# Overview of CEBAF C100 Cryomodule Faults and Mitigation

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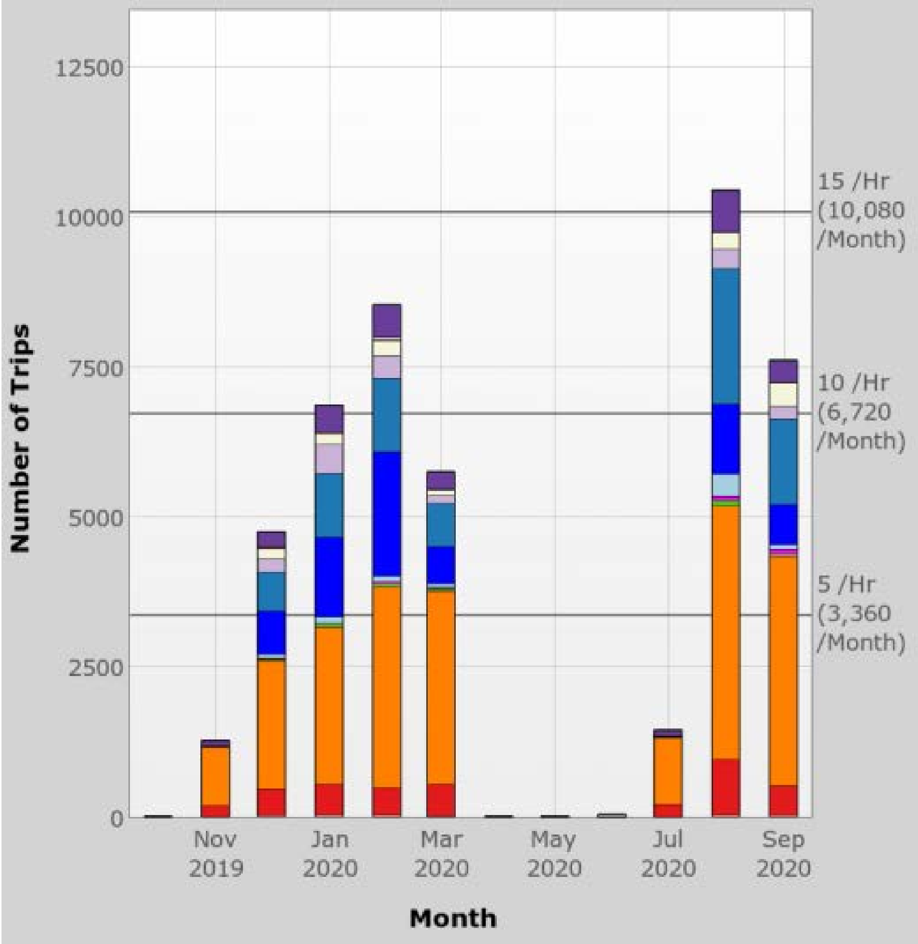
27 Oct. 2020

# Fast Shut Down Trips by Source for FY20

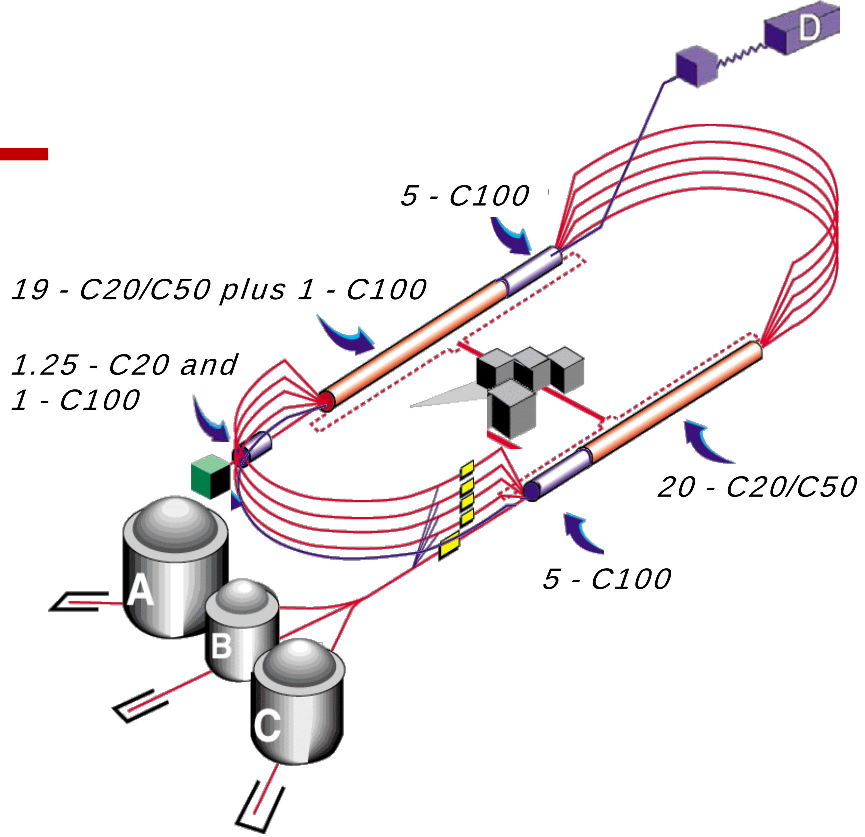
## FSD Trip Summary

**Fiscal Year 2020**



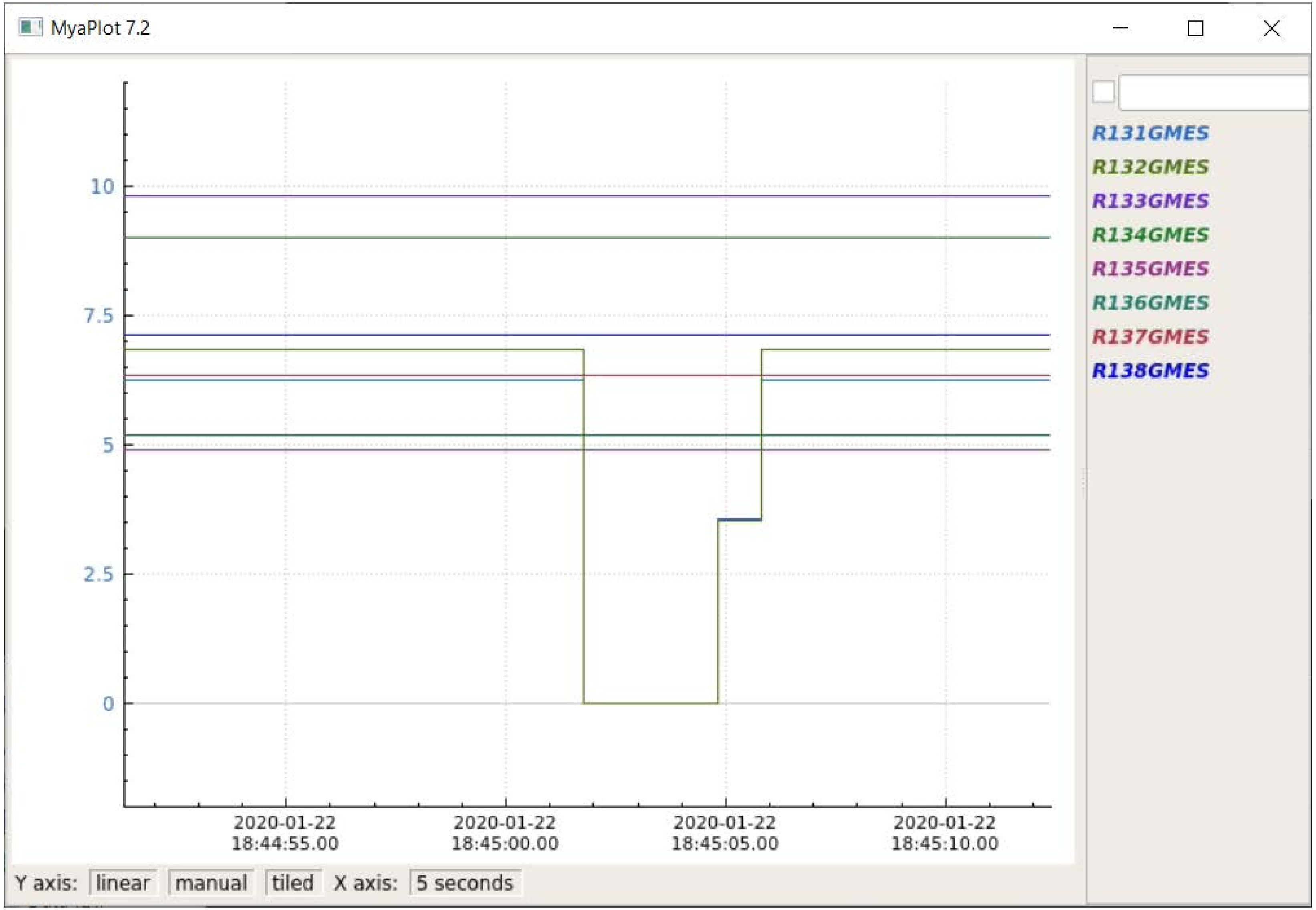

| | Trips | Lost Hrs | Mins /Trip |
|---|---|---|---|
| Control System | 14 | 0.2 | 1.0 |
| Dump (Insert.) | 2,720 | 13.4 | 0.3 |
| Dump (Station.) | 55 | 0.4 | 0.5 |
| Gun/Laser | 105 | 0.8 | 0.5 |
| Hall | 1,361 | 9.7 | 0.4 |
| MPS (BCM/BLA) | 1,791 | 10.2 | 0.3 |
| MPS (BLM) | 7,364 | 40.1 | 0.3 |
| MPS (IC) | 6,569 | 36.1 | 0.3 |
| MPS (Multi/Other) | 779 | 4.8 | 0.4 |
| Magnets | 2 | 0.0 | 0.8 |
| Multiple/Other | 210 | 1.5 | 0.4 |
| Unknown/Missing | 151 | 1.5 | 0.6 |
| Vacuum | 167 | 4.0 | 1.4 |
| RF (C25/C50) | 21,468 | 161.6 | 0.5 |
| RF (C100) | 3,744 | 113.5 | 1.8 |
| RF (Multi/Other) | 173 | 4.1 | 1.4 |
| RF (Separator) | 9 | 0.2 | 1.6 |
| **Total:** | **46,682** | **402** | **0.5** |

- Max Trip Duration: 5 Minutes
- Rate from Period (8784.0 hrs)
- SAD Trips excluded




- **CEBAF has 12 C100 cryomodules with digital low level RF systems and 40-1/4 C20/C50 cryomodules with analog RF controls.**
- **The leading number of fast shutdown (FSD) driven downtime hours was C25/C50 faults which are primarily waveguide vacuum arcs.**
- **C100 faults were the second leading source of FSD trip down time.**

# Typical Trip Recovery for C25 Cryomodule After Arc Trip




- Cavity has to wait a few seconds so that Lorentz force induced microphonics (shaking) stops.
- Then the cavity ramps up over a about 1 second.
- Total recovery time 4 seconds.



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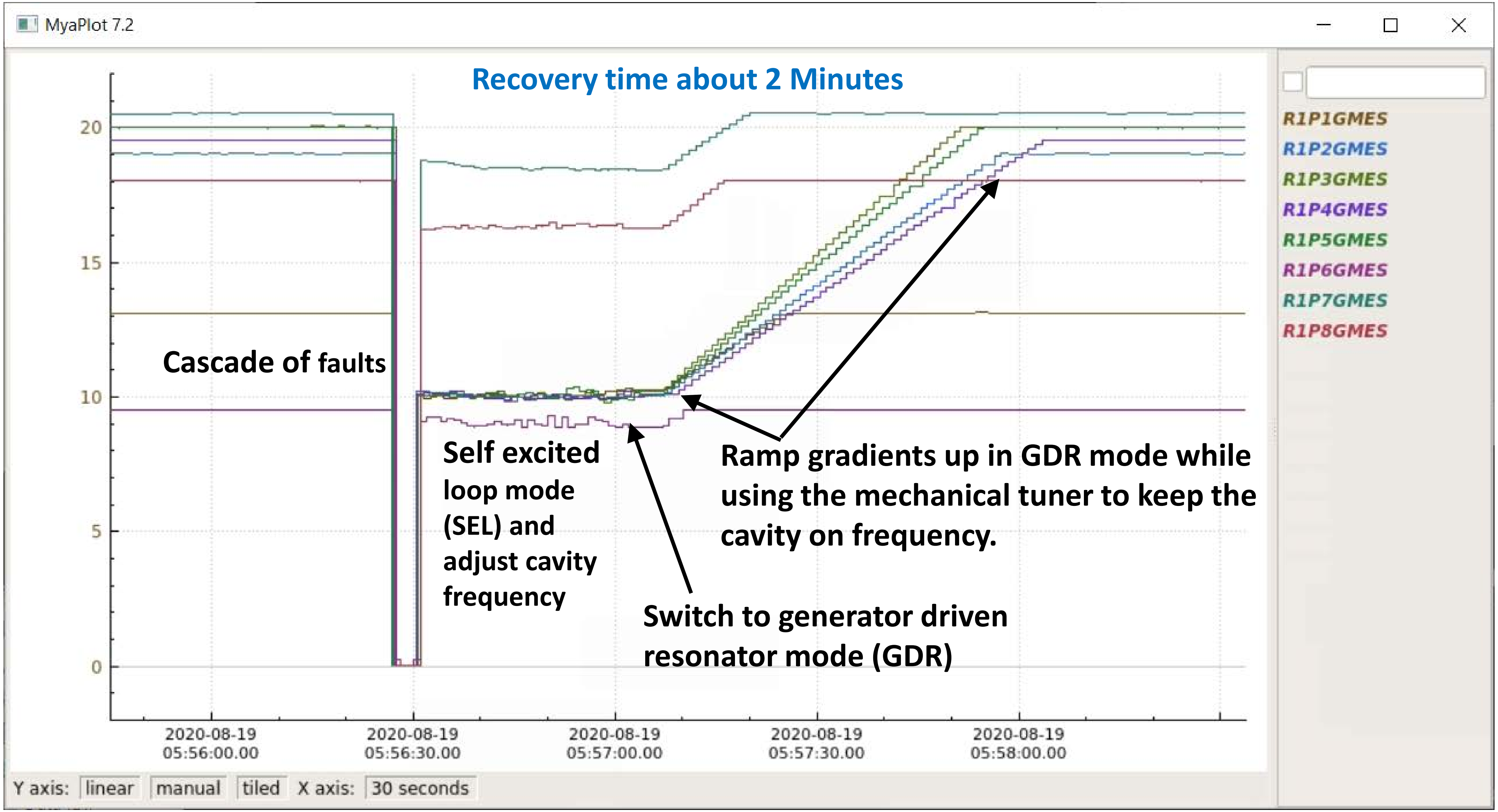
# Typical Reset Cycle for a C100



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# Improvements RF Controls Algorithms, Improved Recovery

- The plan is to
  - Switch to self excited loop, amplitude regulated mode (SELA) when any cavities fault.
  - Turn on cavities in SELA mode with quick ramp up.
  - Adjust the tuners while at gradient
  - Switch from SELA mode to self excited loop, amplitude regulated, phase locked SELAP mode at gradient.
- Work in progress based on the work that JLAB staff did in conjunction with staff from Berkley while developing and testing LCLS II RF systems at JLAB.
- Implement a background process to monitor C100 detune errors.
- Implement a double buffered waveform acquisition routine so that you can look at waveforms while we are running the harvester.
- Better quench detection based on of estimated dissipated power and cavity dV/dt.
- Eliminate the clamp causing the cavity to get driven up or down randomly.

# JLAB Waveform Harvester

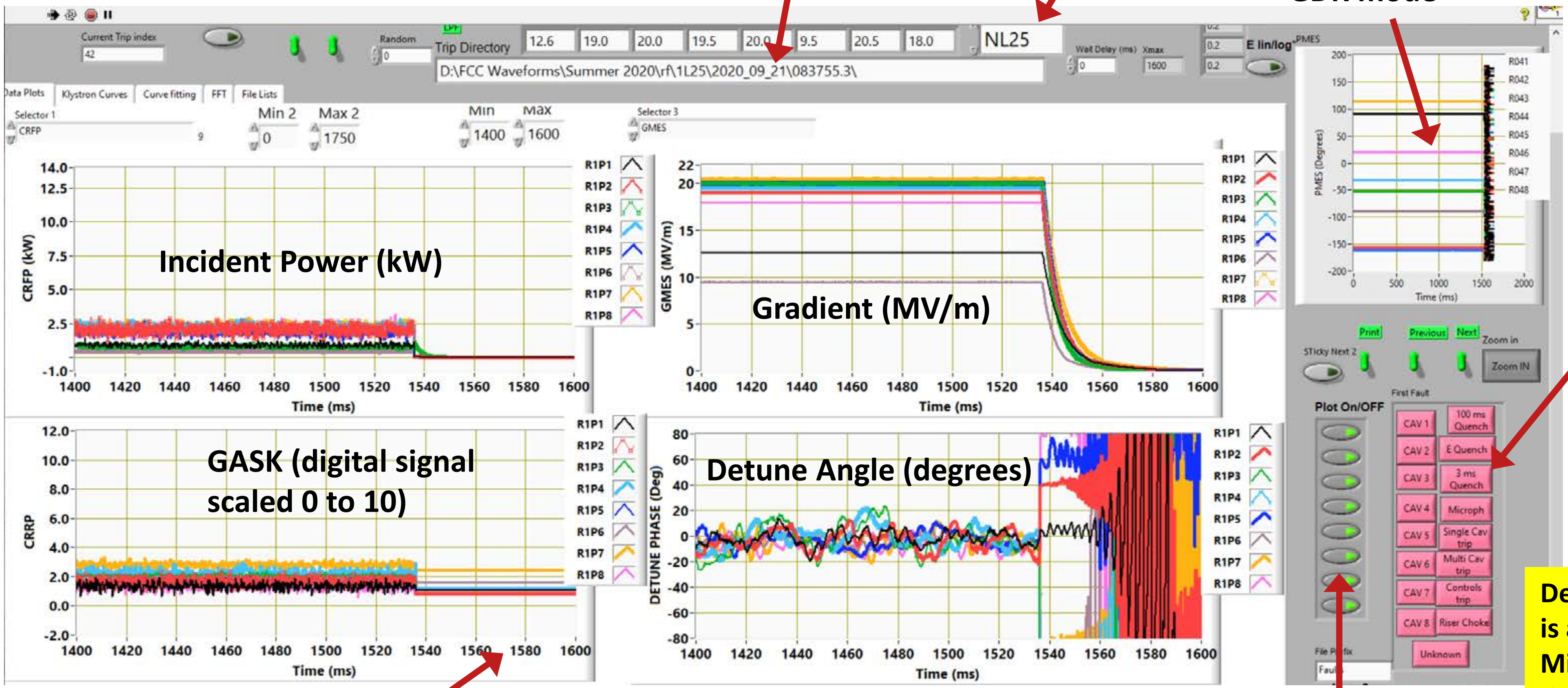
- The cavities in a C100 cryomodules
  - Have a 10% cavity to cavity coupling with respect to frequency detuning.
  - When one cavity trips off the Lorentz force detuning causes enough vibrations in the string to trip the other cavities.
  - In order to avoid additional cavity trips, the entire zone is set to self excited loop mode (frequency tracking) when one of the cavities trip.
  - Switching to SEL mode is also a fault response for various other off normal conditions.
  - It is difficult to determine which cavity initiated the cascade of faults.
  - We needed to verify that the interlocks that we are using are indicating the correct faults.
- Starting in the fall of 2016 the JLAB LLRF and EPICS software groups implemented a waveform harvester for C100 cavities which was triggered by a cavity trip.
- In the spring of 2018 it was configured to synchronously trigger the waveforms for all 8 of the cavities in a zone any time one of the cavities in that zone had a fault.
- The 14 waveform records per cavity are 8,192 points with typical record lengths of 400 ms or 1.6 seconds
- Starting in the fall of 2019 we have had 4 machine operational runs where the faults were classified.
- To date approximately 10,000 faults have been examined and manually classified.
- Work is in progress to transition from manual classification to an automated system based on machine learning.

# Wandering around the waveforms (LabVIEW Interface)

**Directory name with trip time in YYMMDD_HHMMSS.s format.**

**Zone Selector**

**PMES Plot**
**Stable means**
**GDR mode**




**Buttons for manually classifying faults**

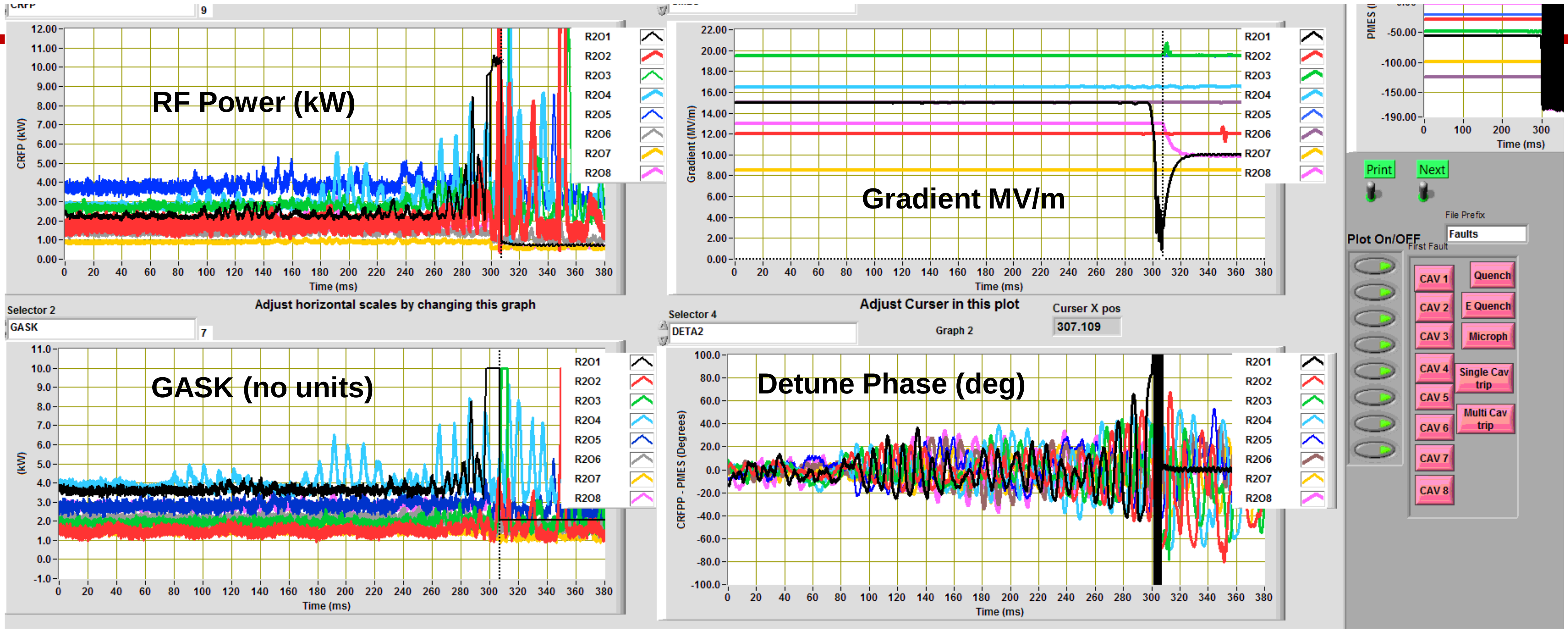
**Detune angle, DETA2, is a measure of Microphonics deltaF α Tan(DETA2)**

**Time in ms**

**Channel On/Off Selector**

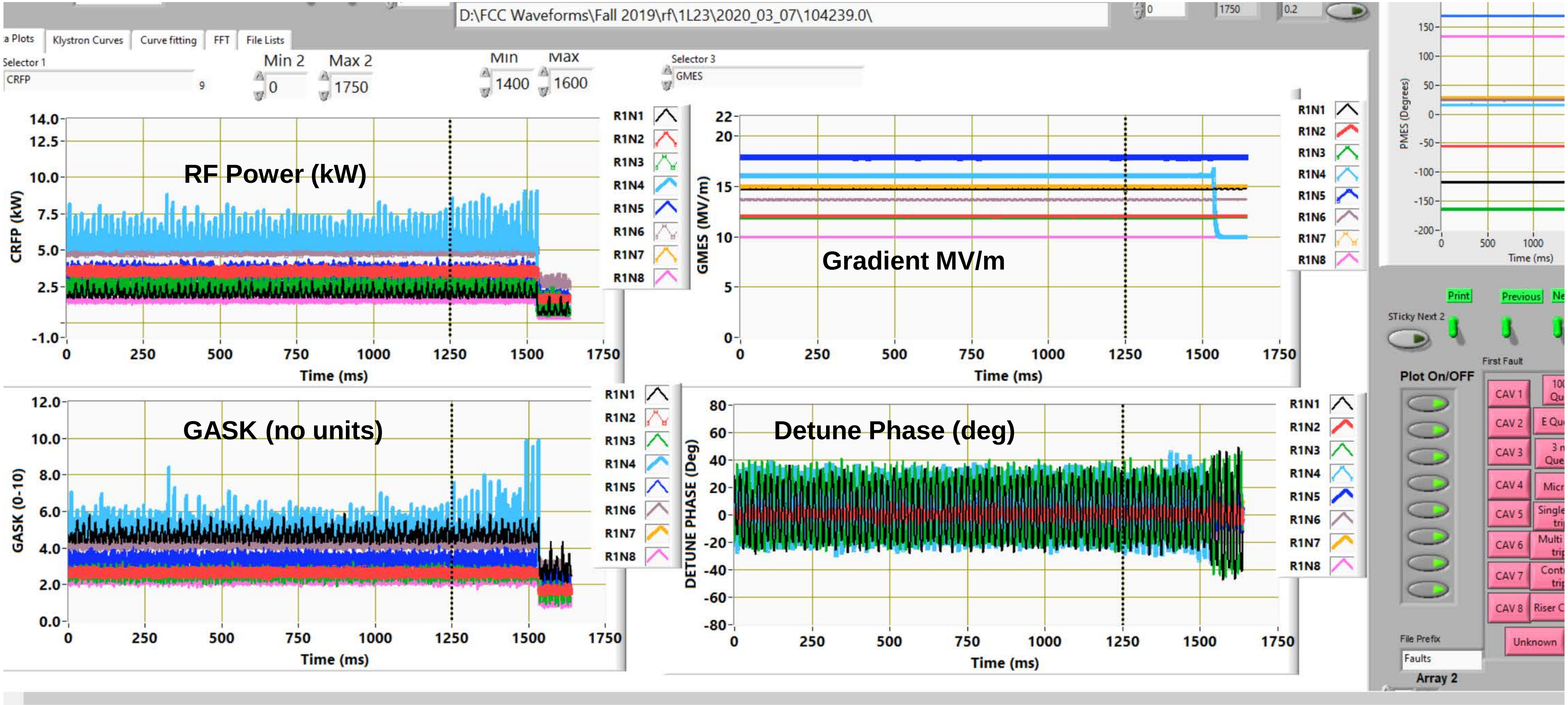
- **DETA2 = Pfwd(Phase) – PTrans(Phase) – TDOFF => zero when cavity is at machine frequency.**
- **GASK requested FCC output "voltage" 0-10, CRFP forward power, CRRP Reflected Power, GMES Gradient.**

# Types of faults, Microphonics Transient Burst




- **Cryomodule is running along relatively quietly, microphonics-wise with an excursion of +/- 20 degrees in detune phase.**
- **A burst of 80 Hz occurred at starting at about 100 mS**
- **At about 300 ms the FCC output drive for cavity 1 (GASK) is clamped at 10; the klystron power is driven to its maximum; the phase gets lost and, in this case, the cavity is driven towards zero.**
- **At about 305 ms cavity 1 switches to SEL mode and with constant forward power and the cavity is driven to about 12 MV/m**
- **The transient in the cavity 1 gradient shakes the entire string (Lorentz detuning) coupling most strongly into cavity 3, which is also switched into SEL mode. This is a typical cascade of faults.**

# Steady State Microphonics Trip No Waveguide Arc or Vacuum Fault




- **1L23 (F100) is different than the C100s in that it has a modal resonance at 50 Hz.**
- **RF System Indicated a gradient error fault.**



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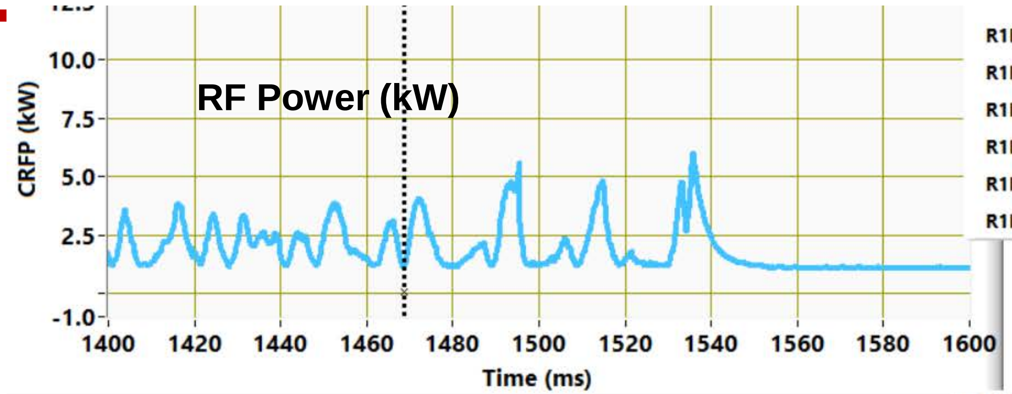
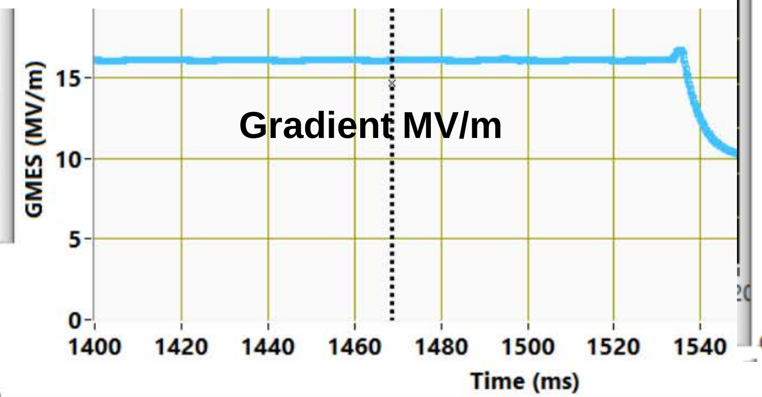
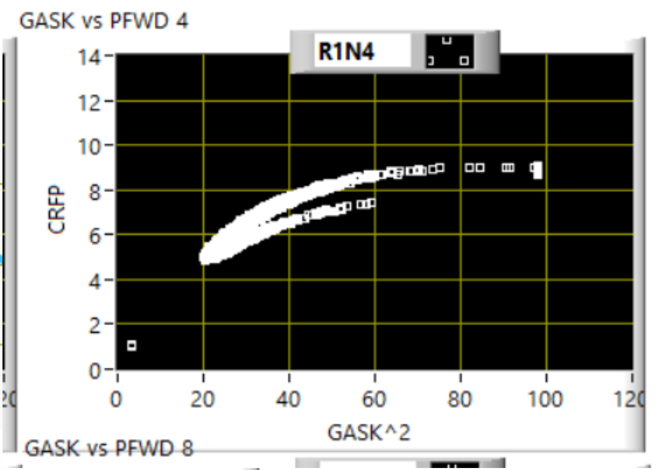
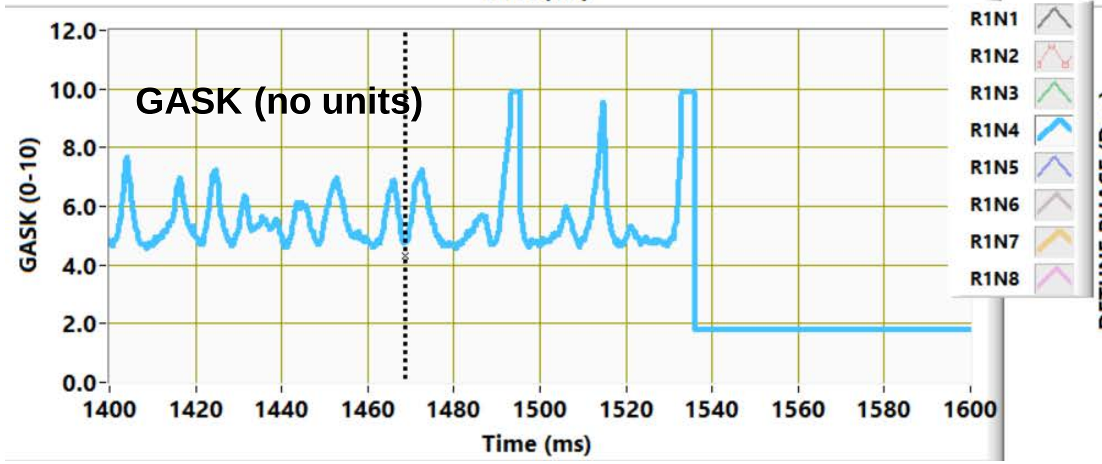
# Same Fault Just Cavity 4, Other Interesting Observations

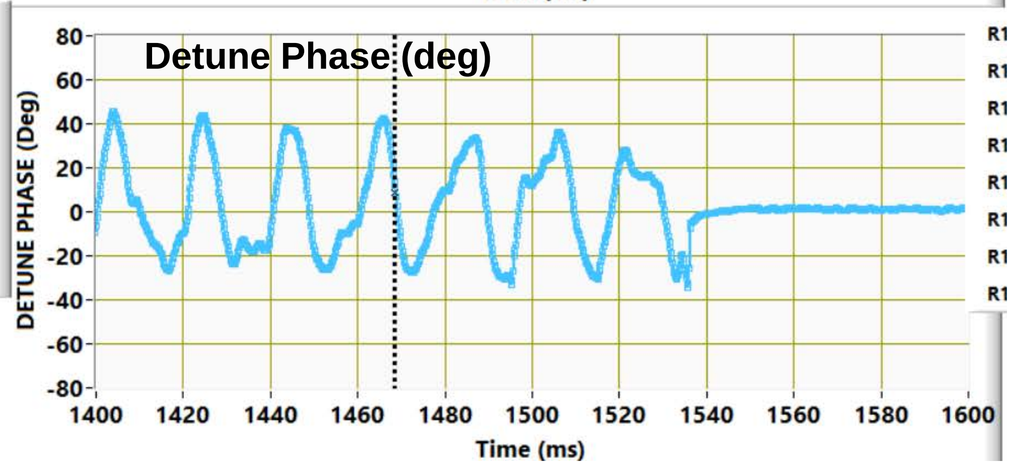


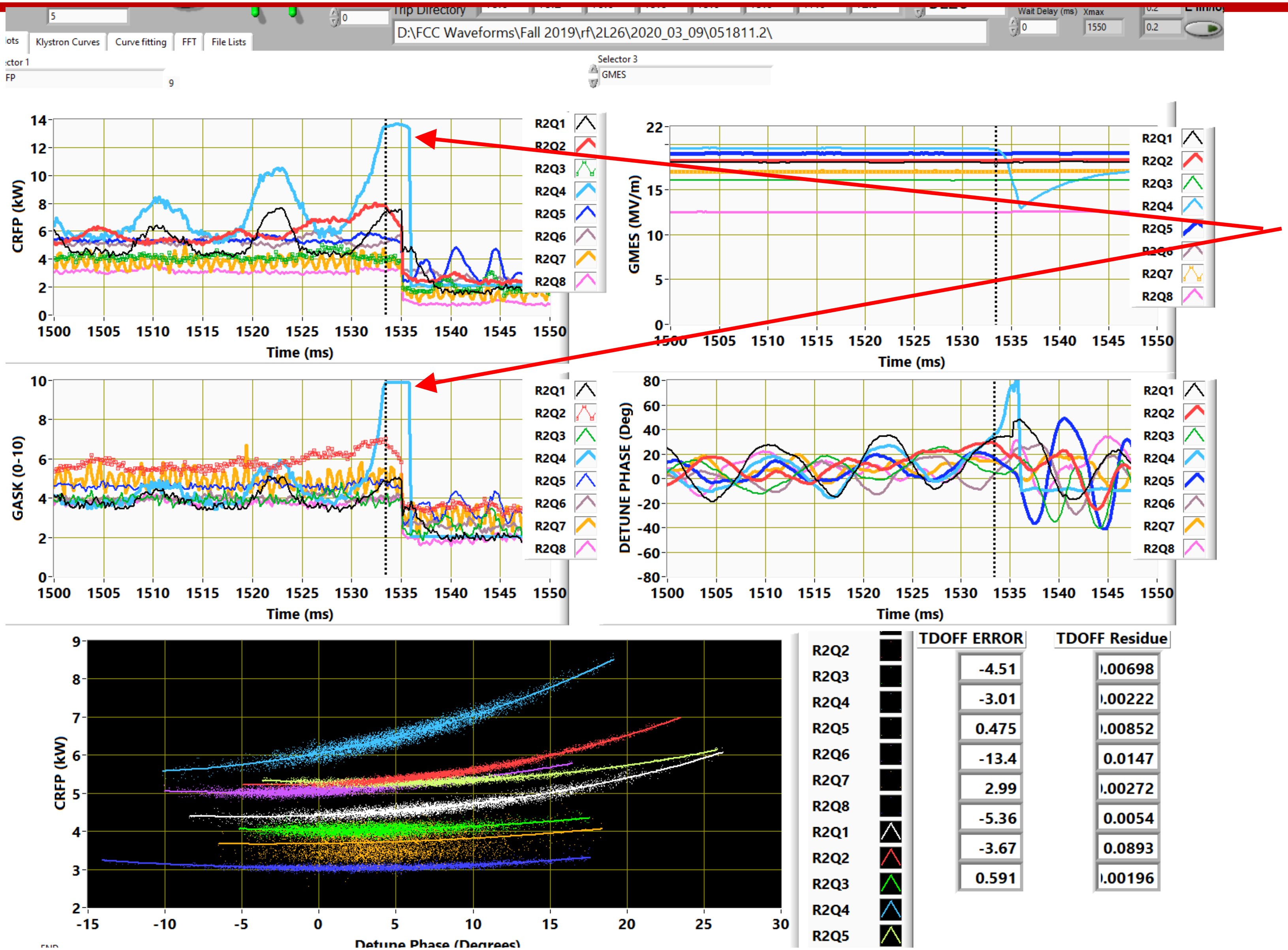

Klystron Power as a function of GASK$^2$




- **Note that GASK has peaks only when the phase goes negative. Also it should not be that large when the cavity is detuned by 35 degrees. This indicates that the cavity was not properly tuned.**
- **Curve fitting forward power to Tan$^2$(DETA2) indicated that it was 12 degrees off from proper tune.**
- **A plot of forward power as a function of GASK$^2$ indicates that the klystron saturated well below the design value of 12 kW. Another contributing factor to it tripping at 35 degrees.**

# Effect of Improperly Tuned Cavity




**GASK pegged at 10 when phase was less than 40°**

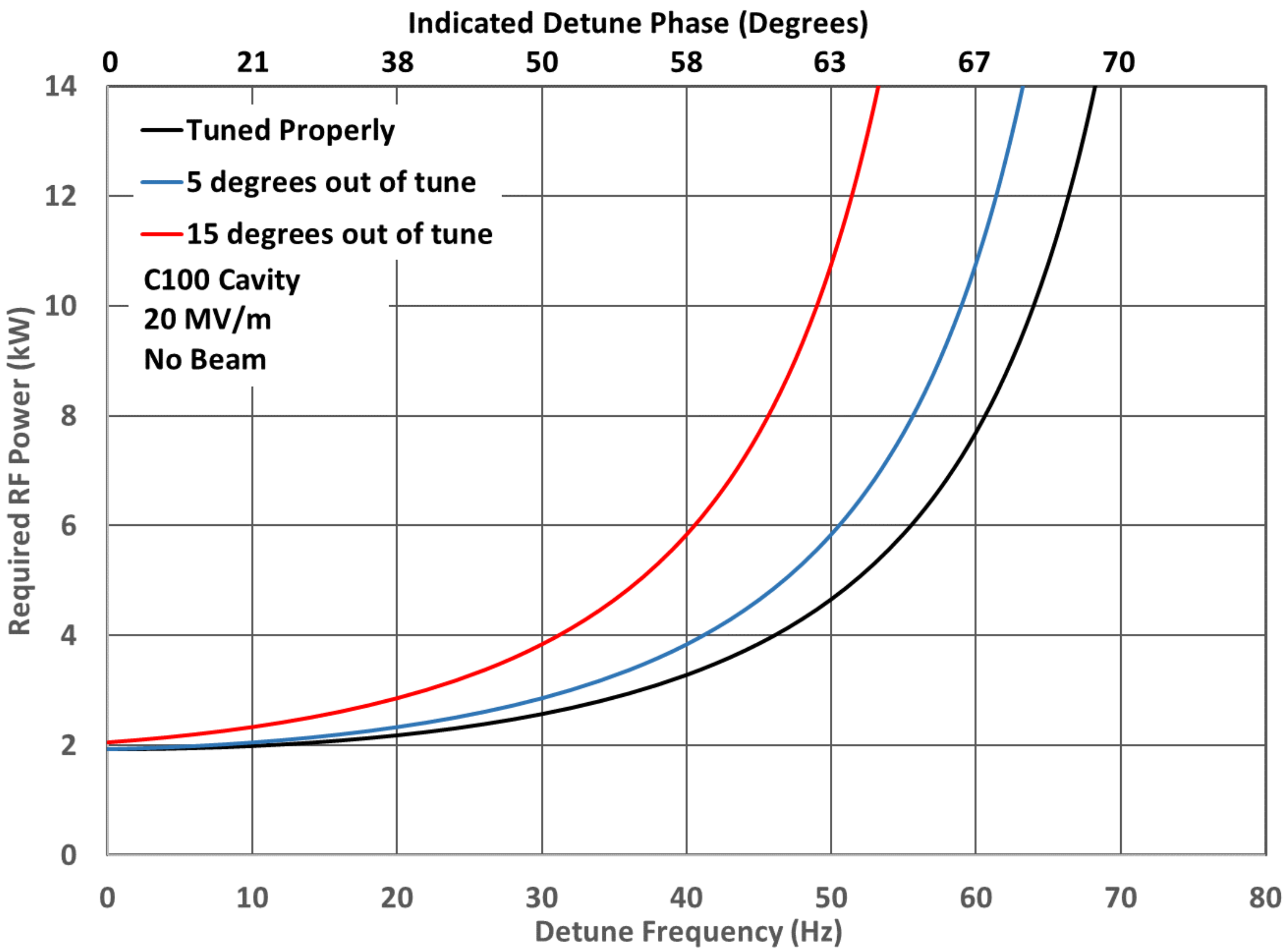
**It should easily be able to go to about 60°.**

**Cavity 4 tuned off resonance by -13.4°.**

**Minimum of 2nd order fit to of CRFP as a function of Tan(DETA2)**

**Method to check for proper tune parasitically during normal operations has been developed and is being tested.**

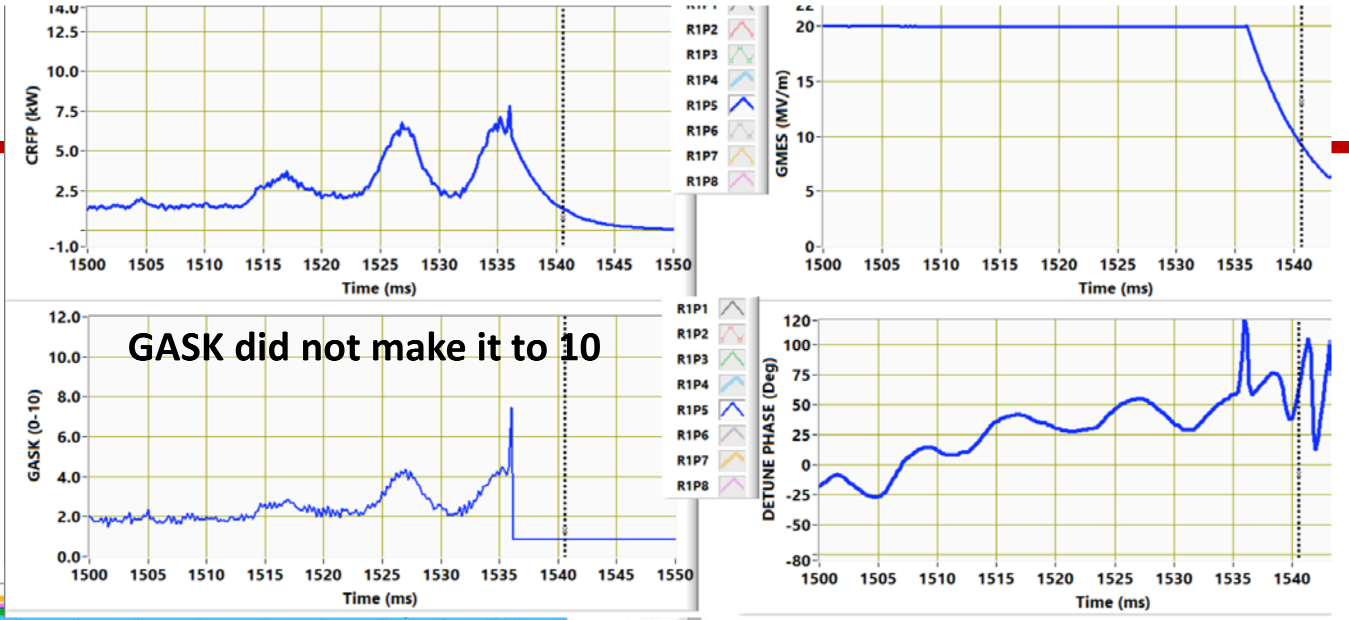
# Impact of Not Being Properly Tuned on RF Power Requirements

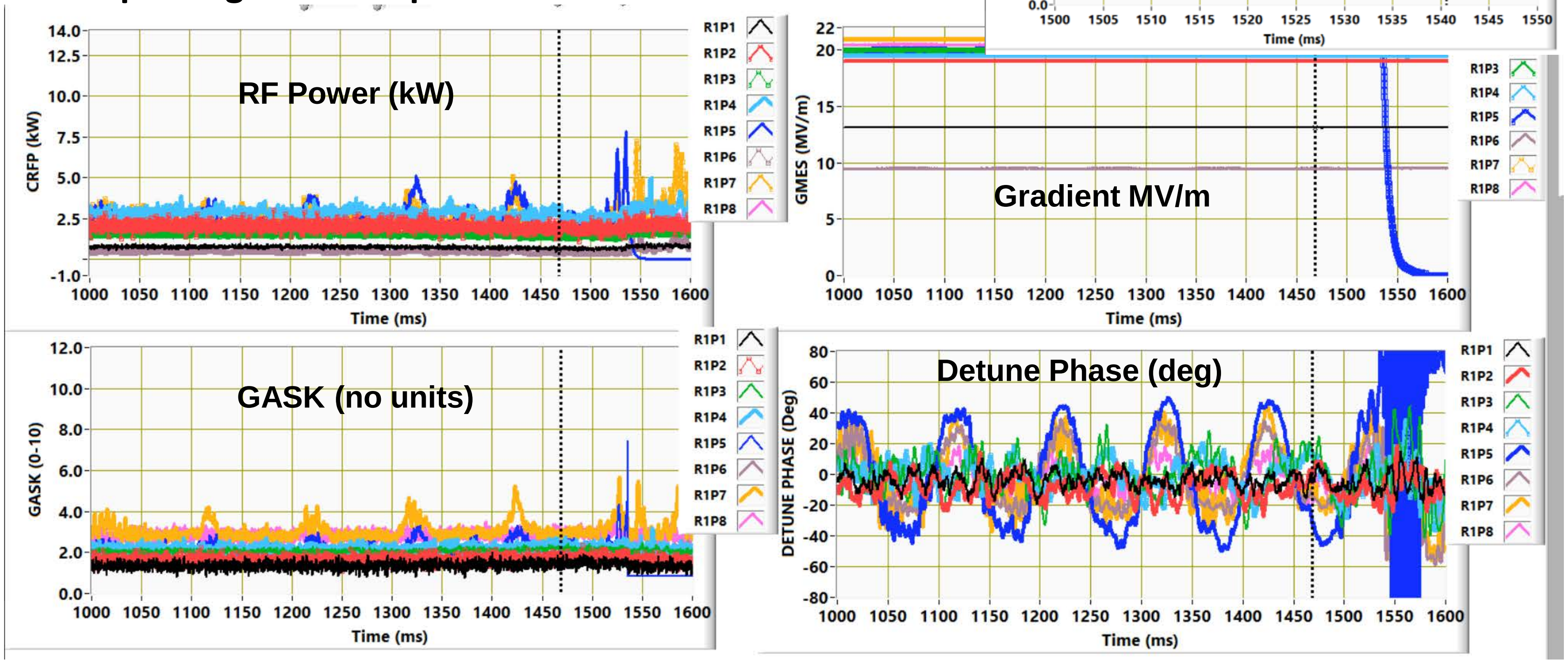



- **Being 15° detune requires 7% more power when with no microphonics**
- **Being 15° detuned requires 35% more power when the detune angle indicates 40°**
- **Being 15° detuned requires 2 times as much power when the detune angle indicates 60°**
- **Being 5° detuned requires 35% more power when the detune angle indicates 65°**

# Arc Trip Due to Microphonics

- During the first review of these trips the interpretation was a microphonics fault.
- Now I check to make sure that GASK saturates before I call it a microphonics fault.
- Even though this is an arc/waveguide vacuum fault improving the microphonics would reduce these faults.



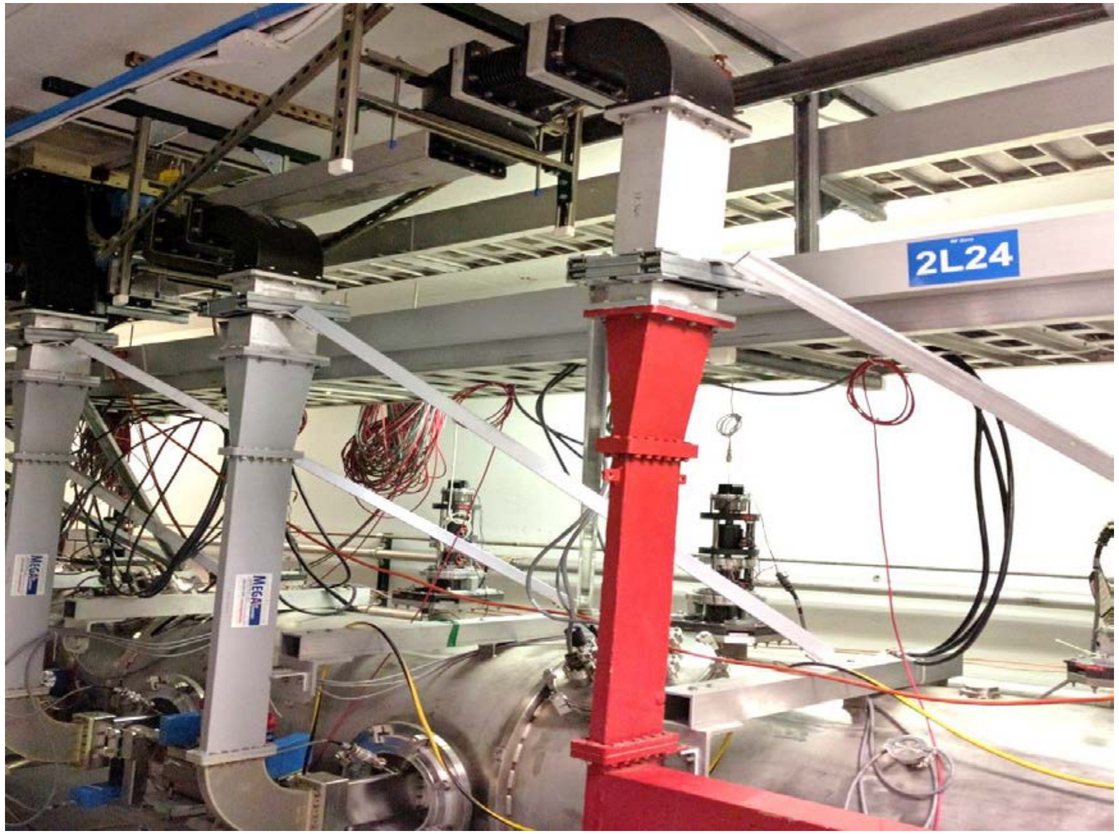




- Sudden change in slope of detune angle just before the trip.
- Detune angle only went to about 60° before trip.
- Checking the archived data indicated a waveguide vacuum spike and an arc fault on cavity 5.

# Microphonics Mitigation

## Struts and waveguide damping

- In order to avoid welding new mounting tabs onto the vacuum vessel, the retrofit design made use of existing mounting tabs and aluminum “unistrut®” type material using standard fittings.  Each waveguide has two struts which act as a three axis constraint.
- The ceiling “retrofit” made use of existing unistrut channels mounted the ceiling and replaced the threaded rod with a box assembly made out of unistrut to better constrain the waveguide.
- Sorbothane® damping material placed between the unistrut waveguide brackets and the waveguide in order to
    - Damp the vibrations which are transmitted to the waveguides from the ceiling.
    - Damp vibrations that are transmitted from the cryomodule (string vibrational modes) to the waveguides.
    - Damp the natural modes of the waveguides.
    - Damp the transfer of the beam vibrational modes from the support structures to the waveguides.
- Installed in zones 2L24, 2L22 and 0L04, more proposed in the future.



# Microphonics Mitigation

## Tuner Damper

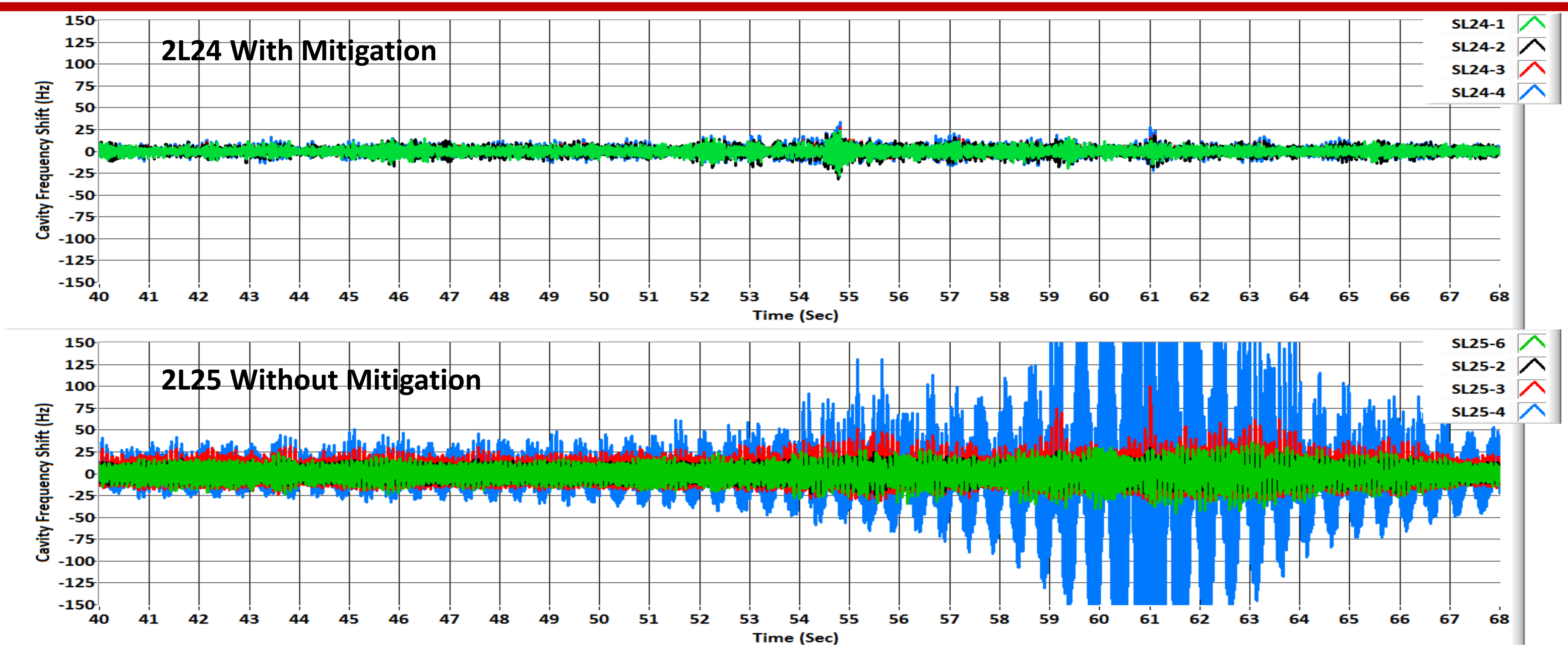
- **The tuner participates in the 10 Hz full string and 20 Hz half string mode. For example in the 10 Hz mode the entire string moves back in forth in the direction of the beam line while the tuner moves in the opposite direction. The concept is that damping applied to the tuner should damp this mode.**

- **The concerns were that we did not want to transfer energy from the insulating vacuum vessel (from the floor and cryo lines) to the cavity string.**

- **The damping properties of the sorbothane were used to damp vibrations of the tuner stack that were driven by the string and half string modes.**

- **The compression was tuned to reduce the impulse hammer transfer function of the 10 Hz mode from the waveguide to delta-F of cavity 5 as well as from the beam beam line to delta-F of cavity 5.**

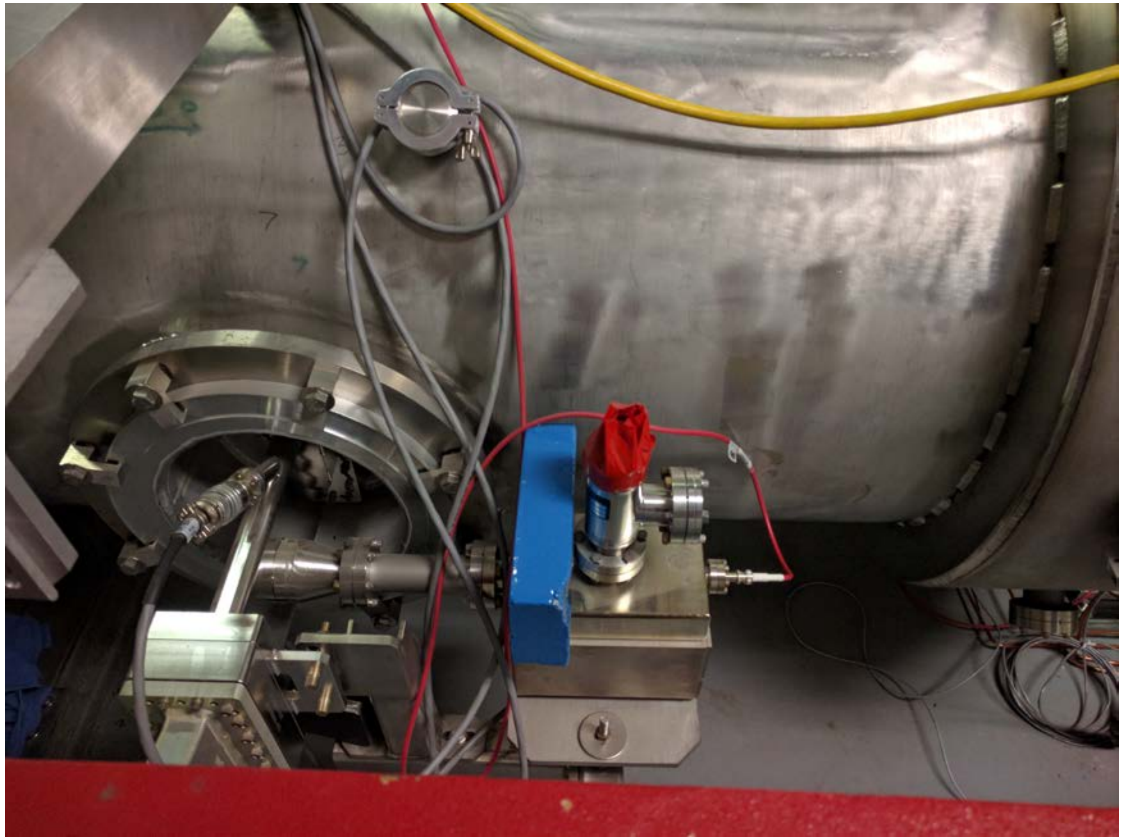
# Effects of Waveguide and Tuner Damper on Induced Microphonics




**Cryomodule SL24 had waveguide struts and tuner dampers, while cryomodule SL25 was in the original configuration. A nitrogen delivery truck drove down the linac service road at about 15 miles per hour.**

- **The first 10 seconds of the graphs indicates the reduction in background microphonics.**
- **The excessive microphonics starting at 52 seconds was due to the truck being driven adjacent to the zone 24 followed a few seconds later passing zone 25.**
- **Cavity 4 probably lost control of the phase at about 60 seconds. It did not trip because it was operated at 3 MV/m.**

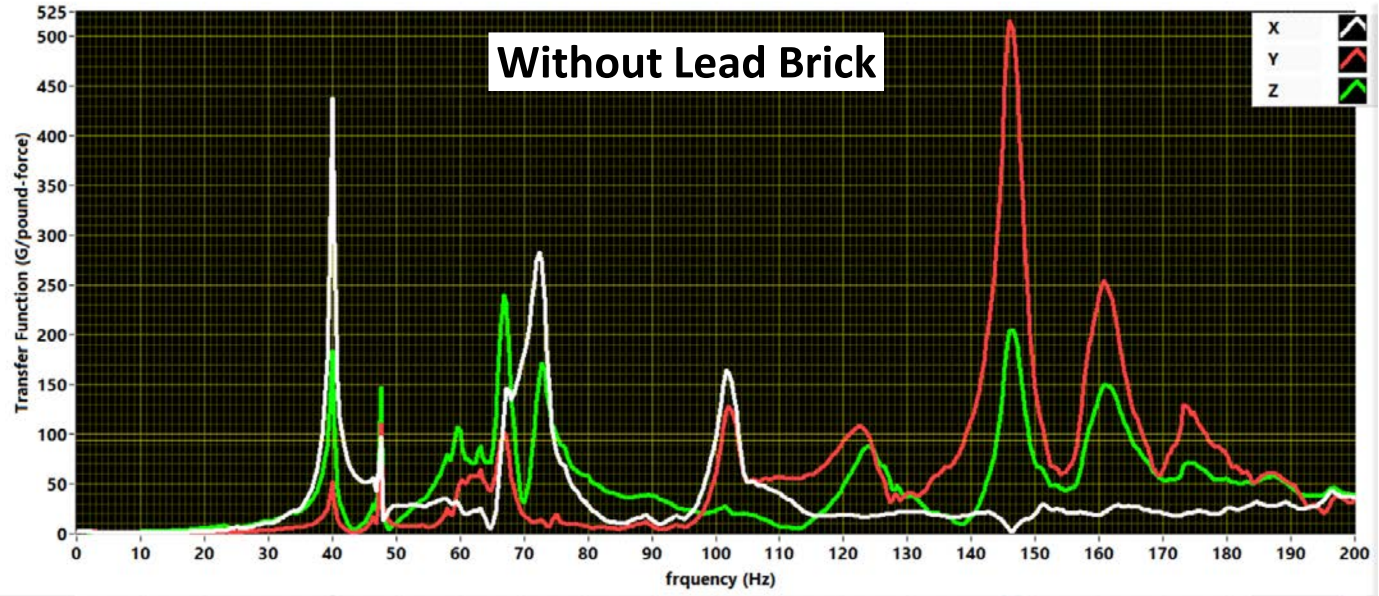
# When You Have to do Something

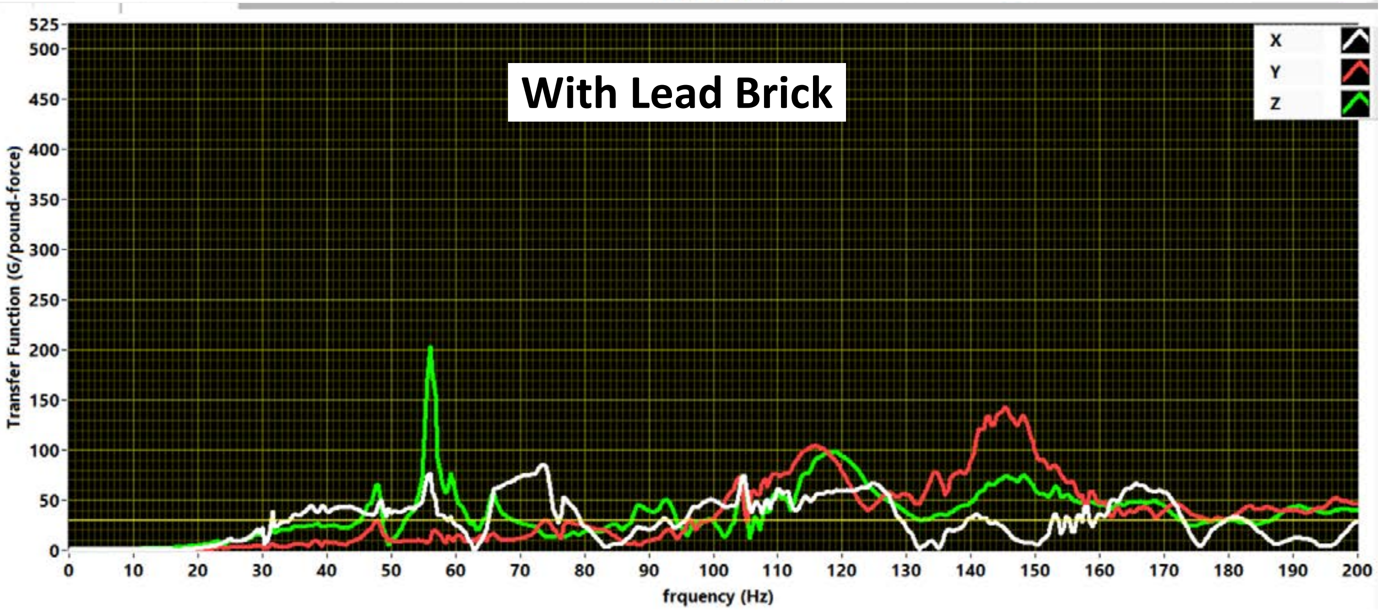


- The cryogenic plant produces floor and piping vibrations at 41 Hz that varies by +/- 1 Hz during the day.
- The waveguide vacuum pump assembly had a modal resonance at 40 Hz making it susceptible to vibrations leading to microphonics.
- Attaching a lead brick with double sided tape shifted the resonance down in frequency thus avoiding the source term.

Polyethylene bead filled fiber bags can be attached to the tuner assembly as a temporary measure to damp microphonics induced by things like the tuner motor operation as well the 10 Hz full string mode.

# Ion Pump 4 Modal Transfer Function With and Without Lead Brick



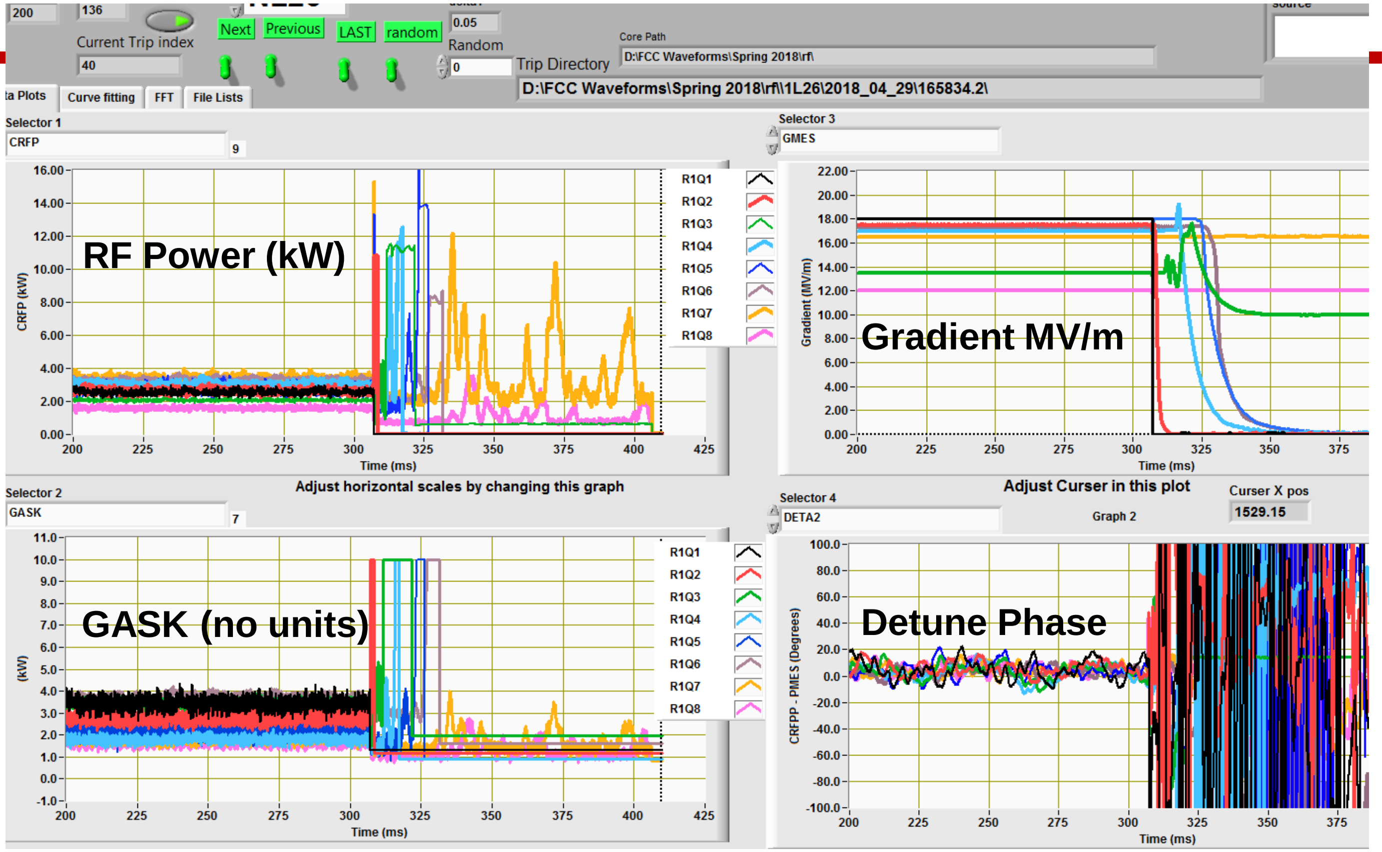

**Without Brick**

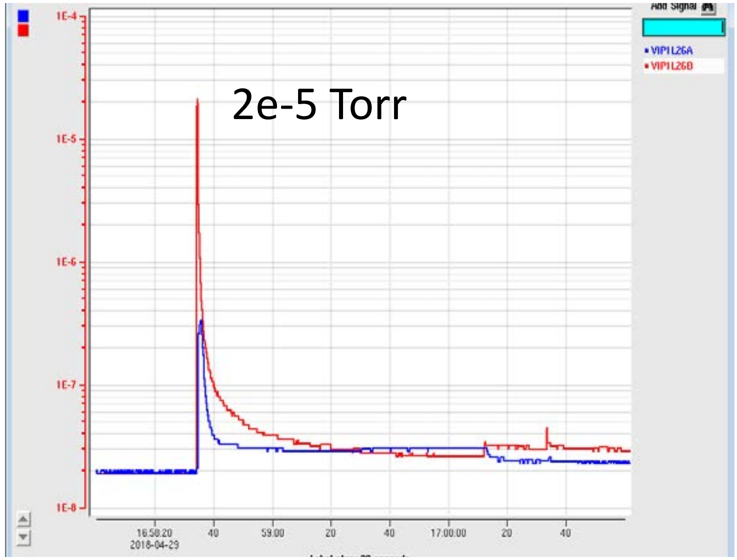
- **40 Hz mode with a Q of 60**
- **47 Hz with a Q of 270**
- **Several modes around 70 Hz with Qs around 30**
- **102 Hz with a Q of 100**
- **146 Hz with a Q of 55**
- **160 Hz with a Q of 33**

- **With Brick**
- **The only easy to identify mode is at 56 Hz with a Q of 69.**
- **This mode is not near modes found in background floor and piping vibrations.**

# Fast "Electronic Quench"

- Fall time of cavity gradient faster than 50 us (one point at this acquisition rate).
- Cavity seemed to be operating normally up until this point.
- Theory -- vacuum burst in cavity releases large quantities of electrons which absorb the energy within the cavity.
- 93% of the fast quenches in the Fall 2019 run were in cavities 1 or 8 the rest were distributed between the other 6.
- Extensive leak checking was done without finding a problem. FE radiation induced photo-desorbtion is likely.

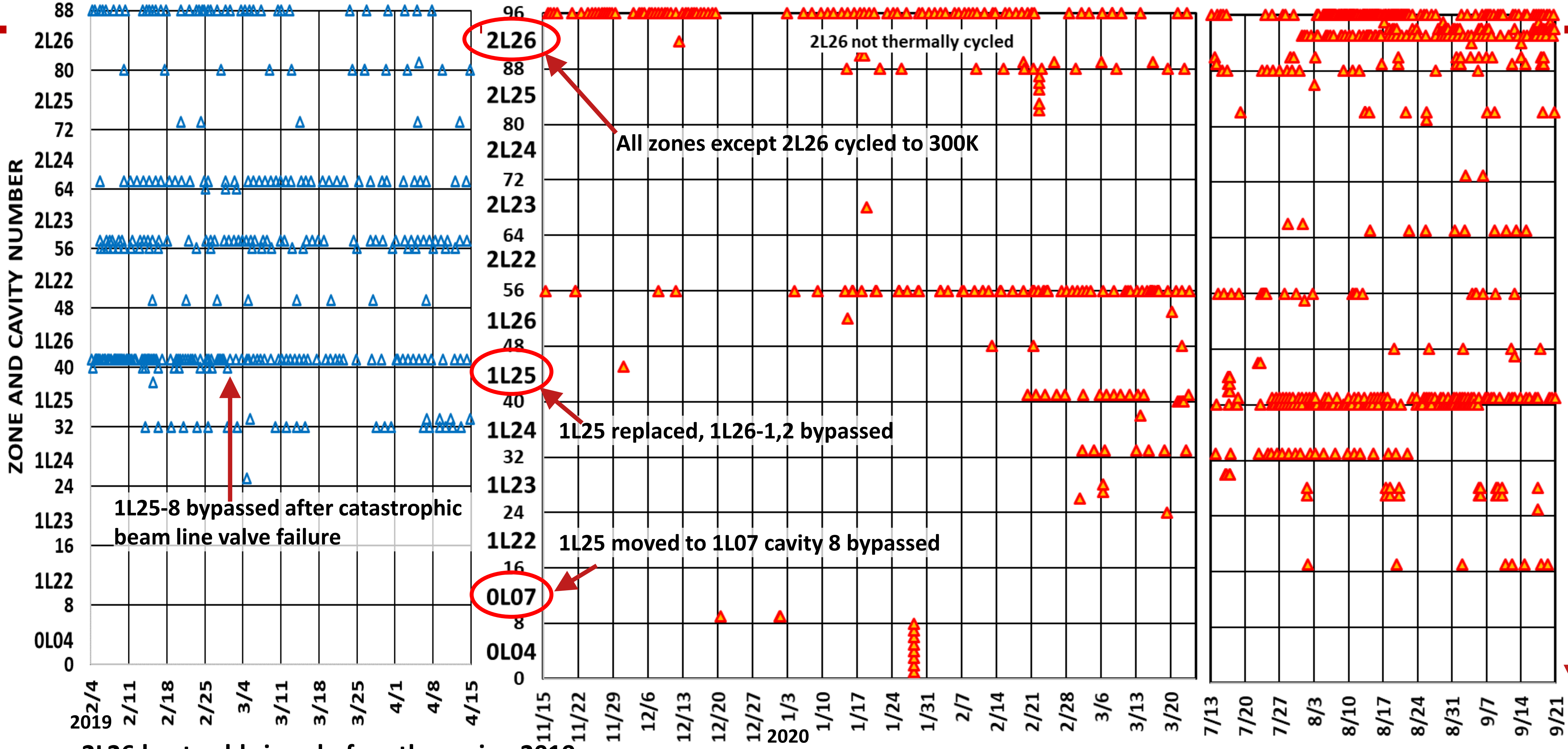



- Corresponding beamline vacuum excursion.
- Red trace is pump next to cavity 1 blue trace is at the upstream end of the girder.
- Peak vacuum signal adjacent to cavity 2e-5 Torr at the other end of the girder was 3e-7 Torr.
- No events were recorded where cavity 1 in one zone and cavity 8 in the adjacent zone had the same fault at the same time which indicates that the event was not due to a vacuum burst in the girder between the cryomodules.

# The Effects of Warming Up Cryomodules On Frequency of Electronic Quenches

North Linac being thermally cycled to 300K
2L26 will be cycled to 300K




- 2L26 kept cold since before the spring 2019 run
- All other cavities warmed up to 300K and girders were pumped on for 2 or 3 months, 1L26 was warm for 5 weeks.

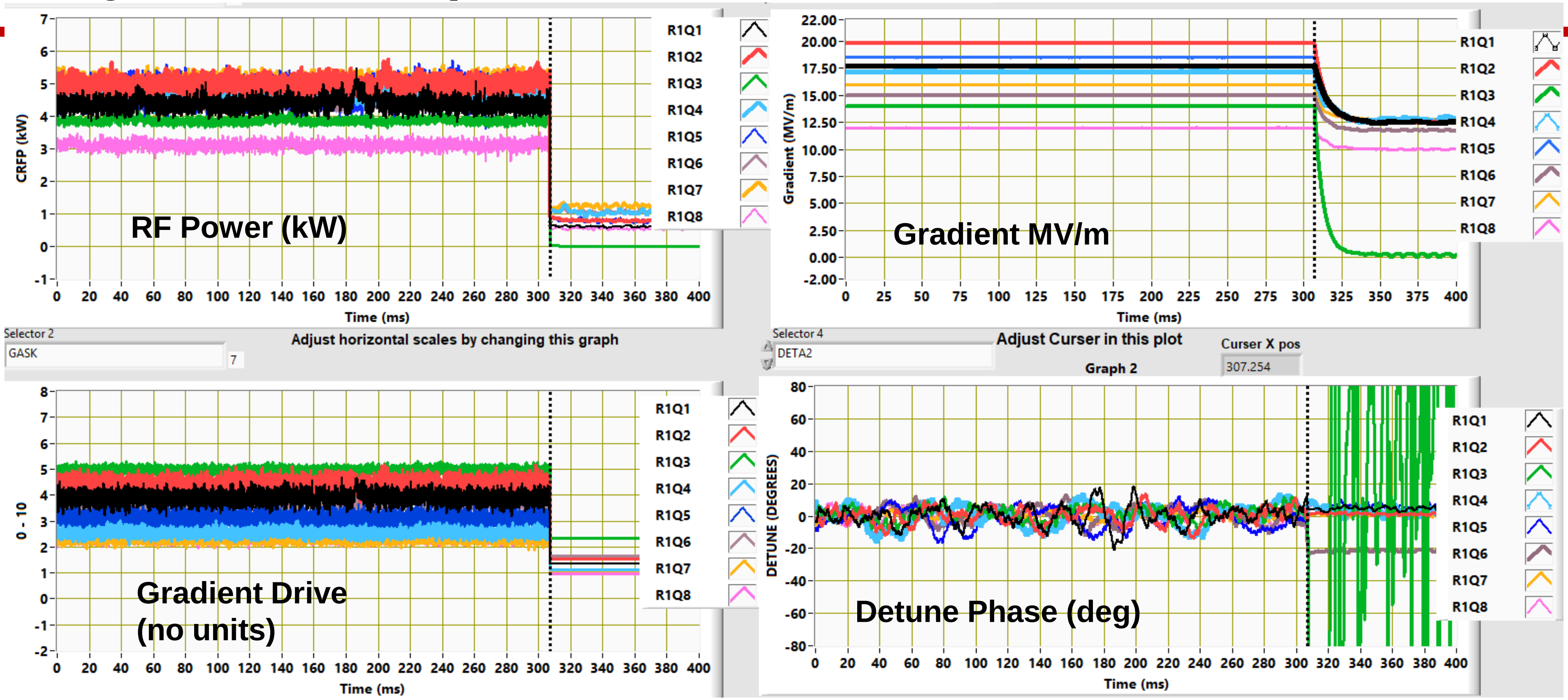
# Valve Failure Due to Radiation and Repeated Actuation

Beam line gate valve bonnet gate with Vulcanized Viton seal

- Viton Seal radiation hardened and had repeated operation due to vacuum spikes caused by electronic quench events.
- Initial symptom valve stuck in an indeterminate position.
- Initial remedial action taken was to lock the valve open and bypass 1L25-8 which would no longer sustain gradient.
- A few months later, when it was removed from the machine the remainder of the similar valves were locked in the open position.
- We are replacing/rebuilding all of the valves in the north linac during the current extended down.
- We are modifying the vacuum interlock logic to avoid closing valves due to transient vacuum events.
- The cryomodules adjacent to this valve were still operational with the cavities adjacent to where this valve was located bypassed. The worst of the two will be removed from the machine in a few weeks for reprocessing.

Beam line gate valve bonnet gate as removed from beam line adjacent to cavity 1L25-8

# Single Cavity Interlock Trip




- Zone running fine and at about 300 ms cavity 3 trips off going to a zero RF power even while GASK is not at zero. This is an indication that the RF switch was open.
- The gradient decays with a nominal turn off decay time.
- Note that the forward power did not jump up before the fault.
- Detailed analysis of the archived fault data indicated that >60% of these faults are quench faults (QNCH) detected by the field control chassis.
- This fault is supposed to be triggered by a 15% reduction in gradient for several milliseconds.



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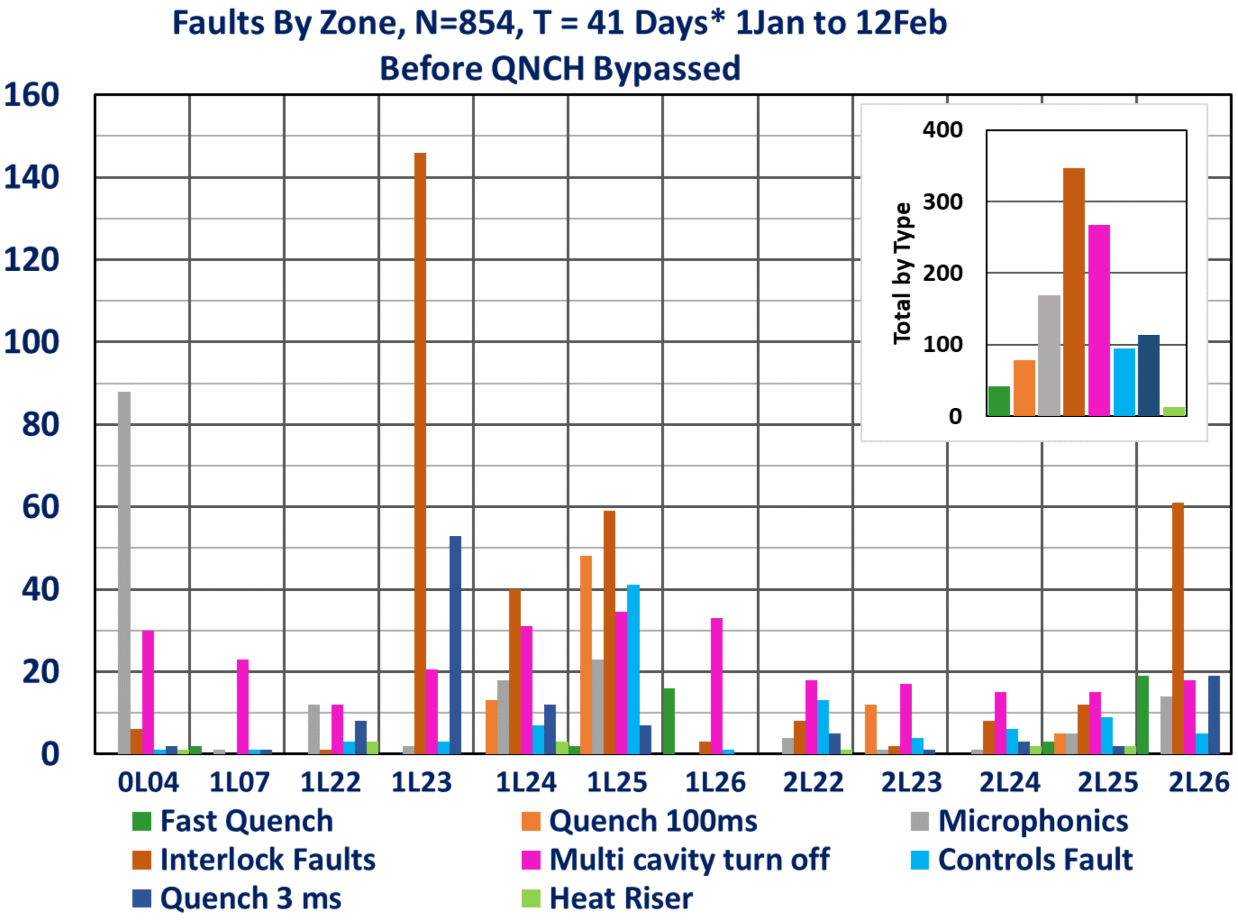
# QNCH Fault Issue (Understanding what to fix)

- In the summer of 2018 I compared the fault logger and archiver indicated that 61% of the waveform indicated interlock faults were due to QNCH faults.
- Lots of other fault types show up as QNCH faults
- This was one of the first data sets so I was potentially identifying 3ms quenches as interlock faults.  (e.g. the total number of single cavity interlock trips was over counted.
- A test was run on a single cavity in the fall of 2018 to see if the faults could be reduced by bypassing the QNCH fault.
- On Feb. 2020 the quench fault was bypassed in 5 zones.
- This was later expanded to the rest of the C100s.
- IOC reboots, may have caused some zones to revert.
- Working on a permanent fix during the current long down.

| | |
|---|---|
| E_Quench | 41 |
| GLDE | 1 |
| PLDE | 1 |
| QNCH | 39 |
| | |
| Microphonics | 163 |
| Other or none | 23 |
| GLDE | 6 |
| PLDE | 69 |
| QNCH | 65 |
| | |
| Quench | 126 |
| Other or none | 3 |
| GLDE | 7 |
| PLDE | 61 |
| QNCH | 43 |
| DETA | 12 |
| | |
| Single Cavity Turn Off | 140 |
| Other or none | 18 |
| GLDE | 0 |
| PLDE | 0 |
| QNCH | 86 |
| DETA | 5 |
| CWAT | 31 |

**Data from the spring of 2018.**

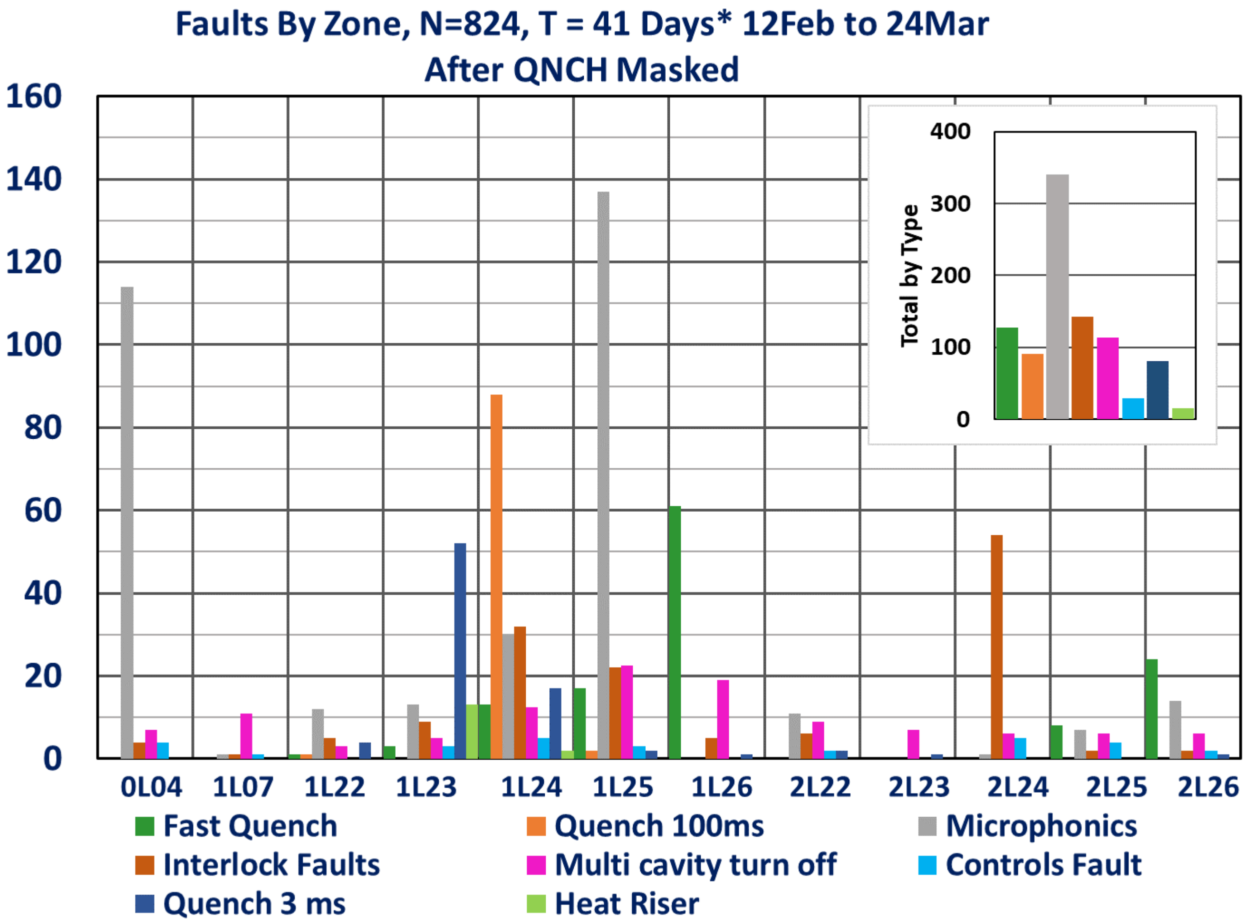
# Fault Statistics Prior to Bypassing QNCH Fault on 5 zones.



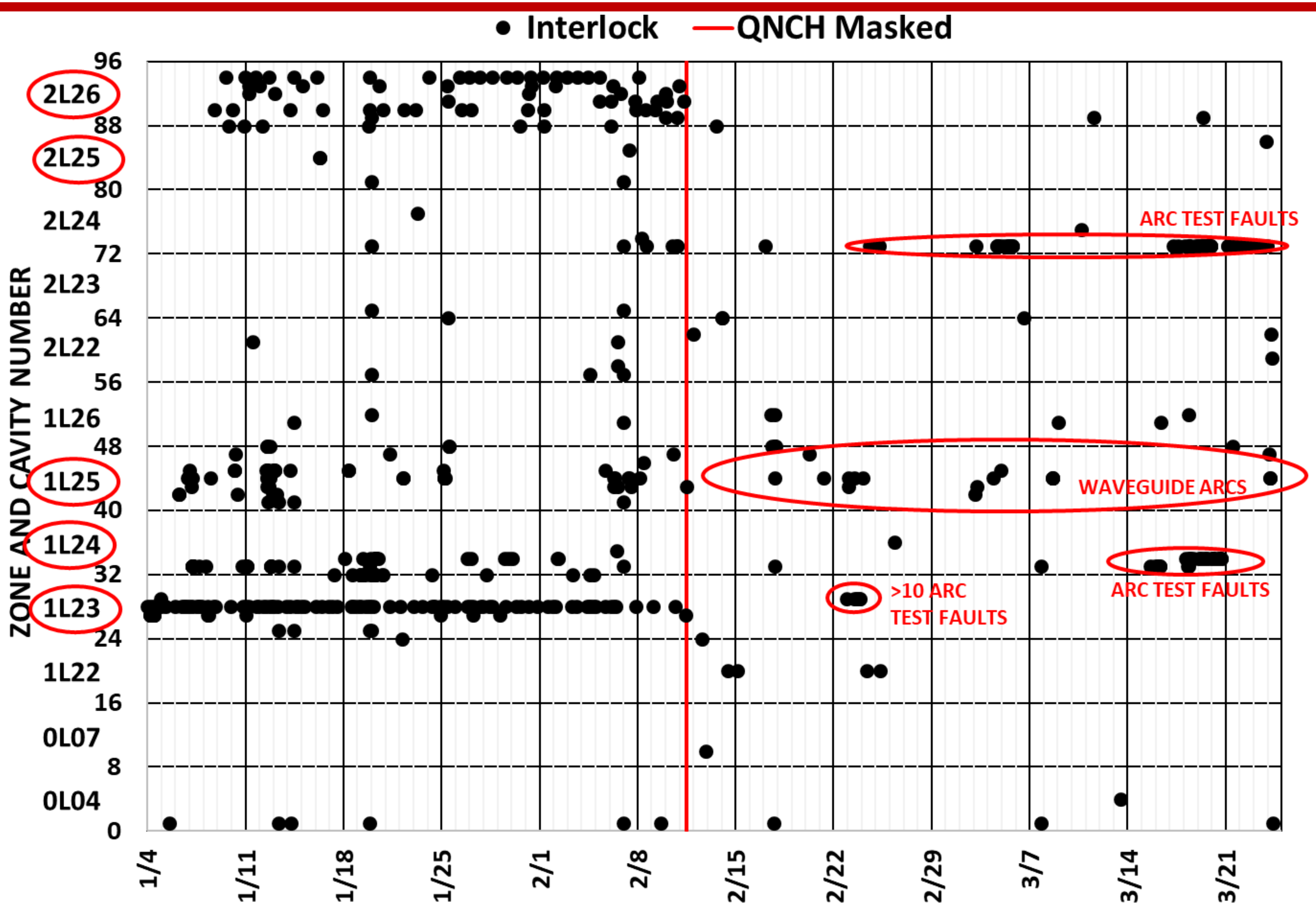

41 days prior to bypassing QNCH faults, 40% of faults were interlock faults

After bypassing the zones

- Most of the faults were Microphonics, or in 1L25 arcs or vacuum faults induced by Microphonics.
- 15% were interlock faults



# Reduction in Interlock Trips When QNCH Interlock Was Bypassed



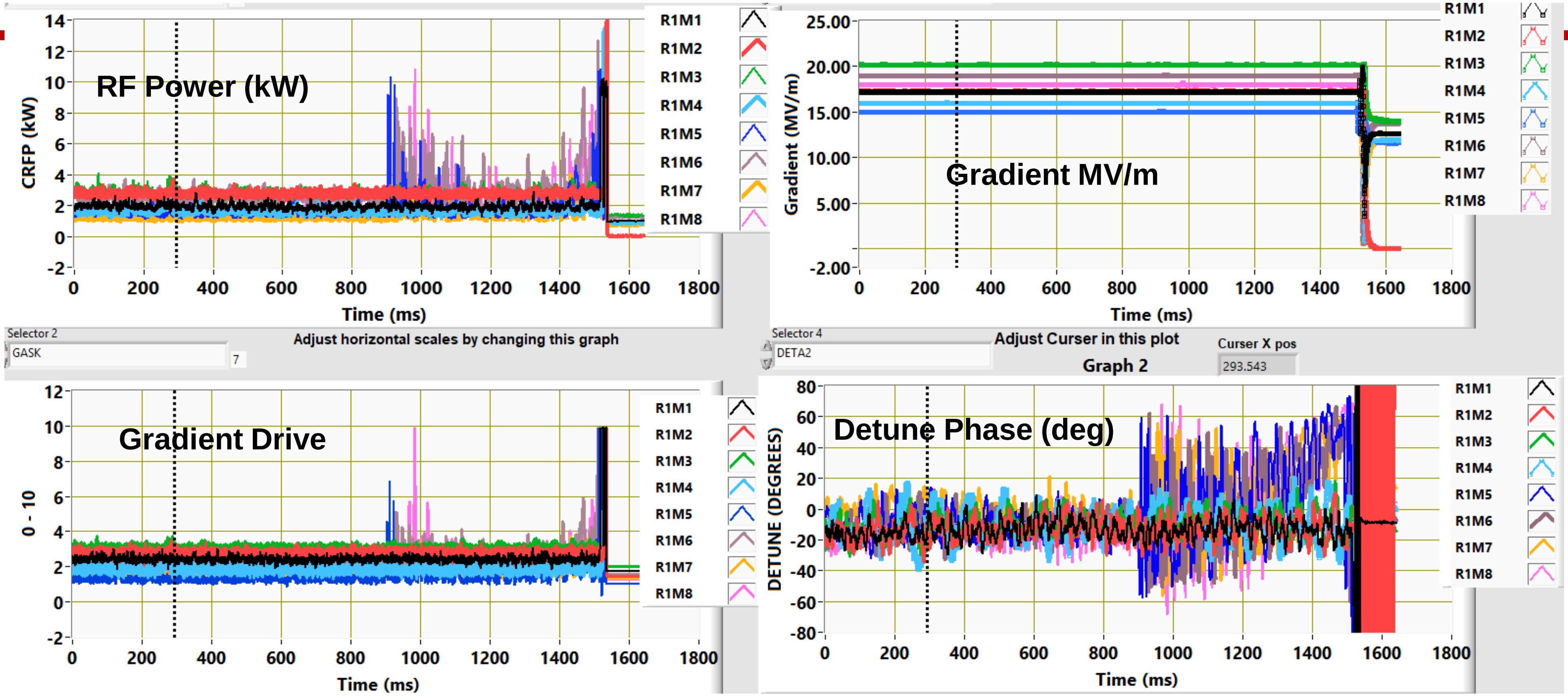

After 5 zones had the QNCH fault bypassed.

- Of the 129 faults identified as interlock faults
- 70% were arc test faults
- 18% were arc or waveguide vacuum faults
- 10% were QNCH faults on zones where it was not bypassed
- 4% were gradient or phase error faults

The QNCH faults were on zones that were not bypassed.

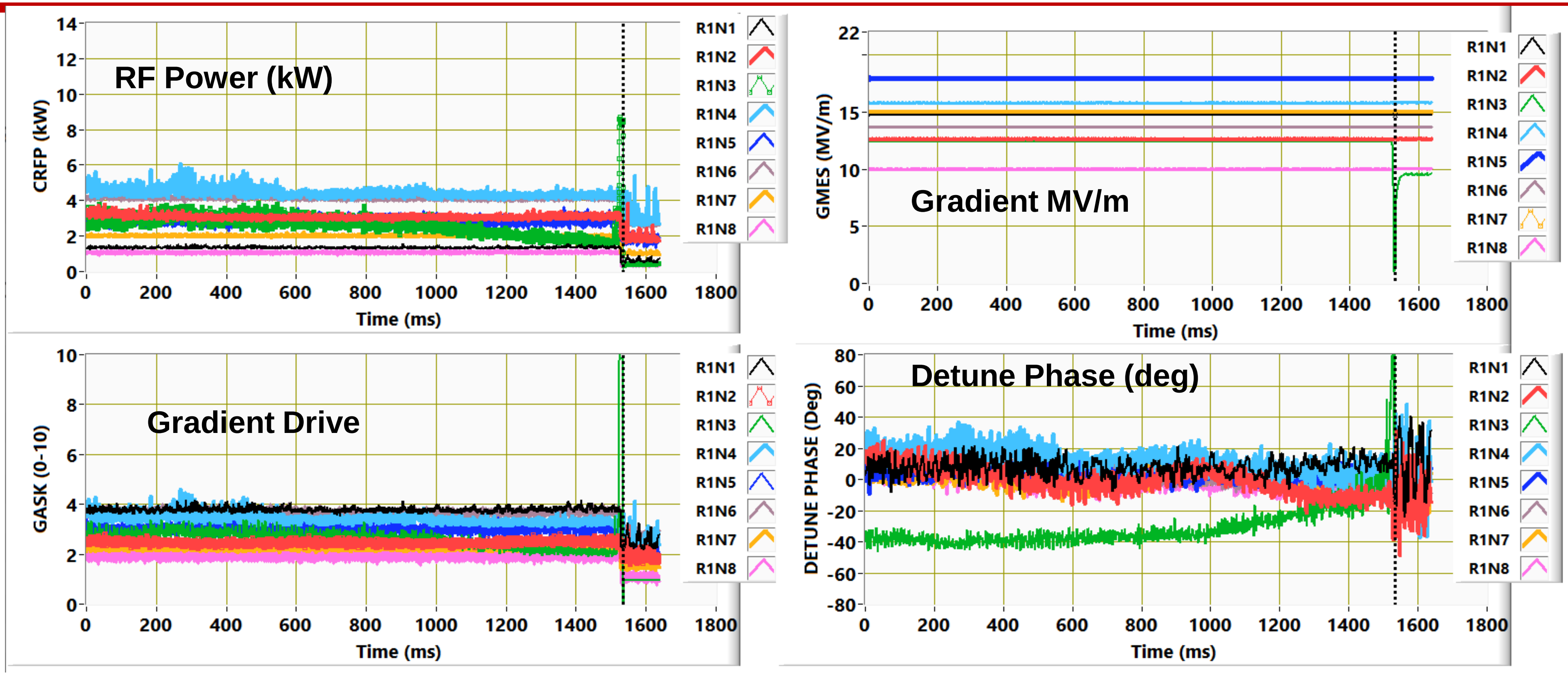
Gradient error faults is the interlock that replaced the functionality of the QNCH fault.

# Heat Riser Choke Fault



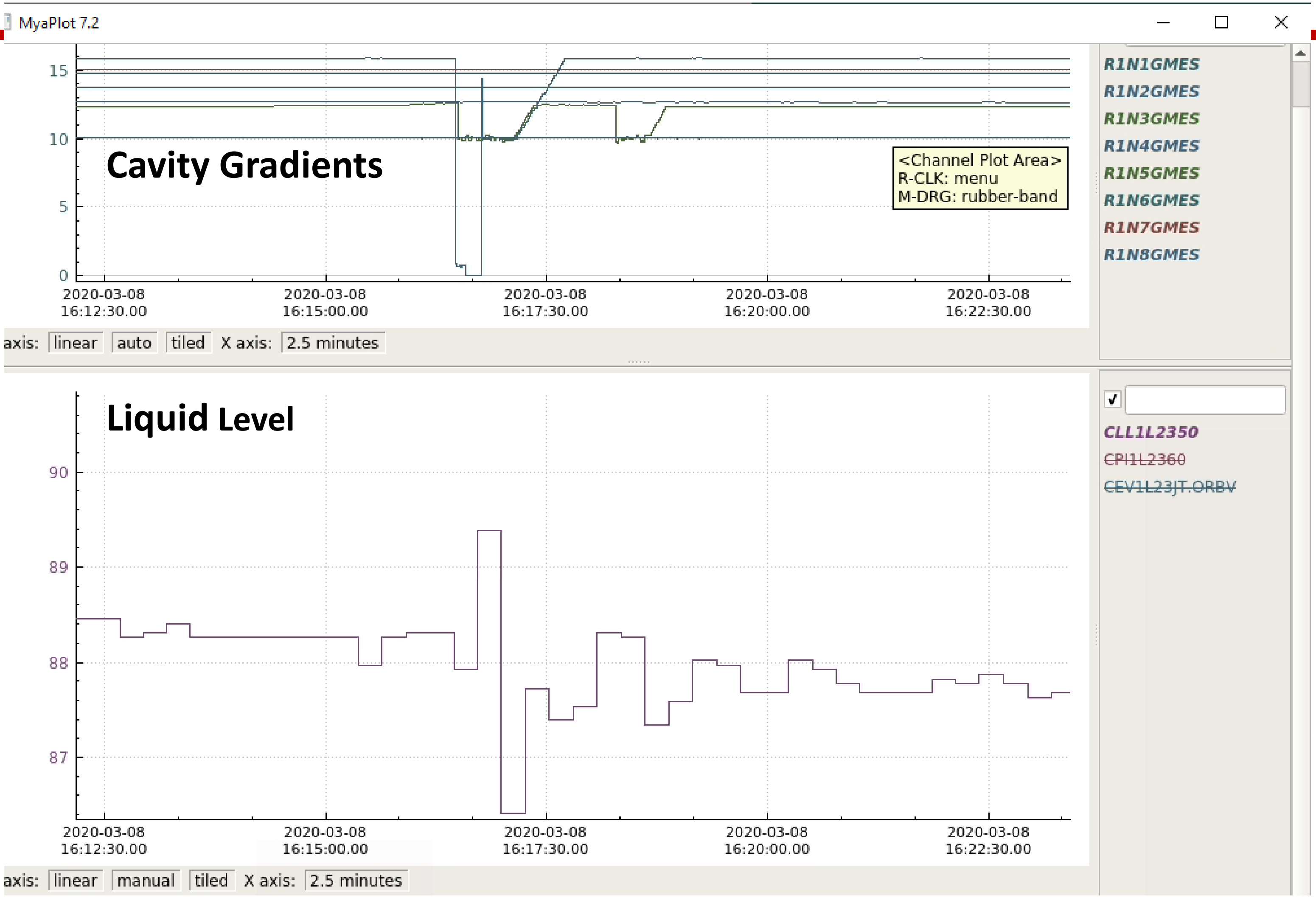

- At the machine operating pressure the heat riser pipe on the C100 cryomodules is about 40 W per cavity. When this is exceeded there is a pressure transient in the cavity in question which affects other cavities in the zone.
- Cavities 5, 6, 7 and 8 had a large detune transient that started suddenly unlike a microphonics fault where such a transient builds up slowly.
- The above fault differs from a microphonic fault in that only 4 of the cavities were affected and that as time went on the average value of the detune phase drifted up on those cavities.
- It is often difficult to determine which cavity actually caused the fault.

# Another Type of Heat Riser Choke



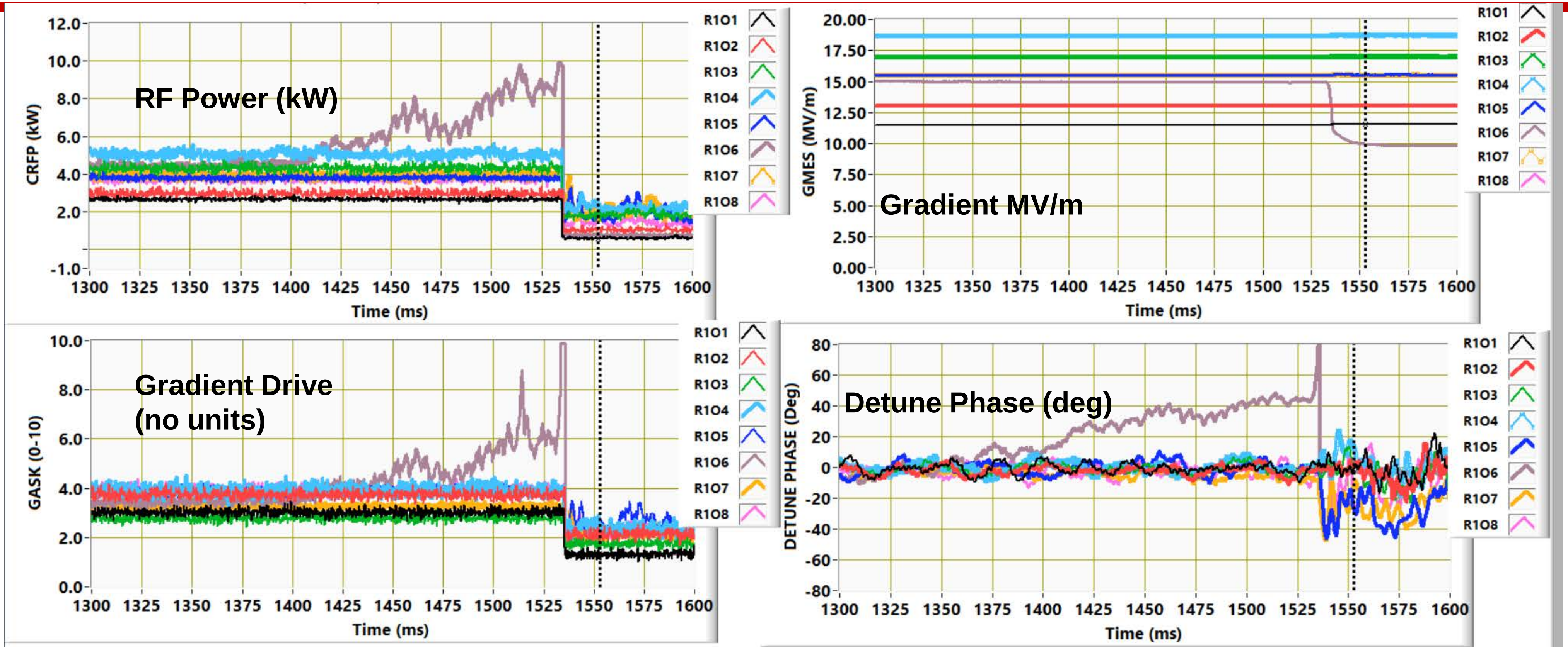

**When this type of event occurs it seems to happen shortly after a nominal heat riser choke as shown in the previous slide or due to a cavity quench that lead to a heat riser choke.**

# Helium Liquid Level Transient Due to a Heat Riser Choke



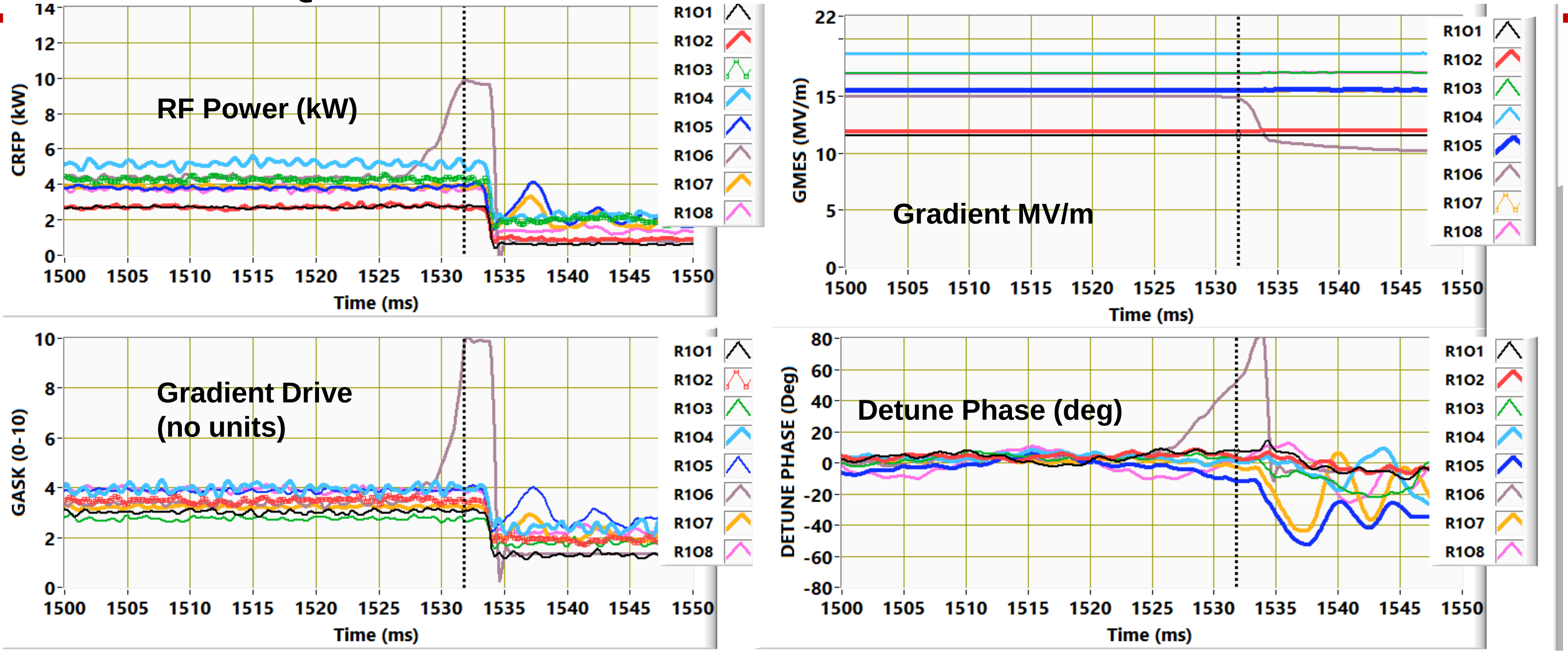

- They are not always this clear but there is usually an oscillation that happens at the sample time of the liquid level sensor.
- The second trip is the event from the previous slide.

# End Group or Partial Quench



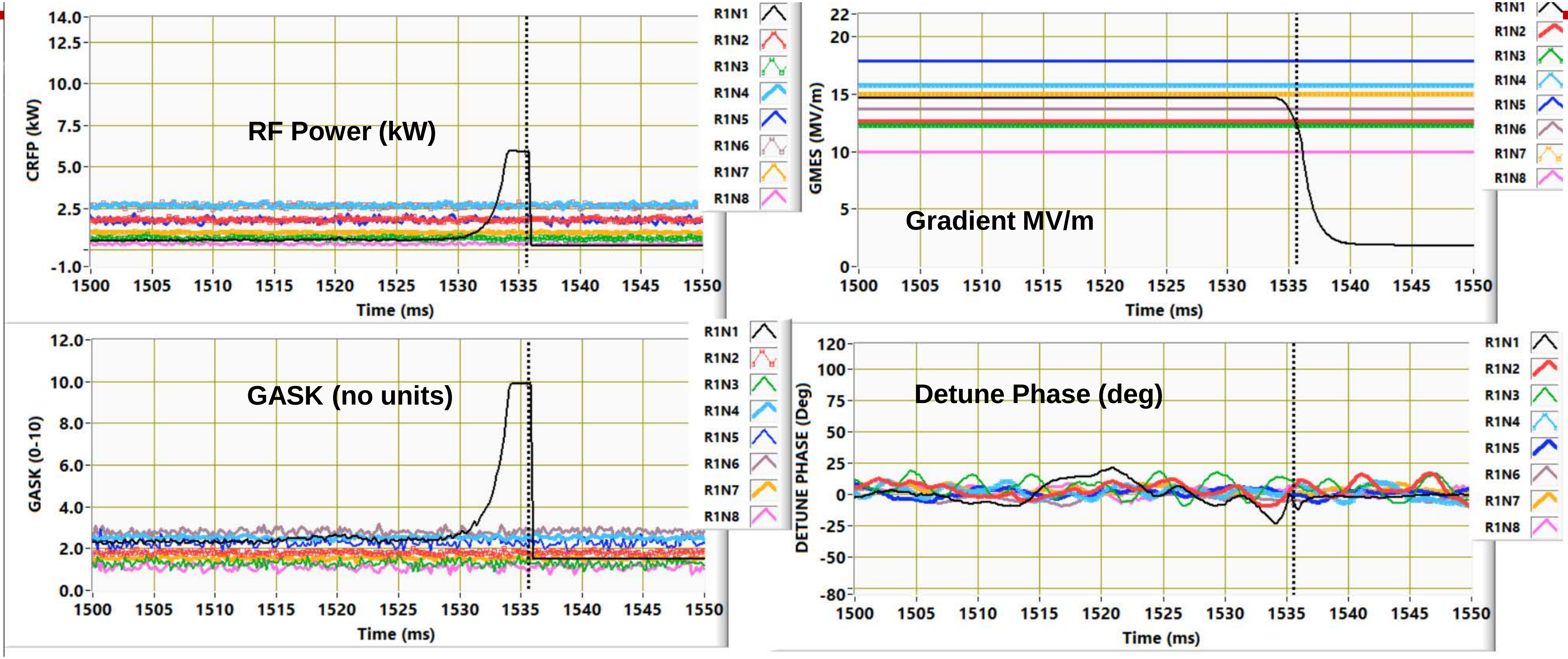

- Cavity shift frequency by about 150 Hz over a 100 ms or so.
- These events typically have minor heat riser chokes.
- Note that this is not a hard quench as the cavity was able to transition to 10 MV/m when it shifted to SEL mode at reduced RF power
- We are confident that this an end group quench which, based on practical experience and simulations done by Ed Daly, takes a few hundred ms to a few seconds to fully propagate.  This is compared to a prompt (in the cell) quench which has a propagation time of 3 to 5 ms.

# 1L24-6 “3 ms” Quench




- The zone was operating fine and cavity 6 decides that it was going to detune of 50° degrees in 5 ms.
- Cavities that have 100 ms Quenches frequently also have this type of quench.
- In both cases the cavities did not actually quench as they transitioned to SEL mode at 10 MV/m without any problems. In both cases there was a minor oscillation in the liquid level which indicates excessive heat into the bath.
- Note that in both this and the last slide the other cavities did not show sudden onset of microphonics which is typical of a heat riser choke.

# Thermal Quench, Classified as 3 ms Quench




- Sudden increase in forward power, while the gradient went down by 0.06 MV/m.
- Very little change in phase.
- The RF went from GDR mode at 500 W to SEL mode at 250 W which is should provide 10 MV/m.
- Review of the archived data and data at the end of this waveform indicated that the cavity was dissipating 150 W at 1.5 MV/m while in SEL mode. Also observed a heat riser choke.

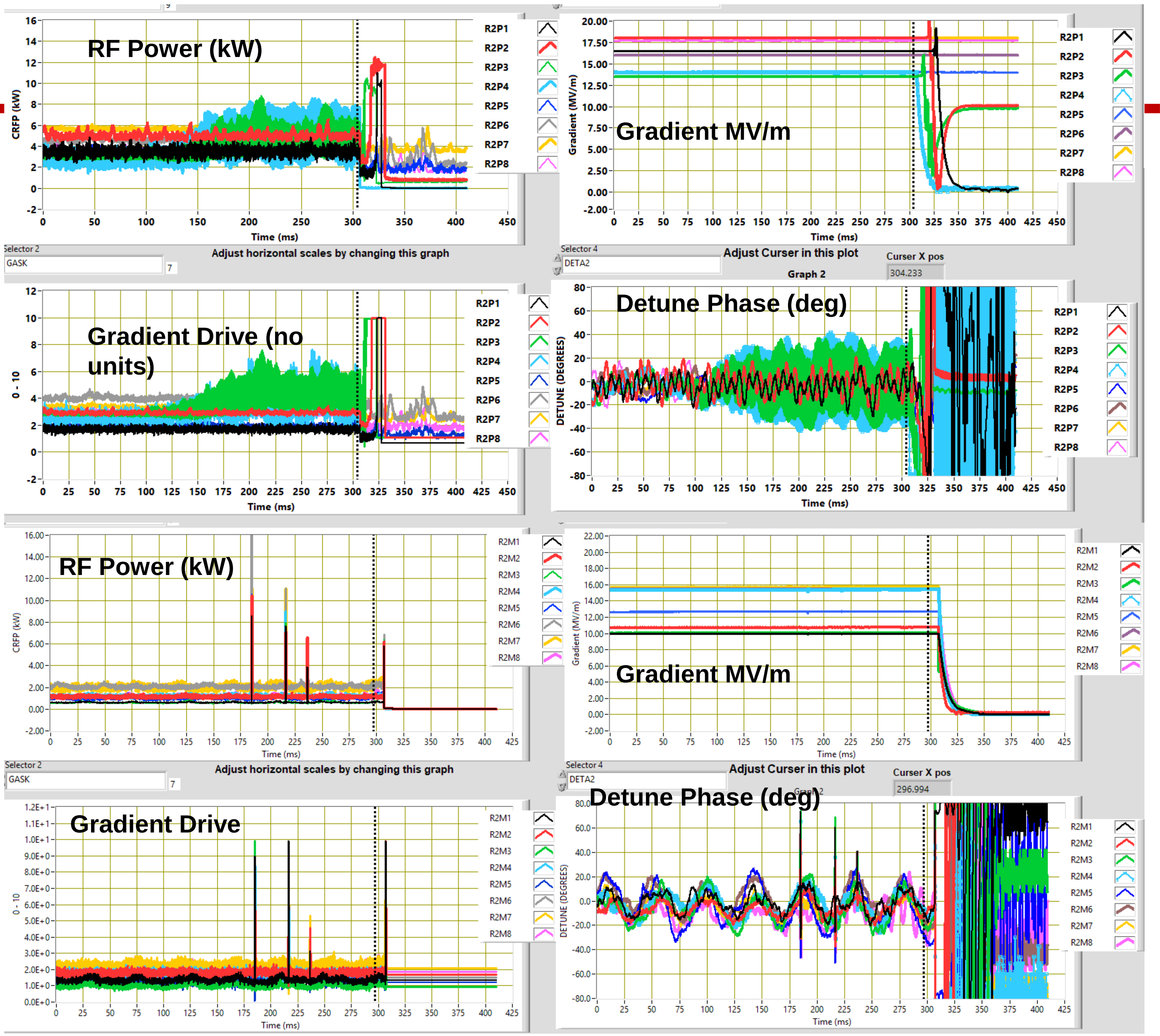
# Examples of Controls Faults

## Loop oscillations

- Probably due to incorrectly set loop phase.
- 4.2 kHz loop oscillations on one cavity probably shaking the adjacent cavity

## “Single Event” noise.

- Frequently the faults is coincident with the 70 MHz PLL on the cavity LLRF systems loosing phase lock.
- This started happening about 18 months ago and has gotten worse.
- There is an active investigation as to the integrity of the machine grounding system.



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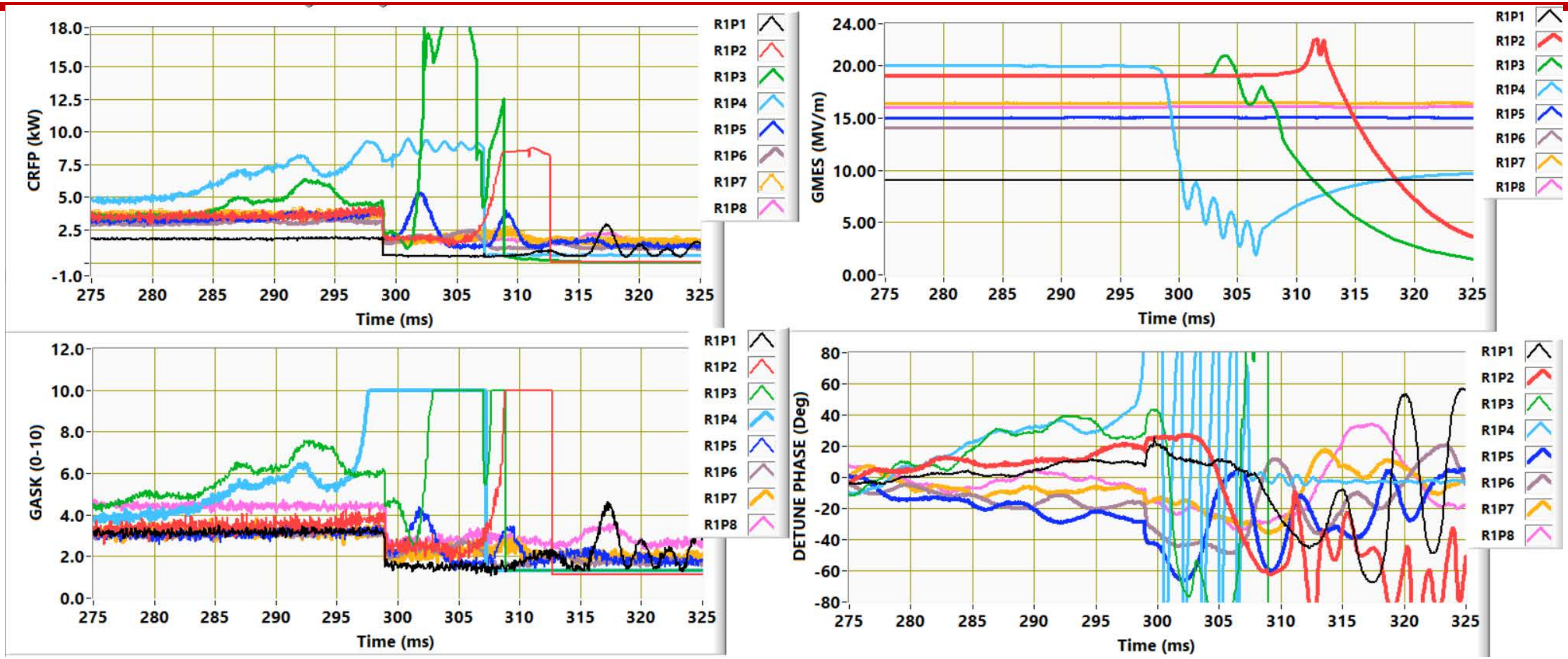
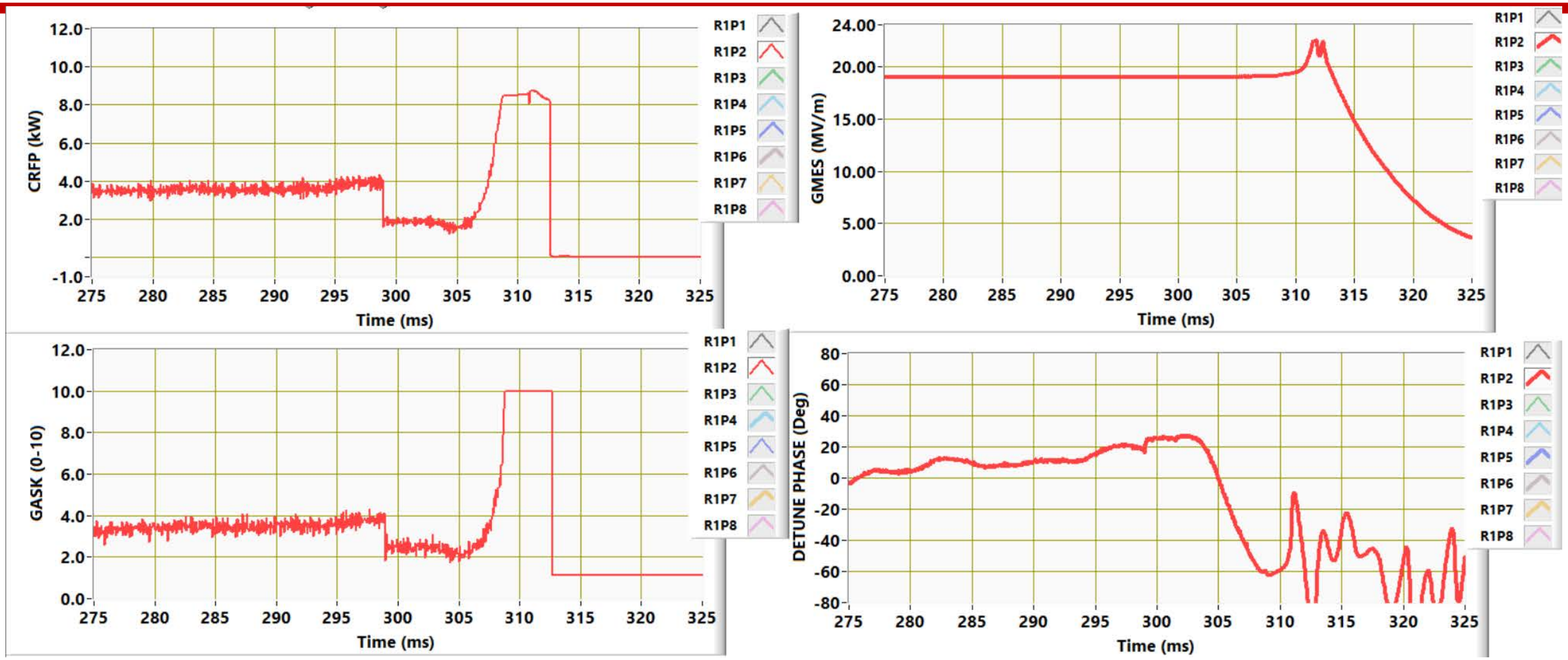
# Confirmed “Anomalous” (no more) Quench Event

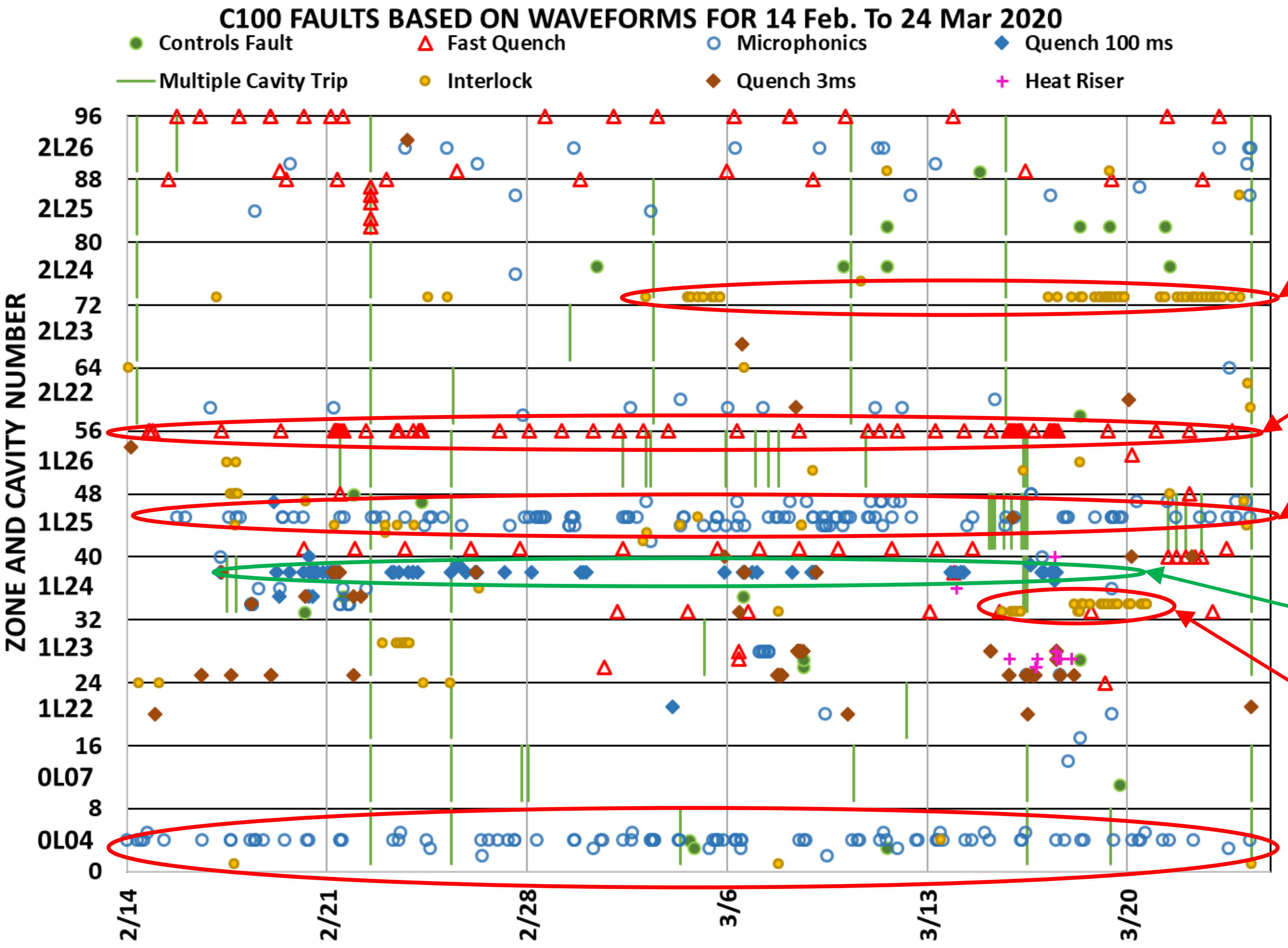



- Typical cascade trip initiated by cavity 4 being 40 degrees off crest and improperly tuned by an extra 4 degrees.
- The step at 299 ms is due to the beam turning off. It is the corresponding step in DETA2 is because the real part of the cavity drive contains the beam current term and the imaginary part contains the cavity detune component.
- As the FCC loses control due to clamping GASK cavity 4 is driven down in gradient and cavities 2 and 3 are driven up in gradient.

# Quench Driven by RF Transient




- Cavity 2 is driven to 22.5 MV/m by a “lost” control loop.
- With beam off (300 ms) Cavity 2, Forward Power of 2.1 kW at 19 MV/m.
- The RF switched off just after 312.5 ms when the cavity was at 20 MV/m which should have had an emitted power of 9.3 kW.
- The indicated emitted power value was about 7.7 kW.
- Testing in CW the next day indicated a prompt quench field of 22.5 MV/m.
- Thus, in this case, the anomalous quench was really a quench driven by the control system losing control.
- This type of phenomena should be eliminated with the new SELA/SLEAP control algorithm.




- Microphonics generally present as faults in cavities 4 and 5 because the adjacent waveguides stiffen the structure in the center.

Arc Test Faults. Tolerated until they can get an access in order to do repairs.

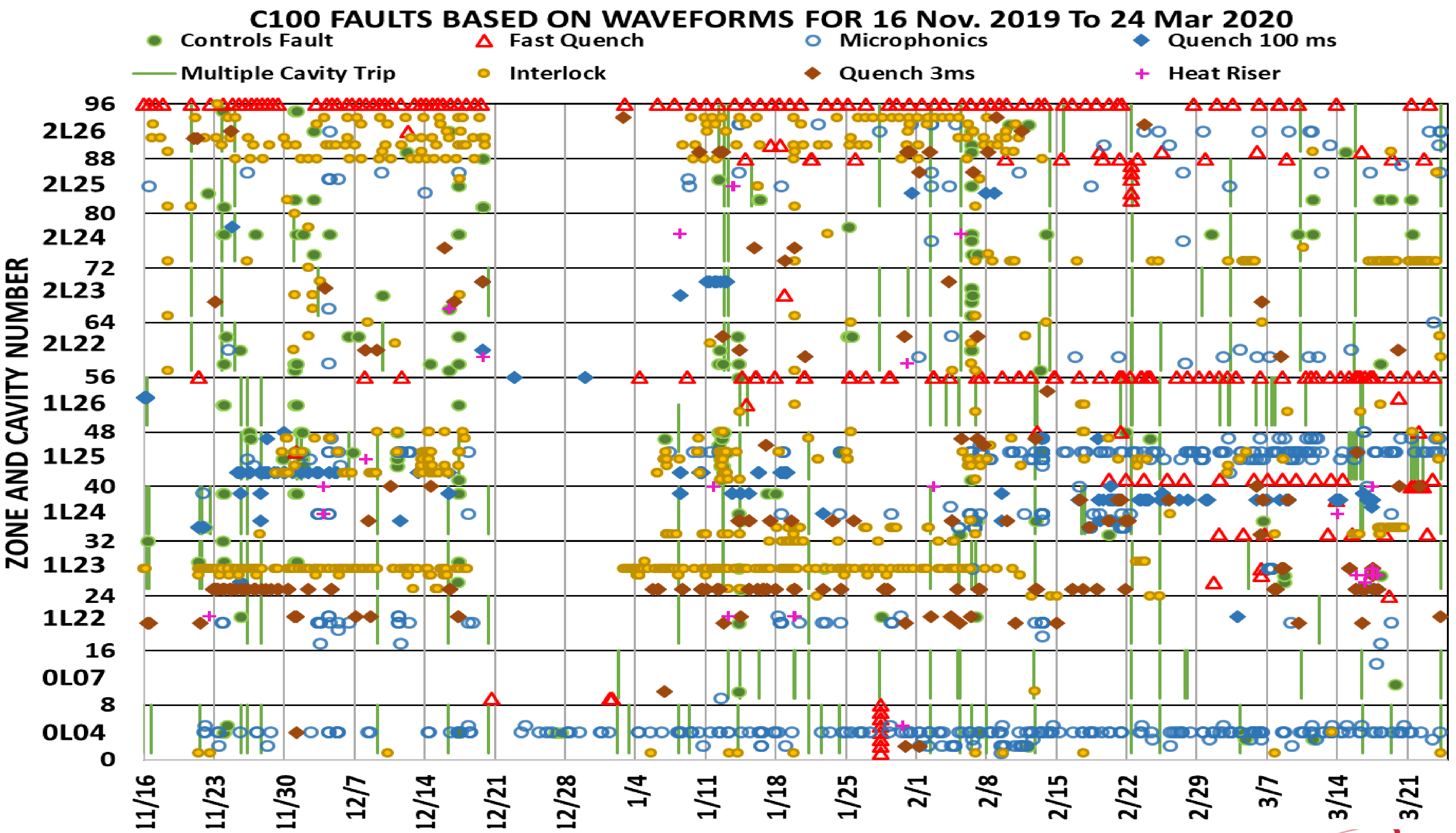
1L26-8 and 2L26-8 tend to have electronic quenches as they are adjacent to the arc vacuum systems.

1L25 has microphonics driven arcs due to a waveguide vacuum issue which is being investigated.

1L24-6 end group quench that comes and goes

Arc Test

0L04 microhonic trips because it only has 8 kW klystrons. We are looking into further hardening of the zone.



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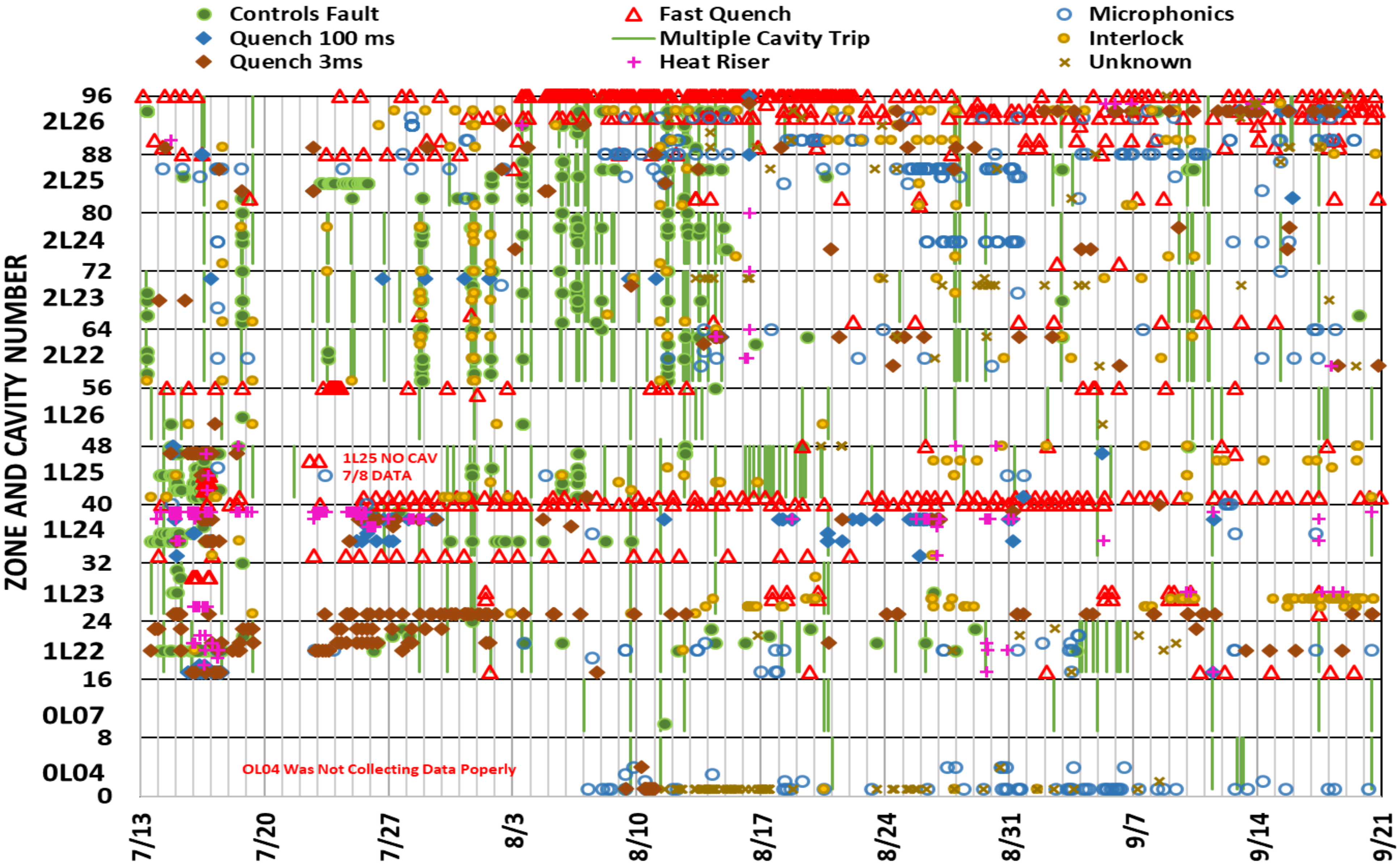
# C100 FAULTS BASED ON WAVEFORMS FOR 14 July To 21 Sept 2020




Starting in early August, 2L26 got worse even after we reduced gradients.

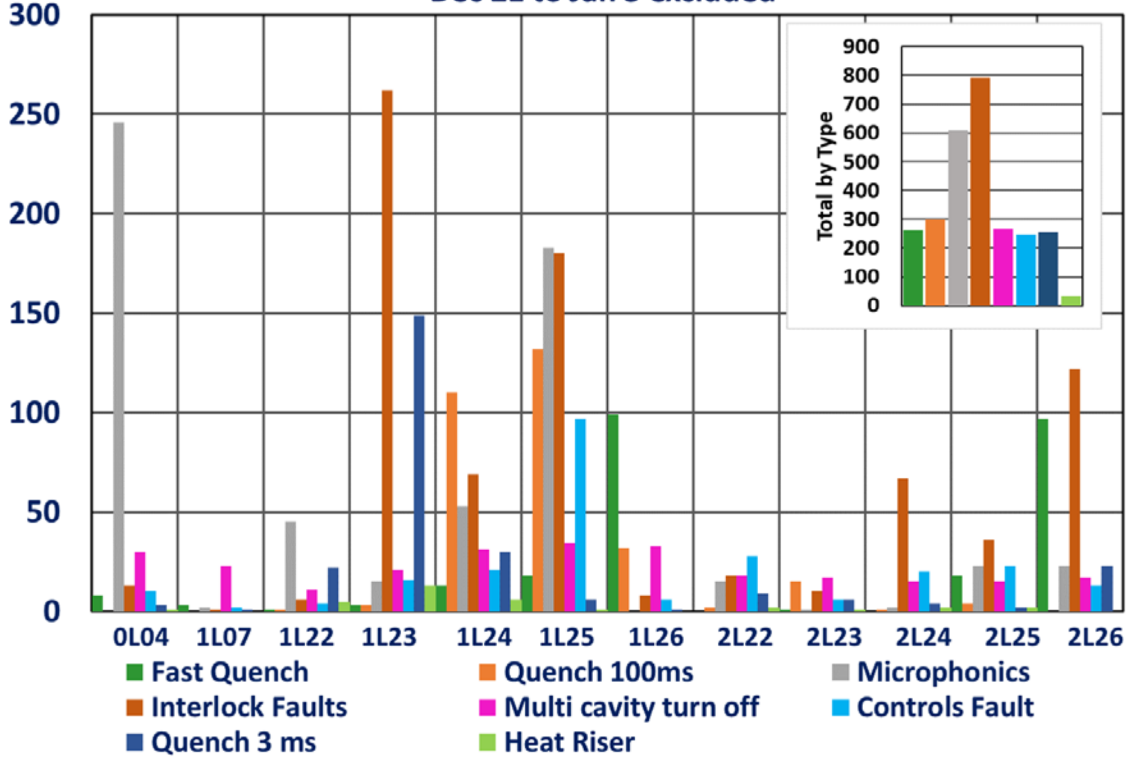
Multiple cavity trip events and controls faults occurring in multiple zones due to noise in the MO system. Indicated by Green vertical lines and green circular symbols.

1L25 Microphonics mitigations installed before run improved things.

# Faults by Zone

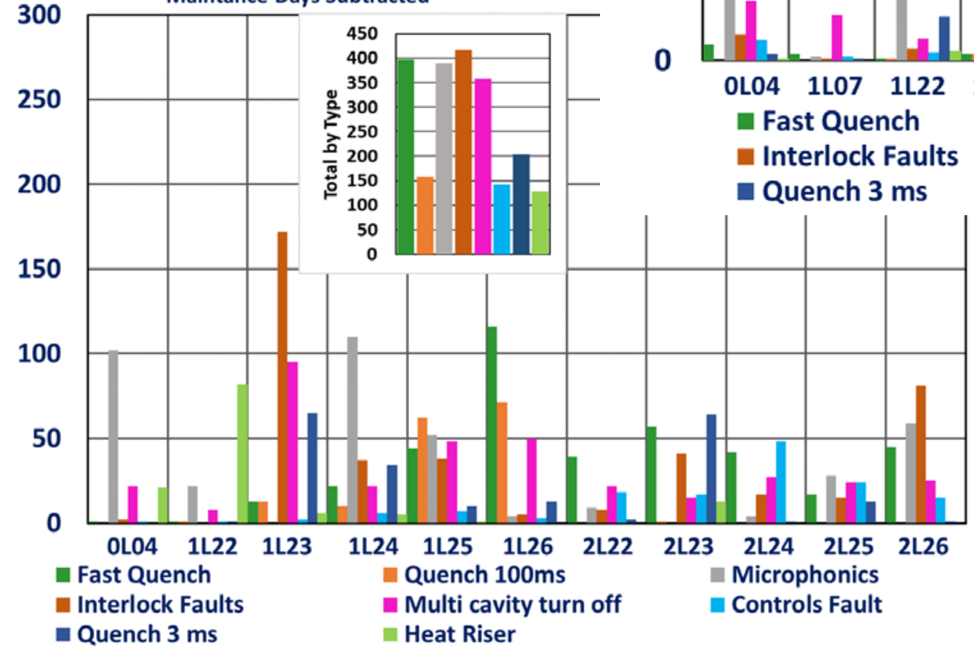
- Additional microphonics mitigations applied to 1L24, 2L25 and 2L26
- C100 cryomodules except for 2L26 thermally cycled to 300K

Faults By Zone, N=2450, T = 103 Days* 14Nov19 to 10Mar20
*Dec 21 to Jan 3 excluded

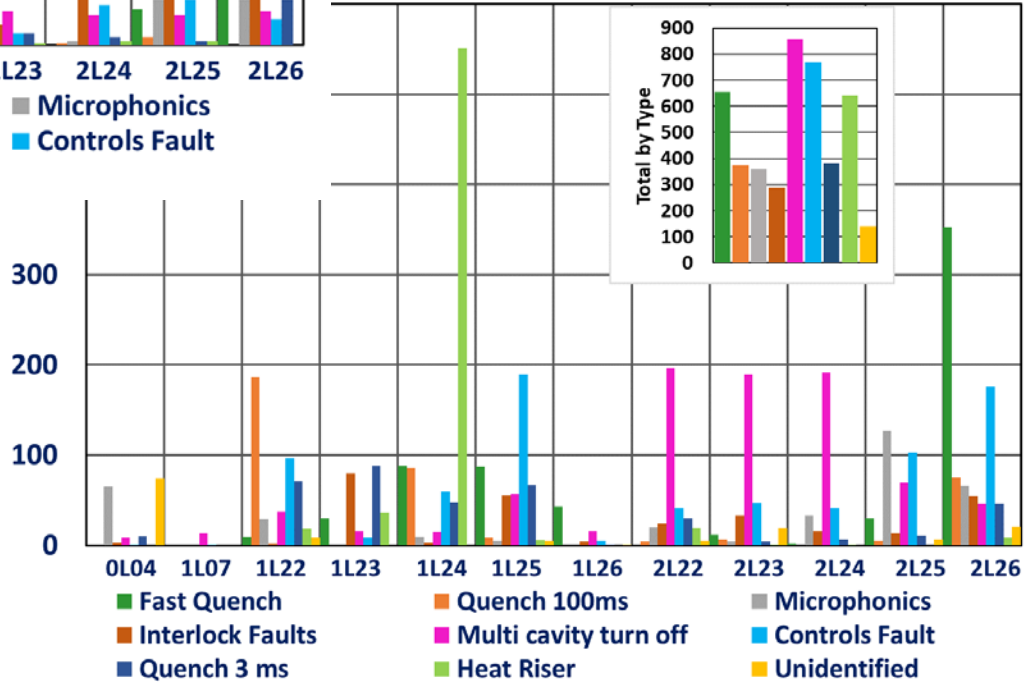



- Microphonics mitigations applied to 0L04, 1L25 and 1L24, 2L25 and 2L26.
- QNCH fault bypassed in the 5 worst zones. Reduced interlock faults.
- Approximately 1000 faults are due to the MO noise issue. (controls and multi cavity faults)
- The excessive number of heat riser faults was due to a pressure oscillation in cryogenic plant which was corrected 3 weeks into the run.

N=2182, T = 79* Days 18 Jan to 15 Apr 2019
*Maintance Days Subtracted




N=4405, T = 71 Days* 14 Jul 20 to 21Sept20



# Motivation for Machine Learning

Chris Tennant, Adam Carpenter, Anna Shabalina, Lasitha Vidyaratne, Kan Iftekharuddin

**Post-Run Analysis**

- use aggregate statistics for data-driven guidance for maintenance and/or upgrade activities
  - ✓ analysis of fall 2018 data indicated three cryomodules in the South Linac were particularly susceptible to microphonic-based faults → provided justification to perform microphonics hardening (installing tuner dampers) → reduced microphonics-based trip rates → gradients could be increased in those cryomodules
  - ✓ analysis uncovered a firmware bug which caused false trips of a type which represented approximately 40% of the faults

**Post-Fault Analysis**

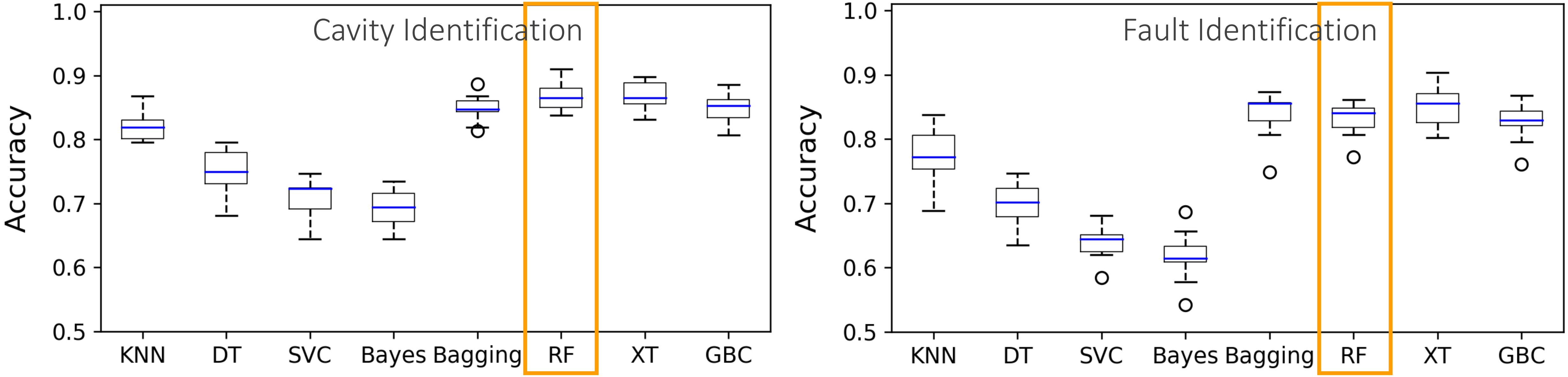
- provides critical feedback to control room operators
- fault types get mapped to actions for the operators
  - ✓ "if Trip *A* happens *X* times within *Y* minutes, drop gradient in the cavity by *Z* MV/m"



ML slides curtsey of Chris Tennant

# Model Evaluation and Selection

- split data into train/test (70%/30%)
- 10-fold cross-validation scores for several different algorithms
  - ✓ ensemble models excel
- perform hyperparameter optimization on Random Forest classifier




| | Cavity Identification | Fault Type |
|---|---|---|
| 10-fold cross-validation (%) | 87.97 ± 1.81 | 85.52 ± 3.65 |
| accuracy (test data) (%) | 87.94 | 87.66 |

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# ML Model Performance

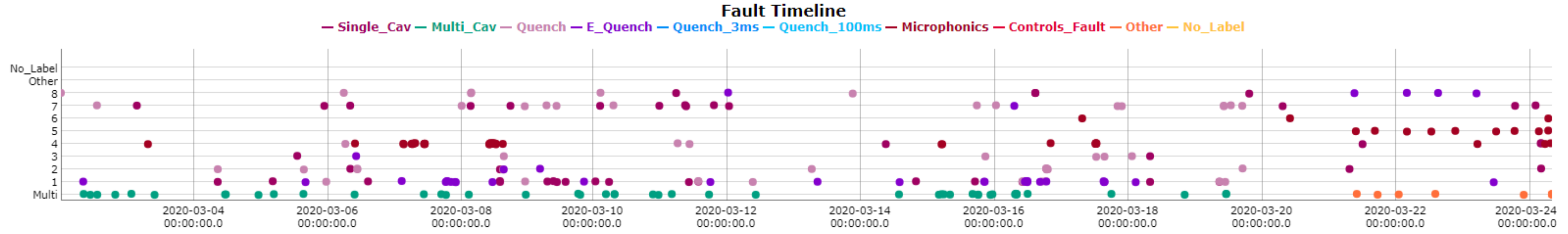
- models were applied to data collected from March 10-24, 2020
  - ✓ physics run was prematurely ended due to COVID-19
- 312 fault events were analyzed by the models
- summary of model performances compared to labeled data

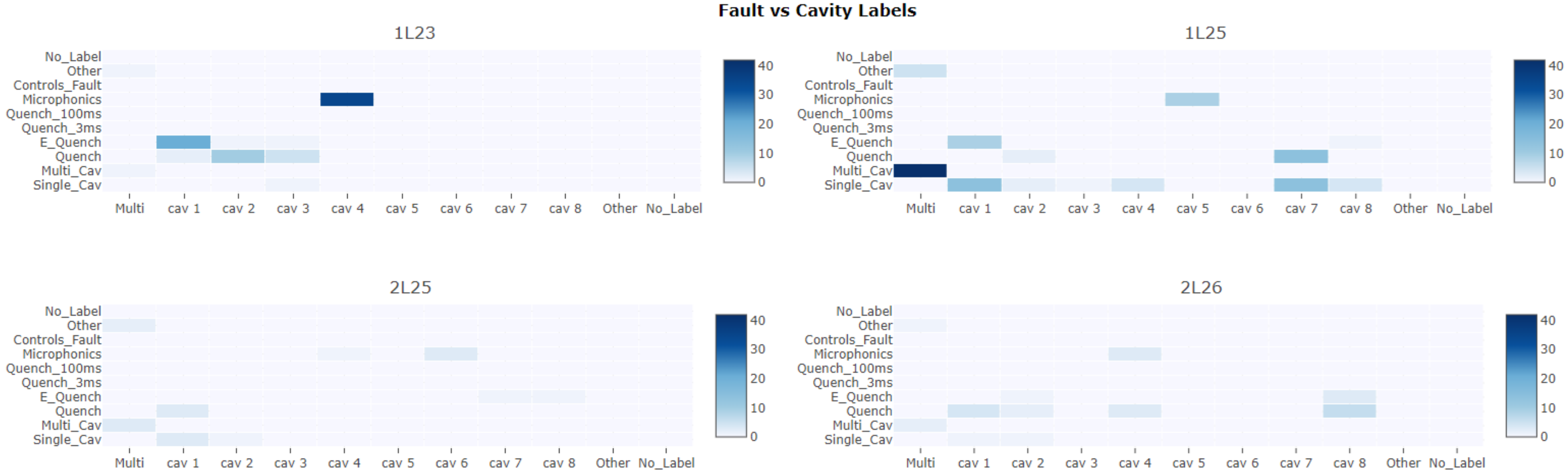
| | Agree | Disagree | Total |
|---|---|---|---|
| **Cavity Model** | 265 | 47 | 312 |
| **Fault Model** | 244 | 68 | 312 |

- cavity model accuracy: 84.9%
  - ✓ testing accuracy: 87.9%
- fault model accuracy: 78.2%
  - ✓ testing accuracy: 87.7%

# Visualization and Communication

- for ML models to be effective, information must be communicated clearly and concisely
- visualize spatial and temporal nature of model predictions




(courtesy A. Carpenter)

# Summary on Machine Learning

- have made significant progress in the last year
  - ✓ have an online machine learning system deployed
  - ✓ excellent initial results on (albeit limited) operational data
  - ✓ system provided feedback to SMEs in the most recent physics run (ended 9/21/20)
  - ✓ continue to accumulate and label data

**Superconducting radio-frequency cavity fault classification using machine learning at Jefferson Laboratory**

Chris Tennant, Adam Carpenter, Tom Powers, Anna Shabalina Solopova, Lasitha Vidyaratne, Khan Iftekharuddin

https://arxiv.org/abs/2006.06562

We report on the development of machine learning models for classifying C100 superconducting radio-frequency (SRF) cavity faults in the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab. CEBAF is a continuous-wave recirculating linac utilizing 418 SRF cavities to accelerate electrons up to 12 GeV through 5-passes. Of these, 96 cavities (12 cryomodules) are designed with a digital low-level RF system configured such that a cavity fault triggers waveform recordings of 17 RF signals for each of the 8 cavities in the cryomodule. Subject matter experts (SME) are able to analyze the collected time-series data and identify which of the eight cavities faulted first and classify the type of fault. This information is used to find trends and strategically deploy mitigations to problematic cryomodules. However manually labeling the data is laborious and time-consuming. By leveraging machine learning, near real-time (rather than post-mortem) identification of the offending cavity and classification of the fault type has been implemented. We discuss performance of the ML models during a recent physics run. Results show the cavity identification and fault classification models have accuracies of 84.9% and 78.2%, respectively.

- recent FOA funding will apply ML to several *other* areas with within the SRF ecosystem
  - ✓ optimize gradient distribution to minimize field emission
  - ✓ detect RF cavity instability
  - ✓ RF cavity fault *prediction*

# Plans to Improve the C100 Fault Monitoring, Fault Recovery and Operation

## Fault Monitoring and Classification

- Develop machine learning processes such that it can be used to provide reliable real time feedback to operations as to the nature of cavity faults.
- Continue to monitor faults manually and use the data to guide system improvements and adjustments in operating gradients.
- Continue the “parasitic” experiments regarding the effects of thermal cycling cryomodules to room temperature in order to improve fault rates from electronic quenches.

## Low Level RF

- Upgrade LLRF firmware/software to substantially improve C100 recovery time.
- Implement background checking of cavity detune offset.
- Add a double buffer for time domain data so that the waveform harvester can run even when other applications are using the same data for other purposes.
- Continue to investigate and mitigate the master oscillator instability (ground fault noise?).
- Design a digital acquisition interface for the C20/C50 RF systems.

## SRF

- Continue to harden cryomodules against microphonics faults.
- Major overhaul of the logic for the C100 vacuum interlock logic in order to avoid closing beam line valves unless necessary.
- Major program in the north linac to replace beam line valves, clean and bake selected girders.
- Develop plasma processing protocols for C100 and C20/C50 cavities.
- Rebuild cryomodules. Current proposal is, 2 cryomodules in FY21, 3 in FY22 and 4 in FY23. Some of which will include replacement of the LLRF systems with digital low level RF systems