Detection Efficiency, Cross Talk and Afterpulsing in Silicon Photomultipliers

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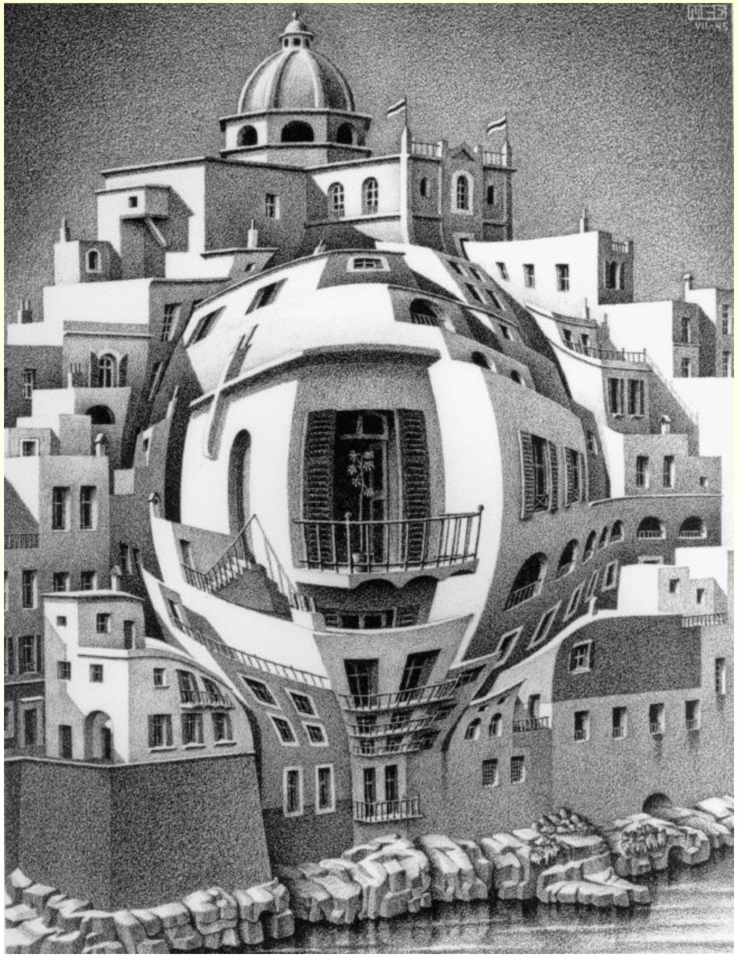
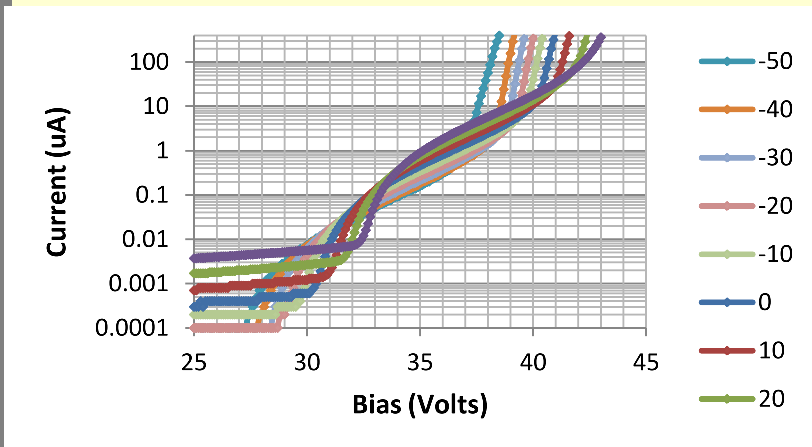
‘Silicon Photomultipliers’ a.k.a. Pixelized Photon Detectors (PPD)

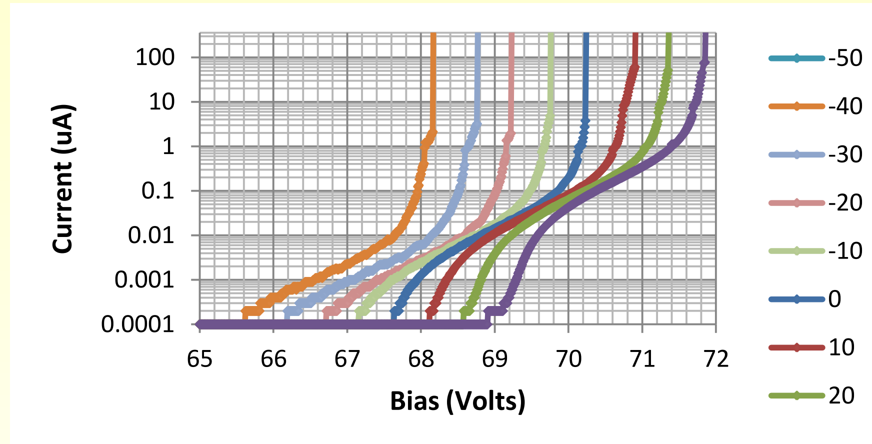
- Novel, very attractive photodetectors:
  - Robust
  - Insensitive to magnetic field
  - Low operating voltage
  - High Detection Efficiency
  - Photon counting, high resolution
- Growing number of vendors, types, formfactors:
  - Which SiPM should I use for my application?
  - What operating condition? How to optimize the operating conditions for a specific measurement?
- For every specific experiment the detailed optimization, calibration and monitoring procedure must be developed
- A general model of operation is necessary for the overall guidance and for the further improvements of the technology

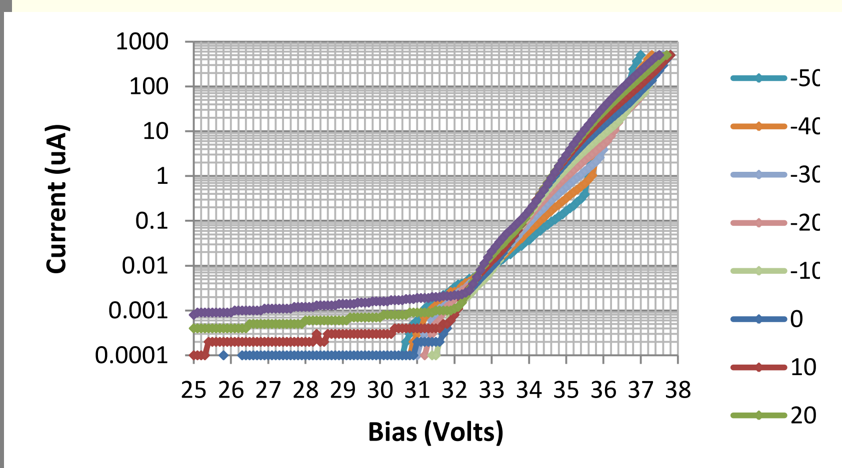
An Unbiased Review of SiPM's

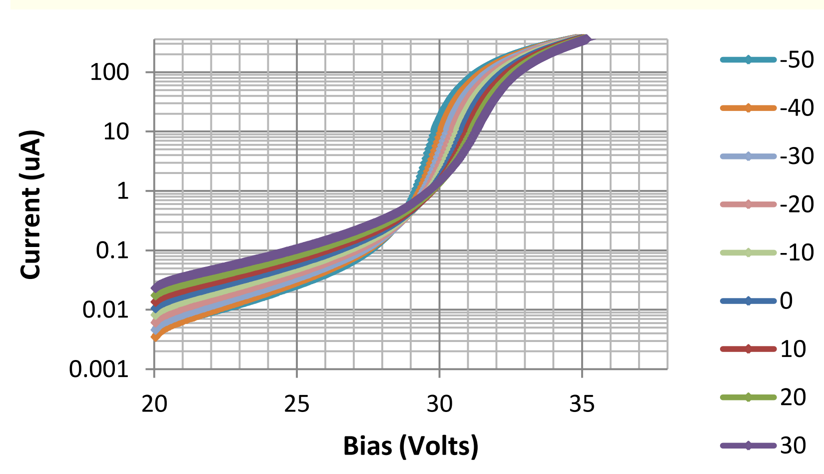


Surprising Variety of SiPM's

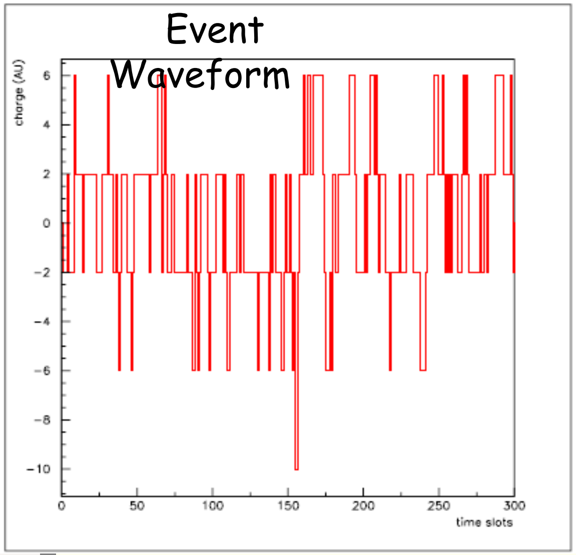


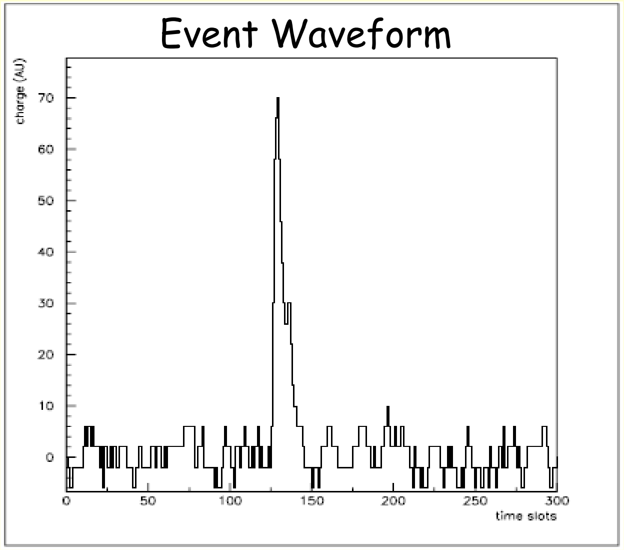


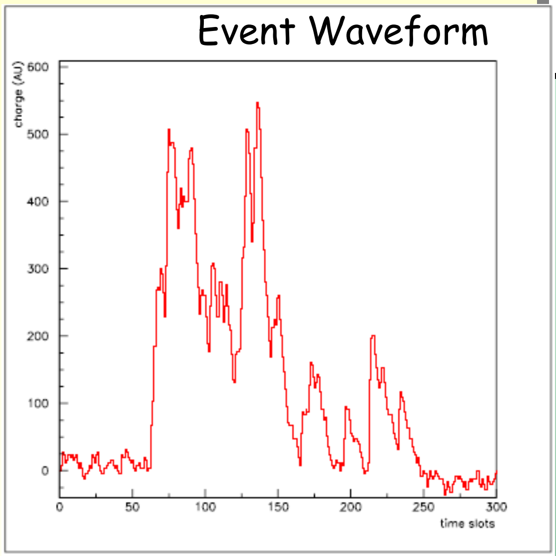




On the Importance of Bias Voltage Optimization







× Too Low Bias Voltage

✓ Optimal Bias Voltage

× Too High Bias Voltage

- These are responses of a SiPM to a single photon signal
- Several hundreds of miliVolts can make a very large difference to the response of the SiPM
- The optimal operating point depends on the experiment in question

Standard Model of the PPD

- There seem to be at least two parameters strongly affecting the response of the PPD to a light signal: temperature and bias voltage
- The principal effect is the variation of the breakdown voltage with temperature. At the fixed overvoltage the dependence of the response with temperature is greatly reduced
- Given an incoming photon:
  - $P_{av}(T,V)$ = probability that an incoming photon will start an avalanche. Amplitude of the single avalanche signal is well defined, but depends on V and T.
  - A random avalanche due to a thermal electron may accompany the photon induced signal at a random time, with probability dependent on temperature and voltage $R_{dark}(T,V)$

Standard Model of the PPD II

- For every produced avalanche (independent of its origin ➔ beware of non-linearities)
  - $P_{ap}(T,V,t-t_0)$ = probability that an avalanche at time t_0 will lead to another avalanche at time t. The amplitude of this avalanche is suppressed by a factor $F_{sup}(t-t_0)$
  - $P_{xtalk}(T,V)$ = probability that an avalanche in a pixel will induce an avalanche in a neighboring pixel (optical cross-talk). This additional avalanche occurs at 'the same' time as the parent avalanche
- In an application where the precise measurement of the light intensity is necessary all these factors: $P_{av}(T,V)$, $R_{dark}(T,V)$, $P_{ap}(T,V,t-t_0)$, $F_{sup}(t-t_0)$, $P_{xtalk}(T,V)$ must be known to model the response of the detector and to interpret the measured signal in terms of the number of photons. The importance of various components depends on the type of the photodetectors.
- Growing number of increasingly detailed models and simulations (Delft, Sherbrook, TRYUMF, Fermilab,…). Need precise data as an input or as a cross-check

Afterpulses vs Cross Talk

- From a perspective of an end-user almost no difference: an apparent increase of the single photon signal at the expense of additional fluctuations ➔ Excess Noise Factor, non-Poissonian fluctuations
- Fundamental difference: cross talk pulse originates in a cell different that the one where the primary photon is detected, whereas the afterpulse occurs in the same cell. Requires spatial information to disentangle (CCD camera or digital SiPM)
- Operational difference: cross talk occurs at the same time as the primary pulse (photon mediated), afterpulse occurs with some delay. (Some component of cross-talk can be misclassified as afterpulses)
- Without the spatial or temporal (waveforms) information the measurements of cross talk and afterpulses are often entangled

Temperature!

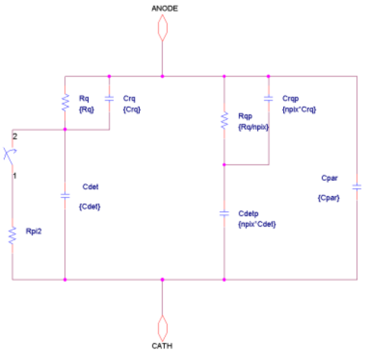
- Behaviour of the SiPM's is a convolution of many effects (PDE, dark rate, afterpulses, recharge,..) It is usually very difficult to provide a reliable measurement of a single factor/function
- Many of these effects are strong functions of the operating temperature ➔ temperature scan provides a strong constraint, or allows to eliminate some effects from the measurement (like dark rate)
- Cryogenic application (Liquid Argon?) require good understanding of the behavior of these detectors at the intended temperatures

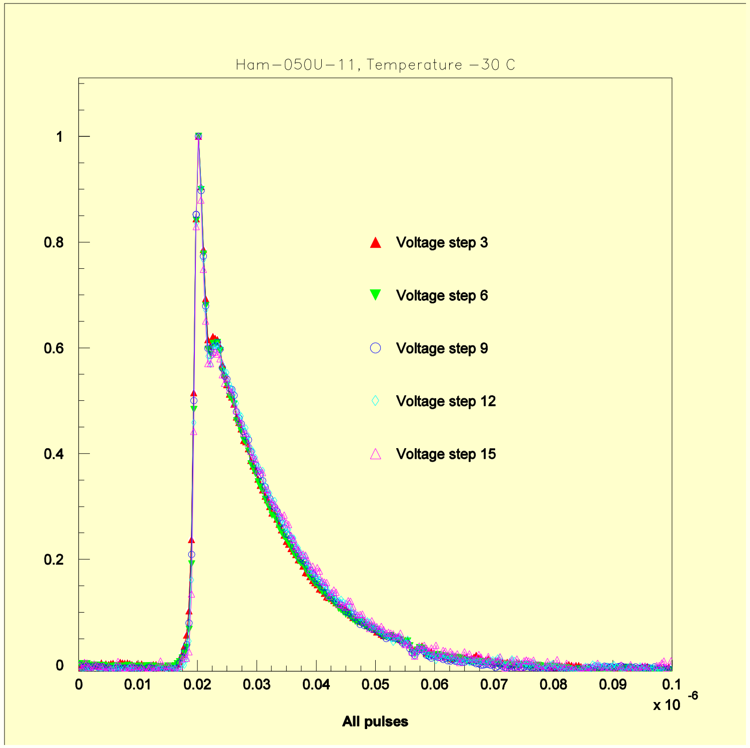
NOTE: most of the results shown will be for Hamamatsu MPPC's

- You have to start 'somewhere'
- They have the shortest range of operating conditions, it may be interesting to understand why

Pulse shapes of the SiPM

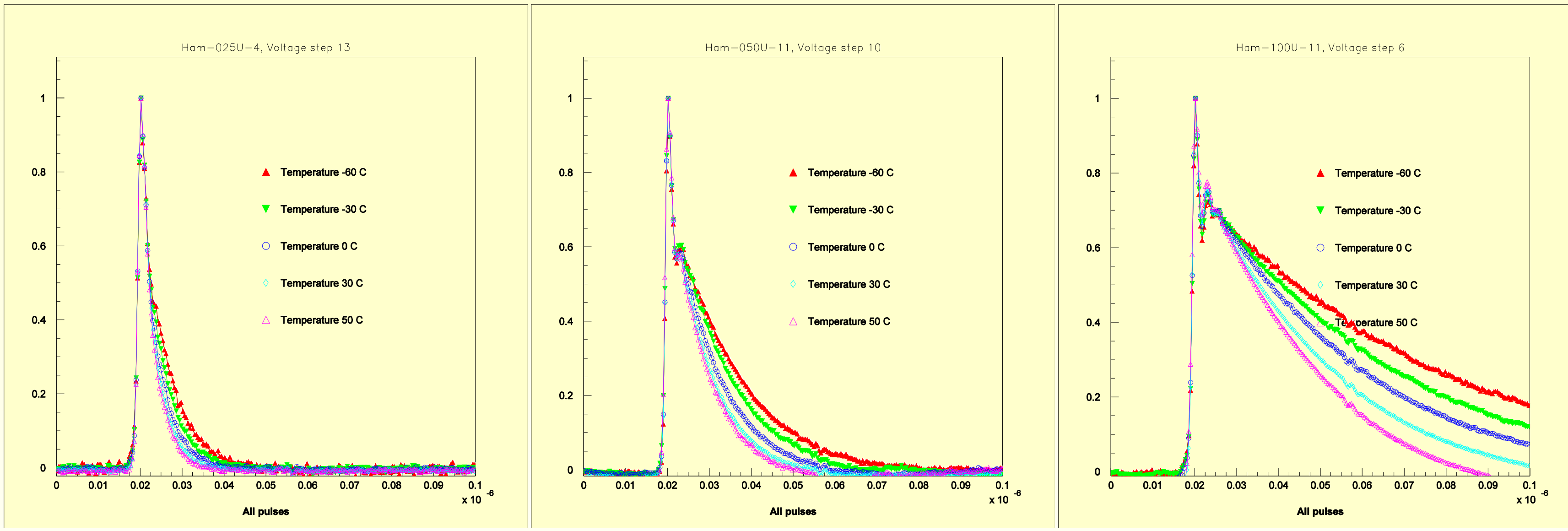
- Observed pulse shape depends on the detector: capacitances and resistances. It also depends on the readout electronics.
- Two components: fast (capacitive) and slow (resistive)
- Pulse shape identical for dark pulses and for photon induced pulses
- Pulse shapes independent of the bias voltage (once single avalanche pulses are selected)





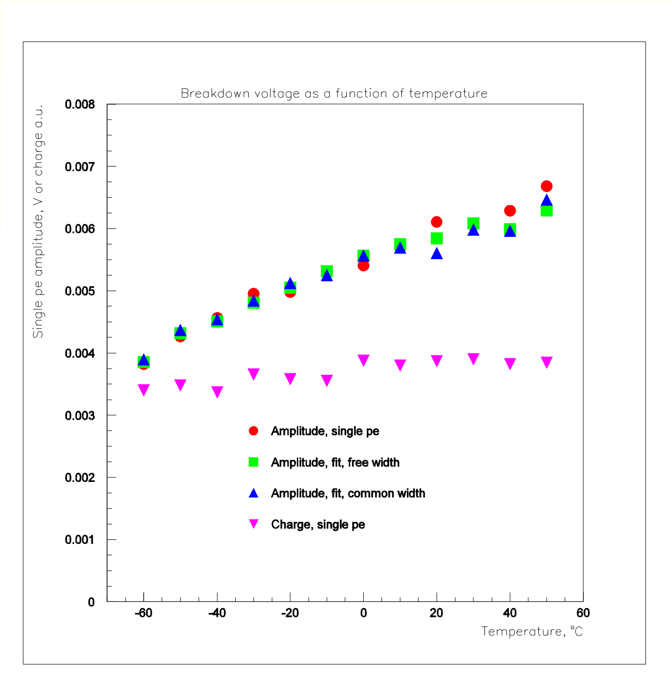
Hamamatsu, 1x1 mm detector, 50 micron pixels

Pulse Shapes II



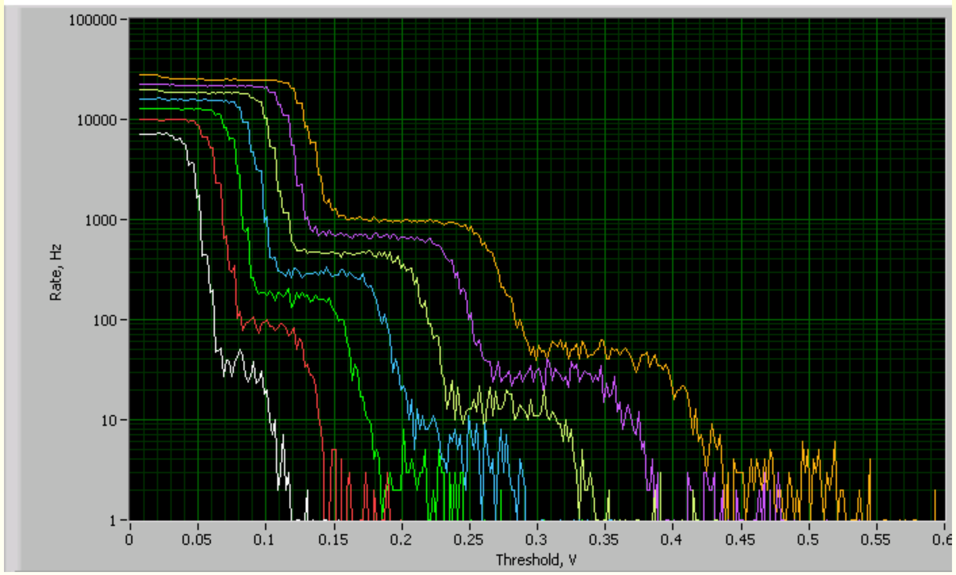
- Pulse shapes (slow component) depends on the RC of the detector:
  - different for 25, 50 and 100 micron detectors
  - changes with temperature
  - division on the total charge between slow and fast components changes with temperature: height of a single avalanche pulse depends on the temperature (at fixed overvoltage)

'Single pe' as a Function of Temperature



- 'Single pe' is often used to define 'gain' of the device.
- 'single pe' defined for a measurement related to a total charge of a single avalanche signal is nearly independent on the temperature
- 'single pe' defined via the amplitude of the signal depends strongly on the temperature
- the difference between these two measures reflects the variation of the actual shape of the signal, due to the variation of the value of quenching resistance.

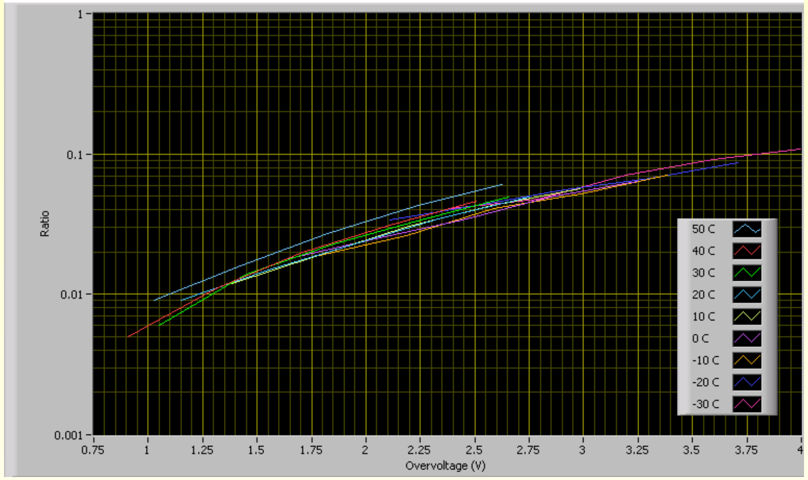
Cross Talk Measurement



- Given the dark current rates, the rate of accidental coincidences of two thermally-induced avalanches is very low
- The primary source of pulses with double (tripple) height is the optical cross talk from the primary avalanche
- The ratio of rates of double-to-single avalanche pulses is a direct measurement of cross-talk probability at a given bias voltage and temperature.

Puzzle: probability of 1→2, 2→3, 3→4 cross talks is nearly the same, How could that be? What does it tell us??

Cross-talk Probabilities

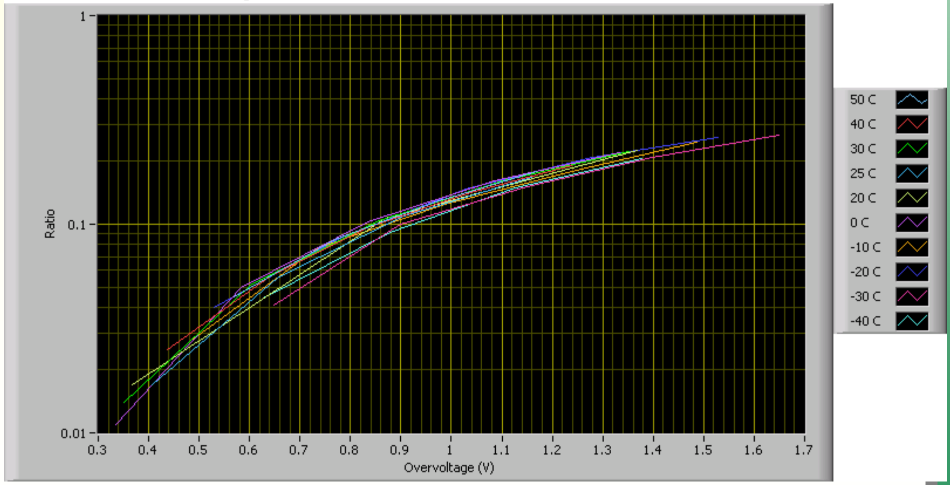


25 μ devices: cross talk in the range of few percent, at typical operating conditions

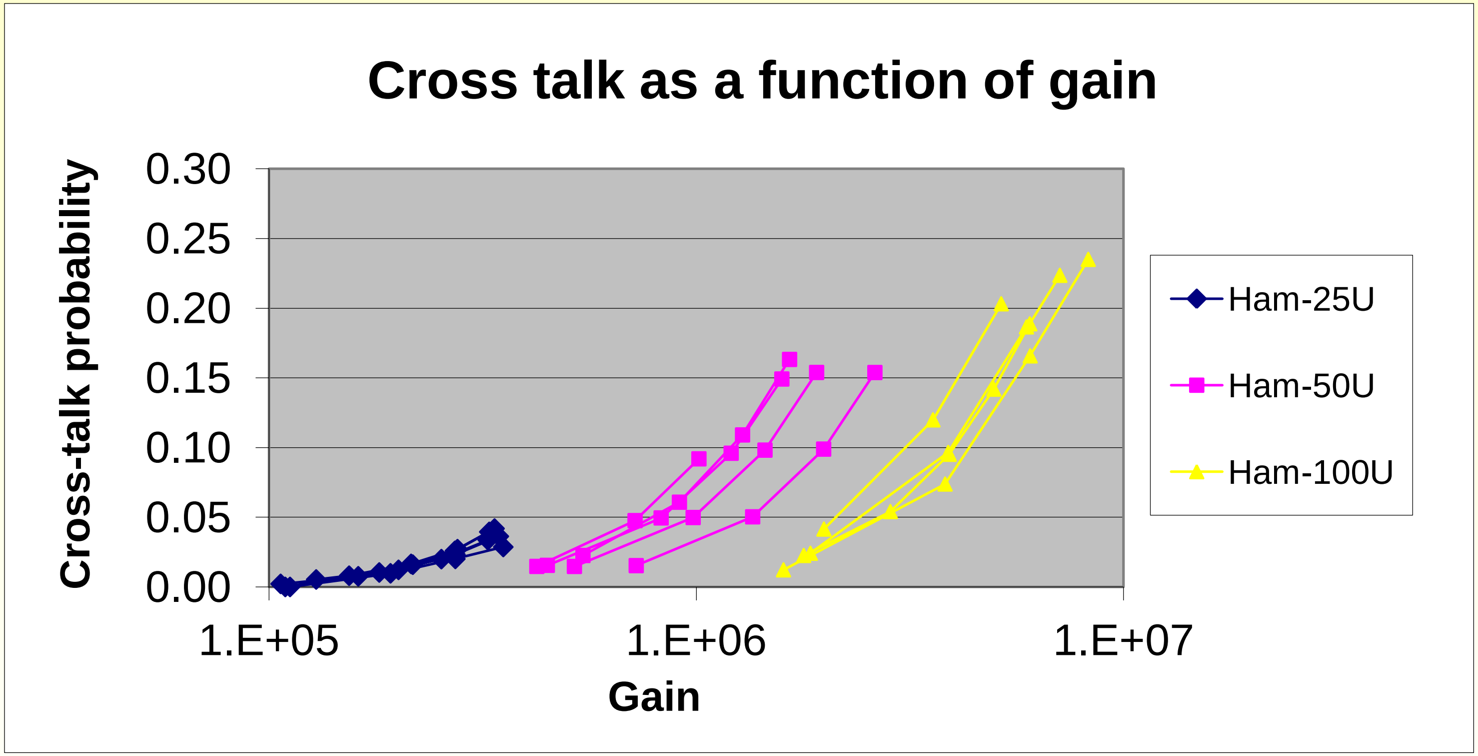
100 μ devices: cross talk at the level of 10-20% for ~ 1 V overvoltage.

Cross-talk probability does not depend on operating temperature of the device.

Crosstalk Probability - Ham-100u_9



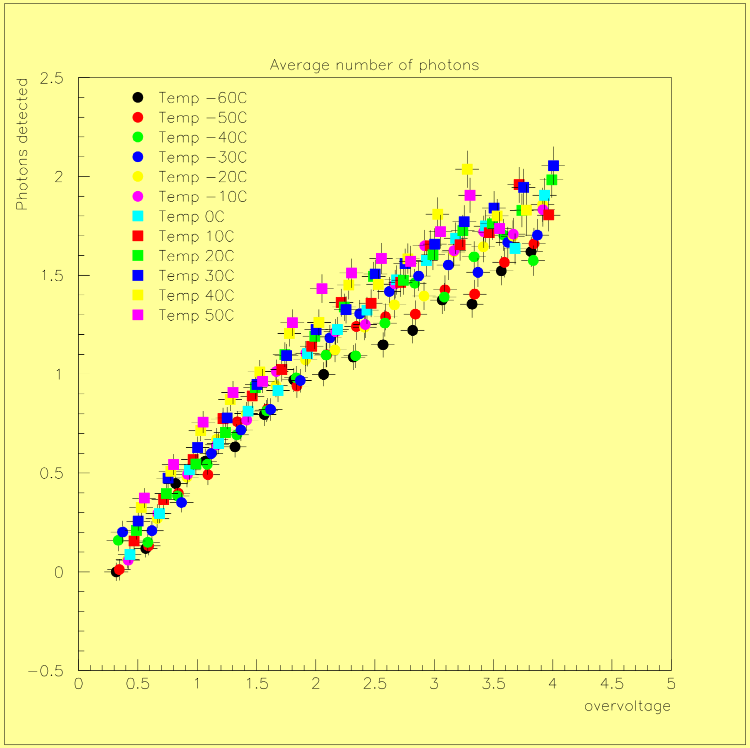
Cell Geometry and Cross Talk



- At the same gain the cross-talk probability is much larger for smaller size pixels
- At the operating point the Hamamatsu detectors have very small cross talk (~few %)

Detection Efficiency

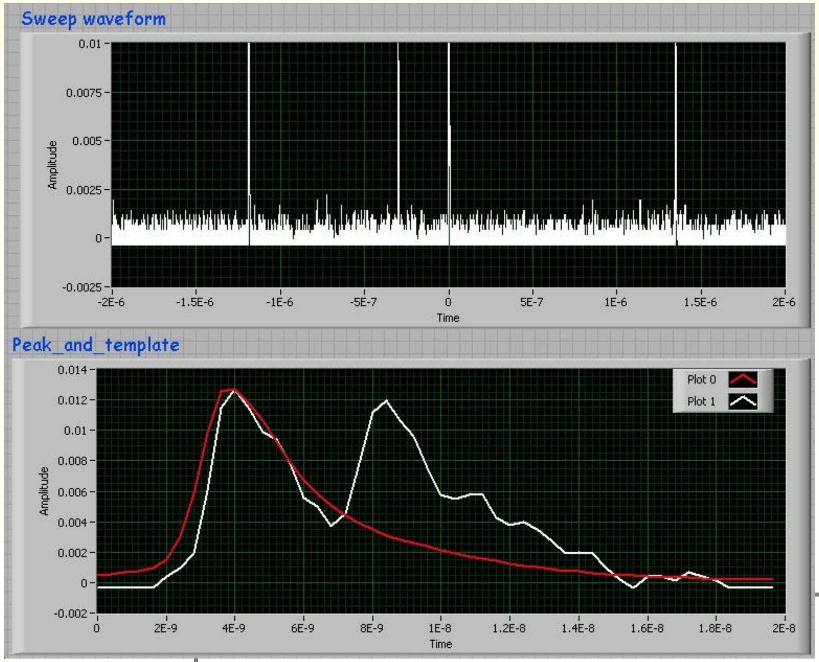
- PDE = Geometry (fill factor) x Quantum Efficiency (wavelength) x Geiger probability



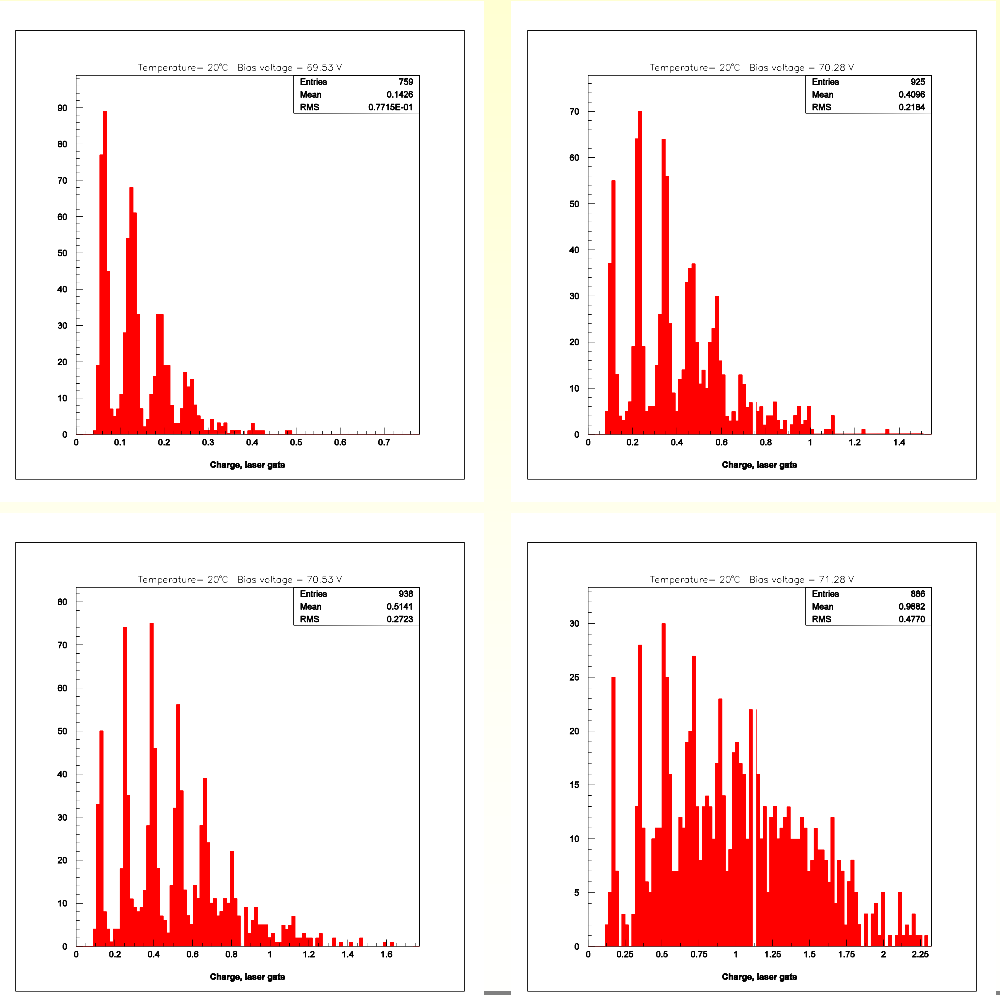
- Absolute detection efficiency is difficult to measure (coming, though)
- detection efficiency is often mis-measured because of afterpulses and cross-talk
- Detection efficiency varies strongly with bias voltage/overvoltage (Hamamatsu 1x1 mm, 25 micron shown here)
- At fixed overvoltage there is a residual dependence of the detection efficiency on the temperature
- at the typical operating voltage the PDE much smaller than the 'maximal' one

Waveform Analysis

- Acquire the complete waveform (triggered by external laser trigger or by a dark pulse) with ~ 2μsec pre-trigger gate
- Store waveform for off-line analysis
- Decompose the waveform in terms of the sequence of the 'standard pulses: WF = $\{N_{pulses}, A_i, t_i\}$



Bias Voltage Dependence of the Response

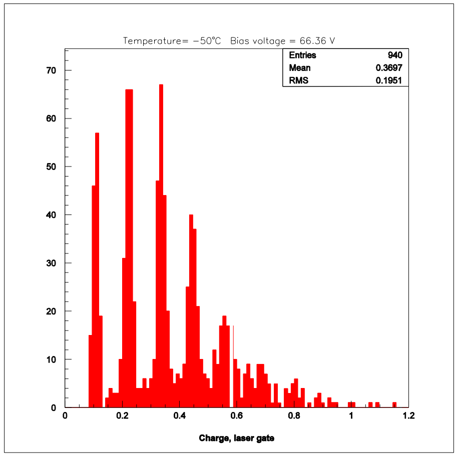


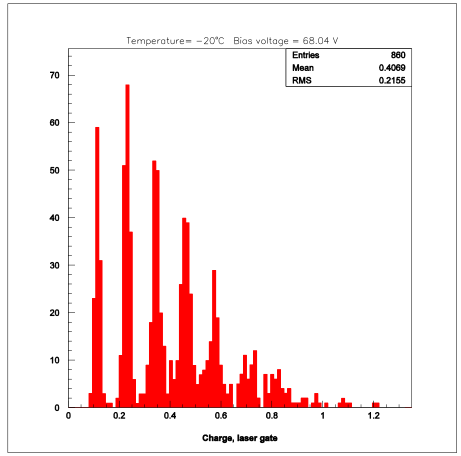
- Response (charge within 100 ns gate) of the detector (25 micron) at T=20C to the laser light with the bias voltage increasing within the range of 1.75 V
- Huge variation of the response

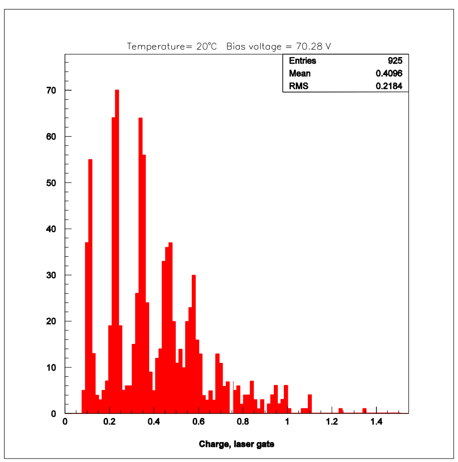
The same laser light intensity!

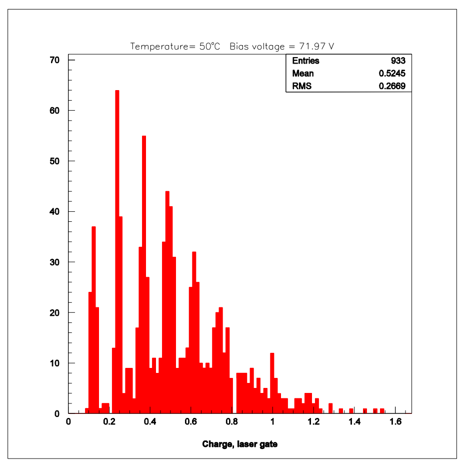
Need a calibration prescription to yield the same measurement in all cases

Temperature Dependence of the Response at Fixed Overvoltage



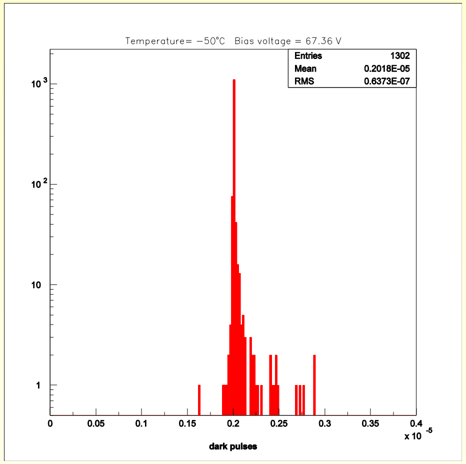


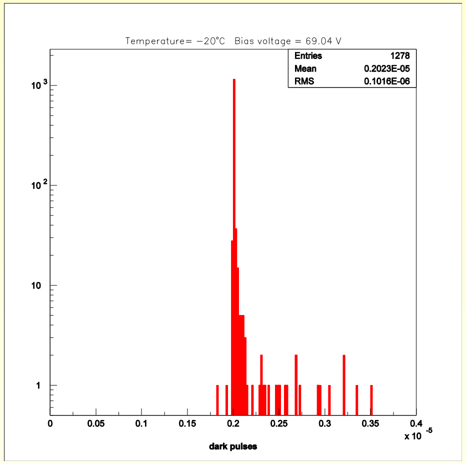


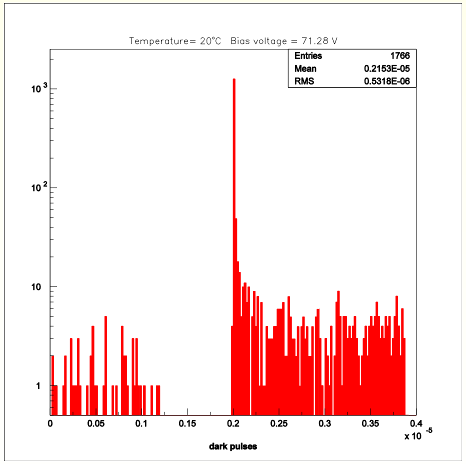


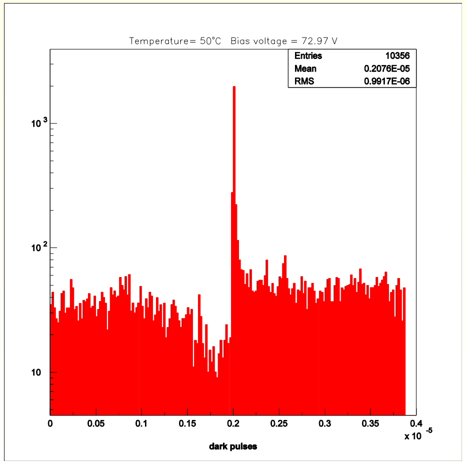
- Response of the detector at -50C, -20C, 20C and 50C to the laser pulse. Detector biased at the same nominal overvoltage.
- Some increase of the response with temperature is observed: indication of the variation of the Geiger probability

Dark Pulses as a Function of Temperature



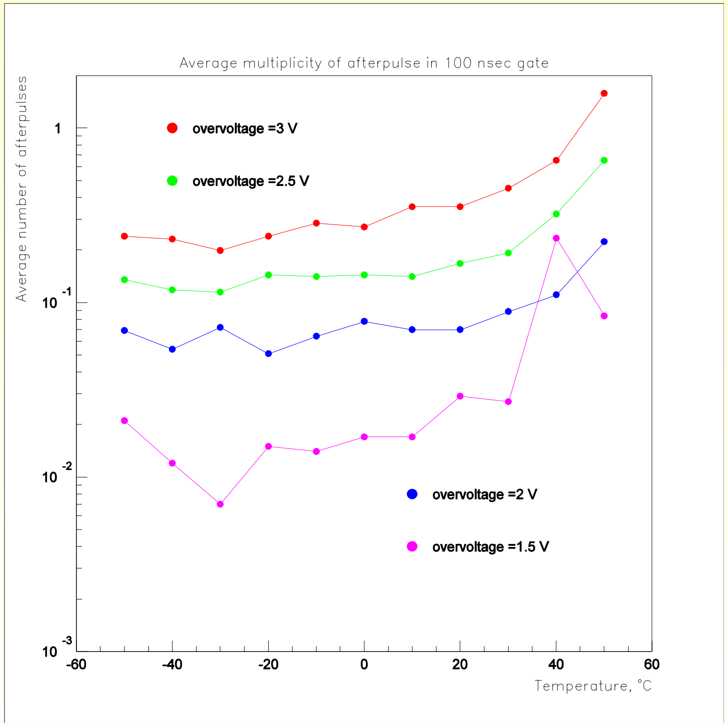






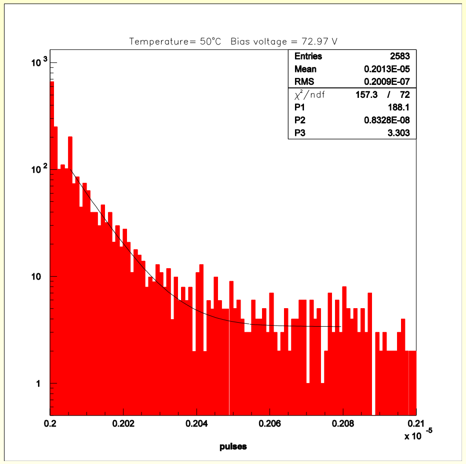
- Record traces triggered on dark pulses (0.3 pe level) at different temperatures and bias voltages
- Shown here: -50C, -20C, 20C and 50C at 3V overvoltage
- Evidence for significant afterpulsing, increasing with temperature

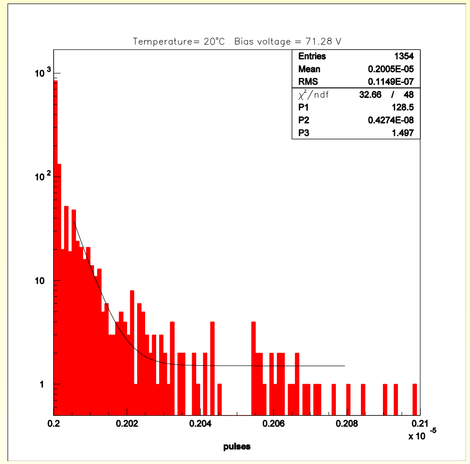
Afterpulsing Probability as a Function of Voltage and Temperature

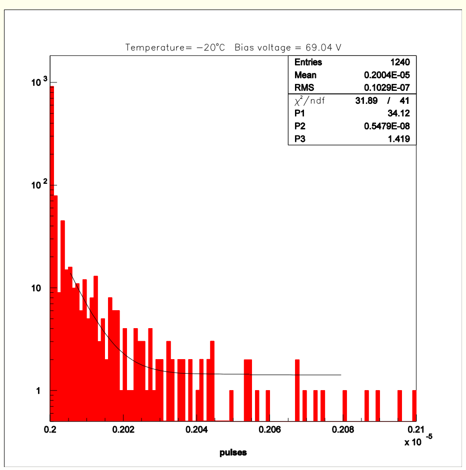


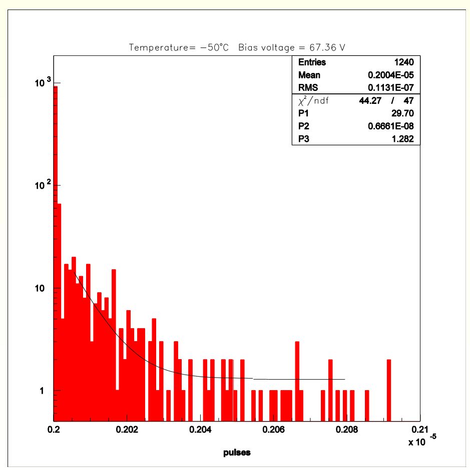
- Total rate of afterpulses may be converted to a multiplicity of afterpulses per a parent avalanche
- Afterpulsing probability increases very strongly with the bias voltage and with temperature

Afterpulses within 100 nsec gate



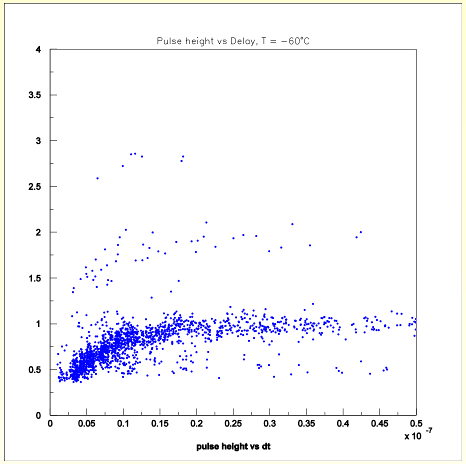


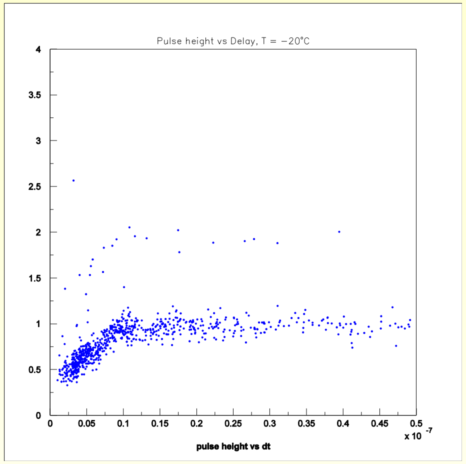


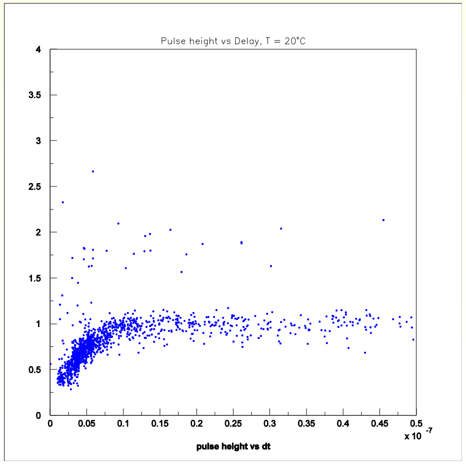


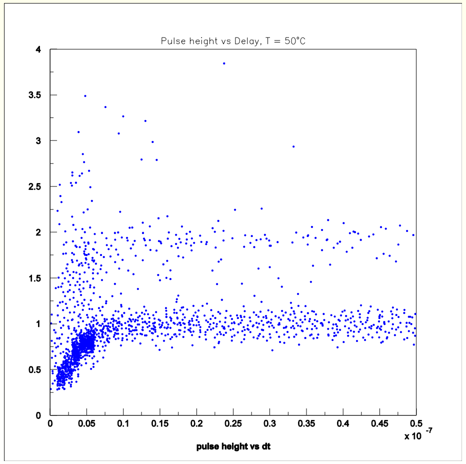
- Studies limited by statistics (DAQ rate of the scope)
- Data at different bias voltages summed at fixed temperature
- Decay time fit at different temperatures: gives the time constant and the overall rate
- dominant time constant is of the order of 5 -10 nsec
- Examples shown here: -50C, -20C, 20C, 50C

Amplitude of Afterpulses









- Amplitude of a pulse is shown as a function of time since the previous pulse
- Examples of data shown at different temperatures
- Clear evidence of the reduction of the pulse height during the pixel recovery time
- Recovery time varies with temperature (as the result of the variation of the value of quenching resistor)

Summary

- TheSiPM's are coming of age. They are interesting devices but they have little to do with photomultipliers. In fact they are silicon implementations of RPC's.
- Afterpulsing is a major detrimental factor afecting the precision of the measurement.
- It is a principal origin of a strong sensitivity of the SiPM's on the bias voltage
- Its importance depends on the specific design: shorter the recovery time more serious the afterpulsing is.
- The principal advantage of 'digital SiPMs' is the active quenching circuitry which eliminates the afterpulsing.