Cryomodule Testing & Beam Operations

An SRF 2023 Tutorial

The 21st International Conference on Radio-Frequency Superconductivity

Tutorial hosted by:

Facility for Rare Isotope Beams (FRIB)

Michigan State University (MSU)

Michael D McCaughan

Saturday, June 24, 2023

Vertical Testing

Prior to cryostat installation, all cavities undergo vertical test…

Vertical Testing & Assembly

Testing ensures cavities meet specifications for:

- Accelerating Gradient
- Qo
- Field Emission onset (if present)
- Measure resonant modes / passbands

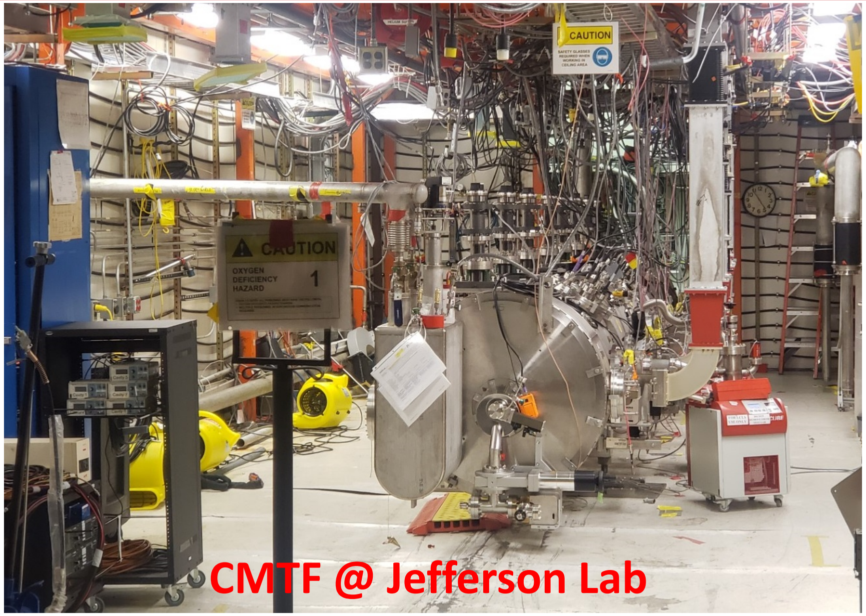
Determines if remediation – for example, high pressure rinsing for field emission – is necessary prior to installation. This could also affect the possible order of cavities in the string.

One needs a safe place for Horizontal Cryostat testing…

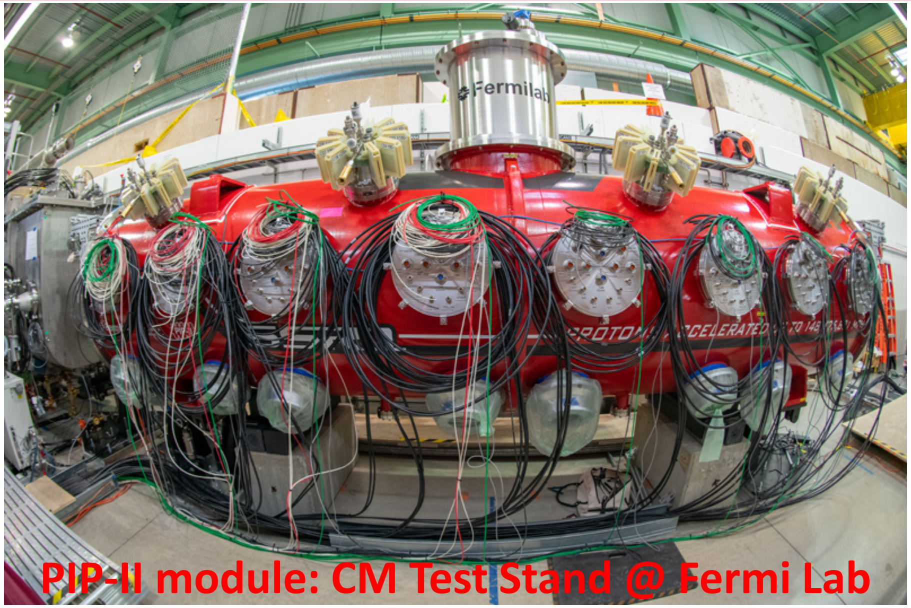
What makes for a good testing facility?

Testing Facility Features

vms.fnal.gov/asset/detail?recid=1962832



CMTF @ Jefferson Lab



PIP-II module: CM Test Stand @ Fermi Lab


CM Test Stand @ AMTF/CEA Saclay

T. Semba at al., Recent Activities in ILC R&D at Hitatchi, Proceedings of EPAC08 (MOPD005), Genoa, Italy.

Hitatchi Prototype ILC CM at STF/KEK Japan

N Walker et al., Performance Analysis of the European XFEL SRF Cavities from Vertical Test to Operations in Modules, Proceedings of LINAC2016 (WE1A04), East Lansing, MI. USA.

Testing Facility Features

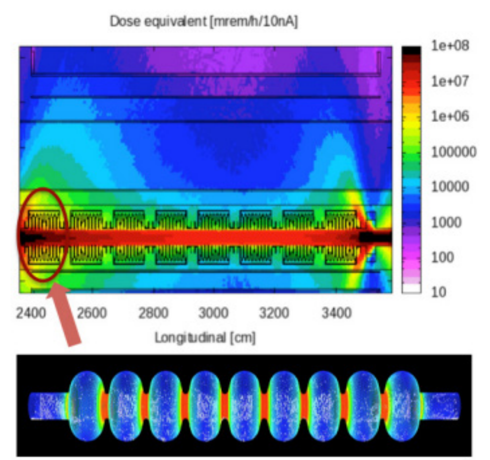
Dedicated Personnel Safety System:

- Prevent access with physical barriers while RF is in operation.
- Interlock to RF power source to terminate power if unsafe condition detected.
- Safety System must include safeguards for cryogenic hazards due to over-pressurization or accidental release during its design:
    - ✓ Include appropriate ventilation in facility design.
    - ✓ Localize stationary sensors for monitoring O_2 availability in environment.
    - ✓ Radiation Detected
    - ✓ Access door opened
    - ✓ Power detected with supply ‘off’
    - ✓ And so on… anything that would make access to the testing facility unsafe.

Testing Facility Features

Shielding:

- Radiation:
  - ➢ Shielding design for a testing enclosure baser on appropriate calculations by subject matter experts.
  - ➢ Monte Carlo simulations with available software (Geant, Fluka, ACE3P, etc.) to ensure design is sufficient.
  - ➢ Ensure appropriate floor/ceiling shielding as well (Prevent Tritium/Skyshine)
  - ➢ Good materials: Lead, Concrete, etc. Borated materials may be mixed in for neutron hardness.
  - ➢ Neutron / Gamma radiation detectors (Ion chambers, scintillators, etc.) must be placed in strategic locations nearby to verify personnel are protected. [Access points, control rooms, neighboring work areas.]



Jefferson Lab

O. Kononenko et al., Advances in Massively Parallel Electromagnetic Simulation Suite ACE3P, Proceedings of IPAC2015 (FRAJI3), Shanghai, China.

Testing Facility Features

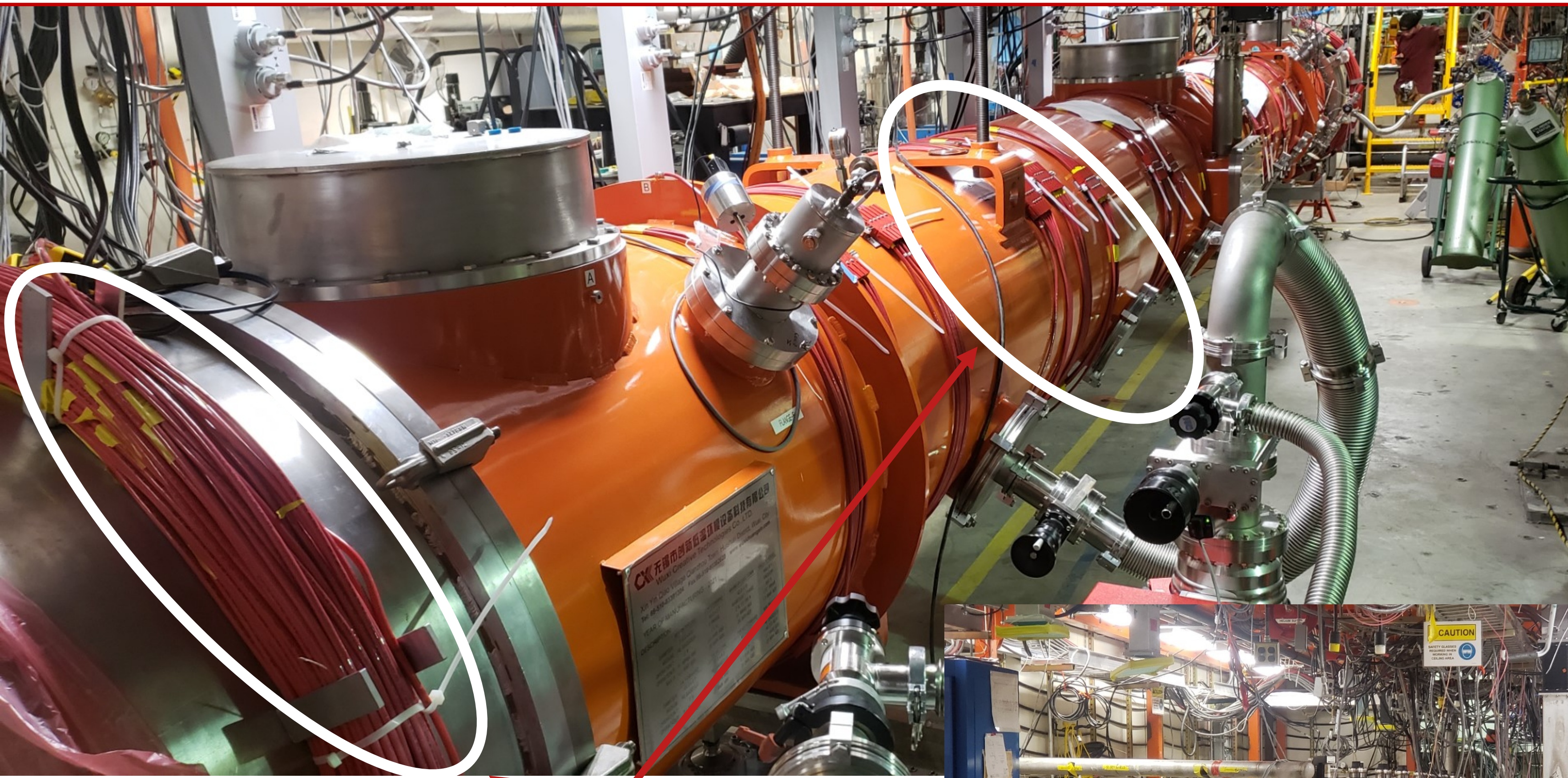
Shielding:

Electromagnetic:

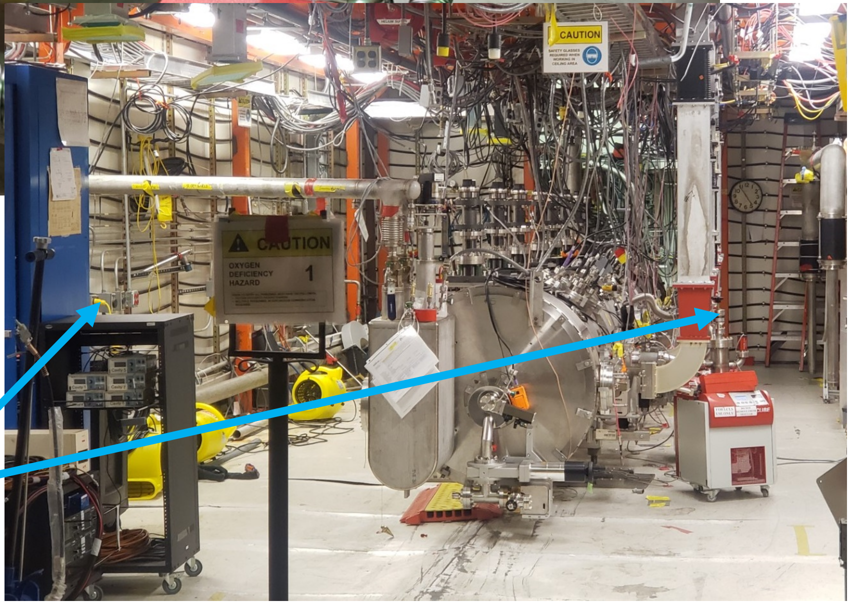
- Magnetic fields cause deleterious effects on Qo (increased heat load and potentially lower operating gradient…) so one wants to eliminate field to the degree possible – particularly before cooling.
- Plan and survey for source terms:
  - ✓ Earth's ambient field [Up to 50 mG depending on latitude.]
  - ✓ Material magnetization in construction / testing [Reinforcement steel in concrete for example]
  - ✓ Others… nearby magnets, space weather, etc.
- Remediation:
  - ✓ Faraday cage inside facility (possibly with active feedback)
  - ✓ Careful choice of construction materials [Facility & Cryomodules]
  - ✓ Sensors to measure fields near cavities in cryomodules
  - ✓ Localized magnetic shielding: μ metal / cryoperm / Electrical Steel / etc.
  - ✓ Localized magnetic coils / cables to create a solenoid around module to De-gauss

Example: Residual field specification (LCLS-II; 2K elliptical cavities):
Bres < 5 mG (0.5 μT) to reach $Q_0 > 2.7\times10^{10}$ / $E_{acc,nom} \geq 16$ MV/m

Magnetic Hygiene Examples:



Cable Windings == Solenoid Field; Vessel Demagnetization



Cables == Degaussing shielding

Powering

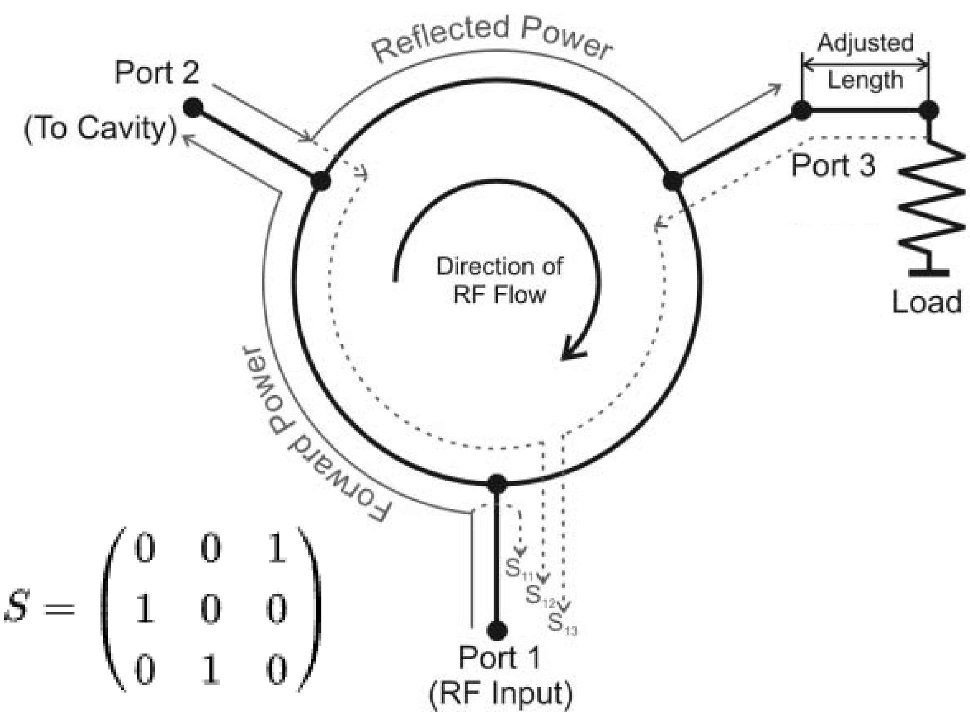
Many Options:

- Klystrons (single or multi-stage) and Solid-State Amplifiers are the two conventional choices.
- May be used (singly or in parallel) to power one or more cavities with appropriate phase delays.
- Cost of operating at frequency & wall-plug efficiency should be considered, as should availability of OTS components for replacement.
- Other options potentially available (Klystrodes / IOTS, Magnetrons, etc.)

news.fnal.gov/2021/05/pip-ii-successfully-accelerates-beam-using-rf-power-amplifiers-from-india/

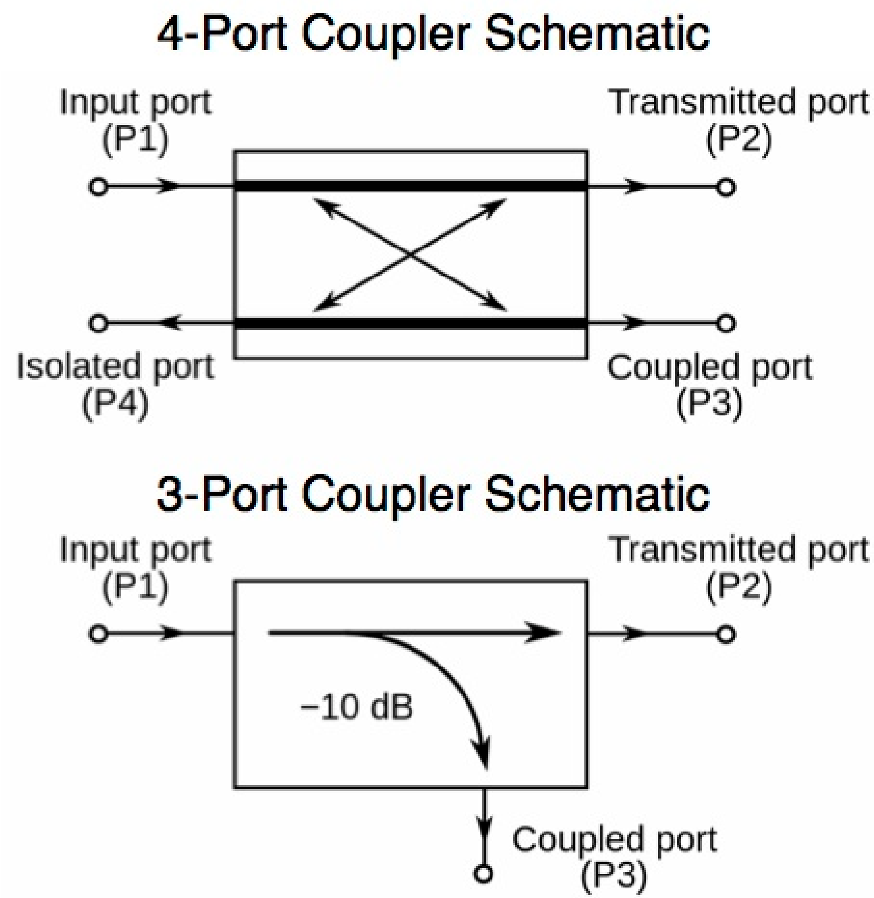
Powering (Continued)

- Directional Couplers / Circulators to protect your power source is highly recommended:



$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

(Circulator)



(Directional Couplers)

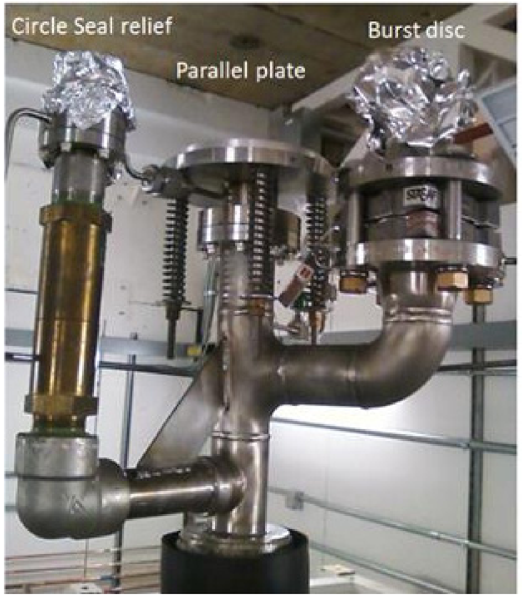
www.researchgate.net/figure/Schematic-Diagram-of-Circulator-with-Termination-Load_fig4_4069732 krytar.com/resources/applications/primers/directional-coupler-primer/

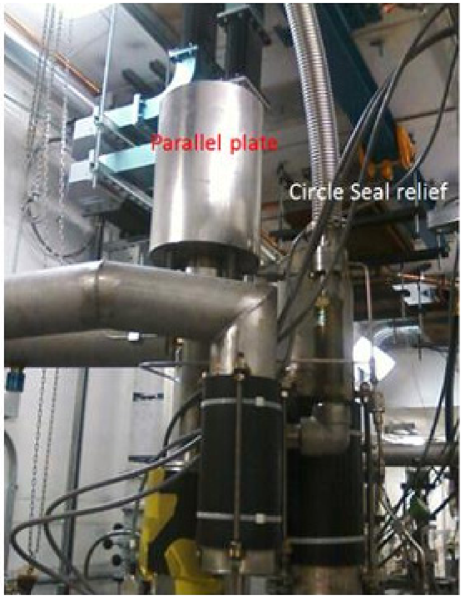
Measurements and Calibration

- Cable Calibration – Warm Network:
  - Power meters will experience signal attenuation between the meter & cryomodule through cable network located between where one is hooking up to test and measuring at their meters.
  - A single mobile power source of appropriate strength may be attached both to the meter and the most distant point in each cable’s path to measure losses so one may calibrate Power meter readings appropriately for the forward / reflected / drive signals.
  - If breaking a connection in the network, it is good practice to remeasure the cable if time is available. How snug or loose a connection is will change the amount of loss.
  - Anything not cryogenically cooled may (of course) be measured in advance of testing. Cold measurements through the cryomodule may be done later after cool-down to complete the calibration data set.

Pressure Testing

- 1 L 2K Liquid Helium expands to ~700L volume at STP.
- If for some reason (power outage) cooling could no longer be maintained, over time. the static heat and lack of insulating vacuum would cause an uncontrolled warm-up of the cryostat.
- Important to ensure the various cooling circuits can endure design pressure so gas can be channeled to reliefs.
- Pressure test ensures each circuit – particularly primary – holds following initial assembly.
- May also place blow-offs etc. in design to relieve pressure in these sorts of events.





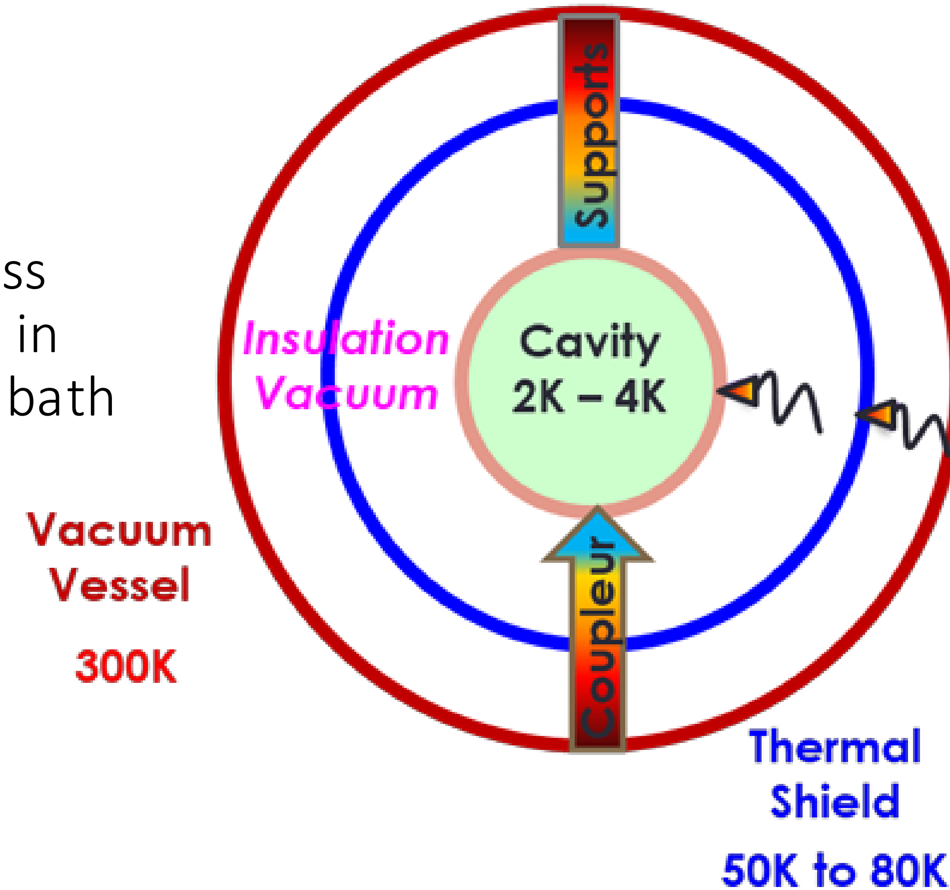
Circle seal relief: 17 psi
Parallel plate relief valve: 45 psig
Burst disk: 51 psig

1 atm == 14.7 PSI
2 atm == 29.4 PSI
3 atm == 44.1 PSI

Sheet metal around parallel-plate; directs gaseous Helium upward.

Vacuum and Leak Checks

- Cryomodule Vacuum Spaces:
  - Insulating Vacuum: Provides thermal isolation from environment
  - Waveguide / Coupler: Suppress electrical discharges (‘arcing’) in RF spaces & isolate cavity/He bath from environmental heating.
  - Cavity or beamline vacuum
  - Others
- Vacuum should be established in all appropriate spaces prior to cool-down. Pumping methods and monitoring will vary from facility to facility.

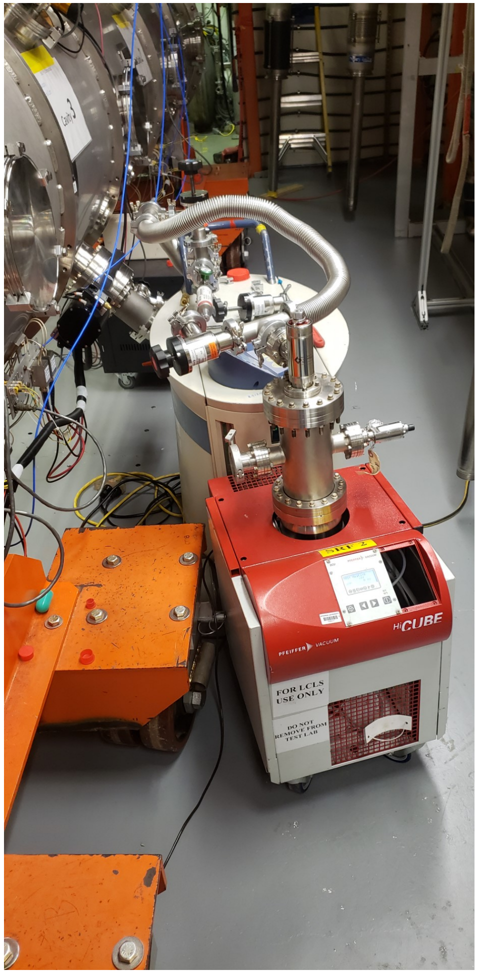


N. Bazin, Basics for Cryomodule Design, Fabrication, and Assembly, SRF'2021 Tutorial, 25 June 2021. indico.frib.msu.edu/event/38/attachments/159/1187/SRF21-tutorials_Cryomodule-NBazin.pdf

Vacuum and Leak Checks (Cont.)

Some good options:

- Turbo-molecular pumps (Backed by dry-sealing pumps: scroll, roots blower, etc. Oil-based pumps are bad as liquid could back-flow into and contaminate vacuum spaces.)
- Ion Pumps of varying pumping speeds [Usually 30+ L/s]
- Non-Evaporative Getter Pumps
- Cryogenic Pumps
- Etc.



Module will cryogenically pump as cooled, but one wants to eliminate contaminants to the degree possible before hand.

Leak checks: Residual Gas Analyzers (RGAs) may be employed, or Sniffer Gauges on pump exhaust:

Hydrocarbons / CO / CO_2 / O_2 / N_2 / Ar: Atmospheric Leak

Cryogenic Gases (He; etc.): Insulating Vacuum Leak

General Monitoring: Radiation hardened vacuum gauges; Cold-Cathode, Convectron, Pirani, Vacuum-Thermocouple, etc.

Testing Pre-flight

Some (perhaps obvious) items prior to testing:

- Grounding: Cavities will be at high fields – good practice to apply a grounding circuit to the cryomodule for instruments.
- Controls: One needs software to interface with the high-power, low-level, and other systems which allow the cryomodule to function. Early discussion with the parties responsible for its creation is essential to your success so you have what you need. Provide them with:
  - Mechanical & Process Drawings
  - Description of Instruments/Manuals for Low-level Interface
  - Expected behaviors / Calibrations / Signal Units (after conversion from voltages)
  - Explanations / Discussion of how the Human-Machine Interface should appear and work. Controls should be intuitive if they are well designed…
  - Time spent on integration is time not wasted in your testing period.

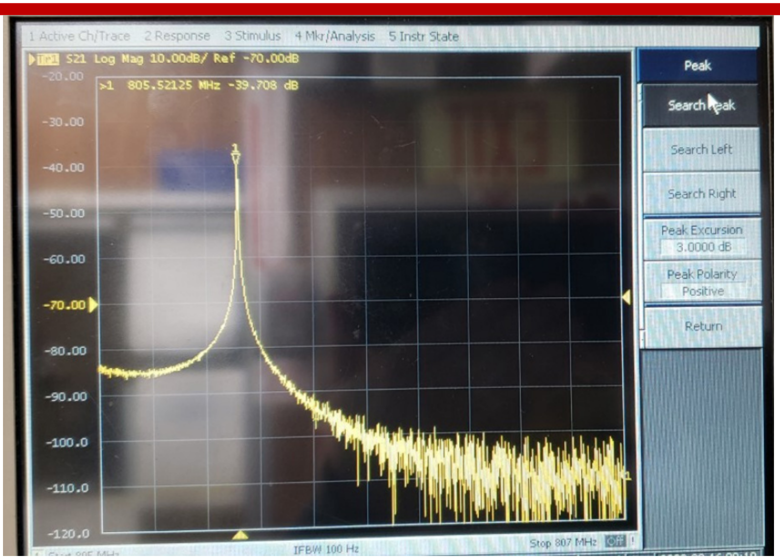
Testing Pre-flight (Cont.)

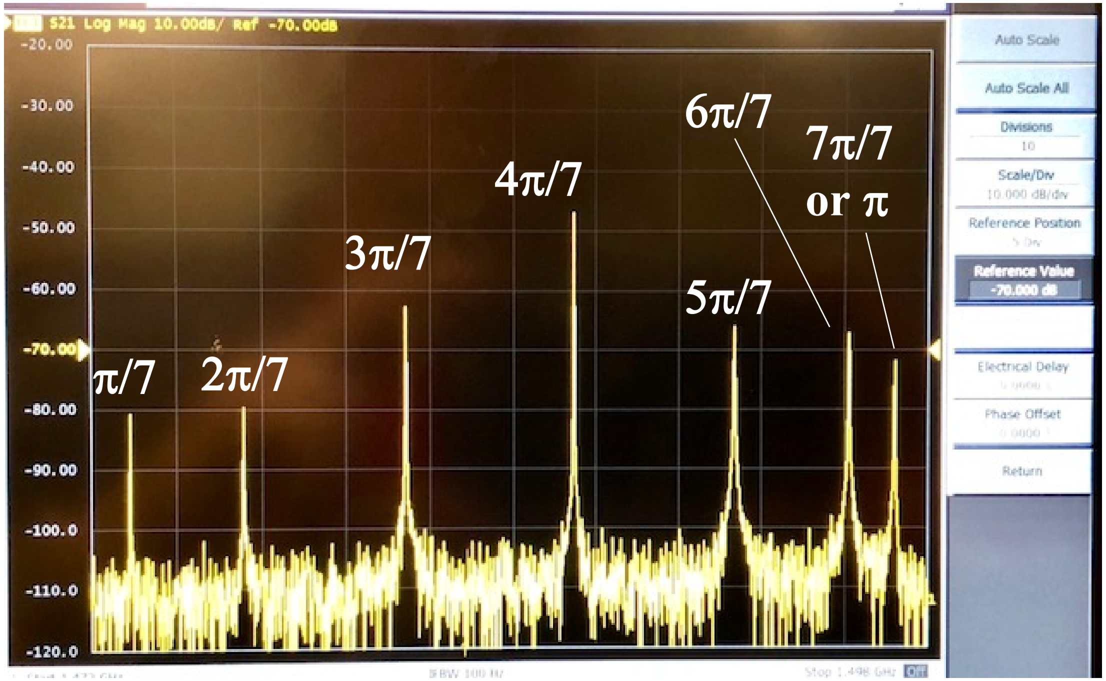
- Diagnostics: Test diagnostics are functional before cooling down; if non-functional this allows time for them to be fixed.
- Cryogenics: Communicate intentions to cool down early; cryogenics is typically a shared utility and adding or removing load to the plant can affect other work areas capacity / schedule.

Warm Frequency Measurements

Methodology:

- $S_{2,1}$ measurement with Network Analyzer between Probe & Reflected Power port (on dir. coupler). [May require use of small amplifiers.]
- Number of frequency modes (aka Pi modes) equal to the number of cell comprising it.
- By convention: Numbering starts at lowest freq. mode and counts upward towards resonance.





- Useful to measure frequencies before cooling down (and compare them to historic data) to determine if limit switch of mechanical stop are required prior to cool down & testing.
- Allow evaluation of potential cell deformation / mechanical issues.
- Measurements vary w/ pressure; be cognizant of conditions [Ins. vacuum space: evacuated vs at atmosphere] as there will be a many kHz frequency shift in data.

Heater Checks

Resistance Measurements prior to cool-down; ensure no circuits open:

- Window / Coupler
- Helium Vessel
- Qo (Sometimes separate from Vessel) [LCLS]

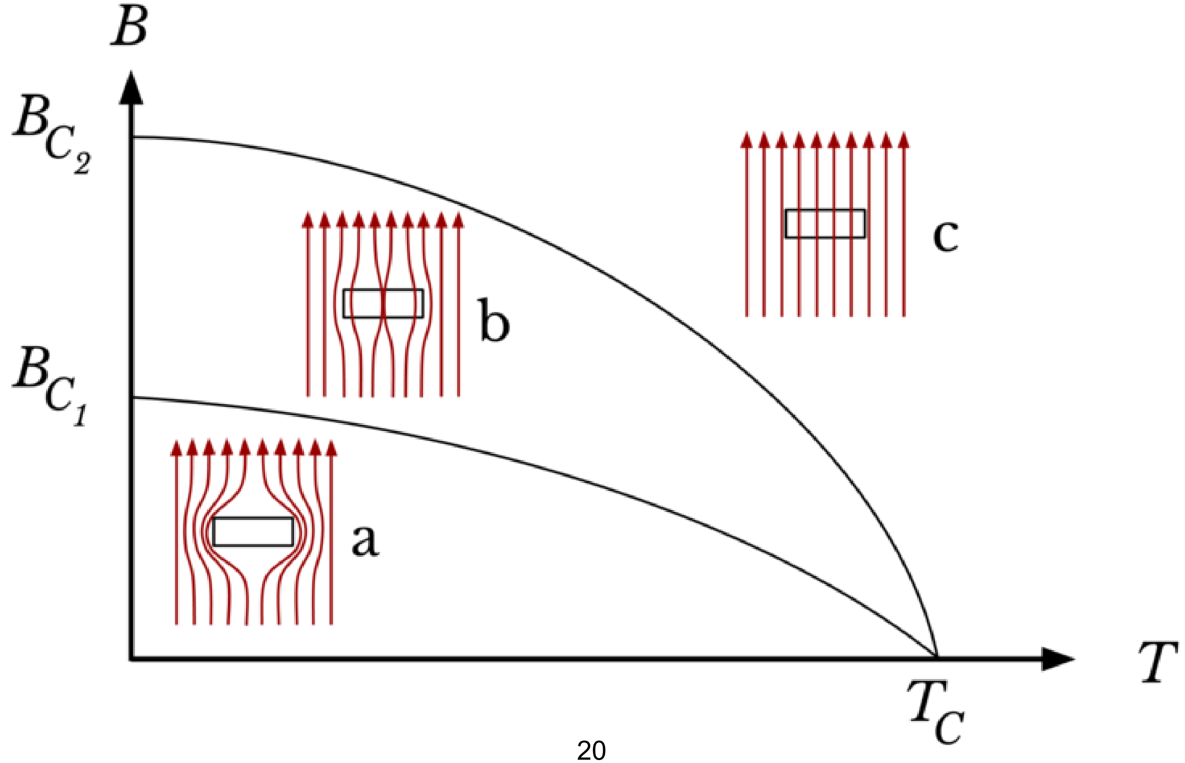
Coupler heaters should also be energized at a small value (few Watts) prior to cool-down to prevent condensation; may not start once cooled.

Qo heaters may be placed more directly in contact with LHe bath for heat transfer efficiency to quickly conduct measurement.

Helium vessel heater trades RF heat off for electric heat to maintain heat load for the cryogenic plant.

Things to Guard Against in Cool-down

- Qo-disease: Hydride formation on interior cavity surface; results in higher surface resistance and lower Qo / accelerating field. Mitigated by fast vacuum cool-down or preemptive high temperature vacuum bake of cavities to out-gas intermolecular Hydrogen. [Danger range: ~60-100K]
- Flux Pinning: Incomplete flux expulsion.



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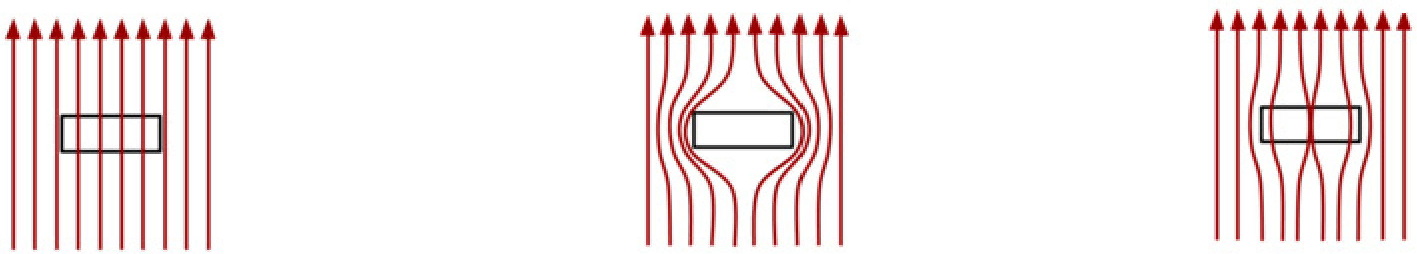
www.classe.cornell.edu/Research/SRF/SrfCavitiesAPrimerTwo.html

en.wikipedia.org/wiki/Type-II_superconductor

Things to Guard Against in Cool-down

- Niobium is a type II superconductor and thus vulnerable to flux pinning and trapped magnetic fields.

  Meissner effect:



Normally Conducting   Superconducting   Flux Pinning

- Magnetic Hygiene: Desirable to eliminate ferromagnetic components to the degree possible and actively cancel ambient magnetic flux. (Example: Magnetic shielding of testing facility and cryomodule, flux gates for monitoring, winding solenoids around module, etc.)
- When flux is trapped it results in higher resistance / lower Qo
- Fast cool down limits amount of time to pin flux.

https://en.wikipedia.org/wiki/Type-II_superconductor

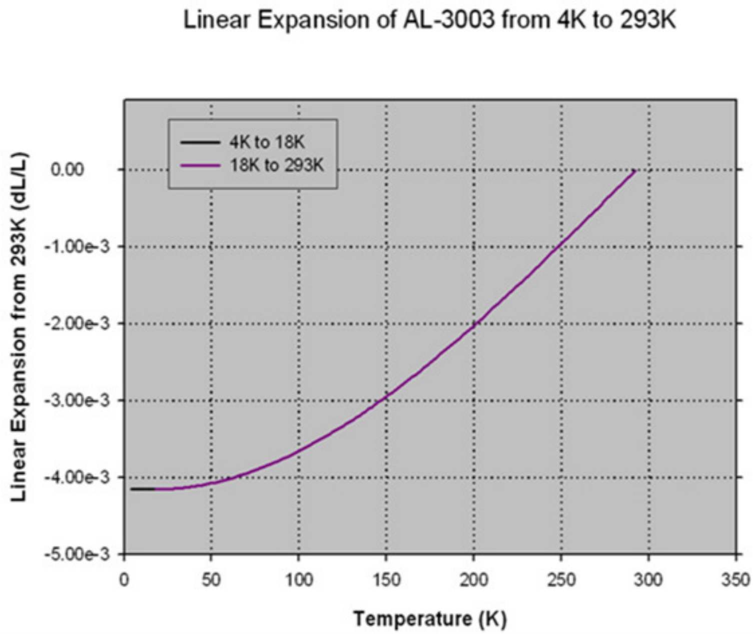
Final Cool-down

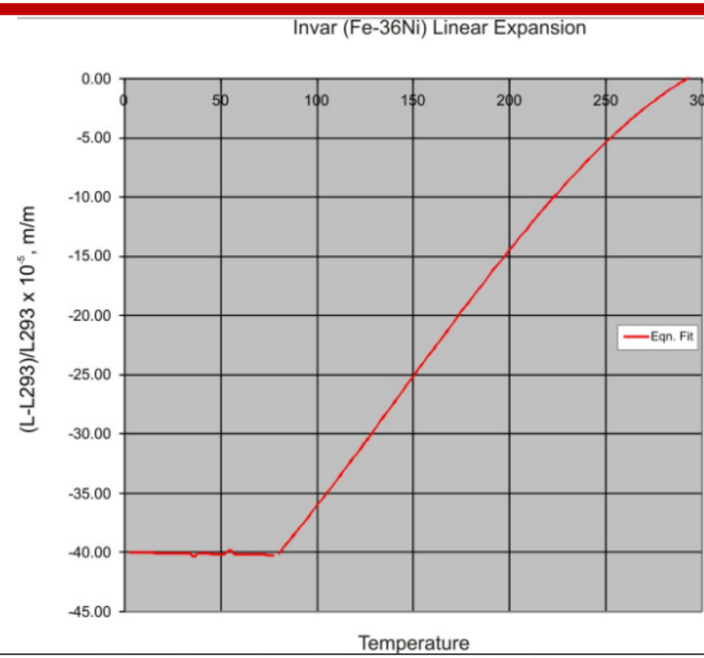
Cool-down Rate:

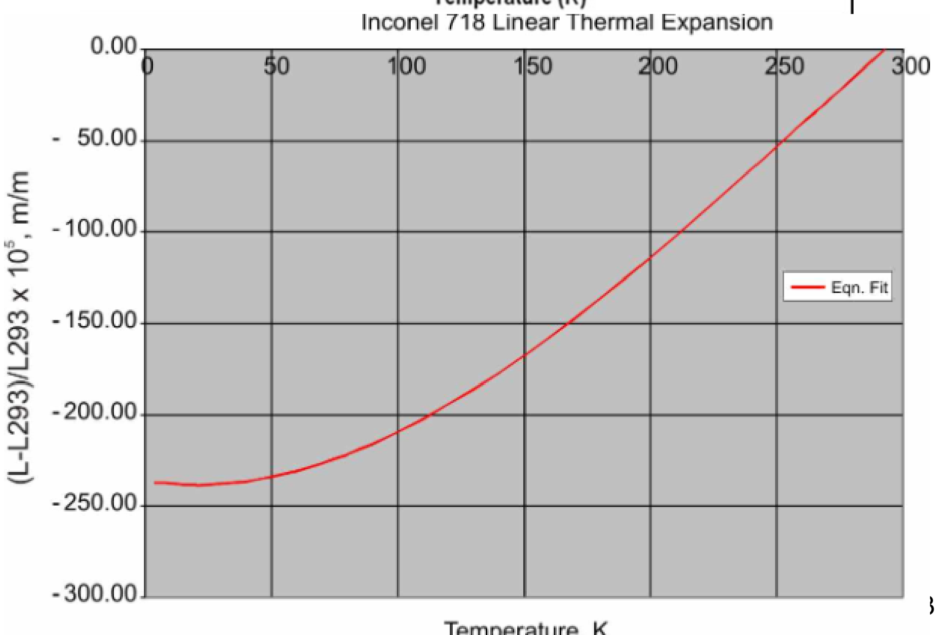
- ‘Goldilocks’ approach:
  - Not too fast: Down to ~100K; thermal stresses from differing contraction rates could cause seals / cracks / leaks to open-up result in damage or inability to cool down…
  - Not too slow: Aforementioned issues – Q-disease, flux pinning, other surface chemistry issues (Hydride / Nitride / Other formation which will affect Qo or the maximum Electric field in testing if recipe didn’t include vacuum annealing.)
  - Just Right: Will vary by system; but - in general - no more than 1K / minute. This allows time for thermal stresses to propagate through the system… By the time one reaches ~100K most of the thermal contraction has occurred and so cool down may speed up from there.

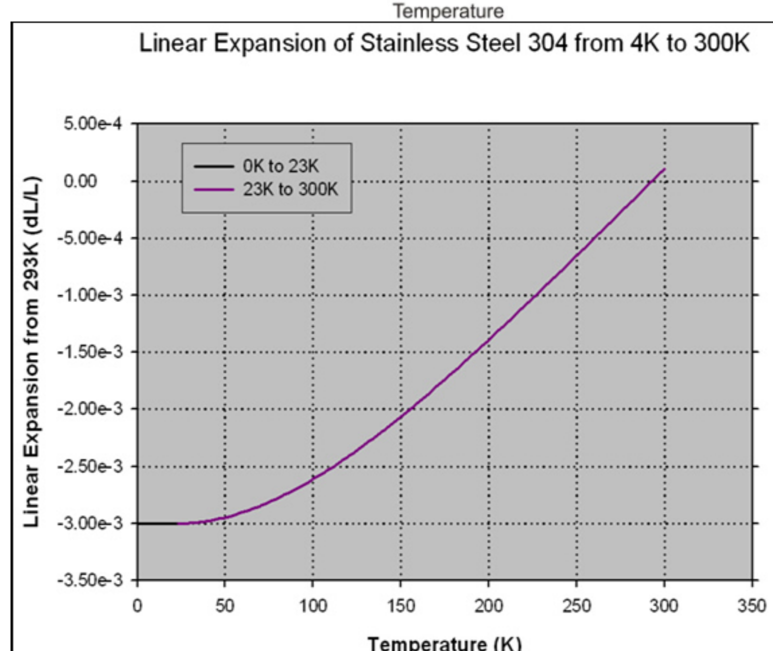
Cool-down

trc.nist.gov/cryogenics/materials/304Stainless/SS-304_Plots/SS-304_Linear%20Expansion.JPG
trc.nist.gov/cryogenics/materials/Invar(Fe-36Ni)/Invar_LE.jpg
trc.nist.gov/cryogenics/materials/Iconel%20718/Inconel%20Linear%20TE.jpg
trc.nist.gov/cryogenics/materials/3003F%20Aluminum/AL-3003_Plots/AL_3003_Linear%20Expansion.JPG



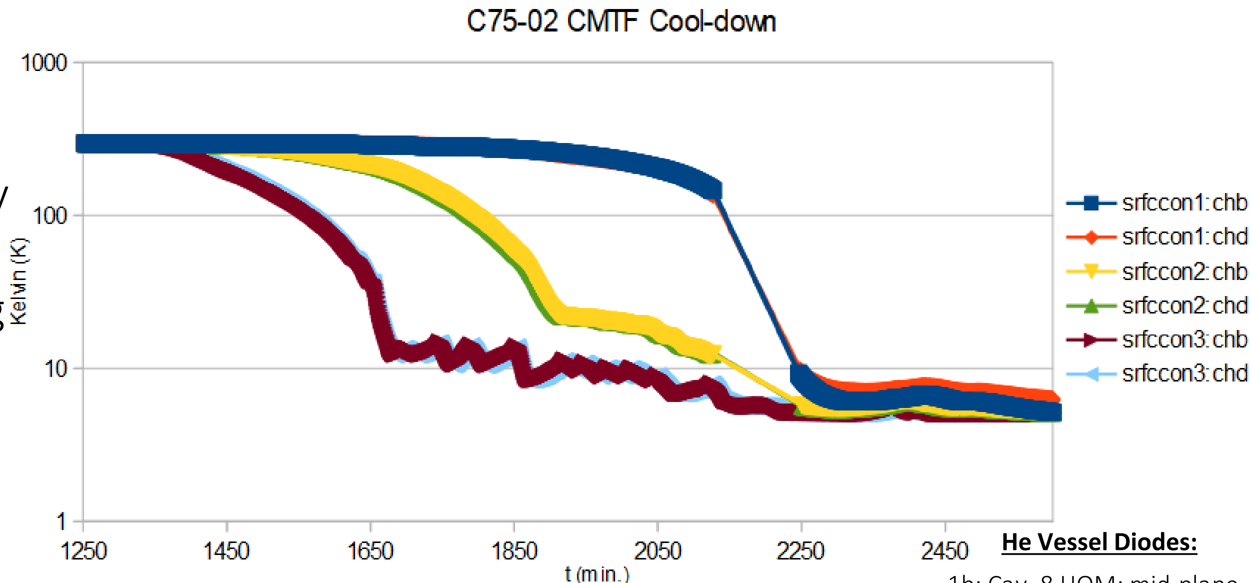






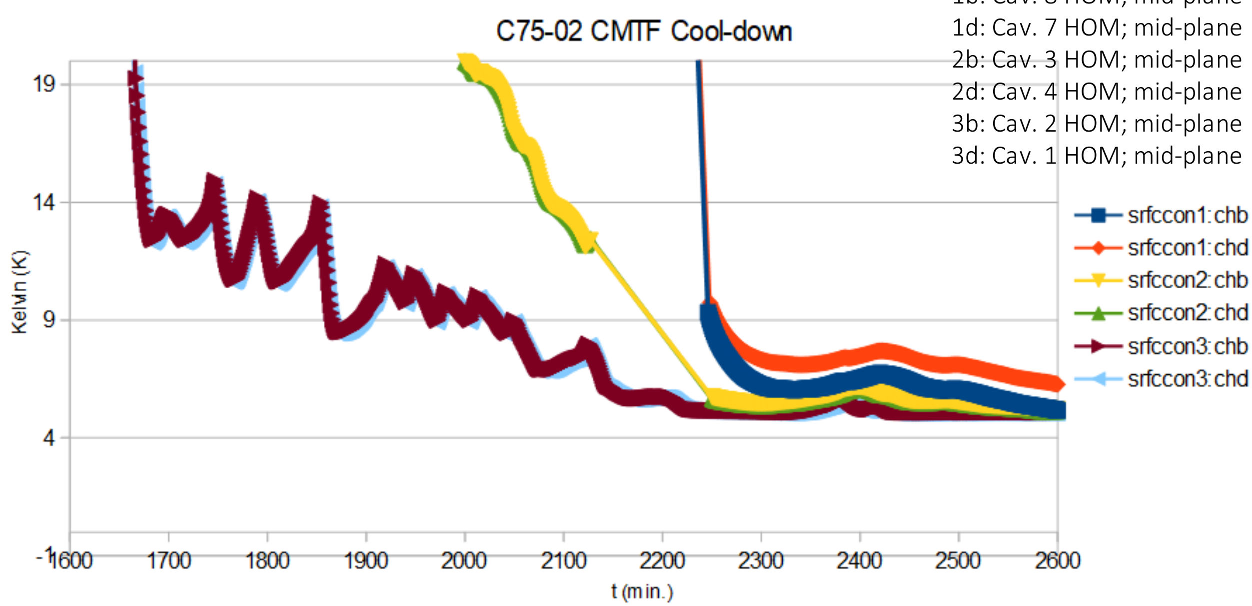
Cryogenic Connection and Starting Cool-down

- Gradual cool down to ~100K.
- Area between ~10-100K == 'Danger Zone'; want to rapidly cool through this region to prevent complications running the cryomodule:
  - Q-disease
  - Flux Pinning
  - Etc.
- Vacuum will improve with cooling due to cryopumping.
- Monitor the obvious: valves, heaters, vacuum / cryogenic signals, etc.
- Sub-atmospheric pump / cool down afterwards (if applicable).



He Vessel Diodes:

1b: Cav. 8 HOM; mid-plane
1d: Cav. 7 HOM; mid-plane
2b: Cav. 3 HOM; mid-plane
2d: Cav. 4 HOM; mid-plane
3b: Cav. 2 HOM; mid-plane
3d: Cav. 1 HOM; mid-plane



Establishing Steady-State Operations

Some pause (~hours) following cool-down is recommended before commencing high-power operations.

This allows:

- Time for valve setting to be established by hand or control loops.
- Liquid level fluctuations to stabilize.
- Pressure inside of the cryomodule to stabilize and settle.
- Some CM components may need more time to equilibrate to 4K/2K due to their thermal mass.
- Electric Heaters to be turned on if necessary to trade off against RF heat. [Some modules have coupler heaters to prevent condensation which should have been activated prior to cool-down]

This period doesn’t have to be fallow:

- Good for instrumentation check-out / calibration
- Heater testing and leak checks (if any appeared) are productive activities
- Initial cold Tuner frequency and Pass-band measurements may be executed.
- Cold cable calibrations.

Cable Calibrations (at 2K)

- Continued from warm measurement.
- Measure loss through the cold part of your Network / Cryomodule. (measured at Antenna / Probe)
- Fold losses into calculations for Power meter levels

While in the process of doing cable calibrations, examine various waveguide / Coax / Heliax and other connections.

Verify:

- All connections are made.
- Cables are all in good repair. (No knicks, cuts, breaks, etc.)
- No loose connections.

Interlock Checks

- Purpose of Machine Protection Interlocks:

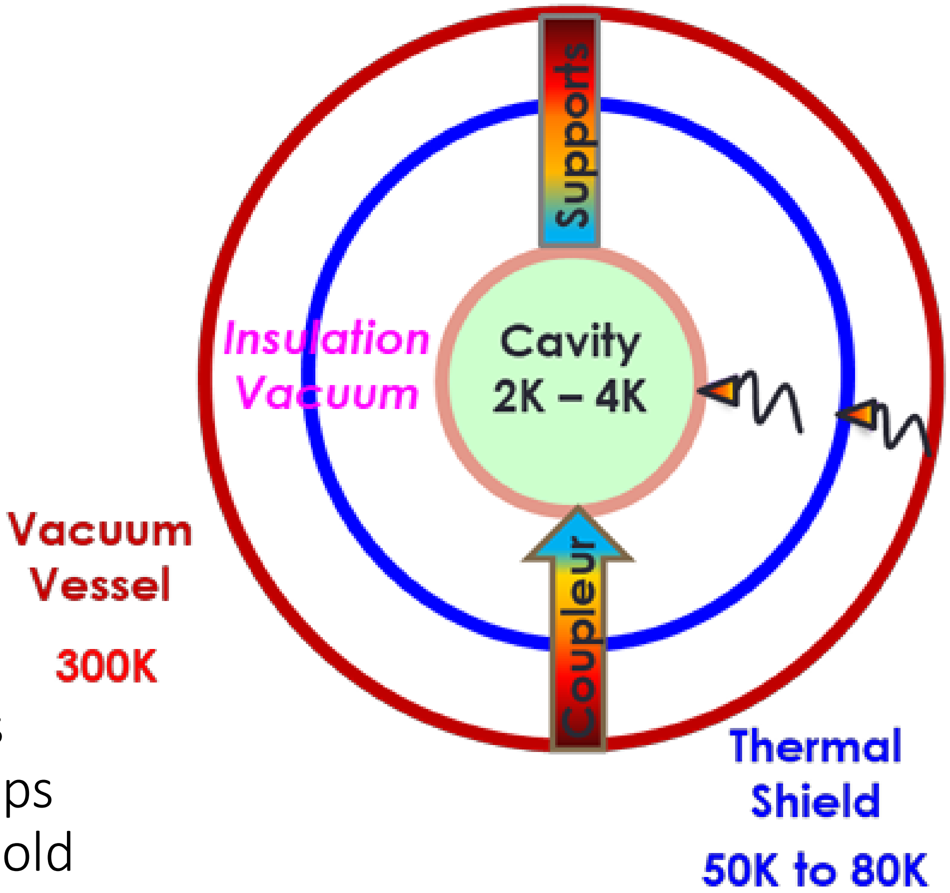
Protect each of the sub-systems supporting the module:

- Vacuum [Insulating, Waveguide / Coupler / Beamline.]
- Arc Detection.
- Infrared / Thermal monitoring of components.
- Cryogenics: Liquid level
- Cryogenics: Pressure
- Quench
- Electrometers
- Tuner limit switches
- Others

All interlocks must be functional to avoid damage to cryomodule.

Vacuum Interlock Checks

- Vacuum was established prior to cool-down.
- Cryomodule Vacuum Spaces:
  - Beamline Vacuum
  - Insulating Vacuum
  - Waveguide / Coupler Vacuum
  - Others
- Thresholds are set for each of the spaces being protected.
- Verification of individual interlocks may be completed by turning pumps off and on OR by modifying threshold level above present readback.



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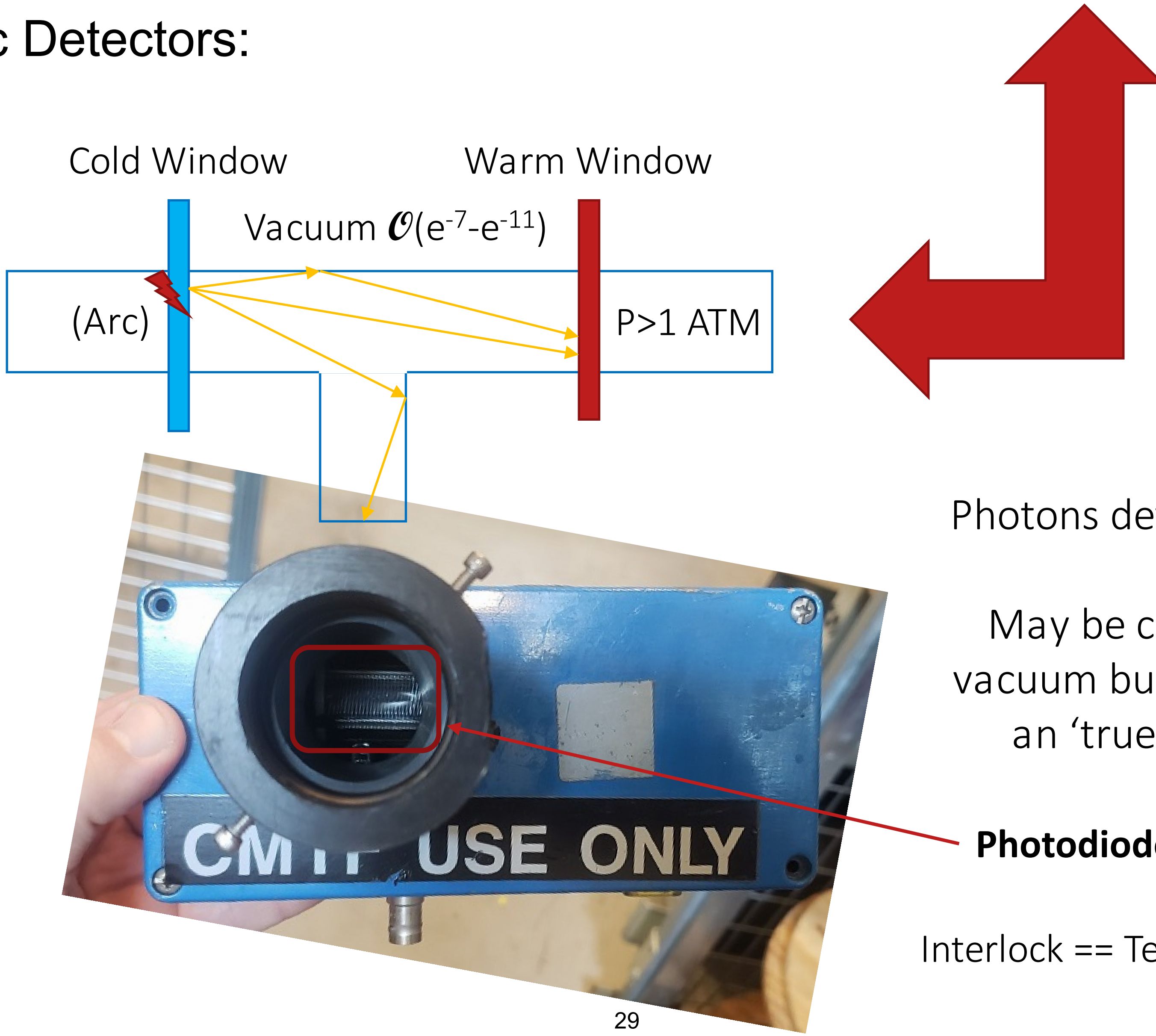
Interlock Checks: Arc Detectors

- Arc Detectors:



Photons detected == Arc;

May be coupled with vacuum burst in event of an ‘true’ arc event

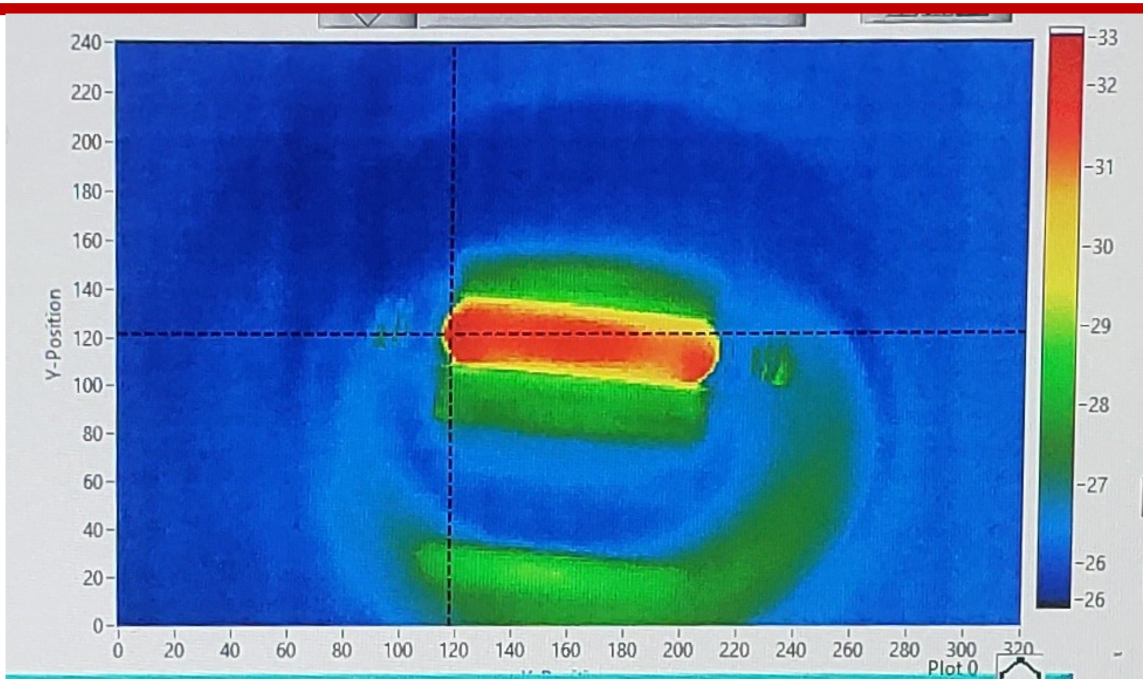
Interlock == Test Diode (LED)

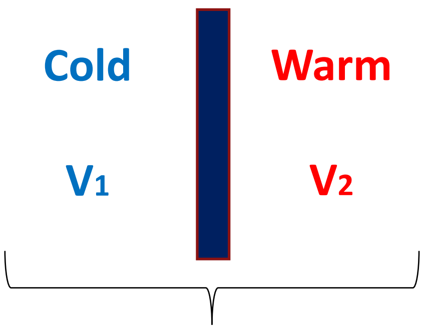
Interlock Checks: Thermal / IR

T > threshold; trip.

- IR sensors:
  - Bolometers
  - Thermopiles
  - Etc.

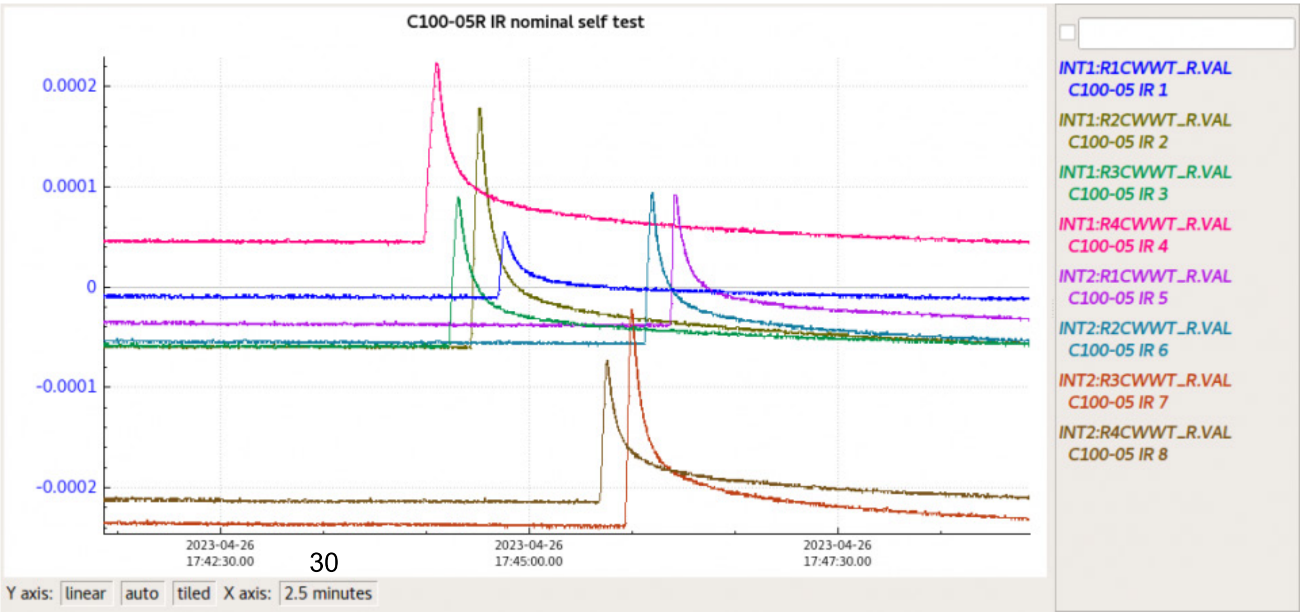
Can be absolute temperature measurement or a relative difference between two points. (thermopile)





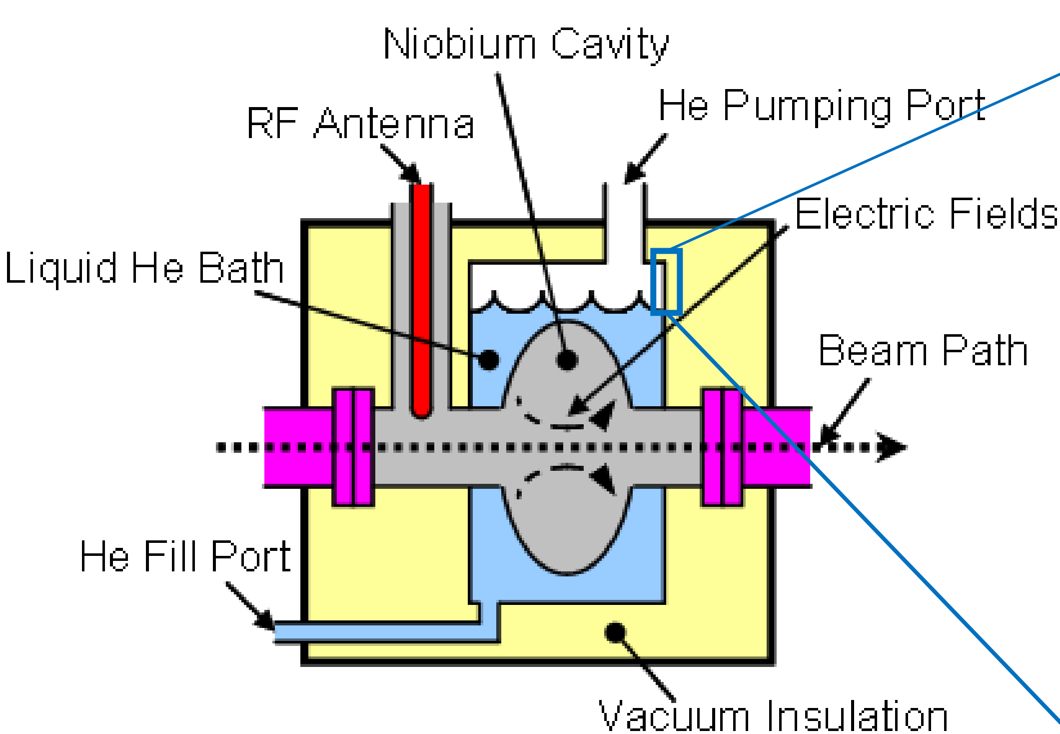
$\Delta V = V_2 - V_1$

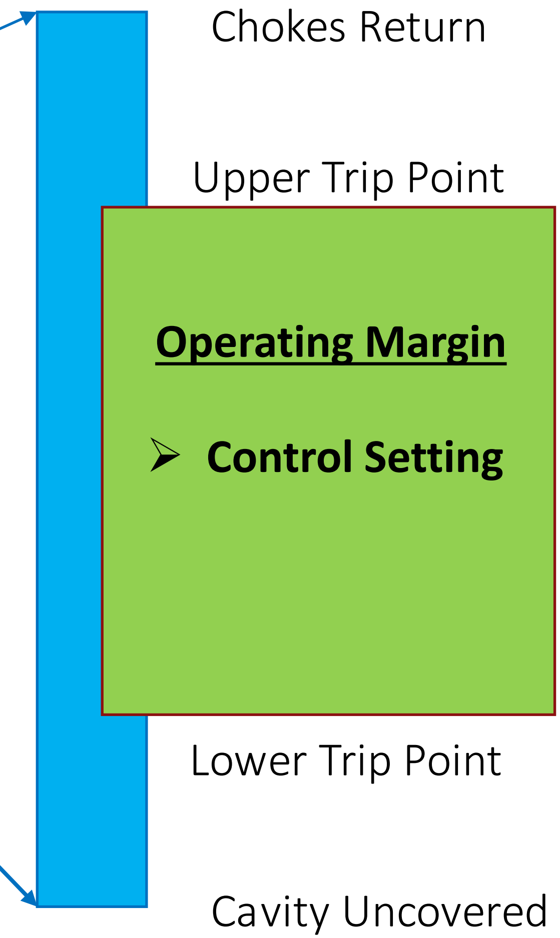
ΔV < threshold; trip.



Interlock Checks: Liquid Level

- Liquid Level:





Verify lower interlock but under filling
OR
Adjusting Trip Thresholds to see fault

en.wikipedia.org/wiki/File:SRF_Cavity_Diagram_1.png

Interlock Checks (Cont.)

- Pressure Interlocks: If P > limit; withdraw RF permit.

Pressure too high – dangerous situation; changes freq. substantially…

- Electrometers / Loss Monitors / Field emission detection:

  Monitored Data > Threshold; withdraw RF permit.

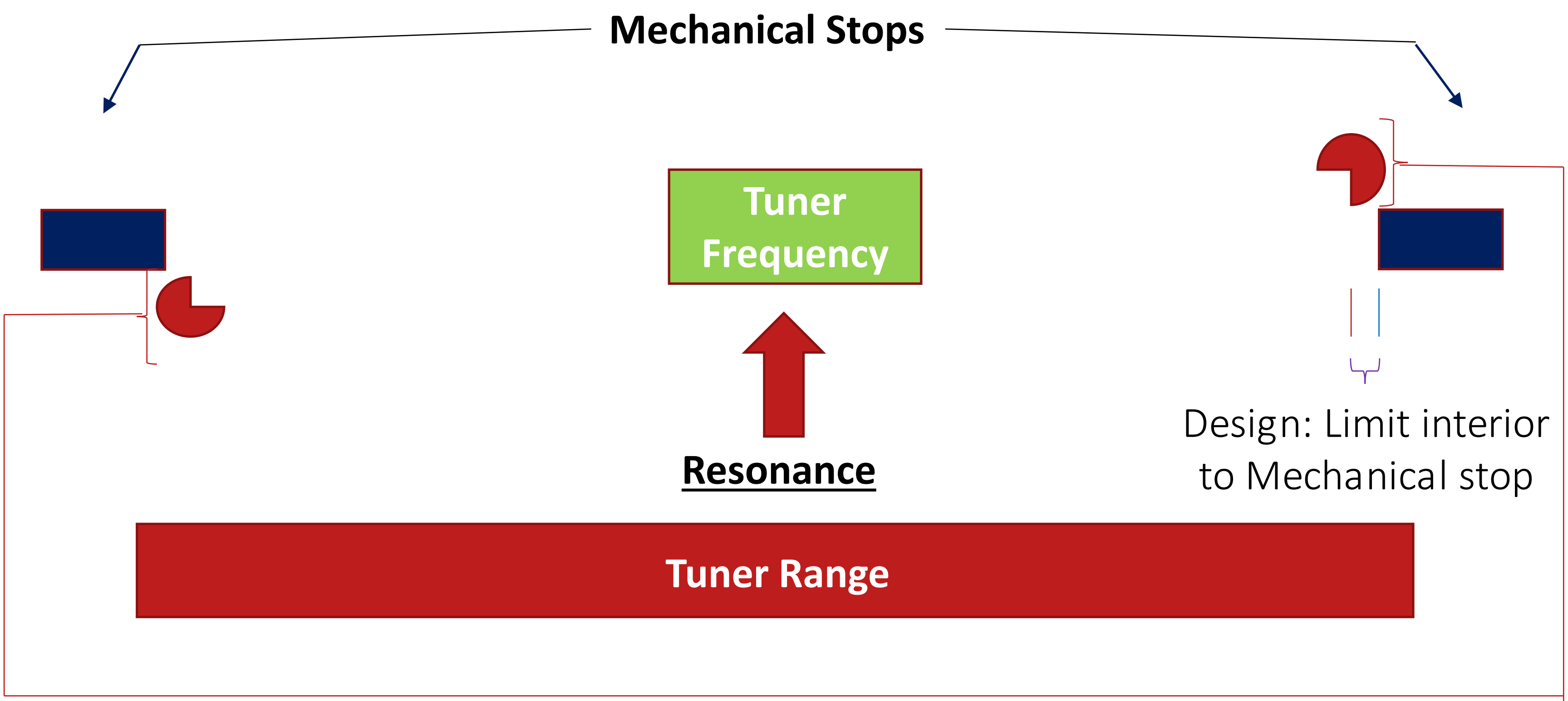
- Quench Protection: Sudden drop in E_{acc} / Rise in P_{refl}

- Other checks of interest (Power loss / fluctuation on a channel, flow rates, power request outside controllable range, etc.)

- Etc.

T. Petersen et al., Fermilab Cryomodule Test Stand RF Interlock System, arxiv:1705.00066 / Fermilab-CONF-16-432.

Tuners Interlocks: Mechanical Stops and Limit Switches



Verify:

- Range centered & design width
- Limit switches actuate and trip interlock
- Limit switches interior to mechanical stop

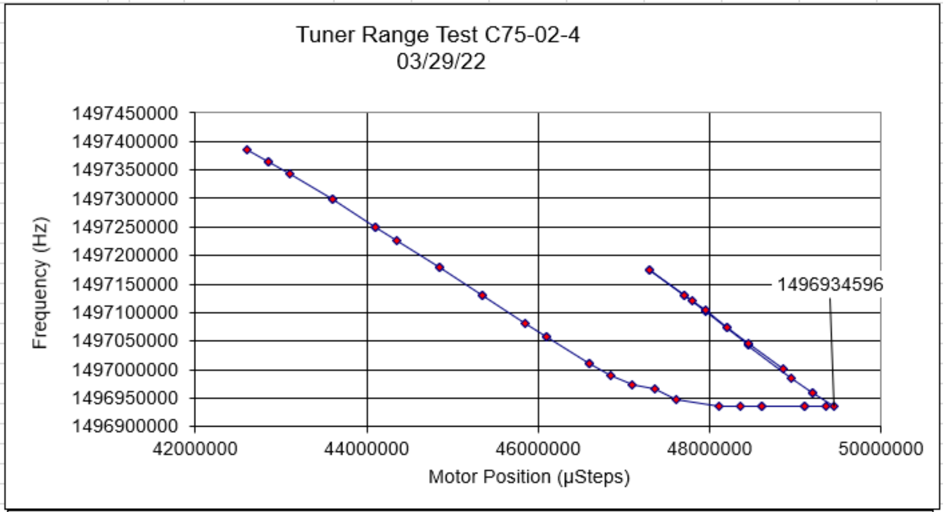
If w/ High Power:

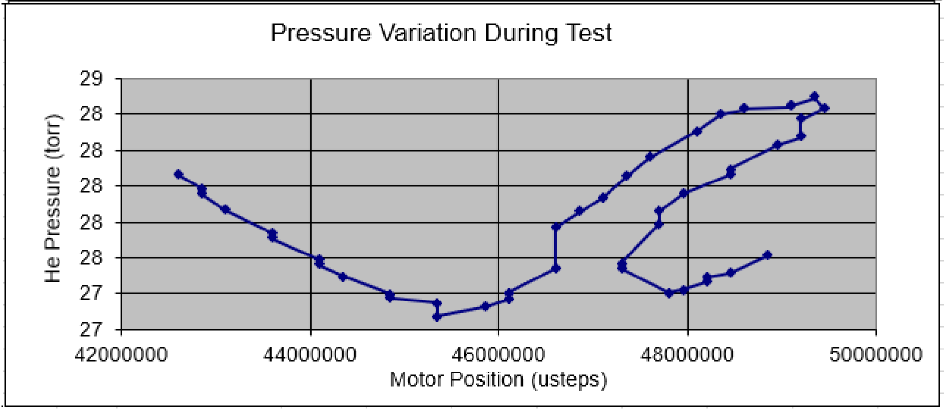
- One may also survey Probe/HOM coupler power levels

Tuner Motor Motion Interlock

Cavity is mechanically deformed by tuner (within limits) to reach operating frequency.

Tuner Frequency Range & Cold Passband Measurements





Procedure:

- Cavity tuned to its upper limit switch post-cool down. Passband frequencies & Qext of Pi-modes may be measured on Network Analyzer.
- Cavity tuned to lower frequency limit (~ -400 kHz) to limit switch; passbands/Qext again measured if desired.
- Cavity tuned to resonant frequency; passbands measured one last time.
- Pressure readings and pressure sensitivity measurement used (later) to correct frequency data to initial measurement pressure.
- Corrected frequency data is then correlated against motor position over the long range & used to compute an average frequency change per tuner motor step increment.

Determine slew rate: (Hz / motor step)
Ensures upper / lower frequency stops in right location or if adjustment required.
(If possible…)

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Tuners: Cold Frequency Measurements – Cool Down

Warm/Room Temp.:

Pressures		
He circuits	1	ATM
Ins. Vacuum	1.10E-04	Torr

SNS PPU-05	Cav 1		Cav 2		Cav 3		Cav 4	
Mode	f (MHz)	Q	f (MHz)	Q	f (MHz)	Q	f (MHz)	Q
π	803.9617029	10229	804.0607367	10254	804.0576611	10227	804.0284779	10233
$5\pi/6$	803.1437032	10345	803.2419919	10405	803.2842042	10357	803.2649987	10351
$4\pi/6$	800.8767547	10445	800.978223	10482	800.9279493	10470	800.8890727	10409
$3\pi/6$	797.7041329	10517	797.8489152	10421	797.8702332	10531	797.8193065	10474
$2\pi/6$	794.589713	10577	794.7169079	10596	794.7863288	10546	794.7089747	10570
$\pi/6$	792.2250109	10544	792.4149021	10555	792.3818215	10489	792.3063221	10511

2K: Note frequency shift with cool down

Cold Frequencies [Upper Frequency Limit]								
	Cav. 1		Cav. 2		Cav. 3		Cav. 4	
PPU	f	Q	f	Q	f	Q	f	Q
6 pi /6	805.188952	409800	805.202887	533220	805.194491	629440	805.171368	666580
5 pi /6	804.356053	453360	804.37317	423070	804.412281	400930	804.399598	364580
4 pi /6	802.088219	471300	802.106257	443160	802.050110	496990	802.017706	496900
3 pi /6	798.909277	794490	798.971433	772090	798.988484	732820	798.943828	742370
2 pi /6	795.792778	1559300	795.834647	1459300	795.899655	1630700	795.828638	1545800
1 pi /6	793.415757	6981000	793.525473	6387500	793.486431	6737600	793.41779	6003100
	Actuates	Lim A	**Not actuating switch**		Actuates	Lim A	**Not actuating switch**	
Ins. Vac.	1.37E-07							
Beam line	4.68E-11							

Tuners: Cold Frequency Measurements - Range

Measure @ 2K:

Cold Frequencies [Upper Frequency Limit]								
	Cav. 1		Cav. 2		Cav. 3		Cav. 4	
PPU	f	Q	f	Q	f	Q	f	Q
6 pi /6	805.188952	409800	805.202887	533220	805.194491	629440	805.171368	666580
5 pi /6	804.356053	453360	804.37317	423070	804.412281	400930	804.399598	364580
4 pi /6	802.088219	471300	802.106257	443160	802.050110	496990	802.017706	496900
3 pi /6	798.909277	794490	798.971433	772090	798.988484	732820	798.943828	742370
2 pi /6	795.792778	1559300	795.834647	1459300	795.899655	1630700	795.828638	1545800
1 pi /6	793.415757	6981000	793.525473	6387500	793.486431	6737600	793.41779	6003100
	Actuates	Lim A	**Not actuating switch**		Actuates	Lim A	**Not actuating switch**	
Ins. Vac.	1.37E-07							
Beam line	4.68E-11							

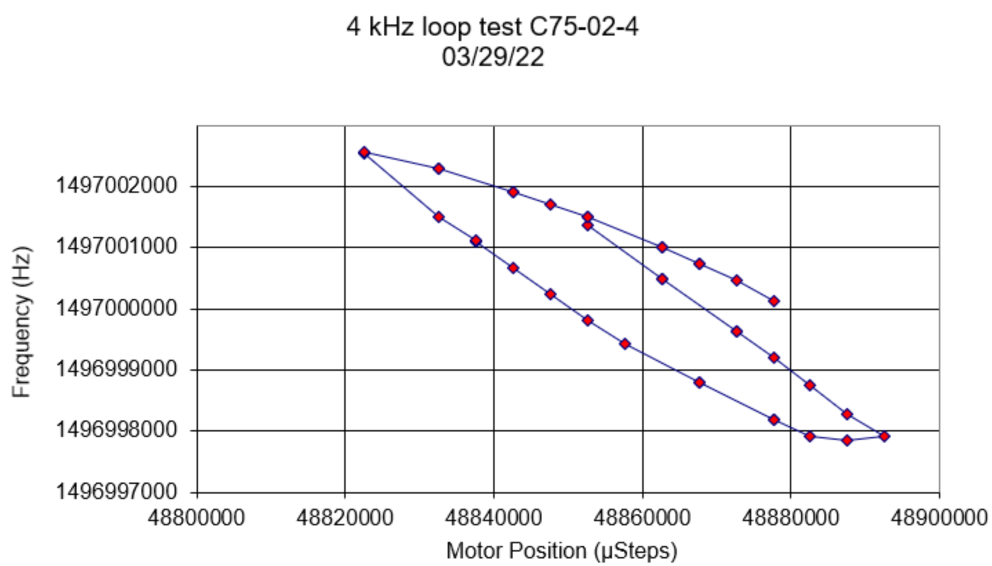
Upper freq. – Lower freq.

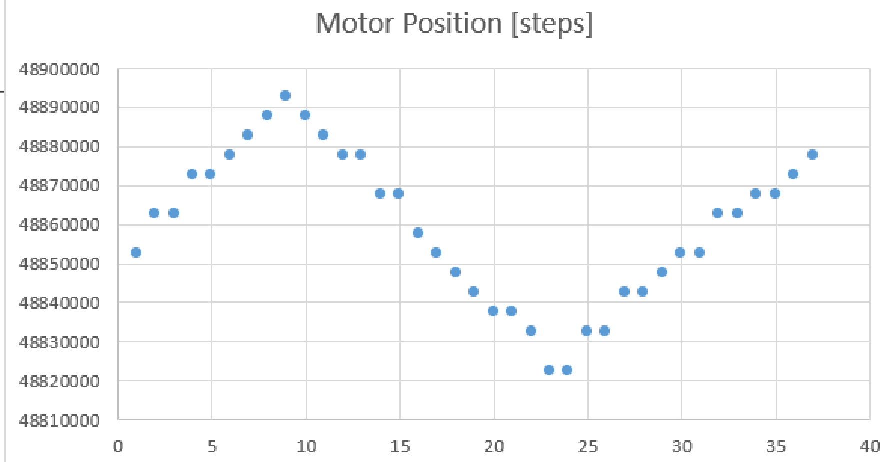
Cold Frequencies [Lower Frequency Limit]								
	Cav. 1		Cav. 2		Cav. 3		Cav. 4	
PPU	f	Q	f	Q	f	Q	f	Q
6 pi /6	804.803136	392490	804.809318	499600	804.808829	583390	804.767287	609960
5 pi /6	803.97888	466100	803.98676	425320	804.037938	399750	804.010078	363860
4 pi /6	801.699395	479500	801.716264	459810	801.663866	510660	801.61546	515690
3 pi /6	798.510244	806350	798.567891	806630	798.59506	747720	798.532138	767720
2 pi /6	795.385768	1556300	795.420313	1522800	795.496909	1612700	795.406591	1595200
1 pi /6	792.998063	7413600	793.104084	6574700	793.071342	5796000	792.985364	6114500
	Not actuating switch		Actuates	Lim B	**Not actuating switch**		**Hits switch/stops motor;**	
Ins. Vac.	1.55E-07							
Beam line	6.27E-11							

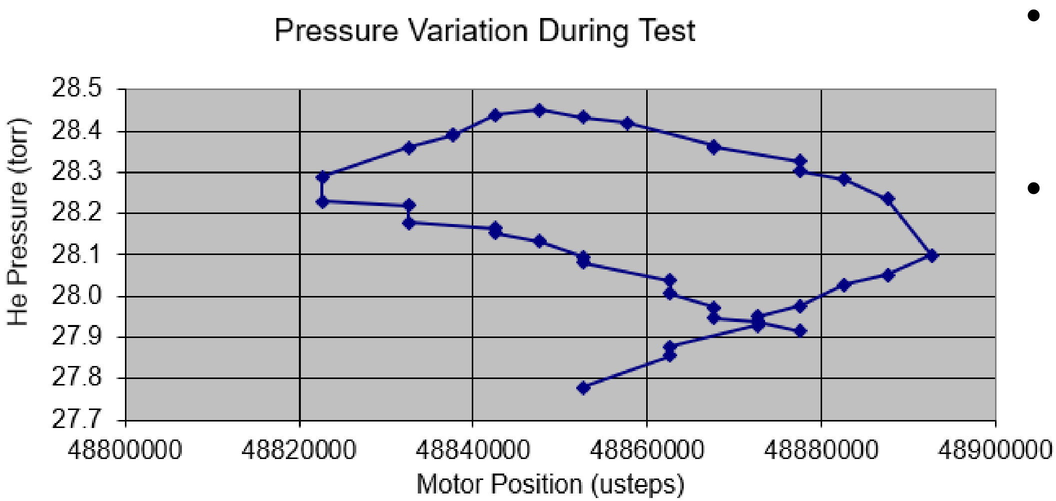
If unable to meet range: Stops/Switched adjustments; stronger torque motors, etc.

Tuners Hysteresis

Tuner Hysteresis:





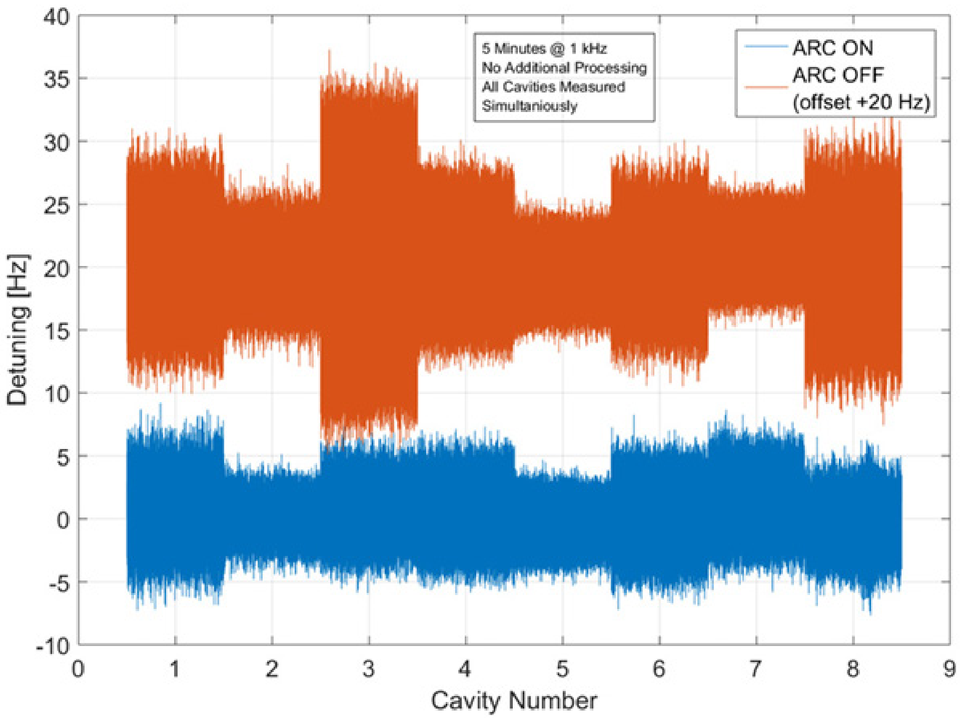


Procedure:

- Frequency & Pressure measured in +/- few kHz loop (meter) about resonance.
- Pressure readings and pressure sensitivity measurement used to correct frequency reading to initial pressure.
- Corrected frequency then able to be correlated against motor position & Hysteresis (Frequency variation over identical motor position) may then measured and averaged.

Tuners: Piezo-tuner Response

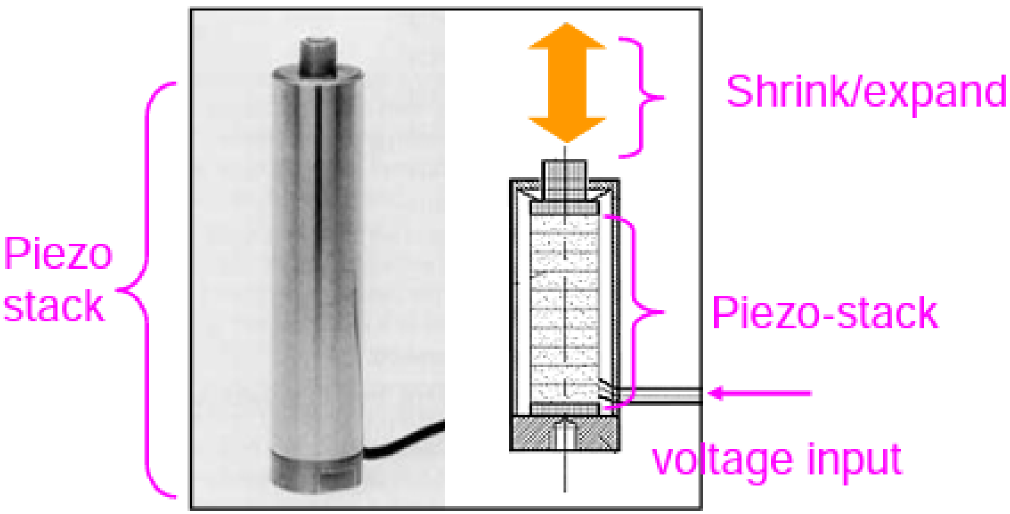
- Mechanical Tuner: Slow changes (< 1 Hz)
- Piezo Tuner: Fast changes (1+ Hz); narrow band – few hundred Hz.
- Schema: Fast Compensation by Piezo for frequency excursions; slow compensation by mechanical tuner to center operating range of piezo tuner. Faster feedback controlled at IOC/FPGA level.
- Helps to mitigate:
  - ➢ Static Lorentz detuning [Powering up cavity]
  - ➢ Dynamic Lorentz detuning
  - ➢ Fast / Microphonics excursions
- Test via signal injection of a periodic / sine wave into tuner input and observe range & response.
- Transfer function measurements may also be made.

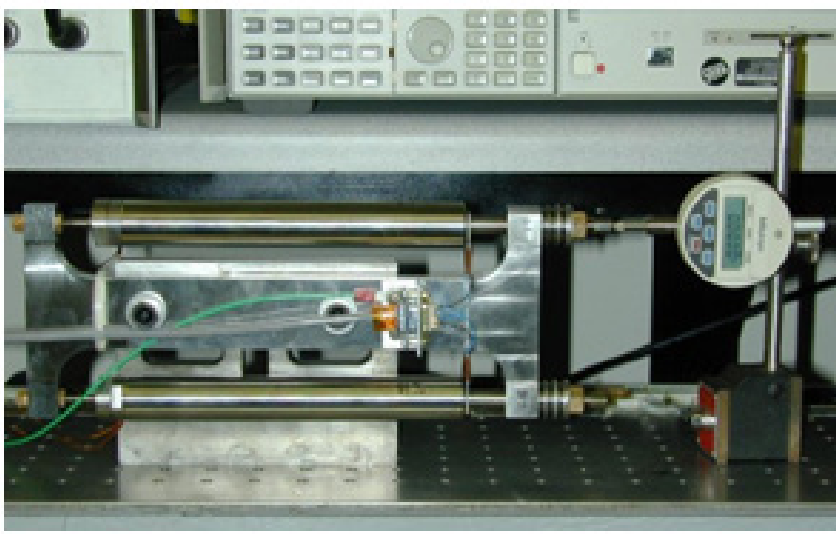


ARC == Active Resonance Compensation (Piezo)

J. P. Holzbauer et al., ACTIVE MICROPHONICS COMPENSATION FOR LCLS-II, Proceedings of IPAC2018 (WEPMI007), Vancouver, BC, Canada

Piezotuners (Cont.)





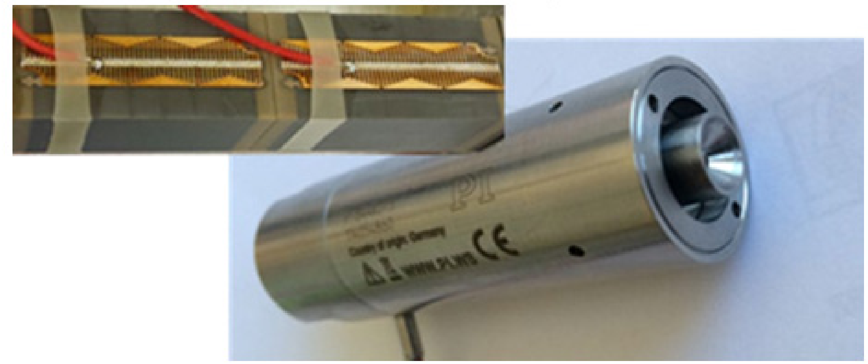


Figure 5: P-844K075 encapsulated piezo actuator. Inside the capsule there are two butted PICMA© piezo stacks.

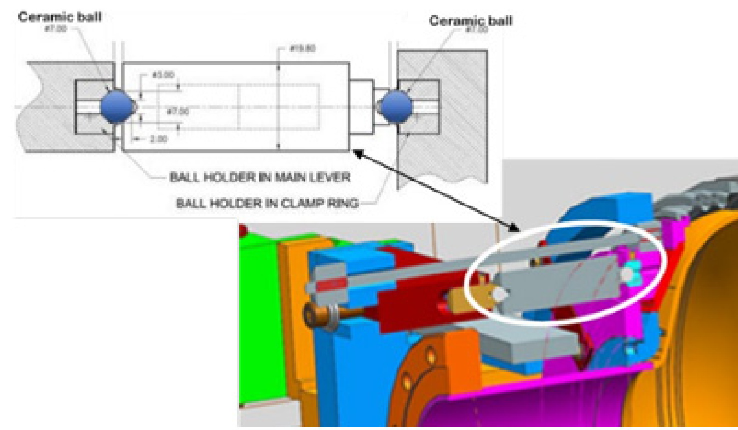


Figure 6: Ceramic balls help prevent development of tensile stress on the piezo. 3D-model of the LCLS II tuner pictured. Piezo actuator installed with 7mm ceramic balls.

S. Di Mitri (Elettra-Sincrotrone Trieste) & M. Venturini (Lawrence Berkeley National Laboratory), Linear Accelerator Design for Free Electron Lasers, Chapter 5: Introduction of Cryomodule. US Particle Accelerator School (USPAS), Fort Collins, CO. June 10-21, 2013. uspas.fnal.gov/materials/13Duke/SCL_Chap5.pdf

Y. Pischalnikov, Review of the Application Piezoelectric Actuators for SRF Cavity Tuners, Proceedings of SRF2021, East Lansing, MI, USA. lss.fnal.gov/archive/2022/conf/fermilab-conf-22-829-td.pdf

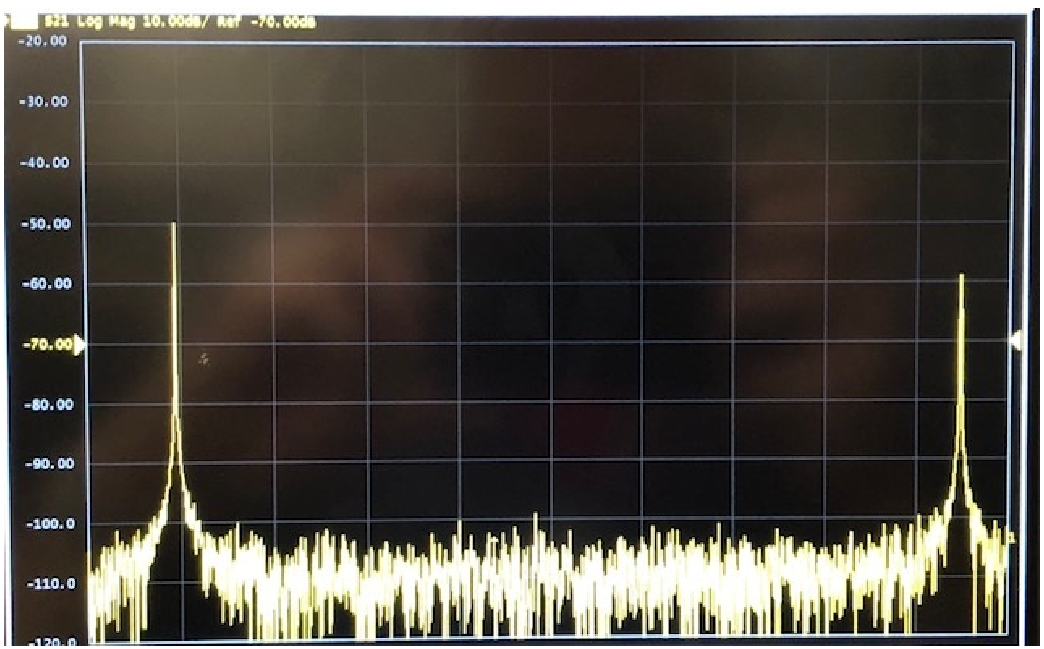
S. Simrock, Control of Microphonics and Lorentz Force Detuning with a Fast Mechanical Tuner, Proceedings of SRF2003 (TUO09), Lübeck, Germany.

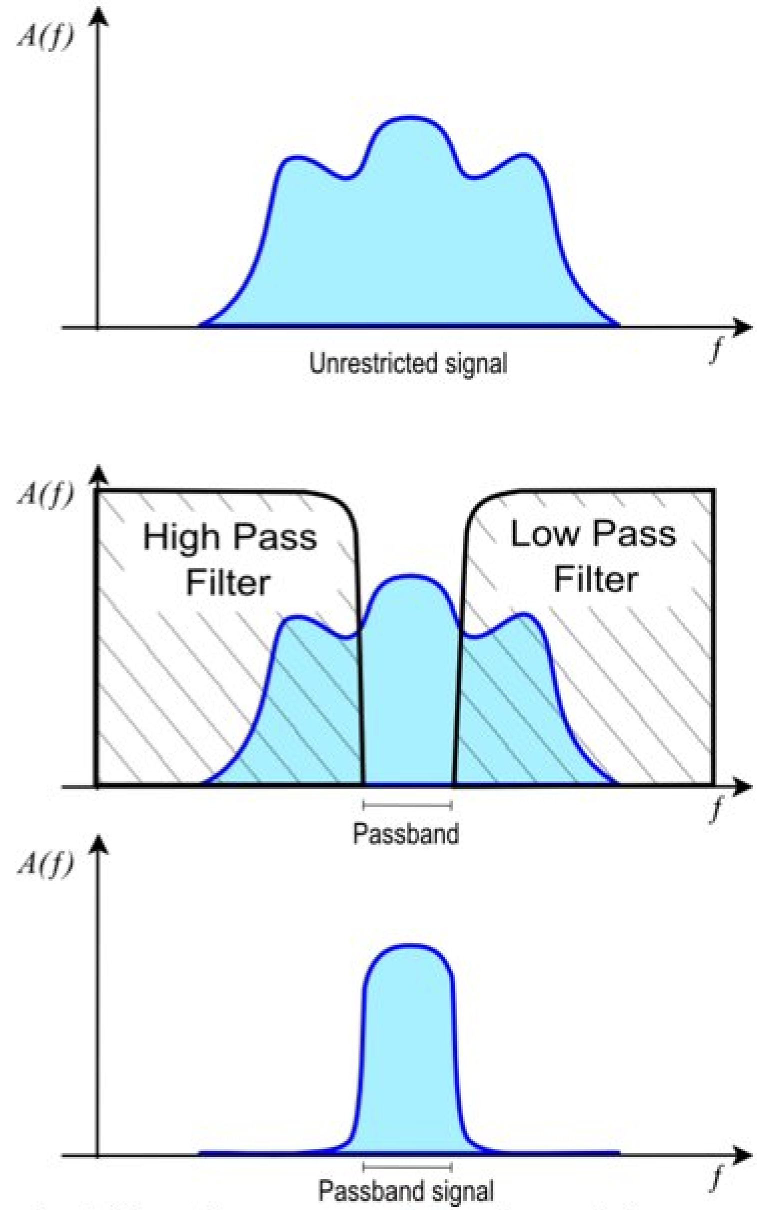
Passbands & Pi-modes

Methodology:

- As with warm measurement; no amplifiers required due to higher cavity Q.

- When measured at operating frequencies (cold) these measurements are also frequency called 'Passband' measurements as they are used to configure filters for Low-level RF system if modes are close together.



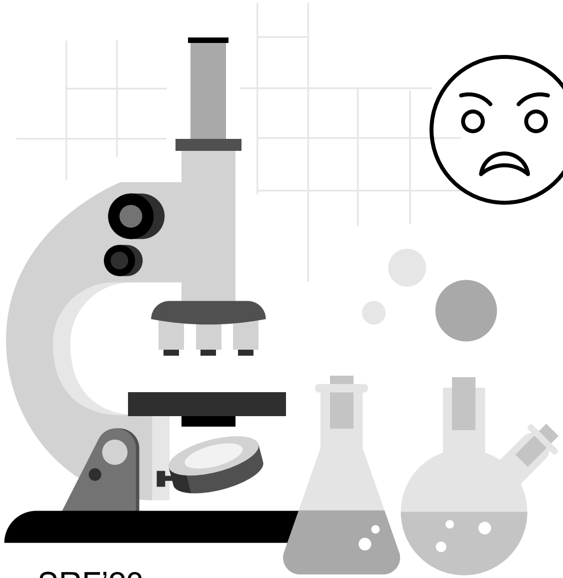


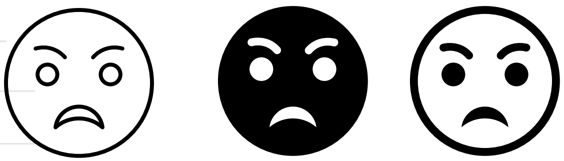
en.wikipedia.org/wiki/Passband

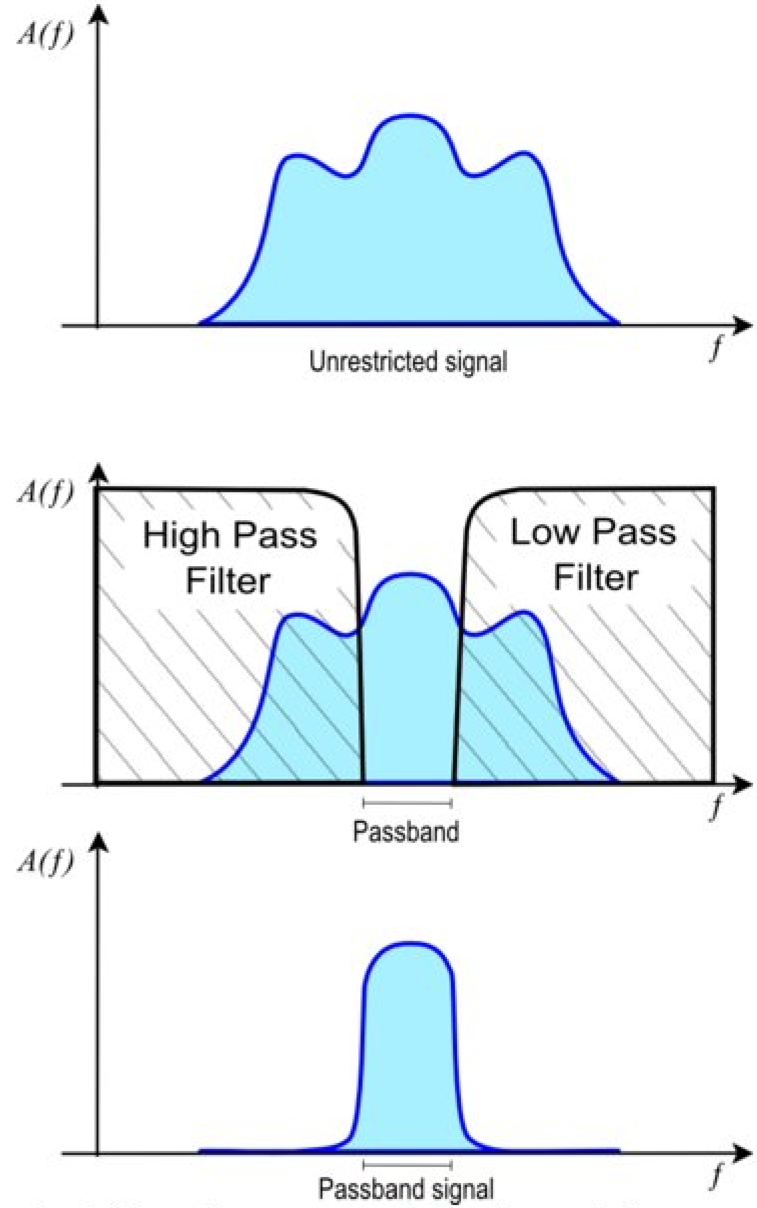
Pass-bands & Pi Modes (Cont.)

Why we care:

- If filters not placed:
  - Power from resonant mode can sometime mix into nearest 1 or 2 Pi modes down.
  - When this mode mixing happens, it would have deleterious effects on the beam bunches and acceleration.
  - No beam == unhappy users







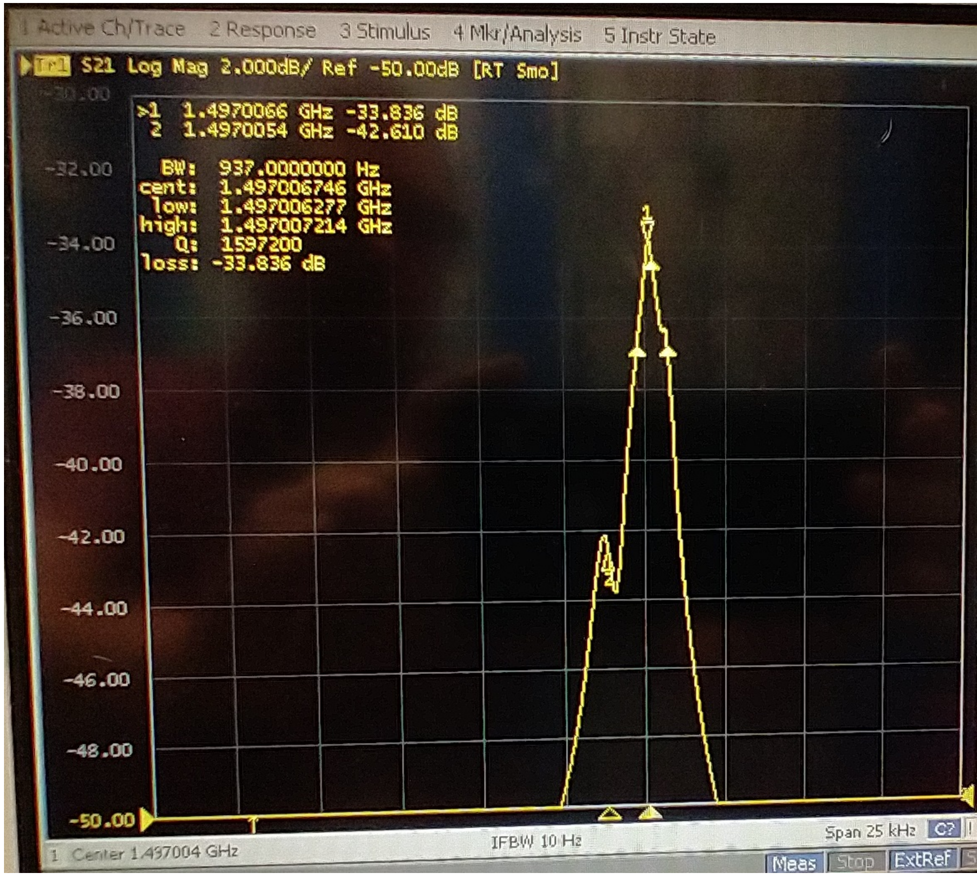
en.wikipedia.org/wiki/Passband

Loaded Q a.k.a. Q_L a.k.a. Q_{ext} a.k.a. Q_{FPC} Measurement

- $S_{2,1}$ Measurement already being performed on cavity.
- Q-factor calculation by NWA (approximate) from bandwidth:

$$Q_L = \frac{f}{(f_{+3dB} - f_{-3dB})}$$

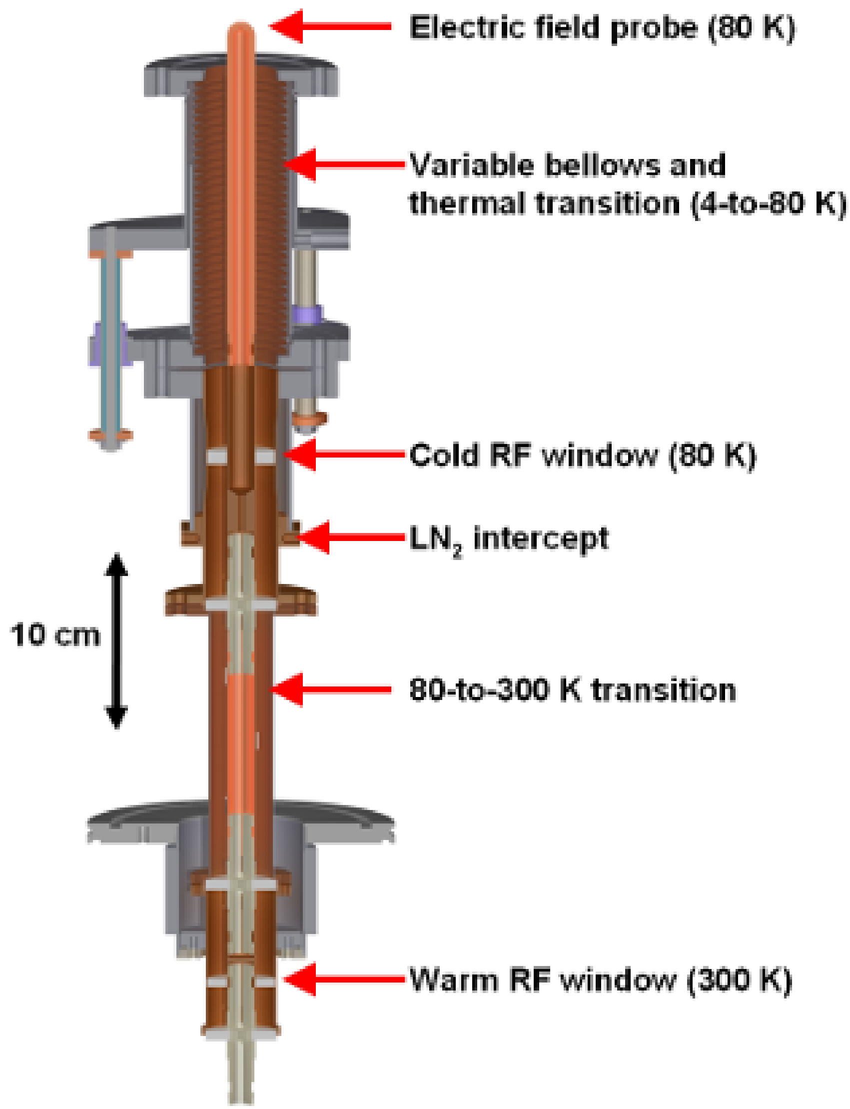
- With the use of a calibration kit with one's analyzer you may also calculate Q_{probe} if desired.



- ➢ Pi-mode frequency and $S_{2,1}$ bandwidth measured; Q_L computed.
- ➢ Loss between insertion point and probe measured. (dB)

$$Q_{probe} = \frac{4Q_L}{10^\wedge(\frac{Loss[dB]}{10})}$$

Coupler Heating and Conditioning



Usually thermally protected; IR sensor or resistive temperature diodes.

May need to 'condition' the coupler with gradually increasing power levels for a shift of two in initial commissioning or after long down periods. Allows for outgassing, gradual warming, and eventually increased operational power range…

Similar process to de-gas waveguide vacuum spaces on start up.

M.P. Kelly et al., A NEW FAST TUNING SYSTEM FOR ATLAS INTENSITY UPGRADE CRYOMODULE, Proceedings of LINAC2010 (THP057), Sep. 12-17, 2010. Tsukuba, Japan

Determining Maximum Gradient

- Cavity tuned to resonant freq.
- Pulsed Mode; low duty factor than designed operation
- Power Meters read in relevant signals:
  - P_{fwd} & P_{refl}
  - P_{drive}: P_{kly} or P_{ssa} or …
  - P_{trans}
  - P_{HOM1}, P_{HOM2}, …

- One can extract Q_{ext}, Q_{FP}, Q_{HOM1}, and Q_{HOM2} pulse-mode power decay measurements.
- Measured gradient scaled v. meter

Determining Maximum Gradient (Cont.)

Once Qs have been measured, they can be factored into calculations:

In Pulse Mode:

- $E_{emit} = \sqrt{p_{emit} * dt(2\pi f)(rQL)}$
- $Q_{fp} = E_{emit}^2 \div p_t(rQL)$
- $E_{pt} = \sqrt{P_t Q_{fp}(rQL)}$
- $E_{emit} = E_{pt}$ *(within error bars; depending on cavity coupling…)*
- $E_{fwd} = \sqrt{P_{fwd} Q_{fp}(rQL)}$

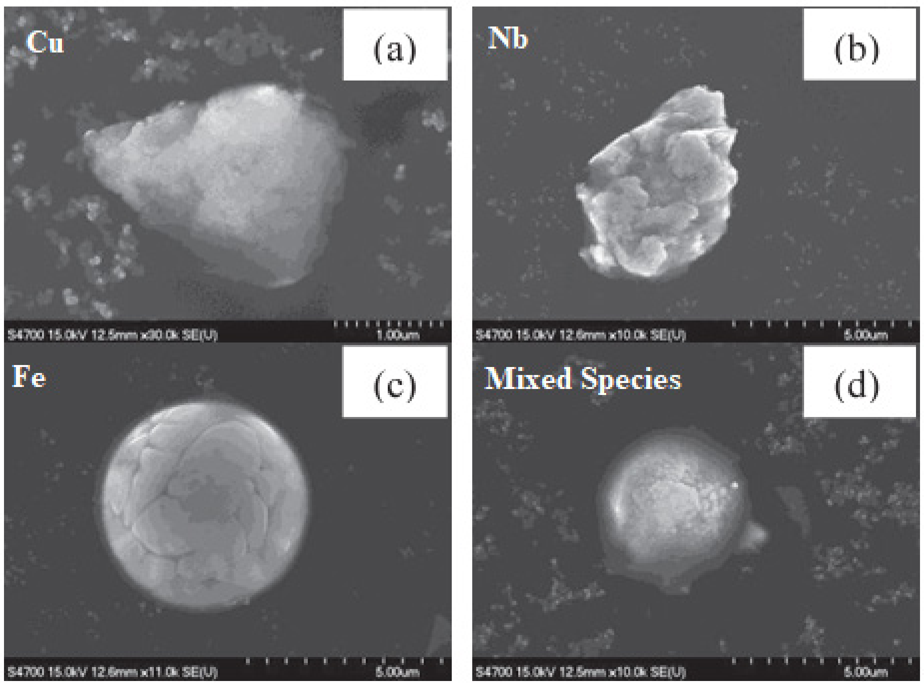
- Lower duty factor is gentler on the cavity when putting power through it for the first time. [Less likely to blow an emitter, allows surface conditioning/degassing in cavity, etc.]
- Increase gradient in 0.2 – 0.5 MV/m intervals until limitation is reached.
- Shorter high voltage pulses good for working through desorption of surface contamination. (Pulse Processing)

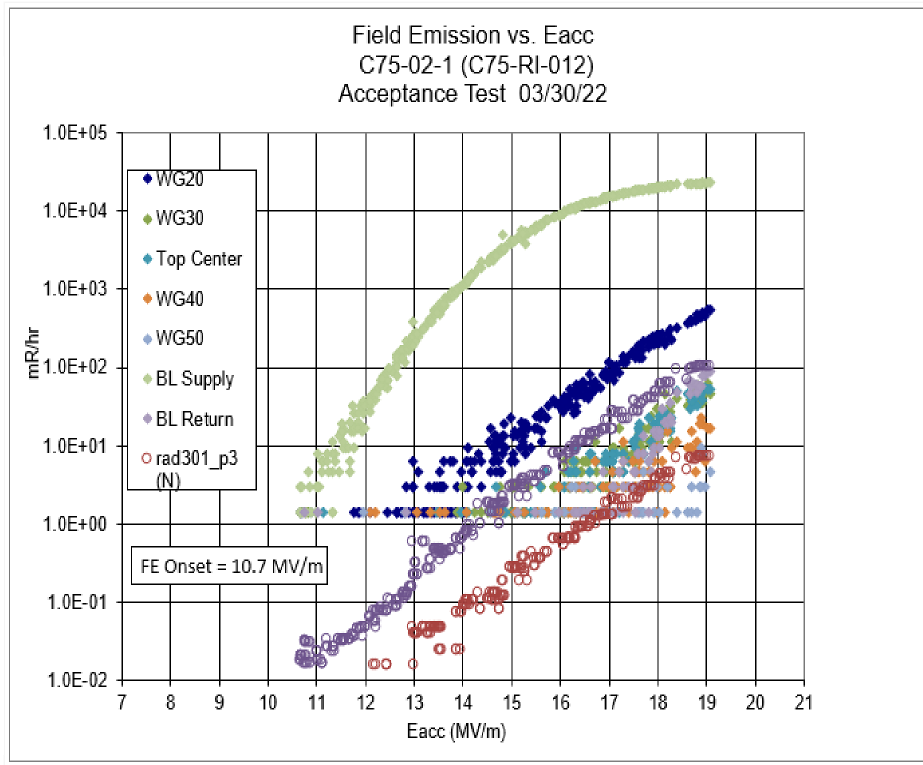
Emax (Cont.)

- After a maximum gradient has been established in lower duty factor mode, one may modify pulse mode to that of operating conditions.
- Repeat process by stepping off a few MV from limiting gradient in the lower duty-factor pulse mode and walking up again in CW.
- When one can no longer go higher in gradient in the operating mode (and unable to coax it further through processing, ‘burn in’, or other activities – this is then Emax (The highest achievable electric field…)
- Multipacting (if encountered) processable by repeated CW quenching near barrier.
- If one is administratively limited only, then one can attempt a 1-hour run to establish if this is a valid operational gradient (hereafter: Eop). If this is not the case (or a trip is experienced) one might lower gradient in half MV/m steps until it is determined where the cavity might run stably.
- Run all cavities simultaneously (if facility allows) to examine dynamic heat load and cavity interplay along with field emission. [Are the Gradients sustainable?]

Field Emission

- Field emission due to contamination or site defects (scratches etc.); field magnification occurs at site of emission.
- Measure between some low gradient (3-7 MV/m) and desired operational gradient earlier measured.
- Step size at discretion of test director [enough for a 'complete' data set…]





R. Geng et al., Nature & Implications of Found Actual Particulates on the Inner Surface of Cavities in a Full-scale Cryomodule Previously Operated Within Beam, Proceedings of SRF2015, MOPB035, Whistler, BC, Canada.

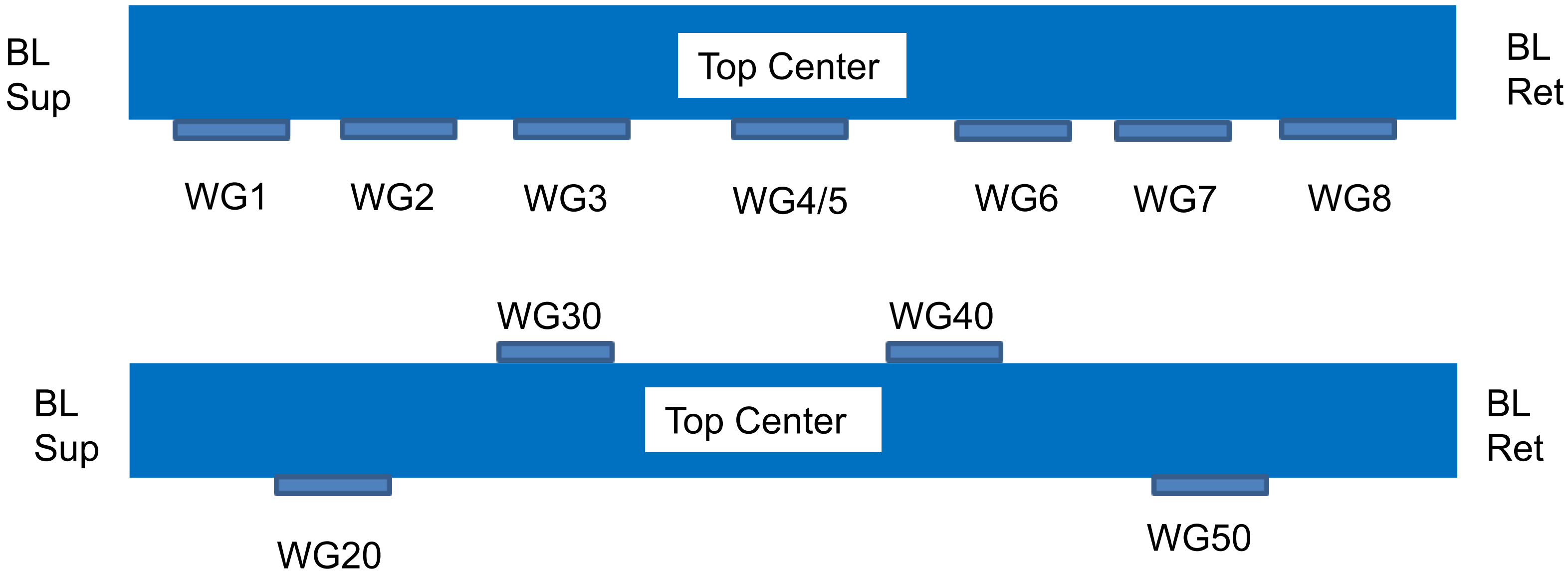
Field Emission (Cont.)

Methodology:

Portable Geiger-Mueller (or other) detectors placed about the module.

For example:

- Each waveguide/Fundamental Power Coupler Pair.
- Fore and Aft of the module along the beamline.



Neutron monitors also desirable… different facilities may measure other places…

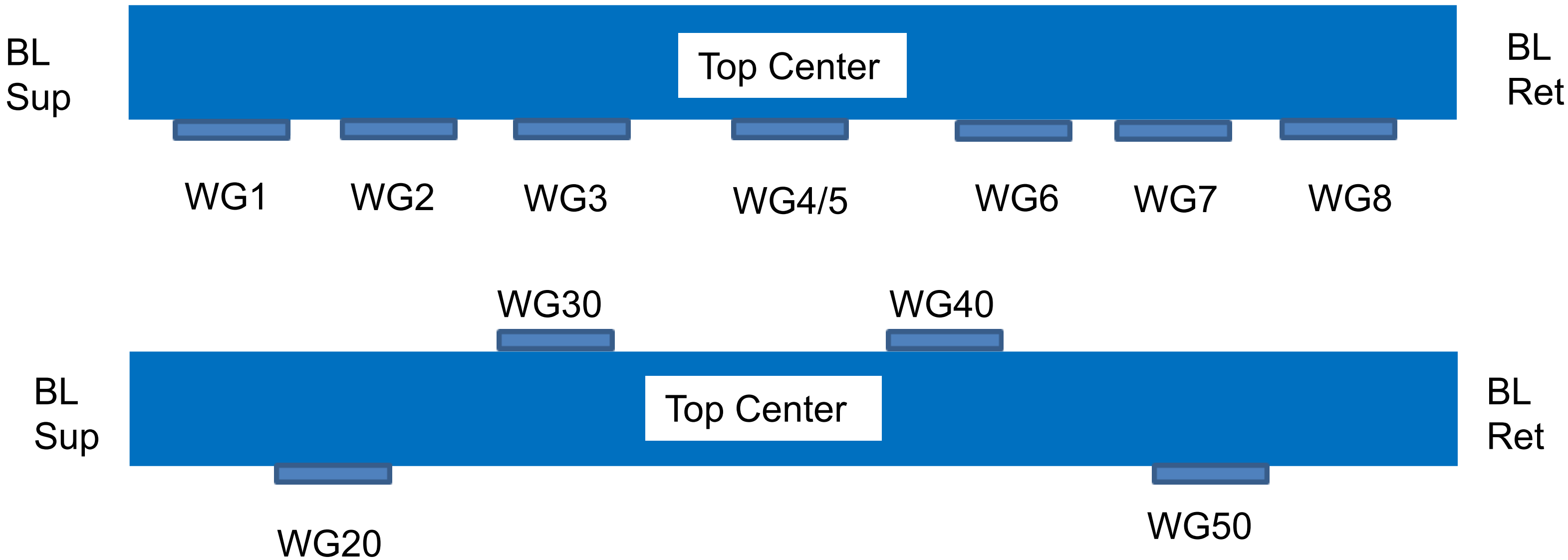
M Drury et al., Results of the 2015 Helium Processing of CEBAF Cryomodules, Proceedings of NA-PAC'16, THA1IO02. 13 Oct 2016.

Field Emission (Cont.)

Methodology:

Analogous or supporting radiation detectors also fine:

- Ion Chambers
- Scintillators
- Proportional Counters
- Photomultipliers (when properly augmented / calibrated)
- Etc.



Ideally: Run cavities below F.E. onset; field emission begets more field emission…
100 mRad/hr perhaps a reasonable compromise; radiative processing discussed later.

M Drury et al., Results of the 2015 Helium Processing of CEBAF Cryomodules, Proceedings of NA-PAC'16, THA1IO02. 13 Oct 2016.

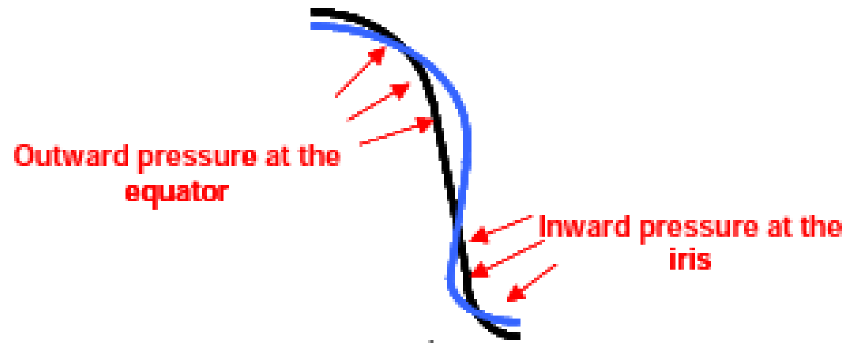
Static Lorentz Measurement

Lorentz Pressure (Cav. Internal Surface):

$$P = \frac{1}{4}(\varepsilon_0 E^2 - \mu_0 H^2)$$

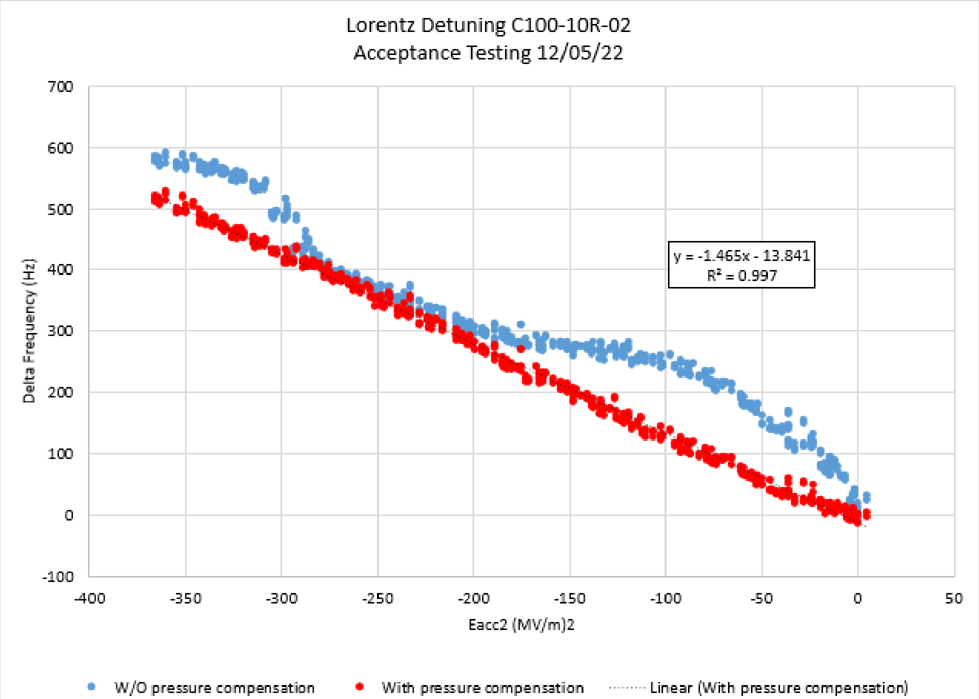
With: $\Delta f = -K_L E_{acc}^2$

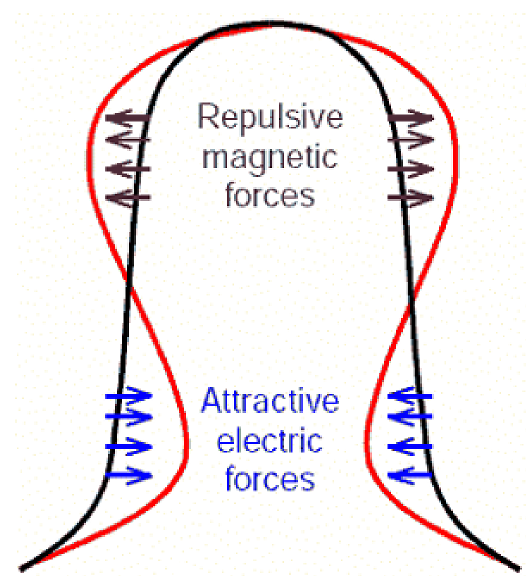
So: $K_L = -\Delta f / E_{acc}^2$



Lorentz pressures.

R Mitchell et al., Lorentz Force Detuning Analysis of the SNS Accelerating Cavities, SRF2001(SA010), Tsukuba, Japan





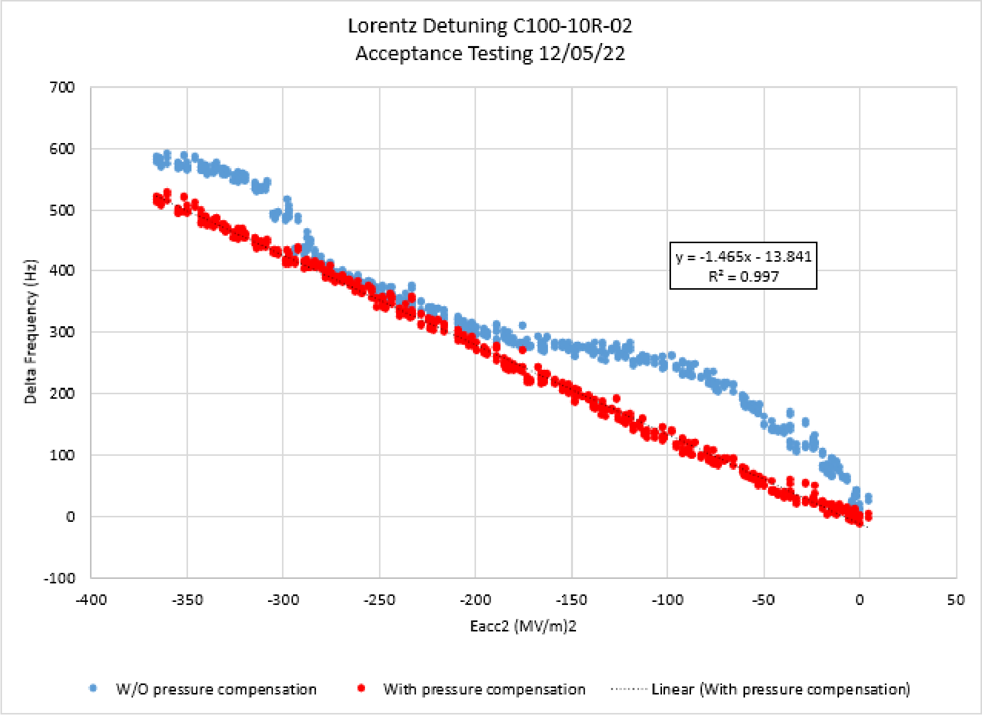
S. Simrock & Z. Geng, LLRF Lecture 2: Sources of Field Perturbations, 7th Intl. Accelerator School for Linear Colliders, India, 2012. agenda.linearcollider.org/event/5636/contributions/25256/attachments/20820/32688/2012_ISLC_lecture_B3_part_1.2.pdf

M. Drury, LCLS-II Cryomodule Acceptance Testing at Jefferson Lab, Prepared for the Cryomodule / Cavity Test Workshop, 29-30 Oct 2015.

Static Lorentz Measurement (Cont.)

$K_L = -\Delta f / E_{acc}^2$

- Take a period when gradient is being ramped up or down – for instance in a field emission measurement post Emax.
- Gradient is ramped (in this case downward) while measuring cavity frequency and pressure.
- Pressure sensitivity data is used to correct frequency data to ab initio pressure / frequency.
- Delta f plotted against E_{acc}^2; trend line slope provides K_L.



One may also make a 'Dynamic' Lorentz detuning measurement as a result of the Electromagnetic field of the beam bunch passing through the cavity.

(Not included here…)

Both compensated by stiffening rings and (piezo) tuners

M. Drury, LCLS-II Cryomodule Acceptance Testing at Jefferson Lab, Prepared for the Cryomodule / Cavity Test Workshop, 29-30 Oct 2015.

Qo Measurements

- Qo = Quality factor; unitless measure of how good of an oscillator you have [Warm copper (~5000) / Superconducting Nb (10^9)]

$$Qo = \frac{\omega U}{Pd}$$

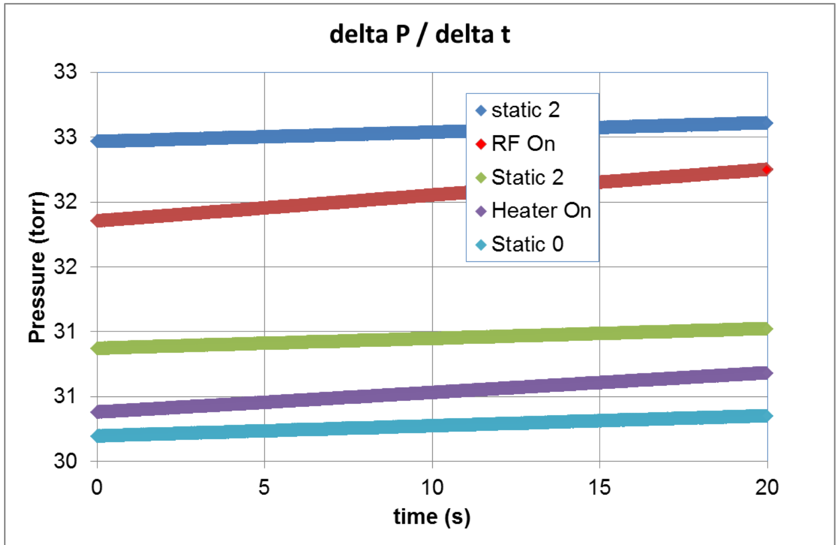
[ω – Resonant frequency (Rad/s), U – Stored Energy (J), & P_d – Power dissipated to maintain U (W)]

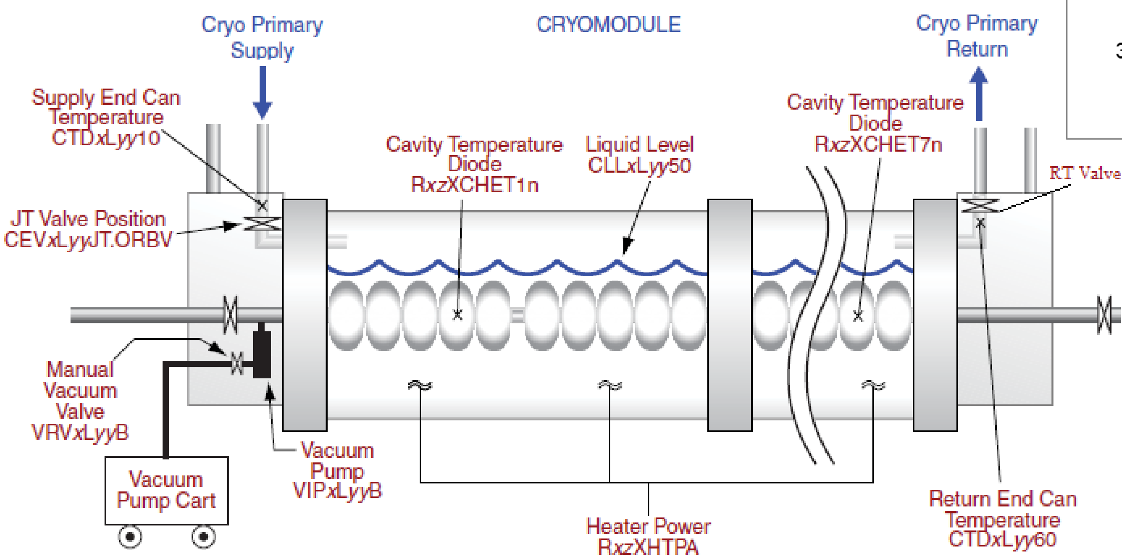
- High Qo desired for:
  - Low shunt impedance
  - Less RF heat produced for same unit gradient
  - Resultingly: Higher usable electric fields / gradients for a given cryogenic load

Qo Measurements (Cont.)

Measurement Methods: Calorimetric

- RF Heat evolved extracted from pressure rise data with the valve closed; calculate Qo.





$$Q_0 = \frac{(E_{acc} \cdot L_{acc})^2}{R/Q \cdot P_c}$$

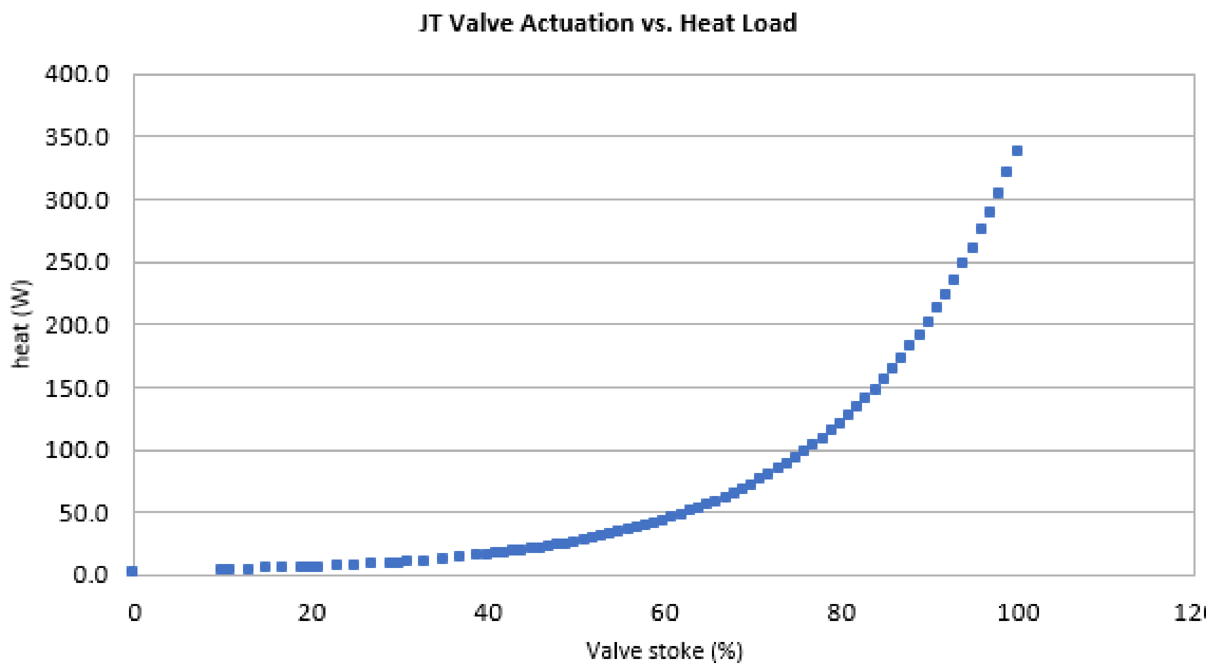
$$Pwr_{RF} = Pwr_{Htr} \frac{(\Delta P_{RF+static} - average(\Delta P_{static1}, \Delta P_{static2})}{(\Delta P_{htr+static} - average(\Delta P_{static0}\Delta, P_{static1})}$$

Qo Measurements (Cont.)

Measurement Methods: Flow rate

- Joule-Thompson Valves: Equal-percentage valves with PI(D) loops used to maintain heat load on plant.
- RF heat load may be extracted from the change in flow rate with an appropriately well calibrated flow meter.
- Potentially – any other methods one could extrapolate the evolved heat from with good resolution.

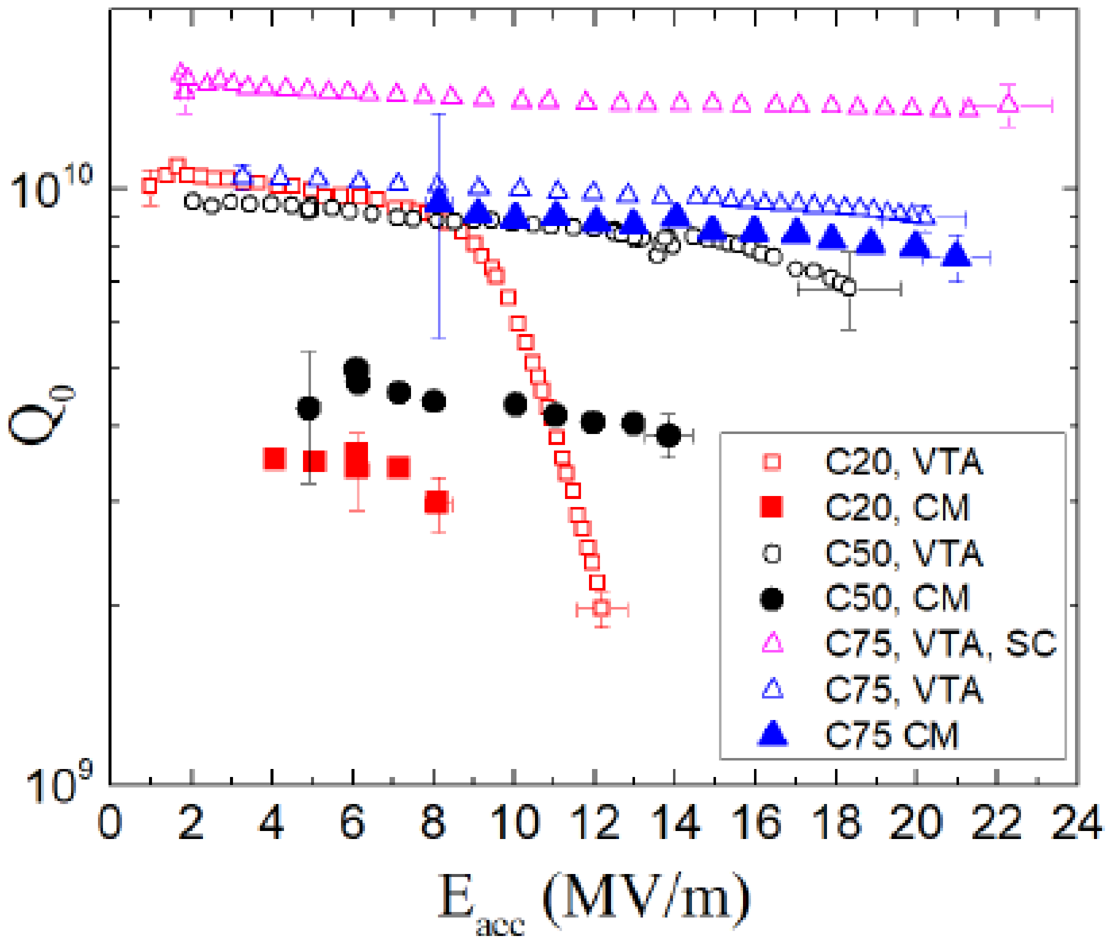
stroke in	% Cv EQ%	flow g/s	% stroke	Heat W
0.5625	100.00	15.00	100	337.5
0.55688	94.95	14.24	99	320.5
0.55125	90.16	13.52	98	304.3
0.54563	85.61	12.84	97	288.9
0.54	81.28	12.19	96	274.3
0.53438	77.18	11.58	95	260.5
0.52875	73.28	10.99	94	247.3
0.52313	69.58	10.44	93	234.8
0.5175	66.07	9.91	92	223.0
0.51188	62.73	9.41	91	211.7
0.50625	59.57	8.93	90	201.0
0.50063	56.56	8.48	89	190.9
0.495	53.70	8.06	88	181.2
0.48938	50.99	7.65	87	172.1
0.48375	48.42	7.26	86	163.4
0.47813	45.97	6.90	85	155.2
0.4725	43.65	6.55	84	147.3
0.46688	41.45	6.22	83	139.9
0.46125	39.36	5.90	82	132.8
0.45563	37.37	5.61	81	126.1
0.45	35.48	5.32	80	119.7



Qo Measurements (Cont.)

Qo Measurements gathered and plotted against accelerating gradient:

[Qo vs E Measurement]



Legend:

VTA: Vertical Test Area
SC: Single Cavity (normally paired)
CM: Assembled Cryomodule

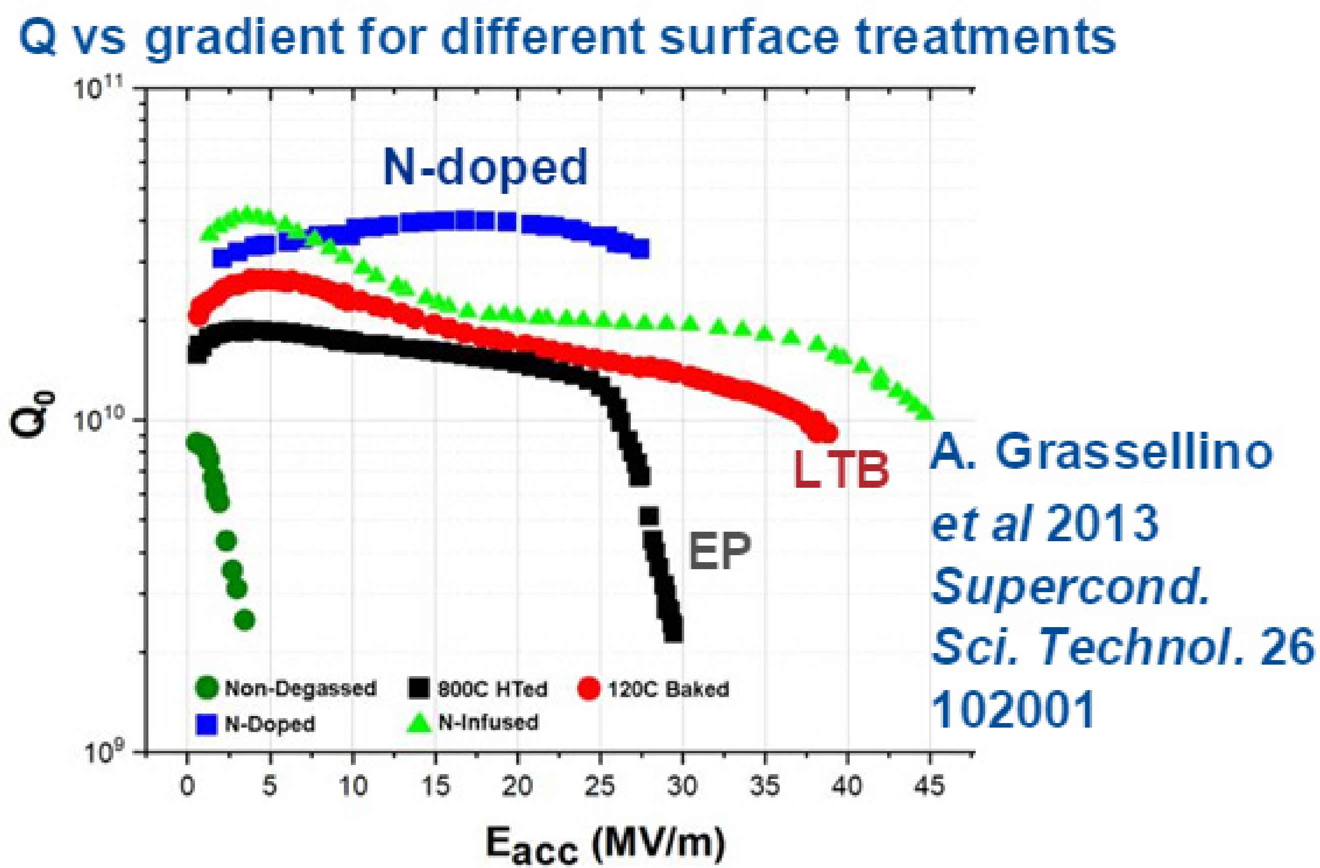
<u>Assembled Qo usually ≤ VTA:</u>

- Cleanliness in assembly
- Additional defects / contaminants introduced.
- Window losses
- Environmental factors:
  - Storage under vacuum
  - Oxidation
  - Etc.

F. Marhauser & G. Ciovati, Evidence of increased radio-frequency losses in CEBAF cavities from the fundamental power coupler cold window, Phys.Rev. AB V24.P092001.

Qo Measurements (Cont.)

- Qo vs E: Anti-Q slope – Produced by surface treatments (ex. Nitrogen or Oxygen doping, others…) Interstitial distribution of impurities lowers mean free path / BCS surface resistance in some cases…



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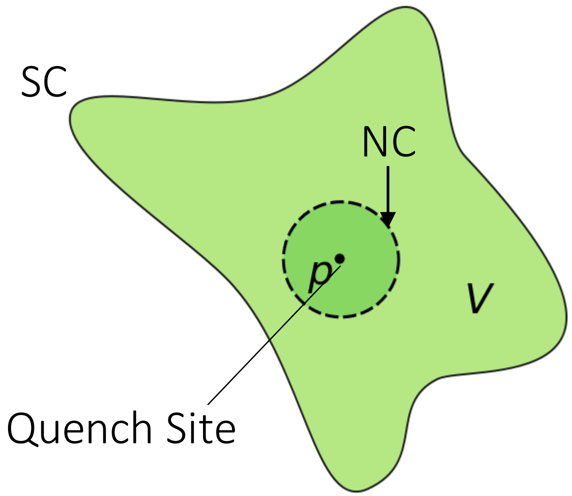
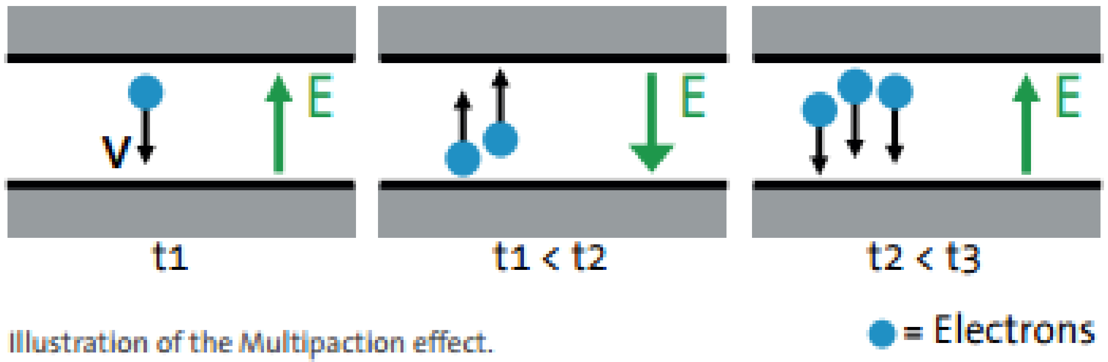
Katrina Howard et al., Analysis of Low RRR SRF Cavities, TTC2022, Aomori, Japan. 11 Oct. 2022. www.ttc2022aomori.org/event/2/contributions/9/

Qo Measurements

- Quenching and Qo: Violent electromagnetic process; can cause flux-trapping resulting in a subsequent drop in Qo. Qo can usually be recovered with a thermal cycle & fast cool down to expel flux.

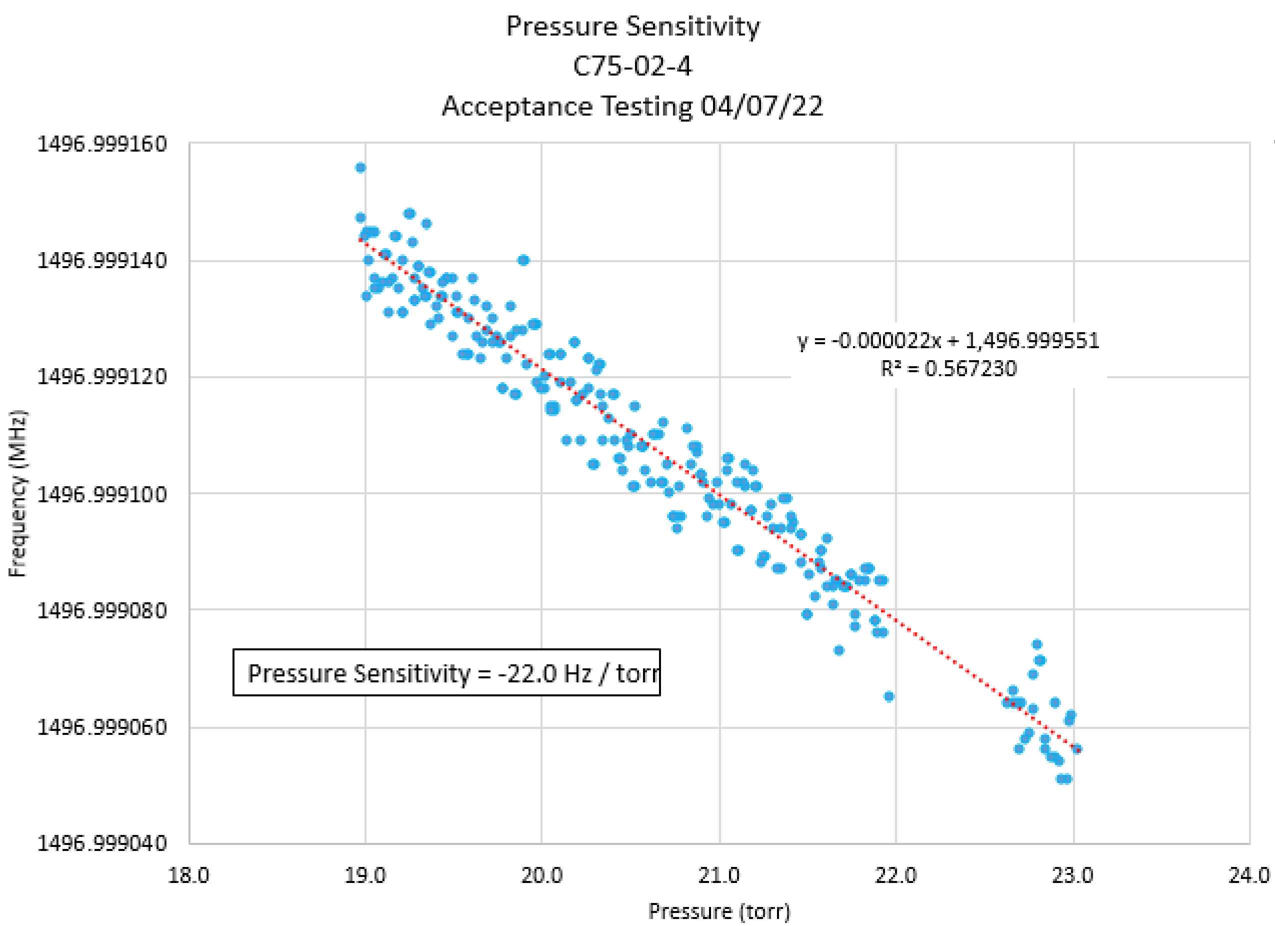




- Resonant Field Emission (aka Multipacting): Emitted Electron travel from somewhere on an RF surface along a trajectory / path an integral number of RF wavelengths long striking another surface and freeing additional electrons. [SEY > 1] The process avalanches until all the available power is taken up by the process.

https://en.wikipedia.org/wiki/File:Neighborhood_illust1.svg
www.everythingrf.com/community/what-is-multi-paction

Pressure Sensitivity



Measurement:

- Cavity on at some fixed gradient; tuners disabled.
- Slew across some wide pressure range – this can be done on pump down following Qo measurement (Pressure rise fine too…)
- Frequency change observed and recorded as the cavity slews through the pressure range.
- Capture change across 2-3 Torr of pressure for good extrapolation.

Pressure sensitivity measurement can be used to correct frequency data during various measurements to ab initio pressure values in data review.

Microphonics Measurements

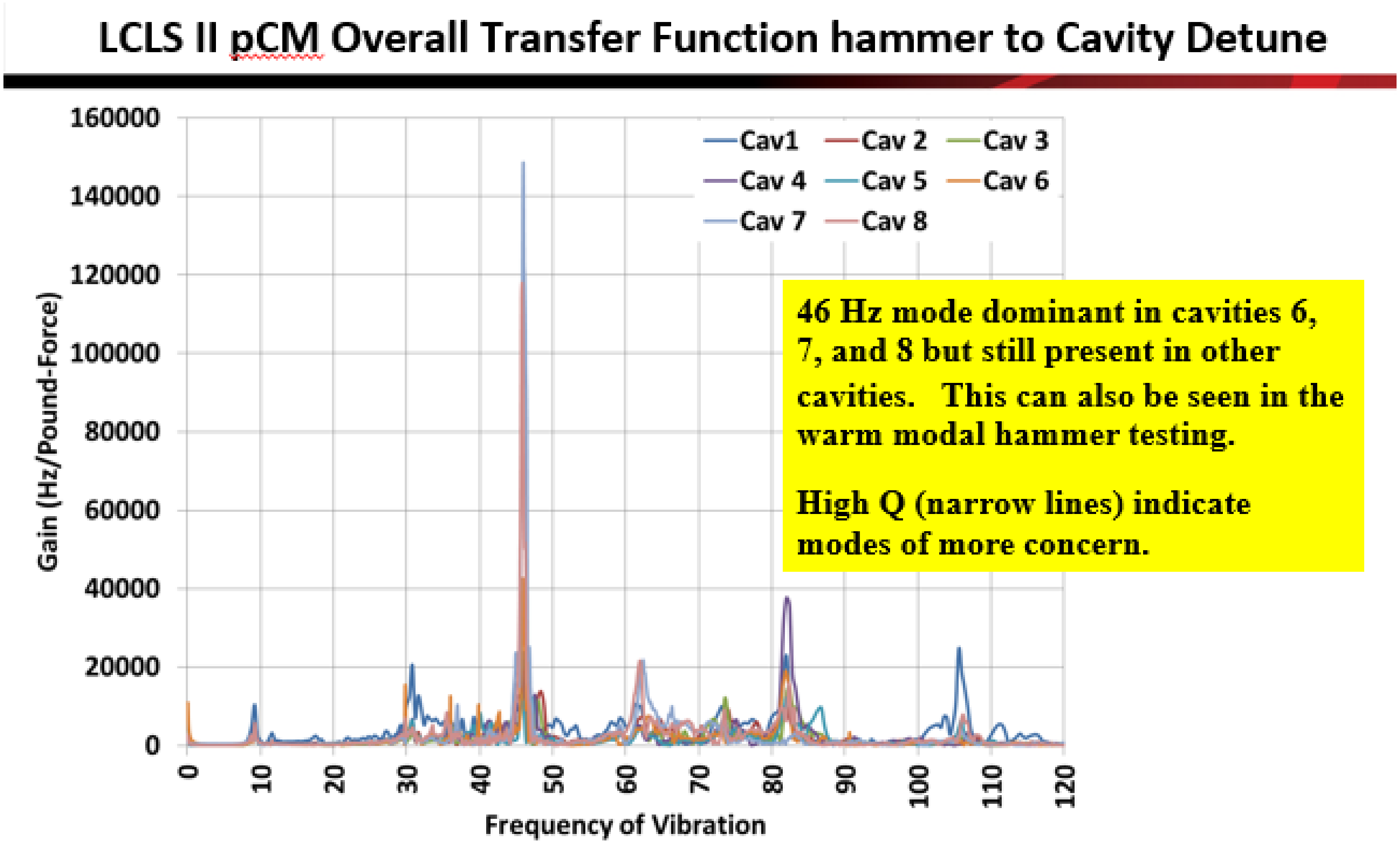
Process:

- Remotely controlled impact hammer or other calibrated method.
- Set to strike location of interest for measurement:
    - Beamline flange
    - Coupler Vacuum Pipe
- Cavity to be measured on tuned up at low power.
- Detune phase shift data taken through other 7 cavities simultaneous to force sensor data.

- Switch powered cavity and repeat – 2 data sets combined to represent all 8 cavities.

T. Powers et al., Microphonics Testing of LCLS-II Cryomodules at JLAB, Proceedings of SRF2019(TUP034), Dresden, Germany.

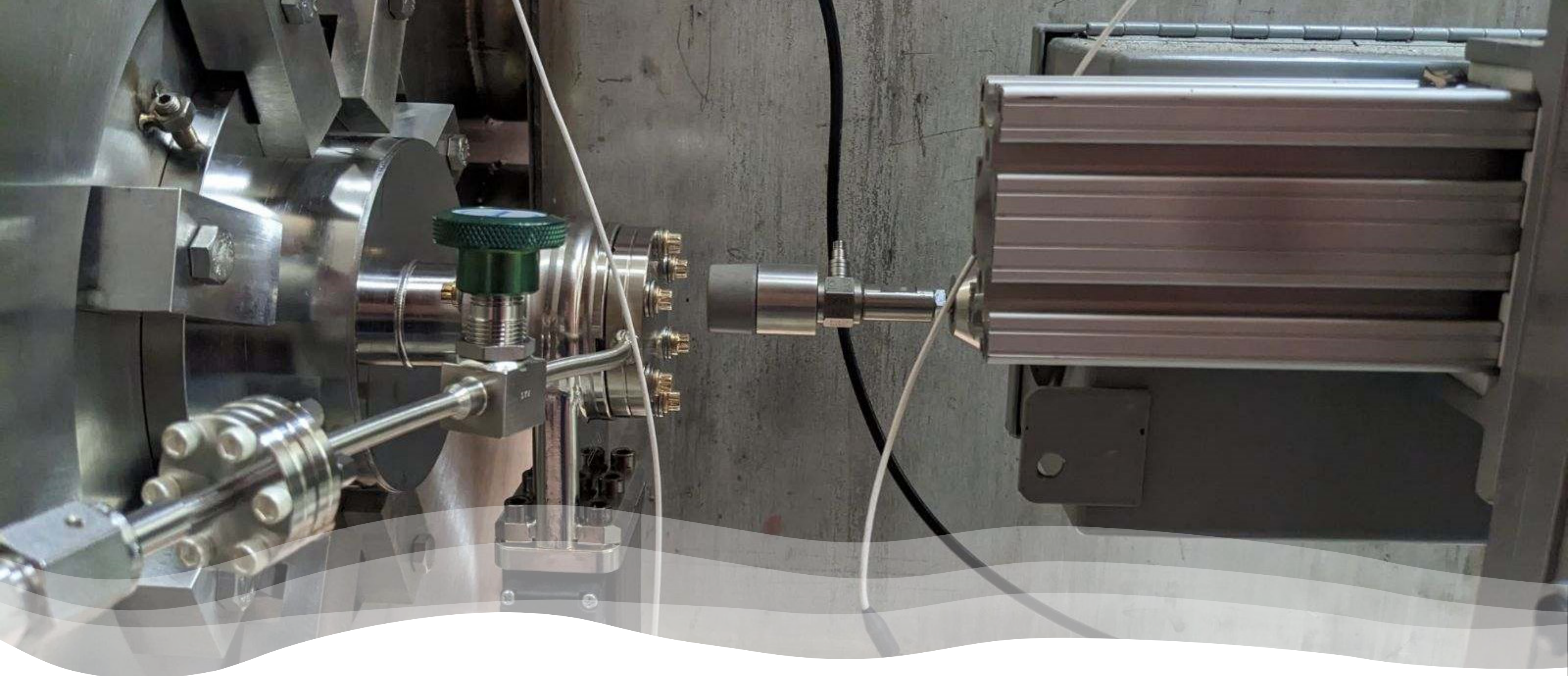
Microphonics Measurements (Cont.)



46 Hz mode dominant in cavities 6, 7, and 8 but still present in other cavities. This can also be seen in the warm modal hammer testing.

High Q (narrow lines) indicate modes of more concern.

Transfer function from cavity 8 beam line strike to cavity frequency shift for all 8 cavities.



Common Testing Locations:

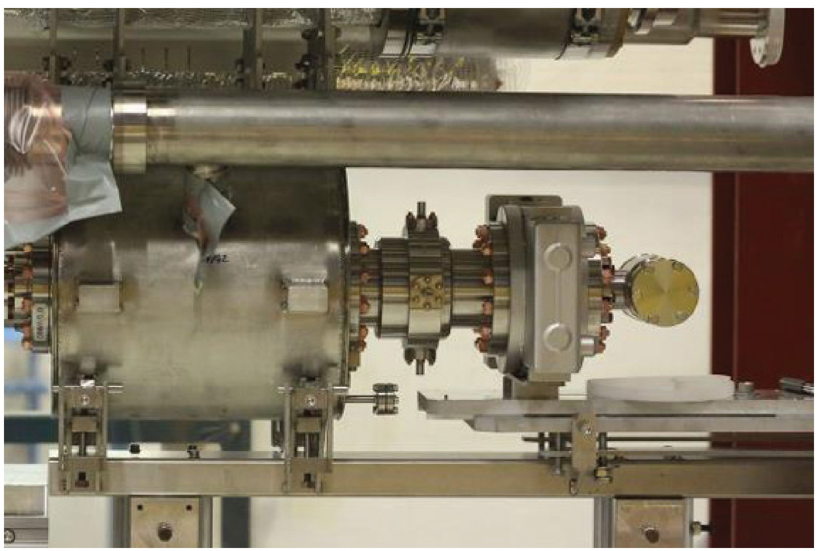
- Beam line flanges
- Vacuum pumping attachment points
- Tuners

Mitigations:

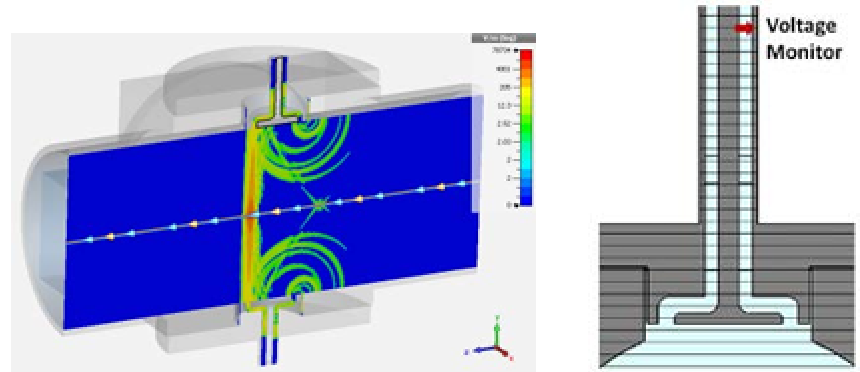
- Prior planning, design, and simulation work
- Stiffening Rings
- Fast tuning schema (Piezos etc.)
- More power

Cold Instrument Tests

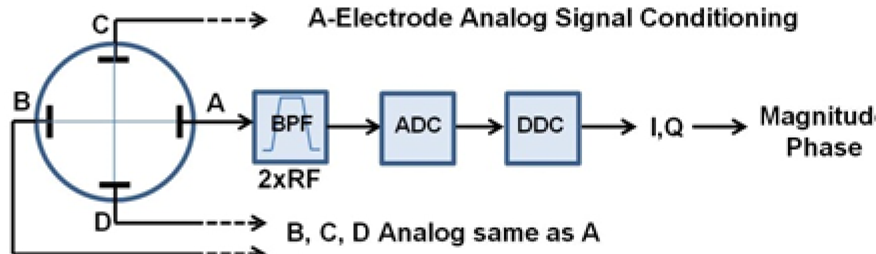
- For modules which have instruments in the cryogenic space the end of RF testing is the optimal time to test them.
- Examples:
  - Magnets
  - Beam Position Monitors (BPMs)
  - Faraday Cup (Measure field emitted current)



Cold Reentrant BPM with its quadrupole installed at the 3.9 GHz cryomodule.



CST model of the button pickup (right) and a snapshot of the instant electric field induced by 1 mm bunch.



Block diagram for BPM electronics.

A. Lunin et al., Development of a Button BPM for the LCLS-II Project, Proceedings of IBIC2014 (TUPF18), Monterey, CA, USA.

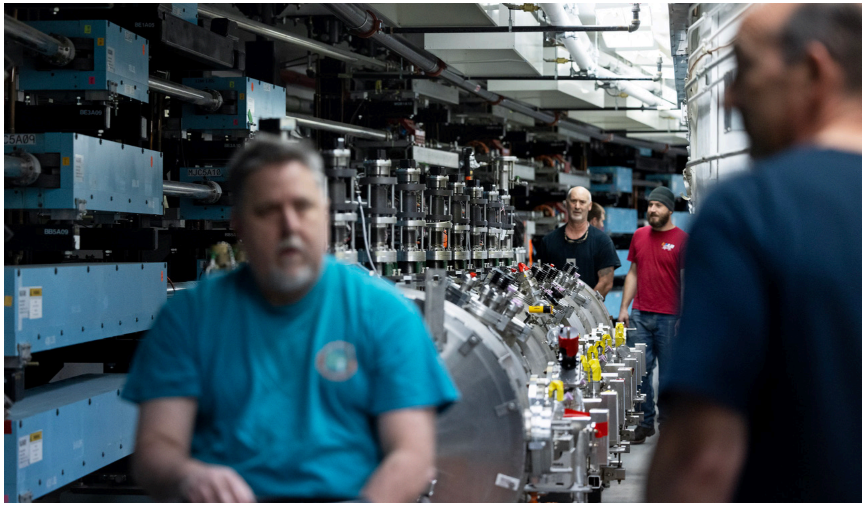
C. Simon et al, Design and Beam Test Results of the Reentrant Cavity BPM for the European FEL, Proceedings of IBIC2016 (TUPG17), Barcelona, Spain.

Data Review

A quick word about data review:

- Someone should always be doing online review of the data in the background when testing:
  - Spot bad data points or measurements that don't make sense – usually due to equipment error or mis-calibration.
  - Head start on final testing report & communication of results.
  - Live updates to management chain about measurement process – everyone is usually interested.
- 'Punch list' activities: Measurements that didn't make sense or were possibly omitted due to time considerations earlier may be completed in the final few shifts prior to warm-up of the cryomodule.
- Warm-up prep post 'Punch List' – Detune cavities to starting position and other preparations…

Warm-up & Transport



Cryomodule warmed up gracefully:

- Driven by static heat and perhaps application of heaters to boil off liquid.
- Static heat alone one liquid gone; gradual warm up for thermal stresses.
- Insulating vacuum bled up to atmosphere once warm.

Module removed and transported with beam line remaining under vacuum. If transport long distance shock sticks can be used to measure forces in travel.

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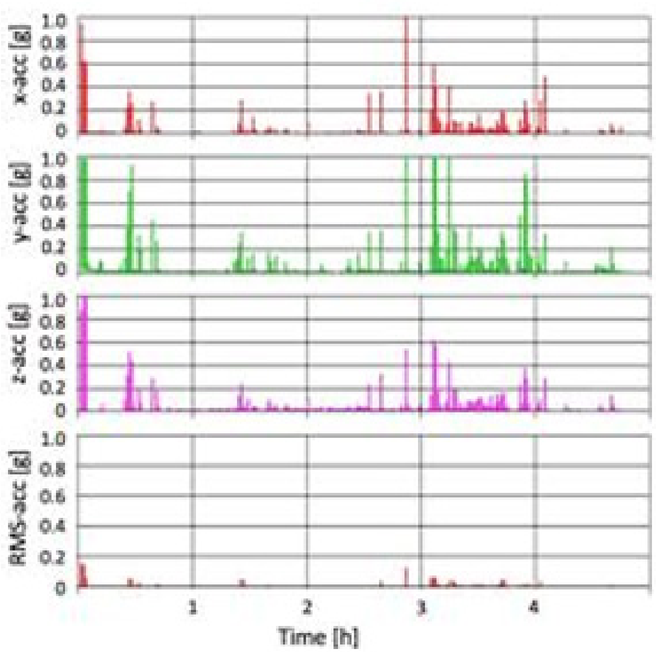
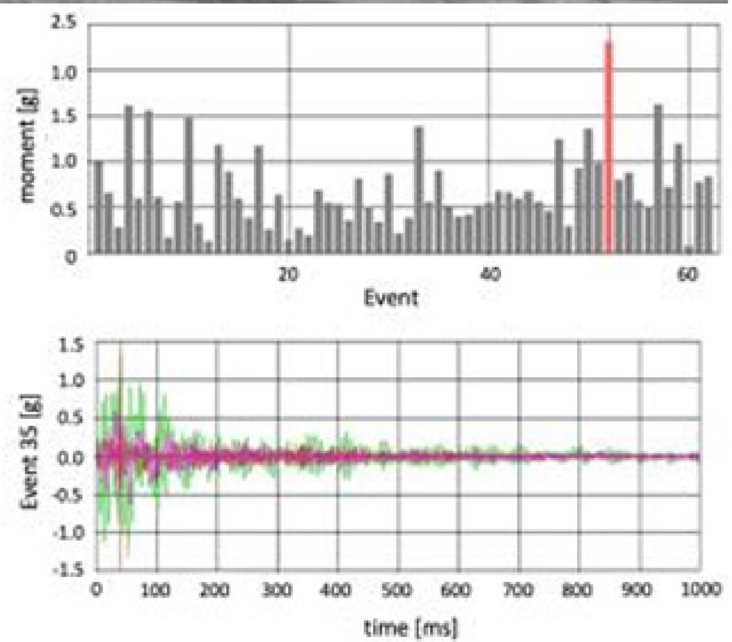
Transport (Continued)





Accelerometer data taken during the transportation of the cryomodule

G Hoffstaetter et al., CBETA Design Report, BNL-114549, CBETA/015b, June 2017. www.bnl.gov/isd/documents/95552.pdf

Testing In-situ

If testing through other than control system (ex. Commissioning cart with power meters) - scale probe values in control system so measured gradients through control system correspond with measured gradients through commissioning setup / power meters.

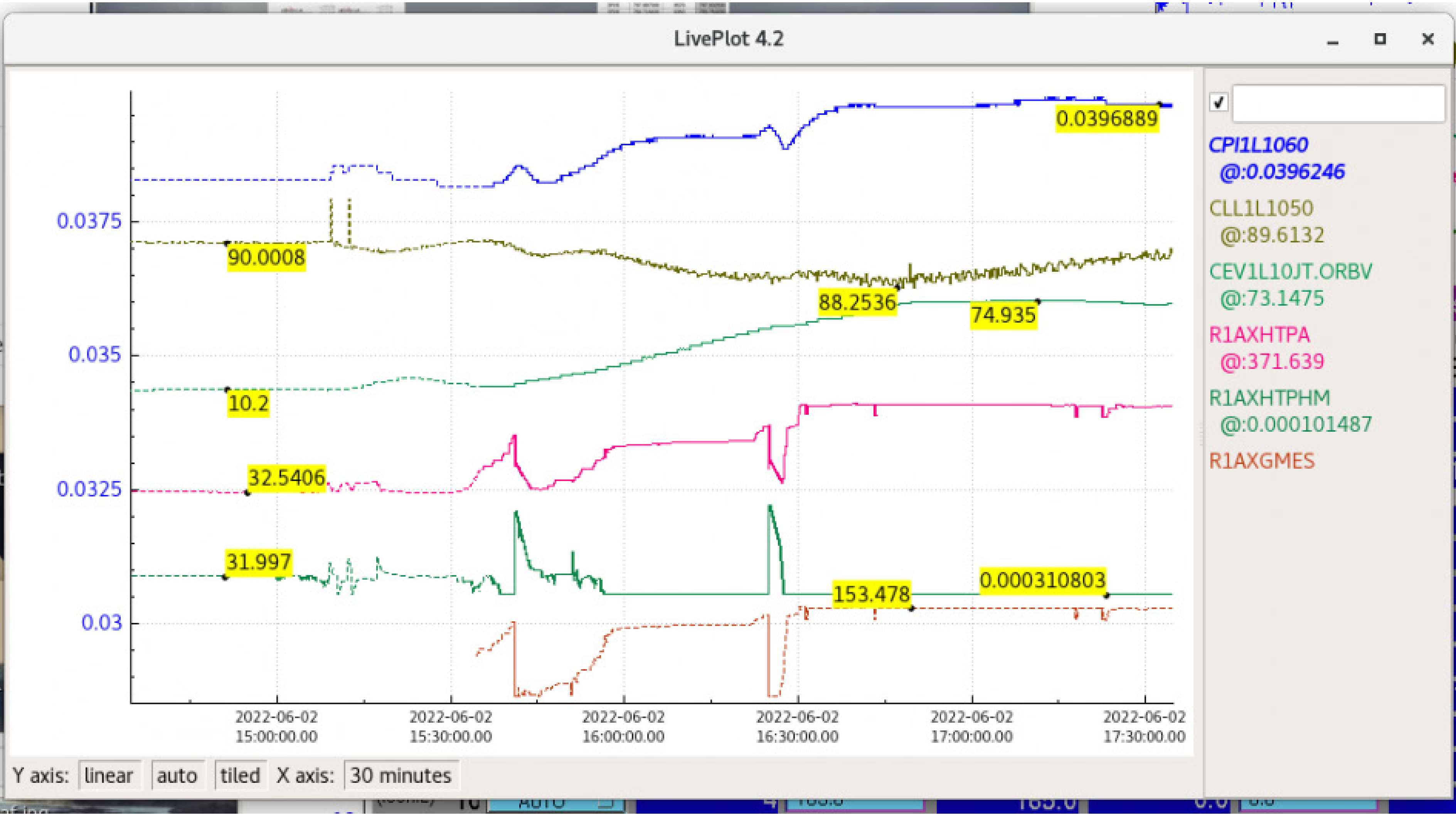
Repeat a sub-set of the earlier test facility testing:

- Emax / Eop measurements (Max gradient + 1-hr run)
- Qo vs. E measurements
- Field Emission measurements

Measurements are repeated to ensure no degradation in transport or new issues which have cropped up.

In addition to the above measurements, a simultaneous run of all the cryomodule's cavities will be executed to ensure heat load, microphonics, etc. are compatible with 1-hr run gradients.

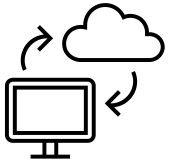
Heat Load

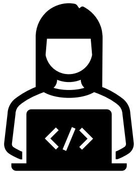

LivePlot 4.2
0.0396889
0.0375
90.0008
88.2536
74.935
0.035
10.2
32.5406
0.0325
31.997
153.478
0.000310803
0.03
2022-06-02 15:00:00.00
2022-06-02 15:30:00.00
2022-06-02 16:00:00.00
2022-06-02 16:30:00.00
2022-06-02 17:00:00.00
2022-06-02 17:30:00.00
CPI1L1060 @:0.0396246
CLL1L1050 @:89.6132
CEV1L10JT.ORBV @:73.1475
R1AXHTPA @:371.639
R1AXHTPHM @:0.000101487
R1AXGMES
Y axis: linear auto tiled X axis: 30 minutes

System Integration

Data Review and Transmittal to Operations:

- Testing facility data [Pressure / frequency corrected]
- In situ testing data [Pressure / frequency corrected]





Ensuring a timely data transmittal to operations allows commissioning data to be incorporated into the necessary software tools / databases for a smooth transition to operations following system integration.

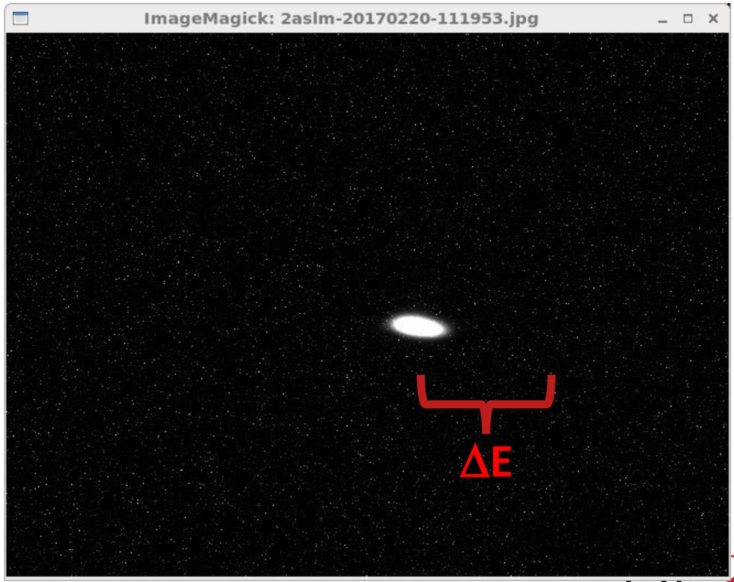
Last-Minute Remediation:

- Final Q_{ext} adjustments with stub tuners (if further adjustments are required…)
- Tuner motors / gear boxes if insufficient torque
- Other repairs possibly discovered in testing…

System Integration

RF calibrations (Beam-Based Calibrations):

- Power meters usually a ~5% number (consult manufacturer's specs)
- Operations usually desires to know gradient to higher precision
- Magnets often mapped to 10^{-5} (or better) precision; one can perform an energy measurement in a dispersive location in the beam line.
- Make energy shifts at the precision at which they can be observed by your diagnostic and scale the gradient read through the control system with observed results / position shifts.

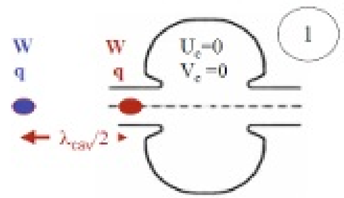


Beam-Loading

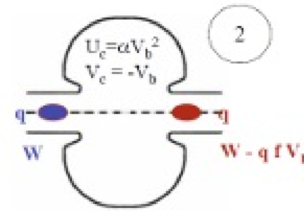
S. Belomestnykh, Tutorial: Beam-cavity interaction & Operational Aspects of SRF Systems with Beam, Prepared for SRF2019, Dresden, Germany. 6/29/2019. accelconf.web.cern.ch/srf2019/talks/satu1_talk.pdf

Fundamental theorem of beam loading

- This theorem relates the energy loss by a charge passing through a structure to the electromagnetic properties of modes of that structure.
- A point charge crosses a cavity initially empty of energy.
- After the charge leaves the cavity, a beam-induced voltage $V_{b,n}$ remains in each mode.
- By energy conservation the particle must have lost energy equal to the work done by the induced voltage on the charge.
- What fraction (f) of $V_{b,n}$ does the charge itself see?



Half an rf period later, the voltage has changed in phase by π



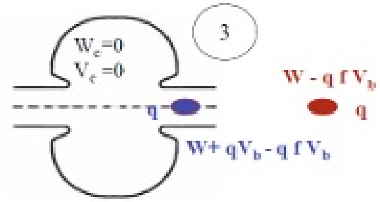
For simplicity:

Assume that the change in energy of the particles does not appreciably change their velocity

Notice:

$\alpha V_b^2 = q f V_b \implies V_b = q f / \alpha$

V_b is proportional to q



Note that **the second charge** has gained energy

$$\Delta W = 1/2\ qV_b$$

from longitudinal wake field of **the first charge**

To summarize:

1. The induced voltage of a beam must have a phase exactly opposite the motion of charge.
2. The particle sees exactly ½ of its own induced voltage

By energy conservation:

$$W + qV_b - q fV_b + W - q fV_b = W + W$$

$$\implies f = 1/2$$

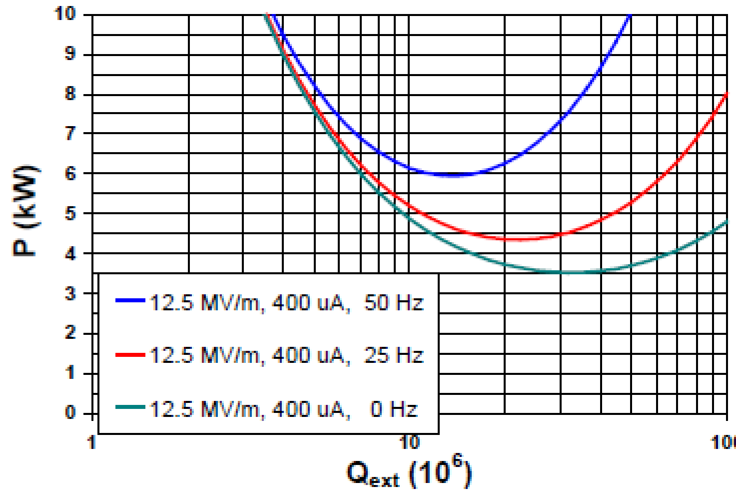
P. B. Wilson, "High energy electron linacs: Application to storage ring RF systems and linear colliders," *AIP Conf. Proc.* **87**, 452 (1981). Also, SLAC-PUB-2884 (Rev.), November 1991.

S. Verdu-Andres, Beam-Cavity Interaction, Tutorial prepared for SRF2021, East Lansing, MI. 25 June 2021. indico.frib.msu.edu/event/38/attachments/159/1145/20210625_Beam-Cavity_SRF21-Tutorials_VerduAndres.pdf

Beam-Loading

- Beam loading results in more power required to maintain the same cavity gradient with continuous (or appropriately phased) beam bunches.

- Not a problem unless power required exceeds that available from your power source.
- If this is the case:
  - Tune the cavity
  - Lower gradient set point
  - Verify Qext minimizes power required at set current/detuning.
  - Better power source

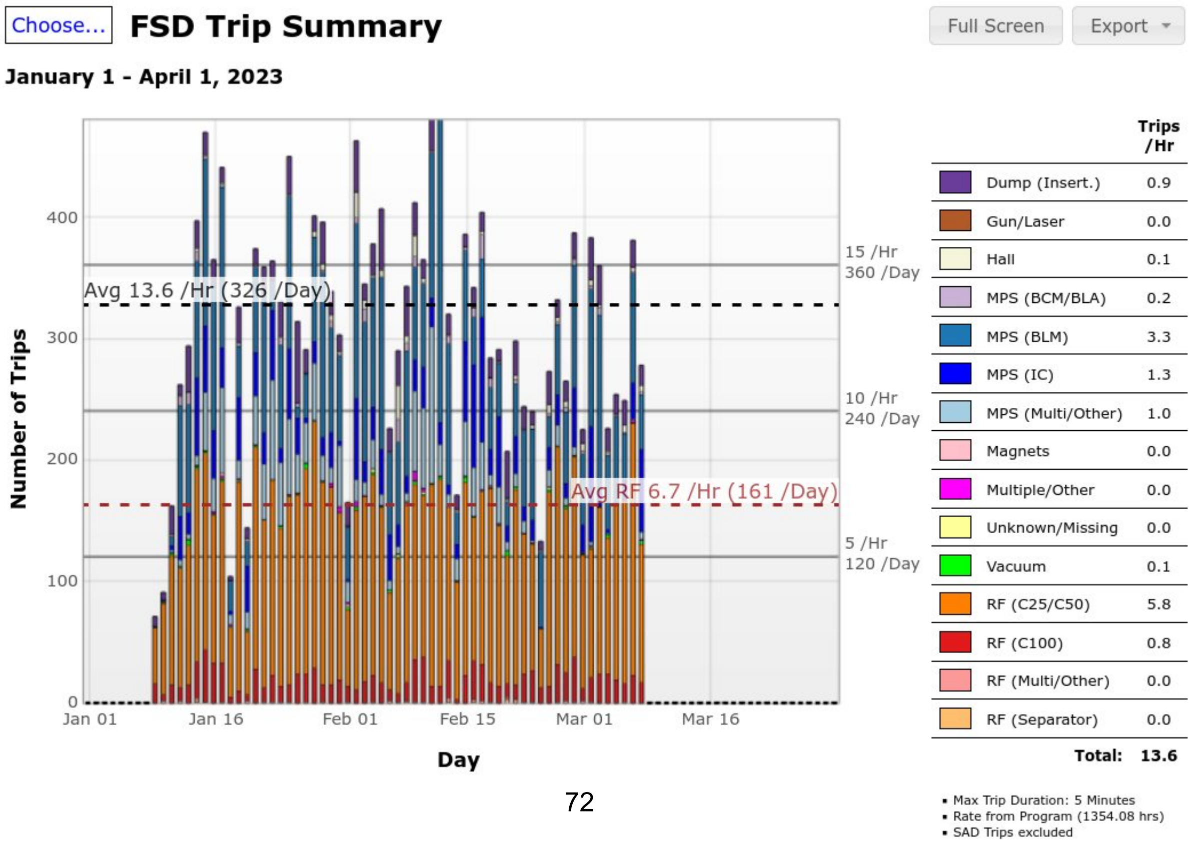


Required RF power vs. external Q at the design gradient of 12.5 MV/m, design current of 400 μA, and maximum detuning of 0, 25, and 50 Hz

J. Delayen, Development of a Cryomodule for the CEBAF Upgrade, Proceedings of SRF1999 (TUP019), Santa Fe, NM, USA.

Integrated Up-Time / Fault Rate

- Goal of experiment: As much beam as possible to get statistics…
- RF (or any) trips take time away – beam trips off, interlock/cavity must be reset and ramp back to design gradient, beam current must ramp back up to target.
- Cost – benefit analysis: Can you tune a cavity / turn it down slightly / etc. in order to lower fault rate while maintaining net beam energy.



Statistical Methods (Basic):

Root Mean Square of Signal:
(Sampling window of choice)

$$RMS = \sqrt{\frac{1}{n}\sum_i x_i^2}$$

Discrete Samples:

Compute:

Arithmetic Mean: & Standard Deviation:

$$\bar{x} = \mu = \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right) = \frac{x_1 + x_2 + \cdots + x_n}{n}$$

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}}$$

σ = population standard deviation

N = the size of the population

x_i = each value from the population

μ = the population mean

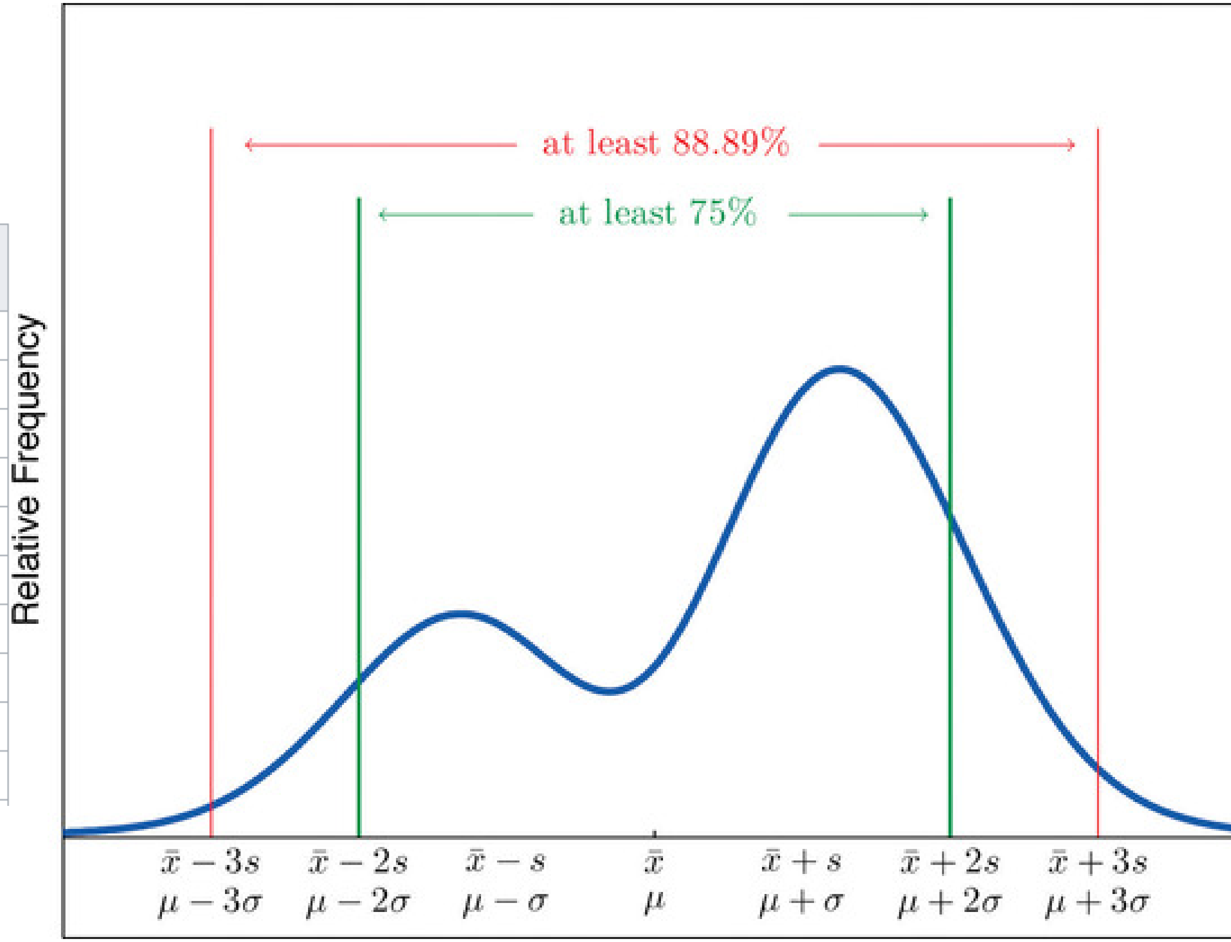
Chebyshev's Theorem

Requirements: Variable under test be both random and have both finite μ / σ

$$\Pr(|X-\mu| \geq k\sigma) \leq \frac{1}{k^2}$$

k	Min. % within *k* standard deviations of mean	Max. % beyond *k* standard deviations from mean
1	0%	100%
$\sqrt{2}$	50%	50%
1.5	55.56%	44.44%
2	75%	25%
$2\sqrt{2}$	87.5%	12.5%
3	88.8889%	11.1111%
4	93.75%	6.25%
5	96%	4%
6	97.2222%	2.7778%
7	97.9592%	2.0408%

(...)



https://en.wikipedia.org/wiki/Chebyshev%27s_inequality

Shafer & Zhang, Introductory Statistics, Open Education Resource (OER) LibreTexts Project. stats.libretexts.org/Bookshelves/Introductory_Statistics/Introductory_Statistics_(Shafer_and_Zhang)

Empirical Rule aka 68–95–99.7 Rule

__Vysochanskij–Petunin Requirements:__ As Chebyschev's, but unimodal only (1 peak in data)

Vysochanskij–Petunin inequality: Refinement on data spread under 95% @ 3σ.

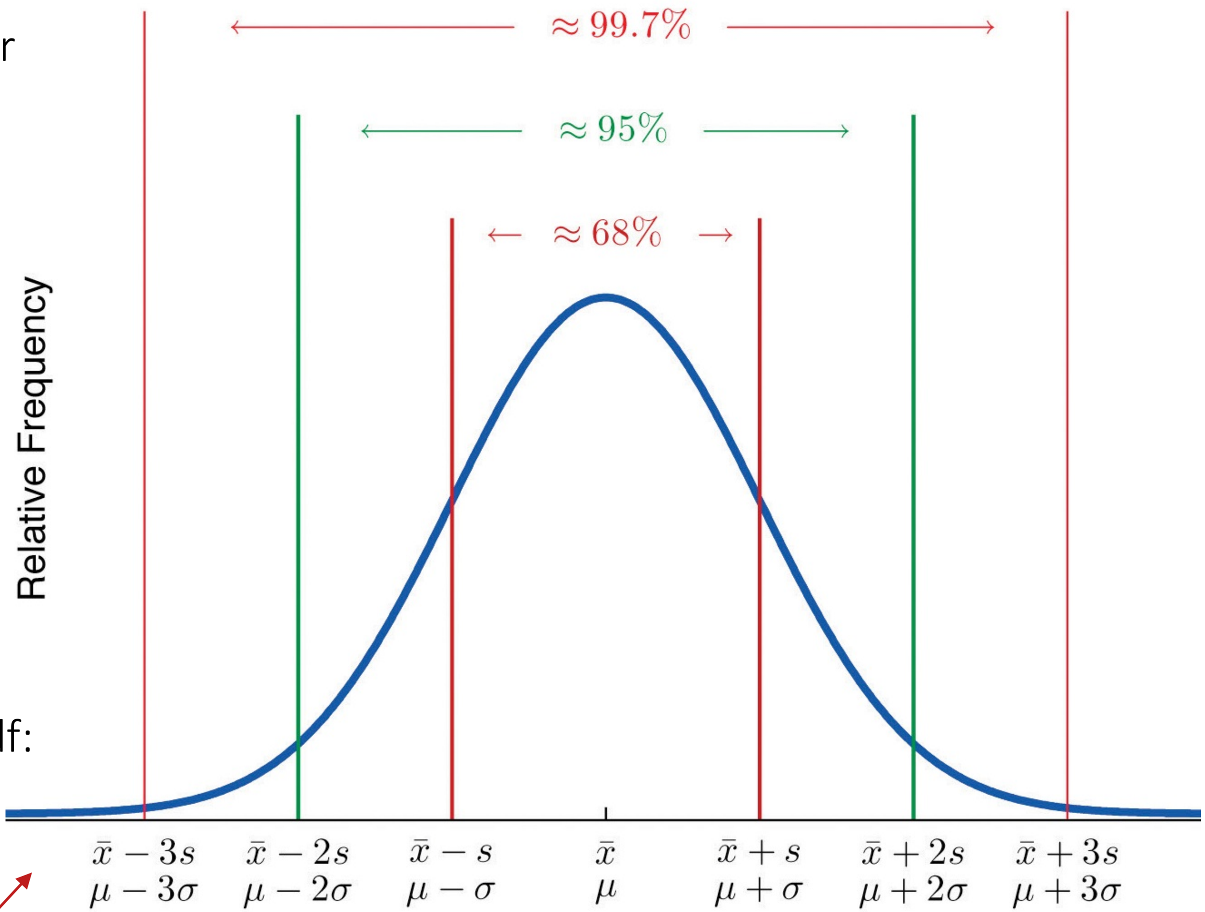
If constraint of 'normality' also employed (as proven by one's favorite test of choice):

- Z / T / Student T Tests
- Kolmogorov-Smirnov
- Shapiro-Wilk
- Pearson's Chi-Squared
- Etc.

Standard / Normal / Gaussian pdf:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

Empirical Rule applies.



Shafer & Zhang, Introductory Statistics, Open Education Resource (OER) LibreTexts Project.
https://stats.libretexts.org/Bookshelves/Introductory_Statistics/Introductory_Statistics_(Shafer_and_Zhang)

en.wikipedia.org/wiki/Vysochanskij%E2%80%93Petunin_inequality

en.wikipedia.org/wiki/68%E2%80%9395%E2%80%9399.7_rule

An Example: CEBAF C20 IR Sensors

IR trip thresholds based on a 2K survey of data – calibrations may wander or sensors fail.

Sensor readbacks surveyed at 2K; difference between set and measured random variable:

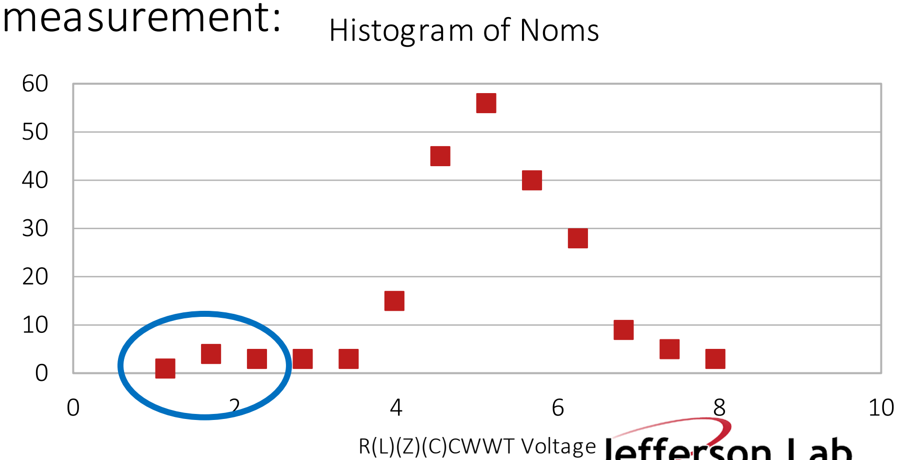
Cavity		Surveyed Nom* (x)	RFCM Nom	x Set – Read	x-m	(x-m)^2	|x| - s	|x| - 2s	|x| - 3s
R121CWWT	1	4.690	4.28	-0.4101435	-0.198385	0.03935662	0.10664187	-0.1968598	-0.5003615
R122CWWT	1	5.057	4.58	-0.477177	-0.2654185	0.07044699	0.17367536	-0.1298263	-0.433328
R123CWWT	1	5.495	4.79	-0.7047511	-0.4929926	0.24304171	0.40124946	0.09774778	-0.2057539
R124CWWT	1	4.288	3.73	-0.558371	-0.3466125	0.12014024	0.25486937	-0.0486323	-0.352134
R125CWWT	1	6.716	5.17	-1.5461538	-1.3343953	1.78061088	1.24265217	0.9391505	0.63564882
R126CWWT	1	4.258	3.54	-0.7184615	-0.506703	0.25674795	0.41495986	0.11145819	-0.1920435
R127CWWT	1	3.081	2.73	-0.3511765	-0.1394179	0.01943736	0.0476748	-0.2558269	-0.5593286

Sensor deviation from mean value by σ, 2σ, & 3σ examined… [Data should be normally distributed; single sensor and window type…]

Apply Empirical Rule: 95% of data should be within 2σ & 99.7% within 3σ.

As found data did not conform, ergo issues with measurement:

- Several sensors were discovered requiring recalibration
- Some sensors taken offline in favor of the use of a bolometer and scheduled for later replacement. (Long-term Radiation Damage)



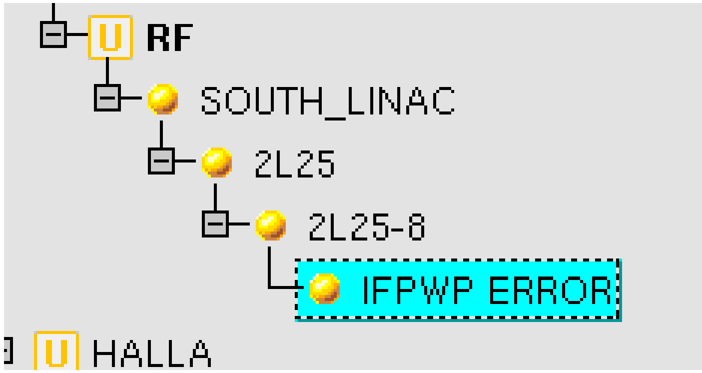
Alarm Handler:

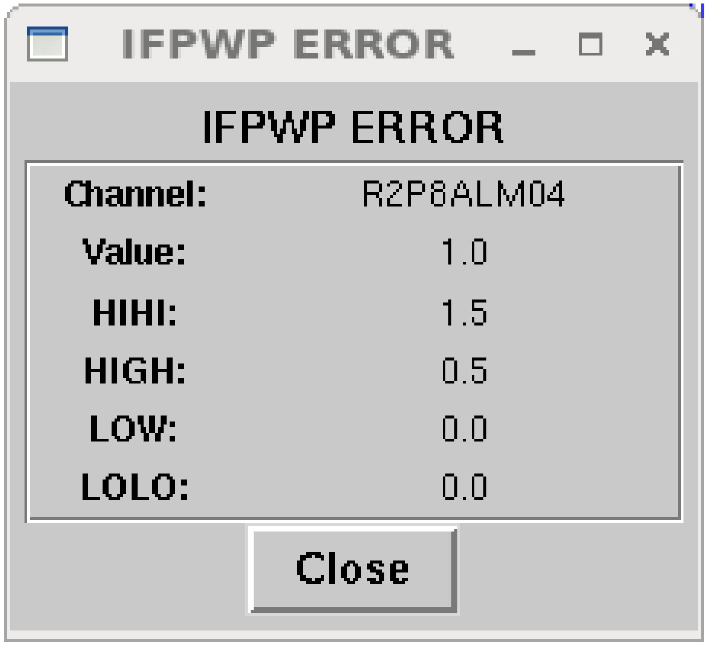
Monitoring signals directly is cumbersome.

Relegate monitoring to an alarm handler which can alert you to when there is something interesting to pay attention to.

<u>Example signals:</u>

- Forward / Reflected Power
- Gradient set point – Measured < Limit
- Gradient & Phase PID loop drives / offsets / PID settings
- Power supply drive / settings
- Local Oscillator/IF Power

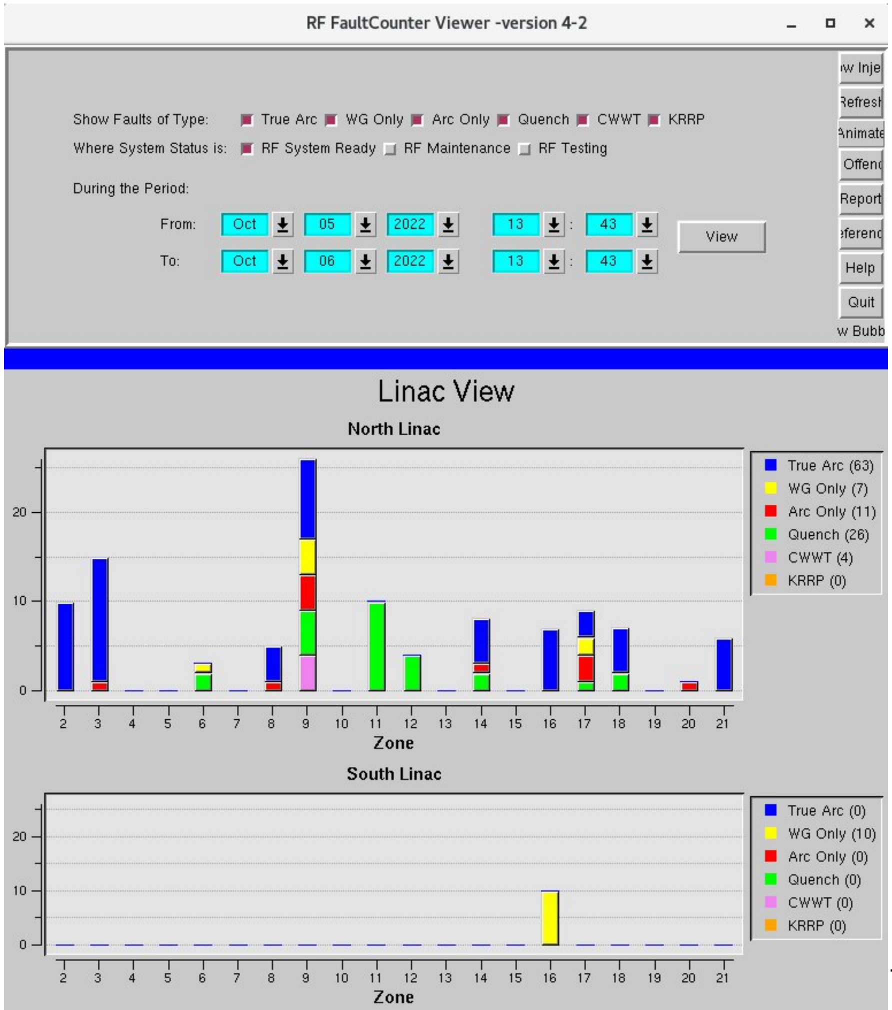


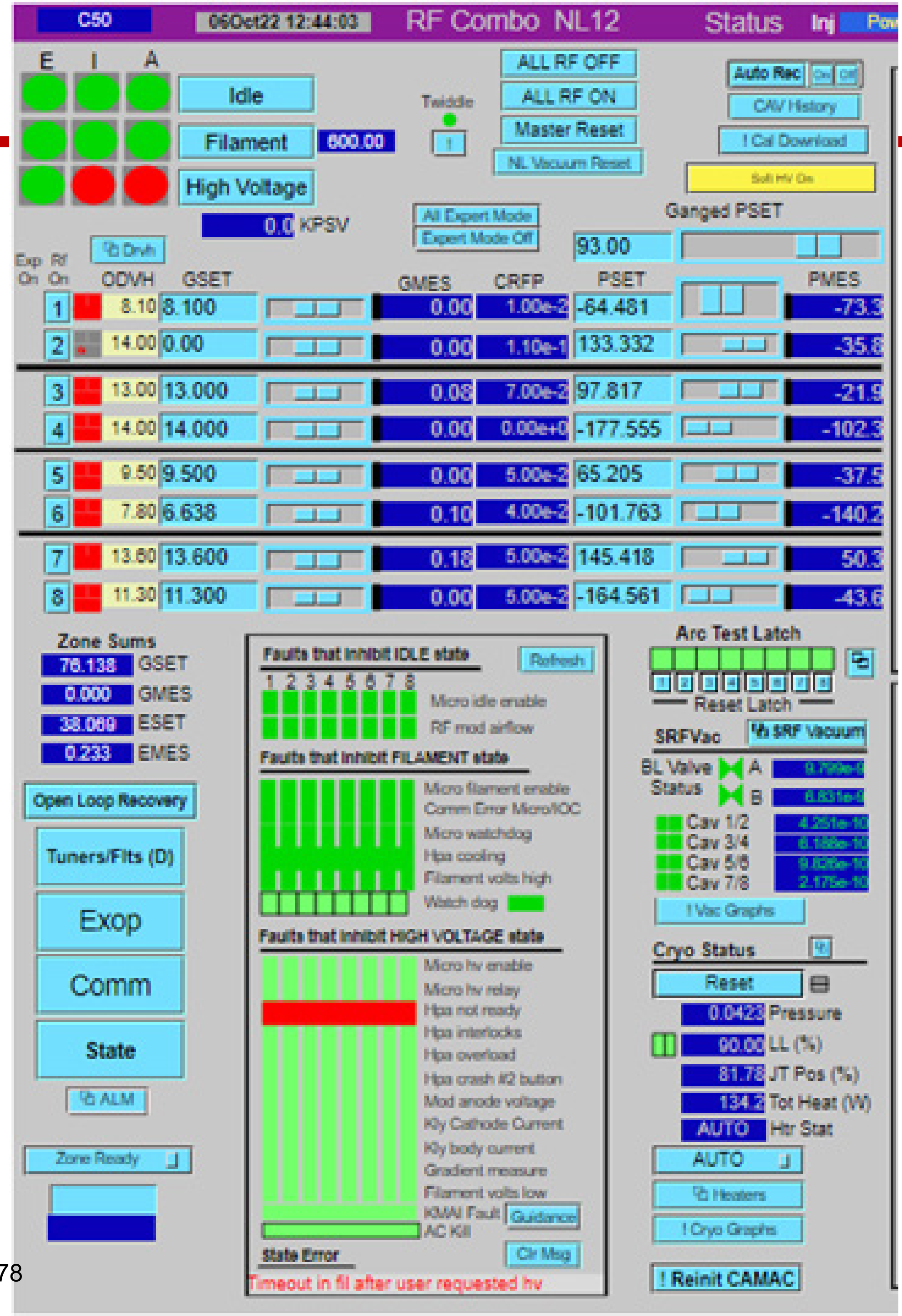


Set reasonable warning/fault limits to alert Operations if issue present – which they can then report to SMEs.

Fault Classification:

Bin various interlock & mechanical faults at low level in control system; archive / record with status word:

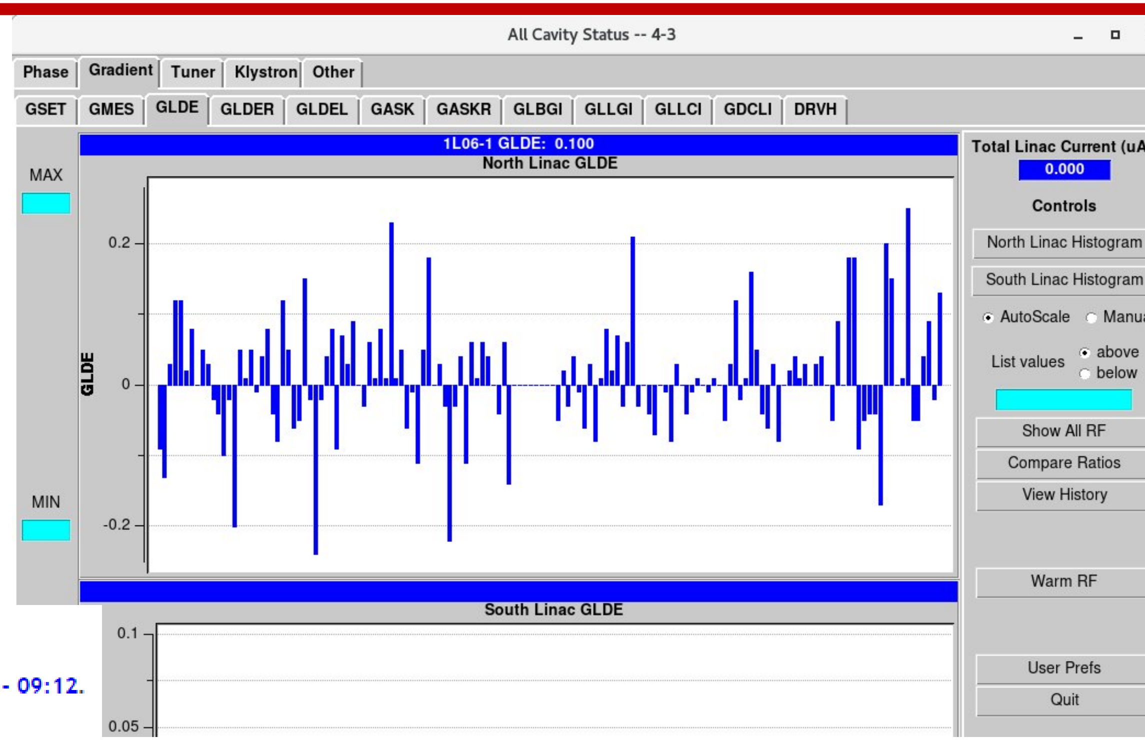




Fault Classification [On-line Analysis]:

An online monitoring tool:

Graphically represents dozens of parameters as compared against other cavities / zones so outliers are quickly distinguished.



RF Health Check MYA

Lognumber 4045254. Submitted by michaelm on Thu, 09/22/2022 - 09:12.

Logbooks: ELOG RFLOG
Tags: Autolog

20 rows, time span -8h to 0
Minimum GMES threshold 2.9 MV/m
CRFP

Cavity	Channel	MAX	MIN	MEAN	SIGMA	RMS
1L25-2	R1P2CRFP	8.84417	0	4.54731	1.59399	4.8186
1L22-6	R1M6CRFP	7.72436	2.45006	4.42161	1.50353	4.67025
2L24-2	R2O2CRFP	8.5291	2.03977	5.04213	1.49719	5.25972

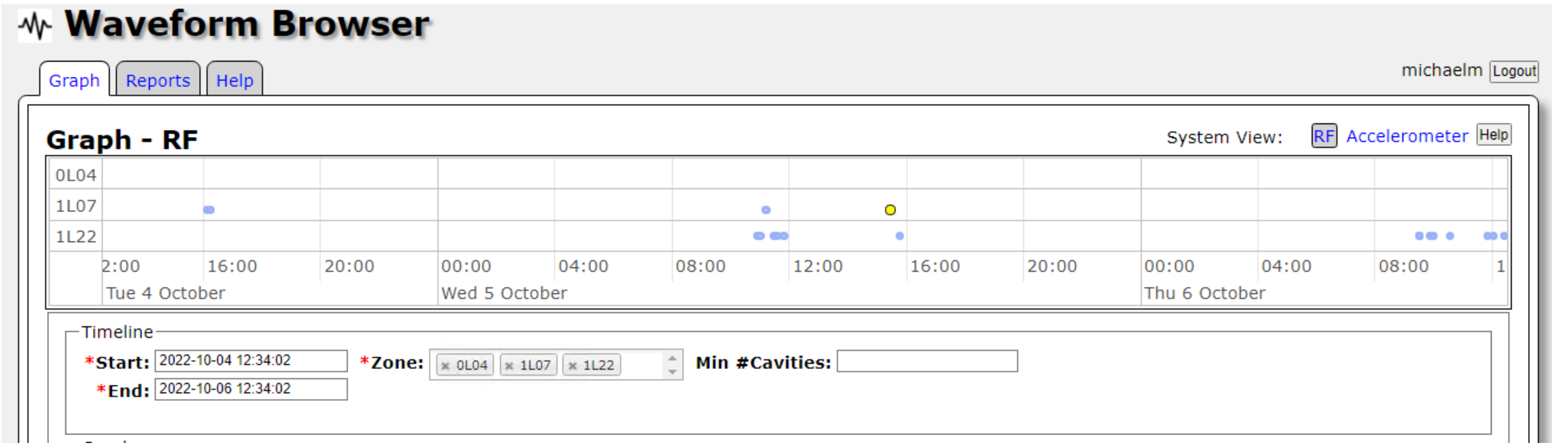
'RF Health Check':

Online and Offline Versions:

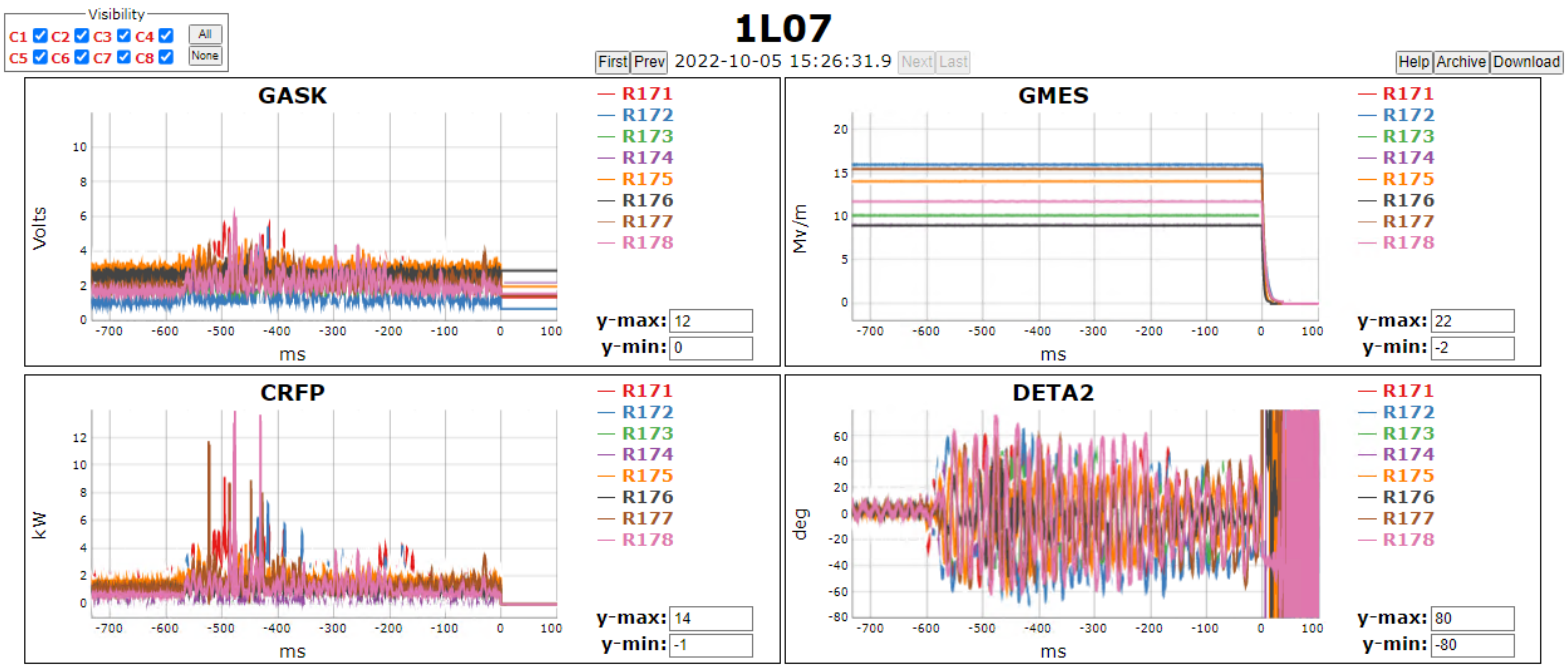
- Online: Collects over 60s window and carries out analysis
- Offline: Definable time scale; nominally 8 hours

Statistics for both exported to the logbook.

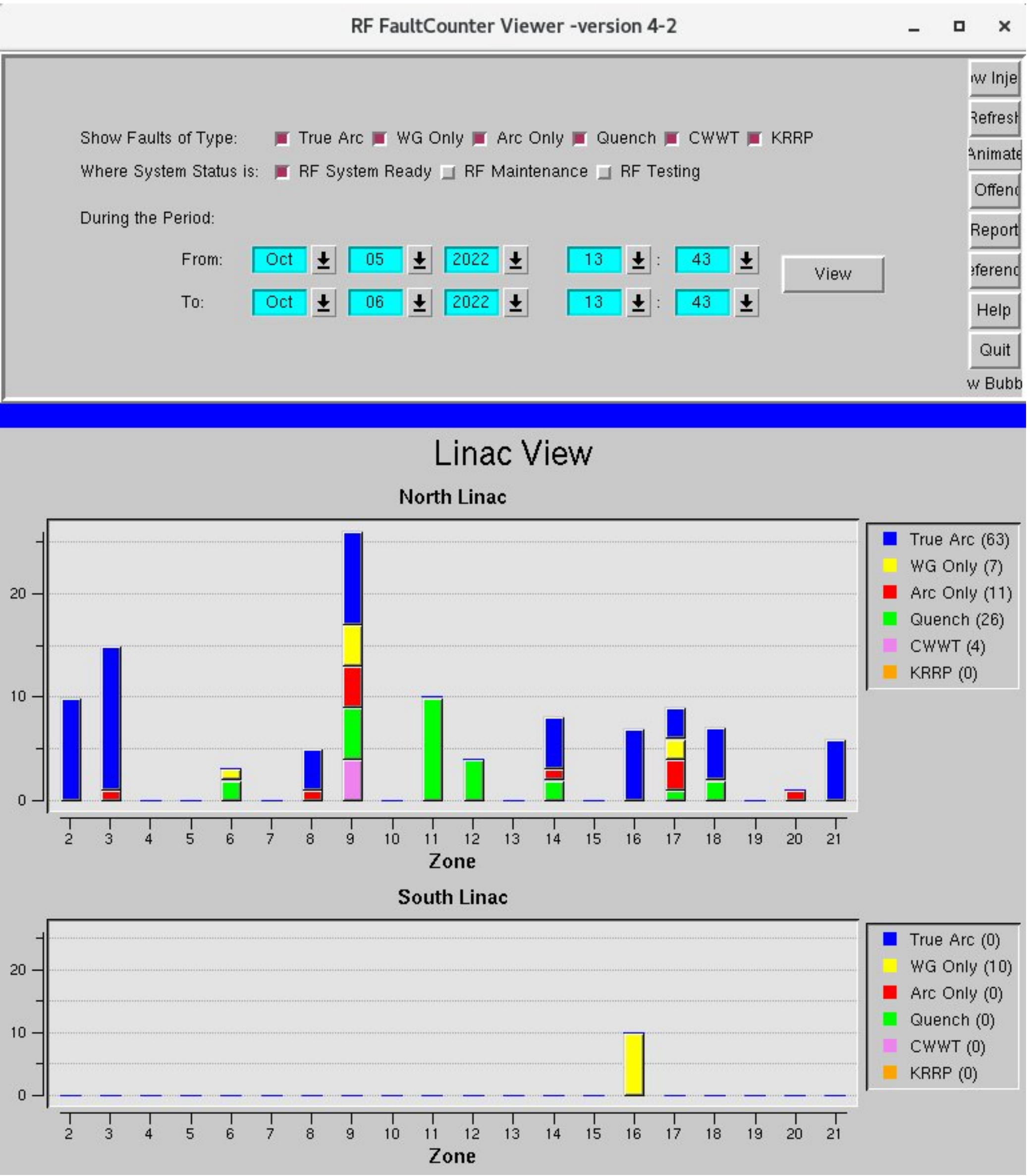
Fault Classification [On-line Analysis]:

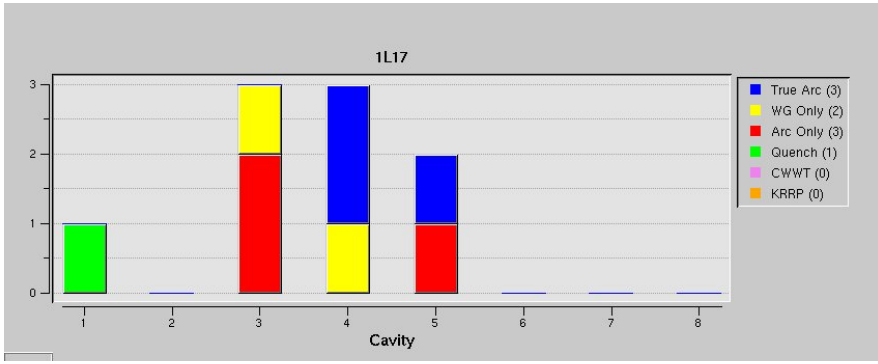


Waveform Browser: At IOC/FPGA level; fast output of waveform records to control system



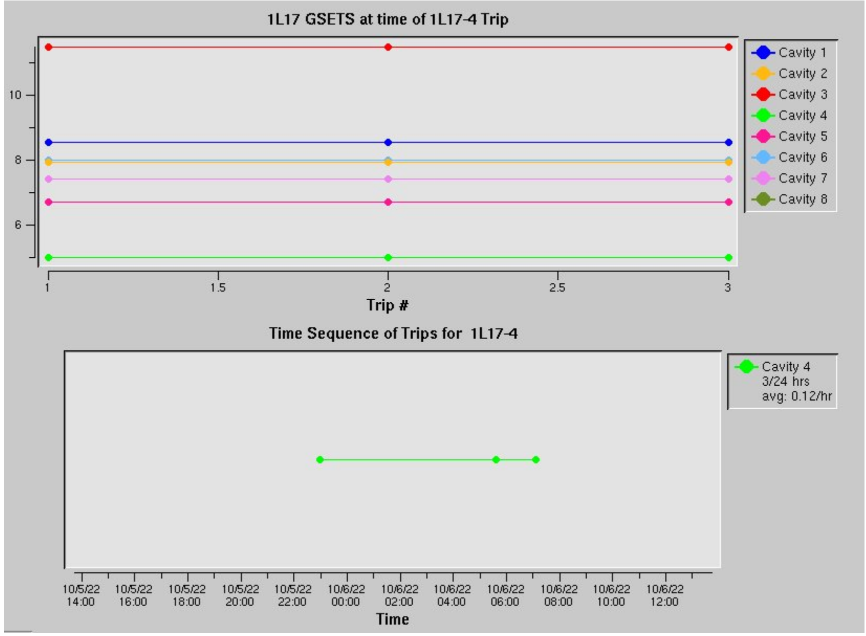
Fault Classification [Off-line Analysis]:



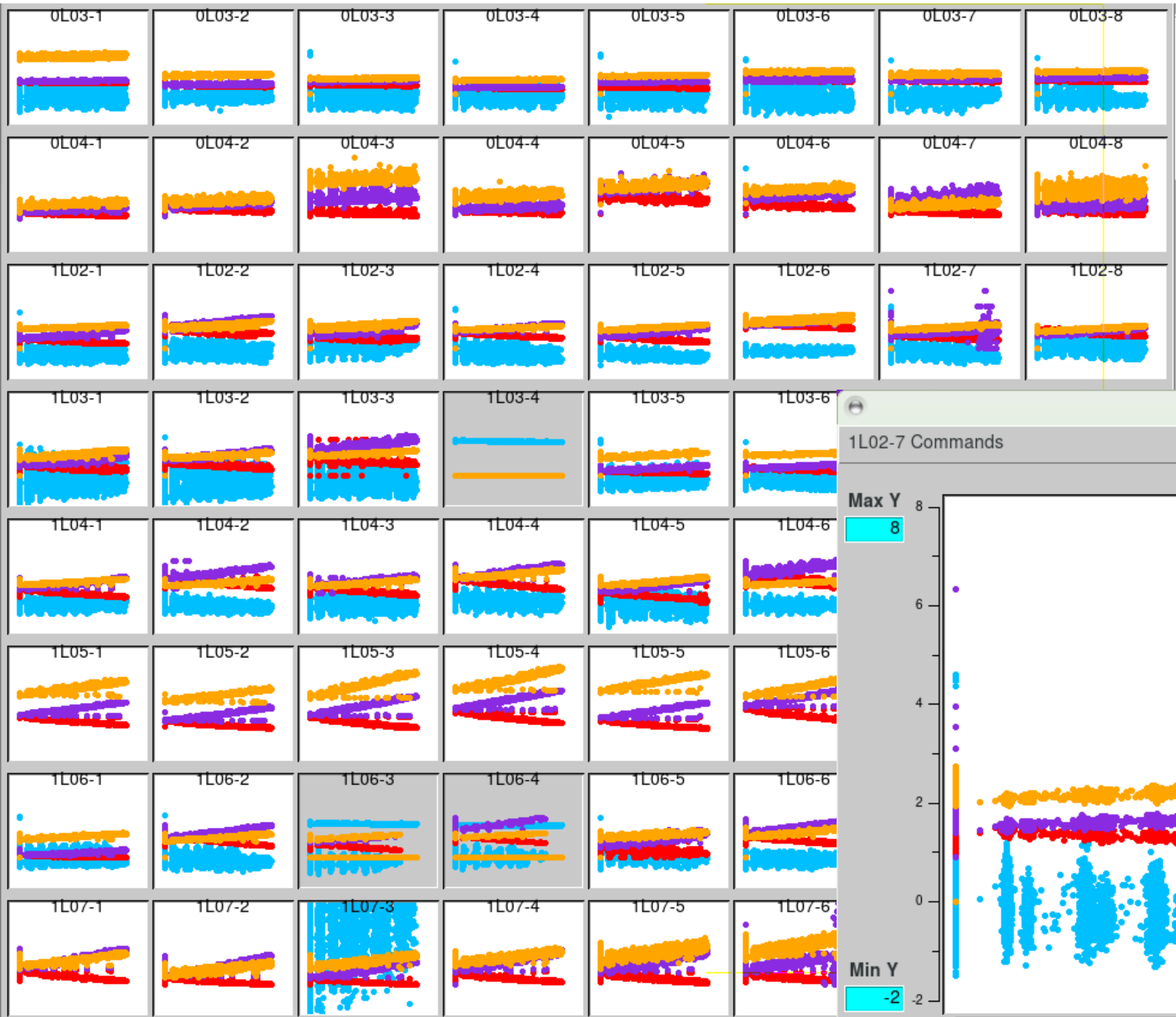


'RF Fault Viewer' (Checked Daily)

Counts tripped bits / fault flags from state machine.

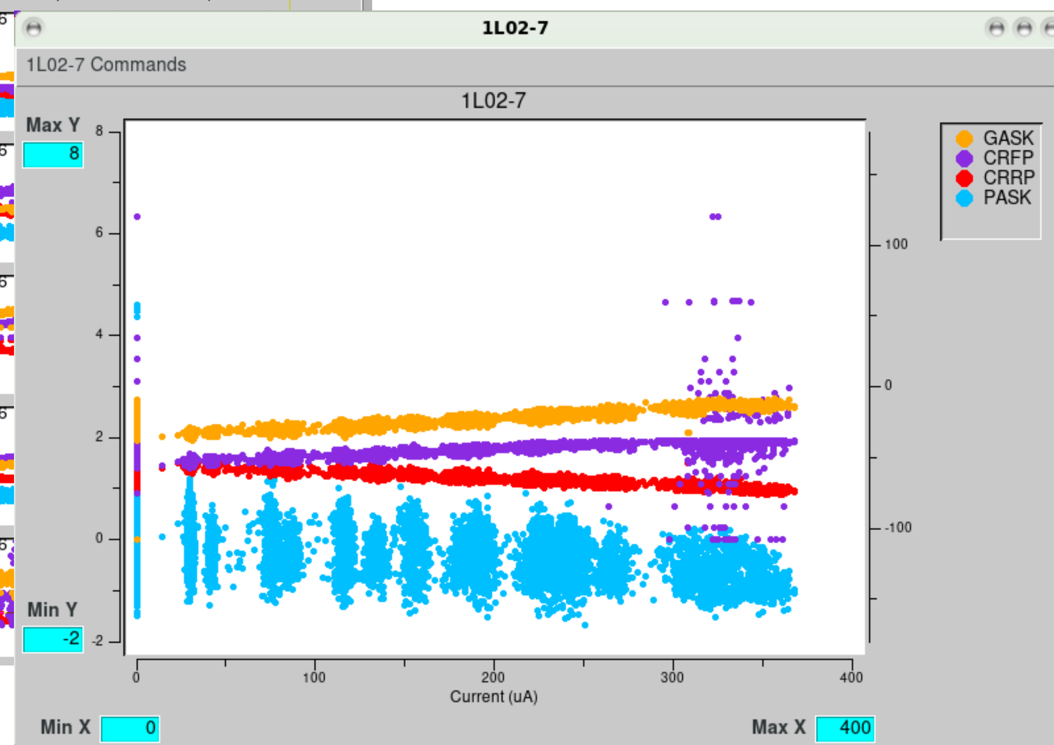


Fault Classification [Off-line Analysis]:

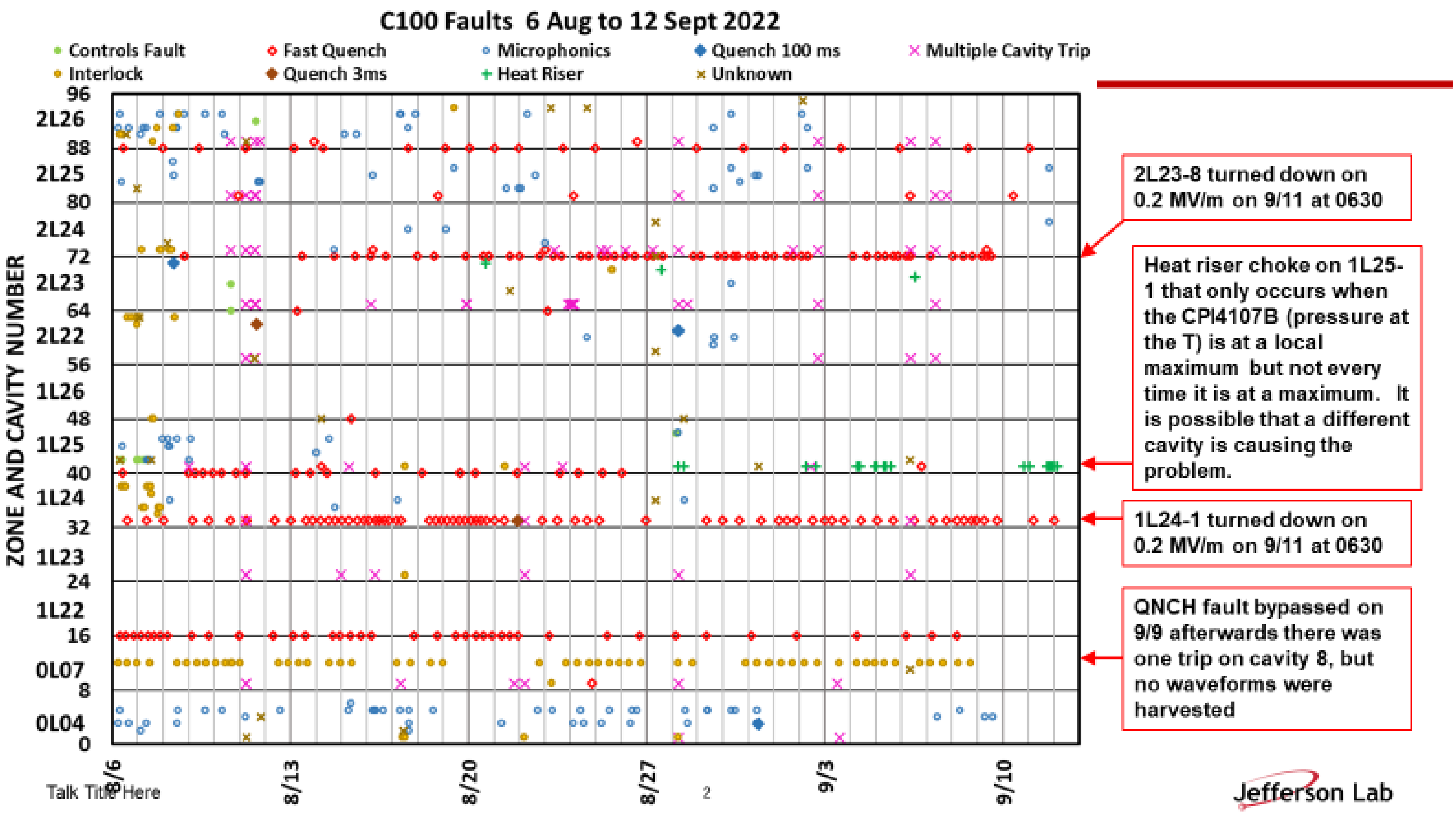


A Visual Analysis Tool – (Used As Needed)

Display a fixed set of common signals (Visually drawn to outliers…)



Fault Classification [Off-line Analysis]:



Fault classification by a Senior Engineer examining waveform data offline which existing tools fail to categorize. Work to automate the process under way through AI/ML.

Artificial Intelligence / Machine Learning Applications:

Example SRF-Related AI/ML efforts under way:

- RF fault prediction: Train model on past fault data to predict future faults from apriori behavior – results thus far encouraging; more effort required.

(L.S. Vidyaratne et al, Initial Studies of Cavity Fault Prediction at Jefferson Laboratory, Presented at ICALEPCS21, WEPV025, Shanghai, China)

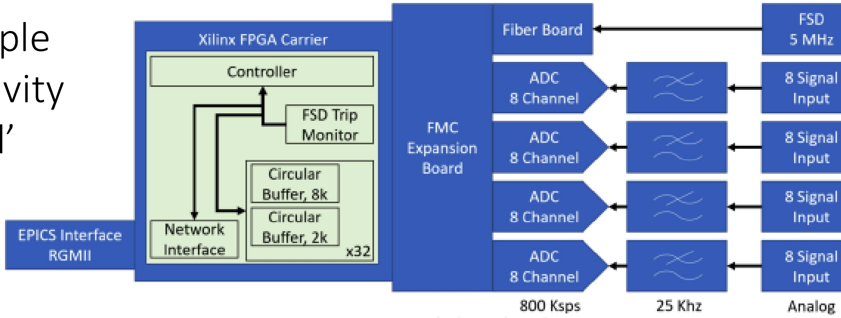
- Field emission management: Radiation detector data gathered while varying cavity gradient & used to develop FE model for cavities which could (theoretically) be used to set gradients. Model results encouraging; tech note forthcoming – plans to incorporate deep learning.

(A. Carpenter et al., Using AI for Management of Field Emission in SRF Linacs, Presented at ICALEPS21, THPV043, Shanghai, China)

- Cavity Instability Detection: High Speed data acquisition (~5KHz) [LLRF reports ~1Hz to control system]; Python-based autoencoder ML model under development – sample measured signal + drive for phase & gradient for each cavity in cryomodule. Model trains on good data; id's 'not good' with 99% accuracy at .001 threshold. 8k fault buffer recorded on fault; harvesting / interpolation algorithms under development.

(D. Turner et al., SRF Cavity Instability Detection with Machine Learning at CEBAF, Presented at NAPAC22, WEPA232, Albuquerque, NM)

(Model Development)



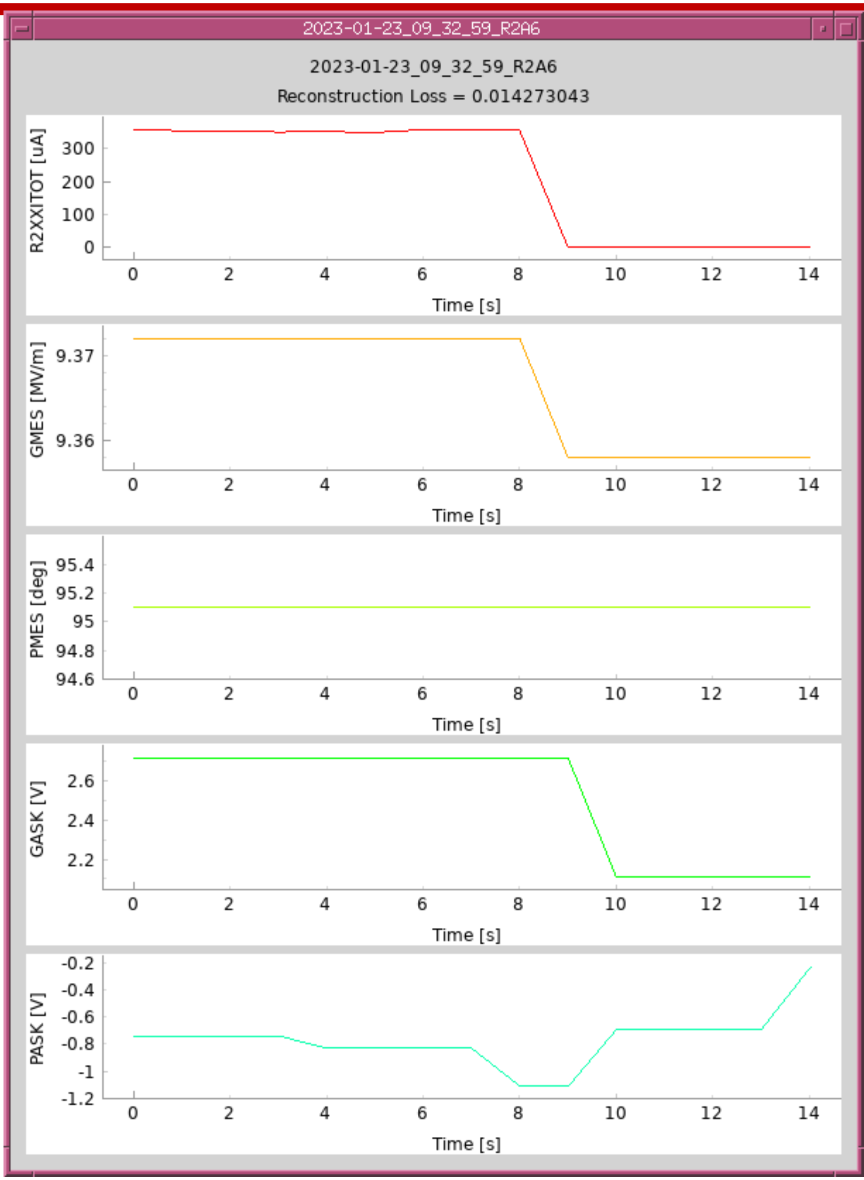
Fast DAQ block diagram.

https://en.wikipedia.org/wiki/File:Spot_the_cow.gif

An Example Tool:

<u>'smartRAT'</u>

- Fast DAQ gathers data (GMES,PMES, GOFF, POFF) at 5 kHz sample rate directly from LLRF + digitized with ADC.
- Python based autoencoder trained on stable data (typical case)
- Signals deviating at 10^-3 level from trained good data identified.
- Results in ~99% accuracy (7 out of 1036 samples falsely identified as bad)
- 'Bad' samples may then be referred / presented to the Operator or to another tool for action.
- Very useful for quick troubleshooting of unstable cavities where DAQ is installed.



D. Turner et al., SRF Cavity Instability Detection with Machine Learning at CEBAF, Proceedings of NA-PAC2022(WEPA23), Santa Fe, NM, USA. accelconf.web.cern.ch/napac2022/papers/wepa23.pdf

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Questions?

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- Discussion -

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- T. Khabiboulline, "Engineering for Particle Accelerators: SRF cavity design, RF measurements and tuning", U.S. Particle Accelerator School (USPAS). 20 June 2017. uspas.fnal.gov/materials/17NIU/SRF%20Cavity.pdf
- T. Powers, Practical Aspects of SRF Cavity Testing and Operations, SRF2019 Tutorial Session. accelconf.web.cern.ch/srf2019/talks/thtu3_talk.pdf

Facilities & Testing:

- T. Xu et al., Completion of FRIB Superconducting Linac and Phased Beam Commissioning, Proceedings of SRF2021(MOOFAV10), East Lansing, MI, USA. indico.frib.msu.edu/event/38/attachments/160/1251/MOOFAV10_Ting_Xu.pdf accelconf.web.cern.ch/srf2021/papers/moofav10.pdf
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References

Others:
- Google...
- JACow (www.jacow.org) - Most conference proceedings
- Journal Preprints (arxiv.org)
- US Particle Accelerator School [USPAS](uspas.fnal.gov) - Backlog of many years of resources/lectures on courses related to various accelerator topics - including those (S)RF related.

Facilities:

- T. Powers et al., Upgrade to Cryomodule Test Facility at Jefferson Lab, Proceedings of SRF2003(MOP26), Lubeck, Germany. accelconf.web.cern.ch/SRF2003/papers/mop26.pdf
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- E.R. Harms et al., Commissioning and First Results from the FERMILAB Cryomodule Test Stand, Proceedings of Linac2016(MOPLR022), East Lansing, MI, USA. arxiv.org/ftp/arxiv/papers/1805/1805.02725.pdf
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Who am I?

Radford University:

- B.S. Physics
- B.S. Applied Mathematics

US Particle Accelerator School

- **MIT**: Fundamentals of Accelerator Physics & Technology
- **Stony Brook University** (Grad.): Accel. Physics
- **Old Dominion University** (Grad.):
  - Collective Effects in Beam Dynamics
  -Modern Computational Accelerator Physics

Position:

SRF Operations; Testing & Measurement Eng.
Thomas Jefferson Natl. Acceleration Facility

Background:

-JLAB Accelerator Operations: 13 years
-JLAB SRF Operations: 14 years [12 matrixed]

American Physical Society #61020066
Society of Industrial and Applied Mathematics: 001031668-0
Society of Physics Students/ΣΠΣ ...

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Scholar (Google): https://scholar.google.com/citations?user=RM_9CIAAAAAJ
inSpire(HEP): http://inspirehep.net/author/profile/M.McCaughan.1