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CEBAF C100 FAULT CLASSIFICATION BASED ON TIME DOMAIN RF SIGNALS *

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Abstract

The CEBAF 12 GeV upgrade project, which was completed and commissioned in 2014, included the construction and installation of 80 7-cell superconducting cavities that were configured in 10 cryomodules. In 2018, the software and hardware in the digital low-level RF systems was configured such that a fault would trigger an acquisition process to record 17 RF waveform signals for each of the 8 cavities within the cryomodule for subsequent analysis. This contribution will describe the types of faults encountered during operation and their signatures in the time domain data, as well as how it is being used to modify the setup of the machine and implement improvements to the cryomodules.

WAVEFORM HARVESTER TOOL

The C100 cryomodules were built without bellows between the individual cavities. This was done as the cryomodules were an upgrade design for an existing machine and there was a fixed slot length. Not having the bellows improves the packing factor of the cryomodules. Unfortunately, it also meant that the cavities are mechanically coupled such that changing the length of one cavity changes the length of an adjacent cavity by 10% of that value. It also means that the cavity to cavity mechanical coupling is stronger than in most cryomodules. Thus when one cavity is turned off or the gradient is reduced, the changes in length due to Lorentz force leads to changes in the length of adjacent cavities. These effects were exacerbated by the mechanical resonances of the structure. Thus when one cavity trips off, the other 7 cavities are effected and several are likely to trip due to vibrational induced detuning. This led to an operational problem the first several years of operating the C100 cavities, namely, “Which cavity tripped first?” The waveform harvester tool was developed in order to address this problem.

An Altera field programmable gate array (FPGA) is the signal processing engine within the JLab 12 GeV RF field control chassis (FCC) [1]. The initial software configuration of the FCC allowed one to view waveform records of the various signals that are present within the FPGA. The waveform harvester tool is the name given to the software/hardware tools that allows the system to capture these time domain signals after a fault and write them to file for later analysis. Each of the 17 harvested waveform signals is 8192 points long. The EPICS interface allows one to vary the sample time between 18 ns and 1.18 ms. The trigger was set up such that about 90% of the recorded data was before the fault and 10% was after the fault. For the standard sample rates of 200 µs or 50 µs per sample, this provided approximately 1500 ms or 400 ms of data before the fault, respectively. This provides insight into the events leading up to the fault, which often times allows one to determine the root cause of the fault.

The initial configuration of the harvester software was such that individual cavities were triggered separately and the relative time between the waveform records of individual cavities was only known to a few tenths of a second. Modifications were made to the triggering software and a chassis to chassis TTL logic timing chain was implemented so that the first cavity that faults triggers the firmware in all of the FCCs in a given cryomodule to record the waveform records synchronously with an accuracy of one data clock. The initial run with synchronous triggering was a three week period in the spring of 2018. In the fall 2018 and winter run of 2019, each about 3 months long, the harvester was run more-or-less continuously, and the data was analyzed by operations staff on a daily basis. Additionally the data was analyzed off-line every few days. Approximately 90,000 waveform records have been recorded. Not all of these events were true faults as many were recorded when the system was recovering from a previous fault. In all about 3,000 faults have been reviewed and classified according to type and root cause.

FAULT TYPES

Initial analysis of the fault records was done by looking at the waveforms as well as reviewing, machine fault logger data, and the slow data which was recorded using the CEBAF archive system. The archive system is a data logging system that records the values of about 350,000 EPICS signals at speeds up to about 10 Hz [2]. Currently harvested data is analyzed by visually inspecting the waveforms. To date automated recognition of only one event type has been implemented. There is ongoing effort to fully automate this process using machine learning algorithms [3].

Microphonics Faults

Microphonics is a term used to describe time domain changes in the frequency of an SRF cavity, generally when the cavity has been perturbed externally. For cavities that have a large loaded-Q, changes in length of a few tens of nanometers is enough to cause frequency shifts sufficient to cause problems. Typically, cavities will vibrate at the modal resonance frequencies of the mechanical structure. For the C100 cryomodules the modes are a 9.5 to 10.5 Hz pendulum mode, a 20 to 21 Hz half string bending mode, a 40 to 45 Hz individual cavity mode and an 80 to 90 Hz tuner stack mode. The cavity vibrations can also be excited

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by external vibrations such as 120 Hz from a vacuum pump which may be attached to the insulating vacuum vessel. Exciting the structure at any of the modal resonances amplifies the excitation and may cause the cavity to trip.

The RF signal that indicates detuning is the relative phase between the forward, power and the cavity gradient signal. In the CEBAF controls this signal is labeled DETA2. Figure 1 depicts the waveforms for a microphonics-induced trip. As indicated by the DETA2 signal, the structure was vibrating in the 10 Hz full string mode. As the mode built up, the RF drive and forward power signals increased to compensate for the perturbation. Eventually the control loop drive voltage signal for cavity 4 got to its maximum value of 10 and the drive phase got lost. In this instance the phase was such that it drove the cavity gradient down faster than the natural decay time of the system. Once cavity 4 tripped off, the remainder of the cavities were switched into self-excited loop (SEL) mode which is a frequency tracking mode of operation. This switch to SEL mode is a standard protocol with the C100 cavities that is used to speed up recovery from a trip.

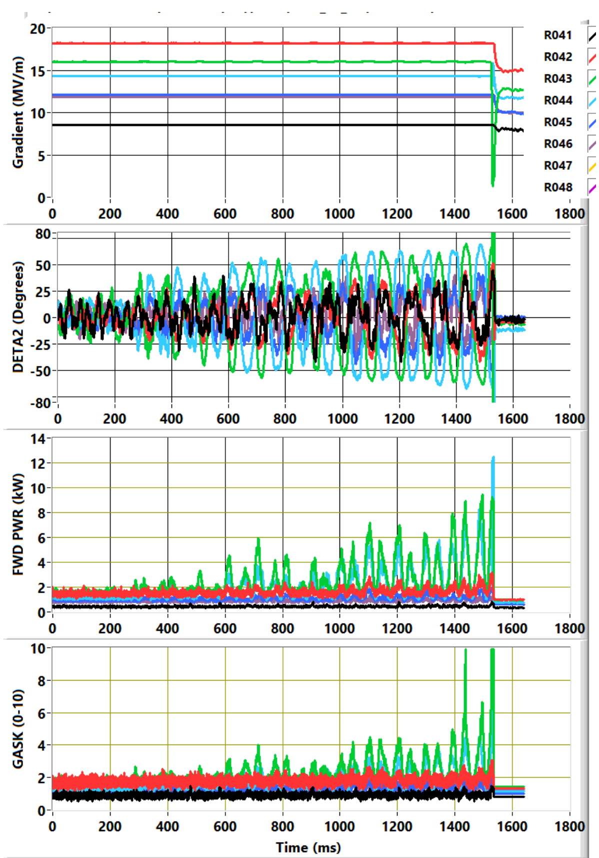

Figure 1: Waveforms for a microphonics-induced fault. The cavity detune is indicated by the detune phase. From top to bottom, the plots display the measured gradient in MV/m, detune phase angle, forward power and a digital signal proportional to the drive voltage.

Fast "Electronic" Quench

Electronic quench is a term that was applied to a type of event during which the stored energy in a cavity decays at a rate much faster than is possible through a normal resistive quench. Typical gradient decay times are less than 10 µs and have been seen to be as short as 100 ns. They are accompanied by a short intense burst of radiation, and if the event occurs on a cavity at the end of a cryomodule, a burst of gas is observed on the beamline ion pump signal. Electronic quenches were observed and reported in the early 1990s [4, 5]. When they were originally observed they were associated with window arcing events. The assumption is that a burst of gas gets into the high field region of the cavity, a large number electrons are stripped off of the gas atoms, are accelerated by the electric field and extract stored energy from the cavity.

Figure 2 displays waveforms from a cryomodule where cavity 8 experienced an electronic quench. Figure 3 is a plot of the vacuum signals for the girder between cavity 1L25-8 and 1L26-1. This vacuum outburst occurred at the same time as the event in Fig. 3. The source of the gas and ignition mechanism are not well understood. It could be from a discharge in the warm to cold transition in the waveguide, but it also could be from the warm to cold beam line transition. During the Fall of 2018 run, more than 93% of the events of this type occurred in end cavities (one or eight) while the remainder were evenly divided among the other six cavity positions. This would tend to point to gas freezing out on the warm to cold transition in the beamline. Extensive leak checking was done on the beam lines where there were problematic cavities without finding any leaks. This would lead one to the hypothesis that the deposited gas was desorbed from the surface due to exposure to strong field emission radiation that is preferentially pumped to the cold surfaces.

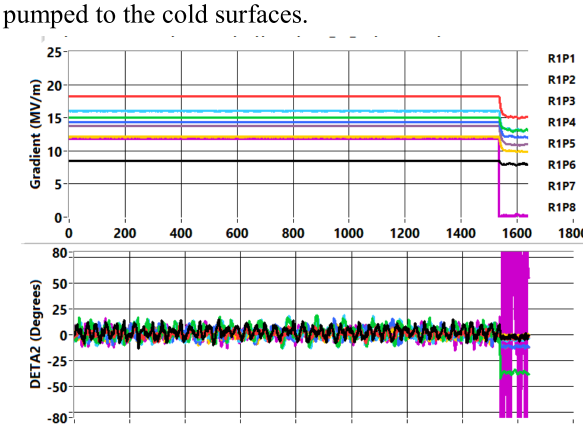

Figure 2: Waveforms for the gradient and detune phase angle when cavity 8 experienced an electronic Quench. The forward power was turned off for cavity 8 and the remainder of the cavities were put into SEL mode immediately after the event.

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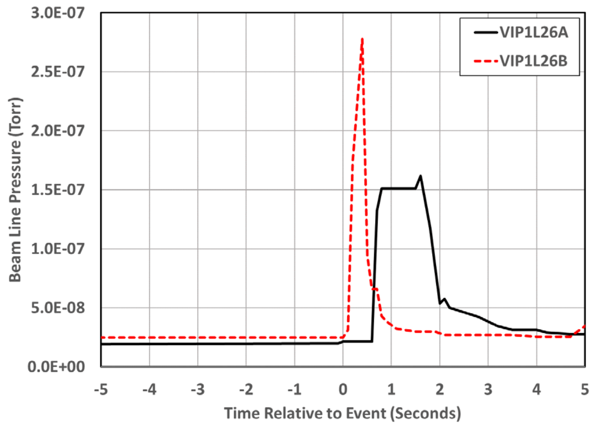

Figure 3: Beam line pressure as measured with ion pumps that are located on the warm beamline on the cavity 8 end of the example cryomodule, 1L25. The ion pump VIP1L26A is on the warm girder about 0.5 m from the cavity 1L25-8, VIP1L26B is about 0.2 m upstream from the cold surface of the cavity 1L26-1 and is about 2 m away from cavity 1L25-8.

End Group Quench

Like many SRF cavity designs, only the cells of these cavities are immersed in liquid helium. The end groups which include the beam pipes, HOM couplers, and wave guide couplers, are conduction cooled. Thus RF heating of these structures can cause the temperature to slowly increase to the point where the end group goes normal conducting. When this happens, the heat spreads into the cells and the cavity quenches. When the quench is initiated by the end group going normal conducting, the propagation for the quench is on the order of 100 ms [6]. During a quench that is initiated in the high field regions of the cells of a cavity, the propagation time is on the order of a few milliseconds. An end group quench fault presents itself as the detune angle of the faulted cavity changing over a few hundred milliseconds, while the remainder of the cavities remain stable. This indicates a frequency shift in the cavity. The waveforms for this type of fault are shown in Fig. 4. Using the detune phase angle, resonant frequency and loaded-Q of the cavity one can calculate the frequency shift during this process. In this instance, the cavity had a frequency shift of about 90 Hz before it faulted with a detune fault.

Heat Riser Choke Fault

The maximum heat flux, q (W/cm^2), through a pipe filled with superfluid helium system is limited by the temperature differential across the pipe and in general scales as the length raised to the 1/m power where m is between 3 and 3.4. It is also a strong function of temperature. This dependence is shown in Fig. 5. When the hot end of the pipe reaches 2.18 K, the pressure in the in liquid that surrounds the cavity goes unstable. This causes the cavity frequency to shift a sufficient amount to cause a trip. The maximum heat capacity, as measured using resistive heaters, of an individual C100 cryomodule heat

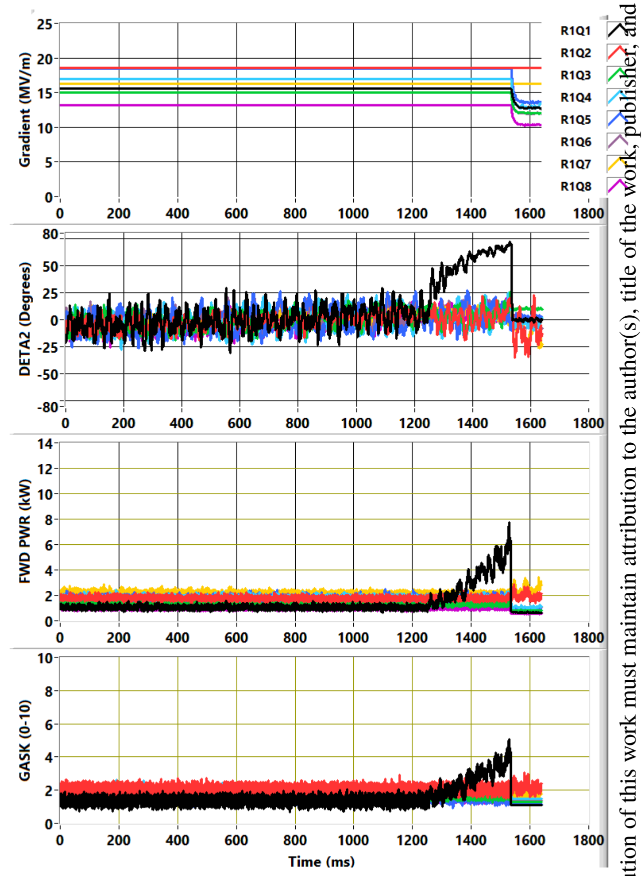

Figure 4: Waveforms for an end group quench fault.

riser pipe at the nominal machine operating temperature is about 40 W. In a C100 cryomodule the design heat load is 30 W per cavity. Excess heat due to field emission, etc. contributes to increasing this heat load. Two cryogenic diagnostics used to detect a heat riser choke are a slight transient in the helium gas pressure in the two phase pipe and an oscillation of a few percent in the indicated liquid level. Figure 6 shows the waveforms for a heat riser choke event. During this event cavities 5 through 8 suddenly went unstable in what appeared to be a microphonic driven instability. It differed from a microphonics instability in that they suddenly turned on rather than growing in time like the DETA2 signal in Fig. 1. Also, only half of the

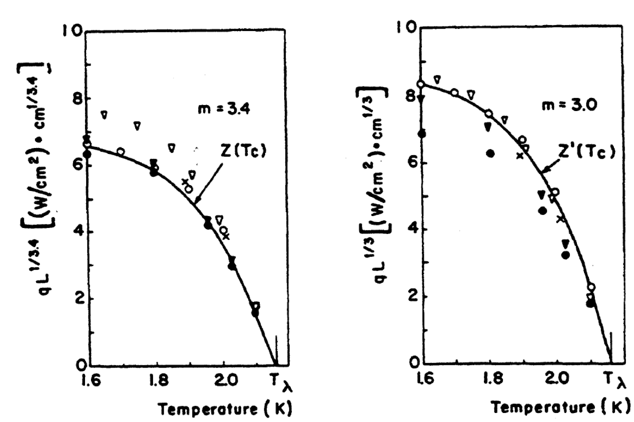

Figure 5: Generalized steady-state limiting heat flux in super fluid helium. [7].

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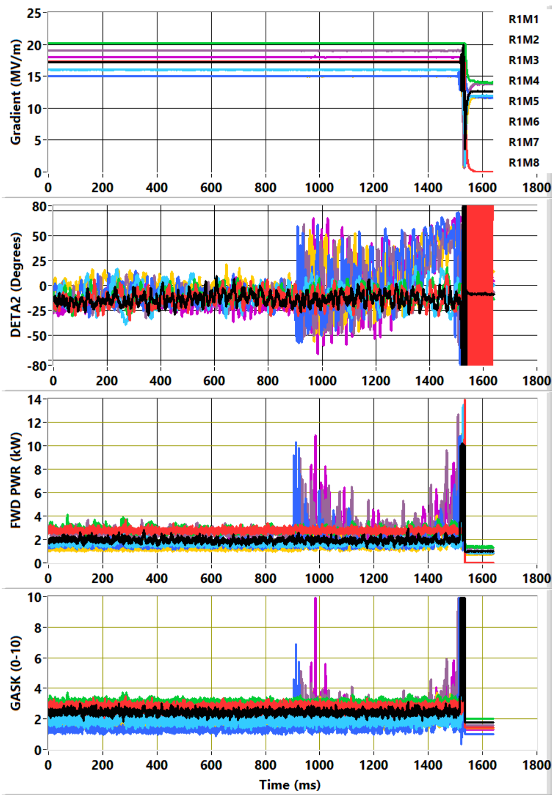

Figure 6: Waveforms for a heat riser choke event.

cavities participated in the detune event and the DC portion of the detune frequency of four cavities walked off in the same direction. All of these features are consistent with a sudden change in the pressure in the helium vessel.

RF Controls Induced Fault

The waveform records are also useful for identifying problems in the controls which can be addressed without reducing the cavity gradient. Figure 7 shows an oscillation in the control loop, probably due to an error in the control loop phase setting. The oscillation in the drive signal is a few kilohertz and appears to be shaking other cavities in the cryomodule slightly. Figure 8 shows an event that is thought to be a grounding problem which occurs on one of the CEBAF linacs during thunderstorms. The problem presents itself as a transients in the phase and power that are very short in duration. All of the C100 RF systems in the south linac had precisely the same perturbations at the same time, leading the RF engineers to suspect noise in a common component such as the master oscillator system. This example shows the value of this data, as otherwise one would not be able to tell if the faults were due to microphonics induced by the thunder rather than electrical interference.

RF Transient Induced Quench Event

One type of event that was puzzling the JLab staff for several years were C100 cavities operating well for months that suddenly would quench at much lower fields than expected. Such an event is shown in Fig. 9. The drive signal

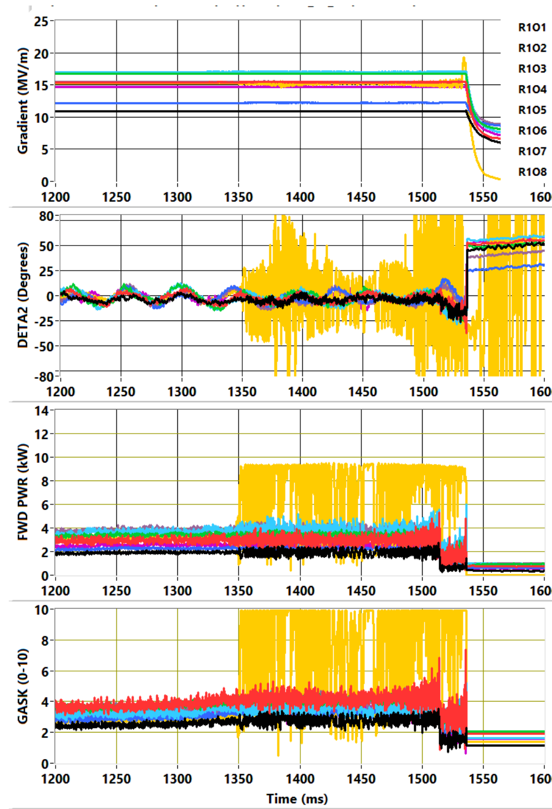

Figure 7: Waveforms indicating a control loop oscillation.

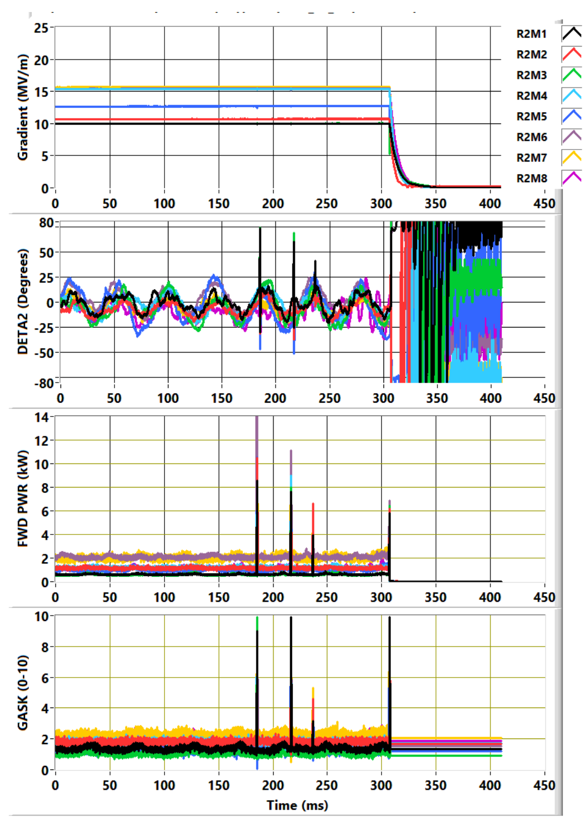

Figure 8: Waveforms that indicate a transient in the RF controls system.

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(GASK) on cavity 4 (blue traces) saturated when something drove it and cavity 3 (green traces) off tune. When the drive signal for cavity 4 reached 10 the control system was saturated and loss phase control. For cavity 4 the RF power and phase were such that it drove the gradient down. The resulting mechanical vibrations which were induced by Lorentz forces caused the other cavities in the zone to detune. At 308 ms the drive for cavity 2 (red traces) also saturated at 10. In the cavity 2 case, the phase was such that it drove the cavity up in gradient to about 22.5 MV/m. Shortly thereafter the quench detection algorithm turned the cavity off with an indicated gradient of 19 MV/m. The day after this event was recorded and analyzed an operator confirmed that the prompt quench field for cavity 2 was 22.5 MV/m. In other similar events the cavity did not switch off and the controls put it into SEL mode, it continued to quench and we got a SEL-quench fault.

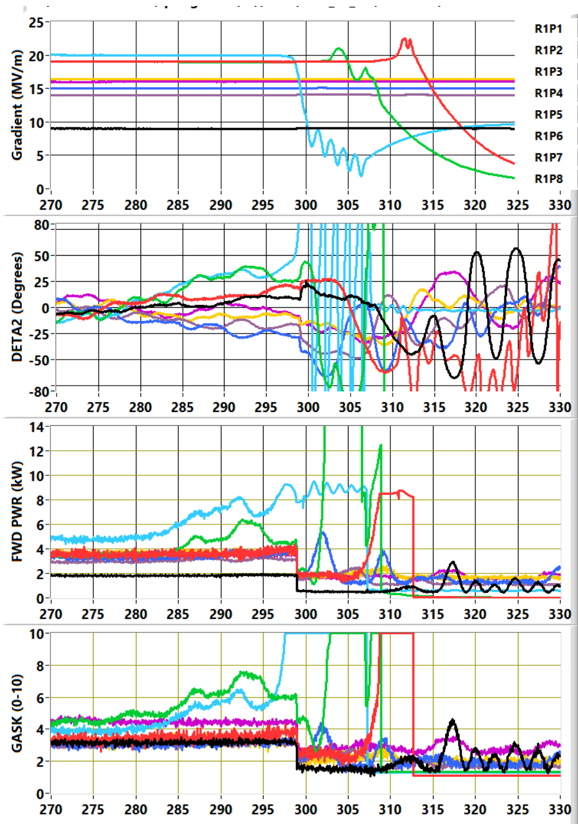

Figure 9: Waveforms which were used to determine that the anomalous quench that we had previously seen on a number of cavities was due to the cavity being driven to a quench field by a lost RF control system.

FAULT STATISTICS

In addition to using the waveforms to determine which cavity caused a given fault and classifying the fault in order to perform remedial action, e.g. turn a cavity down, we can use statistics to determine actions to be performed during maintenance periods. Figure 10 is a plot of the statistics by fault type and cryomodule for 41 days during the fall 2018 run. Based on this data, we did microphonics hardening of cryomodules 2L24, 2L25 and 2L26. This improved the trip rates for microphonics trips on the following run and allowed us to increase the gradients on those cryomodules.

We reviewed all of the faults due to interlock faults and identified the specific interlock fault by looking at the archived data. The majority of the interlock trips that were not due to other factors (such as high power RF interlocks, arc test faults and window temperature faults) were indicated as a quench fault as determined by the RF controls. The controls look at the fall time for the gradient and have a very small gradient error before they trip. Test plans have been developed to modify the quench interlock and the gradient error interlocks in order to reduce what are perceived as false trips.

There were a large number of electronic quenches in 1L25-8 and 1L26-1, which share a common inter-cryomodule beamline. These faults were present in the spring of 2018 and were eliminated after a thermal cycle of the zones to room temperature. However, they returned in cavity 1L26-8 after about a month of operation and in 1L26-1 after about two months of operation. The faults in cavity 1L26-8 which were present in the spring of 2018 ceased after the same thermal cycle have yet to return after 8 months of operation. Work continues in understanding the root cause of these faults.

Further analysis of these events along with the vacuum signals indicated that the vacuum valves were closing on the majority of the electronic quenches in the north linac but not in the south. For an unknown reason the peak vacuum excursions were slightly higher (2×10^{-6} Torr) in the north linac as compared to the south linac which were about 8×10^{-7} Torr. In both cases they were transient pressure excursions with a decay time less than 1 second. Vacuum modeling indicates that most of the 1 second time constant is due to the pumping speed and conduction of the pipes adjacent to the ion pump. It also indicates that the pumping speed for the beam pipe at the entrance to the SRF cavity has a time constant on the order of 100 ms. Rather than simply increasing the set point on the interlock, the data is being used as justification for modifying the vacuum interlocks to delay closing the vacuum valves for a few seconds when the pressure exceeds 1×10^{-6} Torr but is below 2×10^{-5} Torr. The interlocks will still close the beam line valves immediately if the pressure is above 2×10^{-5} Torr.

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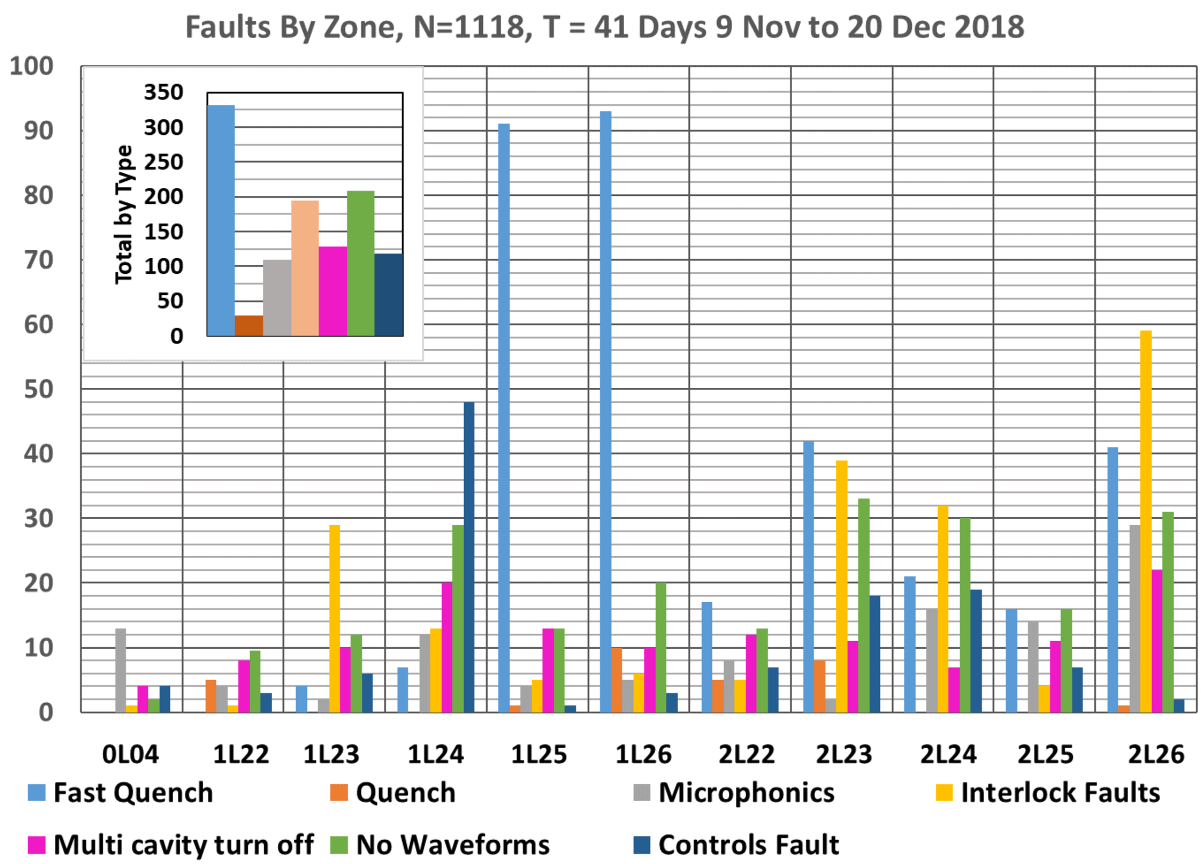

Figure 10: Distribution of faults by zone for the C100 cryomodules for 41 days in the fall of 2019. It should be noted that the harvester was disabled for several weeks for zone 0L04.

MACHINE LEARNING

The current approach to identify the fault type and which cavity caused the fault is to plot the data and manually review it. During a run period this can take as much as a day per week of a system expert's time. Further, it is difficult to train operators how to properly identify the faults which leads to them having to guess which is the faulted cavity and, if the fault is occurring too frequently, to turn that cavity down. The next day the system expert upon review of the log books and the waveform data will determine if the proper cavity was turned down. If it was not, they will turn it back up and adjust the proper cavity.

In the Fall of 2018, a program was initiated to use machine learning to identify the fault type and offending cavity automatically [3]. Data was split into a training (70%) and test (30%) sets. A variety of classification models were trained. Fault identification accuracies on the test data set exceeding 90% were achieved. Identification of the cavity that caused the trip was also tested. For this effort only 4 signals were analyzed which were, GASK, forward power, measured gradient and DETA2. Depending on the method used the accuracy scores were between 86% and 96%. The goal of this program is to deploy deep learning based algorithms in the control room so that the results can be used to guide operations regarding fault type mitigation and potentially fault avoidance in the future.

CONCLUSIONS

Over the last year waveform data for RF signals 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 interlocks. Use of machine learning tools is being pursued which should automate the identification of the faulty cavity as well as the type of fault. A combination of these methods should provide a useful tool for machine operations.

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