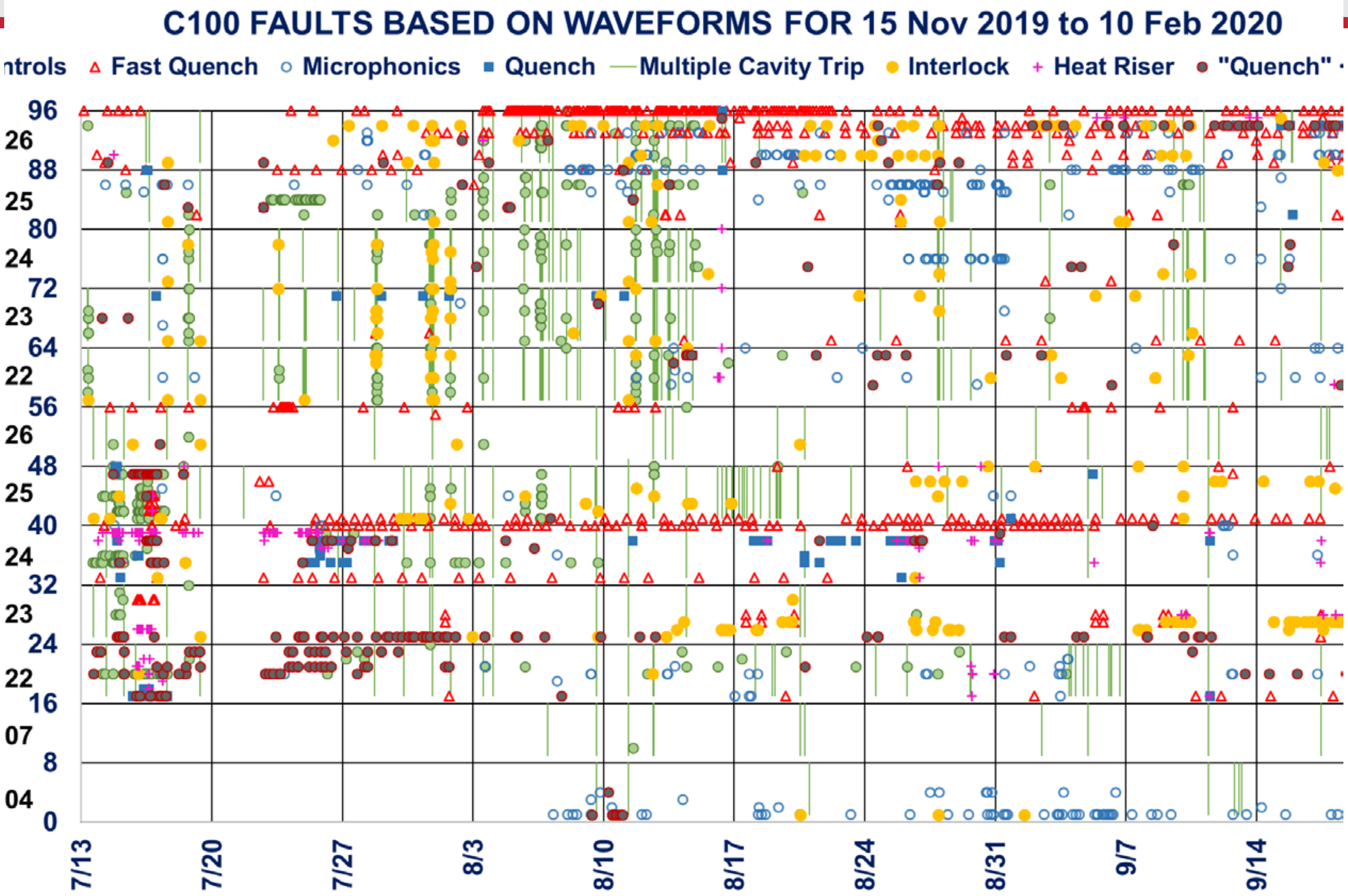
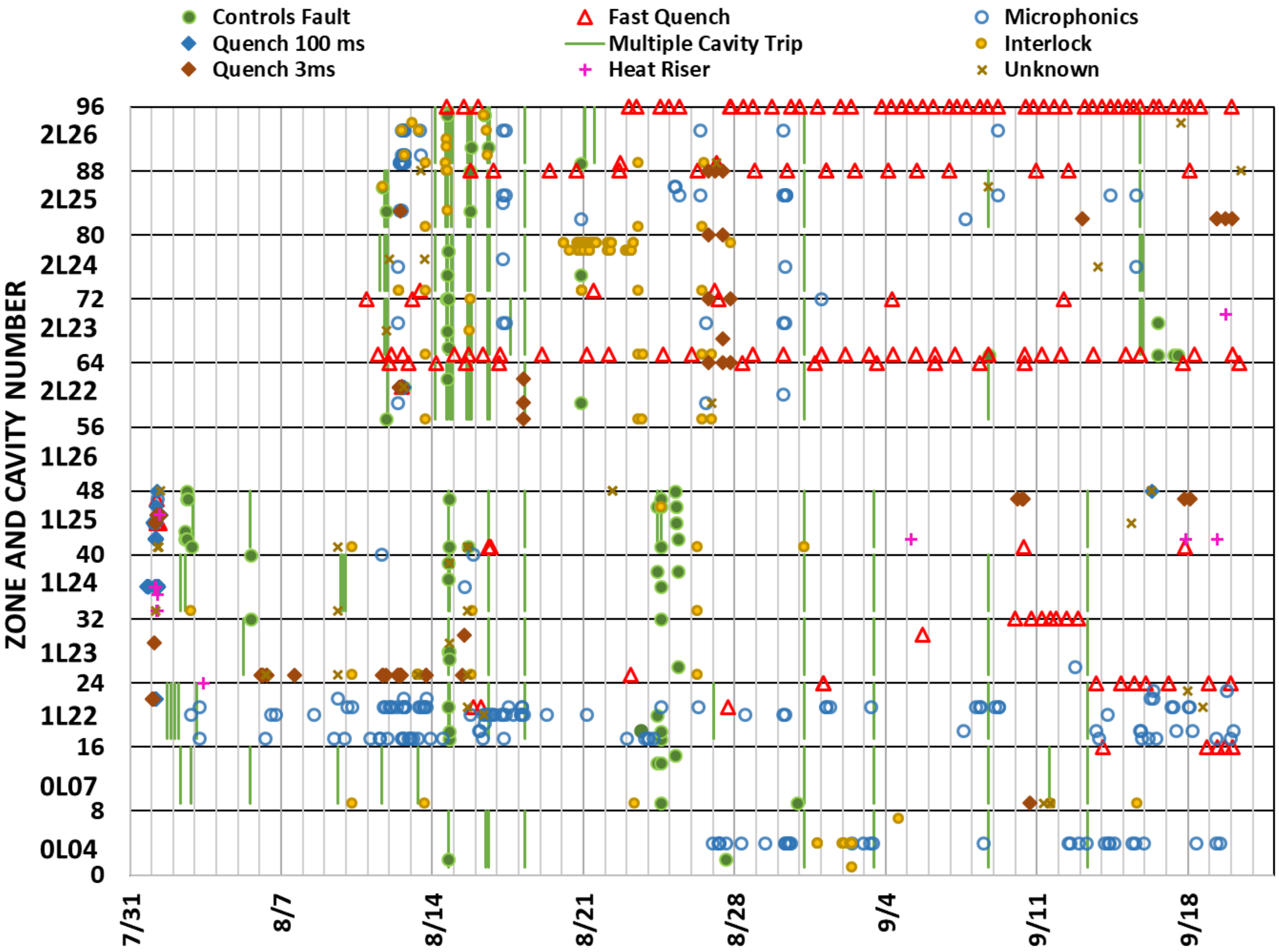
CEBAF Faults Aug 2021



Tom Powers

20 Sept. 2021



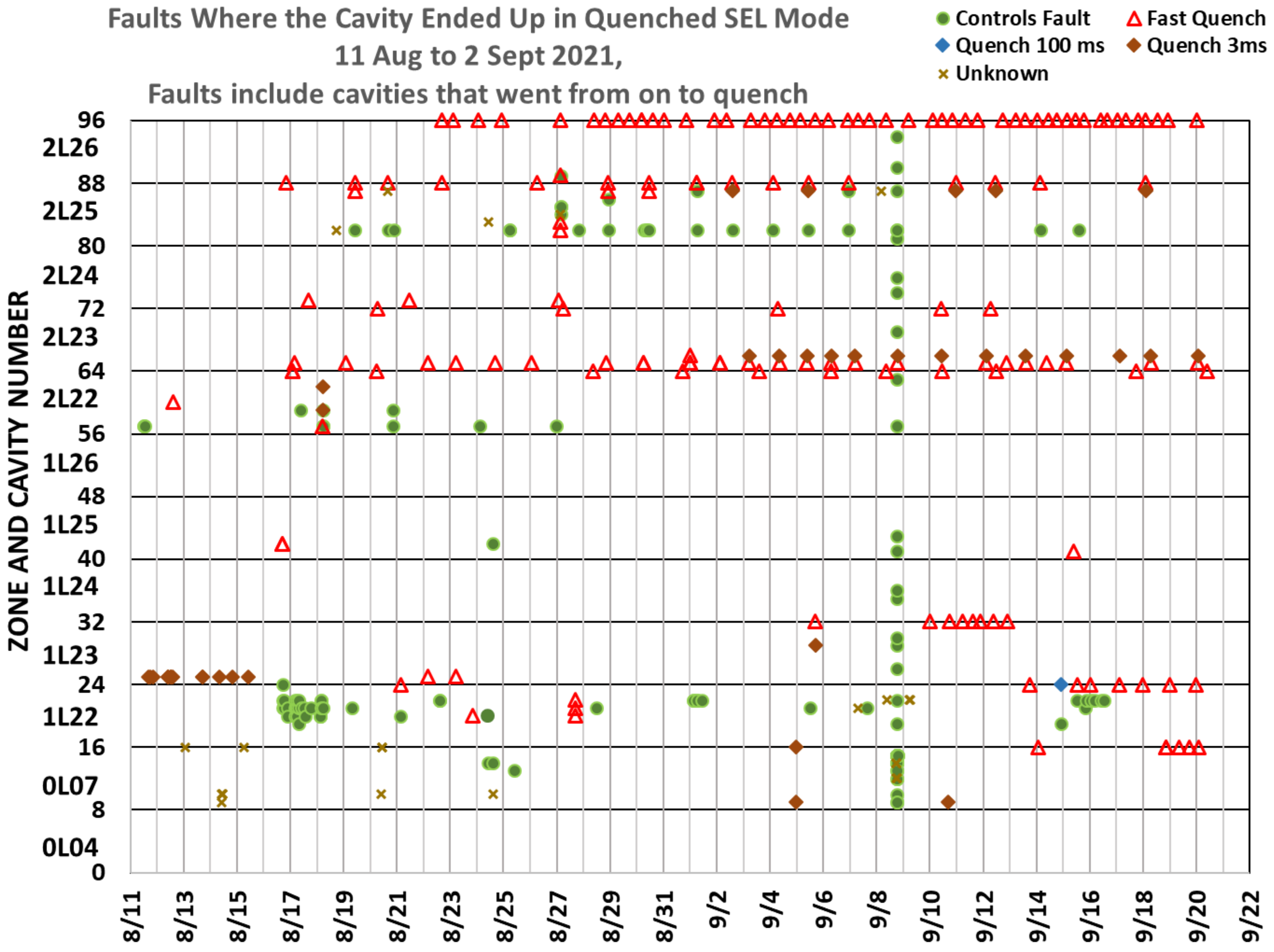
- The clusters green bar multi cavity trips are mostly due to the noise issues in the MO.
- The cluster of interlock faults on 2L24 was something really odd with the arc detectors.
- The interlock faults prior to 8/16 were mostly QNCH faults. Clyde bypassed that fault and set the GLDE fault for 5% and 5 ms.
- The microphonic faults on 1L22 cause a lot of secondary quenches.
- 2L26 and the north linac stopped having a rash of electronic quenches after they were thermally cycled to 300K. . . Time will tell.
- The electronic quenches are still occurring in 2L23 and 2L22 at about the same rate as last Sept.

SL24 Interlock Faults

- In order from top to bottom
  - 8 Arc faults, the regular pattern is the test function.
  - 8 Arc Test Faults
  - Bottom two are the gradients for 2L24-6 and 2L24-7

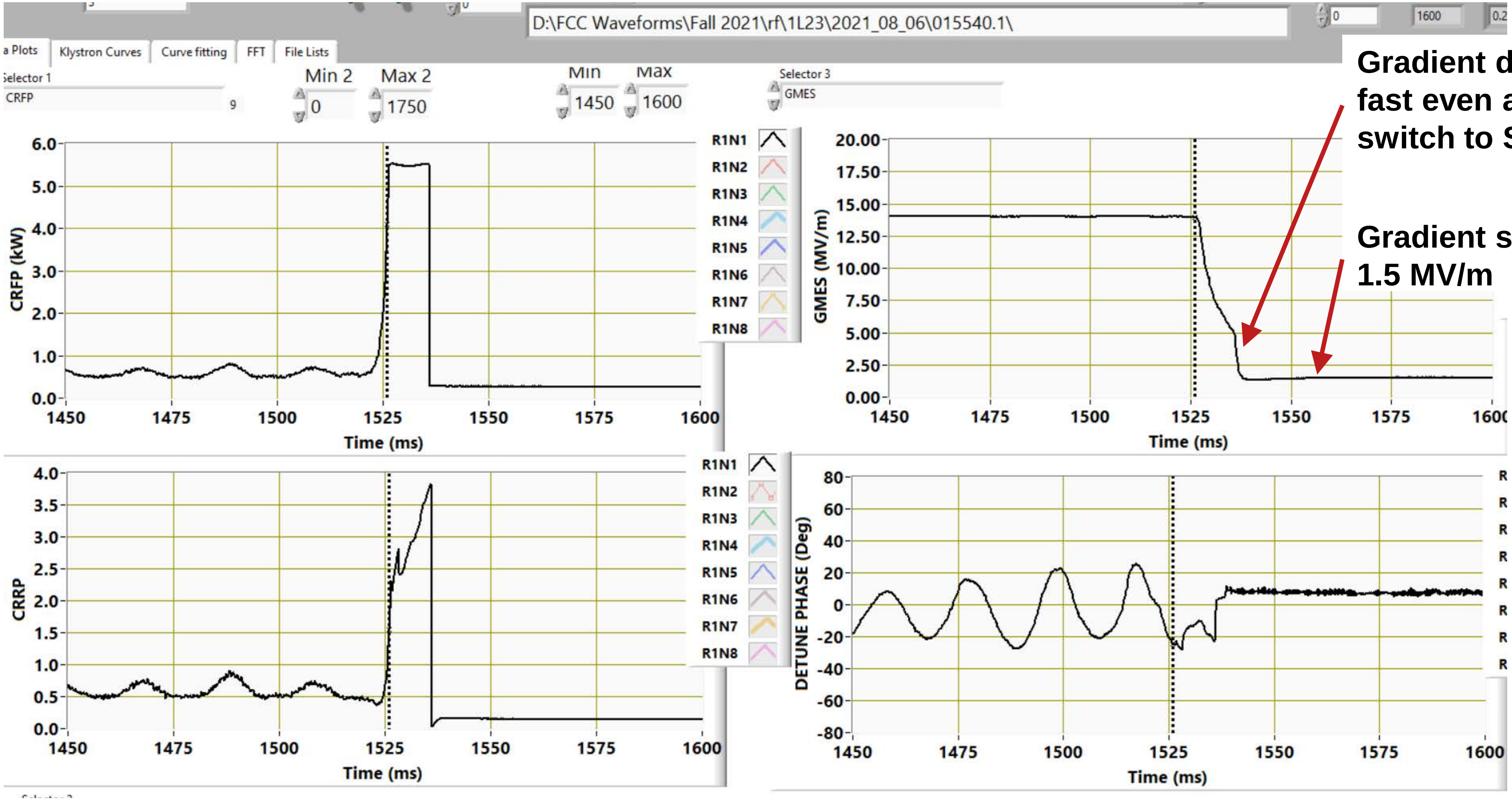
- Lower plot beam line and waveguide vacuums
  - Beam line vacuum (higher pressure)
  - 2L26-6 and 2L26-7 (lower pressure)
  - Log scale with upper marker is 1×10^{-8} Torr

- No conclusions just data.



- We had some discussions regarding why we were seeing quenches in the machine.
- Controls driven quench typically means that
  - GASK went to 10, typically after a different cavity tripped first,
  - Then the cavity was driven up to a prompt quench field.
  - Within 10 or 15 ms after the peak field the cavity was in SEL mode at a low gradient with excessive dissipated power.

Quench Example 1 First Fault is a Cavity Quench

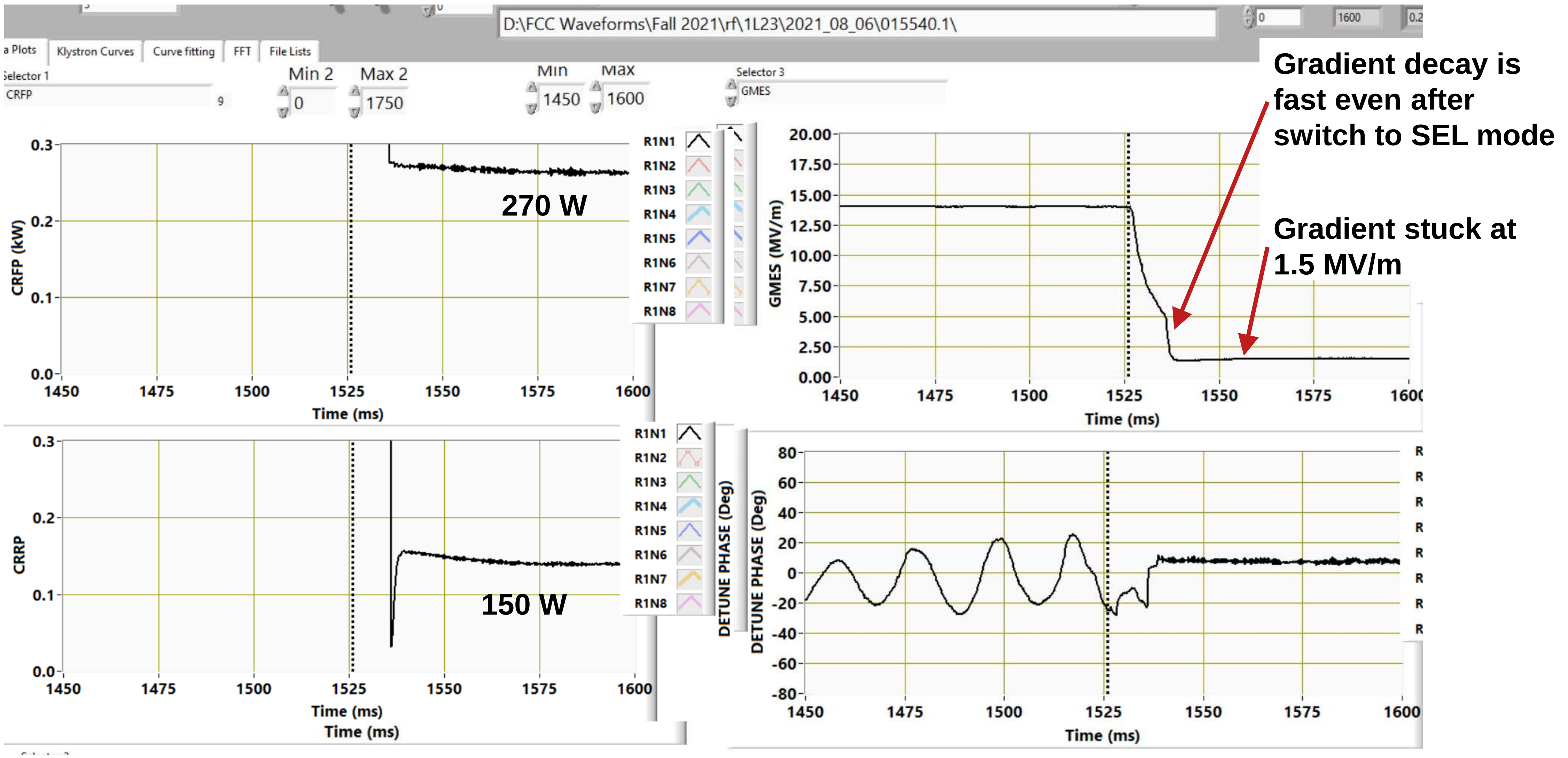


Gradient decay is fast even after switch to SEL mode

Gradient stuck at 1.5 MV/m

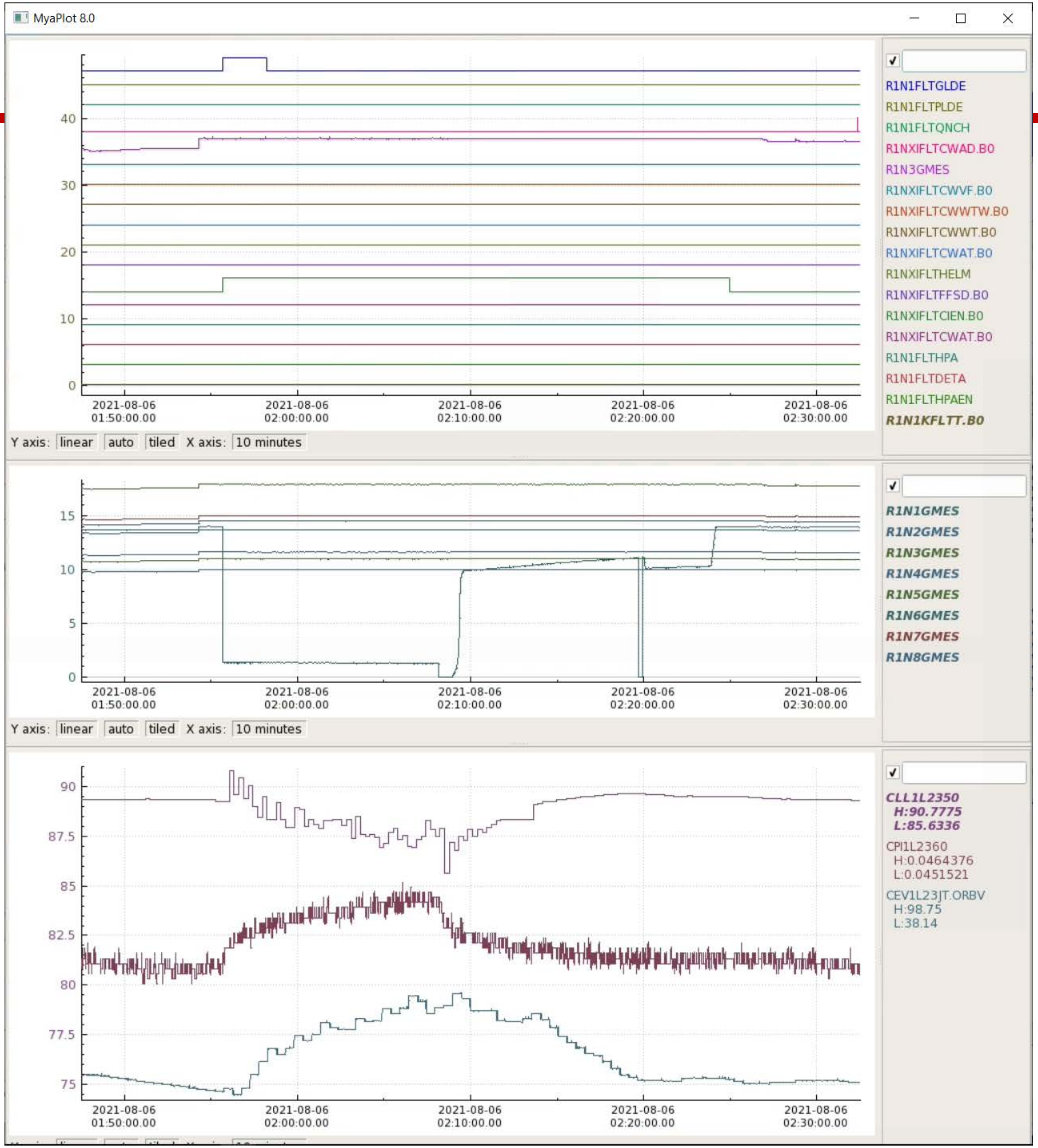
In this case all of the other cavities stayed on with stable gradient.

Quench Example 1 First Fault is a Cavity Quench



In this case all of the other cavities stayed on with stable gradient.

Same Event in EPICS



- The cavity had a GLDE fault and was put into SEL mode with
  - 270 W of forward power, CRFP
  - A gradient of 1.5 MV/m rather than the 10 MV/m that it should have been.
  - 150 W of reflected power, CRRP
  - 120 W dissipated into the bath for 10 minutes ! ! ! !
- Liquid level dropped and oscillated due to heat riser chokes
- JT valve opened up in response
- CM helium pressure increased.

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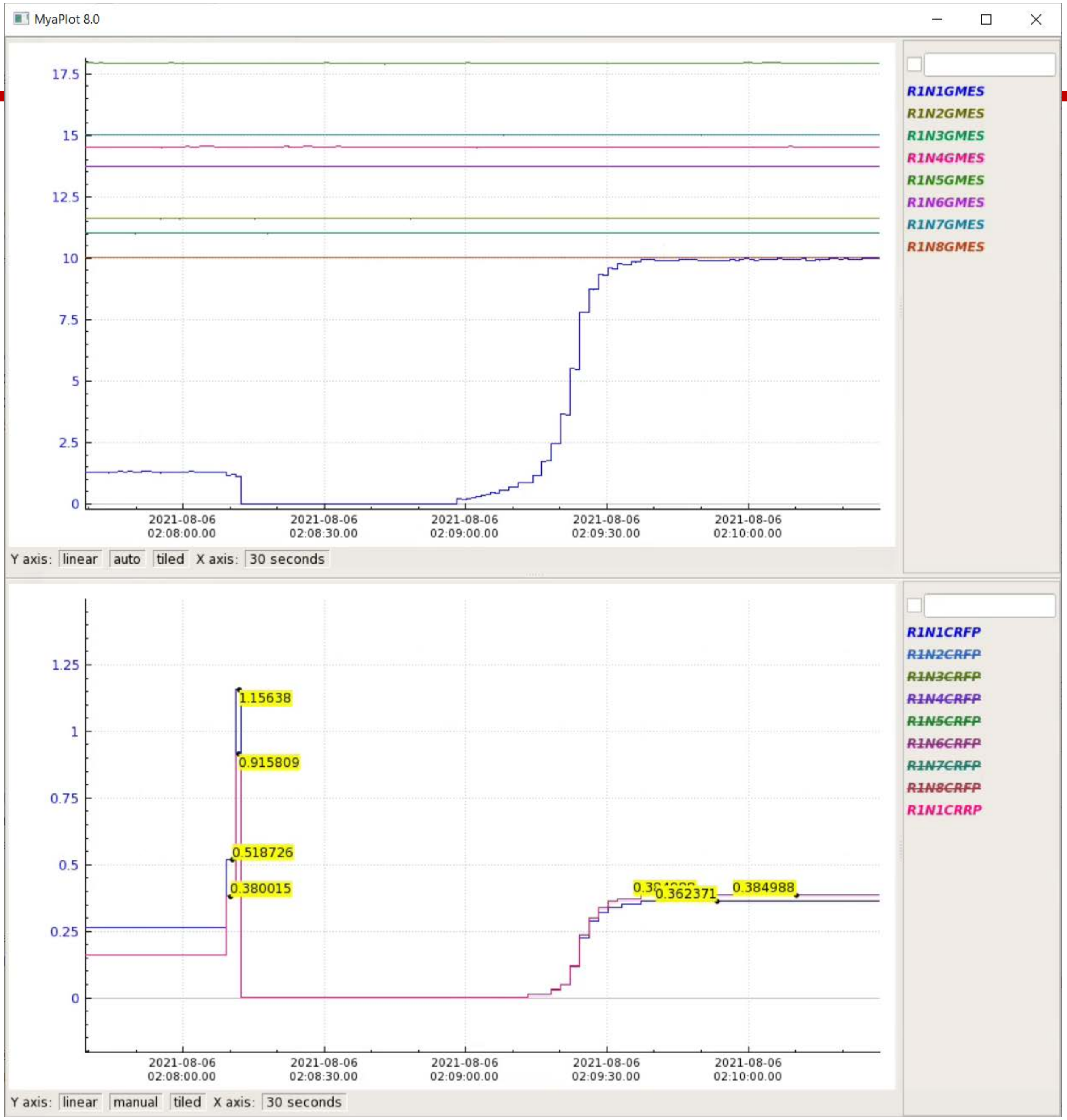

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  - **270 W of forward power, CRFP**
  - **A gradient of 1.5 MV/m rather than the 10 MV/m that it should have been.**
  - **150 W of reflected power, CRRP**
  - **120 W dissipated into the bath for 10 minutes ! ! ! !**
- **Liquid level dropped and oscillated due to heat riser chokes**
- **JT valve opened up in response**
- **CM helium pressure increased.**
- **After 10 minutes the RF tried to increase the power in order to increase the gradient.**
  - **First to 500 W CRFP, 380 W CRRP, still 120 W dissipated.**
  - **Then to 1156 W CRFP, 916 W CRRP, 241 W dissipated**
  - **Then it turned off the RF for about 60 seconds and everything recovered.**

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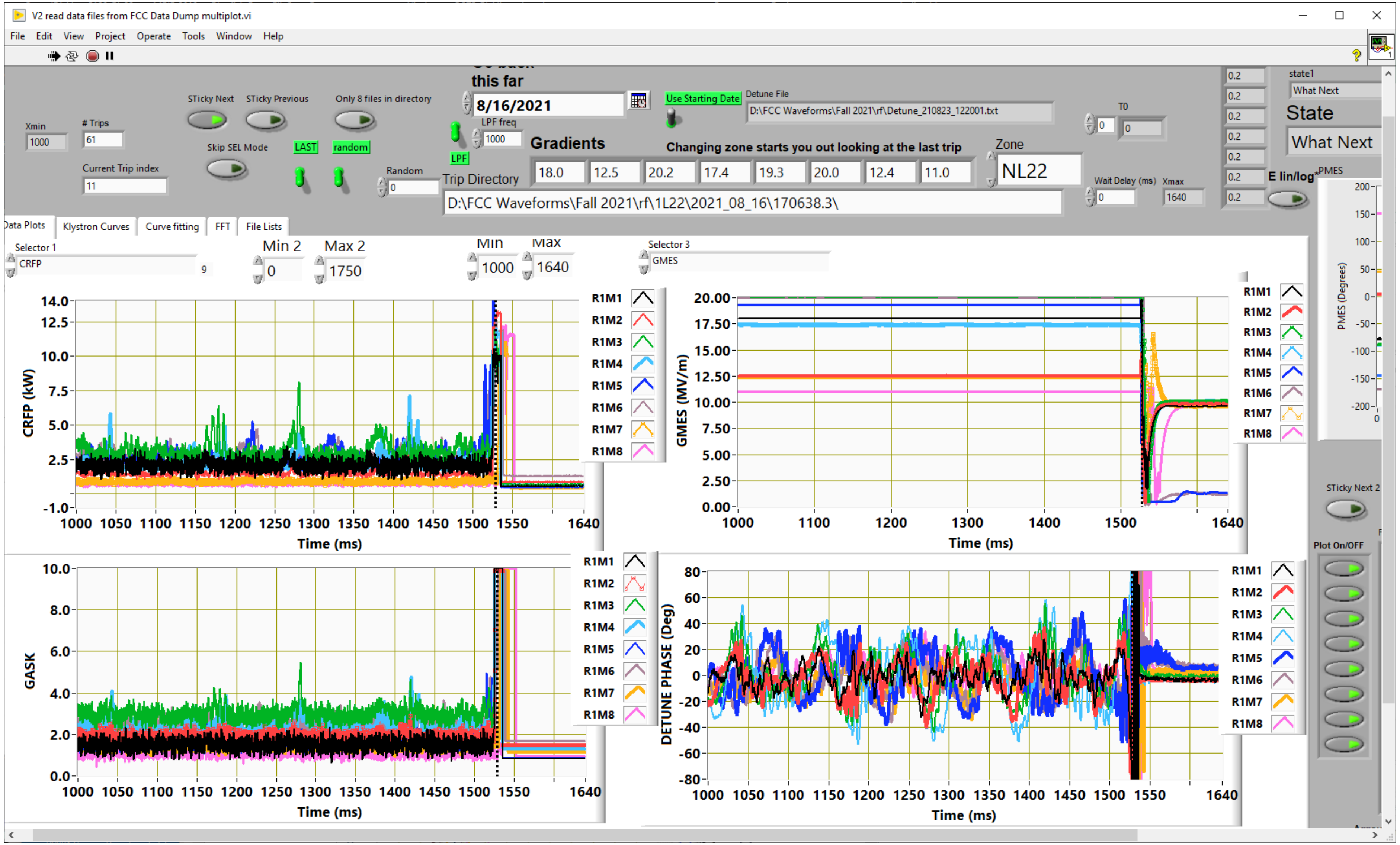
Microphonics Fault Leads to Multiple Quenches



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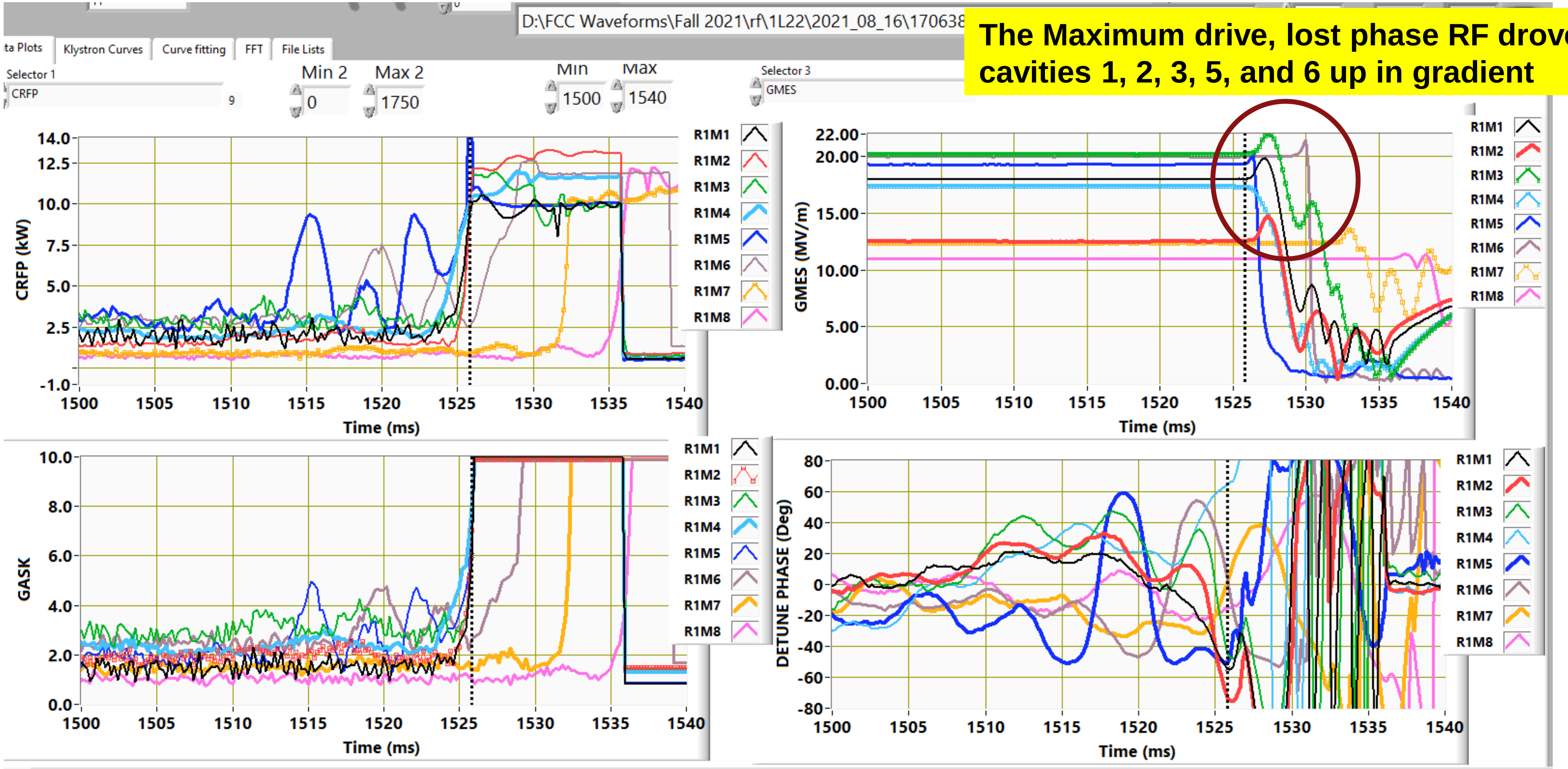
Microphonics Fault Leads to Multiple Quenches

Cavities 1, 2, 3, 4 and 5 GASK all saturated at the same time, 6, 7 and 8 followed soon after.



The Maximum drive, lost phase RF drove cavities 1, 2, 3, 5, and 6 up in gradient

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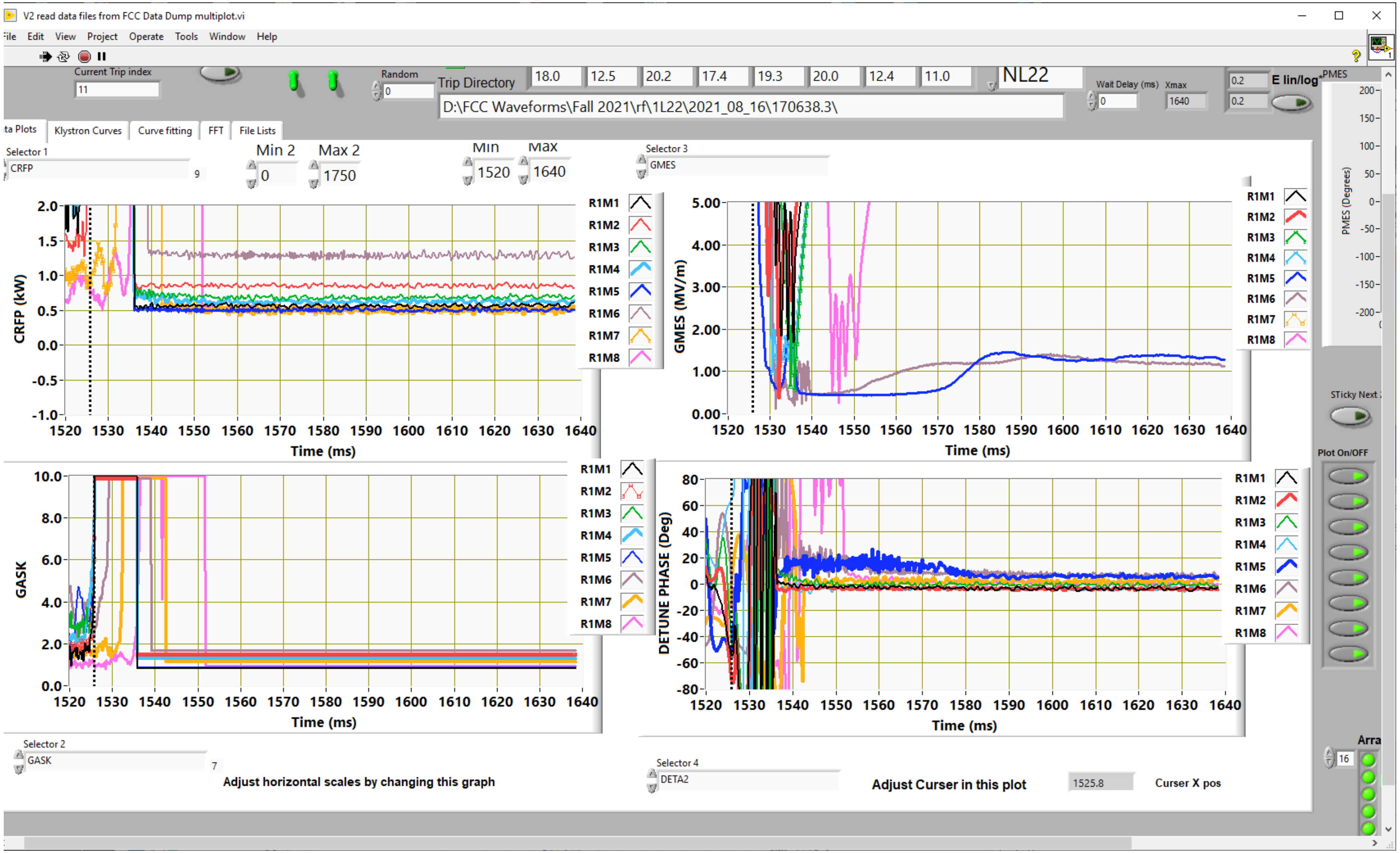
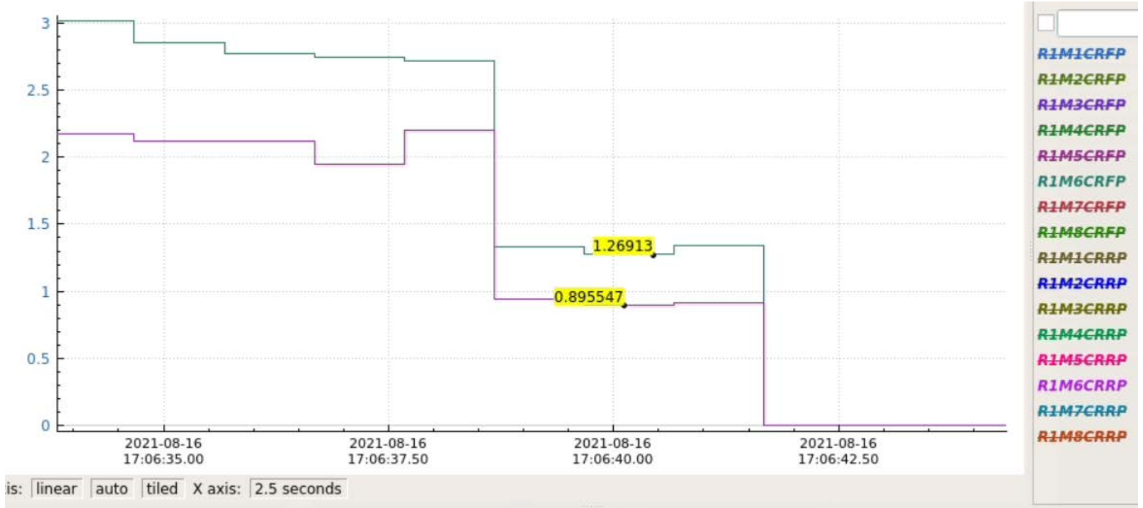
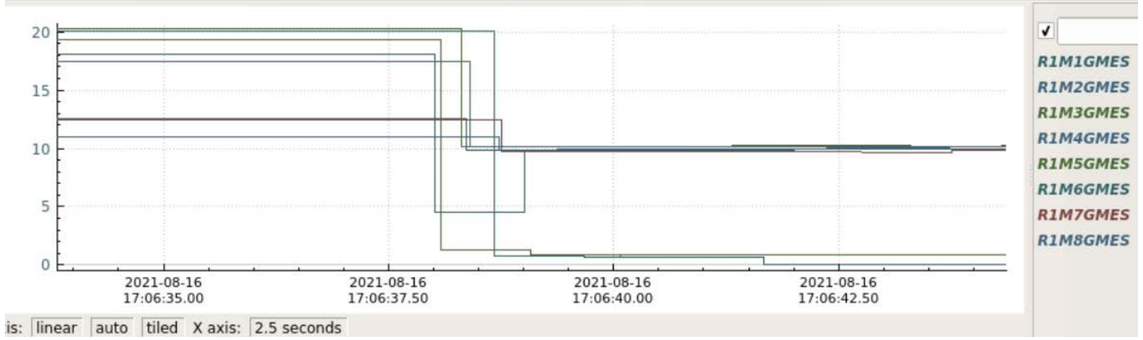
Microphonics Fault Leads to Multiple Quenches



- At the end when they were all in SEL mode cavities 5 and 6 were at just over 1 MV/m
- One would expect the reflected power to indicate a high dissipated power but it was “broken” on this data set.

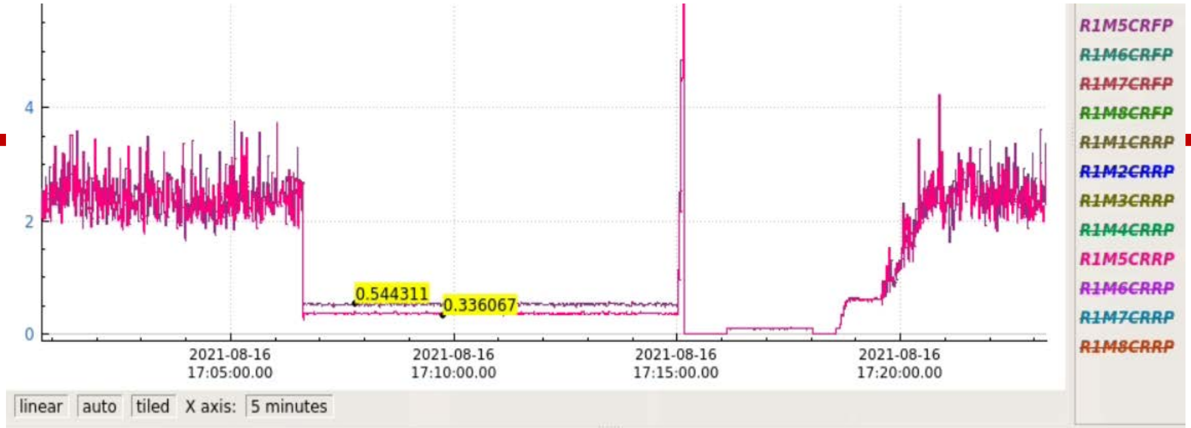
Microphonics Fault Leads to Multiple Quenches

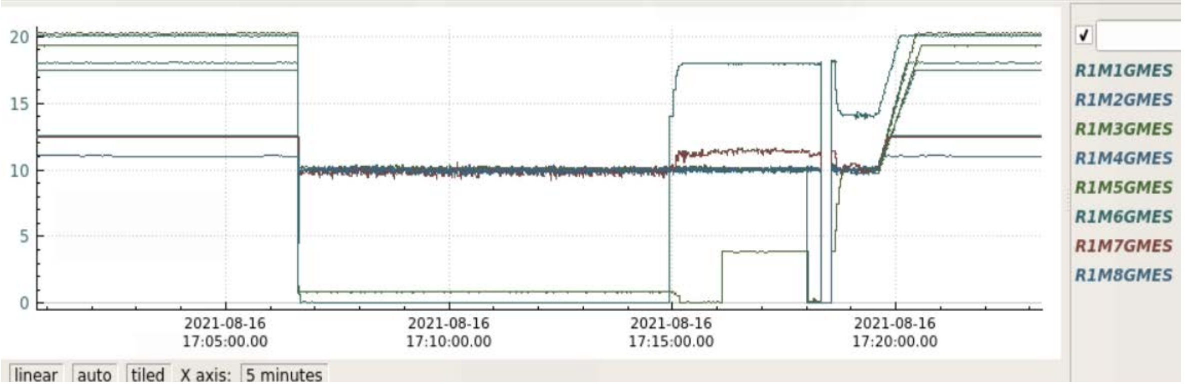




- Cavity 6 was turned off after 2 seconds.

Fortunately this does not happen all that often. That being said if a cavity has not recovered after a few minutes turn it off wait at least 45 seconds and try again.

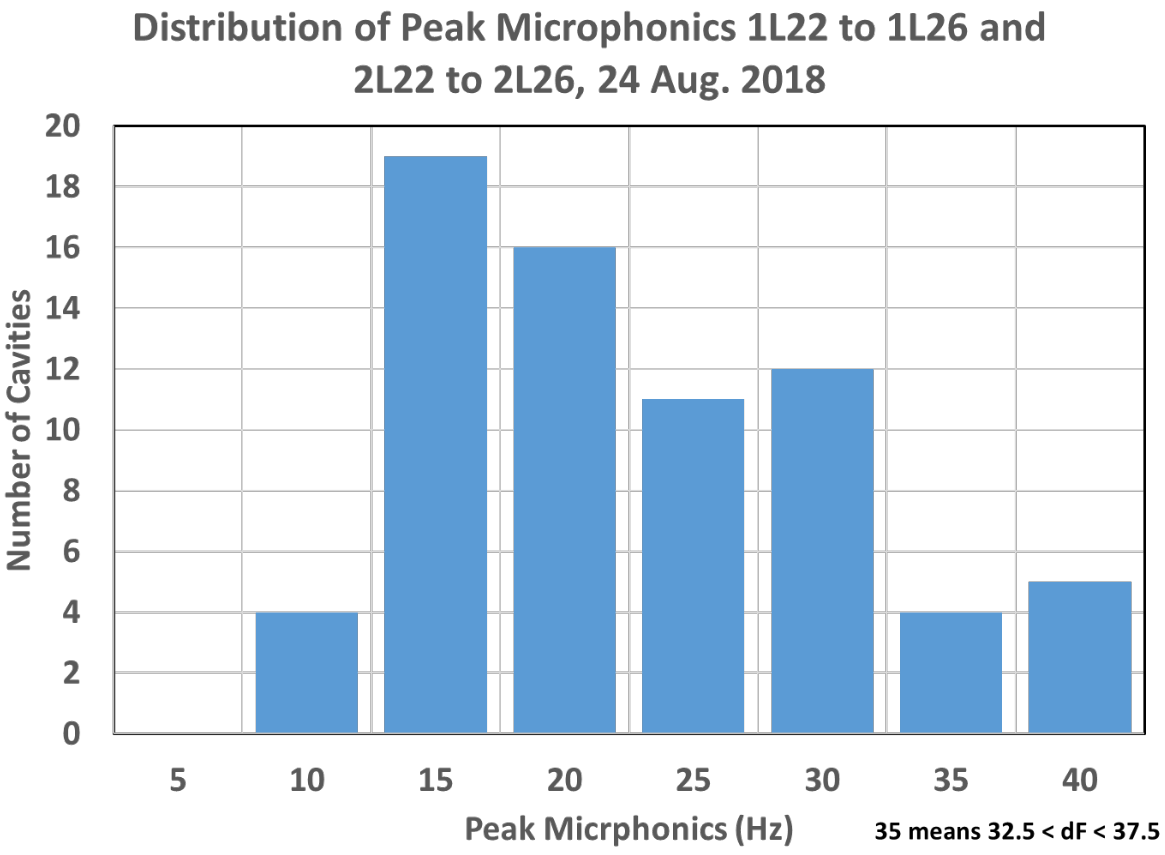


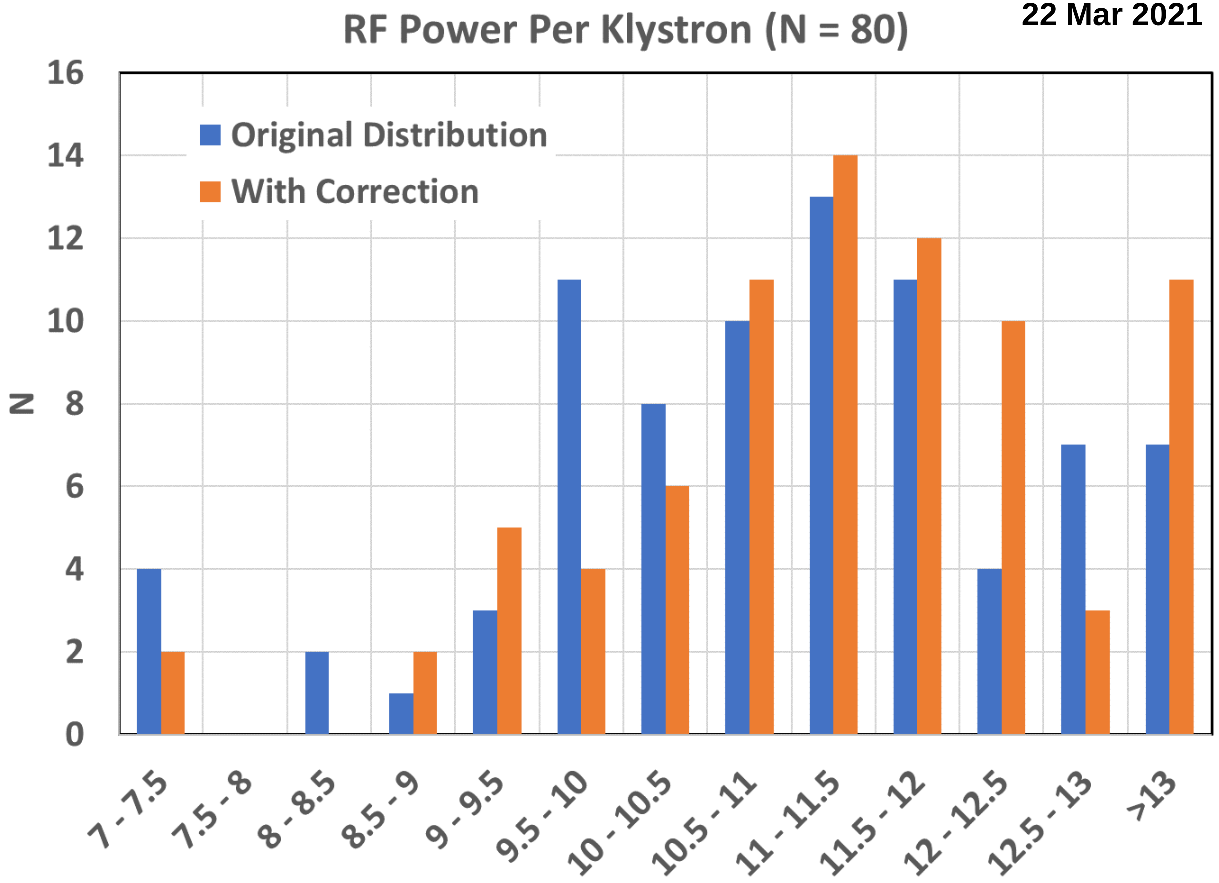


- **Cavity 5 stayed on and quenched for about 10 minutes.**
- **Then like the fault on 1L23-1 it tried to increase the gradient then turned itself off for 10 seconds tried to turn back on with no luck**
- **After 30 seconds still quenched it was turned off for another 5 seconds then was able to recover.**
- **Cryo transients similar to the 1L23-1 event were observed.**

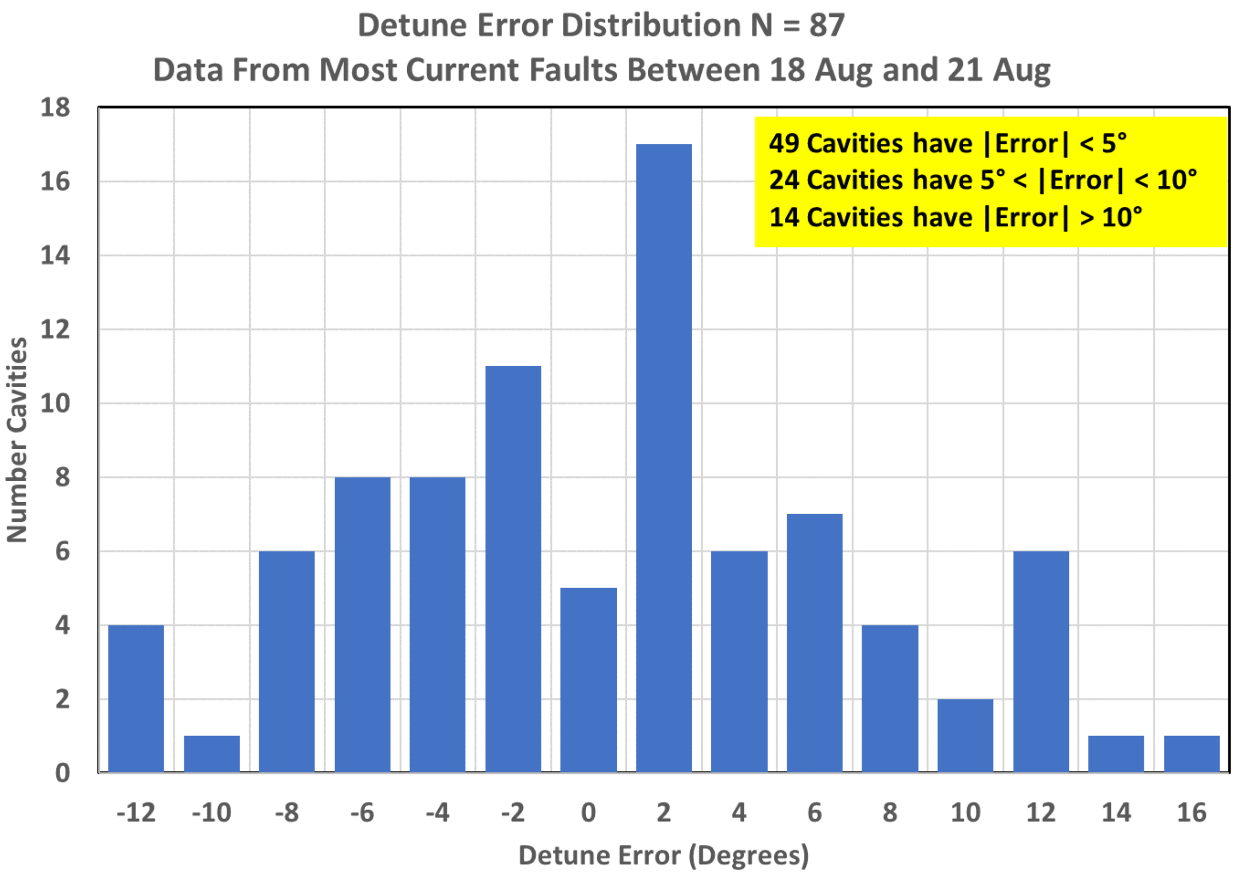
Microphonics and RF power limits for C100s.

- Presented at the RF PIT meeting 22 Mar 2021





- Most C100 cavities do not have HOM filters so you only loose 0.4 dB to waveguide losses
- With a 10% margin that means that the majority of the systems deliver between 10.6 (13 kW) and 8.6 kW (10.5 kW) to the cavities.
- Lets use 35 Hz for the allowed microphonics so that we have a little margin on most of the cavities.



- **Note that 1L07 (the rebuilt SL21 cryomodule) and 1L23 the rebuilt F100 cryomodule can be problematic tuning using this method because they have such low microphonics.**
- **I would suggest a method like I use in the VTA where you step them off in detune phase 5° or 10° then walk them back in 1° or 2° steps.**

Logged in as powers (Logout)

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A fair number (>20 out of 80) of cavities need to have their detune offsets adjusted

Lognumber 3893520. Submitted by powers on Tue, 08/17/2021 - 12:36.

There is 1 comment...

We did this during day shift

by gauthier on Sun, 08/22/2021 - 14:59 *new*

We did this during day shift today. We added the numbers to the offset and it did in fact decrease forward powers.

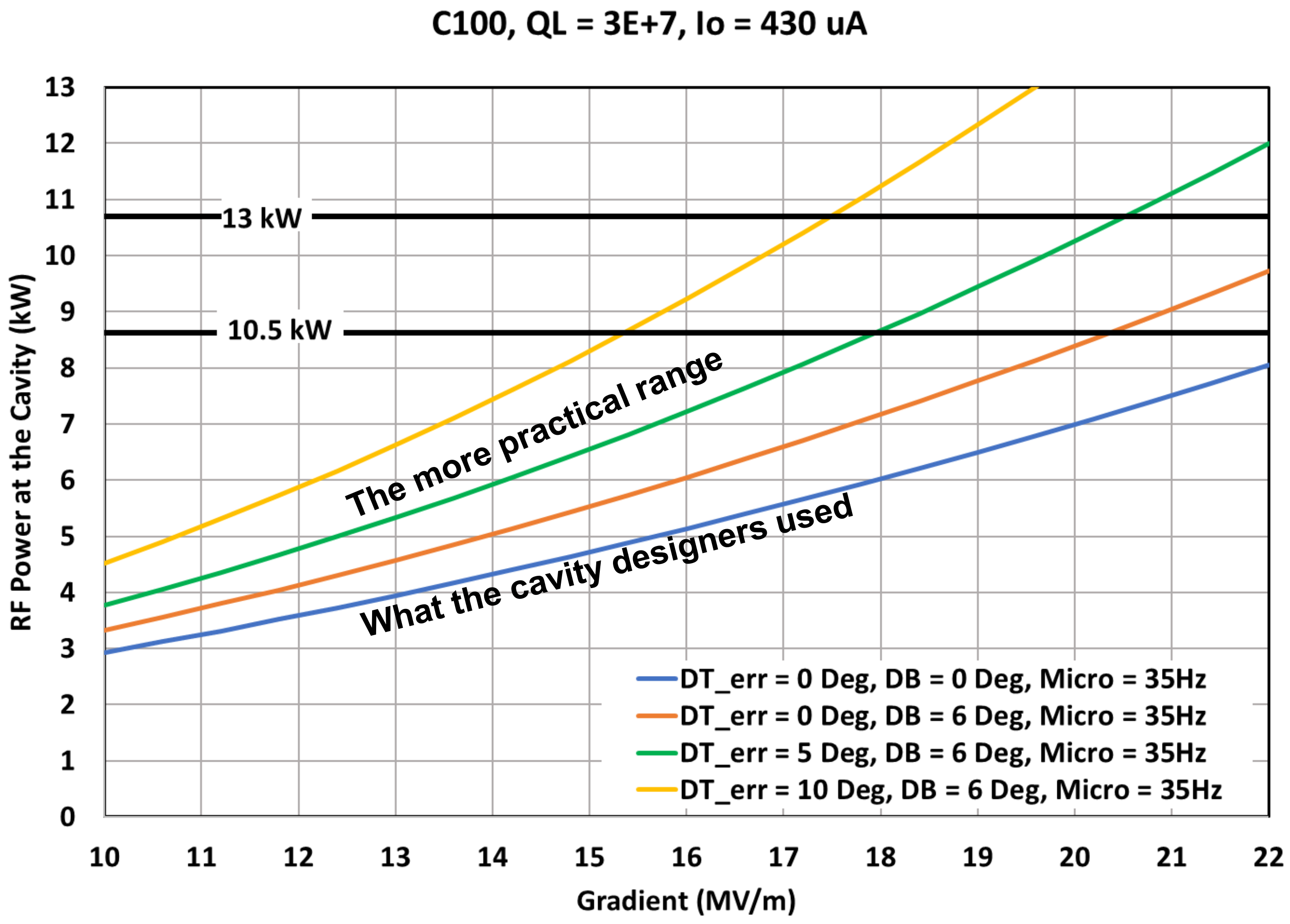
Logbooks: ELOG

Backlinks: Follow-up Re: A fair number (>20 out of 80) of cavities need to have their detune offsets adjusted

Attached Files: Detune_210817.pdf

I have a tool that uses the DETA2 and the forward power to determine how far off from perfectly tuned the cavities are 24 of them are more than 8 degrees out of tune. The full listing is in the attached. I THINK that you have to move the detune offset the amount indicated in the file. Please comment back if that is backwards and you need to subtract the values from TDOFF in order to calculate the correct value.

C100 Design Parameters



- **Spec loaded-Q is 3e7.**
- **The range on loaded-Q is between 2.2e7 and 3.5e7 with a few outliers.**
- **Klystron power varies from cavity to cavity**
- **Detune angle is done differently it is the phase that results from 3 Hz (maybe 4 Hz) detuning with no beam which depending on the loaded-Q is between 6° and 10°. After they get that phase number that sets the target for detuning (I think).**
- **On a good day / cavity the maximum TDOFF is 5° and dead band is 6°.**
- **That puts the maximum gradients with 430 uA between 18 MV/m and 20.5 MV/m with outliers, detune error wise, between 15.2 MV/m and 17.5 MV/m.**

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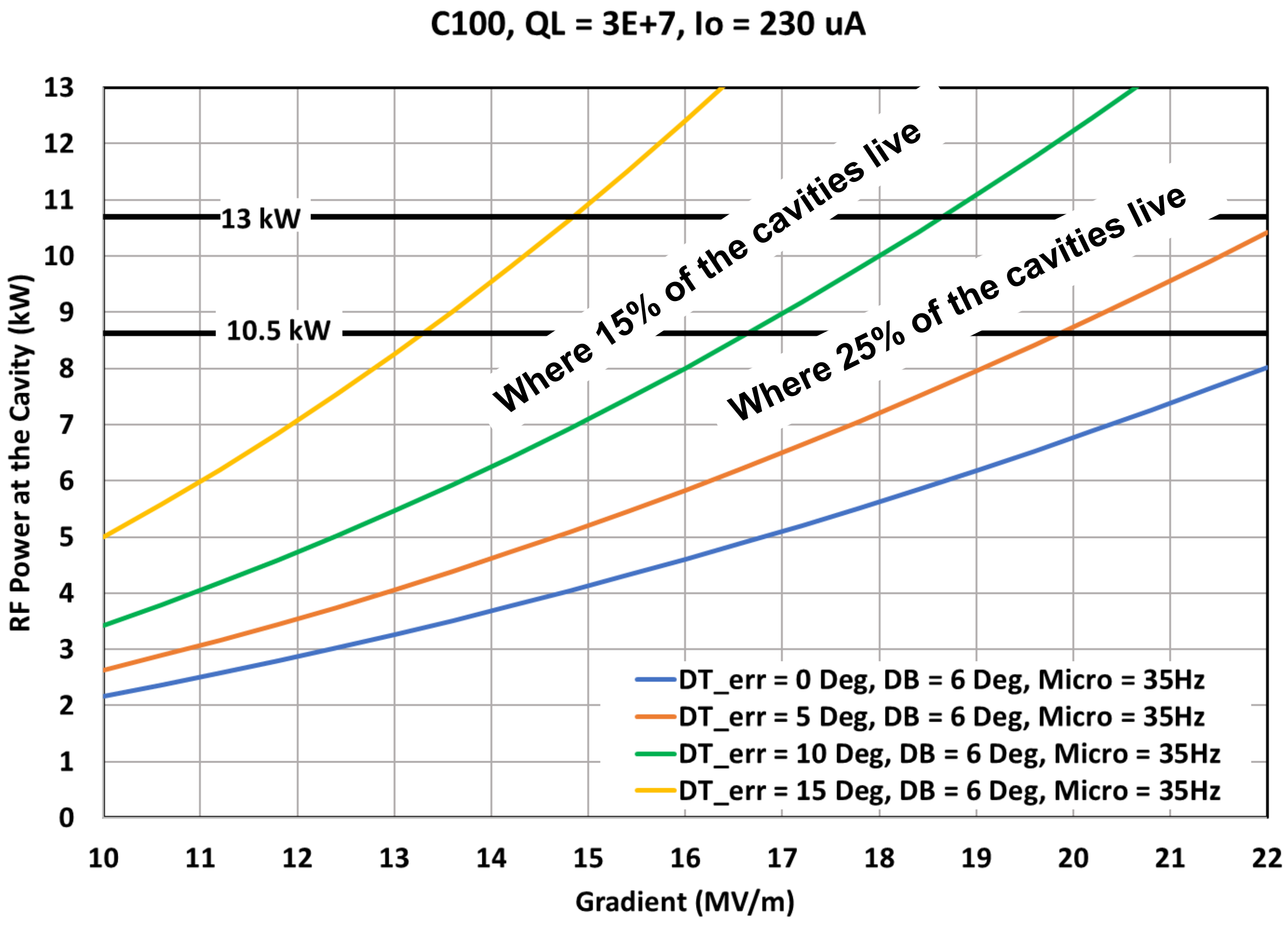
C100 Cryomodules where we have been running for the past few years



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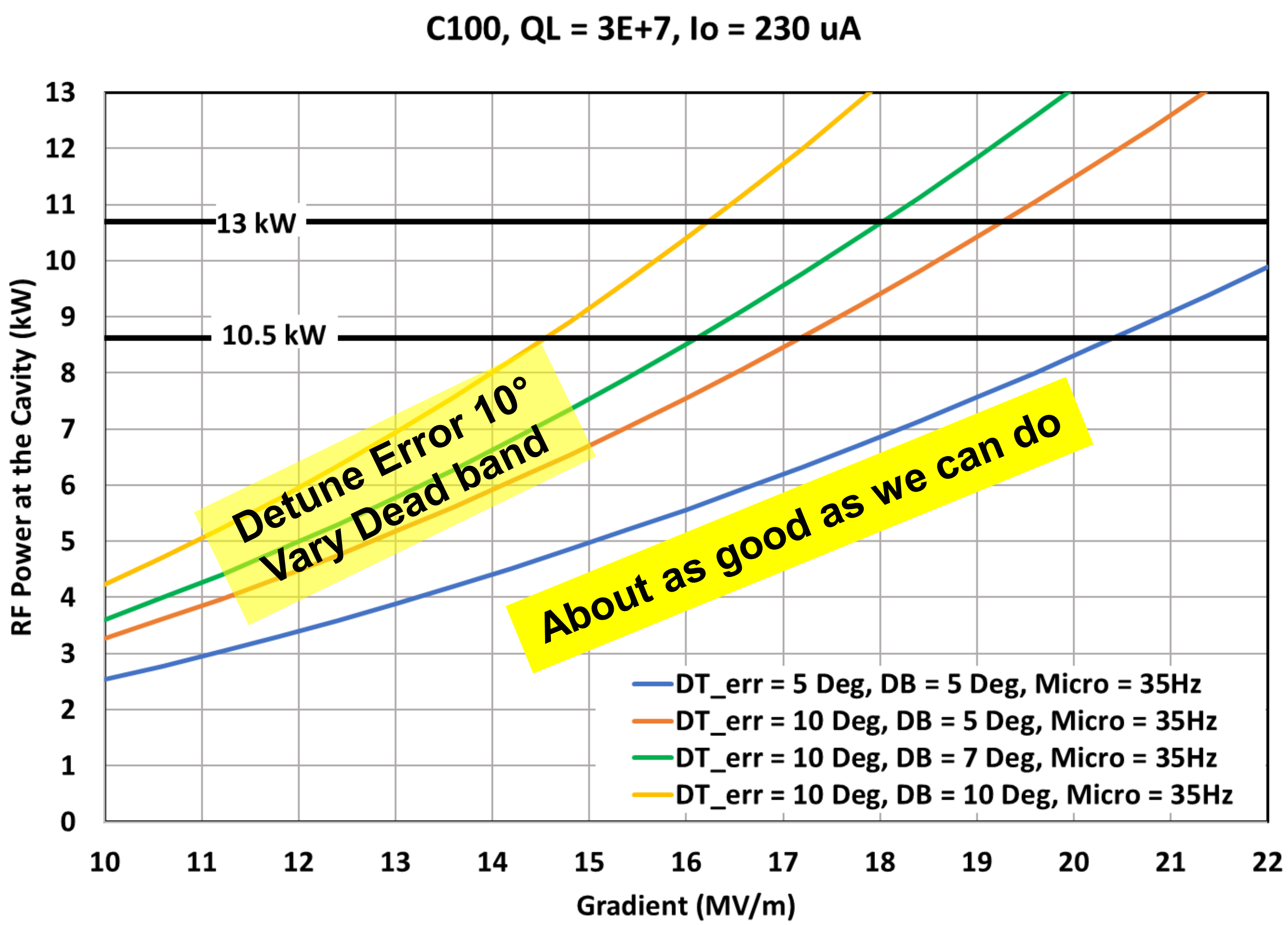
- **On a good day / cavity the maximum TDOFF error plus dead band is 10°, frequently it exceeds 15°.**
- **That puts the maximum gradients with 230 uA between 17 MV/m and 19.2 MV/m with outliers, detune error wise, between 15 MV/m and 17 MV/m..**

C100 Cryomodules where we are now Kind-of Sort-of



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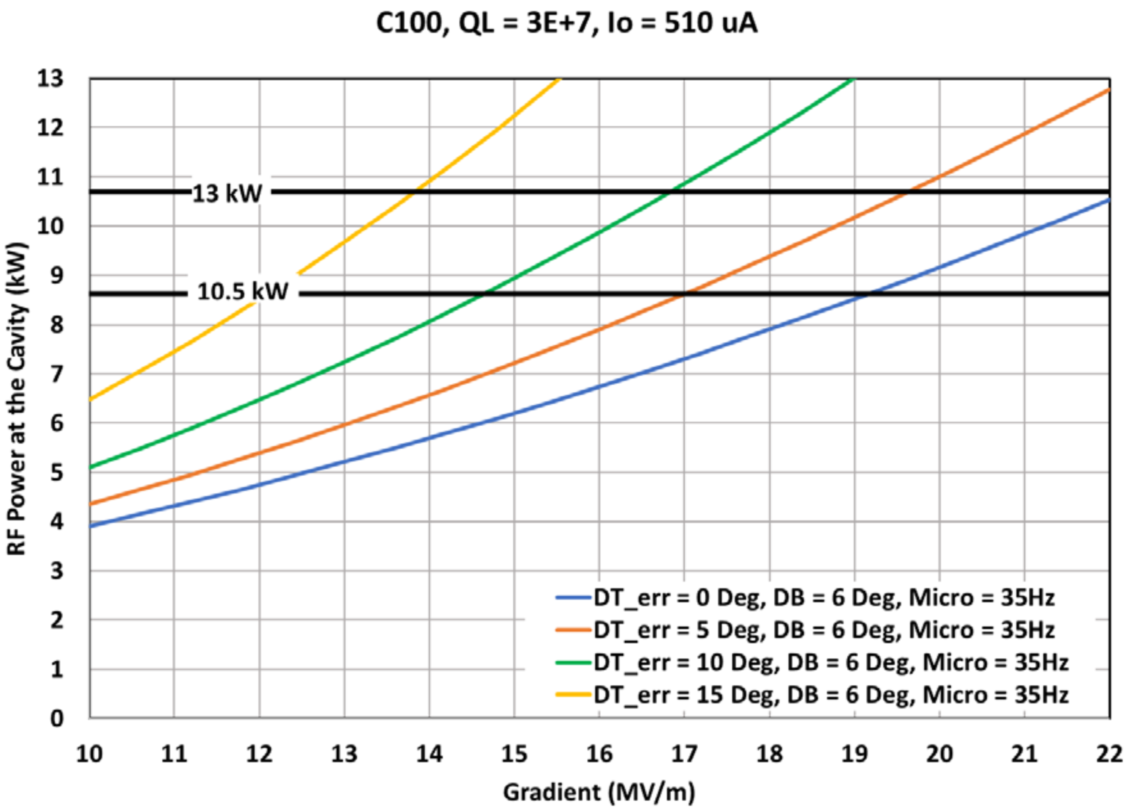
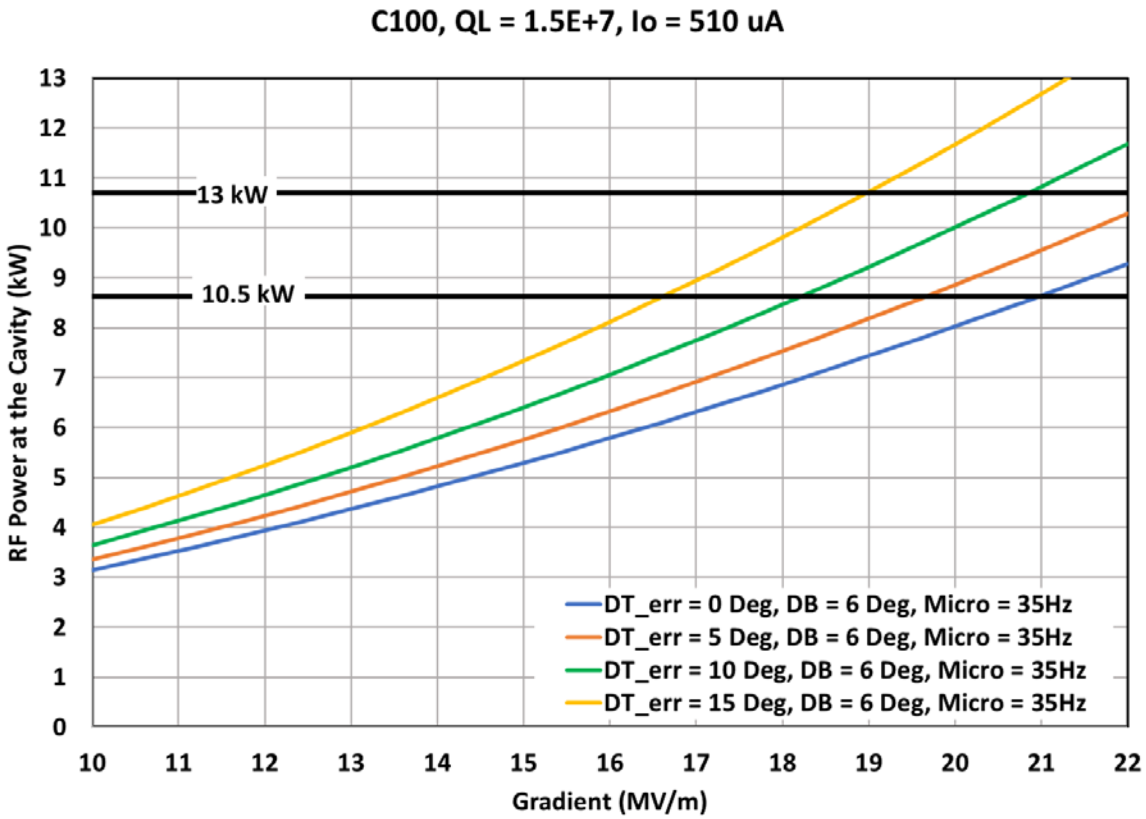
C100 cryomodules where we have a short-ish run scheduled this fall.

510 uA

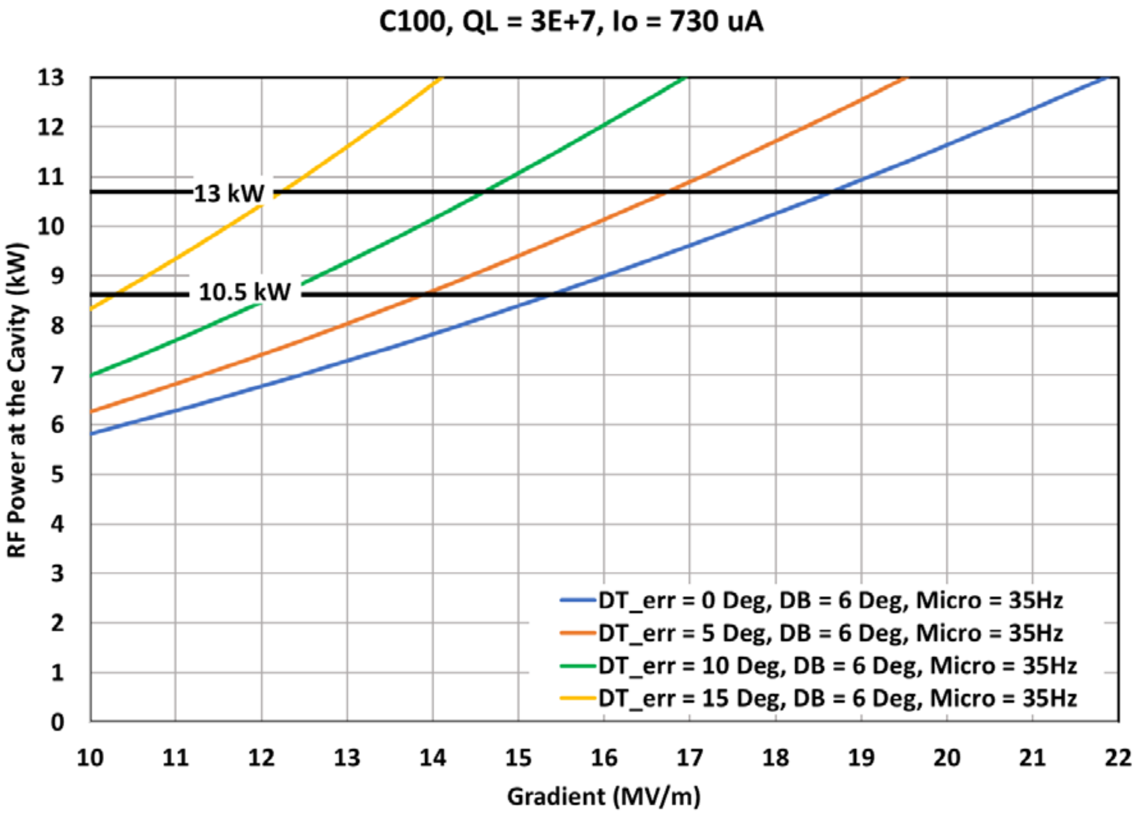


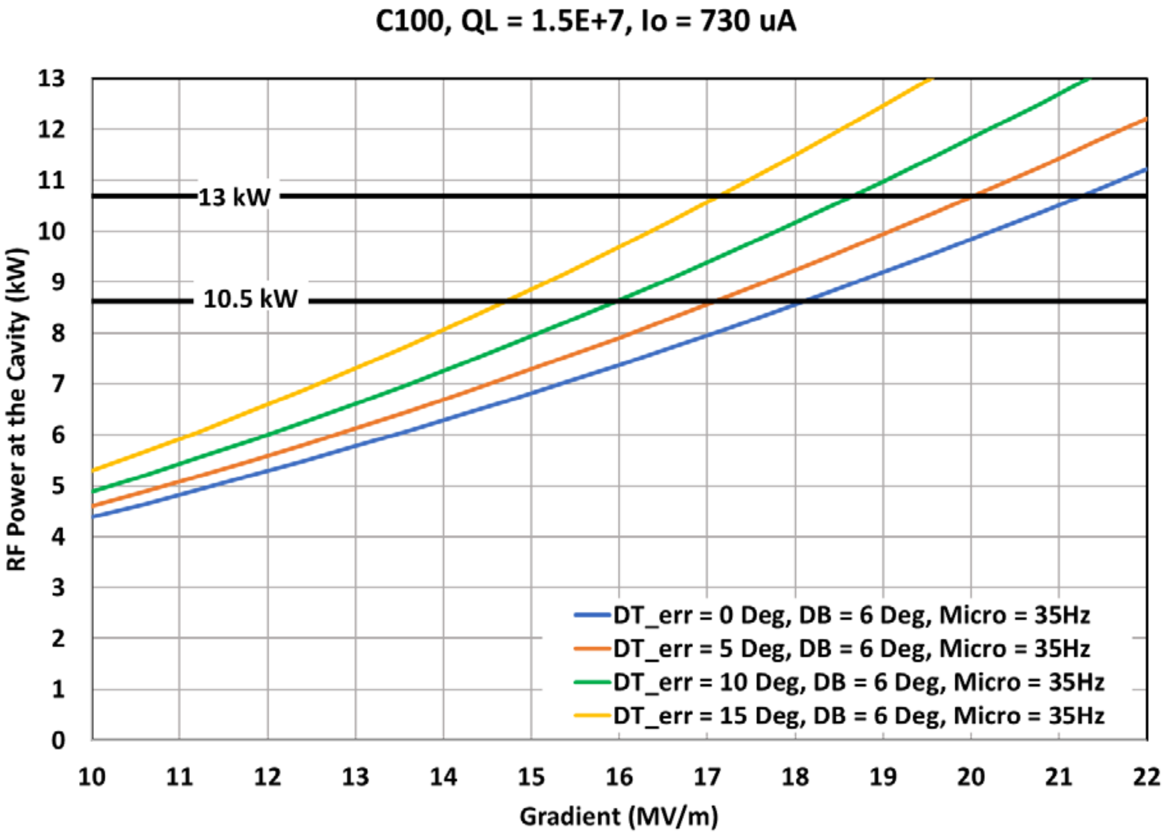


- **If we can keep the detune errors less than 5° and the dead band at 6° we can average 18.5 MV/m and can make 100 MeV on a good cryomodule.**
- **If we miss on the dead band at 6° or the detune error to the level of 10° we can do 85 MeV or so.**
- **Of course all this assumes that we are only limited by RF power**

C100 cryomodules where some hope we will be several years from now.

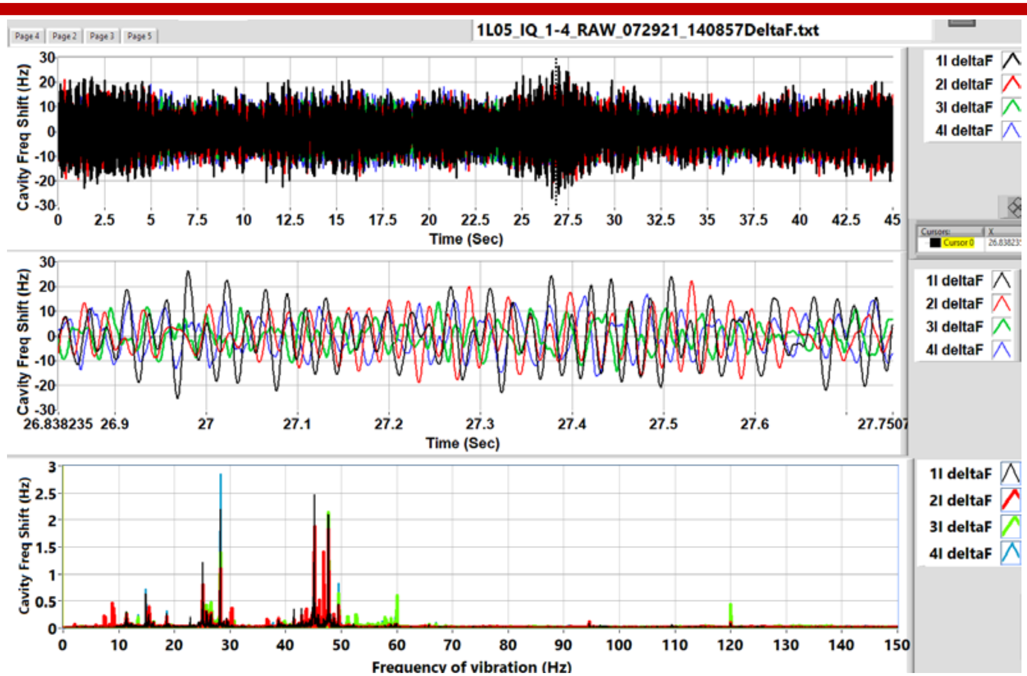
730 uA

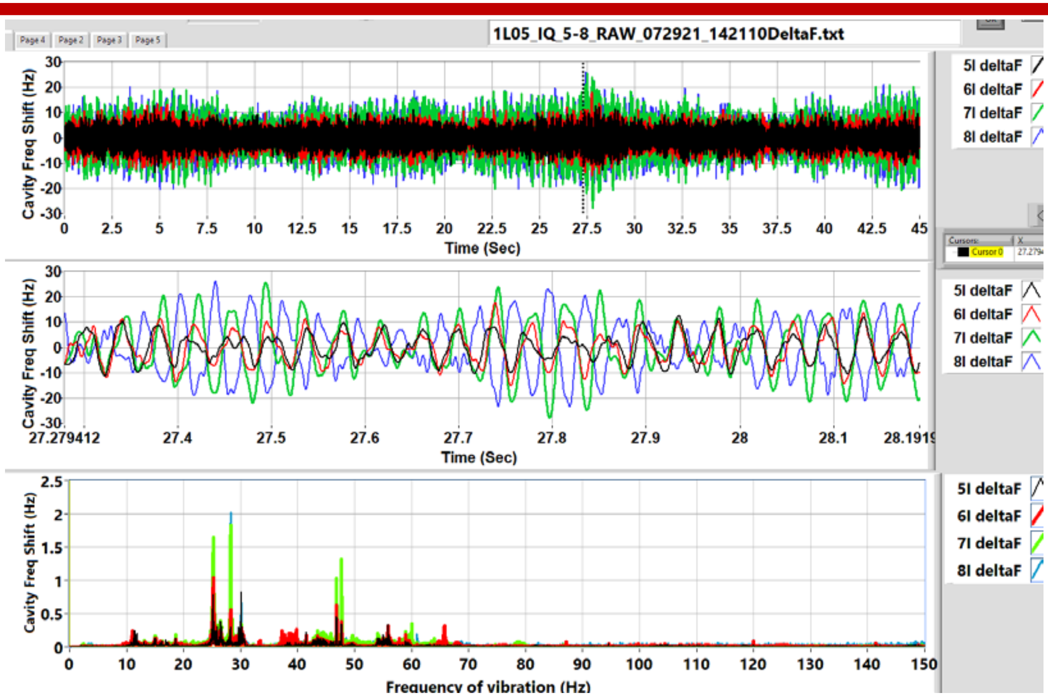




- **Assuming that we can keep the DB at 6 and detune errors to less than 5 including keeping cavities properly tuned.**
- **Using the midpoint of the data keeping the loaded-Qs where they are we might be able to average between 12 MV/m and 14.7 MV/m or between 67 MeV and 82 MeV**
- **If we were to reduce the loaded-Qs to 1.5e7 we might be able to do between 89 MeV and 100 MeV.**

C75-1 Microphonics first results using probe I/Q signals in SEL mode

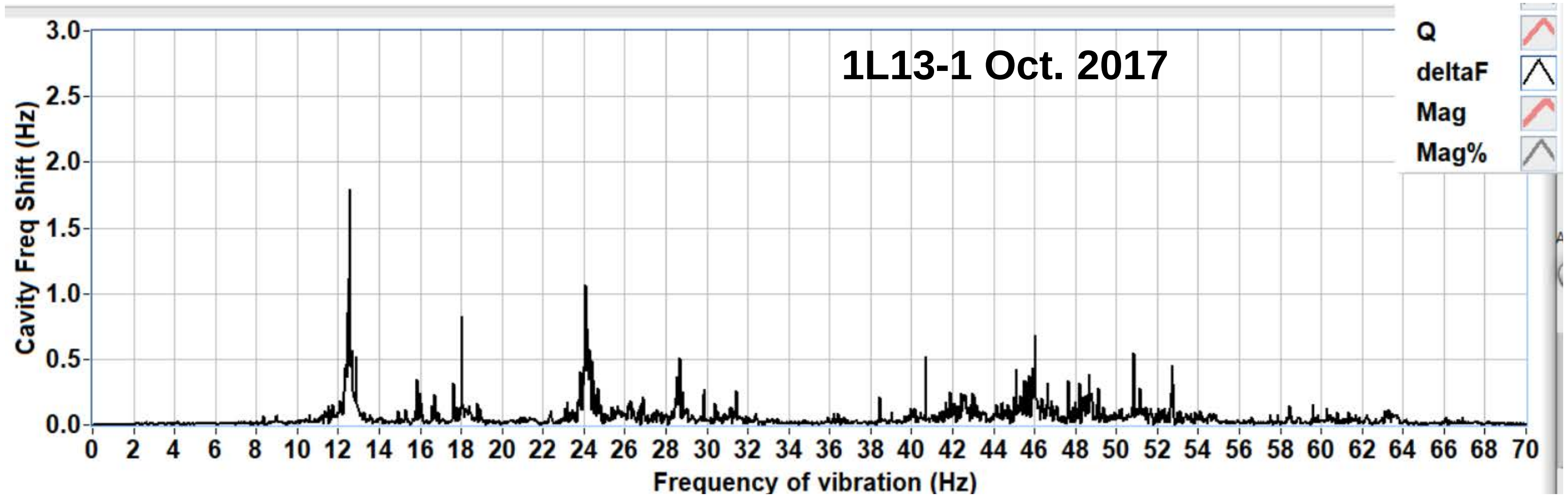


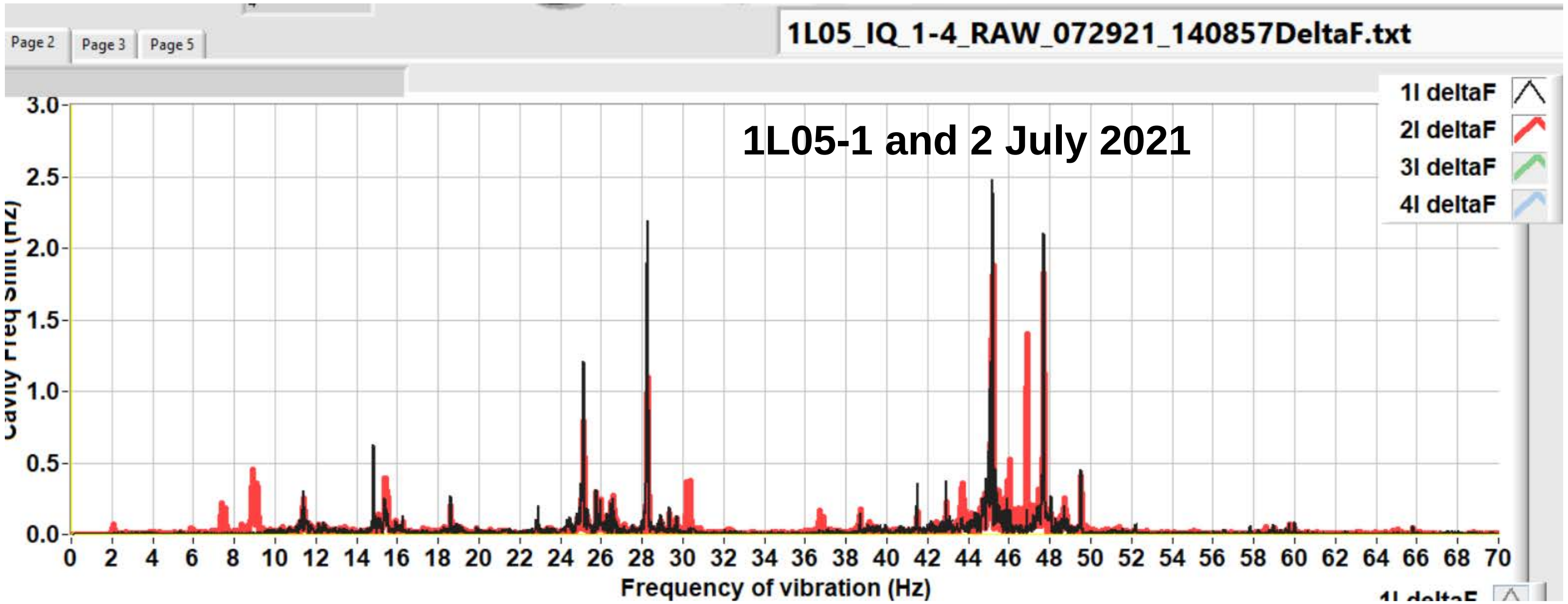


- **Data was filtered with a 2 Hz to 150 Hz band pass filter in order to reduce the noise and remove the DC offset.**
  - **Right side is cavities 1 through 4, left side is cavities 5 through 8.**
  - **Center plots are is the same data zoomed in by a factor of 50, Lower plots are FFTs of the data.**

Cavity	1	2	3	4	5	6	7	8
Peak Excursion (Hz)	27.3	22.2	16.6	19.3	14.4	18.3	28.7	26.7
RMS Value (Hz)	6.9	5.6	4.6	5.6	3.5	4.1	6.7	6.7

Comparison of frequency content between 1L13-1 and 1L05-1/2





C75-1 microphonics on the end two cavities were about 30% higher as compared to the data taken on the prototype C75 cavities in C50-13 which was taken in October 2013.

C50-13 1 and 2 (1L13)

- **The peak microphonics in cavity 1 for these tests was about 12 Hz.**
- **For cavity 2 it was 18 Hz.**

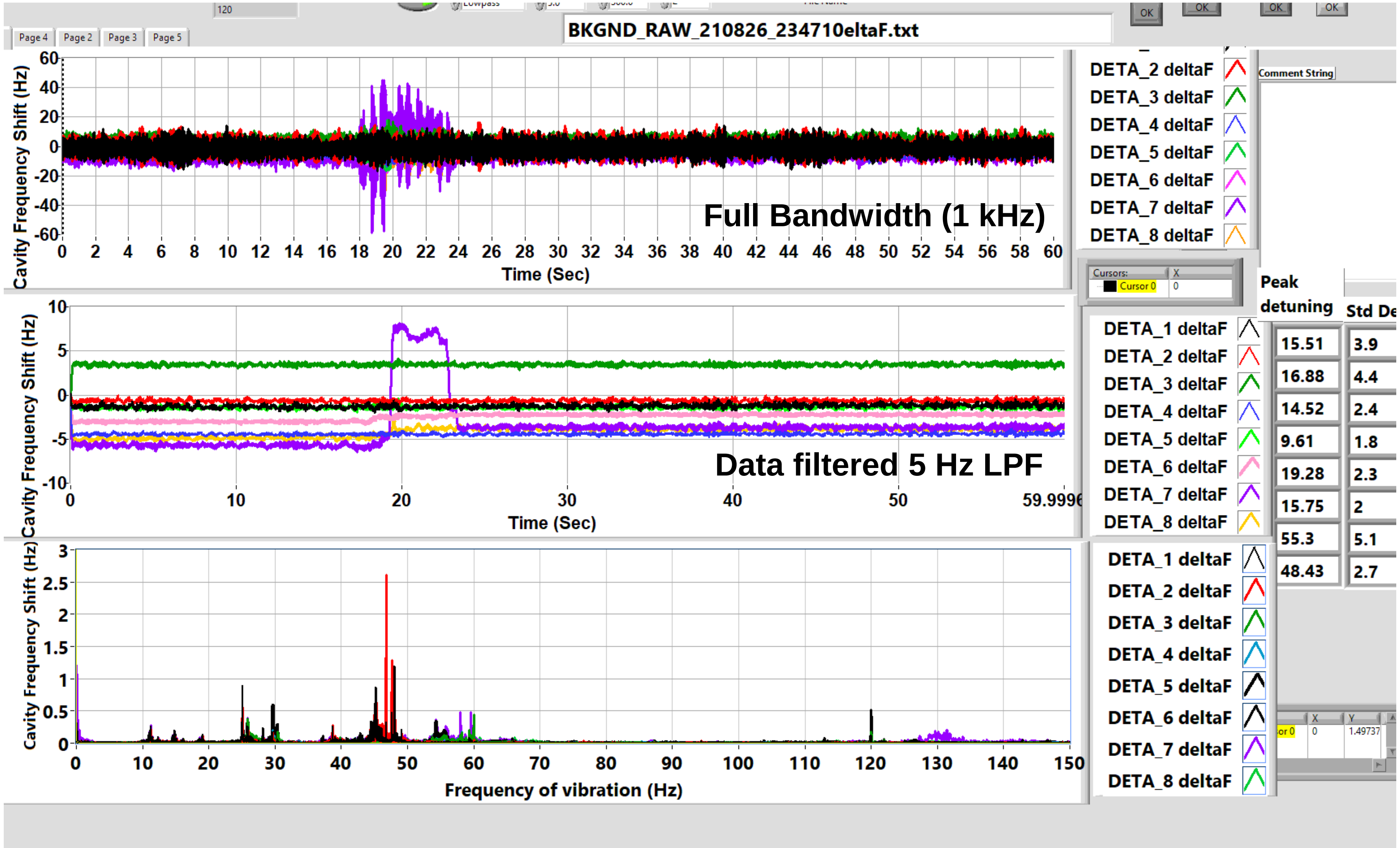
C75-1 cavities 1 and 2 (1L05)

- **The frequency content was substantially different then what was observed in cryomodule C75-1.**
- **It is not clear if this is due to changes in the modal resonances or if there is some different external vibrational sources.**

Data acquisition for transient microphonics studies.

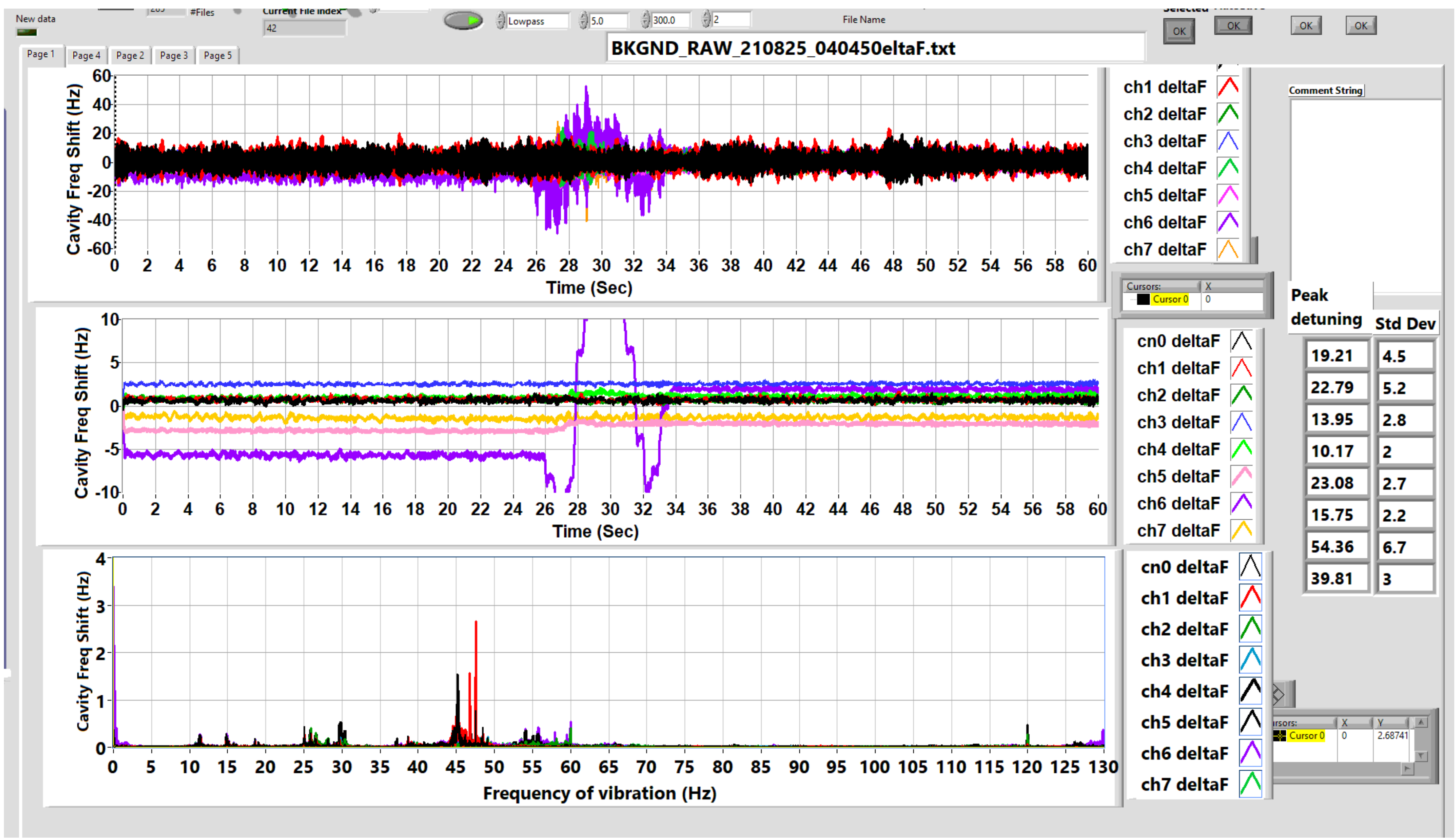
- **I took data when we were in tune beam operations. This is because things get more complicated for converting detune angle to deltaF in the presence of heavy beam loading.**
- **Standard data sets taken.**
  - **DETA2 was acquired using the DB-9 connector on the front of the FCC-3 chassis.**
  - **30 minute files with a few hundred ms between files.**
  - **3 kHz sample rate**
  - **Each 30-minute file was 280 MB of data.**
  - **Data was taken for about 1 week 100 GB of data taken.**
- **DETA2 data was converted to deltaF**
  - **Using the loaded-Q of the cavity which introduces errors as compared to calculating deltaF using I/Q data.**
  - **We had sufficient beam loading such that I could recalculate the loaded-Q values. Unfortunately we were using RF based gradient calibrations rather than beam based.**
  - **Worst case I would expect a 30% error on deltaF until we can get some data based on beam loading.**
- **Part of the standard data set was the peak microphonics on a second by second bases for each 30 minute data set. This was used to track down the transients which are shown in this talk.**
- **Once transients were identified 60 seconds of data containing the transients were saved.**

Example of saved data.



- Upper plot is the full bandwidth (1 kHz) microphonics for each of the cavities.
- Middle plot is the same data with a 5 Hz LPF.
- Lower plot is an FFT of the data set.

Example of the cavity being tuned in the incorrect direction initially.



- Upper plot is the full bandwidth (1 kHz) microphonics for each of the cavities.
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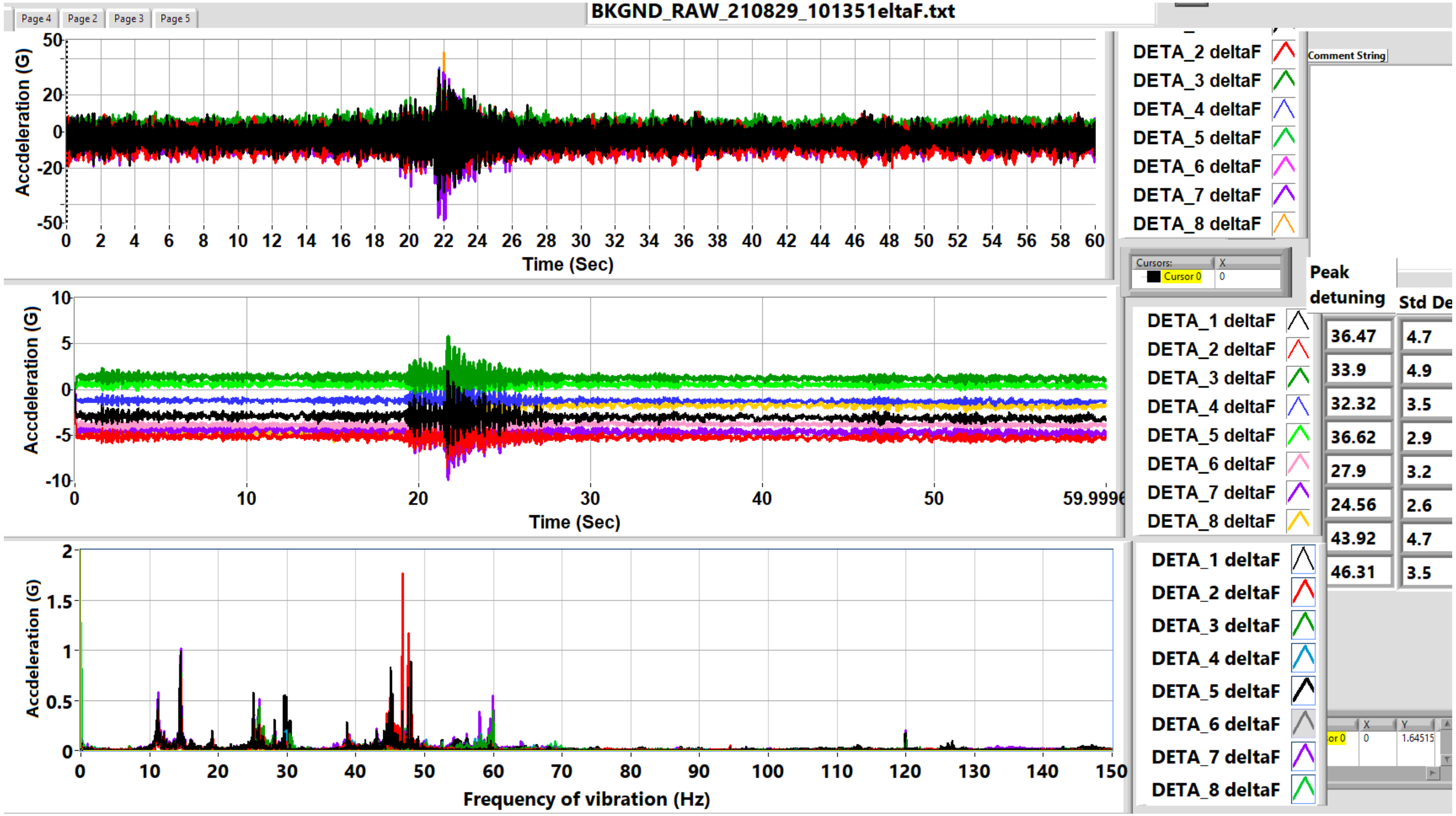
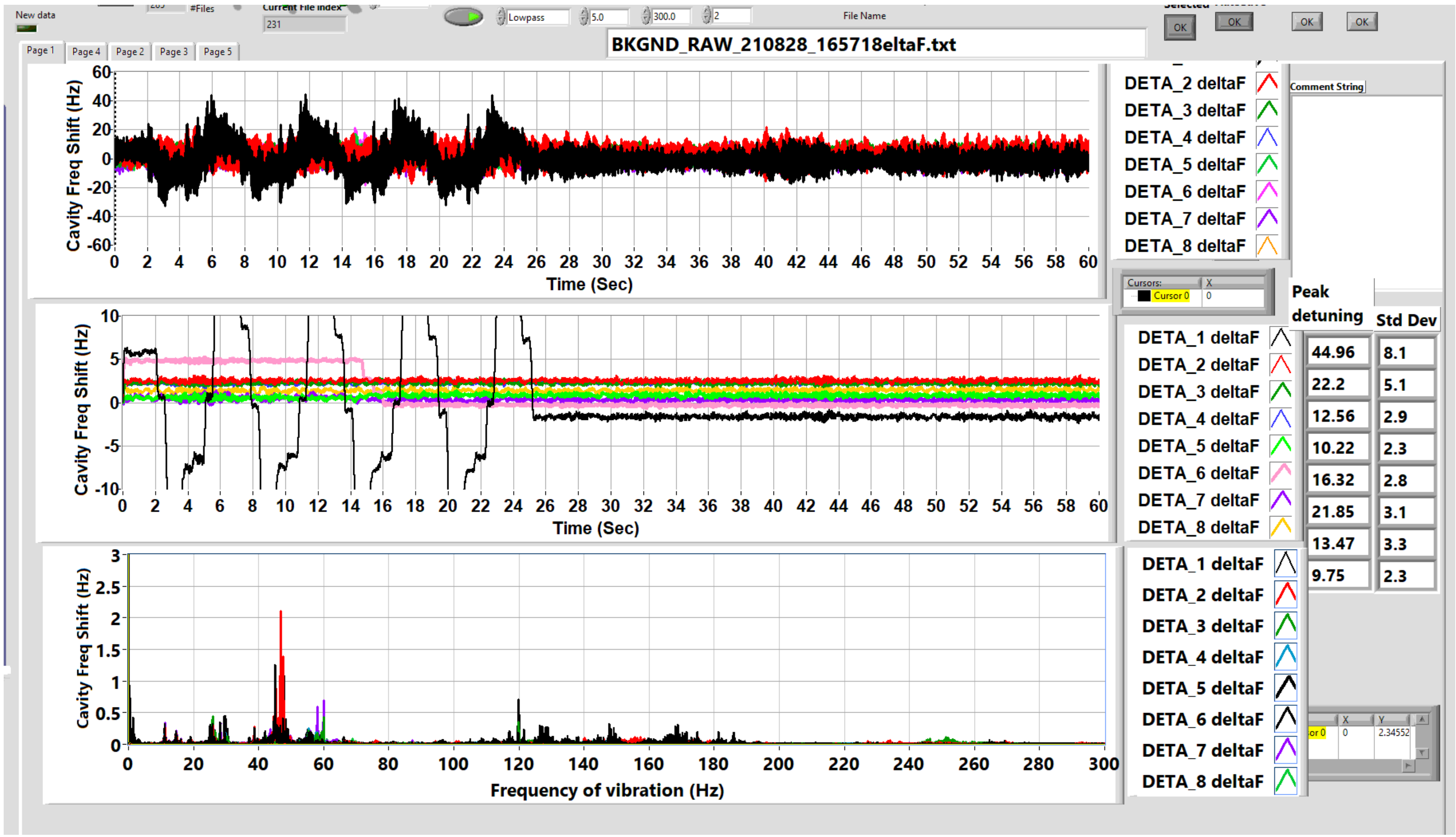
Transient with no tuner operation.

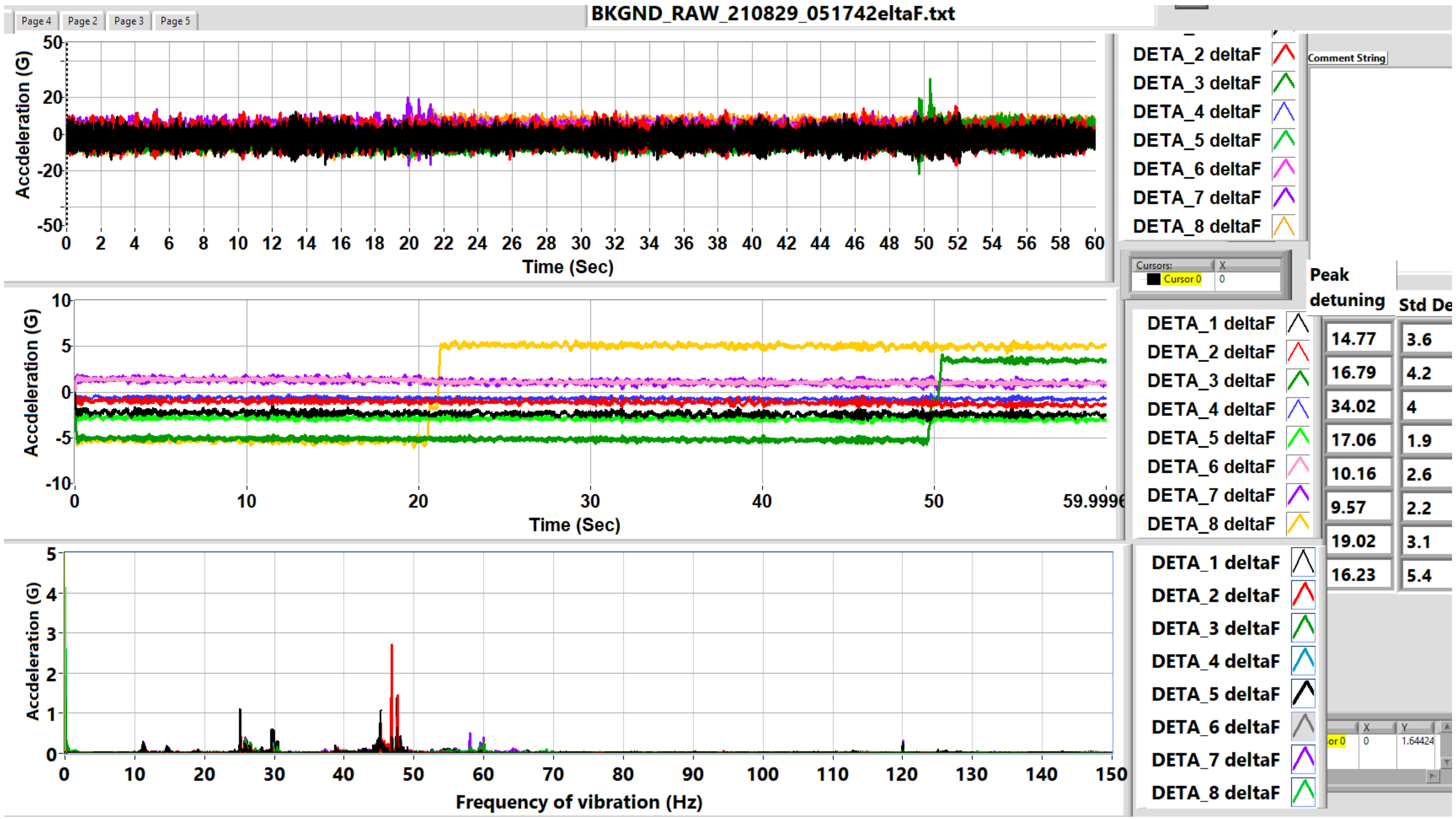


- 5% to10% of the events with excursions above 25 Hz were this type.
- Unknown source but the oscillation was at about 14 Hz.
- Also cavity 1, 3, 5 and 7 go up and down in frequency while cavities 2, 4, 6 and 8 go down and up in frequency.
- This was also observed in the 11 Mode.

Some times the tuning algorithm oscillated.

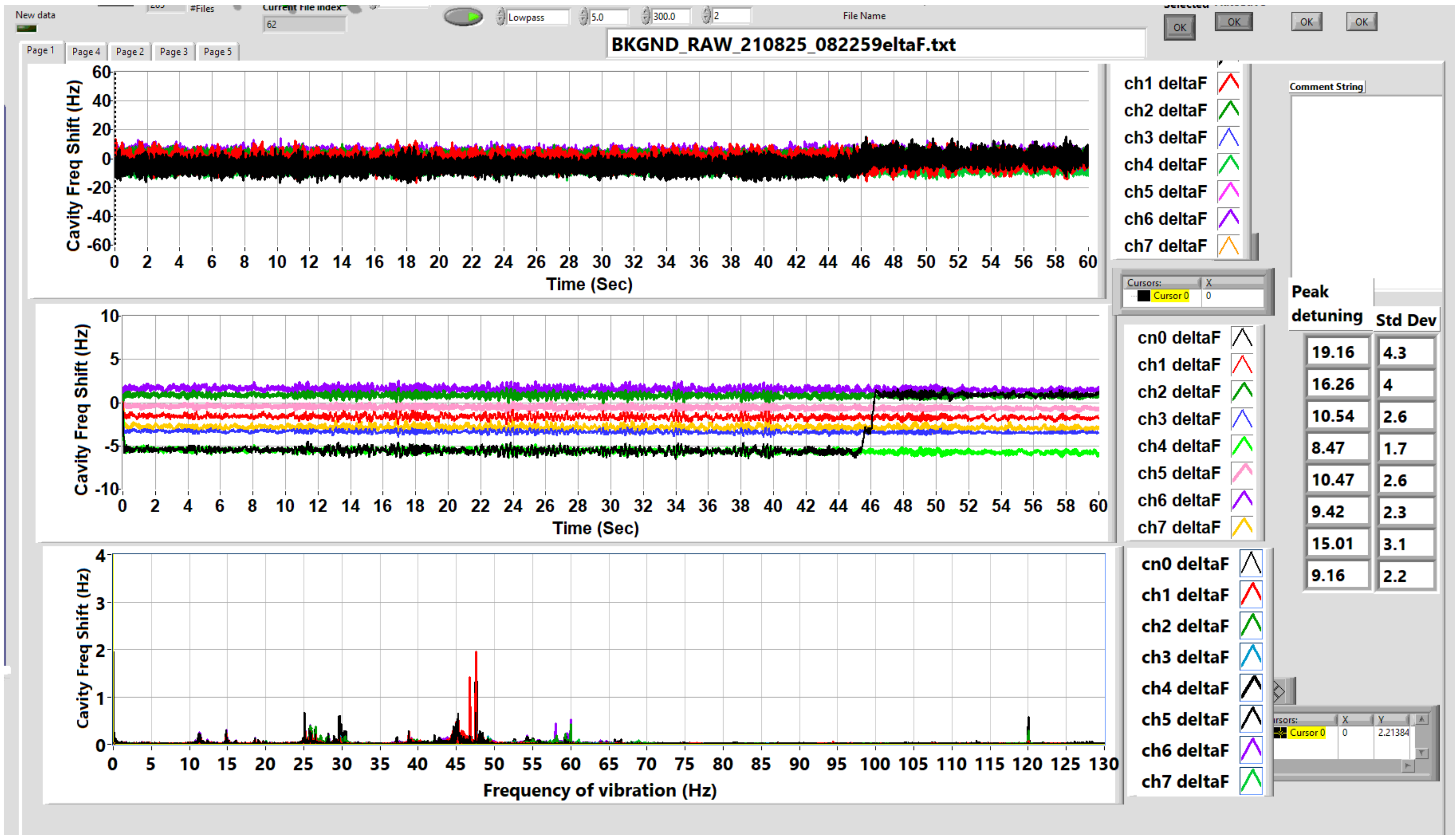


Often times tuner operation caused minimal frequency excursions.

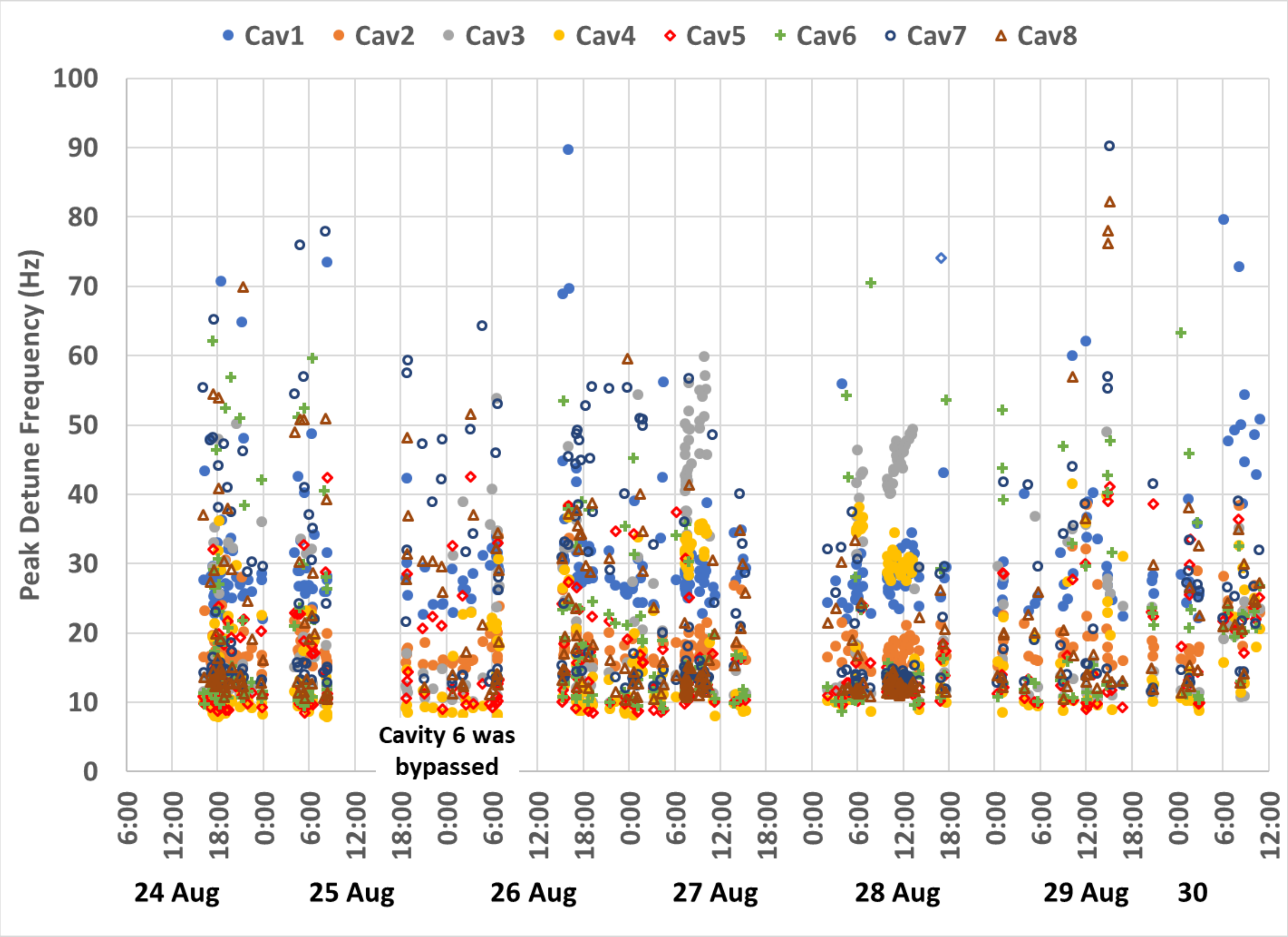


- In both of these tuner operations the microphonics stayed within the +/- 35 Hz band.

Sometimes they caused no measurable increase in microphonics.



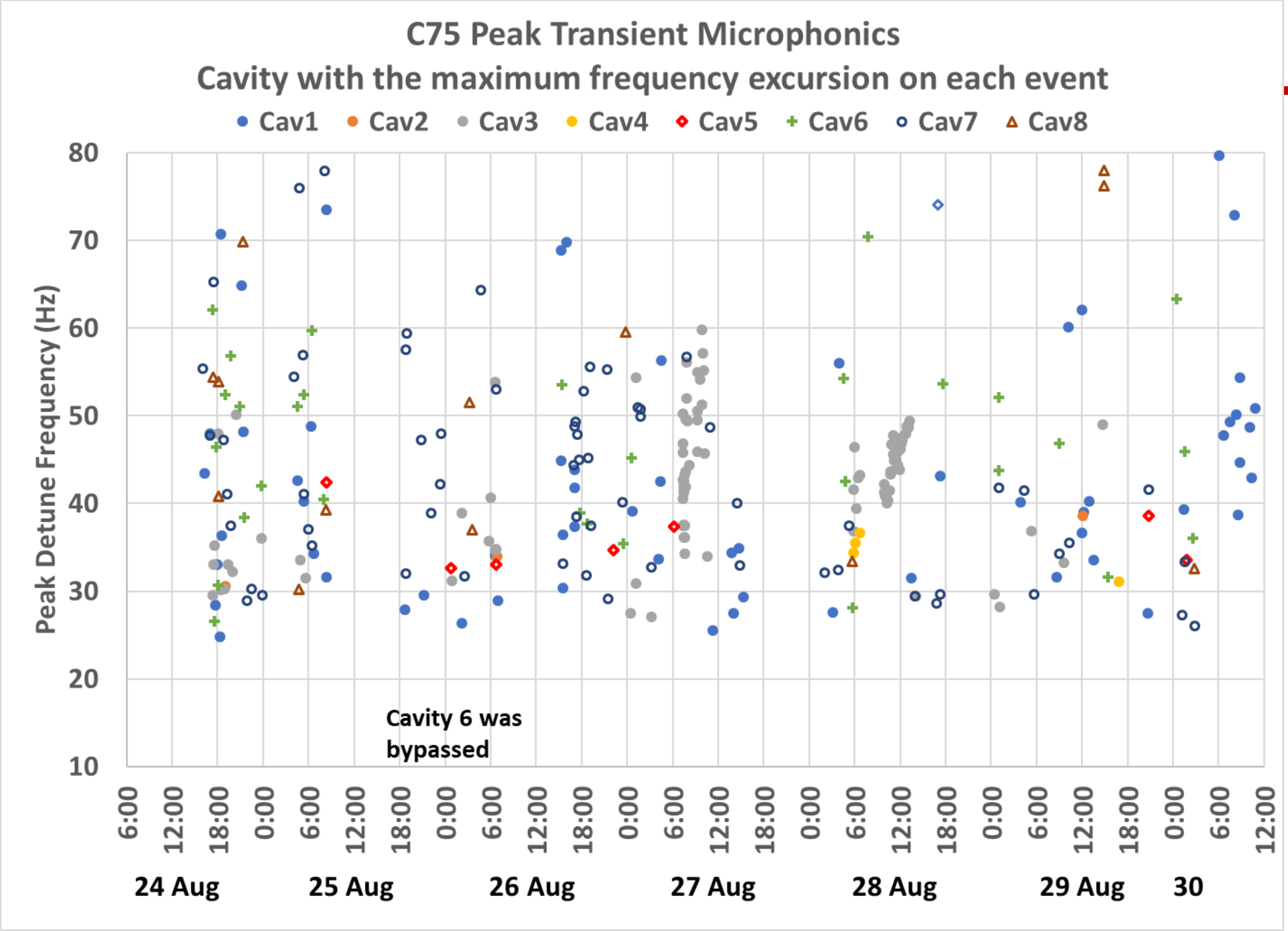
Peak microphonics for each event that was analyzed, N = 283



- **In this case we took the peak microphonics for each of the events.**
- **The data represents the peak microphonics for each of the cavities in 1L05 when a transient was recorded and analyzed.**
- **Thus the cavities with peak microphonics below 20 Hz were not affected by the tuner.**

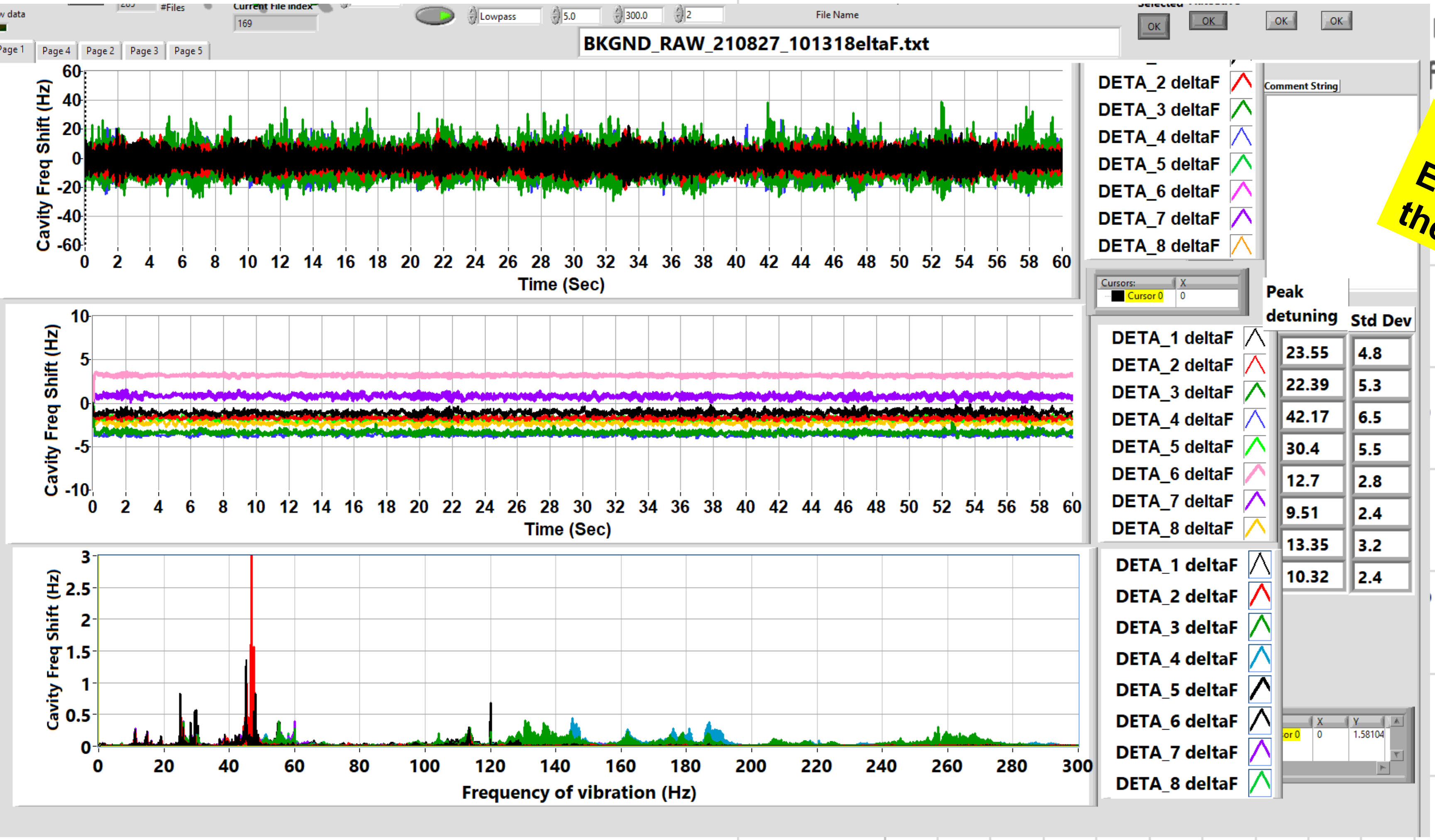
With Beam Loading and at design gradient.

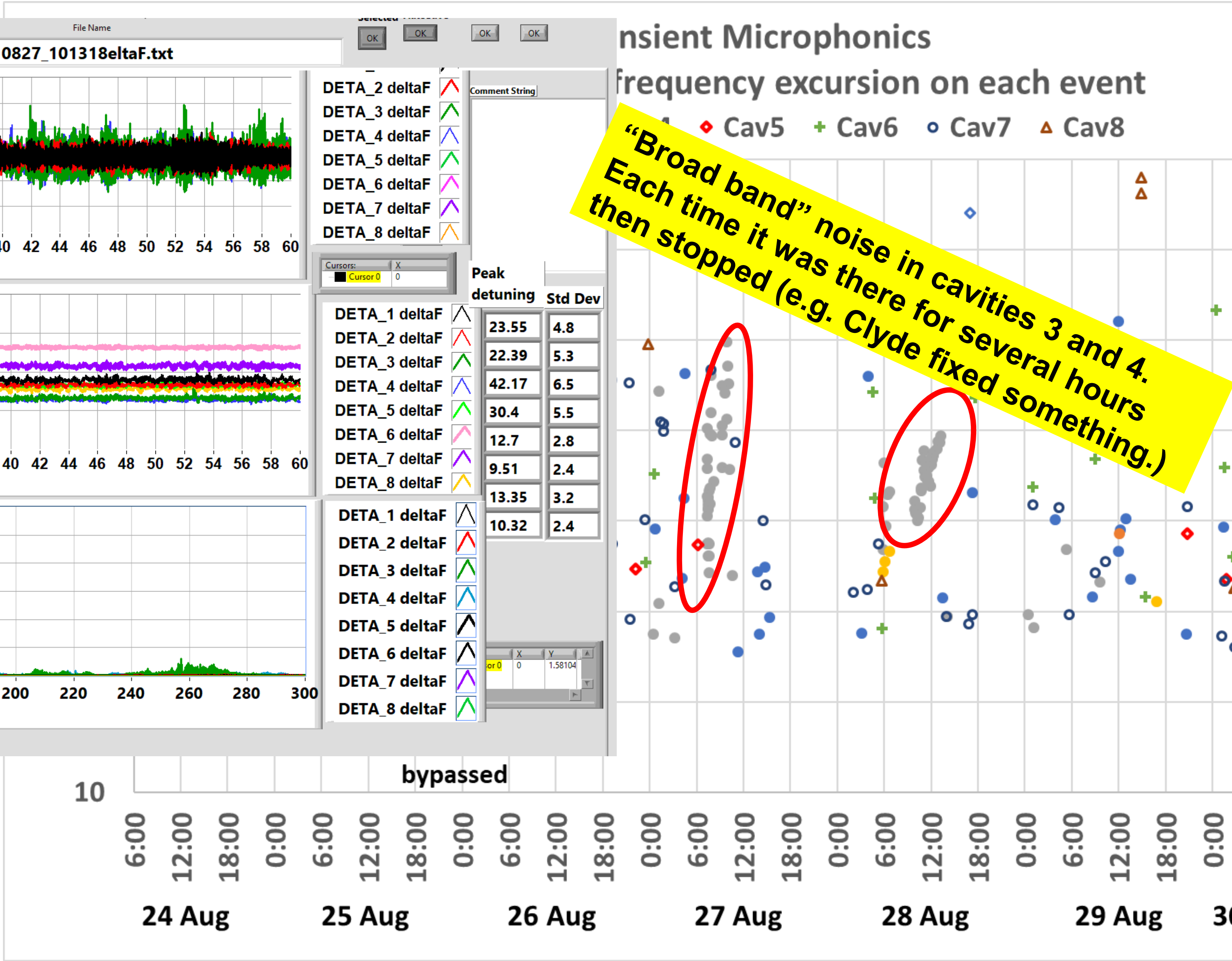
- **Microphonics excursions above 40 Hz cause concerns for trips.**
- **Above 50 Hz will most likely trip.**



- **I have been doing all of my calculations based on 35 Hz of detuning.**
- **The design gradient 18.75 MV/m**
- **Much above 40 Hz would start to get iffy.**
- **Above 50 Hz I would start to expect trips.**
- **We only have two cavities that are near their spec operating gradient.**

Cavity	DRVH	Current
1	13	11
2	11.1	10.5
3	17.8	15
4	20.5	18
5	15.4	14
6	17.5	16
7	18.9	16
8	19.4	18
MeV	66.8	59.25





With sufficient beam loading such noise would make the cavities trip all of the time, where trip means interrupt beam operations.

Effects of microphonics on operational limits with beam

The forward power required to operate a cavity is given by:

$$P_{fwd} = \frac{L}{4Q_L(r/Q)}\frac{\beta}{\beta+1}\left\{\left(E + I_0Q_L(r/Q)\cos(\varphi_{Beam})\right)^2 + \left(E\left(2Q_L\frac{\delta f}{f_0}\right) + I_0Q_L(r/Q)\sin(\varphi_{Beam})\right)^2\right\}$$

For CEBAF cavities $\beta \gg 1$. Thus $\beta/(\beta+1) \cong 1$. Using this and assuming on crest beam reduces the above equation to:

$$P_{fwd} = \frac{L}{4Q_L(r/Q)}\left\{\left(E + I_0Q_L(r/Q)\right)^2 + \left(E\left(2Q_L\frac{\delta f}{f_0}\right)\right)^2\right\}$$

- Nominally δf is the detune frequency due to microphonics. This is what is generally used when determining the loaded-Q that provides for an optimally designed high power RF system.
- There are at least three other parameters in a practical system that introduce "frequency shifts", these are
  - The ability to properly determine the cavity detune offset, TDOFF in CEBAF speak.
  - Any dead band in the tuner algorithm, where dead band is the amount of detuning before the tuner starts to operate.
  - Thermal drifts in the phase "lengths" of the system between the klystron drive output and the probe inputs on the field control chassis (FCC) which contributes to the TDOFF error. (I ignored this one)
- The sum of the detune error, the tuner dead band and the peak microphonics are known as the detune allowance.

The math to account for frequency shifts measured as a phase shift.

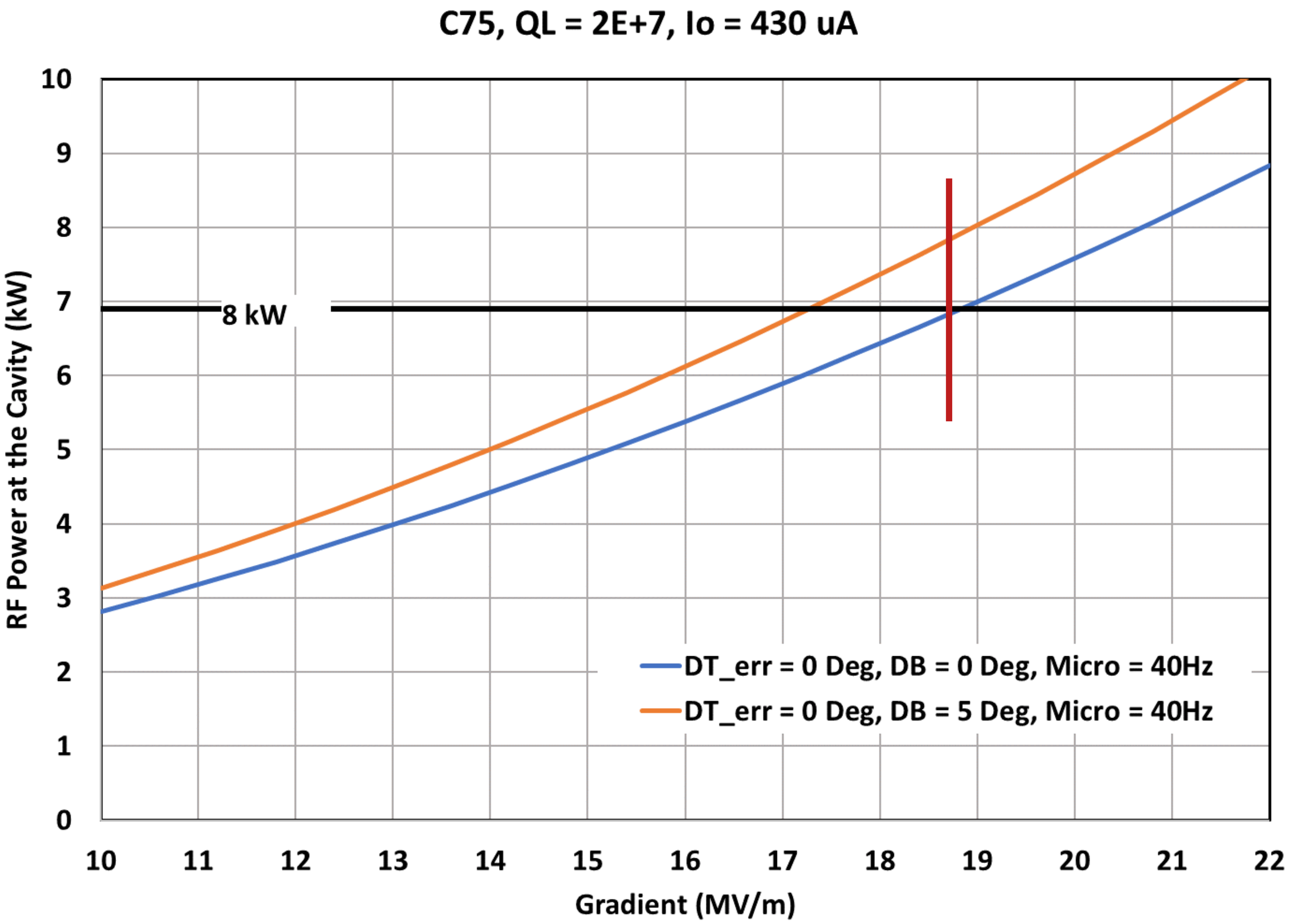
- Unfortunately the detune offset error and the dead band are typically given in degrees of phase while microphonics is given in Hertz.
- After a moderate amount of math for a strongly over-coupled cavity with on crest beam one can determine equation for the forward power is:

$$P_{fwd} = \frac{L}{4Q_L(r/Q)}\left\{\left(E + I_0 Q_L(r/Q)\right)^2\left[1 + Tan^2\left[\varphi_{DB} + ArcTan\left(\frac{2Q_L(\delta f_M + \delta f_{DT})}{f_0}\frac{E}{\left(E + I_0 Q_L(r/Q)\right)}\right)\right]\right]\right\}$$

$$(\delta f_M + \delta f_{DT}) = \frac{f_0}{2Q_L} Tan\left[\varphi_{DT} + ArcTan\left(\left(\frac{2Q_L}{f_0}\delta f_M\right)\right)\right]$$

- Where φ_{DB} is the dead band phase, δf_{DB} is the allowed deadband, δf_{DT} and φ_{DT} are both ways to describe the error in the cavity tune, and δf_M is the frequency excursions due to microphonics which are not compensated for using the mechanical tuner.
- Note φ_{DB} is measured when the cavity is beam loaded and φ_{DT} is determined when no beam is present.
- The dead band for C20 and C50 cavities has historically be set to 10° this was done to avoid tuner wear and because of the dead band and hysteresis in the tuners from the original C20 designs. Also there was a concern with respect to accelerated rotary feedthrough wear.
- There were improvements in the tuner system when they did the C50 program. But the dead band remained 10° in the old RF control modules (RFCMs).
  - Initially this value is what is in the C75 cryomodule. We are currently using something like 6°

What people designed to (maybe)



Assumes

- **8 kW klystron**
- **0.4 dB waveguide losses**
- **5% control margin (this should be 10%)**

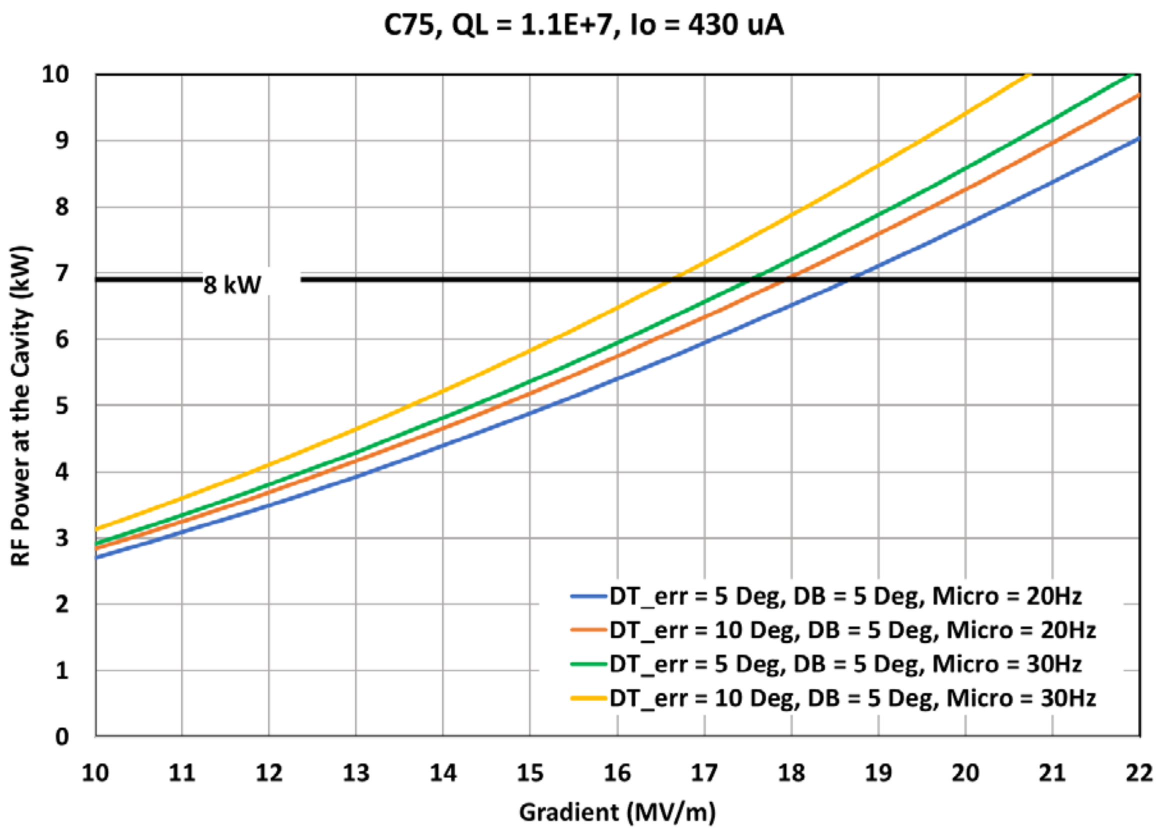
This means that you have 6.9 kW available at the cavity.

The blue curve is more like what people designed to if they were using 40 Hz of microphonics.

It is not clear if they also were assuming 8 kW at the cavity and no control margin.

The orange curve includes a 5° dead band which I doubt was included in the original specification.

Power requirements without tuner driven transients, but with detune errors and dead band allowances.



These plots are more like where the machine is if you exclude transient microphonics.

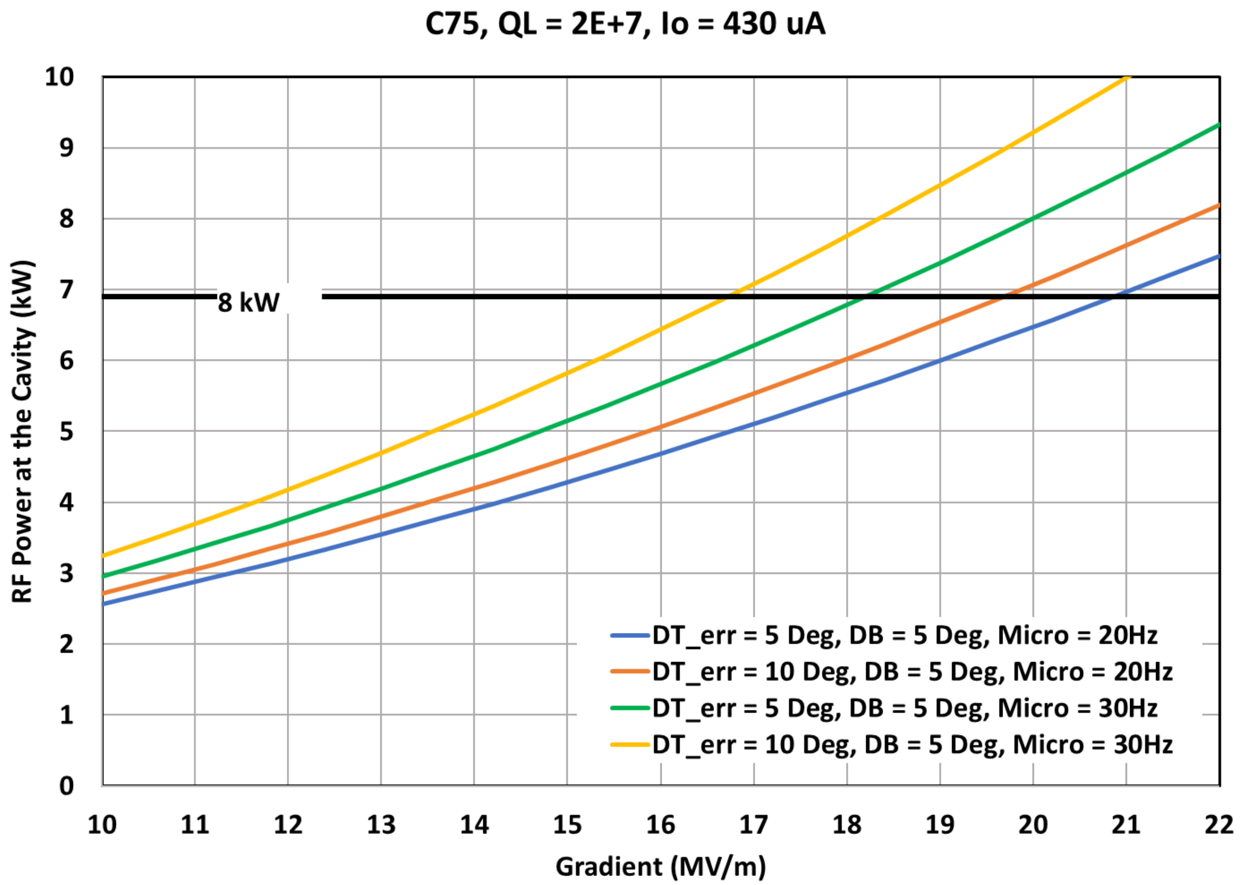
Note currently varies on a cavity by cavity basis and is 1.1e7 < Q_L < 2.1

We could probably make 70 MV/m with this.

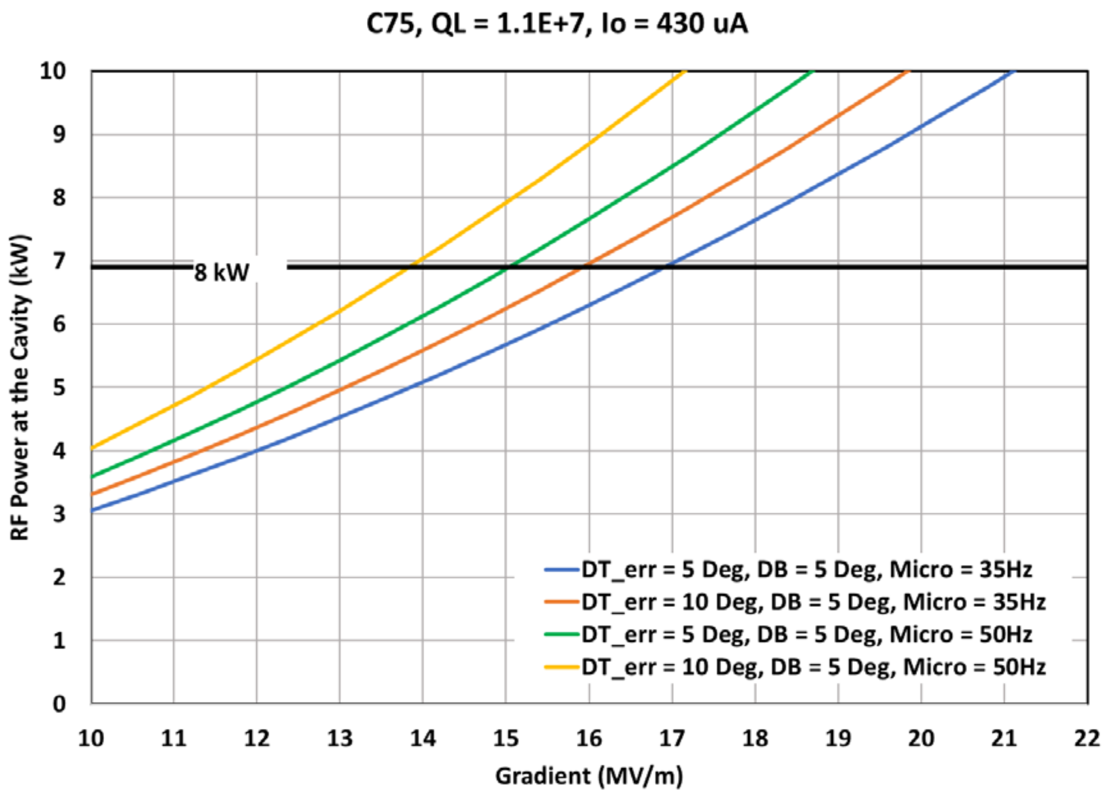
Assumes

- **8 kW klystron**
- **0.4 dB waveguide losses**
- **5% control margin (this should be 10%)**

This means that you have 6.9 kW available at the cavity.



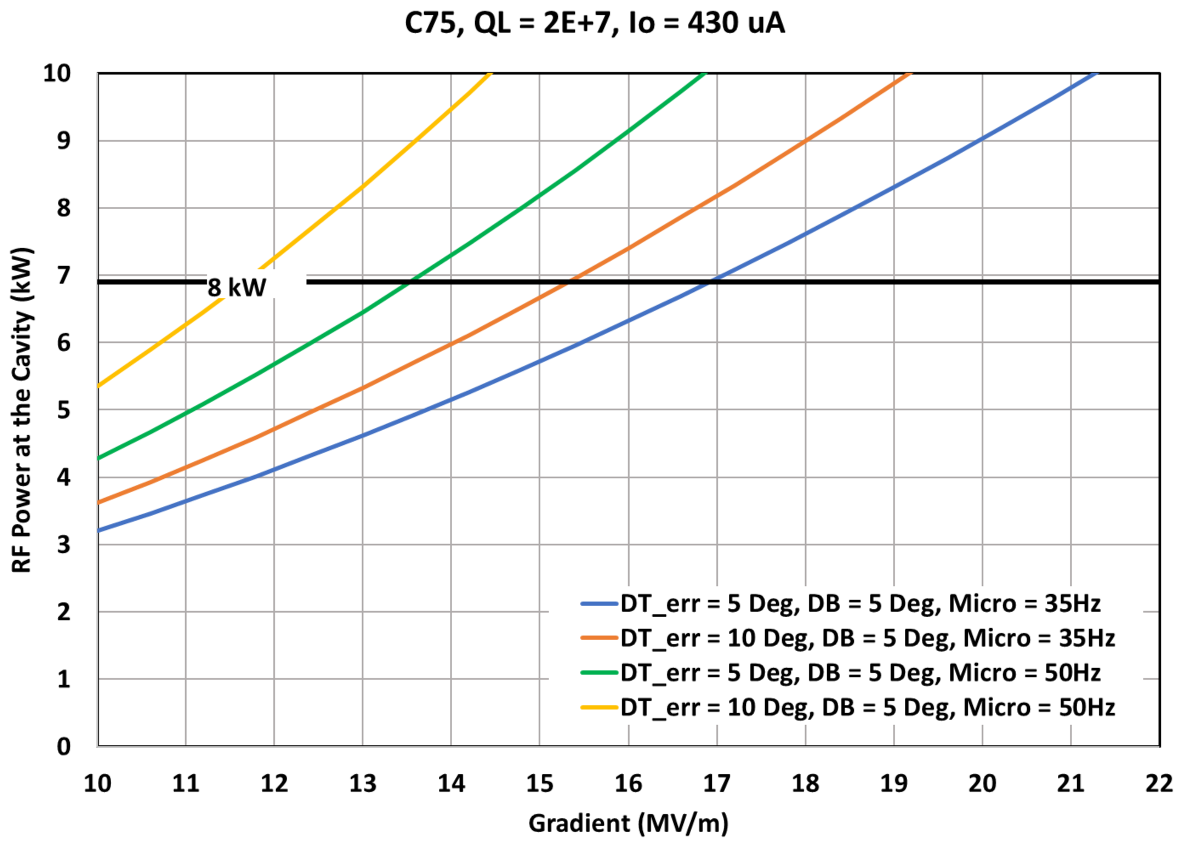
Operationally with tuner driven transients, with detune error and dead band allowances.



Assumes

- **8 kW klystron**
- **0.4 dB waveguide losses**
- **5% control margin (this should be 10%)**

This means that you have 6.9 kW available at the cavity.



These plots are more like where the machine is today if you include transient microphonics.

One would expect a lot of trips due to microphonics if we can not get a handle on the tuner driven excursions.

Comments

Faults

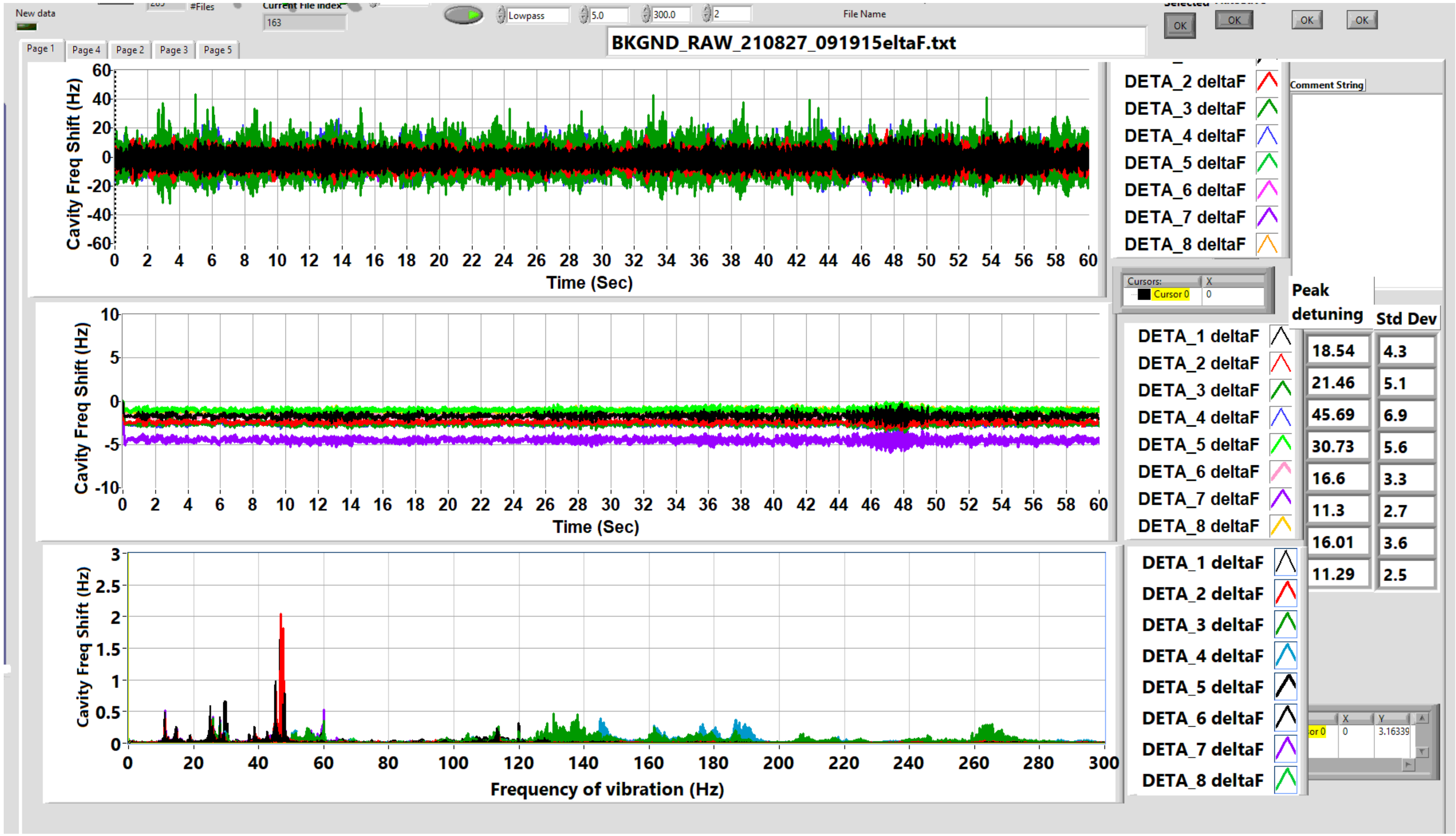
- The C100 cavities are running fairly well with no real pathological problems; there were some at the beginning.
- Cavities are regularly getting driven up to quench fields by a lost control loop.
- Once in a while a cavity will quench in SEL mode and the system does not notice.
- Once in a great while a cavity will require more than 45 seconds to recover from a quench, especially cavities 1 and 8
- Thermally cycling 2L26 lead to a reduction in electronic quenches.
- It would be great to get zone 1L05 harvesting waveforms so that we can better understand operational limits.

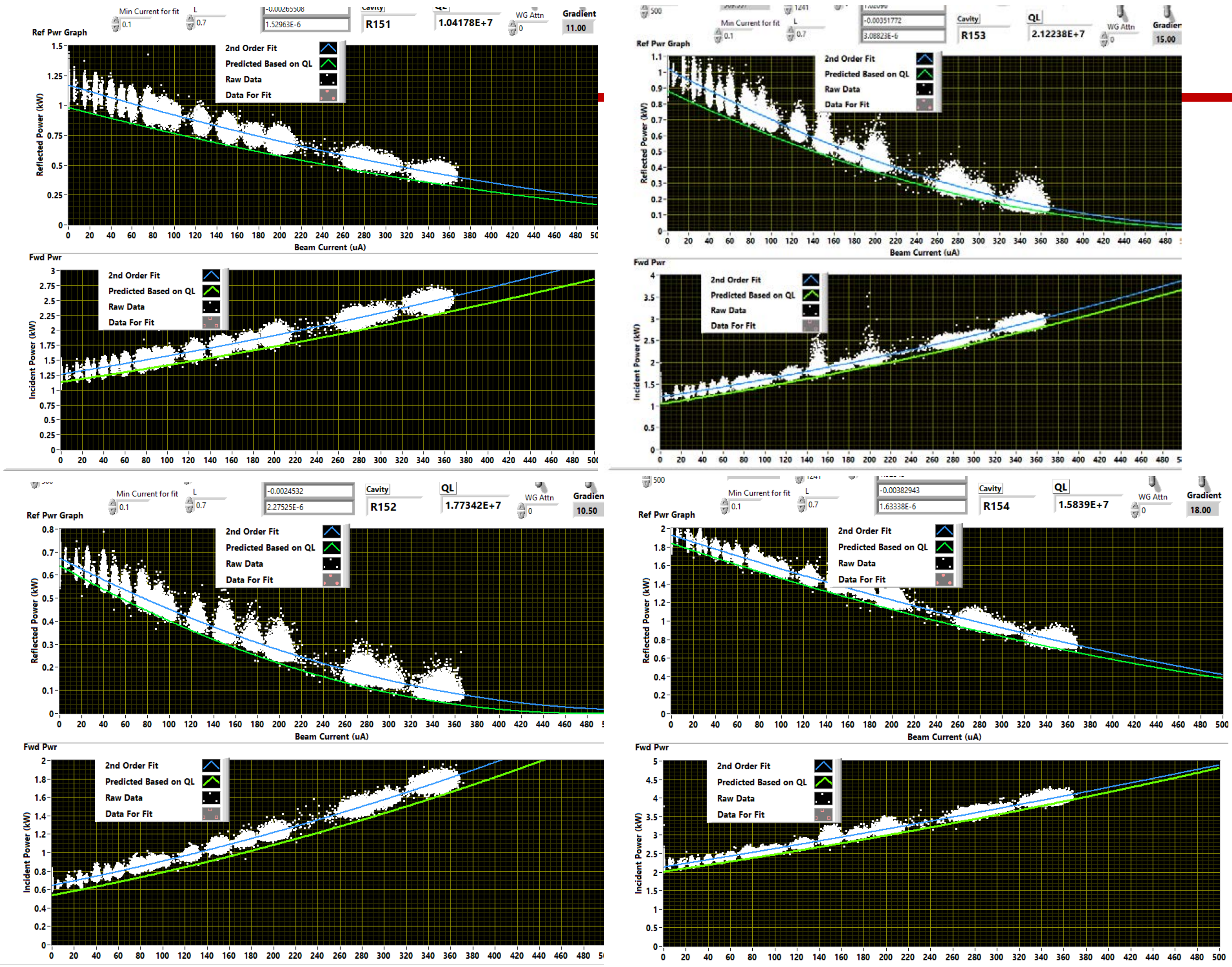
C75

- We are not operating the C75 cryomodule at the drive high limits and it is costing us about 7 MeV.
- The transients produced by the tuners are inconsistent but often could lead to trips if the cavity was beam loaded.
- A fraction of the transients are due to.
  - The tuners overshooting the “zero” value
  - The tuners sometimes starting in the wrong direction (I think this might be mechanical).
- Sometimes a tuner produces lots of microphonics other times it does not. Why?

Backup Slides

Example of cavities 3 and 4 with excessive noise.





Steady state conditions

- **Fits were done but gradient is on based on RF measurements not beam based measurements.**

Inconsistent Results.