Experiment 10

The Speed of Light c

10.1 Introduction

In this experiment you will measure the speed of light, c. This is one of the most fundamental constants in physics, and at the same time the fastest quantity you'll ever measure! By using short pulses of light and a high speed detector you will determine c with good accuracy (few %) in a *direct* time-of-flight (TOF) measurement over distances of only one to two meters.

10.2 Apparatus

Warning! This experiment uses a photomultiplier tube (PMT) that will be ruined if exposed to ambient light when at operating voltages. Please be careful - the PMT must never be exposed to any bright light source while its high voltage is turned on. Permanent damage will result!

A schematic of the set-up is shown in Fig. 10.1. The circuit in Fig. 10.2 sends out short (few nanosecond) light pulses via a green LED (light emitting diode) at frequencies around $f \sim 10kHz$. This frequency is determined by the external dc power supply (150 to 200 Vdc, please do not exceed 200 V!). These light pulses are detected with a PMT which requires negative high voltage in the range of 1800 to 2400 V.

This high voltage is applied to the photomultiplier tube (PMT). The photocathode has a thin layer of a photosensitive substance, typically antimony-cesium alloys. The photocathode will emit a number of electrons proportional to the intensity of light that it receives. These photoelectrons are accelerated by the potential applied between the cathode and the first of a series of electrodes called dynodes. A typical PMT will contain ten to fourteen dynodes. The first dynode is maintained at a positive potential with

respect to the photocathode. Each subsequent dynode is kept at about the same potential difference with respect to the preceding one. The electrons that are emitted from the photocathode are attracted to the first dynode and acquire enough kinetic energy to free additional electrons as they collide with the dynode (secondary emission). This charge multiplication process occurs at each dynode. After the last dynode stage, the electrons are collected at the anode of the tube. The output of the PMT is
therefore a negative current pulse. Our PMT actually has negative HV applied to the photocathode while the anode is grounded. However, this does not change the basic physics of the device.

A pulse from the LED pulser labelled 'start' in Fig. 10.2 and the anode (not dynode!) pulse from the PMT (with some time delay cable) are sent to the start and stop input of a time-to-amplitude (TAC) converter, respectively. The TAC generates an output voltage pulse whose amplitude is proportional to the start-stop time difference, as long as this time difference is within the range selected by a front panel knob. The TAC output is analyzed by a Multichannel Analyzer (MCA), the basic function of which is described at the end of this handout.

This experiment contains an important source of a systematic error which, if not very carefully corrected for, could easily ruin your results quite dramatically. The phenomenon is known as 'time walk', and it plays an important role in high resolution timing experiments in nuclear and particle physics. The principle is shown in Fig. 10.3. If a device (like our TAC) triggers at a fixed voltage or discriminator level, its triggering time will occur later for smaller pulses than for larger pulses, even if the maximum pulse amplitude is reached at the same time. We are assuming here that the pulse rise time remains constant, i.e. is independent of pulse amplitude. In our application this time walk occurs because the PMT signal increases in amplitude as the LED assembly is moved closer to the PMT. Explain why this is the case.

In order to compensate for this PMT amplitude change we have polarizers mounted in front of the LED and the PMT. By rotating the PMT relative to the LED assembly you can change the amount of light hitting the photocathode thereby keeping the output amplitude constant. **NOTE:** it is extremely important for good results to take *all* data points at one and the same PMT amplitude.

10.3 Procedure

1. Familiarize yourself with the hardware. Note that the TAC has a threshold of -250 mV and requires a $\Delta t > 2$ nsec.

2. With a HV of around 1800 to 2000 V for the PMT, the anode amplitude should be

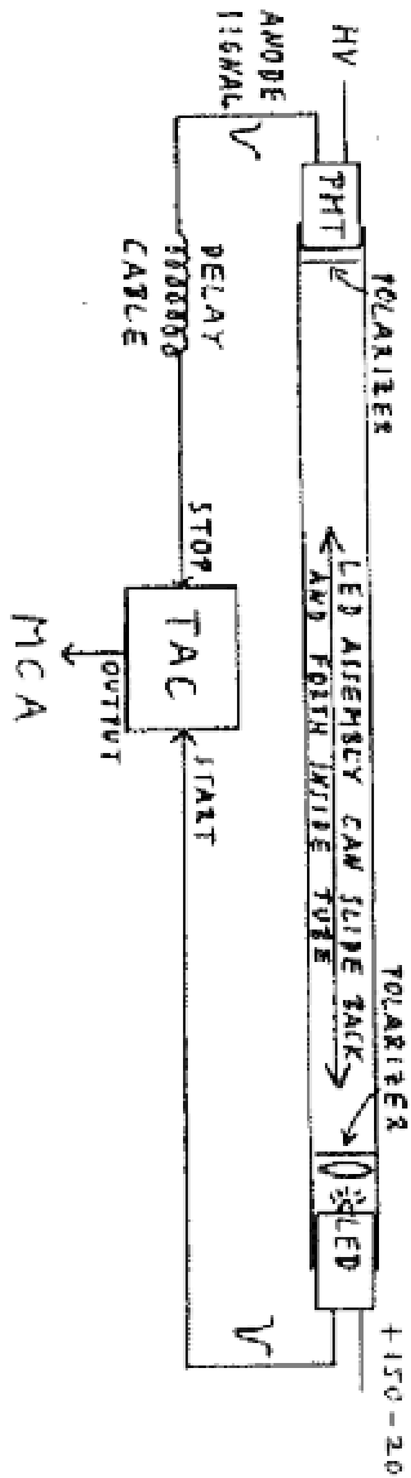

Figure 10.1: Schematic of Speed of Light Apparatus.

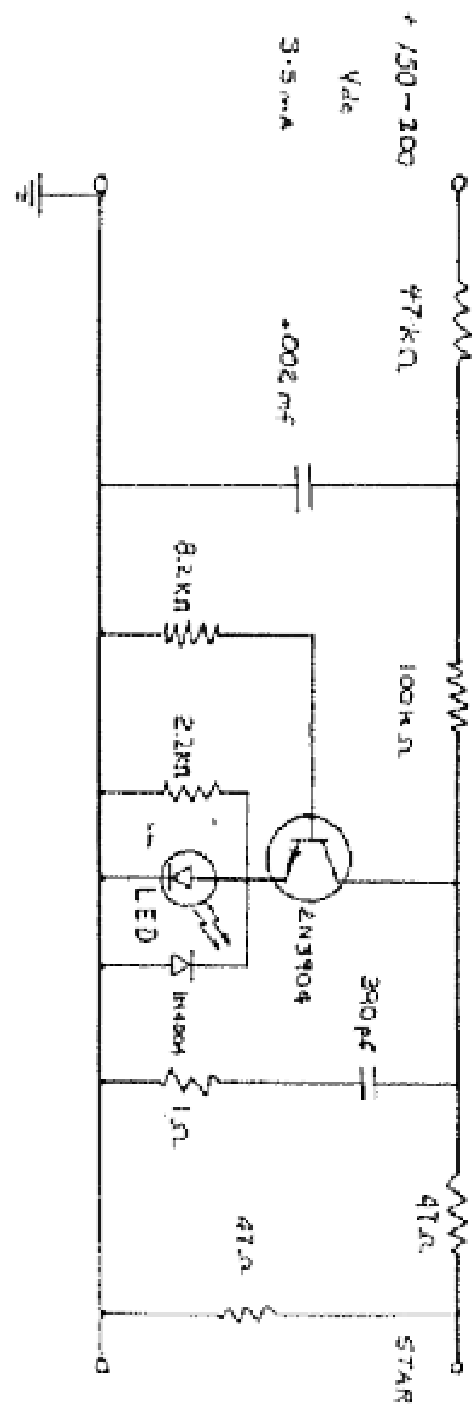

Figure 10.2: Speed of Light LED-pulsing Circuit.

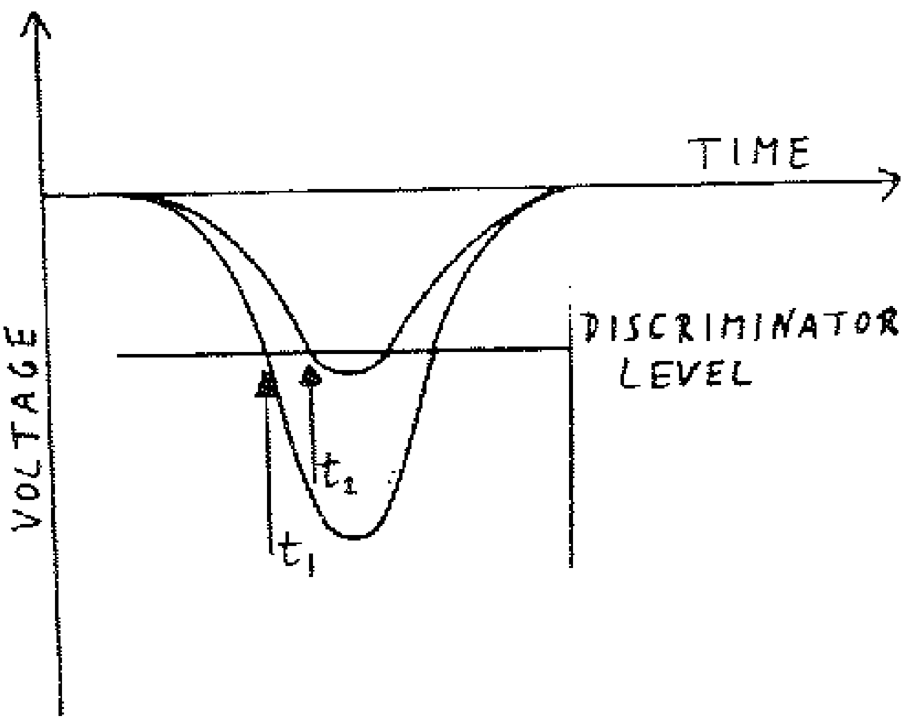

Figure 10.3: Illustration of 'time walk'.

several volts (into 50Ω), even at large distances between LED and PMT. If this is not the case, you need to adjust the relative alignment of LED/lens assembly and PMT. The polarizer should be set for maximum amplitude at the largest distances.

3. Using the oscilloscope, look at both start and stop signals for the TAC simultaneously, and make sure there is sufficient delay between them. Then take some data.

4. Calibrate your system, i.e. by inserting several different cables of known delay, or using a delay box, determine the number of picoseconds per channel. Your time resolution (Full Width at Half Maximum or FWHM of your peak) should be better than 1 ns. Think about this remarkable fact in terms of the distance that light travels in 1 ns! Measure and report your time resolution. In addition, check the linearity of your calibration.

5. Measure the systematic uncertainty due to the time walk. First, estimate the precision to which you can hold the amplitude constant (the uncertainty in the amplitude). Find a way to *measure* the systematic uncertainty on the value of c due to this uncertainty in amplitude. For your measurements, choose a value for the amplitude that will minimize the systematic uncertainty.

6. Take the following data:

   - Measure several times over a short ($\sim 25\ cm$) change in distance and compare the results, including error, with data taken over a *much* larger change in distance ($\sim 150\ cm$). Which set of data would you expect to give better results, and why?
   - Take data at successively larger (or smaller, depending upon where you start) distances and determine c and its error from a least squares fit to your x versus t curve. For a comparison take a few data points without the time walk correction, and determine c from those.
   - Summarize and compare your results (incl. their errors) for c from an overall mean, from your linear least squares fit, and also from your data taken without the time walk correction. What conclusions do you draw?

7. By using error propagation show that the relative error in c is dominated by the time resolution σ_t, and not by the position resolution σ_x.

8. If you are using the PCA3 software as part of your MCA system, CTRL+F2 will erase all data. If you happen to press F2 without holding down CTRL, CTRL+F2 will *not* work until F2 is pressed a second time.

10.4 References

[1] Melissinos and Napolitano
[2] Canberra Model 2044 Time Analyzer manual (available in the lab).
[3] W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd ed., 1994, Springer.