Neutron Monitor Workshop 1(A): Detector Physics and Analog Electronics

Mahidol University

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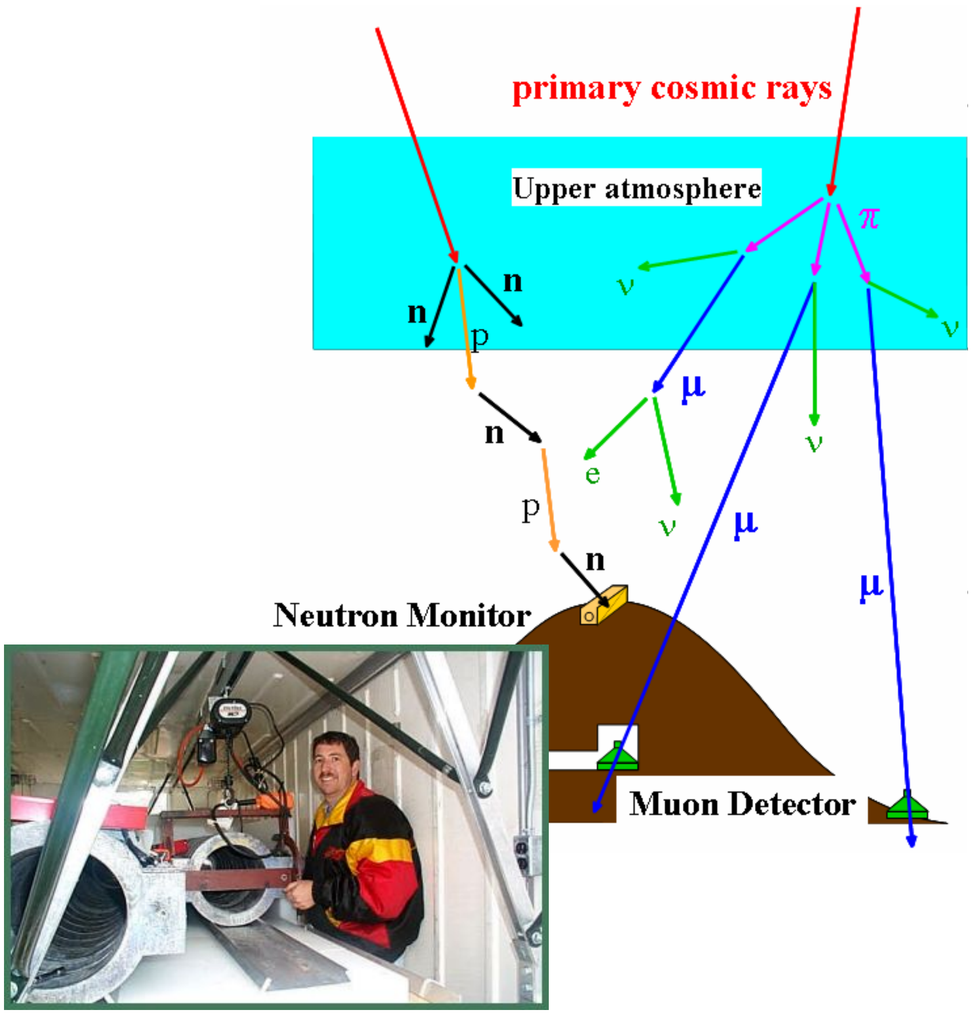
Workshop Series Idea

- Introduce students to technical aspects of neutron monitor operation
- Rotating workshop series that will repeat every two years at a two per year rate
- Independent enough so students can join at any point
- Accommodate wide skill range with an emphasis on “hands on” experience and individual discussion

Workshop Series Plan

1. Detector operation
   A. Detector Physics and Analog Electronics
   B. Art and Science of Soldering
2. Digital Circuits (including theory of the peripheral devices like the barometers).
3. Microcontrollers (including data transfer methods within the electronics system)
4. Real time data acquisition
   A. Principles of Telemetry and Data Acquisition
   B. Data Conversion and Manipulation with Visual Basic

Neutron Monitors

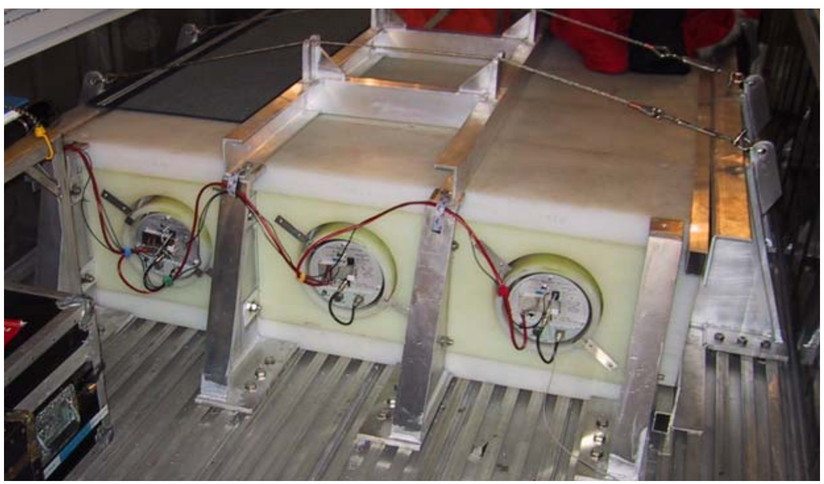


High energy cosmic rays are rare. Observing them at high time resolution requires a large detector.

Ground based instruments remain the state-of-the-art method for studying these elusive particles.

Neutron monitors on the surface record the byproducts of nuclear interactions of high energy primary cosmic rays with Earth's atmosphere.

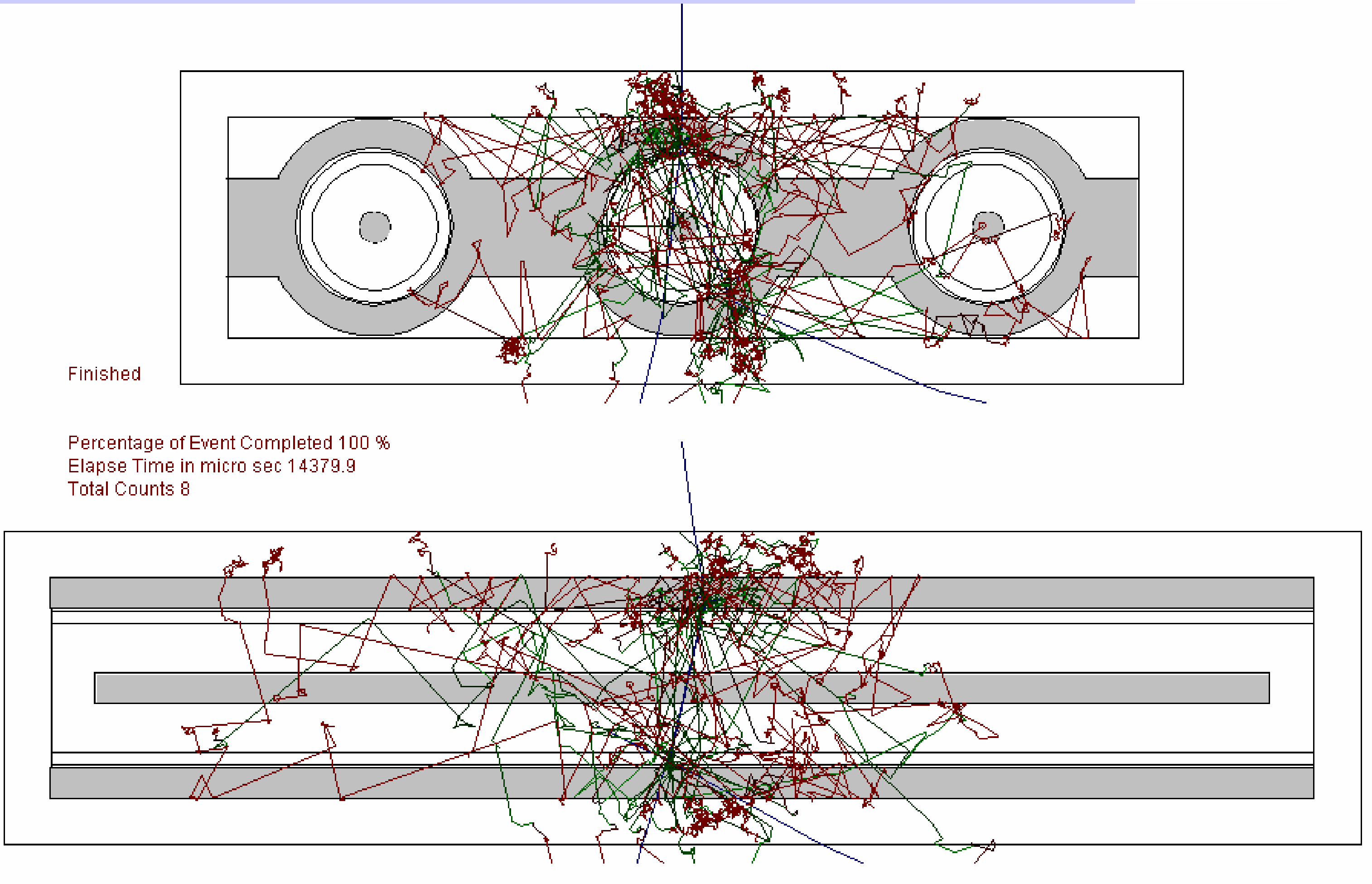
Neutron Monitor Principle



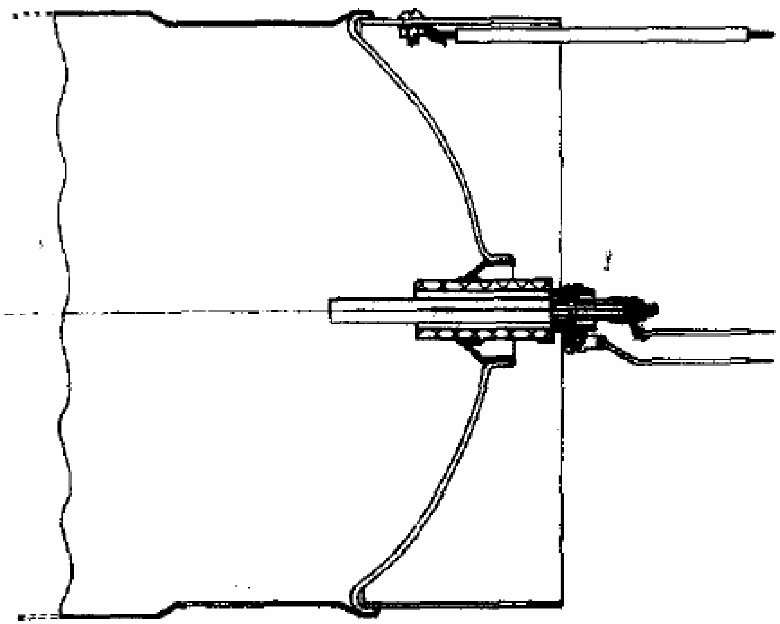
- An incoming hadron interacts with a nucleus of lead to produce several low energy neutrons.
- These neutrons thermalize in polyethylene or other material containing a lot of hydrogen.
- Thermal neutrons cause fission reaction in a ^{10}B (^{7}Li + ^{4}He) or ^{3}He (^{3}H + p) gas proportional counter.
- The large amount of energy released in the fission process dominates that of all penetrating charged particles. There is essentially no background.

Simulated Interaction In a Neutron Monitor

http://www.bartol.udel.edu/~clem/nm/display/intro.html

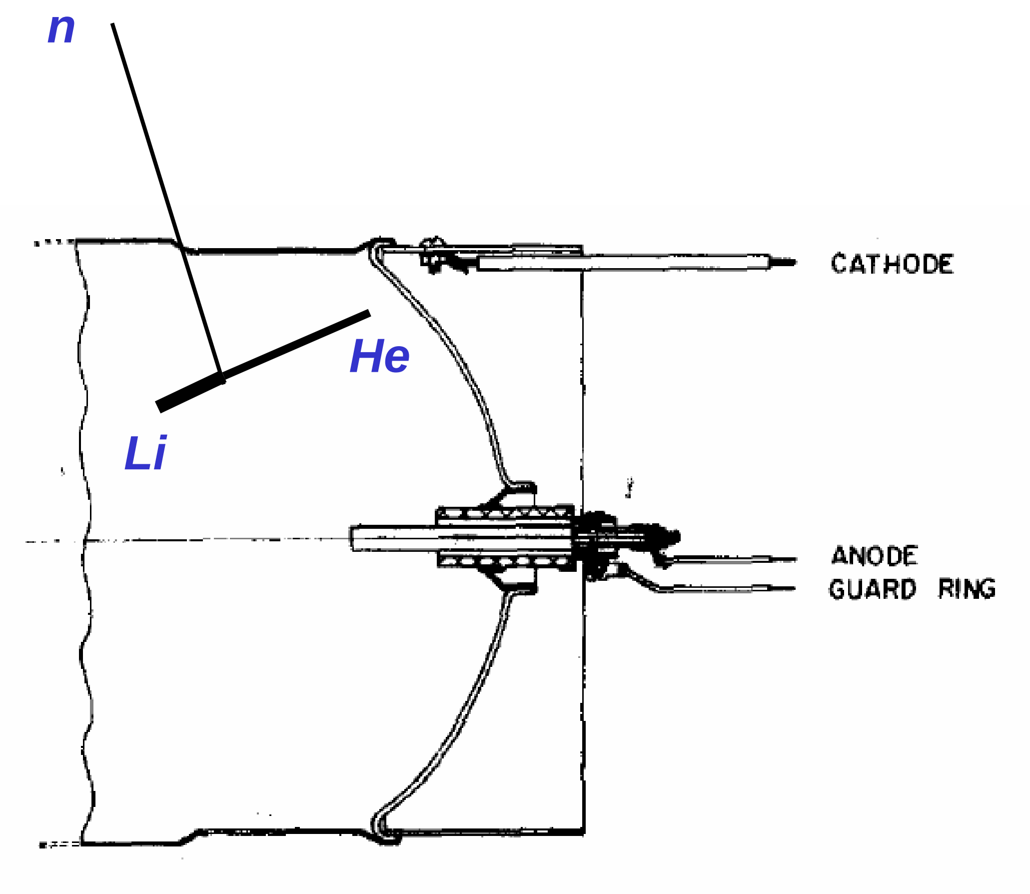


BP-28 Neutron Detector



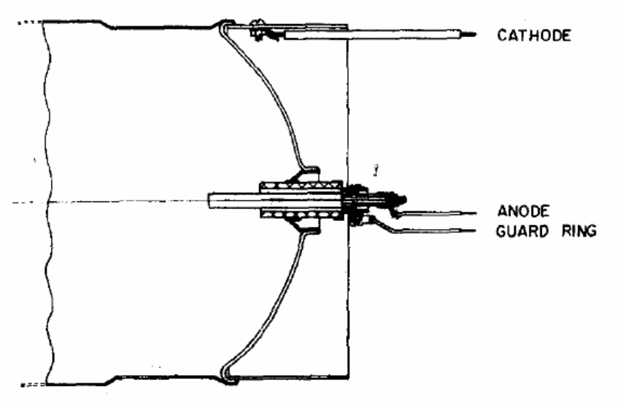
- Stainless steel cylinder 1.90 m long and 15 cm diameter
- Filled to 20 cmHg with 96% enriched $^{10}BF_3$
- 0.2 mm diameter anode wire
- Capacitance is about 20 pF

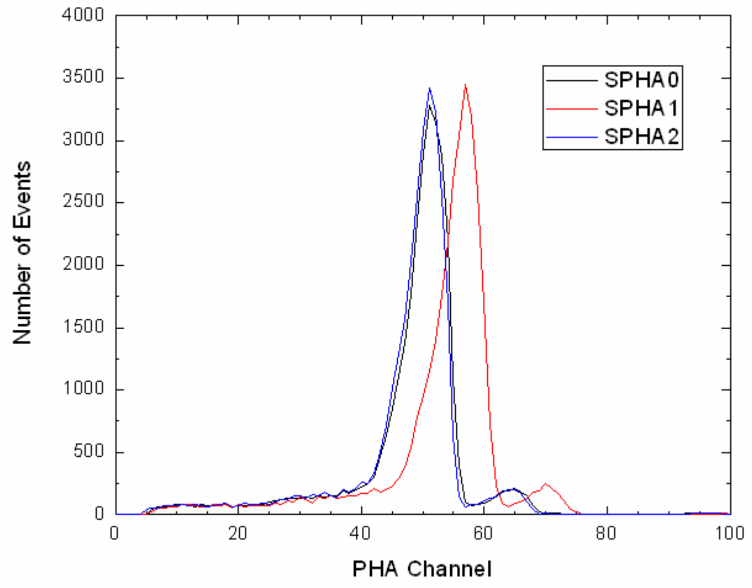
BP-28 Neutron Detector



- ^{10}Boron has a huge cross section for neutron absorption
- It then splits into ^{7}Li and ^{4}He (an alpha particle)
- Unlike ^{235}U you cannot make a bomb out of it because no secondary neutrons are produced

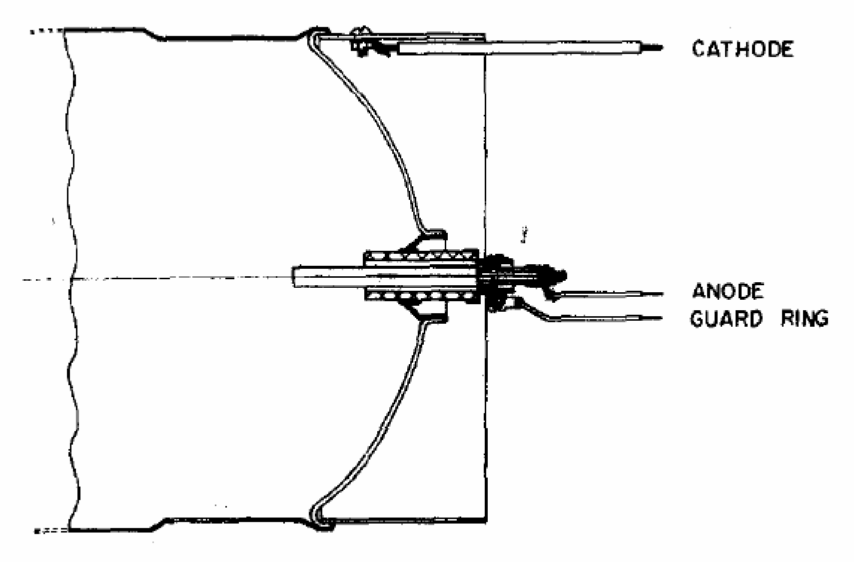
BP-28 Neutron Detector





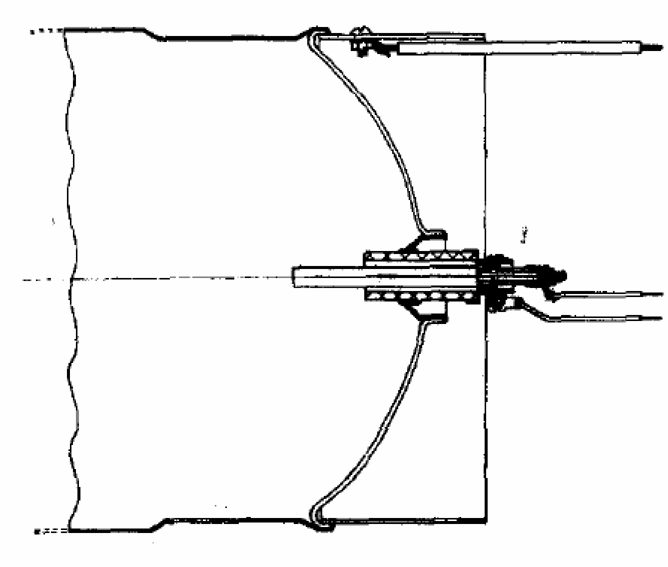
- About 94% of the reactions leave the ^{7}Li in an excited state, releasing 2.30 MeV of kinetic energy
- About 6% go directly to the ground state, releasing 2.78 MeV
- This can produce about 2×10^5 free electrons
- Most of the kinetic energy appears in the alpha particle
- The alpha particle can hit the wall of the detector and not deposit all of its energy

BP-28 Neutron Detector



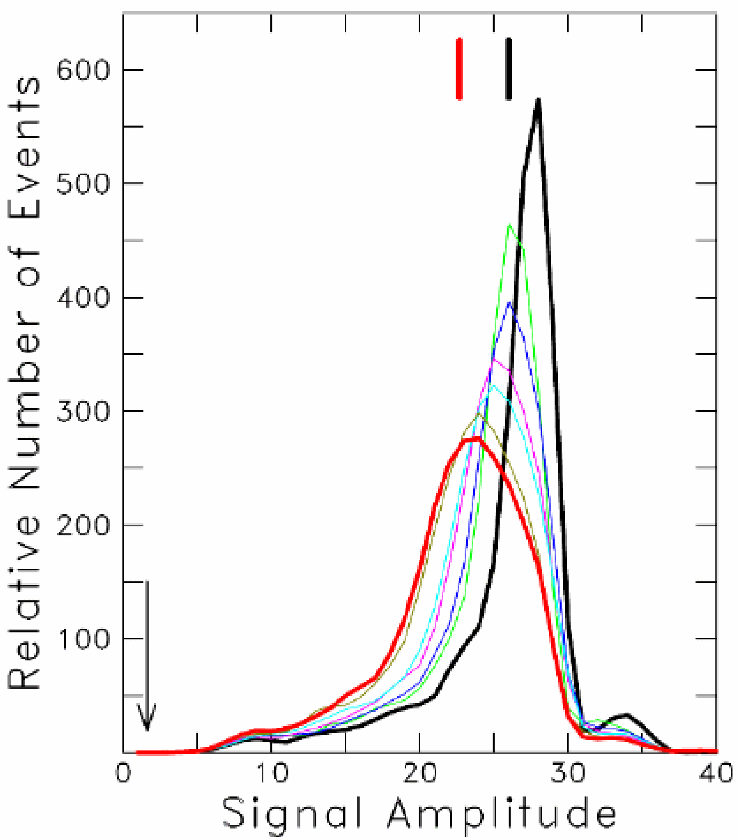
- The cathode is maintained at about negative 2.8 kilovolts
- The anode is near ground
- Electrons drift toward the anode in the resulting electric field
- Using V=Q/C this would produce a signal of about 1.5 millivolts

BP-28 Neutron Detector



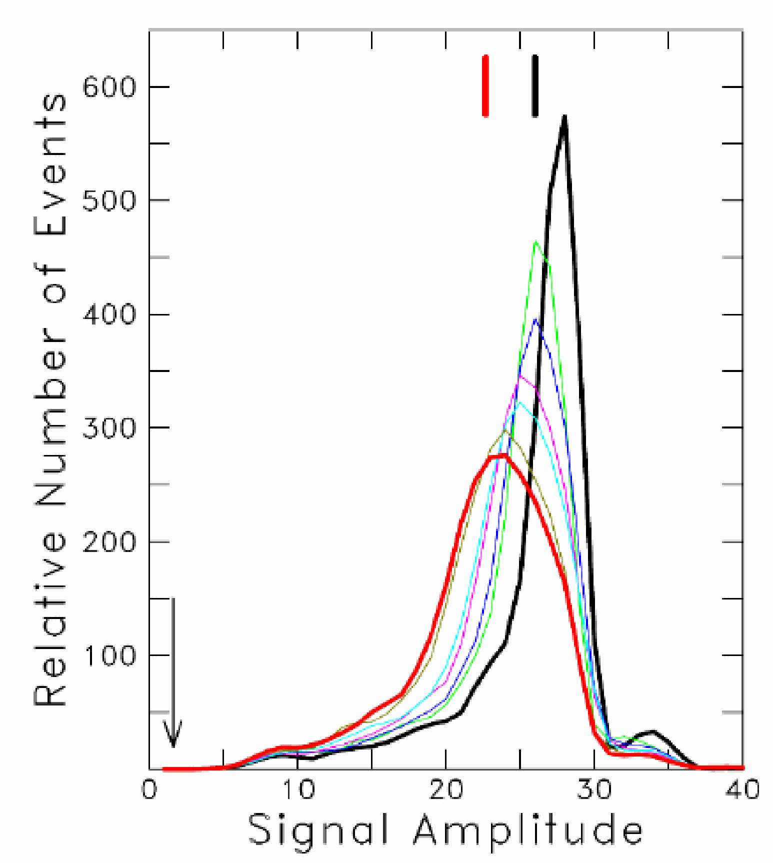
- Actually the signal is amplified somewhat in the strong electric field very near the wire
- Electrons ionize the gas, producing a cascade
- For appropriate potentials, the amplification is **proportional**
- The gain is approximately 20 for the tube in the micromonitor

BP-28 Tubes Degrade With Age



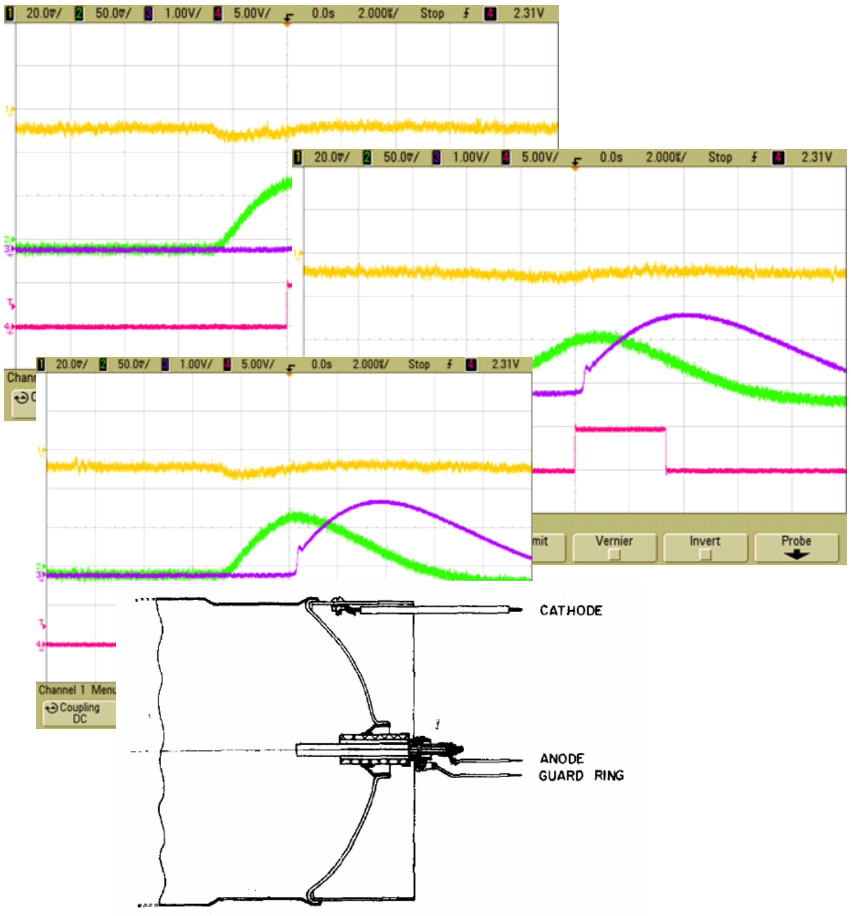
- Spectra taken annually from one of the neutron detectors used at South Pole are shown from the installation of the detector in 1997 (thick black curve) to 2003 (thick red curve)
- The curves are normalized so that all have equal area.
- Each ionization cascade dissociates some of the BF3 and material “plates out” non uniformly on the anode wire, increasing its effective diameter
- Larger diameter → lower field and less amplification

BP-28 Tubes Degrade With Age



- The South Pole monitor had a very high count rate so the process there is rapid
- Despite the broadening of the resolution, the average pulse height has only been reduced by 13% over this interval (vertical lines).
- Because few events have pulse heights near the counting discriminator (arrow), the tube degradation has a negligible impact on count rate.
- This tube should still have a long useful life at the lower count rates on Doi Inthanon, where it now lives

Signal Examples

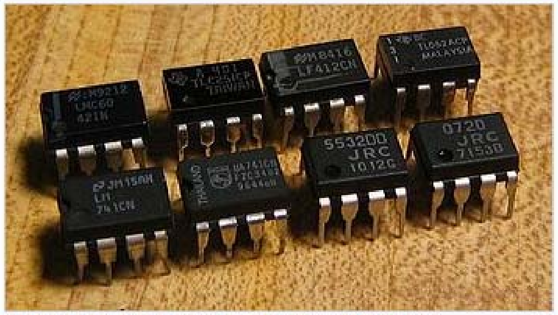


- The primary signals (orange) are all different because the path of the alpha particle is randomly oriented
- If the path is parallel to the wire, nearly all the charge arrives at once
- If it is perpendicular to the wire there is a spread of arrival times
- Our problem is to process these signals so they become uniform (green then blue)
- Then we can produce reliable digital signals (red) to count the interactions
- Now we discuss how to do this

Operational Amplifiers

- To understand electronic circuits fully, it is still necessary to know how resistors, capacitors, transistors, etc., work
- For many purposes, however, the basic building block today is the integrated “operational amplifier”
- The following discussion is mostly extracted from the Wikipedia article

Operational Amplifier



Various op-amp ICs in 8-pin dual in-line packages ("DIPs")

An **operational amplifier**, which is often called an **op-amp**, is a DC-coupled high-gain electronic voltage amplifier with differential inputs[1] and, usually, a single output. Typically the output of the op-amp is controlled either by negative feedback, which largely determines the magnitude of its output voltage gain, or by positive feedback, which facilitates regenerative gain and oscillation. High input impedance at the input terminals and low output impedance are important typical characteristics.

Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices. Many standard IC op-amps cost only a few cents in moderate production volume; however some integrated or hybrid operational amplifiers with special performance specifications may cost over $100 US in small quantities.

Circuit Notation

The circuit symbol for an op-amp is shown in Figure 1

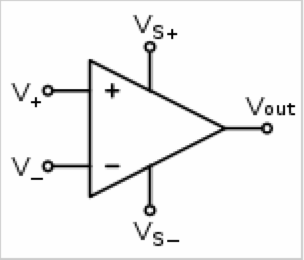


Figure 1: Circuit diagram symbol for an op-amp

where:

- V_+ : non-inverting input
- V_- : inverting input
- V_{out}: output
- V_{S+} : positive power supply
- V_{S-} : negative power supply

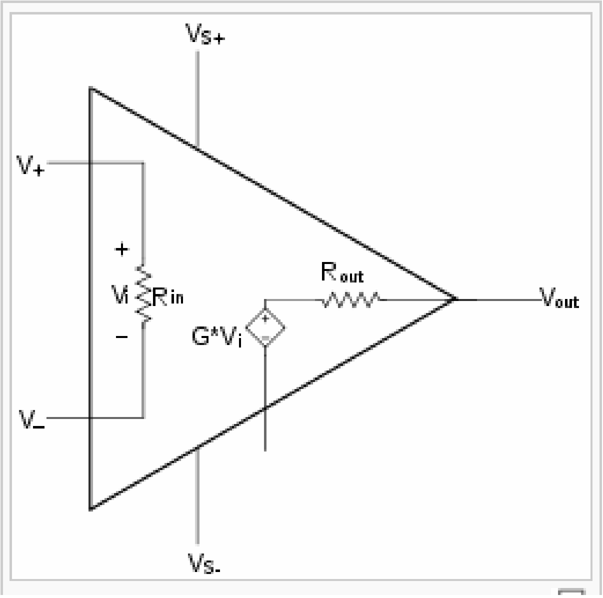
The power supply pins (V_{S+} and V_{S-}) can be labeled in different ways (*See IC power supply pins*). Despite different labeling, the function remains the same. Often these pins are left out of the diagram for clarity, and the power configuration is described or assumed from the circuit.

Ideal Operational Amplifier

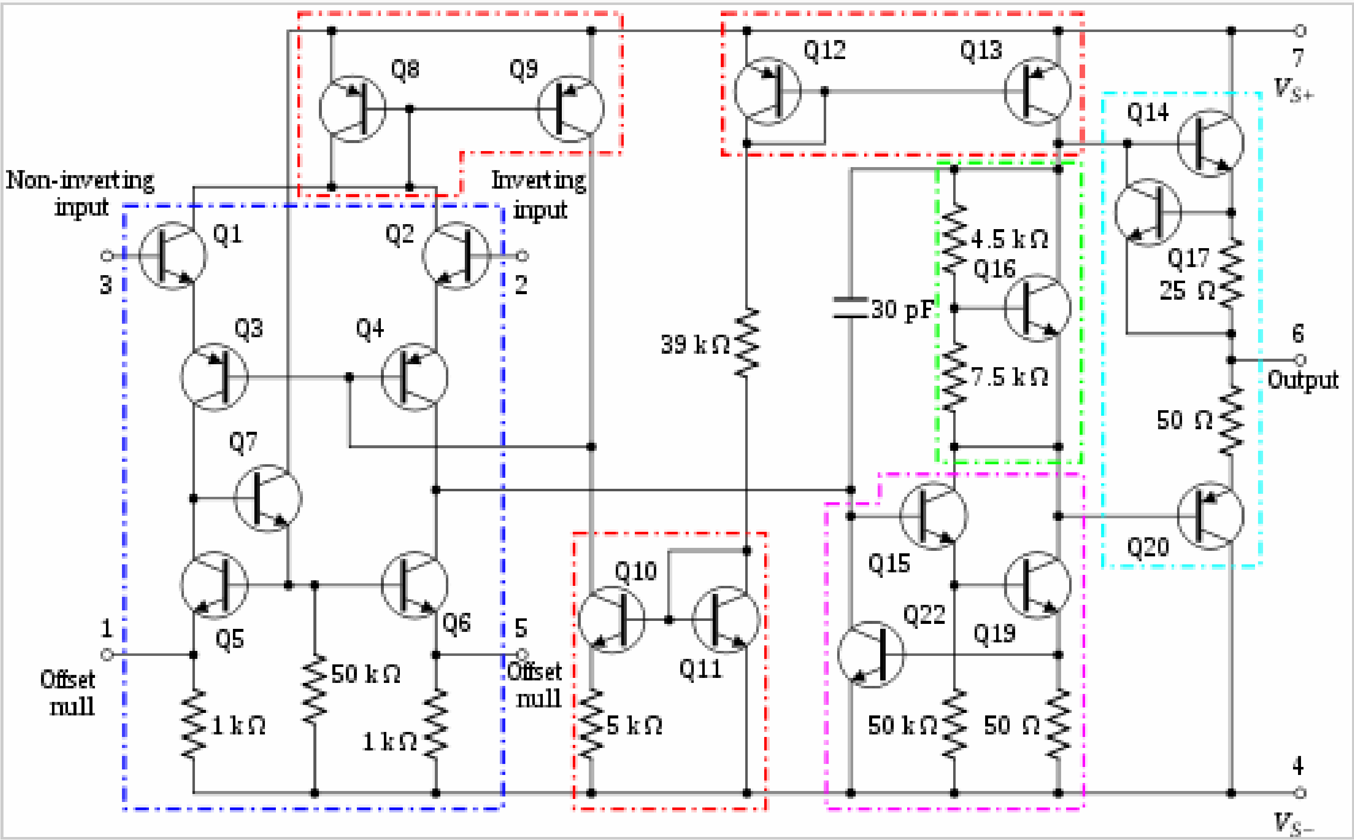
Shown on the right is an example of an ideal operational amplifier. The main part in an amplifier is the dependent voltage source that increases in relation to the voltage drop across R_{in}, thus amplifying the voltage difference between V_+ and V_-. Many uses have been found for operational amplifiers and an ideal op-amp seeks to characterize the physical phenomena that make op-amps useful.

For any input voltages the *ideal* op-amp has

- infinite open-loop gain,
- infinite bandwidth,
- infinite input impedances (resulting in zero input currents),
- zero offset voltage,
- infinite slew rate,
- zero output impedance, and
- zero noise.



How Sausage is Made …



A component level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

Basic Non-inverting Amplifier Circuit

The general op-amp has two inputs and one output. The output voltage is a multiple of the difference between the two inputs (some are made with floating, differential outputs):

$$V_{\text{out}} = (V_+ - V_-) \cdot G_{\text{openloop}}$$

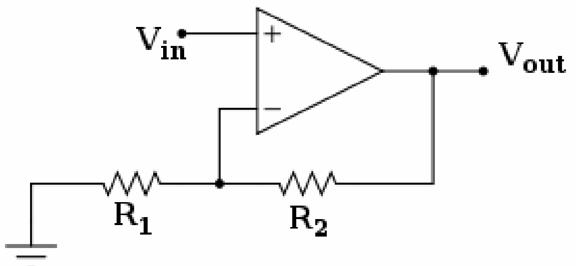
G is the open-loop gain of the op-amp. The inputs are assumed to have very high impedance; negligible current will flow into or out of the inputs. Op-amp outputs have very low source impedance.

If the output is connected to the inverting input, after being scaled by a voltage divider:

$$K = \frac{R_1}{R_1 + R_2}$$

then:

$$V_+ = V_{in}$$
$$V_- = K \cdot (V_{out})$$
$$V_{\text{out}} = G \cdot (V_{\text{in}} - K \cdot V_{\text{out}})$$



Solving for $V_{\text{out}} / V_{\text{in}}$, we see that the result is a linear amplifier with gain:

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{G}{1 + G \cdot K}$$

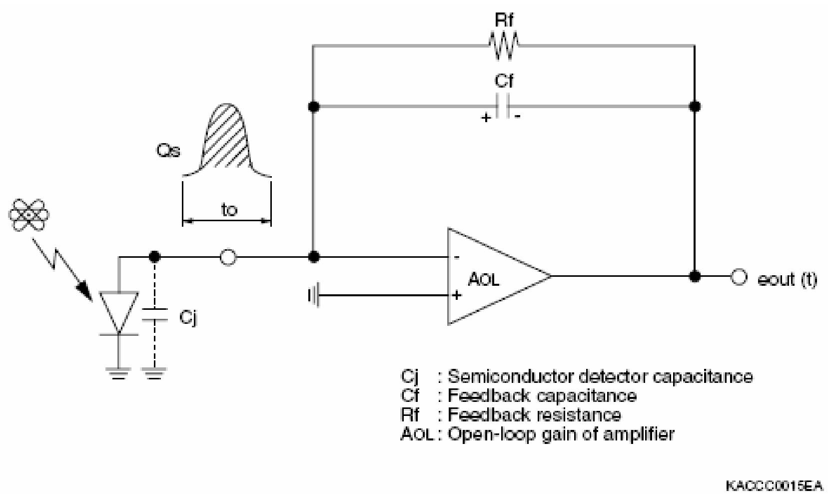
If G is very large, $V_{\text{out}} / V_{\text{in}}$ comes close to $1 / K$, which equals $1 + (R_2 / R_1)$.

- Key Concepts:
  - Because the gain is "infinite" it does not matter what the gain is
  - Properties of the circuit are determined by external components

What We Really Need …

- We really don’t want simply to amplify the voltage on the wire, we want to integrate the charge as it accumulates
- This can be done by including capacitors as feedback elements to produce a charge sensitive amplifier
- The following is from a Hamamatsu document

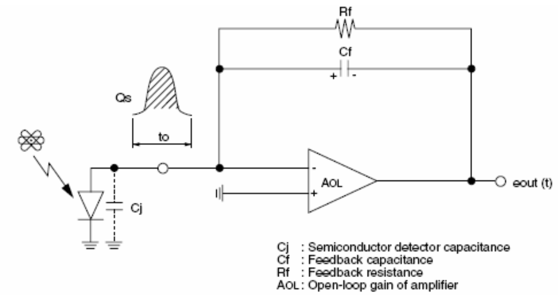
Charge Sensitive Amplifier Principle of Operation



When soft X-rays or gamma rays strike for example a Si semiconductor detector, signal charge pulses *Qs* are generated, with an amplitude according to the particle energy. Due to this charge generation, the input-end potential of the charge amplifier rises and at the same time, a potential with reverse polarity appears at the output end. However because the amplifier's open-loop gain is sufficiently large, the output-end potential works through the feedback loop so as to make the input-end potential zero instantaneously.

- The key concept here is that of a **virtual ground**
- All of the charge is drained from the wire
- The total charge extracted is integrated and held by Cf

CSA Details



As a result, the signal charge pulses *Qs* are all integrated to the feedback capacitance *Cf* and then output as voltage pulses *eout(t)*. At this point, since the feedback resistance *Rf* for direct current is connected in parallel to the feedback capacitance *Cf*, the output becomes voltage pulses that slowly discharge with the time constant determined by $\tau = Cf \cdot Rf$.

If a detector provides a constant charge generation over a time interval t=0 to *to*, the output signal charge *Qs* is given by the following equation using the Laplace transform.

$$Qs\,(S) = Qs\left(\frac{1}{S} - \frac{e^{-Sto}}{S}\right) \qquad \text{.....}\ (2\text{-}1)$$

Similarly, the transmission coefficient *T(S)* is given by

$$T\,(S) = -\frac{1}{Cf} \cdot \frac{1}{S + \frac{1}{\tau}}\ (\tau = Cf \cdot Rf) \qquad \text{.....}\ (2\text{-}2)$$

Thus the output voltage *V(S)* is expressed using Eqs (2-1) and (2-2) as follows:

$$V\,(S) = Qs\,(S) \cdot T\,(S) = Qs\left(\frac{1}{S} - \frac{e^{-Sto}}{S}\right) \cdot \frac{1}{Cf} \cdot \frac{1}{S + \frac{1}{\tau}}$$

$$= -\frac{Qs}{Cf}\left(\frac{1}{S} \cdot \frac{1}{S + \frac{1}{\tau}} - \frac{e^{-Sto}}{S} \cdot \frac{1}{S + \frac{1}{\tau}}\right)$$

$$\text{.....}\ (2\text{-}3)$$

As a result, the output voltage pulse *eout(t)* is given by

$$eout\,(t) = -\frac{Qs}{Cf} \cdot \frac{1 - e^{-t/\tau}}{to/\tau} \qquad 0 \leq t < to$$

$$= -\frac{Qs}{Cf} \cdot \frac{(e^{to/\tau} - 1)}{to/\tau}\, e^{-t/\tau} \qquad to \leq t \qquad \text{.....}\ (2\text{-}4)$$

Because generally $to \ll \tau$, Eq (2-4) can be simplified as follows:

$$eout\,(t) = -\frac{Q}{Cf}\, e^{-t/\tau} \qquad \text{.....}\ (2\text{-}5)$$

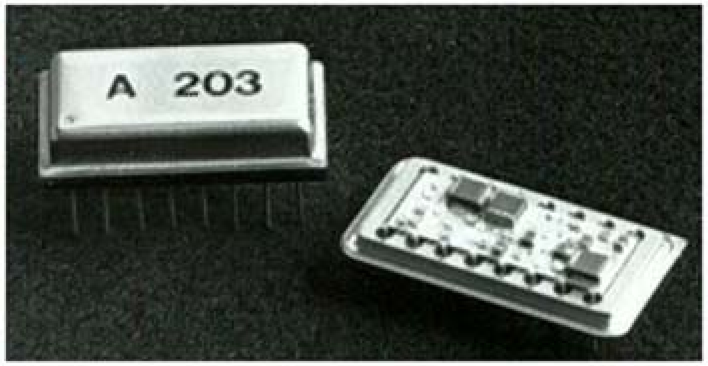
As can be seen from Eq (2-5), the signal charge pulses *Qs* are converted into voltage pulses with amplitude $Vout = -\frac{Qs}{Cf}$, which is damped with time constant $\tau = Cf \cdot Rf$.

The gain of amplifier *Gc*, referred to also as “charge gain”, is given by the following equation:

$$Gc = \frac{Vout}{Qs}\left(= \frac{1}{Cf}\right)\ [\text{V/coulomb}]\ \text{or}\ [\text{V/pico coulomb}]$$

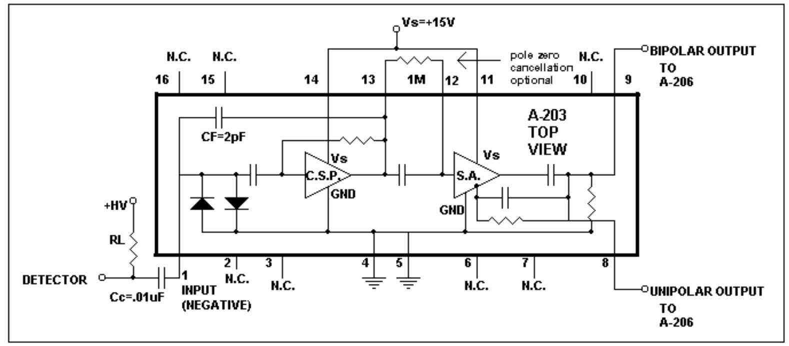
$$\text{.....}\ (3\text{-}1)$$

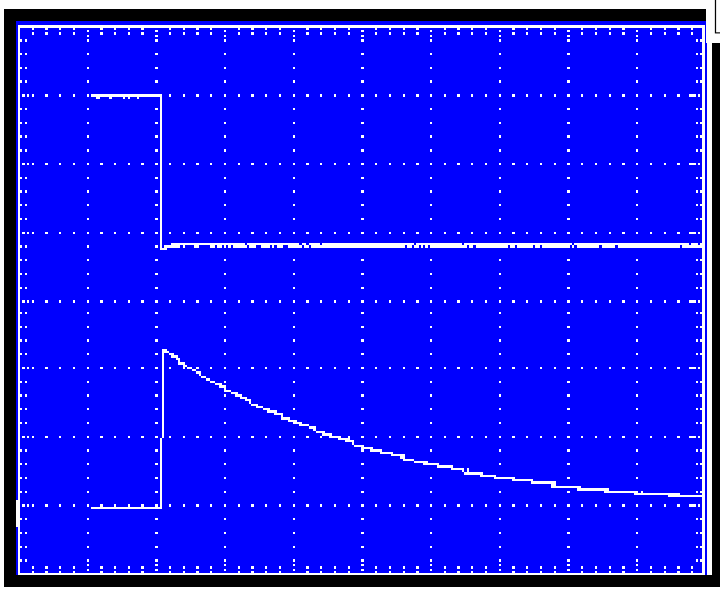
Shaping Stage



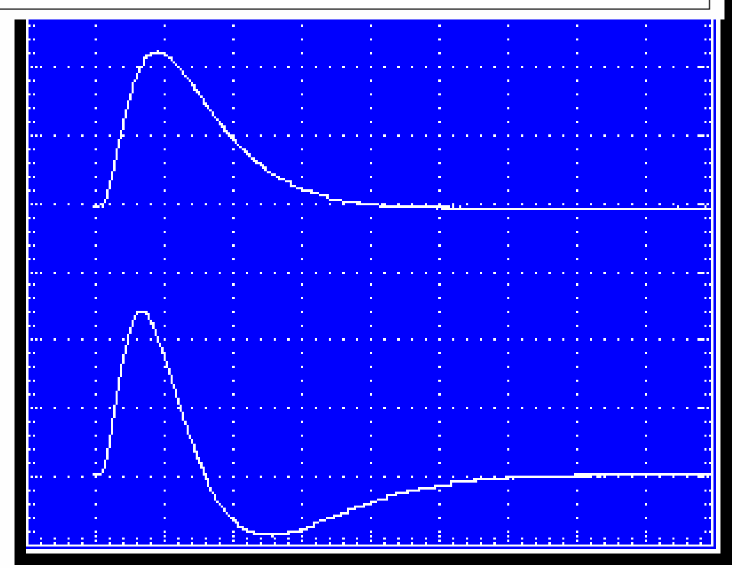
- This type of waveform is still not optimal (I will tell you why later) so typically a shaping stage is added
- Here is a discussion of the very nice but very expensive Amptek 203
- We would have used these except they cost $600 each -- about what the whole remote board costs the way we eventually did it

A203 Charge Sensitive Preamp and Shaping Amplifier



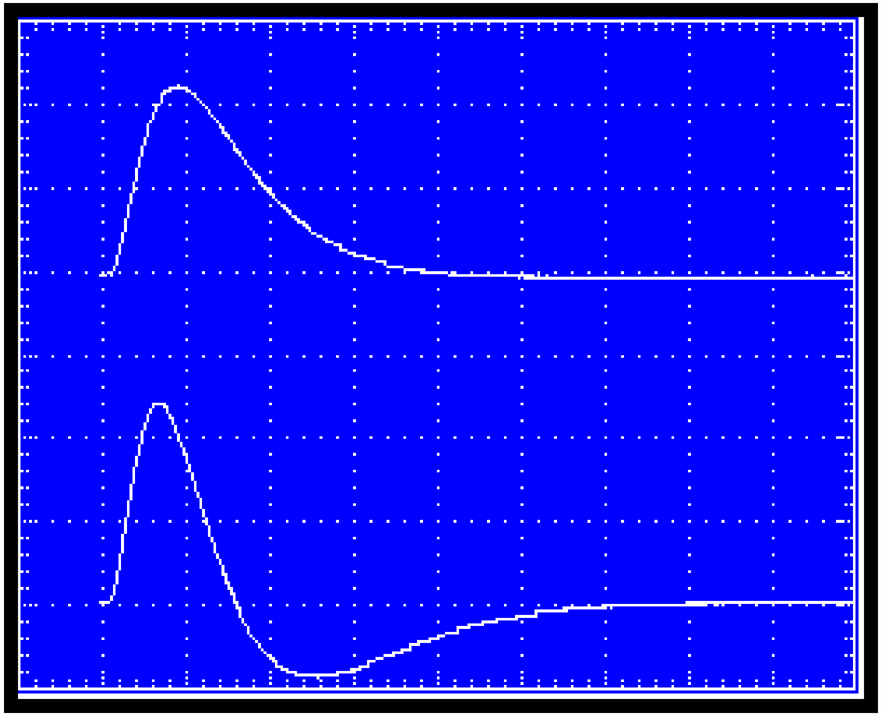


Horizontal Scale: 10μs/div
Vertical Scale: 10mV/div
Top Trace: Input to test capacitor -22mV = 1 MeV(Si)
Bottom Trace: Output of CSP (A-203, Pin 13)



Horizontal Scale: 500ns/div
Top Trace: Unipolar output of SA (A203, Pin 8)
Vertical Scale: 50mV/div
Bottom Trace: Bipolar output of SA (A203, Pin 9)
Vertical Scale: 100mV

Why These Outputs are Nice

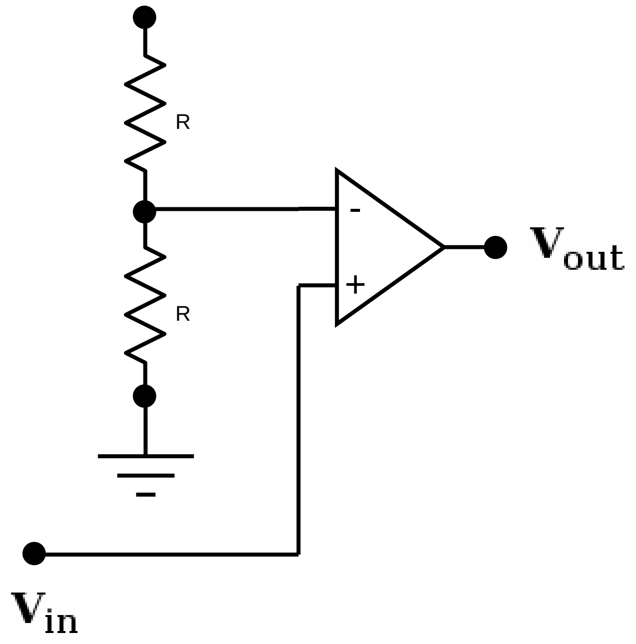


- Height of the pulse is proportional to the total charge on the wire
- Uniform shape with a flat top is easier to measure
- Bipolar output has no "DC" component
- Now we need to
  - Count pulses above a prescribed threshold
  - Accumulate spectra for diagnosis

Discriminator

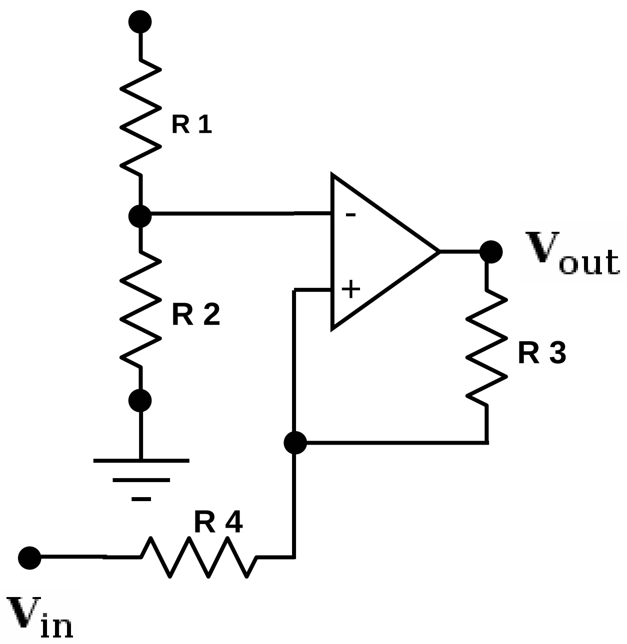
- Computers and logic are simpler if the analog signals are converted to digital signals
- The simplest conversion device is the discriminator, which produces an output signal each time the input exceeds a specified threshold

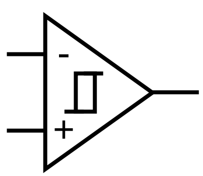
The Simplest Discriminator is Just an Operational Amplifier



- The threshold is set by the voltage applied to the negative input
- When the positive input exceeds this level the output (because of the high gain) goes from zero to full scale
- This is crude but often effective

By Adding a Little Positive Feedback You Make a "Schmidt Trigger "



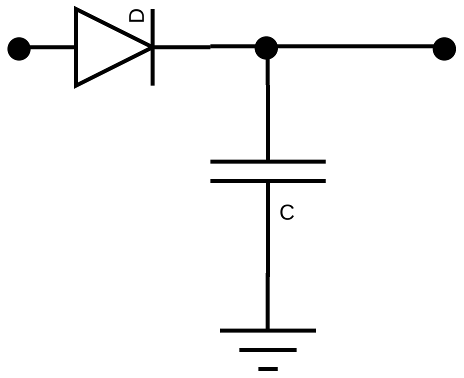


- This type of trigger has hysteresis – it will not "chatter" with near threshold pulses
- It is also available pre-packaged
- We still need to add circuits that make the discriminator output have a length independent of the input amplitude – typically called "one shots"

Signal Amplitude Measurement

- The next simplest thing to do is to measure the amplitude of a signal
- In our case we need to measure the amplitude only once, because the shaping circuit has made the peak voltage of the pulse proportional to the charge
- We start this with a circuit called a "peak detector" which remembers the maximum amplitude of the pulse

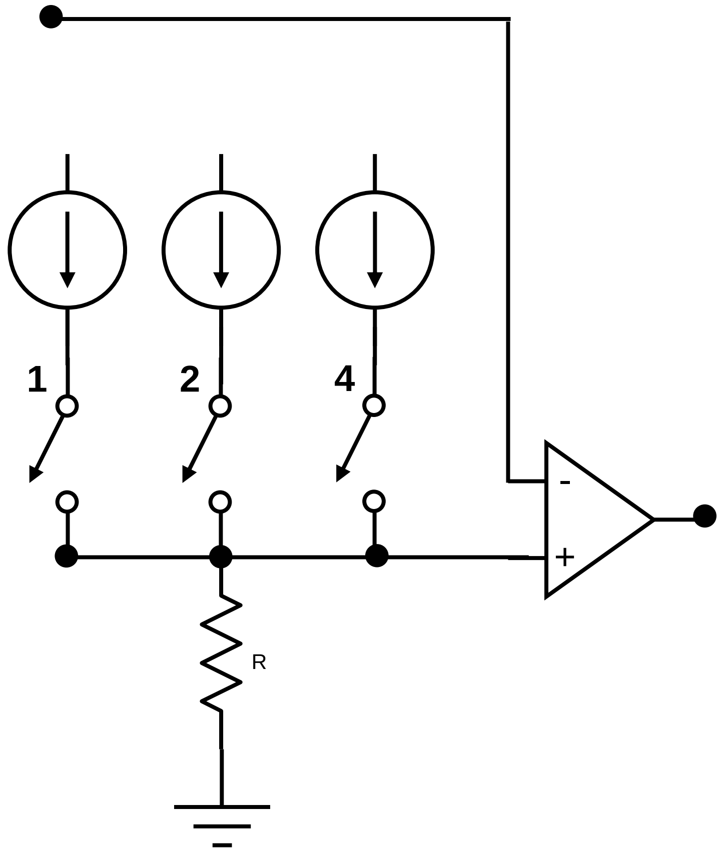
Peak Detector



- The model for a peak detector is just a diode and a capacitor
- The peak detector holds the signal until it can be “digitized”
- Actual circuits use comparators to eliminate the “diode drop”
- They also include provisions for gating the circuit and discharging the capacitor when the measurement is complete

ADC (Analog to Digital Converter)

From Peak Detector

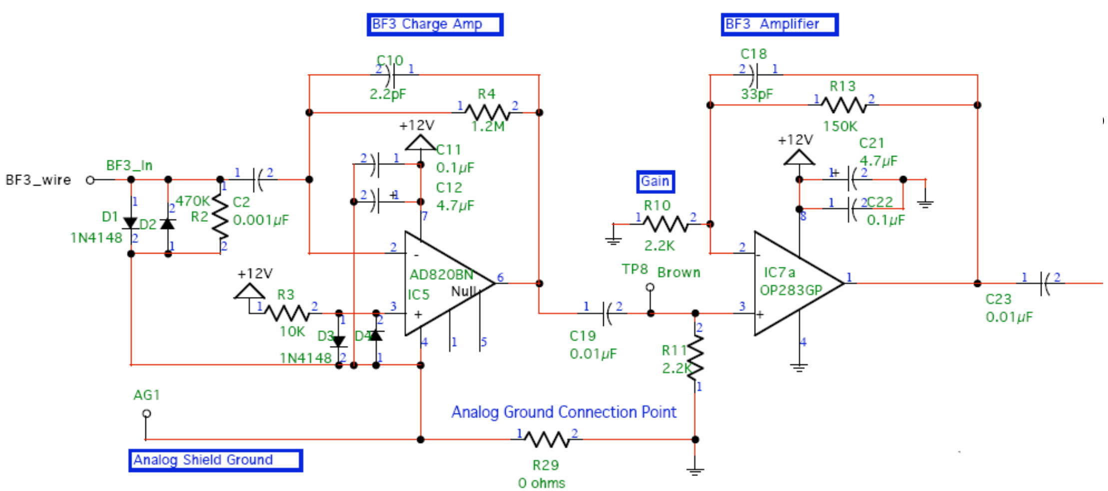


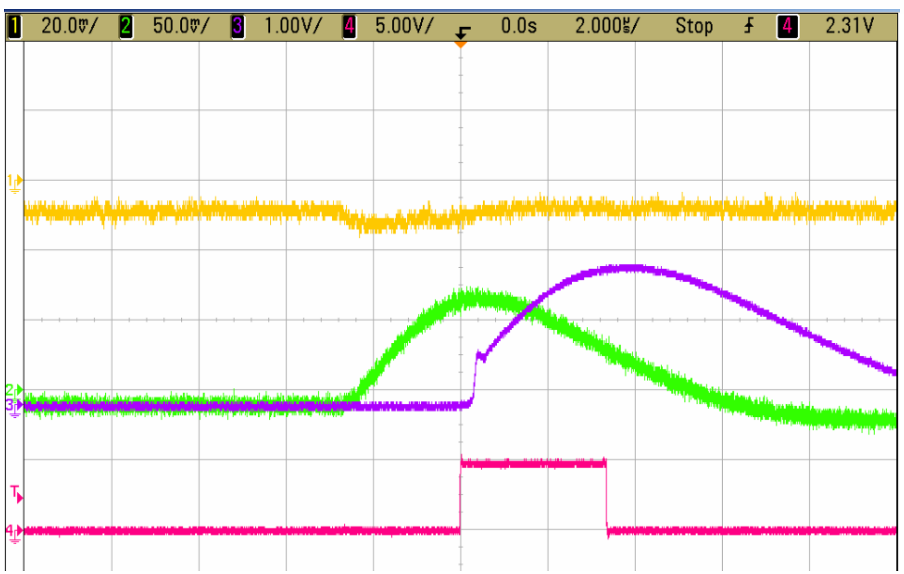
- The "DC" level produced by the peak detector is then measured with an ADC, whichis primarily a digital device
- Logic circuitry generates a voltage output by switching fixed, constant currents onto a fixed resistor
- (You can visualize a constant source as a very large resistor connected to a very high voltage, but the real circuit is more clever than that)
- The logic uses our old friend the differential amplifier as a comparator to determine when it has generated a voltage equal to that on the output of the peak detector
- Details of how logic can "hunts" for the proper voltage will be discussed in some more detail in Workshop 3

Actual Circuits in the "Remote"

- Now I briefly go through the implementation of these concepts in the "micromonitor"
- Alex will then set up a couple of demonstrations of the signals that I have already discussed
- Those who are interested in more details are welcome to stay and ask questions

Charge Amp and Shaper

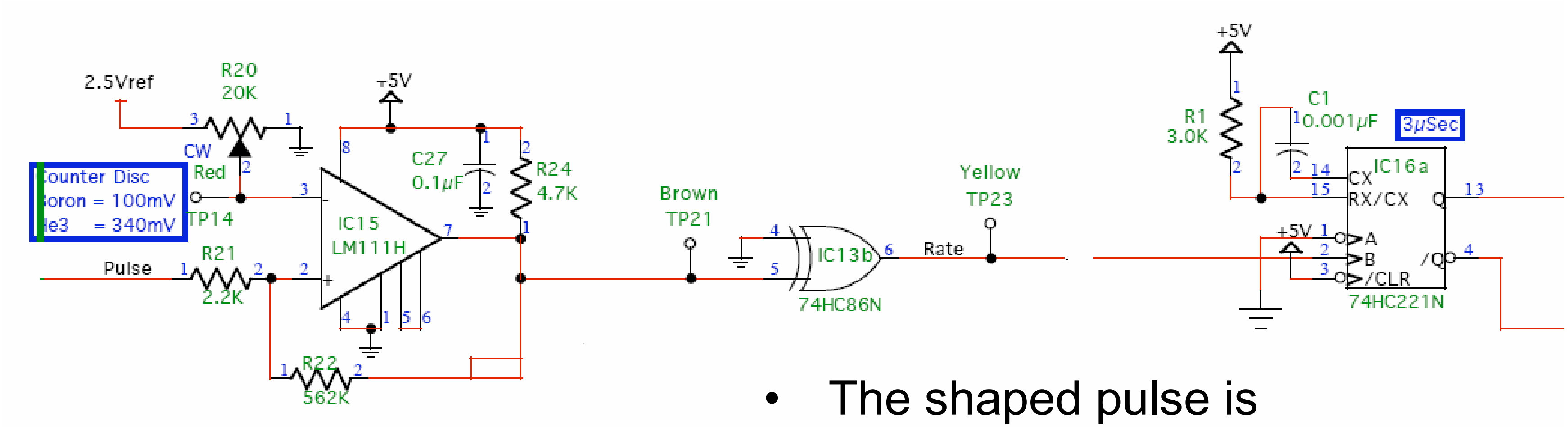


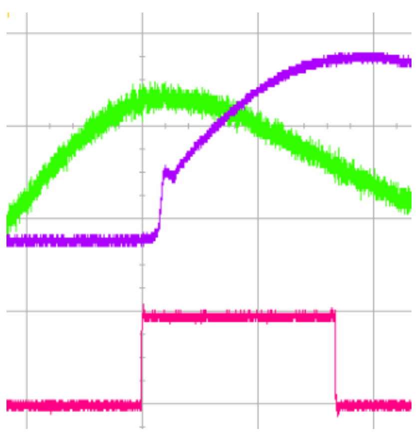


Our circuit has two stages, but due to our decision to use cheap components neither has the pure function of the Amptek system.

- The cost is about \$3.00 vs \$600.00
- For an 18 tube monitor it adds up

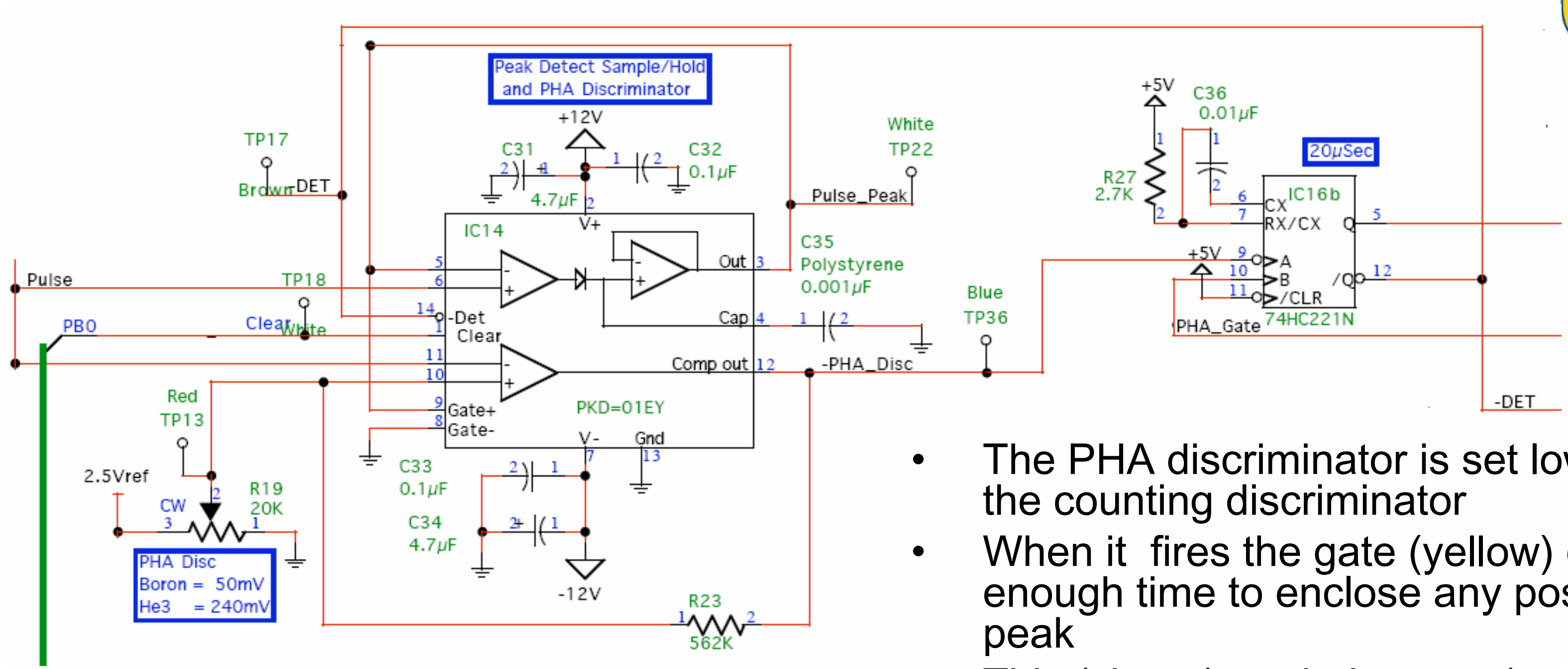
Counting Discriminator

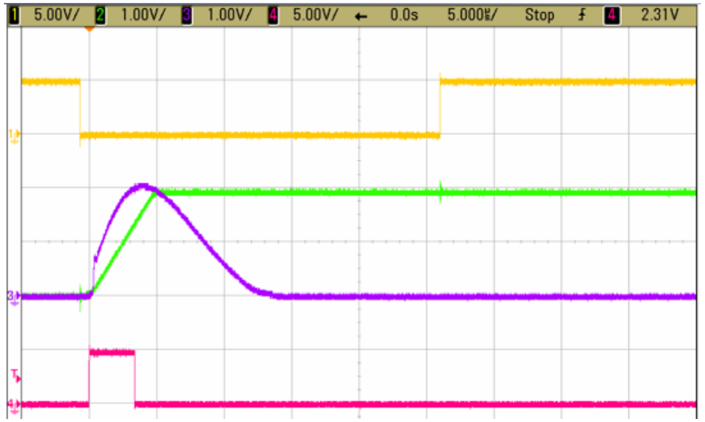




- The shaped pulse is compared with a standard level
- A “one shot” is used to limit the pulse length to 3 microseconds
- Note that the hysteresis circuit “kicks back” when the discriminator “fires”

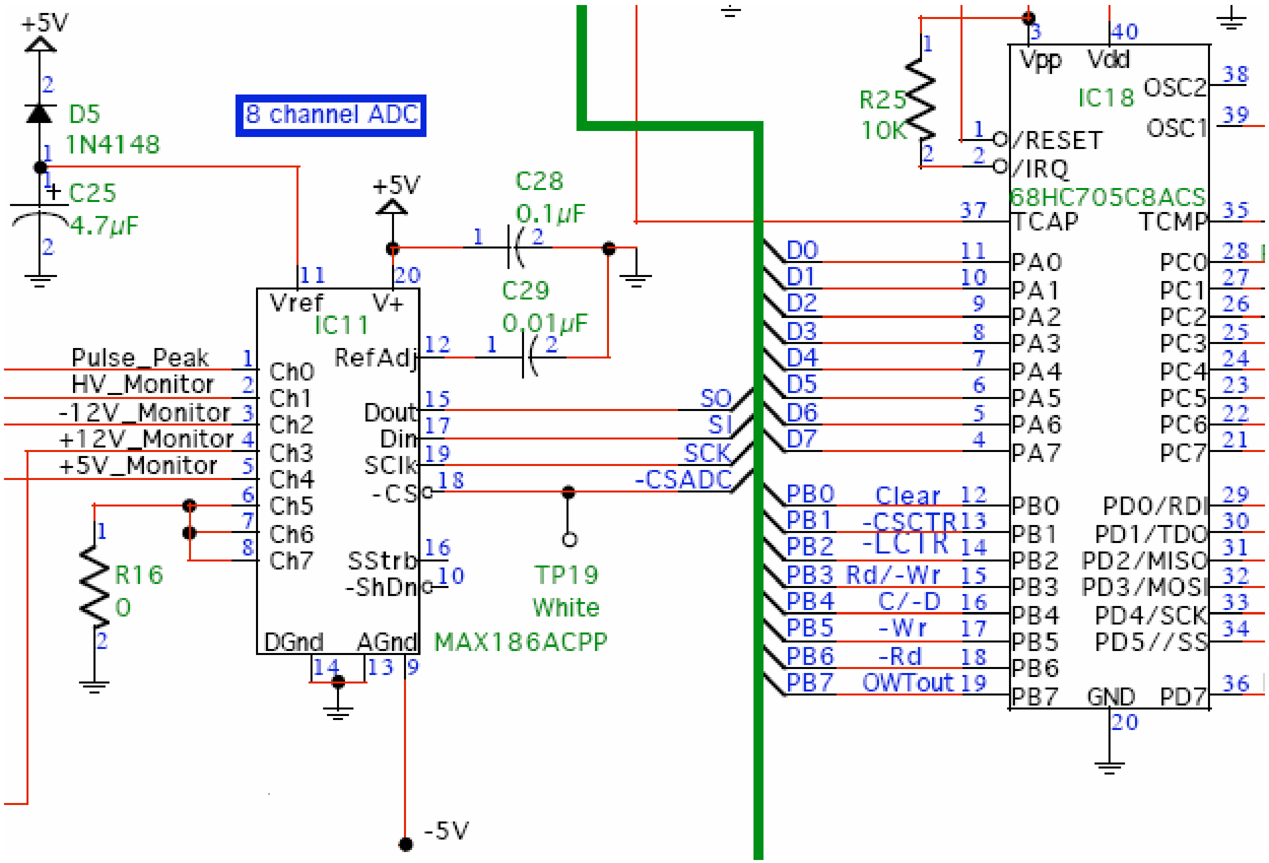
Peak Detector





- The PHA discriminator is set lower than the counting discriminator
- When it fires the gate (yellow) opens for enough time to enclose any possible true peak
- This (cheap) peak detector (green) is not fast enough to follow the signal, and holds it slightly after the real peak
- The clear and reset come much later, when the microcontroller (Workshop 3) has used other circuitry (Workshop 2) to measure the amplitude of the signal
- Note that the counting circuitry is independent of this, and can count at a much higher rate than that at which PHA may be taken

ADC



- The ADC we use has only a few external components
- It is operated by the microcontroller
- Note that the ADC has several inputs that can be selected
- In addition to measuring the pulse height spectrum the ADC is used to monitor various internal volatages