CEBAF C100 FAULT CLASSIFICATION BASED ON TIME DOMAIN RF SIGNALS

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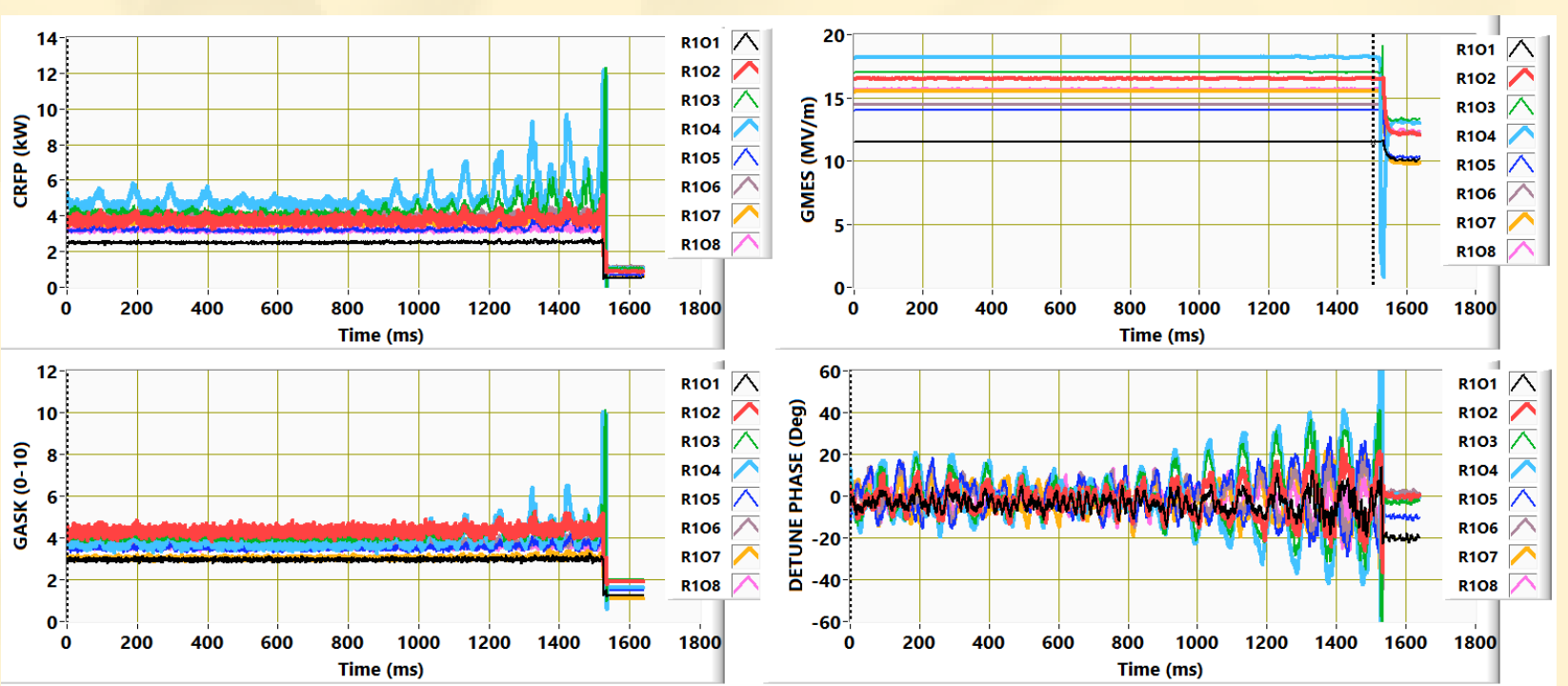
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Abstract

In 2018, the software and hardware in the CEBAF C100 digital low level RF systems were configured such that a fault would trigger an acquisition process which records waveform records of 17 of the RF signals for each of the 8 cavities within the cryomodule for subsequent analysis. These waveforms are especially useful in C100 cryomodules as there is a 10% mechanical coupling between adjacent cavities. When one cavity has a fault and the gradient is reduced quickly and it will mechanically deform due relaxation of the Lorentz force effects. This deformation causes perturbations in the adjacent cavities which, in turn, causes a cascade of cavity faults that are difficult to understand without the time domain data. This contribution will describe the types of faults encountered during operation and their signatures in the time domain data, as well as how the results are being used to modify the setup of the machine and implement improvements to the cryomodules.

Background

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

Since the spring of 2018 there were about 500 faults classified per operational month.

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

C100 Faults Identified Using Time Domain Waveforms From the Winter 2019 Run

C100 FAULTS BASED ON WAVEFORMS FOR 18 Jan to 15 April 2019

Fault Descriptions

Microphonics Driven Trip
- 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 600 ms this excited the 10 Hz full string mode which causes maximum excursions in cavities 4 and 5.
- At about 1525 ms the FCC output drive for cavity 4 (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. Similarly cavity 5 clamps at 1530 ms and is driven up in gradient.
- At 1535 ms a trip in the zone is detected and all of the cavities are switched to SEL mode.
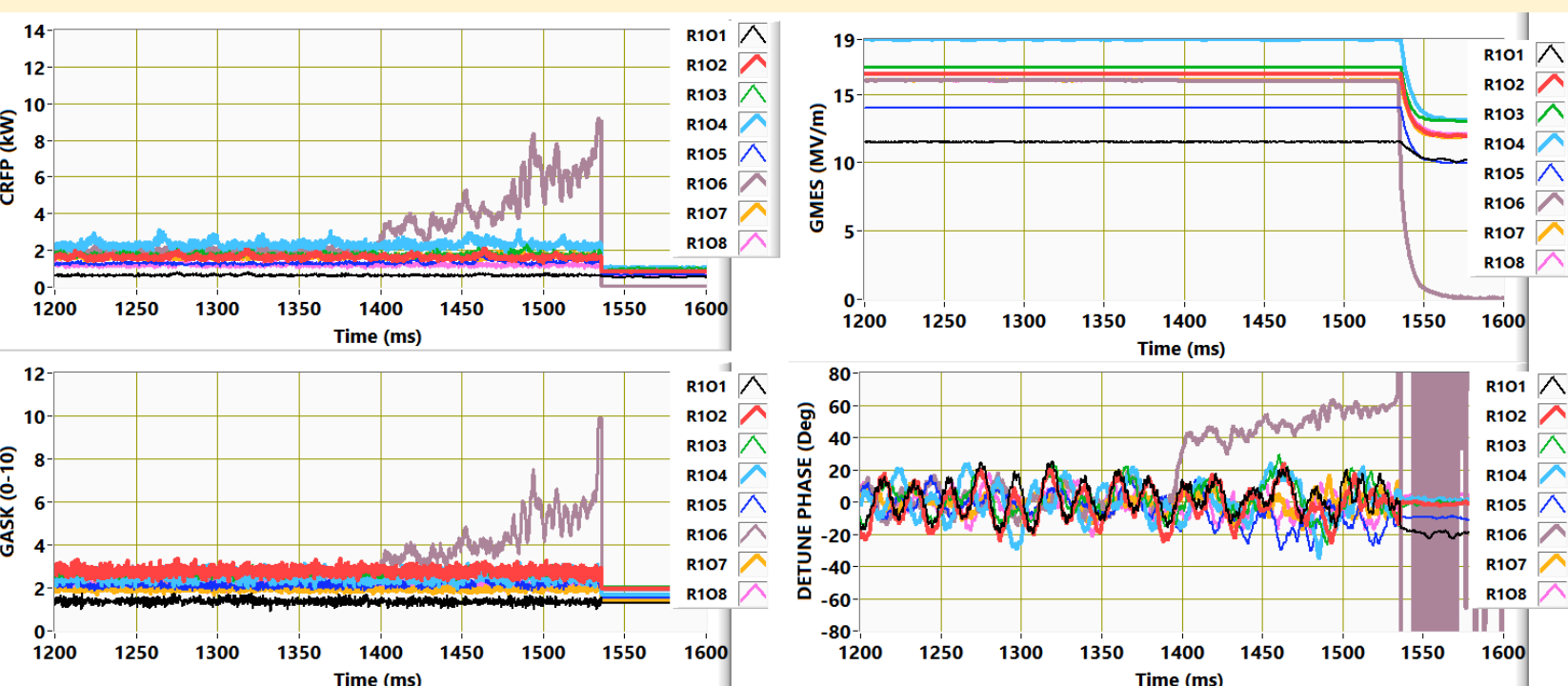

Fast "Electronic Quench"
- Fall time of cavity gradient faster than 50 us (one point at this acquisition rate).
- Cavity seemed to be operating normally up until this point.
- Theory -- vacuum burst in cavity releases large quantities of electrons which absorb the energy within the cavity.
- 93% of the fast quenches in the Fall 2018 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 inner cryomodule warm beam pipe and subsequent freeze out in the beam line warm to cold to cold transition is likely.

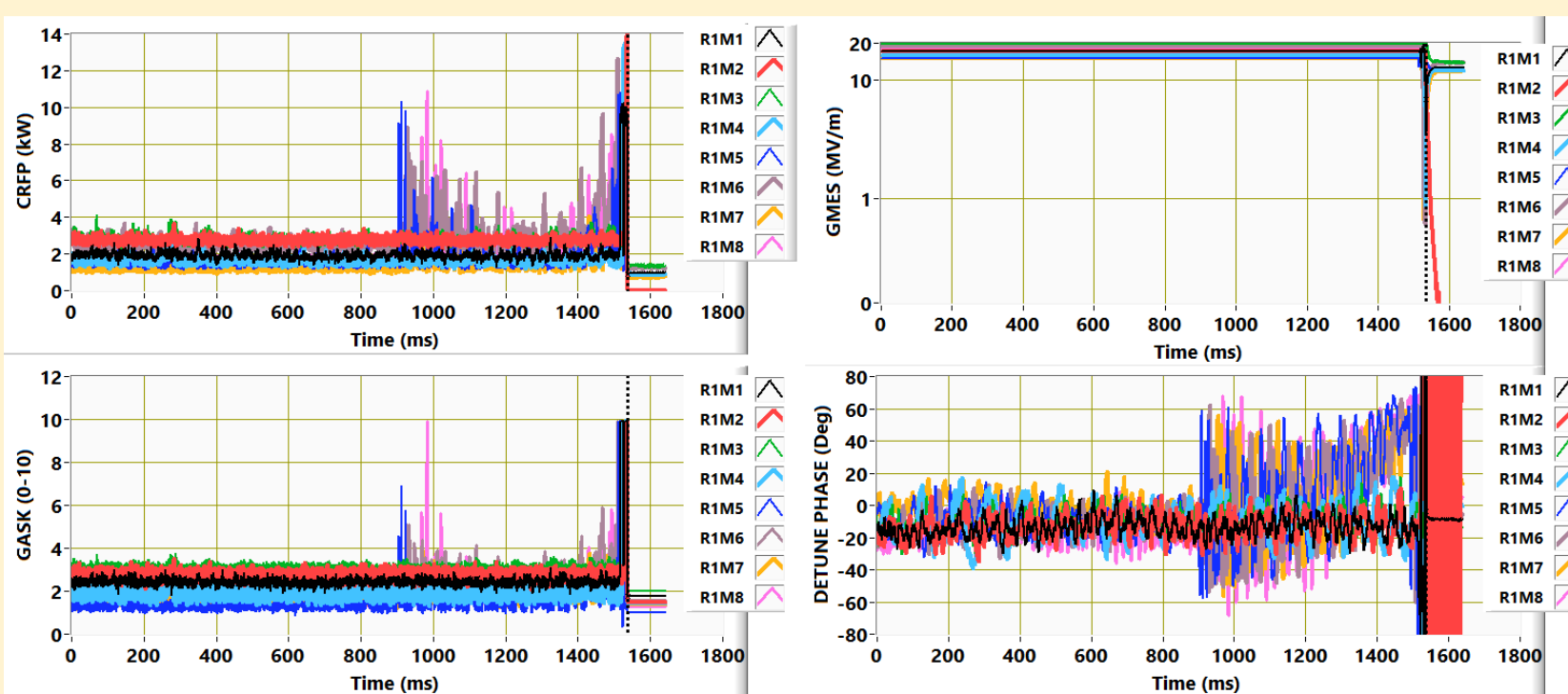### Corresponding beamline vacuum excursion.
- Red trace is pump next to cavity 1 blue trace is at the upstream end of the girder.
- Peak vacuum signal adjacent to cavity 2e-5 Torr at the other end of the girder was 3e-7 Torr.
- No events were recorded where cavity 1 in one zone and cavity 8 in the adjacent 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.

2e-5 Torr

End Group Partial Quench
- When this type of event occurs it will continue to do so every 10 to 30 minutes until the gradient is reduced by at lest 0.5 MV/m.
- We are confident that this an end group quench which, based on practical experience and simulations done in 2003, takes a few hundred milliseconds 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.
- The 3 ms "quench" events are similar except the phase changed 40 degrees in 3 to 5 ms. They might be due to a quench or something else.
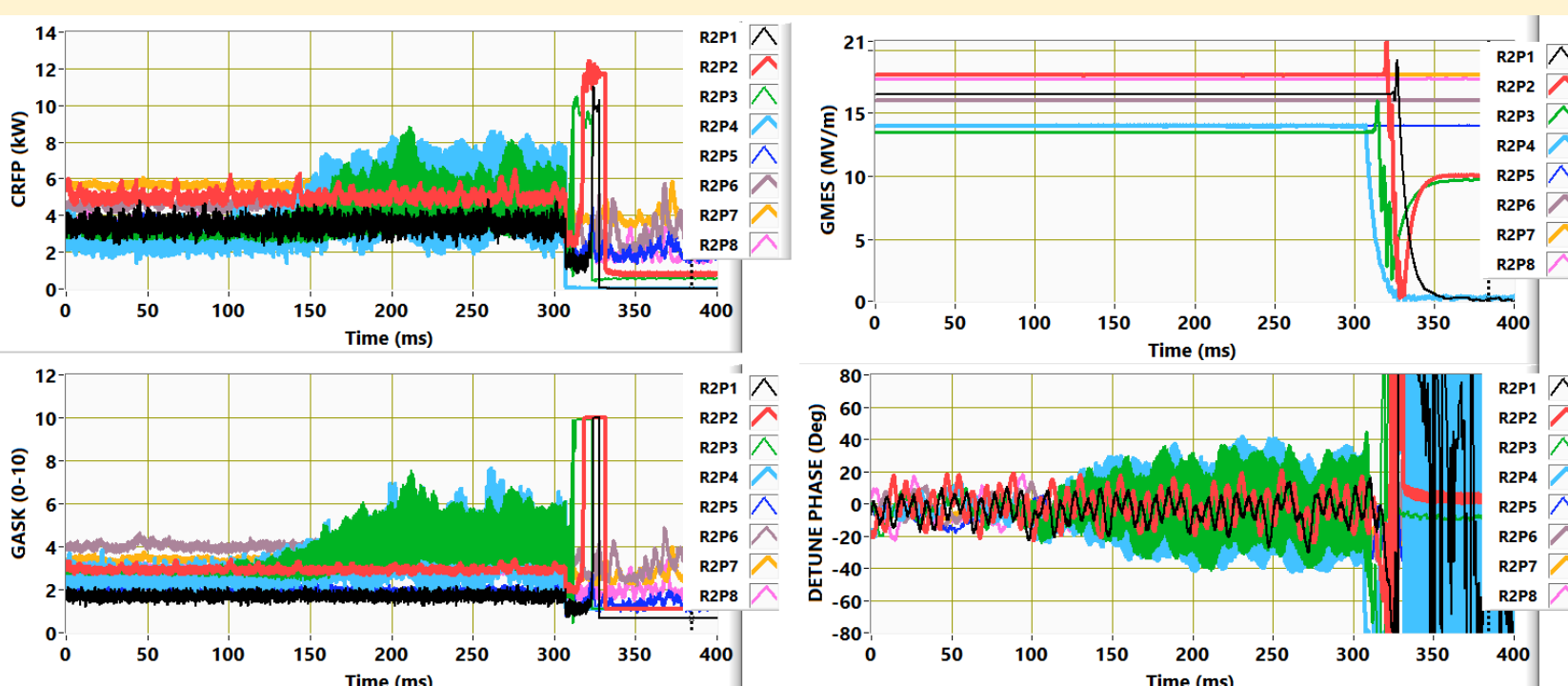

Unknown Event Type
Is it a Quench or Discharge in the Cavity?
- Gradient and detune are "stable" but forward power rapidly increases and the cavity trips.
- Looking at the gradient on a semi-log graph shows an exponential decay as a straight line the slope of which indicates the loaded-Q.
- In this case the loaded-Q is substantially reduced after the event.
- It is possible that it could be a prompt quench, but it is also possible that it is some type of discharge in the cavity which is not seen by the arc detecctor system.
- No beam-line or waveguide vacuum excursions were observed during this event.
- Note: The kink at 1 MV/m is an artifact of the LLRF calibration which is calibrated to be valid for a 26 dB dynamic range with an upper bound of 25 MV/m.

The plot to the right shows the normal gradient decay time after the RF is switched off.

Heat Riser Choke
- At the machine operating pressure the heat capacity of the pipe between the helium vessel and the two phase manifold 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 over time.
- The above fault differs from a microphonic fault in that only 4 of the cavities are affected and that as time went on the average value of the detune phase drifted up on those cavities.
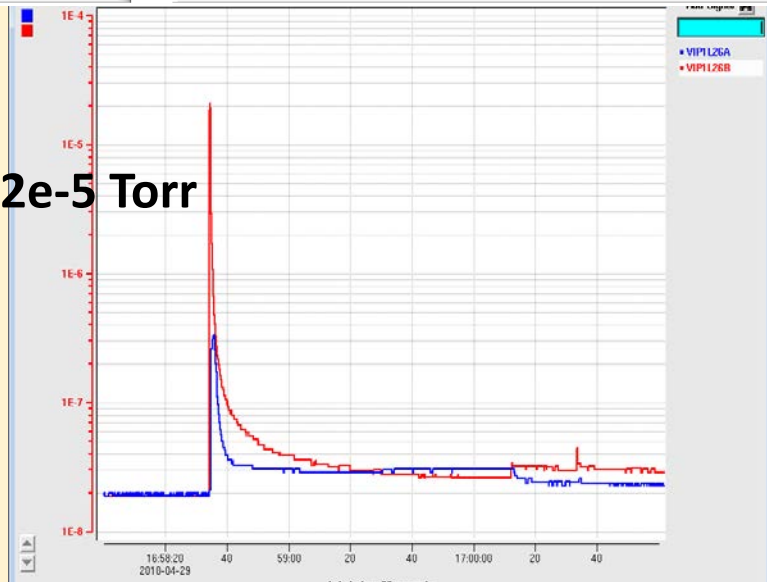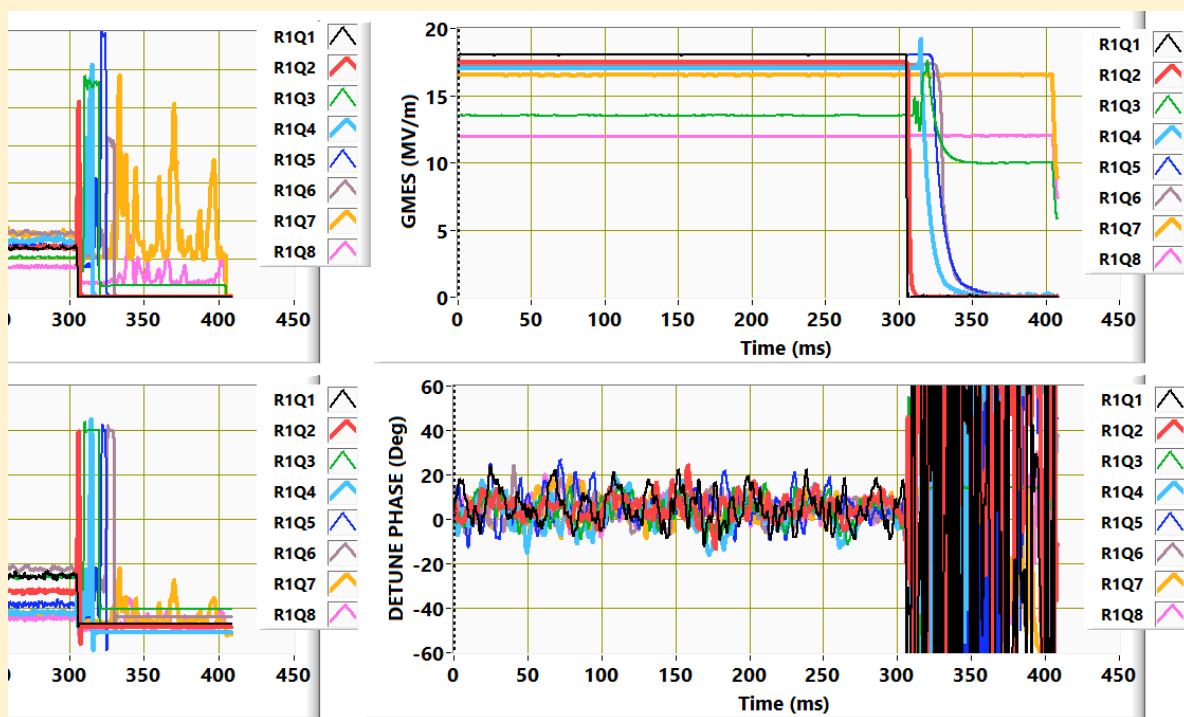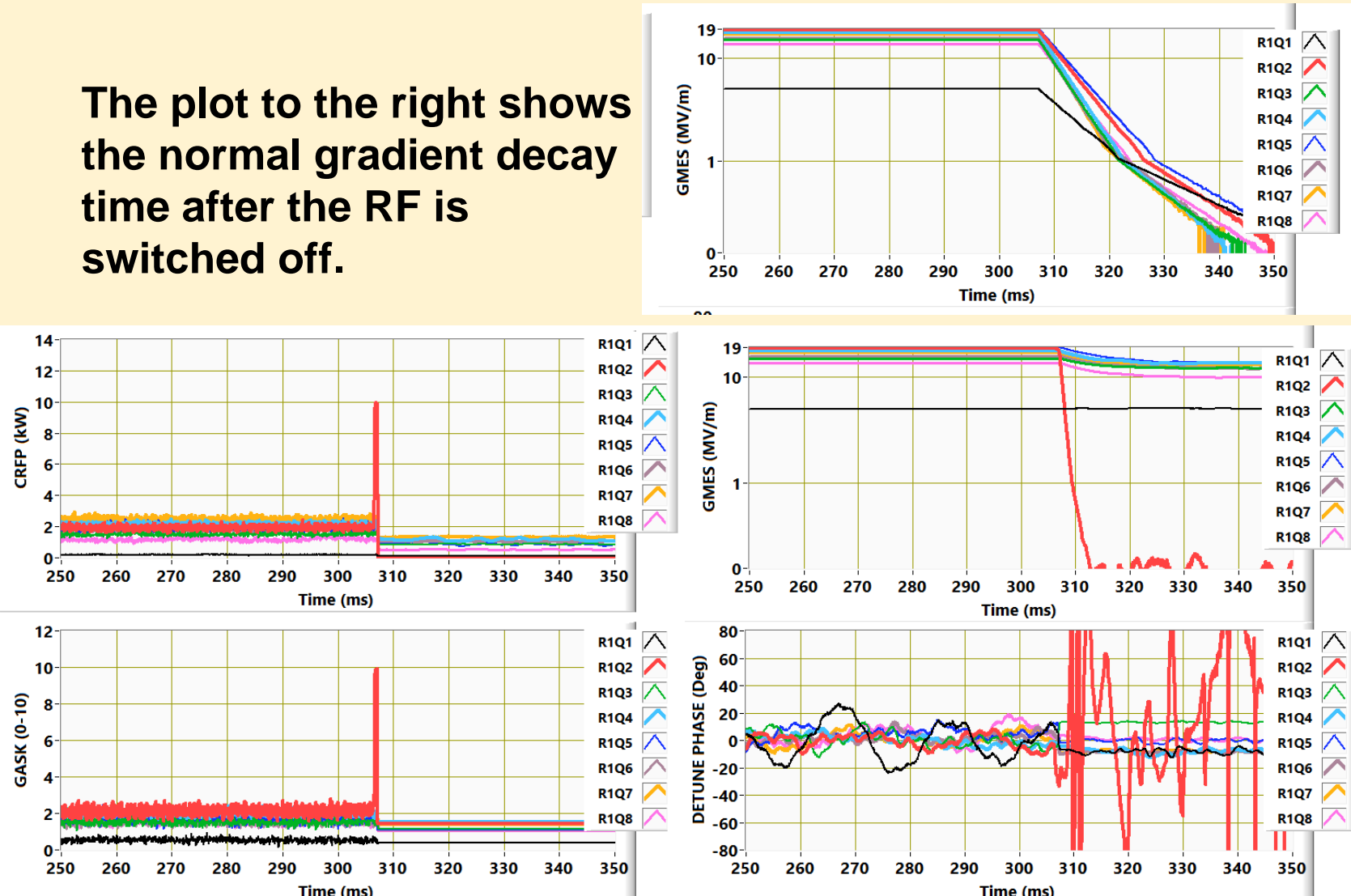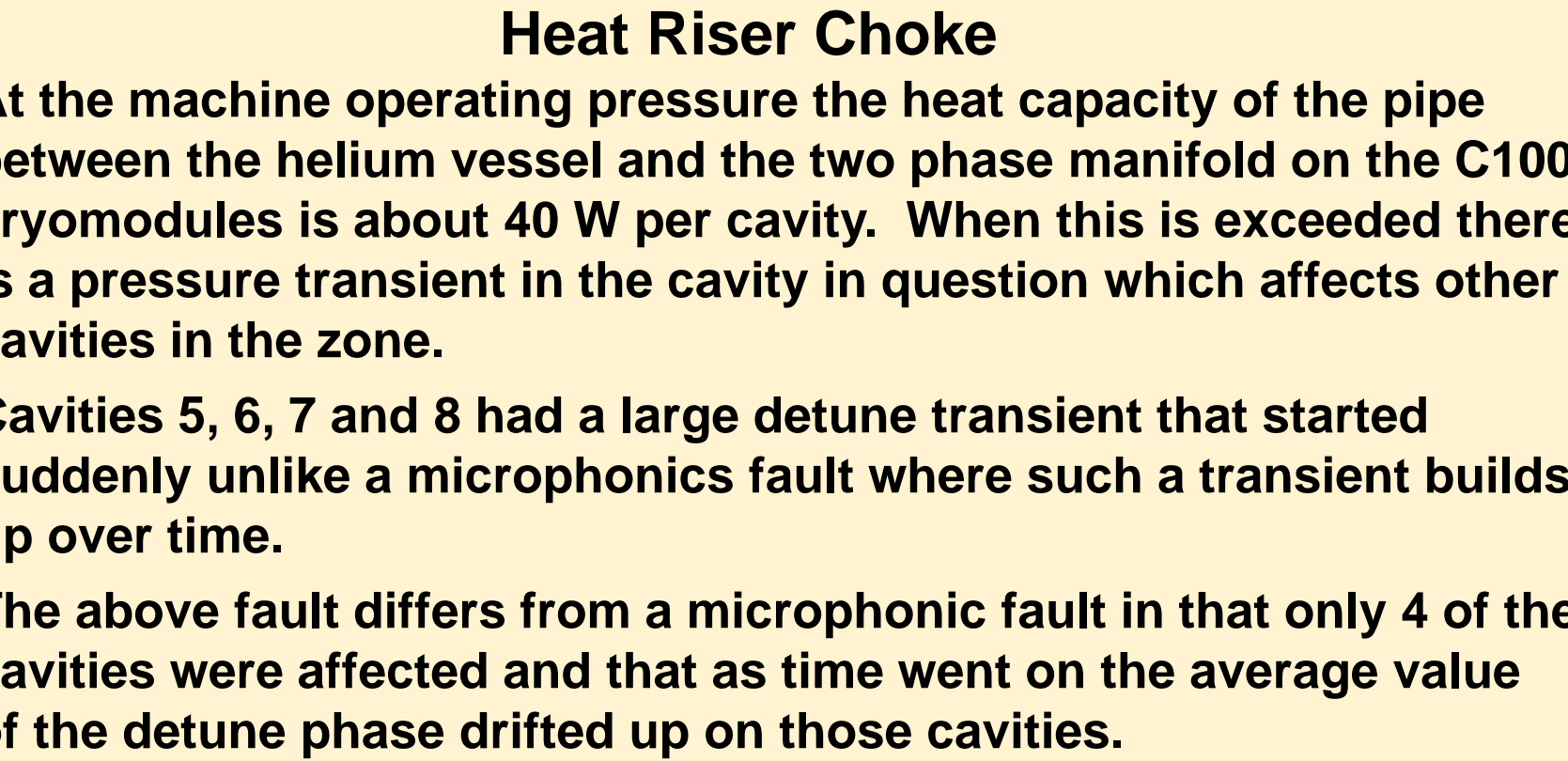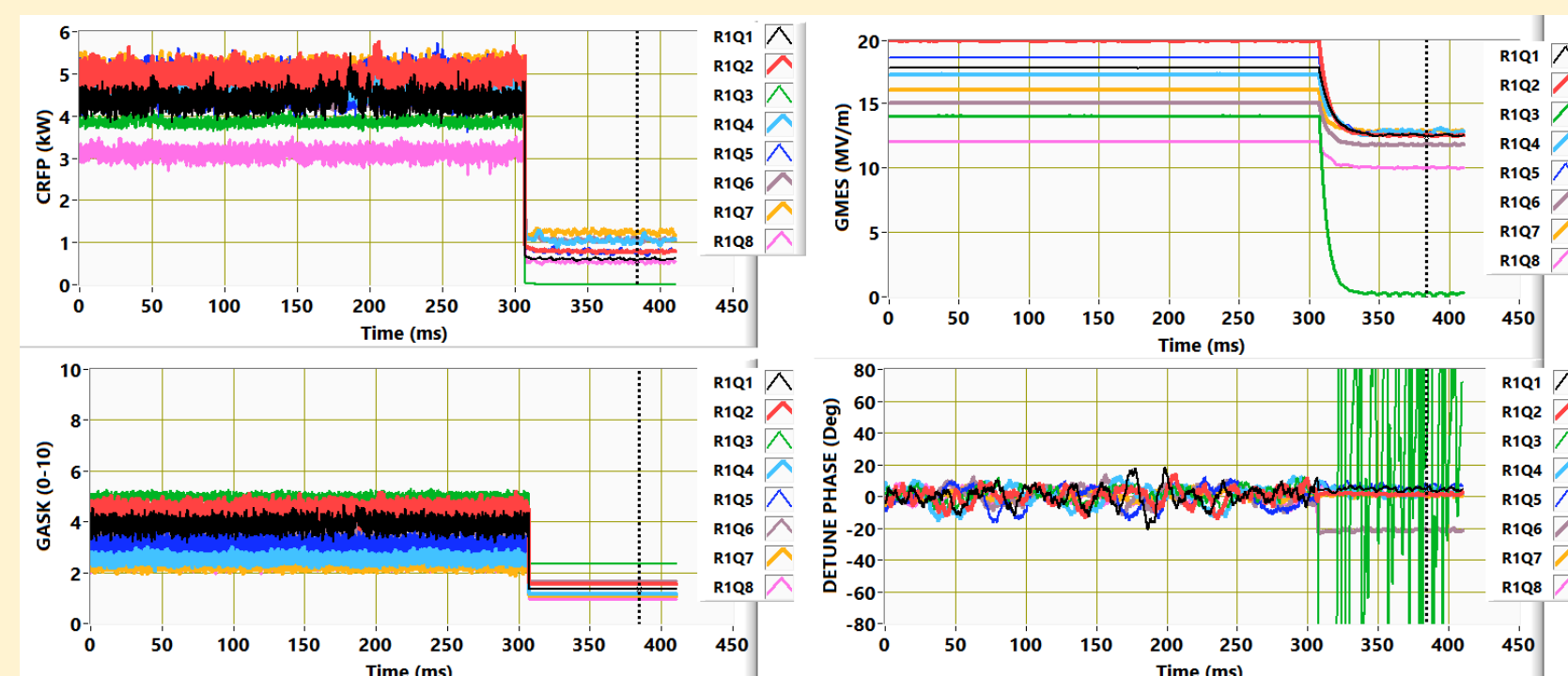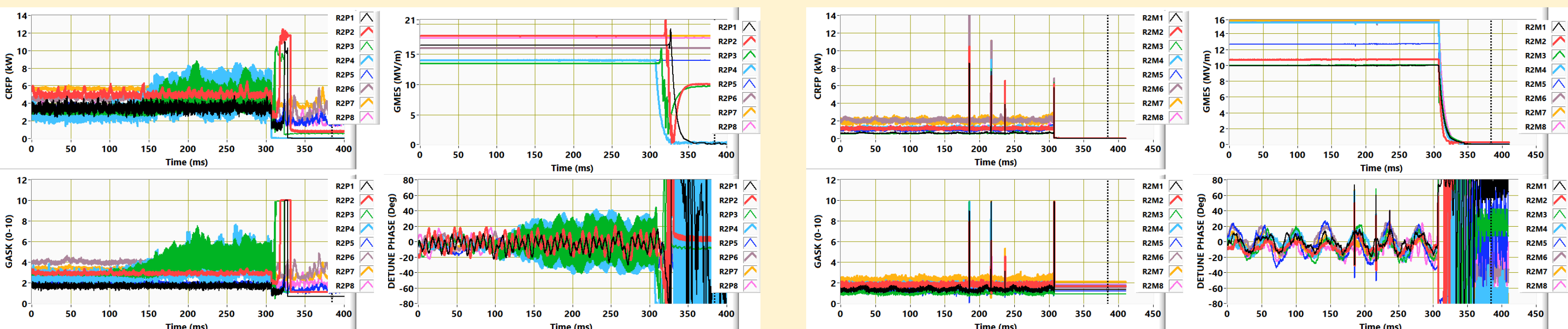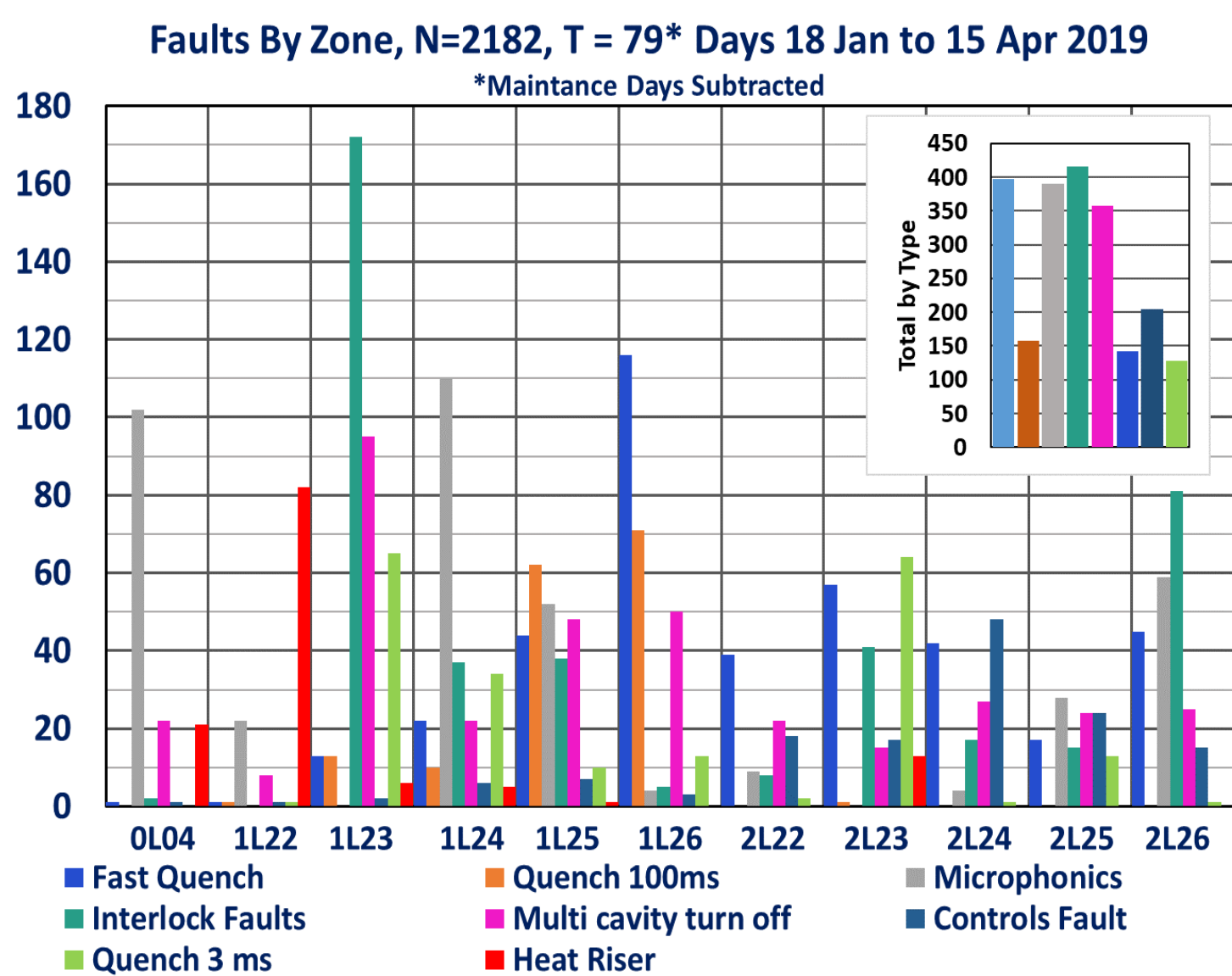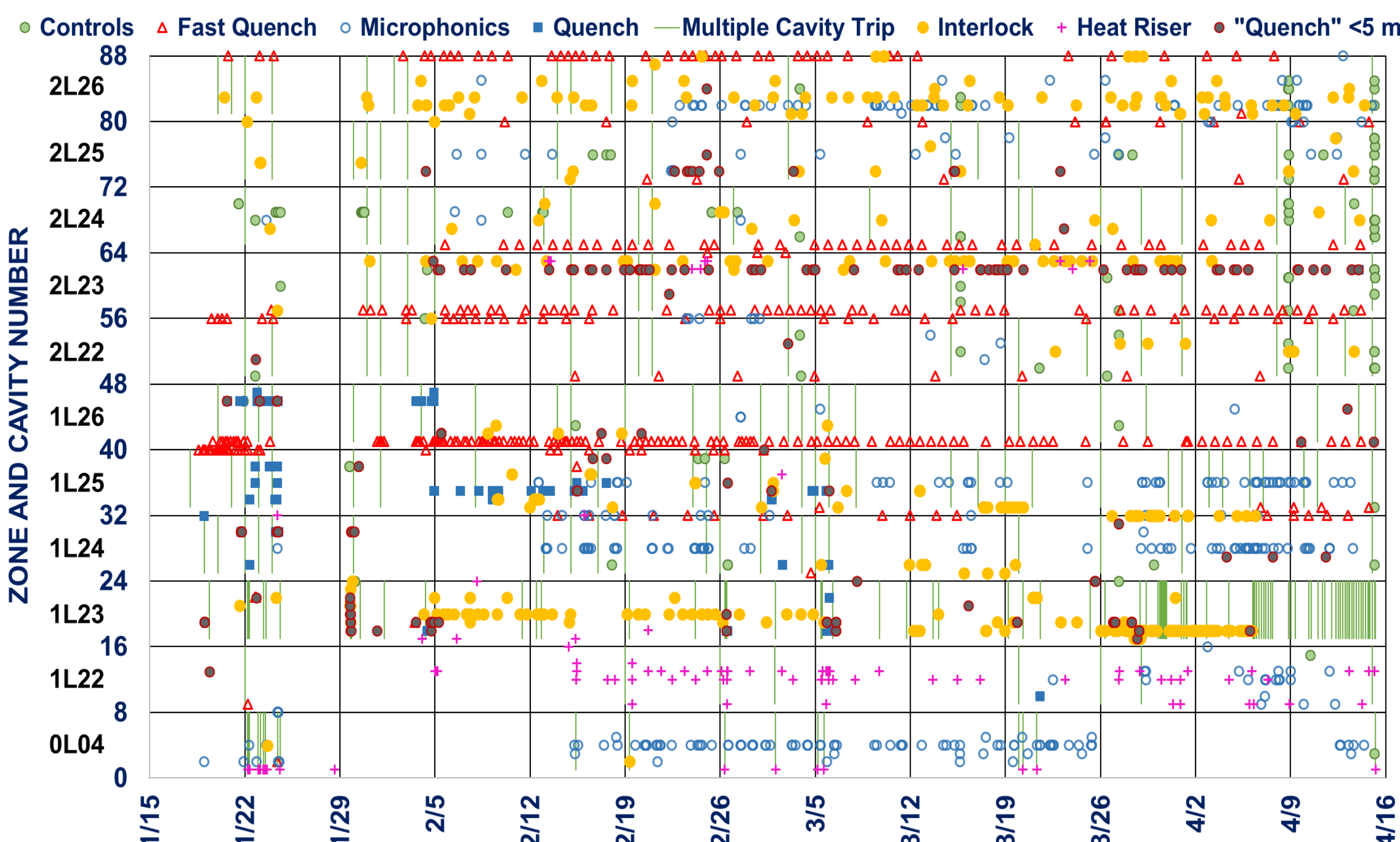

Single Cavity Interlock Fault
- Zone running fine and at about 300 ms cavity 3 trips off going to a zero RF power even while GASK is not at zero. This is an indication that the RF switch was open.
- The gradient decays with a nominal turn off decay time.
- Detailed analysis of the archived fault data indicated that >90% of these faults are quench faults (QNCH) detected by the field control chassis.

RF Controls Driven Faults
- Control loops oscillations due to incorrect setting of loop phase. The oscillating cavity is probably shaking the adjacent cavity at the same 4.2 kHz frequency.
- One interesting nuance in this event is that cavity 2 was driven up in gradient when the phase control was lost. Events were analyzed where cavities were driven to a prompt quench with similar transients.

Single event (50 us sample rate) errors which occur in the south linac during thunderstorms. It is suspected that it is a grounding problem associated with either the MO or LO distribution system.

Examples of Remedial Actions

	MV per CM		Microphonics Trips per Day	
Zone	Dec 18	Spring 19	Dec 18	Spring 19
0l04	82*	91 - 100	0.68	1.29
1L22	91.28	96.39	0.10	0.28
1L23	68.32	68 - 73	0.05	0
1L24	82.39	82 - 86	0.29	1.39
1L25	76.79	60 - 78	0.10	0.66
1L26	87.92	80 - 88	0.12	0.05
2L22	90.86	89 - 91	0.20	0.11
2L23	78.4	75 - 77	0.05	0.00
2L24	67.55	75	0.45	0.45
2L25	77	86.31	0.45	0.35
2L26**	92.68	99.5	0.71	0.74
total	813.19	851.55		
NL	406.7	419.3		
SL	406.49	432.25		

*10 Oct to 26 Nov
**2L26 cavity 6 was not logging waveforms

Microphonics Mitigation
- The injector energy was increased and 0L04 operated at a higher gradient. This led to an increase in the microphonic trip rates as well as several other types of faults.
- The gradients were increased and the microphonic trip rate also went up on 1L24 and 1L25 between the fall 2018 and winter of 2019..
- Poly Bead Bags added to the tuner assemblies on cryomodules 2L24, 2L25 and 2L26 between the two runs. This damped the 80 Hz tuner modal resonance as well as the 10 and 20 Hz cavity string modal resonances.
- This allowed us to increase the operating gradients in the three zones.
- The faults due to microphonics trip rate decreased on 2L24, which, in addition to the poly bead bags, happens to have tuner and waveguide vibration dampers.
- Even with the increased gradients the microphonics trip rates in 2L25 and 2L26 remained constant.
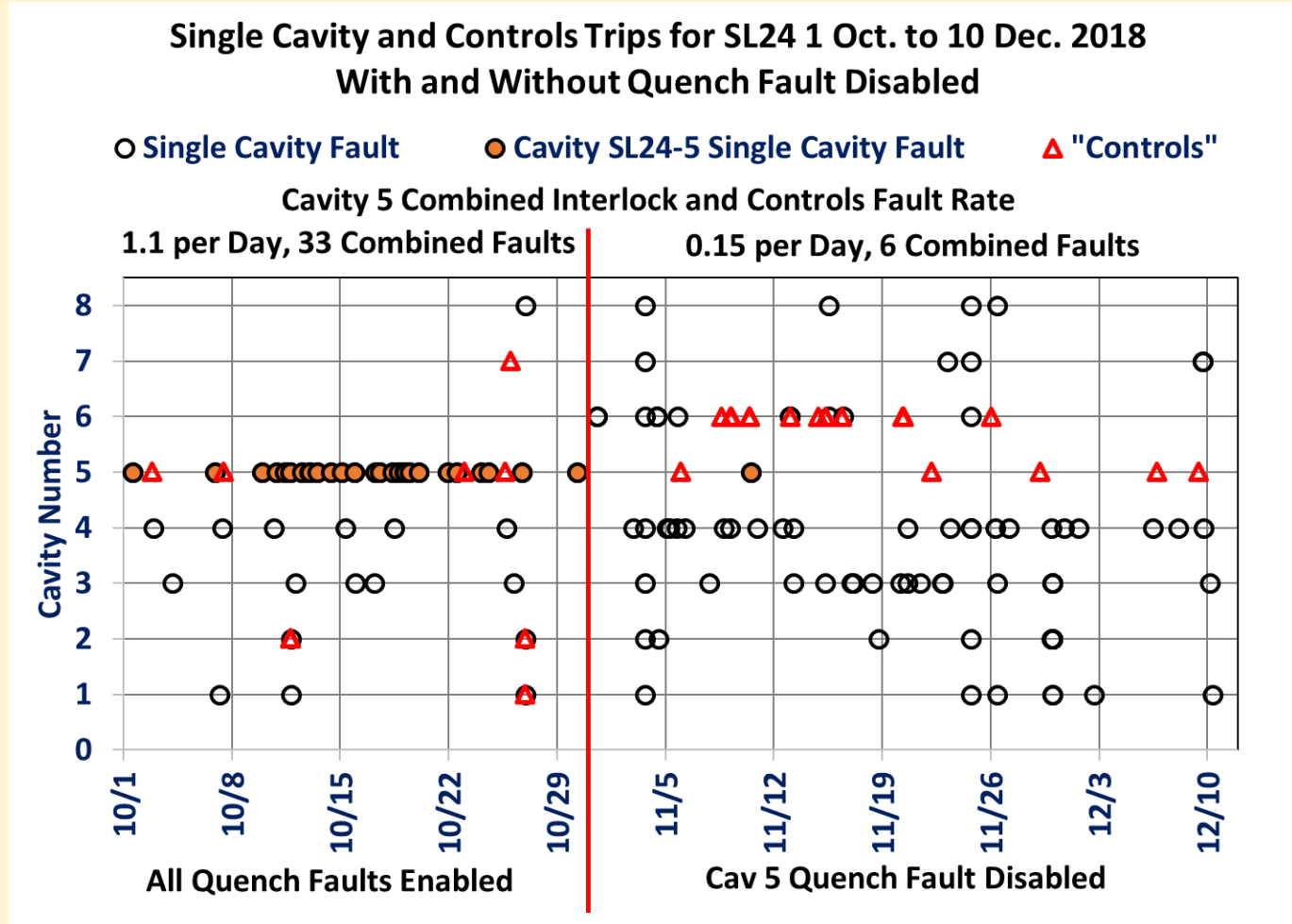
Experiment to Understand a Potential Change to the Interlocks
- We bypassed the quench fault on SL24-5 and used the gradient error fault set to 2% for 100 ms as a surrogate for the quench fault.
- We reduced the number of "interlock" faults which were identified using time domain waveform analysis by a factor of 7.
- There is a change request in place to apply a similar change to 32 cavities where instead of bypassing the quench fault we make it 50% reduction in gradient for 50 us which should make it a good tool to identify electronic quench faults.

Single Cavity and Controls Trips for SL24 1 Oct. to 10 Dec. 2018 With and Without Quench Fault Disabled

Summary and Future Activities

Over the last 15 months RF waveform data for C100 cavities just prior to and after faults has been collected from multiple CEBAF run periods. Several different types of faults have been identified. Manually analyzing the data, although time consuming, is an effective way to identify trends and to correctly decide which cavity was the first to go unstable. The statistics for each run were used to strategically deploy mitigations to problematic cryomodules and to design changes in the cavity and vacuum interlocks.

Our future efforts will be to use the data to focus on eliminating false trips, understanding which cavities to turn up or down, to identify other remedial actions and to modify the cavity interlocks so that they accurately identify faults. We also have an ongoing program to use machine learning tools which should automate the identification of the cavity that was the root cause of the fault as well as the type of fault. A combination of these methods should provide a useful set of tools for machine operations.

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