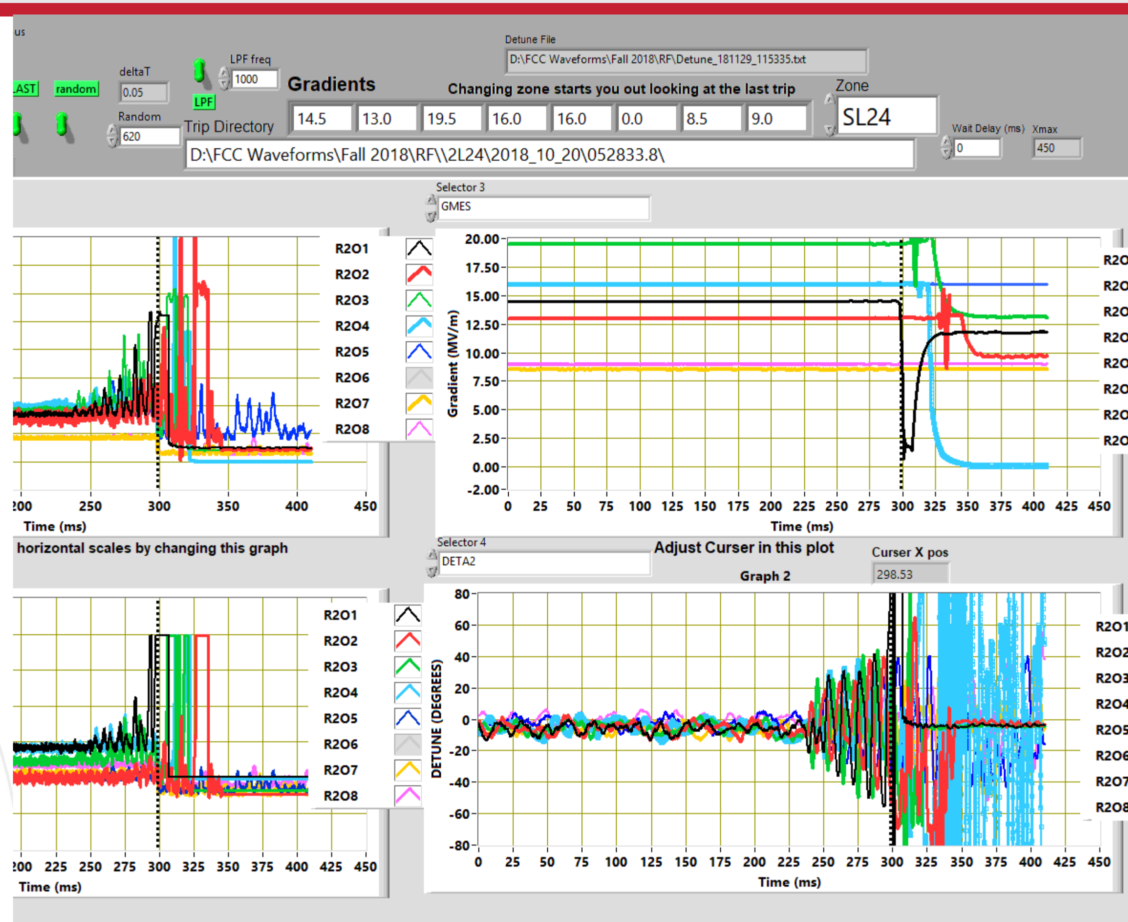
C100 Cavity Faults as Determined By Time Domain Waveforms

Subtitle:
Cavity trips are not always a due to quenches or microphonics.



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With support from Anna Solopova, Curt Hovater, and the JLAB LLRF Group.

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Jefferson Lab

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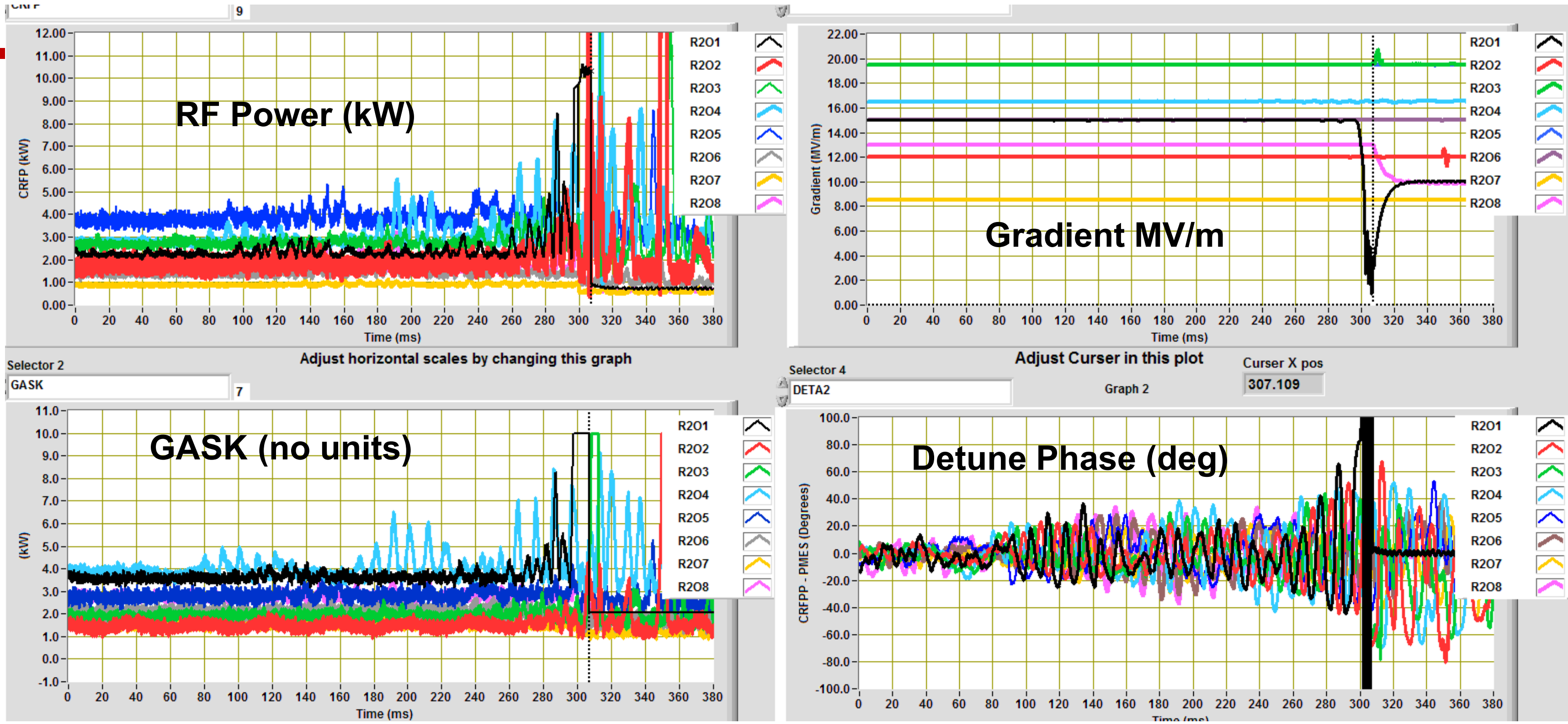
JLAB Waveform Harvester

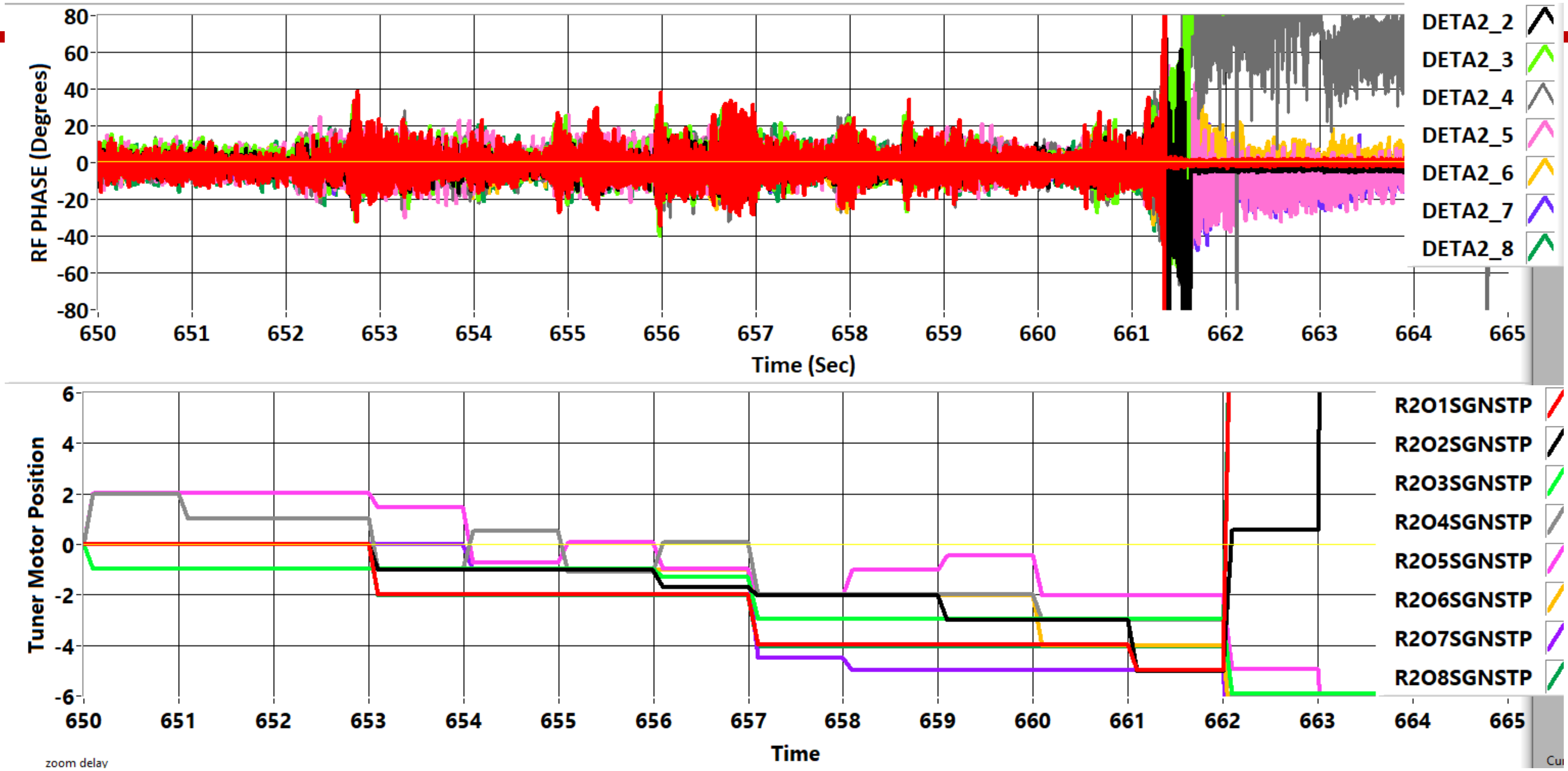
- The cavities in a C100 cryomodules
  - Have a 10% cavity to cavity coupling with respect to frequency detuning.
  - When one cavity trips off the Lorentz force detuning causes enough vibrations in the string to trip the other cavities.
  - In order to avoid additional cavity trips, the entire zone 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
- For the spring of 2018 and fall of 2019 there were about 500 faults classified per month.

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.

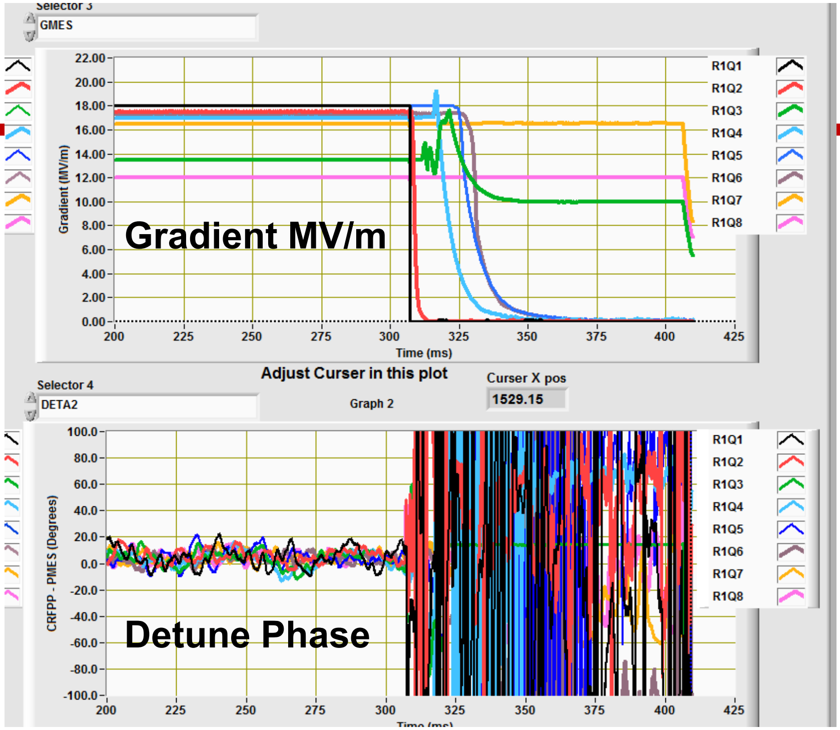
Is It Tuner Motor Induced?

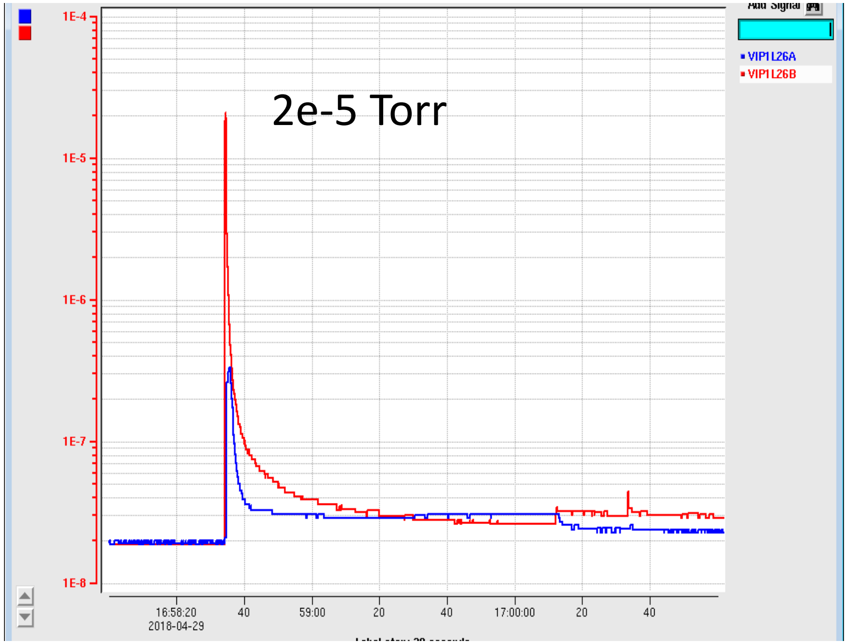


- Data taken using external DAQ module and analog outputs of FCC.
- Upper traces are detune angle (DETA2) taken via analog output ports. Lower is signed tuner steps taken from EPICS. They are updated once per second.
- Note quiet microphonics between 650 and 652 seconds when there is little if any tuner operation.
- Note larger peak microphonics bursts when multiple tuners operate. Detailed analysis indicates that the microphonics bursts has a lot of 80 to 100 Hz content.
- The fault at 661 seconds corresponds with one on the previous slide..

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-disorbtion 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.
- We are making changes to the vacuum interlock logic based on understanding this type of event.

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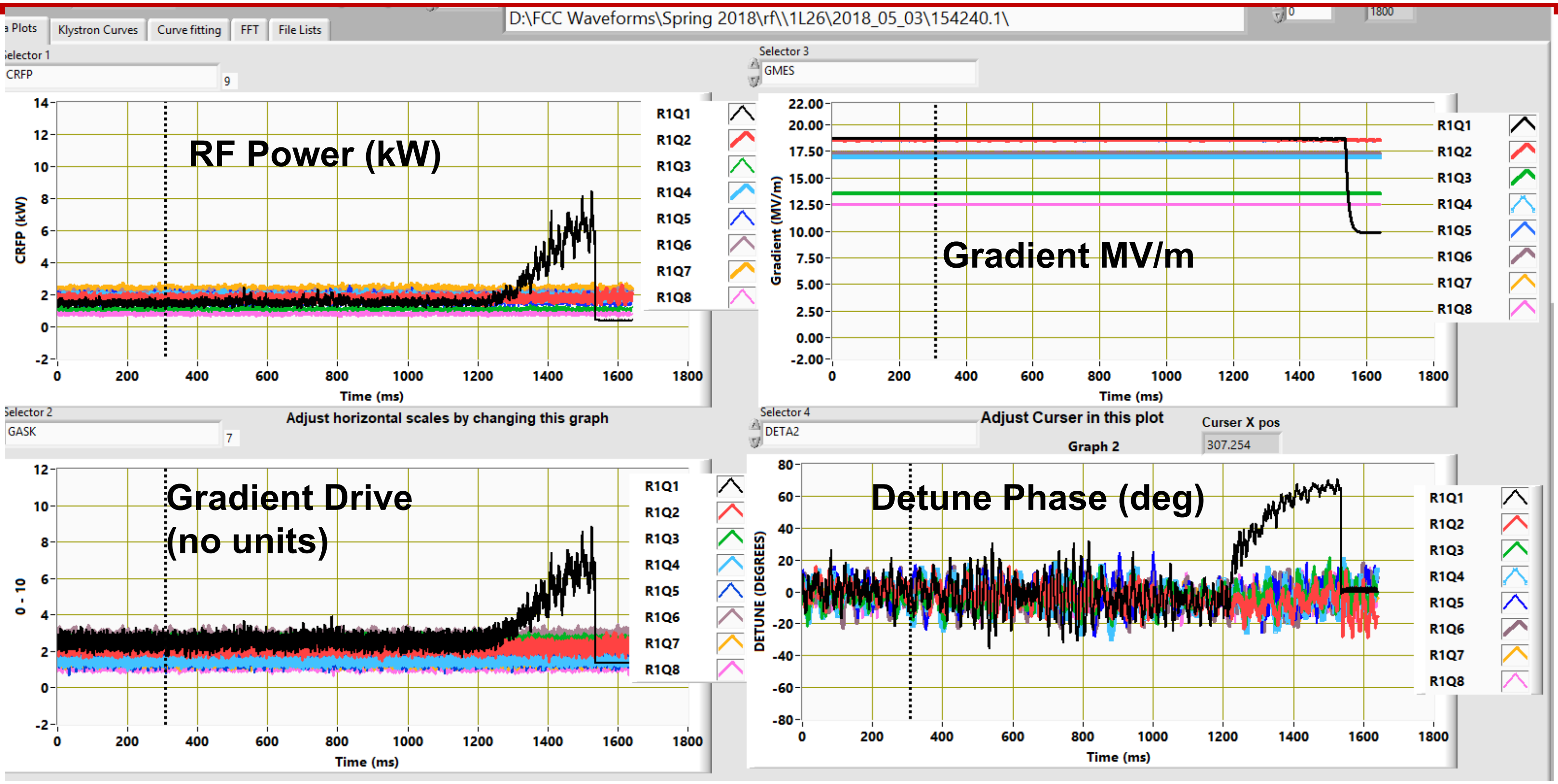
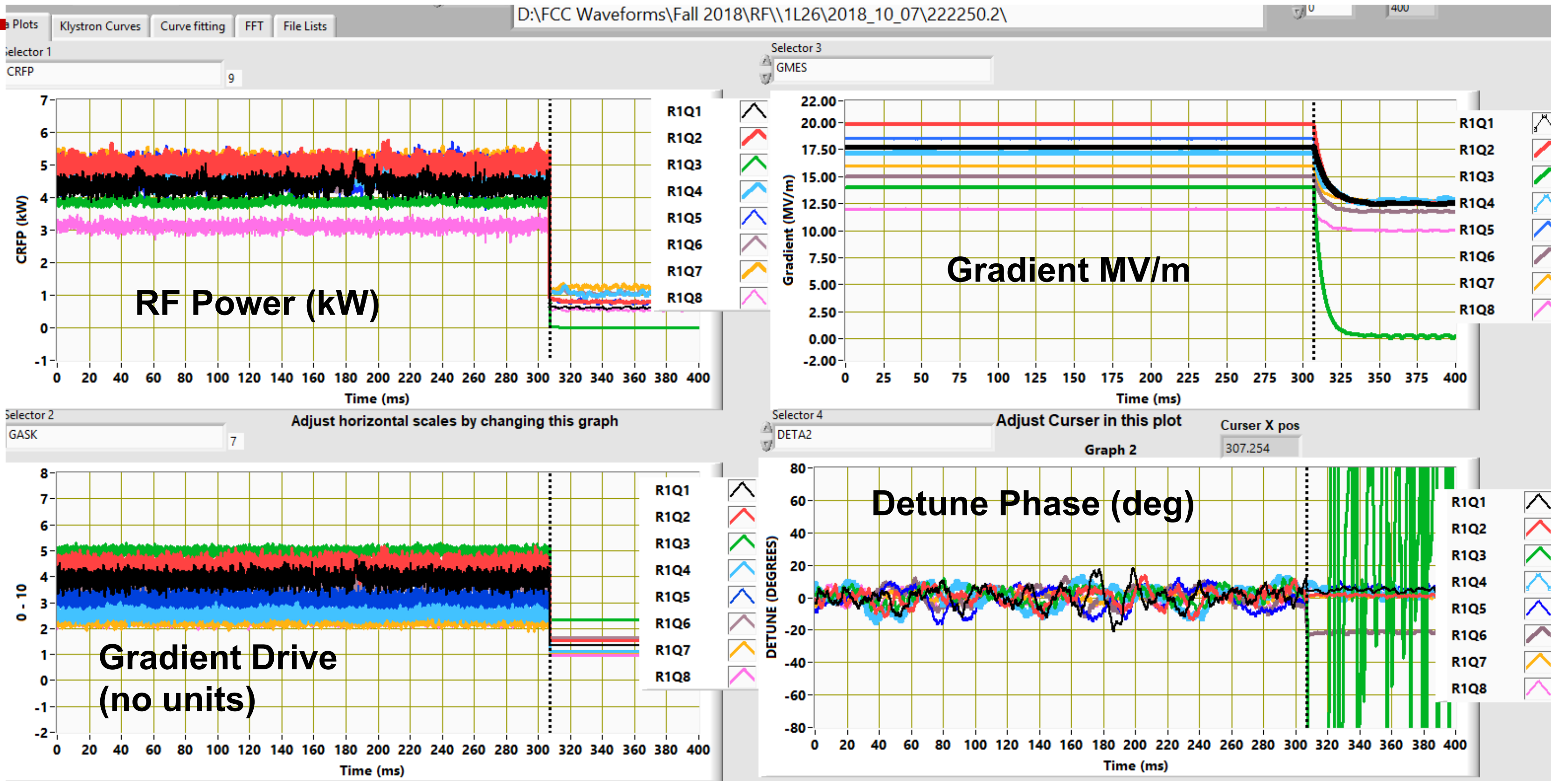
End Group Driven Quench (Most Probably)



Time of Trip
15:42
16:27
17:03
17:11
17:28
17:36
18:59
19:09

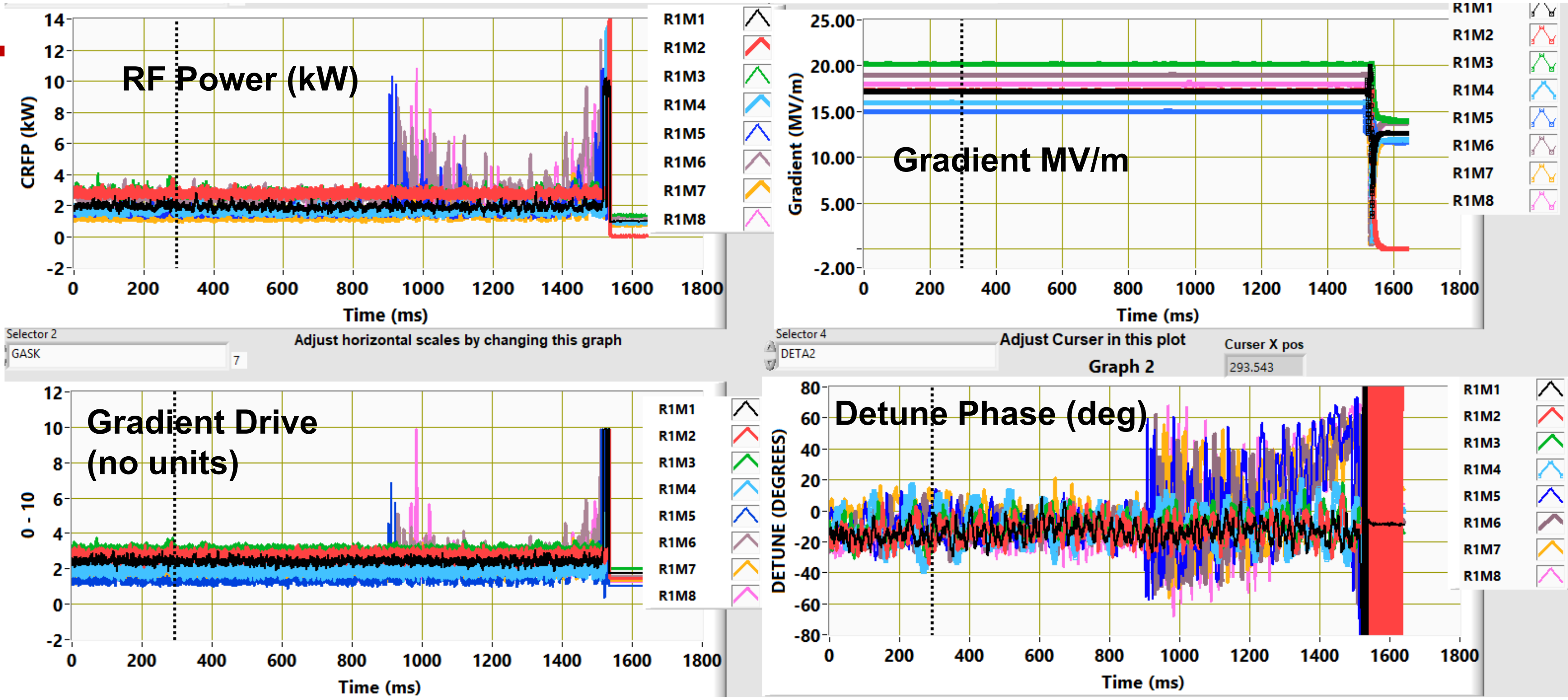
- 8 very similar trips where the detune phase (cavity frequency) walked up in value for a few hundred ms before the RF system ran out of power. This was about 140 Hz detuning.
- After 8 events the operator turned the cavity down by 0.5 MV/m and it stopped tripping.
- We are confident that this an end 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.

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.
- Detailed analysis of the archived fault data indicated that >90% of these faults are quench faults (QNCH) detected by the field control chassis.

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.

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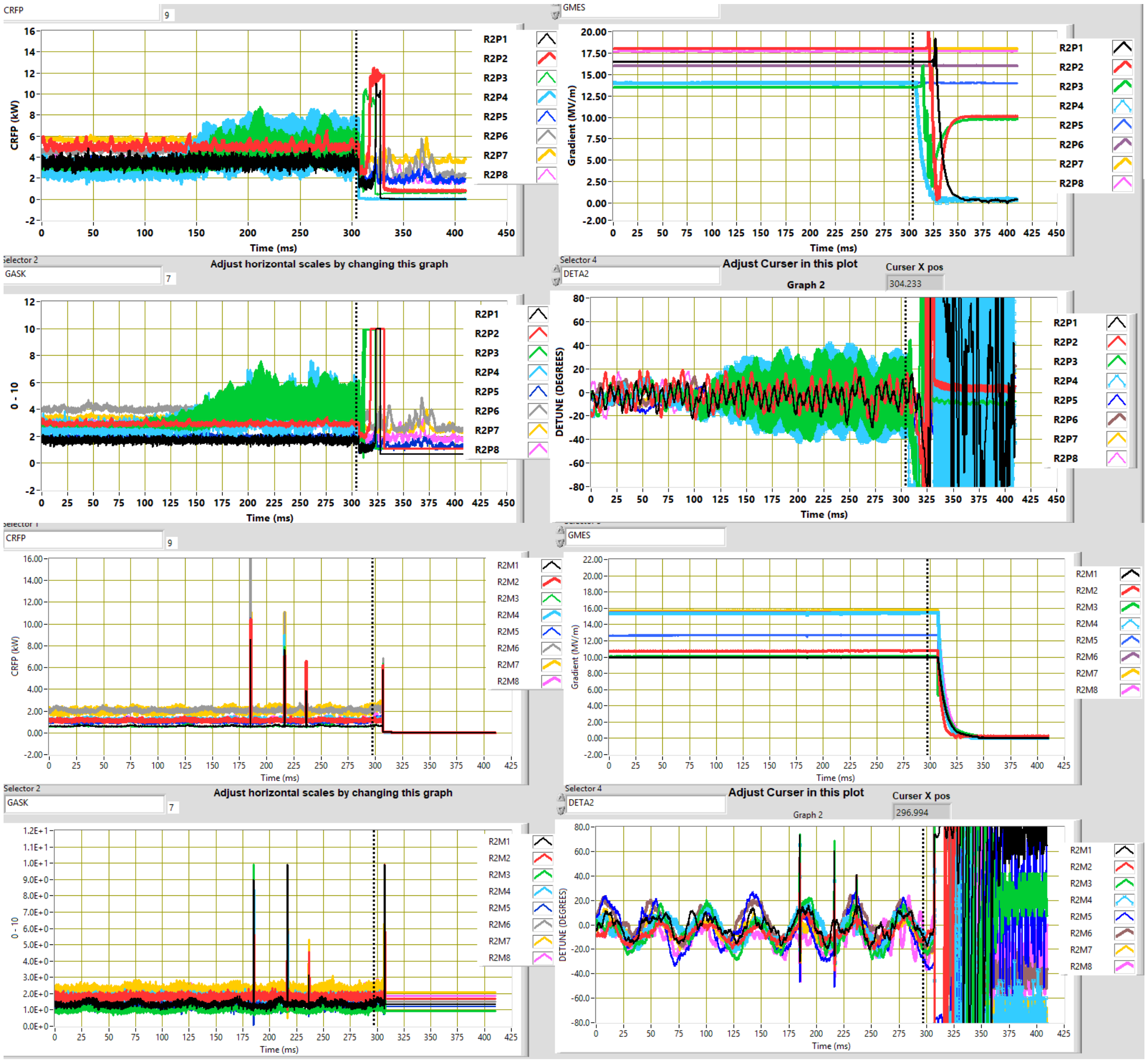
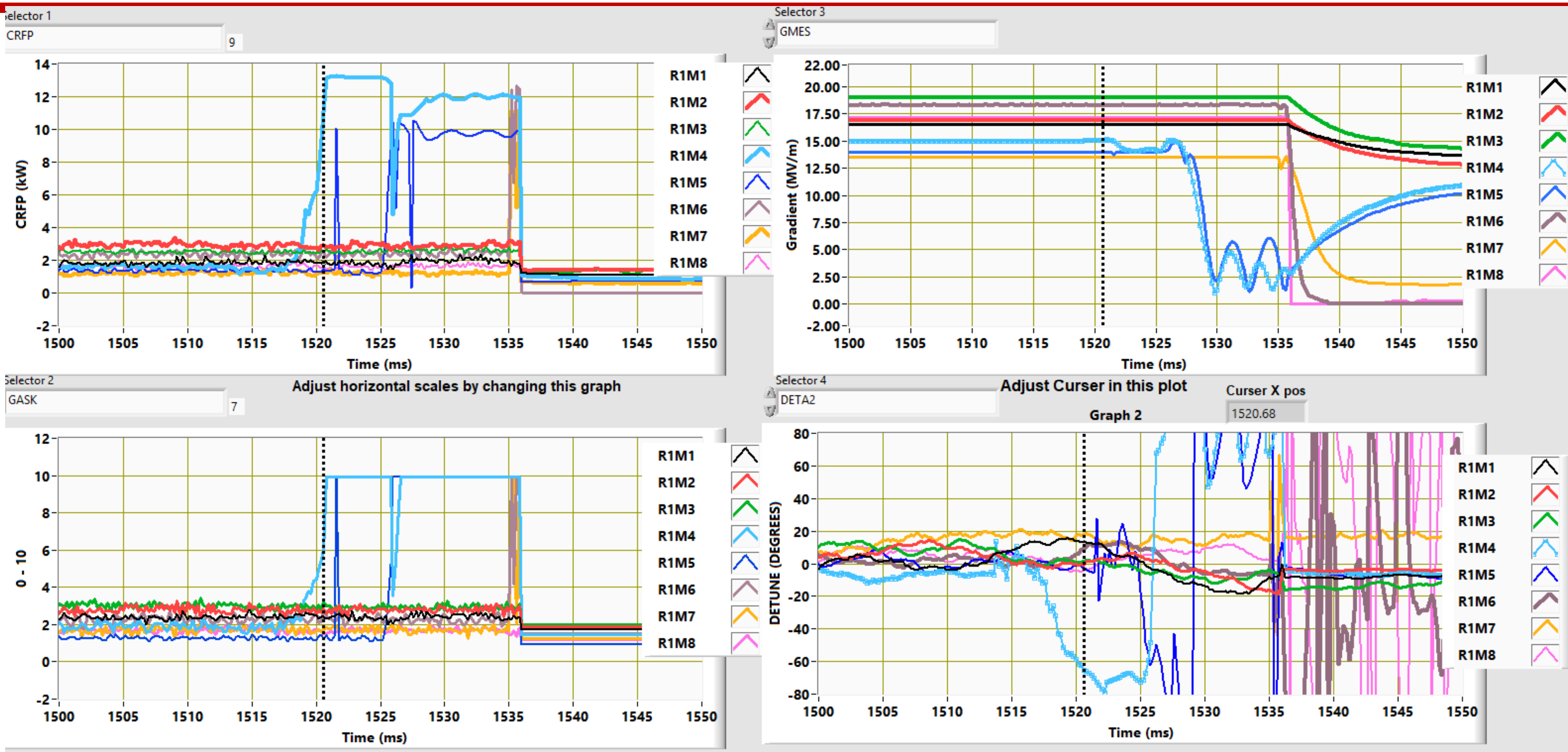
Examples of Controls Faults



- **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.**
- **Although it could be do other sources these trips occurred frequently during thunderstorms mostly in the south linac.**

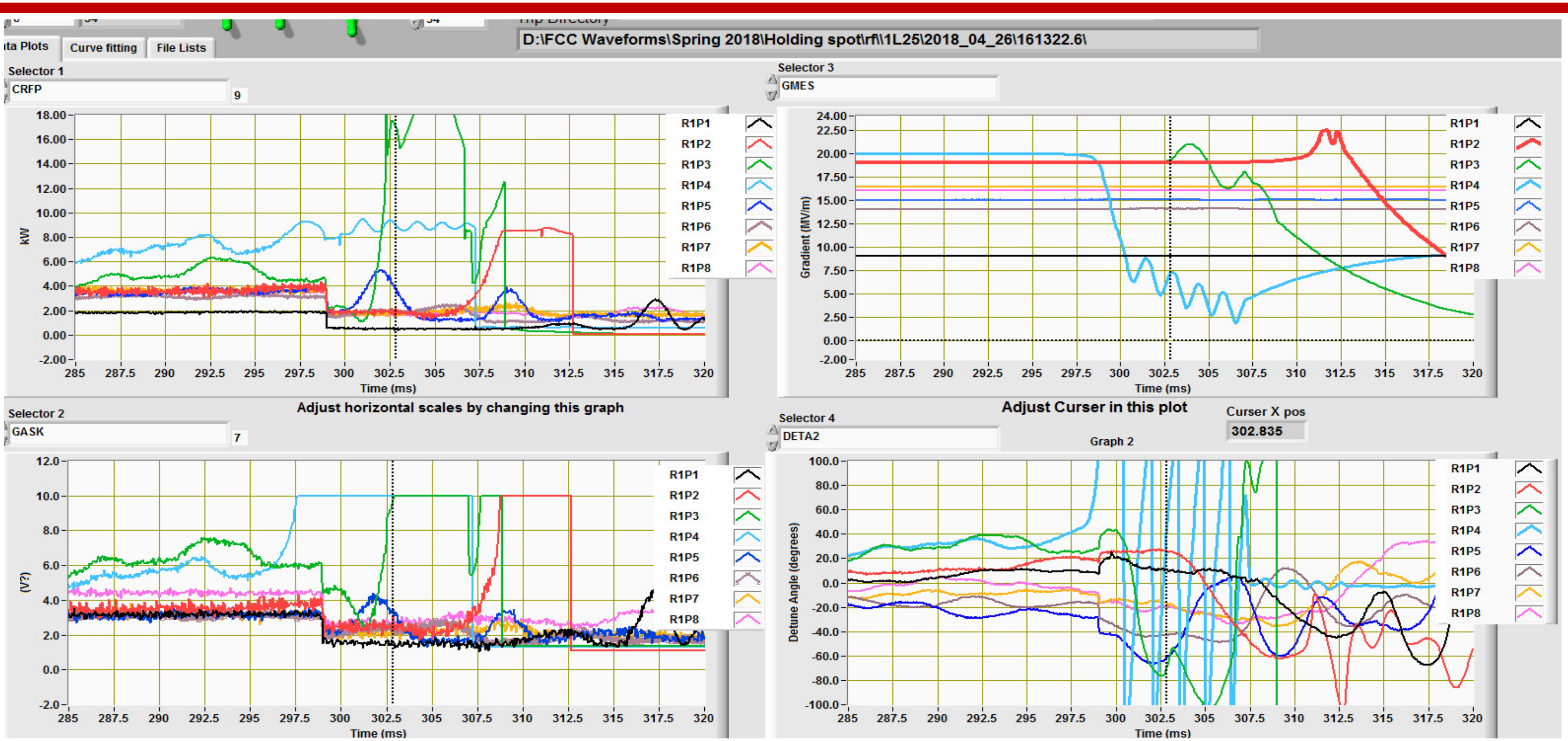
One I Do Not Understand



- The zone was operating fine and cavity 4 decides that it was going to detune 70 degrees in 6 ms often these types of events happen in 2 or 3 ms.

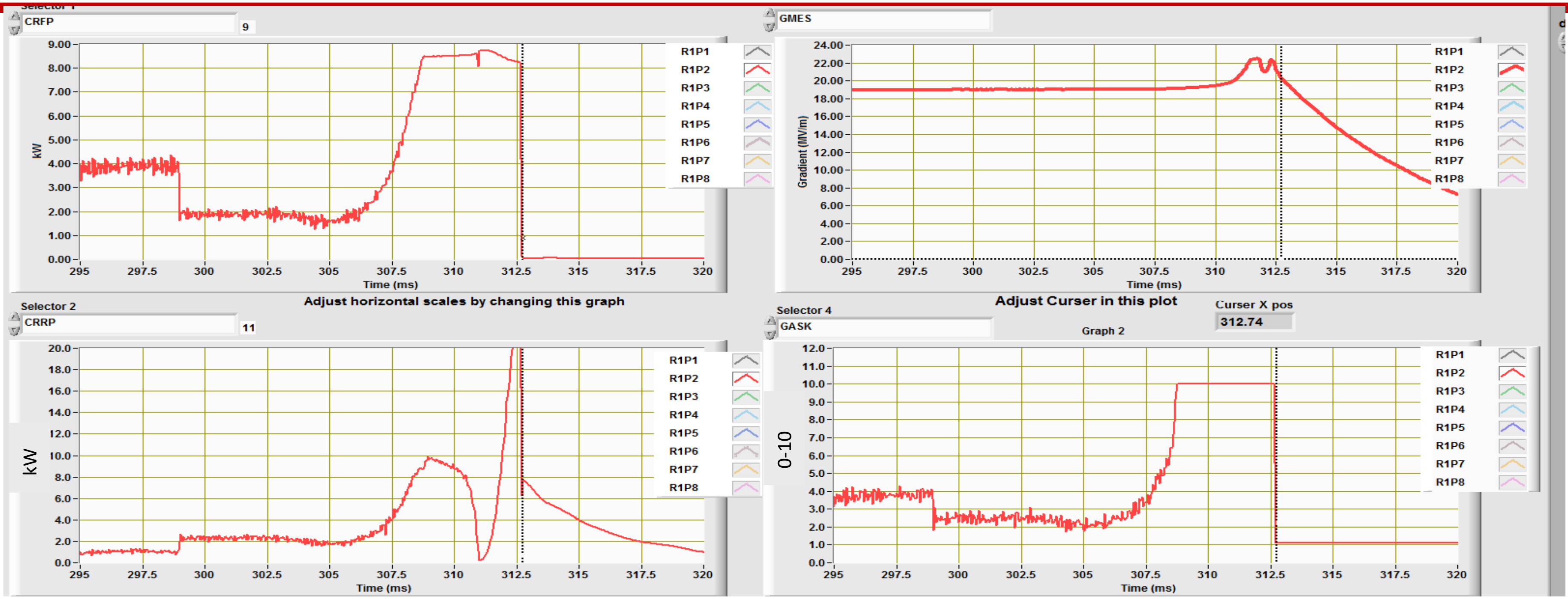
- I do not think that it was a prompt (in the cells) quench or it would not have recovered to SEL mode.

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.

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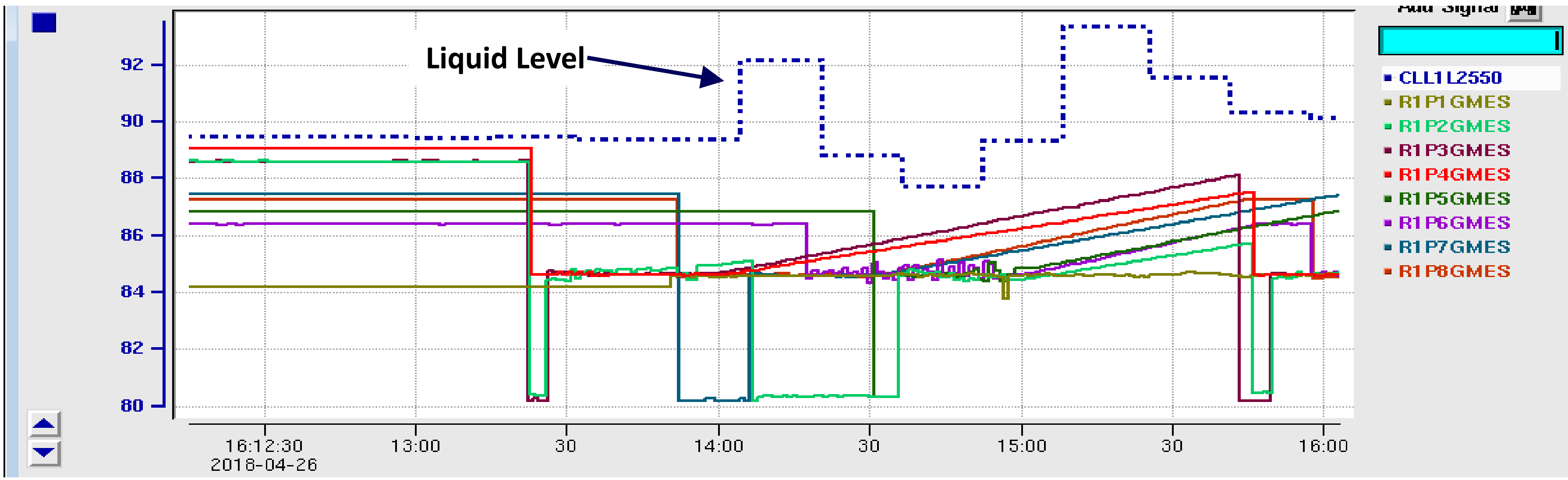
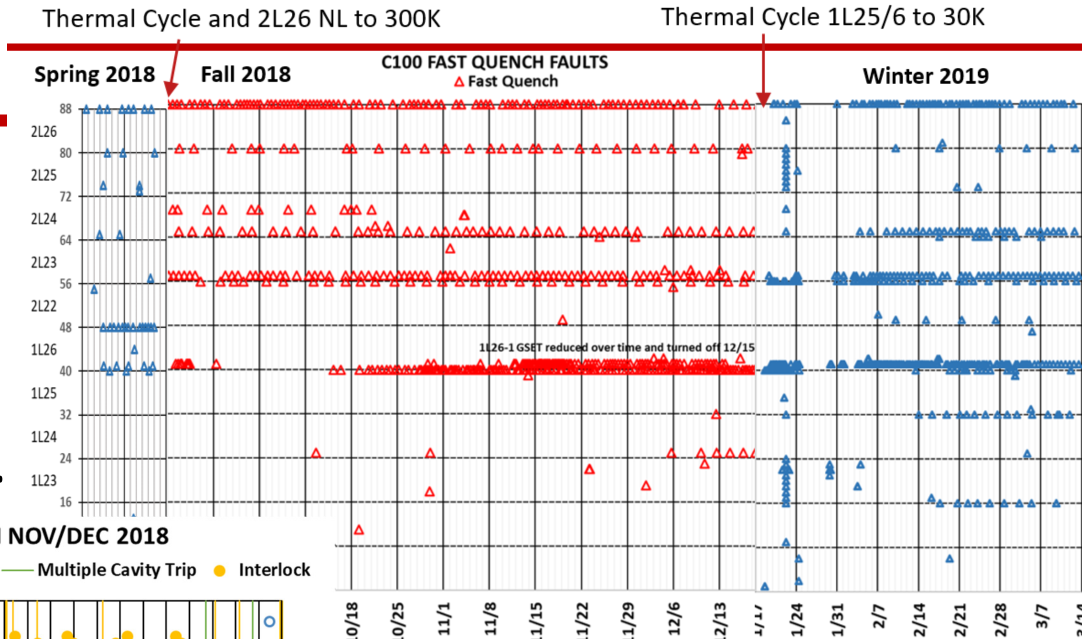
Anomalous Quench as Seen in EPICS

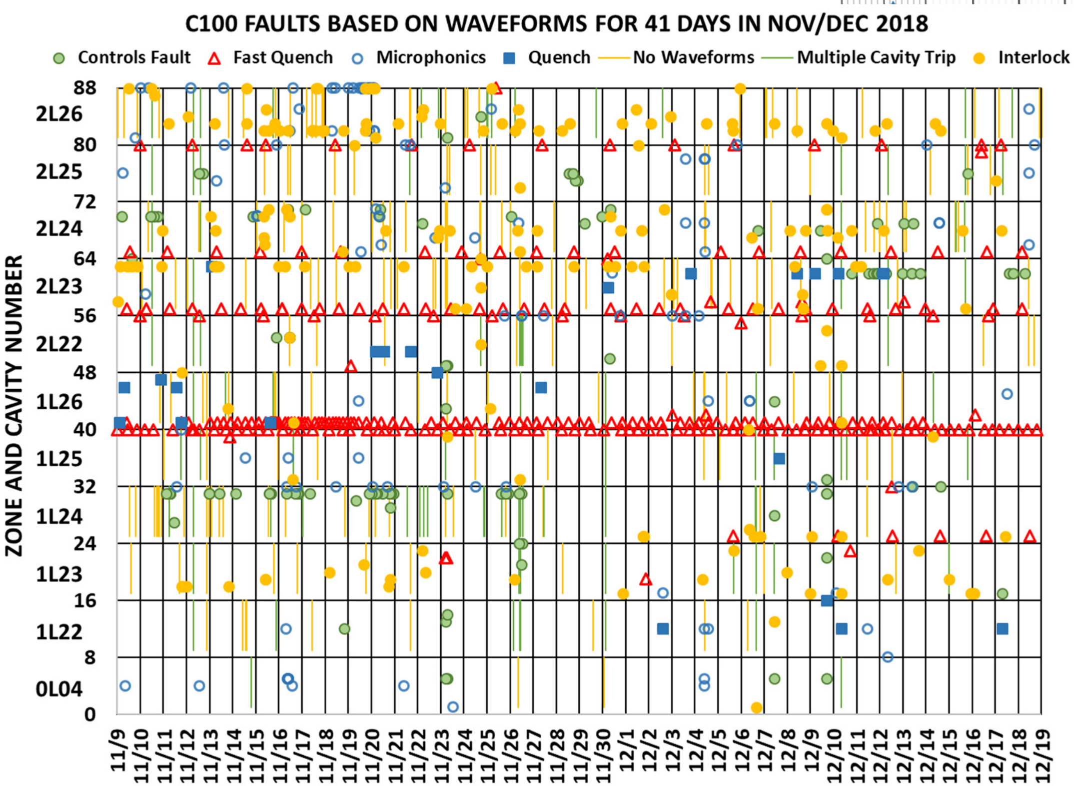


- **Same event as previous slide.**
- **Liquid level oscillation indicates heat riser choke with more than about 50 W of dissipated power. Multiple cavities tripped off.**
- **Operators would see the liquid level oscillation and start randomly turning cavities down.**
- **Experts were seeing what were interpreted as thermal quenches in the cavities at gradients substantially below the prompt quench fields in the cavities.**
- **Unlike the end group driven quenches shown previously these quenches occurred randomly.**

Detailed Fault Analysis

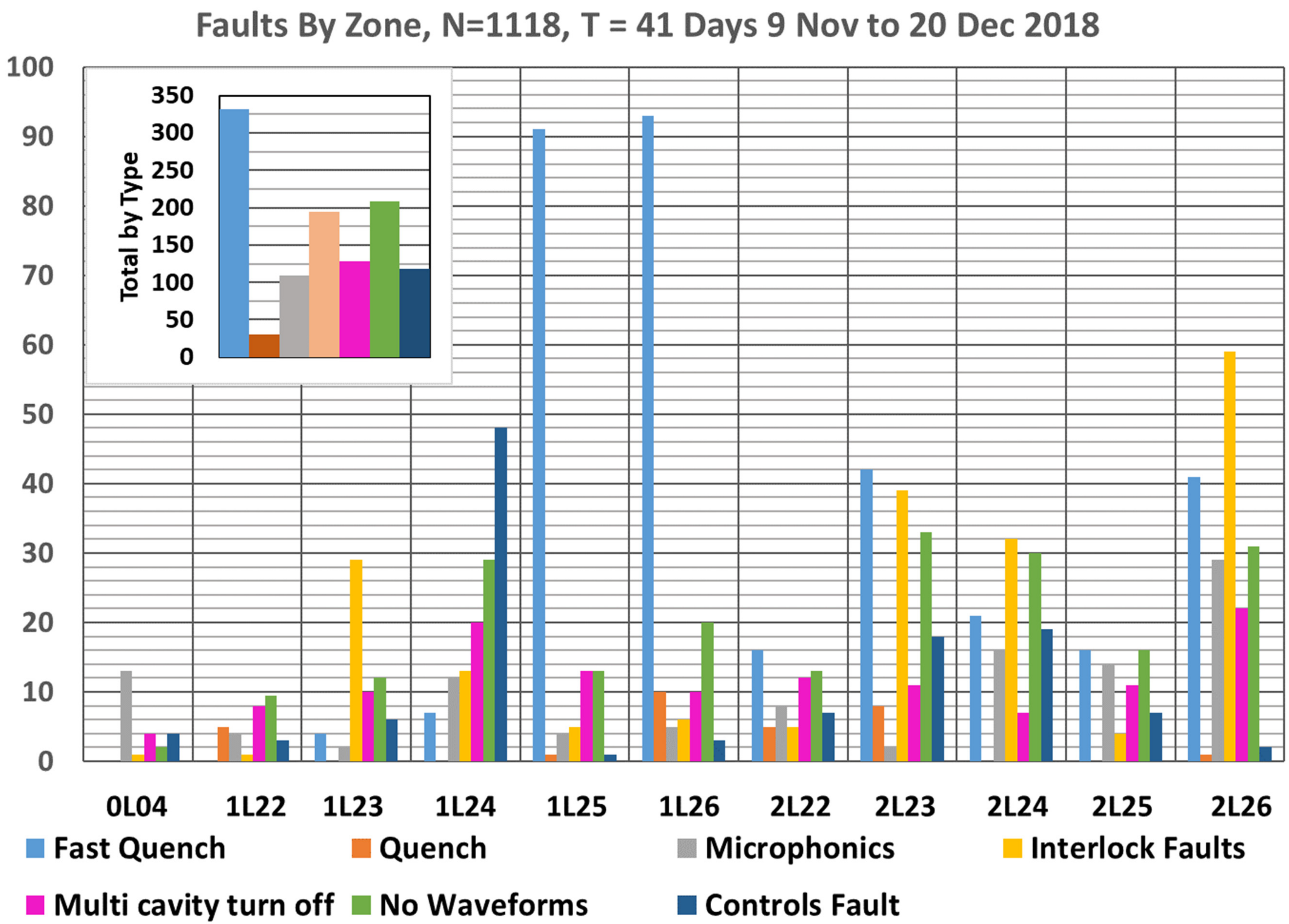
- Manual fault analysis is time consuming taking at least a day a week to review data and build statistics.
- This includes understanding faults that were missed by the harvester.





- Off-line identification of electronic quenches has been automated.
- A program using machine learning is in progress.[1]
  - After manual identification the data is split 70% learning and 30% verification.
  - Accuracies for identifying fault type and offending cavity on the order of 90%.

[1] A. Solopova, et al. "RF Cavity Fault Classification Using Machine Learning At CEBAF" IPAC2019


Faults By Zone, N=1118, T = 41 Days 9 Nov to 20 Dec 2018
100
90
80
70
60
50
40
30
20
10
0
350
300
250
200
150
100
50
0
Total by Type
0L04
1L22
1L23
1L24
1L25
1L26
2L22
2L23
2L24
2L25
2L26
Fast Quench
Quench
Microphonics
Interlock Faults
Multi cavity turn off
No Waveforms
Controls Fault

Summary and Future Work

Summary:

- We are able to better classify faults and identify the offending cavities when there is a cascade of faults.
- We are using the identified faults to improve the LLRF driven interlocks, vacuum interlocks and to better understand the state of the machine.
- We are using fault statistics as a major input as to where to focus our improvement efforts.

Future Work

- Continue to monitor faults manually and develop a guide for operations.
- Develop machine learning tools to take the human out of the initial fault identification loop.
- Use the data to focus efforts on
  - Eliminating false trips,
  - Knowing which cavities to turn up/down
  - Identifying other remedial actions.
  - Modification to the interlocks so that they accurately identify faults.
- Better understand fast quenches.

Acknowledgements

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