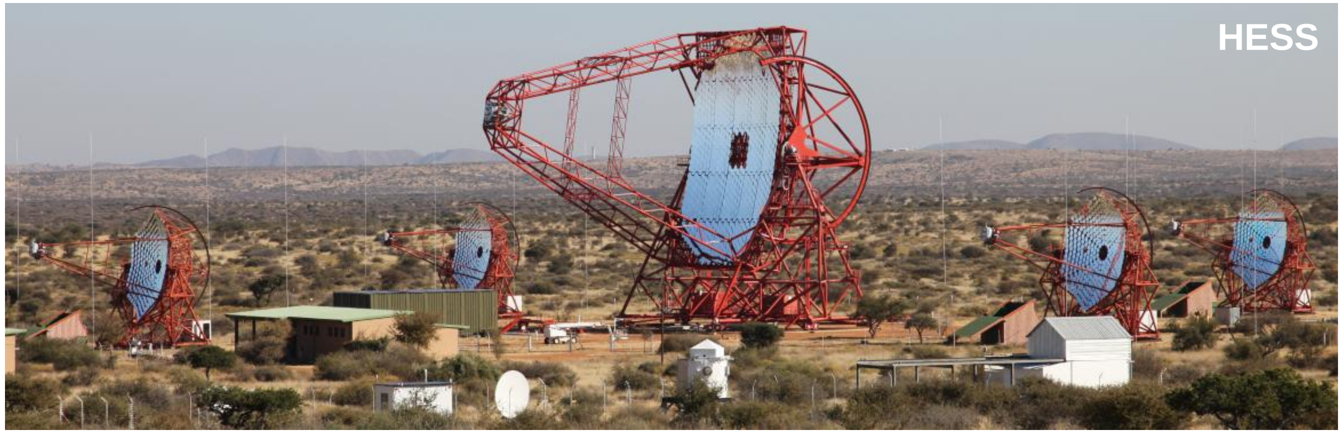
Friedrich-Alexander-Universität
Erlangen-Nürnberg

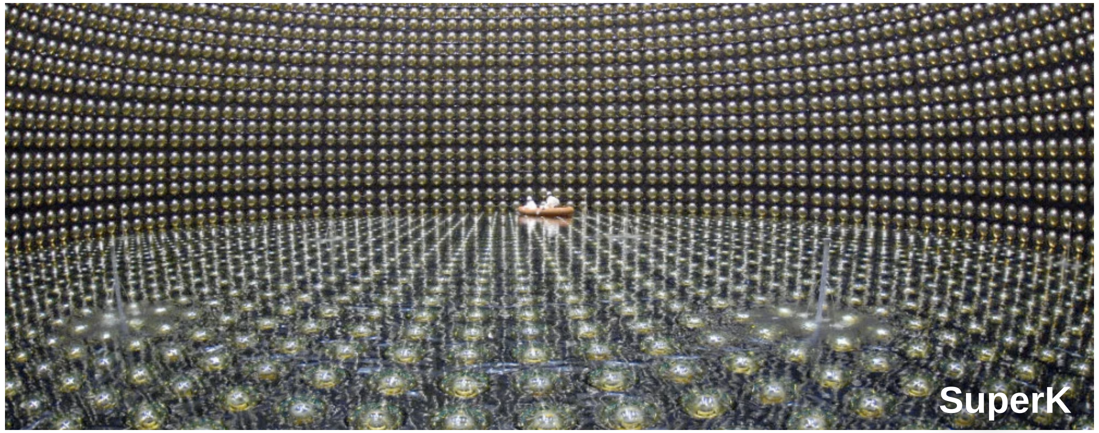
Hardware crash course for analyzers

How-To readout a PMT and effects to know

Dr. Martin Rongen
Bärnfels Astroparticle School 2024
7th October 2024

Archetypical astroparticle experiment (sorry radio)





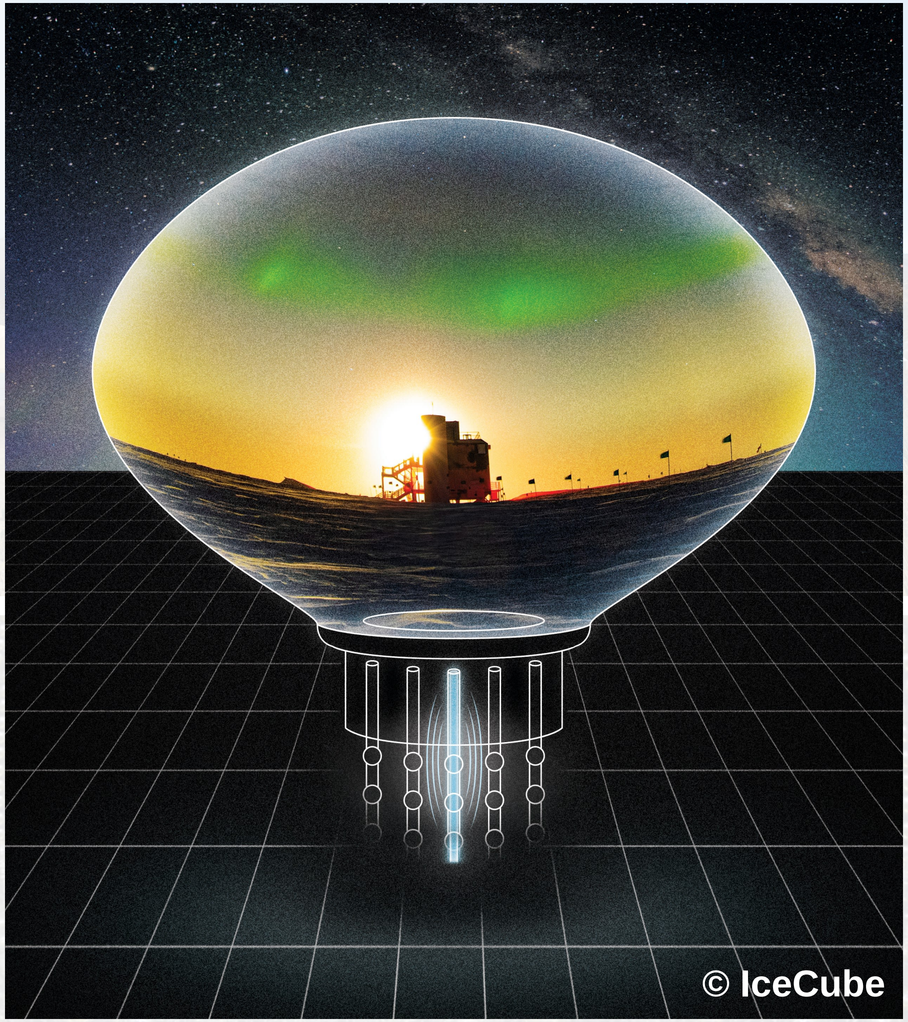
Archetypical astroparticle experiment (sorry radio)

- From a hardware perspective
  all of these experiments are identical:

  arrays of time-sensitive single photon sensors
  (**photomultplier tubes (PMTs)**, sometimes SiPMs)

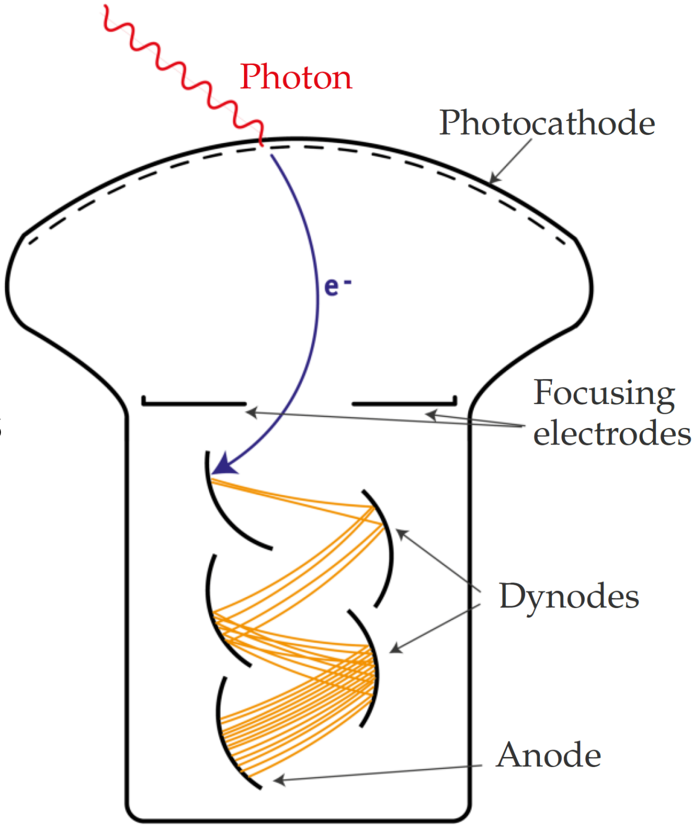
- Physics reconstructions rely on three quantities:
  I. how many photons
  II. when
  III. & where

- Today we want to review how a PMT counts and time-stamps photons, how we digitize this signal and which non-ideal effects YOU need to consider at the analysis level



PMT in a nutshell

- Glass vacuum tube:
  - Entrance window coated with thin alkali metal layer (low work function) where photons convert to electrons and get released into vacuum = photocathode
    (photocathode quickly oxidizes in air,
    if you do not see the golden surface, there is a vacuum leak…)
  - Metal cups on = dynodes on successively higher voltages multiply incident electrons → electron cascade
  - Anode where current pulse is collected for digitization
- Electrical contact to photocathode, electrodes (focusing, dynodes, anode) exposed via metal pins
  → everything else needs to be provided by the user



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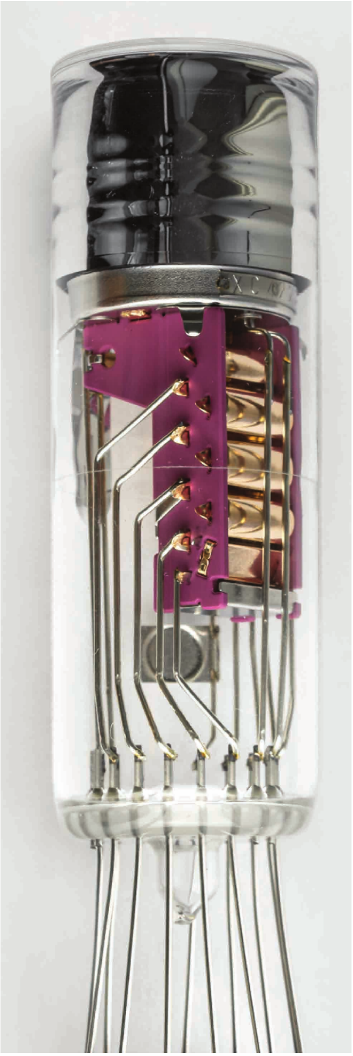

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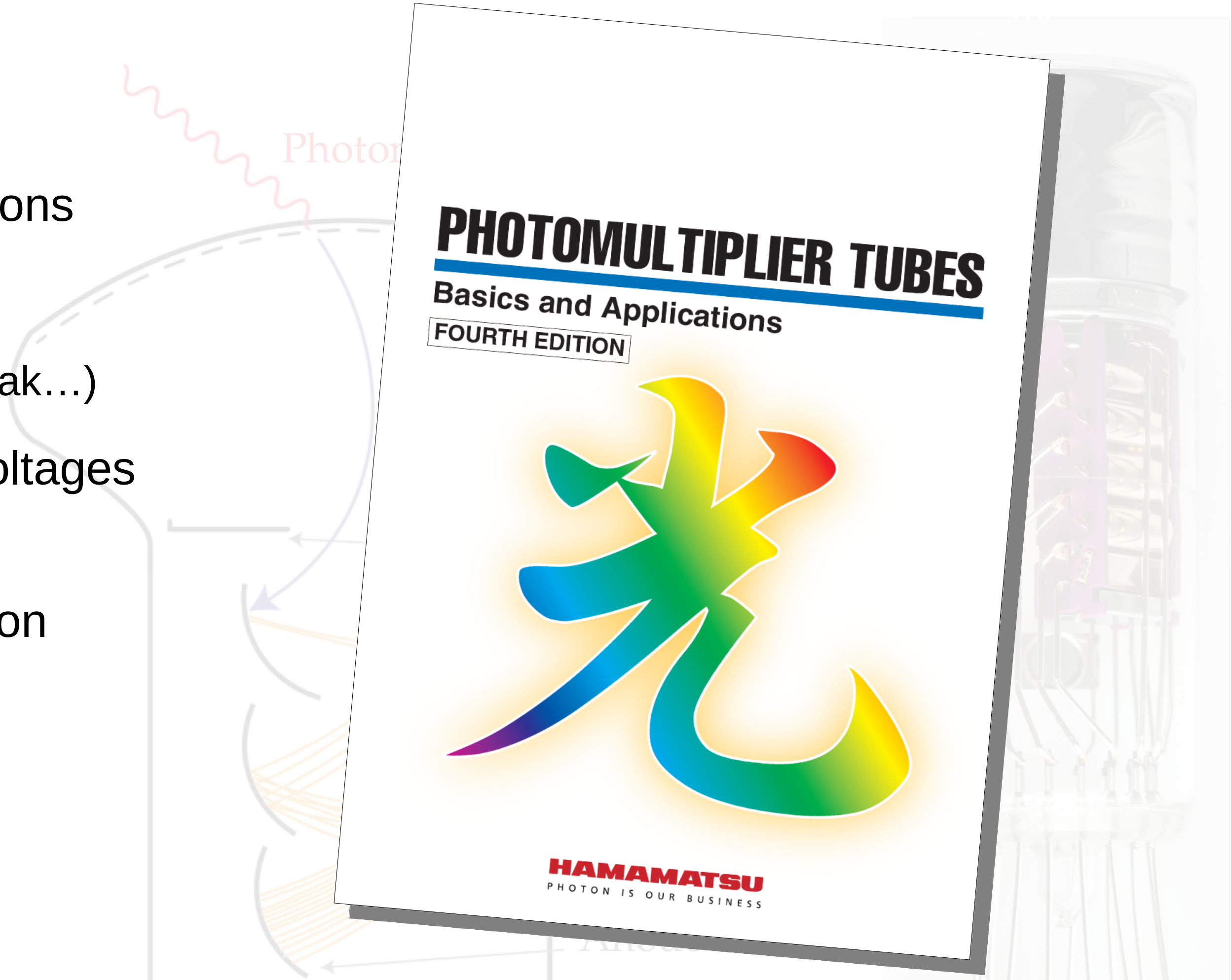


All figures not otherwise referenced will be from this book.

Our road ahead:

I. Choosing a PMT
II. Powering a PMT
III. Digitizing the output signal

IV. Actually doing it …
(hardware demonstration)

V. Non-ideal effects to know

Summary of performance metrics

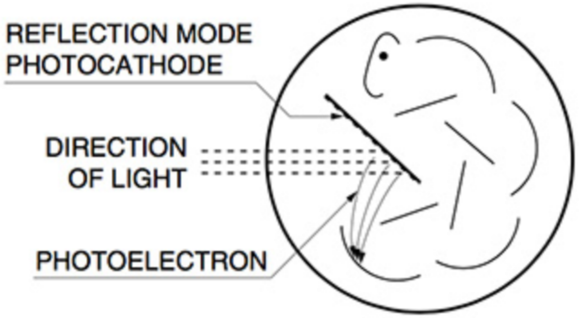
Quantity	Impacts	Given by
Photocathode area	Total effective area	Size
Spectral range & quantum efficiency	Total effective area	Photocathode & glass
High voltage and gain range	Photon counting ability, needed amplifier, dynamic range, ...	Dynode system, voltage divider
Operational & storage temperatures	Can you use it? (Oil well logging)	Glass, manufacturing process
Gain spread	Photon counting ability	Dynode system, voltage divider
Peak-to-Valley Ratio	Distinguish photons from noise	Photocathode uniformity, dynode system, voltage divider, readout electronics, …
Transit time (spread)	Timing resolution	
Pulse rise and fall times	Double pulse separation, peak signal	
Linearity	Dynamic range	
Pre-, Late- & Afterpulse probabilities	Spurious signals	First dynode geometry, impurities
Dark noise	Distinguish photons from noise	Photocathode, glass, impurities
Size, cost, logistics ...	Can you use it?	….

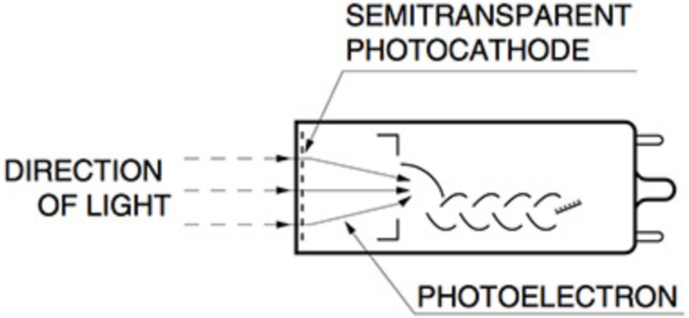
How to choose a PMT? I. General types

- Side-on illumination
  - Most common type for lab equipment (photometers)
  - Often paired with reflection-type photocathodes (thick metal plate inside vacuum housing, with electron emission on the illuminated side)

- Head-on illumination *(what we commonly use!)*
  - Can be made at ANY size
  - Transmission type photocathode (metal coating on glass body)
    - thick enough to absorb photons
    - thin enough to transmit electrons

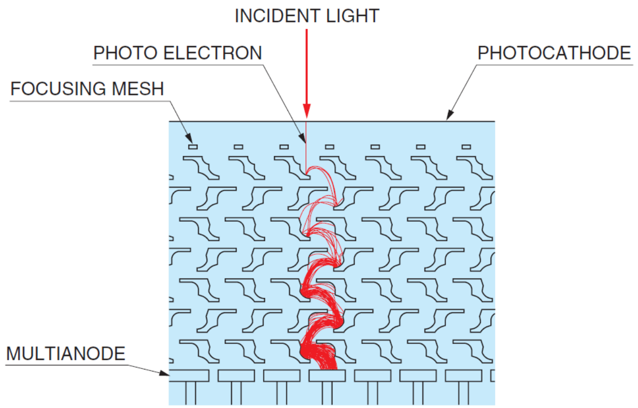
Side-on type Head-on type

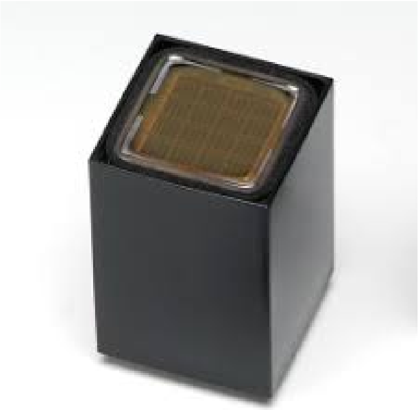




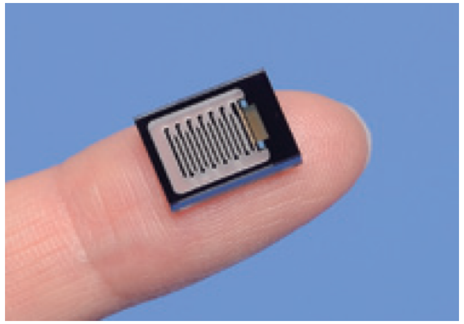
How to choose a PMT? I.b Exotic types

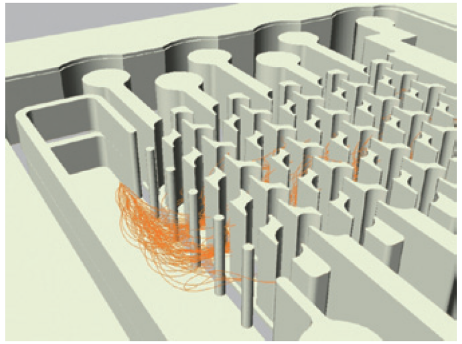
- Multianode (position-sensitive) PMTs
  - e.g. in low-light spectroscopy



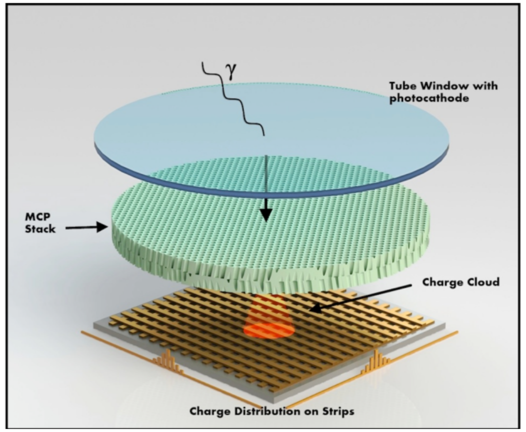


- Micro-PMTs

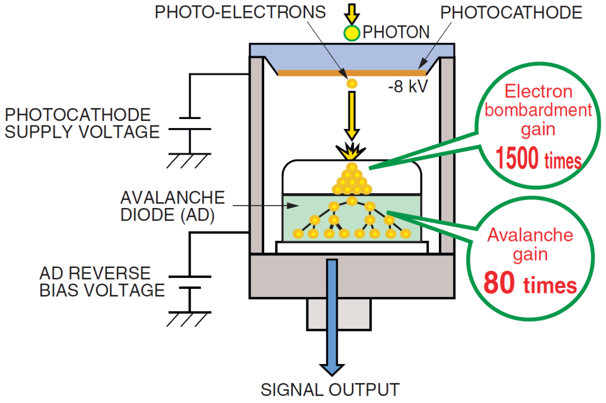


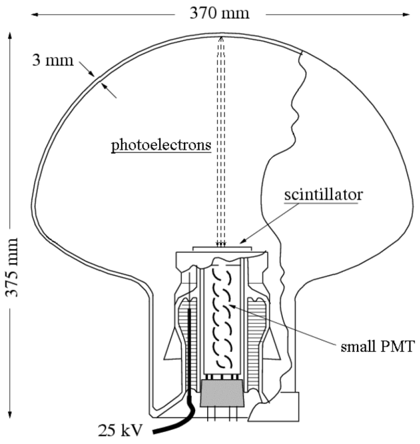


- Microchannel Plate-PMTs
  - MCP as continuous dynode
  - allows for good TTS
  - can be segmented
  - generally not available with large areas



- Hybrid PMTs
  - large HV, large gain, additional particle conversion allows to beat Liouville → large effective area





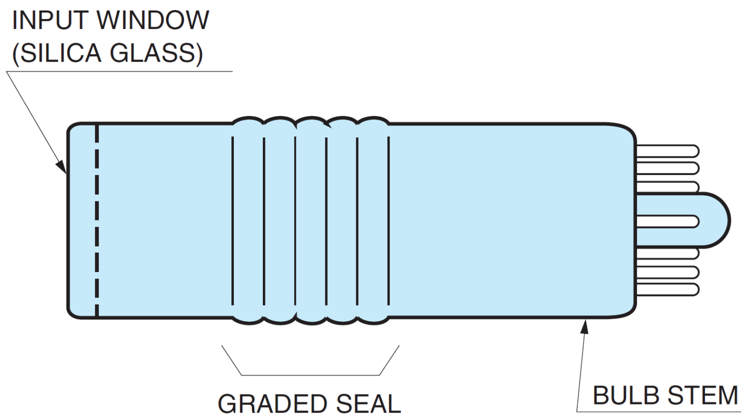
10.1016/j.nima.2009.05.168

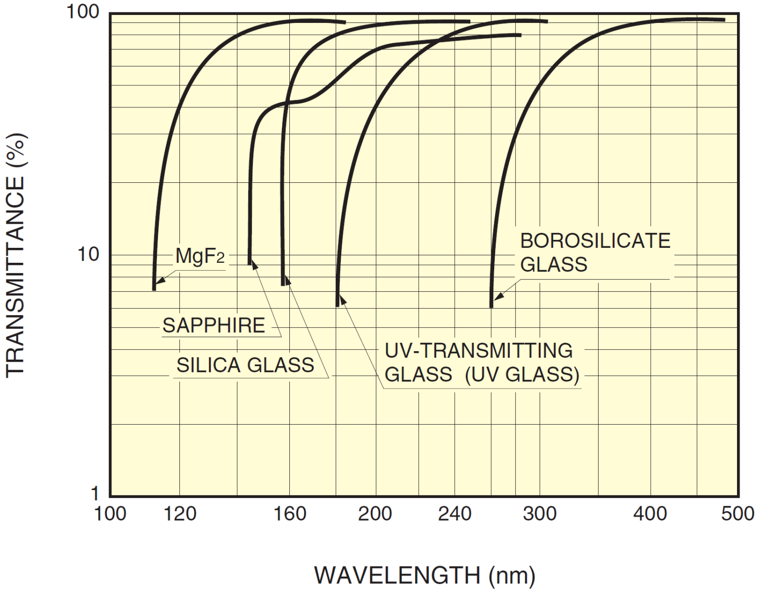
How to choose a PMT? II. Glass

- Main body almost always borosilicate glass with leads/pins made from Kovar (nickel–cobalt alloy) as both have them coefficient of thermal expansion

- Windows glass dictates spectral transparency, radioactive noise:
  - Borosilicate glass:
    - transparent down to ~300nm
    - potassium contamination needs to be controlled in low noise applications
  - Silica glass:
    - UV transparent to 160nm,
    - Needs to be mated to borosilicate body → fragile
    - permiates helium

- Sides of “bulb” often feature light-tight metal coating against unwanted illumination



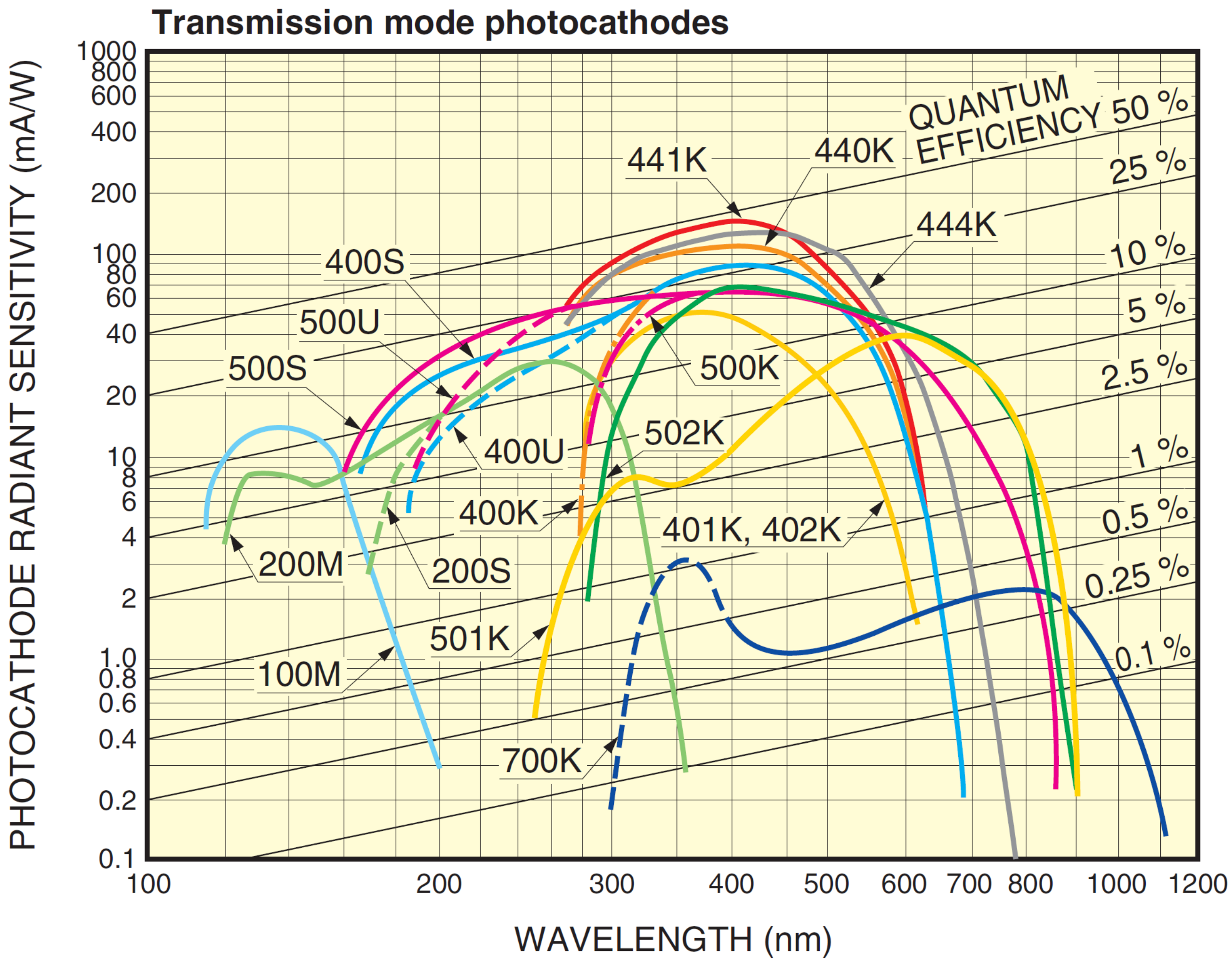


How to choose a PMT? III. Photocathodes

- Photocathode material dictates spectral range, total efficiency and noise rates
  - Low-workfunction group 1 metals
  - Bialkali (Sb-Rb-Cs, Sb-K-Cs) work horse for most applications
  - Multialkali in infrared, Alkali halide in UV

- Aside from the material the deposition process (evaporation temperature, glass material, …) lead to varying quality crystallization impacting QE
  → Post-2007: Super-Bialkali (>30% peak QE)
  & Ultra-Bialkali (>40% peak QE)

- In transmittance type photocathodes, thickness is a balancing act between photon absorption and electron emission



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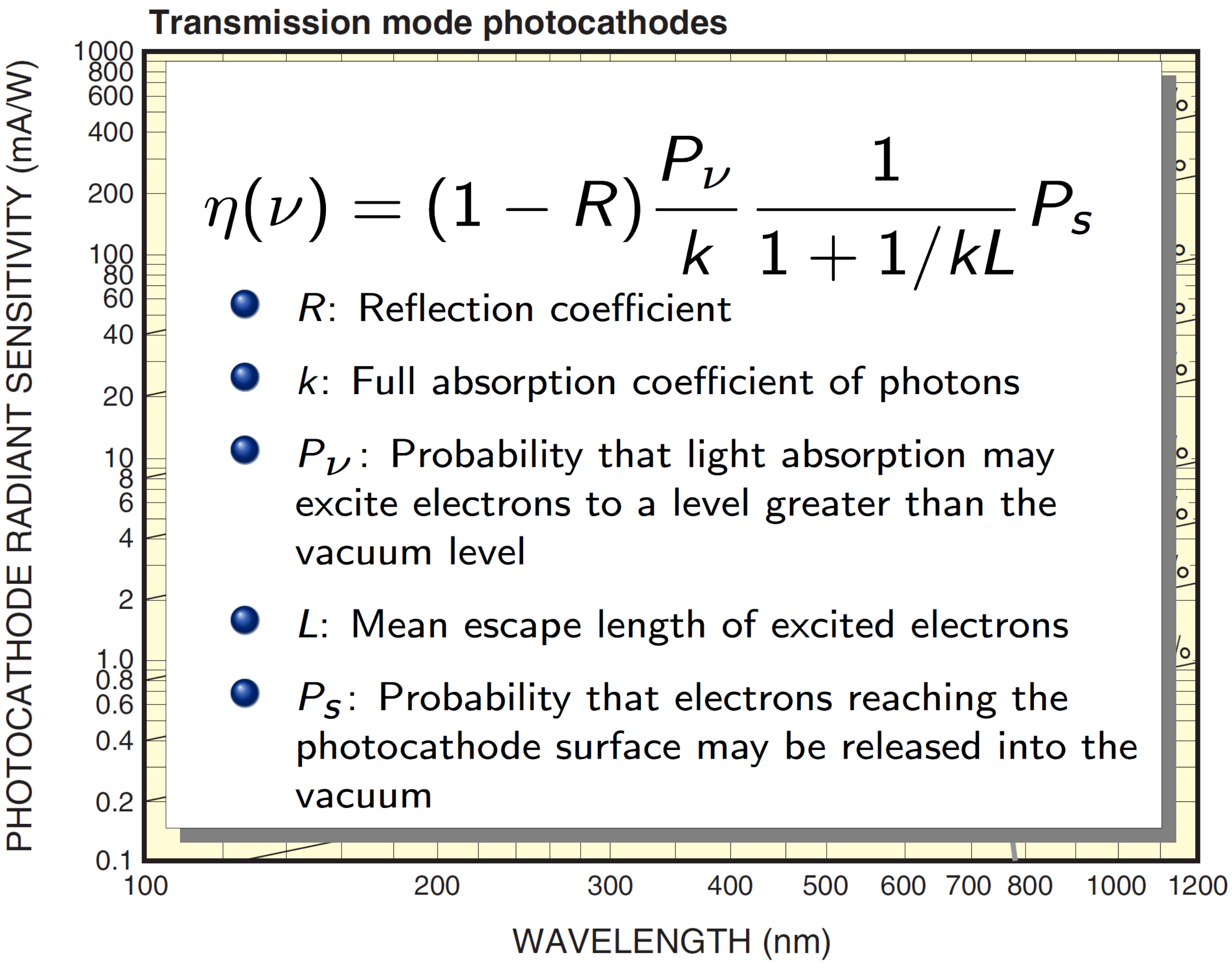


$$\eta(\nu) = (1-R)\frac{P_\nu}{k}\frac{1}{1+1/kL}P_s$$

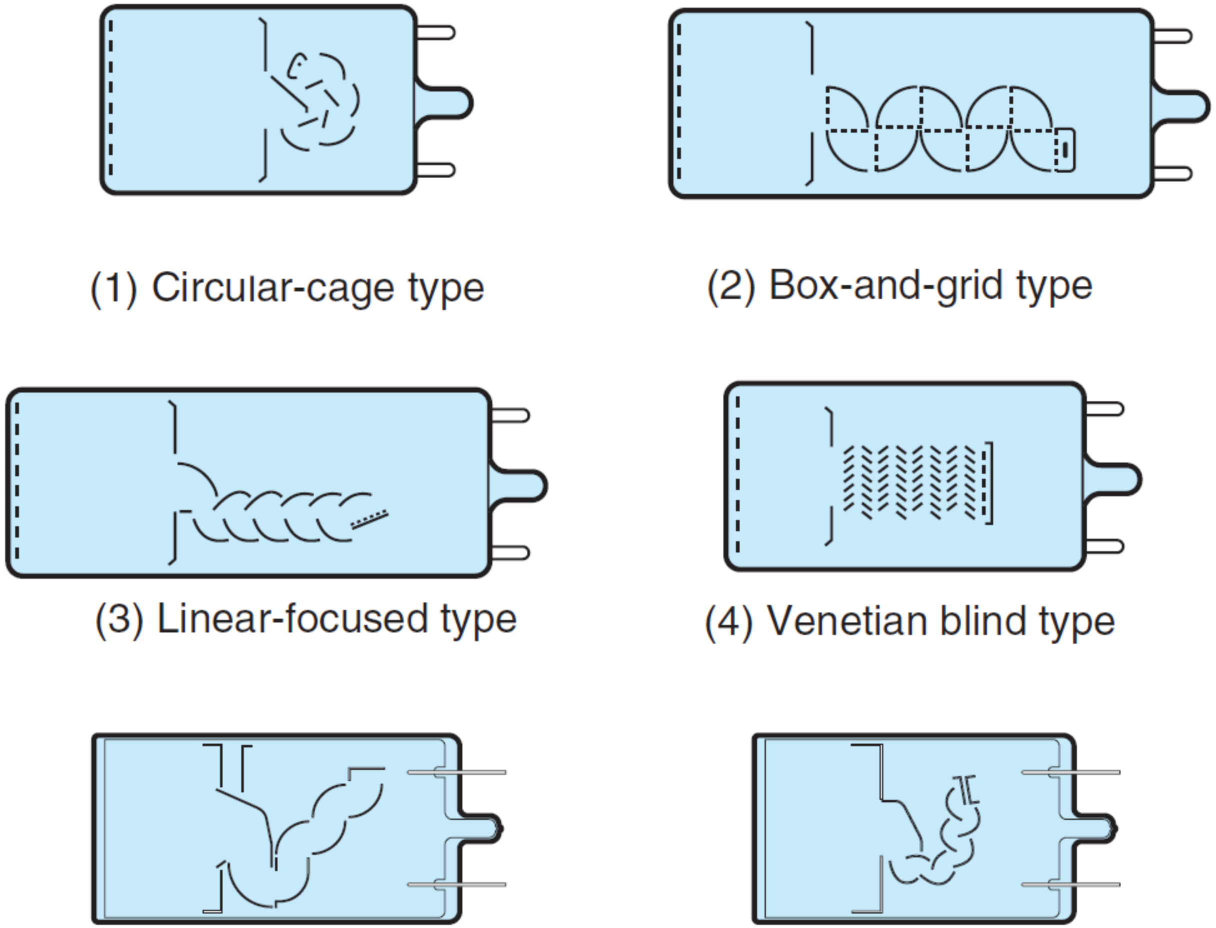
- R: Reflection coefficient
- k: Full absorption coefficient of photons
- P_ν: Probability that light absorption may excite electrons to a level greater than the vacuum level
- L: Mean escape length of excited electrons
- P_s: Probability that electrons reaching the photocathode surface may be released into the vacuum

How to choose a PMT? IV. Dynode chains

- Geometric shape and arrangement of dynodes dictate nearly all PMT performance metric (collection efficiency, gain, timing ….)
- Details very much a trade secret…

- Early types today largely disfavored, e.g.:
  - Box-and-grid has great amplification performance, but easily allow light and ions to pass back
    → messy afterpulsing
  - Venetian blinds avoid this but are not focused
    → bad timing performance

- Instead combined design
  (box-and line, circular & linear focused)
  usually today offer the better performance metrics



(1) Circular-cage type (2) Box-and-grid type (3) Linear-focused type (4) Venetian blind type (9) Box-and-line type (10) Circural and linear-focused type

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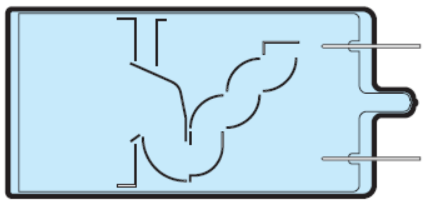
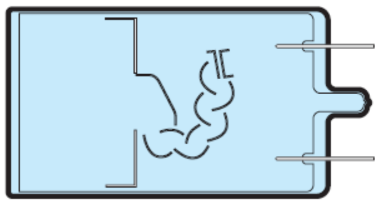
Characteristics / Dynode type	Time characteristics Rise time [ns]	Pulse linearity at 2% [mA]	Magnetic immunity [mT]	Uniform-ity	Collection efficiency	Features
Circular-cage	0.9 to 3.0	1 to 10	0.1	Poor	Good	Compact, high-speed
Box-and-grid	6 to 20			Good	Very good	High collection efficiency
Linear-focused	0.7 to 3	10 to 250		Poor	Good	High-speed, high linearity
Venetian blind	6 to 18	10 to 40		Good	Poor	Suited for large diameter
Mesh	1.5 to 5.5	300 to 1000	500 to 1500*	Good	Poor	High magnetic immunity, high linearity
MCP	0.1 to 0.3	700	1500*	Good	Poor	High-speed
Metal channel	0.65 to 1.5	30	5**	Good	Good	Compact, high-speed
Bombardment type	Depends on internal semiconductor		—	Very good	Very good	High photoelectron resolution



(9) Box-and-line type

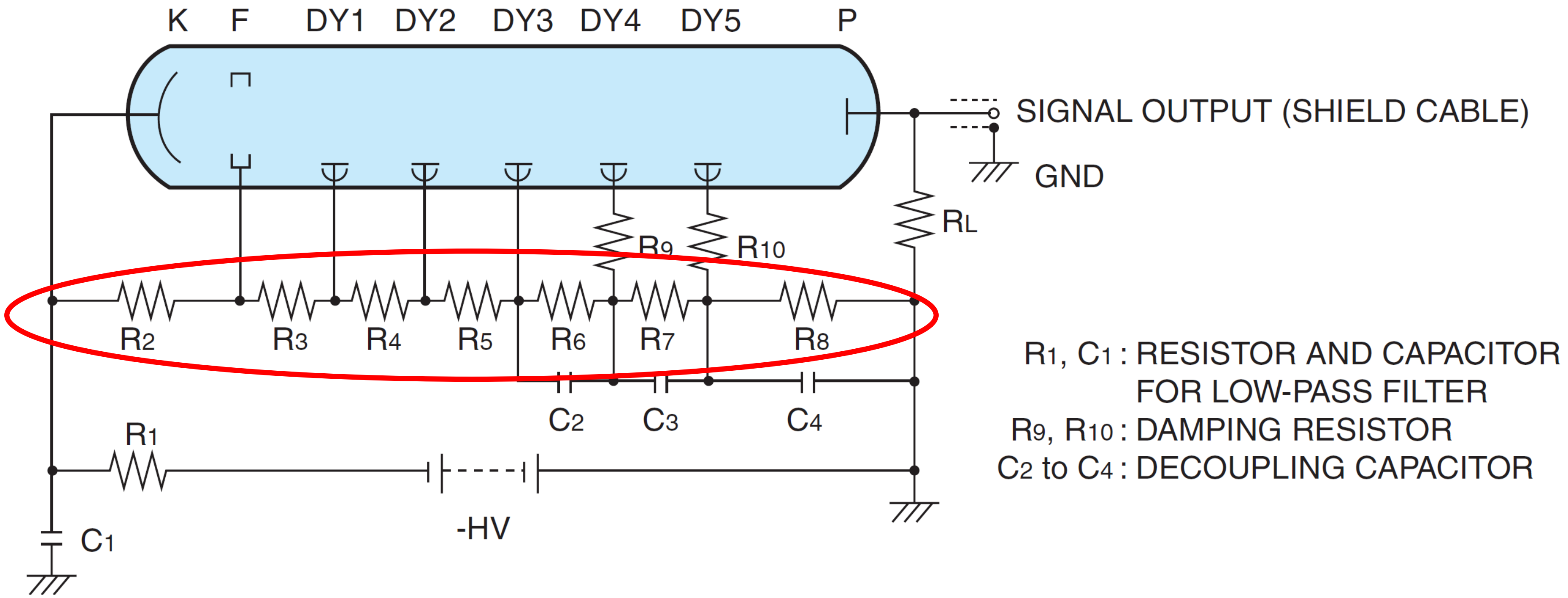


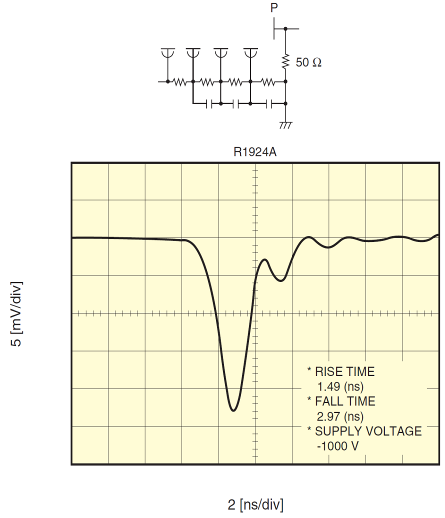
(10) Circural and linear-focused type

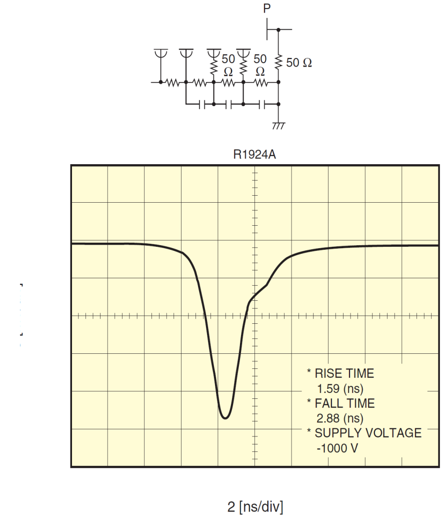
But we don’t (usually) build PMTs...

So know to read the datasheets
and perform your own tests

Basic voltage divider design

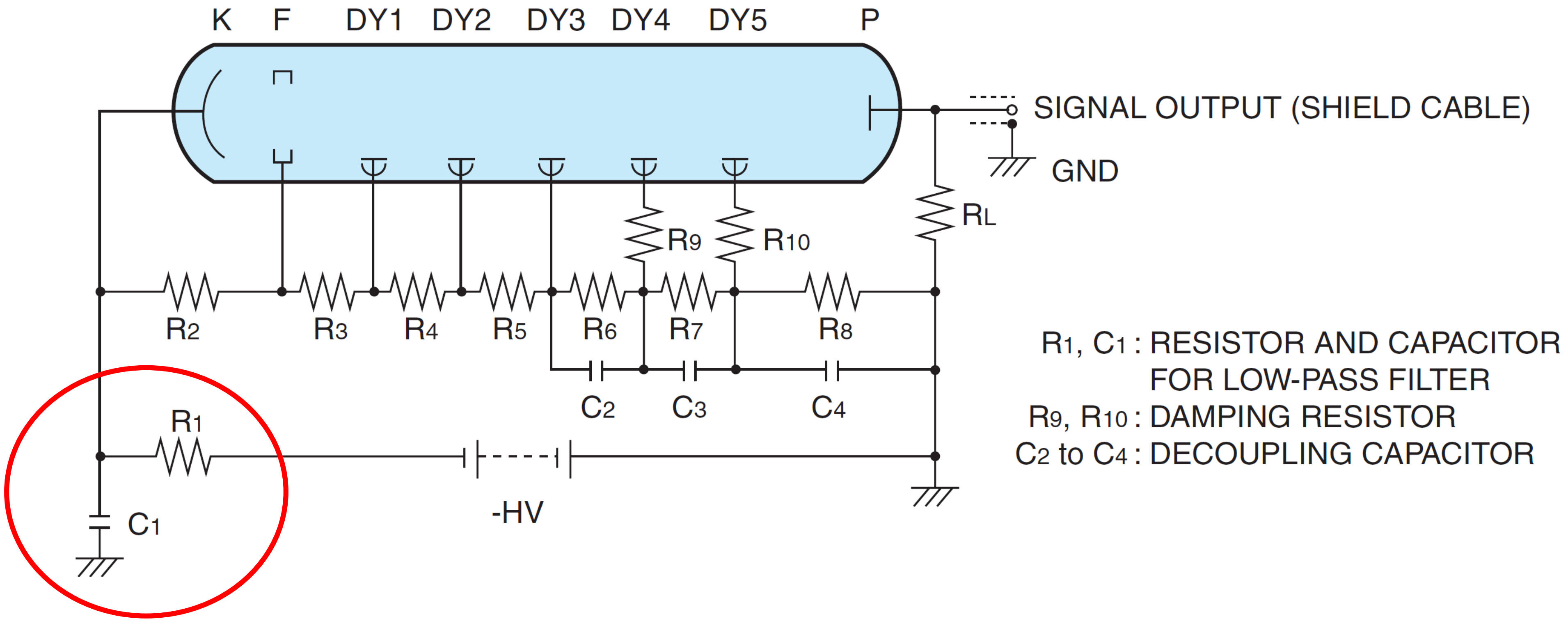


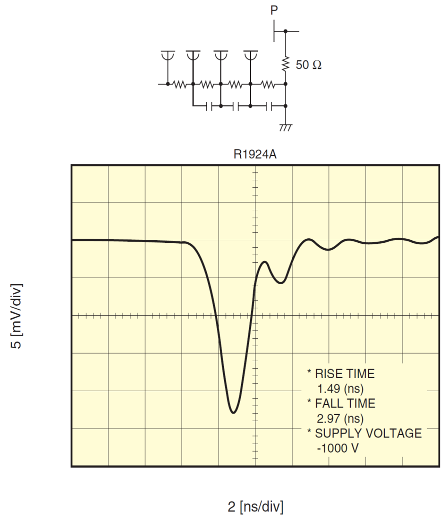


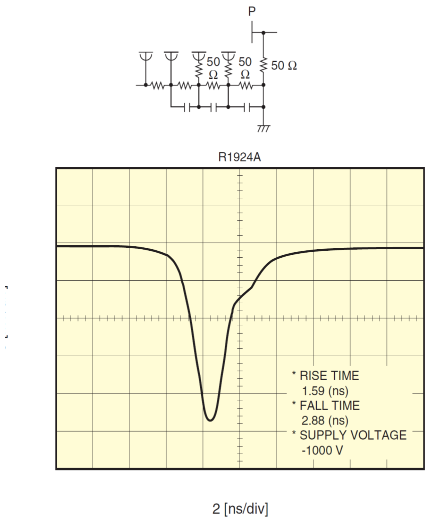


- Voltage divider distributes voltage over dynodes $V_i = V_{total} R_i/R_{total}$
- Ratios are critical and dictate maximum gain, dynamic range, timing, pulse shape … and depend on properties (such as dynode spacing) which are not know to the user
- Usually the manufacturer gives a recommendations in the datasheet
- Total resistance usually ~GigaOhm and dictates total power consumption by PMT

Basic voltage divider design

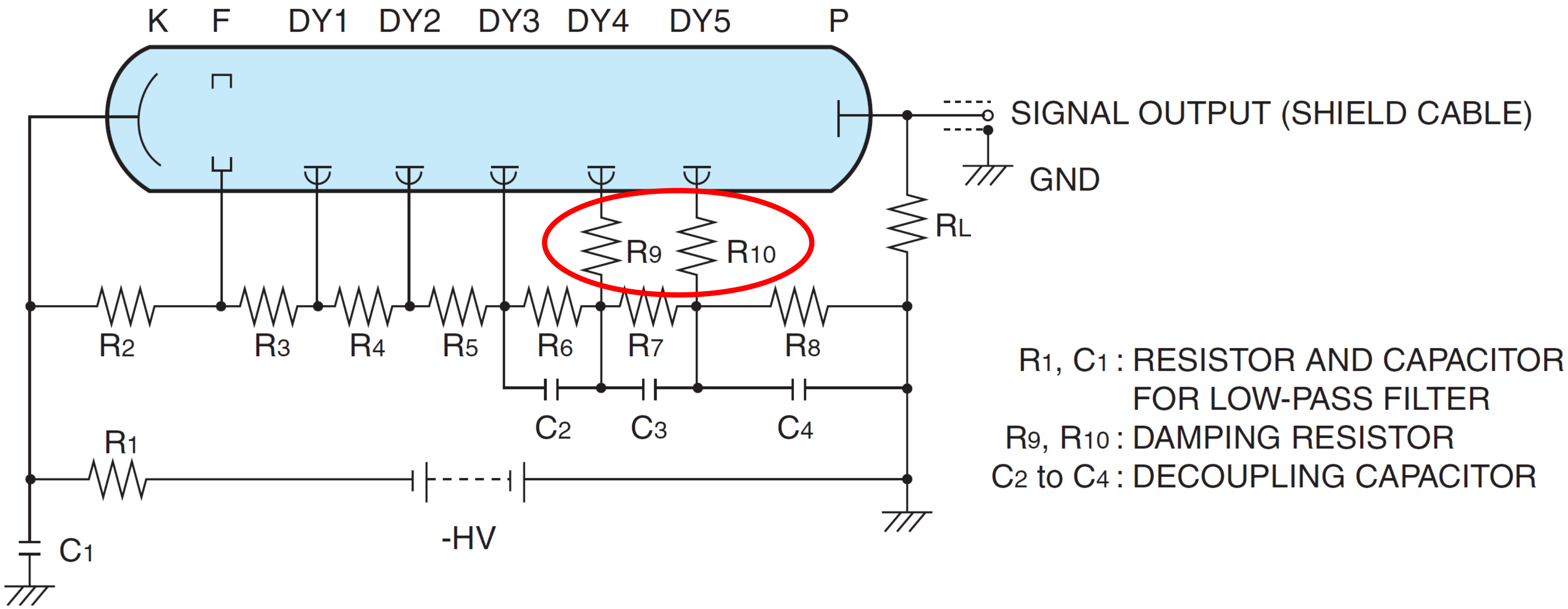


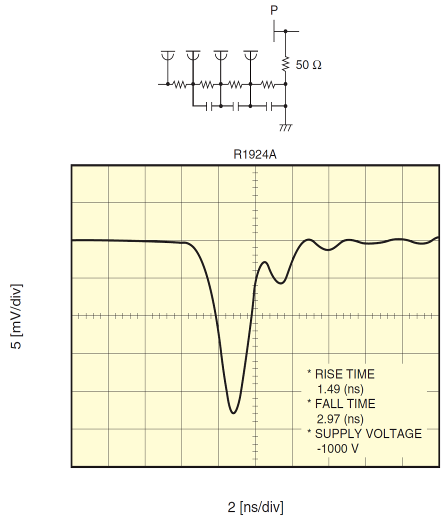


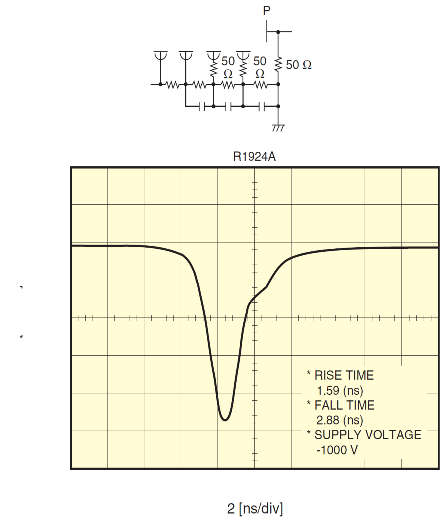


- Noise on HV line will also be present on output signal and impact for example gain spread → common to low-pass filter HV input on base
- Voltage drop over R1 needs to be considered

Basic voltage divider design

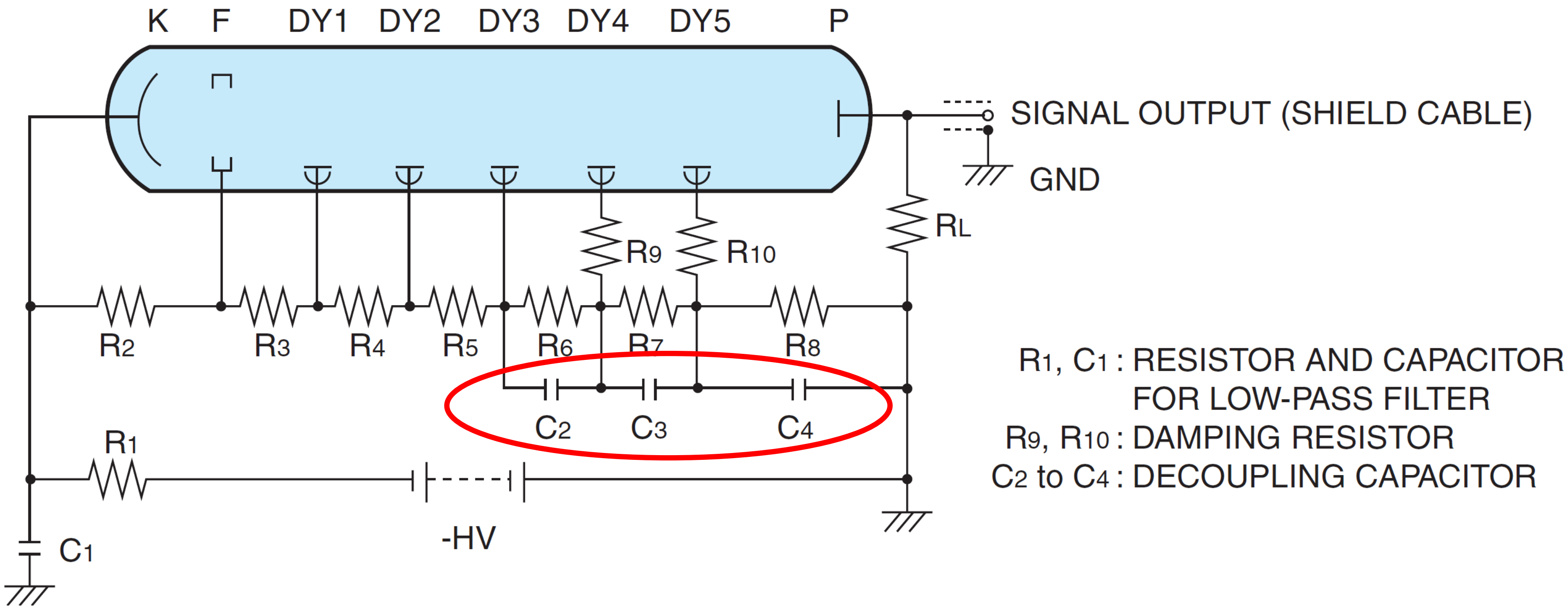


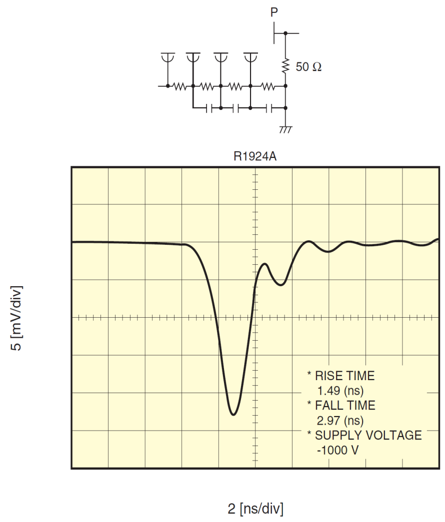


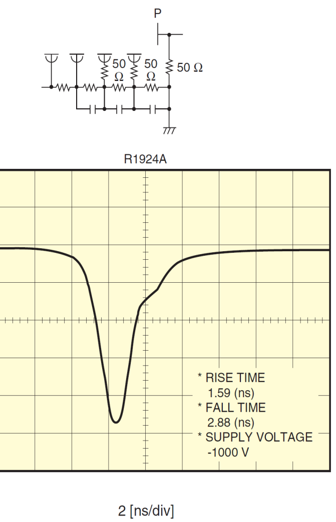


- Parasitic capacitance etc. often result in oscillator behavior for fast pulses → “ringing” → resistor can be used to dampen the oscillator
- As usual with RF circuits, layout of the schematic is also quite sensitive….

Basic voltage divider design

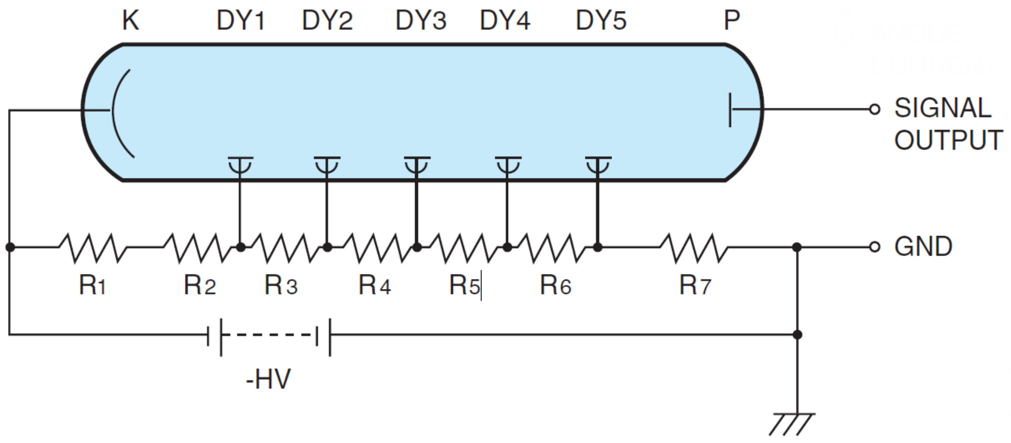






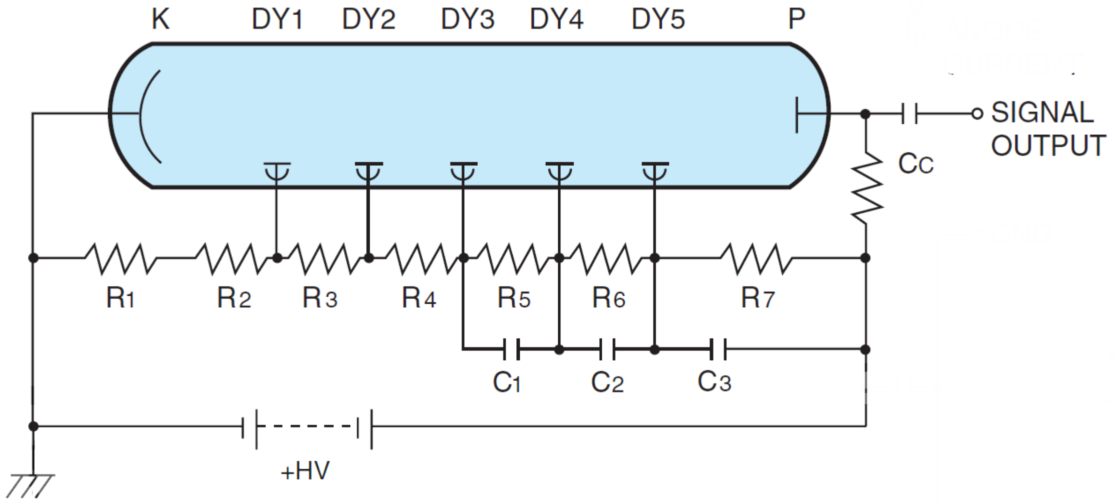
- Light pulse effectively momentarily discharges the PMT dynodes
- Recharge slow due to large resistance of voltage divider
  → in particular on last dynodes (current strongly amplified)
  the voltage can drop significantly for large instantaneous illuminations
  → use decoupling resistors (additional energy storage) to increase dynamic (linear) range

Positive vs. negative HV



Anode grounded scheme – negative HV

- Anode not on HV
  → can directly be connected to readout electronics
- Can record DC signals (background light) and pulses
- Large area photocathodes on HV and proximity to other components can lead to spikes in noise rate

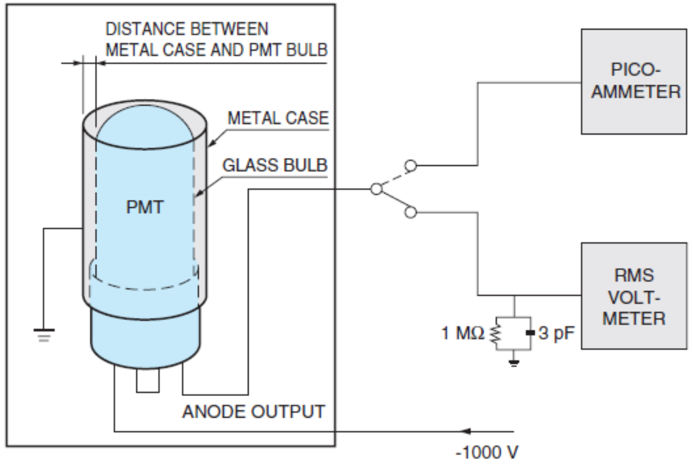


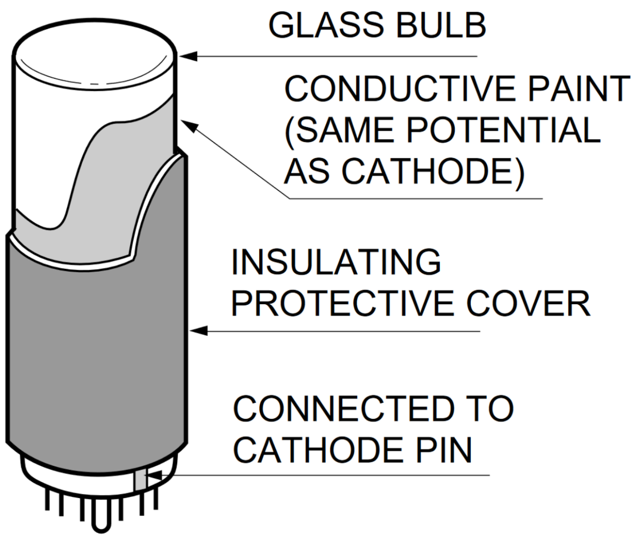
Cathode grounded scheme – positive HV

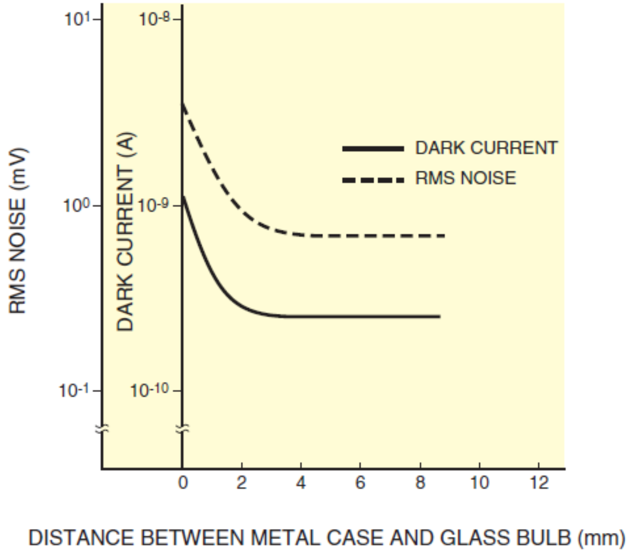
- Signal needs to be decoupled from HV before readout electronics
- Most commonly via decoupling capacitor
- When stored energy is a concern sometimes via (toroidal) transformers
- Both do not pass DC and distort signal

Negative HV and HA coating

- Instability of dark noise rates is often observed with negative HV (photocathode on potential) operation
- The primary effect seems to be scintillation in the glass induced when there is a strong potential difference in the glass, for example from grounded nearby metal objects
- This problem can be reduced by selecting PMTs with “HA coating”:
  - Outside of PMT is coated with conductive paint at photocathode potential (same potential as inside of glass)
  - A further insulating coating is applied







Common types of HV supplies

Laboratory / rack HV power supplies:

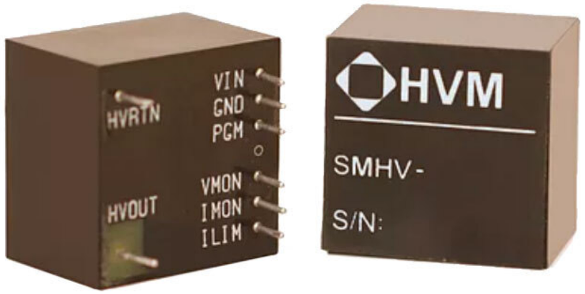
- Plug&Play, versatile (polarity), precise and stable
- Generally more expensive
- Usually not suited for remote, low-power instrumentation

CAEN

Commercial HV bricks

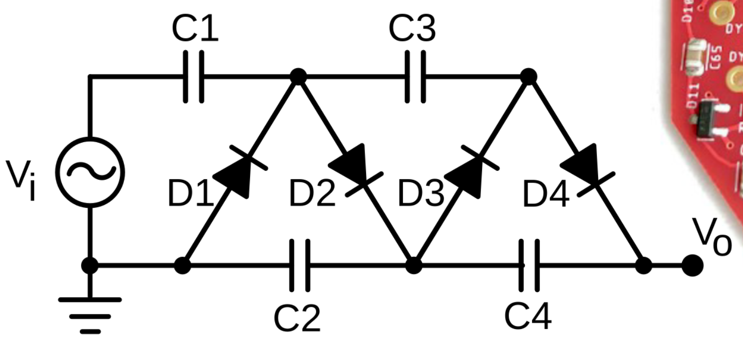
- Simply provide power and a control voltage
- Commonly used in remote instrumenation
- Sometimes stability issues due to high impedance / small load of HV dividers

HVM

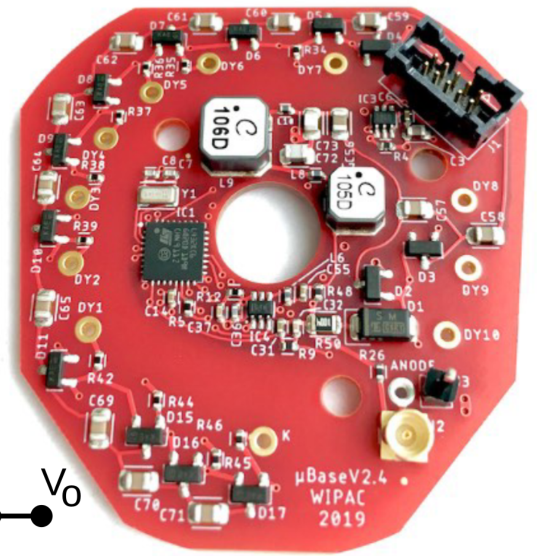


Active bases – i.e. Cockcroft Walton generators:

- Replaces HV divider with staged HV multiplier
- Low power, small footprint
- Only allows integer factors between dynodes
- Hard to get right (transmitted noise, stability, dynamic range)

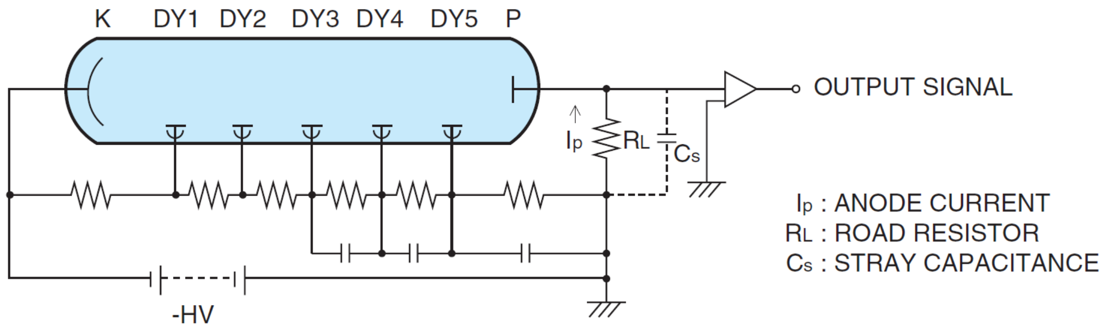


Chris Wendt



Current-to-voltage conversion

- Photomultipliers are current sources,
  we (usually) measure voltages, conversion via:
  - Load resistance (U=RI)
    - Signal grows with resistance
    - RC filter cutoff frequency reduces with resistance $$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$
    - Current through load resistor decreases gain of last dynode
    - In high-frequency applications usually 50-100Ω
  - Charge amplifier (analog integrator circuit with decay time)
  - ...
- Can be further amplified and shaped (spreading signal over longer waveforms)
- These days with modern (fast, low-power, low noise) ADCs load resistance often sufficient



Load resistance circuit

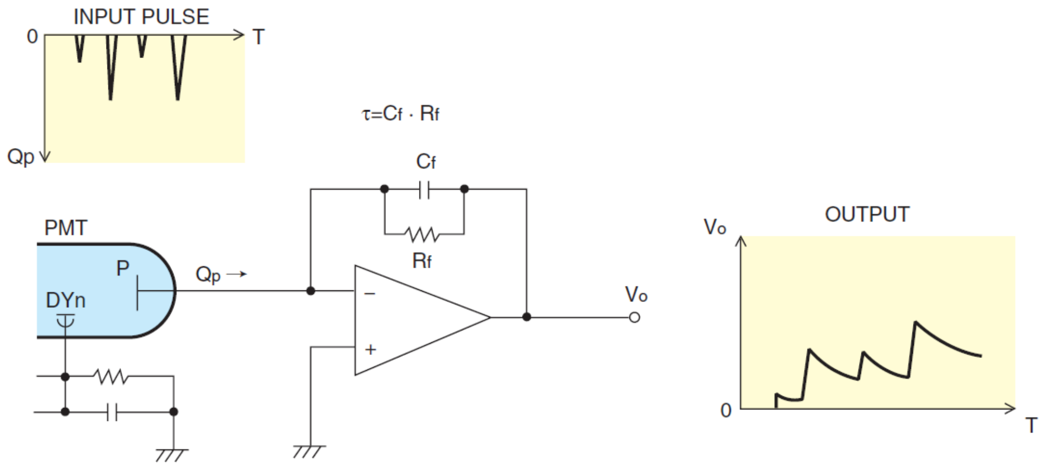


Figure 5-60: Pulse input type charge-sensitive amplifier

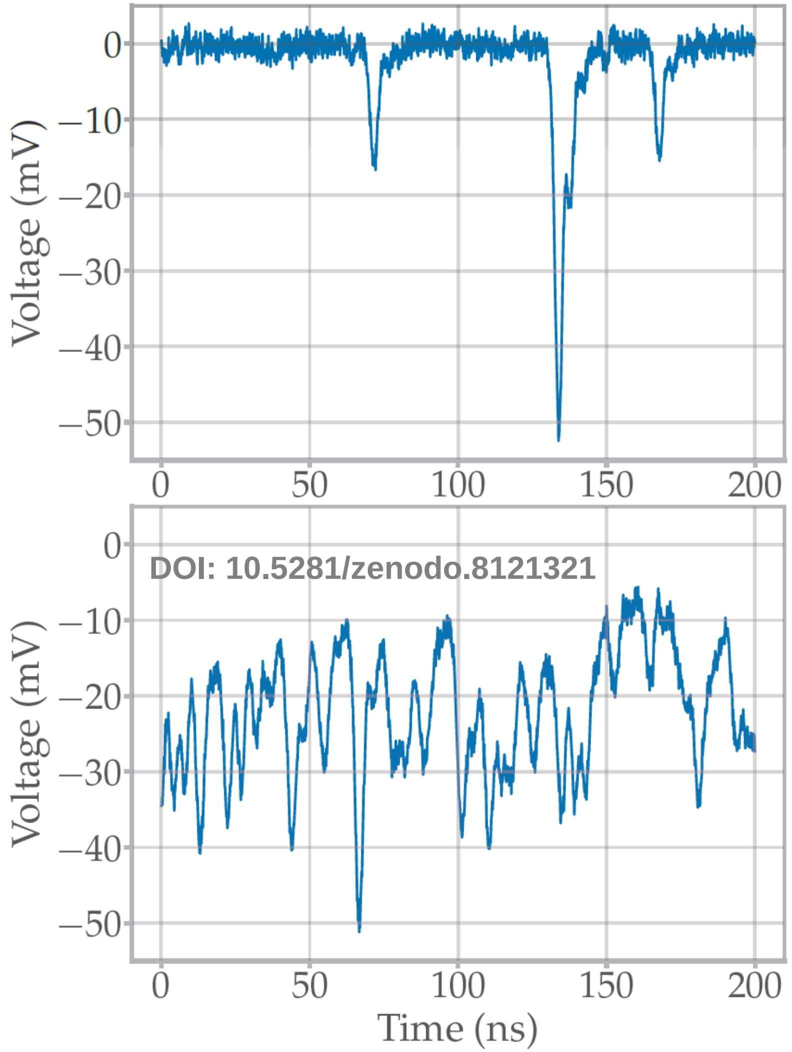
Expected signal and readout schemes

- Current pulse causes a slight HV discharge
  → pulses are generally negative going

- The (intrinsic) rise and fall times usually <1ns to 10ns
- Fall time (voltage divider recharge) usually longer than rise time

- A low illumination individual photons can be distinguished,
  as illumination increases pulses start to overlap,
  until the baseline becomes offset

- In the following we will assume a full waveform (ADC) readout
  but more focused DAQ approaches have their place:
  - Discriminator + scalar and/or time-to-digital converter
  - Time-Over-Threshold
  - Charge amplifier
  - Peak-sensing ADC



What NOT to do with a PMT!

I. Drop it

Implosions result in shrapnel that hurt you and your equipment.
(In 2002 Super-K lost 7000/11000 PMTs in an implosion chain-reaction.)

II. Operate it in light (daylight / moon-light, …) & store in daylight

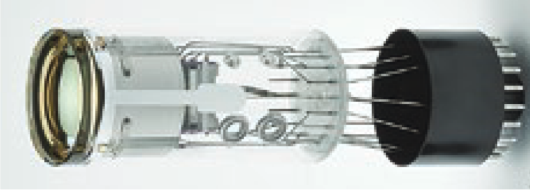
Stresses on the PMT (dynode wear, photocathode aging) drastically increase at large photocurrents.
Even just storing a PMT in daylight can/will degrade the photocathode.

III. Expect it to work straight away

For largely unknown reasons rates tend to be high and unstable after periods without operation and/or after exposure to (even low levels) of light.
Power the tube for about an hour and observe rates...

Hardware demonstration - setup

Hamamatsu R13408 1” Bialkali PMT
with custom passive divider base
(as suggested by Hamamatsu)



Type No.	Spectral response: Range (nm)	Spectral response: Peak wavelength (nm)	Ⓐ Photo-cathode material	Ⓑ Window material	Ⓒ Dynode structure / Stages	Maximum ratings: Supply voltage between anode and cathode (V)	Maximum ratings: Average anode current (mA)	Anode to cathode supply voltage (V)	Cathode characteristics: Luminous Min. (μA/lm)	Cathode characteristics: Luminous Typ. (μA/lm)	Cathode characteristics: Blue sensitivity index Typ.	Cathode characteristics: Ⓓ Radiant Typ. (mA/W)
R13408	300 to 650	420	BA	K	L/8	1750	0.1	1500	70	95	10.0	80

Anode characteristics: Luminous Typ. (A/lm)	Radiant Typ. (A/W)	Gain Typ.	Dark current (After 30 min) Typ. (nA)	Dark current (After 30 min) Max. (nA)	Time response: Rise time Typ. (ns)	Time response: Transit time Typ. (ns)	Time response: T.T.S. (FWHM) Typ. (ps)	Pulse linearity ±2 % deviation (mA)	Pulse linearity ±5 % deviation (mA)	Storage temperature (°C)	Operating ambient temperature (°C)	Type No.
50	4.2×10^4	5.3×10^5	3	30	1.2	13	190	20	50	-80 to +50	-30 to +50	**R13408**

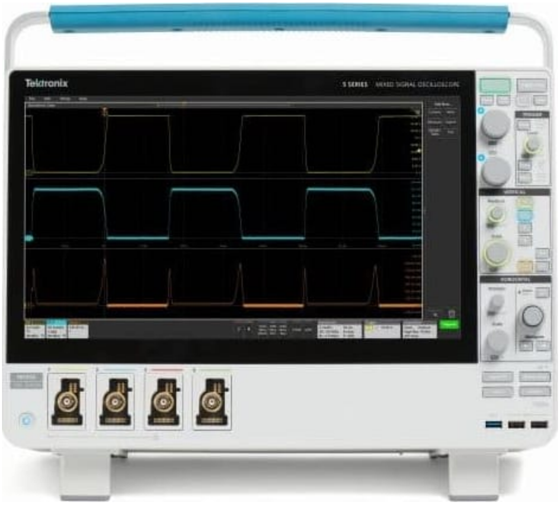
ISEG SHR SR042060 High Voltage

Tektronix MSO54 Oscilloscope
(1 GHz analog bandwidth, 6.25 GS/s)

expensive beast makes live easy

Custom (mrongen.de) LED pulser
@ 375nm ~400ps STD.

actually slower than the TTS,
but compact and can be dimmed to SPE



Hardware demonstration

I. PMT signal demonstration – amplitude triggering on dark noise
  - biased gain spectra, no way to study timing

II. Gain pedestal – triggering on LED sync with LED off

III. Establishing low occupancy single photons – triggering on LED sync

Number of detected photons per pulse follows Poisson statistics: $P(k,\lambda)=\frac{\lambda^k e^{-\lambda}}{k!}$

We observe a given probability that waveforms contain a signal: $x=P(k\geq 1)=1-P(k=0)=1-e^{-\lambda}$

The two-photon contamination for all waveforms/triggers that contain at least one photon is:

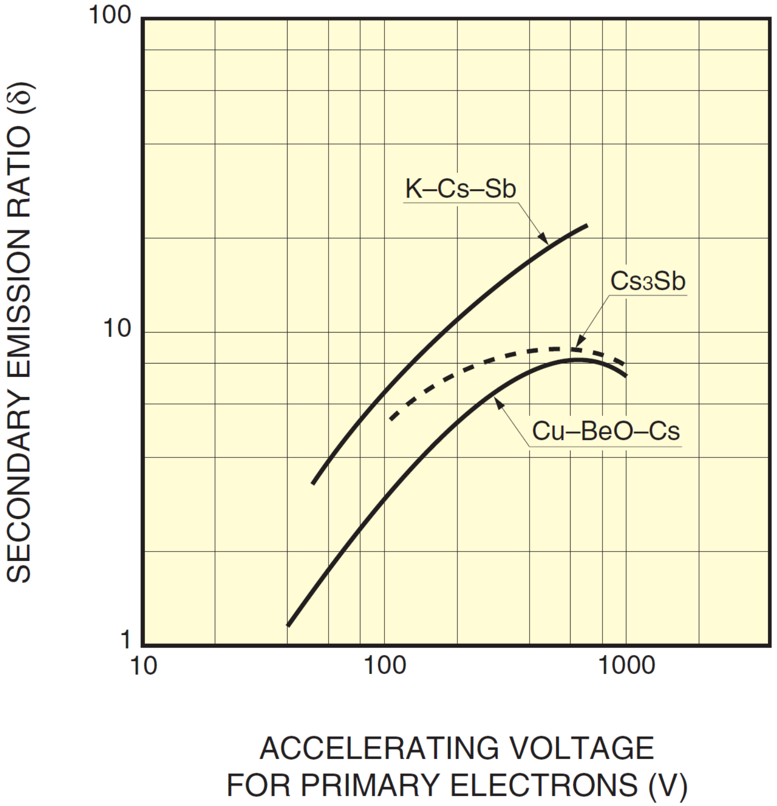
$$P(k\geq 2|k\geq 1)=\frac{P(k\geq 1|k\geq 2)P(k\geq 2)}{P(k\geq 1)}=\frac{1-e^{-\lambda}-\lambda e^{-\lambda}}{1-e^{-\lambda}}=1-\frac{\lambda e^{-\lambda}}{1-e^{-\lambda}}=1+\frac{\ln(1-x)(1-x)}{x}\approx\frac{x}{2}$$

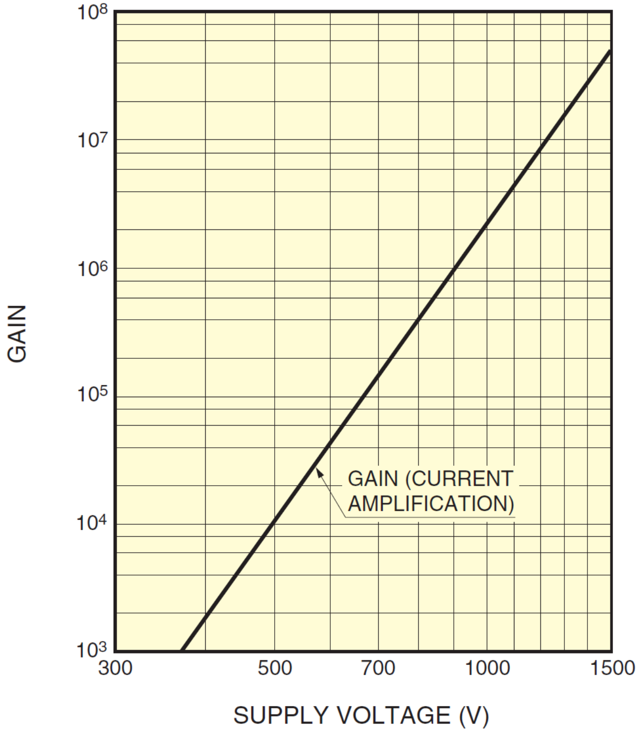
IV. Single photon quantities
  - amplitude and area/charge gain spectra (rough gain calculation (1pC ~ $6.2 \cdot 10^6$ electrons))
  - single photon timing resolution (SPTR)

Gain - theory

- At each dynode each electron undergoes multiplication that follows a Poisson process with the average being called the secondary emission ratio $\delta = \frac{N_{\text{out}}}{N_{\text{in}}} = \alpha \cdot \nu^{\beta}$
- The total gain is the product of all dynodes, where each dynode has a different voltage & efficiency
- Still:

$$G = \prod_{k=1}^{n} \alpha_k \cdot \left(\frac{r_k \cdot V}{\sum_{i=0}^{n} r_i} \right)^{\beta_k} = a \cdot V^b$$





Gain - reality

- From the statistical amplification process we would expect the charge distribution of single photons to be a clean Gaussian
- The width of this Gaussian is the SPE charge resolution
- In addition it is observed that outliers (early electron scattering of a dynode, …) lead to a population of badly amplified PE
- This is region is often modeled as an exponential or exponential & Gaussian
- Optimizing the dynode chain is one of THE trade secrets of PMT companies
- We can poke at it (e.g. x-raying tubes and running electron tracing simulations) but in the end we usually just have to test and choose

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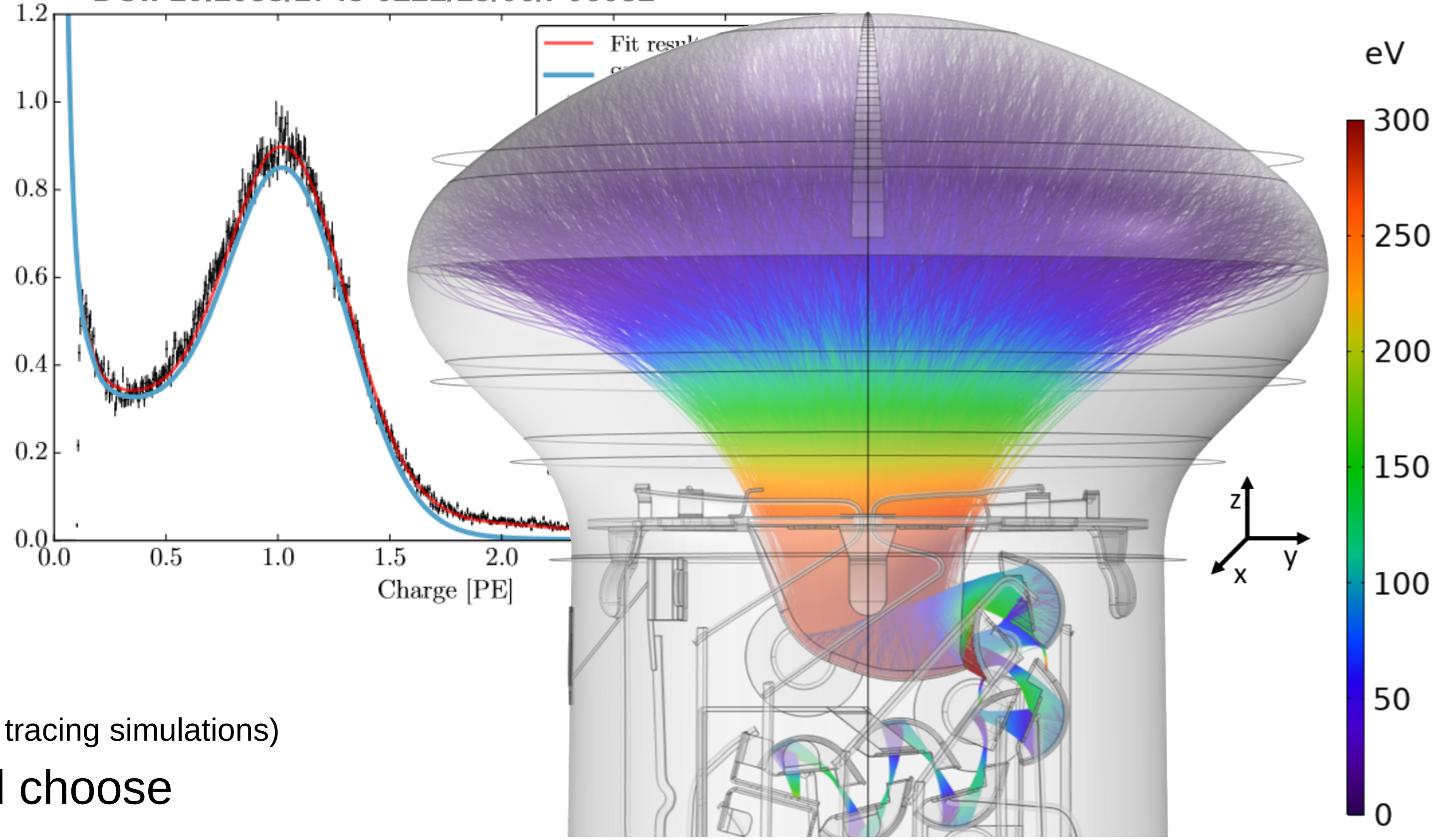
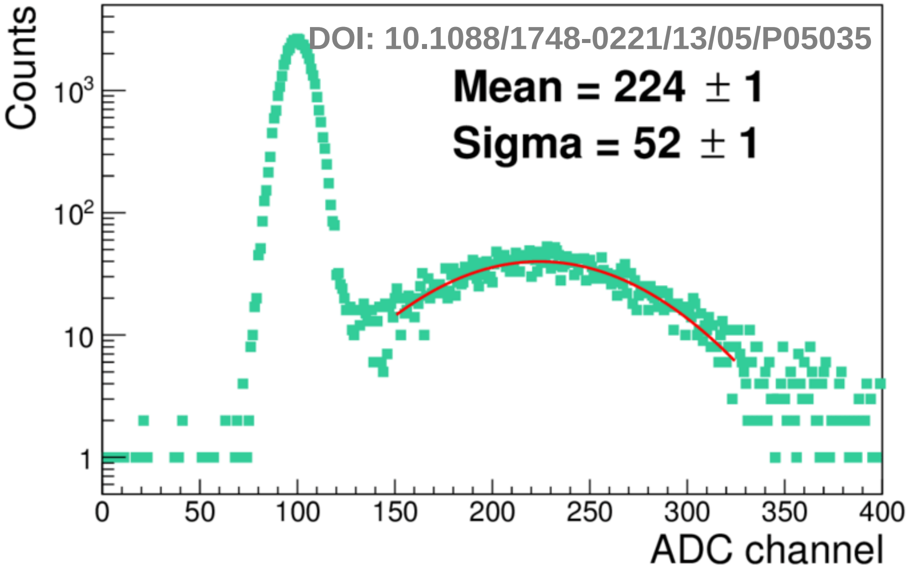
Willem Achermann, 2023

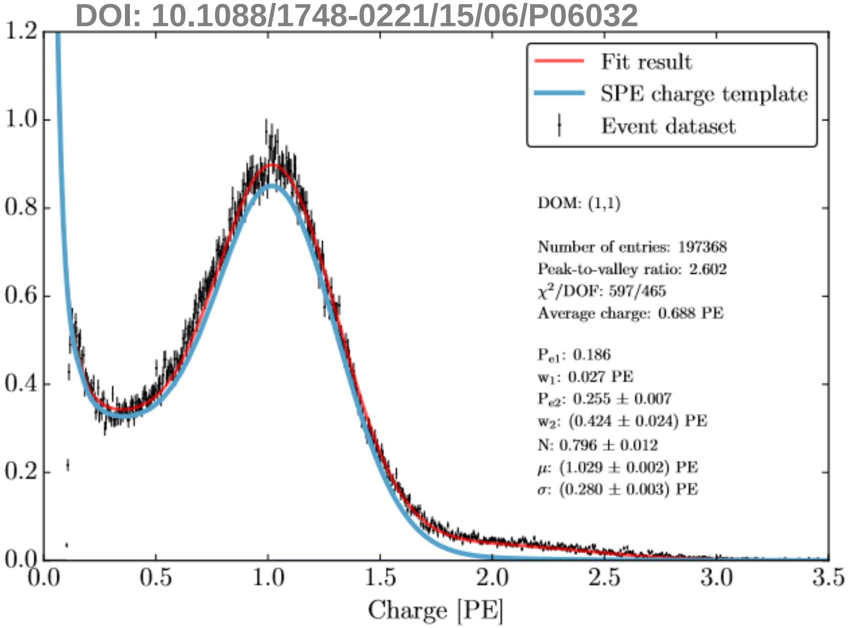


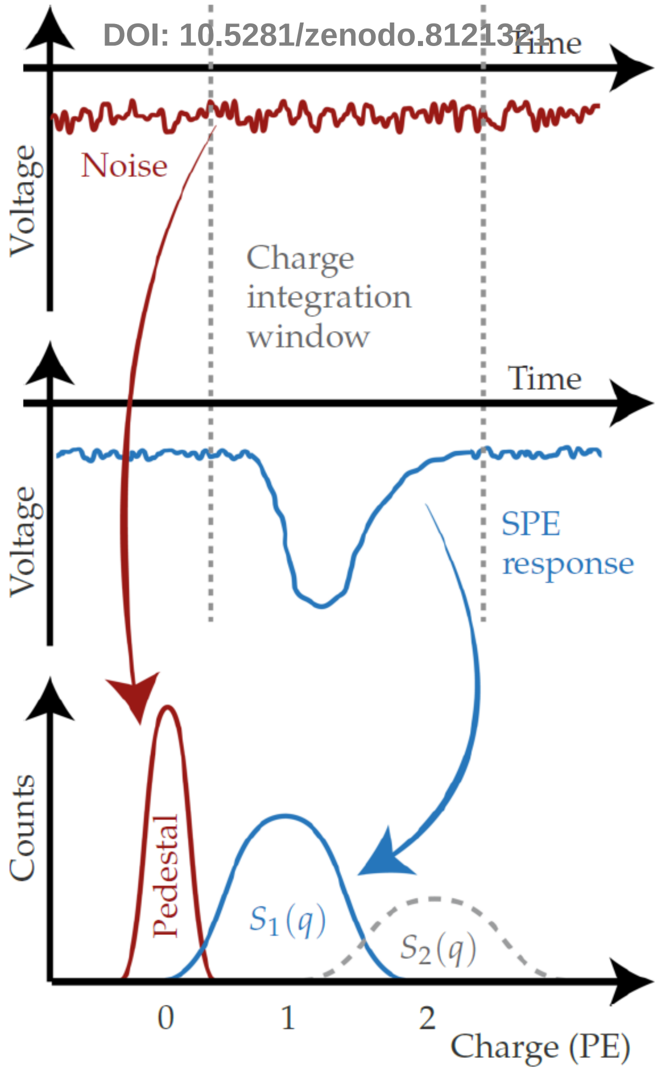
Gain – measurement (Single photon charge spectrum → SPE)

- Find a single photon source (thermal noise, low occupancy photons), integrate the waveform peaks, convert to charge with the known effective impedence
- Don't care about the actual number? Can also just histogram e.g. amplitudes ...

- Badly amplified photons and electronic noise are mostly indistinguishable → peak-to-valley ratio as a metric how well single photons can be identified

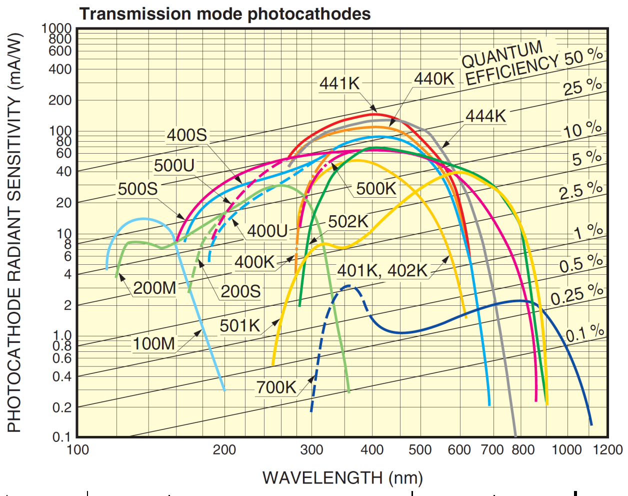




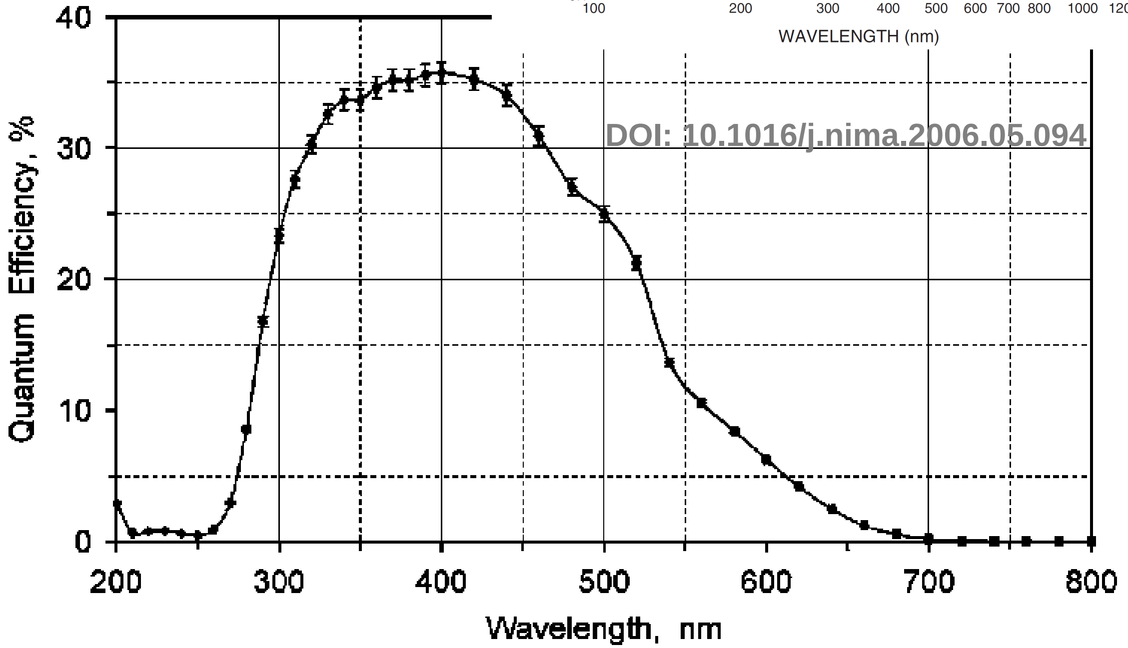


Quantum efficiency

- Probably the most discussed quantity, but once you have decided on a spectral range … the photocathode material is usually locked in with only minor variances between manufacturers and models
- Other losses (like bad charge distribution) usually most important…



- Possible definitions:
  - Probability for a photoelectron to be emitted per photon incident on the photocathode (including glass reflection …)
  - Probability for a pulse to be observed at the anode per photon incident on the photocathode



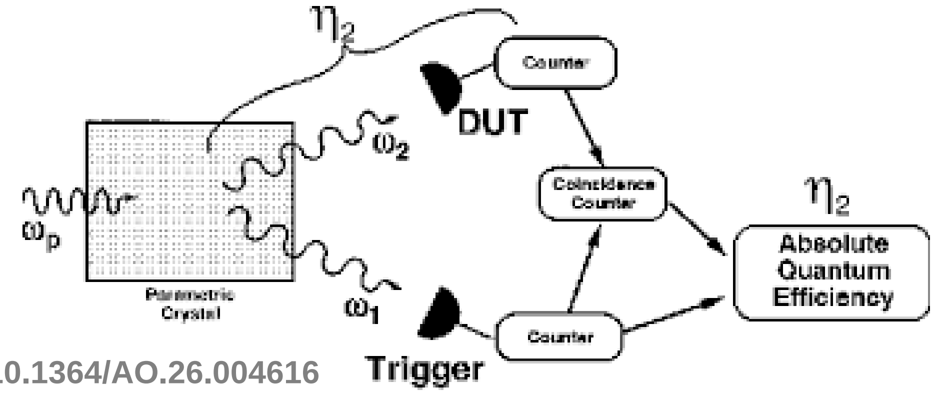
DOI: 10.1016/j.nima.2006.05.094

Quantum efficiency – how it is measured

- **Photocathode current** measurement with a known light source (calibrated bolometrically), PMT manufacturers like this

- **Anode current** or photon counting compared to a reference sensor, this is what we most commonly do

- Parametric down conversion
  - Difficult and only for discrete wavelengths, but the most precise method out there



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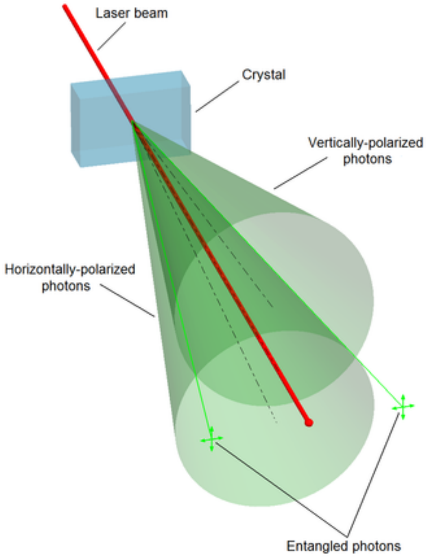
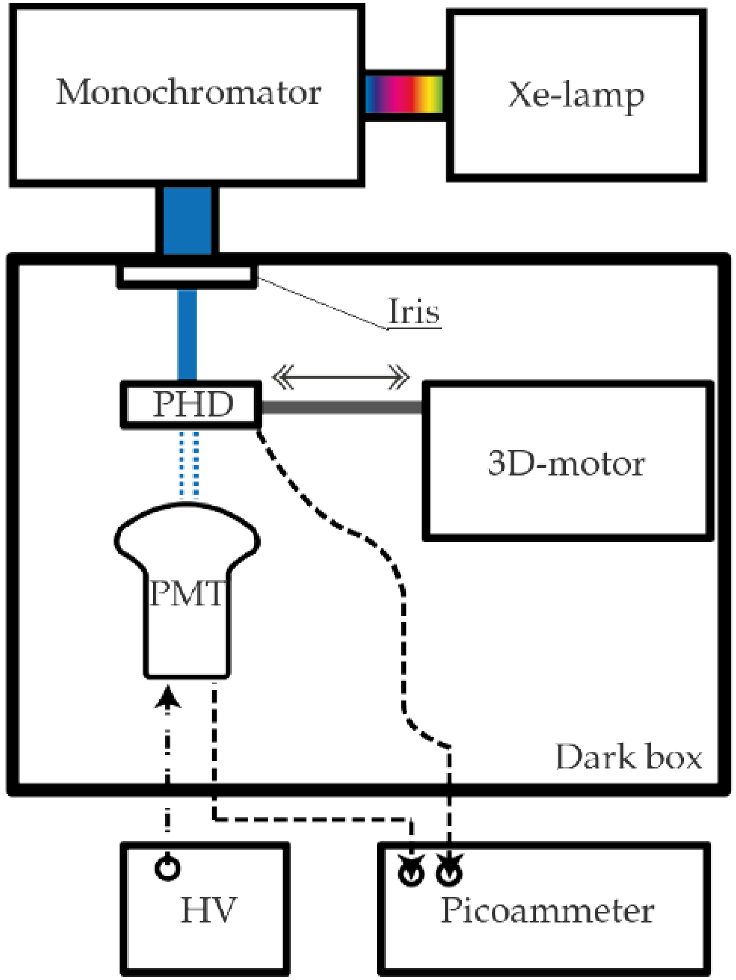


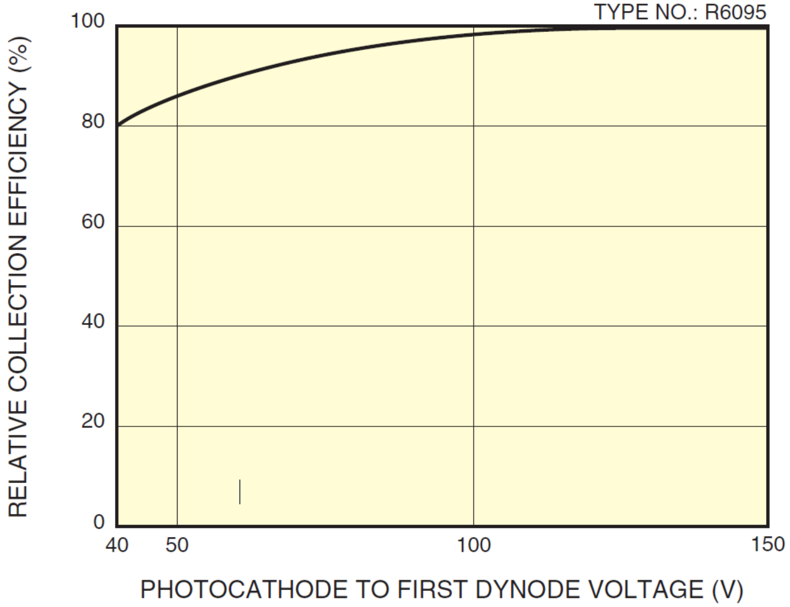
DOI: 10.5281/zenodo.8121321



Other efficiencies to consider

- Collection efficiency:
  Not every photoelectron reaches the first dynode → these are lost
  Generally a large HV (in pulse mode) the collection efficiency is close to unity. But this can be a problem for large-area PMTs.

  → Photocathode current and anode current measurement do NOT measure the same thing.
  We usually do not care for the “naked” quantum efficiency.



- Readout efficiency: Given the SPE charge distribution a portion of photons will always fall within the digitizer noise / below the trigger threshold
  (efficiency problem for SPE measurements, energy uncertainty at MPE)

- Quite often the absolute quantum efficiency doesn’t actually matter as the absolute efficiency (accounting for the experiment specific definitions, data acquisition, etc) can be measured in-situ using standard candles (vertical equivalent muons, MIPs, ….)

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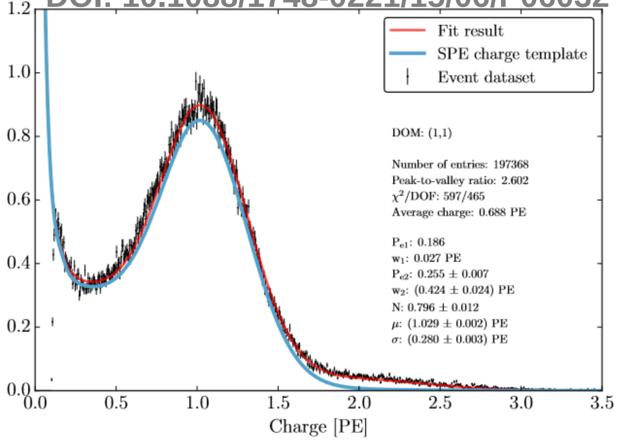
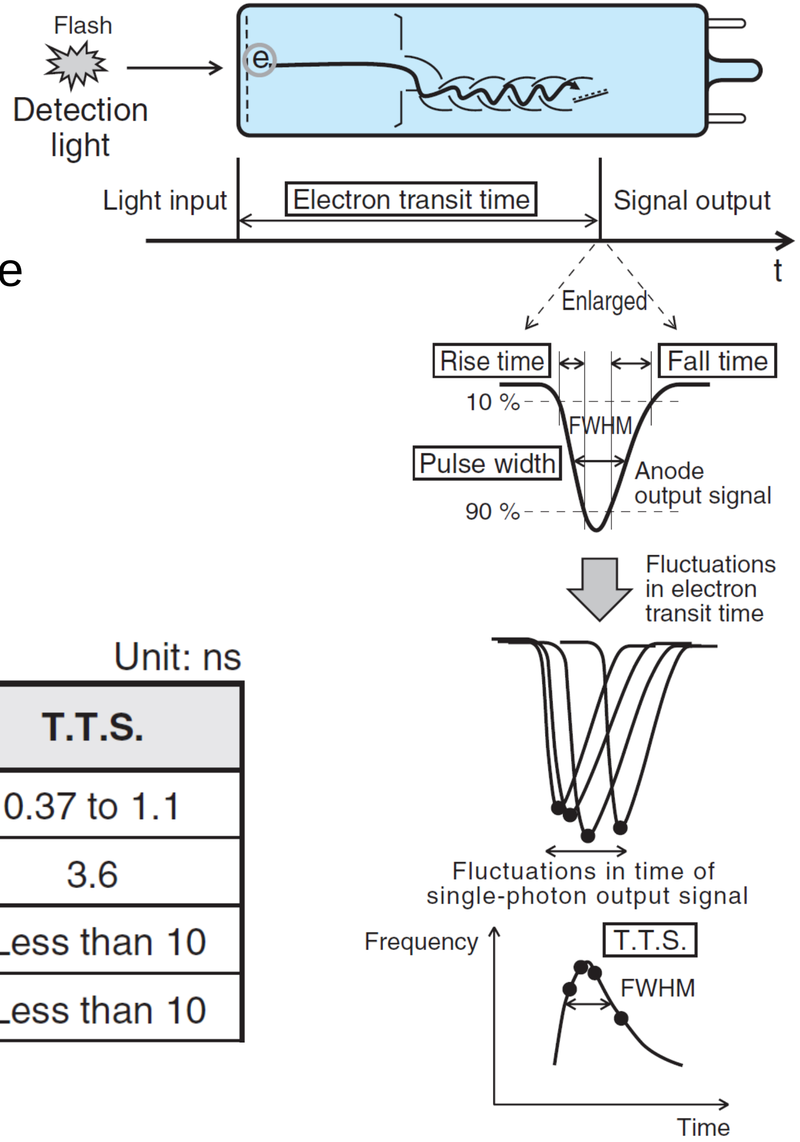


Single photon timing (resolution)

- The timing delay between a photon hitting the photocathode and the current pulse reaching the anode is called the transit time
- There is an intrinsic spread of electron trajectories & a position dependence of the TT on the photocathode leading to the transit time spread (TTS)
- TTS are usually between ~200ps and >10ns (smaller PMTs are better)
- When detecting multiple photons the timing resolution scales as 1/√N

Unit: ns

Dynode type	Rise time	Fall time	Pulse width (FWHM)	Electron transit time	T.T.S.
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	Less than 10
Venetian blind	to 7	25	25	60	Less than 10



Absolute timing base??

- Measuring the TTS is easy (we just did it)
  - Illuminate with a source that has a shorter pulse duration then the assumed TTS
  - Record the waveforms and histogram arrival time extracted from times(
    (through a template fit, digital-constant-fraction discriminator …)

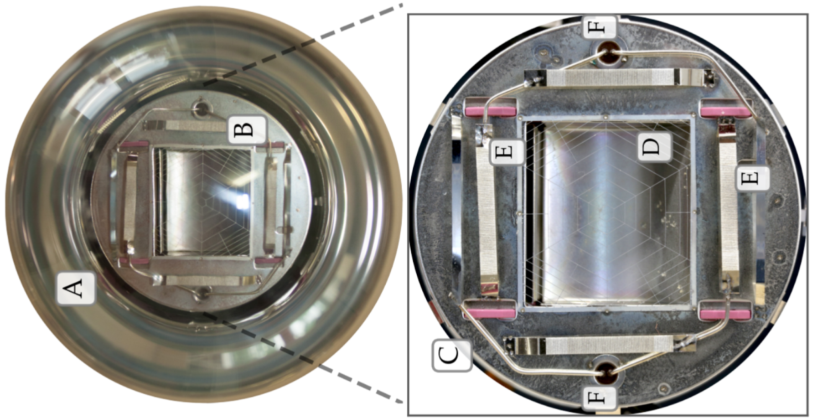
- Measuring the absolute transit time usually relies on a light source
  with a known relation of the electric trigger output to the actual light emission (expensive…)
  and having all other delays (electronic readout) under control…

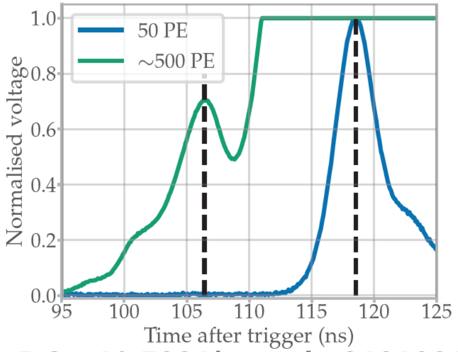
- Luckily we usually do not care to within a few nanoseconds when the photons arrived,
  BUT only care about the relative timing between detectors (transit time is deterministic with voltage & differences easily measured)

Off-time pulses: I. Pre-pulses

- Photon is not absorbed in photocathode
  & by geometric coincidence hits the first dynode
- Photon converts to electron on dynode
  (either on dynode metal itself, or on photocathode bialkali depending on deposition technique)
- Transit time reduced by travel time of electron to first dynode (usually around ½ of total TT)
- Amplitude reduced by amplification of first dynode (~10-50)
- For single photon illumination usually inconsequential, BUT can lead to spurious early pulses under bright illumination

~1% probability per PE





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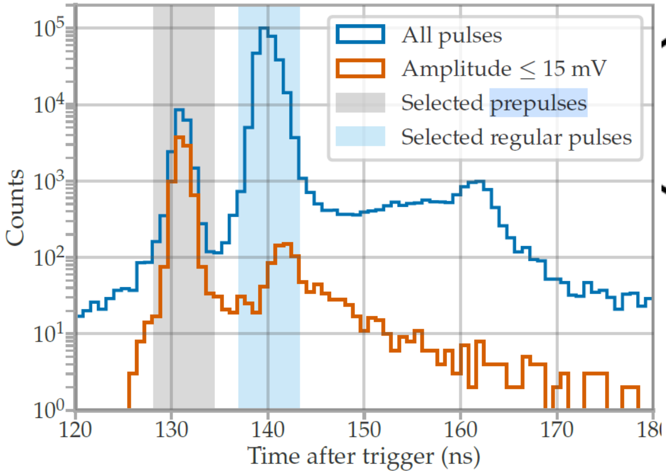
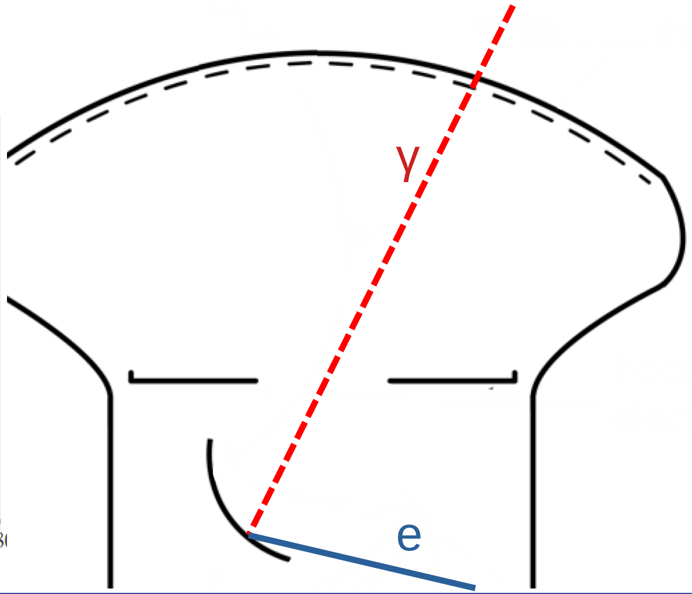


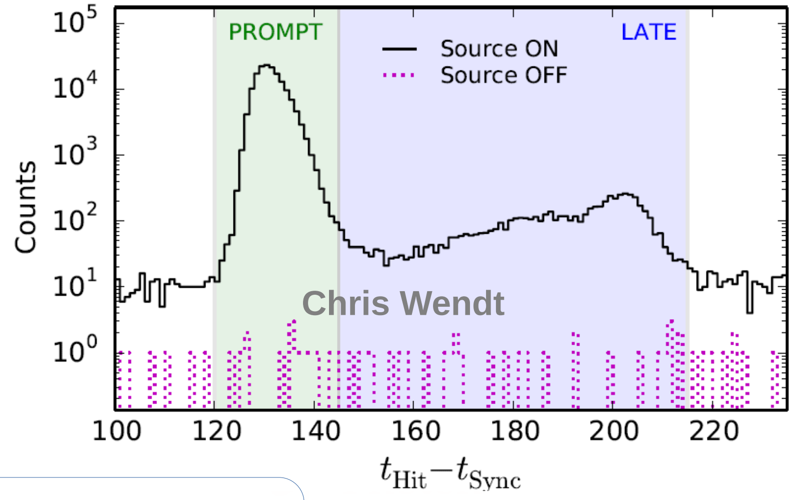


Off-time pulses: II. Late pulses

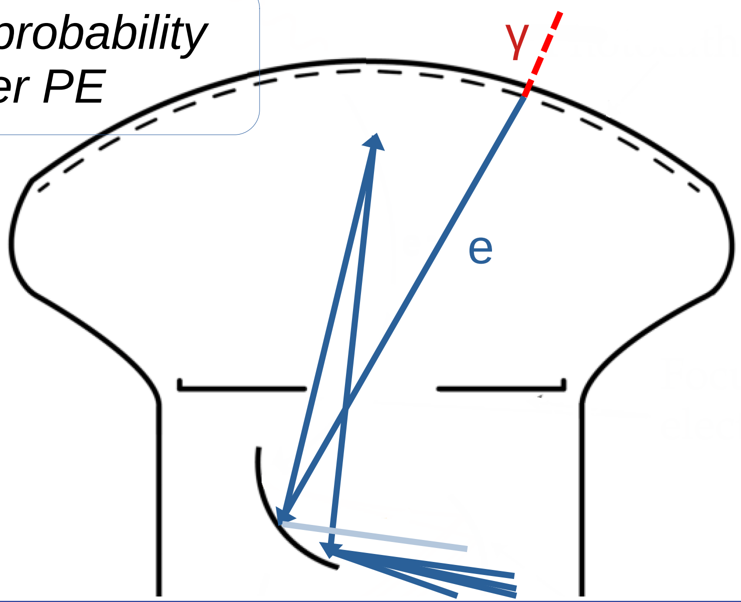
- Electron does not fully convert kinetic energy to secondary electrons on first dynode but bounces of and travels back up to the photocathode before being accelerated down again

  - Elastic scattering:
    - No emission of electrons on first contact → no prompt pulse
    - Delayed by twice the electron travel time to first dynode (time difference of pre-pulses and late pulses correlated)
    - Gain of late pulse SPE like

  - In-elastic scattering:
    - Some initial emission of electrons → small amplitude prompt pulse
    - Electron only travels back partially → smaller delay time
    - Amplitude of late pule reduced (Prompt + late pulse ~ SPE like)



few% probability per PE



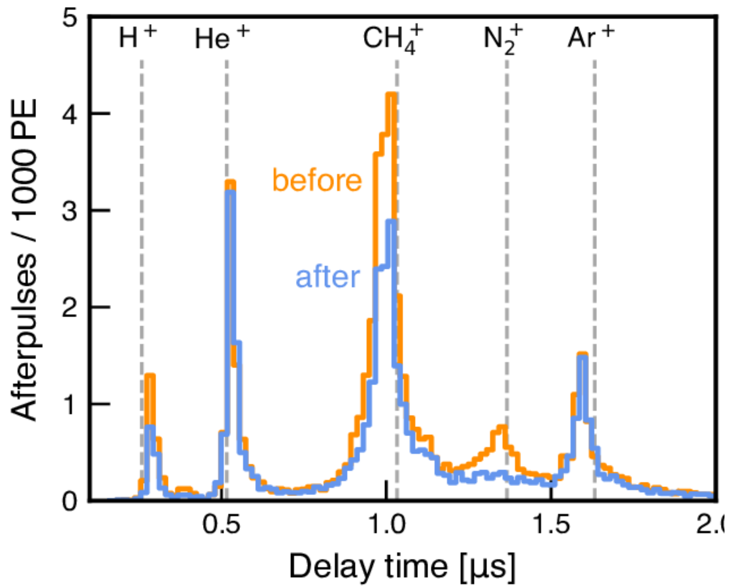
State probabilities

Off-time pulses: III. Afterpulses

- Prompt pulse develops normally, BUT initial photoelectron ionizes residual gas atom close to first dynode
- Ion accelerated to photocathode and releases many electrons on impact → which get amplified again

- Average charge and delay time (typically microseconds) depend on ion mass
- Afterpulse spectrum (sum of ion probabilities) can vary strongly between PMTs and depend on aging and environmental conditions

~10% probability per PE



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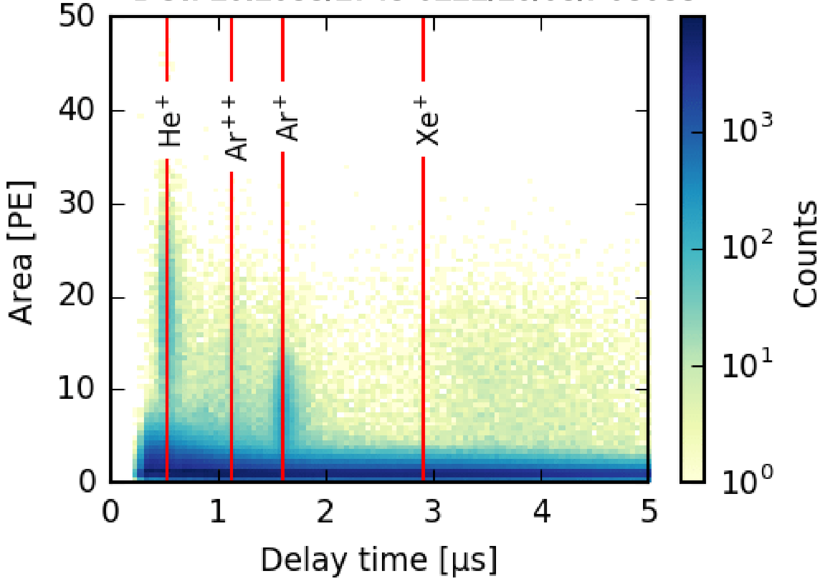
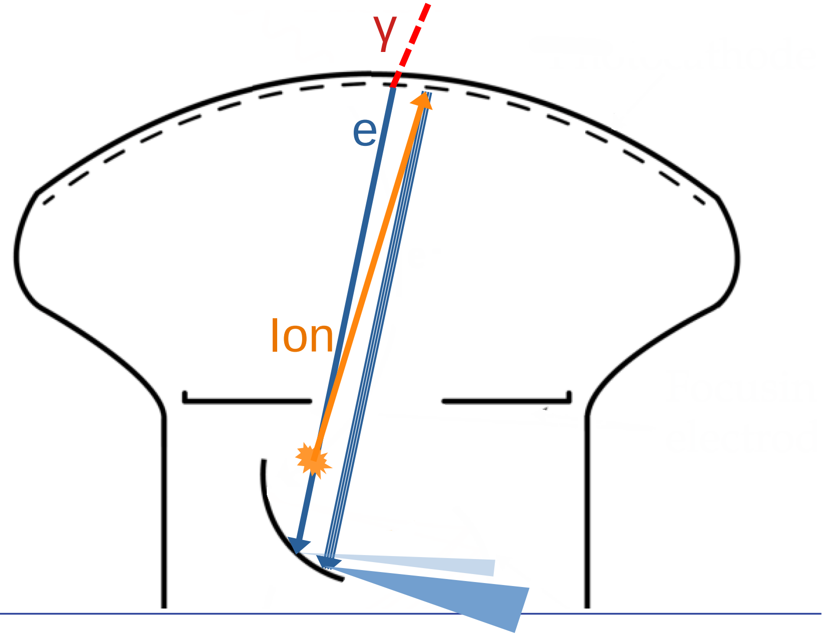




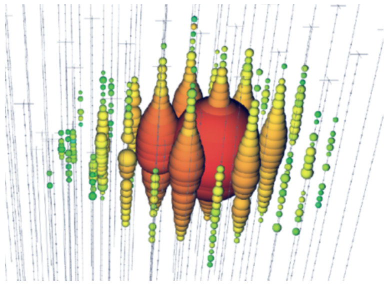
Practical example of afterpulse problems

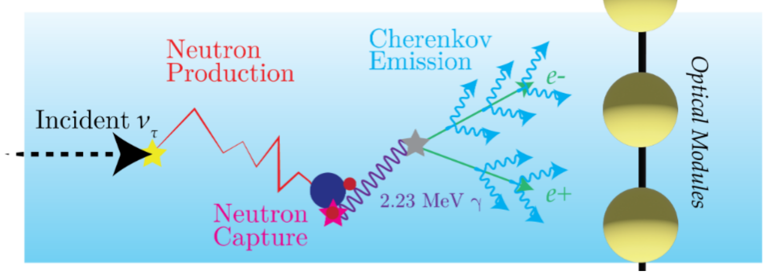
- IceCube sees cascades (balls of light) as a result of both electromagnetic and hadronic cascades

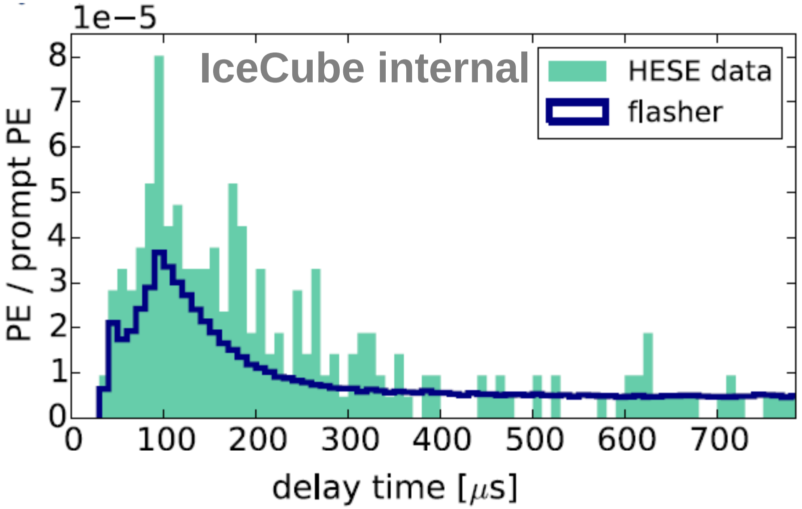
- The event signature is not distinguishable from timing, shape ...
- BUT hadronic cascades include neutrons that do not radiate but get captured and decay after a ~100us resulting in an “echo” event

- On unblinding a set of cascade events ALL were tagged as hadronic
- As a cross-check the analysis was applied to LED light, which was also tagged as hadronic ……

- Independent and Hamamatsu lab measurements confirmed this as a PMT effect, although delay hard to consolidate with ion mass
- Analysis currently on-hold ...







Magnetic & electric field susceptibility

- The electron trajectories can be diverted by EM fields (electric fields can usually be avoided)

- This impact the collection efficiency and gain at the first dynode (overall loss in efficiency and introduces non-uniformities)
- And amplification in the dynode structure

- Nu-metal shields can be employed to dampen fields:-
  - Tubes around dynode structure (in particular when operating in large magnetic fields)
  - Mesh over PMT bulb (in particular for large area PMTs where distance to the first dynode is large)

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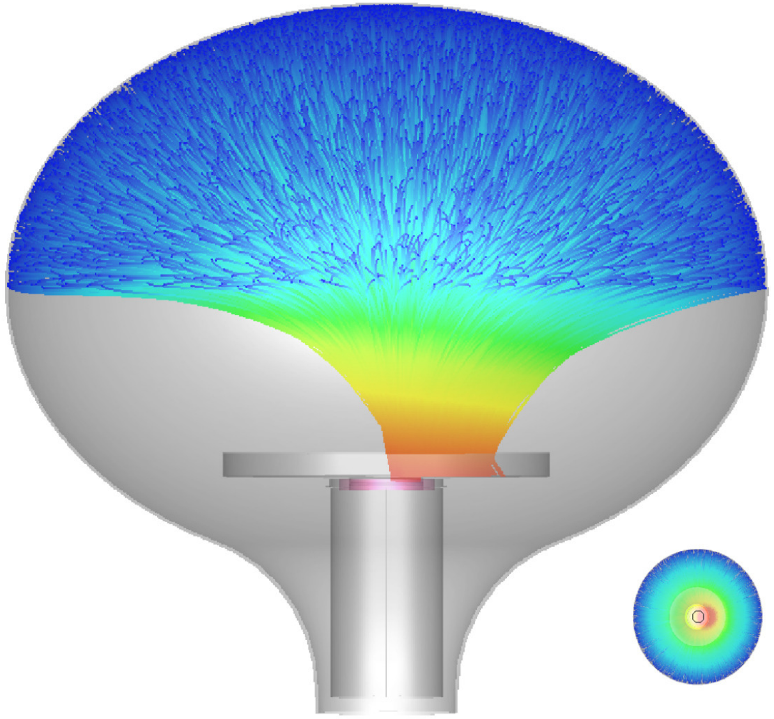


(b) With a transverse magnetic field $\boldsymbol{B}$=50 μT.

Dynamic range – non linearity

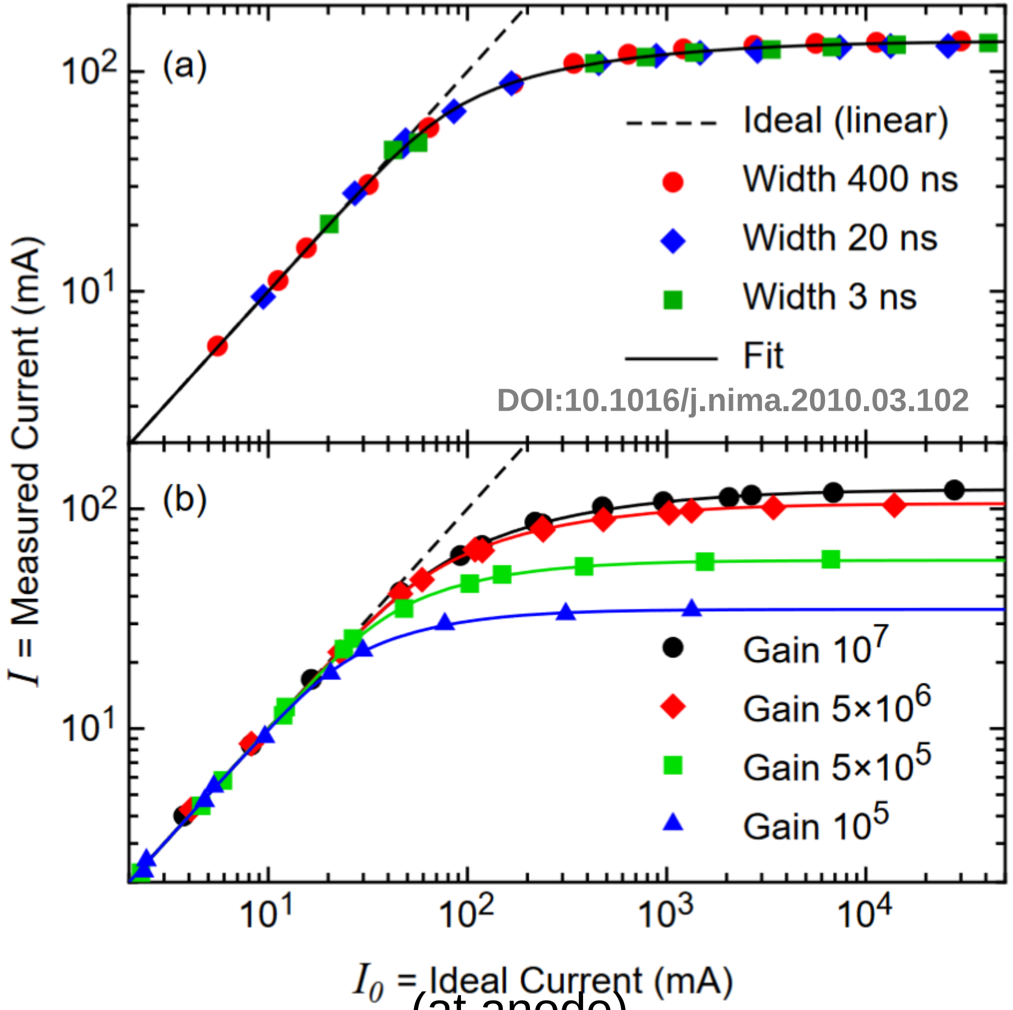
- Resistivity of photocathode limits photocurrent
  - Usually ~1uA → not a limiting factor in pulse-mode operation

- In pulse-mode non-linearity is usually
  a function of instantenious current with two contributions:

  - The recharge rate of the voltage divider on the base (large resistors to limit DC current) is smaller than the instantaneous current draw → voltage drop

  - Large number of electron in the dynode chain (in particular at the later dynodes) results in space-charge effects that reduce gain

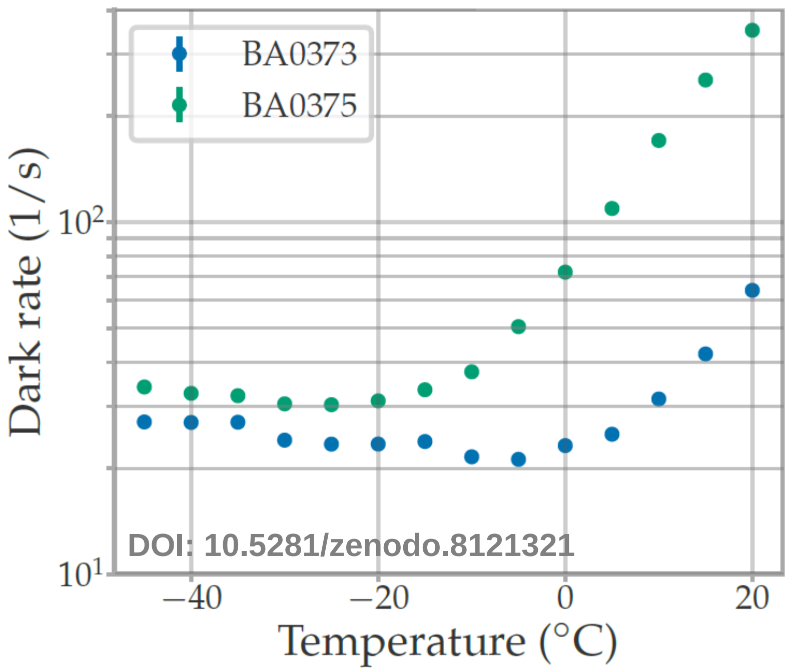
- The exact behavior is usually hard to predict
  and simply solved by design and test iterations

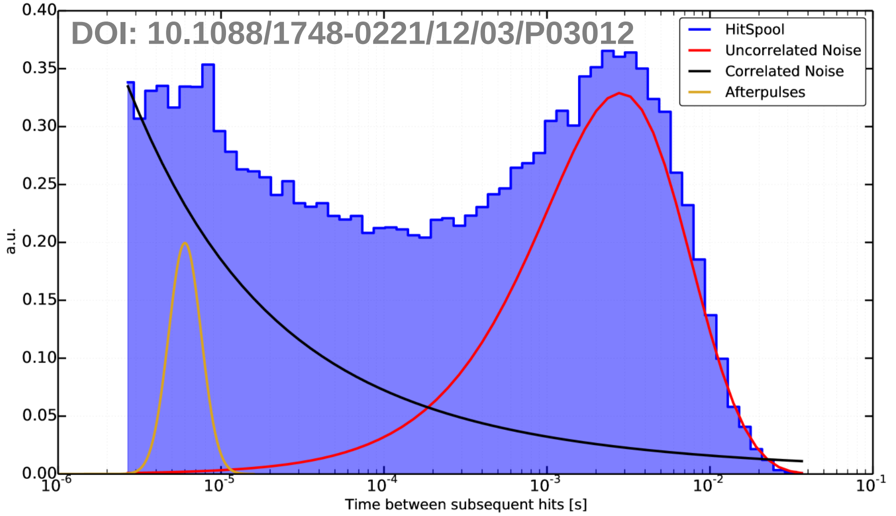


(at anode)

Dark noise – thermal & correlated

- Uncorrelated noise (single photons at random times):
  - Thermoionic emission (usually dominant):
    electrons in photocathode follow Fermi-Dirac energy distribution
    → can spontaniously exceed work function and be emitted
    → strong temperature dependency
  - Field electron emission (only a problem at very high HV):
    electrons being liberated by electric field strength
- Correlated noise (bursts of photons following an excitiation):
  - Cherenkov & scintillation light from radioactive decay in glass
    (dominant at low temperatures)
  - Scintillation from stray photoelectrons hitting glass
    (more prominent with negative HV and without HA treatment)

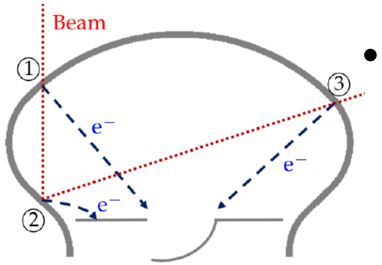




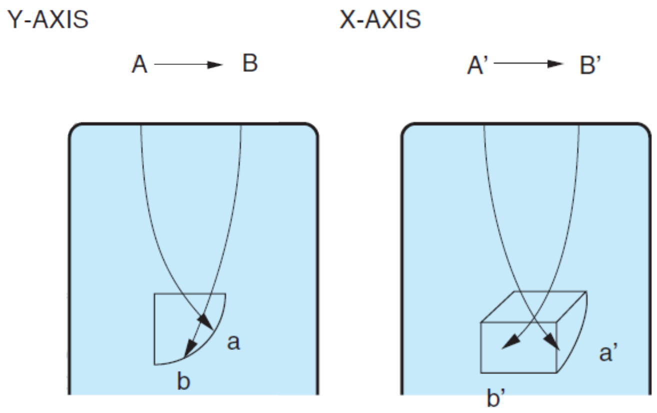
Due to correlated noise, the measured noise rates depend
on the dead-time assumed/configured and are thus somewhat definition dependent

Uniformity (without magnetic fields) (Details I/III)

- Modern photocathodes tend to be very uniform
  → non-uniformity introduced through collection efficiency
  & double detection possibilities for light hitting reflective coating at large radii



- Most other quantities depend on the electron trajectory to the first dynode → gain, transit time, TTS show radial dependence and asymmetry with respect to the first dynode



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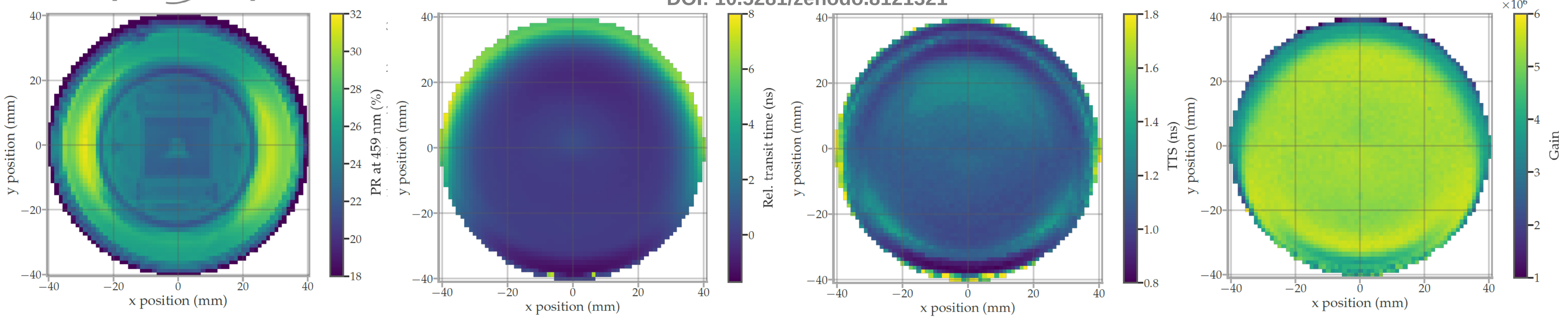
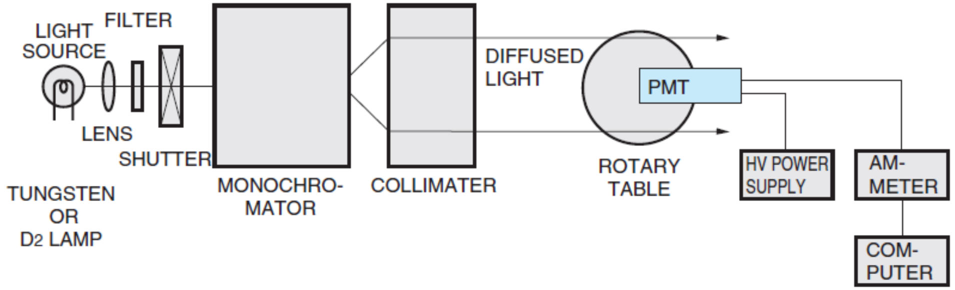


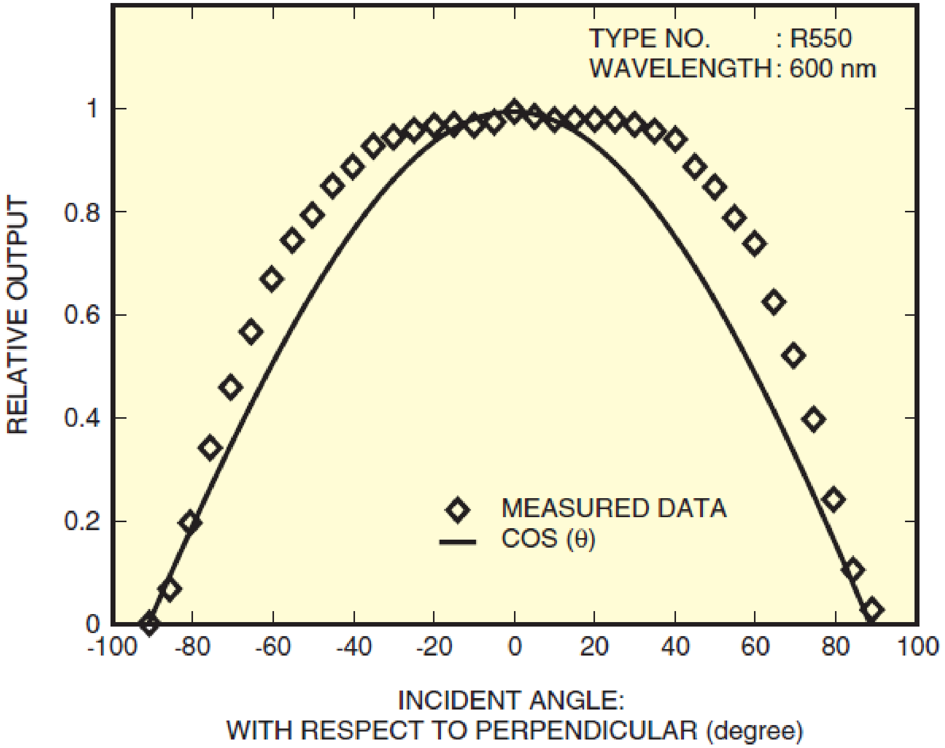
Angular response (Details II/III)

- For non-normal incidence angles the projected thickness of the photocathode increases → higher absorption probability

- The electrons diffuse semi-randomly
→ the electron emission is nearly unaffected

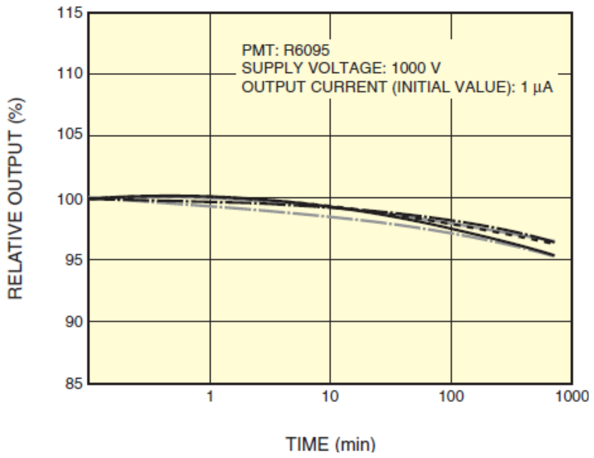
- For non-normal incidence angles the sensitivity increases!
- But this only matters for spot illumination…
otherwise the reduction in projected area wins out

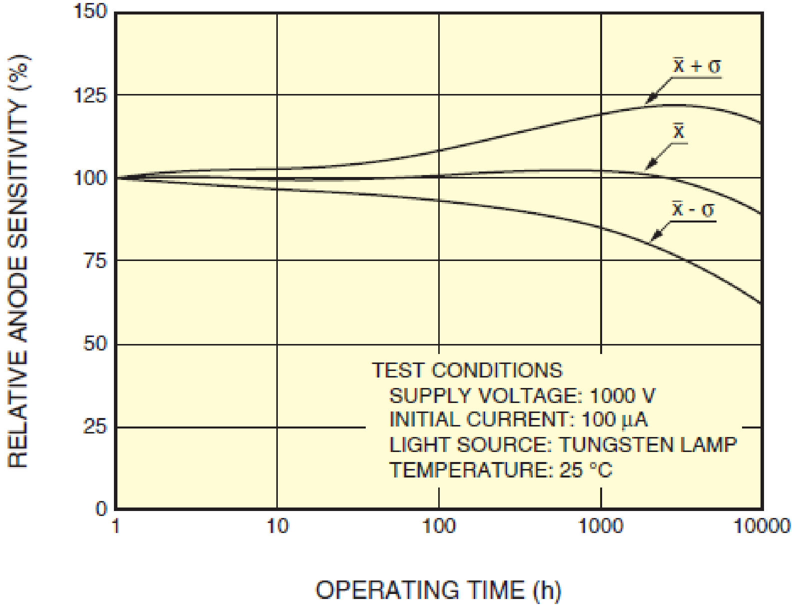




Ageing (un-)intended (Details III/III)

- PMT sensitivity, noise, gain & timing and their stabilities can drift (changes within a few hours) and exhibit (individual) lifetime trends
- Initially the sensitivity and noise rates tend to be excessively high
  → many manufacturers "hot-age" tubes before shipping,
  but dark rates can still decrease by ~50% within a year
- Similar artificial aging can also be used to temporarily reduce the afterpulse probability (except for inert gases like helium)
- Keep light levels low, keep them at a fixed temperature and avoid ANY mechanical stresses PMTs will generally last forever…
  (we regularly recycle PMTs from old experiments for new ones)





What about SiPMs? - How are they different?

- Not a vacuum tube but a semiconductor device
- Signal from an array of avalanche photodiodes is summed
  - Photon hitting a single APD triggers an avalanche breakdown resulting in a fixed signal

- Similar QE (larger IR coverage)
- Small photocathode areas (usually around 5mmx5mm)

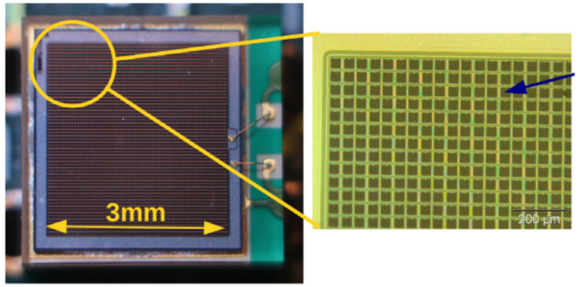
- Much, much higher single photon noise per photocathode area

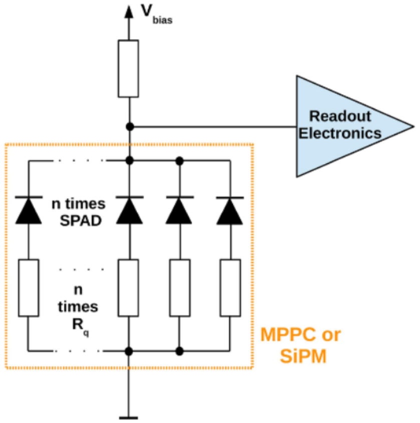
- Much better charge resolution (finger-spectrum)
- Cheap (dozens $ vs. hundreds of $)

- Predictable combinatorial non-linearity

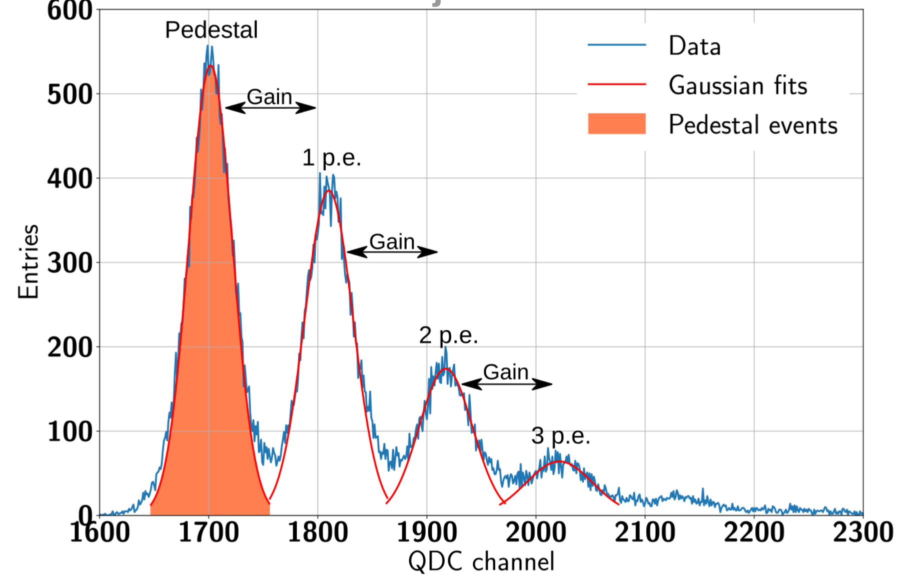
- Low voltage (~30V) operation
- Can't break it by dropping, over-illuminating it ...

DOI: 10.1088/1361-6560/ab7b2d





DOI: 10.1016/j.nima.2018.01.029.



What about SiPMs? - When (not) to use them?

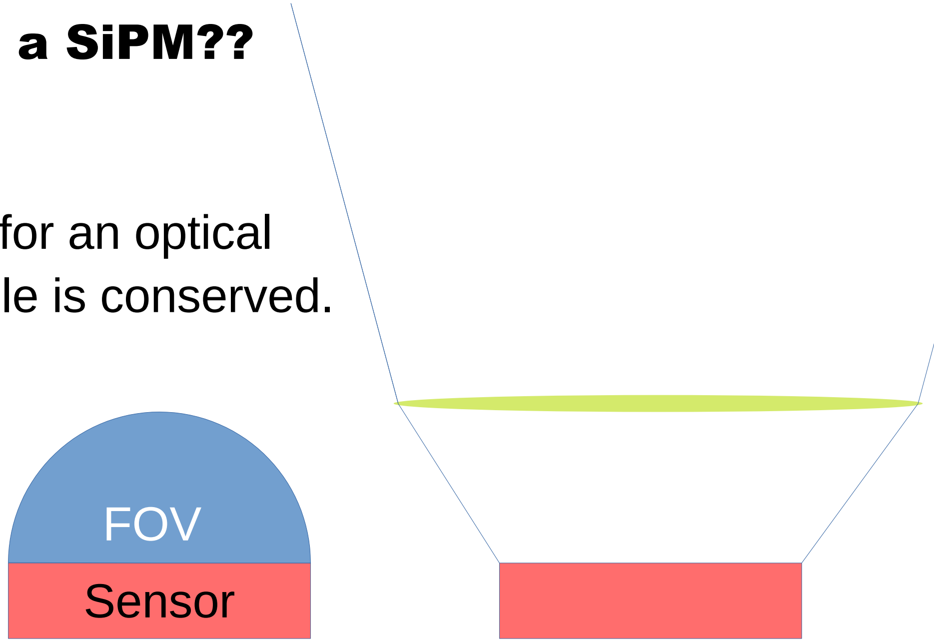
Do you have plenty of signal? → SiPM (you don't care that they are small, can cut on SPE noise, ...)

Are you signal limited?? → PMT

Why can we not simply concentrate the light onto a SiPM??

Conservation of phase space (Liouville's theorem) tell us that for an optical detector the product of collection area and observed solid angle is conserved.

If you know where the light is coming from (telescope) light concentration is possible. Otherwise not.



The End

of PMTs being the primary sensor for many (astro)particle physics experiments is not in sight…

Things not discussed:

- ✗ Polarization dependencies
- ✗ Wavelength & temperature dependencies of gain, timing, ...
- ✗ Extremely high-/low-temperature environments
- ✗ ….