Tests and performance of multi-pixel Geiger mode APD's and APD's for the CMS ECAL

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Motivation

- At Beaune-05 NDIP conference several groups reported about development of multi-pixel Geiger-mode APDs (G-APDs)
- The G-APD parameters (gain, PDE, excess noise factor, timing response) were reported to be similar or even superior to the parameters of PMTs
- During last 2 years new G-APD structures have been developed. Improved performances of these photosensors were reported by different investigators
- These results increased an interest to G-APDs from HEP, astroparticle and medical communities
- Correct evaluation of the G-APDs parameters and their influence on detector performance became very important
- However measurements of these parameters (especially QE) is not an easy task taking into account small sensitive area (typically 1 mm^2) and rather high dark count rates at room temperature.

Outline

In my talk:

- I will briefly describe the experimental technique we use to characterize G-APDs
- The results of our studies of recently developed G-APDs from 3 producers will be reported:
  - PDE(U)
  - F(U)
  - N_{dark}(U)
  - Gain(U)
  - K_V(U)
  - K_T(U)
  - PDE(λ)
- Main parameters of the G-APDs will be compared with the parameters of an APD operated in linear mode (S8148 HPK APD)

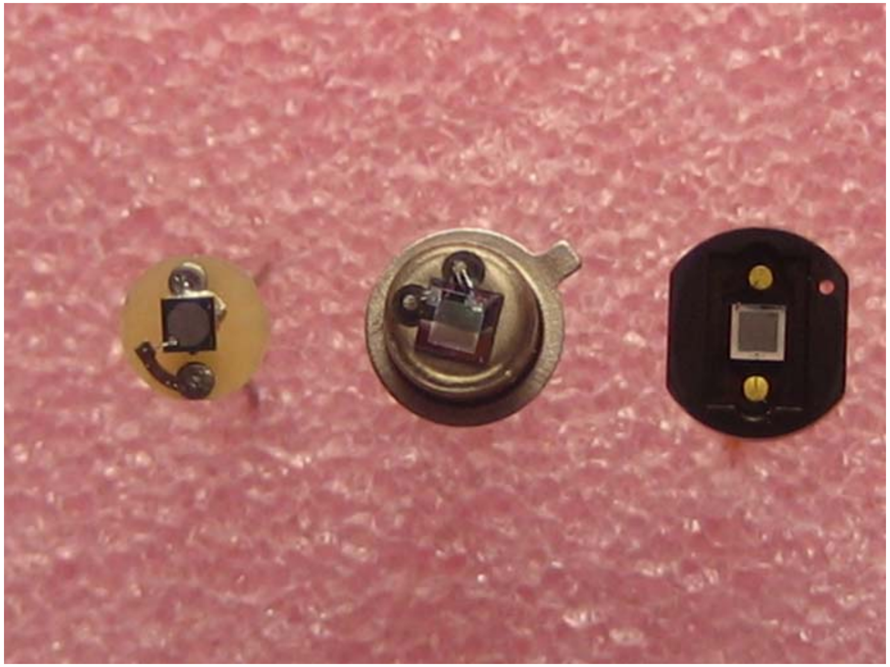
G-APDs studied

G-APDs	Producer's reference	Package	Protection	Substrate	Area [mm^2]	# of pixels	VB(T=22 C) [V]
CPTA/Photonique*	SSPM_0701BG_PCB	PCB	No	p-type	1	556	30.7
Dubna/Mikron**	pMP-3d-11	TO-18	Epoxy	p-type	1	1024	39.4
Hamamatsu***	S10362-11-050C	Ceramic	Epoxy	n-type	1	400	68.8

*) http//www.photonique.ch

**) http//sunhe.jinr.ru/struct/neeo/apd/

***) http//www.hamamatsu.com

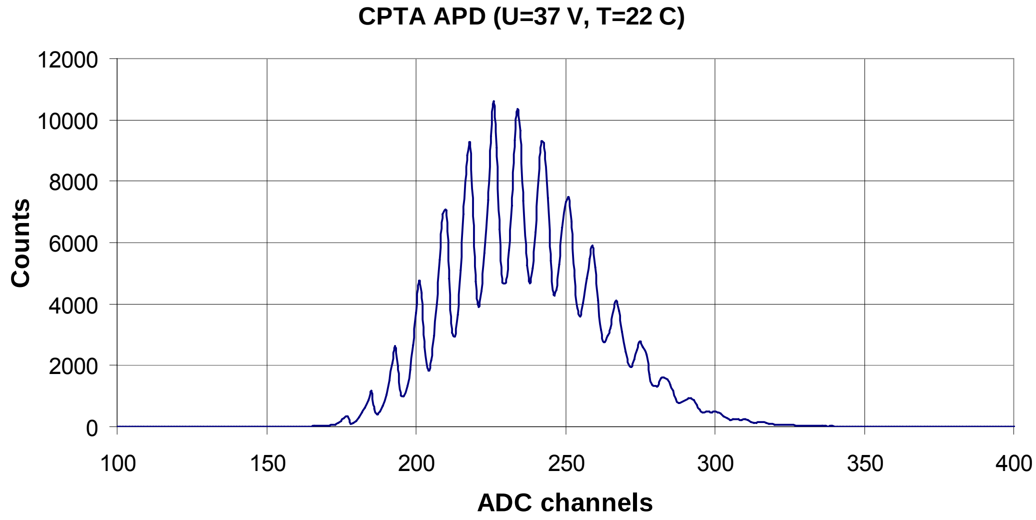


Set-up

- MPGM APD and XP2020 PMT were illuminated with the parallel light from LED through 0.5 mm diameter collimator
- Mechanical system allowed precise positioning (<50 mm) of the APD and PMT in all 3 dimensions
- LEDs with the peak emission of 410 nm and 515 nm were used in this study
- APD was connected to fast linear transimpedance amplifier (gain~20)
- Temperature - monitored using Pt-100 resistor
- Currents were measured using Kethley-487 source-meter
- Amplitude spectra were measured using LeCroy 2249 W CAMAC ADC
- LeCroy 623B discriminator and 250 MHz scaler were used for signal counting
- “Optometrics” spectrophotometer was used for spectral response measurements
- Low temperature measurements were done inside the freezer

LED spectrum (low light)

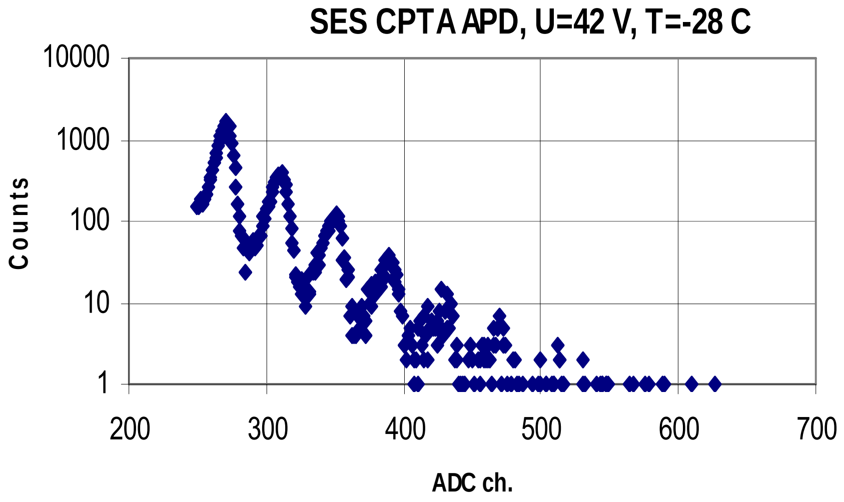
MPGM APDs have very good pixel-to-pixel signal uniformity. Pedestal is separated from the signal produced by single fired pixel Q_1 .

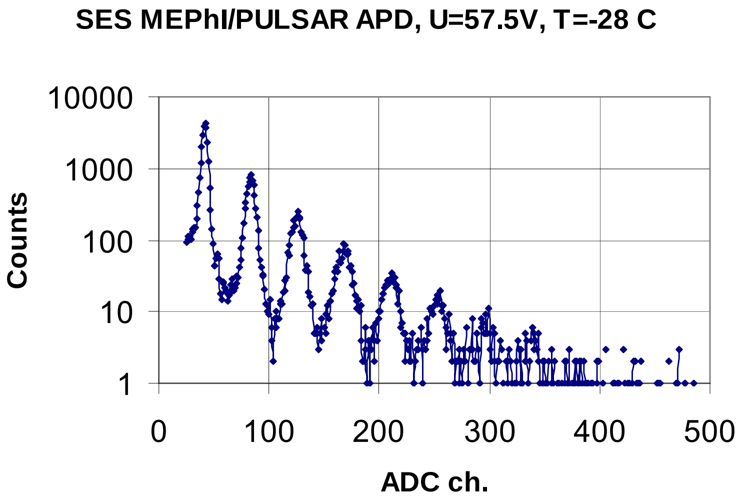


Single electron spectrum

When $V-V_b>>1$ V typical single pixel signal resolution is better than 10% (FWHM)). However photons produced during the pixel breakdown can penetrate another pixel and fire it. As a result more than one pixel is fired by single photoelectron.

(Y. Musienko et al., A 567 (2006) pp.57–61)





Parameter definition: Gain

Each pixel works as a digital device – 1,2,3... photons produce the same signal $Q_1 = C_{pixel} * (V - Vb)$ (or Single Pixel Charge).

Multi-pixel structure works as a linear device, as soon as $N_{pe} = N_g * QE << N_0$, N_0 – is a total number of pixels/device

Measured charge :

$$Q_{output} = N_{pe} * Gain ,$$

It was found by many groups that : Gain ≠ Q_1 ,

More than 1 pixel is fired by one primary photoelectron!

$$Gain = Q1 * n_p ,$$

where n_p is average number of pixels fired by one primary photoelectron.

PDE measurements

Photon detection efficiency (PDE) is the probability to detect single photon when threshold is <Q1. It depends on the pixel active area quantum efficiency (QE), geometric factor and probability of primary photoelectron to trigger the pixel breakdown P_b (depends on the $V\text{-}V_b$!!, V_b – is a breakdown voltage) :

$$PDE = QE{*}G_f{*}P_b$$

For G-APDs with low dark count rate (<3 MHz) pedestal events can be easily separated from the event when one or more than one pixel were fired by the incident photons. In this case we can use well known property of the Poisson distribution :

$$\langle Npe\rangle = -\ln(P(0))$$

This equation works even in the case of the photodetector with very high multiplication noise !!!

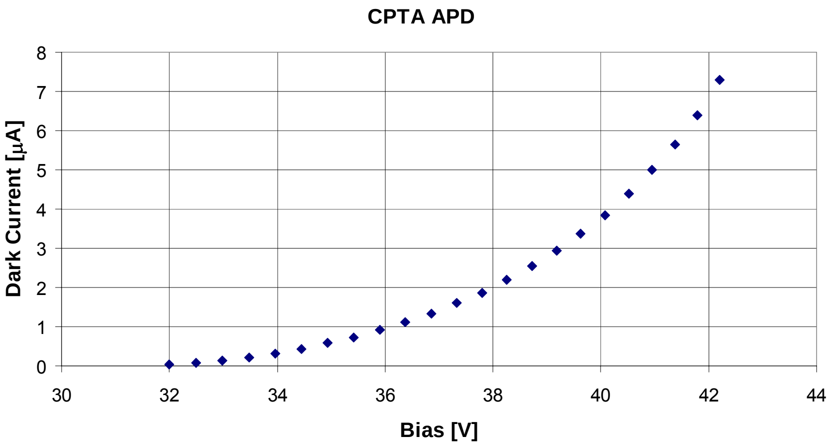
("Peak" counting method overestimates the <Npe>. Method which uses the width of the signal distribution underestimates the <Npe>).

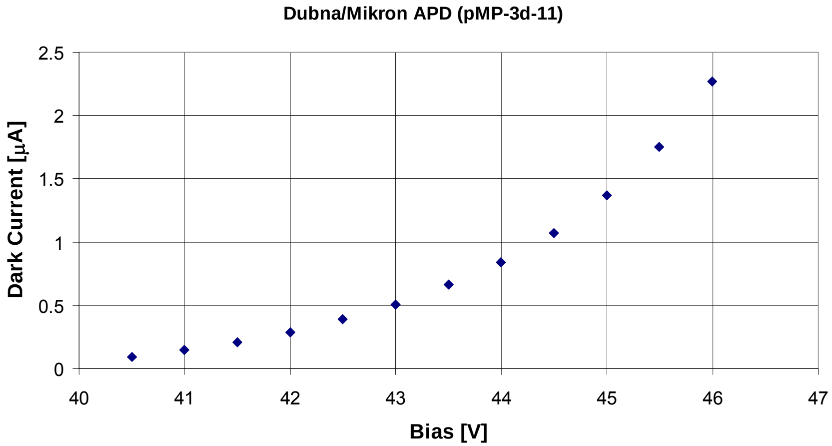
Number of incoming photons ($N\gamma$) from LED pulse can measured with calibrated PMT (XP2020 PMT, for example). Then:

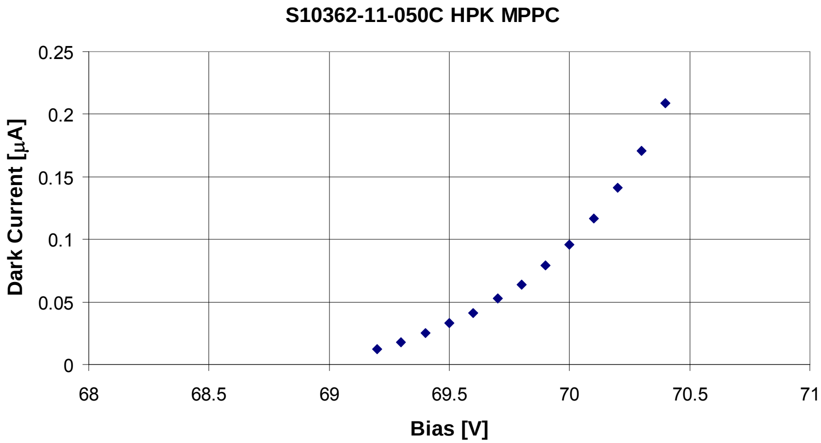
$$PDE(\lambda) = Npe/N\gamma$$

LED emission spectra must be measured as well (in pulsed mode !!!)

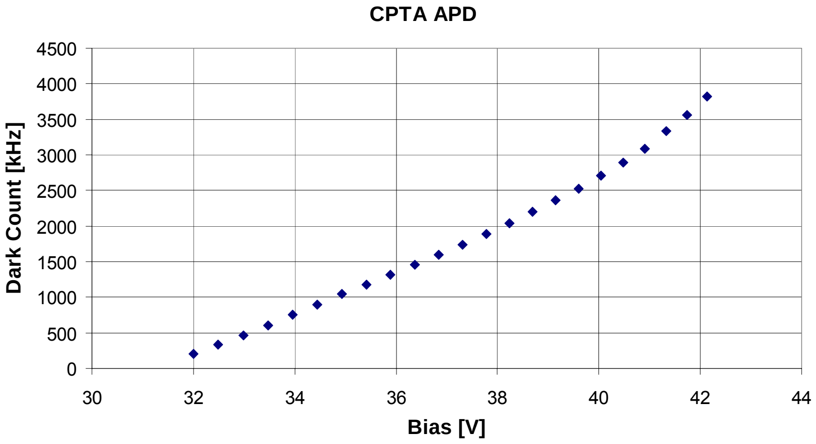
Dark current vs. Bias (T=22 C)

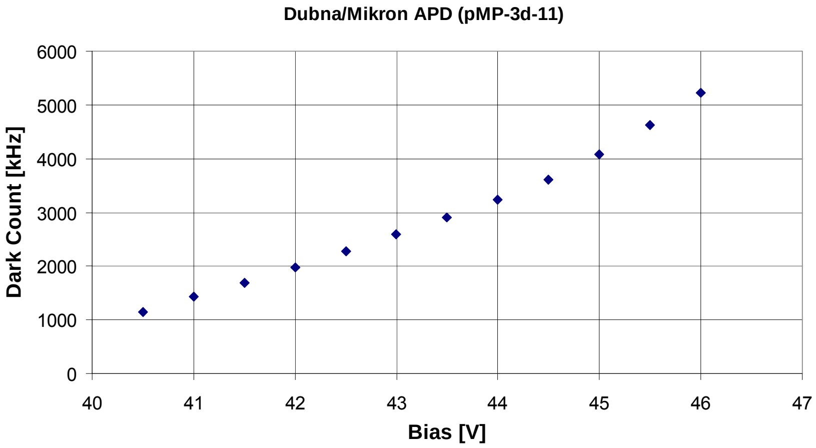


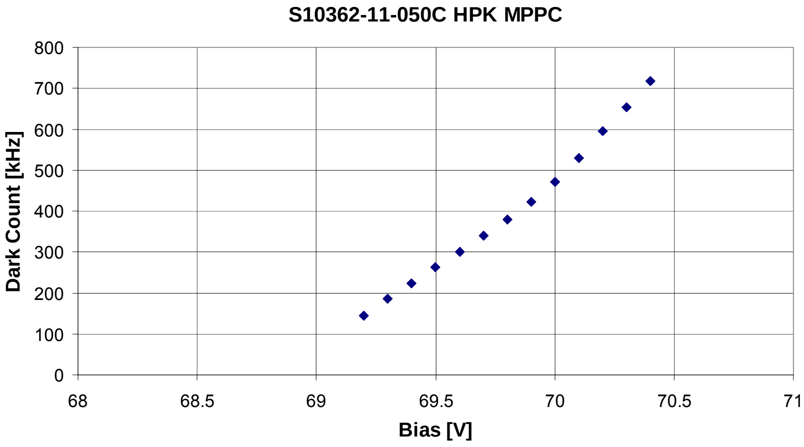




Dark count vs. Bias (~0.5 p.e. threshold, T=22 C)

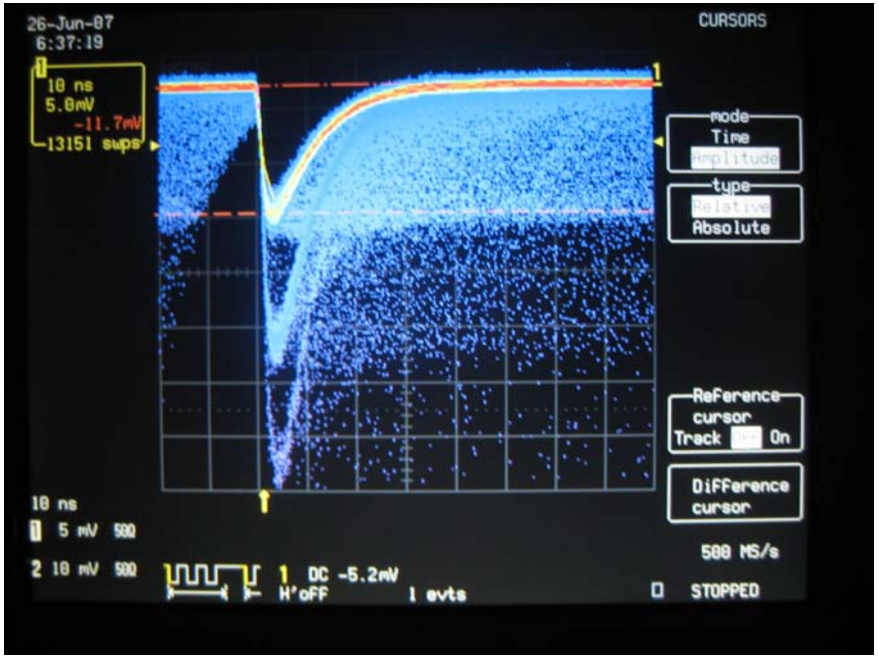

CPTA APD


Dubna/Mikron APD (pMP-3d-11)

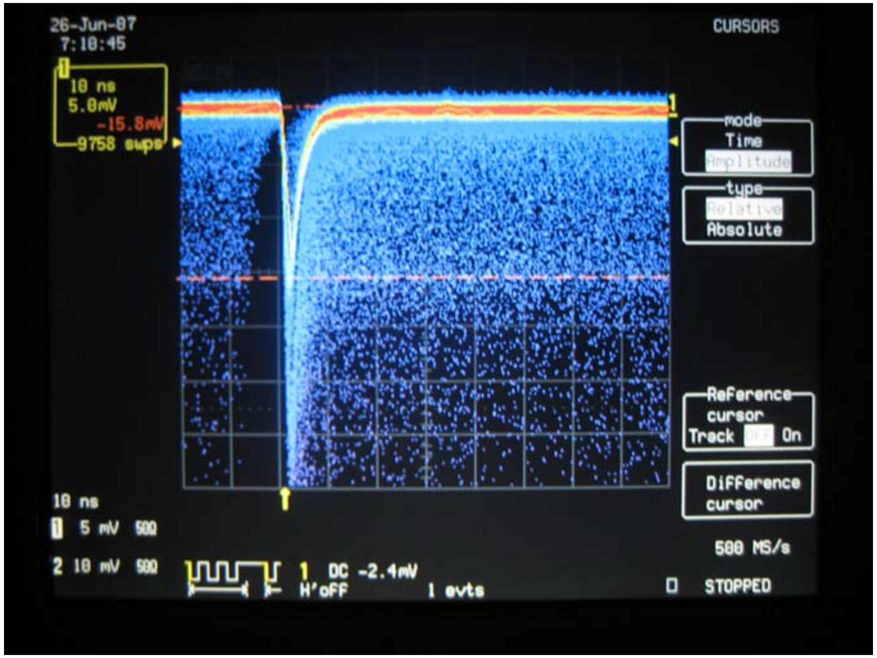

S10362-11-050C HPK MPPC

Signal shape (HPK and Dubna G-APD)

Hamamatsu G-APD



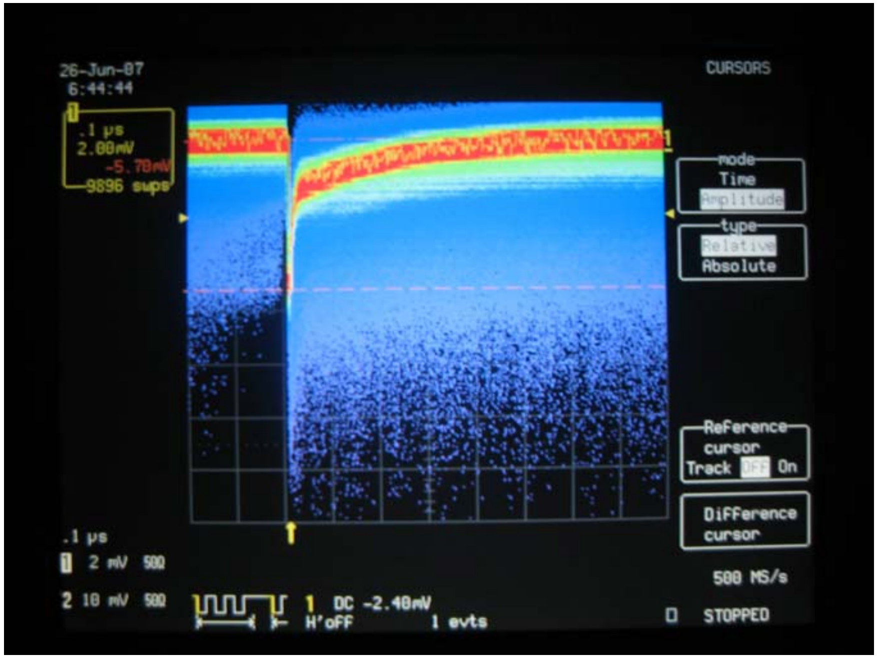
Dubna/Mikron G-APD

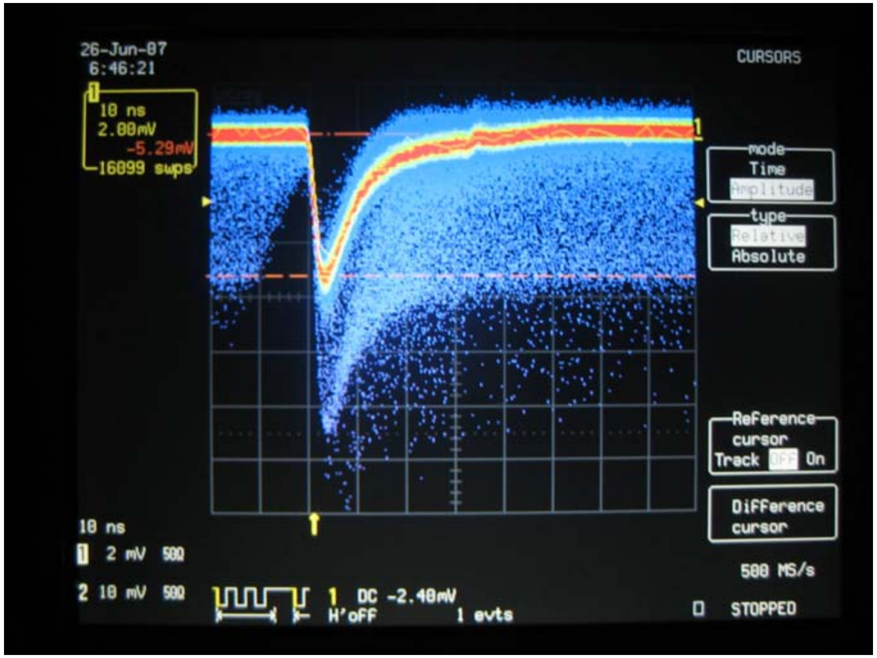


Signal shape (CPTA G-APD)

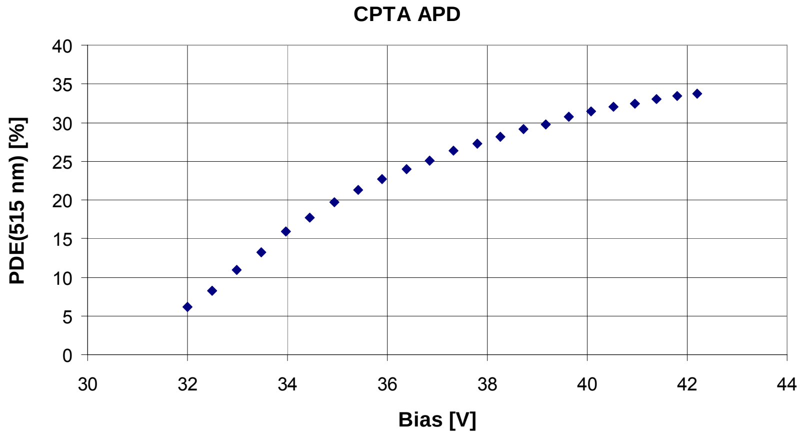
Direct signal (R_L=50 Ohm)

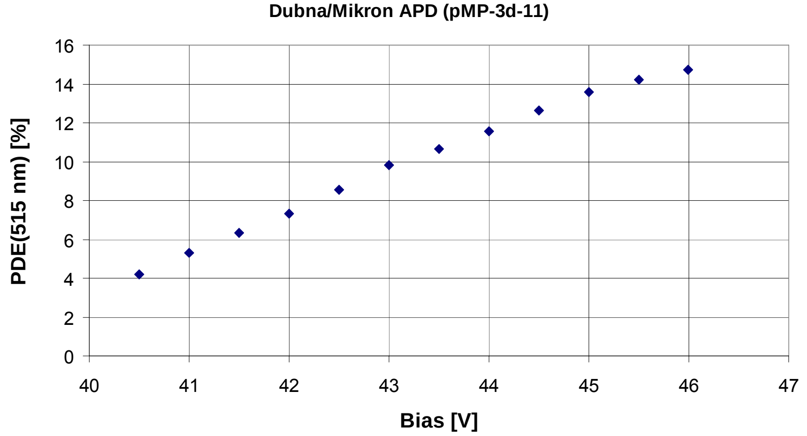
After tail cancelation using C=0.47 nF (R_L=50 Ohm)

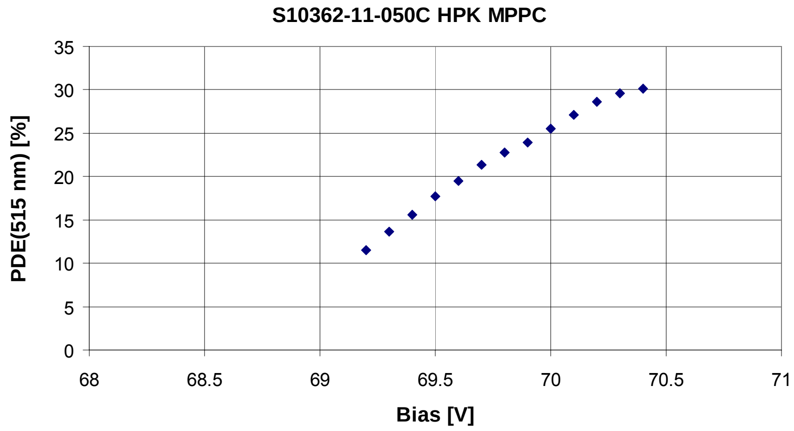




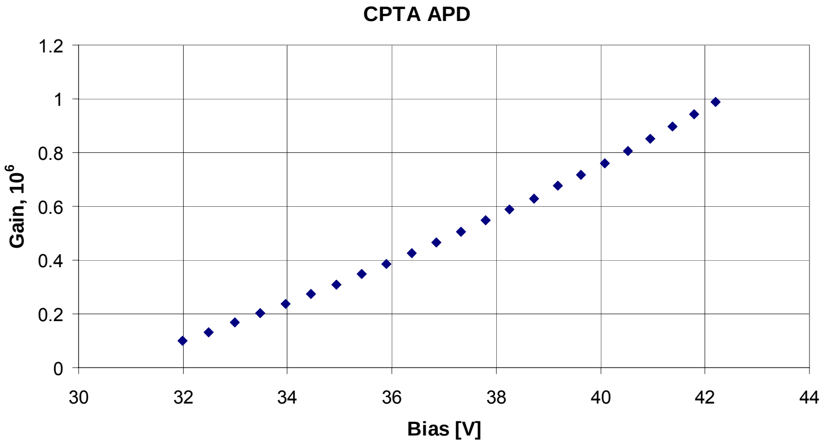
Photon detection efficiency vs. Bias

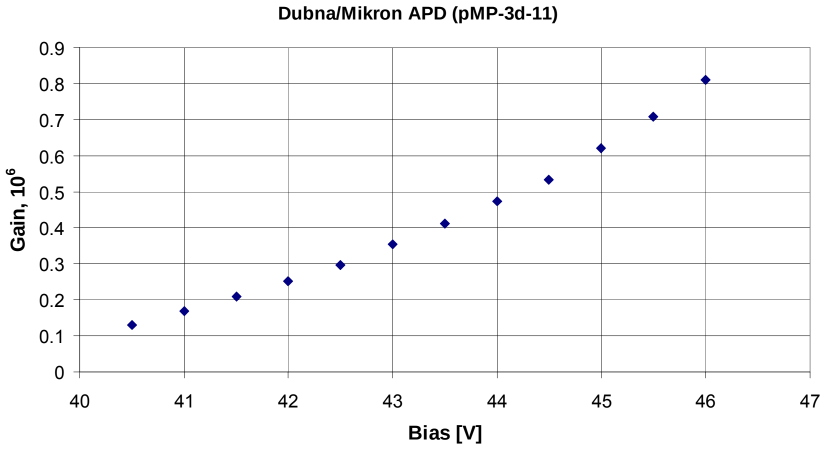


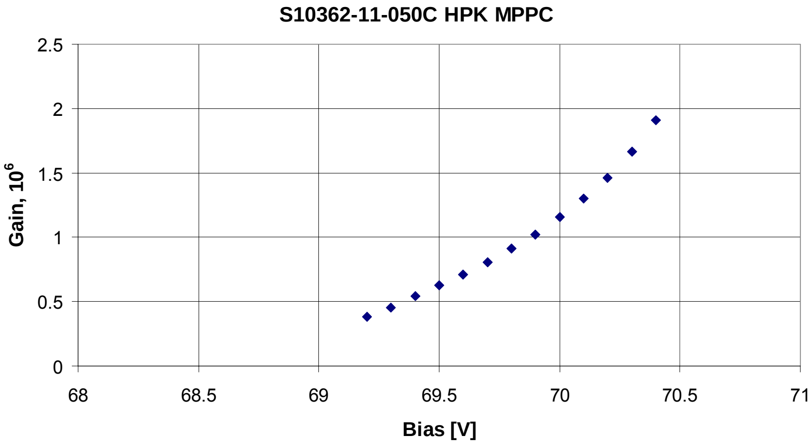




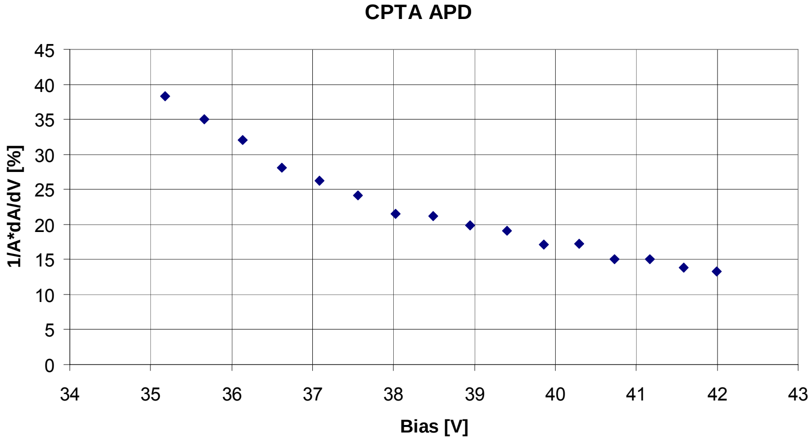
Gain vs. Bias (T=22 C)

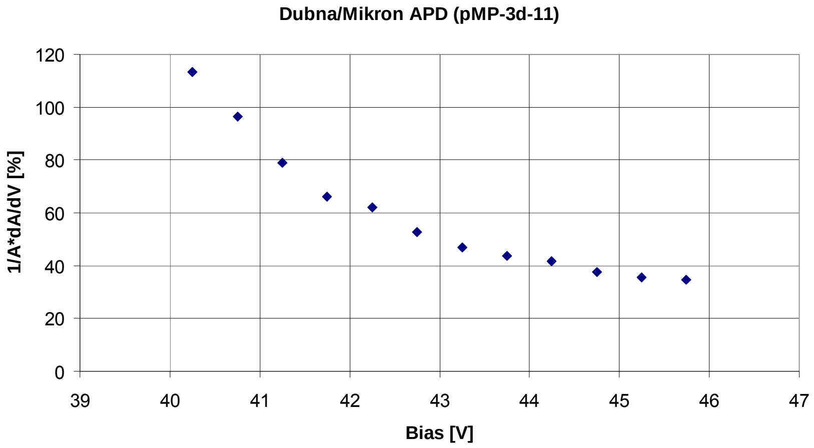

CPTA APD


Dubna/Mikron APD (pMP-3d-11)

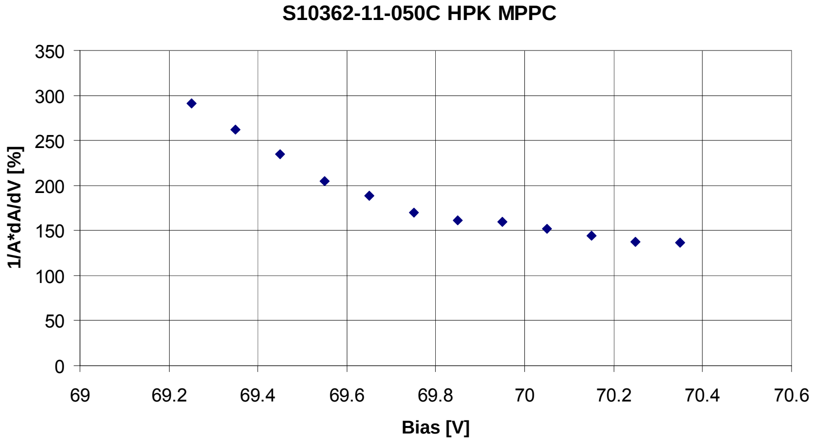

S10362-11-050C HPK MPPC

G-APD voltage coefficient

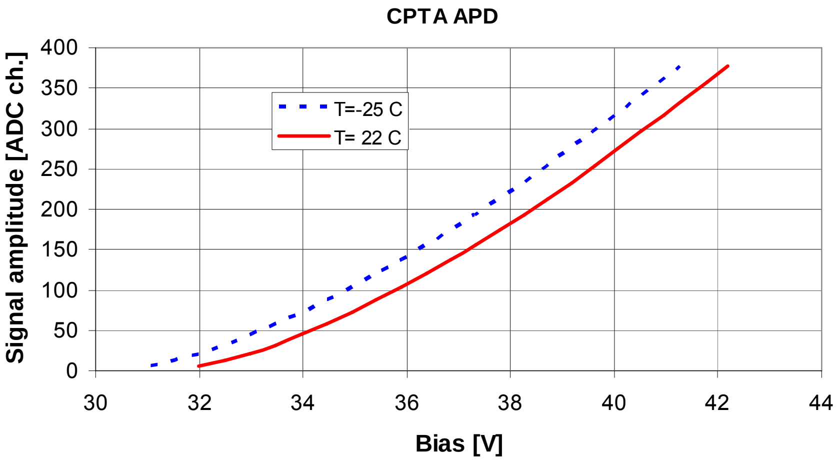

CPTA APD

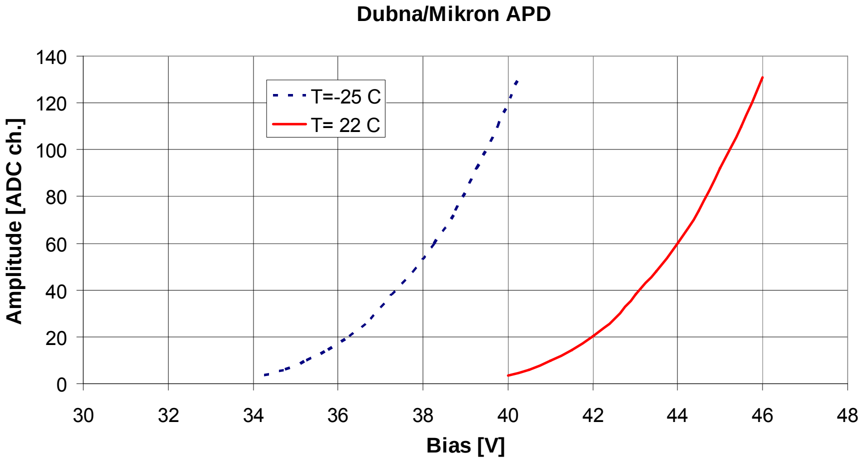

Dubna/Mikron APD (pMP-3d-11)

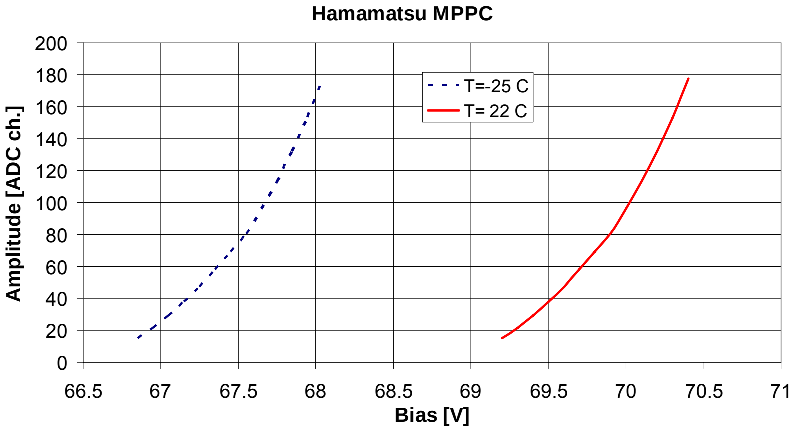
$k_V=dA/dV*1/A$, [%/V]


S10362-11-050C HPK MPPC

Temperature sensitivity


CPTA APD

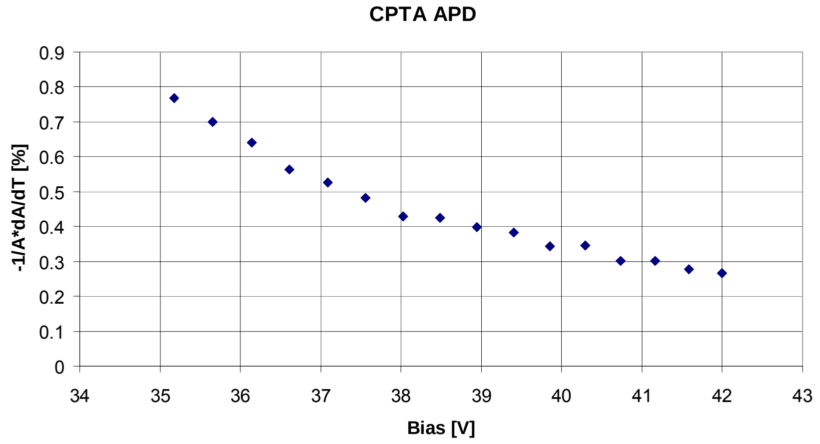

Dubna/Mikron APD


Hamamatsu MPPC

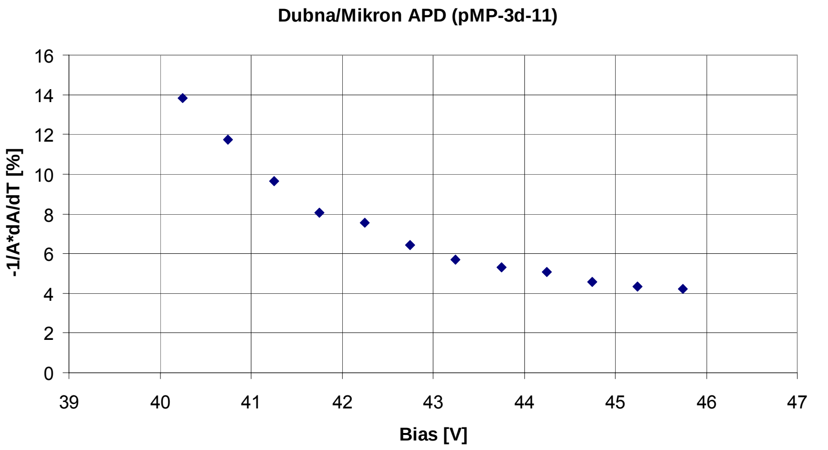
CPTA/Photnique:
dVB/dT=-20 mV/C
Dubna/Micron:
dVB/dT=-122 mV/C
Hamamatsu:
dVB/dT=-50 mV/C

LED signal was measured in dependence on bias at 2 temperatures. During low temperature measurements (T=-25 C) G-APDs were placed inside commercial freezer (LED was kept at room temperature)

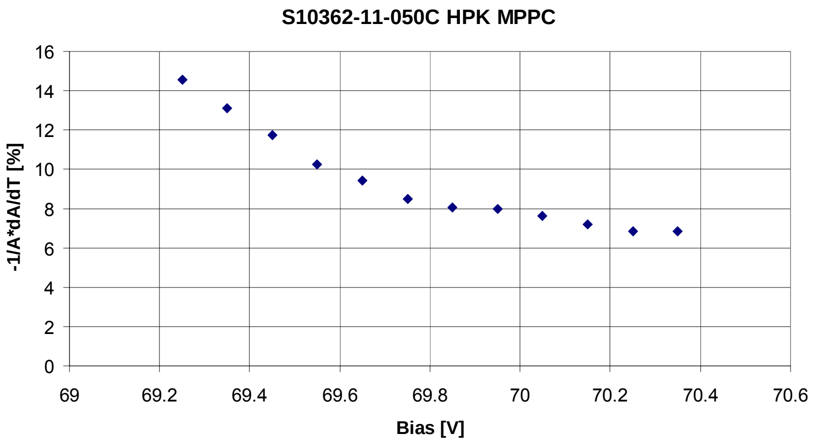
G-APD temperature coefficient



CPTA APD



Dubna/Mikron APD (pMP-3d-11)



S10362-11-050C HPK MPPC

$k_T = dA/dT*1/A$, [%/°C]

Excess noise factor (I)

Excess noise factor can be measured from the width of single electron spectra and calculated using:

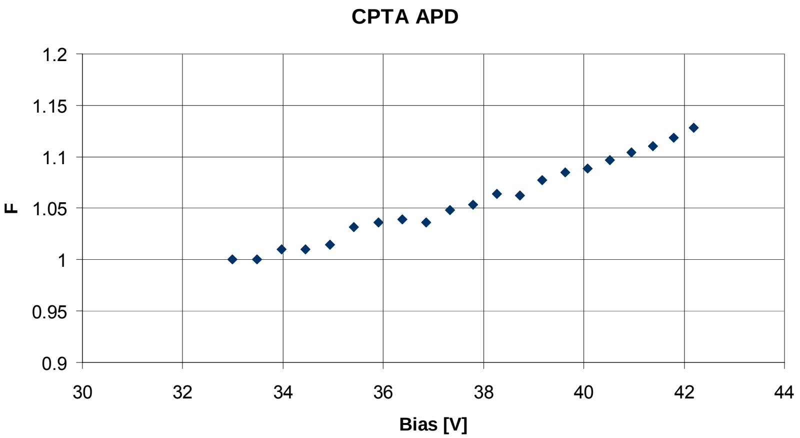
$$F=1+var_1/<A_1>^2 \quad (2),$$

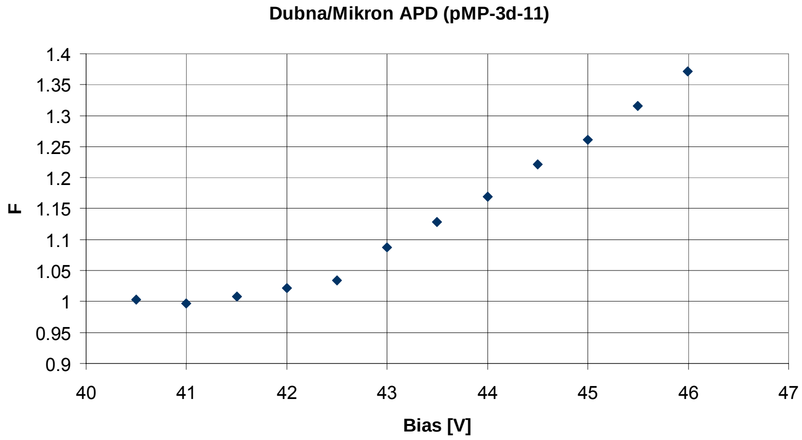
where $<A_1>$ is average amplitude produced by single electron and var_1 its variance.

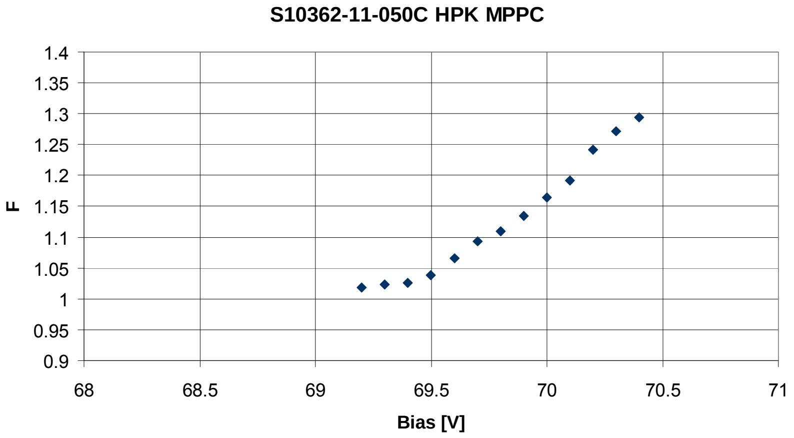
Another way (gives the same result) is to compare the N_{pe} calculated from equation (1) and from N_w from the width of the measured spectra (number of measured photoelectrons should be small (P(0) should not be very low) . This method is easier to use:

$$F=N_{pe}/N_w \qquad (3),$$

Excess noise factor (II)


CPTA APD

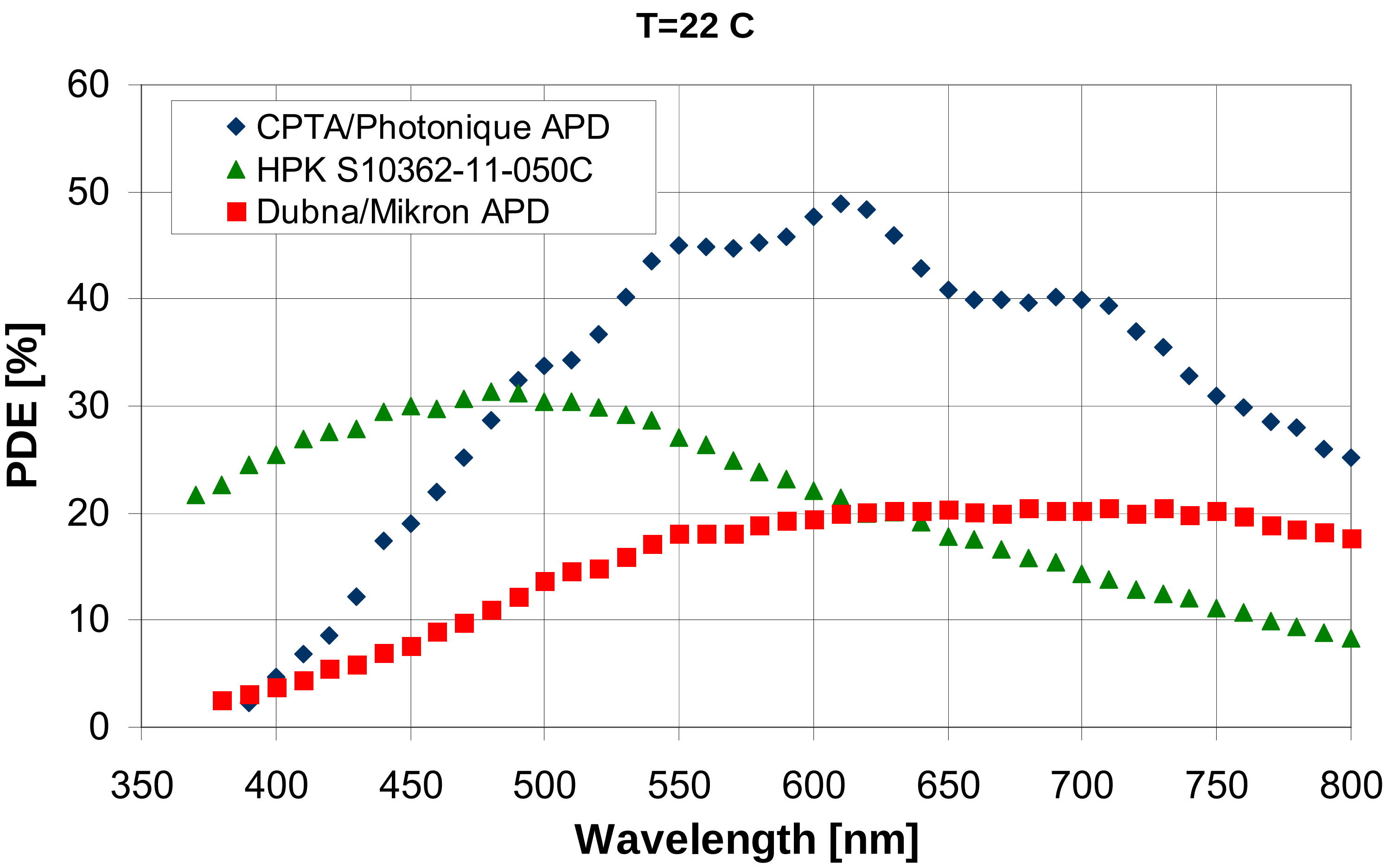

Dubna/Mikron APD (pMP-3d-11)


S10362-11-050C HPK MPPC

G-APDs spectral response (I)

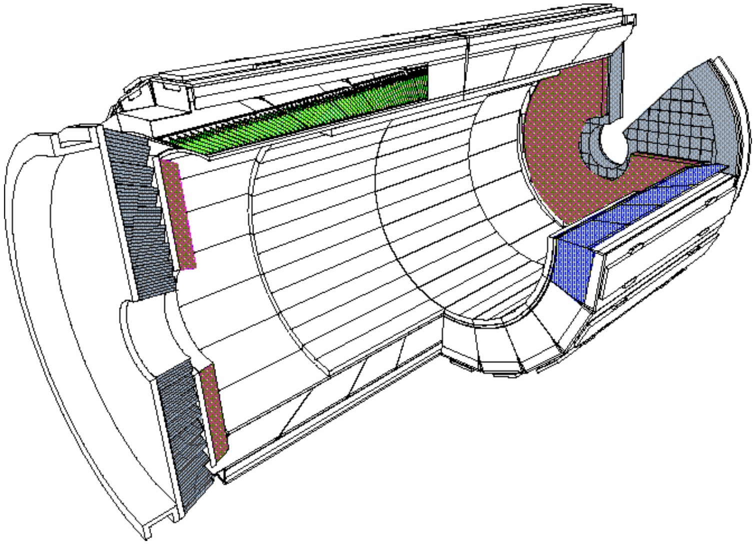
For the spectral response measurements “Optometrics” SDMC1-03 spectrophotometer was used. We also used a calibrated PIN photodiode as a reference. Spectrophotometer light intensity was significantly reduced using gray filters to the level when the maximum current measured with the APD was only ~30% higher than its dark current. This was done to avoid the non-linearity effects caused by high pixel illumination. Photocurrent measured with the APD was compared with the photocurrent measured with the PIN photodiode. In addition the measurements with the LED pulsed light were used for absolute spectral response calibration (at least 2 different LED measurements were done for each APD).

G-APDs spectral response (II)

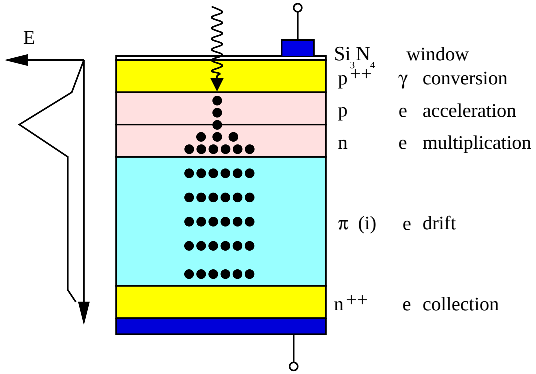


S8148 HPK APD developed for the CMS experiment

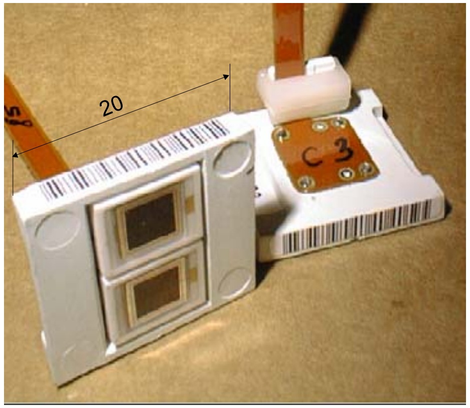
The CMS electromagnetic calorimeter was built with $PbWO_4$ crystals.
61,200 barrel crystals to read out.
Two APD’s per crystal mounted in capsules



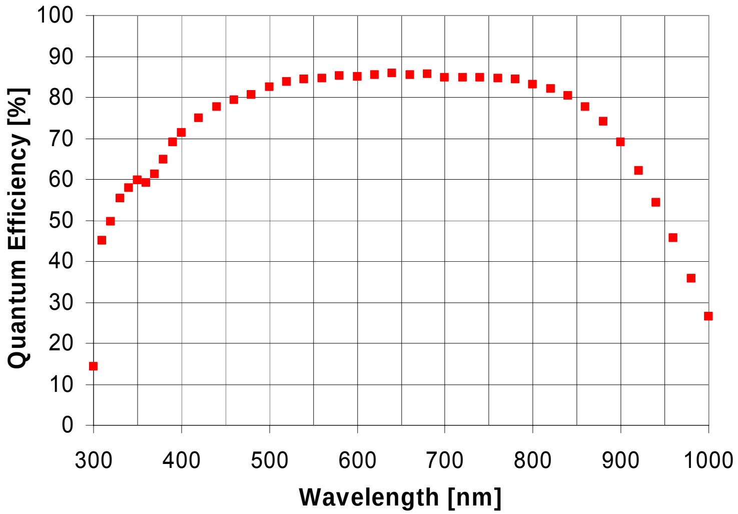
Schematic structure of APD

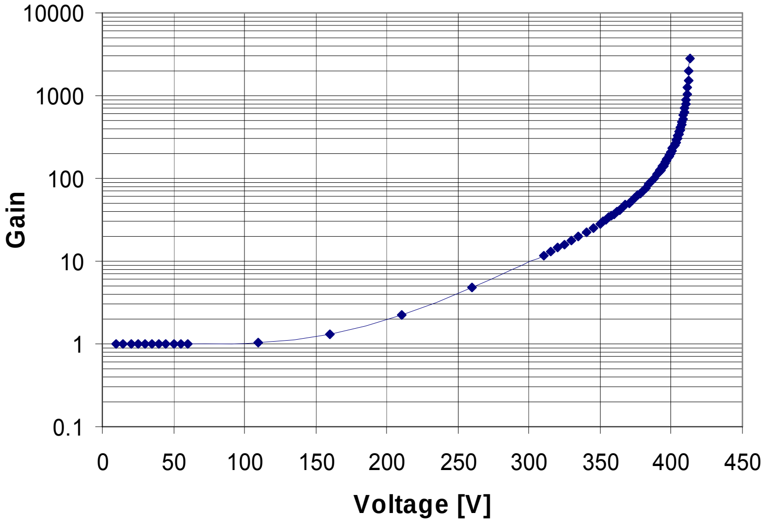


Capsule with 2 APD’s



S8148 performances (I)



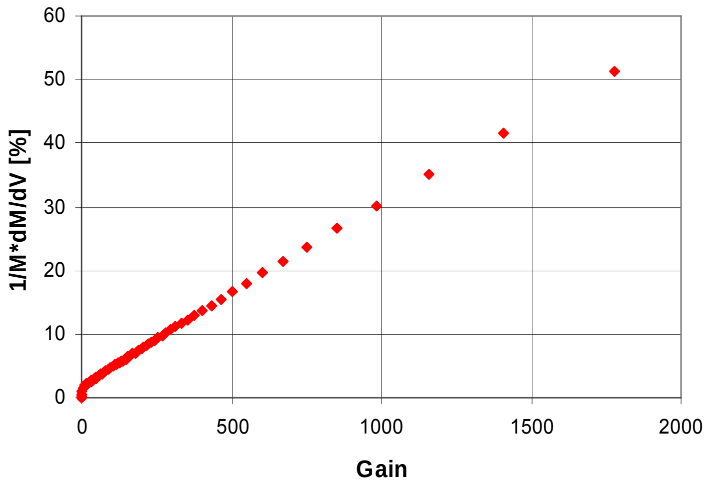


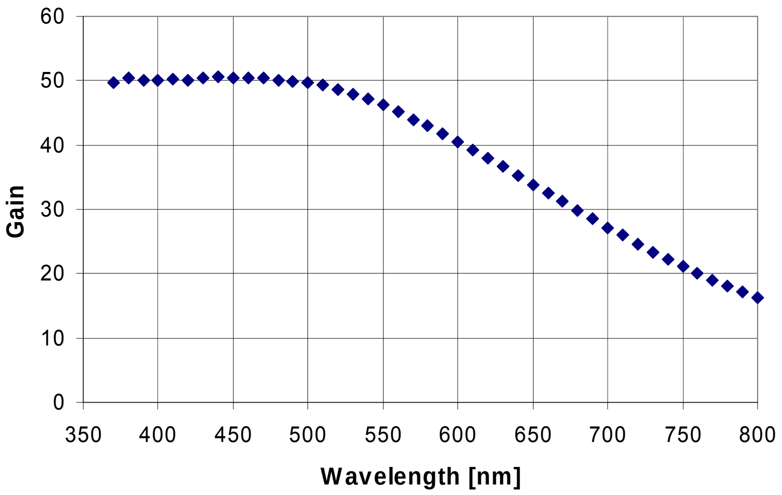
Summary of APD parameters

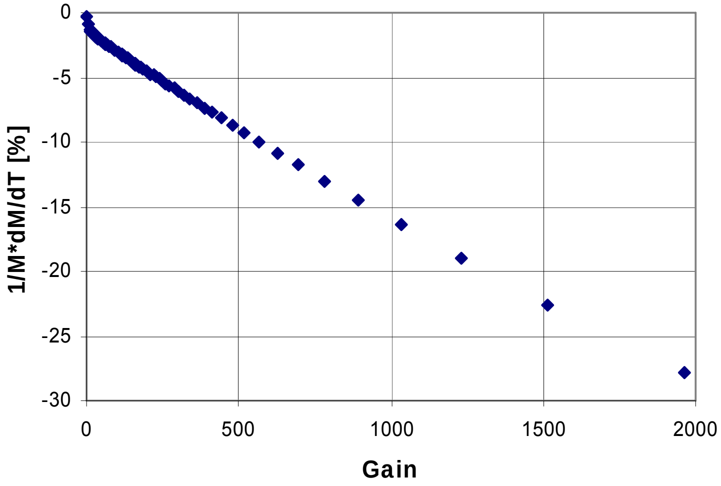
Active Area	$5x5\ mm^2$
Operating Voltage @ M=50	~380 V
Capacitance @ M=50	80 pF
Serial Resistance	< 10 Ω
Dark Current @ M=50	< 10 nA
Excess Noise Factor @ M=50	2.1
Quantum Efficiency @ 420 nm	73 %
dM/dV x 1/M @ M=50	3.1 %
dM/dT x 1/M @ M=50	-2.4 %

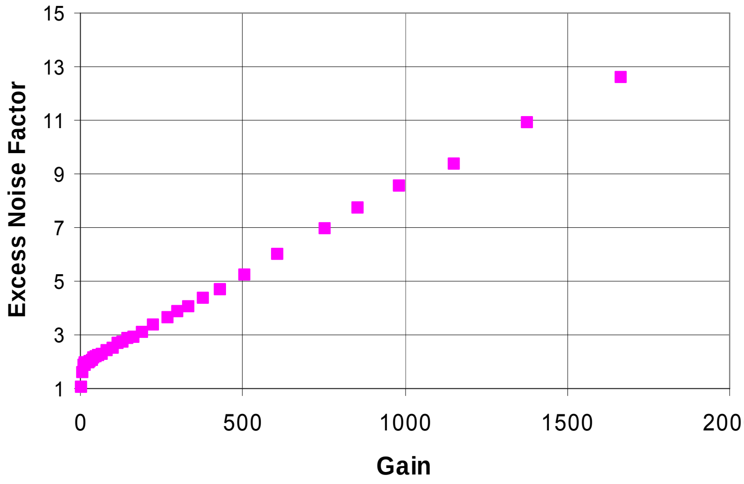
K. Deiters et al.,
NIM, A461 (2001) 574

S8148 performances (II)









Summary

- Recently developed G-APDs from 3 producers were studied in CERN APD Lab using technique developed by our group
- Such G-APD parameters as photon detection efficiency, excess noise factor, dark count, gain, voltage coefficient of the gain, temperature coefficient of the gain and their dependence on the bias voltage were measured for 3 G-APDs at room temperature
- Dependences of the G-APDs PDEs on the wavelength of light were also measured
- Main parameters of the S8148 HPK APD operated in linear mode were presented and compared with the parameters of the G-APDs