Characterization of Silicon Photodetectors (Avalanche Photodiodes in Geiger Mode) at Fermilab

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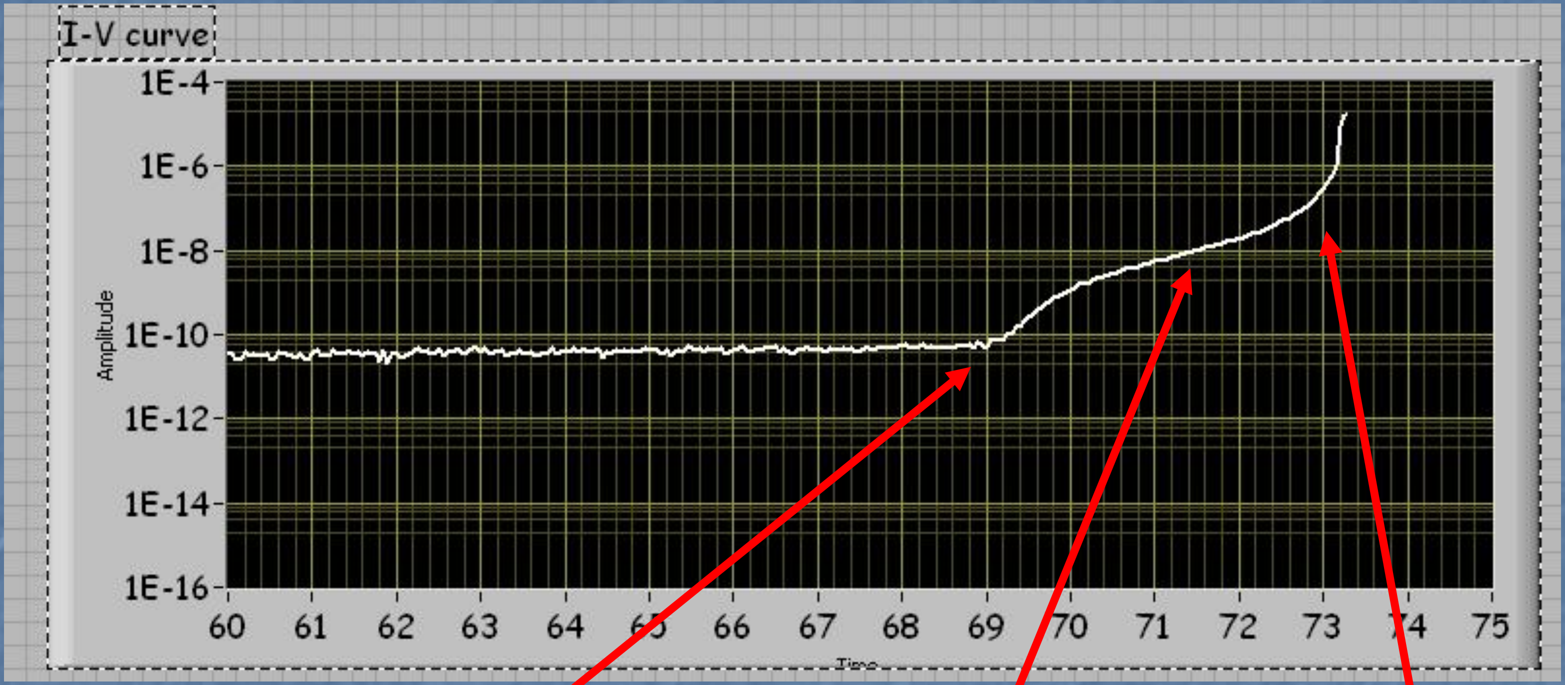
Motivation and Goals

- Develop a complete characteristics of the detector response to the external light signal
  - As a function of the light source characteristics (intensity, duration, time structure)
  - As a function of the operating conditions (voltage, temperature)
  - light impact point onto the detector (inter/intrapixel uniformity)
- Develop algorithm for readout strategy and calibration procedure (integration time, cross-talk, after-pulses treatment, etc..)
- Determine the electrical characteristics of the detectors as an input to the dedicated readout ASIC
- Studies of Hamamatsu 025, 050 and 100 detectors

Step 1: Database of Static Characteristics

- Develop an automated procedure for static characterization (breakdown voltage, resistance) as a function of the operating temperature
  - Keithley 2400 source-meter
  - Dark box
  - Peltier cold plate
  - Labview controls/readout
- Create a database of the samples, enter the static and image data

What does the IV plot tell us?



Break-down voltage of the detector

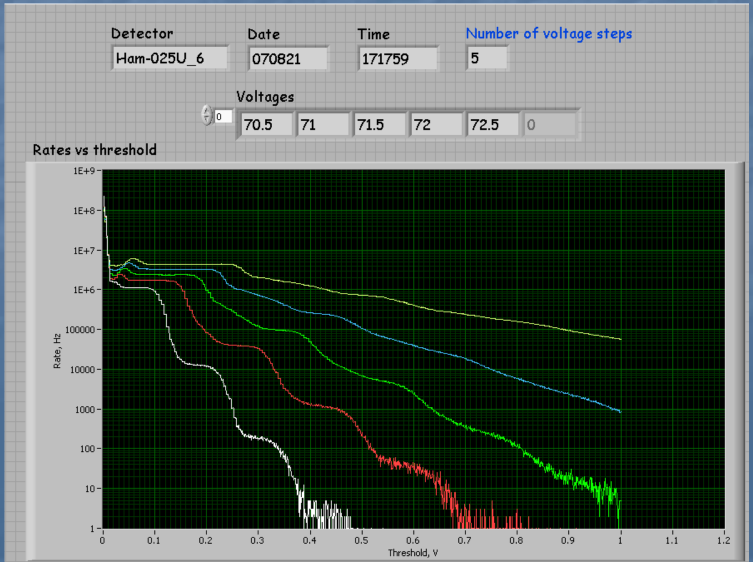
Increase of gain x (mostly) increase of afterpulsing

Afterpulsing probability ~ 1, run-away

I-V characteristics as (one of the) tool for the detector acceptance?

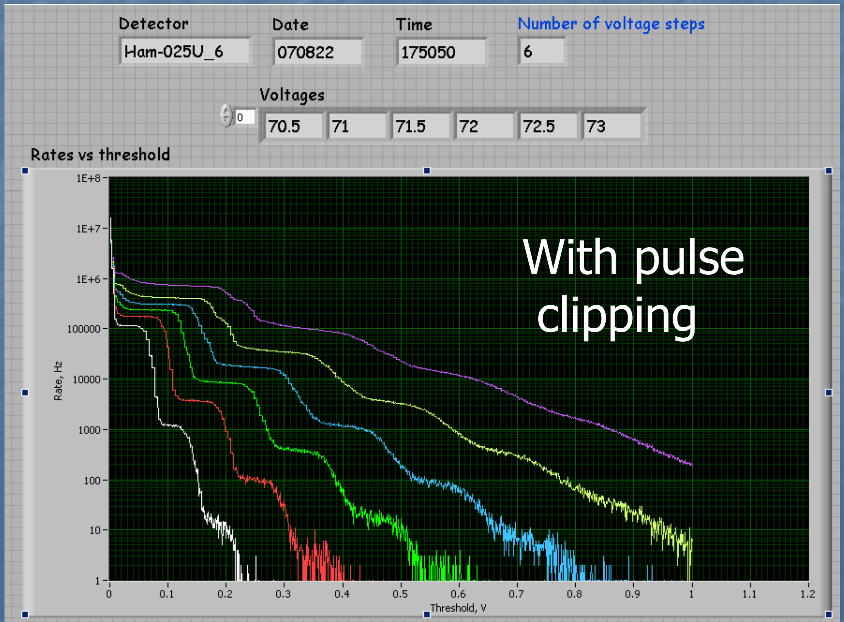
Step 2: Determine Rates and Spectrum of 'Dark Pulses'

- At different bias voltages
- Vary the trigger threshold
- Count pulses
- Clip pulses with ~5 nsec clipping cable to reduce the afterpulsing effect



Detector: Ham-025U_6
Date: 070821
Time: 171759
Number of voltage steps: 5
Voltages: 0 | 70.5 | 71 | 71.5 | 72 | 72.5 | 0

Rates vs threshold



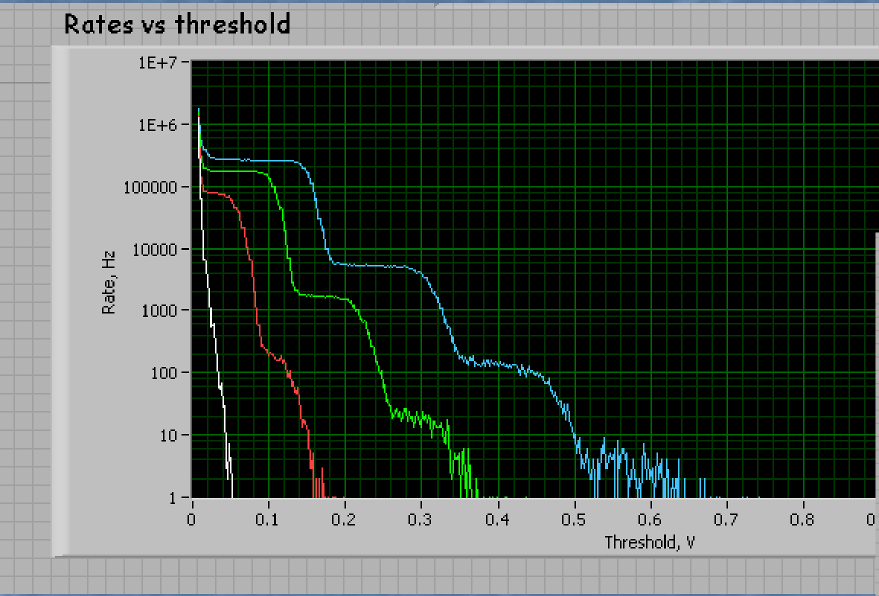
Detector: Ham-025U_6
Date: 070822
Time: 175050
Number of voltage steps: 6
Voltages: 0 | 70.5 | 71 | 71.5 | 72 | 72.5 | 73

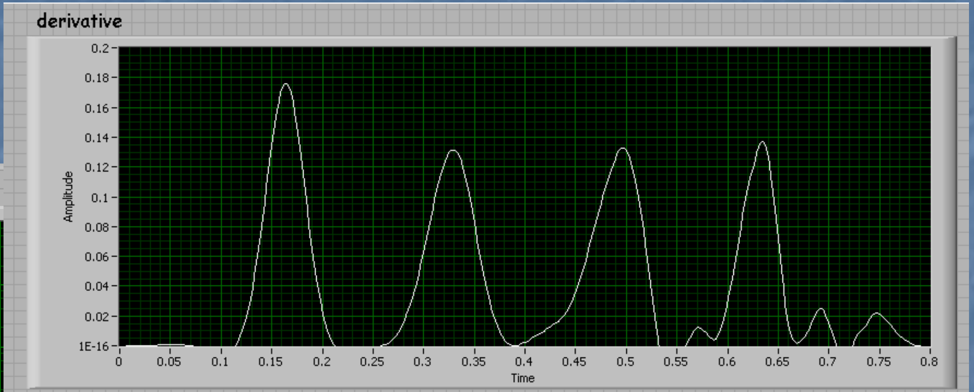
Rates vs threshold

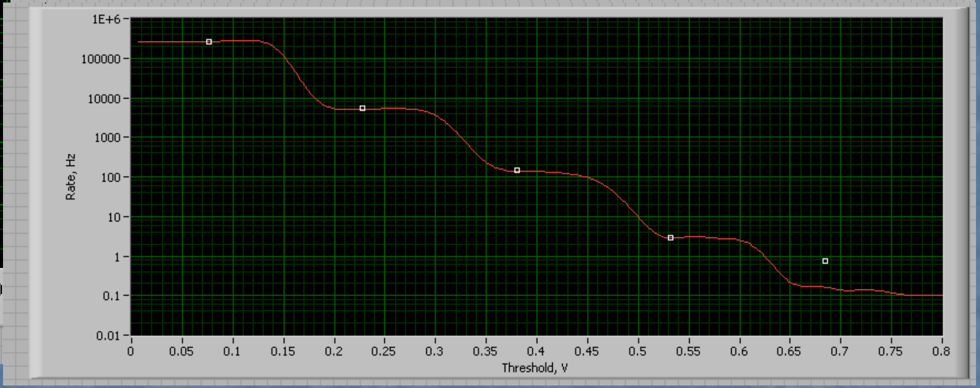
With pulse clipping

Dark Pulses: Rates and Spectra at Different Bias Voltages (Room Temperature)

Differentiate ➔ pulse height spectrum





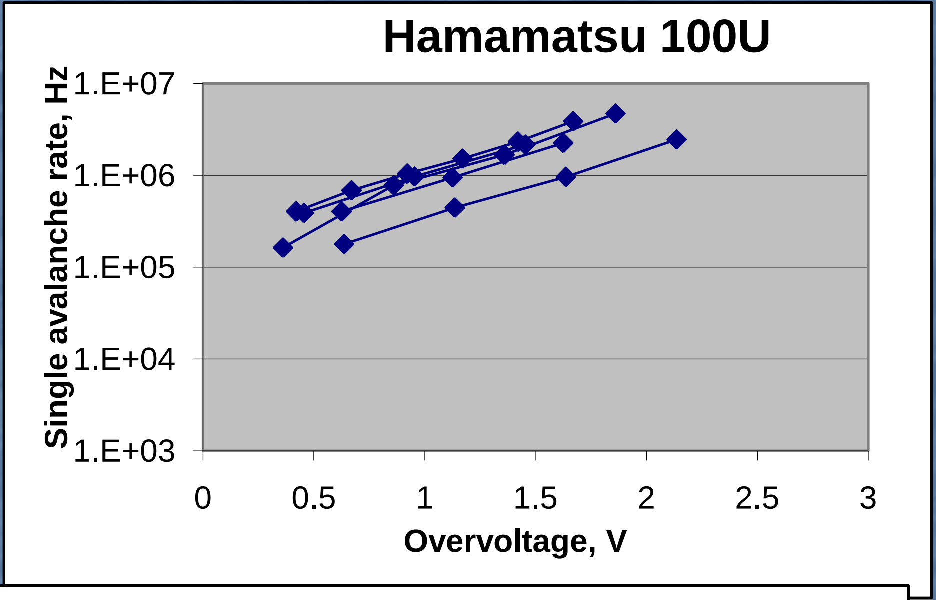


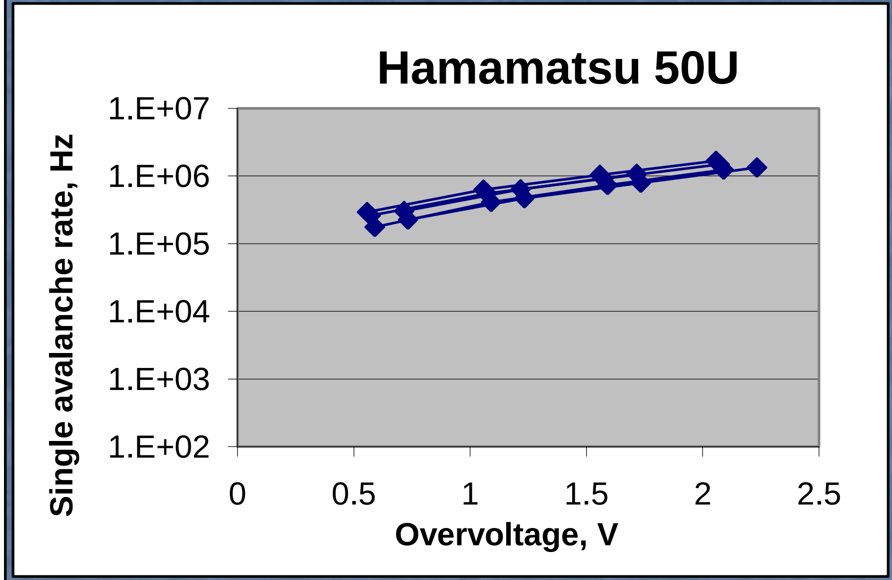
- Define 1,2,3,4 ‘pe’ rate ad a rate at 0.5, 1.5, 2.5, 3.5 of a single peak height

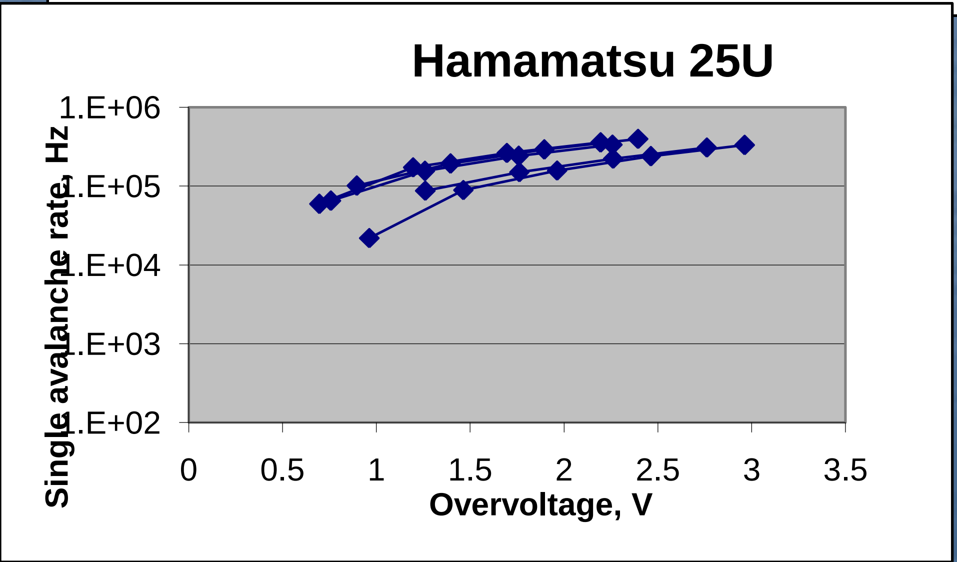
- Note: this is ‘pe’ are not really photoelectrons. No light is present

- 2,3,4 ‘pe’ pulses are the results of cross-talk: A single avalanche set by a thermal electron sets off an avalanche(s) in neighboring pixel(s)

Dark Pulses Rates as a Function of Bias (Over)Voltage

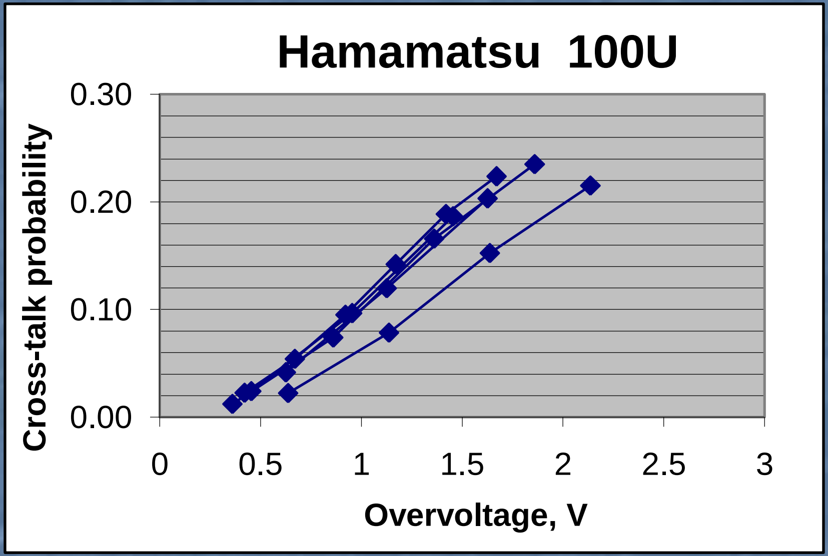


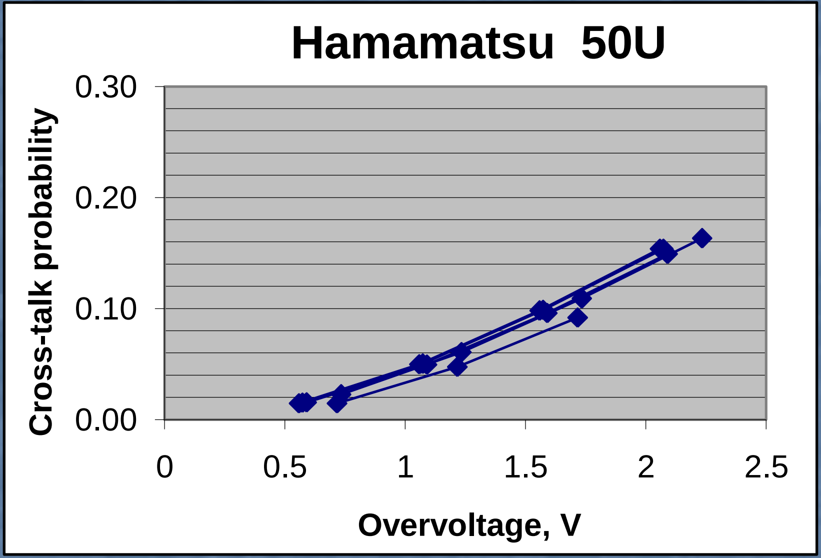


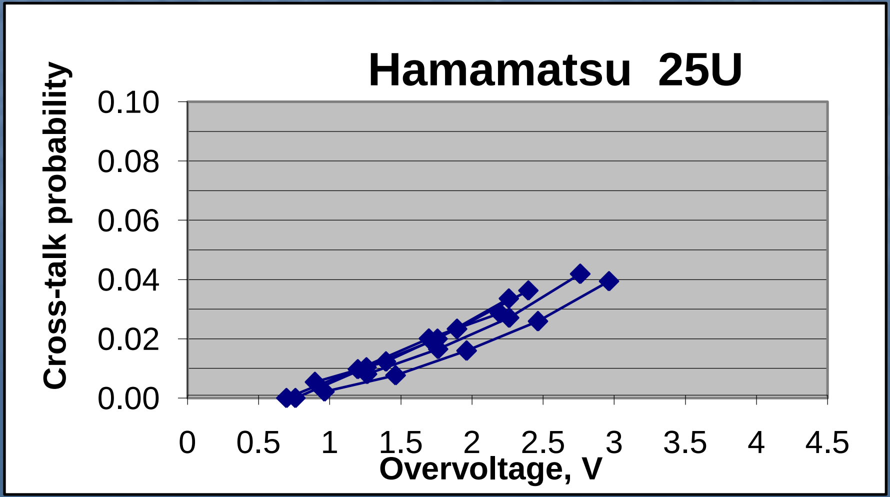


- Dark pulses rate grow ~ exponentially with overvoltage
- At the same overvoltage: R(100)~ 3xR(50) ~ 9xR(25)

Cross Talk Rates as a Function of Bias Voltage



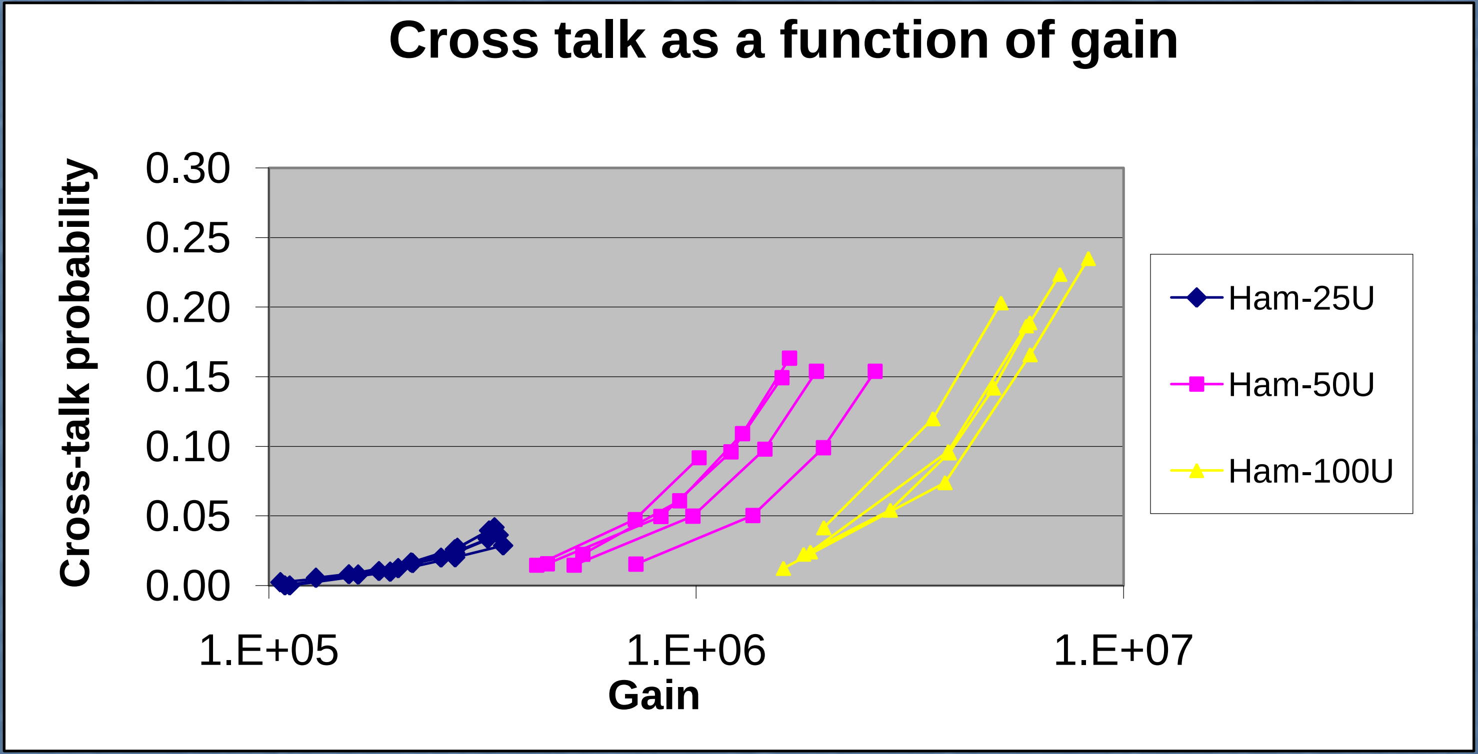




- Cross talk probability increases with the bias voltage
- Cross talk probability is bigger for larger sixe pixels

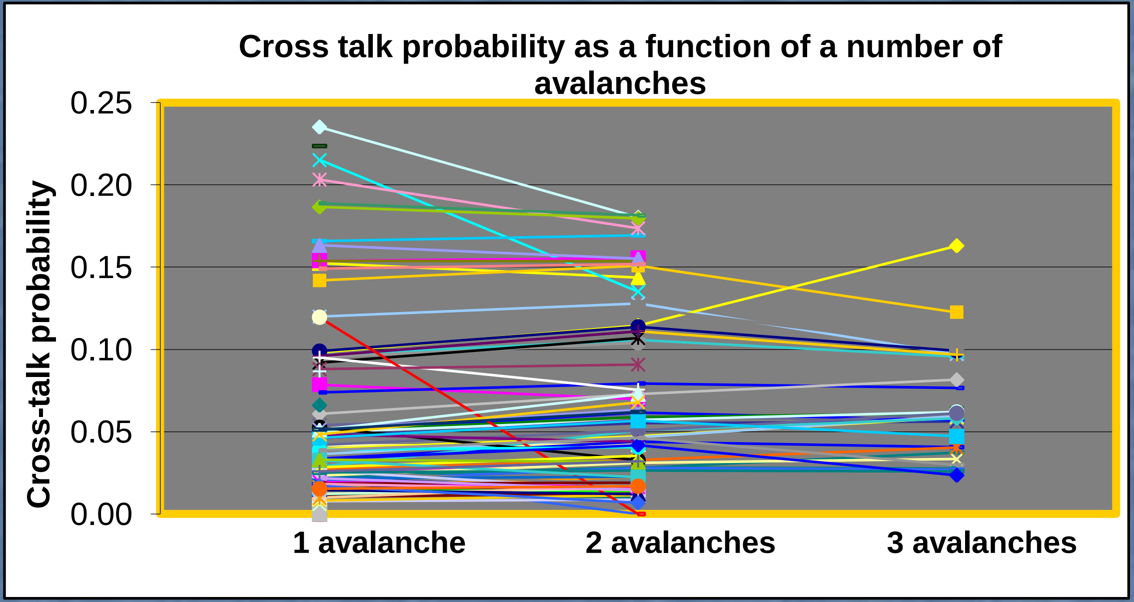
But… The cross talk is mediated by infrared photons produced in the avalanche, hence is ought to be proportional to the gain. And different size pixel detectors have different gain !

Cross Talk Probability as a Function of Gain



- 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 %)

Cross-talk Probability as a Function of Avalanches

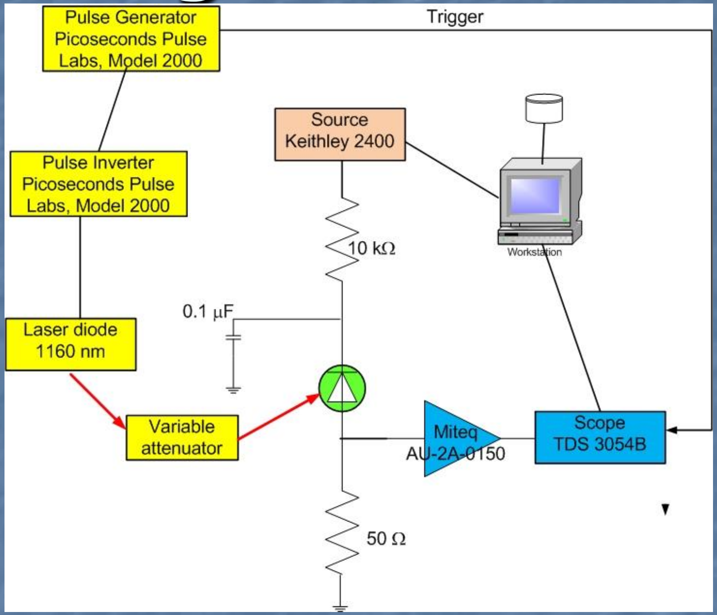


Naïve expectations:

- with two avalanches present the number of photons is doubled, hence the cross talk probability ought to be higher
- Ditto for three avalanches present

Naïve model doesn't hold: some conspiracy between the solid angle and the photons mean free path??

Step 3: Characterization of the Detector Response to a Light Pulse



- Light source:
  - Short pulse duration (<1 nsec)
  - Variable light intensity
  - Absolute light calibration

- Readout strategy:
  - Trans-impedance amplifier

    (MITEQ amplifiers: AU-2A-0159, AU-4A-0150, AM-4A-000110)
  - Tektronix 3054B digital scope
  - LabView DAQ and analysis program
  - Root-based analysis environment
- Most of the results shown for Hamamatsu 025U detector

Snapshot of Several Regimes at the Same Time

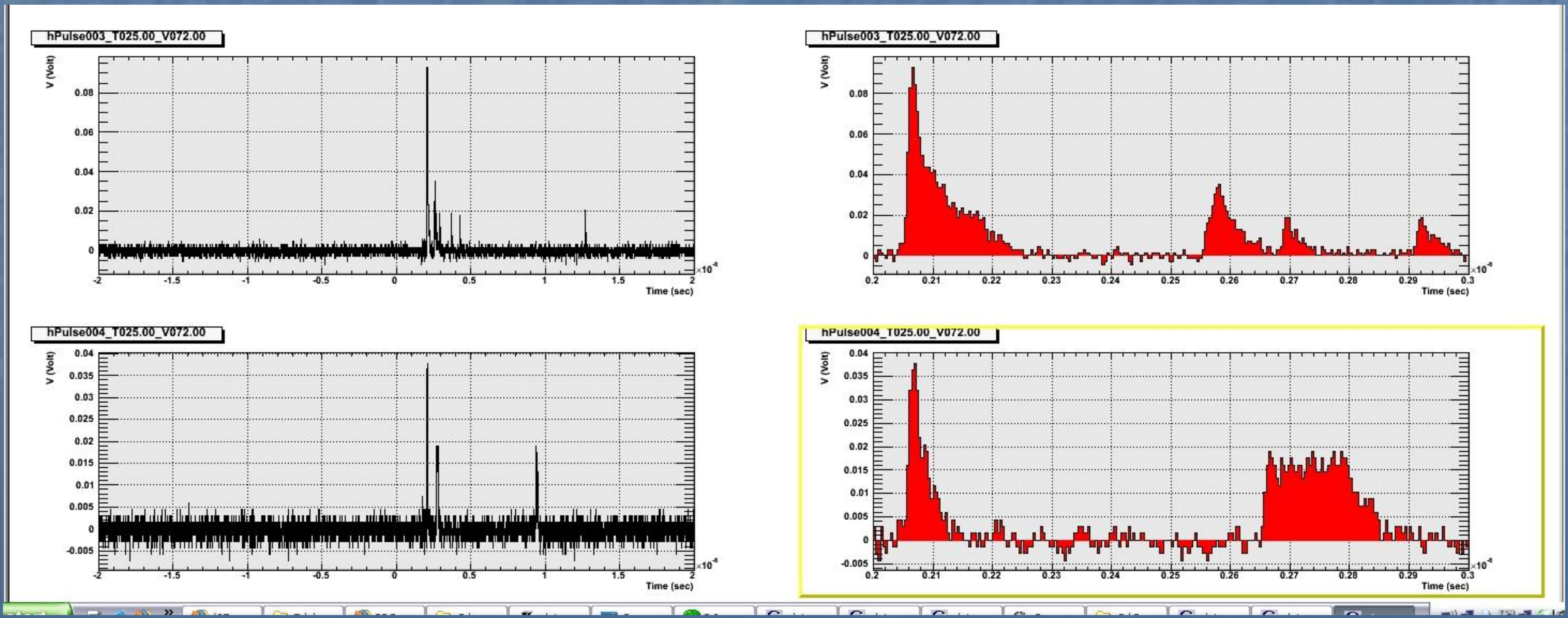
- Acquire 4 μsec long waveform with laser pulse positioned in the middle
- -2.0 – 0 μsec: 'quiet state' of the MPPC:
  - Dark rate
  - Gain
  - Cross talk, afterpulses
- 'Laser gate':
  - Response to the light input
  - Cross talk
  - Afterpulses
- 'Post laser gate'
  - Afterpulsing, recovery

Examples: 72.0 V

Full trace (4 μsec)

Laser pulse

100 nsec gate after laser pulse



Salient Features: Detector Instabilities

- Often called cross-talk, afterpulsing, etc.
- These instabilities determine the nature of the response of the detector in a manner which depends on the temporal characteristic of the measured light and/or on the characteristics of the read-out electronics
- It is very important to understand their origin and to reduce their incidence
- Why bother? These additional pulses effectively provide additional 'gain'. Yes, but this extra gain fluctuates → excess noise factor.

(Naïve Understanding) of Two Popular Models

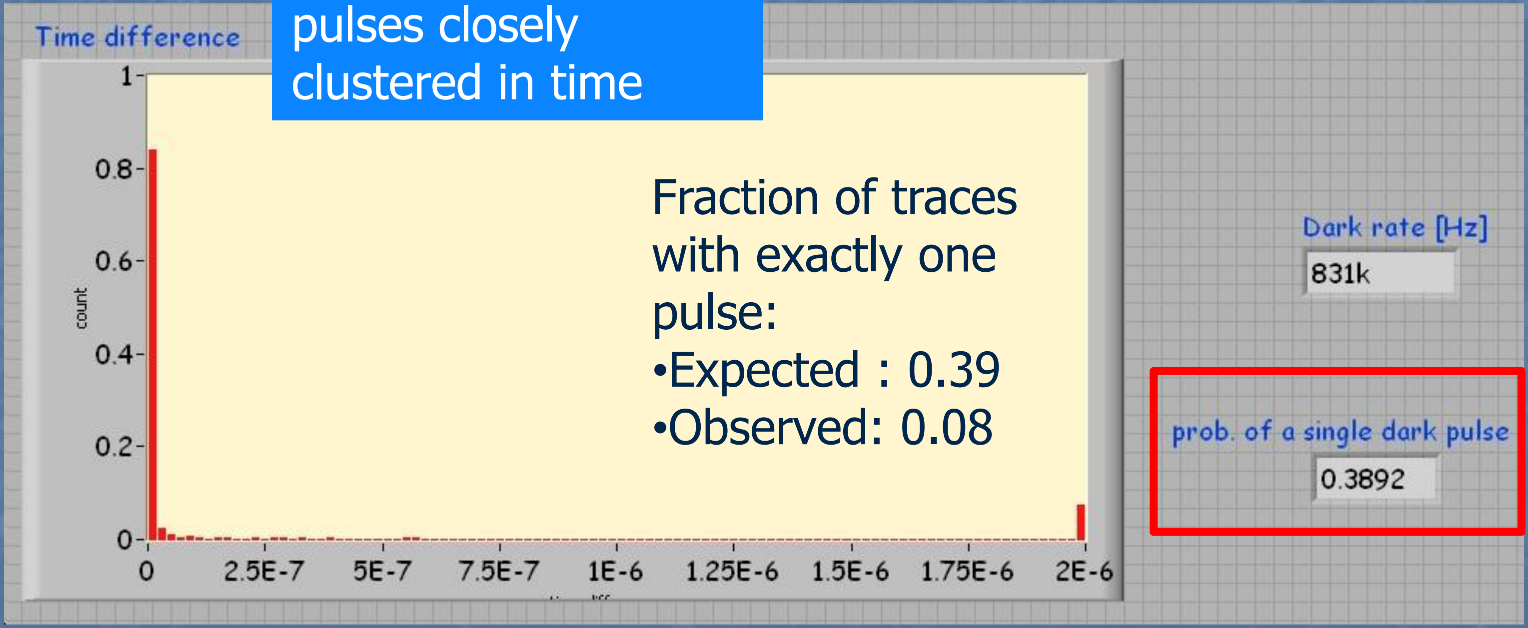
- Photon-mediated cross talk: Infrared photons created in the avalanche initiate a response in the neighboring pixels.
  - Remedy: trenches for optical isolation
  - Naïve expectation this cross-talk will be 'in-time' with the original signal. This is a very small effect (as shown)
- Carriers produced in the avalanche trapped in traps. Traps have finite lifetime and release electrons which create subsequent avalanches.
  - Remedy:
    - No traps (material purity)
    - long recovery time of a pixel
- There are likely more effects which need to be understood. Operating voltage seems to be of critical importance.

‘Quiet Time’ – Thermal Electrons-Induced Avalanches?

- Have N scope traces. Count the peaks found = M
- ‘Raw’ dark rate = $M/(N \times \Delta t)$. But they should be uncorrelated ➔ Poisson distribution
- $P(0) = N_{empty}/N = \exp(-N_{ave})$
- ‘True’ dark rate = $N_{ave}/\Delta t$
- ‘ ‘Raw’ – ‘True’ Rates = A’fterpulse’ rate
- Fraction of single pulses + Poisson statistics => another estimate of afterpulsing probability

Time Difference Between Dark Pulses (Vbias =72.75 V)

Large number of pulses closely clustered in time

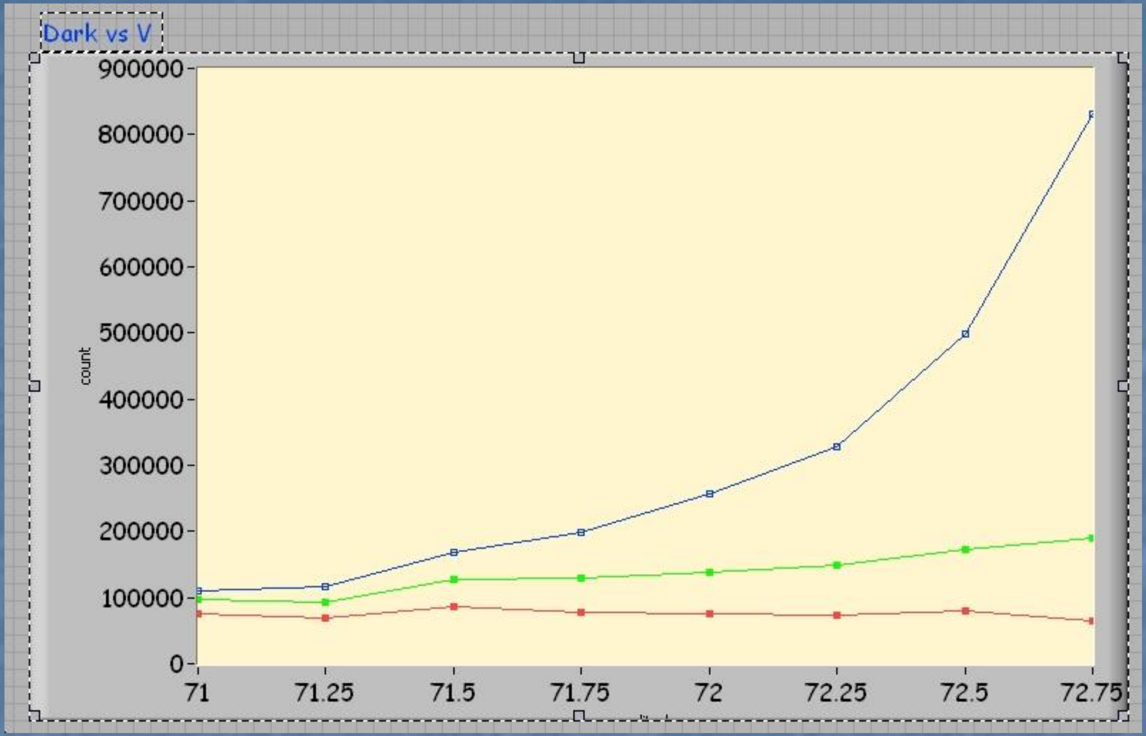


Dark rate [Hz]
831k

prob. of a single dark pulse
0.3892

Fraction of traces with exactly one pulse:
- Expected : 0.39
- Observed: 0.08

‘Dark’ Rates vs Voltage



‘Raw’ rate

‘True’ rate

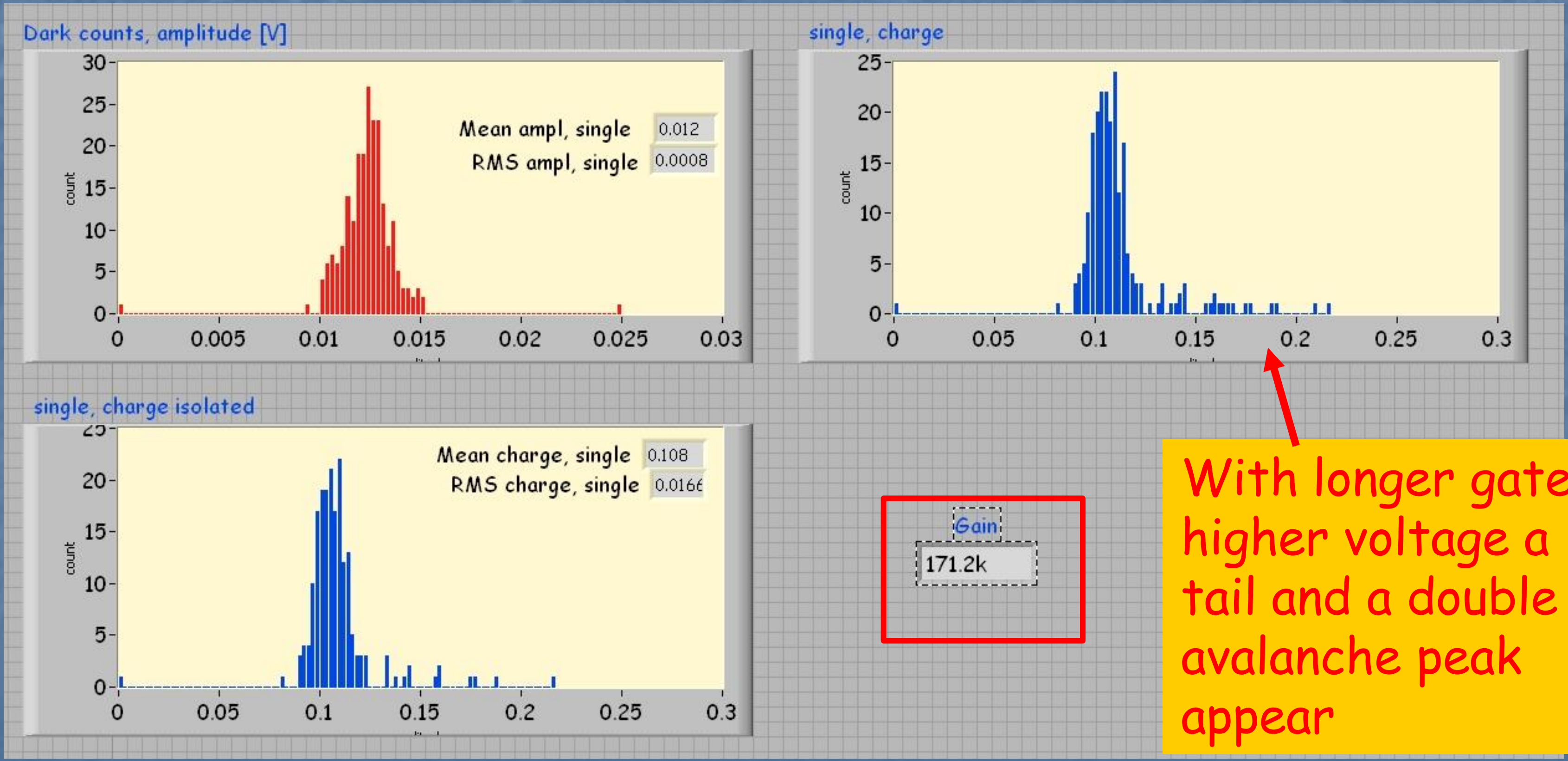
‘True’ rate, single peak method

- ➢ Rate of ‘true’ dark counts increases slightly with bias voltage(reflecting the increase of the probability that a free electron will start an avalanche). This is expected as the rate of free carrier generation depends on the temperature and not the bias voltage.
- ➢ Observed exponential growth of the dark rate is caused by afterpulsing
- ➢ At the higher bias voltage ‘dark’ pulses come in clusters

Single (Isolated) Dark Pulses: Self-Calibration of the Detector

- Detect pulses in the ‘quiet time’
- Plot the peak value of the detected pulses:
  - $\Delta V/V \sim 8\text{-}10\%$
- Integrate the charge within some gate (8ns)
  - To reduce impact of the afterpulsing require no other pulse within 50 nsec
  - $\Delta Q/Q \sim 10\text{-}15\%$
- Width of the ‘calibration pulses’ represents uniformity of the response over the front face of the detector

Single (Isolated) Dark Pulses: Self-Calibration of the Detector



Mean ampl, single 0.012
RMS ampl, single 0.0008

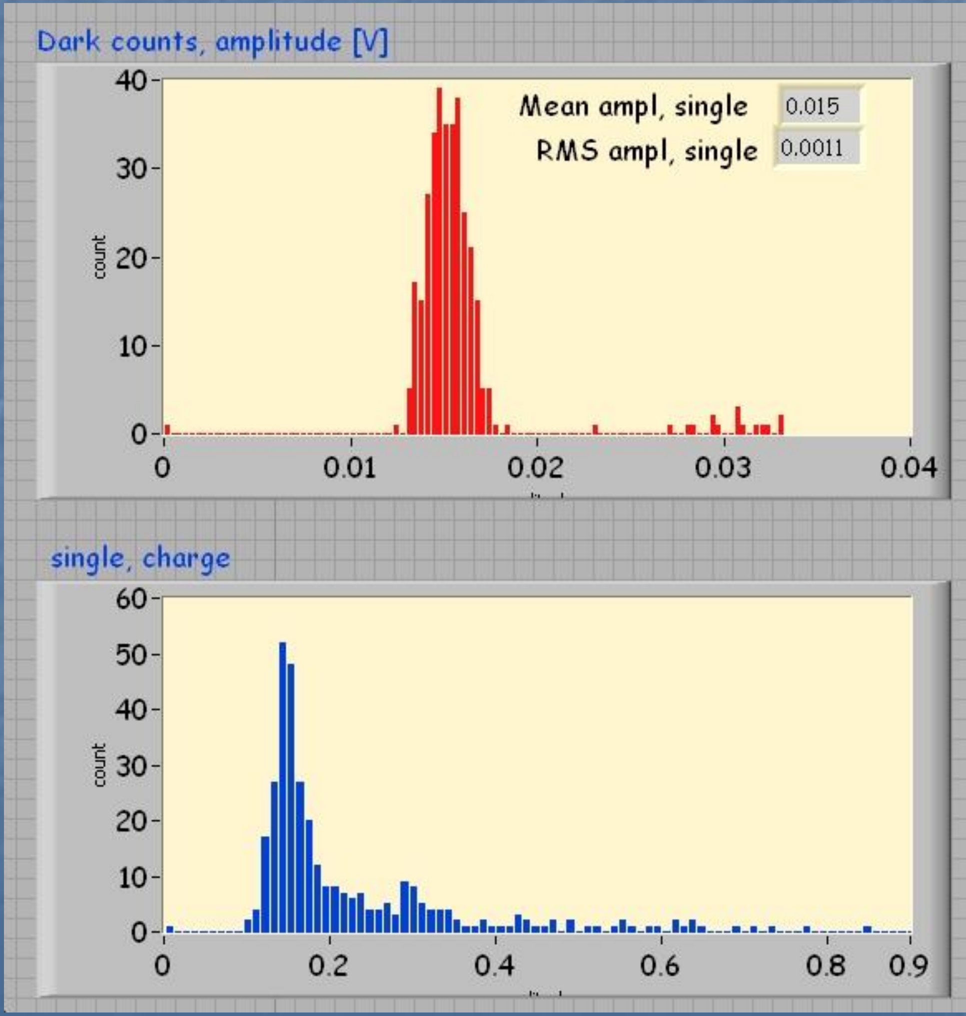
Mean charge, single 0.108
RMS charge, single 0.0166

Gain 171.2k

With longer gate or higher voltage a long tail and a double avalanche peak appear

Dark Counts: Comment About the Rates

- 71.5 V, integration gate of 50 nsec
- Dark count rate: what is the reduction when cutting at 1.5 pe?? It depends on the definition of 'rate':
  - Factor of 30-50 if measure the amplitude, bias voltage dependent
  - Factor of 5-10 if measure integral within some gate (gate dependent)



Dark counts, amplitude [V]

Mean ampl, single 0.015

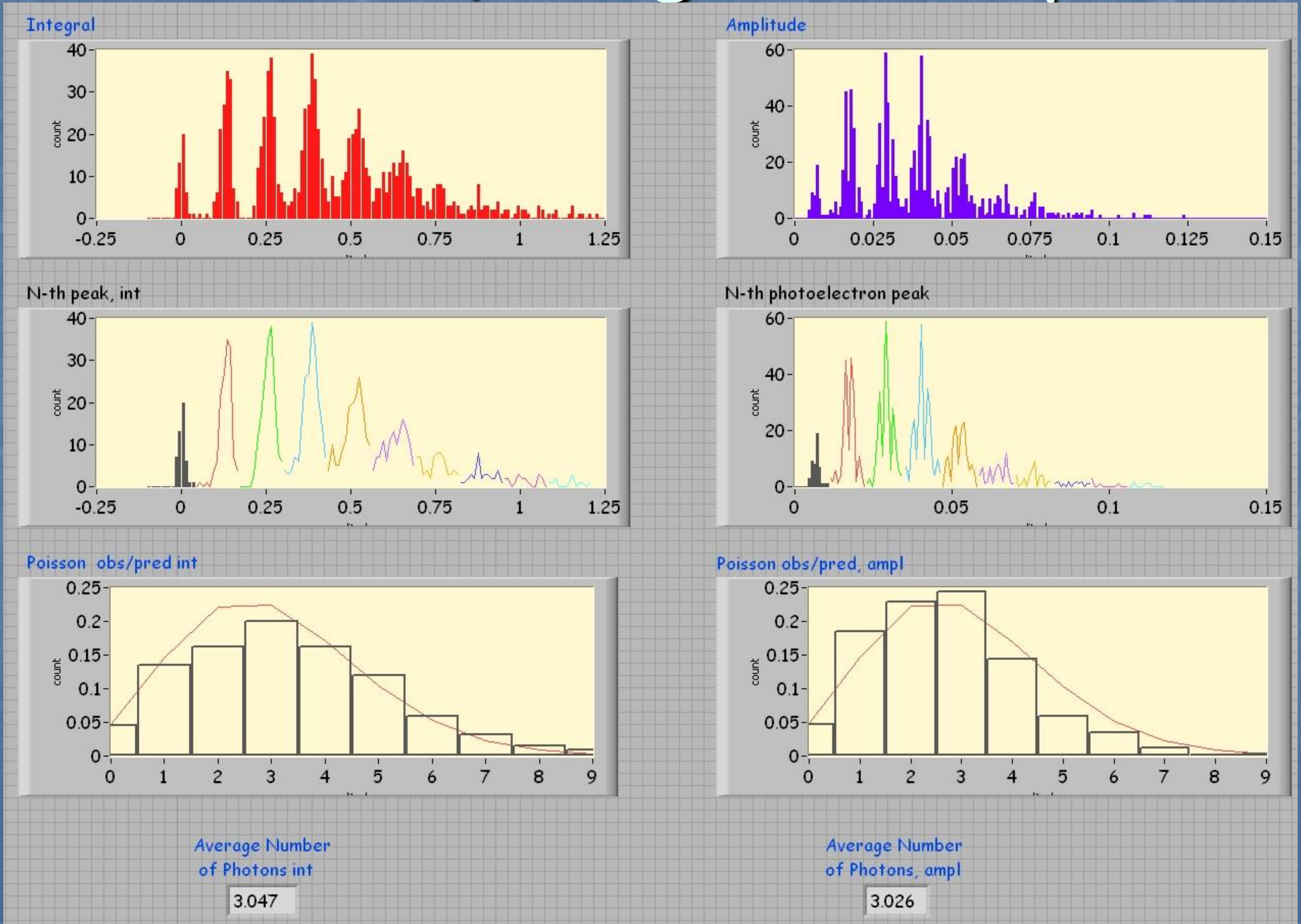
RMS ampl, single 0.0011

single, charge

Analysis of the 'Laser Gate' Data

- Two possible measures of the signal:
  - the peak amplitude
  - Integrate the charge within some gate (30 nsec shown thereafter)
- Use Fourier analysis to determine the fundamental frequency
- Automatically partition the spectrum into 0-1st-2nd-3th-etc… peak
- Compare with the expected Poisson distribution. Any additional contributions (like afterpulses) will shift the distributions towards the higher values

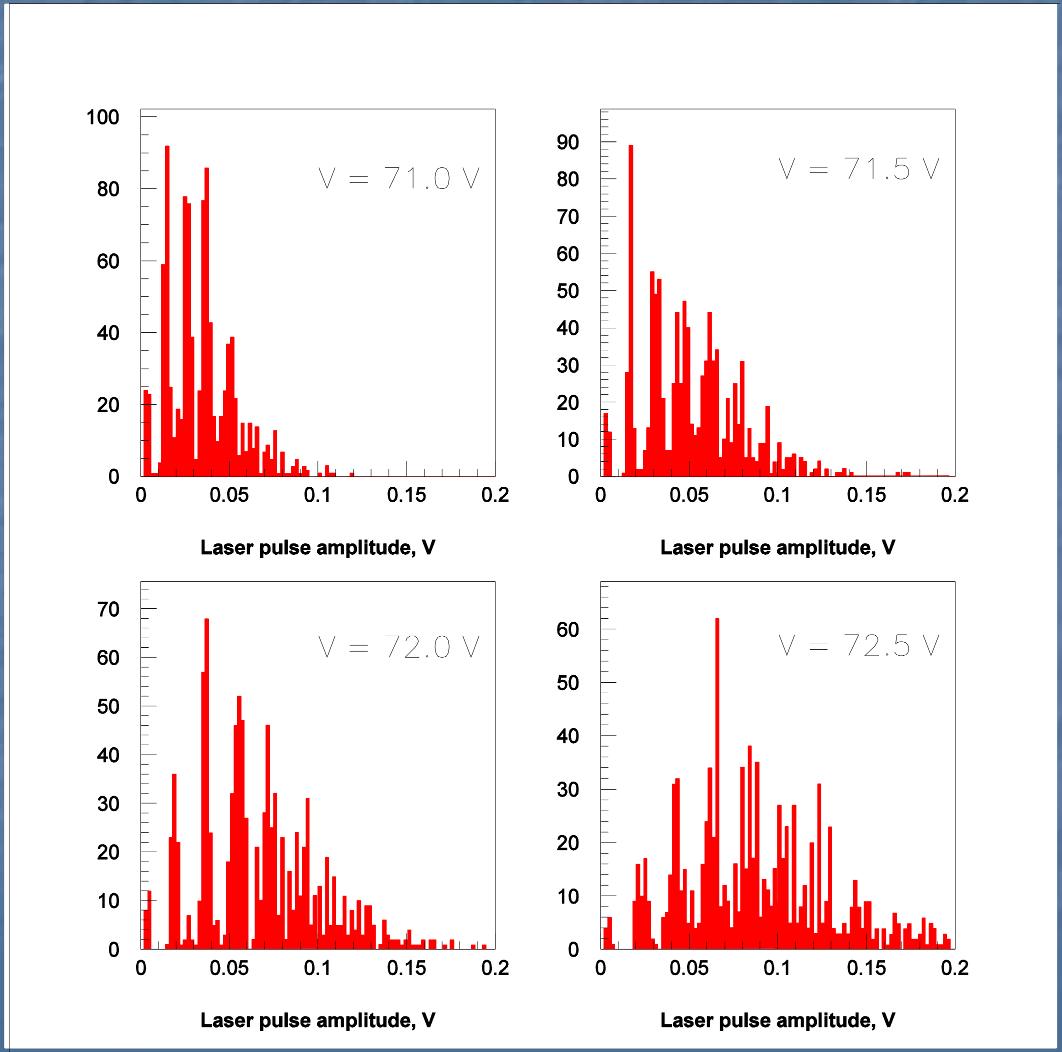
Reconstructing the Poisson Distribution (Charge and Amplitude)



Average Number of Photons int
3.047

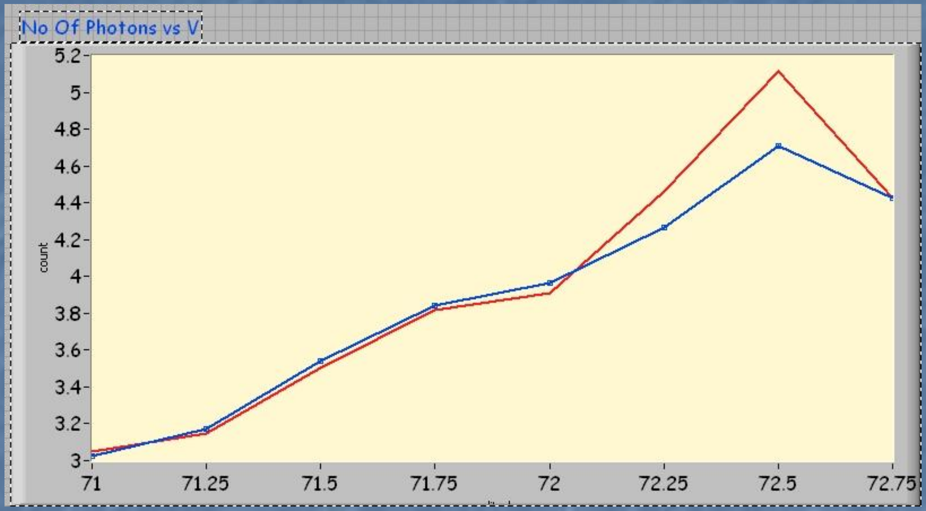
Average Number of Photons, ampl
3.026

Laser pulses vs Bias Voltage: Amplitude



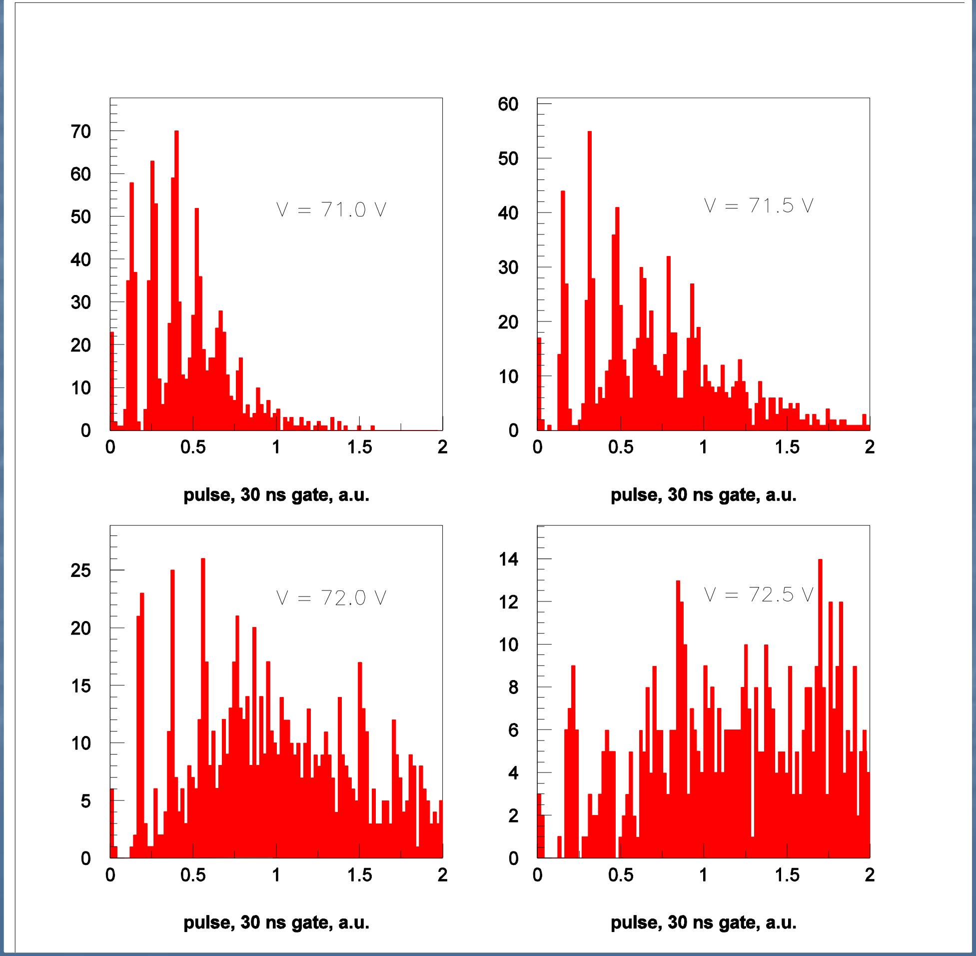
Notice the decrease of the number of zero's and the general shift to the right: increase of the detection efficiency with bias voltage

Detection Efficiency vs Bias Voltage



- Fractional content of the ‘zero’ bin -> average number of photons detected
- Good agreement between ‘charge’ and ‘amplitude’ –based measurement
- PDE increases by a factor of ~ 1.5 between 71 V and 72.75 V

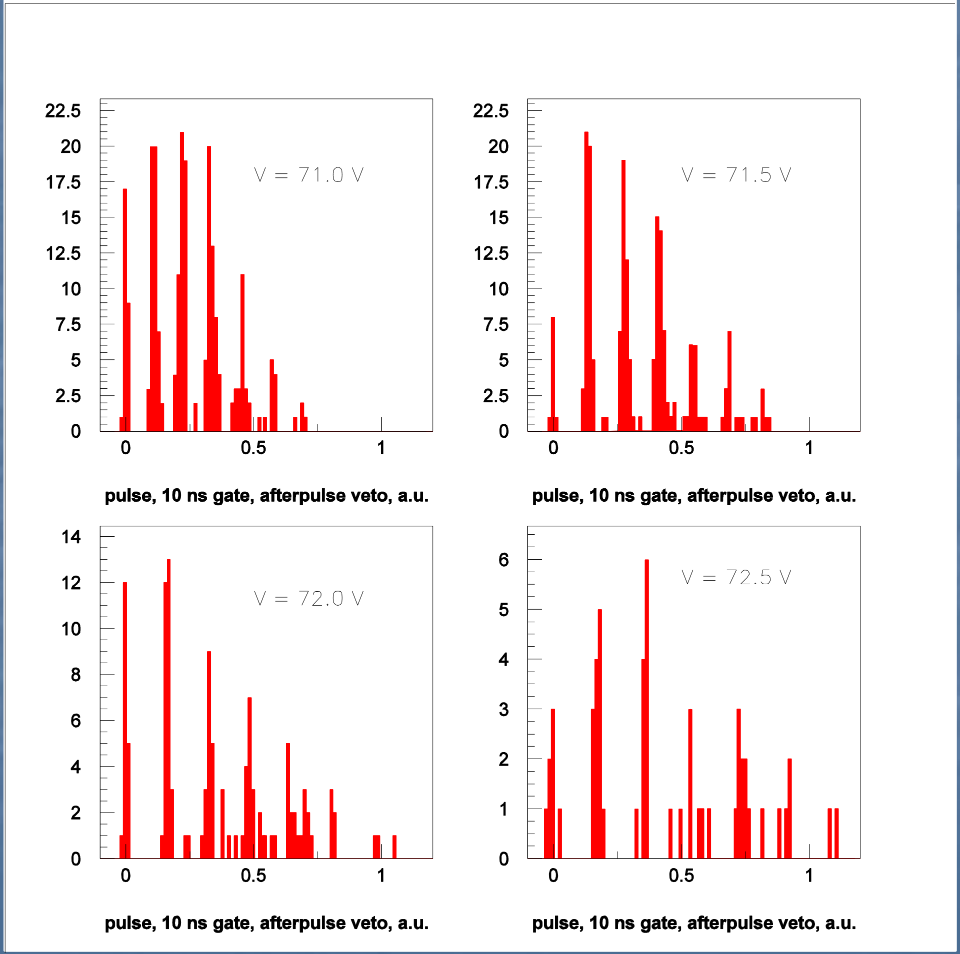
Charge of the laser pulse in 30 nsec gate



With the increasing bias voltage afterpulses increase the response, but degrade the ability to detect individual avalanches.

This is caused by additional pulses or parts of thereof sneaking into the integration gate.

Charge of the Laser pulse in 10 nsec gate with afterpulse veto



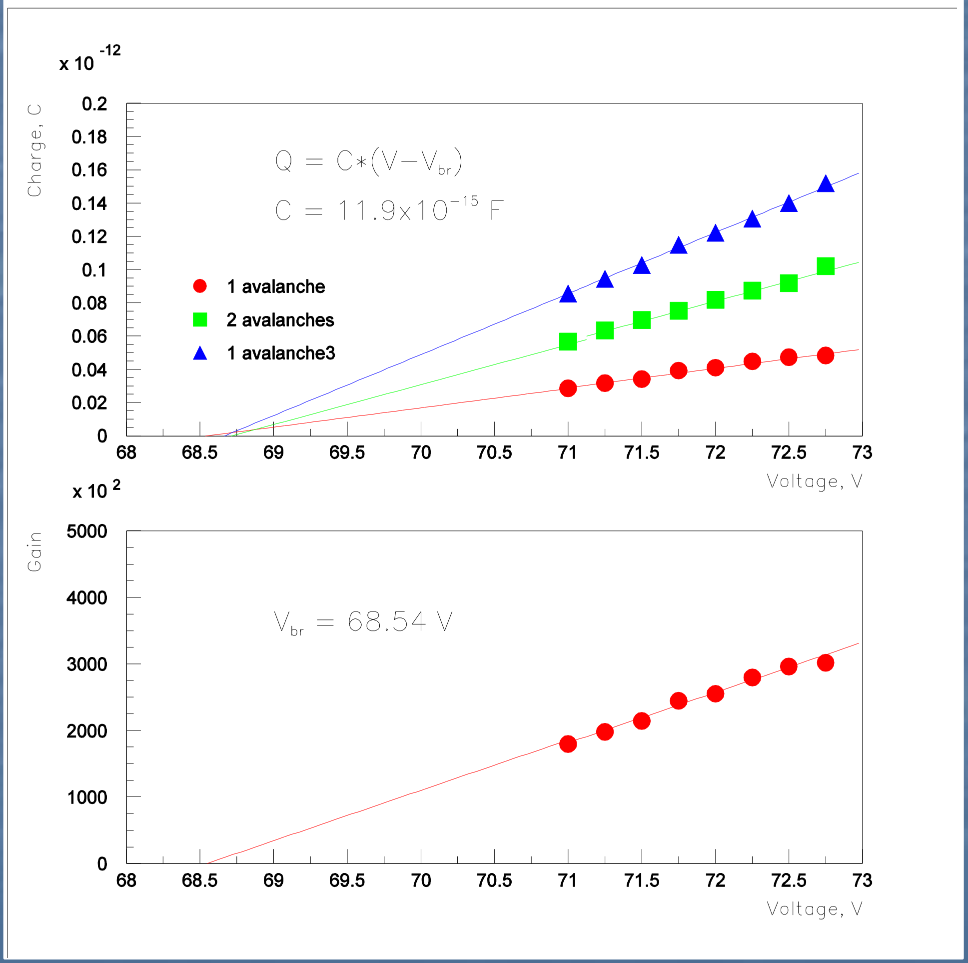
Require that [Q(30) Q(10)]<0.15xQ(10), i.e. no afterpulse immediately following the laser pulse.

Ability to count individual avalanches restored.

This is not a very practical solution in real life applications, though. It may be, perhaps, of some use in situations where:

- Arrival time of the light pulse is known (timing of the gate)
- Input light pulse has small duration (~ 1-2 nsec)

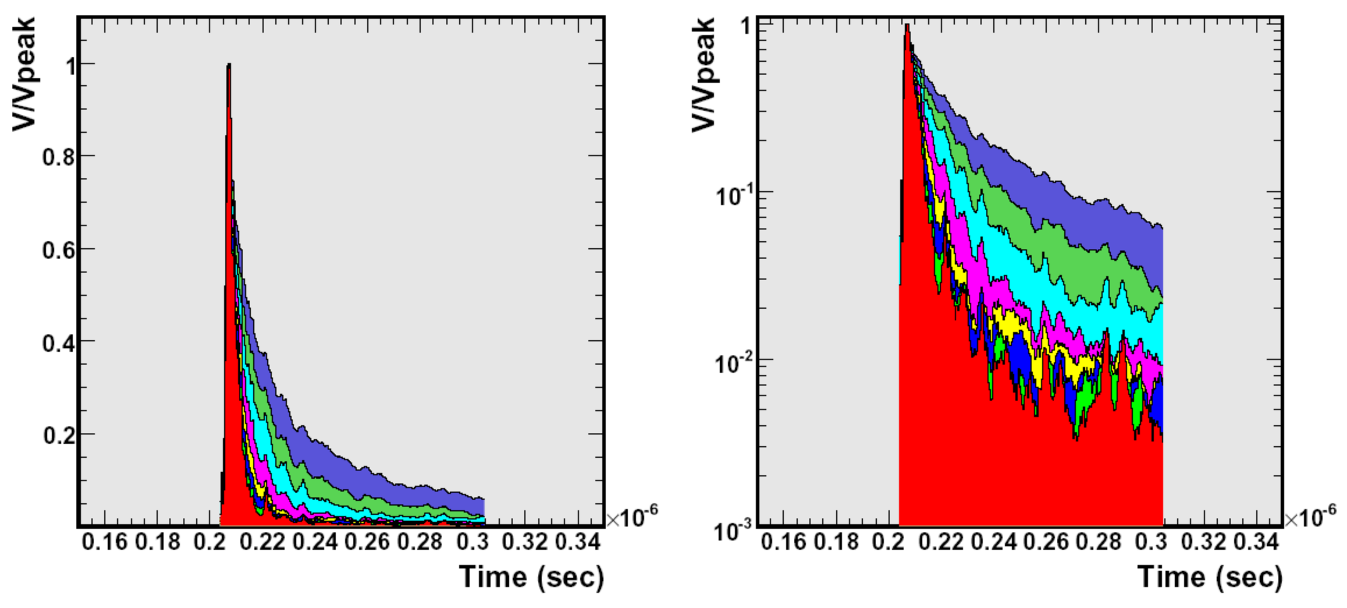
Gain/linearity at low light levels



Integrate 1,2,3 avalanches peaks in 10 nsec gates (afterpulses vetoed)

- Q(N) = NQ(1)
- Q = C*(Vbias – Vbr) ➔ C = 12fF
- Vbr = 68.5 V

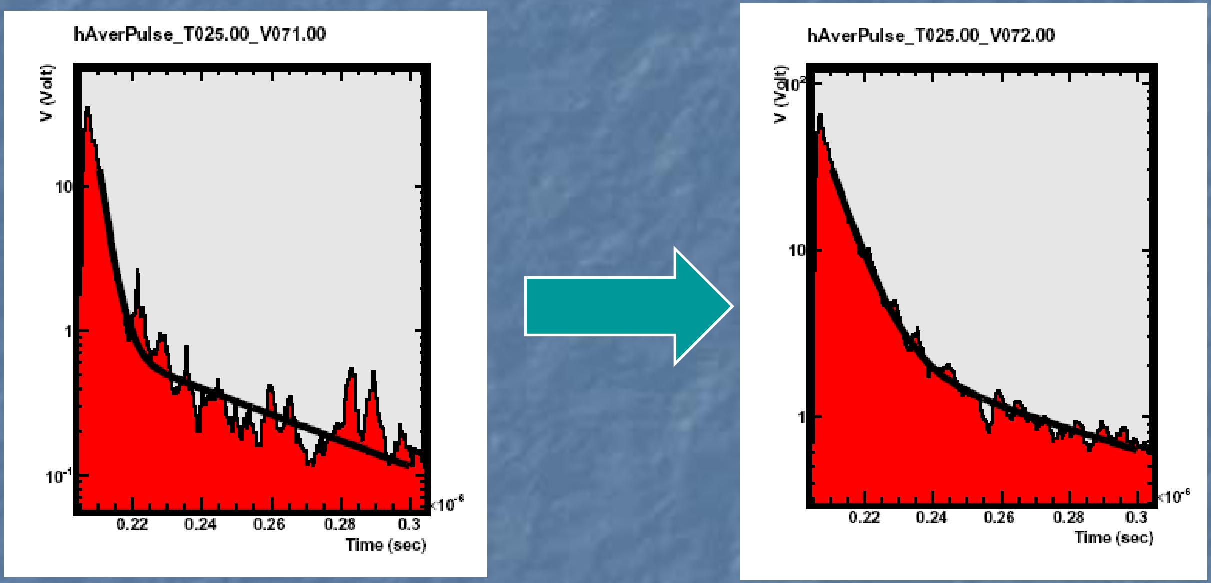
Output Pulse Shape as a Function of Bias Voltage

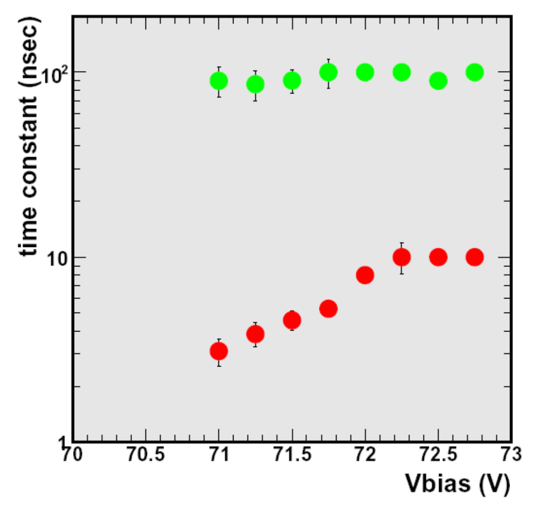


- Average pulse shape of the response to the laser light as a function of the bias voltage (red – Vbias =71 V, blue – Vbias = 72.75 V)

- Clear evidence for afterpulsing component growing with the voltage making pulses bigger and longer.

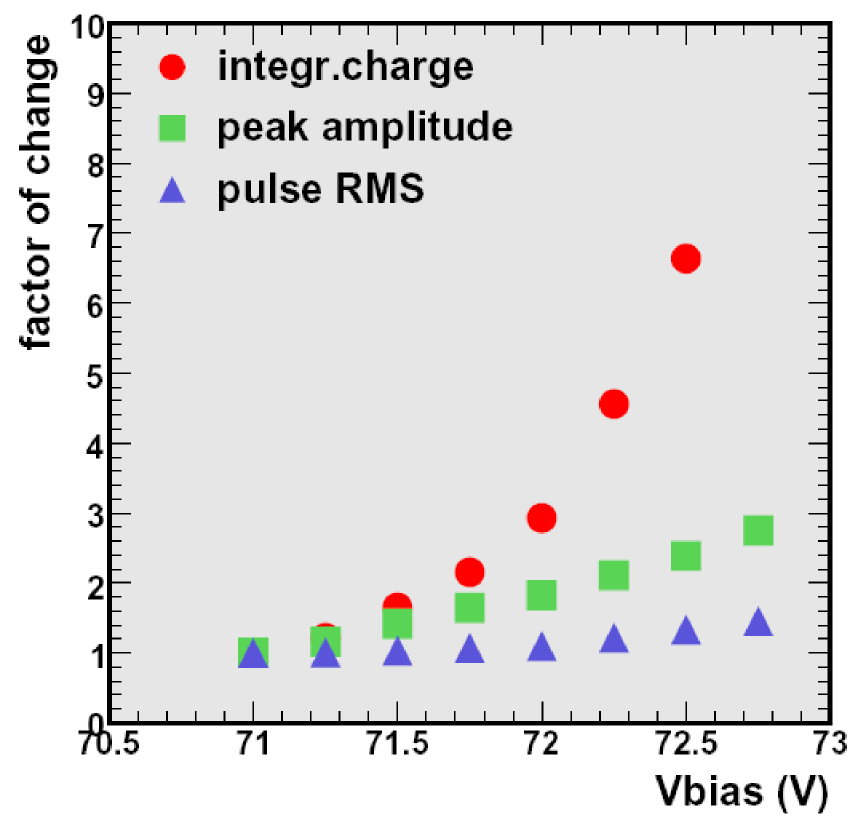
Changes of pulse shape with bias voltage





Two components of the signal. Afterpulsing has decay time of about 100 nsec

Variation of 'observables' with Bias Voltage



- Different measures of the signal show different variation with the bias voltege (at fixed temperature and the same light signal). For 1.5 V variation of the bias voltage the peak amplitude grows by a factoe of about 2.5, whereas the integral of charge in 100 nsec gate changes by a factor of 7
- Need to keep the voltage (and temperature) very stable or need to devise a precise calibration procedure.

Conclusions

- Hamamatsu MPPC have relatively low dark pulses rate. This rate increases rapidly with the bias voltage due to afterpulsing.
- Pixel-to-pixel cross talk is very small (few percent) at low overvoltage. It grows to about 20-30% for 100 micron pixel devices, but it is always much smaller than the afterpulsing
- Detector instabilities (mostly afterpulsing) are major contribution to the detector response. Their practical consequences depend on the readout details and the experimental conditions (temporal structure of the measured light pulses)
- Detailed studies of the detector response as a function of the bias voltage and temperature are necessary to develop a precise calibration procedure to exploit fully the measurement capabilities of MPPC in the calorimetry-type applications