Characterization and Optimization of Silicon Photomultipliers for the Development of Intraoperative Beta Probes

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Introduction

The precise localization and complete surgical excision of tumors are one of the most important procedures in the treatment of cancer. In that context, inside body delineation of tumor boundaries labeled with positron radiotracers opens up new prospective to help surgeons to discriminate with higher sensitivity malignant tissues from surrounding normal tissues. The IMNC laboratory has already developed prototypes of intra operative beta probes.

TRIOP: A bi-modal probe (Auto-fluorescence and positron) for brain cancer surgery

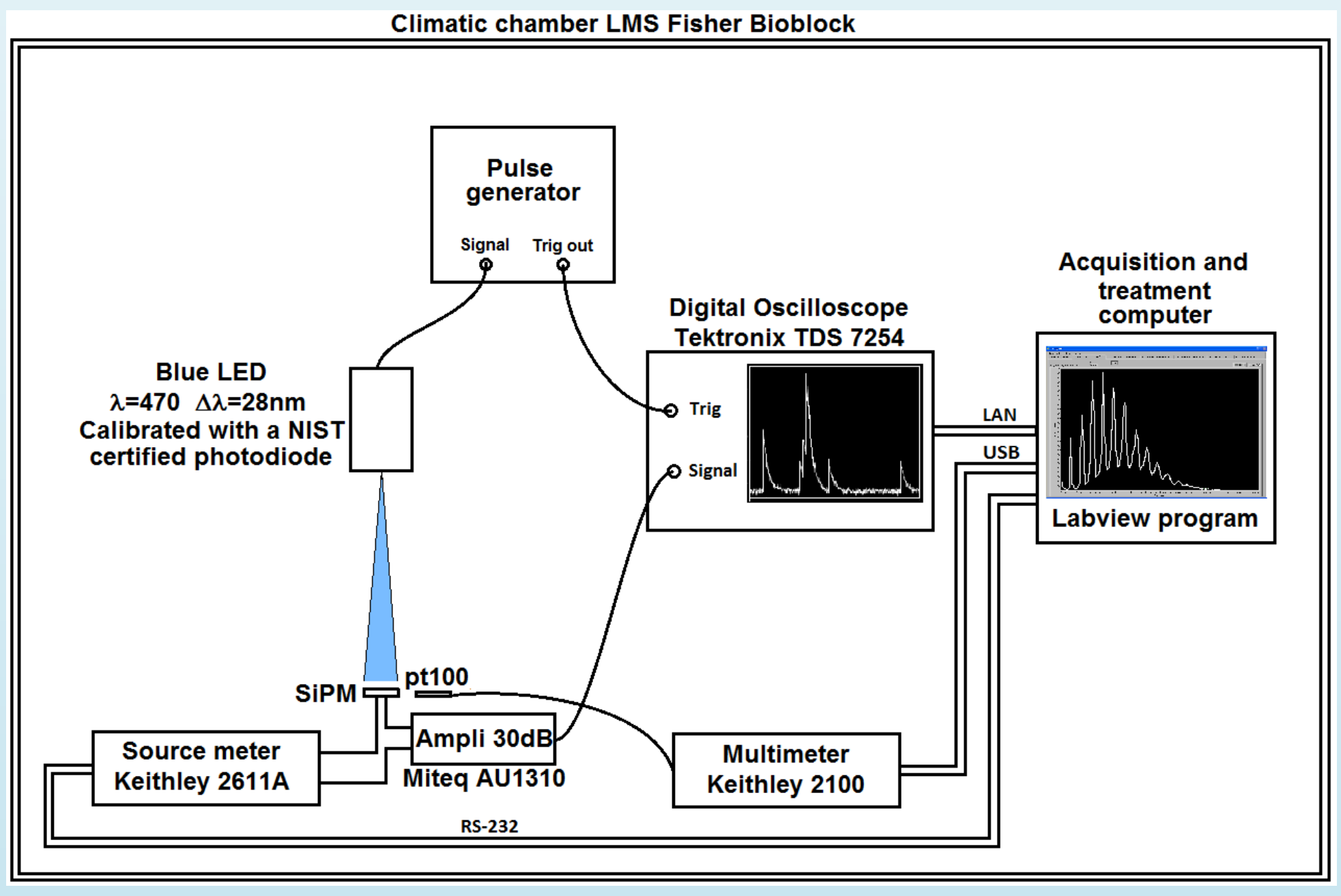
Bogalhas et al,
Phys Med Biol, 2009

The key parameters when trying to improve the efficiency and reliability of positron intraoperative probes for real-time tumor localization are low energy sensitivity, compactness, low weight, simplicity of implementation (low power consumption, stability) and versatility (geometry and size of the sensitive field of view). Silicon Photomultipliers (SiPM) have the potential to fulfill all these needs and to overcome the main drawbacks of current technologies. However, further developments are still necessary to achieve a reliable compact photosensor system that could notably impact the performances of future miniaturized probes for cancer surgery.

This comprehensive study aims to evaluate SiPM performances as photodetectors for intraoperative beta probes. We focused our measurements on temperature and bias voltage effects on the noise, absolute detection efficiency and total gain. The impact of these parameters on beta sensitivity was quantified using a simple physical model.

Materials and Methods

Experimental Setup

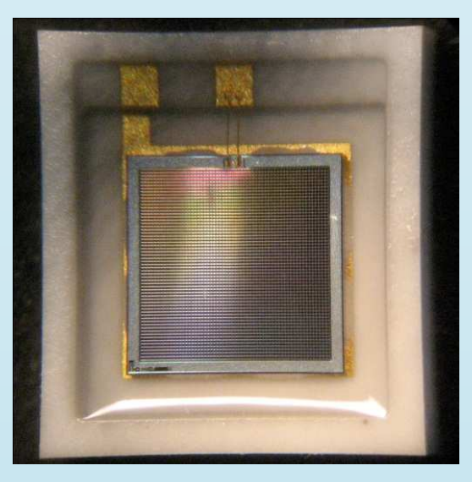


The climatic chamber ensures a tunable and stable temperature ($\Delta T=\pm 0{,}1$ ℃)

The amplified signal was sampled by a TDS 7254 digital oscilloscope (2.5 GHz, 40 GS/s). The automatic data acquisition and analysis of the SiPM signals have been done on Labview programs (baseline subtraction, peak detection, integration).

4 SiPM devices from Hamamatsu have been tested :

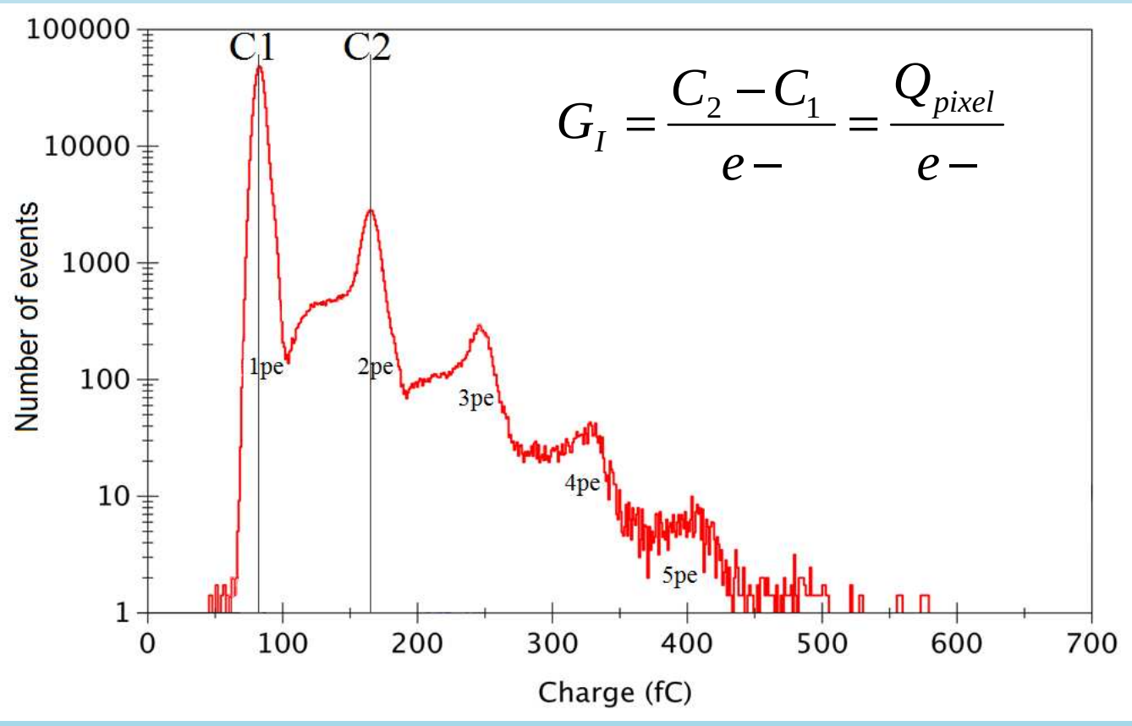
- 1x1mm²/25µm (S10362-11-25C)
- 1x1mm²/50µm (S10362-11-50C)
- 3x3mm²/25µm (S10362-33-25C)
- 3x3mm²/50µm (S10931-50P, low noise)



Intrinsic Gain, Breakdown voltage and DCR measurements

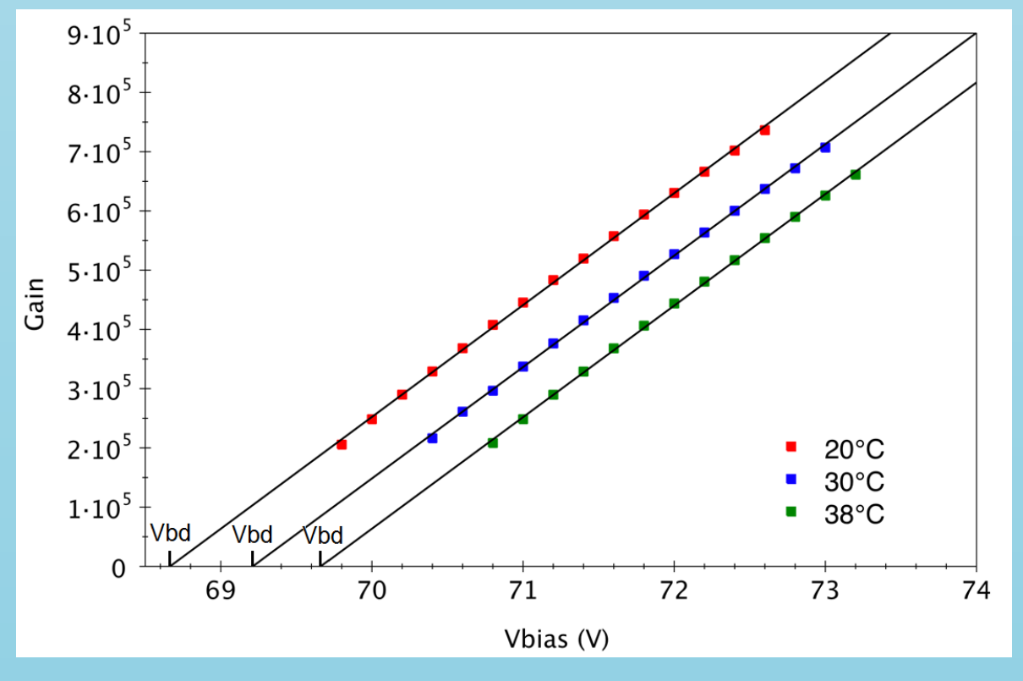
These Parameters were measured from the dark noise signal (LED turned off). Each detected signal was integrated according to the recovery time of the SiPM (from 40ns to 150ns).

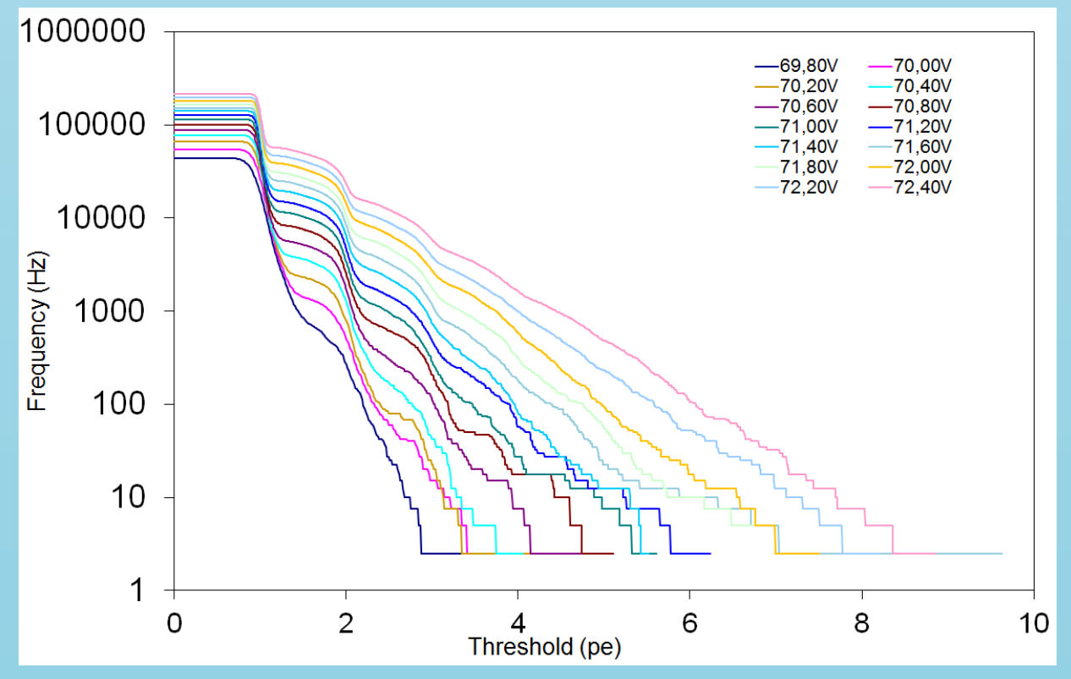
Intrinsic gain G_I is the average output charge developed by one fired cell Q_{pixel} normalized by the elementary electron charge



$$G_I = \frac{C_2 - C_1}{e-} = \frac{Q_{pixel}}{e-}$$

Charge spectrum distribution normalized to the equivalent number of photoelectrons (pe) (i.e. number of fired cells)



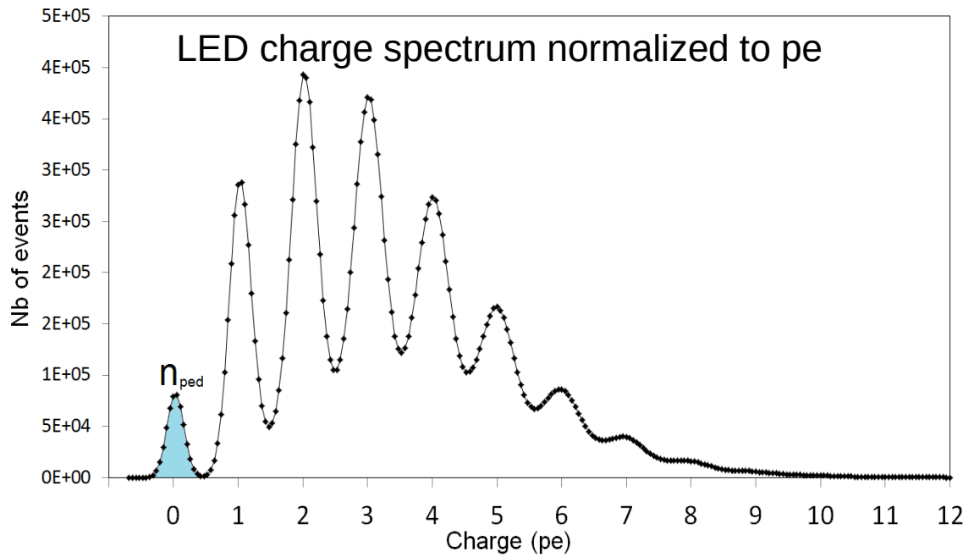


- ⇒ Breakdown voltage (V_{BD}) determinated by extrapolating to zero gain using a linear fit
- ⇒ Bias voltage over breakdown $\Delta V = V_{bias}-V_{BD}$

- ⇒ Dark count rate (DCR) as a function of the bias voltage and the threshold level (pe)
- ⇒ 1 Hz threshold level to achieve a 1Hz DCR

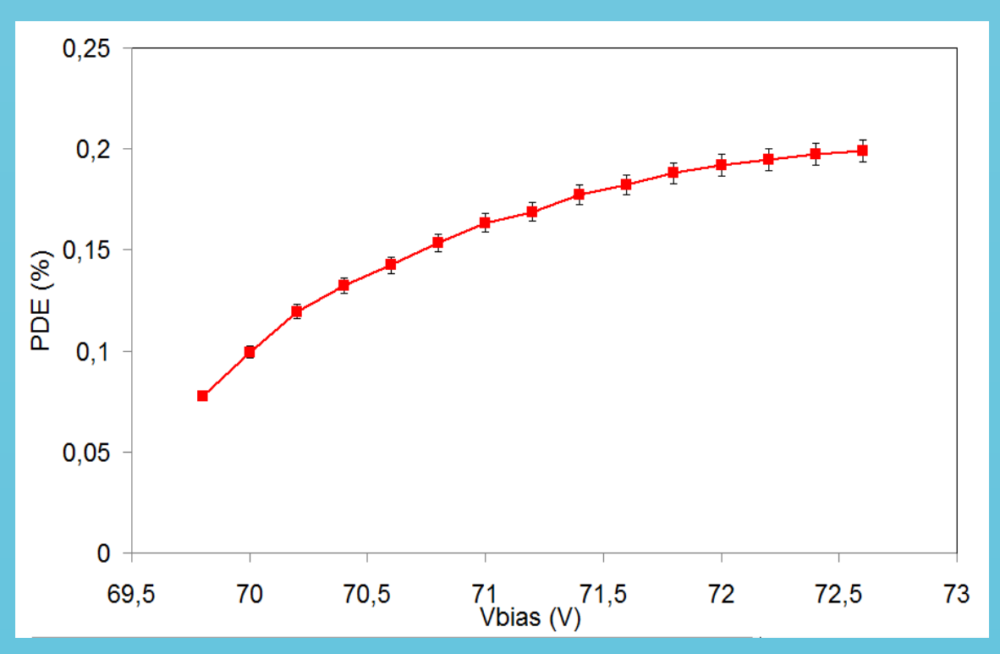
PDE and Total Gain measurements

LED turn ON (incident light flux N_{ph}~ 0,5photon/pulse, FWHM pulse width < 30 ns). The output signals from the SiPMs on the LED flash was detected within a coincidence time window after the LED trigger (95 ns) and integrated to obtain the charge spectrum.

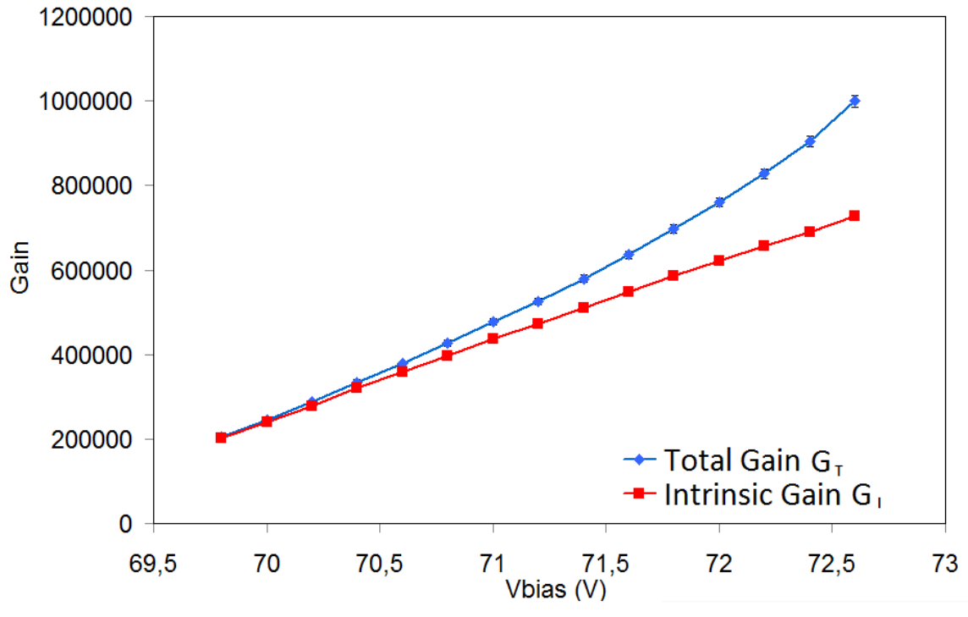


- n_{ped} : number of events in the pedestal peak (zero photons detected)
- n_{tot} : total number of events in the spectrum
- C_{mean} (pe) is the mean charge of the spectrum
- Same measurements without light have been made to estimate the dark noise contamination (n^0_{ped}, n^0_{tot} and C^0_{mean})

$$PDE = \frac{N_{pe}}{N_{ph}} = \frac{1}{N_{ph}}\left(-\ln\left(\frac{n_{ped}}{n_{tot}}\right) + \ln\left(\frac{n^0_{ped}}{n^0_{tot}}\right)\right)$$



$$G_T = \frac{C_{mean} - C^0_{mean}}{N_{pe}}.G_I$$



Photon Detection Efficiency (PDE) is the mean number of detected photoelectrons (primary triggers) N_{pe} divided by the mean number of incident photon N_{ph}

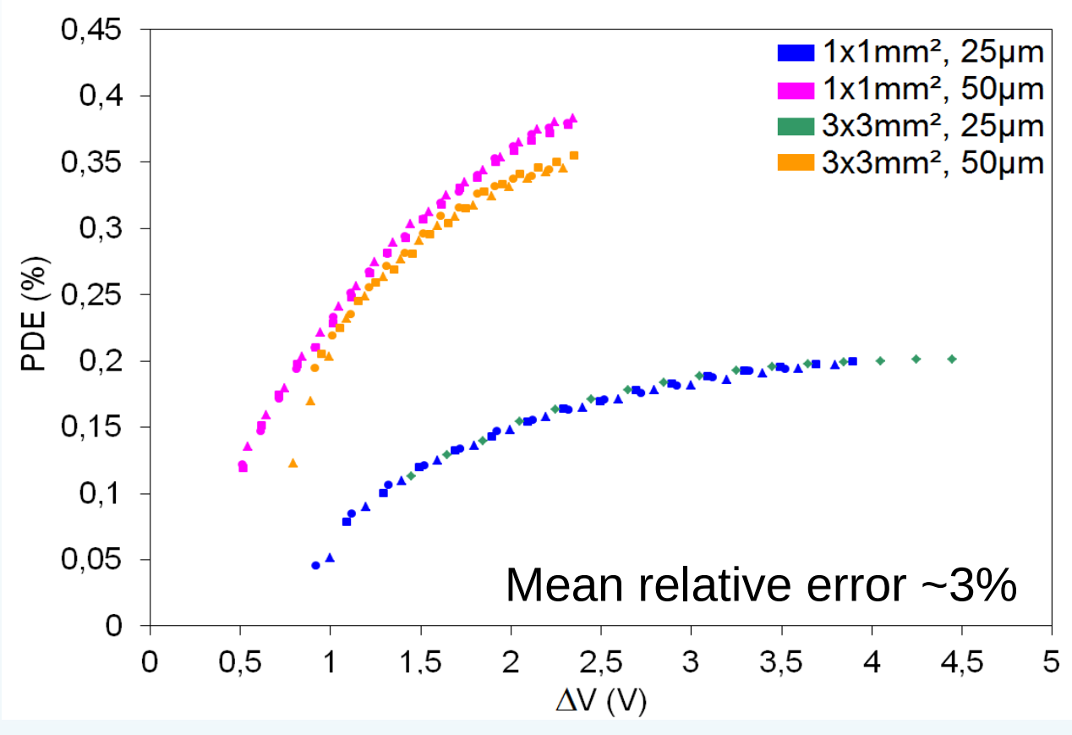
Total Gain G_T is the mean output charge (e^-) developed by a primary discharge and accounts for the effect of optical crosstalk and afterpulses on the real gain of the SiPM.

G_T = average number of cells fired by a primary trigger x G_i

Experimental Results

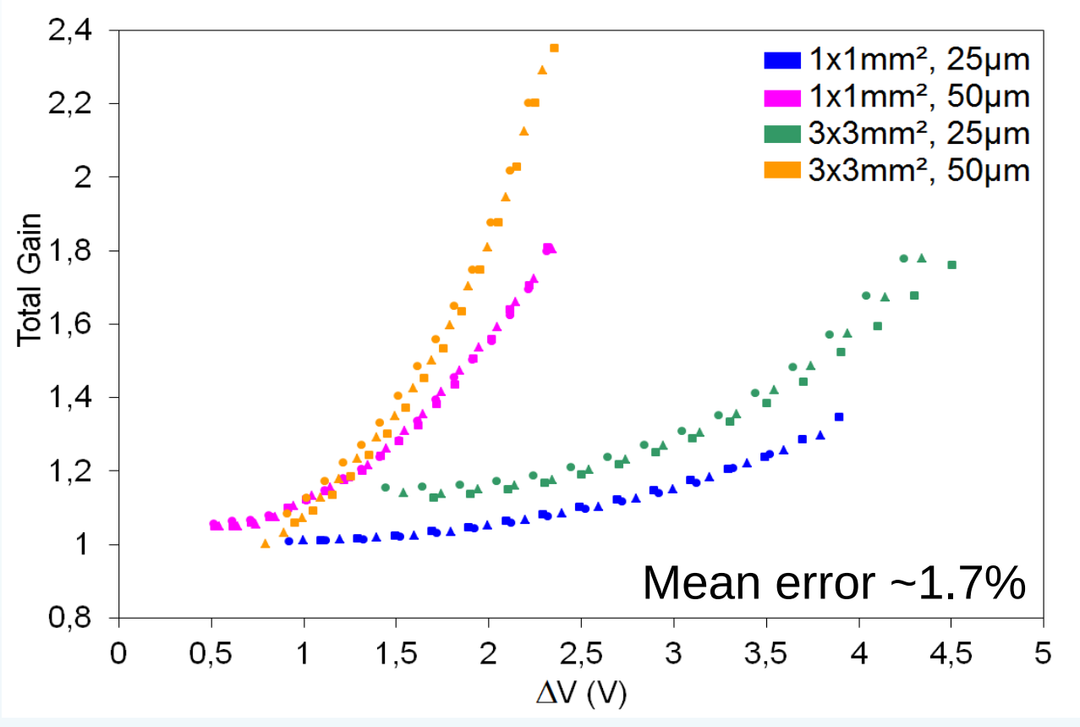
These measurements have been made at 3 temperatures T : 20℃ (□), 30℃ (Δ) and 38℃ (○)

Photon detection efficiency



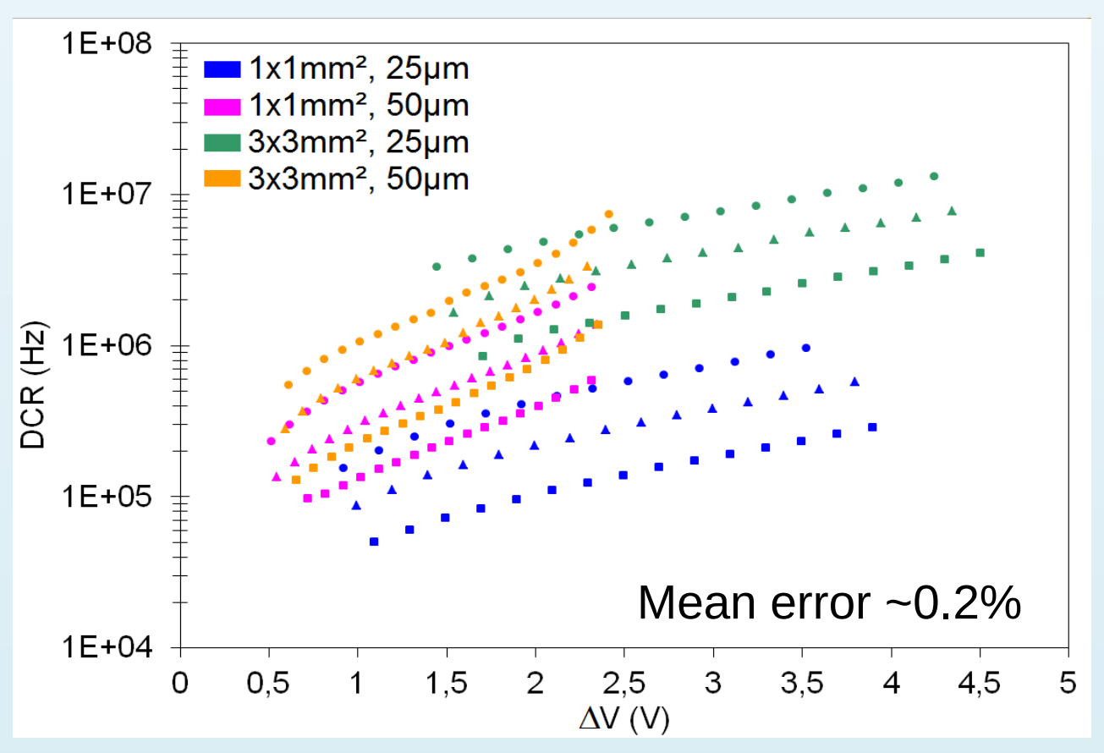
- Increases with increasing V_{bias} due to the voltage dependence of the triggering probability of Geiger discharge
- Independent on temperature at constant ΔV
- Up to 20% for 25µm cells and more than 35% for 50µm cells

Total Gain

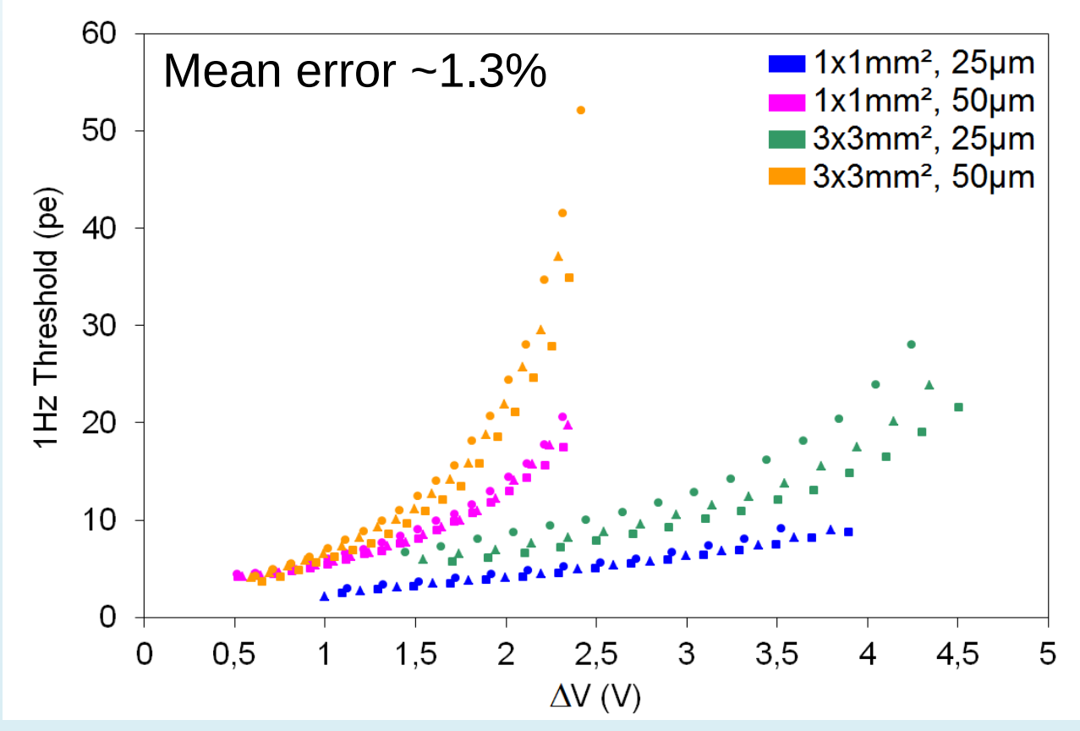


- Increases with V_{bias} due to increasing probabilities of optical crosstalk and afterpulses
- Increases with cells number and size
- Almost independent on temperature at constant ΔV
- Up to 1.3 pixels fired by a primary trigger for the 1x1/25µm and 2.4 for the 3x3/50µm device

DCR and 1Hz Threshold

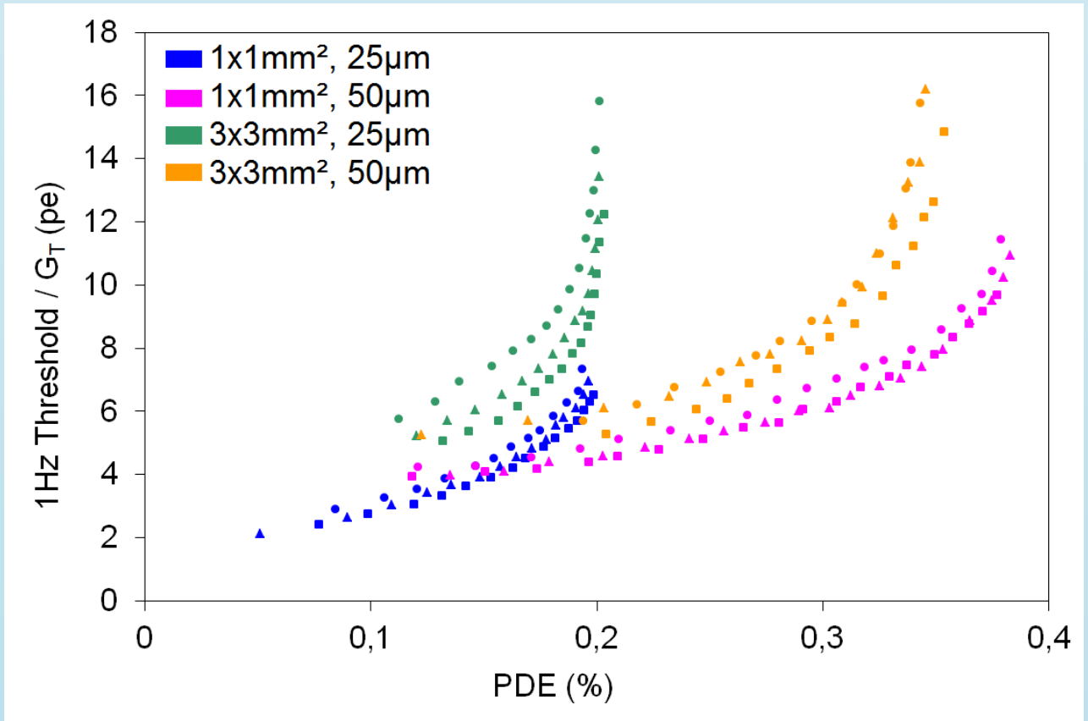


- Increases with V_{bias} and cells number and size
- X 4 between 20℃ and 38℃ at a given ΔV (i.e. constant gain), whatever the SiPM device



- Follows an exponential growth as a function of V_{bias} at fixed T
- Depends on G_T and DCR : the temperature dependence is related to the DCR level
- The mean relative increases for a given ΔV is around 10% for 1x1mm² SiPMs, 18% for 3x3/50µm and 27% for 3x3/25µm

Beta sensitivity : a trade-off between Dark noise and PDE



- The ratio between the 1Hz threshold and G_T is an indicator of the noise-to-signal ratio for beta detection
- Noise-to-signal ratio increases much faster than PDE with V_{bias}, especially for 3x3 mm² SiPM devices

Beta sensitivity prediction

The expected beta sensitivity S_β of a the SiPM/plastic scintillator assembly can be approximated by the relation:

$$S_\beta = \sum_{n=n_T}^{\infty} FT^{-1}\left(\sum_{\mu=1}^{\mu_{max}} N(\mu)\exp\left(\mu.PDE.\frac{FT(Q)-1}{1-\alpha FT(Q)}\right)\right) \quad \text{with} \quad \alpha = 1 - \frac{1}{G_T}$$

(following the model described by Balagura et al, Nucl Instr and Meth A, 2006)

FT and FT^{-1}: Fourier transform and its inverse

N(µ): normalized distribution of incident beta events in term of the average number of photons in the scintillation light pulse (N(µ) follows the shape of the beta spectrum if the scintillator is thick enough)

μ_{max} : maximum number of impinging photons corresponding to the endpoint energy of the beta spectra

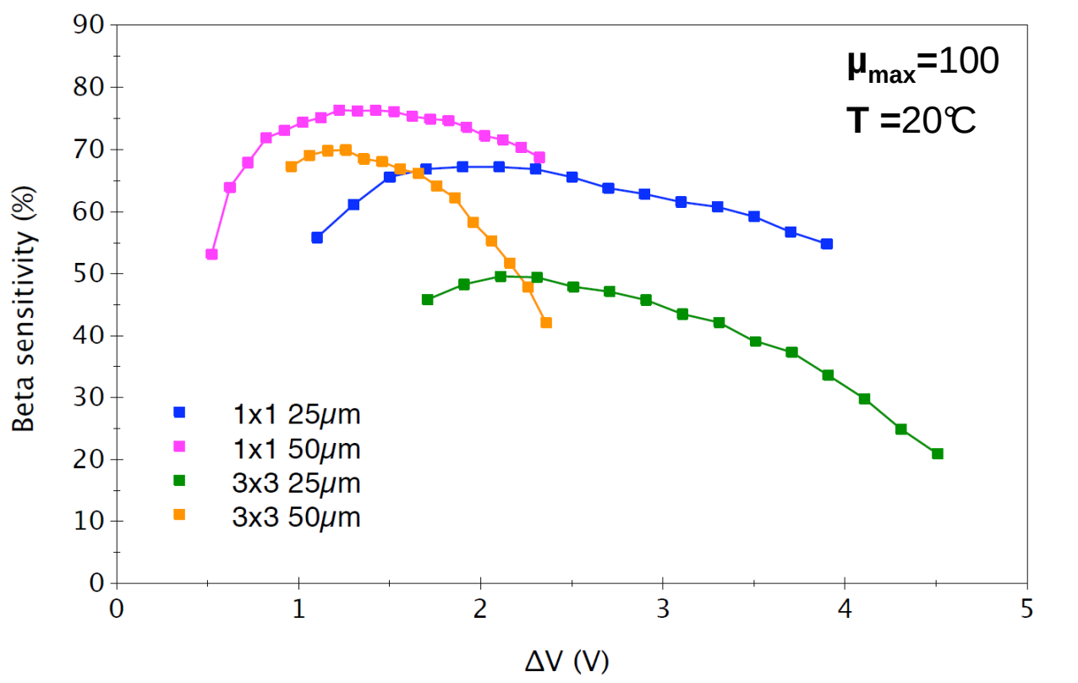
PDE: Photon Detection Efficiency

Q: signal charge distribution of one single fired cell (Gaussian shape) normalized to photoelectrons

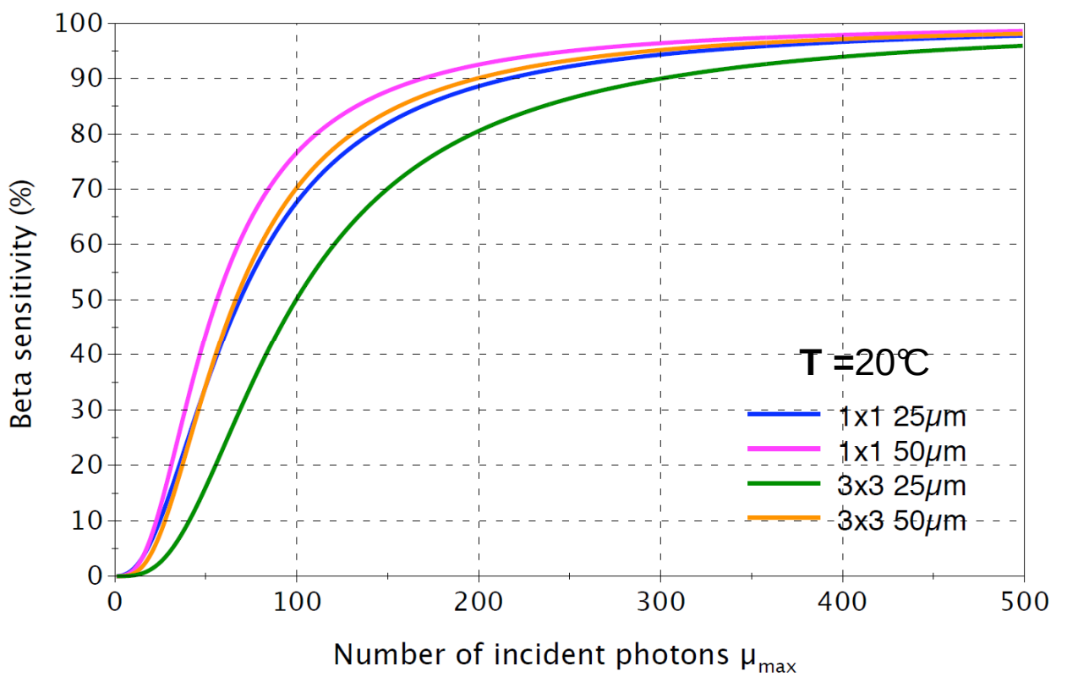
G_T : total Gain (number of cells fired by a primary photon

n_T : 1 Hz threshold (pe)

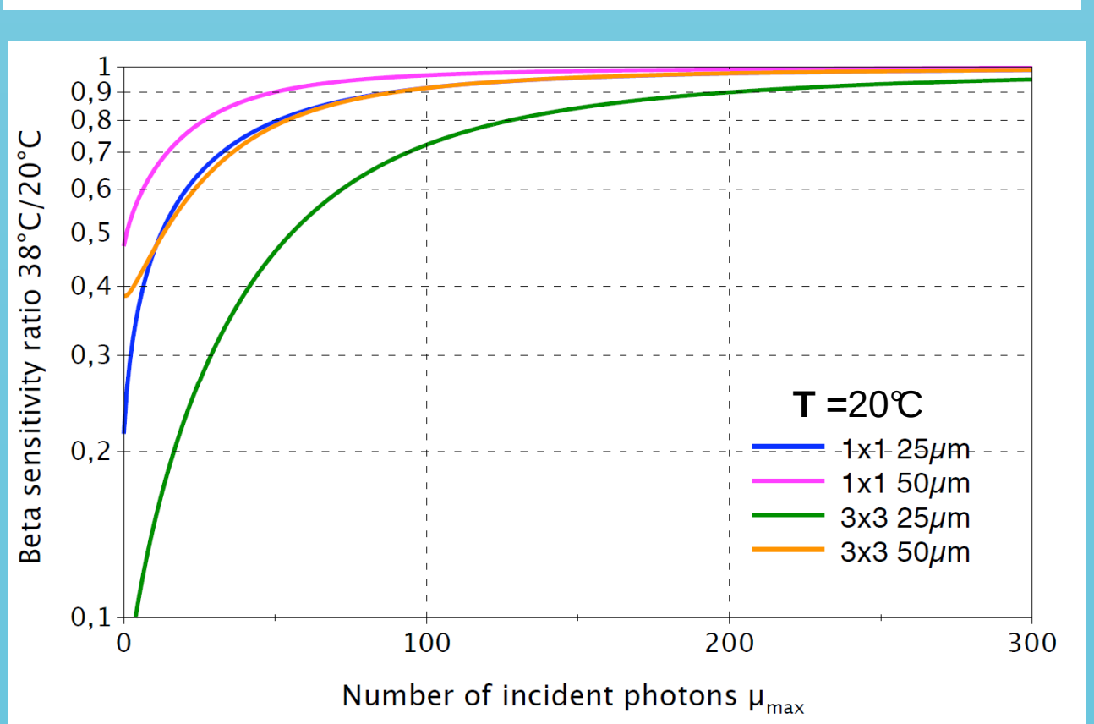
The expected beta sensitivity S_β was computed as a function of μ_{max} for the energy distribution of a ^{18}F source. The parameters (n_T, PDE, G_T and Q) were set according to the measurements for each temperature, V_{bias} and SiPM device.



- S_β reaches an optimal value for $\Delta V/V_{bd}$ around 3% for SiPMs with 25 µm cells, 2% for 1x1mm²/50µm and 1.5% for 3x3mm²/50µm
- Above this level, the variation of S_β is dominated by the dark noise and the sensitivity decreases
- Optimal ΔV are almost independent on temperature and μ_{max}



- S_β achieved at an optimal ΔV value are closed to 90% when μ_{max}=170 photons for 1x1mm²/50µm, 200 for 1x1mm²/25µm and 3x3mm²/50µm and 300 for 3x3mm²/25µm
- S_β achieved with 3x3 mm² SiPM devices are limited by the higher occurrence of crosstalk and afterpulses
- 3x3 mm²/50 µm SiPM appears as the best compromise between sensitivity and light collection efficiency



- SiPMs with good beta sensitivity are also less sensitive to temperature variation
- The drop of S_β between 20℃ and 38℃ at **μ_{max} =** 100 photons is around 30% for 3x3mm²/25µm but only 5% for 1x1mm²/50µm

Conclusion and perspectives

- Intrinsic features of SiPMs can provide high beta sensitivity despite their high thermal noise
- Influence of temperature on dark noise and PDE are significant but can be accurately compensated by controlling the SiPM bias voltage over breakdown
- Experimental validation of the beta sensitivity model is currently under progress and additional measurements with SiPMs from different manufacturers will be done
- This study will be used to optimize the design of our new miniaturized SiPM-based beta probe dedicated to brain tumor surgery