Design and commissioning of a Silicon Photomultiplier-based dosimeter for Low Dose Rate (LDR) oncological brachytherapy

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Brachytherapy (BT) is a form of radiation therapy where a sealed radiation source is positioned within or close to the cancer volume. Source positioning is vital to ensure irradiation of the tumour while ensuring minimum exposure to nearby critical organs. Brachytherapy is divided into Low Dose Rate (LDR) and High Dose Rate (HDR).

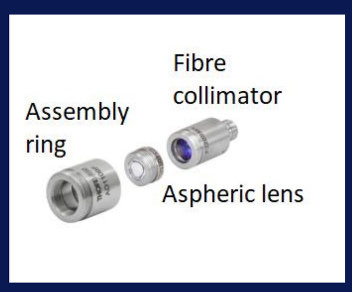
ORIGIN is a research project funded by the European Union, aiming to perform brachytherapy for cancer treatment more effectively through advanced real-time dose mapping and source localization. This is achieved through a novel 16-optical fiber-based system, providing real-time dose measurements by pulse counting.

A dosimeter prototype employing room temperature Silicon Photomultipliers (SiPMs) for scintillation light sensing was qualified using an LDR source (^{125}I). It was found to be in compliance with the TG43-U1 standard. However, the measurement distance range was constrained by sensitivity and Dark Count Rate (DCR) [1].

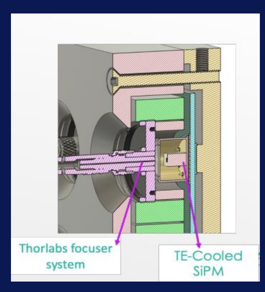
This poster reports the solution implemented to overcome the limitations of the initial prototype, based on the use of TE-Cooled sensors together with an optical system focusing light on the SiPM surface.

The ORIGIN Dosimeter

Optical fiber with a scintillating tip: allows point-like dose measurement.



Optical system: focuses the light on the SiPM (improved acceptance).



TE-cooled SiPM: allows stable counting capability.

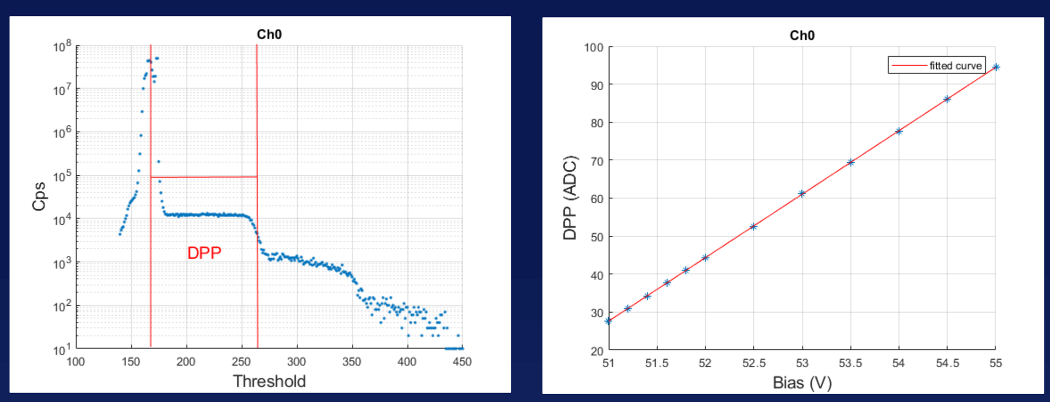
The ORIGIN Dosimeter: dose mapping and source localization by using 16 point-like measurements.

Requirements	LDR-BT
Sensitivity to Dose	Up to 3 cm
Spatial Resolution	3 mm @ 3 cm
Dose Rate Range	0.4-2 Gy/h
Statistical Precision	5% in 0.5 s

System qualification performed by measuring:
- Minimum Detectable Light (MDL) $= 3\sqrt{DCR \cdot \Delta t}$: represents the minimum amount of light that the dosimeter can distinguish from the background.
- Sensitivity: the minimum variation in the radiation current that can induce a noticeable change in the Photon Counting Rate (PCR).
- Equalization: defines the best technique to minimize the MDL and sensitivity channel-to-channel variation.

1. Breakdown Voltage (V_b)

Procedure to measure the Breakdown Voltage:
1. Staircase* performed at different voltage values.
2. Peak-to-Peak (ΔPP) measurements ⇒ first step inflection point – baseline.
3. V_b defined as the voltage where the ΔPP = 0 (extrapolated by a linear fit).



Results from the 16 channels:
- Mean V_b: 49.03 ± 0.18 V.
- V_b spread: 0.4%.

*Typical plot where the Dark Count Rate (DCR) is represented as a function of the threshold set at the discriminator.

2. Dark Count Rate (DCR) stability

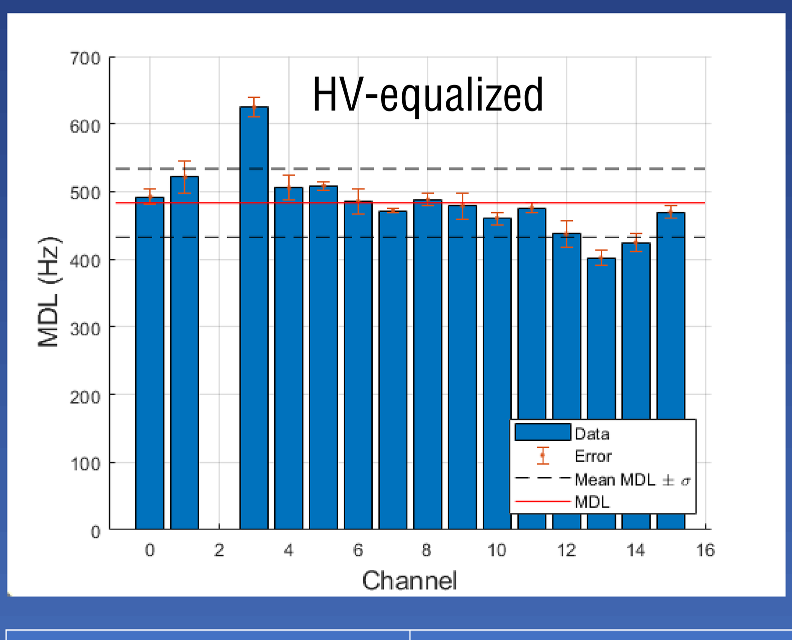
DCR stability is measured by using 1-hour long run without radiation source on the sensors.

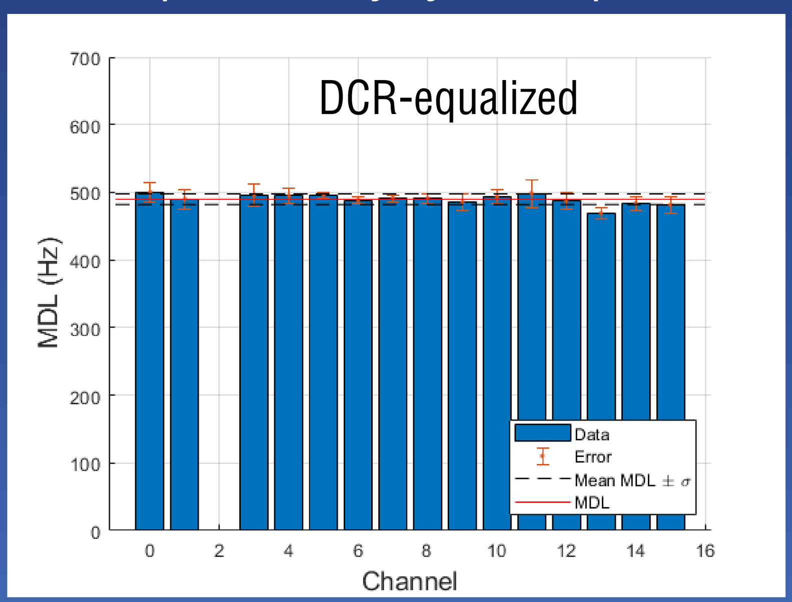
Results from the 16 channels:
- Poissonian single channel standard deviation.
- Stability assessed at 99% confidence level.

3. High Voltage (HV) vs DCR Equalization

HV equalization:
- Apply +6 V_{ov} to all SiPMs to get the same PDE.
- Disadvantage: large spread on the DCR and MDL.

DCR equalization:
- Adjust the HV (~6 V) to get the same DCR for all SiPMs.
- Disadvantage: PDE variation from 50 to 55% even though it can be compensated by system equalization.



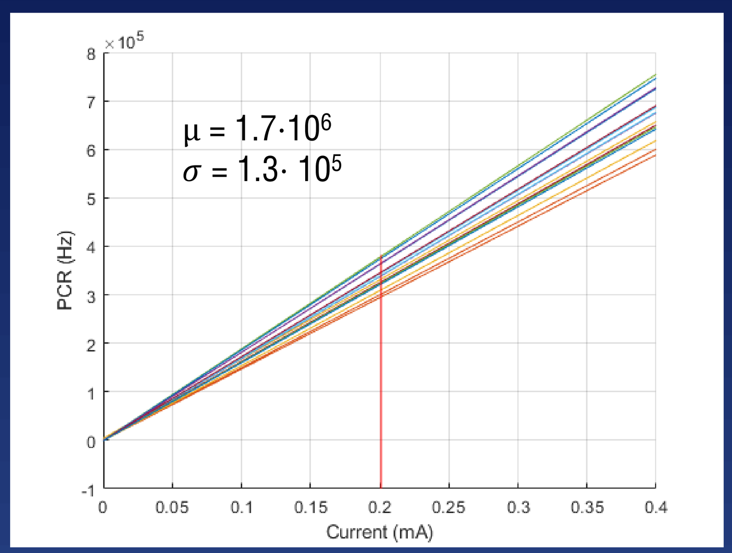


Parameter	HV	DCR
Mean DCR	13.1 ± 2.9 kHz (22.3%)	13.3 ± 0.43 kHz (3.0%)
Max DCR variation	12.7 kHz (96.9%)	1.7 kHz (12.8%)
Mean MDL	483.1 ± 50.5 Hz (10.5%)	490 ± 7.9 Hz (1.6%)
Max MDL variation	222.4 Hz (46.04%)	30.8 Hz (6.3%)

$$MDL = 3\sqrt{DCR \cdot \Delta t}$$

4. Sensitivity Measurement and System Equalization

Sensitivity measurement:
1. Single fiber connected to the i-th SiPM and illuminated with X-rays (25 kVp, 0.04-0.4 mA).
2. Photon Counting Rate is measured against X-Ray intensity.
3. The angular coefficient defines the Sensitivity (Hz/mA).

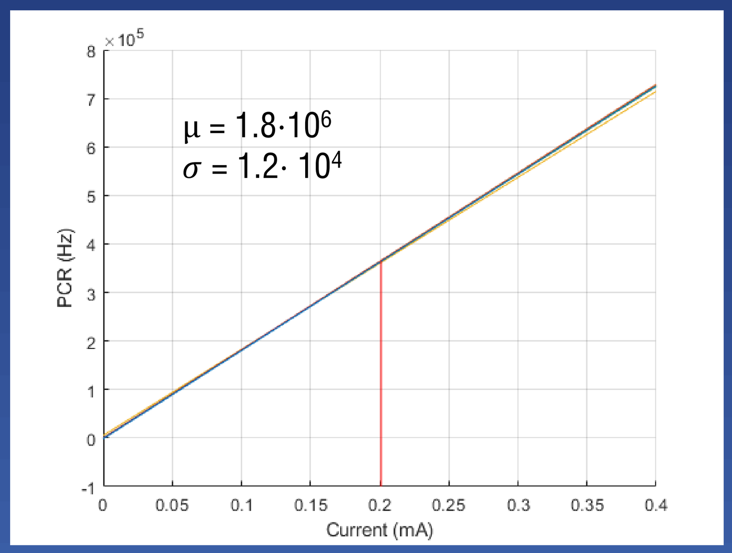


Sensitivity equalization:

Normalizing coefficients are defined as:

$$K_i = \frac{PCR_1}{PCR_i},$$

where PCR is the Photon Counting Rate from the i-th SiPM at fixed current (0.2 mA).



Results obtained after DCR equalization:
- Sensitivity: 1.8x10^6 Hz/mA.
- PCR spread pre-equalization: 7.6%.
- PCR spread post-equalization: 0.4%.

Conclusion & Perspectives

The TE-cooled ORIGIN Dosimeter shows a significant improvement:
- Reduced DCR and improved MDL (≈ 2 times better).
- Higher sensitivity (≈ 3 times better).

Results that should enable the collaboration to meet the project specifications. A measurement campaign is on-going to verify the system sensitivity up to 3cm and to fully qualify the system in clinical environment.

TE-cooled ORIGIN dosimeter:
- Mean DCR: 13.3 kHz.
- Mean MDL: 490 ± 7.9 Hz.
- Sensitivity : 1.8*10^6 Hz/mA.

Room Temperature dosimeter prototype:
- Mean DCR: 90 kHz.
- Mean MDL: 840 Hz.
- Sensitivity: 6.7*10^5 Hz/mA.

[1] M. Caccia et al. "Characterisation of a Silicon Photomultiplier based oncological brachytherapy fiber dosimeter". Submitted to sensor.