Light Detection

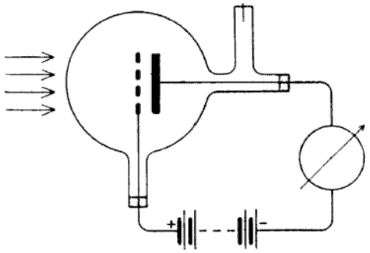
Summer Particle Astrophysics Workshop 2023

(EIEIOO)

PMTs, SiPMs,...

Peter Skensved
Queen's University

Photo Electric Effect



P Lenard, 1902

- Certain materials emit electrons when exposed to light
- Effect discovered (rediscovered) many times during the 19th century
- Four basic observations
    - If we see electrons the number emitted scales with the intensity of the incident light
    - Energy of electron does not depend on intensity of light
    - Above a certain wavelength no electrons are emitted regardless of the intensity of the incident light
    - The electron energy increases with decreasing wavelength of the incident light
- Explained by Einstein in 1905 *(Nobel Prize in 1921)*
-

Last 3 observations make little sense from a classical physics perspective !

Einstein to the rescue ...

- ➢ The photon energy is quantized and is proportional to ν . Energy conservation implies that the electron kinetic energy is then given by :

$$E = h\,\nu - W \qquad (\,W \text{ is work function of material}\,)$$

- ➢ The constant *h* is the <u>same</u> as the one introduced earlier by Max Planck in 1901 to explain "black-body" radiation

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Note that classically an electromagnetic (plane) wave can have *any* energy – the energy is related to the surface integral of Poynting's vector which is proportional to $|\,\mathbf{E}_0\,|^2$. Quantization is totally foreign to classical physics.

So - given photosensitive material and sufficient "amplifier" gain we can use the photoelectric effect to detect single (or a small number of) photons :

At ~ 10^7 gain : 1 photon => 1.6 pC which is relatively easy to measure with standard electronics .

Since $c = \nu\,\lambda$ we can also write $E_\gamma = h\,\nu = h\,c\,/\,\lambda = \hbar\,\omega$

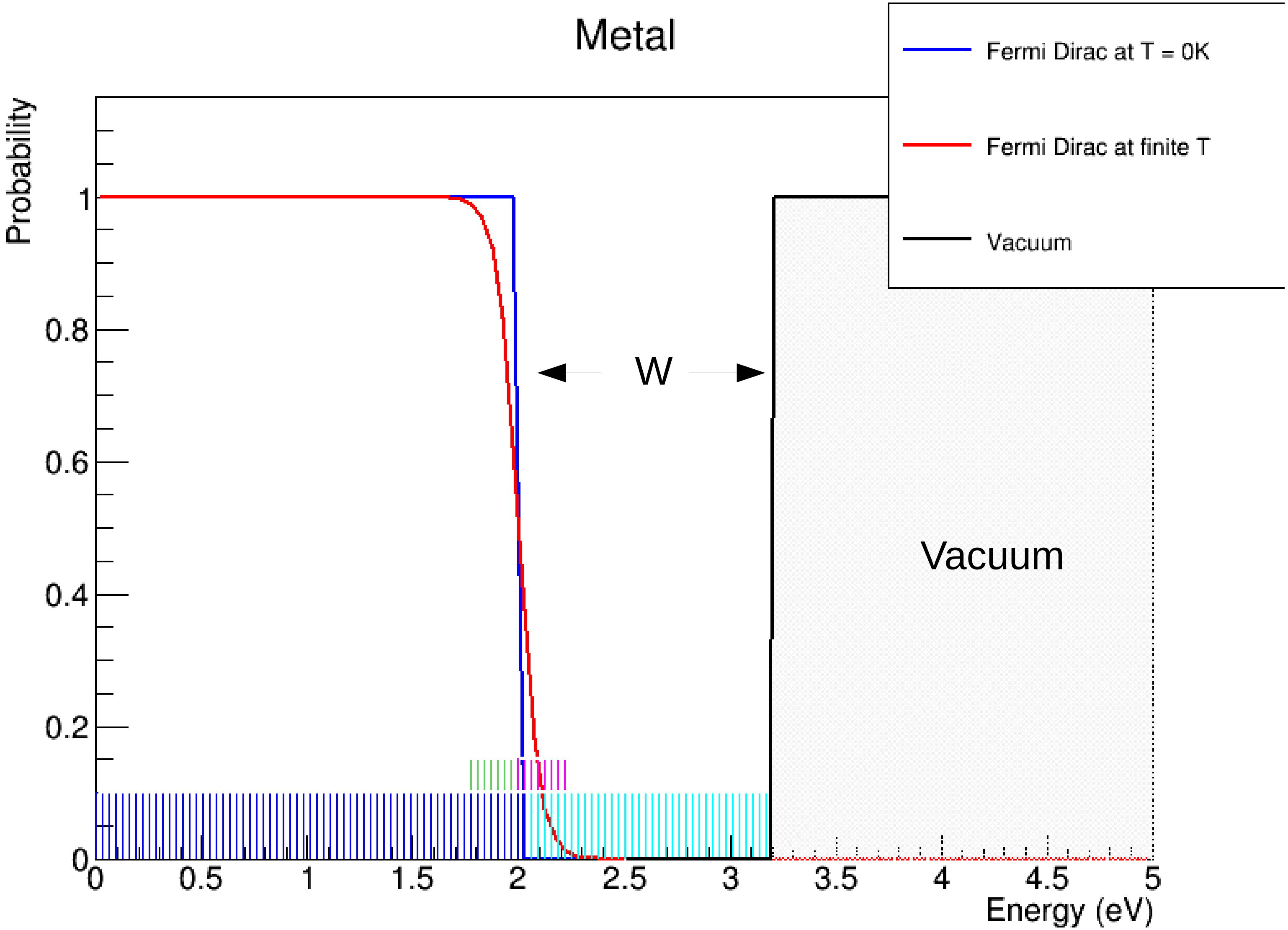
A bit of Solid State Physics ...

- Simplest model of a material is the Free Electron Fermi Gas Model
- Treat electrons as non-interacting, classical objects
- Electron energy is just kinetic the energy :

$$\varepsilon = \frac{\hbar^2 \boldsymbol{k}^2}{2 m_e}$$

- At T = 0 fill states up to Fermi energy ε_F (or Fermi wavevector $\boldsymbol{k}_F$)
- ε_F depends on particle density only
- Remarkably successful model despite the crude assumptions....
- Properties of a material at finite T depends on density of states *g(ε)* and probability that level at *ε* is occupied (Fermi-Dirac statistics) :

$$f_{FD}(\varepsilon) = \frac{1}{1 + \exp\left(\frac{\varepsilon - \varepsilon_F}{kT}\right)}$$



Filled states
at T=0

Empty states
at T=0

W = Workfunction

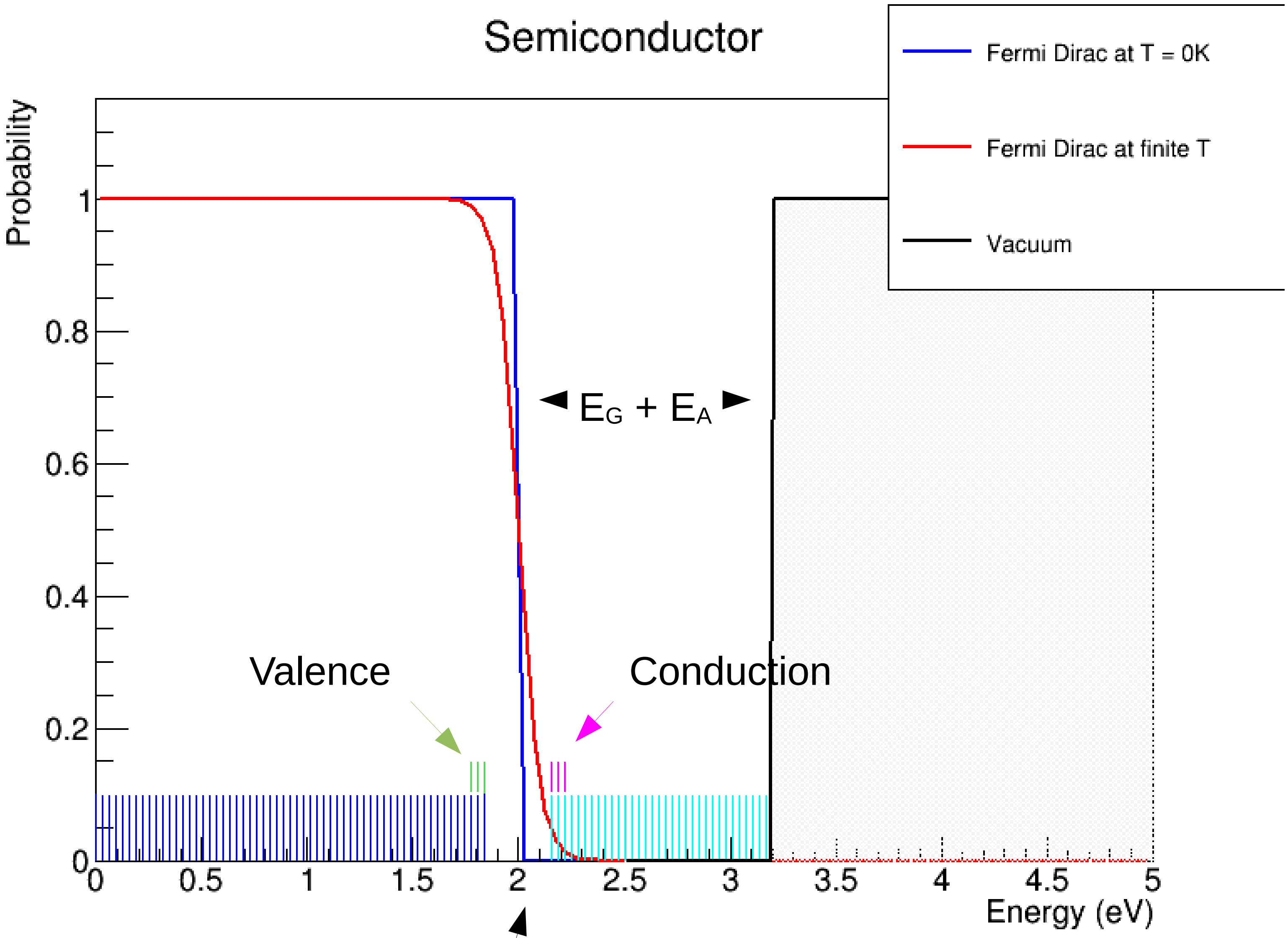
Many electron-hole pairs => High conductivity

Semiconductors

In real life the levels are not equally spaced, there are gaps due to atomic effects. For a semiconductor the Fermi energy happens to sit in a gap. That is – the gap separating the valence and conduction bands is a few electron volts. The electron kinetic energy is given by :

$$E = h\nu - E_G - E_A$$

Affinity and gap energy is used
instead of workfunction



Filled states
at T=0

Gap

Empty states
at T=0

E_G = gap energy, E_A = Affinity

Semiconductors *cont'd.*

In real life the levels are not equally spaced, there are gaps due to atomic effects. For a semiconductor the Fermi energy happens to sit in a gap. That is – the gap separating the valence and conduction bands is a few electron volts. The electron kinetic energy is given by :

$$E = h\nu - E_G - E_A$$

Affinity and gap energy is used instead of workfunction

As for metals, the Fermi-Dirac function tells us the probability that a given level is occupied . At finite T the "tail" of the F-D function overlaps the conduction ban leading to fewer free electron – hole pairs compared to the metal case and thus finite conductivity

(higher temperature required and lower number of pairs compared to metal)

Semiconductors *cont'd*.

What happens when a photon strikes a semiconductor depends on the wavelength of the photon and where the band gap in the semiconductor is located :

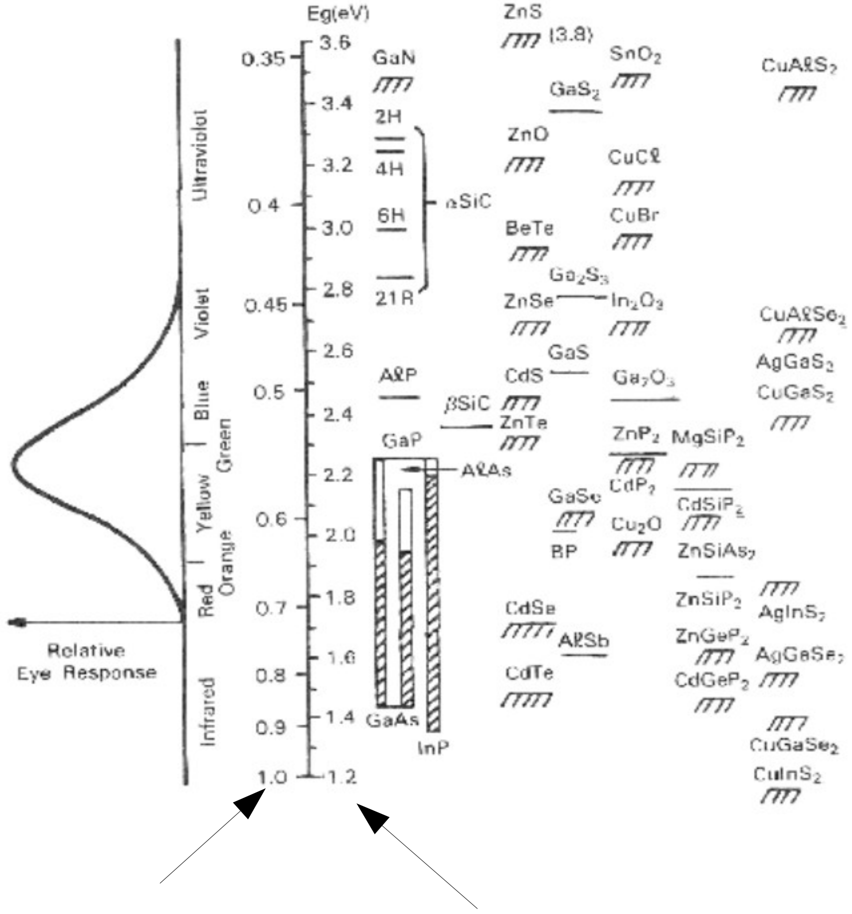
Low energy photons can create an e^- - hole pair with finite lifetime (photovoltaic effect) .

If we introduce a p-n junction and apply a voltage things are much more interesting. We can make “detectors”

Of special interest are materials where the band gap is in the visible or near UV

Some example materials :

Photon energies, wavelengths and semiconductor ban



Wavelength in microns

Energy in eV

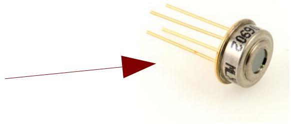
Semiconductors *cont'd.*

There are several different regimes for semiconductor devices :

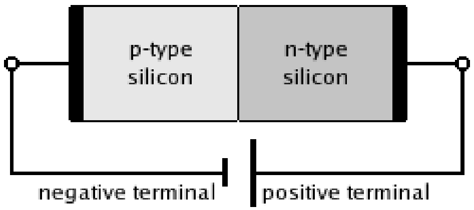
- Photovoltaic – *no bias, voltage builds up* *(solar panel)*
- Photoconductive – *reverse bias creates depletion region* *(photo diode)*
- Avalanche – *very high reverse bias resulting in an avalanche*
  - (Near or above) breakdown mode in the extreme

We're mostly interested in single photon detection and usually require fast timing *(< 10 ns)* so only the avalance mode is really of interest for physics applications.

A CdS photocell is an example of a photoconductive device



Reverse bias means cathode driven positive wrt. anode



Rest of slides ...

- We now have the theoretical background necessary to understand the behaviour of real light detecting devices
- Look at “classical” (PMTs) first
- Then transition (quickly) through some hybrid designs
- End up with solid state devices
-

Photomultipliers : How do they work ?

- Photon strikes (thin) photocathode & creates free photo electron (PE)
- PE is accelerated by voltage between cathode and first dynode
  - Electron(s) hitting dynode creates several secondaries (***g*** ~ 3– 7)
  - Secondaries are accelerated to next dynode
- Repeat for *n* stages . Total Gain ~ g^n

gain in excess of 10^7 achievable

from http://weather.nmsu.edu/Teaching_Material/SOIL698/Student_Reports/Spectroscopy/detector.htm

MiniBoone PMT

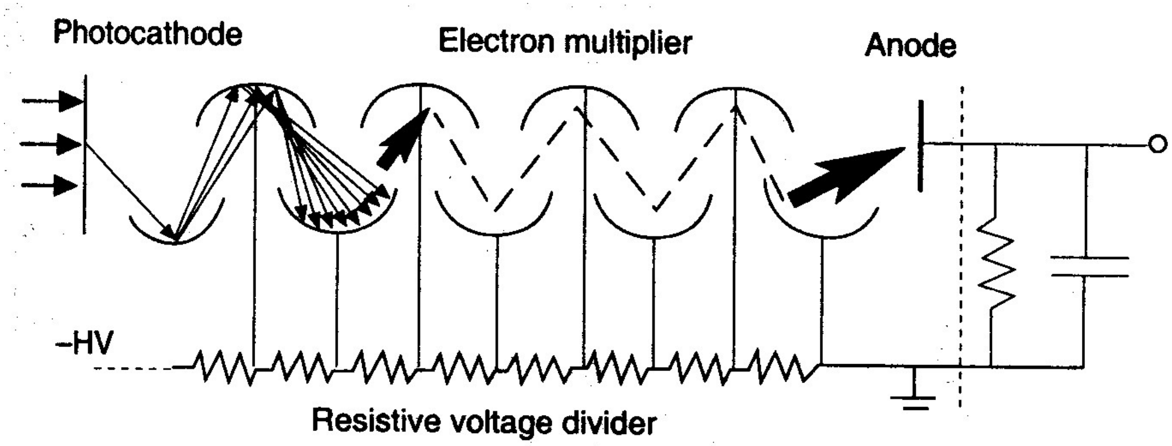
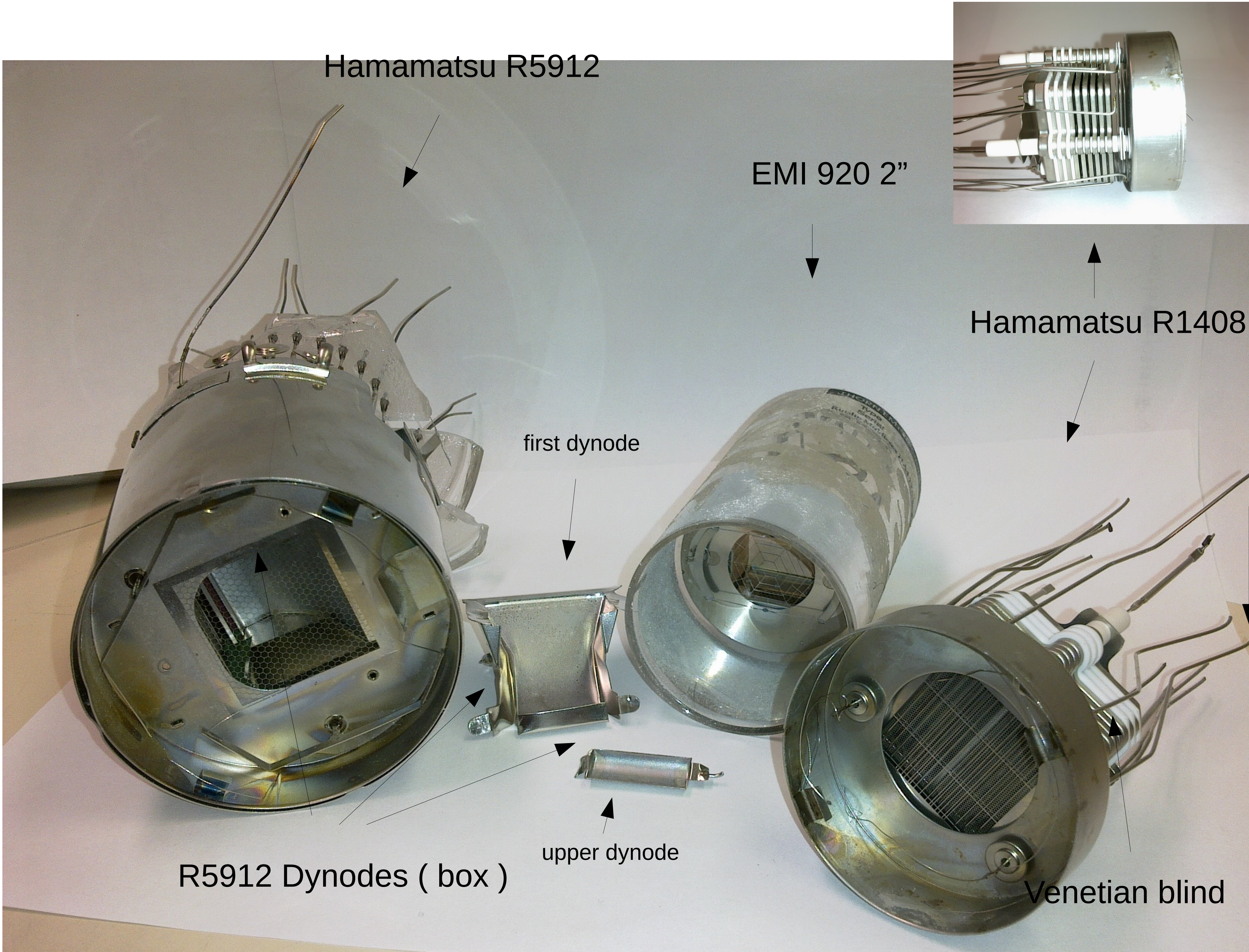


Fig. 3.22 The construction of a photomultiplier.

from Sayer



Hamamatsu R5912

EMI 920 2”

Hamamatsu R1408

first dynode

R5912 Dynodes (box)

upper dynode

Venetian blind

PMT Glossary ...

- Quantum efficiency – *PE per incident photon (usually in %)*
- Collection efficiency – *probability of PE hitting first dynode*
- Gain – *Electrons out per PE in*
- Dark current - *Rate due to “noise”*
- Timing – *RMS of arrival times (also referred to as Transit Time Spread)*
- Charge resolution – *Ability to separate 0, 1, 2, … PE distributions*
- After pulsing, Late pulsing, Pre pulsing – *see below*
- Magnetic field sensitivity -
- Dynamic range -
- Saturation -
- Linearity -
- Cathode uniformity -
-

Photocathodes ...

- Making photocathodes is black magic ..
- For the most part mixtures of Na, K, Cs, Sb, …
- Use special crystalline form to get higher QE *(Hamamatsu sorcery ..)*
- Usually unstable so must be evaporated onto glass after PMT is evacuated
- Very thin layer for transmission type cathodes *(~ 25 nm)*
- Thickness is a compromise between photon absorption and PE emission
- Has high (complex) index of reflection *(real part ~ 3.5)*
- Large reflection at photocathode / vacuum interface

Photocatode materials become insulators at low temperature. Cryogenic PMTs need extra conductive layer to avoid buildup of charge

(MiniClean PMTs have Pt underlay)

Quantum Efficiency

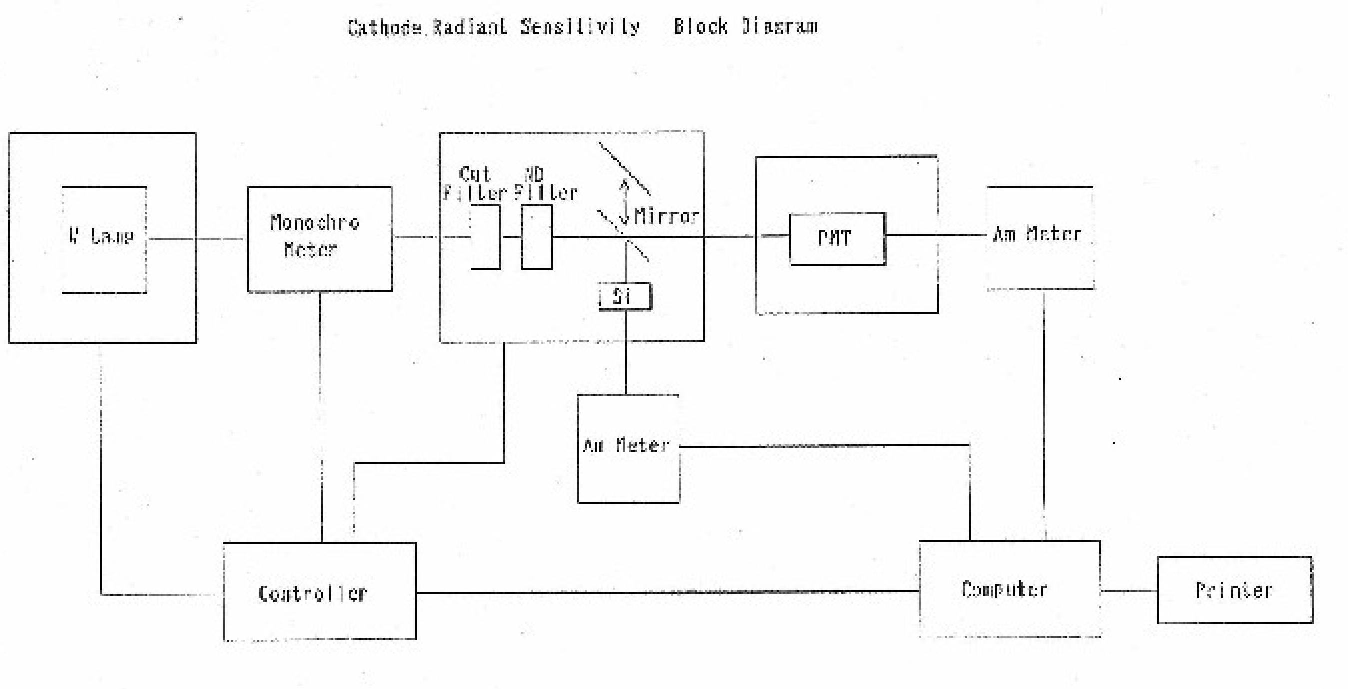
QE of a PMT is measured by shorting all dynodes, applying a small voltage and exposing the tube (full surface) to a lamp. The QE is then basically current out over current in.

Relative QE is usually quite accurate, absolute not so much …

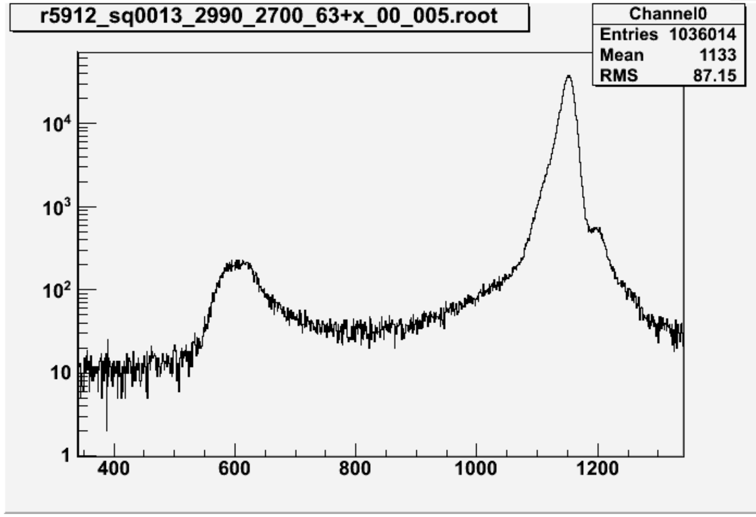
Note that QE includes geometry, reflections, glass in addition to the actual magic ingredients in the photocathode.

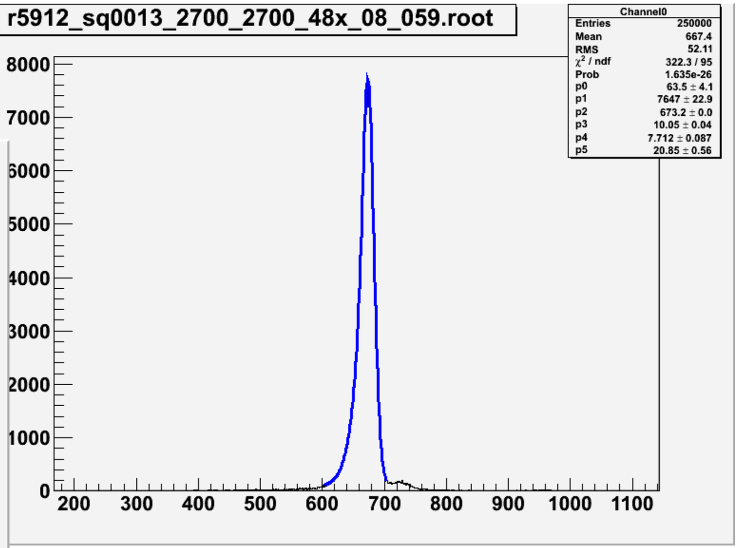
May also include components from other (non-sensitive) parts of the stack

Note that you cannot always use published QE directly in a Monte Carlo without removing other factors !



R5912HQE DEAP Timing



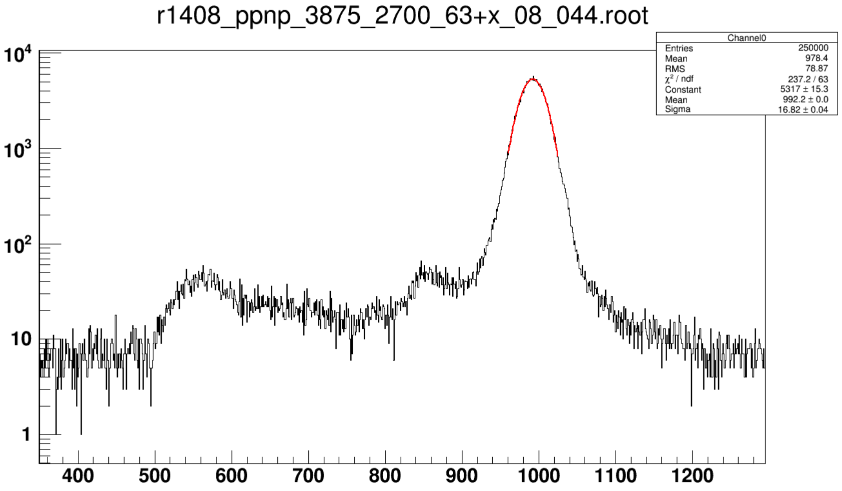


Prepulsing : Electron skips first dynode

Late pulsing :
Electrons scattered off first dynode back into vacuum

~10 channels / ns

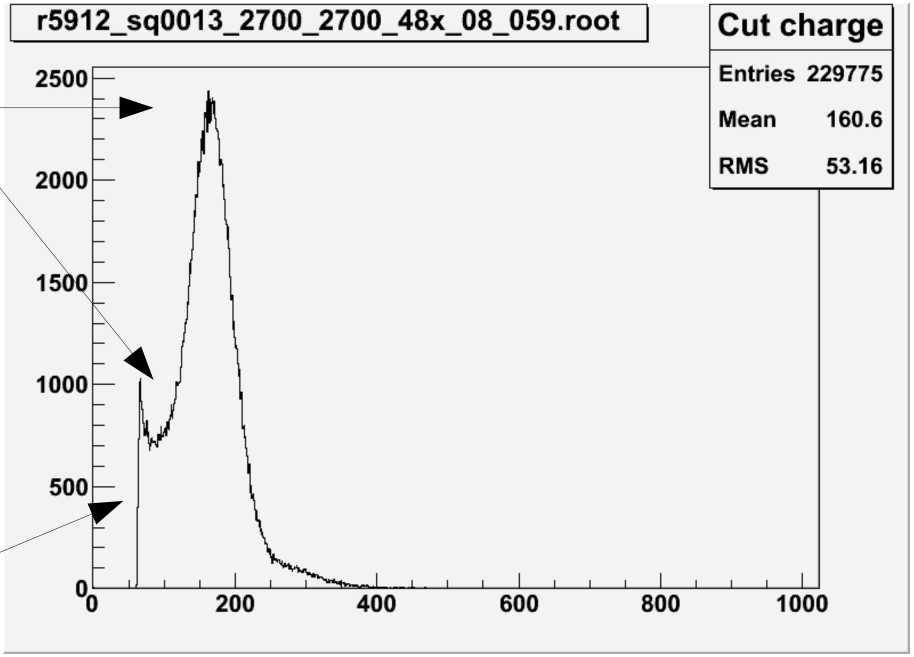
R1408 SNO Timing



Note different late pulsing features !

Good P/V

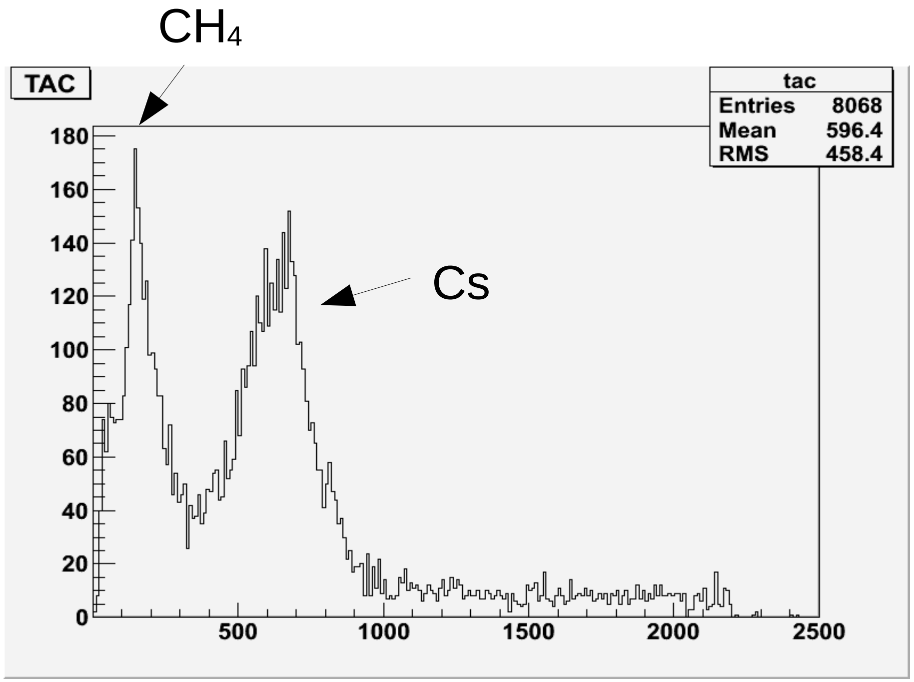
Dynode noise



Single PE spectrum (gated on prompt time from Č source)

Afterpulsing

- Photoelectron hits (neutral) atom and ionizes it . Ion is accelerated to photocathode and knocks off one or more electrons.
- These electrons look exactly like photoelectrons
- Drift times are long *(0.5 to 10 μs)*
- The observed AP charge depends on the mass of the ion
- Timing scales with square root of C – D1 voltage and square root of ion mass.
- *R5912HQE Afterpulsing Distribution (10 ns / ch)*



PMTs should not be exposed to helium as it diffuses through everything …

Helium would be at extreme left (no sign of it in this PMT …)

Summary (PMTs)

- ✓ Can detect single photons
- ✓ Built-in amplifier with gain of 100,000 to 10,000,000
- ✓ Reasonably linear at low light levels if designed correctly
- ✓ Efficiency of up to 30% *(claims of higher but beware …)*
- ✓ Can have 3 orders of magnitude dynamic range
- ✓ 1 – 2 ns timing if designed correctly
- ✓ Simple (passive) design

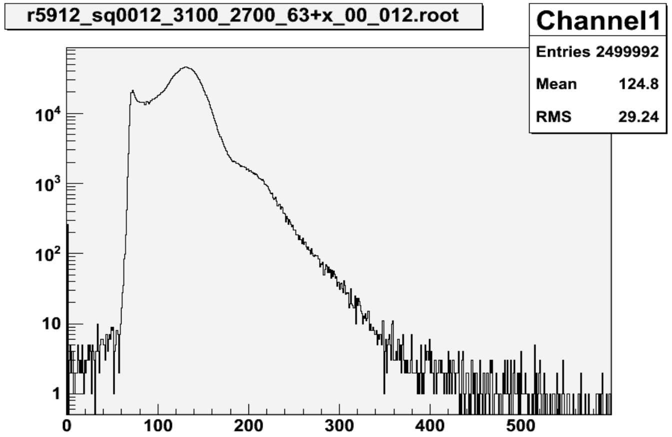
- ✖ Requires HV
- ✖ May saturate at high rates or for large pulses *(space charge affects field between last dynodes – leads to pulse distortion)*

Improvements to PMTs

Charge resolution is pretty bad for a standard PMT. We cannot do anything about Poisson statistics but we might be able to “fix” D1 contribution if we can increase the gain :

⇒ GaP(Cs) coated D1

R5912HQE



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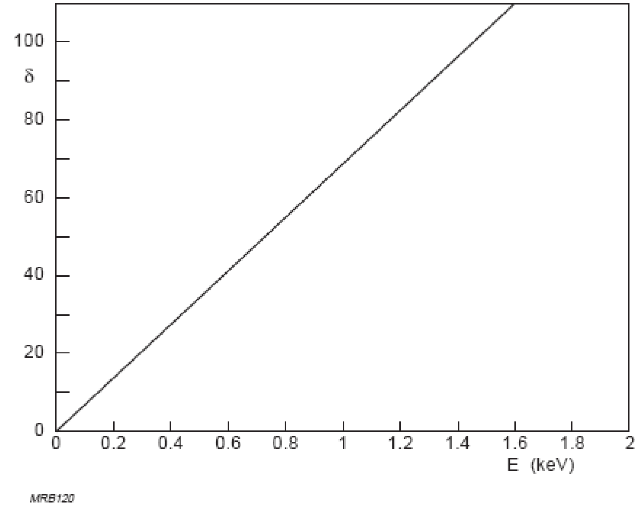
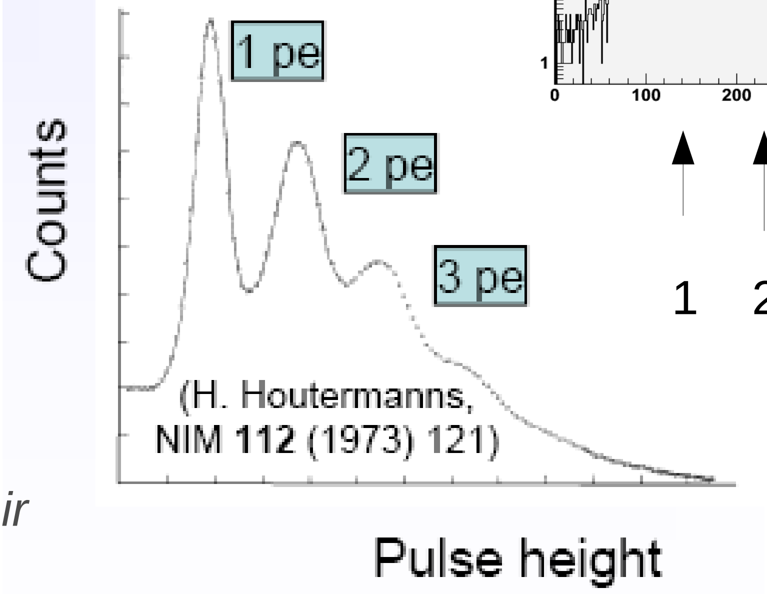


Fig.1.10 Secondary emission coefficient of GaP(Cs) as a function of incident primary-electron energy

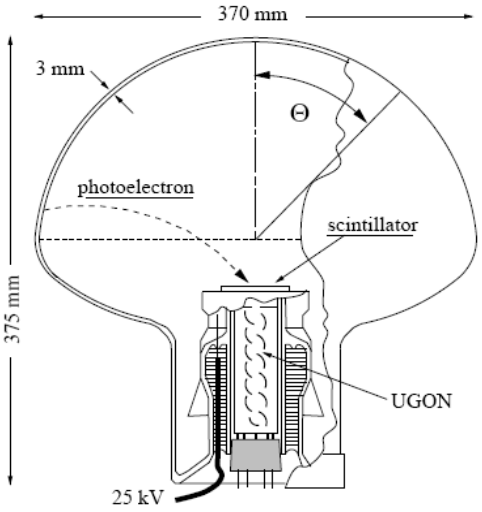


(H. Houtermanns, NIM 112 (1973) 121)

Note : Charge comparison is not quite fair (low occupancy for R5912HQE)

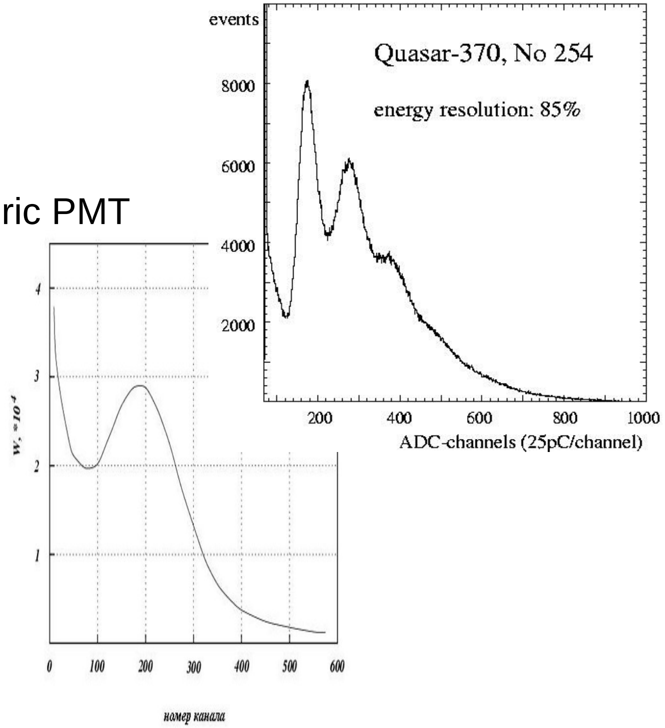
“Smart PMTs”
(Electro-Optical PMTs, QUASARs)

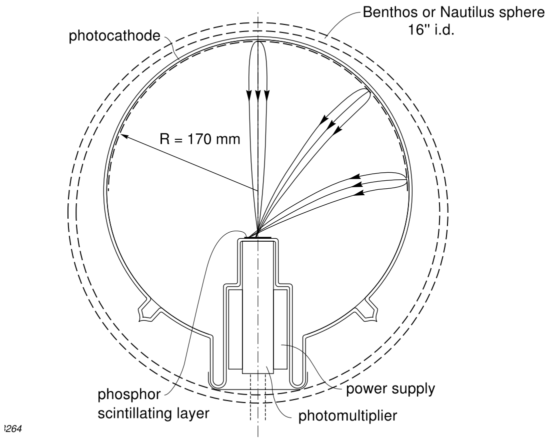
- Lake Baikal, DUMAND (now defunct) …
- Large photocathode plus very high voltage (~25 kV) to focus PE onto scintillator
- Conventional small, flat faced PMT detects scintillation light



QUASAR-370

Generic PMT





.18 Smart photomultiplier combination in a glass pressure sphere for deep underwater muon and neutrino detectors (DUMAND)

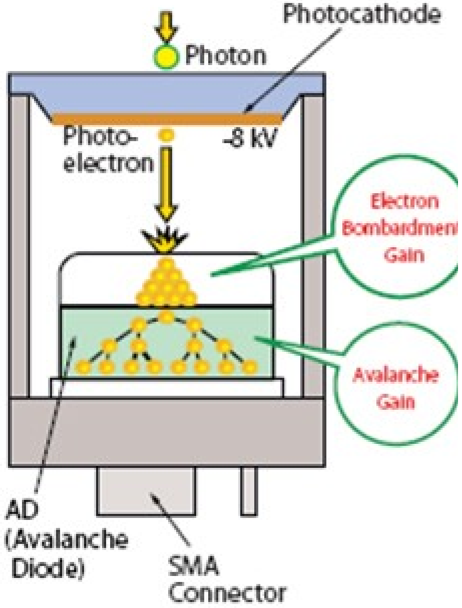
DUMAND

Hybrids PMTs (HPDs)

- Combine PMT and semiconductor technology to improve performance *(half and half ….)*
- Use “front end” PMT, high voltage and “back end” semiconductor
- Superb charge resolution – can easily separate 1,2,3, … PE
- Claimed to have little afterpulsing *(really ??)*
- Very good timing *(~ 50 ps)*

Hamamatsu 13” HPD

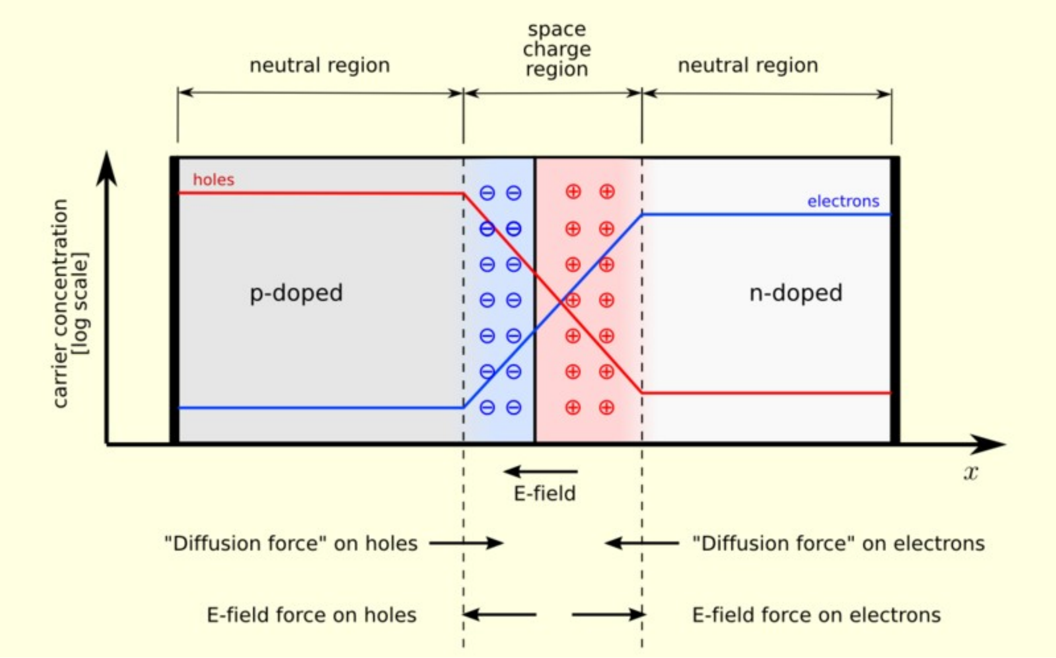
Smart PMTs repackaged ….

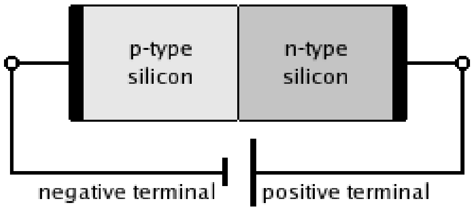


8 kV voltage results in first stage gain of x 1600

Let us go back to solid state devices instead ...

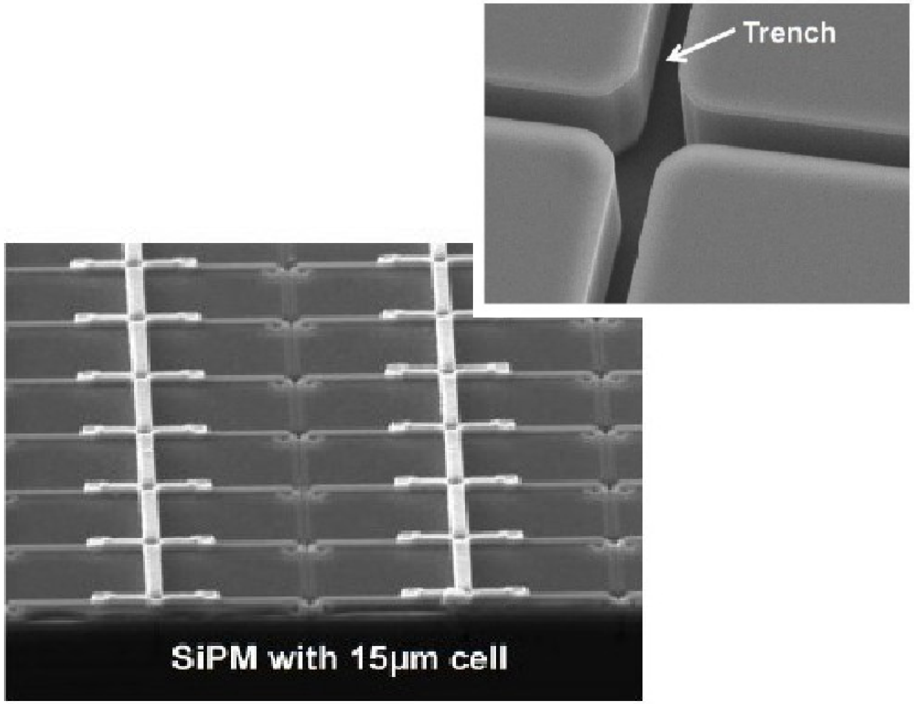
- We've already ruled out photovoltaic devices as they're too slow and too low in gain
- We want a fast device with very high gain (and low noise, etc., etc.)
- That brings us to reverse biased p-n junctions and thus APD's
- Doping and voltage controls performance

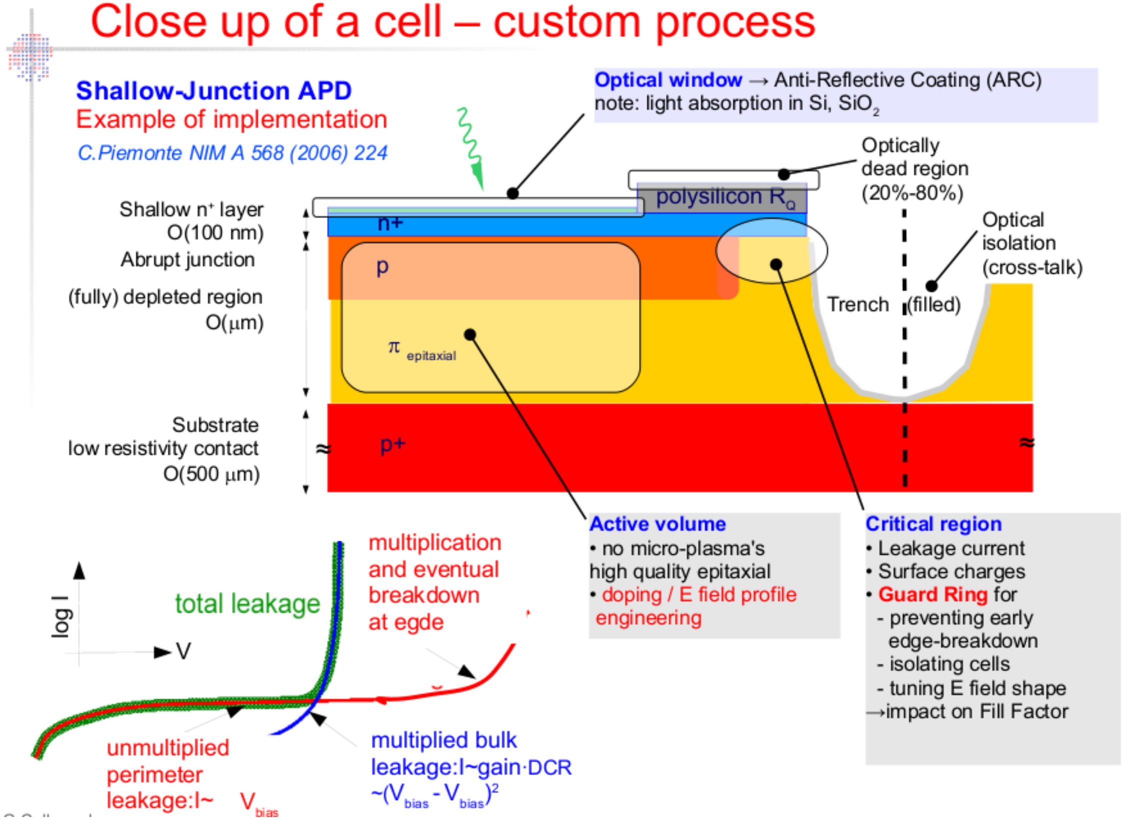




APDs

- At high bias they will operate in Geiger mode, at lower bias they require tens of photons to trigger
- APDs are quite small *(usually a few mm dia. , maybe up to ~ 1 cm)*
- Usually high noise *(usually OK at cryogenic temperature)*
- Gain is lower than PMTs *(getting better as time progresses ...)*
- Very temperature dependent

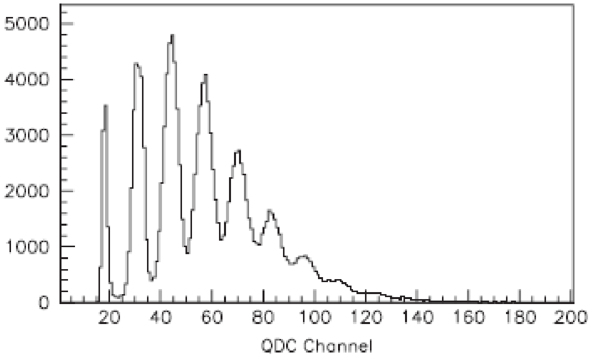




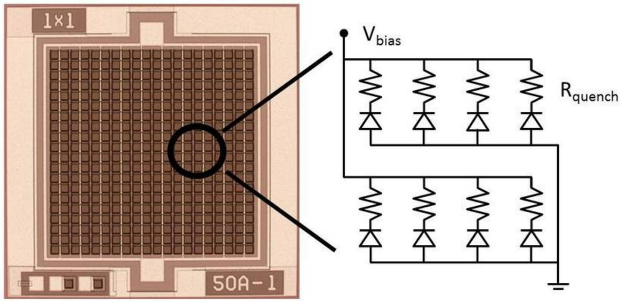
Close up of a cell – custom process

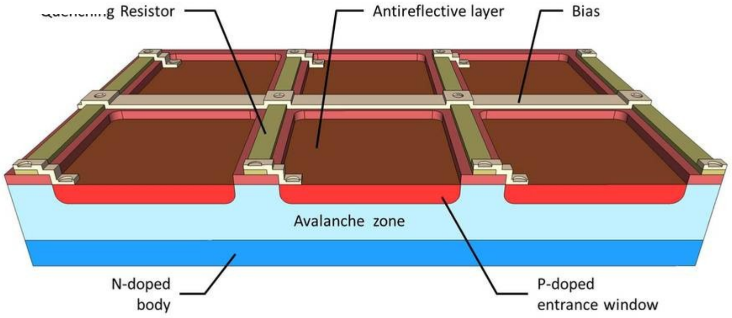
Early SiPMs

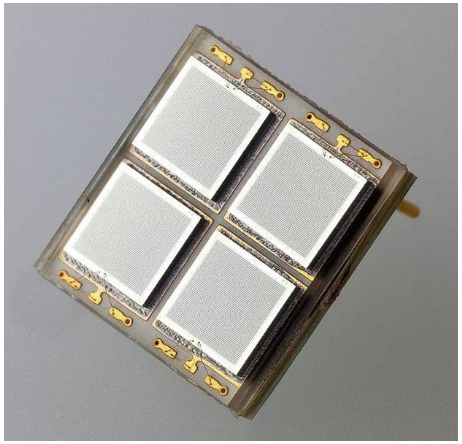
- Large number of small (10-100 microns) APDs mounted on a Si substrate operated in Geiger mode
- Also referred to as SPADs *(Single Photon Avalanche Diodes) ,* microcells or pixels
- Up to ~1000 APDs per square mm
- Typically 35% QE, ~ 10 ns timing, ~ 10^6 gain



from V. Saveliev, NIM A **535**, 528 (2004)







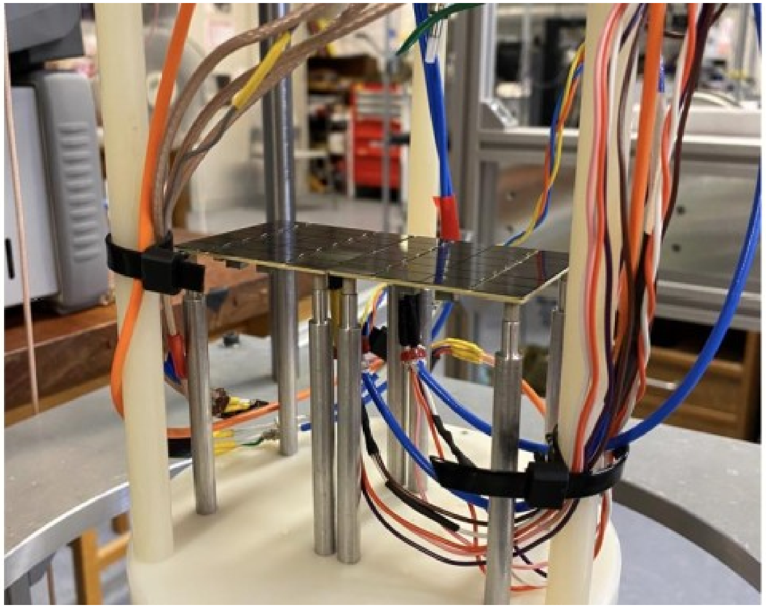
KETEK SiPM

DarkSide-20k PDU (Second generation)

Each quadrant in this 20 cm x 20 cm device is made up from four 5 cm x 5 cm tiles with a summed analog output. Each tile can be controlled individually. The electronics is mounted on the motherboard behind the SiPMs.

The total area of DS20k covered by SiPM’s (inner + veto) exceeds 25 m^2

DarkSide PDU



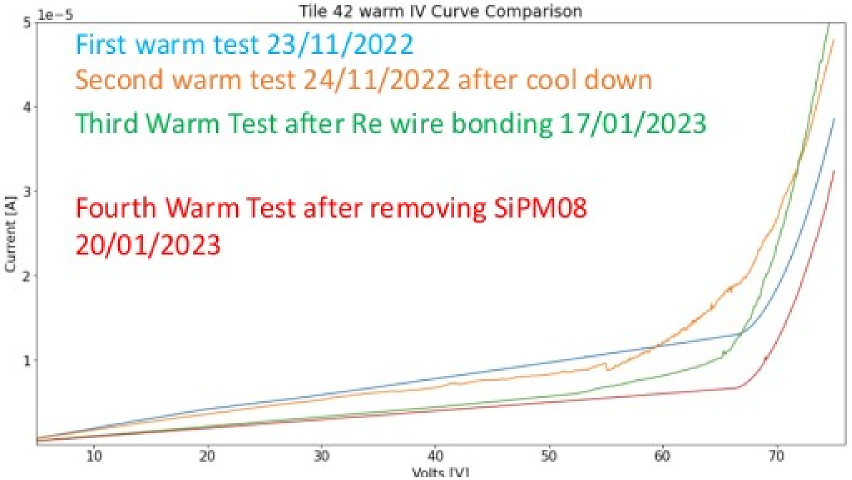
vPDU Cold Test Setup

SiPMs from Foundazione Bruno Kessler (FBK) in Italy

I-V Curves are a useful diagnostic tool

Expose SiPM to small amount of light, increase voltage (**V**) and measure DC current (**I**) at output :

For a good SiPM the current increases rapidly beyond breakdown voltage. Ideal shape is slow rise followed by sharper rise at “knee” (== breakdown) . This tile required (re-)work . The notes in the figures show the path to a working SiPM :

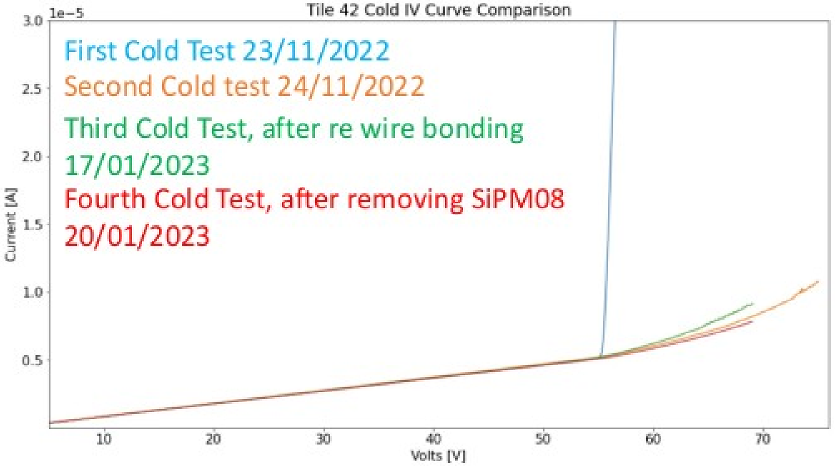


First warm test 23/11/2022

Second warm test 24/11/2022 after cool down

Third Warm Test after Re wire bonding 17/01/2023

Fourth Warm Test after removing SiPM08 20/01/2023



First Cold Test 23/11/2022

Second Cold test 24/11/2022

Third Cold Test, after re wire bonding 17/01/2023

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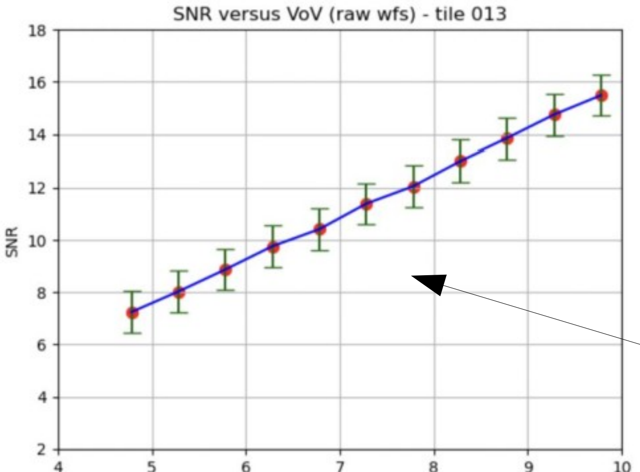
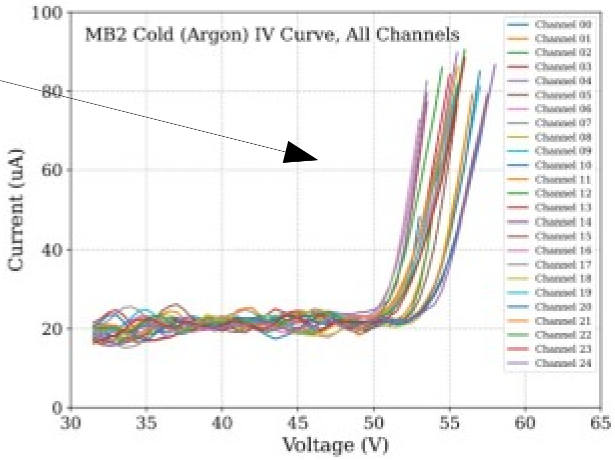
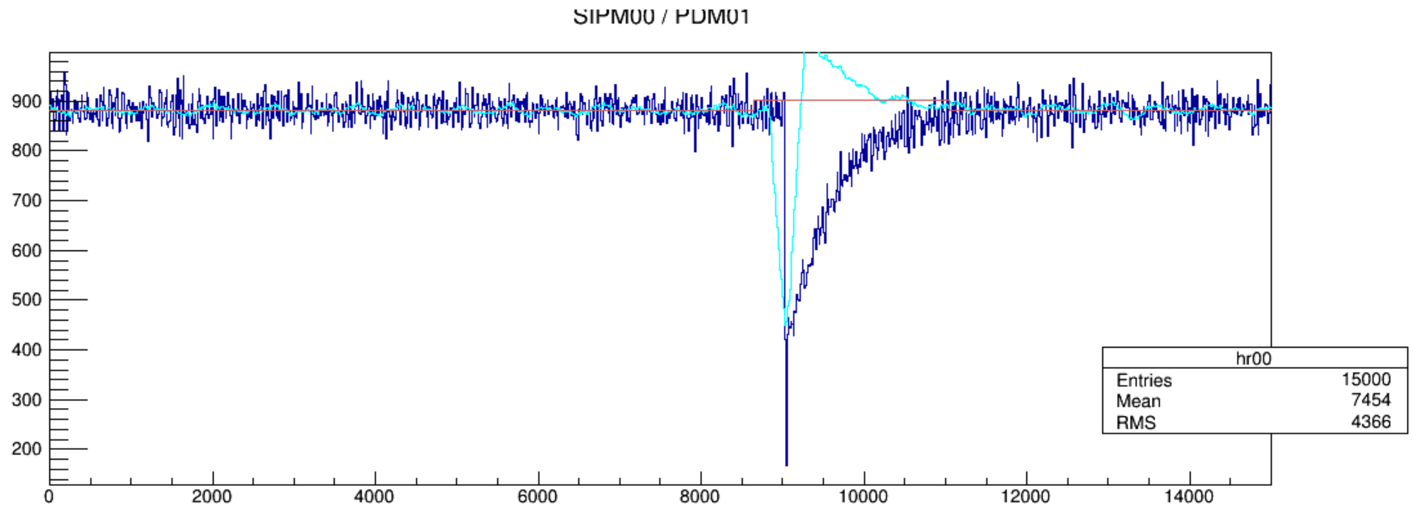


Cold I-V curves from NTF for 25 individual 5 cm by 5 cm tiles

Parameters are usually measured as a function of voltage above breakdown voltage (***VoV***) .

This shows the Signal to Noise Ratio (***SNR***)



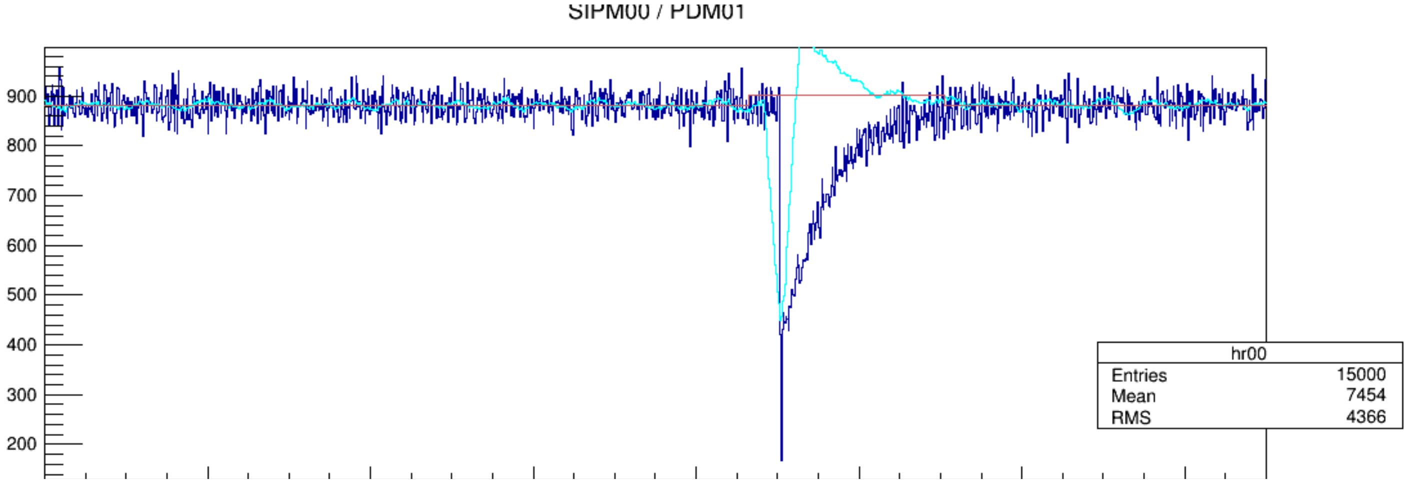


Cool single PDU to 77K, apply 6VoV, shine pulsed laser light on it and digitize output (250 MHz sample rate)

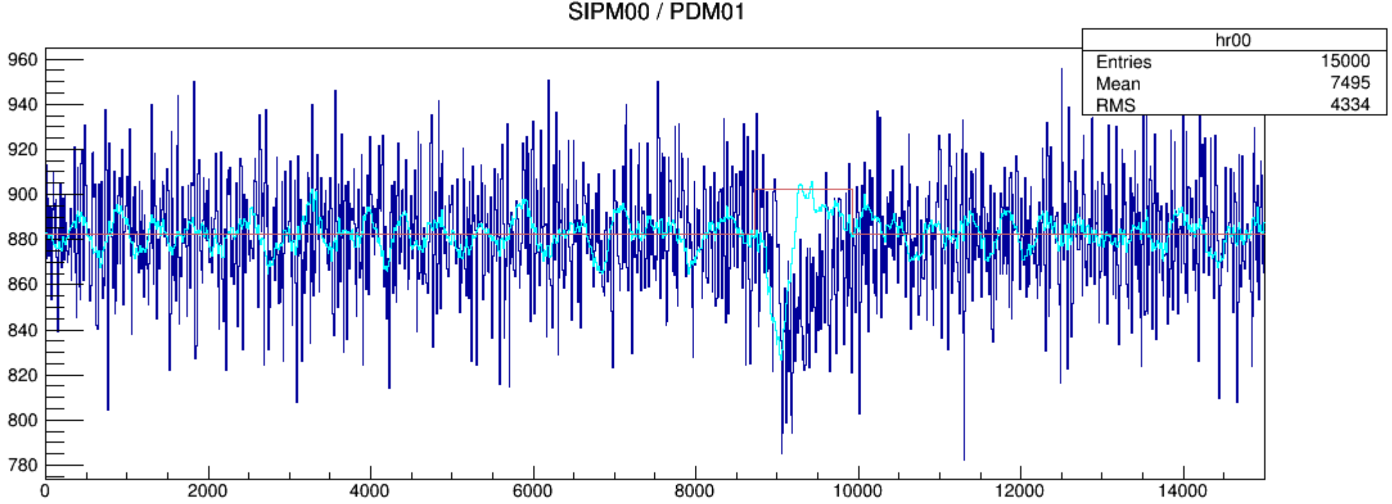
Blue trace is data, cyan is output of (differential zero-crossing type) pulse finder, red/brown is ZLE finder

Sharp spike followed by exponential looking tail (recharge following avalanche breakdown)

Looks good … *(except that …...)*

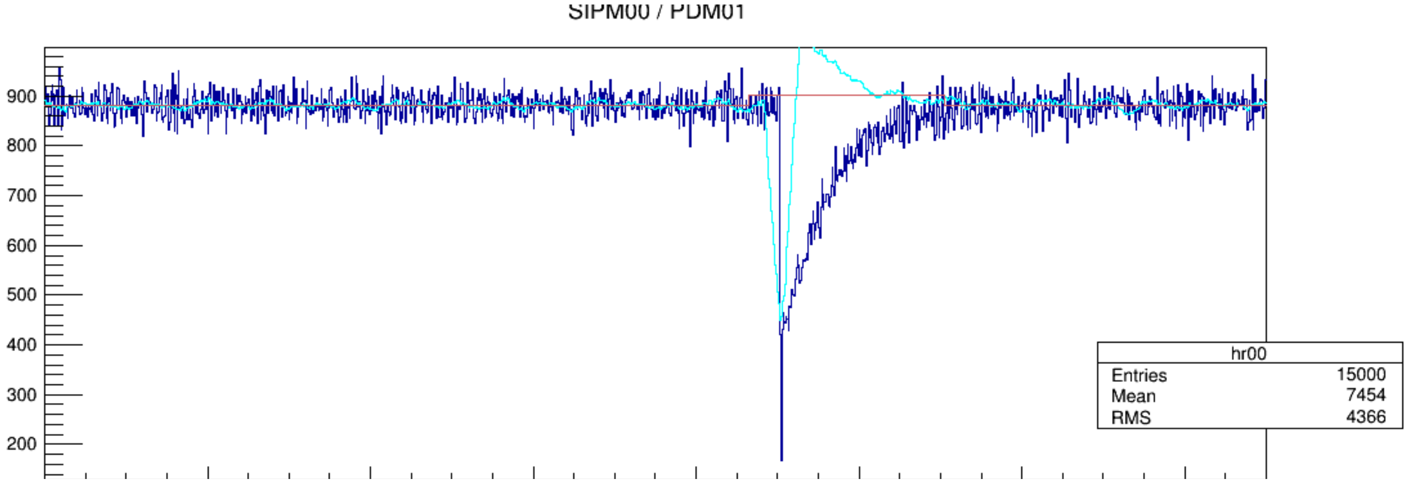


This is a~10 PE signal !

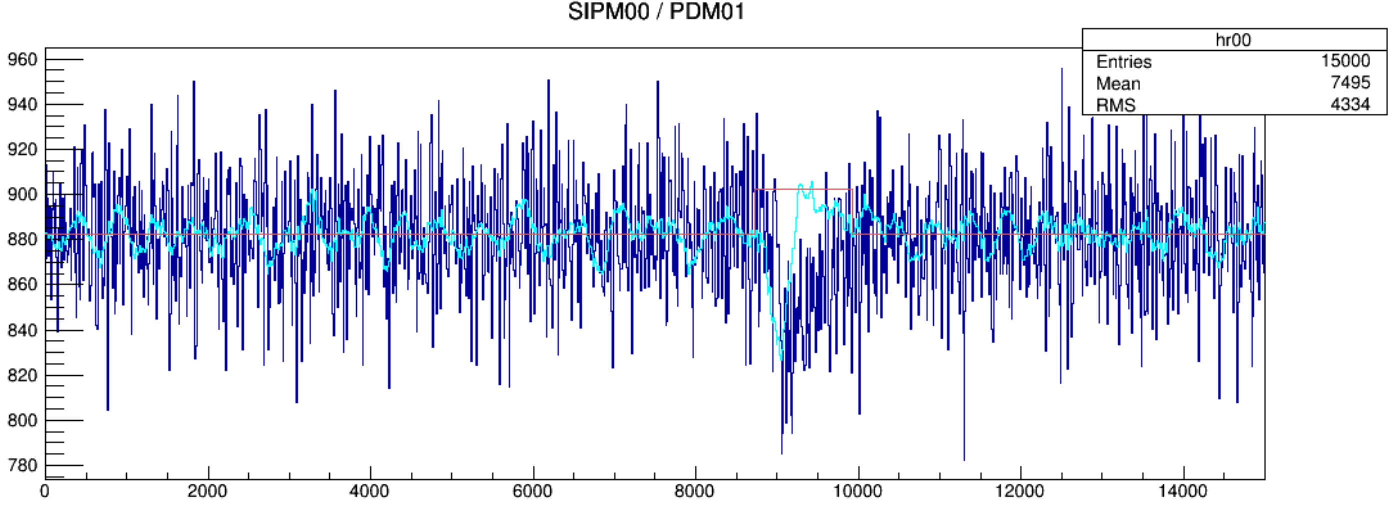


- and this is a 1 PE

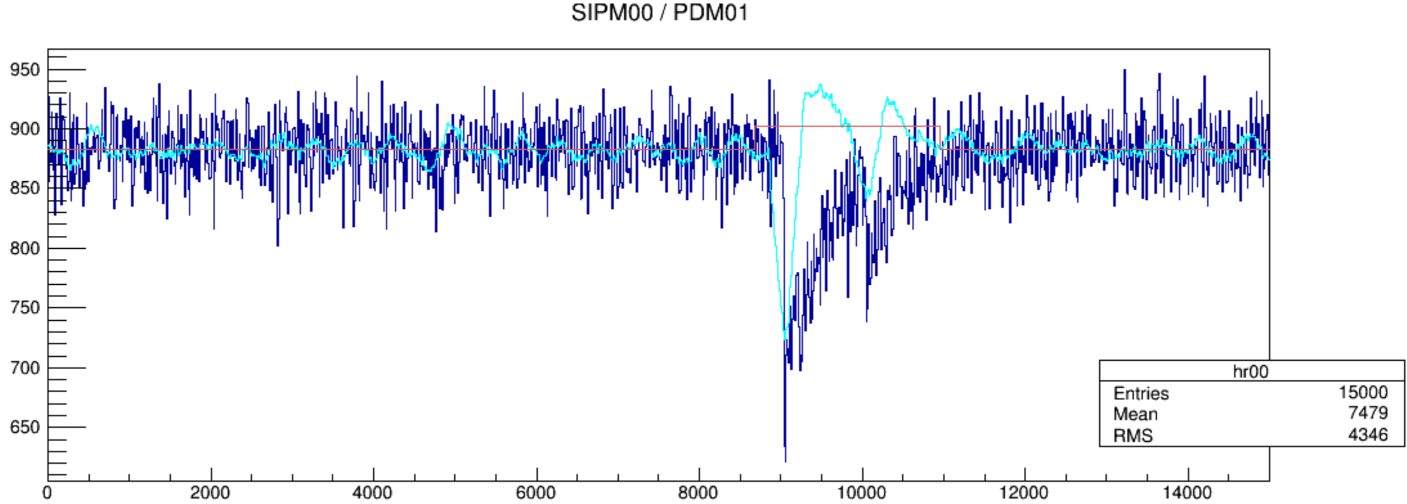
Single PE are not easy to find. Signal to noise ratio is extremely important. We need to use all the tricks in the book to separate real pulses from noise. Exponential nature of response helps here.



~10 PE



1 PE

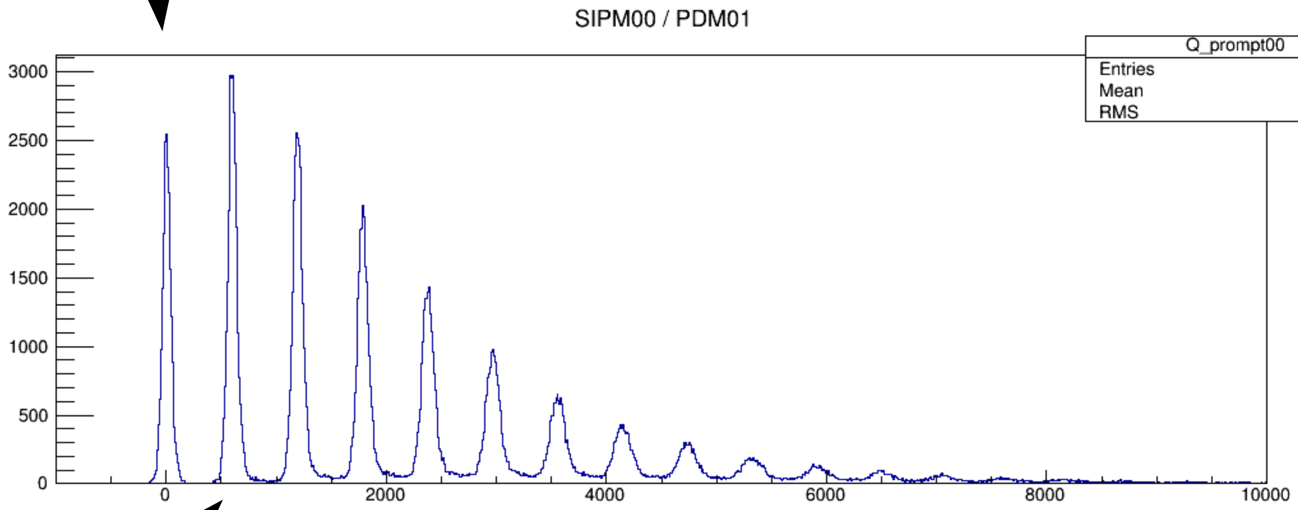


~4 + 1 PE

Afterpulsing event. Pulse height depends on state of recharge

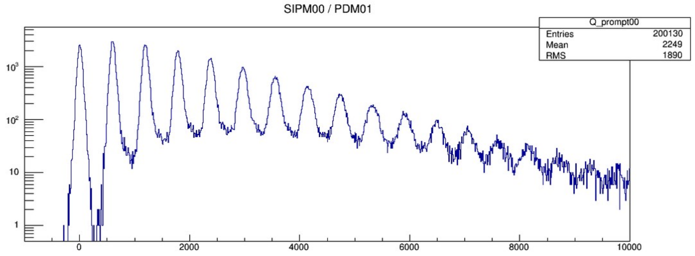
“Finger” plot

“0” photons



1 PE

2 PE

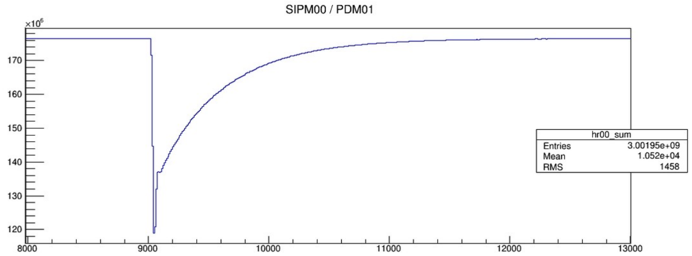


16 PE (!)

Just because we see events with ~ 16 PE doesn't mean we detected 16 photons …

Mean number of photons on SiPM is estimated to be ~2

PE distribution is not Poissonian !



Average pulse shape

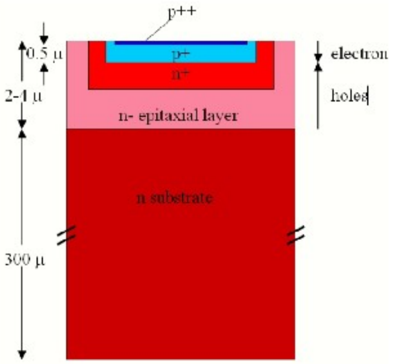


Figure 2.5: Architecture of an SiPM cell. The p on n struct
light. Image from [9].

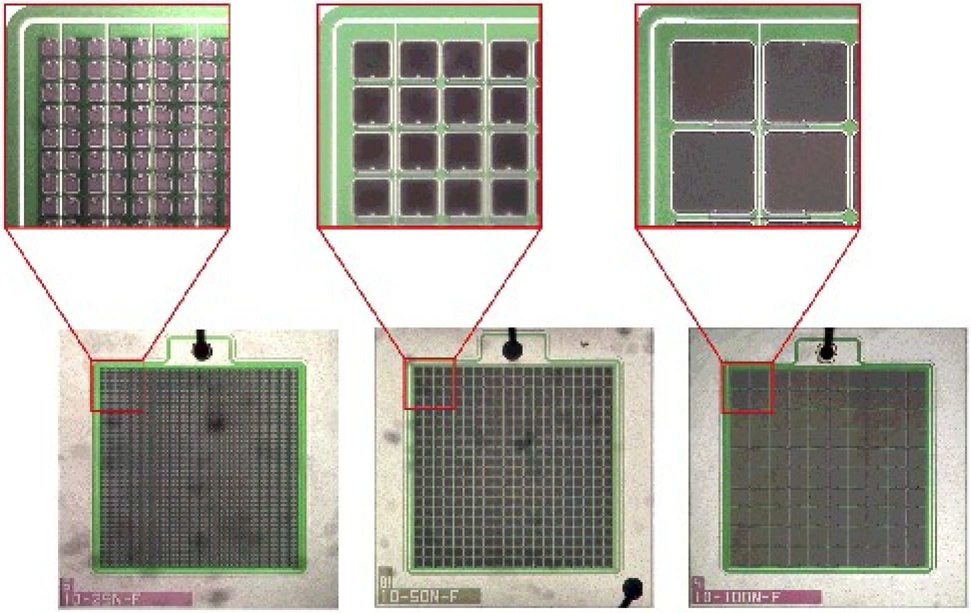


Figure 2.7: Magnified view of pixels in an SiPM. The black squares are the active area whereas the green spaces in between the cells are needed for quenching resistors and separation of the cells and cannot detect photons. Taken from [10].

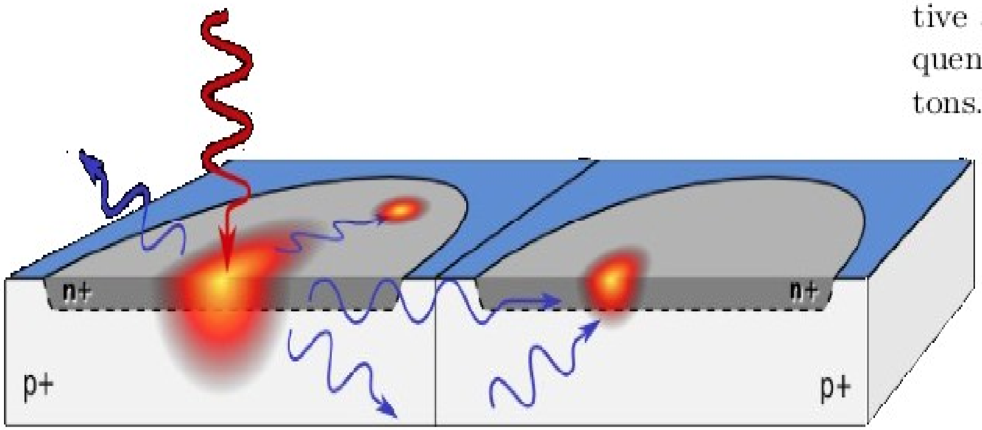


Figure 2.11: Schematic image of optical crosstalk in SiPMs. A photon coming from the initial avalanche enters an adjacent cell and triggers a secondary avalanche. Image adapted from [18].

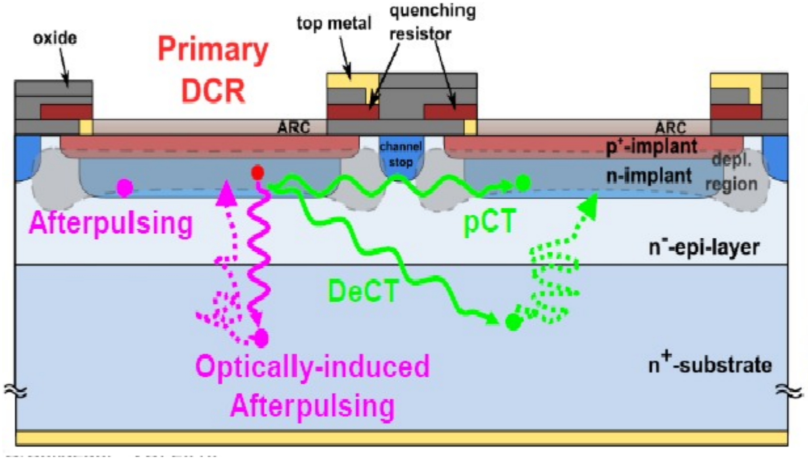
Cross talk can be a problem

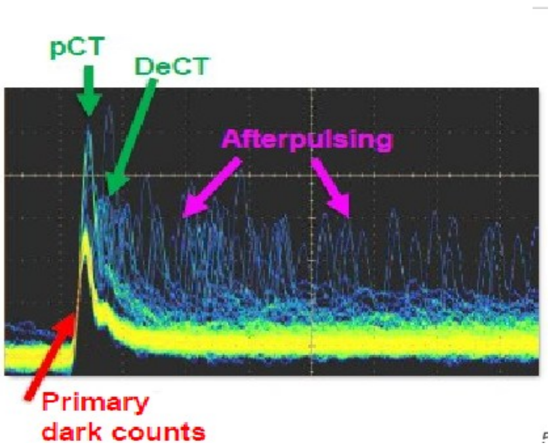
Electron-hole pair can be trapped at boundaries for hundreds of ns. Will cause afterpulsing

Mitigating cross talk is difficult (“black magic” like photocathode “black magic”)

- isolate cells (infilling)
- make device opaque to IR photons
- try to control diffusion of pairs from “dead” regions

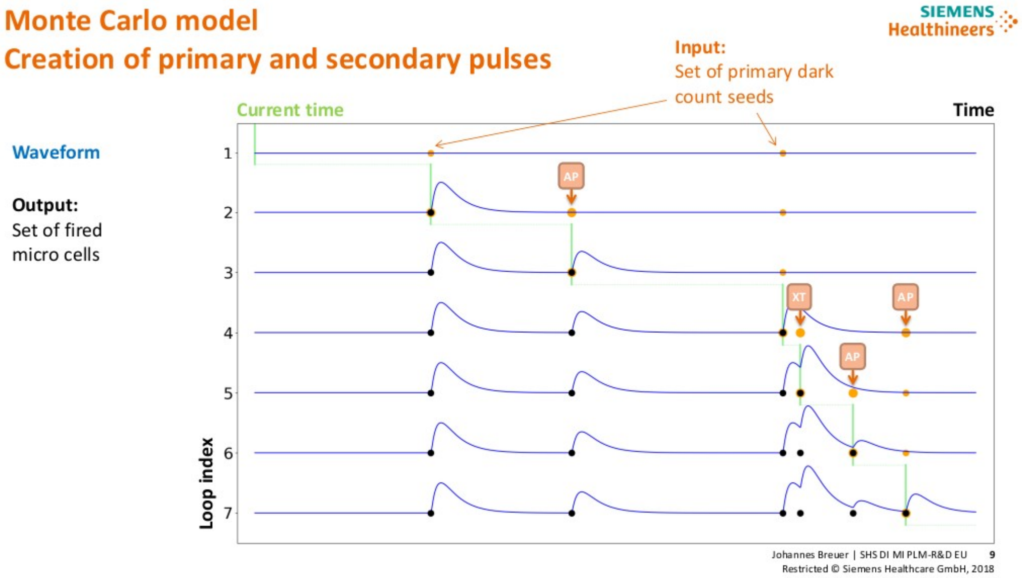
….





Develop statistical cascade model to correct charge response.

→



Monte Carlo model
Creation of primary and secondary pulses

SIEMENS Healthineers

Input:
Set of primary dark count seeds

Waveform

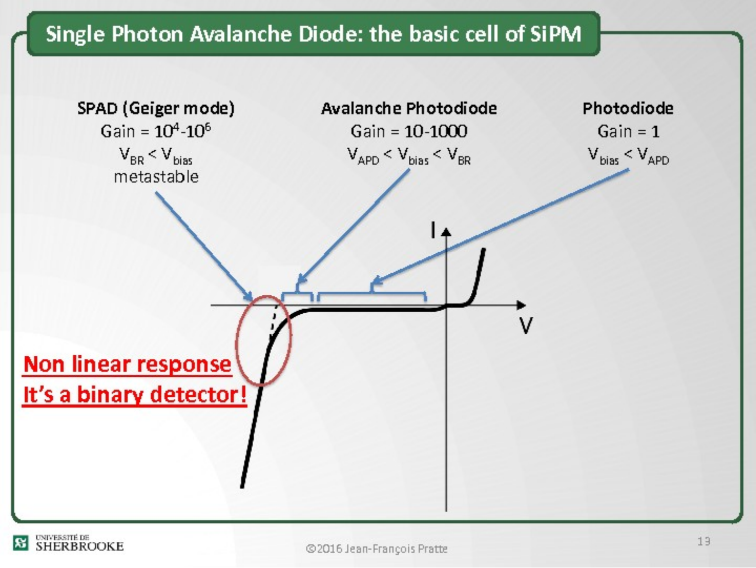
Output:
Set of fired micro cells

Johannes Breuer | SHS DI MI PLM-R&D EU 9
Restricted © Siemens Healthcare GmbH, 2018

“Digital SiPMs” for ARGO

Originally developed for nEXO at U. Sherbrooke

Operate each SPAD at very “high” voltage so that device effectively becomes digital in nature. Get a set of “1”'s or “0”'s from cells instead of analog signal.



Single Photon Avalanche Diode: the basic cell of SiPM

SPAD (Geiger mode)
Gain = 10^4-10^6
$V_{BR} < V_{bias}$
metastable

Avalanche Photodiode
Gain = 10-1000
$V_{APD} < V_{bias} < V_{BR}$

Photodiode
Gain = 1
$V_{bias} < V_{APD}$

Non linear response
It’s a binary detector!

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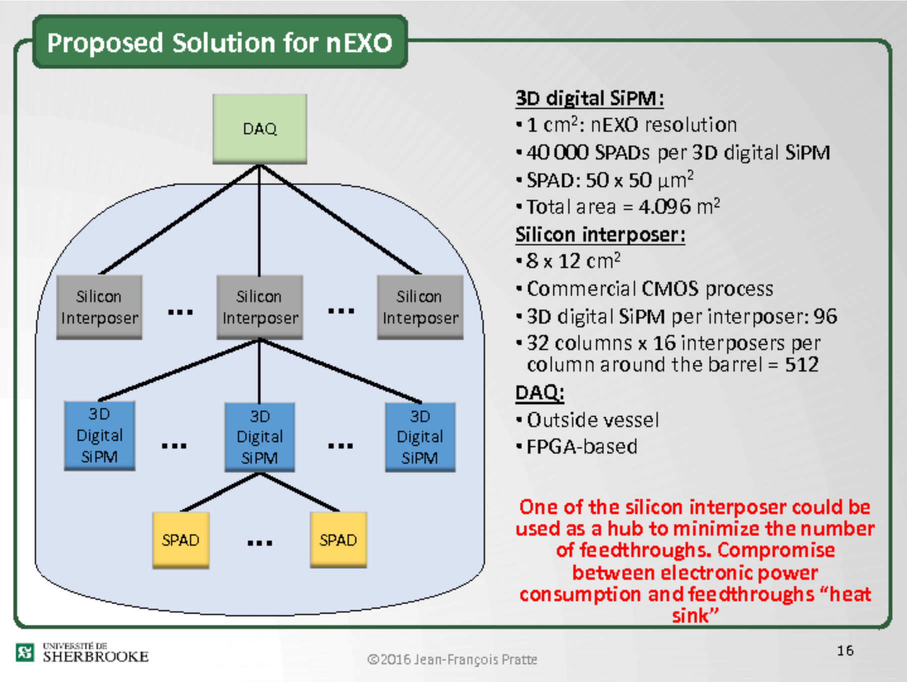
Holy grail is to put everything including digital electronics on 3D tile . This will reduce noise and allow remote control over which cells to turn on and off.



Proposed Solution for nEXO

3D digital SiPM:
- 1 cm^2: nEXO resolution
- 40 000 SPADs per 3D digital SiPM
- SPAD: 50 x 50 μm^2
- Total area = 4.096 m^2

Silicon interposer:
- 8 x 12 cm^2
- Commercial CMOS process
- 3D digital SiPM per interposer: 96
- 32 columns x 16 interposers per column around the barrel = 512

DAQ:
- Outside vessel
- FPGA-based

One of the silicon interposer could be used as a hub to minimize the number of feedthroughs. Compromise between electronic power consumption and feedthroughs “heat sink”

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The End ...