SiPM based detectors in science

1st Quali-Start-Up Science Lectures

September 15, 2017 | Daniel Durini

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- What kind of radiations do we normally want to detect in different scientific experiments… and how can we do it
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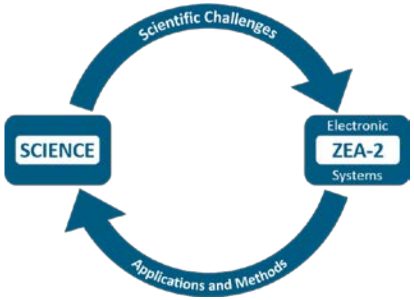
- How do we use SiPMs at the ZEA-2?

ZEA-2 – System House for Science

We develop complex electronic and information technology system solutions for science and research.

These systems incorporate the aquistion of a physical event up to the extraction of information.

The application comprehensive concepts are based on existing as well as in-house developed technologies.



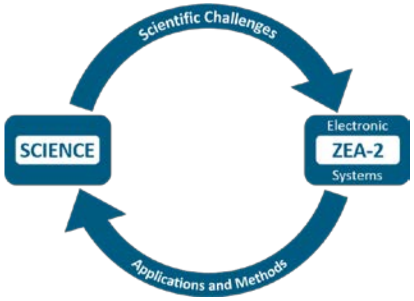
ZEA-2 – System House for Science

Facts & Figures

- Approx. 90 employees
  - approx. 50 scientists, engineers und technicians
  - approx. 10 PhD students
  - approx. 13 students
  - 4 administrative staff members
  - approx. 15 apprentices
- Tasks inside Forschungszentrums Jülich
  - Development projects in all research areas
  - Third-party projects for pre-development
  - Supply of internal services
    - IT, prototype manufacturing, mechanical workshop

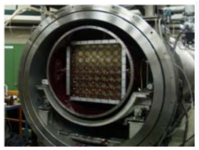
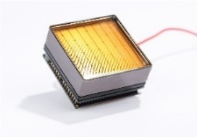
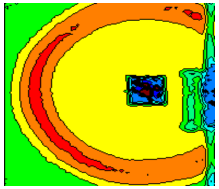
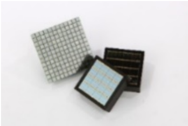
Capabilities

- Application Knowledge
  - Detector systems (From sensor to GUI)
  - Control and measurement methodologies
- Hardware Systems
  - Analog, Digital, Mixed signal, HF
  - Prototype lab, PCB design, SMD assembly
  - FPGA based readout electronics
  - Fast bus systems and optical links
- Software Systems
- Microelectronics
  - Chip design team
  - Prototype test facility
- Modelling and Simulation

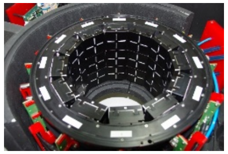


ZEA-2 – Detector Systems

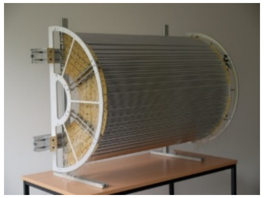
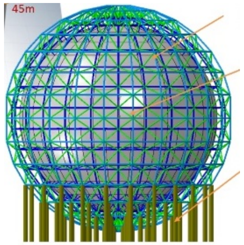
Neutron Detection

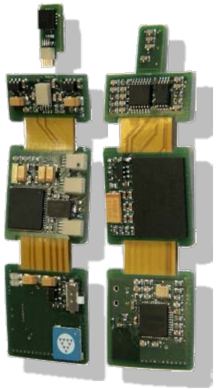
Detector Systems for Positron Emission Tomography (PET)



Detection Technology in Nuclear and Particle Physics


Environmental Imaging




- ZEA-2 develops complex, modular and large-scale networked detector systems using state-of-the-art implementation methods and generic approaches including silicon (semiconductor) based high integration ("System-on-Chip") solutions
- Our systems include all the stages required by a scientific instrument, starting with the detection of the physical event and ending with the extraction of information and a digital user interface
- The great variety of applications and an interdisciplinary team are great assets that allow us getting the most out of designed experimental environments
- Our system solutions rely on commercially available technologies as well as on self-developed ones

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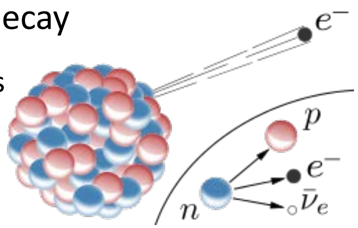
JÜLICH
FORSCHUNGSZENTRUM

What kind of radiation do we normally want to detect in different scientific experiments

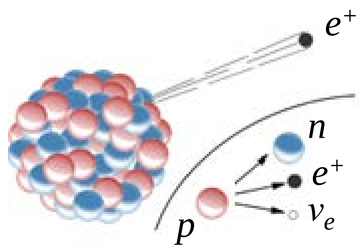
Charged particulate radiation

Fast electrons:

- Beta (β) particles (positive –*positrons*- or negative –*electrons*-) emitted in nuclear decay
  - ➢ An unstable atomic nucleus with an excess of neutrons may undergo β^- decay



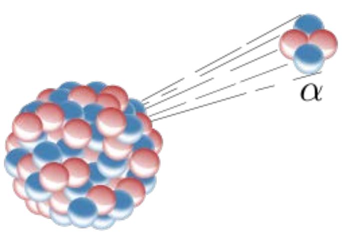
  - ➢ Unstable atomic nuclei with an excess of protons may undergo β^+ decay, also called *positron decay*

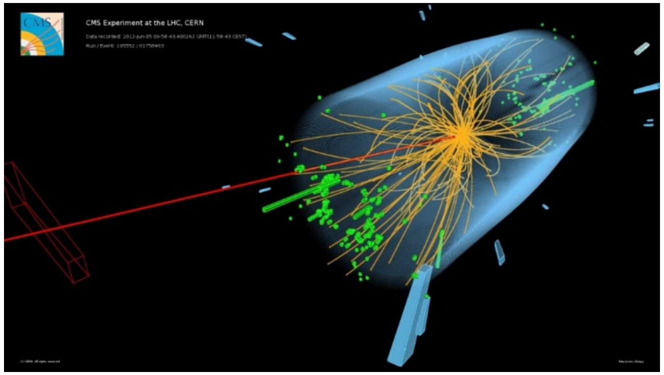


- Fast electrons produced by any other process

Heavy charged particles:

- Alpha (α) decay, radioactive decay in which an atomic nucleus emits an α-particle: nucleus of a ^{4}He atom with 2*p* + 2*n*
  - ➢ *and thereby 'decays' into an atom with a mass number that is reduced by 4 and an atomic number that is reduced by 2*



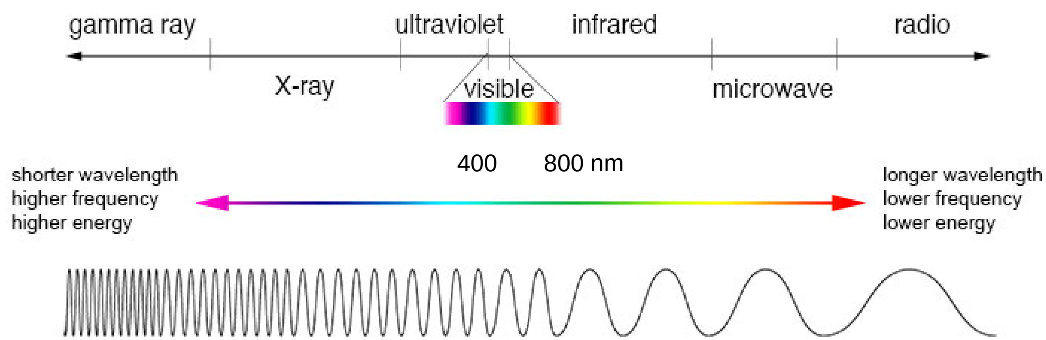


Source: G. F. Knoll, *Radiation Detection and Measurement*, 4th Ed. , Wiley, USA, 2010
Illustrations: *Wikipedia.org*

What kind of radiation do we normally want to detect in different scientific experiments

Uncharged radiation

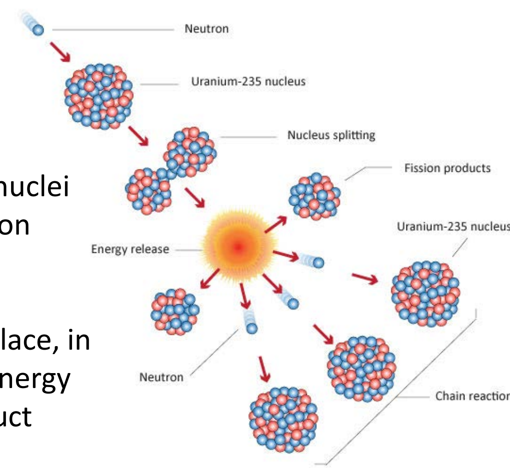
Electromagnetic radiation

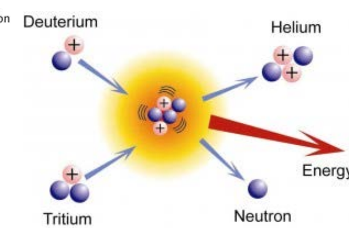


Source: http://imagine.gsfc.nasa.gov/Images/science/EM_spectrum_compare_level1_lg.jpg

Neutrons

- **Large (significant) neutron sources:**
  - **Nuclear reactors:** where spontaneous fission of certain nuclei (e.g. ^{235}U, ^{233}U or ^{239}Pu) can sustain a fission chain reaction
  - **Fusion Systems:** where a nuclear fusion reaction takes place, in which two or more atomic nuclei collide at a very high energy and fuse together producing a free neutron as a byproduct
  - **Spallation Sources:** high-flux neutron sources in which protons that have been accelerated to high energies hit a heavy target material causing the emission of neutrons



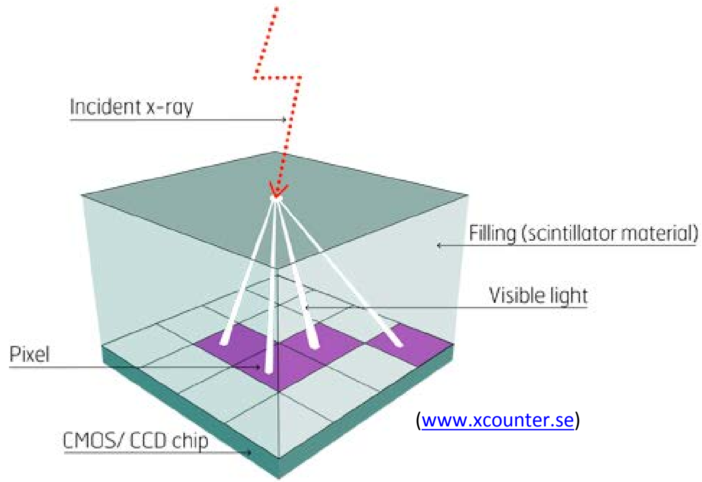


Source: http://www.nuclear-power.net

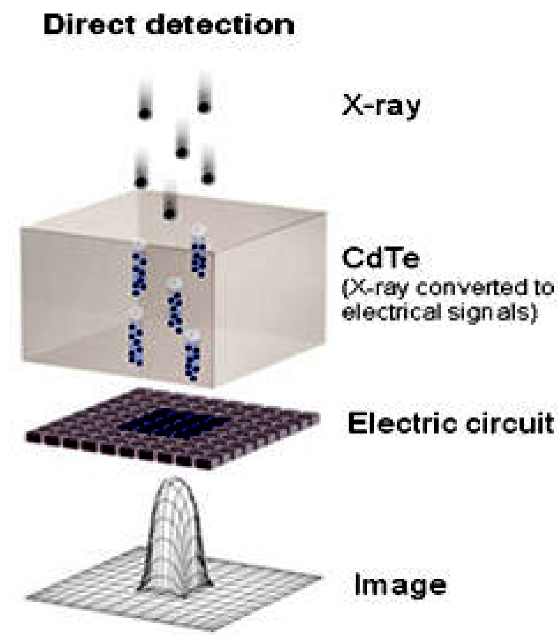
… and how can we do it

For high-energy photons and different particles:

- There are materials used for direct conversion: Diamond, CdTe or CdZnTe, even Si, among many others
- Or, there are also scintillator materials!



(www.xcounter.se)



(www.scint-x.com/)

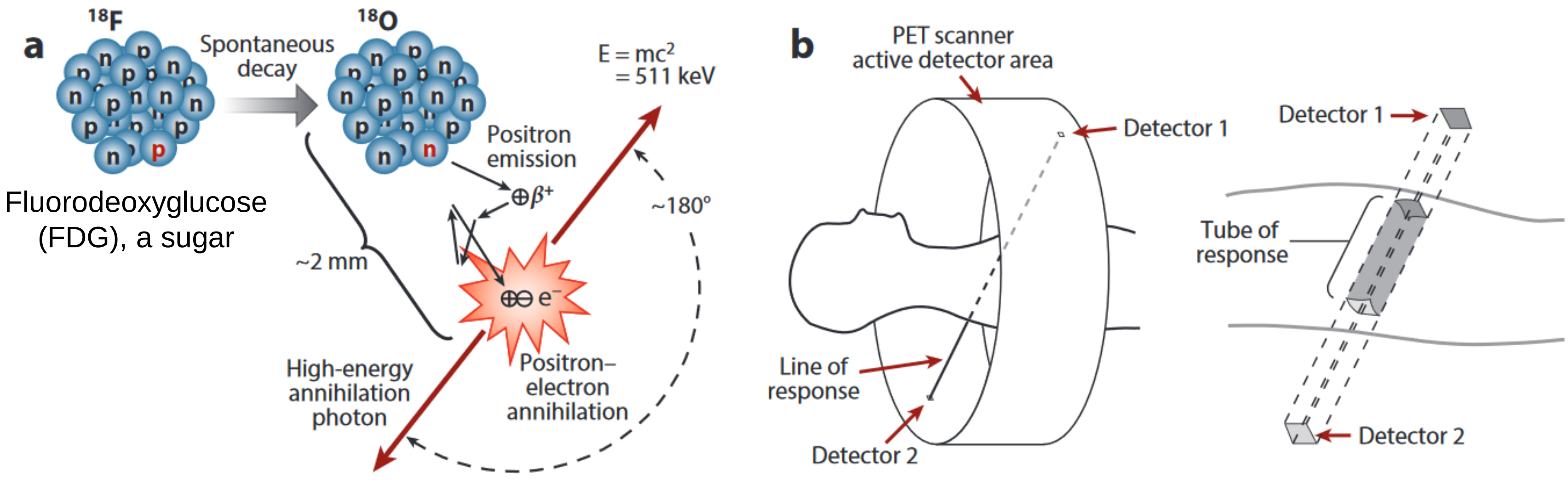
Scintillation → ionization produced by charged particles excites a material causing light to be emitted during the de-excitation:

- fluorescence is photoluminescence or scintillation with a fast decay time (ns to µs) and
- phosphorescence is the same, only with a much slower decay time (ms to seconds).

And now, two actual examples of scientific applications ZEA-2 is involved in…

Positron Emission Tomography (PET)

PET is used to observe metabolic processes in a human body (clinical applications), a body of small animals (pre-clinical), or in plants

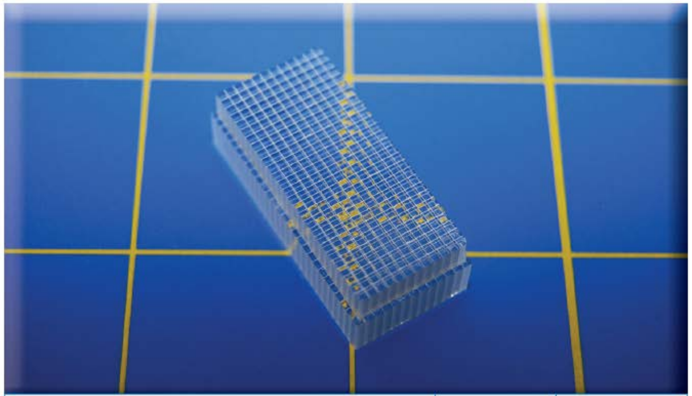


Source: J. J. Vaquero and P. Kinahan, Annu. Rev. Biomed. Eng. 2015, 17: 385-414

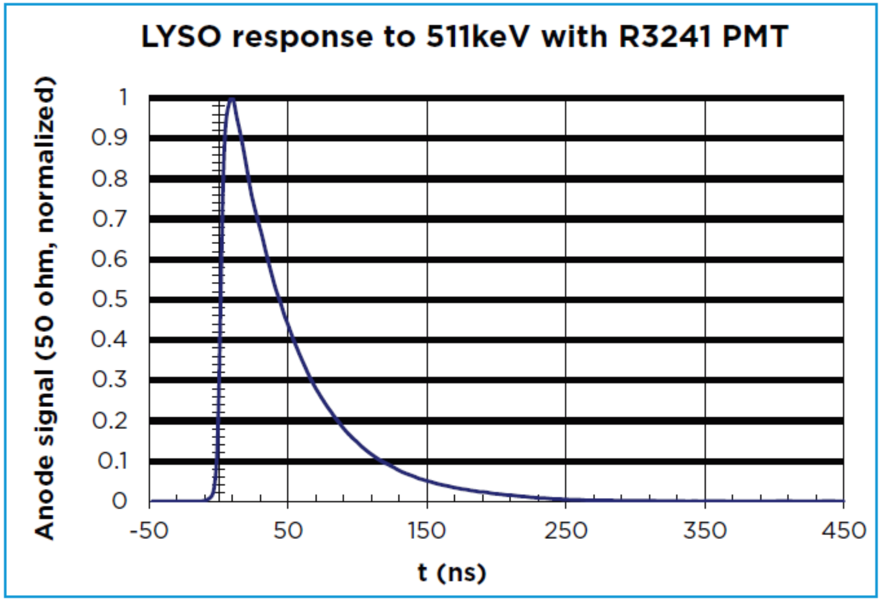
- Required **time resolutions** of the photodetector: **< 500 ps**
- Required **spatial resolutions**: 1 – 2 mm
- Only coincident pairs of gamma photons must be detected
- PET is currently being combined with other techniques, e.g. MRI, for better diagnostics → **high magnetic fields**
- Researchers from the Jülich Institute for Plant Research (IBG-2) are applying PET to carry out plant phenotyping → other type or radiotracers (e.g. ^{11}C in CO_2)

Positron Emission Tomography (PET)

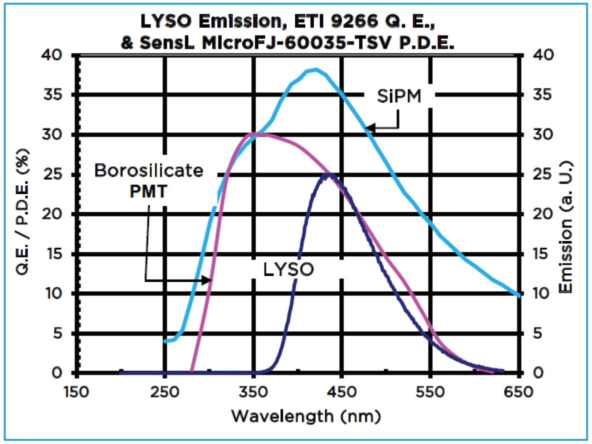
We chose to follow the scintillation approach



Properties	Standard LYSO	*Enhanced* LYSO
Density [g/cm³]	7.1	
Hygroscopic	no	
Attenuation length for 511keV (cm)	1.2	
Energy resolution [%] @ 511 keV	9.5	8 - 8.5
Wavelength of emission max [nm]	420	
Refractive index @ emission max.	1.81	
Decay time [ns]	45	35
Light yield [photons/MeV]	30000	35000
Average temperature coefficient from 25 to 50° C (%/°C)	-0.28	
Photoelectron yield [% of NaI(Tl)] (for γ-rays)	75	



Expected light yield (E_γ=511 keV): 15 330 ph /360°



SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

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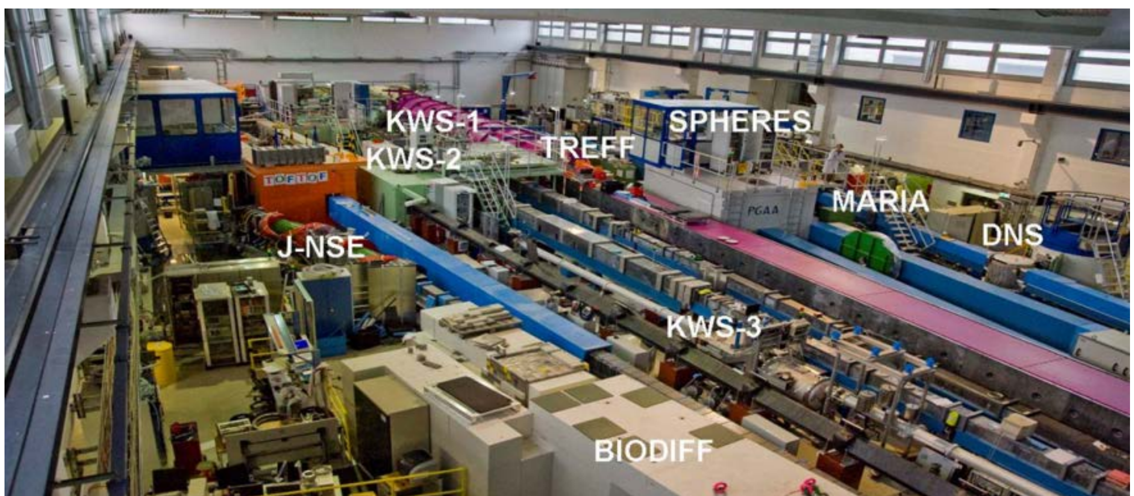
Small-angle neutron scattering (SANS) experiments:

- Are used for soft and condensed matter investigations
- Neutrons have no electric charge → can penetrate deep
- Neutron magnetic moment enables investigation of magnetic properties of matter
- Thermal and cold neutrons deposit only minimum amounts of energy into it
- The world-wide shortage of the preferred ^{3}He gas triggered novel approaches for neutron detection → e.g. **scintillation based detectors**

Since 1969: Development of detector systems for neutron and gamma detection

- 11 systems operational at FRM-II; 2 in construction
- Systems at ILL Grenoble and SNS Oakridge
- Upcoming experiments at ESS Lund



Experimental hall at FRM-II Garching, Munich

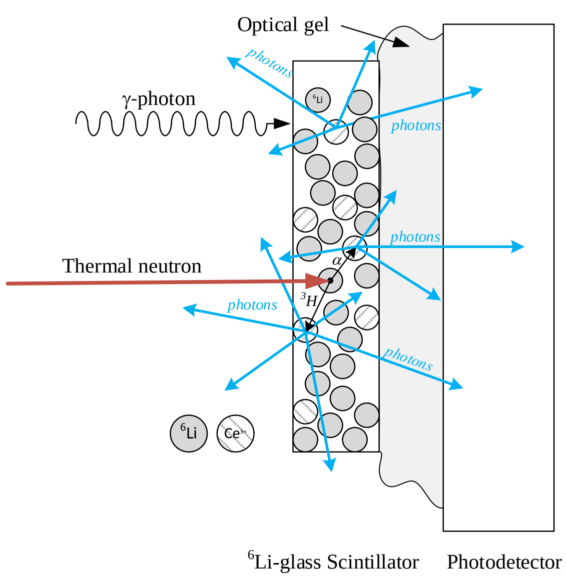
Nuclear reactions to convert neutrons

Traditional and new thermal-neutron scintillators

Host	Dopant (conc mol%)	Density ρ (g/cm^3)	ρZ_{eff}^4 ($\times 10^{-6}$)[a]	Abs. Length at 1.8Å (mm)	Light yield photons per Neutron	Light yield photons per MeV gamma	α/β Ratio	λ_{em} (nm)	τ (ns)
^{6}Li-glass	Ce	2.5		0.52	~6000	~4000	0.3	395	75
^{6}LiI	Eu	4.1	31	0.54	50,000	12,000	0.87	470	1400
^{6}LiF/ZnS	Ag	2.6	1.2	0.8	160,000	75,000	0.44	450	>1000
$LiBaF_3$	Ce,K	5.3	35		3500	5000	0.14	190–330	1/34/2100
$LiBaF_3$	Ce,Rb	5.3	35		3600	4500	0.17	190–330	1/34/2400
$^6Li_6^{dep}Gd(^{11}BO_3)_3$	Ce	3.5	25	0.35	40,000	25,000	0.32	385,415	200/800
$^6Li_6^{dep}Gd(^{11}BO_3)_3$	Ce	}3.9		}1	40,000	30,000		420	200/800
$+Y_2SiO_5$	Ce				—	30,000		420	70
$Cs_2^6LiYCl_6$	Ce (0.1)	3.3		3.2	70,000	22,000	0.66	380	~1000
					—	700		255–470	3
$Cs_2^6LiYBr_6$	Ce (1)	4.1		3.7	88,000	23,000	0.76	389,423	89/2500

[a] As an indication of gamma-ray detection efficiency by photoelectric effect ρZ_{eff}^4 values are presented

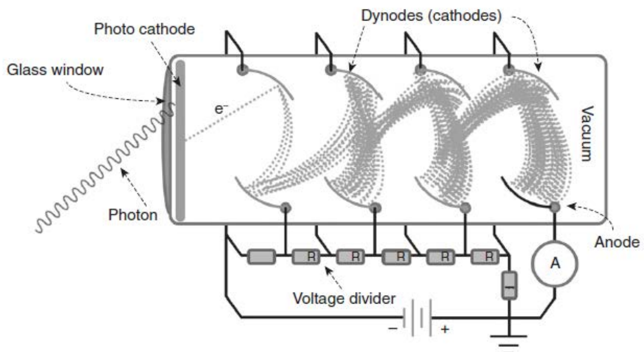
Source: C.W.E. van Eijk et al. / Nuclear Instruments and Methods in Physics Research A 529 (2004) 260–26

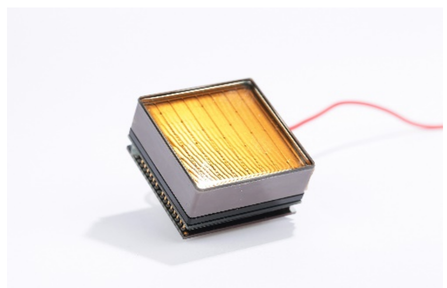


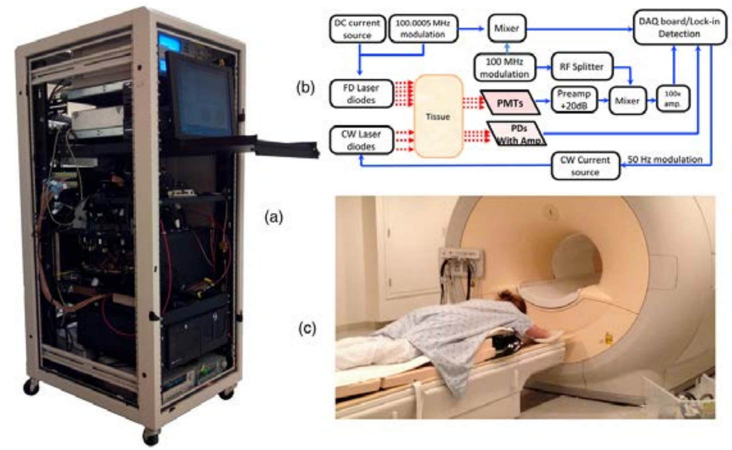
- Required **time resolutions:** < 200 ns (Expected neutron repetition rates > 5 Mcps)
- Required spatial resolutions: ~ 1 mm
- Expected light-yield (solid angle) → 6,000 ph/n
- Good neutron/gamma discrimination (10^5)
- Possibility of operation in magnetic fields

What type of photodetectors should we use?

Photomultiplier Tubes (PMT)







Source: El-Ghussein et al. "Hybrid photomultiplier tube and photodiode parallel detection array for wideband optical spectroscopy of the breast guided by magnetic resonance imaging", SPIE *Journal of Biomedical Optics* 19(1), 011010 (January 2014)

Time resolutions: ~ 6 ns

Possibility to detect 1k – 50k photons: internal amplification of ~ 10^6

Modular assembly: flat-panel multi-anode PMT (e.g. Hamamatsu H8500/H10966)

Spatial resolution: multi-anode size 3 x 3 mm² or 6 x 6 mm²

Low power consumption, low bias voltages: Bias voltage 1 – 2 kV

Possibility of operation in magnetic fields: no

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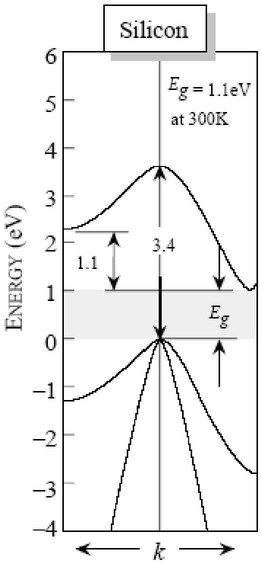
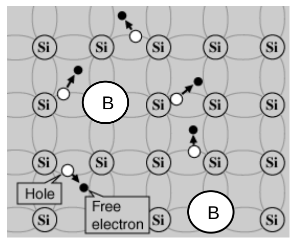
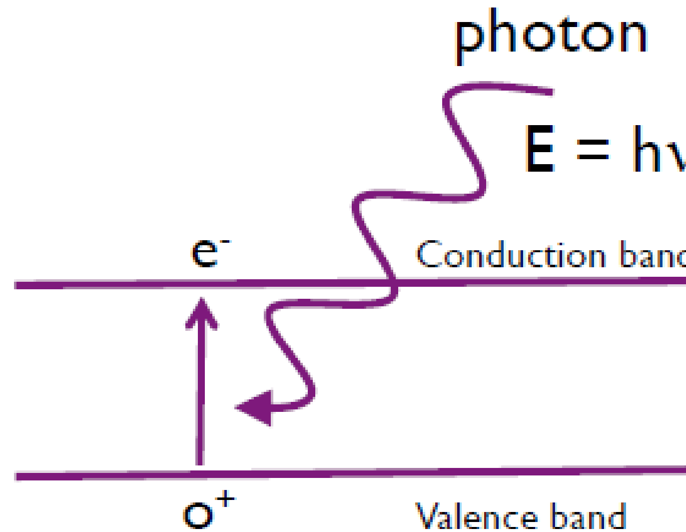
Silicon and visible light



Electron crystal momentum dependent band structure diagram of silicon (Si), an indirect semiconductor (Singh, 2003).



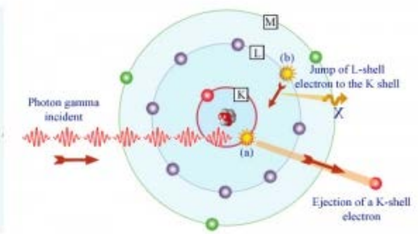


1. Photon absorption in Silicon causes a generation of electron-hole pairs (Photon energy must be larger than E_g, and impurity doping helps!)

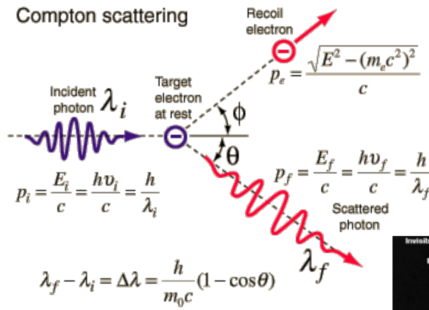
2. The electrons and holes must be separated to avoid their recombination (we need electrical fields for that: *p-n* junctions or reverse biased gates!)

3. Silicon has a combination of unique properties:
   - the best/most suited material for integrated circuits!
   - Right bandgap to detect visible light (and more)
   - Absorption of visible light in a few µm thickness

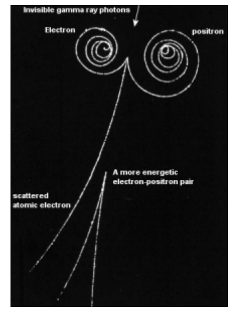
Electromagnetic radiation and Silicon



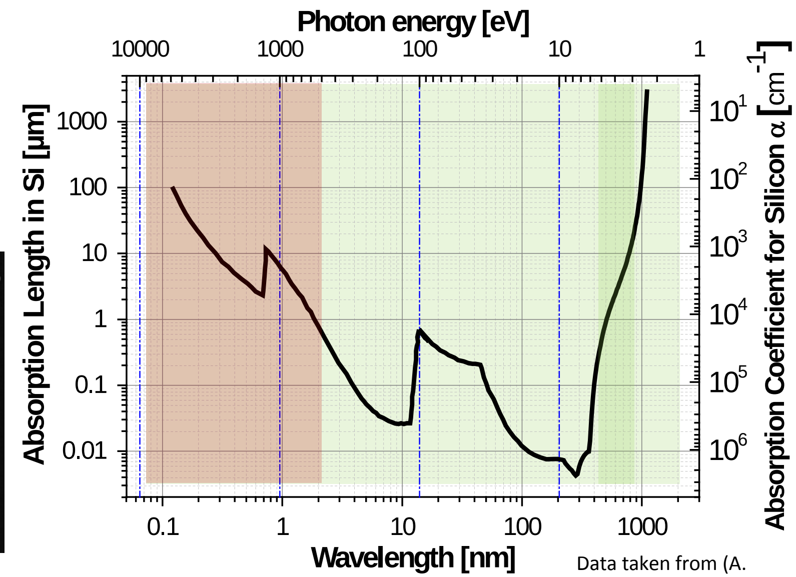
Photoelectric effect



Pair production

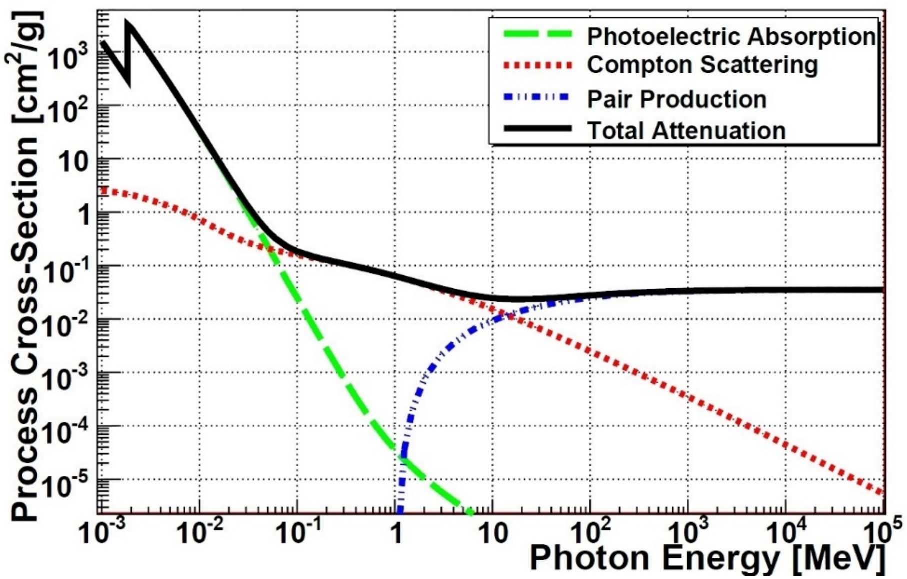


http://www.nuclear-power.net



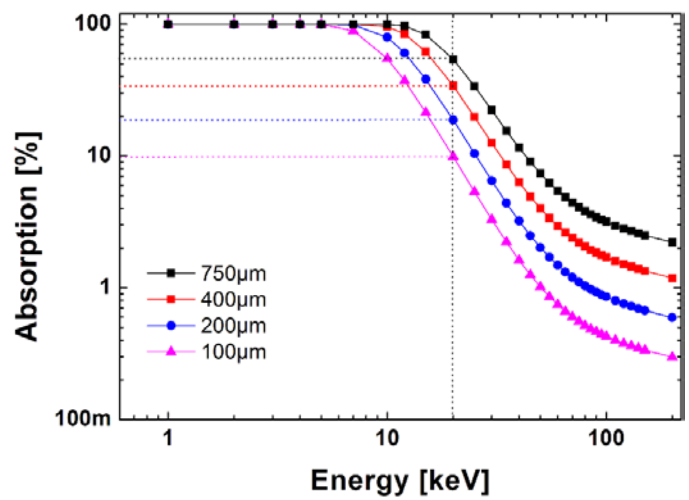
Data taken from (A. Theuwissen, 1996) and (M. A. Green *et al.*, 1995)

Photon Absorption in Silicon



Source: Spieler H. (1998) Lecture Notes – Physics 198, UC Berkeley

X-ray absorption in silicon

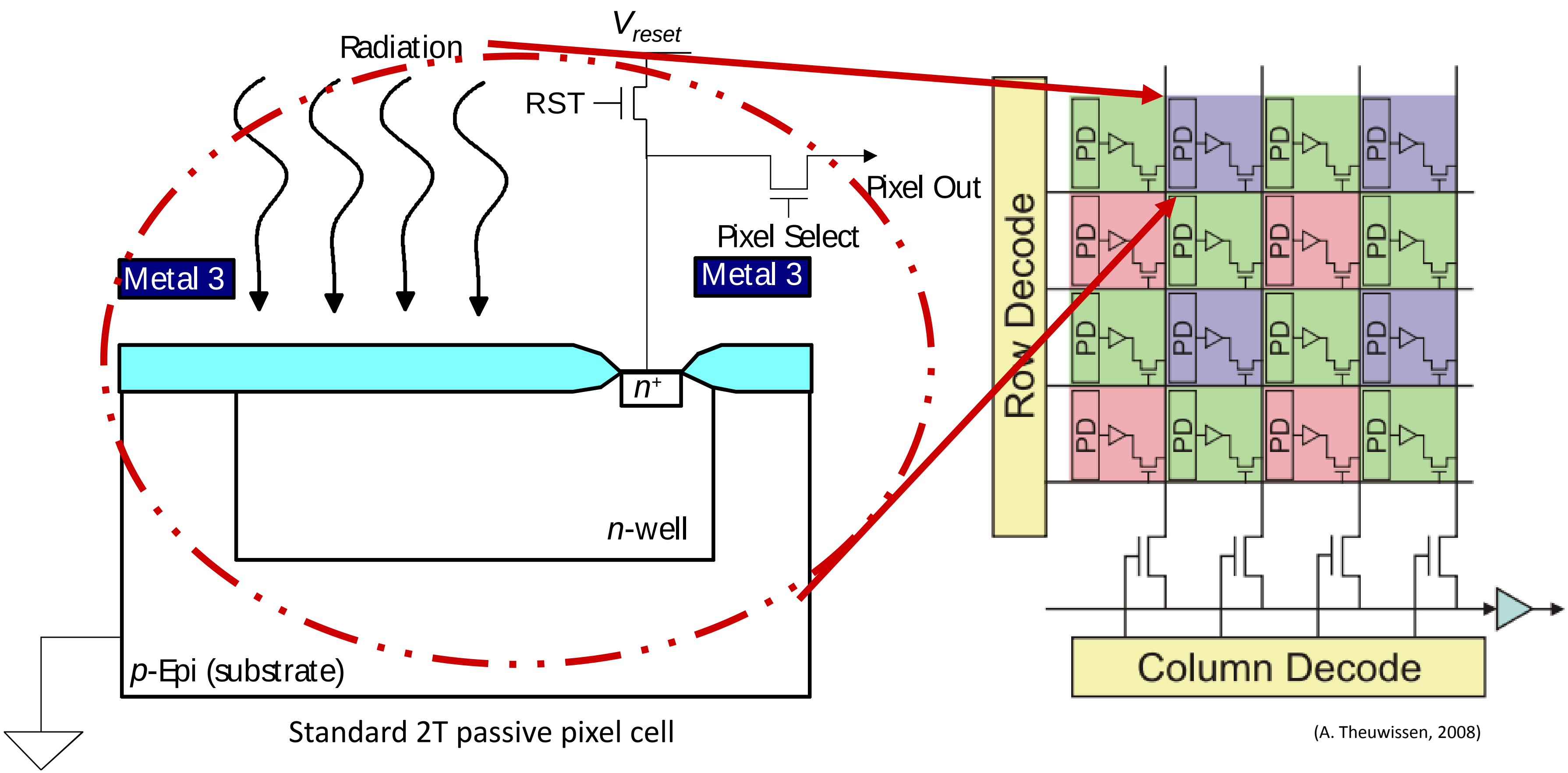


CMOS Imaging: Passive Pixel Sensors

Separating the electrons from the holes, properly **collecting** the electrons from a well defined area for readout, and **sensing** the resulting output signal gives us the required information to define a "picture cell" (or **pixel**).

An array of pixels gives us an imager!

A CMOS pixel based on a reverse biased *p-n* Junction (**passive pixel** structures):



Standard 2T passive pixel cell

(A. Theuwissen, 2008)

What about single-photon counting and nanosecond time resolutions?

To obtain near single-photon counting capability in silicon, it is necessary to:

- Drastically **reduce noise** (maximize SNR)
- Add internal signal amplification (e.g. avalanche processes): APD, SPAD, EMCCD
- Have really fast pixel response

“Standard” silicon based imagers need long times (of at least hundreds of µs) for the reset, charge-collection and readout operations.

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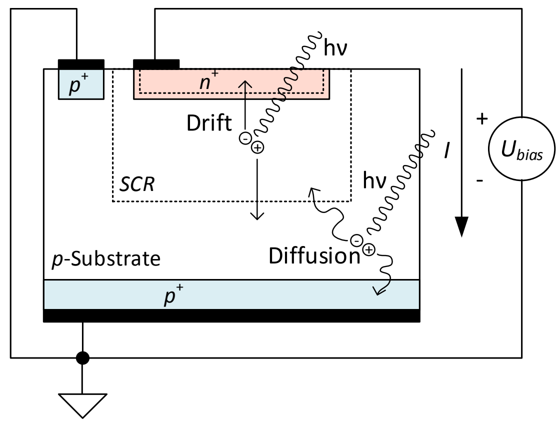
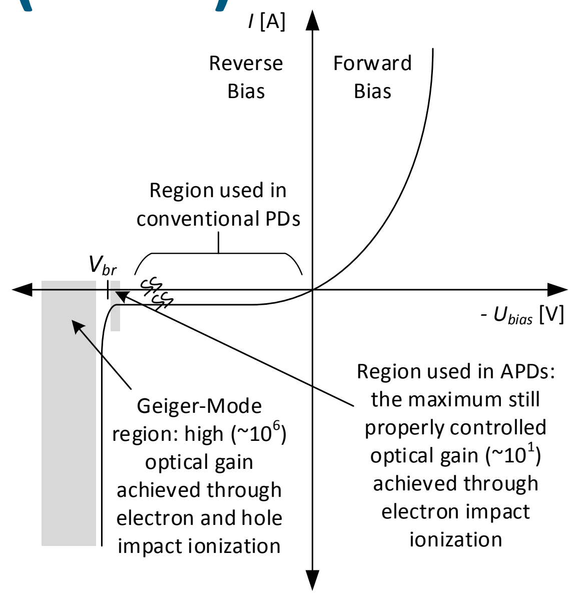
Single-Photon Avalanche Diodes (SPAD) and Silicon Photomultipliers (SiPM)

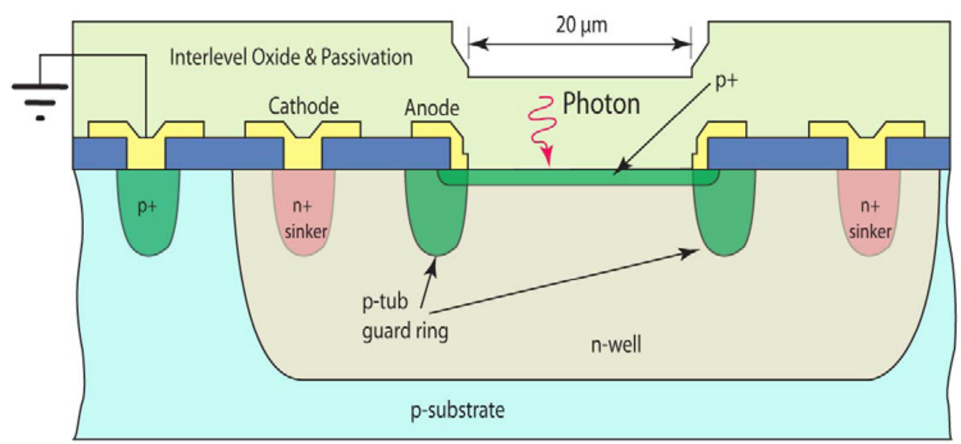




Source: D. Durini et al. Chapter 11 in B. Nabet, *Photodetectors. Materials, Devices, Applications*, Elsevier, 2016

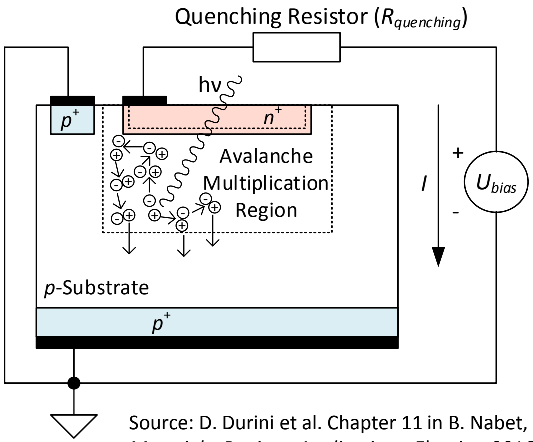
Single-Photon Avalanche Diodes (SPAD) offer:

- Near single-photon counting with nanosecond time resolution: no need for charge collection (each impinging photon can be detected)
- Analog or digital readout
- Pixelated readout (SPAD-imagers) or single outputs (SiPM)
- Nevertheless (as always) there are issues:
  - DCR
  - After-Pulsing
  - Crosstalk…



Silicon Photomultipliers (SiPM)

You can use passive quenching resistors (as in analog SiPMs)



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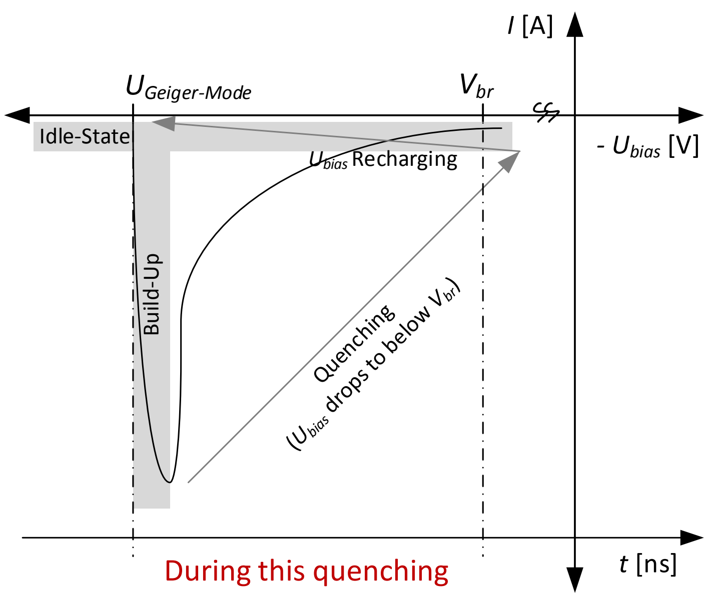
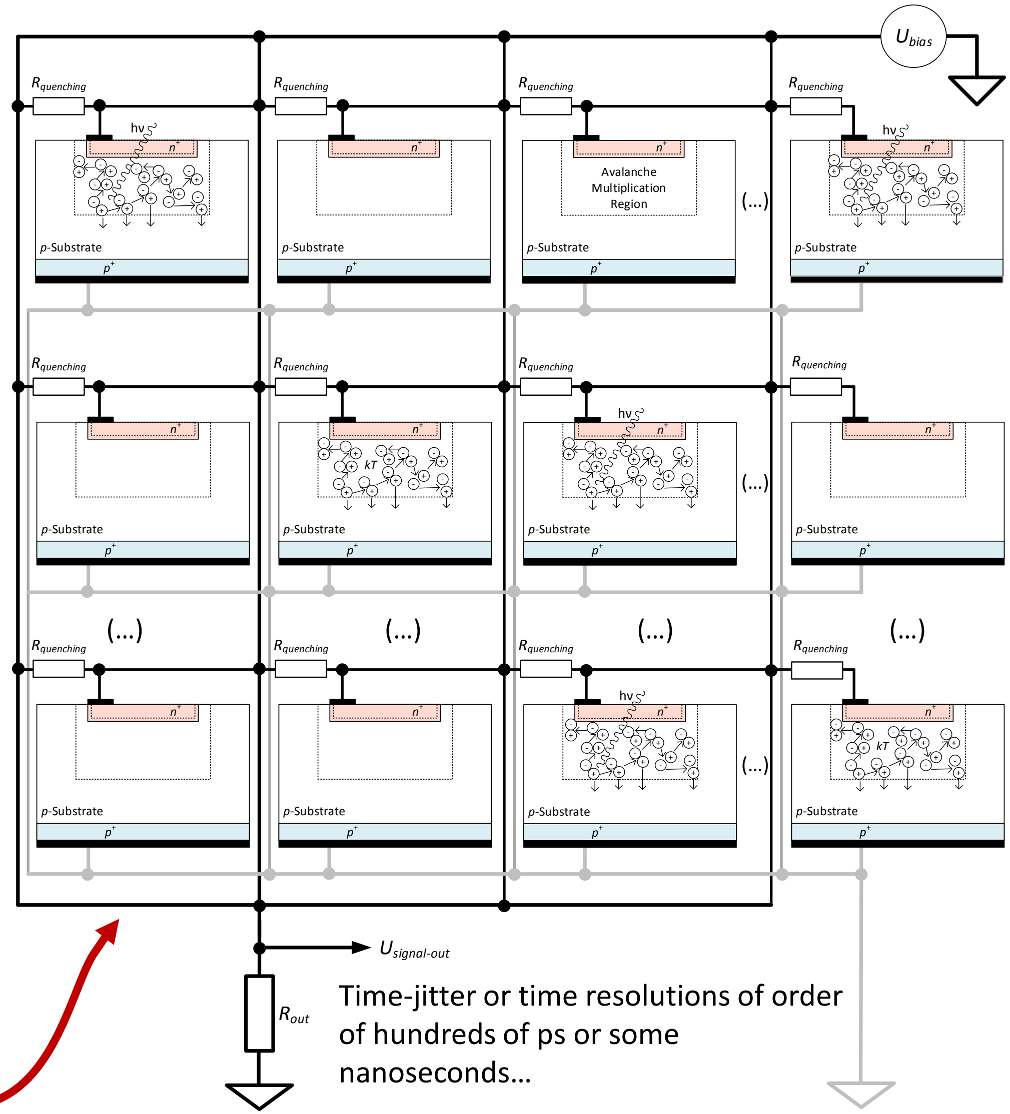


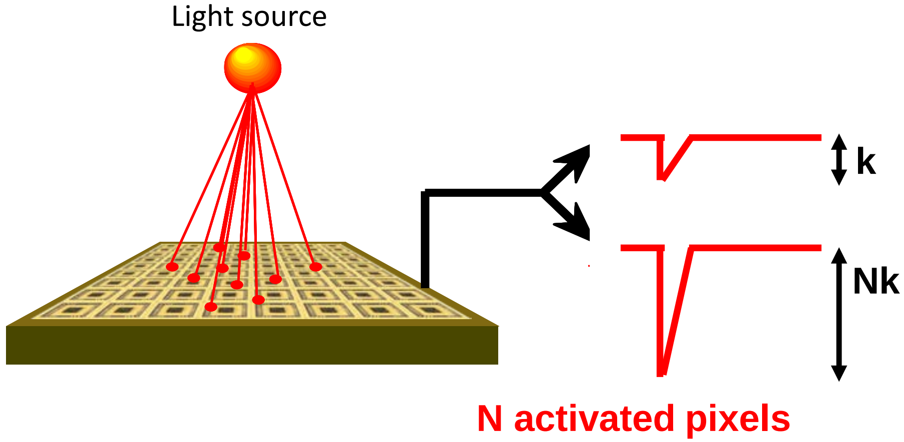
During this quenching time, the SPAD is "blind": Geiger-mode limitation

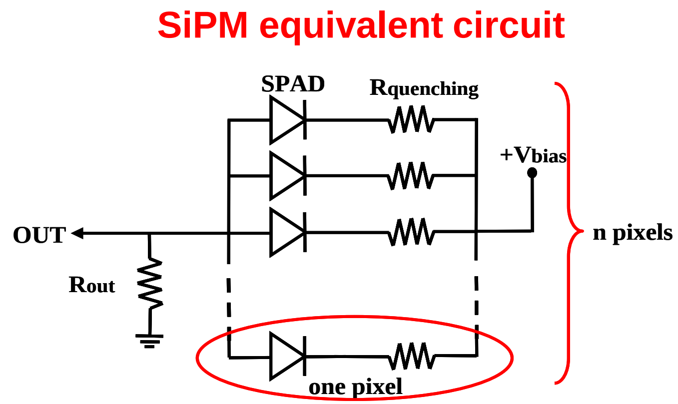


Time-jitter or time resolutions of order of hundreds of ps or some nanoseconds…

Silicon Photomultipliers (SiPM)

SPAD gives no information on light intensity → The Geiger-mode limitation can be overcome by the SiPM approach





Source: M. Mazzillo, "Highly Efficient Solid-State Optical Detectors for Healthcare Applications", Fermilab Seminar, Batavia, May 11, 2012

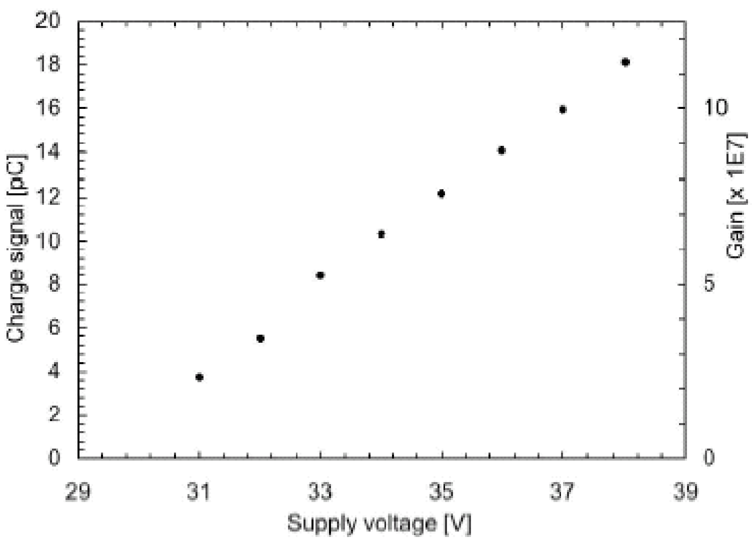
- SiPM structure is based on a 2D pixel array of SPAD pixels (cells) each of which connected to an integrated decoupling quenching resistor
- Each cell operates as an independent photon counter (Geiger Mode) and gives the same signal when fired by a photon
- Since all the cells work on a common load, the amount of charge collected at the SiPM output is given by the analog superposition of the binary signals produced by all the fired pixels

Excellent photon resolving power for weak photon fluxes

Silicon Photomultipliers (SiPM)

The gain (G) is defined as the average amount of charge (Q) flowing in the photodiode during the avalanche event divided by the elementary charge (*q*)

Gain vs Supply Voltage

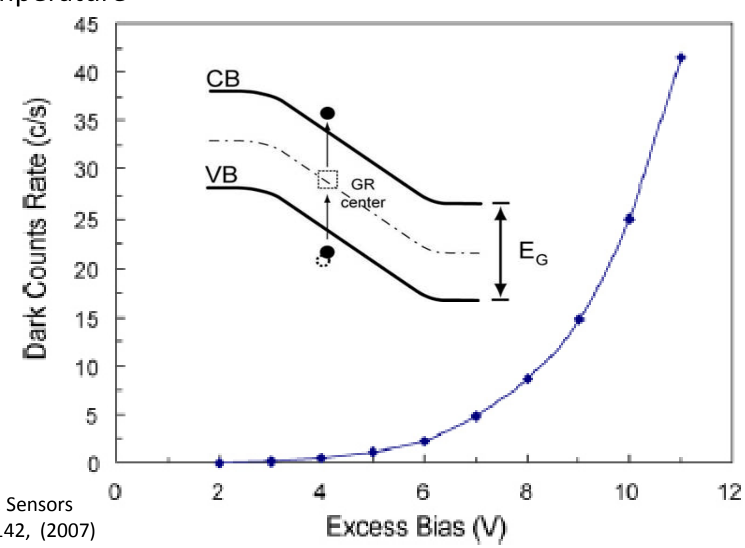


Source: P. Finocchiaro et al., IEEE Transactions on Nuclear Science, Vol.52, No.6, 2005

But, not only photons generate electron-hole pairs…

Dark Count Rate (DCR) describes the rate at which thermally generated charge carriers are starting the avalanche processes in a SPAD structure

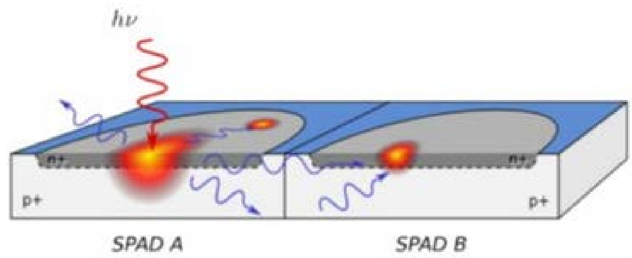
- According to the *Shockley-Read-Hall* (SRH) theory, the thermal generation of electron-hole pairs in the depletion region is due to generation-recombination (GR) centers, i.e. localized electron energy levels at about mid-gap, or
- diffusion of thermally generated charge carriers from the quasi neutral regions into the depletion (or SCR) layer, and
- from band-to-band tunneling dominating at low temperature



Source: F. Zappa et al., Sensors and Actuators A, Vol. 142, (2007)

Silicon Photomultipliers (SiPM)

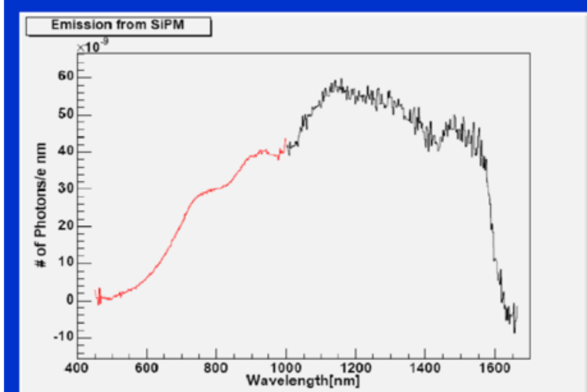
Cross-talk effects between SiPM neighboring cells (SPADs) due to hot-carrier emission and detection



A. Lacaita et al., IEEE TED, 1993

The only really effective solution is introducing physical barriers (trenches) between neighboring SPADs!

Entire emission spectrum



The largest error is ≤ 19.7 % for the „worst" wavelength range < 600 nm

Wavelength range	450 – 1600 nm	< 1117 nm
This measurement	3.86×10^{-5} ph/e	1.69×10^{-5} ph/e
Lacaita, et al., 93		2.9×10^{-5} ph/e

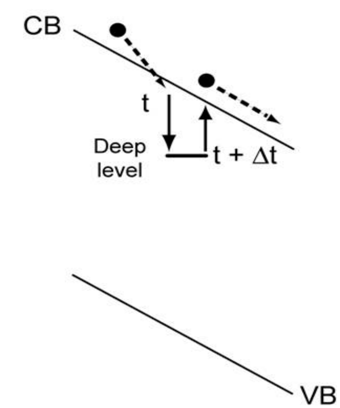
Tuesday, 17 June 2008

R. Mirzoyan: Light Emission from Si; NDIP08, Aix-les-Bains, France

After-pulsing is caused by carriers trapped by deep energy level defects in the multiplication region that get eventually released in a time window from a few nanoseconds up to several microseconds → they re-trigger a Geiger event correlated with the previous avalanche pulse

- After-pulses depend on the trap concentration in the junction depletion layer as well as on the number of carriers generated during a Geiger pulse

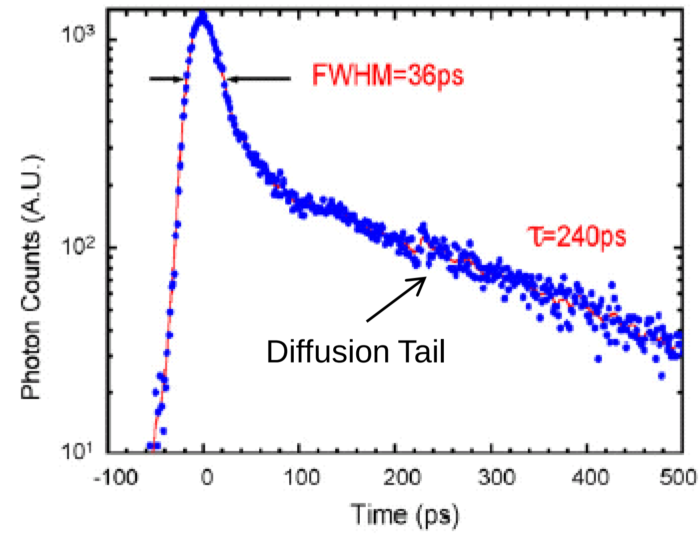
Carrier Trapping and Delayed Release → Afterpulsing



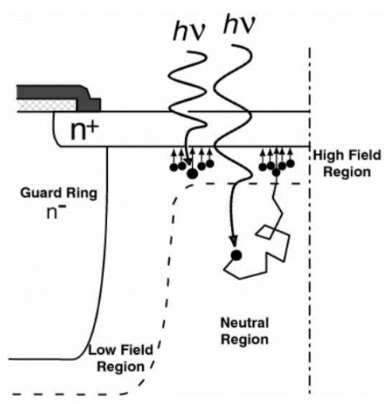
Silicon Photomultipliers (SiPM)

Timing resolution (TR) or timing jitter is defined as the FWHM of the statistical distribution of the delay between the true arrival time of the photon at the sensor and the measured time marked by the output current pulse leading edge

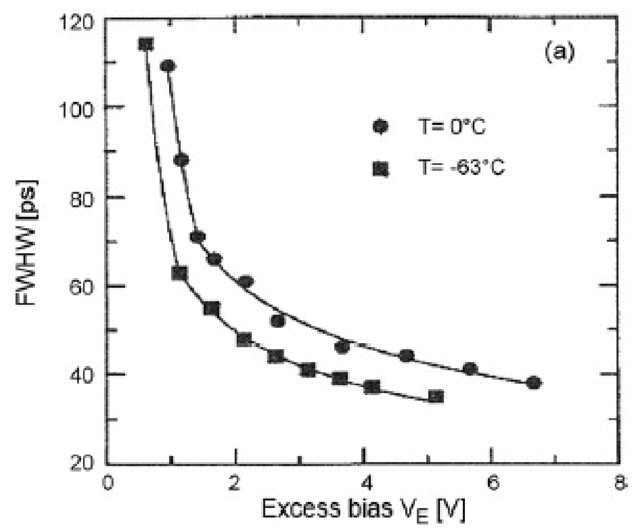
- Carriers photogenerated in quasi neutral regions below the depletion layer are responsible for the so-called diffusion tails particularly marked in the infrared wavelength range



Source: F. Zappa et al., Sensors and Actuators A, Vol. 142, (2007)



Source: M. Ghioni et al., Journal of Selected Topics in Quantum Electronics, Vol. 13, No. 4, (2007)

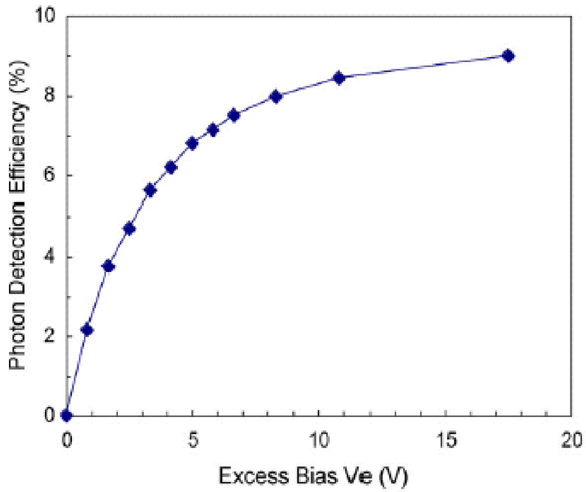


F.Zappa et al., Sensors and Actuators A, Vol. 142, (2007)

Reducing the quenching time (Geiger-mode limitation), also helps…

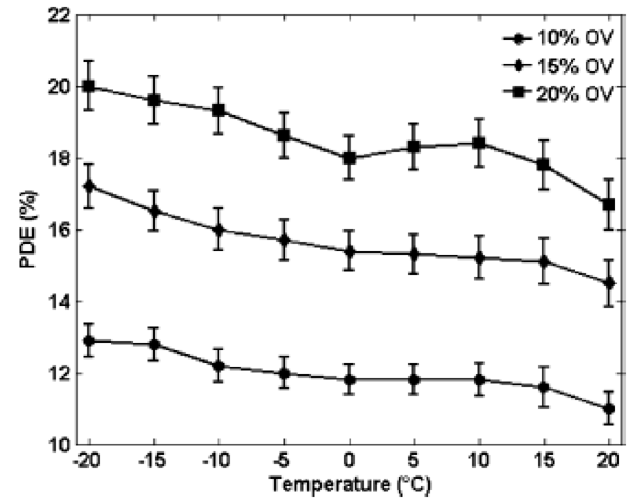
Silicon Photomultipliers (SiPM)

Photon Detection Efficiency (PDE)

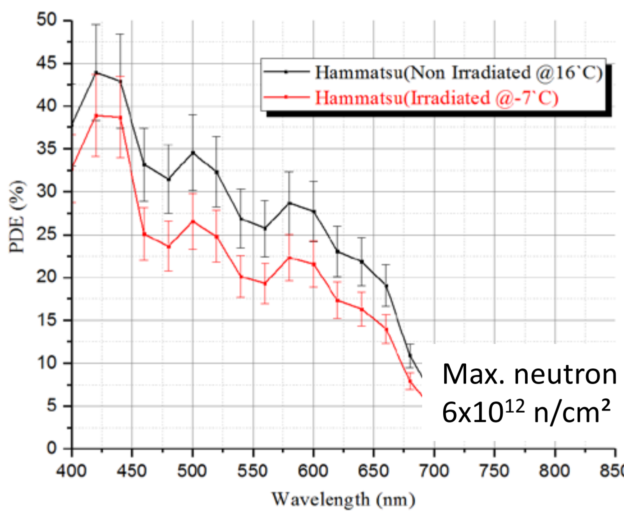


Source: F. Zappa et al., Sensors and Actuators A, Vol. 142, (2007)

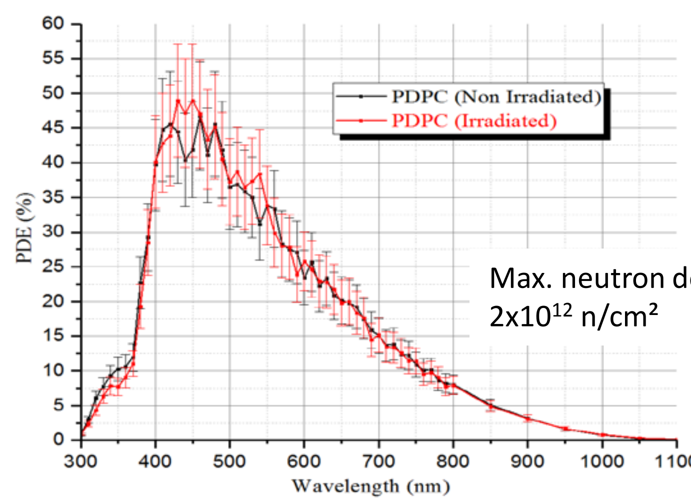
SiPM PDE at 420 nm ΔPDE/ΔT= -0.3%/°C



Source: M. Mazzillo et al., IEEE Transactions on Nuclear Science, Vol.56, No. 4, 2009



Max. neutron dose: $6x10^{12}$ n/cm²

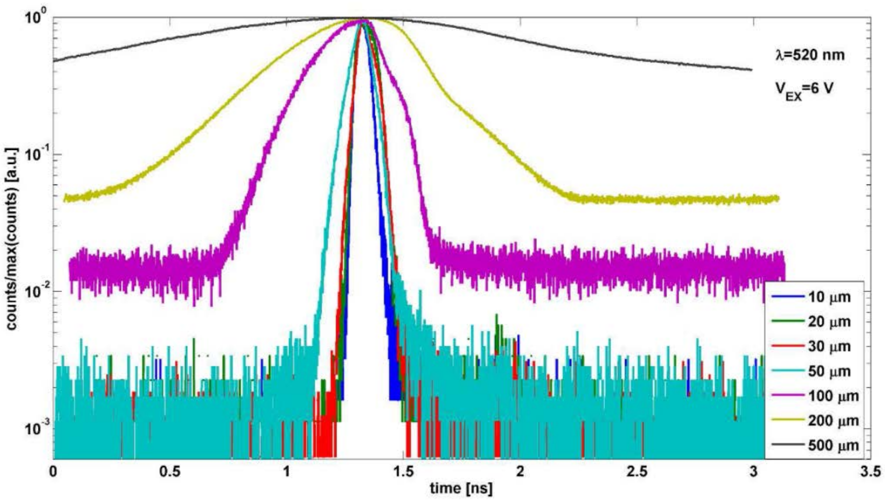


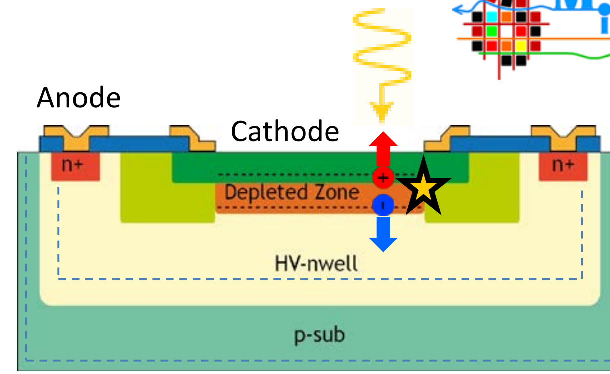
Max. neutron dose: $2x10^{12}$ n/cm²

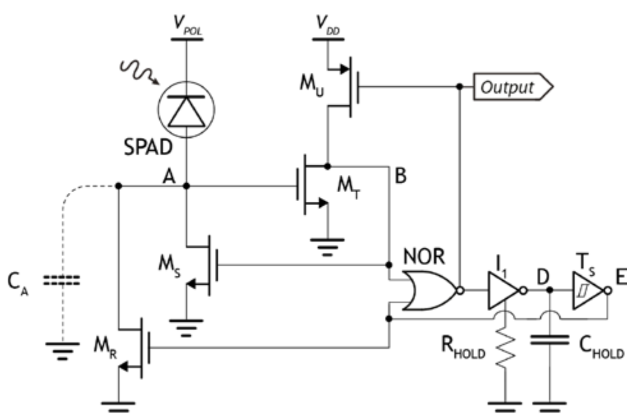
Source: S. Kumar et al. *IWORID* 2017

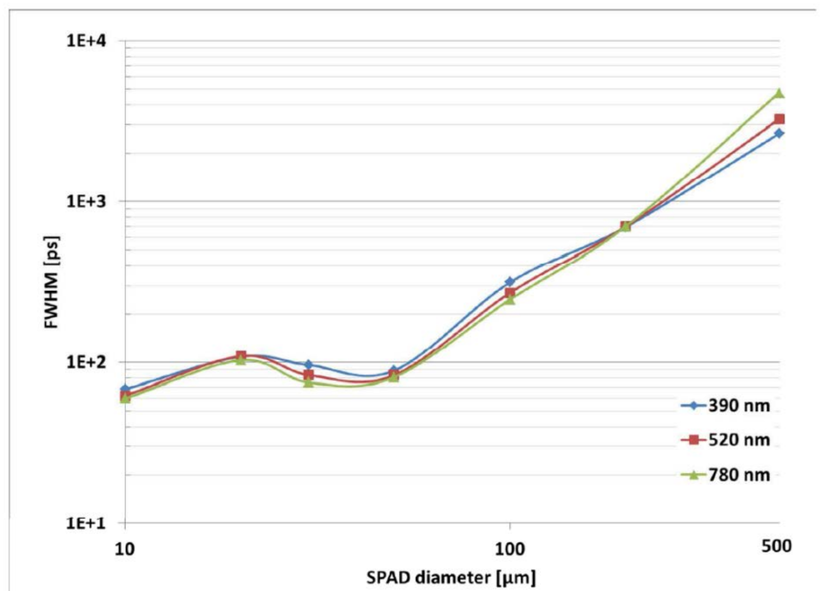
Silicon Photomultipliers (SiPM)

Active quenching circuits (as in digital SiPMs or SPAD arrays)









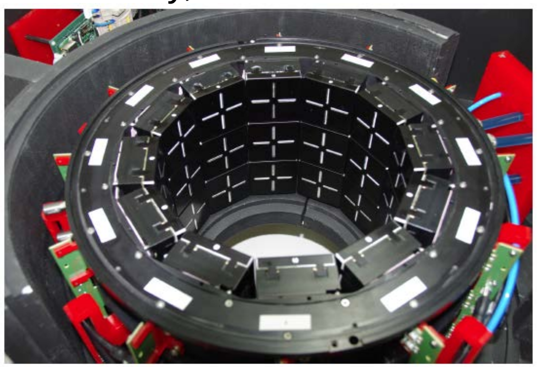
Results obtained using the on-chip integrated quenching circuit with tunable hold-off time and reduced electronics

Source: F. Villa et al. , "SPAD Smart Pixel for Time-of-Flight and Time-Correlated Single-Photon Counting Measurements", *IEEE Phot. Jour.*, Vol. 4, No. 3, Junio 2012, pp. 795 – 804

Table of Contents:

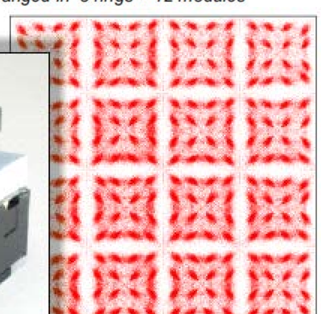
PhenoPET Project at FZJ

- **Radiotracer**: (half-life time 20 min) **carbon isotope ^{11}C** which can be administered to a plant as **$^{11}CO_2$**
- **Scintillator:** matrix of 16x16 individual **LYSO scintillator crystals** (1.85x1.85x10 mm^3)
- **Photodetector:** Philips DPC-3200-22-44. Three 12-module detector rings cover a transverse field of view (FOV) of 18 cm in diameter and 20 cm axial height.
- **DAQ:** is performed on **FPGAs** within the detector module. For **further processing and coincidence sorting**: central Concentrator Board based on Kintex-7 FPGA Mini-Modules (*Xilinx*), 12 sector boards connect 3 modules and route the data via HDMI cables using one LVDS pair per module for 50 MB/s data rate. Finally, a USB 3.0 connection sends the data with up to 300 MB/s to the PC.



The Detector Modules are arranged in 3 rings × 12 modules

Opened detector module showing the four scintillator matrices.



Floodmap Image

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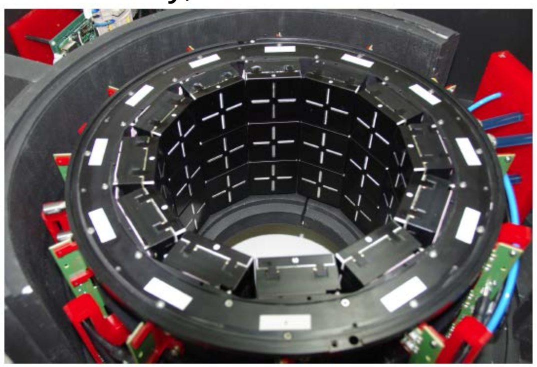

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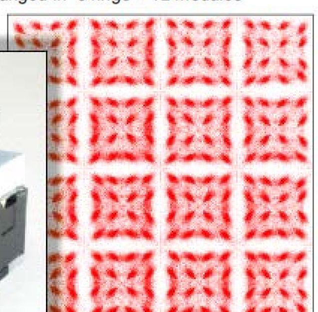
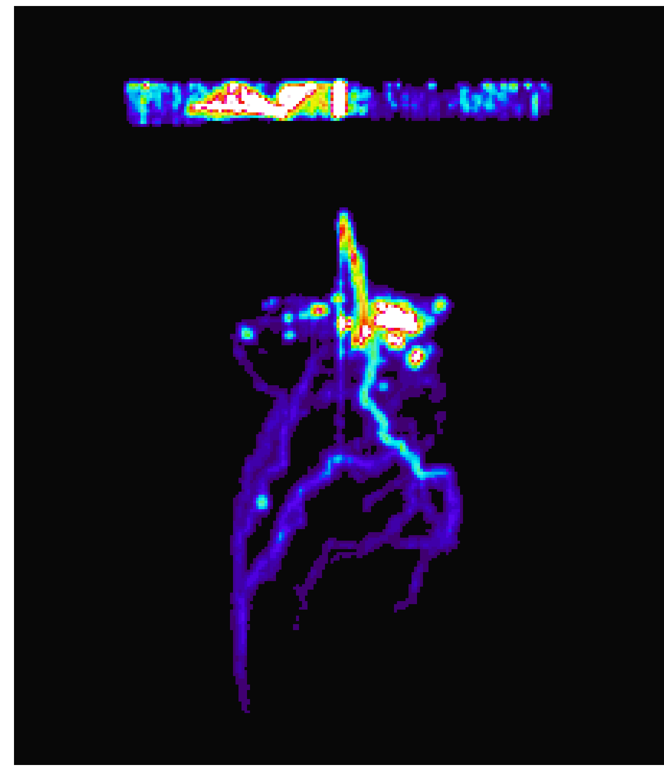


Floodmap Image

A PET image obtained using the PhenoPET system of the roots of a green bean plant.

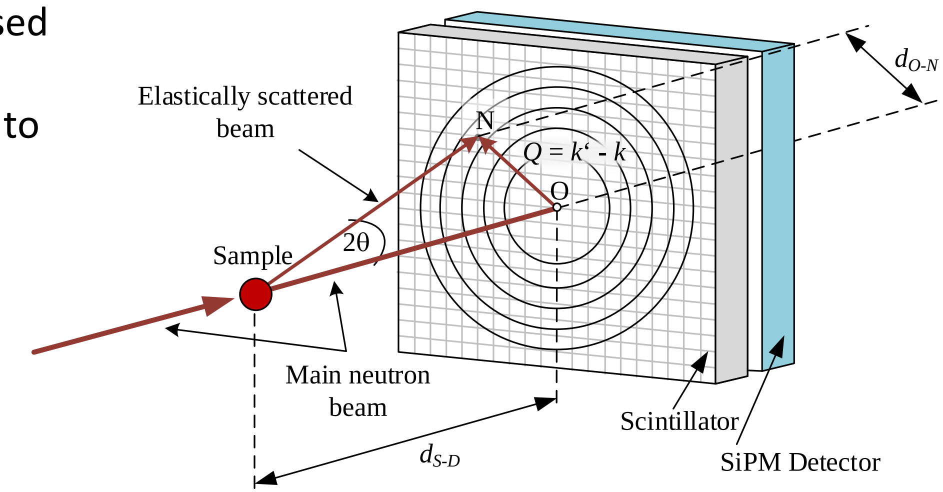


Courtesy of Dr. Siegfried Jahnke IBG-2, and Dr. Jürgen Scheins INM-4, Forschungszentrum Jülich GmbH

SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

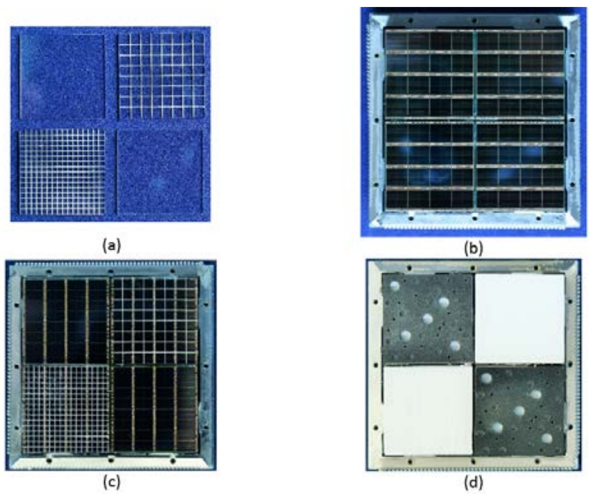
We propose using a 1 mm thick Ce-doped ^{6}Li-glass scintillator (GS20) and an array of SiPM photodetectors:

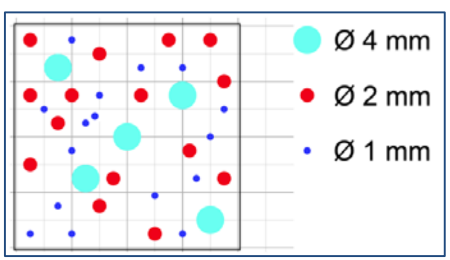
- Near single photon counting
- Low bias voltages (27-70 V) and power consumption
- Acceptable space resolution (< 2 mm sq.)
- Neutron counting rates much higher than those achieved by current ^{3}He based detectors (1 m²), and
- Insensitivity to magnetic fields up to several Tesla

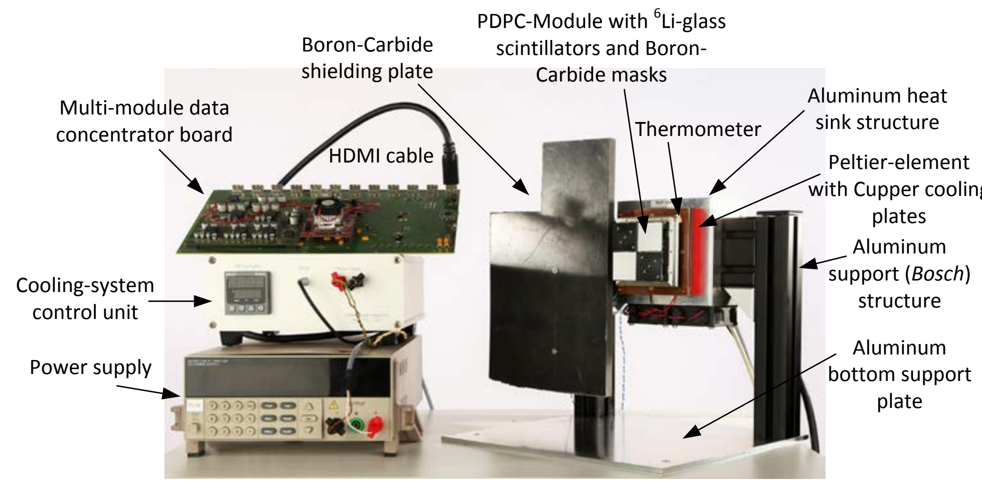


SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

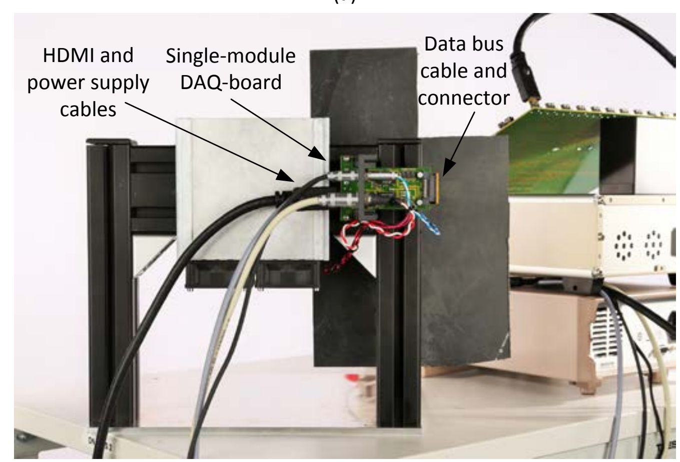
PDPC Demonstrator A:





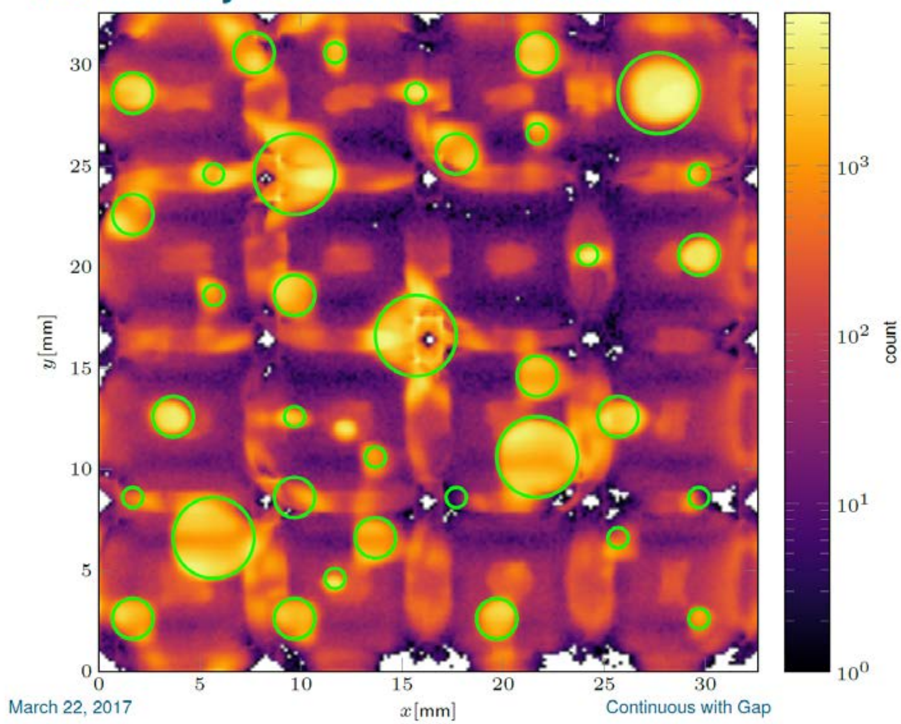


(a)

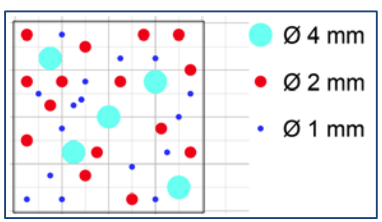


(b)

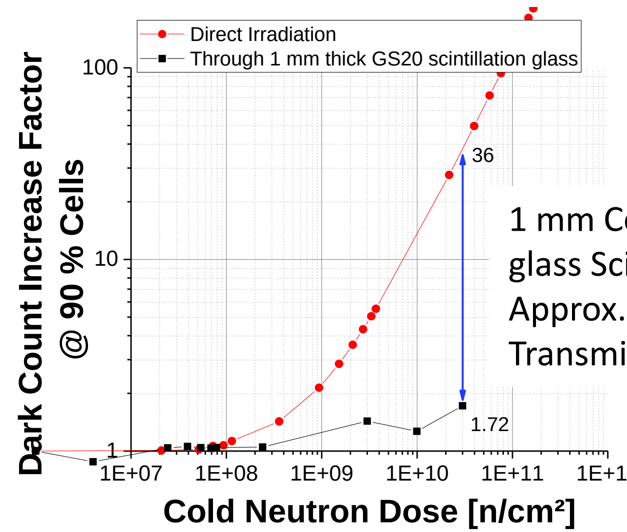
SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments



Source: M. Herzkamp et al. *IWORID* 2017



Radiation hardness is an issue:



1 mm Ce-doped ^{6}Li-glass Scintillator
Approx. Transmission: ~ 5%

Specifications

From PDPC specifications:		
Dead Time	≈ 700 ns per die	PDPC Readout
Time Resolution	$\gtrsim$ 20 ps (depends on trigger scheme)	TDC resolution
From measurements in Garching:		
Detection Efficiency	$(75 \pm 5)\,\%$ @ 5 Å	$4 \times 4\,mm^2$ Scintillator
Linear up to	> 20 kc/s per Die > 320 kc/s per Tile > 110 Mc/s on $60 \times 60\,mm^2$	$4 \times 4\,mm^2$ Scintillator
Spatial Resolution	$2 \times 2\,mm^2$ $\lesssim$ 1 mm	$2 \times 2\,mm^2$ Scintillator Continuous with gap

Challenges and Perspectives

- **Compact and low-power consuming DAQ systems** including digitation, signal processing, data processing, communication interfaces and saving the obtained data at an external memory storage unit
- **Higher SNR and DR**: lower dark currents (DCR) and background signals, direct signal processing and ADC at the detector level, or other cleverer solutions (ToT, TDC, etc.) → integrated solutions (VLSI)
- Special attention has to be put on the **3D-integration technology**: integrating the best from all possible worlds (detector front-end, analogue signal processing, digital signal processing) → **this is the new present!**
- There are huge issues still to be solved regarding **radiation hardness** (ionization radiation and/or sub-atomic particles) on the detectors as well as on the readout circuits for scientific, space and medical applications

Thank you for your attention!

Any questions?