

Light Sensors for the CTA Project

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The most complex light sensors



These seemingly best-known imaging light sensors measure colour in the a relatively wide band (400 – 700 nm) as well as the light intensity within a

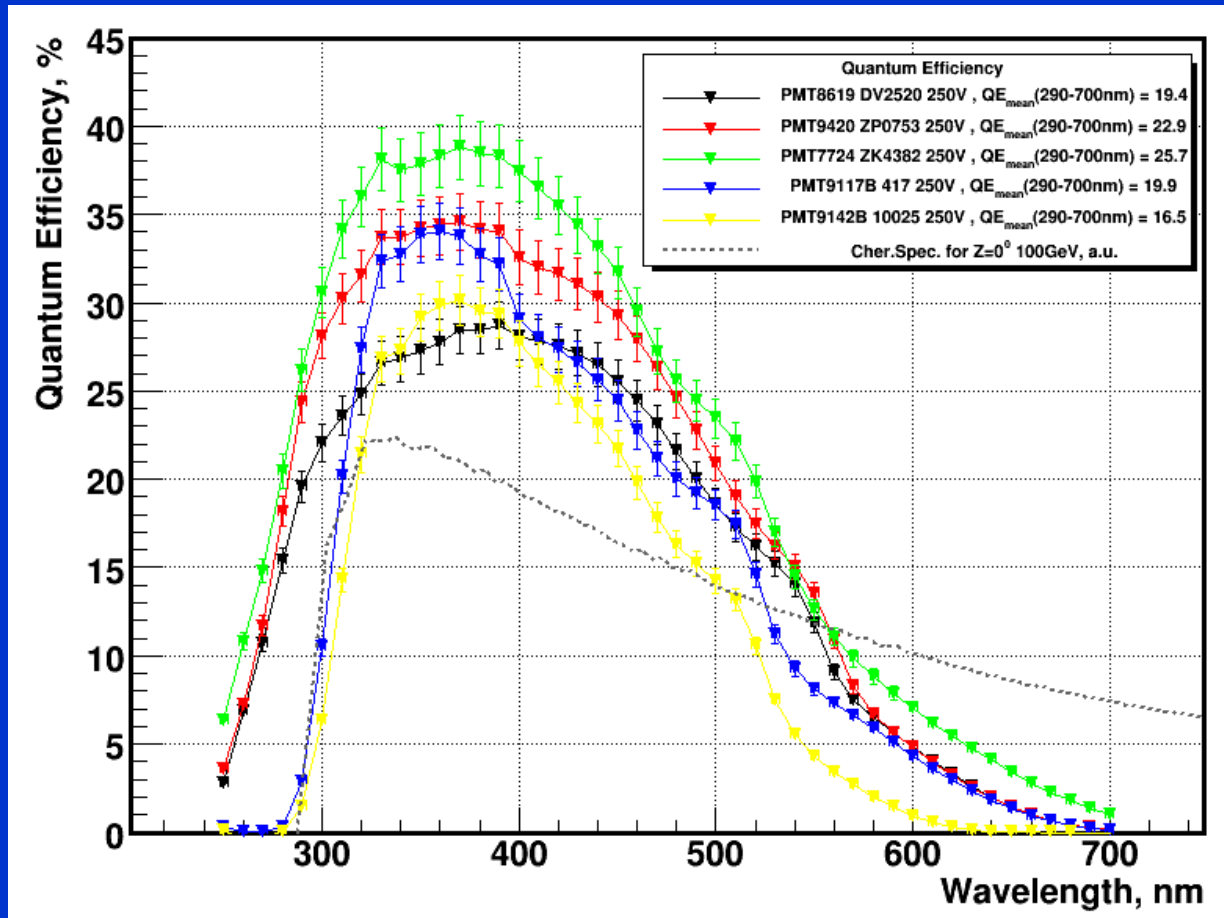
- dynamic range of 13 orders of magnitude !
- angular resolution $\sim 1'$ (oculists call it 100 % sight)
- integration time ≥ 30 ms,
- threshold value for signals
 - 5-7 green photons (after few hours adaptation in the darkness)
 - 30 photons on average in the dark

Photograph of the 576-pixel imaging camera of MAGIC-I. In the central part one can see the 396 high resolution pixels of 0.10° size. Those are surrounded by 180 pixels of 0.20° .



Instrumental/technological improvements

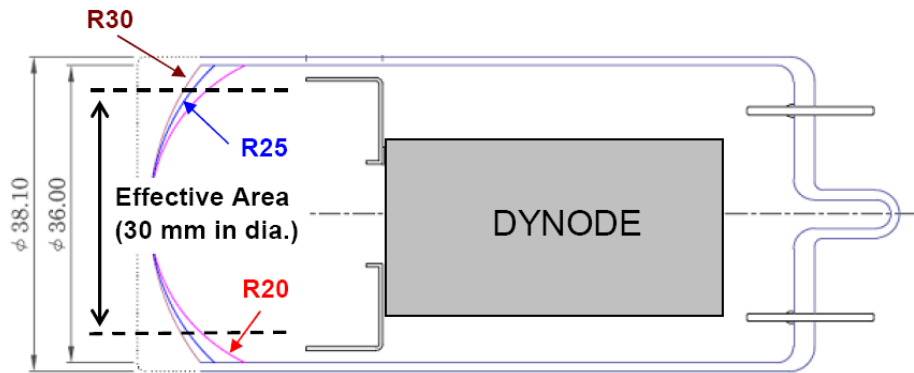
Running target: light sensor improvements. Successfully pushing the PDE higher up. Shown for several types of PMTs



- Some 6 years ago we have launched a QE improvement program with manufacturers Hamamatsu (Japan), Photonis (France) and Electron Tubes Enterprises (England).
- The results were very encouraging
- Since about 1.5 years a new program has been launched for CTA; the results are shown on the left

PMTs: improve the TTS and the Collection Efficiency

R9420MOD & R8619MOD Window Curvature vs TTS and CE



This sketch shows PC (Plano-Concave) window, but CC (Concave-Convex) window will be made for CTA experiment.



Date: Jul.14.2010

Serial Number	SK (uA/Lm)	SKb	SP (A/Lm)	Q.E. (%)			Operating Gain = 5E+04		Candidate
				300 nm	350 nm	400 nm	voltage (V)	AP/Noise(%)	
XA7105	63.9	10.6	14.3	22.5	25.7	25.5	950	0.0149	
XA7106	67.7	10.8	38.7	24.4	27.1	26.1	851	0.0133	
XA7107	96.8	12.2	56.9	24.1	26.9	26.4	845	0.0152	
XA7108	80.9	11.6	67.1	25.6	28.8	27.1	807	0.0172	
XA7110	128	14.8	71	33.3	36.4	35.2	861	0.0194	1
XA7111	77.2	11.7	47.9	24.9	28.1	27.5	827	0.0142	
XA7112	76.2	11.8	41.1	25.4	29.0	28.1	855	0.0138	
XA7113	71.9	10.5	34.4	24.9	28.0	27.2	846	0.0191	
XA7114	66.6	10.7	33.5	22.5	25.6	25.0	862	0.0223	
XA7115	85.2	12.7	53.2	28.2	32.1	31.8	821	0.0189	2
XA7116	133	14.6	72.1	32.3	34.9	33.1	876	0.0302	
XA7118	99.3	13	16.5	28.2	31.2	29.8	1005	0.0161	3
XA7119	123	14.6	54.5	33.5	36.5	34.9	896	0.0266	4
XA7120	125	14.4	49.7	31.2	33.4	31.7	882	0.0182	5
XA7121	124	14.5	59.1	31.8	34.4	32.6	863	0.0258	6
XA7122	124	14.9	43	33.8	34.1	33.0	917	0.0304	
XA7123	129	14.9	43.6	30.5	34.4	34.0	926	0.0511	
XA7124	132	15.1	33.3	31.9	35.9	35.1	954	0.0342	
XA7125	101	14.3	13.8	32.0	34.8	33.3	1027	0.0119	7
XA7126	111	14.9	47.7	33.6	37.6	36.9	884	0.0152	8
XA7127	90.1	12.9	33.2	29.1	32.8	32.6	892	0.0146	9
XA7128	73.6	11.7	18.8	26.4	29.9	29.3	922	0.0282	
XA7129	80.7	12.1	19.5	26.8	30.4	29.8	930	0.0186	10
XA7130	99.1	14.1	21.1	31.8	35.9	35.2	964	0.0135	11
XA7131	101	14	26.7	32.6	36.2	35.1	951	0.0137	12
XA7132	99.6	13.9	12.6	32.5	35.5	34.2	1034	0.0139	13
XA7133	103	14.5	22.1	34.4	38.4	37.4	960	0.0152	14
Ave-1	98.6	13.2	38.7	29.2	32.4	31.4	904	0.0202	
Ave-2	110.4	14.1	38.5	31.5	34.7	33.6	925	0.0215	

Ave-1: Average of all tubes

Ave-2: Average of tubes with light blue color

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HAMAMATSU
HAMAMATSU PHOTONICS K.K. Electron Tube Division

The most recent production of PMTs by Hamamatsu Photonics

Already now they came very close to requested parameters

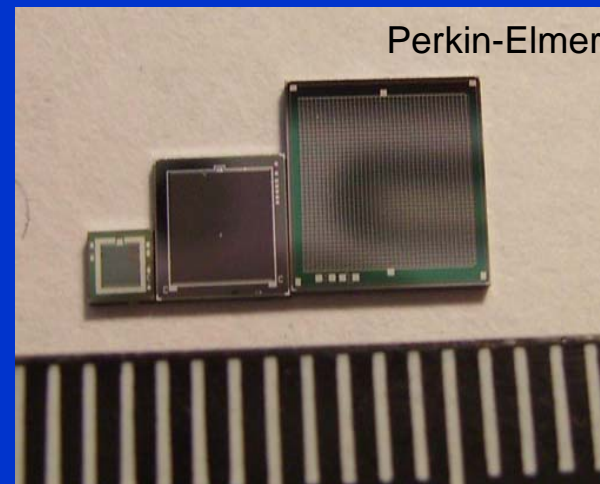
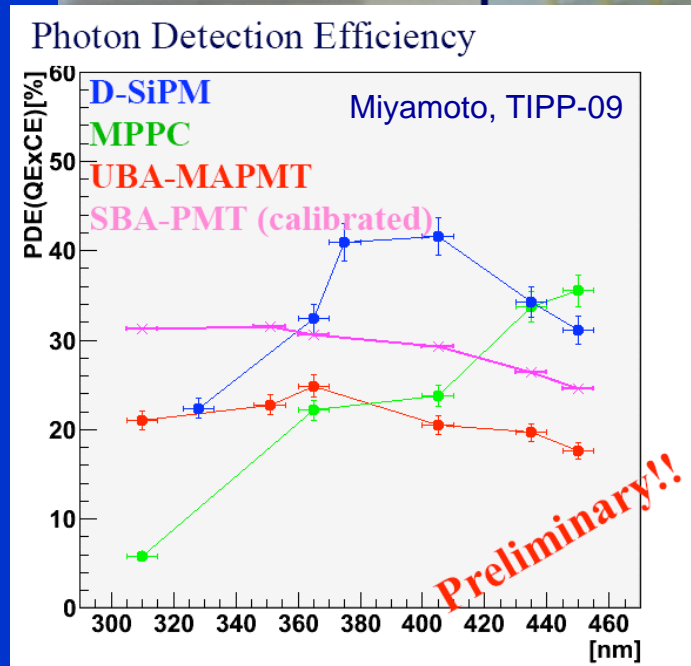
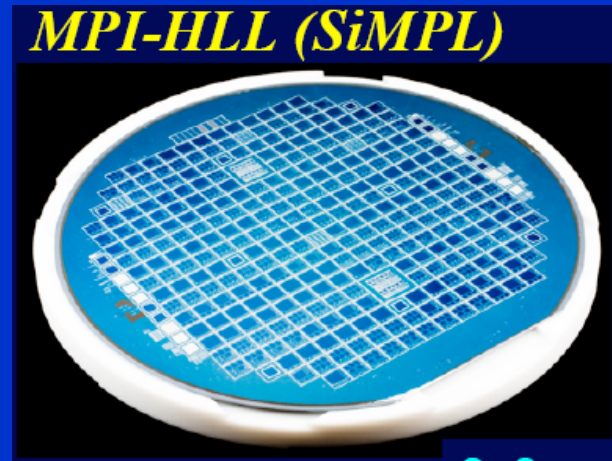
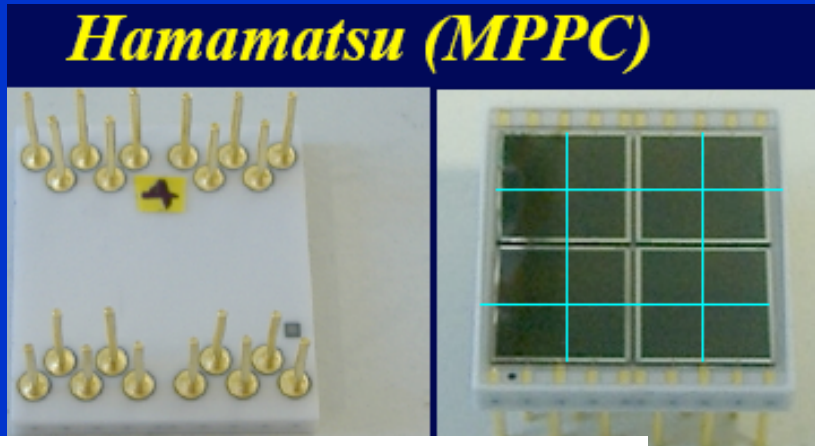
The <QE> peak is approaching ~ 35 %. The ph.e. collection efficiency is 95-98 %.

Requested afterpulsing < 0.02 %.

More improvements requested like much less variations in the gain of dynodes

Currently launching a 2-year development contracts with Hamamatsu and ETE (England)
Financial support by CTA

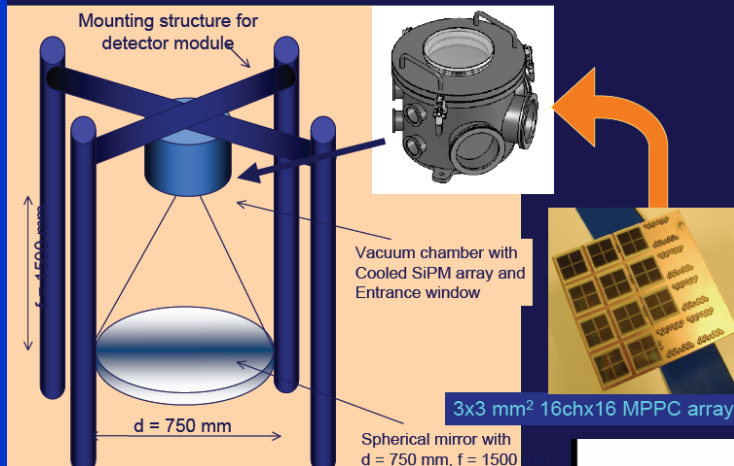
Few examples of SiPMs, still under development



SiPMs with ~ 50-60% PDE and low cross-talk (< 1%) could be anticipated already in this year

Outlook

- Telescope with MPPC array camera



4-SiPMs of 5x5 mm², includes cooling, signal shaping



A 22mmx22mm SiPM based pixel for a telescope

The same as on the left but 4-times larger



PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009

SiPM development and application for astroparticle physics experiments

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Abstract: A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to $2 \cdot 3 \times 10^6$), very low power consumption with low bias voltages (30-70V), immunity to the magnetic field. In the last few years, UV sensitive SiPMs with a p-on-n structure have been developed by a few companies such as Hamamatsu, Photonics, ZeoVite Photonics Inc., and institutes such as the MPI-HL (Max-Planck-Institute for Physics - Max-Planck-Institute Semiconductor Laboratory) as well as the MPI-MEPH (Max-Planck-Institute for Physics - Moscow Engineering Physics Institute) for astroparticle physics applications. Here the current status of the SiPM development in MPI and HL, MPI and MEPH, and the study of the application to imaging atmospheric Cherenkov telescopes (IACTs) MAGIC/MAGIC-II [1] and CTA [2], and a fluorescence telescope in the space JEM-EUSO [3] will be reported.

Keywords: Imaging Cherenkov, Imaging fluorescence, SiPM

I. INTRODUCTION

The high PDE of these devices will allow us to lower the threshold energy of gamma ray detection down to 10 - 20 GeV in case of MAGIC telescopes, and ensure the detection efficiency of UHECRs above $(2-3) \times 10^{19}$ eV

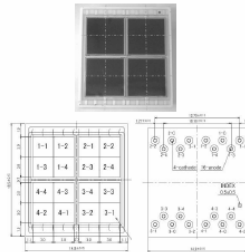


Fig. 1. Top, Left/Center: Blue print of 16ch (4x4) of 3x3 mm² MPPC array device (front/back). Bottom: Photo of 16 ch MPPC array device.

SOME EXAMPLES OF SHOWERS RECORDED BY MAGIC AND THE G-APD PIXEL

EVALUATION OF IMPROVEMENT: Shower Signals: G-APD vs PMT

NOTE: G-APD SIGNAL MUST BE CORRECTED FOR OPTICAL CROSS-TALK

FINDINGS

- The tests IN 2000-2003 have confirmed that Cherenkov light from air showers can be detected.
- P-on-n type G-APDs are available now with high sensitivity in the "blue", matched to Cherenkov spectrum (but UV sensitivity can still be raised by design or use of WLS)
- Tests confirmed 2x gain compared to flat window, standard bakelite PMTs, about a factor 1.6 improvement compared to advanced hemispherical pins with diffuse lacquer coating and special light collectors as in the MAGIC camera (the 50chx50ch MPPC)
- No cooling necessary: intrinsic noise = night sky illumination rate
- Clip cable or dUT. Amplifier allows to shorten pulse width
- The currently available densely packed arrangement of 16 MPPCs of 3x3 mm each is already suitable for pixels of a high resolution imaging camera in IACTs

Further improvements of G-APDs for very astronomy possible:

- Widening of high PDE spectral range
- Adding WLS in plastic coating to enhance UV sensitivity
- Blue-time of < 1 ns
- faster recovery time
- Use of micro-lenses or micro light-catchers to overcome dead-area between cells -> higher PDE -> further increase in PDE by 20-30% (provided if previous are used)
- 5ch or 10x10 mm MPPC with 100x100 μm cell size but no degradation in read time

NOTE THE MAIN PROBLEM: G-APDs CAN HAVE A HIGH QE OVER WIDE SPECTRAL RANGE BUT THE CURRENTLY TOO HIGH GAIN OF LARGE CELL TYPE DEVICES PREVENTS THE OPERATION AT HIGH OVERVOLTAGE

- PDE IS WELL BELOW QE BECAUSE HIGH GAIN CAUSES HIGH OPTICAL CROSS-TALK (=0 PHOTONS/10⁹)
- MUST OPERATE G-APDS WITH LOW OVERVOLTAGE
- THE KEY REQUIREMENT: LOWER THE GAIN PER CELL OF 100x100 μm TO OPERATE AT < 4 V

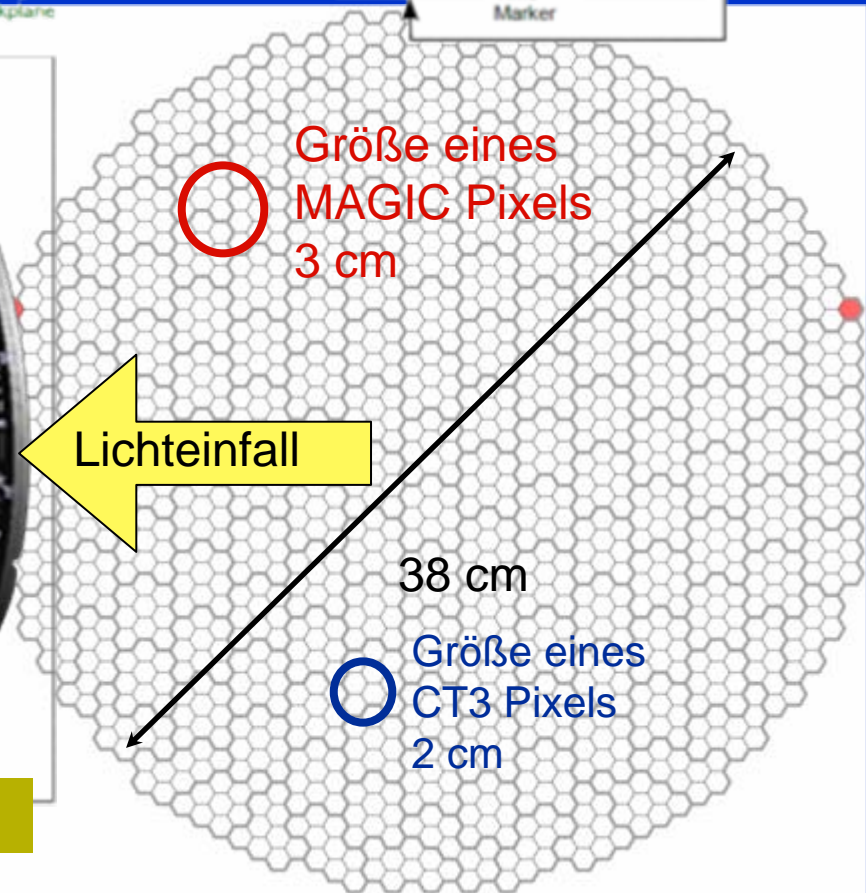
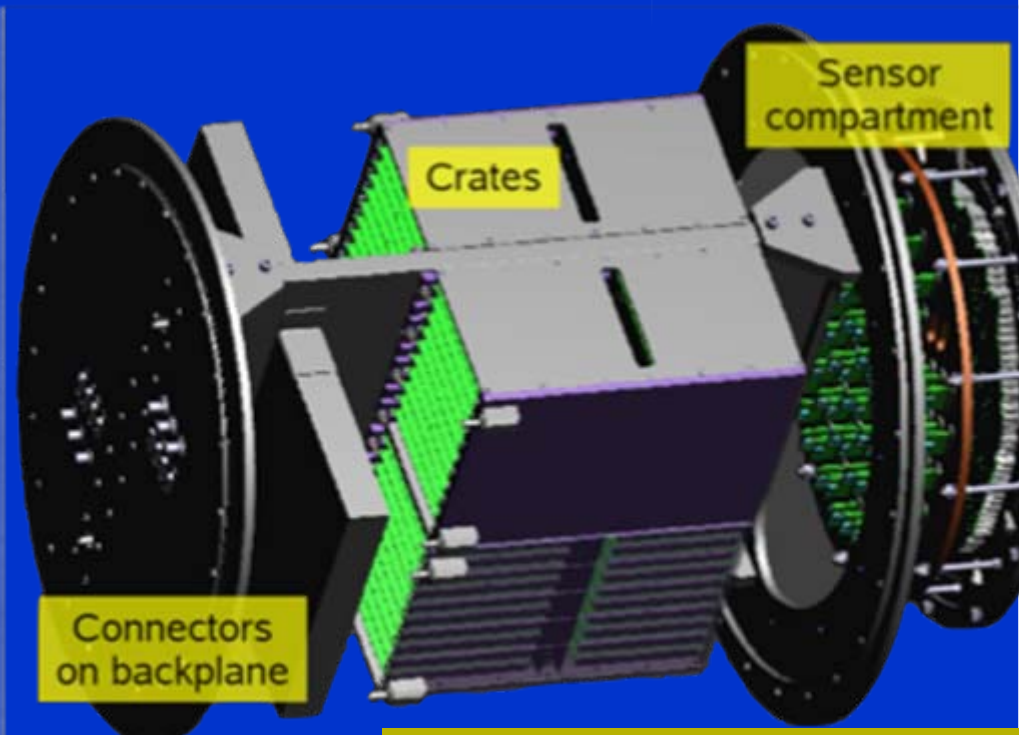
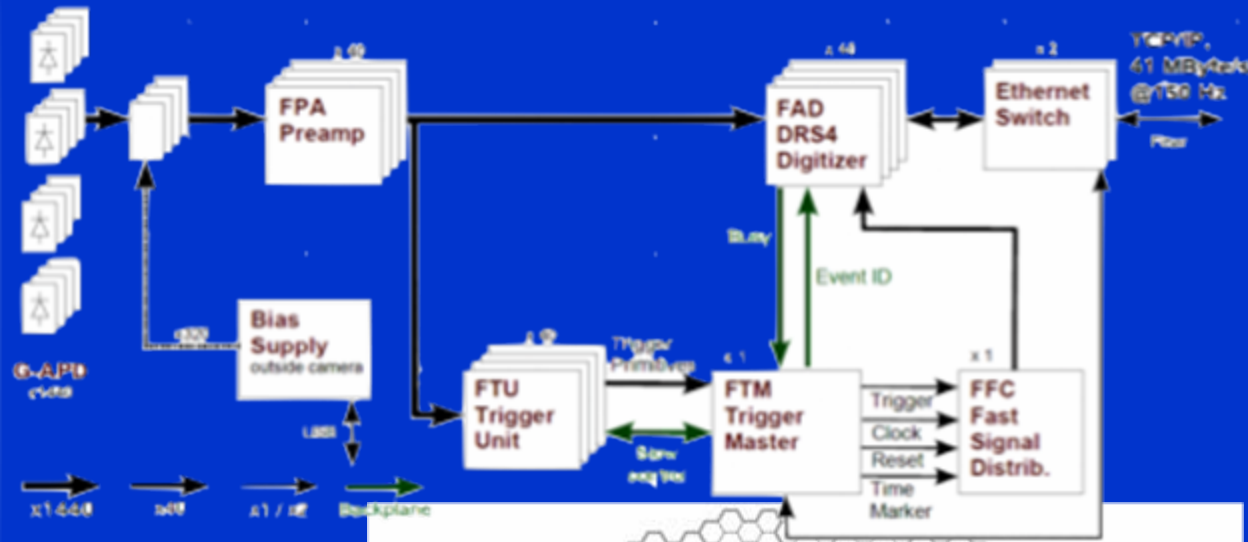
PDE collection efficiency

CE G-APD	0.65
CE w/ Ba PMT	0.9
CE ShS PMT	0.9
CE ET RICH PMT	
Qv Magic	0.95
CE w/ Ba PMT	
Mesh diodes	0.65

CONCLUSIONS:

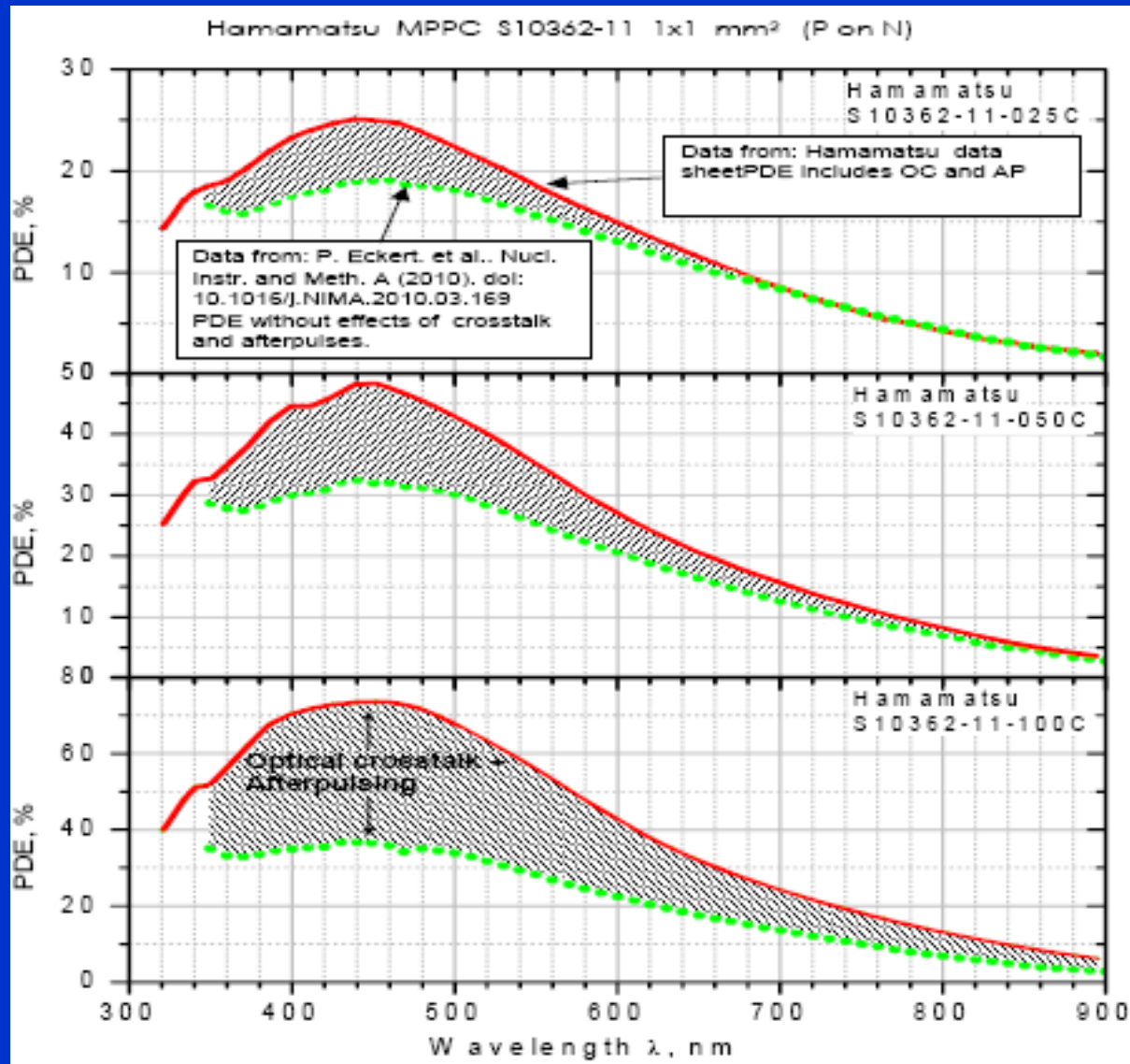
2010: 1440-Pixel G-APD-Kamera

DAQ in Kamera integriert



Detail structure of the camera

High Optical cross-talk and afterpulsing

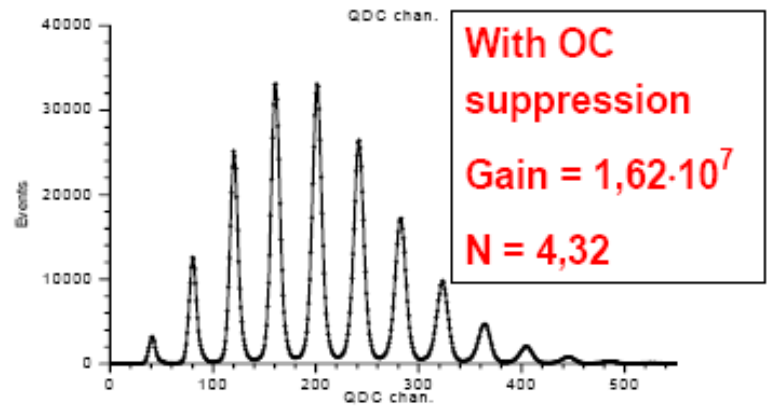
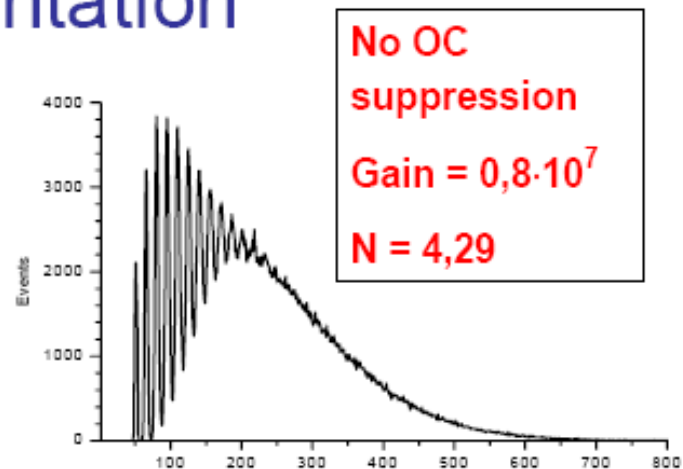
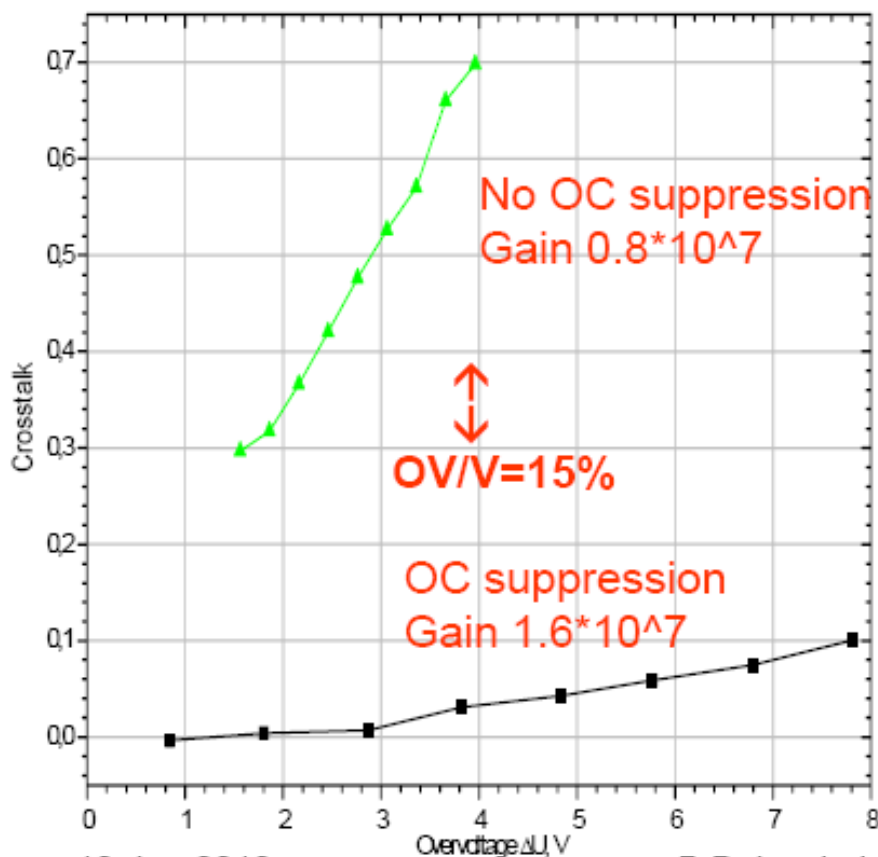


Current status of SiPM and the prospects

- Currently there is a lot of enthusiasm about the new devices but the deep understanding is not simple, it comes only slowly
- It is not easy to measure the PDE, that shall be disentangled from the X-talk and afterpulsing.
- The afterpulsing in PMTs is a ~1% effect (@single ph.e.) while for current MPPC's (Hamamatsu) it is a 20-30 %
- Often real value of PDE is \ll than the claimed (advertised) one. The reason is low applied overvoltage.
- For ~100 % Geiger efficiency and a high PDE one needs to apply overvoltage ~15 %. Most commercially available devices cannot do this yet
- Hamamatsu, Philips, Perkin-Elmer, Zecodec,... and more companies are working on it.

Prompt OC suppression using Si damaged by ion implantation

(Patent pending)



SiPM 1x1 mm²

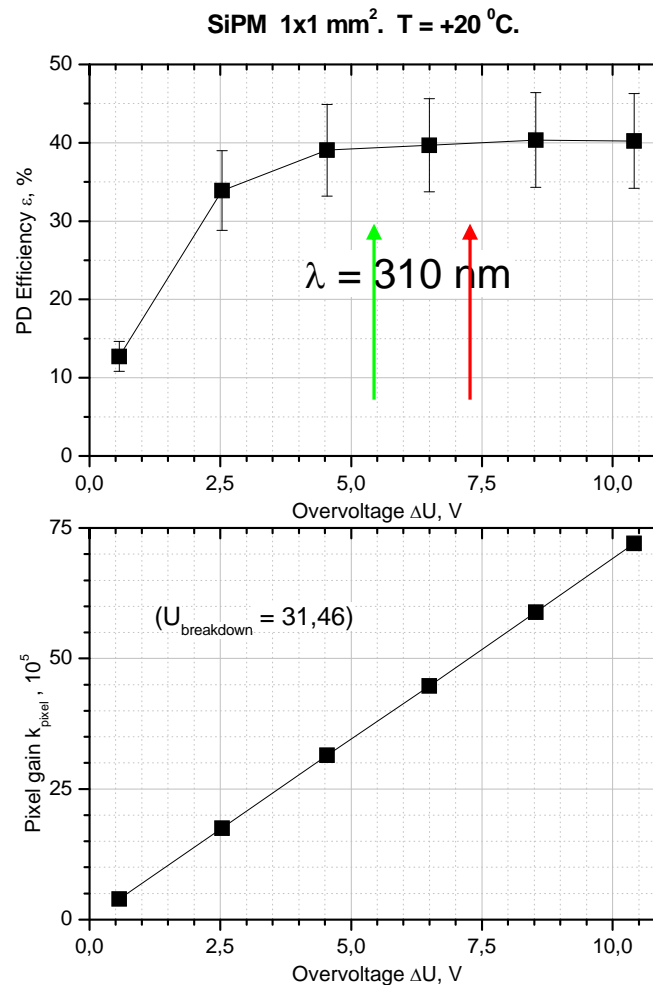
10-Jun-2010

B.Dolgoshein Silicon PM

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A PDE and gain of a 1x1 mm² SiPM produced by team of Dolgoshein in cooperation with PEI measured at +20°C

Overvoltage = operational voltage – breakdown voltage



→ Overvoltage +15%

→ Overvoltage +20%

Conclusions

- It is very likely that in a time scale 1-2 years from now one can buy SiPMs with outstanding characteristics, probably from several manufacturers.
- Their sizes could span initially 1-3-5 mm, but later perhaps also until 8-10 mm.
- SiPM cost will be reduced due to the availability of full CMOS designs. Several USD per mm² is not unrealistic.
- They could offer PDE of 60-65 %, x-talk < 1% and low temperature and voltage dependences.
- These devices are going to substitute classical PMTs and APD in many applications, including those in physics instrumentation in, for example, nuclear medicine (time-of-flight PET,...).

Optical Crosstalk OC

P. Buzhan, B. Dolgoshein, et al., 2009

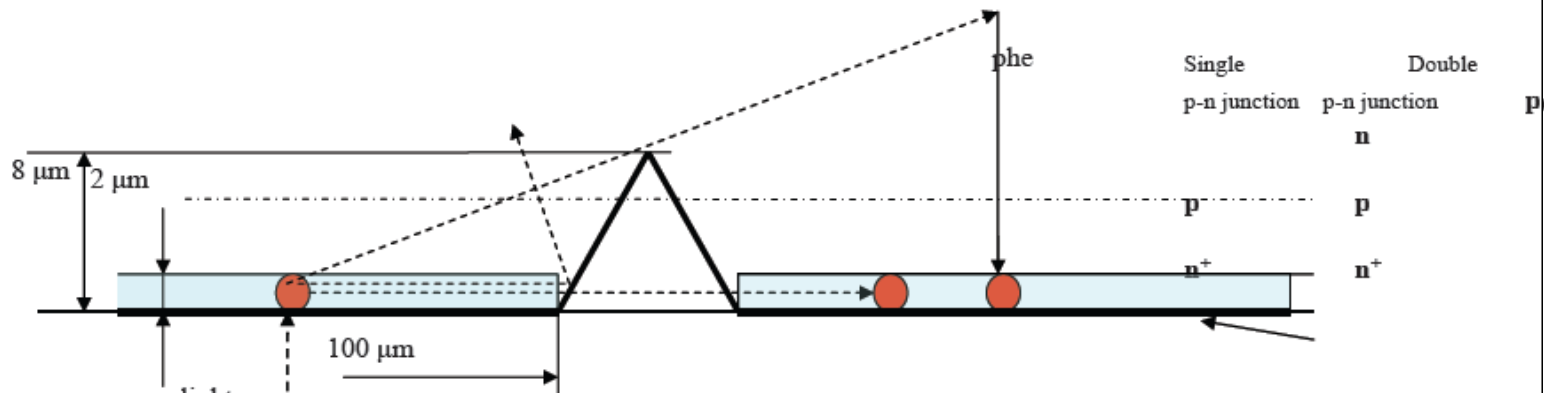
OC has two components

FIRST: phe's are induced in high electric field depletion region of neighbouring pixels

→ this mechanism is very fast: $\sim 1\text{ns}$ (prompt OC)

SECOND: The same in undepleted region and then the diffusion (or drift) to high electric field Geiger region of neighbouring pixels

→ this process is delayed: later than 1ns

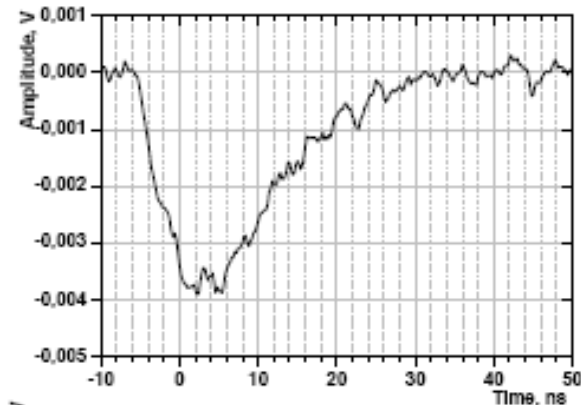


Timing by 5x5mm² SiPM: signal shape

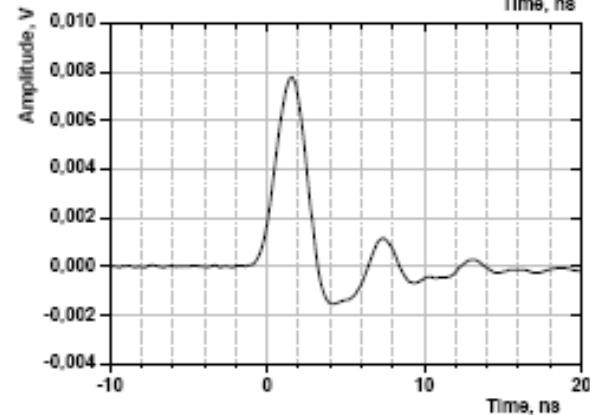
→ Because high SiPM output capacitance (~160pF)

a special FE electronics has been developed:

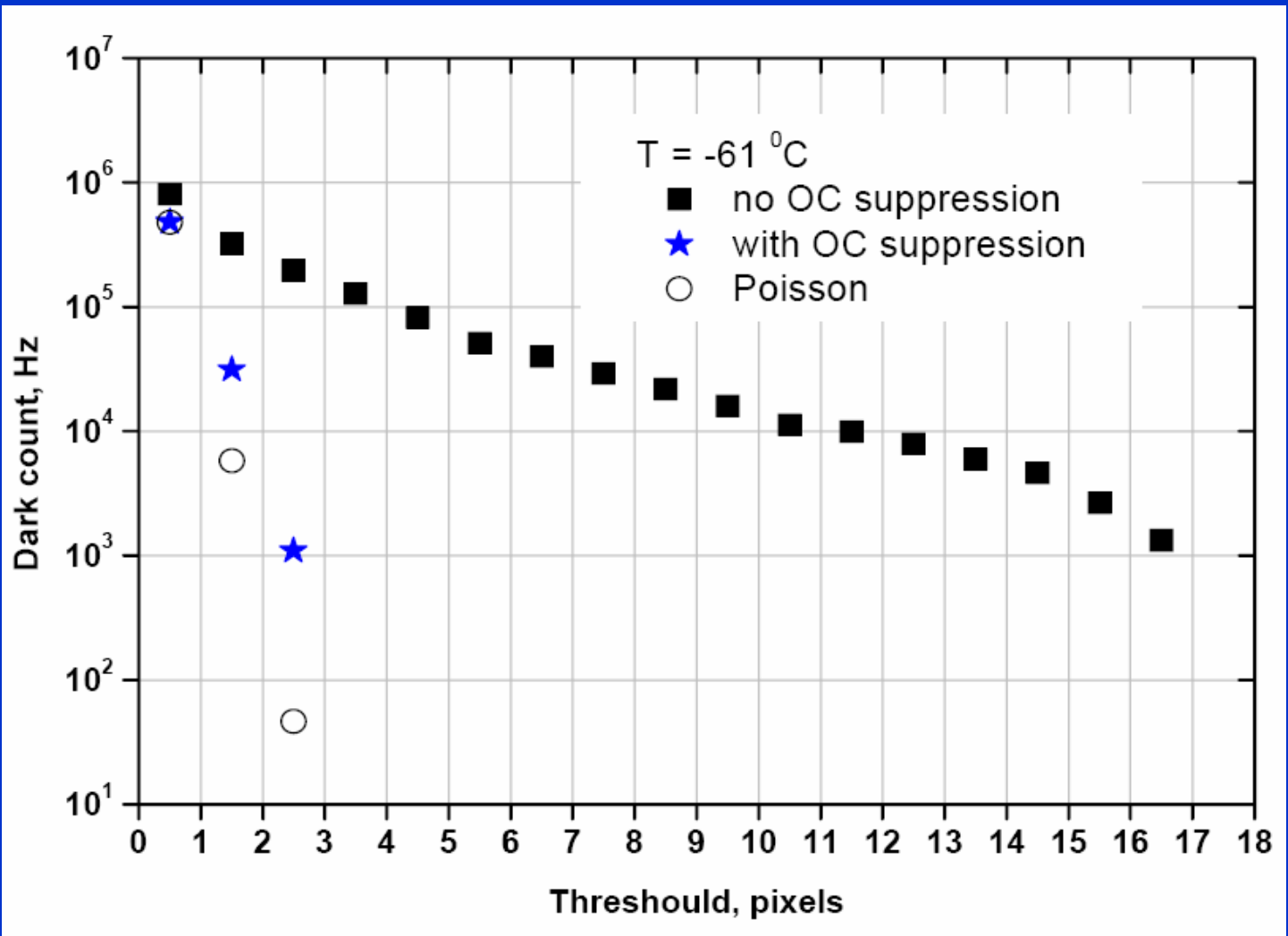
low input impedance (a few Ohm)
current amplifier+shaper



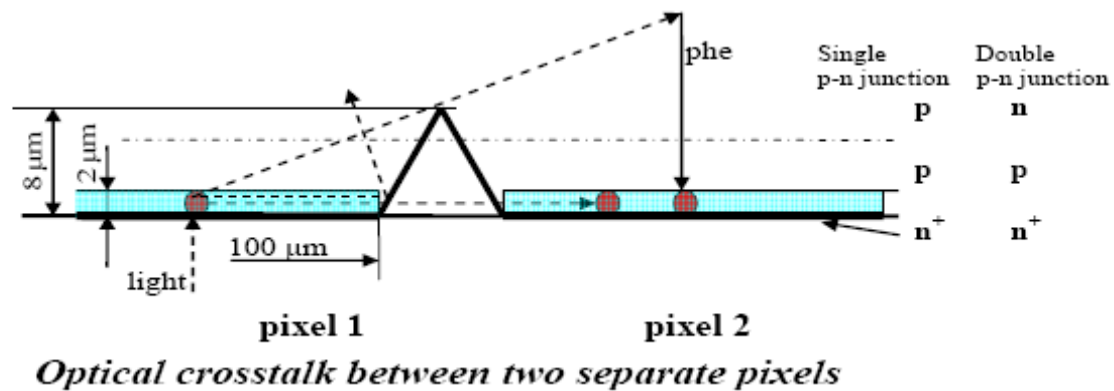
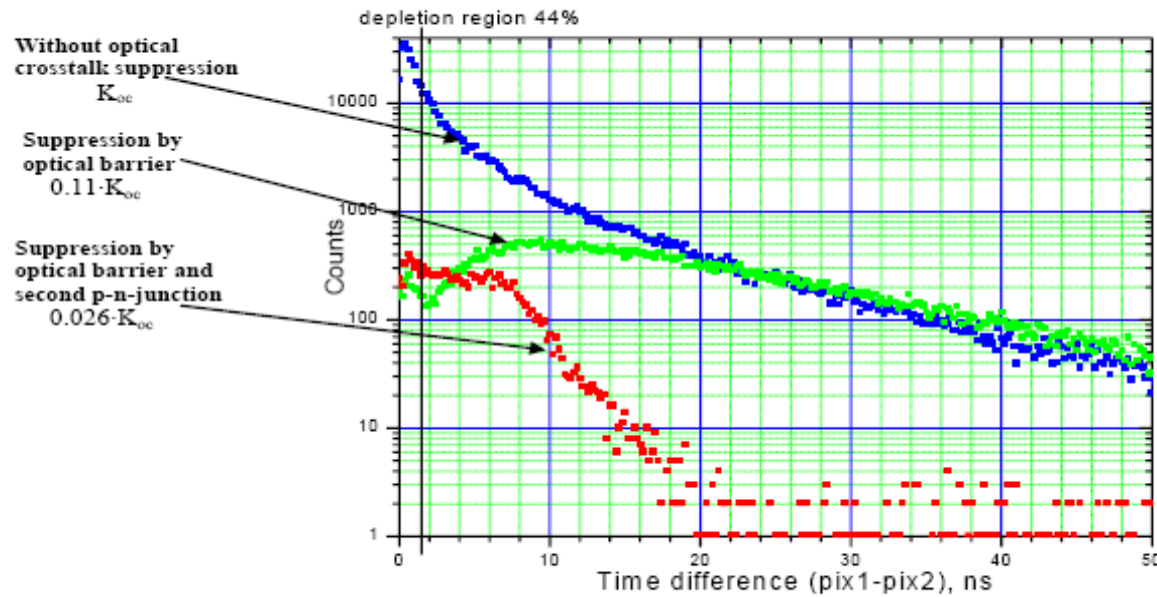
50 Ohm
FWHM
15ns



~ 7 Ohm
+shaper
FWHM
2,5ns



Optical Crosstalk studies



Results of Optical Crosstalk studies

two separated pixels
pixel size 100 μ m, pitch 130 μ m
gain 2×10^7
recovery time $> 1\text{ms}$
PDE=35%

OPTICAL CROSSTALK:

- prompt ($< \sim 1\text{ns}$ phe in depletion region) ~50%
- delayed ($> \sim 1\text{ns}$) ~50%

OPTICAL CROSSTALK

SUPPRESSION FACTOR:

- with optical barriers (tranches, 8 μ m deep) ~9
- with optical barriers + second n-p junction ~4.5
- Total: ~40

Digital SiPM

→ single pixel dark count rate is lower by factor of 1.5-2 (~physical limit)
→ digital output is more convenient for system integration

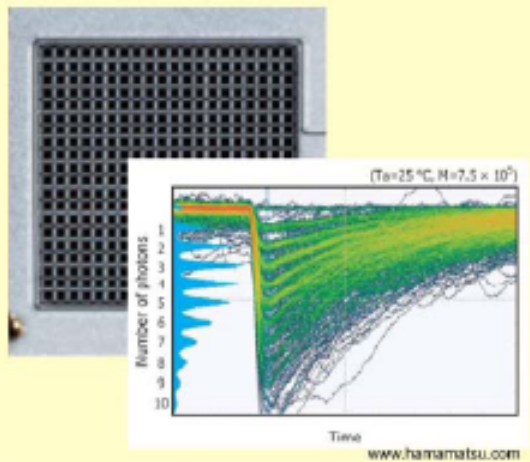
→ PDE loss (filling factor is less due to electronics on chip)
→ problems with Optical Crosstalk and Afterpulsing have to be solved

PHILIPS

Digital Photon Counting – The Concept

Intrinsically, the SiPM is a digital device: a single cell breaks down or not

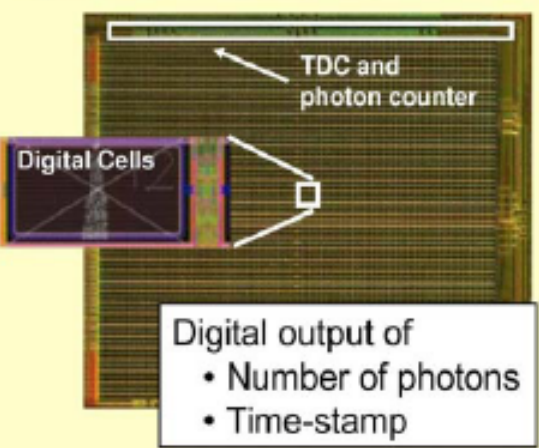
analog SiPM



The image shows a physical analog SiPM chip on the left. To its right is a plot of 'Number of photons' versus 'Time'. The plot shows a series of pulses, with a color-coded area under the curve. Text in the plot indicates $(T_{\text{arr}}=25^{\circ}\text{C}, M=7.5 \times 10^2)$. The y-axis ranges from 0 to 10, and the x-axis is labeled 'Time'. The website www.hamamatsu.com is mentioned at the bottom of the plot.

Summing all cell outputs leads to an analog output signal and limited performance

digital SiPM (dSiPM)



The image shows a physical digital SiPM chip on the left. To its right is a diagram of a readout electronics block labeled 'Digital Cells'. An arrow points from the chip to the electronics. The electronics block is labeled 'TDC and photon counter'. Below the electronics, a box lists the 'Digital output of' as:

- Number of photons
- Time-stamp

Integrated readout electronics is the key element to superior detector performance

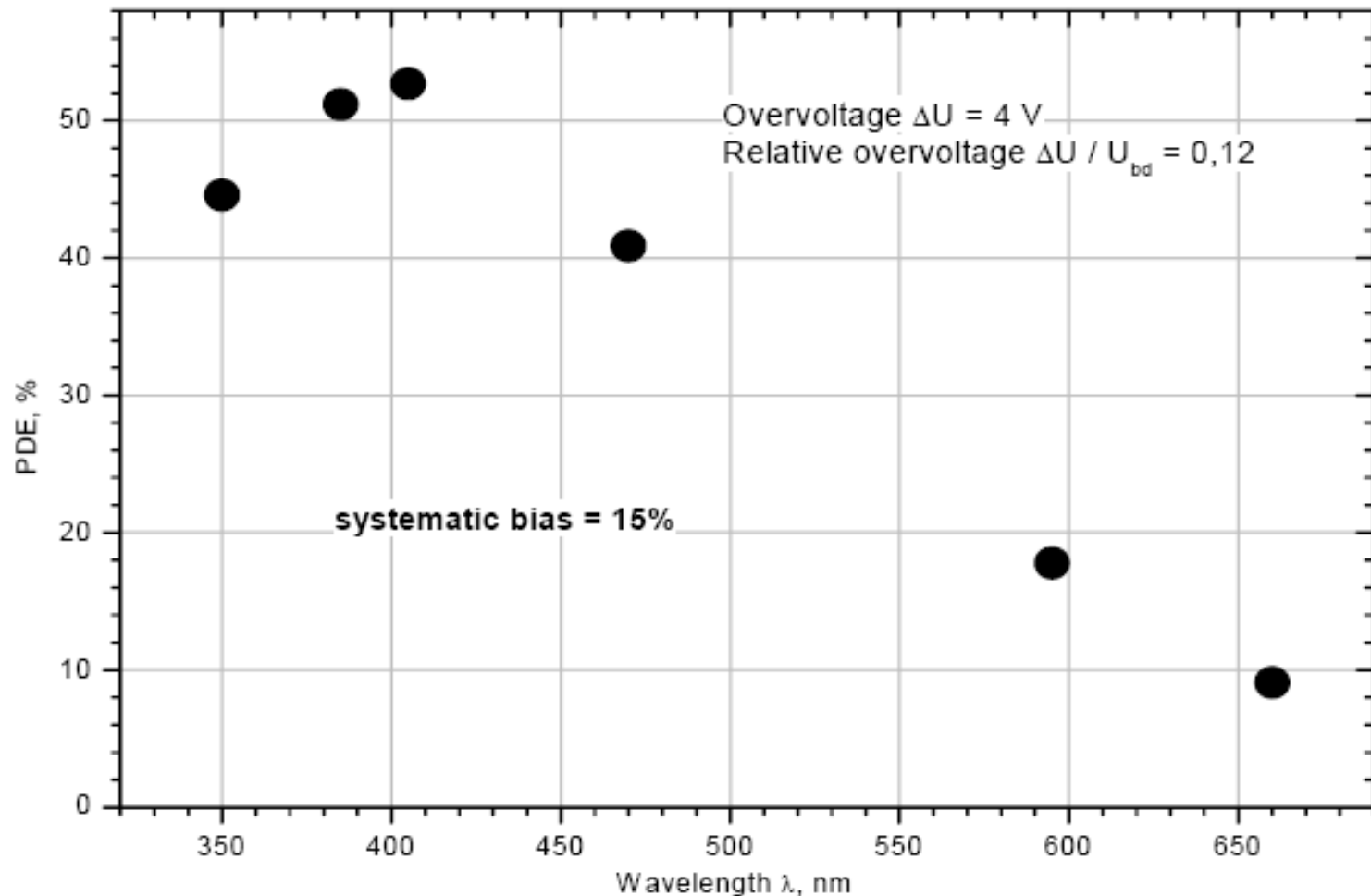
www.philips.com/digitalphotoncounting

Philips Digital Photon Counting, October 27th, 2009

Fabrication cost?

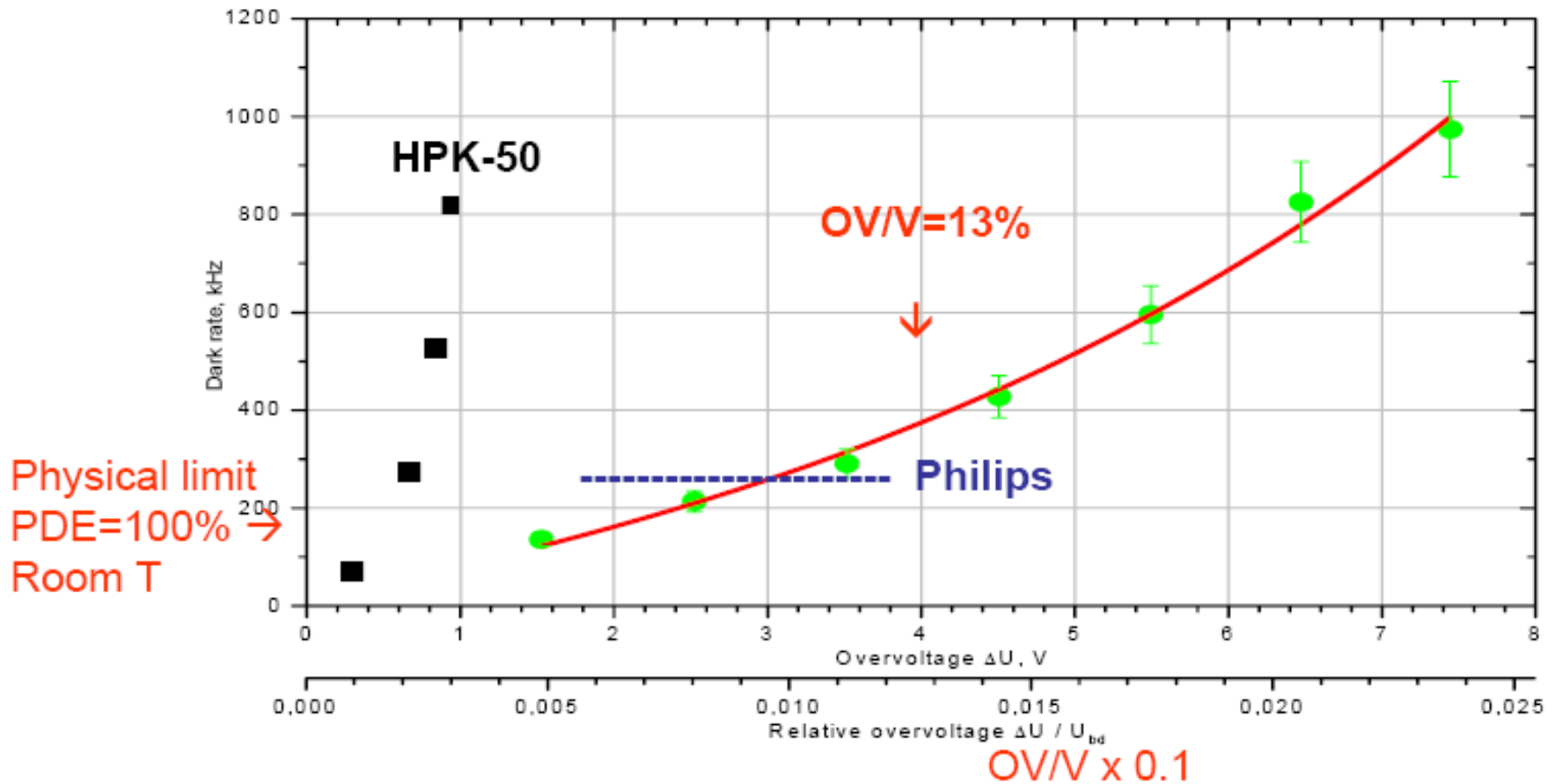
PDE ,SiPM p on n,3x3 mm², OV/V=12% +OC suppression Test-product of PEI

SiPM 3x3 mm² P on N (pixel size 100x100 μm, geom. eff. = 0,6) T = -50 °C



Dark count rate: SiPM 1x1mm², OC=4%, AP=1% room temperature

SiPM 1x1 mm² P on N, (pixel size size 100x100 μm) with OC and AP suppression



The 17m \emptyset MAGIC IACT project for VHE γ astrophysics at $E \sim 25 \text{ GeV} - 30 \text{ TeV}$

wwwmagic.mppmu.mpg.de



Thursday 21th October
2010

R. Mirzoyan: Light Sensors for the
CTA Project

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