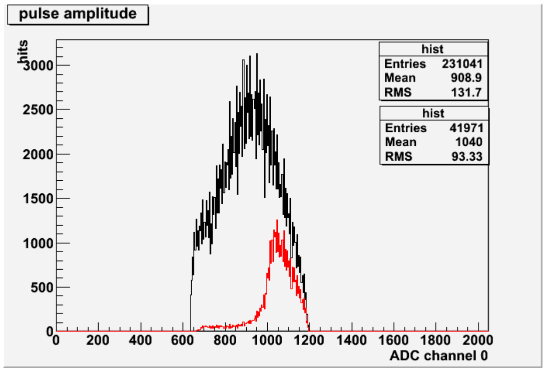
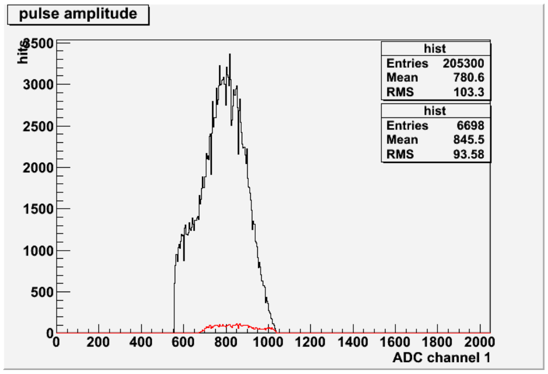
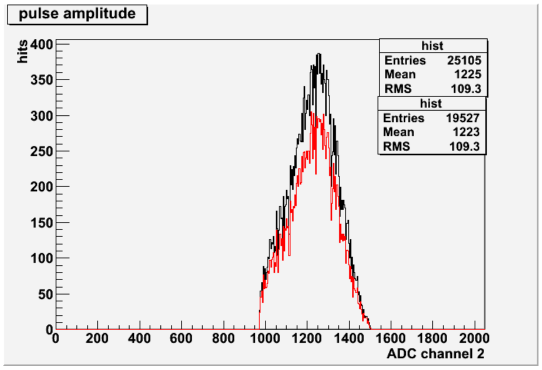
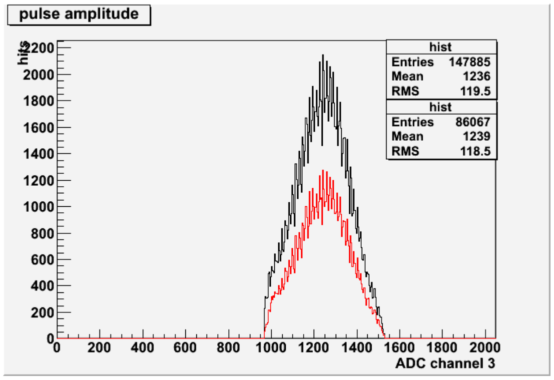
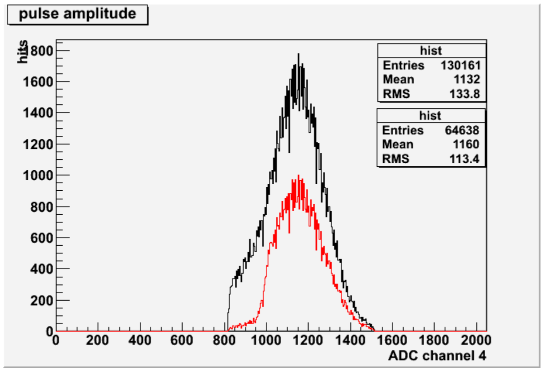
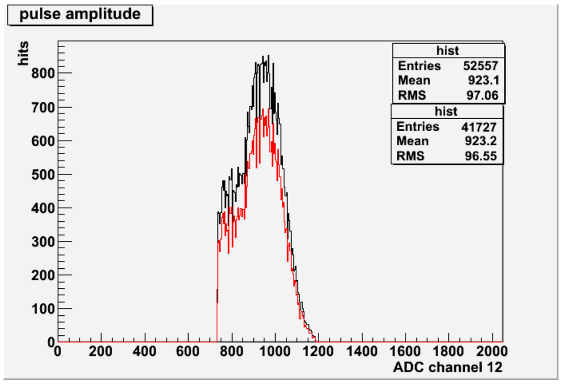

pulse amplitude
hits
0
500
1000
1500
2000
2500
3000
hist
Entries 231041
Mean 908.9
RMS 131.7
hist
Entries 41971
Mean 1040
RMS 93.33
0 200 400 600 800 1000 1200 1400 1600 1800 2000
ADC channel 0

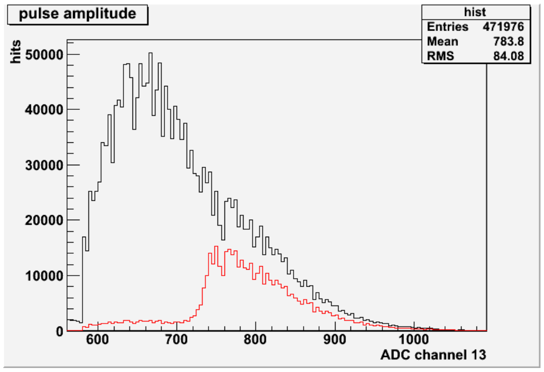

pulse amplitude
hits
0
500
1000
1500
2000
2500
3000
3500
hist
Entries 205300
Mean 780.6
RMS 103.3
hist
Entries 6698
Mean 845.5
RMS 93.58
0 200 400 600 800 1000 1200 1400 1600 1800 2000
ADC channel 1

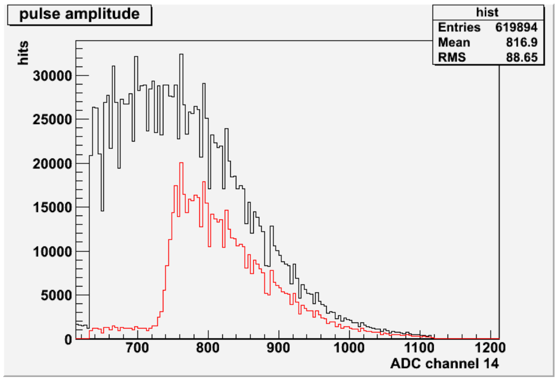

pulse amplitude
hits
0
50
100
150
200
250
300
350
400
hist
Entries 25105
Mean 1225
RMS 109.3
hist
Entries 19527
Mean 1223
RMS 109.3
0 200 400 600 800 1000 1200 1400 1600 1800 2000
ADC channel 2


pulse amplitude
hits
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
hist
Entries 147885
Mean 1236
RMS 119.5
hist
Entries 86067
Mean 1239
RMS 118.5
0 200 400 600 800 1000 1200 1400 1600 1800 2000
ADC channel 3


pulse amplitude
hits
0
200
400
600
800
1000
1200
1400
1600
1800
hist
Entries 130161
Mean 1132
RMS 133.8
hist
Entries 64638
Mean 1160
RMS 113.4
0 200 400 600 800 1000 1200 1400 1600 1800 2000
ADC channel 4


pulse amplitude
hits
0
100
200
300
400
500
600
700
800
hist
Entries 52557
Mean 923.1
RMS 97.06
hist
Entries 41727
Mean 923.2
RMS 96.55
0 200 400 600 800 1000 1200 1400 1600 1800 2000
ADC channel 12


pulse amplitude
hits
0
10000
20000
30000
40000
50000
hist
Entries 471976
Mean 783.8
RMS 84.08
600 700 800 900 1000
ADC channel 13

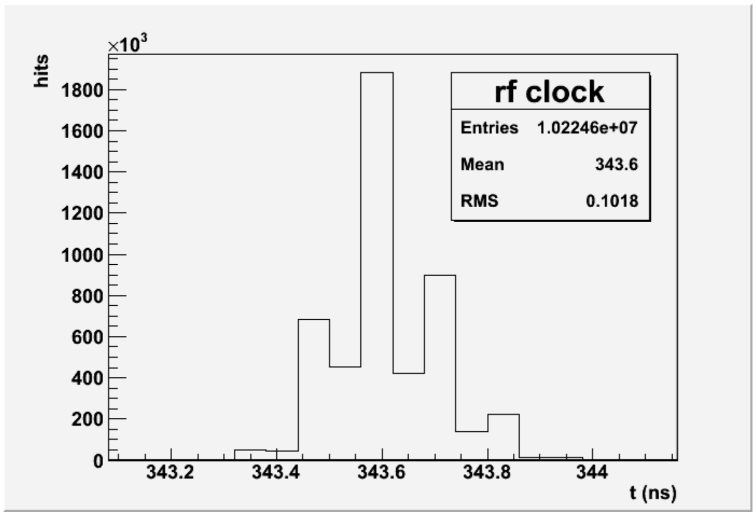

pulse amplitude
hits
0
5000
10000
15000
20000
25000
30000
hist
Entries 619894
Mean 816.9
RMS 88.65
700 800 900 1000 1100 1200
ADC channel 14

From the above, it would be interesting to check our assumptions about gain and thresholds on the discriminators. The stated adc gains are 500 mV full-scale for channels 0-4 and 1000 mV full-scale for channels 12-14. The discriminators are all set at 60 mV threshold, according to the above notes (for most of the runs).

channels 0-4: threshold = (1000 - 380) / (4096 - 380) * 500 mV = 83 mV
channels 12-14: threshold = (750 - 480) / (4096 - 480) * 1000 mV = 75 mV

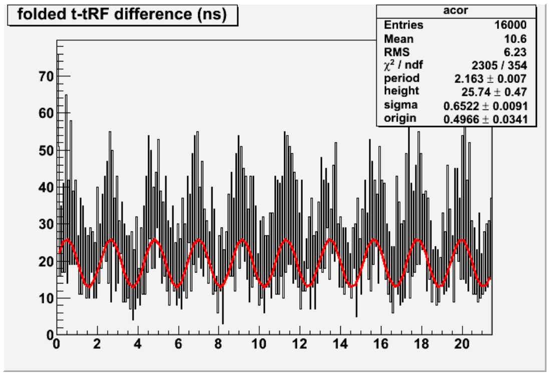
This is within a factor 2 of the nominal value of 60 mV. Either there may be an offset built into this discriminator setting, or else the voltage corresponding to full-scale may be off from the nominal value in the FADC by about 30%. That seems like a large margin of error. Without a scan of the reverse bias potential on the SiPM, it is impossible to know what the gain was in the SiPM pixels to better than about 30% anyway.

According to the F1TDC User's Manual, the tdc values returned by the F1TDC are all synchronized to a common clock within the module. This means that I can subtract the T values from the SiPM signals from that of the RF clock and get a valid time difference. Some events have more than one RF clock T value in them. Below I show a histogram of the difference between two RF times for those events with more than one.

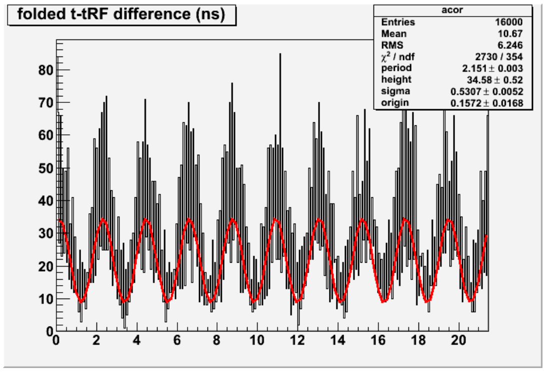


Difference between two sync pulses of the accelerator RF clock

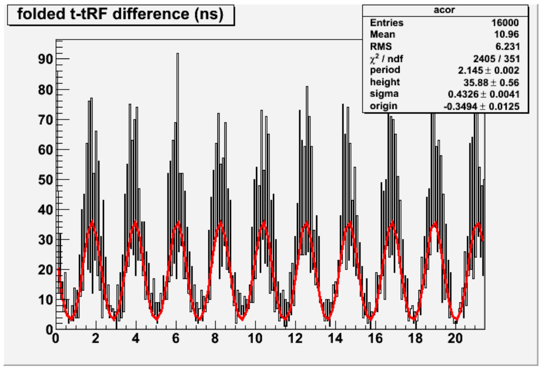
Next I show some time difference spectra for SiPM channel relative to the first RF clock pulse in the event. To reduce broadening due to time walk in the leading edge discriminator, I have cut on the pulse height in a narrow window (50 adc counts) in each of these spectra. The peaks repeat every 2 ns for the full 500 ns trigger window, so I wrap the T values at 20 ns.



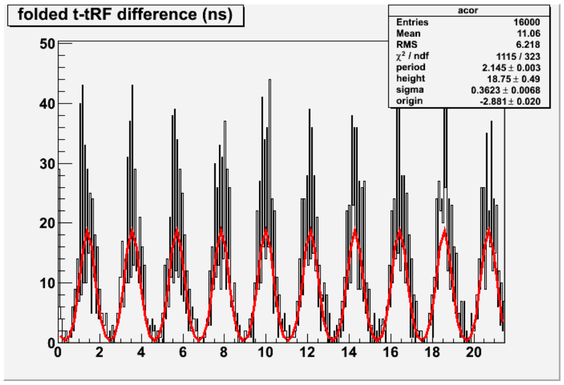
channel 4, 1050<Amax<1100



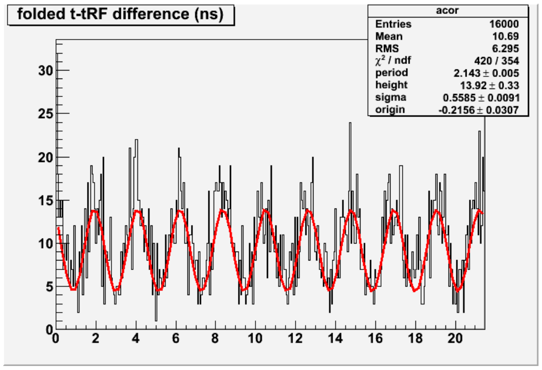
channel 4, 1100<Amax<1150



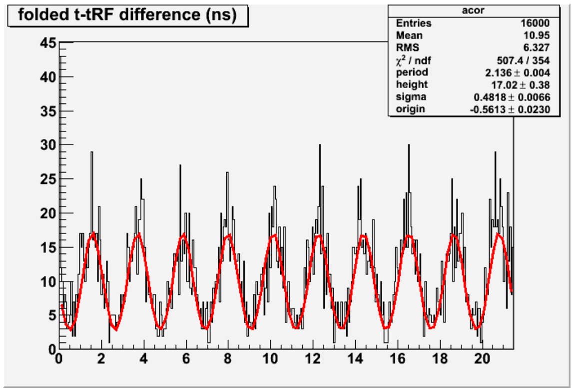
channel 4, 1200<Amax<1250



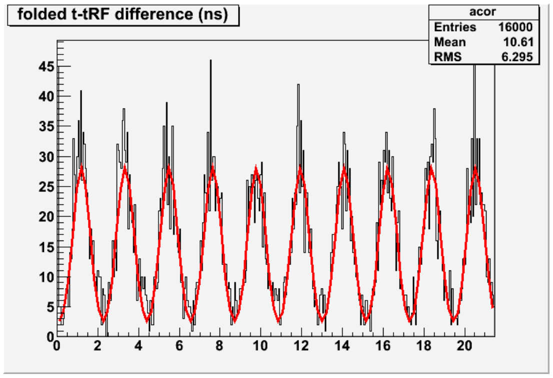
channel 4, 1300<Amax<1350



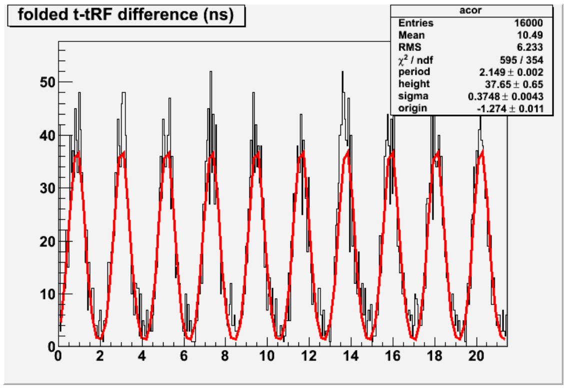
channel 12, 750<Amax<800



channel 12, 800<Amax<850

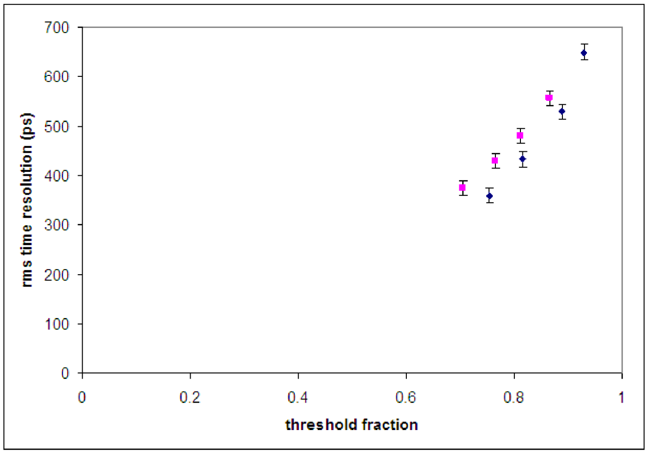


channel 12, 850<Amax<900



channel 12, 900<Amax<950

The trend is toward improved time resolution as the maximum pulse height over threshold increases, as expected. Unfortunately we are unable to reduce the threshold to the desired level around 30-50% of maximum pulse height. The best we can do at this point is plot the resolution as a function of threshold/Amax and visually extrapolate to the desired region.

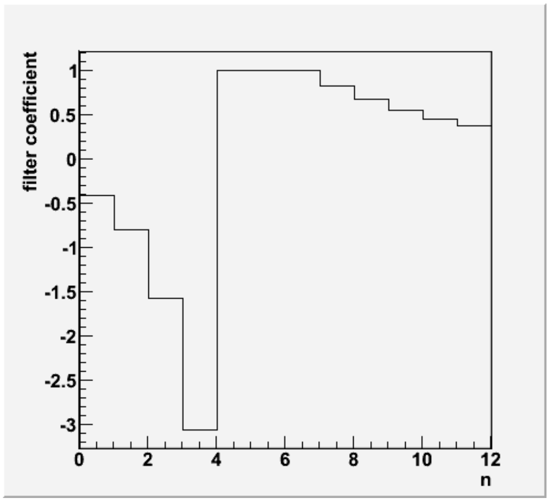


RMS time resolution against the RF clock vs Athresh/Amax

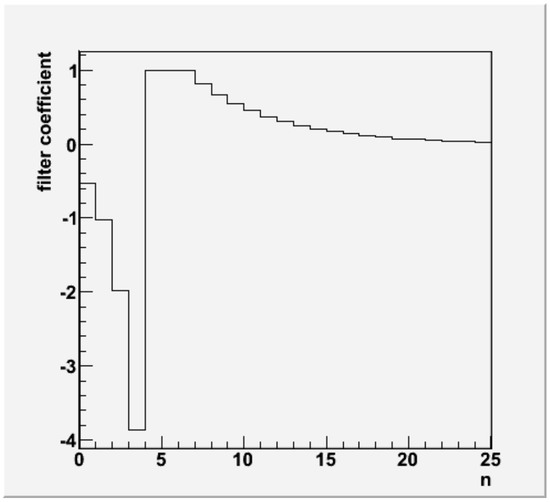
## Optimized extraction of Q and T from a sampled waveform

So far I have been using the maximum pulse height in a the waveform sampled by the FADC as a proxy for the amount of light collected in a pulse. I can do better than this by applying a linear filter first, and then taking the maximum pulse height. As a by-product, I can also obtain an estimate for the leading edge time T, which might be competitive in resolution with what is obtained using the TDC.

First I develop a hypothesis for the Q filter. Below are two hypothetical filter sequences of different lengths, plotted as histograms. They are designed to return zero for a dc signal and turn a SiPM pulse into a bipolar blip whose maximum positive amplitude estimates the pulse integral and whose zero-crossing estimates the leading edge timing. The zero-crossing of the Q filter to estimate the leading edge time has many of the desired properties of a T filter (using the entire pulse waveform, independence of amplitude) but it may not be the optimal choice. Later on I can try to optimize a separate filter for extracting T.

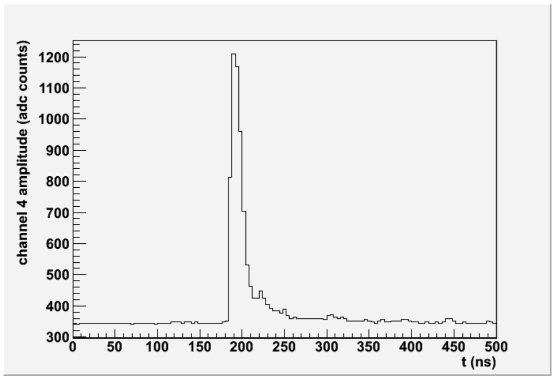


simple Q filter of length 12 (Q12)

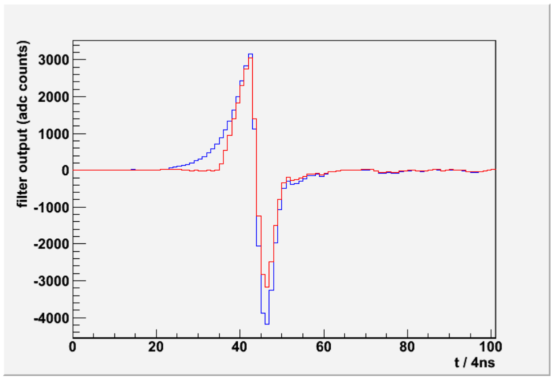


simple Q filter of length 25 (Q25)

The simple Q filter of length 12 displayed above was employed to produce the results shown next. Here is an example trace from channel 4, followed by the trace after the 2 Q filters illustrated above have been applied to it. Notice that the maximum of the output pulse does not depend very much on filter length. This maximum is the filter's estimator for Q. There is some dependence in the amplitude and zero-crossing time on the details of the filter, which is analogous to dependence on the gate width and threshold for conventional pulse integrators and leading-edge discriminators. These need to be measured for each channel-filter combination and stored as calibration constants.

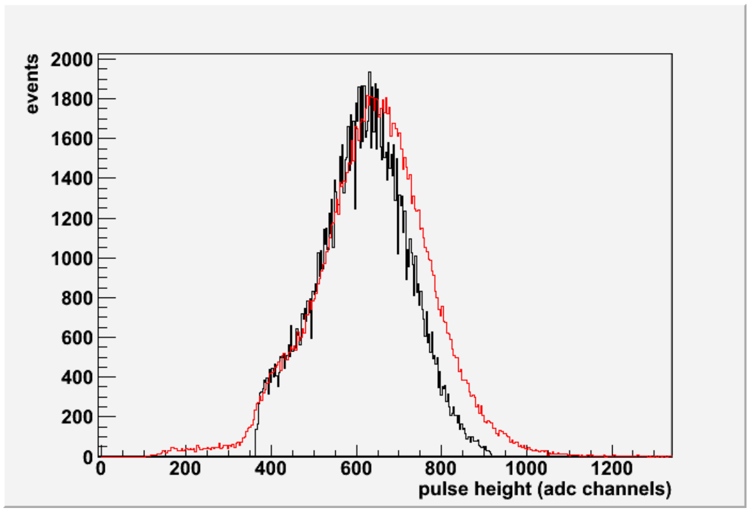


input pulse waveform from channel 4



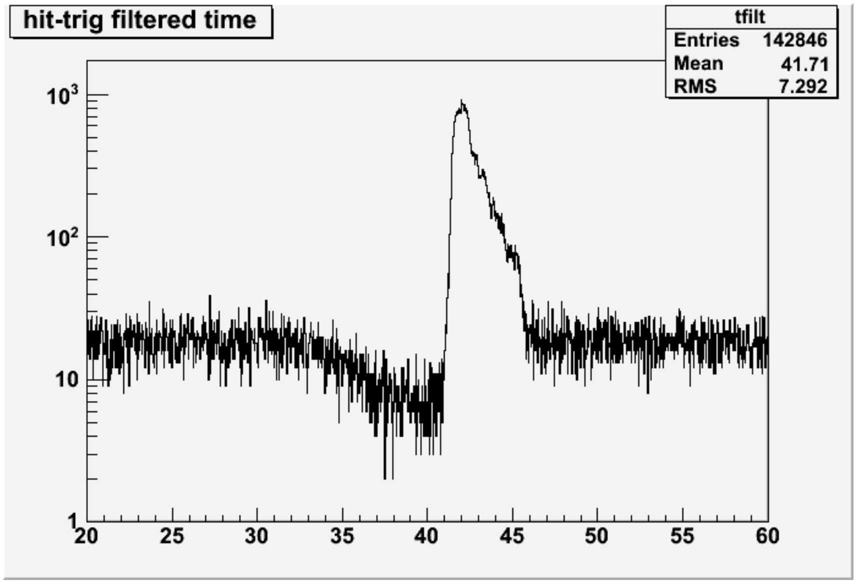
filter output from Q12 (red) and Q25 (blue)

The pulse height spectrum is compared with the Q12 spectrum for channel 4 below. The magnitude of Q12 has been adjusted to give the same most-probable value for the pulse height. The difference between the two distributions comes about from the fact that the maximum of the pulse falls in a random position from event to event with respect to the ADC clock. Because of this, the Q12 value is a more reliable estimator than the maximum of the unfiltered ADC waveform. However there is not much qualitative difference between the two spectra.



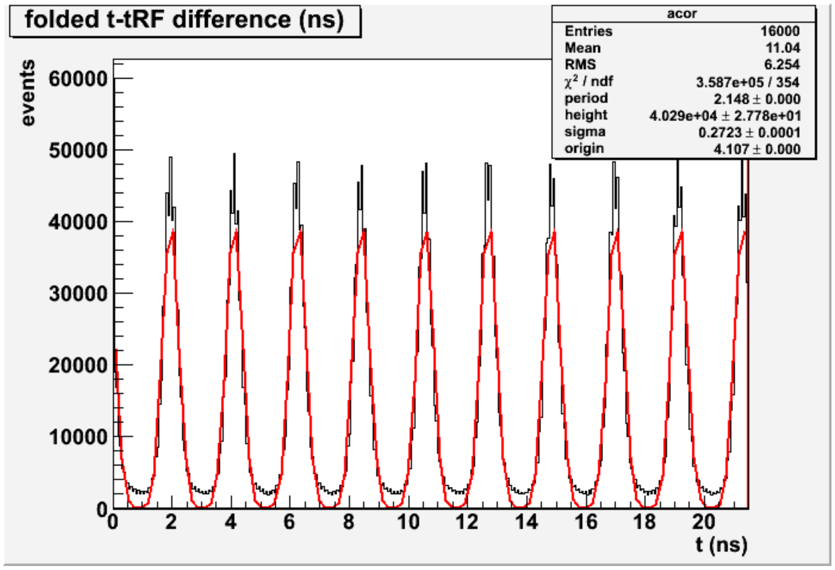
Spectrum of Q12 for channel 4 (red) compared with the maximum pulse height seen in the unfiltered spectrum (black). The pedestal has been subtracted from the unfiltered pulse height, and the magnitude has been rescaled to make the most-probable pulse heights match.

The time of the leading edge in the FADC waveform, as estimated using the zero-crossing of the Q12 filter, is shown below. However the FADC clock is not synchronized to anything in the experiment, so the only thing this plot can indicate is how the trigger is formed. It is not surprising that the peak is about 20 ns wide.



Unsubtracted leading edge time of SiPM pulse for channel 4, in units of FADC samples (4ns)

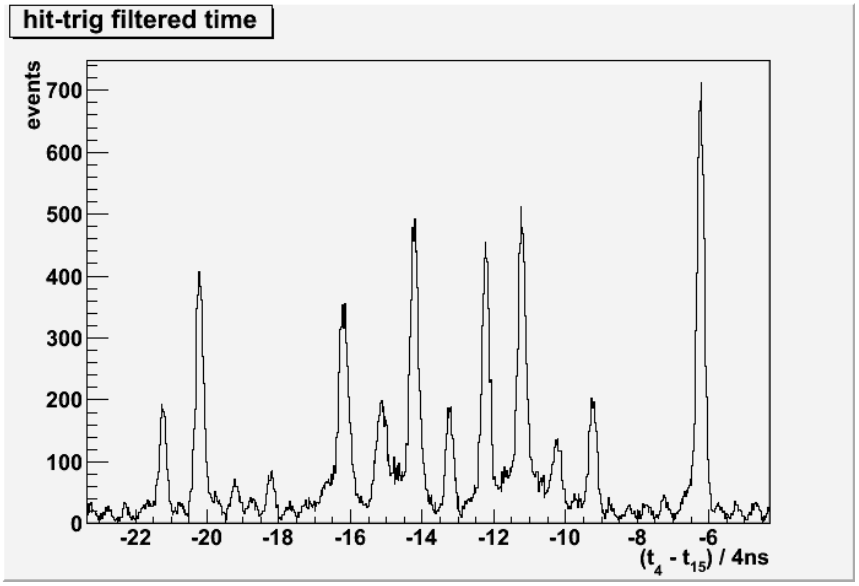
The only way to obtain a time resolution measure from these data is to take the difference between two signals when both a present in a single event. On channel 15 in the ADC there was an output from the discriminators for one of the two trigger phototubes. There is also a "trigger" signal supplied to one of the TDC inputs. To get an idea of the time resolution of the trigger signal, I look at the trigger TDC value relative to the TDC from the accelerator RF.



Trigger t relative to the RF t, in nominal TDC ns. One can see from the value of the period that the TDC clock is about 56 ns/tick instead of the nominal 60 ns/tick that is stated for hi-res mode.

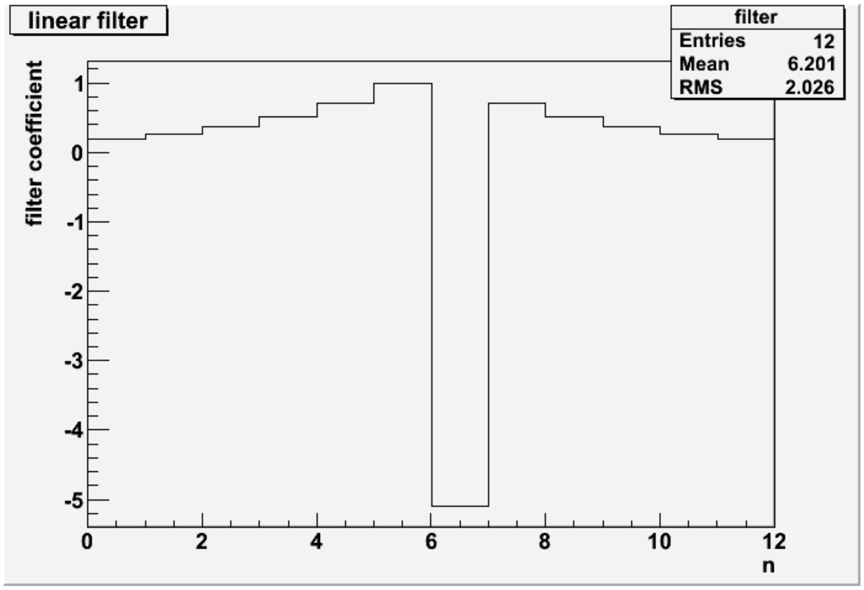
The intrinsic time resolution of the RF signal itself is 100 ns / sqrt(2) = 70 ns. This leads to an intrinsic time resolution of 265 ns for the discriminated trigger signal. This is about what one would expect for a CFD without time-walk correction. Unfortunately one cannot do an offline time-walk correction because the analog signal was not digitized.

Knowing the intrinsic time resolution of the trigger signal, this signal can now be used as a time reference for leading-edge times extracted from the FADC waveforms. Below is the time difference spectrum between channel 4 leading-edge time and channel 15 (digital trigger signal) leading-edge time, both of them in units of FADC ticks (4 ns).

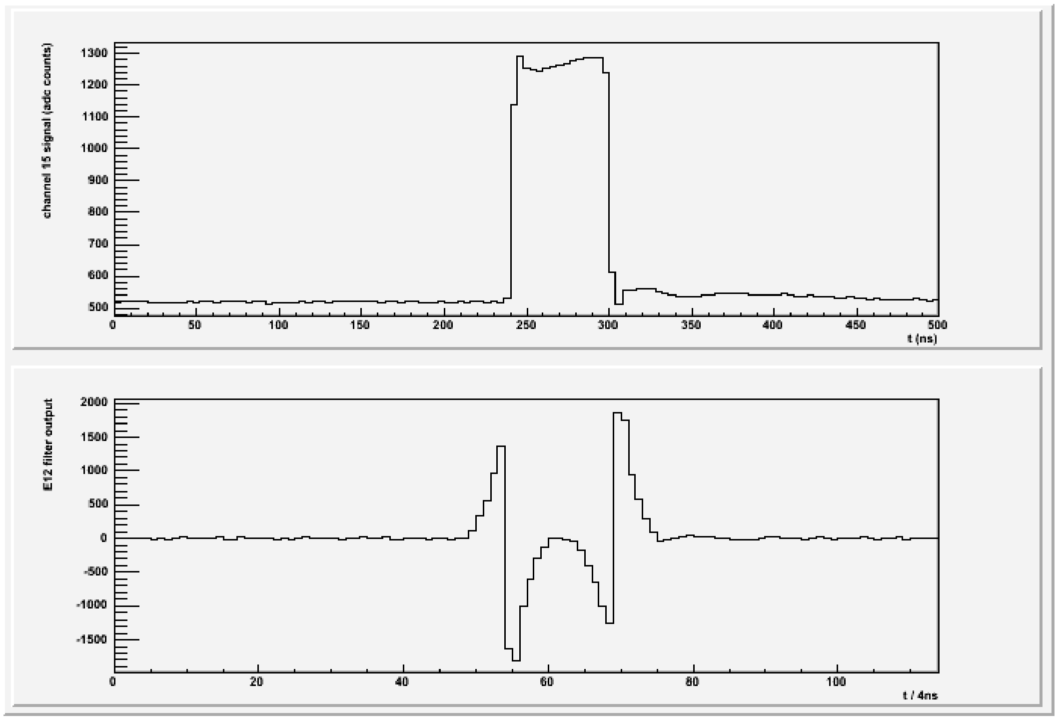


Time difference spectrum between channel 4 leading-edge time using the Q12 filter and the leading-edge time of the trigger signal in channel 15 extracted using the E12 filter. These two linear digital filters Q12 and E12 are described in the text.

Because the square pulse fed into channel 15 is a very different shape from a SiPM pulse, I designed a different filter, called E12, to pick off its leading edge. It is also of length 12, but its shape is designed to produce a clean bipolar pulse when it reaches a step, such as occurs at the leading edge of a discriminator output. That step rise-time is on the same order as the FADC sampling period, so there is some loss of resolution involved in extracting a leading edge time for channel 15. The shape of E12, and its effect on a sample signal in channel 15 is shown below.



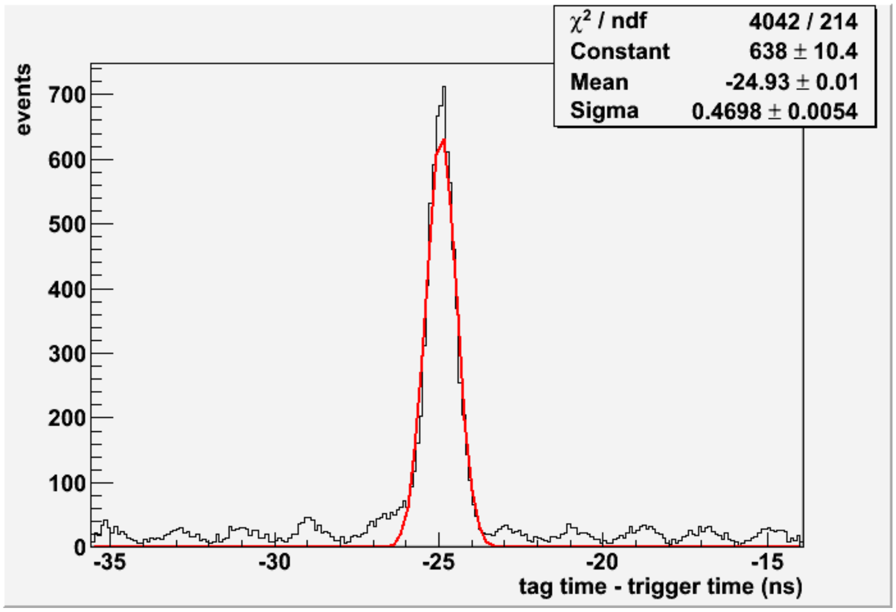
E12 filter used to extract a leading edge time from a digital pulse waveform



Sample waveform seen in channel 15 (upper panel) and output signal from E12 (lower panel).

Several peaks of various heights are seen in the time difference (chan 4 - chan 15). Across the bottom of the plot one sees a regular sequence of small peaks spaced 2 ns apart. These correspond to random coincidences between the scintillating fiber and the trigger scintillator. Some of these peaks are strongly enhanced, to varying degrees. I do not understand what is causing this. Perhaps each one represents a different run period, when the voltage on the trigger phototube was varied, the threshold on the discriminator was changed, or perhaps changes in beam current caused changes in the operating characteristics of the phototube and base. Further studies are needed to discover whether all of these peaks are present during a given run period, or whether they come and go throughout the run, and show up superimposed on the final plot when all runs are added together, as was done here. I can think of lots of reasons why the peak in the time difference spectrum might be wider than expected, but why it would be broken down into many narrow spikes is mysterious.

Assuming that any one of these spikes can be used to estimate the intrinsic time resolution of the SiPM leading-edge times as derived from the digital filter acting on the FADC waveform, I fit the largest one to a Gaussian peak. The result is shown below. Converted to ns, this gives an aggregate time resolution of 470 ps. Subtracting 300 ps for the resolution of the trigger time reference gives an intrinsic time resolution of 360 ps for the SiPM leading-edge time extracted from the FADC waveform by this method.



Gaussian fit to the most prominent peak in the time difference spectrum obtained from filtering the FADC waveforms to extract a leading-edge time, and subtracting their values.

The extracted value of 360 ps for the SiPM leading-edge timing from the FADC waveform assumes that one is able to achieve 300 ps on the digital signal in channel 15 by the same method. This can be checked by looking for events with more than one trigger signal visible in the channel 15 waveform, and taking the difference between the leading-edge times from the two pulses. This should not be difficult to do because the rates in the trigger phototubes where several hundred kHz.