Lab1: Nuclear Electronics

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1 Statement of Purpose

The purpose of the Nuclear Electronics lab was to serve as an introduction to the equipment used in Nuclear and Elementary particle physics labs all around the world. This was helpful in allowing us to use the equipment prior to introducing a radioactive source and measuring actual physical phenomenon. Specifically, providing an opportunity to determine what to pay attention to when building experiments. In order to do so, we simulate the fast pulses we would expect to receive when making measurements. The physical phenomenon we expect to observe in this lab occur on such small timescales that it is important to simulate these signals with a pulse generator. We expect to learn how to use a Nuclear Instrumentation Module (NIM), as well as adding in additional units to perform other necessary signal processing and logical procedures. We also expect to learn about the effects that cabling can have on the signals we are observing, to understand the necessity of terminating a signal and wave-propagation theory.

2 Theory

2.1 Coaxial Cables

Figure 1: Cross-section of Coaxial Cable

Most of the cables used in this lab were BNC Cables, which are types of coaxial cables. Coaxial cables are composed of a central copper core, a dielectric insulator, woven copper shield, and outer plastic sheath. This configuration of materials allows for the isolation of the internal signal from external electromagnetic sources. The electromagnetic field in the wire, the signal, only exists in the space between the inner and outer conductors. With this design, we don't have to worry about where we place the cable relative to other electromagnetic sources.

2.2 Propagation Speed

The theory behind a signals propagation speed can be viewed in the framework of light traveling through different mediums. In our case, we know that the speed of light in a vacuum is a maximum in which nothing can travel faster. Therefore, in the case of our signal traveling a length of wire, we can infer that the signal's speed of propagation is some fraction of the speed of light, c. The formula for finding propagation speed in a medium is as follows:

$$V_p = \frac{c}{\sqrt{\epsilon_r \mu_r}}$$

where V_p is the speed of propagation, c is the constant speed of light, ϵ_r is the relative permittivity, and μ_r is the relative permeability. These two values can also be combined into one constant, κ, the dielectric constant of the medium. The standard coaxial cables usually have a value of $\mu_r = 1.00000037$ and $\epsilon_r = 2.25$. Plugging those values in gives us the theoretical value shown below:

$$V_p = \frac{c}{\sqrt{\epsilon_r \mu_r}} = \frac{c}{\sqrt{\kappa}} = 0.66c$$

Which is in agreement with what we are told by professor and TA, and will therefore be used as a comparison for calculated values later on.

2.3 Reflected Waves

When discussing reflected waves, it is helpful to think of the classical mechanics problem of a wave traveling down a string to either an open or fixed end. In both cases, we see reflection of the original wave. However, the shape of the reflected wave differs for each case. For a fixed end, the reflected wave will be inverted and traveling in the opposite direction (up the string), while for an open end, the reflected wave will have the original orientation (not inverted) and be traveling in the opposite direction (up the string). This reflected wave will always interfere with the original signal, unless we take extra steps to minimize this reflection.

In the context of our lab, this process describes impedance mismatch, which will cause interference due to reflected waves. This is the reason as to why we cannot directly plug a BNC cable directly into the oscilloscope. Due to the large impedance of oscilloscope ($1M\Omega$), there will be an inverted reflected signal sent back up the wire. This case would be akin to sending a wave down a string to a fixed end.

Taking all of this into account, we can define a ratio of the reflected voltage relative to the original (signal) voltage $\rho = \frac{V_r}{V_0}$. Using a little bit of math, we get the following relation:

$$\rho = \frac{V_r}{V_0} = -\frac{I_r}{I_0} = \frac{R - Z}{R + Z}$$

where I_0 and I_r are the original current and reflected current (respectively), R is the termination impedance, and Z is the cable impedance. We want to minimize ρ as much as possible. For example, if we use a cable with $Z = 75\Omega$ a terminator with $R = 50\Omega$, we get $\rho = -0.2$, and that $V_r = -0.2V_0$. However, if we were to plug a cable directly into the oscilloscope, we would use $R = 1E6\Omega$, giving us $\rho = 0.999$, showing that the reflected voltage is almost equal to original voltage (signal), resulting in a lot of interference.

3 Apparatus

There were a few different configurations used to perform the measurements in this lab. The following configuration describes the general configuration for finding the characteristic impedance as well as propagation speed of the mystery cable:

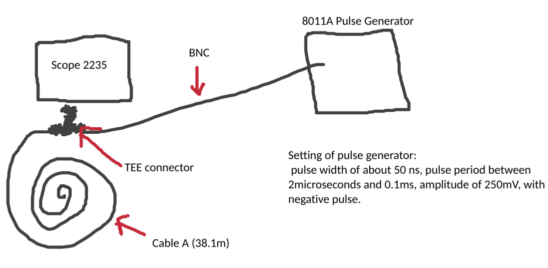

Figure 2: Configuration for mystery cable impedance and propagation speed

We also had a few other configurations when learning how to use the discriminator and logic units:

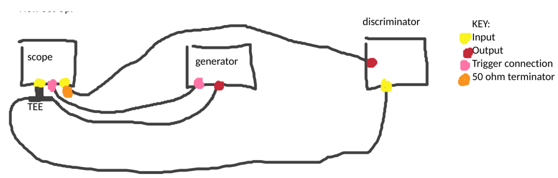

Figure 3: Configuration for Discriminator

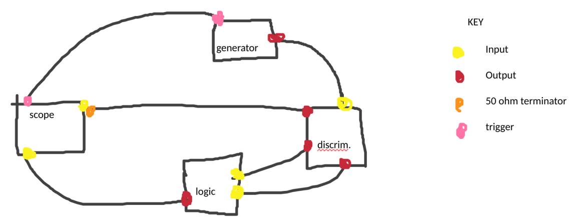

Figure 4: Configuration for Discriminator and Logic Unit

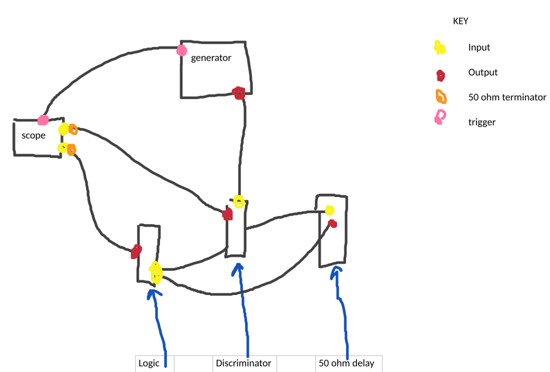

Figure 5: Configuration for Discriminator, Logic Unit, and Delay

4 Procedures

There were a few main concepts in this lab: Termination and Cable Impedance, Propagation Speed, and Discriminators and Logic Units. Termination and Cable Impedance had a similar procedure in determining propagation speed, so those procedures described first, followed by the procedures for Discriminators and Logic Units:

4.1 Termination and Cable Impedance

The general apparatus for this section can be viewed in Figure 2. Initially, the Pulse Generator was attached to directly to the oscilloscope (no termination). The signal generated was a negative square wave with a pulse width of $50ns$, a pulse period of $2\mu s$, and amplitude of $250mV$, shown in Figure 6. This configuration differed from Figure 2 in that the BNC cable was plugged directly into the oscilloscope, and there was no TEE connecting to a second cable.

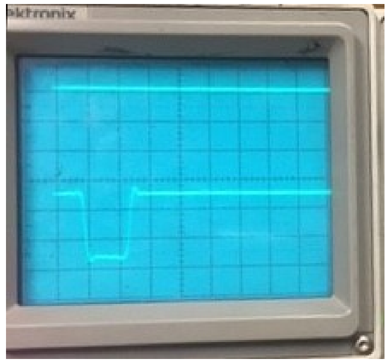

Figure 6: Signal from pulse generator w/ pulse width $50ns$, pulse period $2\mu s$, and amplitude $250mV$.

The next configuration added in a 50Ω terminator using a TEE connected on the oscilloscope. Figure 7 shows the signal on the oscilloscope, with and without a terminator. Adding the terminator resulted in a decrease in amplitude.

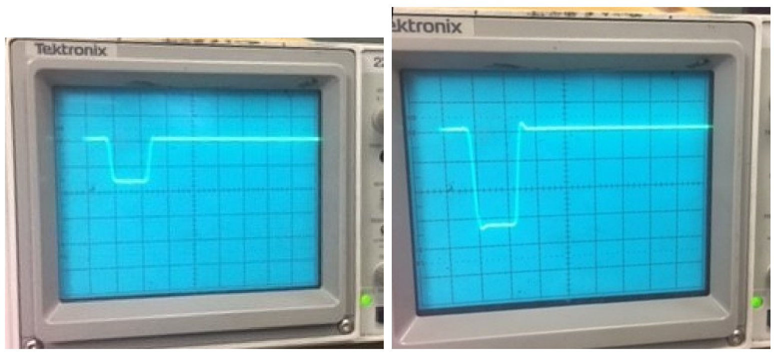

Figure 7: Left: With terminator. Right: Without terminator

We then replaced the 50Ω terminator with a $10ns$ cable, and used a pulse width of $20ns$ and $220ns$.

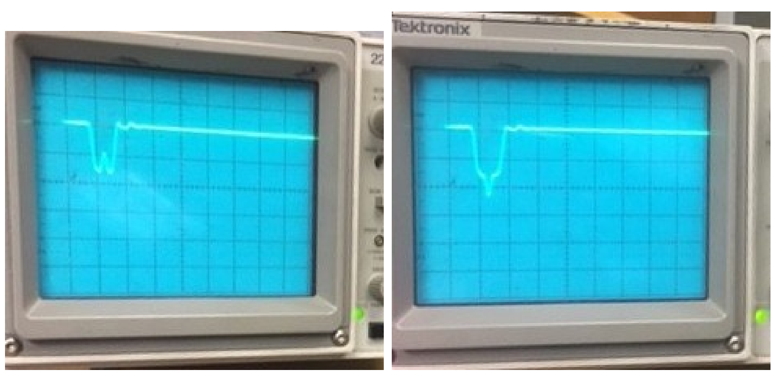

Figure 8: Left: $20ns$ pulse width. Right: $220ns$ pulse width

Finally, we added a 50Ω terminator at the end of the cable and recorded a few different pulse widths. What we see is a constant amplitude with an increasing pulse width.

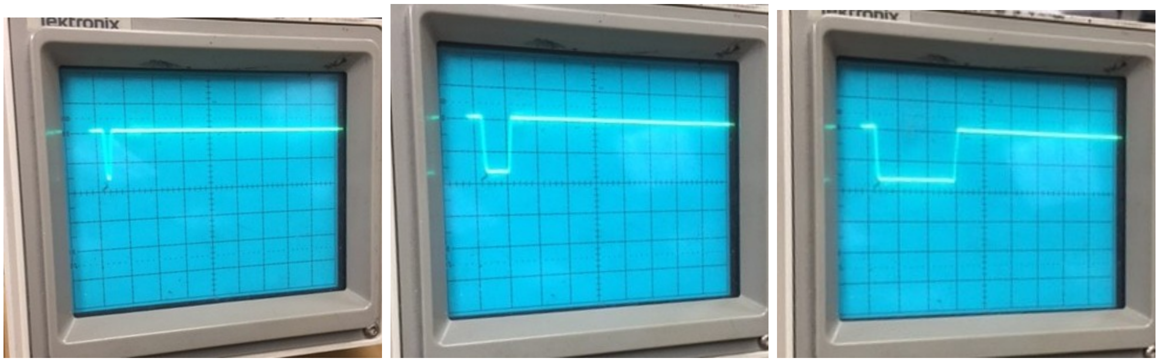

Figure 9: Left: $25ns$ pulse width. Middle: $415ns$ pulse width. Right: $610ns$ pulse width.

Using the prior mentioned procedures, we were able to validate that the signals received were expected based on the presence of a cable and terminator, as well as understand the effect that termination has on a signal. For the theory behind why we see the signals on the oscilloscope, refer to section §2.3

4.2 Propagation Speed

Next, we used a similar configuration, except replacing the cable coming out of the TEE connector with the "mystery" cable. Our task for this cable was to find the characteristic impedance of the cable.

In order to do so, we attached an adjustable termination box to the end of cable, and varied the termination on the box until we saw a complete cancellation of the signal on the oscilloscope. This signified that we had reached the impedance of the cable using the adjustable termination box, causing an inverted signal of the same voltage to travel down the cable, resulting in the cancellation seen on the oscilloscope.

The impedance of the adjustable termination box was then measured using a Digital Multi-Meter, and noted for each of our group members, resulting in three separate measurements for the characteristic impedance of the "mystery" cable. There is some systematic uncertainty in this step, in that the dial adjusting the termination box was very imprecise, as well as any fluctuations we may have seen on the oscilloscope. Determining the presence of cancellation was done through visual inspection, which could also be another source of systematic uncertainty.

With this same set-up, we were able to measure the propagation speed. We created a signal, shown below in Figure 10:

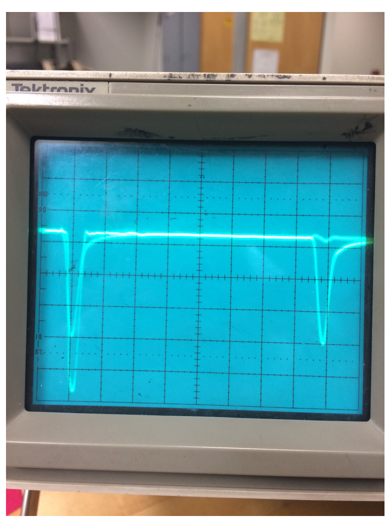

Figure 10: The original signal, as well as the reflected signal.

In order to determine the propagation speed, the time-separation between the reflected signal on the right and the original signal on the left was measured visually from the oscilloscope. However, it is important to note that the time-separation displayed on the oscilloscope is the duration it takes for the signal to travel twice the length of the cable, thus requiring a division by 2 to accurately measure propagation speed. Once this time was determined, the length of the cable was read off, and divided by the new propagation time to give a propagation speed.

This procedure is inherently uncertain in that the time-separation was measured using visual inspection, rather than some timed readout through some other device.

4.3 Discriminator and Logic Unit

The entire previous configuration used to determine propagation speed was taken down, and replaced with the configuration shown in Figure 3.

At this point, most of the data for this lab had been collected. The next procedures were used to gain experience and an understanding of how discriminators and logic units worked. The discriminator used was the LeCroy 821 Quad Discriminator with a threshold range of $-30mV$ to $-1000mV$, a maximum pulse rate of $110MHz$, pulse width range of $5ns$ to $1\mu s$, and a $9.5ns$ output delay. The other discriminator available for use was a Phillips 704, with threshold range from $-10mV$ to $-1V$, greater than $300MHz$ maximum pulse rate, pulse width range of $2ns$ to $50ns$, and a less than $8ns$ output delay.

A negative square wave was generated using the pulse generator, and the threshold on the discriminator was initially varied, and then settled upon $400mV$. The below pictures show the signal generated by the discriminator (bottom signal) after varying the threshold.

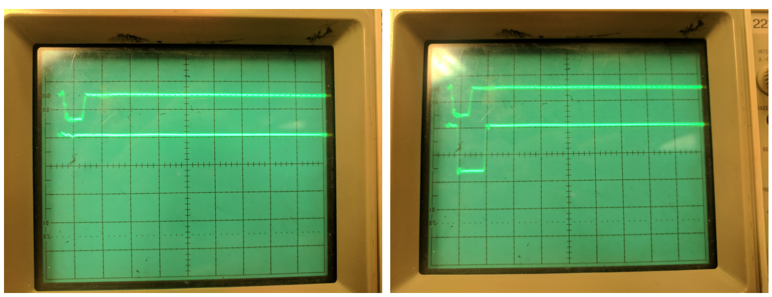

Figure 11: Left: Threshold set to generate no signal. Right: Threshold set to generate signal.

Next, we attached the logic unit and experimented with the results of different configurations. We learned how to create specific gates (OR, AND, NOT, NOR) using different numbers of inputs (from 1 to 4). The signals generated were very similar to the signals generated by the discriminator depending on the configuration of inputs, and will not be reproduced here.

Finally, we determined the maximum delay in which the logic unit could compare two input signals, using the configuration in Figure 5. Stringing together different cables and essentially adding in more delay (on top of the cable delay), we were able to delay the output signal from the input, shown below.

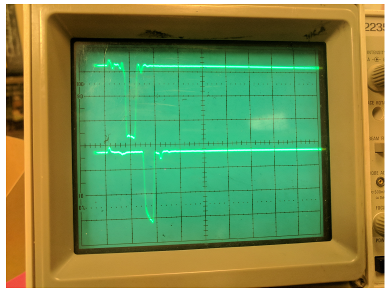

Figure 12: The top signal shows the original signal, while the bottom signal shows the signal after it has been delayed $19ns$.

5 Data

A few sets of data were collected: The characteristic impedance of the "mystery" cable, as well as the propagation speed of the "mystery" cable.

Table 1: Propagation Speed Measurements and Calculations

Cable Length	Time-Separation	Propagation Speed	Error
$23.65m$	$0.125\mu s$	$1.89E8\frac{m}{s}(0.631c)(1.61\frac{ns}{ft})$	5.33%
$1.93m$	$10ns$	$1.9E9\frac{m}{s}(0.64c)(1.6\frac{ns}{ft})$	3.4%
$38.1m$	$0.195\mu s$	$1.95E9\frac{m}{s}(0.642c)(1.56\frac{ns}{ft})$	2.24%

The error mentioned in Table 1 is relative to the theoretical value of $\frac{2c}{3}$ as confirmed in § 2.2, and by professor and TA.

Table 2: Characteristic Impedance of Mystery Cable ($38.1m$)

Diego	Lily	Dan	Average	Uncertainty(1σ)
69.5Ω	73.7Ω	72.5Ω	71.9Ω	± 1.77

6 Analysis

6.1 Characteristic Impedance of Mystery Cable

The data for characteristic impedance of the mystery cable consist of three data points taken by each group member. These three values were then averaged, and presented with a one standard deviation uncertainty. The averaging was simple $(69.5 + 73.7 + 72.5)/3 = 71.9$. The standard deviation is then calculated using:

$$\sigma = \sqrt{|x - \bar{x}|^2}$$

These were the only calculations necessary for the characteristic impedance and termination section of the lab.

6.2 Propagation Speed

After collecting the time separation data through visual inspection, the propagation speed was calculated using simple python code to easily switch between units with the help of the Astropy package members Astropy.units and Astropy.constants, and the defined functions below:

```
def calc_speed(distance ,time):
    speed = distance/time
    return speed

def calc_error(speed):
    tru_speed = (2./3.)*const.c
    err = abs(speed - tru_speed)/tru_speed
    return err

def meterspsec_to_nspfoot(v):
    inverse_v = 1./v
    inverse_v = inverse_v.to(u.ns/u.imperial.foot)
    return inverse_v
```

The "*calc_speed*" function is pretty self-explanatory and does not require further explanation. However, "*calc_error*" calls on a few other functions and variables, mainly "abs" and "const.c", where "abs" returns the absolute value of its argument, and "const.c" is the speed of light, set to $c = 2.9979246$ x $10^8 \frac{m}{s}$. This function compares the input value to the theoretical value calculated in § 2.2 and confirmed by professor and TA.

Finally, the "$meterspsec\_to\_nspfoot$" function stands for "meters per second to nanoseconds per foot" and inverts the input velocity "v", and convert the value to $\frac{ns}{ft}$ using the "$inverse\_v.to$" method. Using these few calculations, functions, methods, and variables, the values in Table 1 were added. There were no graphs to be made or distributions to be fitted, due to the small samples of data collected. However, for visualizations of our experimental process, including most of the traces seen on the oscilloscope, refer to section §4.

7 Results

The results can be viewed above in Tables 1 and 2, as well as throughout the procedures. Since much of this lab consisted of little data gathering, the focus of this lab was to become comfortable using the equipment as well as learnign what to expect. This is important so as to minimize the amount of time required to set up an apparatus when observing the effects of a radioactive source. Due to the constant hazard of working with radioactive sources, this lab is essential in practicing minimizing exposure time.

The precision used for the Characteristic Impedance measurements were held at three significant figures, so the calculations performed are only presented to three significant figures. However, our average value was a bit off from the characteristic impedance reported by the manufacturer of 75Ω, giving us an error of 4.1%. So thankfully, we weren't too far off.

As for the precision of our propagation speed measurements, this varied from cable to cable, most notably in the cable length and time-separation. The lowest number of significant figures was used for the $1.93m$ cable, due to its fast time-separation of $10ns$. Therefore, we used two significant figures for those calculations. Then calculated values for the other two cables following the same pattern, in that they all use the minimum number of significant figures present in each measured parameter. Both the $23.65m$ and $38.1m$ cables use three significant figures in their calculations.

8 Discussion

The results mentioned in the past few sections are very close to theoretical or reported values. For the characteristic impedance of the mystery cable, much of the measuring or conditions were determined by eye (visual inspection), which is inherently incredibly uncertain. This can explain our large variance of values between 69.5Ω and 73.7Ω. Yet all of our measured values are below the reported value. This might indicate a systematic error lurking within our configuration. During our class discussion, one student suggested there might be a significant difference in measuring the impedance of the adjustable termination box using the digital multimeter based upon the box's orientation (verticle versus horizontal). However, this was discussed after the experiment had concluded and could not be tested.

As for the propagation speed, each calculated value was compared to the theoretical value of $2c/3$. Our percent error is relatively small for each cable, our maximum being 5.33%, and minimum 2.24%. These are incredibly close to the quoted theoretical value, so we can conclude that our results are in agreement with the theory. However, during our class discussion, my presentation partner Austin brought up the possibility of differences in propagation speed between a coiled and straight cable. Unfortunately, I was unable to find sources to validate this claim.

Overall, our measured and calculated values very closely agree with theoretical or manufacturer reported values. If we wanted to improve on this further, we would find ways to more precisely determine the measured values, perhaps by using an instrument that could provide a readout rather than our use of estimation through visual inspection. We could also test whether or not the measured impedance of the adjustable termination box varies with orientation. Both of these steps would be immensely helpful in reducing our uncertainties. Nevertheless, this experiment was a sucess.

9 References

[1] Leo, W.R.; Techniques for Nuclear and Particle Physics; Second Edition; p. 263, 273, 269-279
[2] Phillips Scientific; Quad 300MHz Discriminator; p1
[3] Teledyne LeCroy; LeCroy 821 Quad Discriminatorl p1 p2