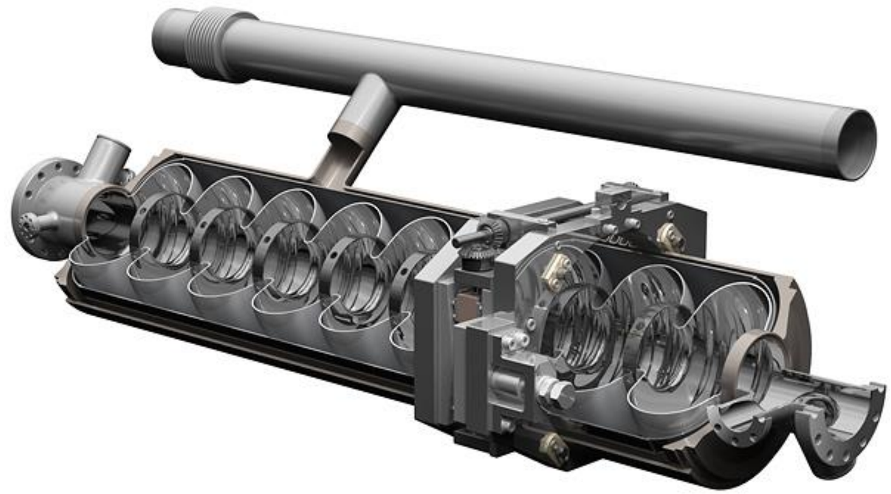


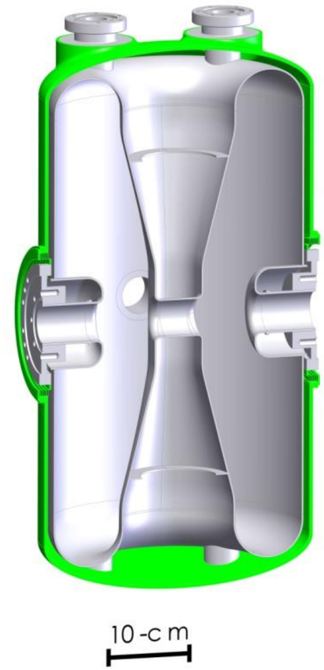


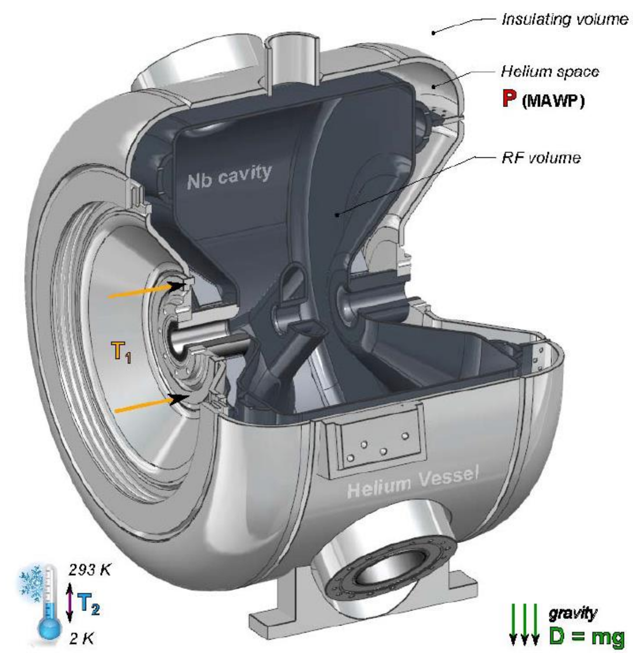
PIP-II

What is an SRF Cavity?

- Cryogenic operation has massive implications
  - Generally thin walled, made of formed and welded 3-4 mm sheet Niobium (mechanically weak)
- Because of the lower mechanical stiffness:
  - More internal mechanical resonances
  - Vulnerable to external pressure and pressure changes
  - Change in internal Lorentz force can cause major detuning

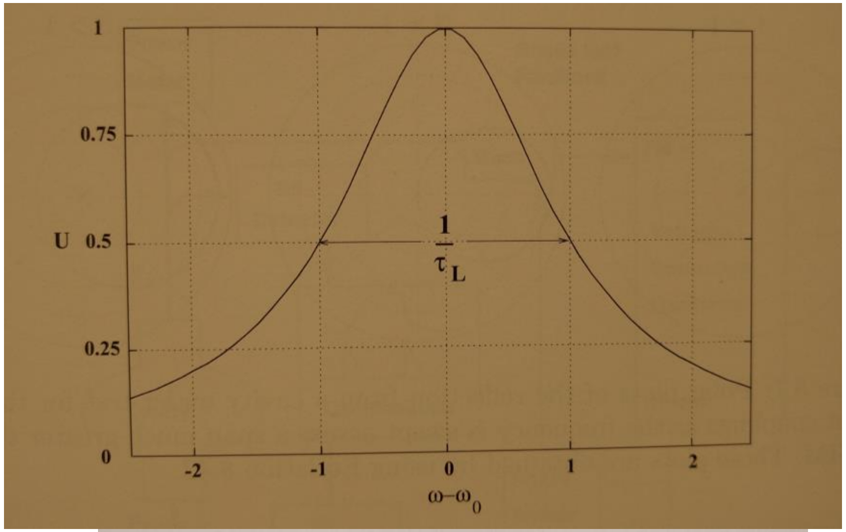


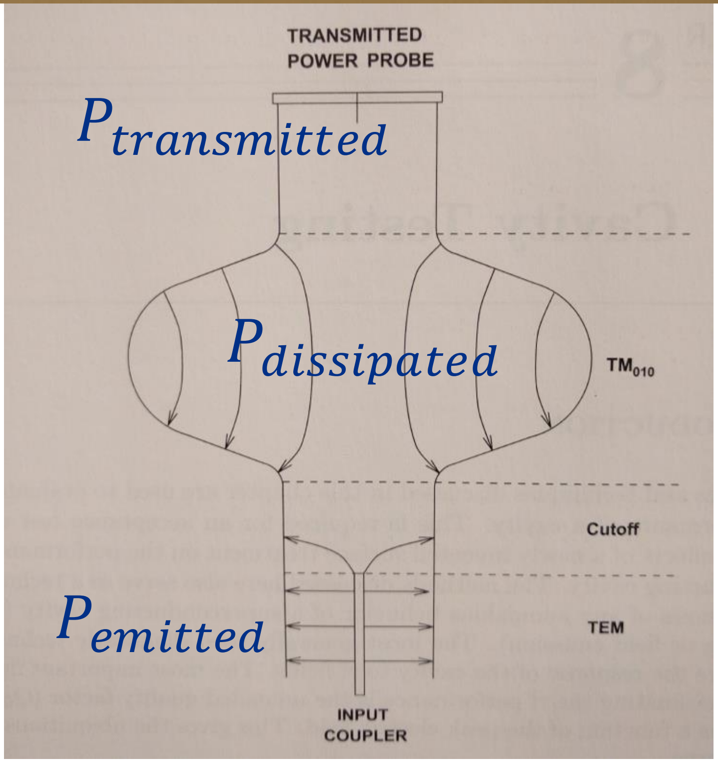




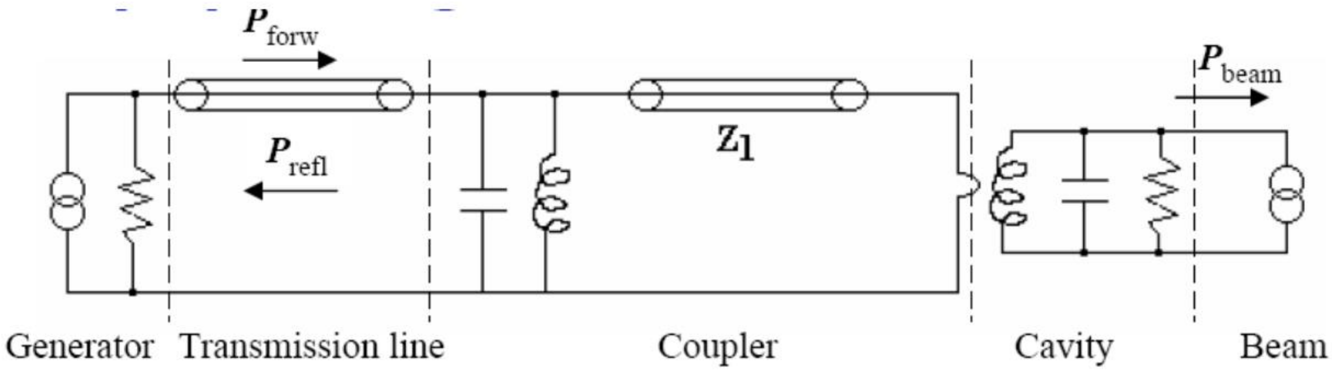
Losses and Quality Factors

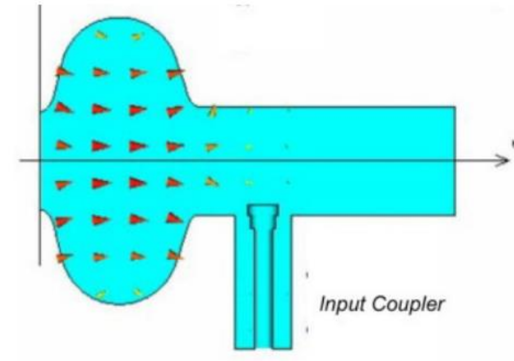
- Intrinsic Quality Factor
  - $Q_0 = \frac{\omega U}{P_d}$
  - Losses in the cavity itself are very low because of the material (efficient storage of energy)
- Loaded Quality Factor
  - $Q_L = \frac{\omega U}{P_{tot}} = \frac{\omega U}{P_e + P_d + P_t}$
  - Instead of the internal cavity losses, now we have to take account for all the cavity losses (couplers, walls, etc.)
  - Define: $\beta_X = \frac{Q_0}{Q_X}, \mathrm{Q_X} = \frac{\omega U}{P_X}$

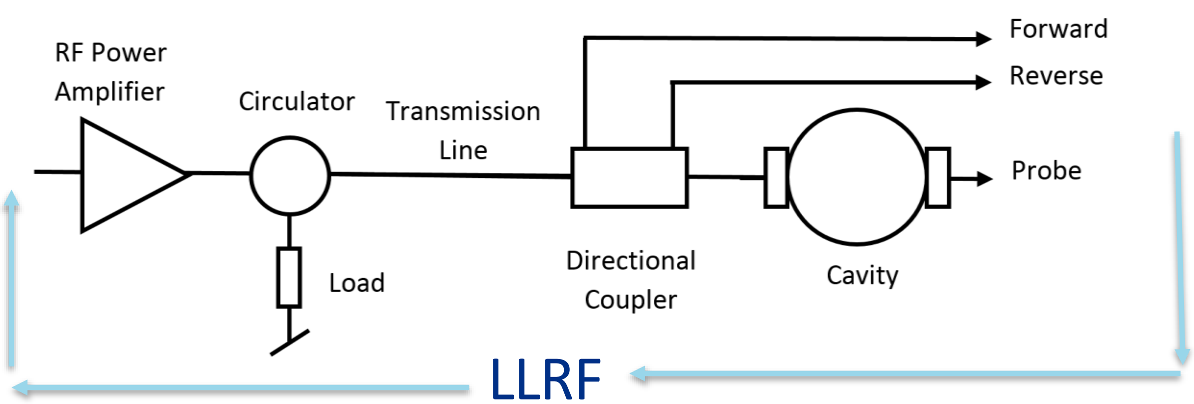




Equivalent Circuit for Driving a Cavity







Many models are simplification, but all the relevant parts are there:
Generator, Transmission Line, Coupler, Cavity, Beam

Vertical Test Measurements

- The probe is generally approximated to be very weakly coupled ($\beta_t \ll 1$) because we desire it to be a small diagnostic signal (< 1 mW).
- So, let's assume that we're driving the cavity with one coupler only for now.
- What we're looking for:
- Cavity response to a driving signal.
- $P_f, P_r, P_t, Q_0, Q_e, Q_t$ (we'll deal with probe signals later)
- Going through the circuit analysis:
- $\Gamma(\omega) = \frac{\beta_e - 1 - iQ_0\delta}{\beta_e + 1 + iQ_0\delta}, \delta = \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}$
- On Resonance: $\Gamma = \frac{\beta_e - 1}{\beta_e + 1}$

Production Testing of SRF Cavities

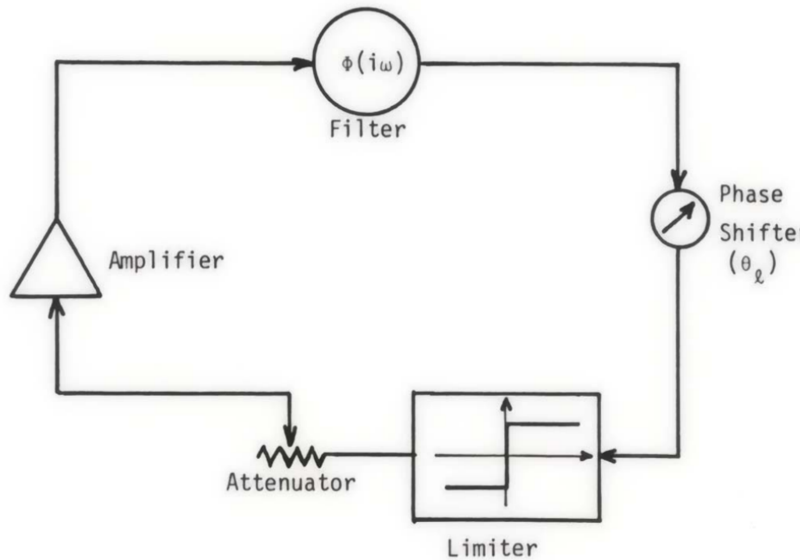
- Qualification of SRF cavities starts with matched, or nearly matched cavity testing ($\beta_e = 1, \Gamma = 0$).
- $P_d = \frac{\omega U}{Q_0} \approx \frac{(2*\pi*1.3E9[Hz]*3.7[J])}{3E10} = 1[W]$
- A 1 [W] amplifier can get $\sqrt{1012 * 2\pi * 1.3E9 * 3.7} = 5.5\ MV$!
- Full gradient is $\sim 35\ MV/m$, so that's pretty good!
- For a copper cavity, this would be half a kilowatt or more!
- Keep in mind that CW copper cavities exist!
  - Advanced Photon Source Cavities require 200 kW at 352 MHz, although most of that goes into the beam (1 MV, QL ~21e3, 100 mA of electrons), but it's a multi-MW class RF system! 20% of power going to the cavity. Compare to 0.05% for LCLS-II.

Functionality we need

- Some way to power the cavity
  - lock to cavity resonance
  - control forward power, etc.
- Some way to find the cavity frequency (don't really know at first, not easy because bandwidth is quite narrow)
  - Loaded Q can be ~1e11 in extreme cases, very narrow bandwidth, long filling time $\tau_L = \frac{Q_L}{\omega}$
- Calibrate everything so we can accurately assess cavity parameters (static and dynamic)
- Maybe pulse or modulate amplitude to help with conditioning
- Quench detection, a nice to have, but not necessary
  - Quench is a breaking of the superconducting state, creates a thermal run away and dumps power into cryogenics

Self-Excited Loop - Concept

- A Self-excited loop is:
  - A high-gain, positive feedback loop that is unstable and operates at a limit cycle determined by a non-linear element
  - An oscillator
- Basic elements:
  - Band pass filter
  - Phase shifter
  - Limiter



Finds resonance easily, simply tracks resonance as it moves

SRF Cavity Testing Process (Vertical Testing)

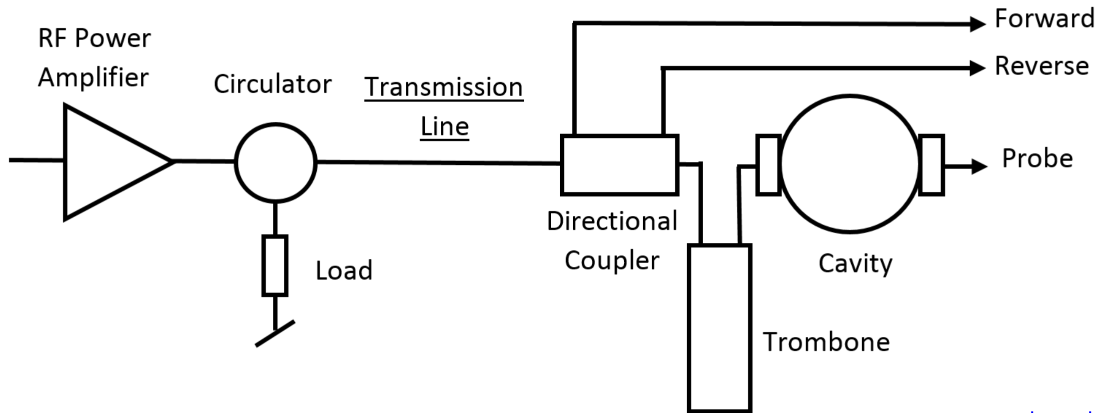
- Cavity Cooldown
- Vacuum/Instrumentation Check
- Calibrate external RF Cables (input and pickup warm/cold cables)
- Find cavity frequency, lock to cavity at low power
- Dynamic RF calibration (Loaded Q, coupling constants, gradient calibration)
- Power rise up to higher gradient, CW or pulsed
  - Watch for radiation/multipacting/quench
  - Condition away radiation if possible
- QvE measurement of Quality Factor
  - Potential calorimetric measurements as well

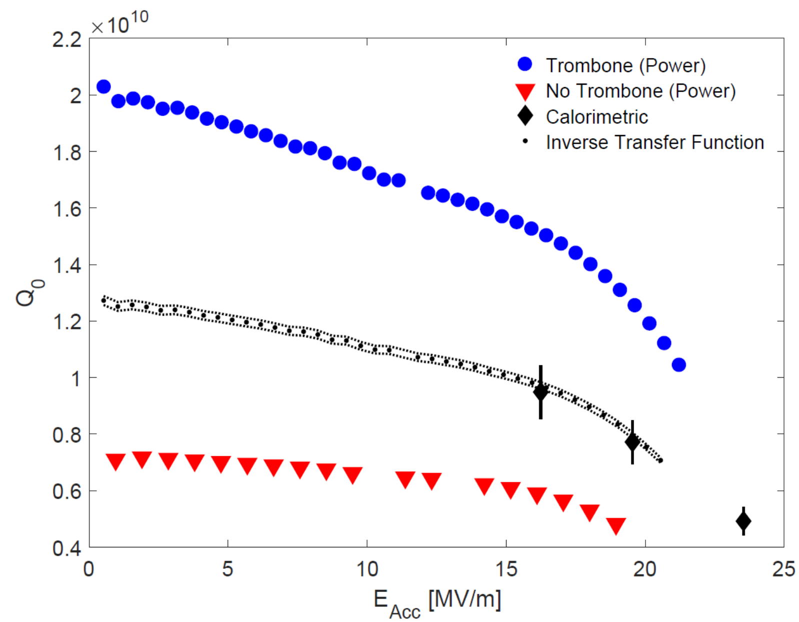
Cavity Test Summary

- Need to:
  - Find resonance, excited it, track frequency, stable field levels
  - Calibrations
  - Basic UI and controls
  - Relatively low power
  - Data logging and plotting
- Nice to have:
  - Interlocking, maybe quench detection
  - Fancier UI and automation is nice

RF Circuit Systematic Error

- Calibration procedure assumes perfect RF components
- Directional couplers and circulators are inherently limited
- Especially when the input coupling isn't close to matched, these can be sizable systematic errors
- Digital techniques and phase shifters can be used to identify and correct for these systematic errors



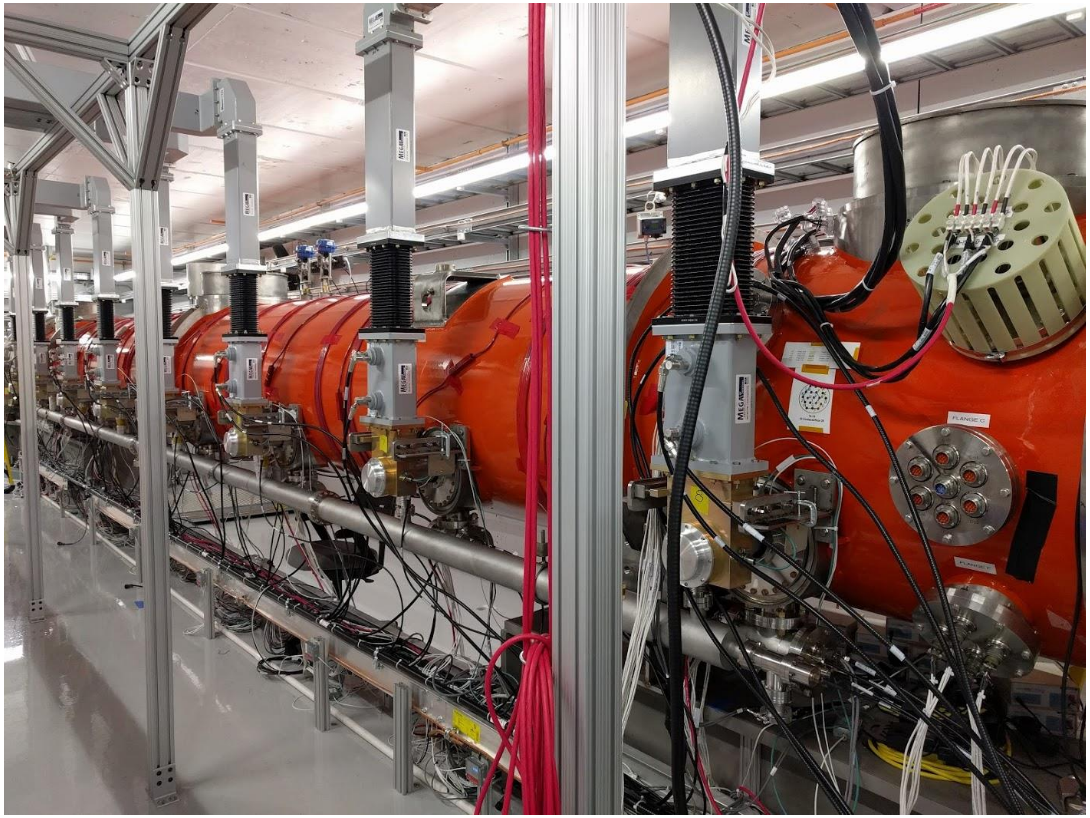


https://arxiv.org/abs/1602.02689

https://arxiv.org/abs/1804.04747

Cryomodule Testing

- The goal of production testing of cryomodules is to achieve as close to machine operational conditions as possible
  - Cool and stabilize at 2K
  - Complex Vacuum Pumping
  - Controls and Interlocks
  - Stability (Harder than it sounds!)
  - Real coupler, real coupling
  - HPRF/LLRF
  - Lots of Instrumentation
  - Sometimes beam
- Includes verification of all details
  - Cavities, tuners, couplers, instrumentation, cryogenics



Should look very similar to the real machine, that’s the goal!

Cryomodule Testing Needs

- We must prove the cavities (and other things) can operate in a linac 'realistic' condition
  - All same from previous plus
  - Resonance Control
  - RF Protection Interlocks
  - SELA, SELAP functionality
  - Advanced UI and automation
  - Multi-cavity control system
- Intentionally very similar to machine operation
  - Likely run on a reference oscillator to fake up real machine reference
  - System we will use at PIP2IT for HB650 is very similar to real LCLS-II commissioning screen

PIP-II HB650 Cryomodule - Testing at PIP2IT

464739 Rev. NONE ~~~ *Unpublished - Revision Pending*

PIP-II

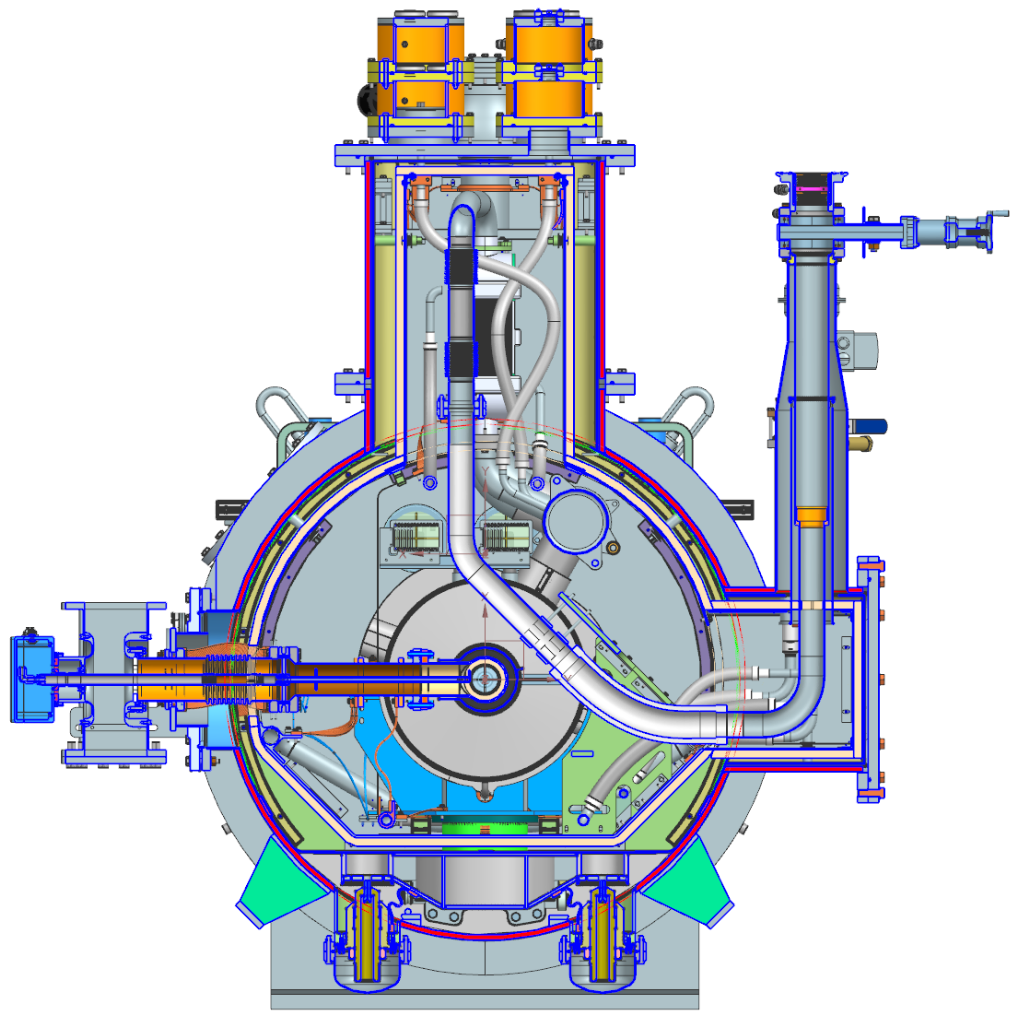
What is an SRF Cryomodule?

- 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

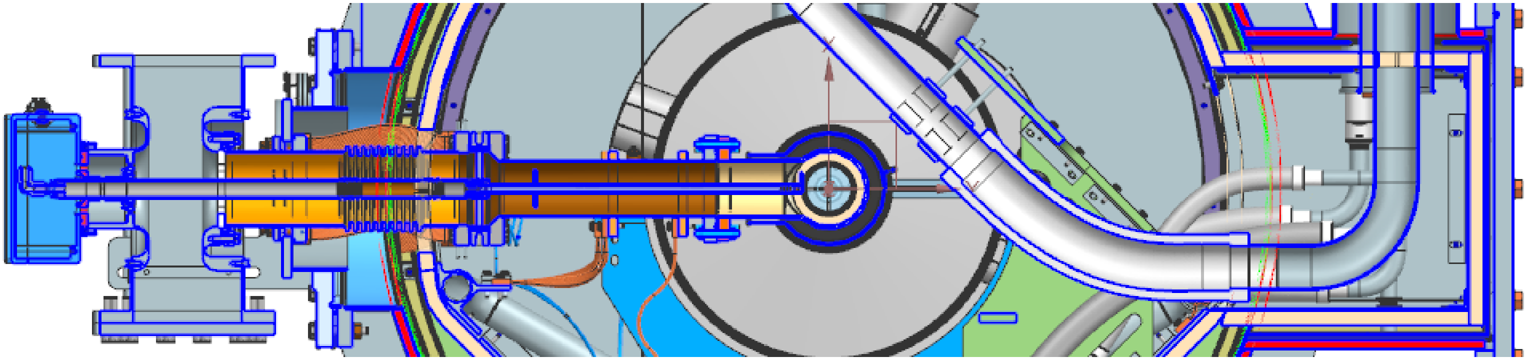
HB650 Cryomodule Cross-Section (PIP-II)

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

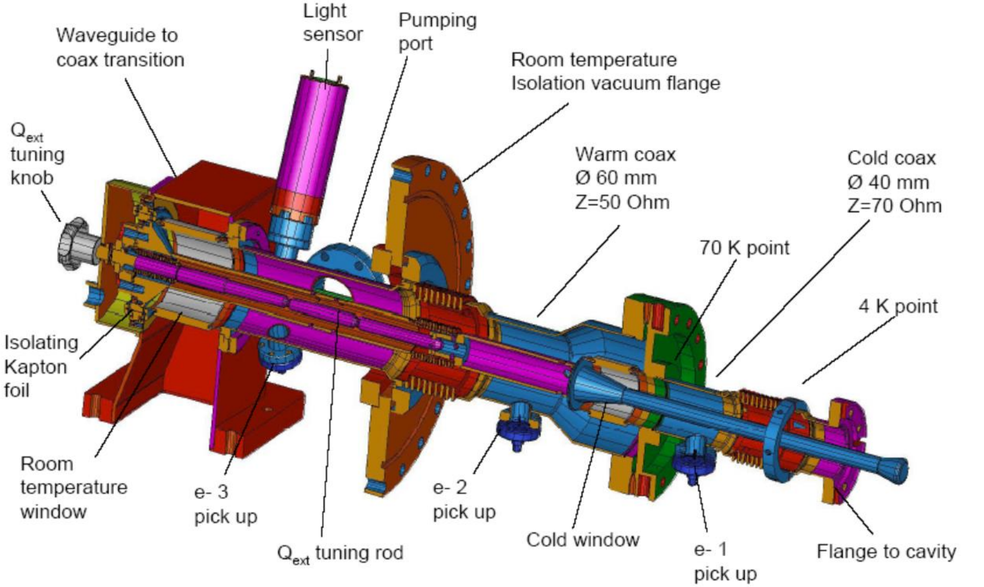
- 300K to 2K transition
- Clean Vacuum to Air
- High power RF (kW to MW)
- Thin-walled bellows and copper plating
- Ceramic Windows
- Thermal intercepts, static/dynamic heat loads
- Significant alignment, contraction, movement requirements
- Challenging assembly



High-Power Couplers



- [LLRF Control of High Loaded-Q Cavities for the LCLS-II - C. Serrano]()
- We need to demonstrate ability to control the cavity tightly like in the real machine
- $Q_L \approx 4e7$

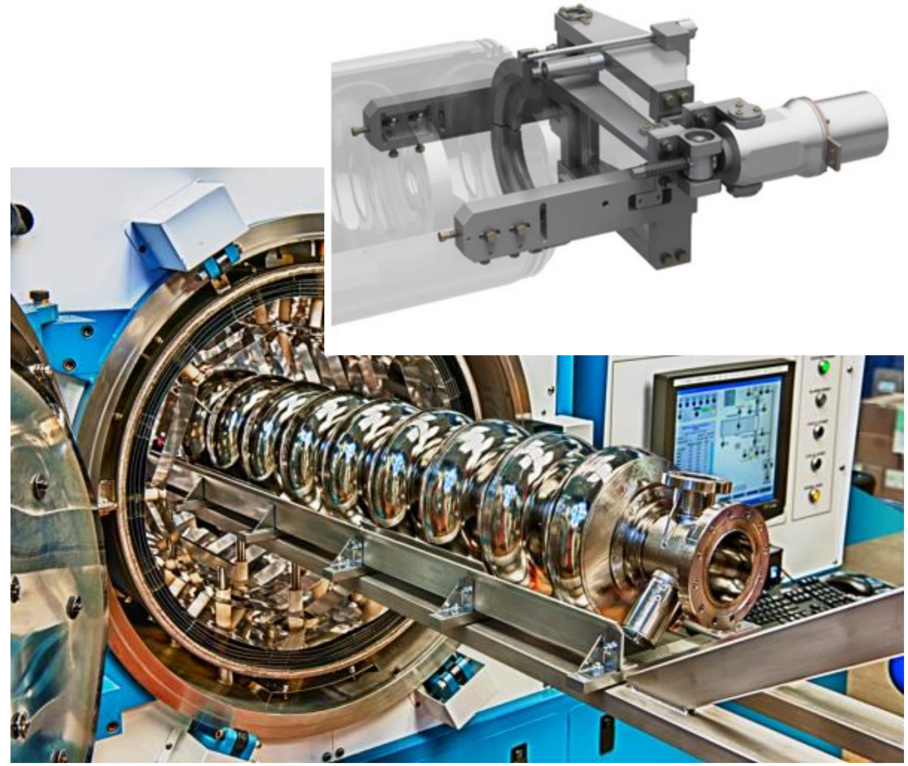


http://arxiv.org/ftp/arxiv/papers/1501/1501.07129.pdf

Design Topics for Superconducting RF Cavities and Ancillaries - H. Padamsee

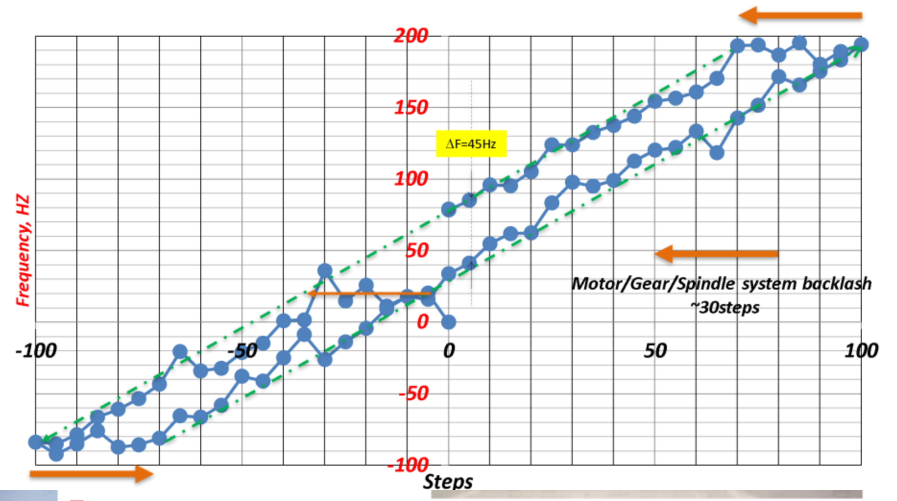
LCLS-II Cavity Microphonics

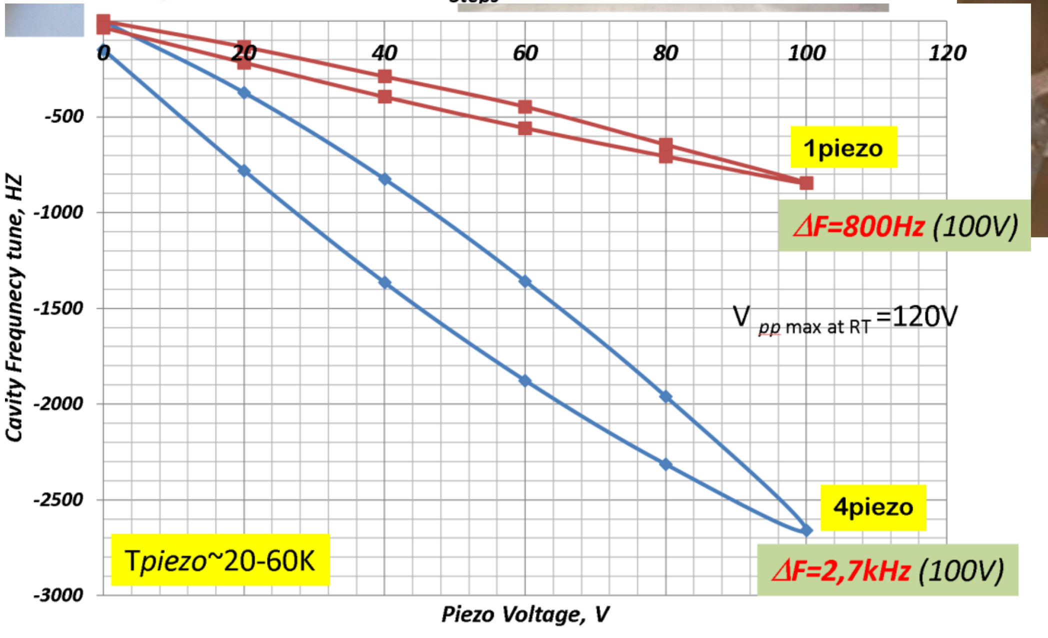
- Cavity frequency is proportional to length (in this case)
- Optimization for LCLS-II gives enough RF power to control only ~13 Hz of detuning of the cavity
- $\frac{\Delta \mathrm{f}}{\mathrm{f}} \approx \frac{\Delta L}{L}; \frac{13\ Hz}{1.3E9\ Hz} \cdot 1m \approx 10\ nm$
- At this level, many effects 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*

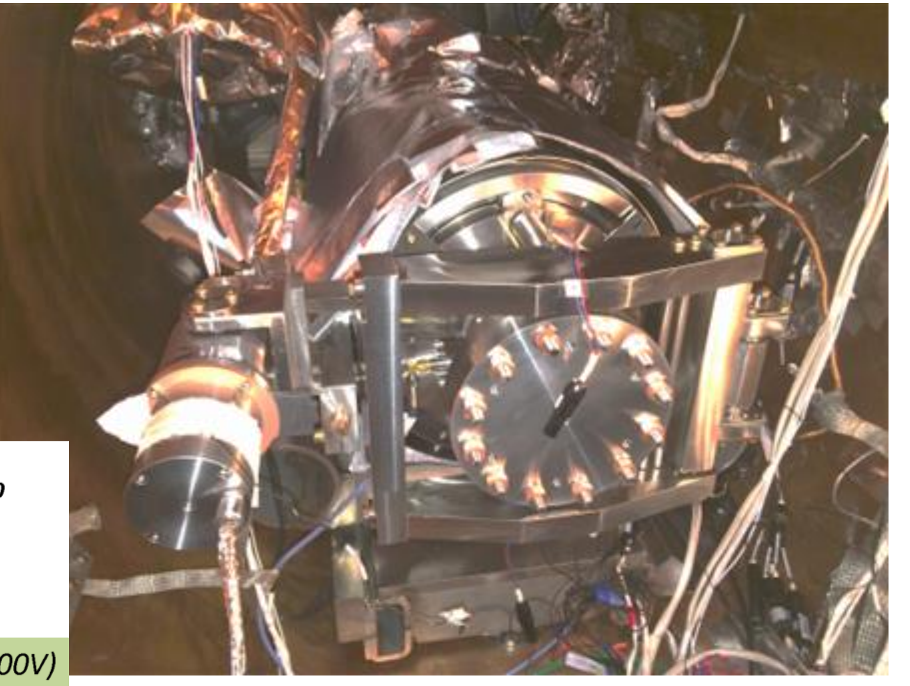


Bare LCLS-II 1.3 GHz cavity after baking (lower), model of LCLS-II cavity end-level tuner (above)

Controlling Cavity Frequency







Fast tuner and slow tuner, need to be able to control and do studies of performance

Slow Feedback?

Credit: Y. Pischalnikov

LCLS-II pCM Microphonics

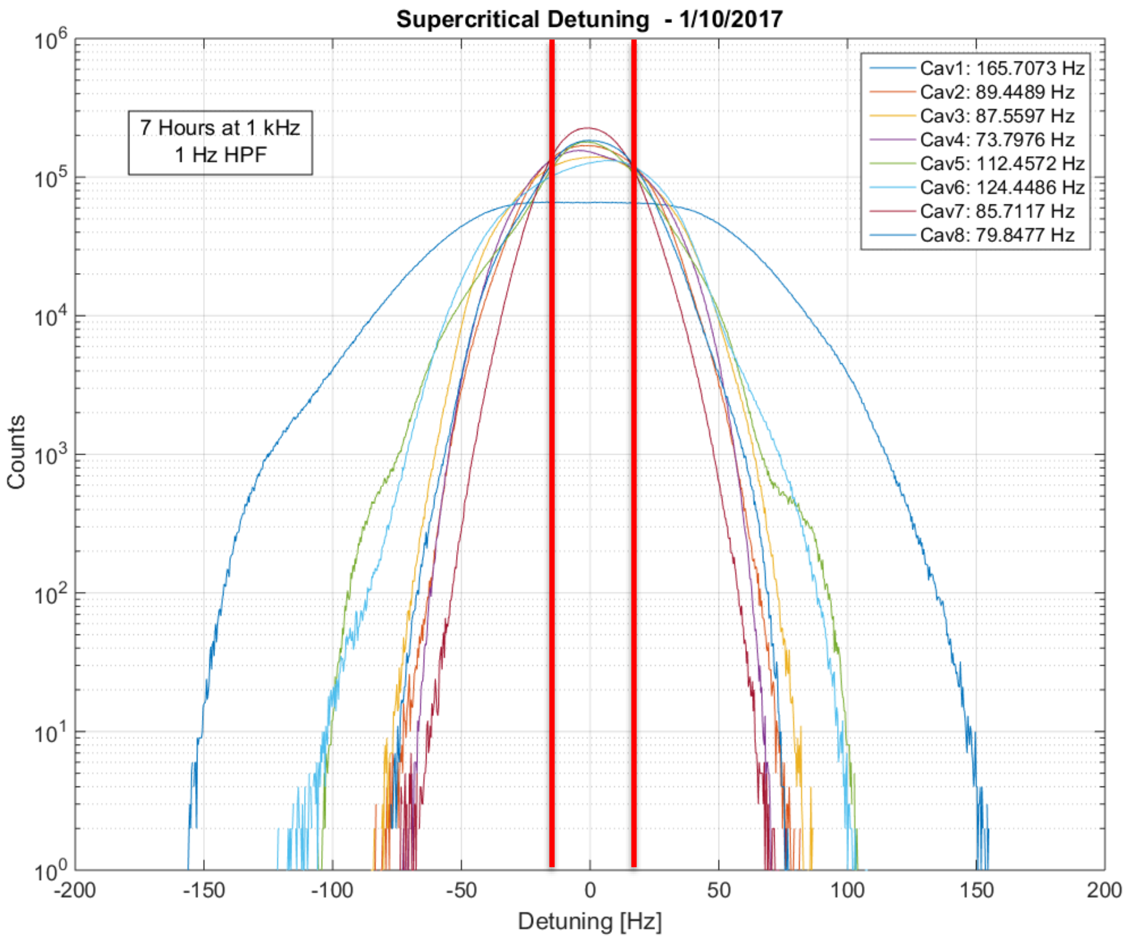
Capturing microphonics of all 8 cavities in SEL

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.

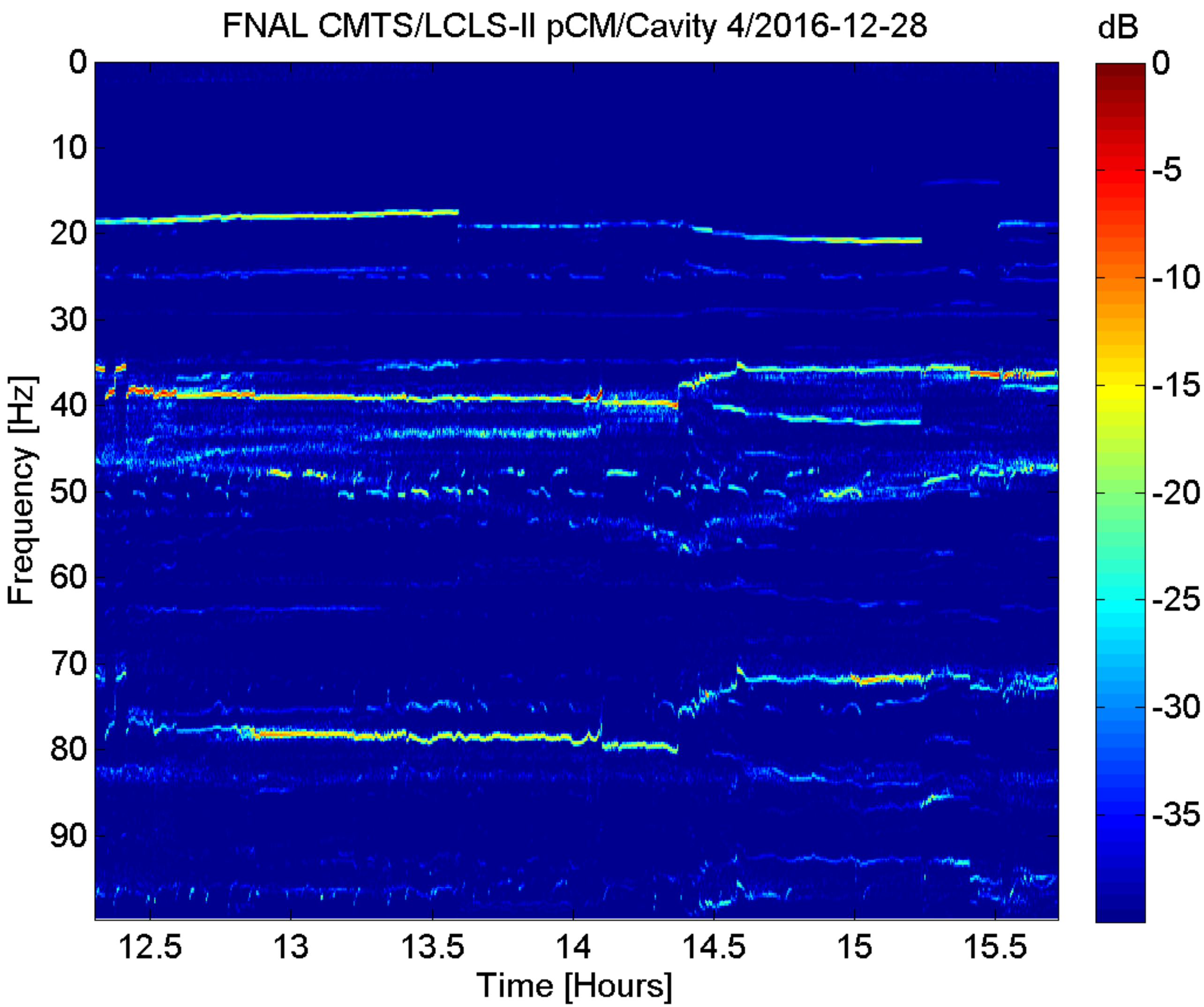
Working group formed, about a dozen people, all stakeholders included in a strongly collaborative effort.

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

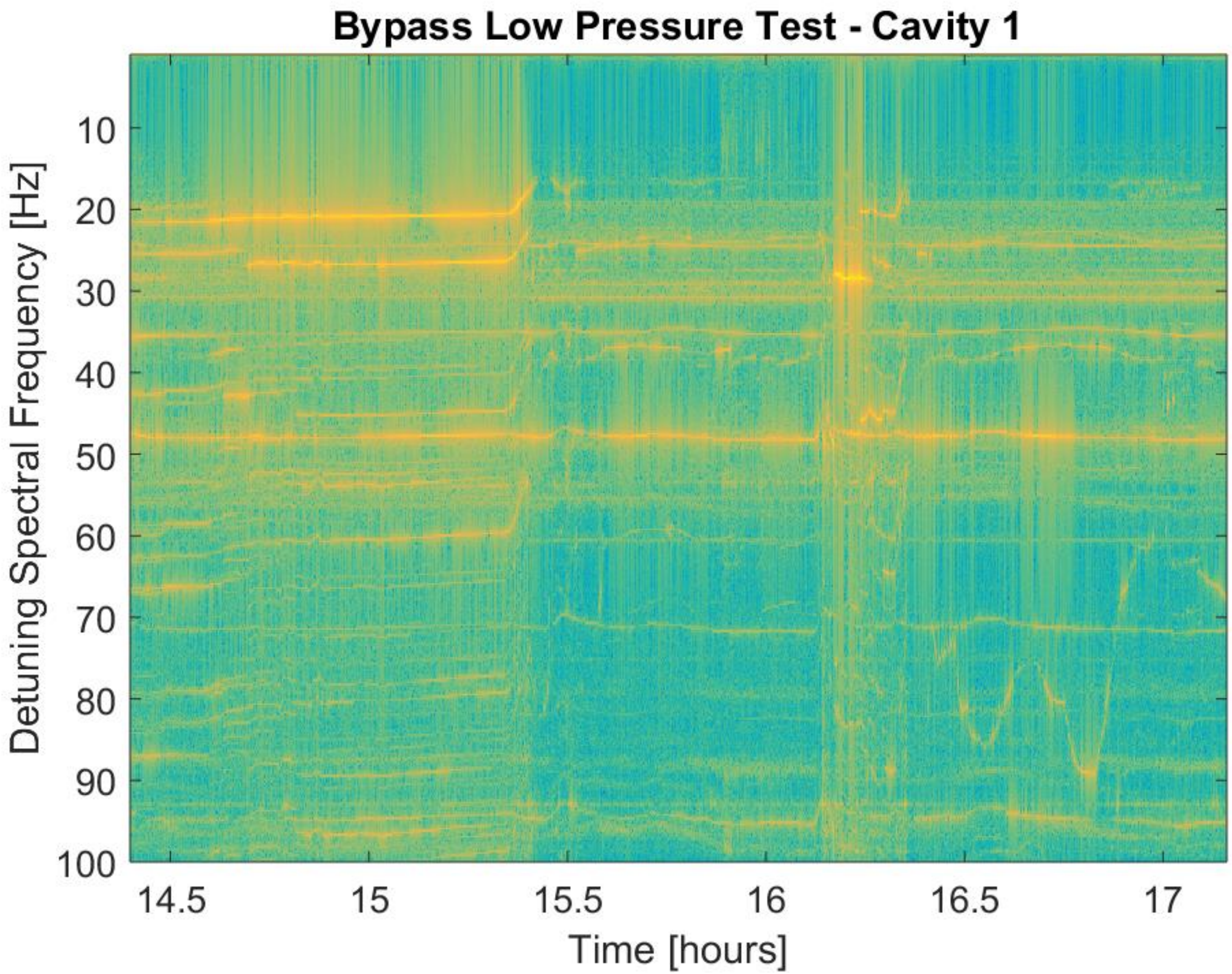


Dynamic Frequency Behavior

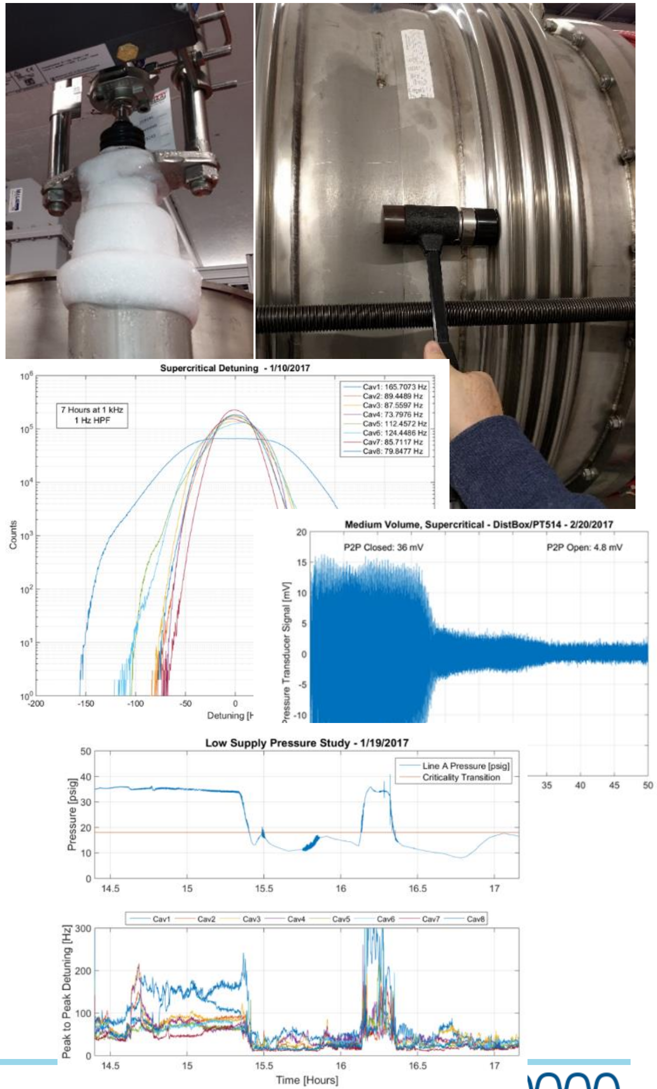
- Vibration lines shift rapidly frequency and amplitude
  - Not mechanical resonances
  - Narrow-band cryogenic source(s) exciting wide-band, low frequency mechanical response



Critically Transition



- 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

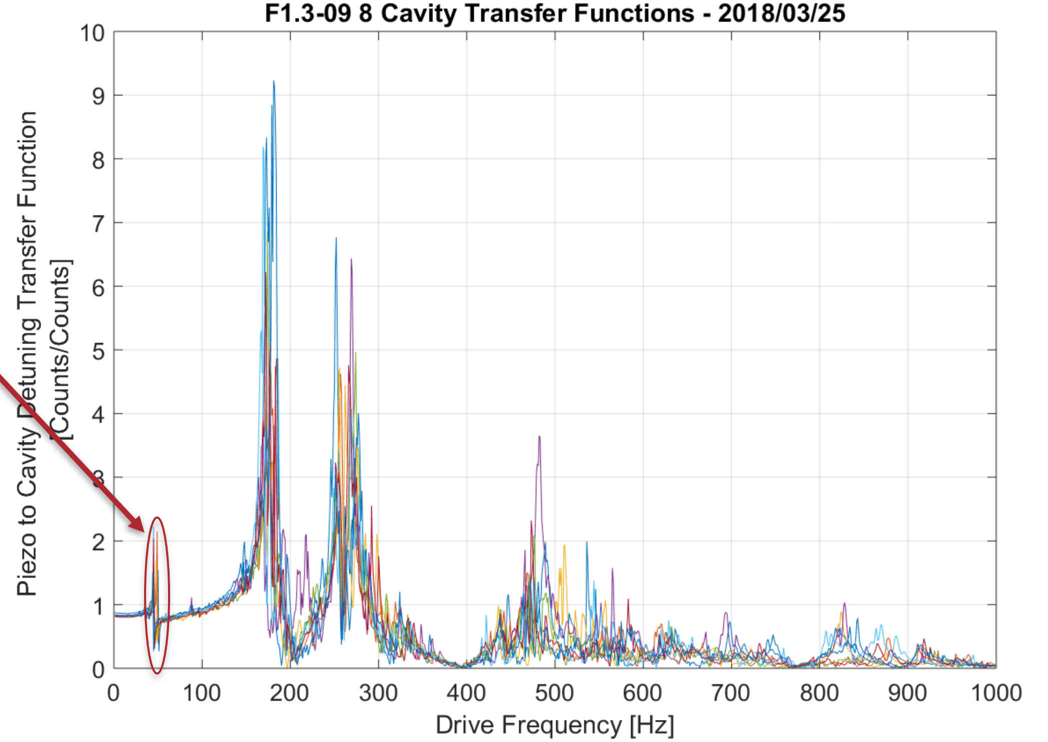
-Dependent on cavity position

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

-90 degrees out from piezo

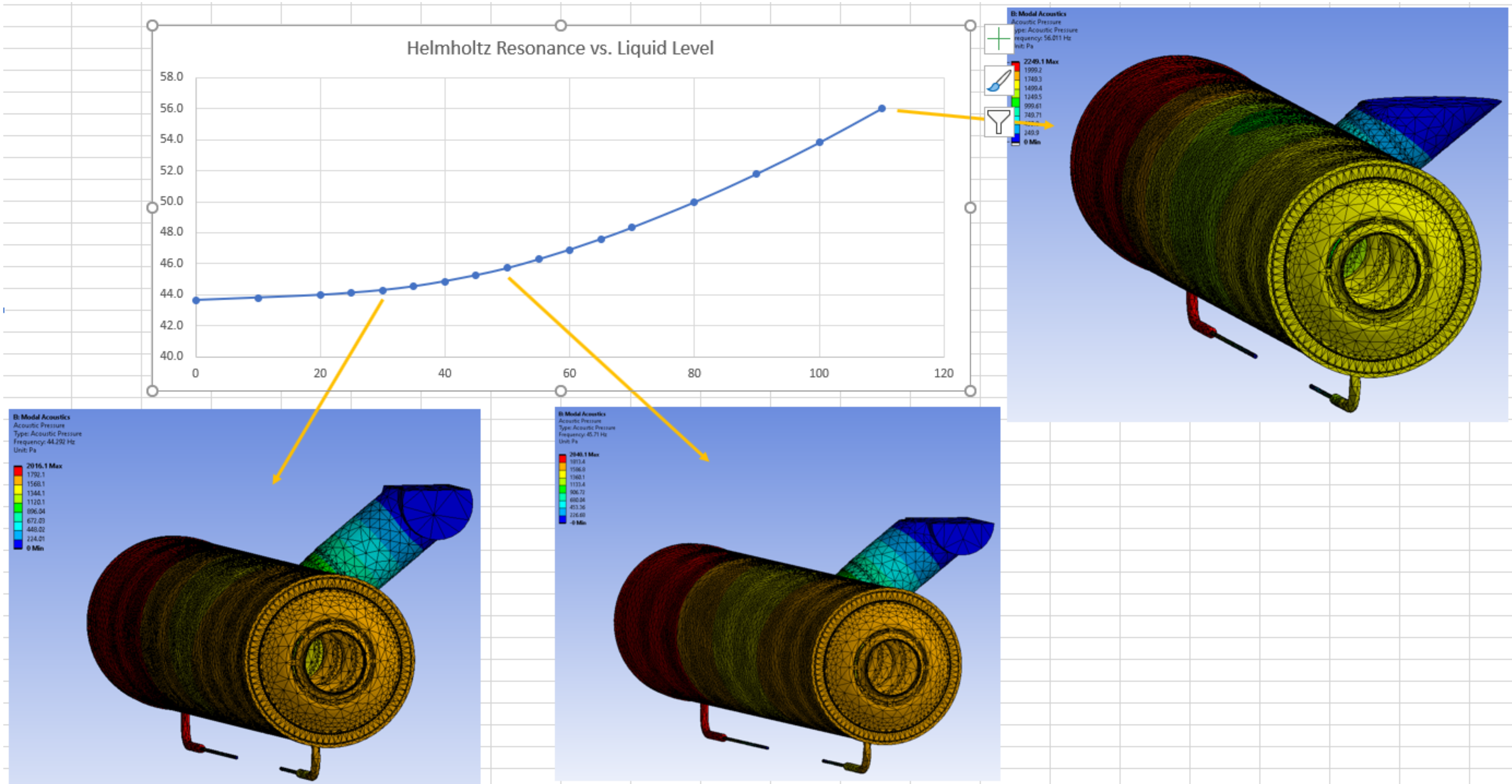
-Varies with liquid level

-Severely suppressed at 4K



Measurement requires integration of resonance control, LLRF, data logging

Helmholtz Resonance of 1.3 GHz Cavities



PIP-II

RF Protection Interlocks

- RFPI is critical to protect the more complex and delicate hardware involved (coupler, amplifier/circulator, etc.) at higher powers

6.0 RFPI Interlock Verification Top

6.1 The following inputs and outputs are to be verified individually before RF is applied.

Enter the active RFPI channel (Station 1-6) :

	Verified	Trip value	LLRF Permit	SSA Permit	PLC Permit	DC Permit
Reflected power interlock	☐	kW	☐	☐		
Forward power interlock	☐	kW	☐	☐		
FEP	☐	µV	☐	☐		
Gallery leak antenna	☐	dBm	☐	☐		
Cave leak antenna 1	☐	dBm	☐	☐	☐	
Cave leak antenna 2	☐	dBm	☐	☐	☐	
Coupler Bias voltage (tunnel)	☐	kV	☐	☐	☐	
HV Coupler Bias current (DCPS)	☐	mA	☐	☐	☐	
Coupler Air flow	☐	CFM	☐	☐	☐	
RTD #1	☐	K	☐	☐	☐	
RTD #2	☐	K	☐	☐	☐	
PLC Permit*	☐		☐	☐		
Vacuum Permit	☐		☐	☐		
Coupler vacuum guage	☐	Torr				
Cryo Permit	☐		☐	☐		
He Pressure (Cryo)	☐	Torr				
He Level (Cryo)	☐	%				
Safety Permit	☐		☐	☐	☐	☐
SSA Ready	☐					

Responsible Authority/Designee: *Date:*

SELA and SELAP

- SEL controls on fixed forward power, using the cavity as a filter to drive on resonance
- Real accelerators need fixed frequency drive and strong phase and amplitude control (relative to a master reference)
- SELA closes the loop around gradient, adjusting forward power to stabilize (not hugely different dynamics than SEL)
- SELAP closes the loop around the phase vs reference as well, providing stable accelerating voltage and phase for beam operations
  - Depends on extra forward power to account for cavity detuning

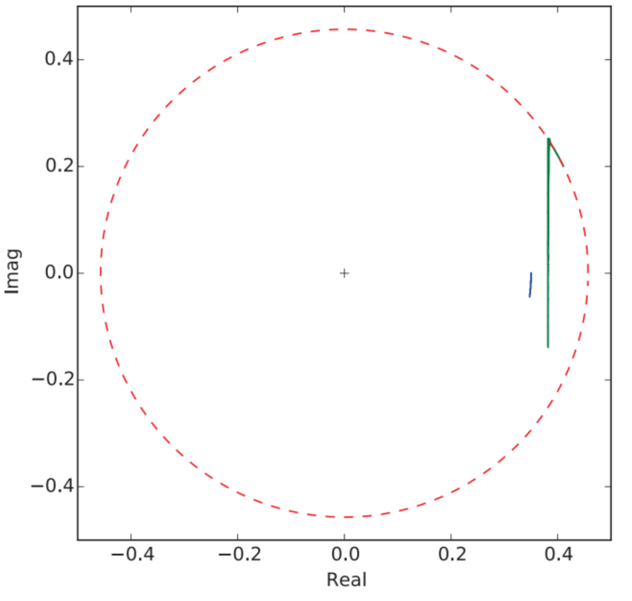
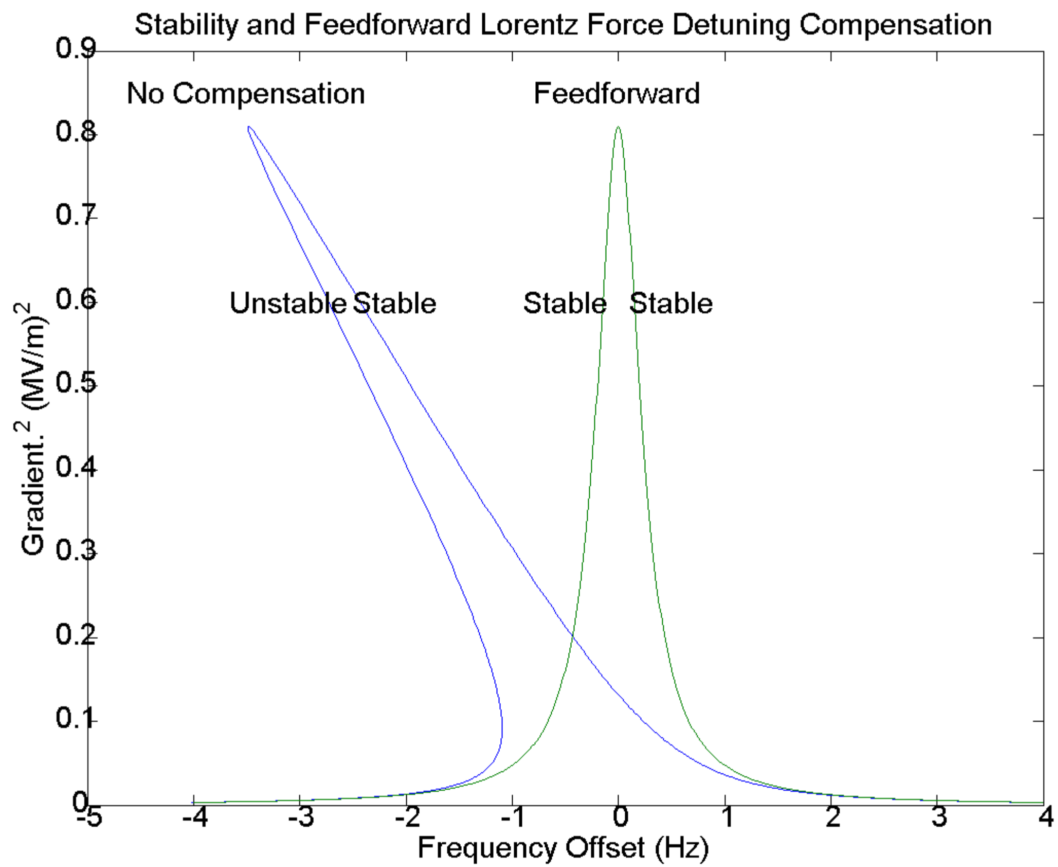


Figure 7: Locus of SEL operations in the complex plane.

L. Doolittle et. al., 'HIGH PRECISION RF CONTROL FOR SRF CAVITIES IN LCLS-II', SRF17, frxba02

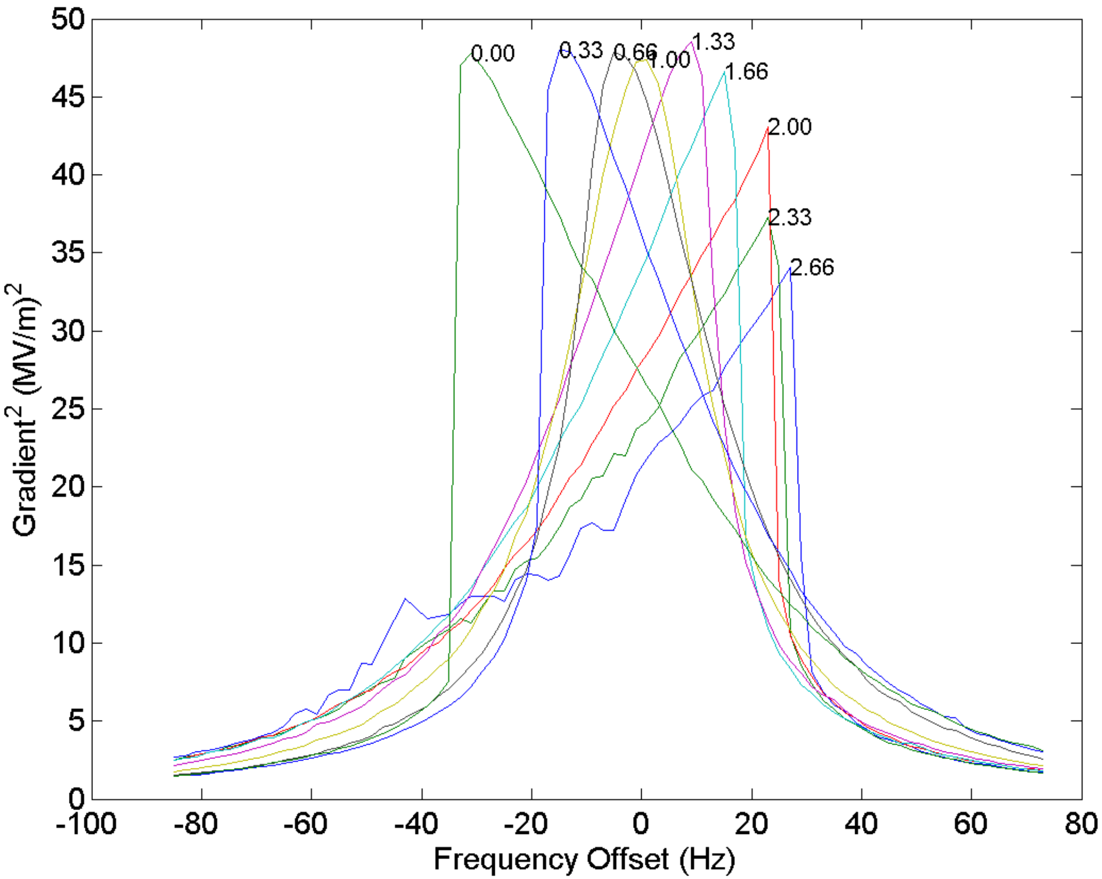
Ponderomotive Instabilities

- Lorentz force detunes cavity proportional to the square of the gradient
- If detuning is more than several bandwidths cavities can become unstable
- Small perturbations near the peak can cause the cavity field to suddenly crash to zero
- Cavity becomes very difficult to control



Feed-Forward Ponderomotive Stabilization

- Possible to remove the instability using piezo feed-forward tied to cavity square of gradient
- Demonstrated for both
  - SSR1 spoke resonator and for
  - multi-cell elliptical cavities



LLRF in a real machine

What do we need in a Real Machine vs CM Test?

- From a user point of view… not much? Obviously, there is a ton ‘under the hood’ for the LLRF (and all) technical team, but potentially:
  - REAL commissioning UI and controls interfaces
  - All functionality including slow (fast?) resonance control

- The one big one is: AUTOMATION
  - There are dozens of modules in a real machine, and there must be the functionality to automate and scale routine procedures (characterization, online calibration, interlock reset, bring up to power, etc.)
  - Now, the functionality has to be within shouting distance of something a non-expert operator can interact with, and should be there a path towards

Questions to Answer (Hopefully successful)

- What is an SRF Cavity, and why is it different from a normal conducting cavity?
  - Very high quality cavity, so very low intrinsic bandwidth
- What is required to test a single cavity?
  - Calibration, SEL functionality, basic data capture
- What more do you need to test an integrated cryomodule?
  - All that plus, SELA, SELAP, multi-cavity control, advanced data capture, RF Protection Interlocks, basic resonance control
- What more would you need to commission and run an SRF machine?
  - That, and: High quality commissioning and control screens, phase reference, timing system, advanced resonance control