Development and **A**pplications of **SiPM** to Medical Physics and Space Physics **(DASiPM)**

(3 Year Project)

Activities and Funding @ INFN Pisa

A. Del Guerra

The DASiPM Project

- We propose a project to develop and apply a promising new photodetector technology in which there is a rapidly growing interest from many different areas of the physics community.

- The semiconductor photodetectors in question have a performance approaching that of a traditional PMT, but with additional advantages.

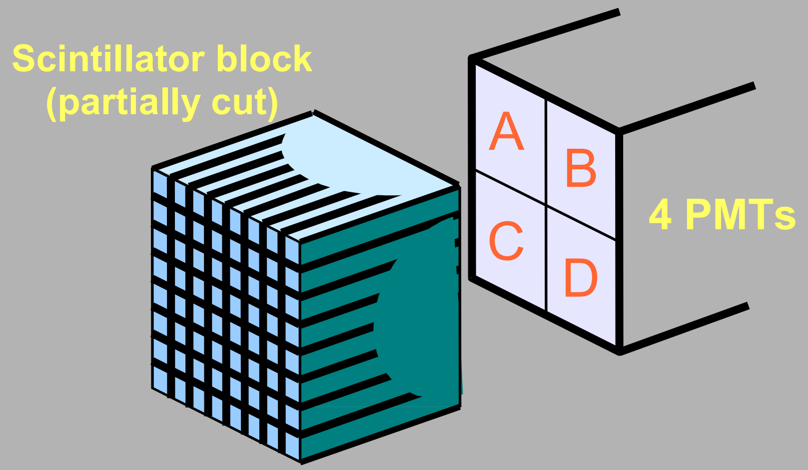
- This project involves the chosen two applications, of PET (Positron Emission Tomography) in nuclear medicine and TOF (Time of Flight) in astrophysics, to demonstrate the foreseen benefits of this detector.

- It would bring together the expertise of five different INFN groups

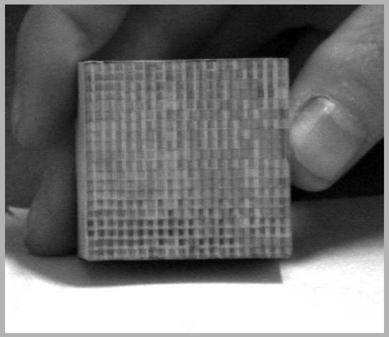
- INFN Pisa	Detector characterisation and application to PET
- INFN Trento	Design and production of the devices
- INFN Bologna	Application to TOF in astrophysics
- INFN Perugia	Mask design and electronic readout
- INFN Bari	Electronics development (IC)

Detectors for PET

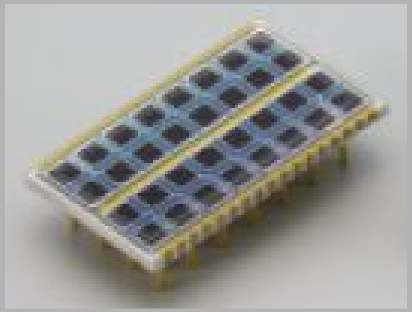
- Classic block detector (BGO then LSO) is still used but *limited in spatial resolution*



- For higher resolution, PSPMTs and pixellated scintillator arrays are used but they are of *limited size and expensive.*



- Now people are looking to arrays of semiconductor detectors- ie) APD matrices.
  - *- limited gain*
  - *- expensive*
  - *- limited size*



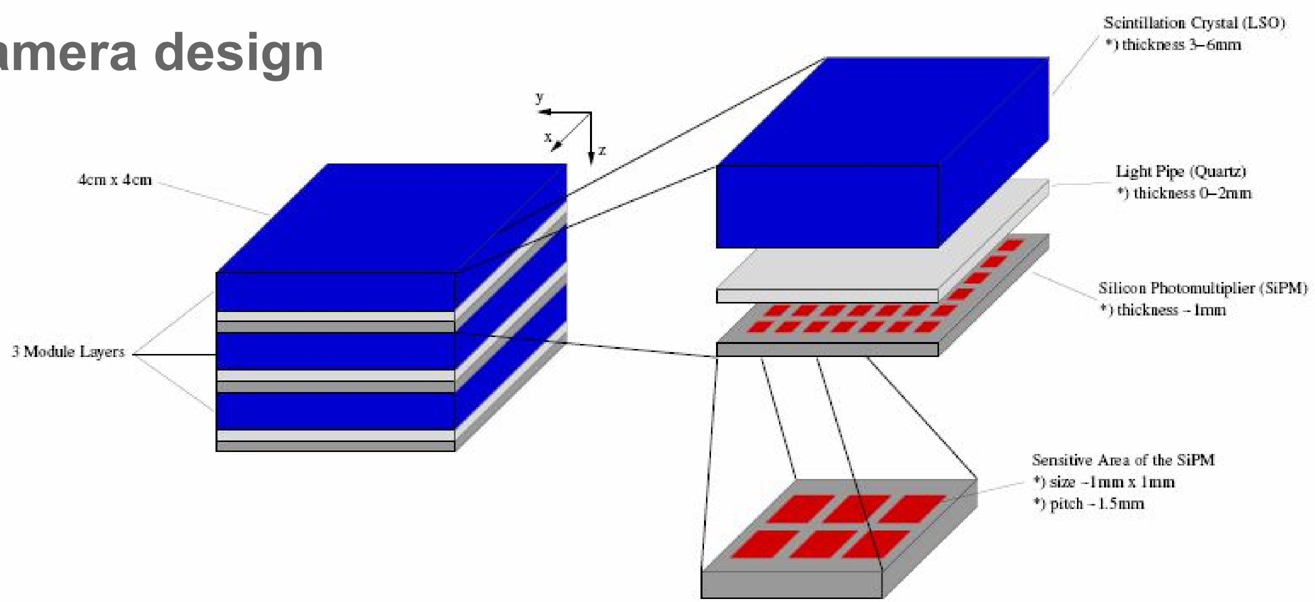
SiPM Application at Pisa – gamma camera for PET

- We plan on using the SiPM matrices to form a miniature, high-resolution gamma camera, based upon the Anger design.
- The scintillator is a continuous piece and scintillation light produced from gamma rays is detected by a number of the SiPM elements in the matrix. By calculating the centre of mass of these signals, we can reconstruct the interaction coordinates (X,Y).
- By stacking multiple copies of this camera, we can have high detection efficiency, whilst having depth-of-interaction (Z) information by using the first interaction.

- We have made simulations to optimise the design parameters and have calculated an expected spatial resolution of 0.6mm FWHM.
- The FWHM and position reconstruction deteriorate towards the camera edges, but we are currently studying a way to recover this information using the photon distribution skewness.

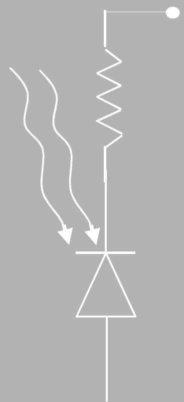
Benefits of this SiPM γ-camera design

- low bias (50V)
- signals have high S/N
- compact
- fast
- good XYZ resolution
- no dead space
-cheap and simple design

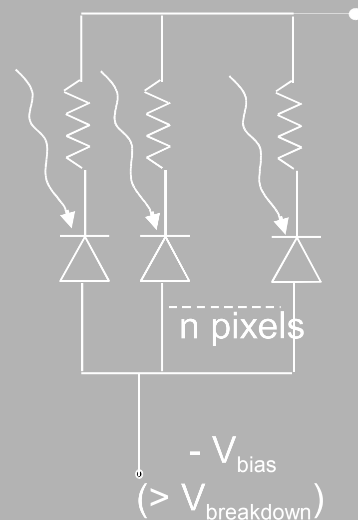


The Silicon Photomultiplier (SiPM)

GM-APD + $R_{quenching}$



Output signal is independent of number of photoelectrons (binary device)



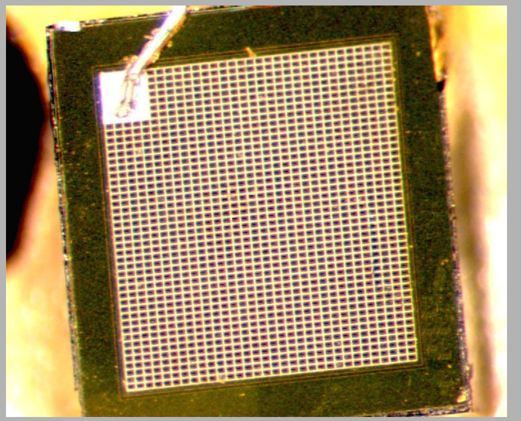
SiPM

- matrix of n pixels (~1000) in parallel
- each pixel: GM-APD + $R_{quenching}$

Output signal is the sum of the signals from all fired pixels (analogue device)

As developed by CPTA, Moscow

- p-n junction diode biased above the breakdown voltage
  - *Depletion region: ~5µm thick, Avalanche region: ~1µm thick.*
- The surface is split into microcells – that act like miniature, independent and identical Geiger-mode APDs
  - *This is achieved by depositing the n^+ layer in 30µm^2 cells*
  - *In this way the avalanche region is localised to each cell.*



- Avalanche is passively quenched by a resistive layer
  - *The SiC has high resistivity meaning a thin layer can be used.*
- A semi-transparent metal layer forms the electrode
  - *This results in a proportional signal for moderate photon fluxes* ($N_{photon} < N_{cells}$)

SiPM Characteristics

- SiPM has potential as a replacement for traditional vacuum tube PMT

  - Benefits include
    - High internal gain (10^6) at low bias voltage (~50V)
    - Excellent photon counting capability
    - Fast response time (~1ns); small recovery time (~few ns)
    - Noise (dark counts) limited to few photoelectron level
    - Insensitivity to magnetic fields
    - Compact and rugged

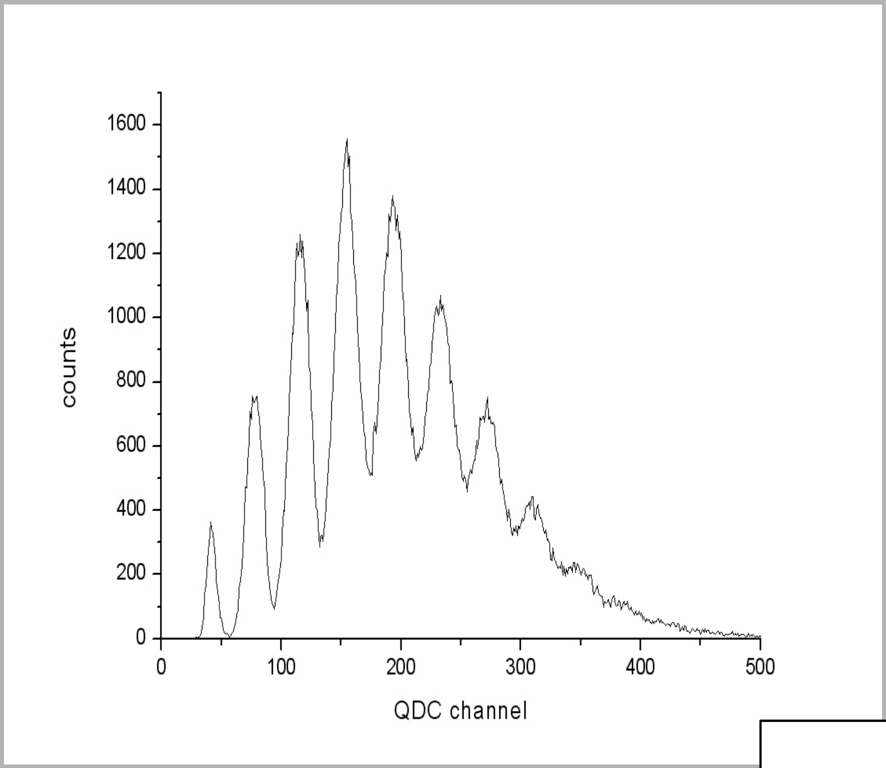
  - Drawbacks/Limitations
    - Low detection efficiency (ave. 2.5% over LSO emission)
    - Limited dynamic range (1000/mm^2 – max nr. of pixels)
    - Not yet available in matrices

- SiPM – under development in the frame of INFN-IRST collaboration

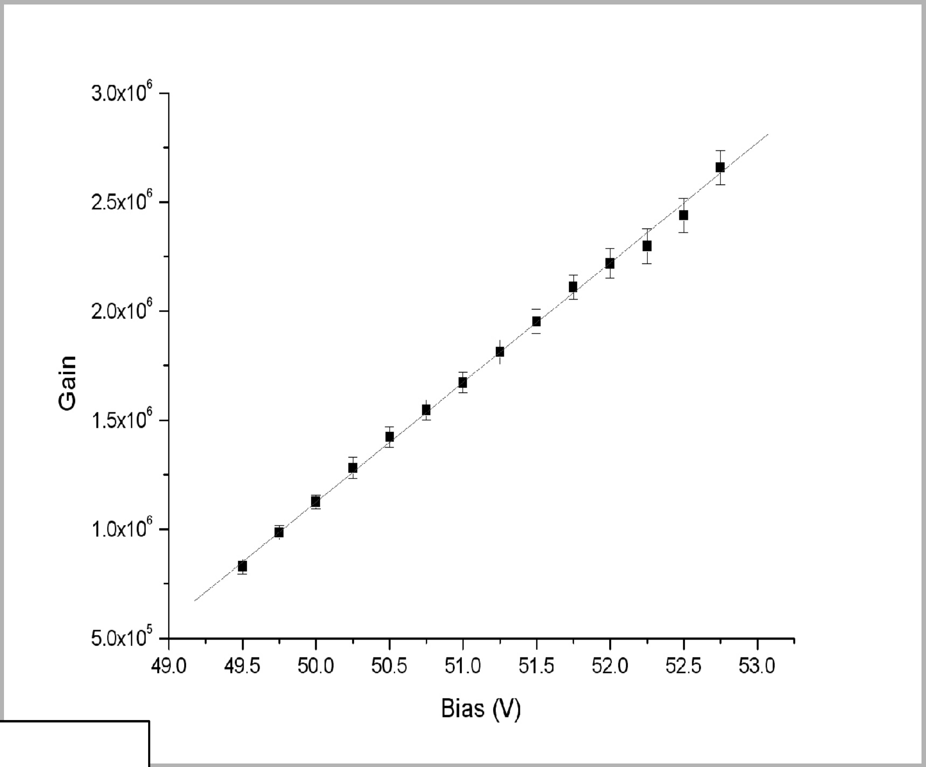
SiPM Results - Gain

- The amplitude of the Geiger avalanche signal is determined by the series quenching resistance

We tested with low light level, pulsed LED



SiPM gain plotted as a function of bias



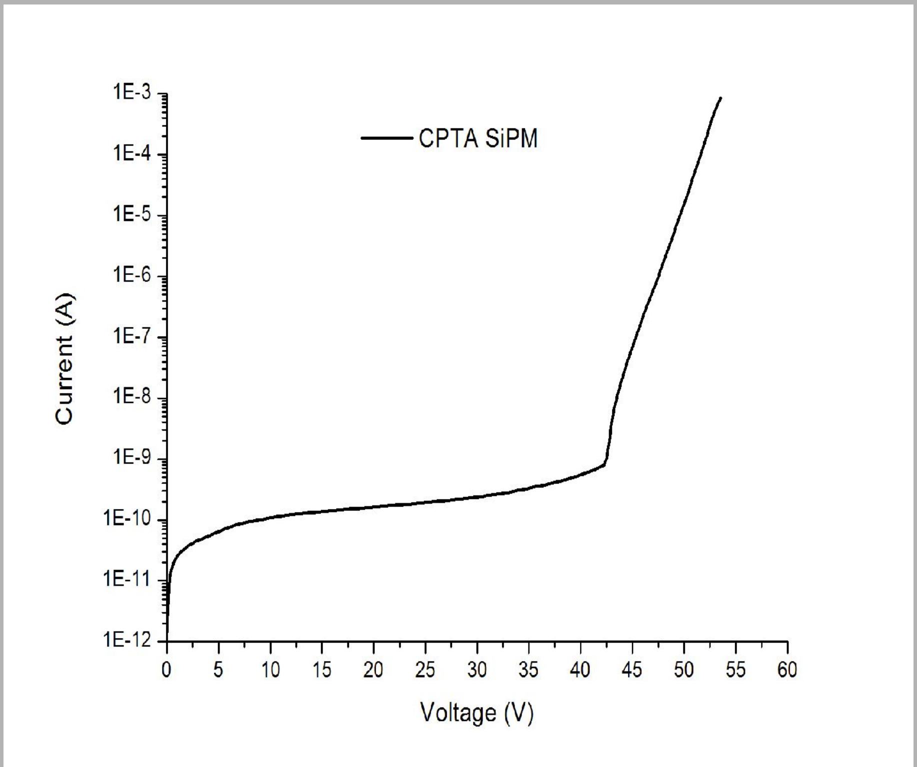
The well-resolved single photoelectron peaks allow one to have an absolute calibration of the gain.

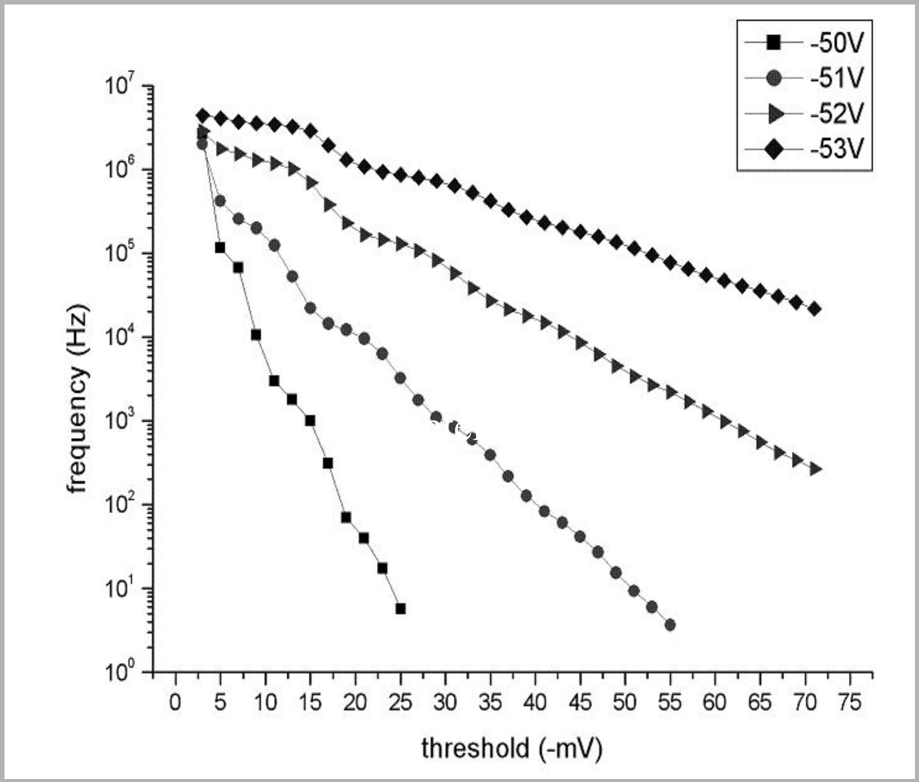
$$Gain = \frac{Q_{one\,\mathrm{pixel}}}{\mathrm{e}}$$

Gain is comparable to PMT

All measurements were made at *ROOM TEMPERATURE*

SiPM Results – I/V & Dark current





The number of false photon counts per second registered by a photon counting detector in the absence of light

Dark counts due to...

- Thermally generation of charge carriers

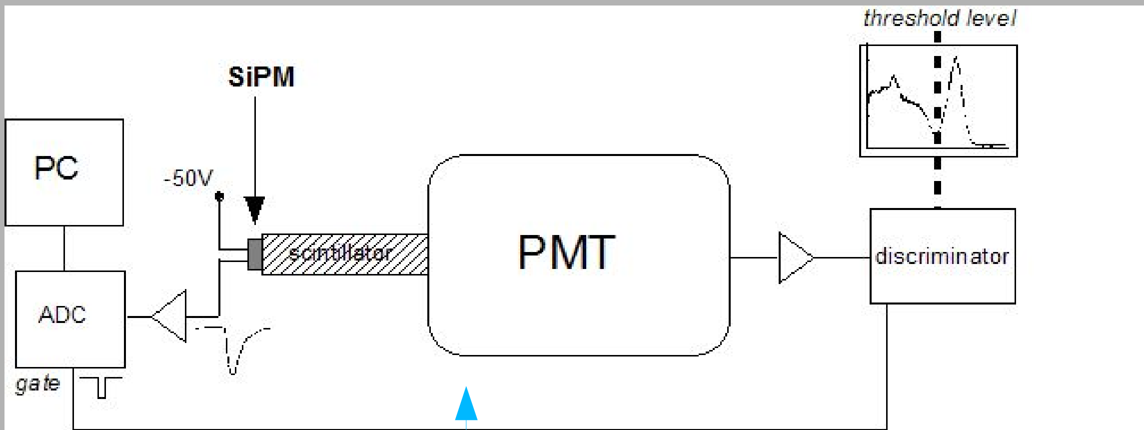
  - Depends on the density of defects

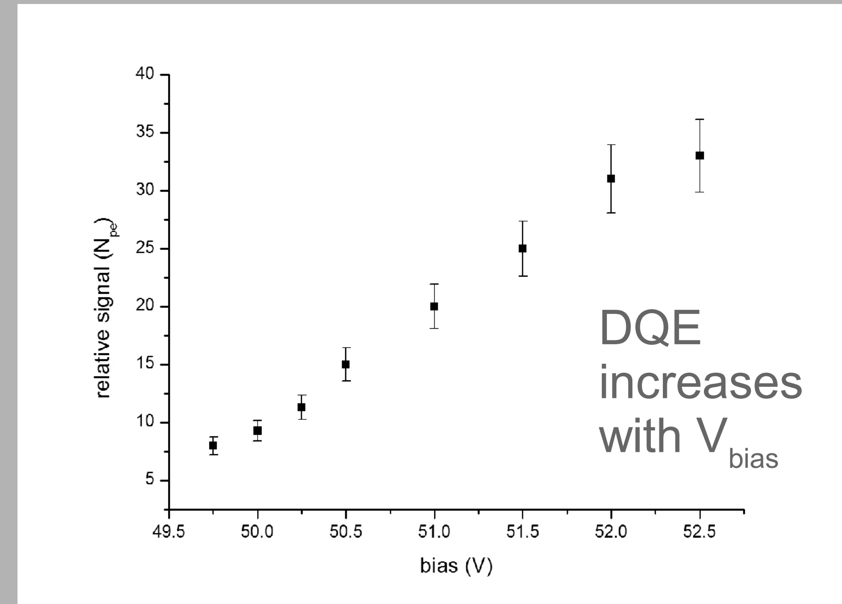
  - Volume

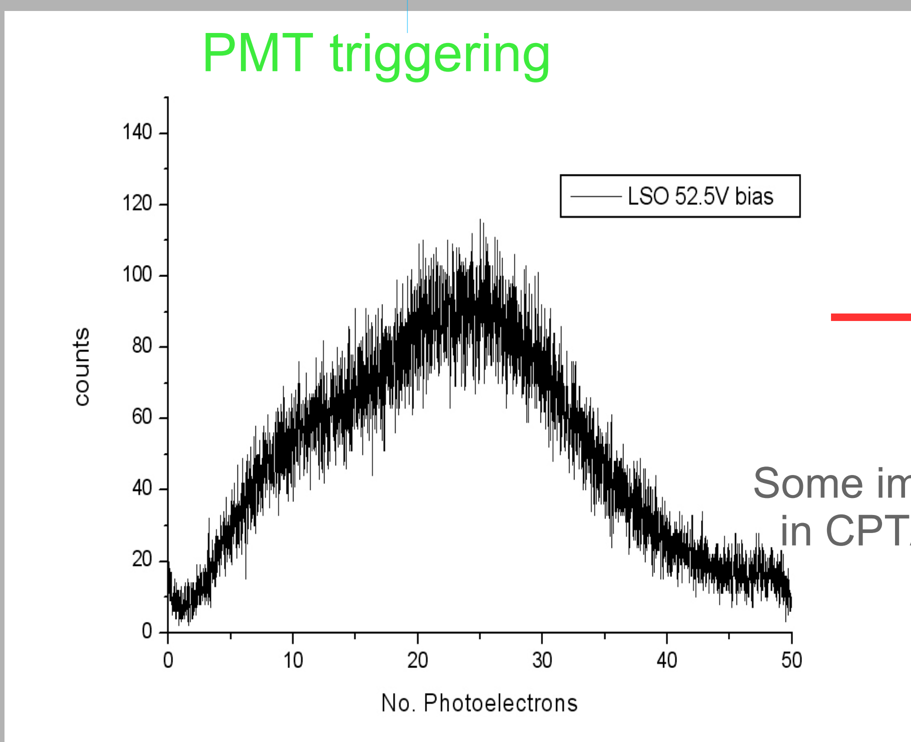
- Optical cross-talk

  - Hot carrier luminescence 10^6 carriers → 30 emitted photons in the visible range
  ref: A. Lacaita, IEEE TED, vol. 40, 1993

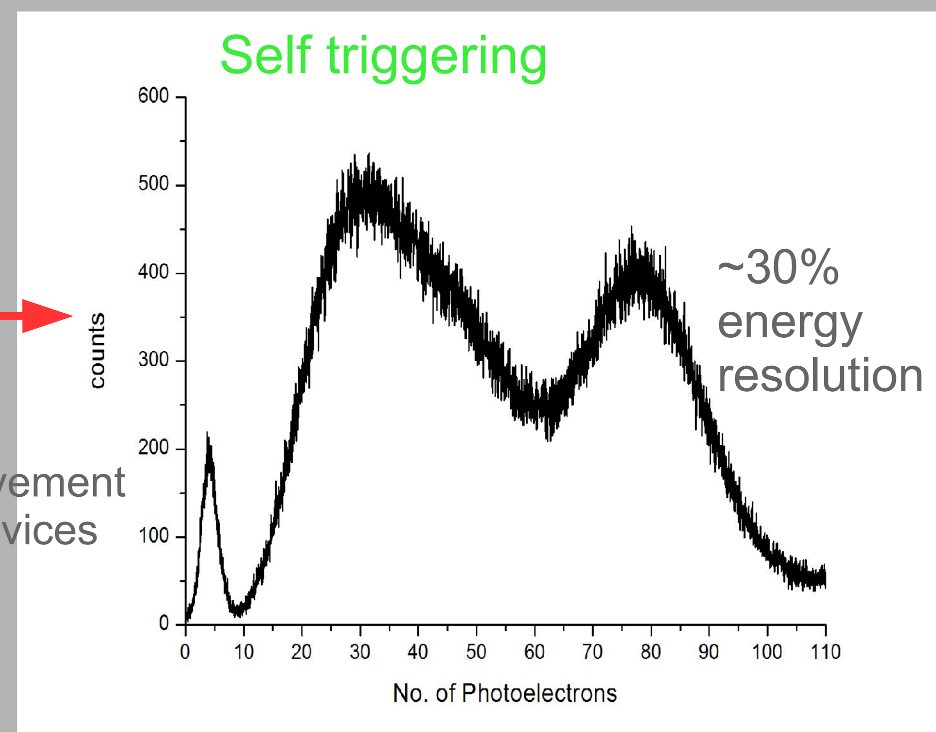
SiPM Results – Scintillator readout







Some improvement in CPTA devices

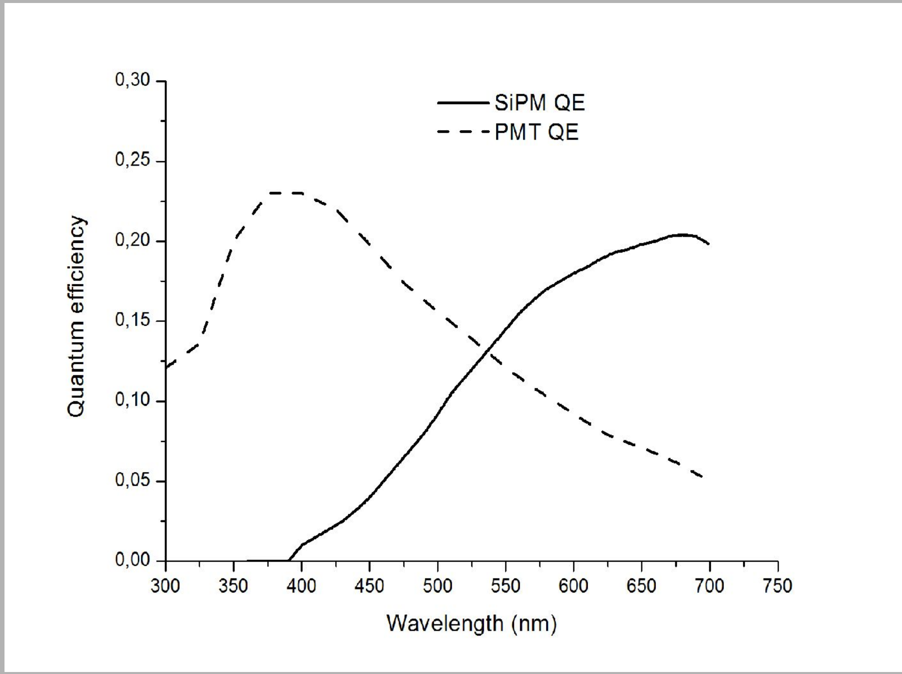


Quantum efficiency

Probability that a photon emitted by a light source gives an output pulse after impinging upon the detector:

$$\eta = \frac{nr.of\ output\ pulses\ recorded}{nr.of\ photons\ emited\ by\ light\ source}$$

$$\eta = \varepsilon_{geom} \times QE_{tot} = \varepsilon_{geom} \times QE \times \varepsilon_{avalanche}$$



ε_{geom} - geometrical efficiency : $\sum A_{pixel}/A_{total}$

QE_{tot} - total quantum efficiency :

- quantum efficiency QE
- avalanche efficiency $\varepsilon_{avalanche}$

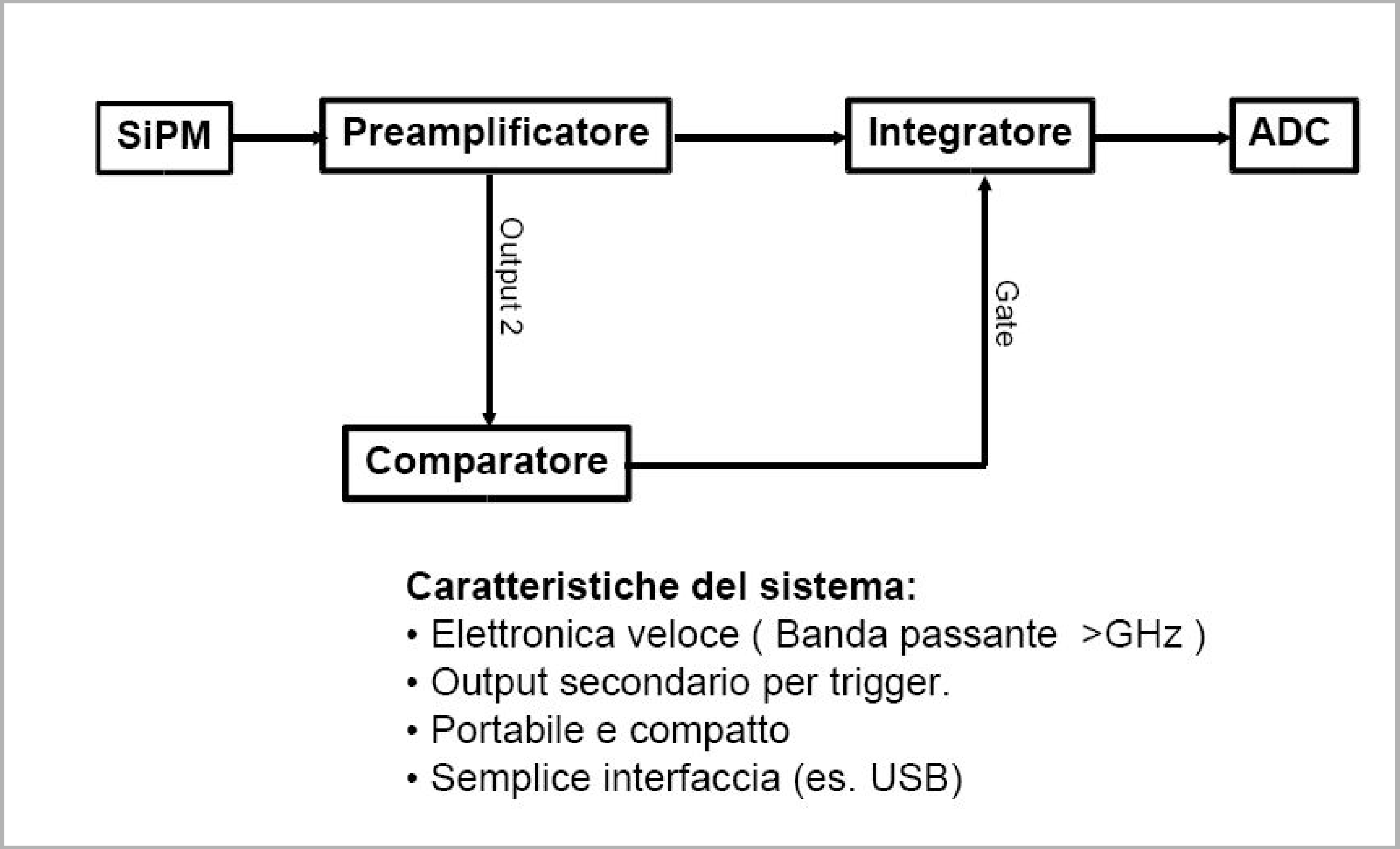
Key element of SiPM efficiency: geometrical factor

Typical values obtained: 0.3

SiPM Electronics development

- The signal pulses from the SiPM are very fast so to best characterise the performance of the SiPM, we require electronic readout that is fast and self triggering.

- We are developing dedicated SiPM readout based on a fast integrator, as shown below.



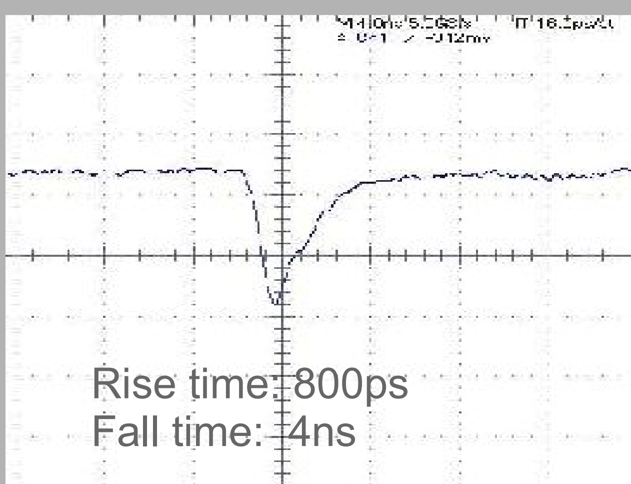
- The amplification stages employ the Gali5 chip, produced by minicircuits, that has a large bandwidth (a few Ghz)

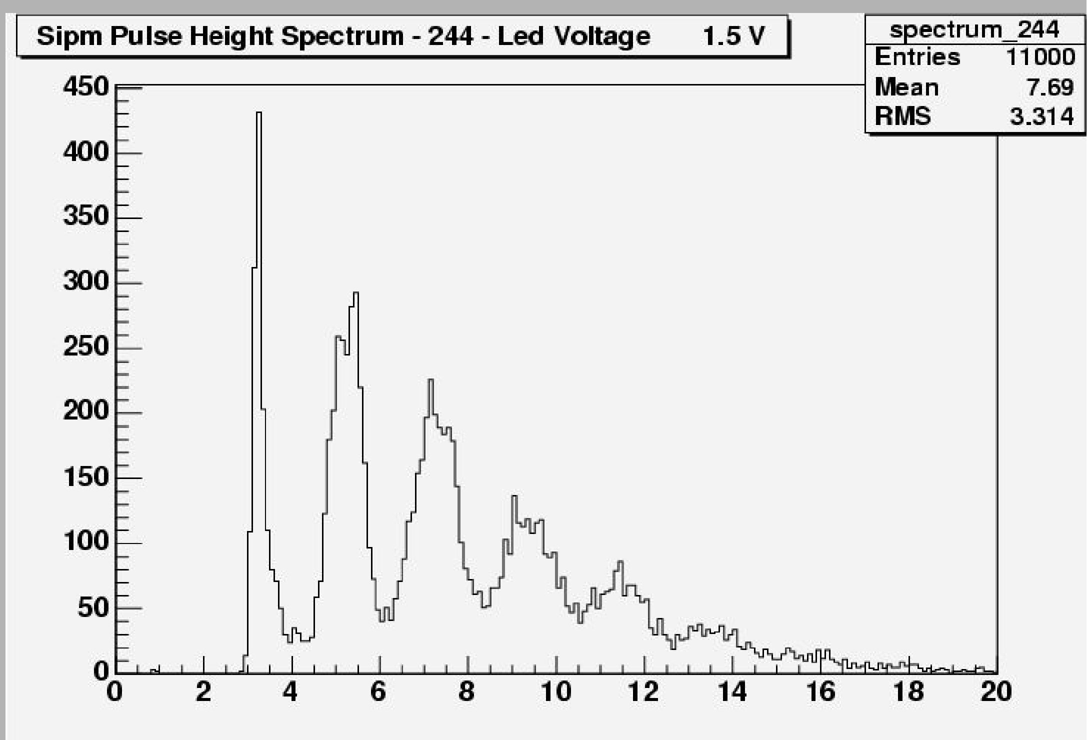
- The preamplifier board has two outputs: the second output is sent to a comparator to make the trigger

SiPM - Timing

- Rise time is related to the time required for the electrons to cross the depletion region (a few 100ps),
- Fall time
  - Recombination time of the electrons in silicon (a few ns) for small signals
  - Characteristic microcell discharge time (RC≈50ns) for larger signals
  - When used with scintillators the timing is dominated by their timing characteristics

We are working with two groups in Pisa in order to characterise the timing performance of the SiPM.
- MAGIC @ INFN – 4Ghz digital sampling system (DRS)
- Laser group @ CNR-Pisa – use of fs laser pulses





Current SiPM Development at IRST

- Simulations, design, process (IRST) - finished
- First run (starting ~ May, will finish ~ September)
  - Aimed to optimisation of the key points of SiPM
    - doping profiles (dopants concentration, geometrical dimensions) – to obtain an uniform electric field
    - antireflective coating (layers of SiO_2&Si_3N_4) – for optimisation of QE in the blue region
    - quenching resistance (implant dose)
    - optical isolation (different approaches for trench realisation)
- Characterisation
  - Electrical, optical and functional – set-up under working

3 Year Project Plan

- Year 1
  - TN: 2 production runs to produce optimised SiPM pixels
  - BA: development of discrete front end
  - BO: SiPM pixel testing for TOF applications
  - PG: readout development
  - PI: SiPM pixel testing for PET applications
- Year 2
  - TN: 2 production runs to produce small SiPM matrices
  - BA: 1 production run of front-end ASIC
  - BO: TOF prototype development
  - PG: readout prototype
  - PI: SiPM matrix testing for PET
- Year 3
  - TN: 2 production runs to produce 5x5 cm^2 SiPM matrices
  - BA: Final production of front-end ASIC
  - BO: TOF hodoscope proof of principle (testing at CERN)
  - PG: final readout production
  - PI: Proof of principle testing of gamma camera for PET

Pisa workplan

1. Testing of optimised SiPM for readout of scintillators appropriate to PET -

- quantum efficiency that is extended into the blue with respect to current devices, in order to be better matched with LSO.

- characterisation tests using light sources and scintillators to compare their performance with existing SiPM technology.

2. Testing of a first 2x2 element test matrix -

- Such a test matrix will not yet have to be adapted to deal with the large number of signal tracks.

- again characterise individual pixels within using light sources and scintillation pixels

- cross talk between the SiPM elements.

- uniformity of the operational characteristics of the individual SiPM elements, QE, gain, dark rate etc.

- Develop methods for studying these parameters via scanning SiPM pixels in the matrix that could be semi automatic.

Cont'd

3. Testing of larger ~2x2cm^2 matrix (20x20 elements) of SiPM test devices and integration with multichannel electronics

- This step will require the integration of two major developments;
    - Large scale SiPM array that accommodates large numbers of signal outputs,
    - development of a readout ASIC to handle large numbers of SiPM signals.
- First we will implement some surface scanning to check the uniformity of the SiPM elements that comprise the matrix
- Preliminary imaging tests. coupling this matrix to a scintillation pixel matrix and a continuous piece of scintillator.
    - investigate whether the light yield is within the dynamic range of the SiPM and what photopeak resolution is obtained.
    - map the spatial resolution in X and Y by scanning small cross-section scintillation pixel Na^{22} source in coincidence with the scintillator-SiPM camera.

4. Testing of full size 5x5cm^2 matrices of SiPM elements and integration into a gamma-camera prototype

- **Proof of principle prototype**
- construction of two cameras - will require some mechanical and electronic design, we will set up the two heads in opposing geometry and with electronic coincidence circuitry.
- The first measurements will utilise a Na^{22} point source, which after reconstruction will give us the reconstructed image resolution.
- After such time that the system and reconstruction algorithms (which will be first developed and used on simulation data) are optimised, we will use small animal PET phantoms in order to further characterise the system.

Requested funding – Year 1

- Receiving initial SiPM *samples* from ITC-IRST
- **Actions:** These samples will be characterised using our standard tests for; Dark rate, gain, signal to noise, detection efficiency, optical cross talk, after pulsing, timing, dynamic range.

- Necessary funding to implement actions

  - VME charge integrating ADC (CAEN V792) (5k€)
  - VME TDC (CAEN V775) (5k€)
  - Laser diodes of different wavelengths (3k€)
  - Laboratory consumables (PCB printing, components, cables) (2k€)
  - 1 month spent each at Perugia and Bari collaborating on electronics development, plus collaboration meetings (6k€)
  - 2 international conferences (IEEE NSS-MIC 2006, USA & EuroMedIm, France) (5k€)

TOTAL YR1: 26K€

Requested funding – Year 2

- Receiving initial SiPM *matrices* from ITC-IRST
- Receive *test readout solutions* from Bari and Perugia

Actions: SiPM matrix elements subjected individually to the standard characterisation tests. Develop scanning techniques to perform *en masse*. Couple to scintillator test matrices for preliminary imaging tests.

- Necessary funding to implement actions

  - Various scintillators; Matrices of LYSO, with pixel pitch matching that of SiPM separation and size to match matrix + LaBr slabs (5k€)
  - Motorised translation stage (4k€)
  - 1 set of production masks (for ITC-irst) (15k€)
  - Laboratory consumables (PCB printing, components) (1k€)
  - 1 month spent each at Perugia and Bari collaborating on electronics development, plus collaboration meetings (6k€)
  - 2 international conferences (IEEE NSS-MIC 2007, USA & EANM, Europe) (5k€)

TOTAL YR2: 36K€

Requested funding – Year 3

- Receiving SiPM *larger area matrices* from ITC-IRST

- Receiving *custom front end electronics* and *readout architecture* from Bari and Perugia

- **Actions:** Utilise scanning characterisation of larger SiPM matrices. Integrate new readout systems and characterise basic performance. Couple SiPM matrix with various scintillators to form basic imaging system. Use ^{22}Na source scanning to determine system spatial resolution. Form two head PET prototype and characterise with phantoms.

- Necessary funding to implement actions

  - Various scintillators; continuous, polished samples equal to SiPM matrix size, 3mm, 5mm and 10mm thick of either LYSO or LaBr (2k€)

  - Mechanical supports, gantry, housing (4k€)

  - 1 set of production masks (for ITC-irst) (15k€)

  - Laboratory consumables (Probes, cables, optical glue, sources) (2k€)

  - 1 month spent each at Perugia and Bari collaborating on electronics development, plus collaboration meetings (6k€)

  - 2 international conferences (IEEE NSS-MIC 2008, Europe & NDIP France) (5k€)

TOTAL YR3: 34K€

Pisa personnel and funding – year 1 summary

***Pisa** collaborators*		
Name	*Title*	*FTE/year*
Alberto Del Guerra	P.O	0,6
Deborah Herbert	Bors. INFN	0,7
Nicola Belcari	Ass. Ric.	0,8
Antonietta Bartoli	Dott.	0,5
Manuella Camarda	Spec.	0,7
Sascha Moehrs	Dott.	0,7
Walter Bencivelli	P.A	0,3
TOTALE:		**4,3**

+

- Galeotti (1 man month)
- Morsani (support)

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Pisa funding 2006 (k€)	10	5	6	5	**26**

Total project funding and personnel

Group	*2006 (k€)*	*2007 (k€)*	*2008 (k€)*	**Group total (k€)**
BA	12	12	11	**35**
BO	12	10	11	**33**
PG	23	23	10	**56**
PI	26	36	34	**96**
TN	22	22	21	**65**
Total	**110**	**103**	**72**	**285**

Group	*FTE/year*
BA	1,6
BO	1,2
PG	2,7
PI	4,3
TN	2,5
TOTAL:	**12,3**