**Code + Analysis Tools**

*Mean, RMS, Gain, ENC*

The software for testing and analyzing functional test results in provided by BNL. \*\*Talk about software procedure in more depth here\*\* The functional test procedure, with all setting enabled, runs through different configurations of baselines (collection vs induction mode) peaking times (maybe, not sure), and gain measurements (maybe other settings, etc…). For each functional test, a check setup is performed quickly, enabling a snapshot of the ASIC performance before more in depth tests are run. One particular settings configuration is then run through a full functional test; charge is injected into the ASICs mounted onto the FEMB, where voltage is slowly increased stair-wise over time until a peak voltage is reached. Each voltage increase corresponds to a particular Subrun; A total of 36 Subruns are run for each channel. Waveform .root files are produced consistenting of all 36 voltage increases. Included in each subrun is a compilation of nearly 80 pulses that are shaped from the injected charge. An example waveform is given in pic4\_HealthyWaveform. As can be seen from pic4, the waveform is comprised of multiple voltage increases from 0 injected charge initially, all the way to some saturation point (around 30 SRs), due to ASIC only being 14-bit (max adc = 14000 or so). Abnormal/non-optimal ASIC performance, such as higher baseline, high noise, or non-linearity of the waveform should be evident from analyzing the waveform .ROOT file. The FEMB + ASIC analysis includes a calculation of baseline and noise measurements (Pedestal Mean and RMS), ENC (equivalent noise charge… can talk more on this if needed) and Gain measurements for each of the 64 channels (4 ASICs on board). These measurements are automatically processed from waveform .ROOT files and .list files are produced for each channel, consisting of each functional measurement. Summary plots are also produced for a visual representation. FFT’s of the noise are provided in the summary plots, too. An example of a summary plot is given in pic5\_SummaryPlot. Gain measurements are the sole indicator of ASIC performance under this FEMB software. Gain is calculated via the inverse slope of a section of the waveform, in units of [e-/adc]. If the gain value is outside a value of [10:400], the software determines the channel as Fail. If at least one channel out of 16 fails on a given ASIC, the ASIC is marked as Fail. Gain is an indicator of ASIC linearity, an ability of an ASIC to amplify charge into voltage in a linear manner is of paramount importance. As we will see in later sections, this software should analyze the Gain throughout the entire waveform, or at least until saturation, to fully characterize abnormal channel behavior. Functional measurements are pulled directly from the .list files and subsequently analyzed in further detail. An example of a .list file is given in pic6\_listfile.

*Linearity*

Since we have identified linearity as a primary indicator of ASIC performance, in both RT and CT, the gain measurement performed over a small section of the waveform is inadequate for waveforms with non-linear behavior outside the region of interest of the software. We add Linearity analysis on top of the functional parameters already discussed as our primary analysis of ASIC health and performance. ASIC Linearity is calculated by extracting the maximum pulse amplitudes for the first 30 Subruns (voltage levels) in a given channel waveform .ROOT file. The first Subrun contains no injected charge, while the later Subruns (30+) are saturated, since the ASIC is only 14-bit (has a maximum ADC value of ~14000). The linear profile of sample points is then plotted and fit to quantify the linearity of each channel. A linear least-squares fit is generated of the form: a[0] + a[1]\*x. We use the linear coefficient value, a[1]. An example of a 16-channel waveform profile with the associated linear fits is shown in pic7\_linear. Notice it is clear when a given channel is non-linear, as is the case with Ch4. After each ASIC channel has been analyzed, a histogram is produced containing all 1600 linear coefficient values. The mean of the RT[0] distribution, which is well approximated as normal, is then defined as Linearity = 1; all subsequent distributions are thus normalized to the initial warm temperature measurements with no history of cryocycles. The RT[0] distribution is shown in pic8\_RT0LinearDistribtion. Although the ASICs were optimized for cryogenic temperatures, and thus the normalized linearity could be chained to the first CT measurement, as we will see the linearity profiles in warm are ‘more’ linear than in cold. To avoid super-linear normalized values, we thus chain everything to RT[0]. In addition, CT[5] measurements represent ASICs with a small cryocycle history, whereas RT[0] is a sample population with no prior exposure to sub-100K temperatures. What is important for this analysis is to compare the cryocycled distributions within a given RT or CT set of measurements. Though there will be a difference between, say RT[5] and CT[5] linearity, it is of importance to focus on any distribution shift between, say CT[20] and CT[100]; this change will be indicative of a change to the internal structure/circuitry and performance of the chips as they are subjected to prolonged extremes.

*Pulse Parameters – Integrated Charge and FWHM*

Because signal processing is the primary importance of the CE system, it is valuable to understand the how the charge injected by the power supply and shaped by the ASICs changes as they are subjected to progressive cold-cycling. Two pulse parameters we quantify here are the Full Width at Half-Maximum (FWHM) of the pulses, and the total Integrated Charge (IC) of the pulse (area under the pulse curve). The value of the IC within DUNE will correspond to an ionizing particle’s energy – the drift electrons ionized from the Argon nuclei that drift towards the collection and induction planes is deposited as charge. Similar to the Linearity analysis, IC and FWHM are derived from the waveform .ROOT files produced by the functional tests. Each channel waveform is composed of thousands of injected bipolar pulses (or unipolar if in collection mode) at various increasing voltage levels. There are about 77 pulses per Subrun, over 35 total Subruns. We compose a hit-finding alrgorithm using a peak-finding SciPy package (SciPy.signal – find\_peaks, peak\_widths) to identify the positive pulses within a given waveform. The FWHM and IC is then ultimately calculated. Due to abnormal pulses in failed and suboptimal ASIC channels, the algorithm must be robust enough to capture some irregularly-shaped pulses, yet ignore ‘pseudo’-pulses mimicked by the Pedestal. We want to capture the irregular pulses to properly quantify changes in the ASIC population as a function of cryocycling - if the ASICs change how they shape injected charges. A pseudocode structure is given below of the hit-finding algorithm + the extraction of the FWHM and the IC. The original waveform files are first read into .dat files; these .dat files contain all X and Y points of the waveform.

1. Read in compressed .list files generated by analyzing .ROOT waveforms
2. Find Pulses
   1. Use SciPy.signal find\_peaks package to search for ‘hits’ above a Pedestal baseline value of 3000 within a given Subrun.
   2. Log the x-point and y-point values of that peak into an array, while only saving the inner 50 peaks (out of a possible 77).
   3. Calculate FWHM by finding the value of the peak width at relative height = 0.5 (using Scipy.signal peak\_widths package).
   4. Impose width criteria – reject any pulses with widths outside some optimized window. This is optimized after many iterations – it helps to eliminate ‘pseudo’-pulses.
   5. Extract all x-points and y-points around an identified peak. This range is optimized after many iterations. An example of a captured pulse is given in pic9\_pulse. We wish to capture all of the charge (area under the pulse curve) without picking up unnecessary pedestal noise.
3. Calculate and perform a proper Pedestal subtraction
   1. Due to the known pedestal depression in CT over 16-channels (inner channels have lower Pedestal values, likely from packing stresses in the cold), if one applies a constant pedestal subtraction (based off CT distribution mean), the sagged-wire effect will be visible in the IC over 16-channels. This is seen in pic10\_pedestalSag. A proper pedestal calculation is performed by averaging the value of all x-points between the pulse intervals. This is calculated on a channel-by channel basis.
   2. A pedestal subtraction, with one averaged value over a given channel, is applied to the all y-points for each pulse. The IC of an ASIC (over all 16 channels) after proper pedestal subtraction is shown in pic11\_pedSubtraction. We observe the sagged-wire effect is no longer visible.
4. Remove disconnections from data set
   1. There exists a population of channels with Pedestal mean = 6000 adc, previously discussed. These channels failures have no true injected pulses and have been identified as socket-related failures. Since their baselines are above 3000 adc, pedestal noise mimicking true pulses is sometimes picked up. This can lead in a minor shift to the expected value of an IC distribution. Though the value is small (much smaller than a healthy pulse with amplitude 10000 adc), it still exists as a potential source of error in IC measurements. We wish to still keep the pulses in a channel that are abnormal (below optimum value, but greater than the 3000 adc threshold) but not are disconnections. We throw out any pulses containing pedestal-calculated values between 5750 adc and 6250 adc. The disconnections have a narrow distribution centered around 6000 adc, so this removes a vast majority, if not all, psuedo-pulses caused by high baseline disconnections.
5. Perform Integration of pulses.
   1. Simpson’s rule is used to calculate the area under each pulse curve. The difference in integration techniques has been shown to be minor (less than 0.1%).

Values of channel IC and FWHM can then be exported to histograms to analyze their distributions. Individual ASIC plots are generated containing information about each of their 16-channels. These individual ASIC plots are used to check for abnormal pulse features. A summary snapshot of a waveform, its pulses with the FWHM identified, and a specific pulse (same as pic9) is shown in pic12\_pulse\_and\_waveform.

The central 50 peaks are selected from the ~77 pulse sample to eliminate overlap with neighboring Subruns. Subruns have an inconsistent number of points (time ticks), deviating slightly from 25,400 (Check this). If all 77 pulses are used, some pulses thought to be contained in Subrun[10], lets say, may actually belong to Subrun[11], and thus will be at a higher voltage level – meaning the IC will be higher for a small section of the pulses. To avoid manually analyzing the pulses, we rely on automation and select only the central 50 peaks to avoid any overlap. We still obtain over 75,000 pulses for a complete data set of 100 ASICs when selecting the central 50 peaks, so we have large statistics to afford.

The algorithms used in extracting IC and FWHM are the same between RT and CT filetypes. Consistency is maintained across all cryocycles. The baselines show larger spread (high RMS) and higher values in RT, while in CT they are lower and far less noisier (by a factor of 7). It is far easier to reject ‘background’ pseudo-pulses in CT analysis rather than RT. The code is optimized to effectively extract pulses in both.

Processing 25,400 data points over all 35 Subruns for each channel, of 16 on 100 ASICs is an expensive computational task. Since the integrated charge and FWHM are only two of several functional parameters we wish to analyze, computational brevity is chosen to efficiently analyze the set. If all 35 Subruns are analyzed, for all 100 ASICs, the corresponding file size would be in access of 100 GB for the RT data alone. Since it is necessary and unavoidable to process all 1600 channels for each cryocycle, we turn to selecting only one Subrun (one voltage level) within a waveform for analysis. We chose Subrun[20] (insert voltage level) for analysis for several reasons. Firstly, it is an ideal balance; the Subrun far enough away from saturation (typical pulse amplitude of ~8000, whereas saturation is typically around 13500), while being in a high-enough voltage region, away from the Pedestal. Since the baseline values are around 1600 adc for CT (~200 mV – convert everything to voltage), we achieve a large SNR for the pulses in SR[20]. Secondly, SR[20] is ideal for IC because some ASICs in LN2 display irregular waveforms that prematurely saturate. This leads to highly non-linear profiles. If the IC was performed in early subruns, the IC would appear nominal. The later Subrun analysis clearly shows the IC is lower for that specific channel, since the value of early saturation is lower than the ideal voltage level. This can be seen in later sections, when discussing the faults of the FEMB functional Gain P/F criteria.

As stated above, we have an extremely large sample size for IC and FWHM statistics. If all channels are healthy, and all pulses are properly extracted, each cryocycle histogram contains 80000 pulses. These functional parameters thus represent the best-sampled distributions of the tools we employ for analysis.

The large file sizes described above apply to the linearity analysis. Ideally, a full averaging of the pulse amplitudes over all pulses in each Subrun would more accurately reflect the linearity of the ASIC. In light of computational ease, only the maximum pulse amplitude is found in each subrun, before being extracted for further analysis. The difference between the maximum pulse amplitude and the average amplitude is small for healthy ASICs – of negligible difference. The difference is likely amplified for abnormal channels, with a small number of pulses that are picked up by the hit-finding thersholds. However, the non-linear nature of the abnormal channels is readily identified regardless of any difference in value between average and maximum. The nominal distribution is what is analyzed and compared through cryocycles, while noting the number of channels outside 10% ideal linearity. Either way, average and maximum would both find themselves outside the nominal, regardless if their inherent differences are of order 5% or so. The overall ease of computation outweighs the possible difference between the true average amplitude and the maximum for this report. (Also, all channels are cross-checked with other functional parameters, so if there was a massive inherent difference it would be easily identified).