Failure of the Constant Fraction Discriminator

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In order to understand the inefficiency of the calorimeter trigger in the HyperCP experiment, we have studied the behavior of the constant fraction discriminator (CFD) when two pulses that are close together in time are sent through it. A pulse separation of 19ns was used since that was the bunched-beam spacing in the experiment. In this memo, I will first describe how the constant fraction discriminator works and the reasons for using that particular type of discriminator; then, I will describe the apparatus we used to test the CFD; finally, I will describe in what situations the constant fraction discriminator fails to give output, thus reducing its efficiency.

I. How a CFD Works:

Discriminators generate precise logic pulses in response to input signals exceeding a given threshold. There are two main types of discriminators, the leading edge discriminator and the constant fraction discriminator. The leading edge discriminator is the simpler of the two types. Given an input pulse, the leading edge discriminator produces an output pulse at the time when the input pulse crosses a given threshold voltage. This, however, causes a problem in situations where the timing is important. If the amplitude is changed, but the rise time of the input pulse remains the same, a sort of "time walk" occurs (Figure 1). That is, an input pulse with smaller amplitude but with the same rise time as a larger pulse will cross the threshold at a later time. Thus, the timing of the output pulse is shifted by this change in amplitude.
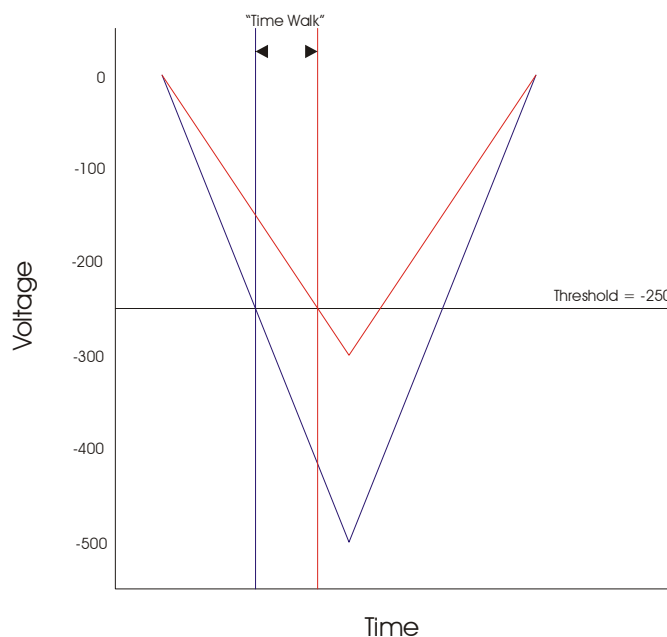

Figure 1: Leading Edge Discriminator and "Time Walk"

The constant fraction discriminator alleviates this problem by using a constant fraction, f, of the input pulse to precisely determine the timing of the output pulse relative to the input signal. It does this by splitting the input signal (Figure 2): attenuating one half so that it is a certain fraction, f, of the original amplitude (Figure 3), and delaying and inverting the other half (Figure 4).
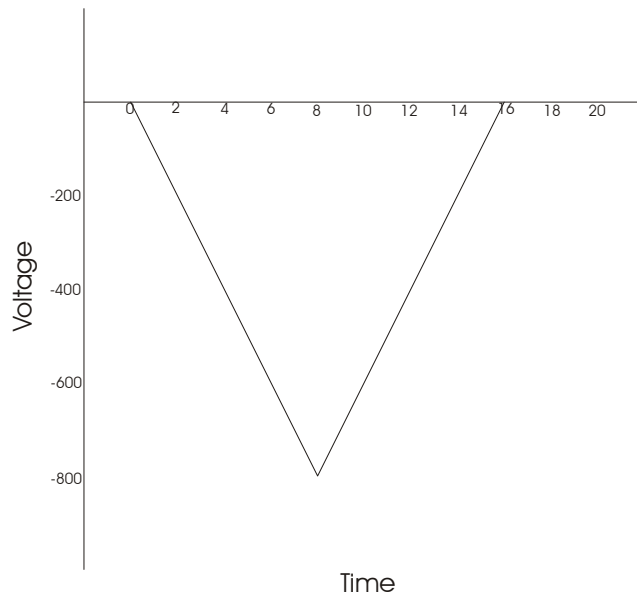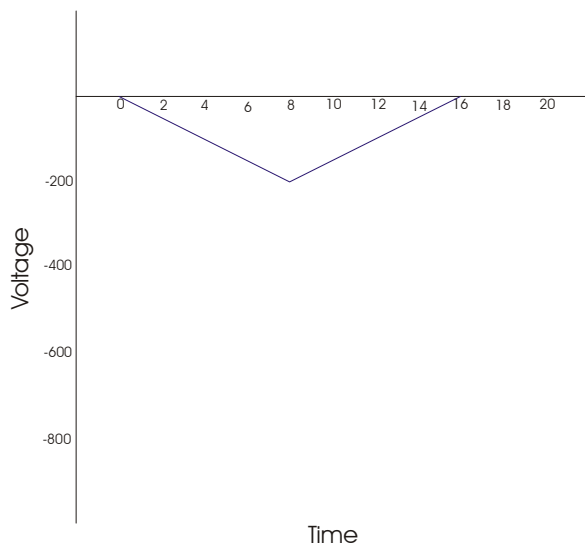
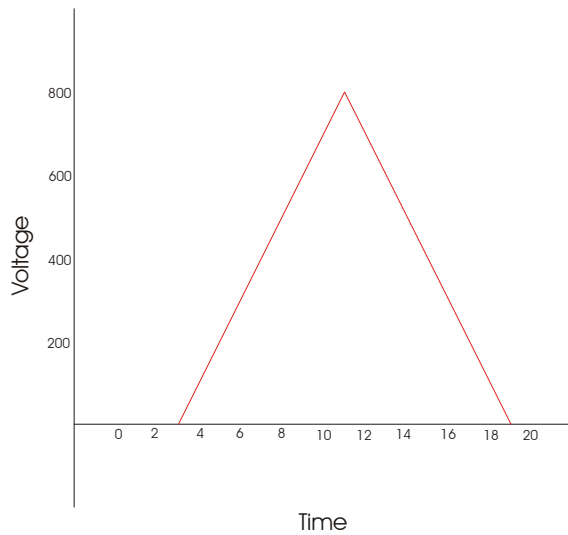Figure 2: Input Pulse to CFD

Figure 3: Attenuated Pulse

Figure 4: Delayed and Inverted Pulse

The attenuated pulse and the delayed and inverted pulse are then added together, and the zero crossing is computed (Figure 5).
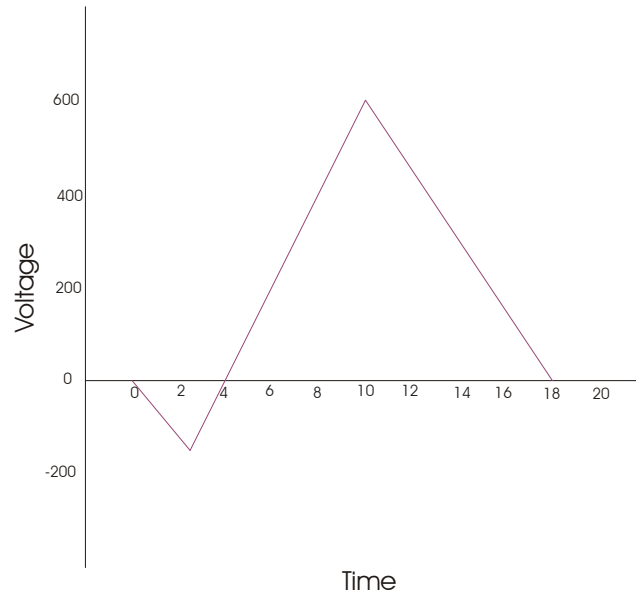

Figure 5: Sum of Attenuated and Delayed and Inverted Pulses

The zero crossing gives the time at which the CFD should create an output pulse, and is always independent of amplitude. For a simple linear ramp, like the one shown above, the equations for its input pulse, attenuated pulse, and delayed and inverted pulse are as follows:

$$delay = t_d, \quad fraction = f, \quad initial\ amplitude = A,$$
$$input\ pulse \quad V_i = -At,$$
$$attenuated\ pulse \quad V_a = -fAt,$$
$$delayed\ and\ inverted\ pulse \quad V_d = A(t - t_d).$$

To find the zero crossing, set $0 = V_a + V_d$ and solve for t:

$$0 = -fAt + A(t - t_d),$$
$$t_{cross} = \frac{t_d}{(1 - f)}. \tag{1}$$

For the Phillips Scientific Model 715 Constant Fraction Discriminator that we used, $f = \frac{1}{3}$.

Ideally, the delay is chosen such that the maximun of the attenuated pulse crosses at the desired fraction of the delayed pulse. In that case, $t_{d\_ideal} = t_{rise}(1 - f)$. However, if the delay is chosen smaller than t_{d_ideal}, the CFD operates at a fraction less than f. With our pulse and a delay of

3

3ns, the effective fraction is approximately 0.1. From equation 1, we see that t_{cross} is independent of the amplitude of the input pulse. The CFD has a monitor output feature, which outputs the bipolar signal created by summing the attenuated and the delayed and inverted pulses, so that we can view how it is calculating the zero crossing. Below are some examples of the monitor output for varying attenuations of the input pulse; attenuations are measured in decibels (dB) where n dB attenuation gives a pulse with amplitude $0.9^n A$, A is the initial amplitude of the pulse.
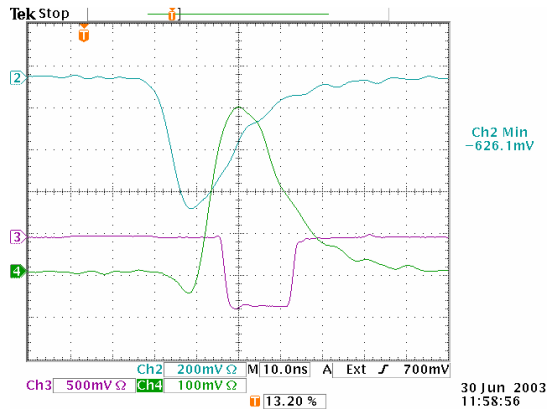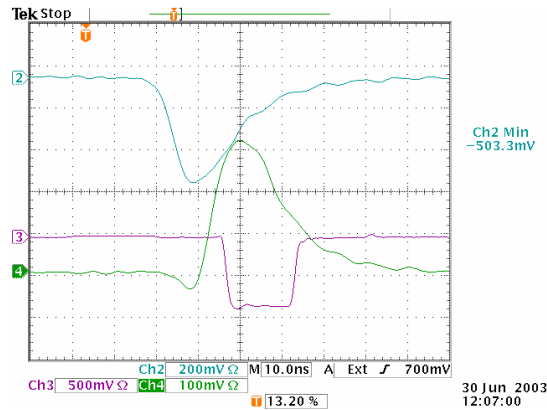

Figure 6: No Attenuation on Input Pulse

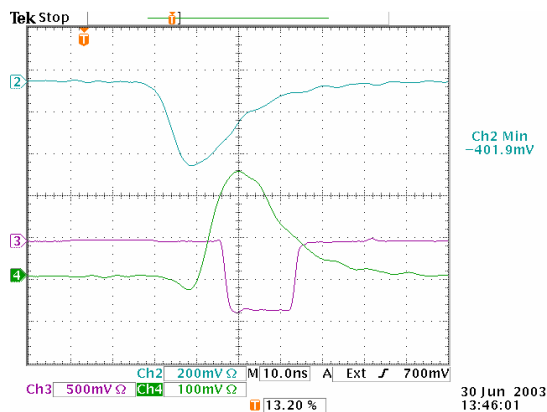Figure 7: 2dB Attenuation on Input Pulse

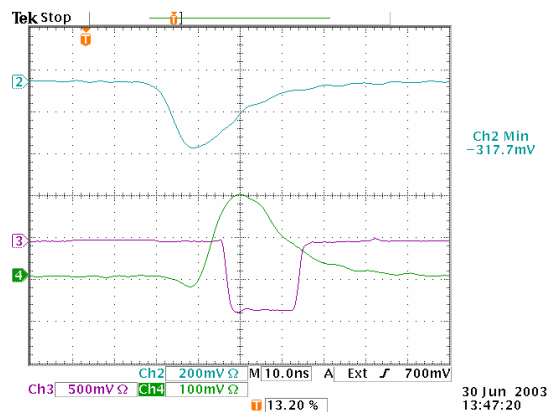Figure 8: 4dB Attenuation on Input Pulse

Figure 9: 6dB Attenuation on Input Pulse

For Figures 6-9: The x-axis is set at 10ns per division, y-axis specifications for each channel is given below with what each channel represents.
        Channel 2 (Blue) – Input Pulse, 200mV per division
        Channel 3 (Pink) – CFD Output, 500mV per division
        Channel 4 (Green) – Monitor Output, 100mV per division
The amplitude of the input pulse is given on the right-hand side of each figure where it says "Ch 2 Min."

Notice how the zero crossing on the monitor output for Figures 6-9 remains at about 40ns from the edge of the field of view, and the CFD output begins at about 47ns. This is an example of

how the timing of the zero crossing remains constant with amplitude and how the CFD timing is related to the timing of the zero crossing.

II. **Apparatus:**

A schematic of the apparatus we used to test the constant fraction discriminator is shown in Figure 10.
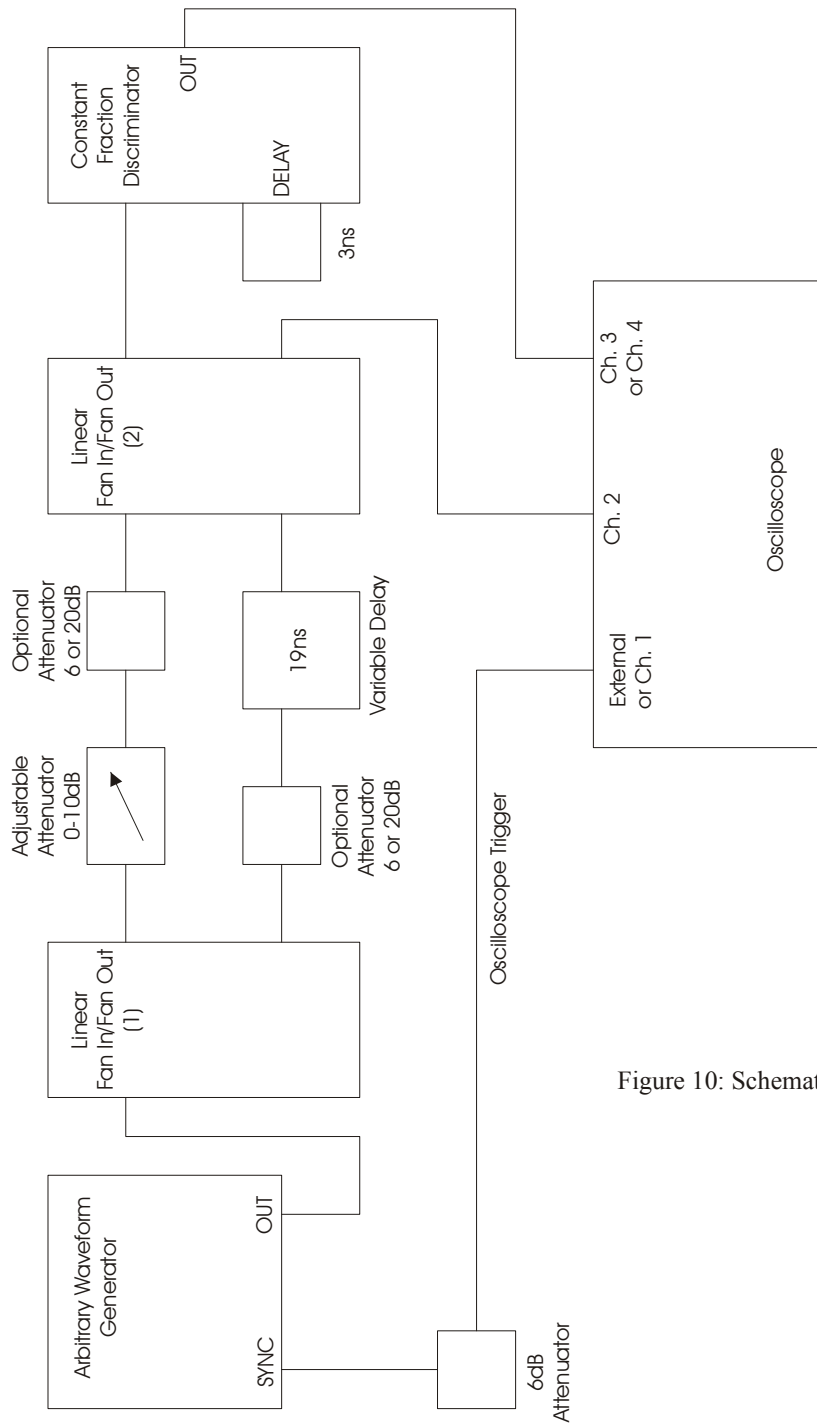
Figure 10: Schematic of Apparatus

First, the arbitrary waveform generator was used to generate the input pulse (Figure 11), which was to be a representation of what the output from the calorimeter in the HyperCP experiment would have looked like.
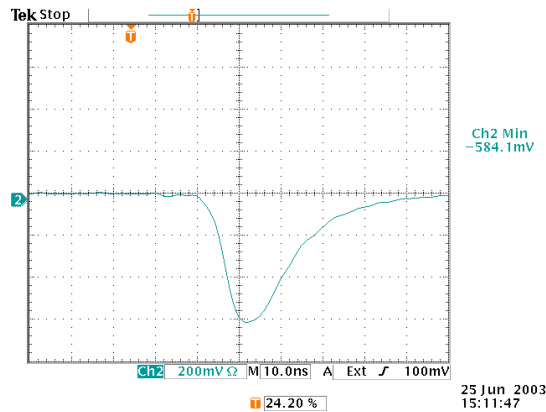
Figure 11: Input Pulse

We created the input pulse by using the oscilloscope to average the output of a photomultiplier tube responding to light produced in a scintillator exposed to ^{108}Ru. It has a rise time of about 10ns with a longer trailing edge and amplitude of about 600mV (584.1mV according to the oscilloscope). The SYNC output on the arbitrary waveform generator was mainly used as the trigger source for the scope, but it was also used in some circumstances as a reference to test the timing of the CFD output relative to attenuation to make sure it remained constant.

The first linear fan in/fan out (FI/FO) was only being used as a fan out, so that the input pulse can be split. One copy of the input pulse goes through the adjustable attenuator (0-10dB attenuation) and an optional attenuator of 0, 6, or 20dB; it becomes what I shall refer to as the "first pulse." The other copy of the input pulse also goes through an optional attenuator of 0, 6, or 20dB and then is delayed by 19ns; this becomes what I refer to as the "second pulse." Both of these pulses are used as inputs in the second linear fan in/fan out to create one double pulse as output (Figure 12).
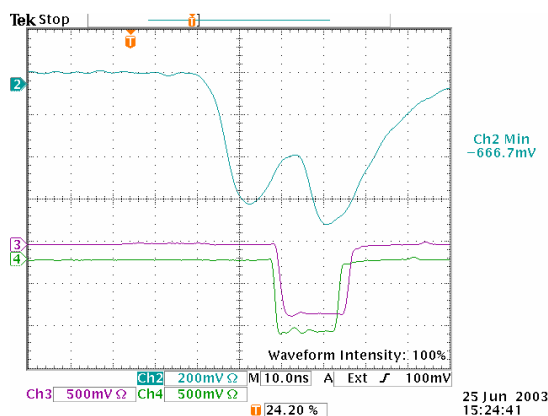
Figure 12: Double Pulse

This output from the second linear FI/FO was read out as channel 2 (blue) of the oscilloscope and is sent to the constant fraction discriminator, a Phillips Scientific Model 715. At some times,

output from the second linear FI/FO was sent to two different CFDs to compare the functionality of the two. One of the CFDs was an older one from Fermilab and its output is shown on channel 4 (green) of the oscilloscope when present. Then other CFD is a new one shown on channel 3 (pink) of the oscilloscope, which was first used on June 18, 2003, and behaves slightly better than the older CFD.

III. __Results__:

        The constant fraction discriminator is supposed to provide output whenever the input pulse (coming from the second linear fan in/fan out) is above the threshold of 275mV, the threshold used for the HyperCP CAL(Cas) trigger. In the case of our double pulse, the output from the CFD should be triggered off of the first pulse until it goes below threshold, then it should be triggered off of the second pulse. When the CFD changes which pulse it is firing off of, the timing of the output pulse should change by 19ns, the amount we delayed the second pulse by.

        However, this was not the case. For each CFD, there was a range of amplitudes of the first pulse for which it did not fire at all! For the new CFD, it stopped giving output when the first pulse was close to threshold, which occurred at about 285mV (Figures 13, 14, and 15).
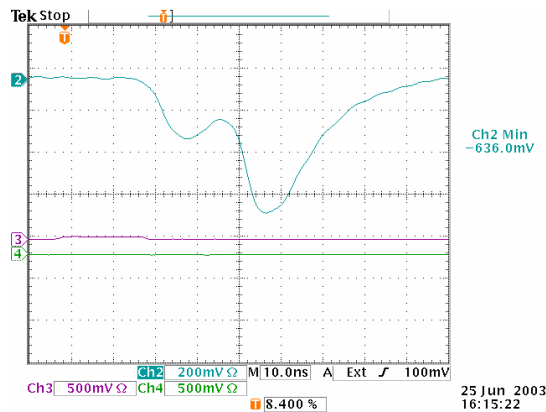

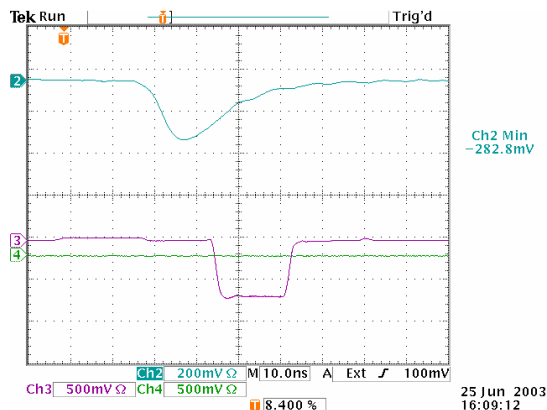Figure 13: Double Pulse, 7dB Attenuation on First Pulse

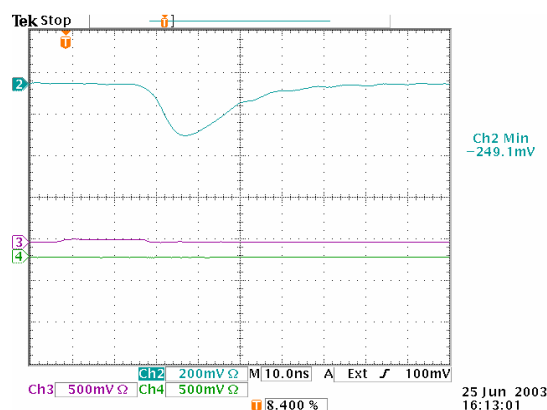Figure 14: First Pulse 7dB Attenuation   Figure 15: First Pulse 8dB Attenuation

In Figure 13, the first pulse is attenuated by 7dB. Even though the total pulse height for the double pulse is 636mV, clearly above threshold, we can see that both CFDs have stopped providing output. Figure 14 shows just the first pulse with 7dB attenuation and amplitude of 282.8mV, very close to threshold. Here we can see that the new CFD is still providing output, while the Fermilab CFD is not. Figure 15 shows only the first pulse with 8dB attenuation, and here we can see that both of the CFDs have stopped firing since the pulse, at 249.1mV, is below threshold.

The new CFD did not begin firing off of the second pulse until the first pulse had become much smaller, about 130mV in amplitude (Figures 16 and 17). The Fermilab CFD behaved in the same way, but the range of amplitudes for which it did not work was much larger, from about 315mV to 100mV.
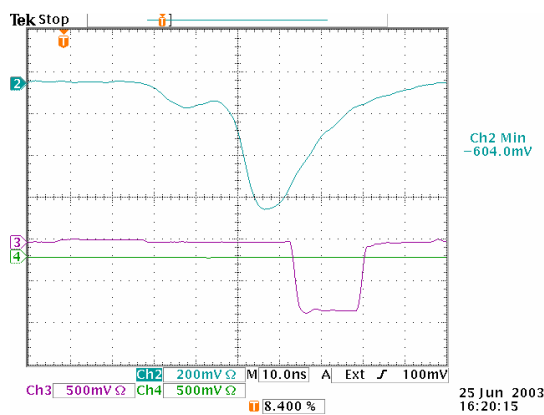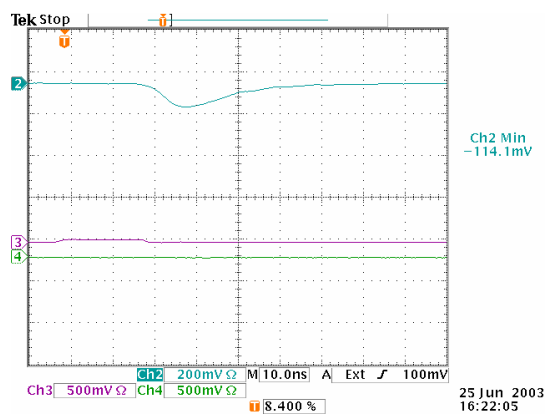

Figure 16: 15dB Attenuation on First Pulse   Figure 17: First Pulse 15dB Attenuation

For Figures 12-17: The x-axis is set at 10ns per division, y-axis specifications for each channel is given below with what each channel represents.
Channel 2 (Blue) – Input Pulse, 200mV per division
Channel 3 (Pink) – New CFD Output, 500mV per division
Channel 4 (Green) – Fermilab CFD Output, 500mV per division
The amplitude of the input pulse is given on the right-hand side of each figure where it says "Ch 2 Min."

In Figure 16, we can see that the timing of the output pulse has shifted about two divisions, 20ns, from where it had been in Figure 14, when we only had the first pulse as input. This shows that the CFD has begun triggering on the second pulse rather than the first one. Figure 17 simply shows the size of the first pulse when the CFD began to fire again, 114.1mV. Basically, the first pulse must be at least that small for the CFD to begin triggering on the second pulse.

Table 1, below, summarizes these results. Attenuation is listed in dB, and the amplitudes of the first and second pulses are each measured separately without the other one present. The output columns (New and Fermilab) give a simple yes or no value as to whether there was an output logic pulse from the CFD or not. The pink areas are the regions in which the new CFD failed to provide any output; this occurred between attenuations of 7dB and 13dB, roughly equivalent to a voltage range of 285mV to 150mV. The green areas are regions in which the

Fermilab CFD failed to provide output; this occurred between attenuations of 6dB and 16dB, which is roughly equivalent to a voltage range of 315mV to 110mV.

Attenuation (dB)	Amplitude (mV)		Output New CFD		Output Fermilab CFD	
	pulse 1	pulse 2	both	pulse 1	both	pulse 1
0	625	590	Y	Y	Y	Y
1	550	590	Y	Y	Y	Y
2	490	590	Y	Y	Y	Y
3	440	590	Y	Y	Y	Y
4	395	590	Y	Y	Y	Y
5	350	590	Y	Y	Y	Y
6	315	590	Y	Y	N	N
7	285	590	N	N	N	N
8	250	590	N	N	N	N
9	225	590	N	N	N	N
10	200	590	N	N	N	N
11	185	590	N	N	N	N
12	165	590	N	N	N	N
13	150	590	N	N	N	N
14	130	590	Y*	Y*	N	N
15	120	590	Y*	Y*	N	N
16	110	590	Y*	Y*	N	N
17	100	590	Y*	Y*	Y*	Y*
18	90	590	Y*	Y*	Y*	Y*
19	80	590	Y*	Y*	Y*	Y*
20	70	590	Y*	Y*	Y*	Y*

Table 1: Input Pulse Amplitude and CFD Output
Y: Output triggered on first pulse
Y*: Output triggered on second pulse
N: No output

Changing the amplitude of the second pulse has virtually no effect on the behavior of either CFD, although only data for the new CFD is shown below. A single pulse (Figure 18), a double pulse with no attenuation (Figure 19), and a double pulse with 20dB attenuation on the second pulse (Figure 20) all provide the same output from the CFD.
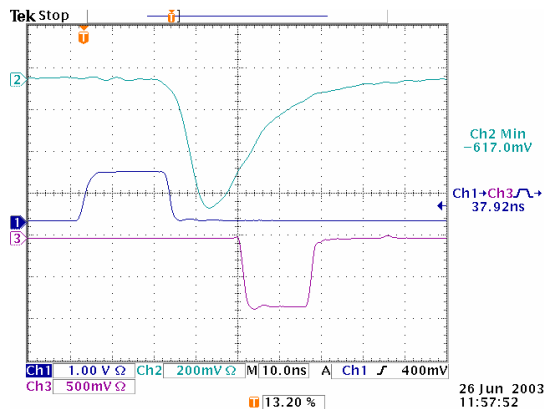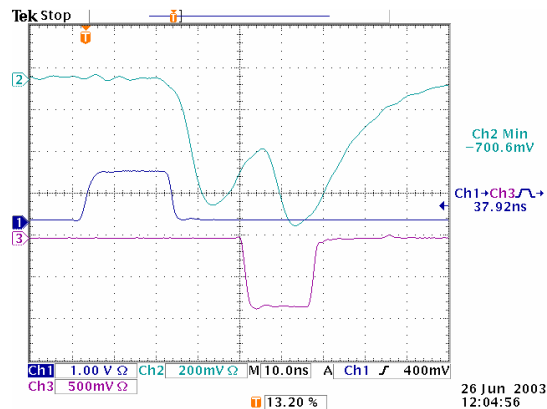
Figure 18: First Pulse Only
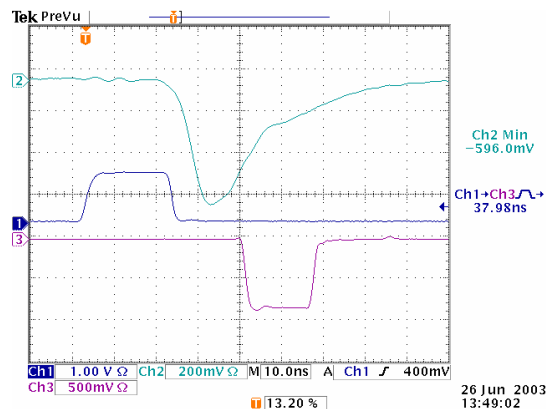

Figure 19: Double Pulse

Figure 20: 20dB Attenuation on Second Pulse

The timing of the CFD output for Figures 18-20 is all about the same. The delay between the rising edge of the SYNC output from the arbitrary waveform generator and the falling edge of the CFD is listed on the right-hand side of each figure, and is about 37.9ns for each. Therefore, the presence, nor the attenuation of the second pulse, affects the timing of the CFD output.

The CFDs also behave properly when the first pulse is far enough below threshold that they are firing off of the second pulse and the attenuation of the second pulse is varied. As before, the timing is unaffected to within about 1ns since the pulse has moved by about 20ns. In that case, the CFDs stop providing output when the second pulse has reached threshold, as expected. Figure 21 shows the double pulse with 20dB attenuation on the first pulse, where the attenuation on the first pulse is large enough that the CFD is triggering off the second pulse. Figure 22 shows the double pulse with 20dB attenuation on the first pulse and 7dB attenuation on the second. Here, the amplitude of the double pulse has reached 281.2mV, which is close to the set threshold value of 275mV, and the CFD has stopped firing.
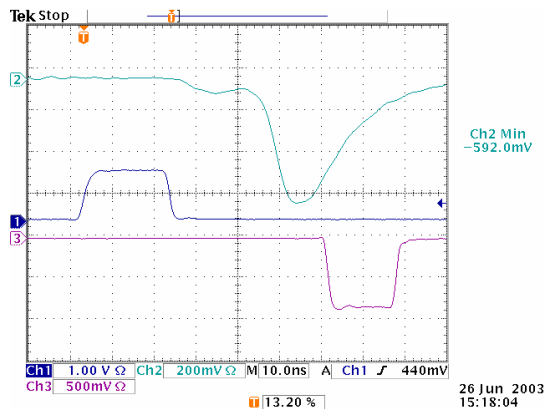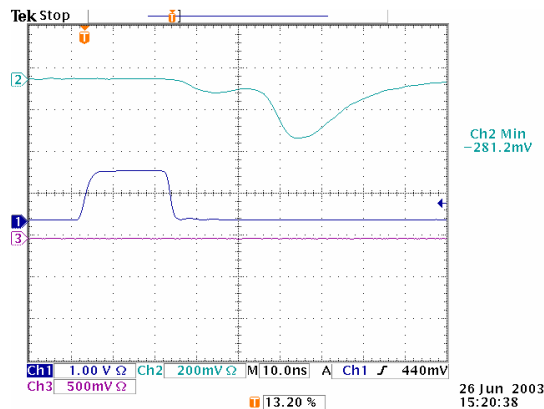
Figure 21: 20dB Attenuation on First Pulse

Figure 22: 20dB Attenuation on First Pulse, 7dB on Second

For Figures 18-22: The x-axis is set at 10ns per division, y-axis specifications for each channel is given below with what each channel represents.

Channel 1 (Dark Blue) – SYNC Output, 1.0V per division
Channel 2 (Blue) – Input Pulse, 200mV per division
Channel 3 (Pink) – New CFD Output, 500mV per division

The amplitude of the input pulse is given on the right-hand side of each figure where it says "Ch 2 Min." The delay between the rising edge of the SYNC and the falling edge of the CFD Output is also given on the right-hand side for figures 18-20.

IV. **Conclusion**:

The Phillips Scientific Model 715 Constant Fraction Discriminators that we used did not behave exactly as expected. When the constant fraction discriminators received two input pulses that were close together, 19ns apart, the constant fraction discriminator failed to provide an output in certain cases. If the first pulse were below threshold, yet larger than about 130mV for the new CFD, 100mV for the Fermilab CFD, the CFD would not fire, even if the second pulse were above threshold. This seems to be a problem with how quickly the constant fraction discriminator can discriminate pulses. In the cases where the CFD does not fire, it behaves as if it were only reading the first pulse, determining that it is below threshold, and does not even look at the second pulse. When the first pulse becomes small enough, the CFD is not able to discern that it is a separate pulse, and therefore is able to fire on the second pulse. In all other cases the CFDs behaved as expected, attenuating the second pulse has no effect on timing or output whether the first pulse is above or below threshold. It is only in the case of attenuating the first pulse that any inefficiency is discovered.