PHYS 575A/B/C

Autumn 2015

Radiation and Radiation Detectors

Course home page:

http://depts.washington.edu/physcert/radcert/575website/

3: Fast pulse signals and detector data acquisition

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Course calendar

Tonight

week	date	day	topic	text
1	10/1/15	Thurs	Introduction, review of basics, radioactivity, units for radiation and dosimetry	Ch. 1, notes
2	10/6/15	Tues	Radioactive sources; decay processes;	Ch. 1, notes
3	10/13/15	Tues	Photomultiplier tubes and scintillation counters; Counting statistics	Chs. 3, 8, 9 (I-V)
3	10/15/15	Thurs	**LAB: Room B248** Scopes, fast pulses; PMTs and scintillation counters; standard electronics modules	Chs. 4, 9, 16, 17
4	10/20/15	Tues	Overview of charged particle detectors	Ch. 4
4	10/22/15	Thurs	**LAB: Room B248** Coincidence techniques; nanosec time measurement, energy from pulse area	Chs. 17, 18
5	10/27/15	Tues	Interaction of charged particles and photons with matter	Ch. 2
6	11/3/15	Tues	Other photodetectors; gas and solid-state detectors	Chs. 5, 6, 7 Chs. 11, 12, 13
7	11/10/15	Tues	Detecting neutral particles; Data acquisition methods	Ch. 14, 15, 18
8	11/17/15	Tues	Cherenkov detectors; Case studies: neutrino detectors (Super-K)	Ch. 19, Notes
9	11/24/15	Tues	Case studies: classic detectors (cloud and bubble chambers, nuclear emulsion), high energy accelerators	Ch. 19
10	12/1/15	Tues	Case studies: contemporary leading-edge detectors (ATLAS, Auger)	Notes
11	12/8/15	Tues	Student presentations	-
11	12/10/15	Thurs	Student presentations	

LAB session **this Thursday**

- Meet in room B-248, not here
- 6:30 to 9pm
- BEFORE class, read handouts posted on website:

"Documents for lab sessions (writeups and handouts)"
http://depts.washington.edu/physcert/radcert/575website/lab_documents/Lab_1/

1. Lab safety, radiation safety documents (MUST READ BEFORE LAB!)
2. How to use an oscilloscope (if you have never used one)
3. Procedures for Lab session 1: Oscilloscopes and pulses

- Tonight:

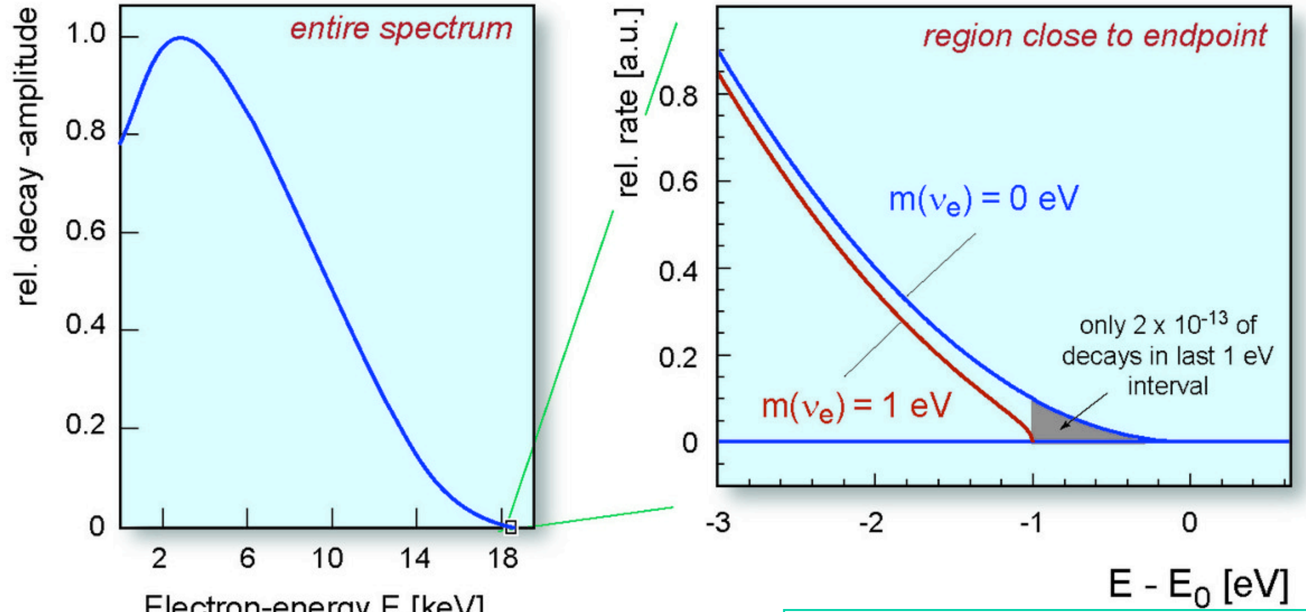
1. Introduction to fast pulse signals, processing, and hardware (prep for lab session)
2. Begin discussion of "interactions of charged particles with matter" (energy loss processes in detectors and shielding)

Last time

β spectrum endpoint → neutrino mass

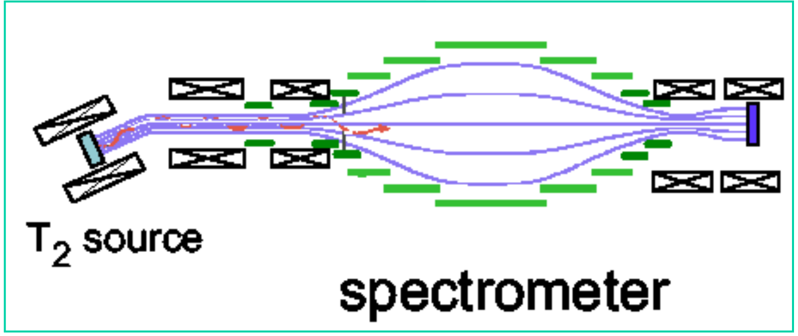
- Direct measurement of electron neutrino mass by decay kinematics
- Endpoint observation is very difficult!

  Only one decay in 10^{13} is near the endpoint



Spectrometer en route to lab

KATRIN experiment to measure endpoint (UW participants)



Mass measurement experiment

- UW physicists are doing a major experiment to measure neutrino mass via beta decay endpoint measurement: KATRIN (www.katrin.kit.edu)
- Tritium (^3H) beta-decay endpoint experiments: neutrino rest mass means electron spectrum is distorted near the endpoint

- Nuclear chemistry:

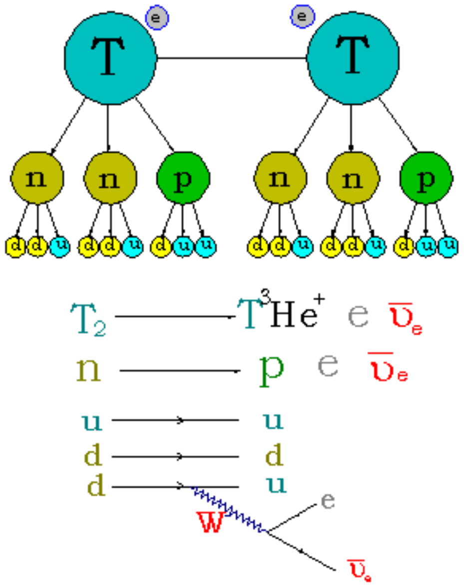
  $T_2 \rightarrow T + {}^3He$ + particles
- At the particle level:

  $n \rightarrow p + e^- + \upsilon_e$
- At the quark level

  $d \rightarrow u + W^-$

followed by weak interaction:

$W^- \rightarrow e^- + \upsilon_e$



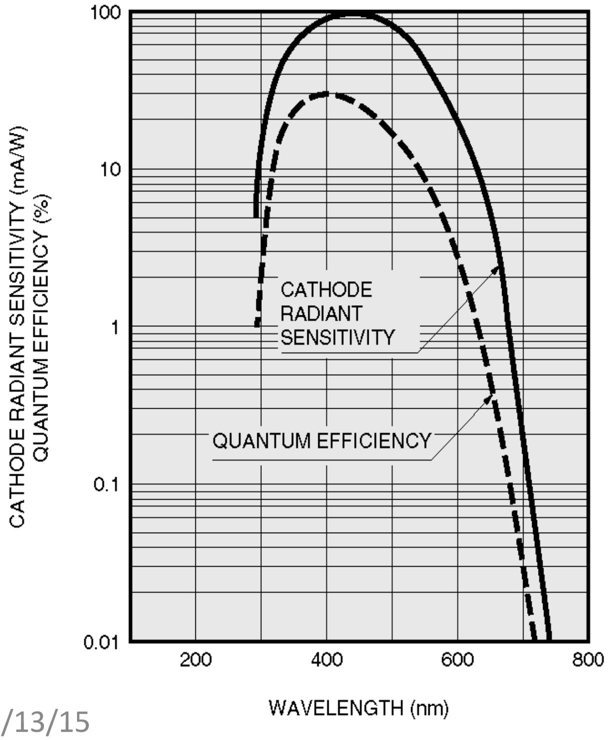
Prior limit from tritium decay endpoint experiments: $m_\upsilon < 4$ eV

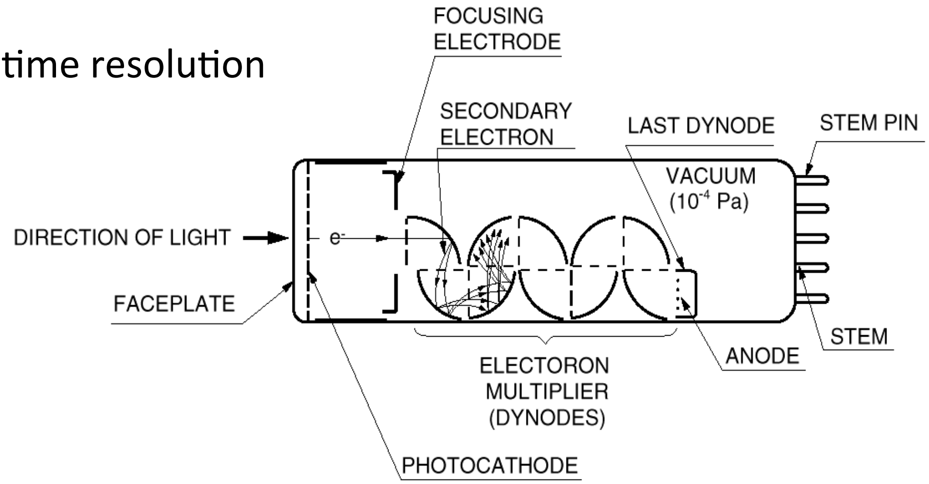
- Challenges:
  - Need pure T_2 source output
  - Need to know T_2 rotation/vibration mode energies/populations precisely
  - Need fraction of eV precision from spectrometer

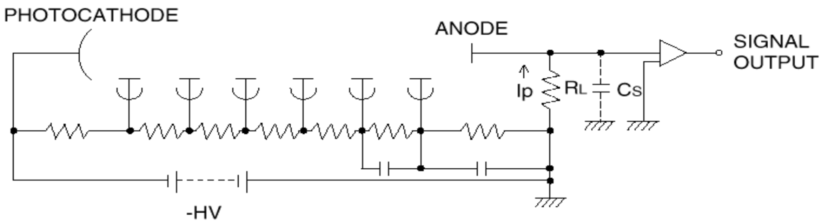
Photomultiplier tubes (PMTs)

PMT = light detector sensitive to single photons

- *photocathode* emits *photoelectrons* (pe's) when hit by a photon (quantum efficiency ~ 25%)
- *dynode* chain multiplies photoelectrons by acceleration and secondary emission: requires kV power supply
  - typically 10 stages, 10^6 multiplication
- Fast signal with good photon arrival-time resolution
  - ~ -1V pulses, 1~10 nsec resolution







see http://usa.hamamatsu.com/electron-tube/pmt/

Different shapes and sizes

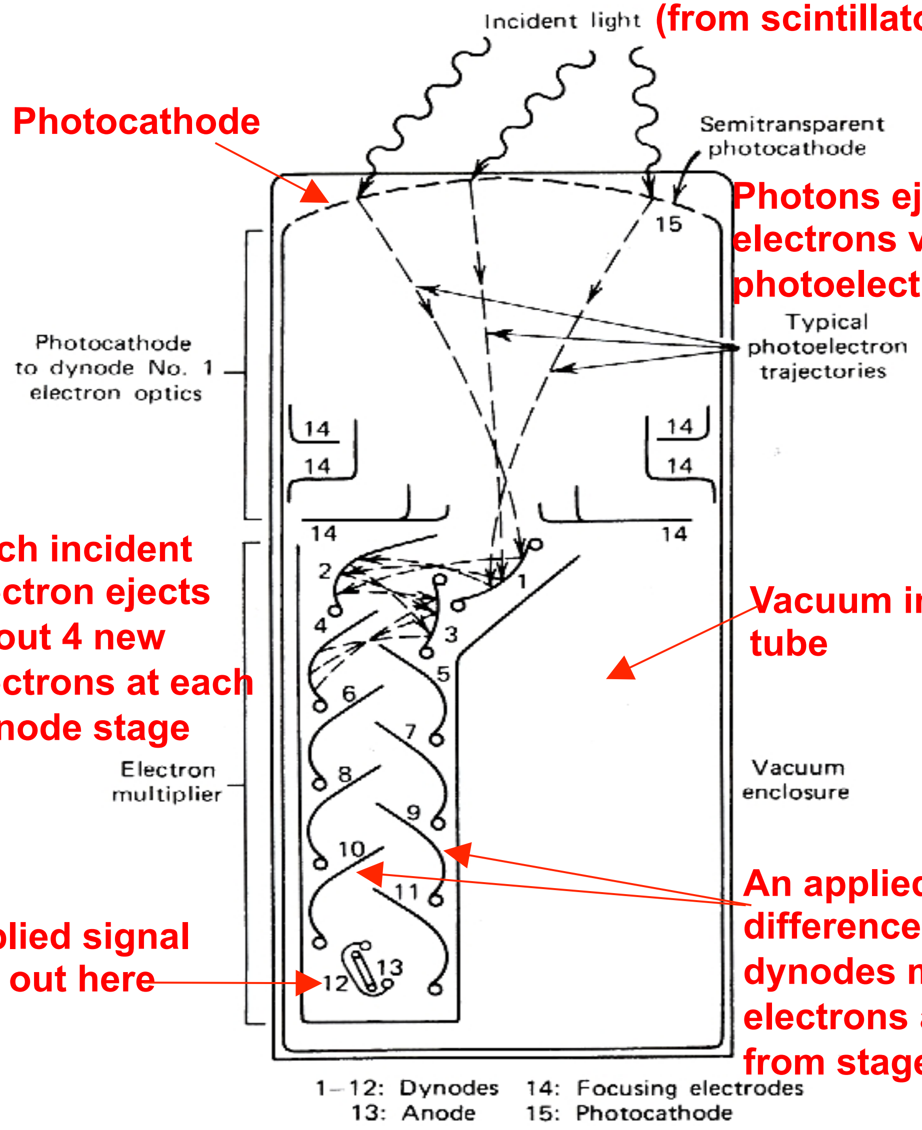
1 cm to 20 cm PMTs

4x4 multi-anode PMT
(position sensitive)

50 cm PMT in implosion-proof housing

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The Univers

Photomultiplier Schematic



(from scintillator)

Photocathode

Photons eject electrons via photoelectric effect

Each incident electron ejects about 4 new electrons at each dynode stage

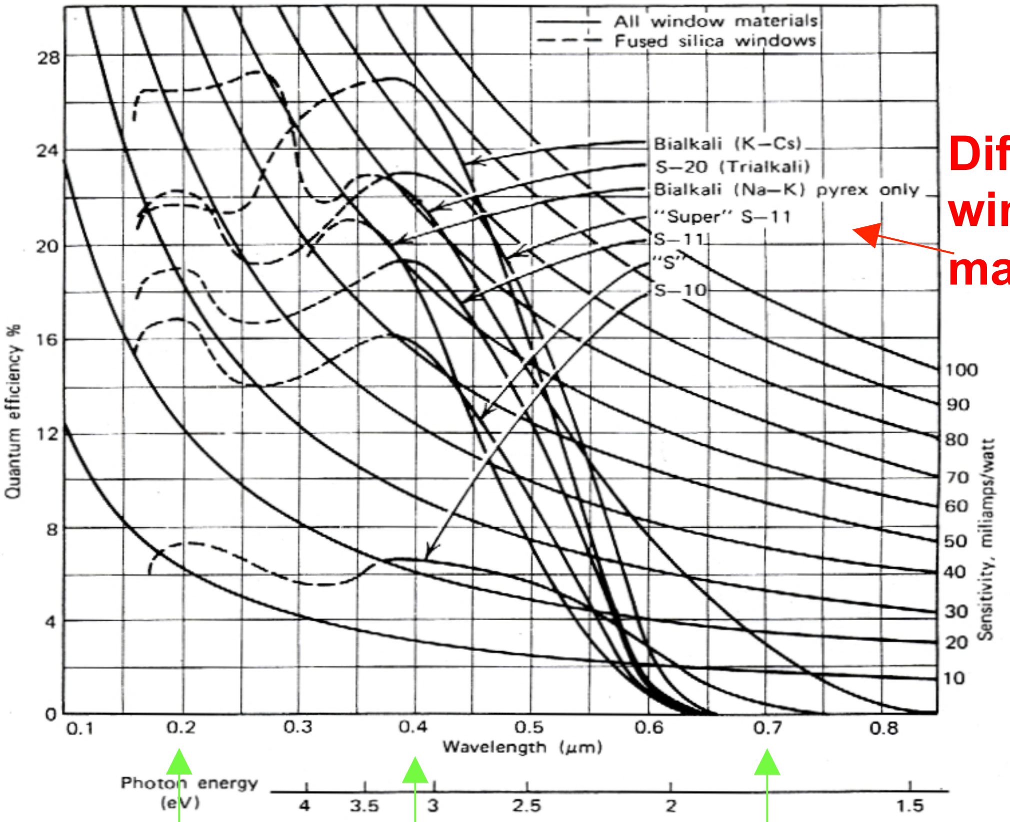
Vacuum inside tube

An applied voltage difference between dynodes makes electrons accelerate from stage to stage

"Multiplied signal comes out here

Light Transmission Through the Entrance Window

(photocathode coating is on inside surface)



Percent of light which passes

Different window materials

Wavelength of light

200 nm

400 nm

700 nm

1 nm = 1 nanometer = 10^{-9} meter

Note:

20% transmission typical for 400 nm light

Fused silica extends transmission into lower wavelengths

Less than 400 nm is ultraviolet light

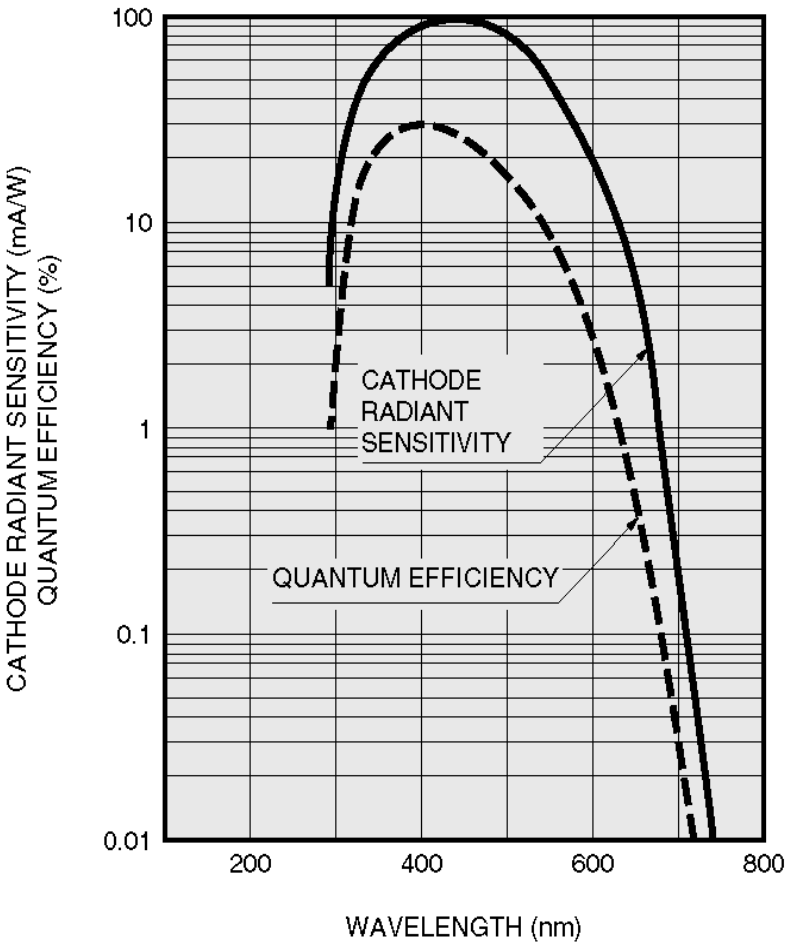
Photocathode properties

- Photocathode composition
  - Semiconductor material made of antimony(Sb) and one or more alkalai metals (Cs, Na, K)
  - Thin, so ejected electrons can escape
- Definition of *photocathode quantum efficiency*, $h(\lambda)$

$$h(\lambda) = \frac{\text{number of photoelectrons emitted}}{\text{number of photons incident on photocathode}}$$

- Typical quantum efficiency is 25%
- Need to match light output spectrum of detector with photocathode response spectrum.

Typical Photocathode Response Curve



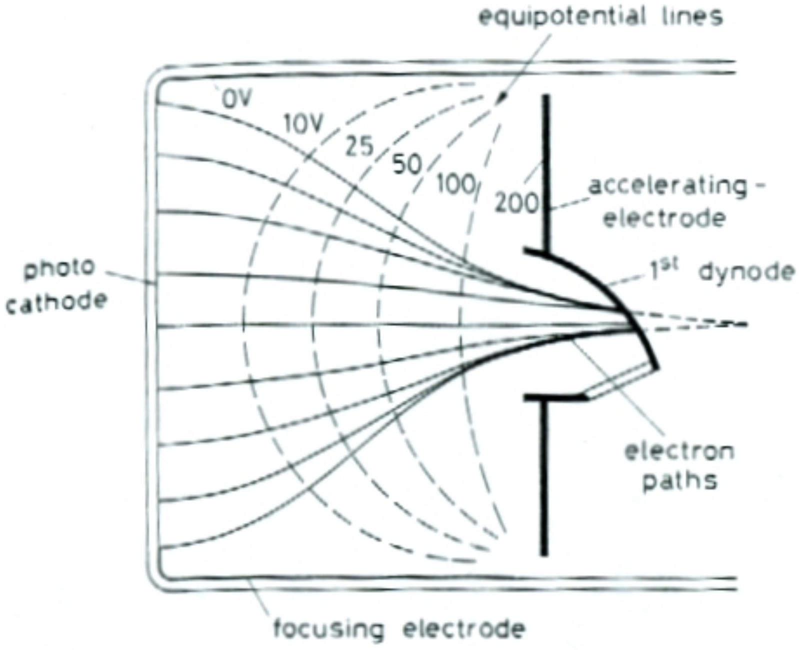
Note: Quantum efficiency > 20% in range 300 - 475 nm

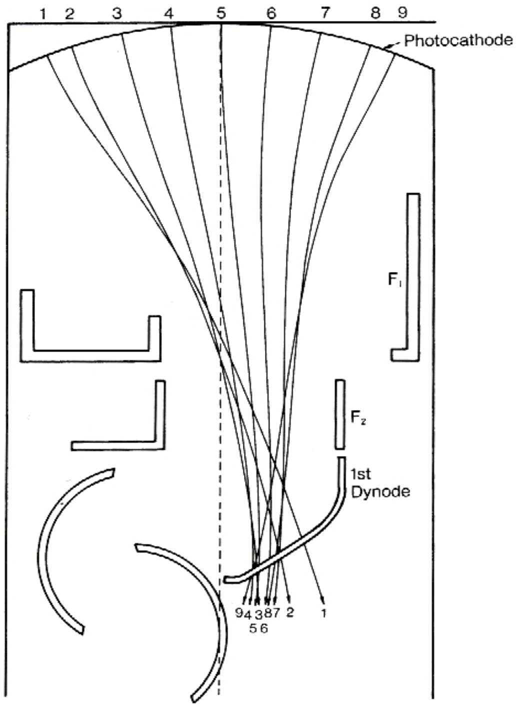
Peak response for light wavelengths near 400 nm

Photoelectron Trajectories to First Dynode

Critical stage: inefficiency here makes PMT useless

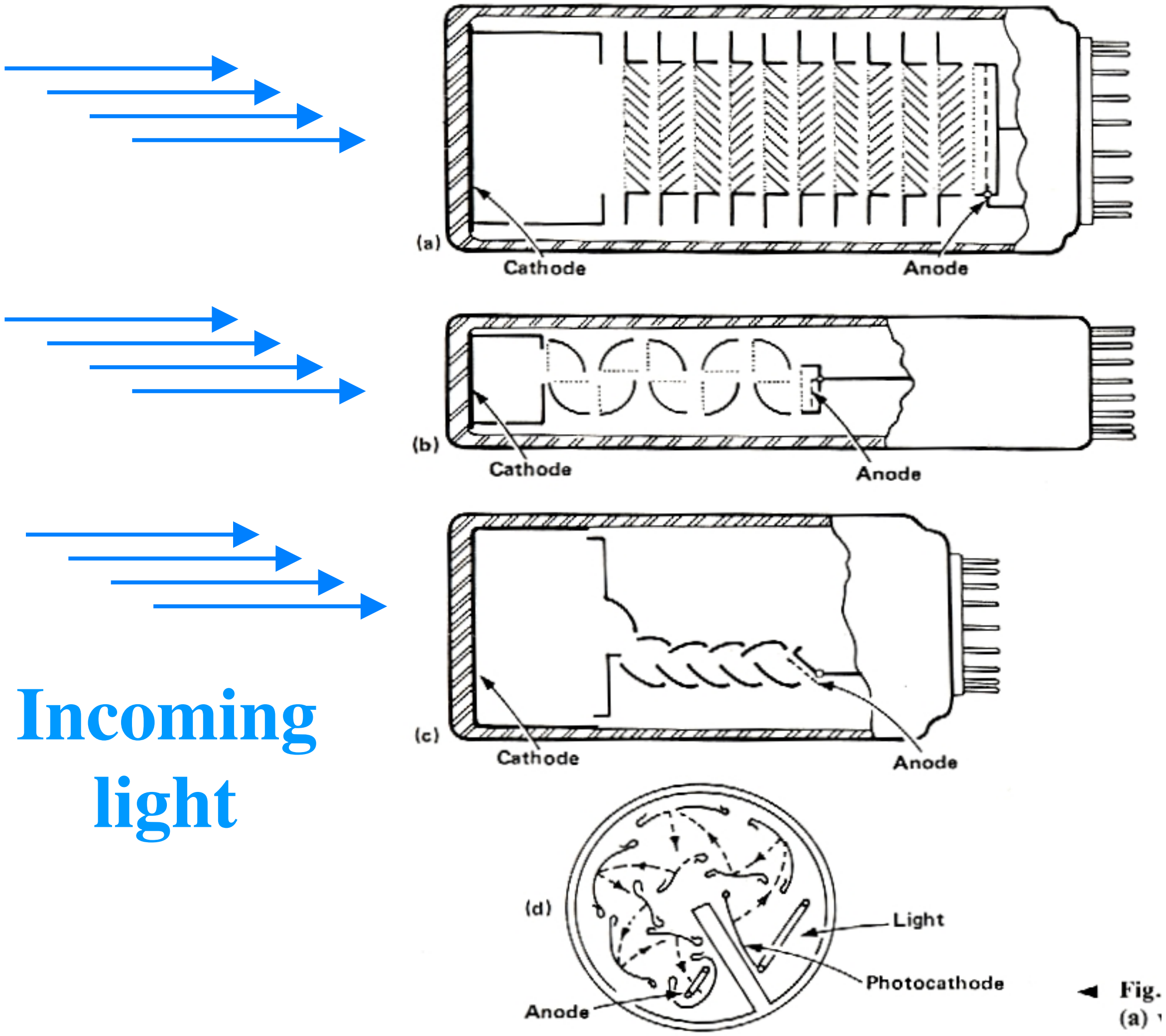
Longer path makes trajectory shaping and focusing less sensitive to small errors in electrode placement





Different Types of Dynode Chains

Subsequent stages are typically closer together to minimize stage jumping (produces “prepulsing”)



venetian-blind dynodes

box-and-grid dynodes

Incoming light

Sensitivity to Earth's Magnetic Field

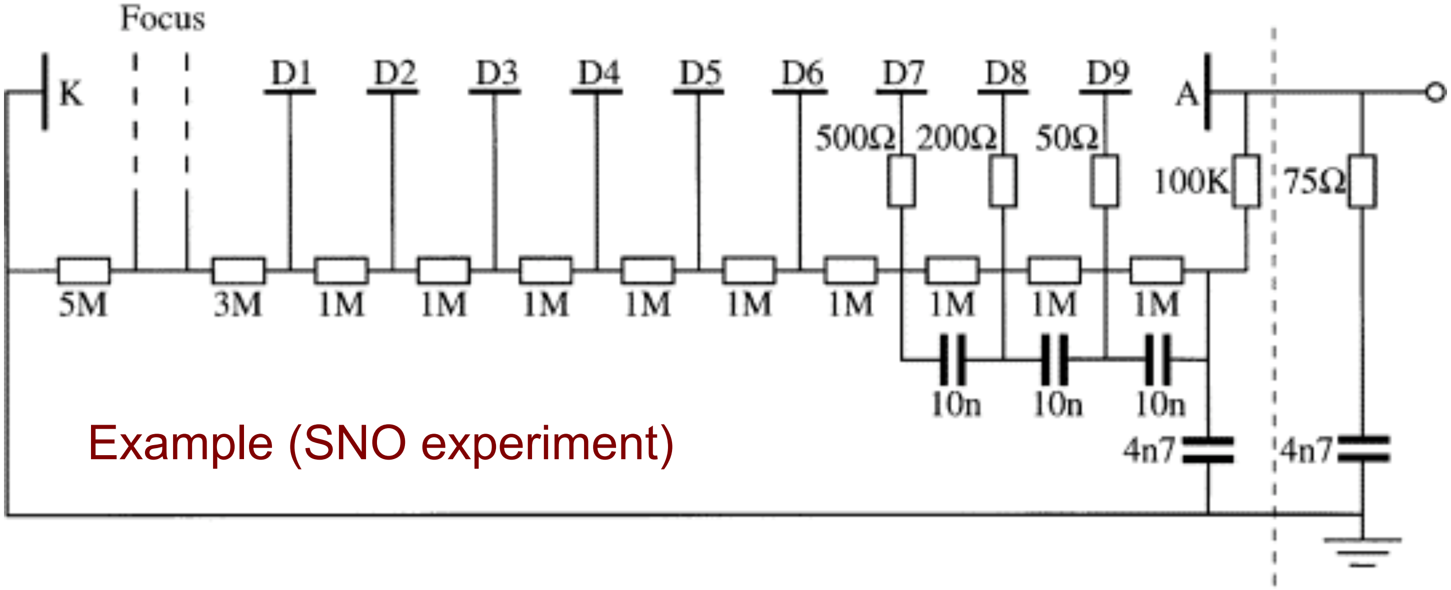
- Earth's magnetic field is typically 0.5 - 1.0 Gauss (10,000 gauss = 1 tesla)
- Trajectories of charged particles moving in a magnetic field will curve, depending on field orientation.
- Can cause photoelectrons and secondary-emitted electrons not to reach next stage.
- First few stages, when there are few electrons, most vulnerable.
- Use of magnetic shields
  - Should extend shield beyond front of tube.
- Alternatives
  - Use Helmholz coils to cancel field
  - Use solid-state devices! (tiny paths)

Photomultiplier Tube Gain

- d = average number of electrons generated at each dynode stage
  - Typically, $d \sim 4$, but depends on dynode material and the voltage difference between dynodes.
- n = number of multiplication stages
- Photomultiplier tube gain $= d^n$
  - For n = 10 stages and $d = 4$, gain = $4^{10} = 1 \times 10^7$
  - This means that one electron emitted from the photocathode ("photoelectron", 1 pe) yields 1×10^7 electrons at the signal output.
    - Over a 5 ns pulse duration this corresponds to 33 microamps, easily detected signal

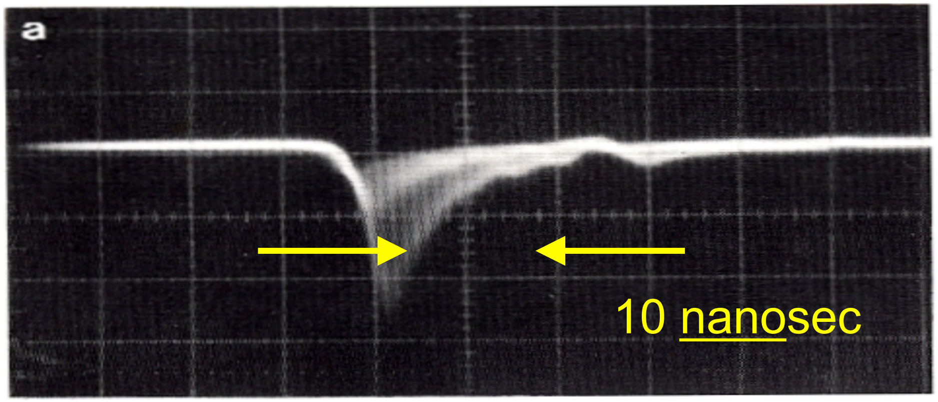
PMT bases – define output signal properties

- PMT typically has HV ~ 500-2500 VDC applied
  - Change HV to change gain
  - May have shielding (housing) tied to + or - terminal
- Built into tube socket housing is
  - resistive divider chain, sets proportions of accelerating voltages between dynodes
  - load resistance determines output signal voltage, given current / pe



Example (SNO experiment)

Oscilloscope Traces from Scintillation Counters

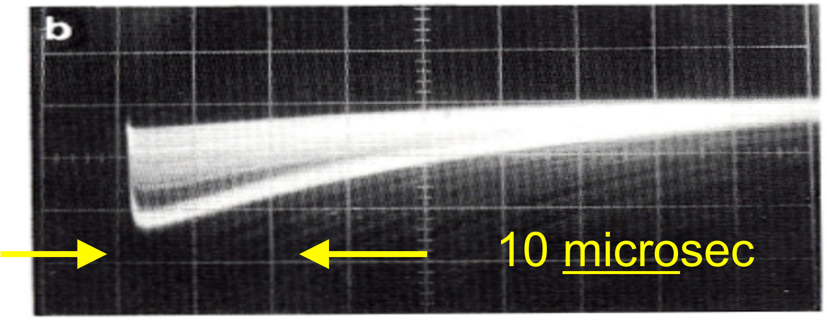


Plastic scintillator

Plastic

Vert. scale : 0.2 V/cm
Hor. scale : 10 ns/cm
Source : ^{207}Bi 10μCi

10 nsec / division



Inorganic crystal, NaI

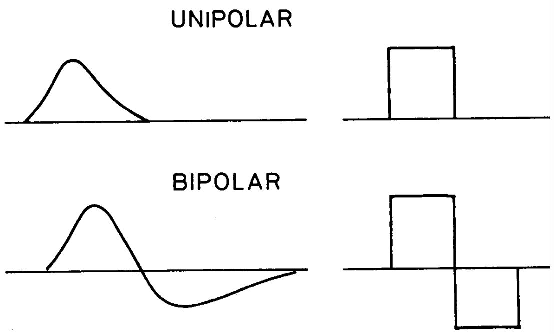
NaI

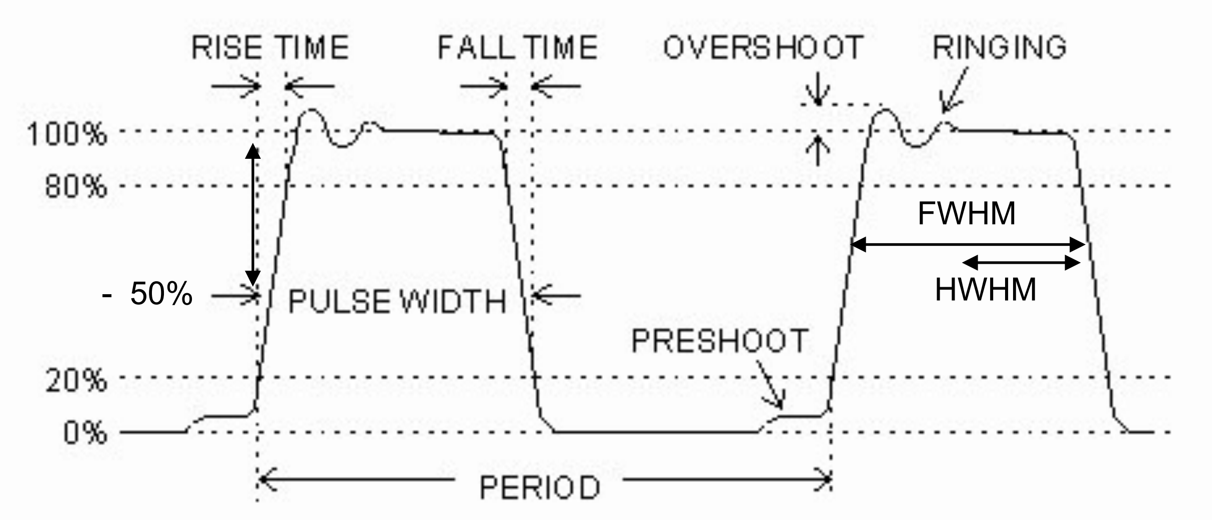
Vert. scale : 0.2 V/cm
Hor. scale : 5μs/cm
Source : ^{137}Cs 10μCi

5000 nsec / division (Longer time scale for fluorescence to occur)

Fast pulse signals

- Particle and nuclear physics detectors typically produce pulses on the order of 1 ~ 10 nanosecond (ns) duration
- Pulse taxonomy





  - People use different definitions of rise time - check what is specified:
    - 10-90% time, 20-80% time, time for 3 dB rise or fall...

Review of dB (deci-Bels)

Bel → named after A.G. Bell (by Bell Telephone Co.)

Recall: *Decibels* as measure of a ratio:

- dB = $-20 \log_{10} (v_2 / v_1)$ for *amplitude* ratios

Note: since *power* $p \sim v^2$, if we want intensity or power ratios

dB = $-20 \log_{10} (v_2 / v_1)$ in terms of *amplitudes*

$= -10 \log_{10} (v_2^2 / v_1^2)$ (sqrt = divide $\log_{10}$ by 2)

so $= -10 \log_{10} (p_2 / p_1)$ in terms of *power*

Ratio	dB (power)	dB (amplitude)
0.8	1	2
0.5	3	6
0.10	10	20
0.01	20	40

So a *power* ratio of 3 dB corresponds to *voltage* ratio of 6 dB

Fourier analysis of pulses

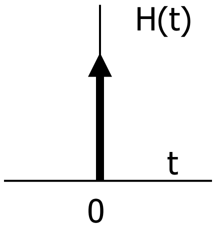
- Any pulse (signal h(t) with limited time span) can be represented by Fourier sum (or integral) of sine waves of many different frequencies
  - spectrum = plot of relative amplitude (or intensity) vs frequency
- Fourier Transform gives *spectrum* H(f) of signal function h(t) :

$$H(f) = \int_{-\infty}^{+\infty} h(t)\exp(i2\pi f t)dt \leftrightarrow h(t) = \int_{-\infty}^{+\infty} H(f)\exp(-i2\pi f t)df$$

FT and inverse-FT transform representation between f and t spaces:

$$FT[h(t)] = H(f), \qquad FT^{-1}[H(f)] = h(t)$$

- *Sharp* pulse (eg, delta-function) has *broad* spectrum and vice versa
- Example: Dirac delta-function = sharpest possible pulse



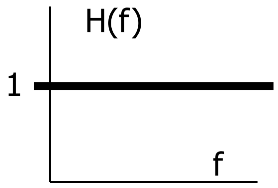
Let width of pulse➔0 while keeping area=const=1

So h(t)=∞ for t=0, h(t)=0 everywhere else,

h(t)=δ(t) Dirac *delta function*

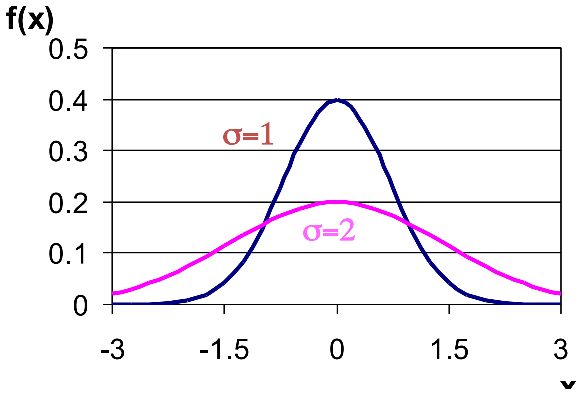
(or Heaviside *unit impulse*) FT(δ) = 1 (flat)

➔h(t) is totally localized, H(f) is totally unlocalized!



Fourier analysis of pulses

- Another example: Gaussian-shaped pulses

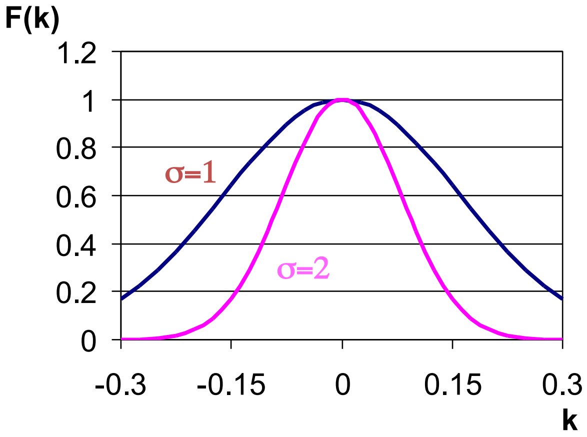


$$f(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-t^2/2\sigma^2}$$

$$F(f) = e^{-\pi^2(2\sigma^2)f^2} \qquad \text{(another Gaussian)}$$

$$\text{Full width } = \frac{1}{\pi\sqrt{2\sigma^2}} \qquad \text{(~ inverse of f(t) width)}$$

$$\text{Height (at f } = 0) = 1 \qquad \text{(independent of } \sigma\text{)}$$

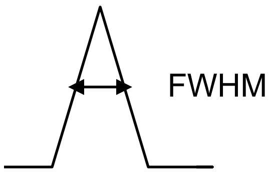


So: narrower f(t)=broader F(f) and vice versa

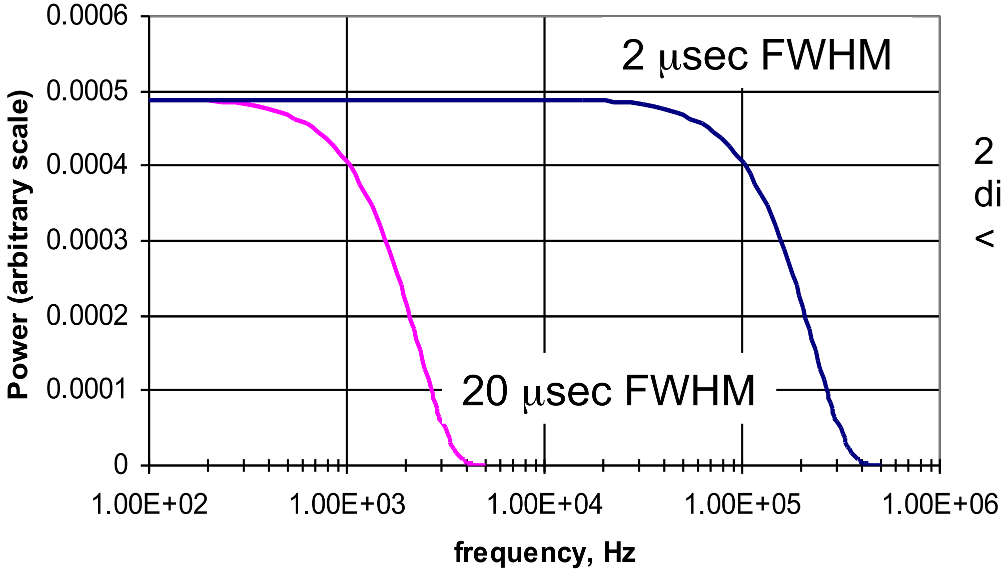
Both f(t) and F(f) are semi-localized: degree of localization depends on σ

- Transmission lines and electronics must have large *bandwidth* to retain fast rise/fall of signals
  - Limited bandwidth --> clips off higher frequencies
  - Loss of 'sharpness' : waveform is low-pass filtered!

v(t) for triangular pulse:

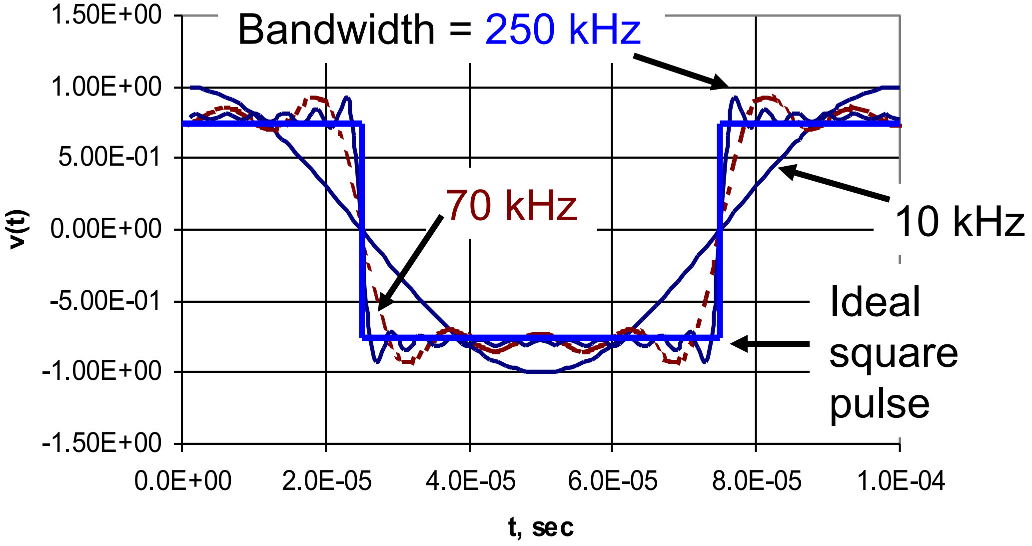


Spectra for narrow and wide triangular pulses



2 μsec pulse will be distorted if system has < 500 kHz bandwidth

Effects of bandwidth on a 50 microsec square pulse



Transmission lines

- At high frequencies, transmission lines are waveguides

  Characteristics of lossless ideal cable with vacuum/air dielectric

  - Impedance $Z_0 \sim \ln(b/a)$ where b,a=outer, inner diameters *
  - Losses are minimum for b/a=3.6
    - This ratio gives Z=50 ohms: *standard*

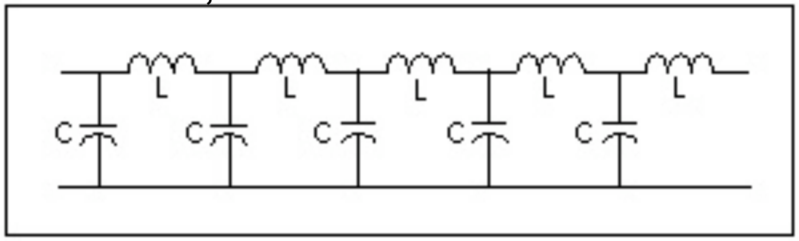
      ("impedance of free space" = 300 ohms → impedance of twin-lead)

      Note: would need b/a~1800 to get 300 ohms!
  - $v_{PROP} = (\mu\ \varepsilon)^{-1/2}$ m/sec, usually expressed as

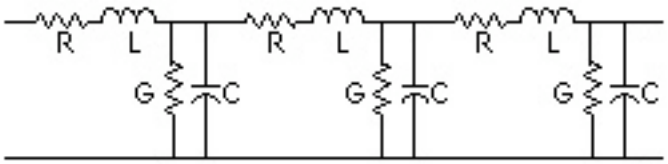
    $T = 1/\ v_{PROP}$ = delay in nsec/meter

    (~5 nsec/m, or 1.5 nsec/ft for standard 50-ohm cable)

Ideal, lossless



Real, with attenuation and leakage



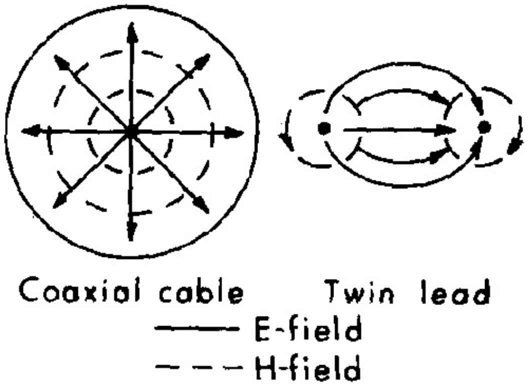
* Recall: Impedance Z = factor representing effective resistance to AC currents = $R + X_C + X_L$
$I_{RMS} = V_{RMS}\ /\ |Z|$

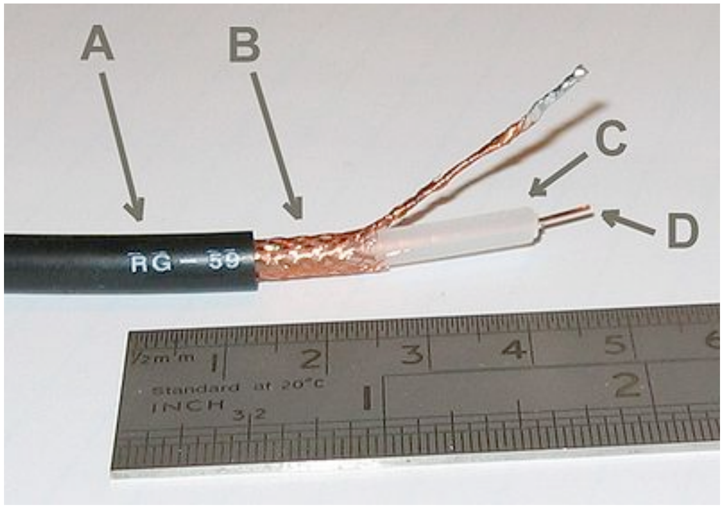
Real transmission lines

– Coaxial cable

Not the same as ordinary shielded cable for audio !

- For MHz frequency signals, acts as a waveguide
- Coaxial cable has
  - A. Outer insulating/ protective jacket,
  - B. Braided or foil shield that forms a return conductor,
  - C. Dielectric with carefully controlled dimensions and properties
  - D. Center conductor





Coax properties

- For an ideal lossless cable the velocity of signal propagation is given by $v = 1/(\mu\varepsilon)^{1/2}$
  - Not vacuum values of μ, ε, but values for dielectric used
- Most cables use a solid dielectric and have signal propagation velocities about 2/3 the speed of light in vacuum
  - Cables with air dielectric having transmission speeds close to the speed of light in vacuum are available
  - Rule of thumb: In vacuum light travels about 1 foot per ns, in 50 ohm coax it is 1.5 ns per foot
- Impedance Z_0 is independent of the length of cable
  - Depends only on geometry and material (dielectric)
- Standard widely used cables have characteristic impedances of 50 ohms, 75 ohms, and 93 ohms
- Cables are usually specified by an RG/U designation (*Radio Guide, Universal* – from a WW-II-era mil spec) that sets standards – we will use 50 ohm RG58 cable in the lab

Impedance matching: avoiding reflections

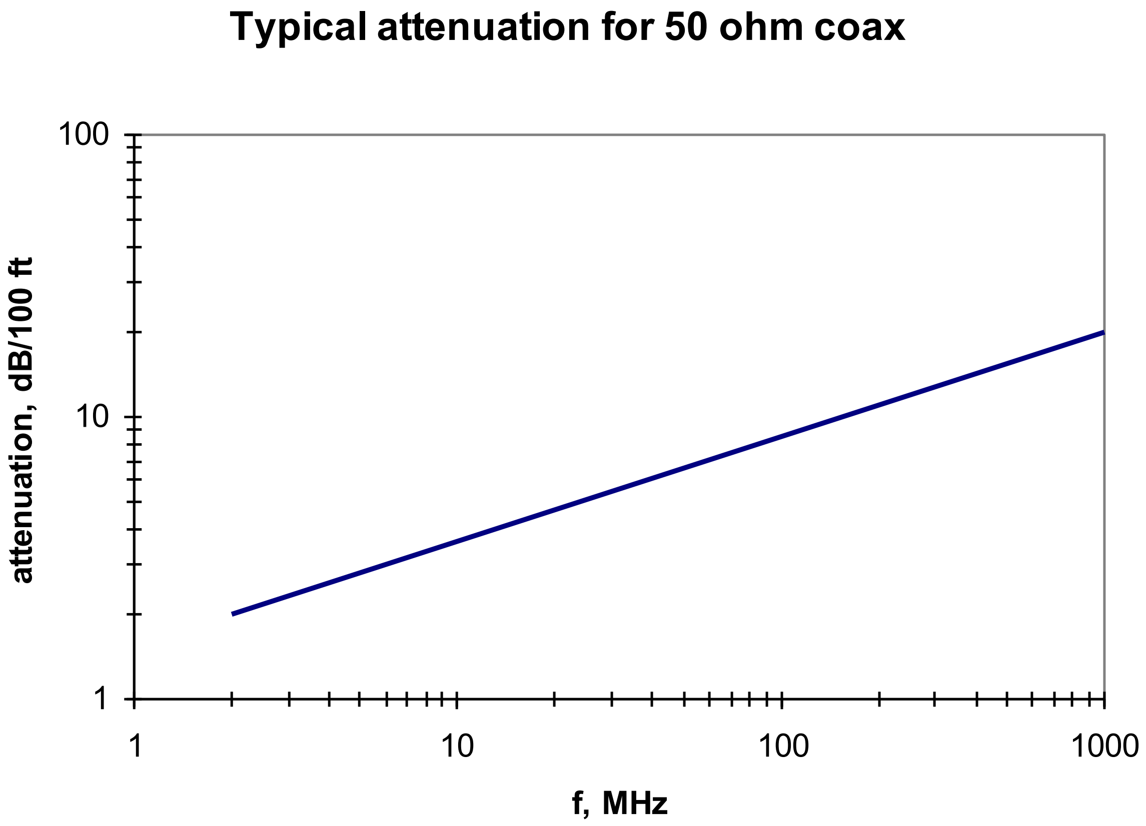
- Reflections
  - Signal propagating in coaxial cable satisfies the wave equation
  - General solution: a superposition of waves propagating in both +z *and* –z direction (z = along length of cable)

    $V = f(z-vt) + g(z+vt)$, where V is voltage.
    - Signal reflections will overlap and interfere with the original signal and distort measurements
    - Reflections result from changes in impedance in the signal path, such as an open-ended, or shorted line
      - Equivalent to an interface with different index of refraction in optics
  - Match impedance of load to impedance of the line, and reflections can be avoided
    - If 50 ohm cable goes into a high impedance (eg, oscilloscope input) we must add a 50 ohm "terminator" to make effective cable length infinity
    - In lab this week you will explore the effects of properly and improperly terminated cables.

Fourier: Coax cable = a filter

- Real cables' losses are frequency dependent:

Frequency dependence means pulses will be *distorted* when sent over long cables



Commercial Coaxial Cable

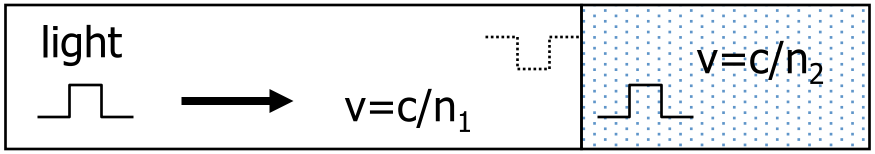
- Real cables:

Typical applications:

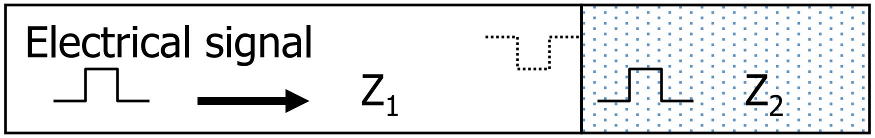
Type	Application	connector
RG58	signals	BNC
RG59	high V	SHV
RG8	High power	RF
RG174	miniature	LEMO

	AWG	Dielectric	D (mm)	d (mm)	ε_r	Nom. Imp. (ohms)
RG-8	11	Polyethylene	7.239	2.497	2.3	50
RG-58	20	Polyethylene	2.946	0.861	2.3	53.5
RG-59	22	Polyethylene	3.708	0.686	2.3	75
RG-122	22	Polyethylene	2.438	0.686	2.3	50
RG-174	26	Polyethylene	1.524	0.439	2.3	50
RG-213	13	Polyethylene	7.239	1.903	2.3	50
RG-214	13	Polyethylene	7.239	1.903	2.3	50
RG-223	19	Polyethylene	2.946	0.912	2.3	50
RG-316	26	TEFLON	1.524	0.439	2.1	50

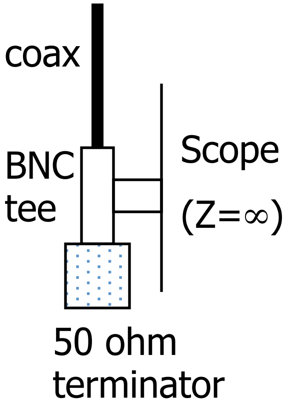
- Termination and impedance matching:
  - Analogy to optical media interfaces



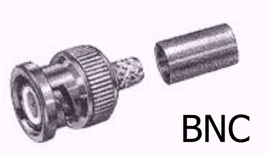
Reflections if $n_2 <> n_1$, with phase flip if $n_2 > n_1$



Reflections if $Z_2 <> Z_1$, with phase flip if $Z_2 < Z_1$



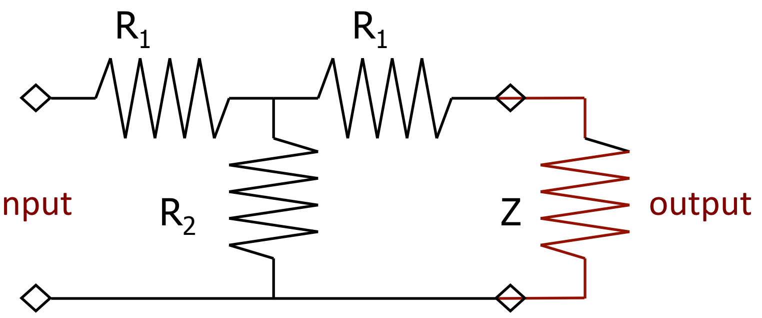
connectors



Electronics for signal processing

- Digital vs analog circuits
  - Rule of thumb: Digitize signals as soon as possible!
    - Digital signals are robust against noise, distortion
    - Data not degraded by long cables
    - Circuits easily designed using off-the-shelf chips
- Real-time electronics vs offline electronics
  - Analog "fast electronics" usually must operate in real-time
    - Edge arrival time is often important physics data
  - Digitized data can be buffered and handled in batches
- Passive vs active analog pulse circuits
  - Many functions do not require active circuitry (expensive, if fast!)
    - attenuators
      - simple resistive networks, but must balance Z
    - Splitters or fan-outs (Y or multibranch)
    - Clippers (shorten pulse length)
    - shapers/filters: analog RLC networks, or digital filters
      - Finite Impulse Response (FIR) filters can be simply implemented using specialized signal-processing chips (DSPs, PALs, ASICs)

Passive pulse-handling circuits: Attenuator, splitter, clipper



Tee attenuator circuit:

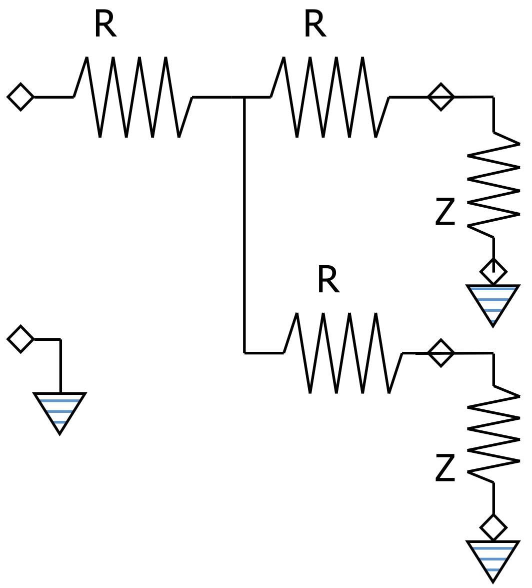
$R_1=Z(a-1)/(a+1)$,

$R_2=Z(2a)/(a^2-1)$

for attenuation factor a

Splitter circuit: For n branches,

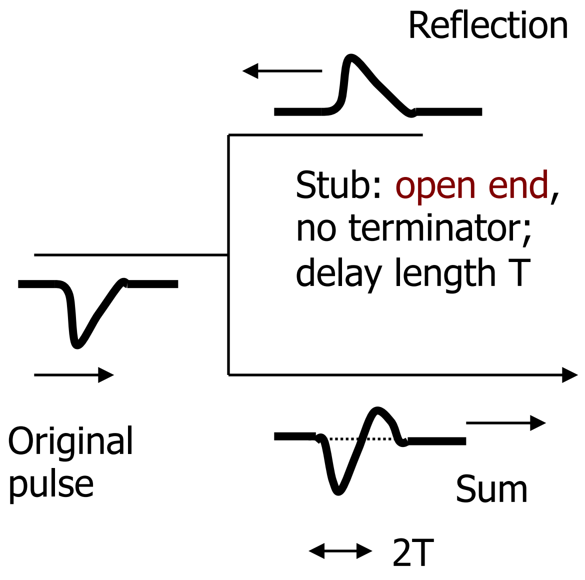
$R=Z(n-1)/(n+1)$ (n=2 shown)



Clipping pulses with a cable stub:

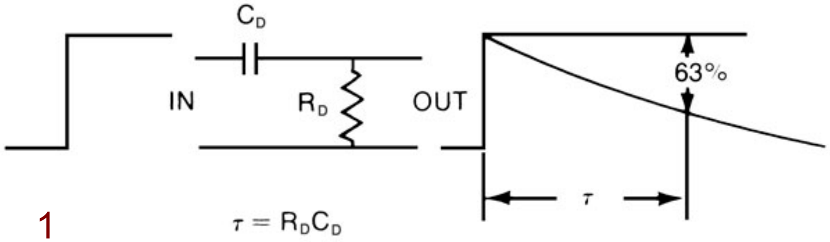
Reflected pulse adds to make net signal cross zero at t=2T

(T=delay of stub)

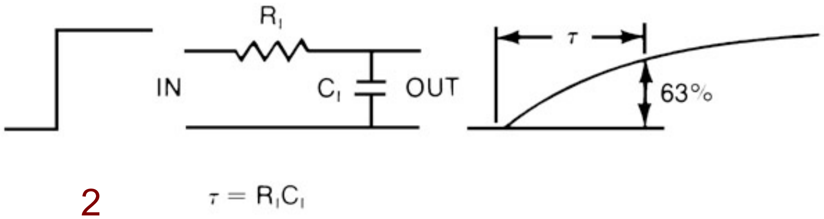


Stub: open end, no terminator; delay length T

Pulse shaping with simple RC filters

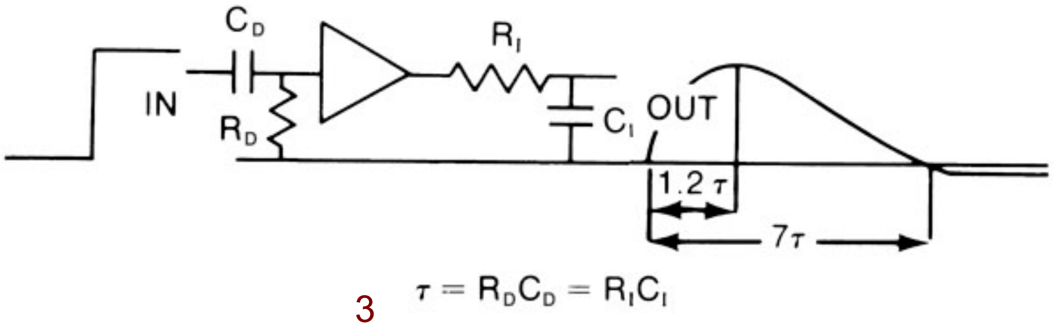


1



2

1. CR differentiating circuit (High-pass filter, finds edges)
   - output from a fast input pulse will drop to 0.63 of peak in time t = RC
2. RC integrating circuit (low pass filter, smooths edges)
   - output from a fast input pulse rise to 0.63 of peak in a time t = RC
3. CR-RC Pulse shaping provides both low frequency (differentiation) and high-frequency (integration) filtering, which improves signal to noise
   - Relative size of RC time constants for differentiator and integrator segments determines shaping effects



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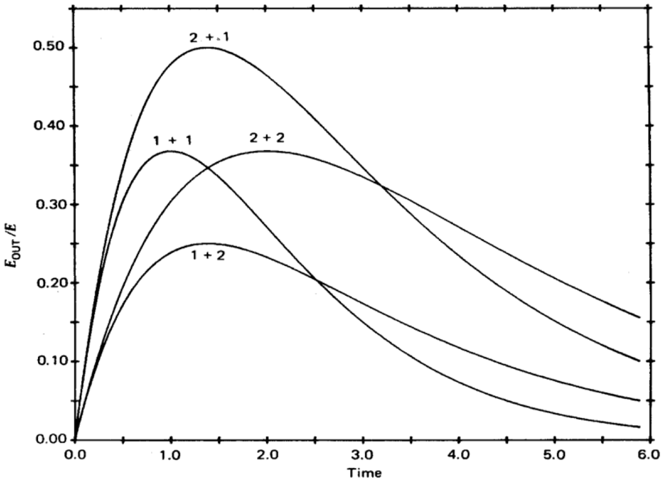
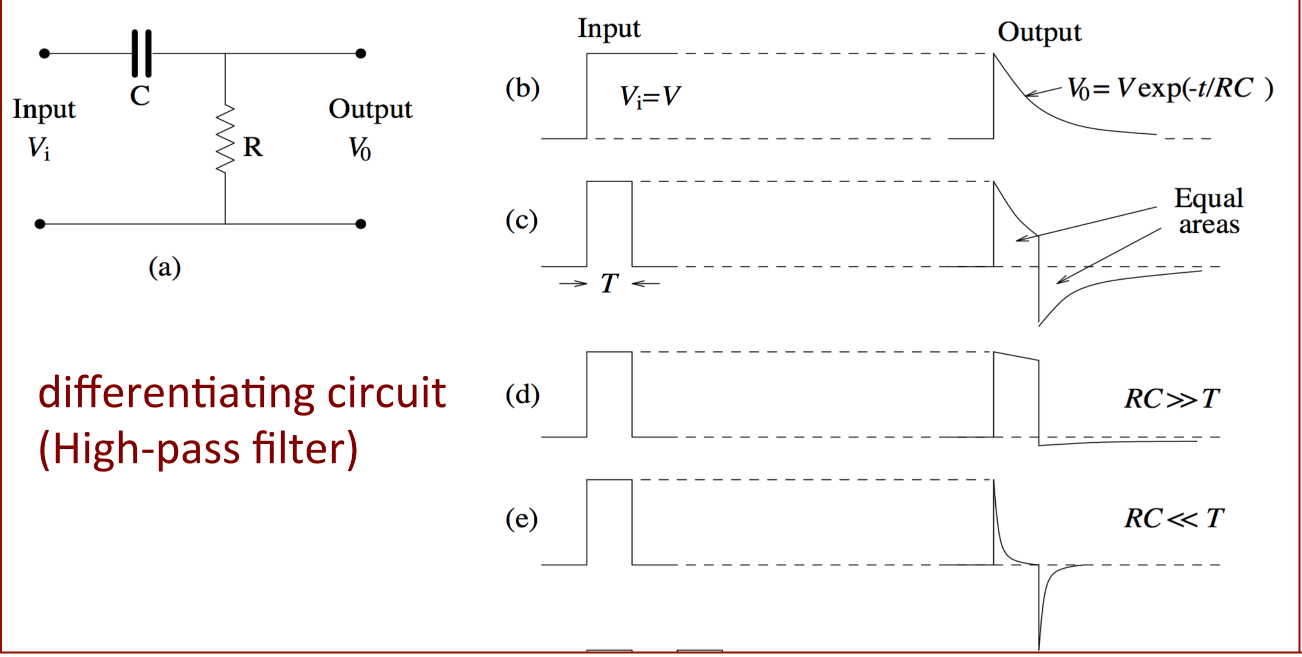
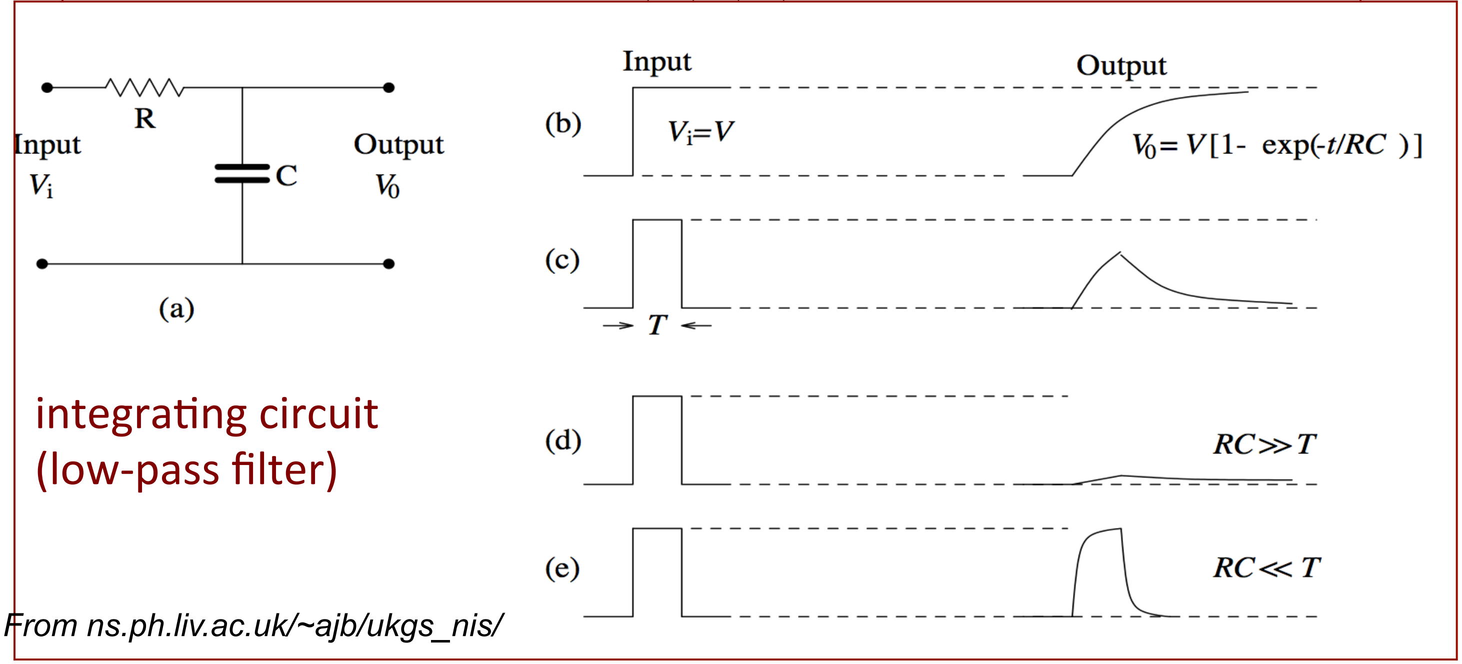




differentiating circuit
(High-pass filter)

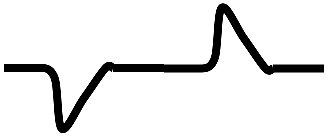


integrating circuit
(low-pass filter)

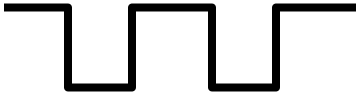
From ns.ph.liv.ac.uk/~ajb/ukgs_nis/

Pulse processing electronics

- Analog pulses (raw signals from detector elements)
  - May be any polarity, height (max |volts|), duration, area
  - Functions needed:



    - Amplify
    - Reverse polarity, or change shape
    - Convert to digital pulses with correlated properties
      - Eg, digitize pulse duration (t above some threshold), or pulse area
- Standardized (digital) pulses
  - Polarity, height, duration specified by industry standard
  - Functions needed:

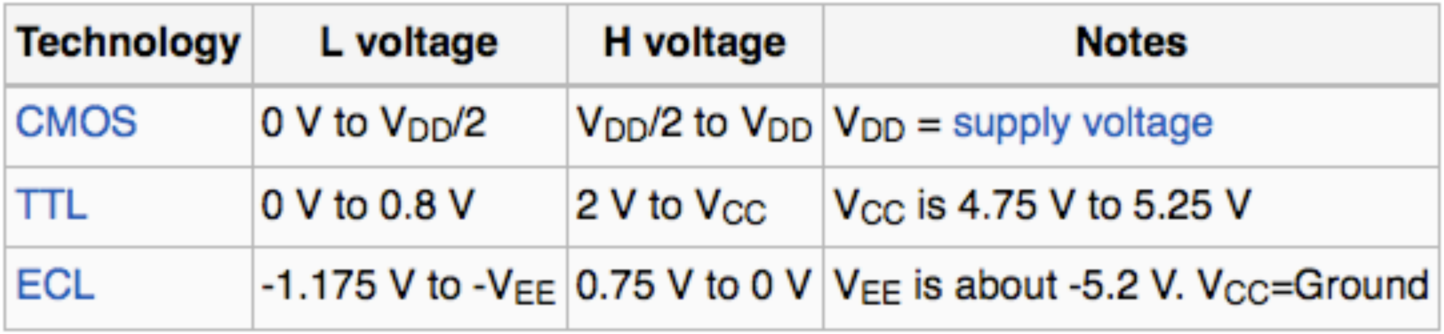


    - Apply digital logic (AND, OR, EXOR, NOT)
    - Convert to different standard (eg, NIM to TTL)
    - Timing, shape: delay or stretch pulse to adapt to different standards

- **Analog functions:**
  - Amplification or baseline shift
  - Active fan-in/fan-out
    - multi-input or -output 1:1 amplifier
  - Discriminator
    - output standard digital pulse if analog input exceeds threshold
  - Analog to digital converter
    - ADCs: digitize pulse height or area
    - DACs: reverse ADC function - convert number to voltage
  - Time-to-digital converter
    - TDCs: digitize pulse arrival time; also TACs, time to analog converter
  - Single or Multi-channel analyzer, or pulse height analyzer
    - MCA/PHA: makes a *histogram* of pulse heights or areas
    - SCA: 1-bin MCA, counts pulses falling within narrow height range
- **Digital functions (for standardized logic pulses):**
  - Coincidence
  - Logic functions (AND, OR, EXOR, NOT)
  - Scalers (pulse counters)
  - Storage: FIFO or LIFO buffer registers
  - Computer interface for digital data logging/transmission

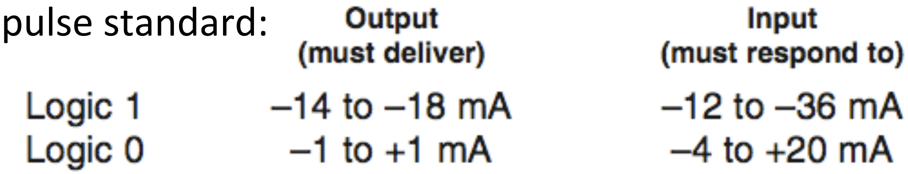
Digital logic level standards

- Industry standards for signal levels allow manufacture of interchangeable pulse-handling hardware
  - Low and High (0 and 1) levels for electronics industry standards



Technology	L voltage	H voltage	Notes
CMOS	0 V to $V_{DD}/2$	$V_{DD}/2$ to V_{DD}	V_{DD} = supply voltage
TTL	0 V to 0.8 V	2 V to V_{CC}	V_{CC} is 4.75 V to 5.25 V
ECL	-1.175 V to $-V_{EE}$	0.75 V to 0 V	V_{EE} is about -5.2 V. V_{CC}=Ground

  - Nuclear and particle physics needs created more industry standards
    - NIM negative-going (fast logic) pulse standard:

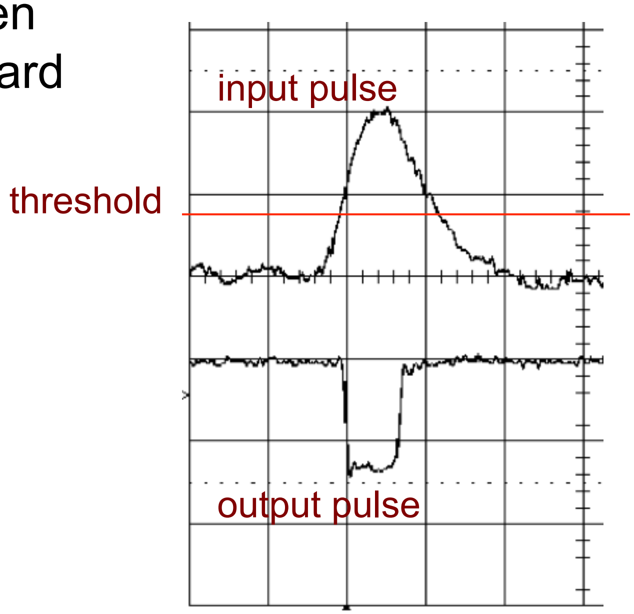


	Output (must deliver)	Input (must respond to)
Logic 1	–14 to –18 mA	–12 to –36 mA
Logic 0	–1 to +1 mA	–4 to +20 mA

    - CAMAC: interface for PCs, formerly commonly used, now obsolescent
    - VMEbus (Eurobus): developed for Motorola 68000 processors, widely used

Discriminator modules for pulse selection

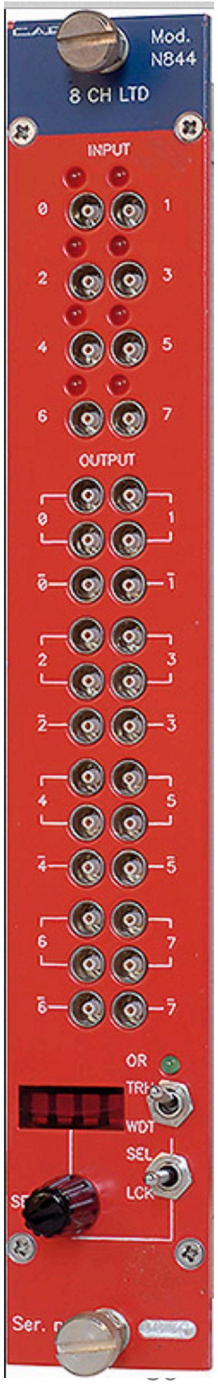
- Used to ignore low-level noise in signals from detector elements.
  - Respond only when input pulse exceeds chosen threshold V
- Standard output pulse is produced only when input goes over threshold, according to settings chosen
- Output pulse shape set by NIM standard
- Output pulse duration can be set
- Typically, 8–32 inputs/module



Example of commercial module: CAEN N844

8 Channel Low Threshold Discriminator

- Individually programmable thresholds
- Programmable output width

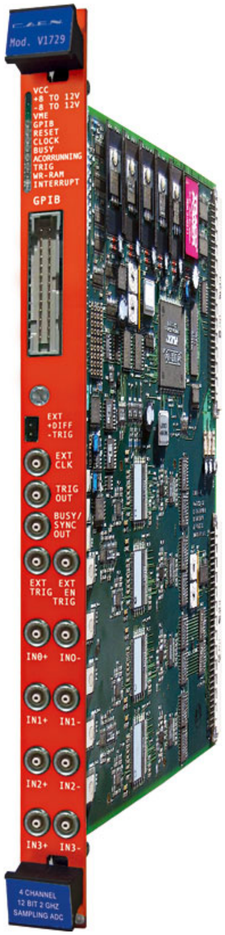


Digitizing analog pulse data

- General philosophy: digitize as soon as possible
  - Analog signals are vulnerable to distortion, E-M noise
  - Digital signals are robust; error-correcting codes can reduce data loss due to dropped bits
- Analog to Digital converters (ADCs)
  - Capture waveform vs time samples, or calculate area under pulse
  - Samples analog signal at regular intervals - limits response
    - Nyquist limit - Fourier components of signal with f > (sampling rate/2) are lost
  - Voltage value (= real number) is truncated to integer (0-4096, etc)
- Time to Digital converters (TDCs)
  - Measure time difference between two signals
    - Fast, stable clock counter is started on one signal, stopped on the other
    - Sensitive to threshold levels! Uncertainty introduced if rising edges of signals jitter
  - Today: few ns resolution is simple, < 1 ns is still hard (=expensive)

Example of a high-end ADC (courtesy of our neighborhood CAEN rep):

CAEN V1729: 4-ch. 12-bit 2 GHz sampling ADC

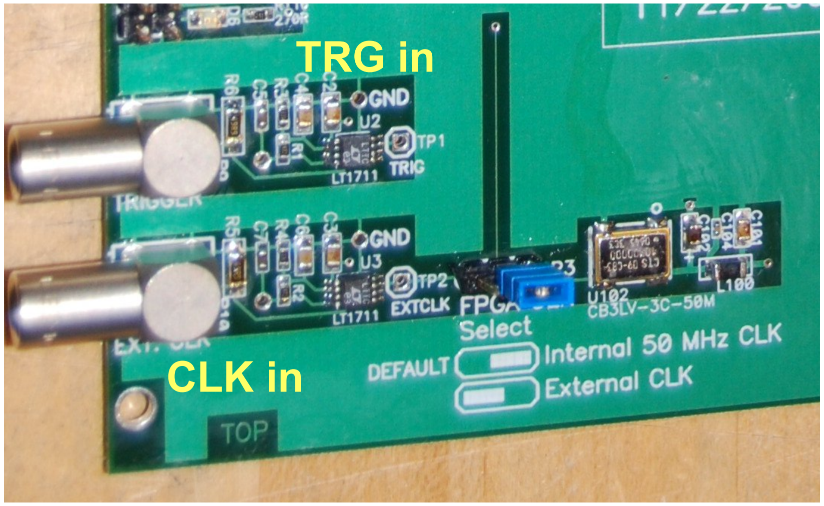


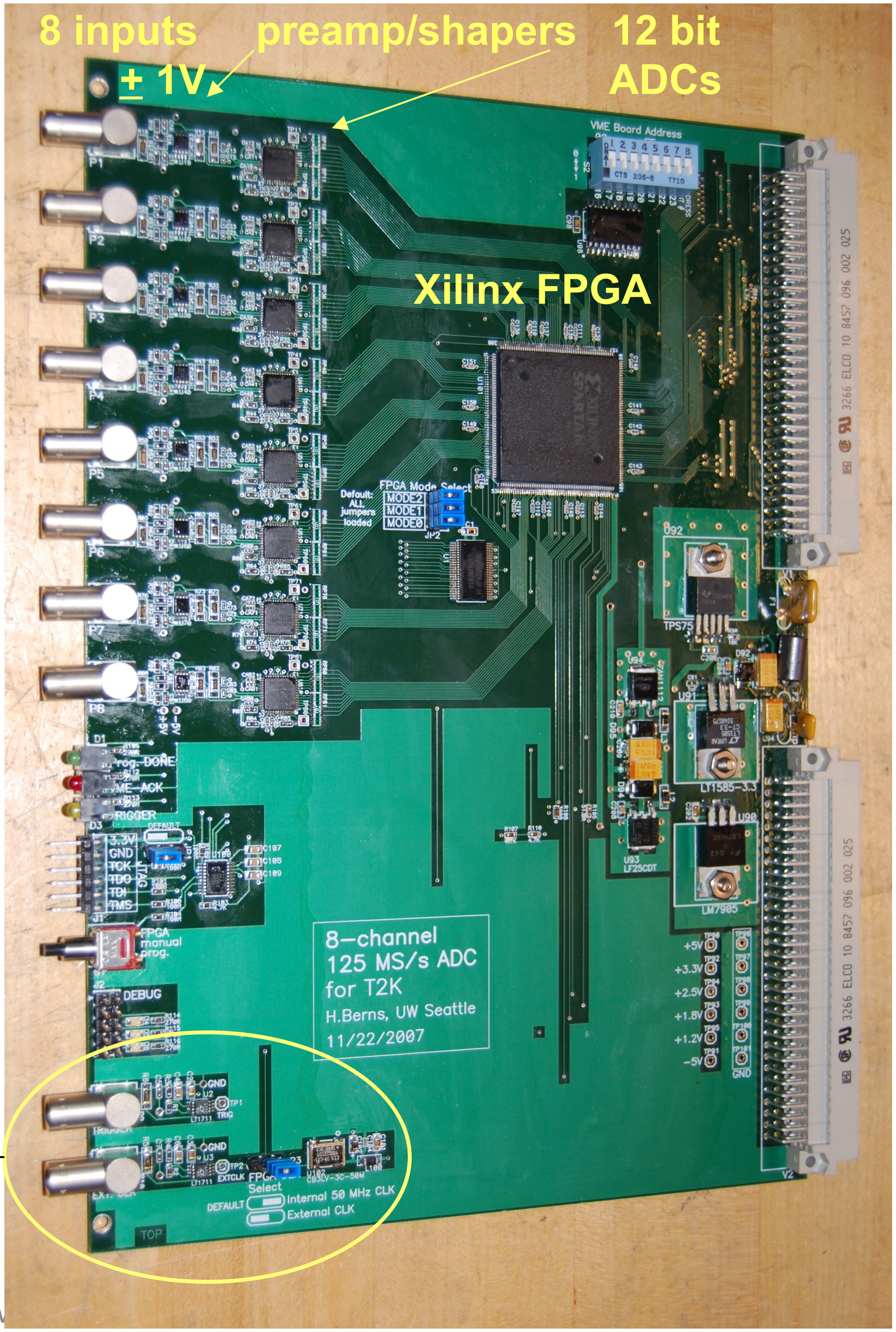
- 4 channels per module
- 300 MHz bandwidth
- 1 or 2 GHz sampling frequency
- 12 bit A/D conversion
- Full scale range +/- 0.5V (250uV LSB)
- 2520 sample points (circular analog memory)
- Four trigger mode operation
- VME 6U module, 1 unit wide
- Cost: $9191 per module
- Available now (e.g. for CERN)

- Note: VME module heights are given in 'U', 1U= 43.60mm
(6U is most common size)

UW FADC (Flash ADC)

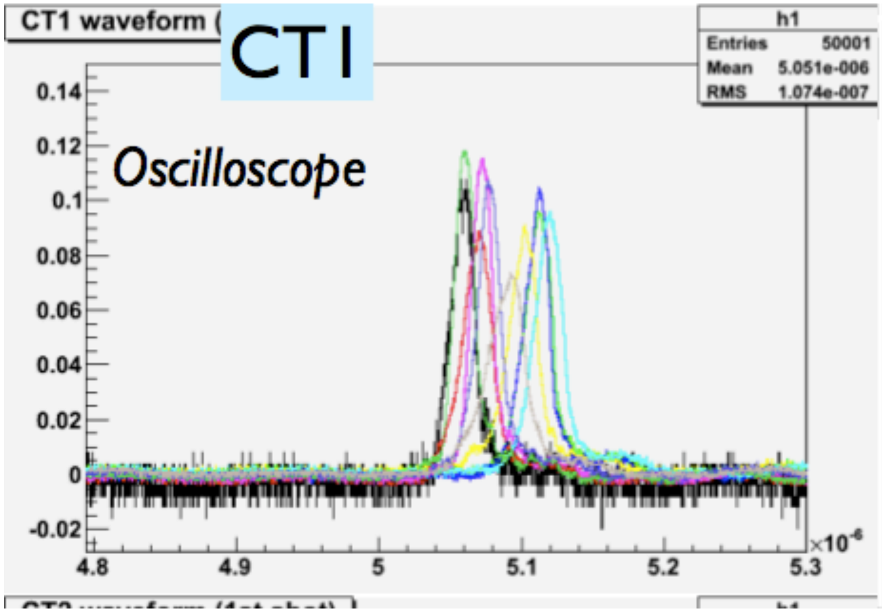
- 14 boards built here for T2K neutrino experiment at JPARC accelerator in Japan
- 8 channels per board, 160MHz sampling,
- Why build our own?
  - Cost! Parts + labor ~ $1500 each
  - Mainly: Customizable features
    - Input pulse shaping and output data content are exactly what we wanted,
    - no need to adapt our DAQ to a commercial module's specs
- Used pulse shaping with RC ~ 100 ns
  - Signals are ~ 25ns wide = only 4 samples
  - But: we only want pulse area (energy)



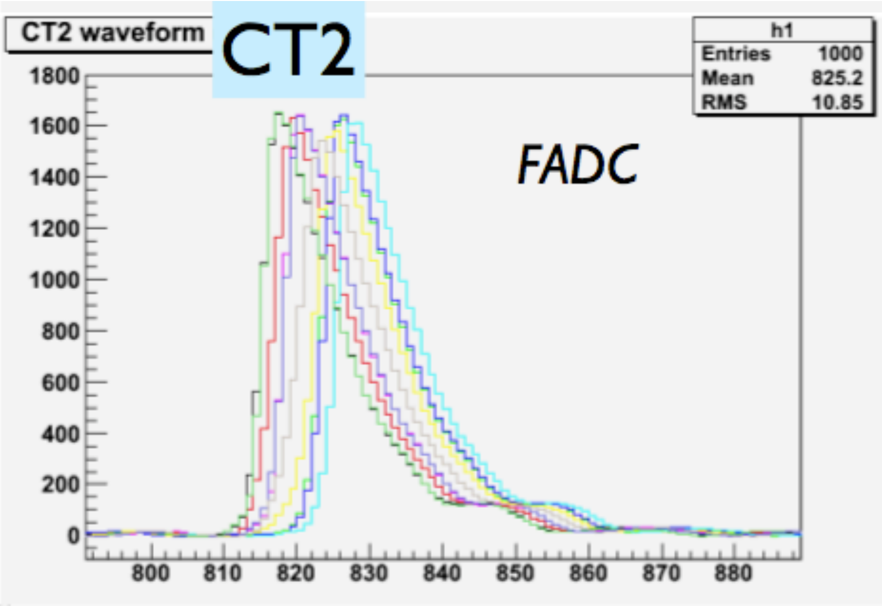


Case study: Plots of input vs output of UW FADC board

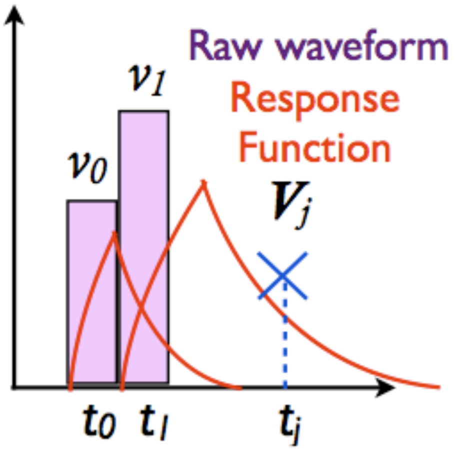
Raw signals from oscilloscope
with 0.2 ns resolution



Digitized signals from UW ADC



- Area under ADC output is proportional to raw pulse area
- Arrival times (leading edges) are in correct time order
- Each sample (voltage at time t) in raw signal contributes an RC decay waveform to output

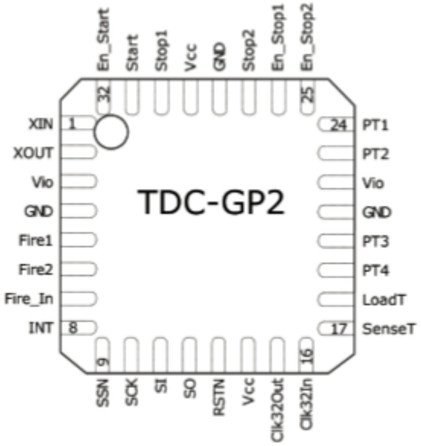


Examples of TDCs:

VX1190A-2eSST CAEN VME module for $10K (for 128 channels!)

128 Channel Multihit TDC (100/200/800 ps)

- 3 programmable ranges: 100 ps LSB (19 bit resolution), 200 ps LSB (19 bit) and 800 ps LSB (17 bit)
- ECL/LVDS inputs automatically detected
- 5 ns Double Hit Resolution
- Leading and Trailing Edge detection
- Trigger Matching and Continuous Storage acquisition modes
- 32 k x 32 bit output buffer
- MBLT, CBLT and 2eSST data transfer
- Multicast commands
- Geopraphical address supported



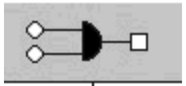
…or a $50 ASIC chip (2 channels)

- 2 channels with typ. 50 ps resolution rms
- Measurement range 3.5 ns to 1.8 µs (0 to 1.8µs between stop channels)
- 15 ns pulse-pair resolution with 4-fold multihit capability
- 4 events can be measured arbitrarily against each other
- Trigger to rising or/and falling edge
- Windowing for precise stop enable

Digital logic

- Logic modules:
  - AND (coincidence)

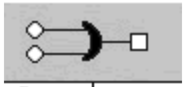
AND



Input	Output
0 0	0
0 1	0
1 0	0
1 1	1

  - OR (logic fan-in)

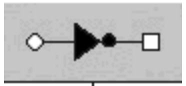
OR



Input	Output
0 0	0
0 1	1
1 0	1
1 1	1

  - NOT (logic inverter)

NOT



Input	Output
0	1
1	0

  - Boolean logic (*=AND, +=OR, ! = NOT)
    - DeMorgan's Laws: !(A * B * C...) = !A + !B + !C ...
  - *Majority logic* units: standard module with flexible, front-panel settable logic options:
    - 4-fold AND: A*B*C*D
    - 4-fold OR: A+B+C+D
    - 3-fold majority: A*B*C+B*C*D+C*D*A+B*A*D
      - (i.e., output when *any 3* inputs are high)
    - 2-fold majority: A*B+B*C+C*D+D*A+B*D+A*C
      - (i.e., output when *any 2* inputs are high)

Coincidence modules for trigger selection

- Used to apply selection logic to signals from detector elements.
  - Record data only when coincidence occurs
- Standard output pulse is produced only when inputs overlap in time, according to settings chosen
  - Fixed logic: inputs are set for AND (all required), OR (any subset) or NOT (veto), fires only when inputs meet these criteria simultaneously
  - Majority logic: some number of inputs must meet criteria set
- Typically, 4 inputs/module, 2 to 4 modules per NIM slot

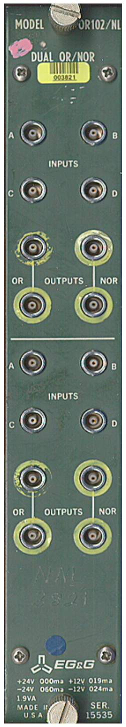
Example of commercial module: CAEN N405

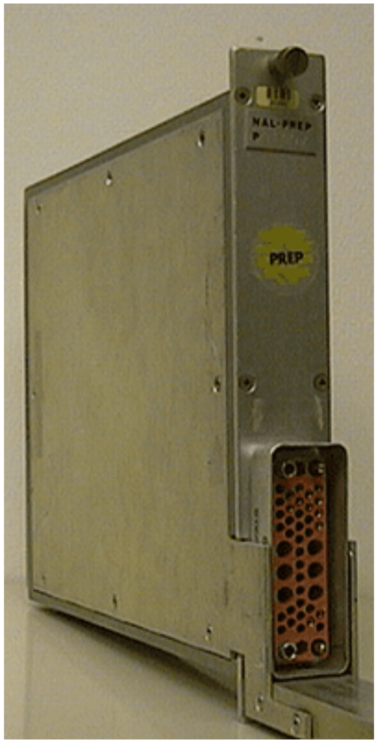
Triple 4-Fold Logic Unit/Majority with VETO

- Three independent sections with 4 standard NIM inputs each
- AND, OR, MAJORITY function selectable for each section
- One auxiliary NIM output per section whose width is equal to the coincidence duration
- NIM shaped outputs with Fan Out of two
- One negated NIM shaped output per section
- One VETO input per section
- Front panel trimmer for output width adjustment on each section

Standard NIM Modules

- NIM = Nuclear Instrumentation Module, standardized since 1950s
- *NIM bin* holds 12 *modules*, simply provides DC power and gate (enable) signal via backplane connector



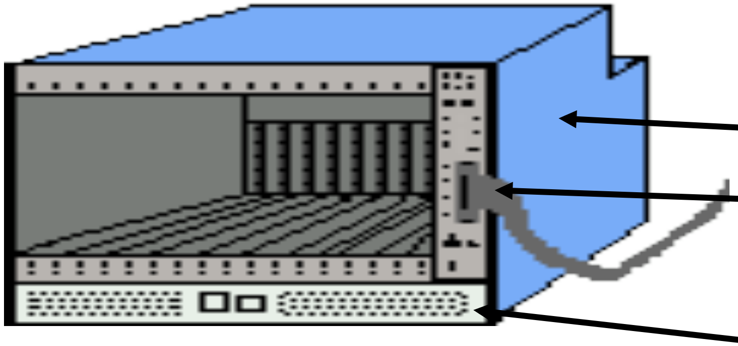


Signal definitions for several commonly-used digital logic families:

Level	NIM	TTL	ECL
Logic 1	-0.8 V (~16mA into 50 Ω)	+2~5 V	-1.75 V
Logic 0	0 V	0~0.8 V	-0.90 V

CAMAC standard modules

- CAMAC=Computer Automated Measurement And Control (1970s)
- CAMAC *crate* provides 25 module *slots*, with internal *dataway* = power, control signals and data bus
  - Much greater control of modules than NIM
  - Much more compact than NIM
- Normally slots 24-25 are occupied by double-width *crate controller* = microcomputer linked to outside
  - dataway includes
    - 24-bit parallel read and write lines
    - 24 “N-lines” (lets controller enable module N)
    - 24 LAM lines (look at me: lets module interrupt controller)



CAMAC Crate

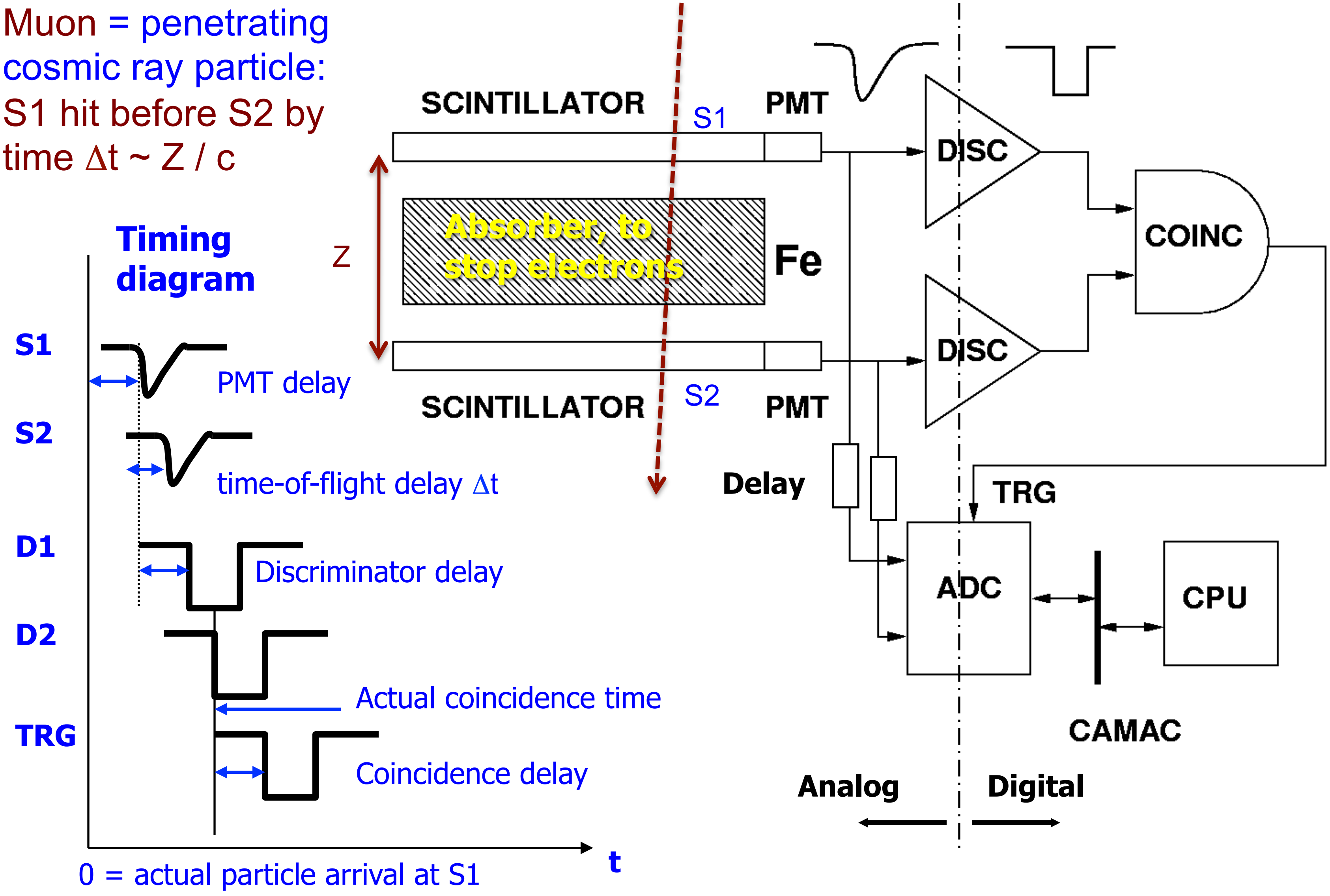
Controller with interface cable to computer

Power supplies

8-channel CAMAC ADC module

Example: muon detector logic

Muon = penetrating cosmic ray particle: S1 hit before S2 by time $\Delta t \sim Z / c$



0 = actual particle arrival at S1

Using the muon detector DAQ

- Data acquisition (DAQ) is a crucial part of experiments

For the muon detector setup discussed:

- Analog-to-Digital Converter (ADC) provides PMT pulse area
  - Proportional to energy loss by muon in scintillator
  - Raw PMT outputs are split (to discriminator, and ADC) and delayed
    - Trigger signal from coincidence module needs time to form and arrive
    - ADC starts measuring V vs t when trigger arrives, stops after some set interval
    - ADC sampling at 250 MHz (once per 4 ns) is commonplace
- Discriminator outputs could also be sent to a TDC (time to digital) to measure muon time of flight
  - S1 = start signal, S2 = stop signal
  - Can measure 0.1 ns intervals with common equipment
- ADC/TDC have ready/busy/done flags to allow data output
  - VME or other bus interfaces are used with realtime software
  - Host CPU must be fast enough to handle DAQ data rates