FIRST RESULTS OF AN ONCOLOGICAL BRACHYTHERAPY FIBER DOSIMETER

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ORIGIN optical fibre dose imaging for adaptive brachytherapy

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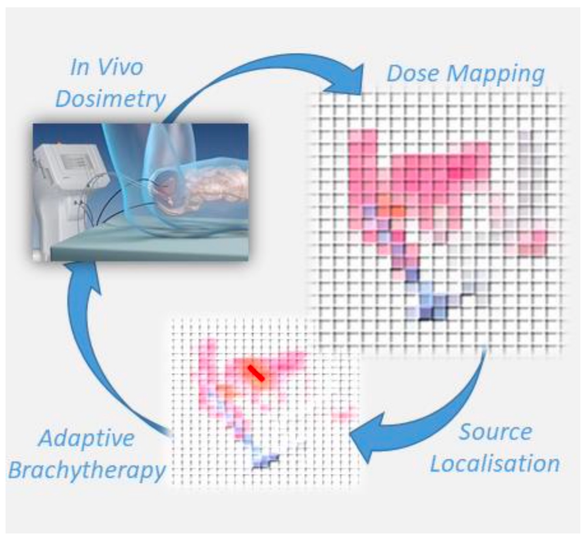
The ORIGIN project aims to deliver photonics-enabled, adaptive, and more effective diagnostics-driven brachytherapy for cancer treatment through advanced real-time radiation dose imaging and radioactive source localization. This goal will be achieved by developing a 16 to 32 optical fiber-based system with scintillating light detected by Silicon PhotoMultiplier (SiPM). In brachytherapy, the radioactive source is implanted into the patient's body and clinical treatments are categorized as either Low Dose Rate (LDR: 0.4–2 Gy/h) or High Dose rate (HDR: >12 Gy/h). Identifying a combination of scintillating material, SiPM detector, and readout electronics is a complex process, since in the LDR case the key indicators are sensitivity and minimum detectable signal, while in the HDR case an extended linearity range is instead crucial. The first characterization obtained both in the laboratory and in the clinical environment are reported.

THE ORIGIN PROJECT

Brachytherapy is divided into LDR, where the radioactive sources (^{125}I), known as seeds, remain implanted permanently, and HDR, where higher activity sources (^{192}Ir/^{60}Co) are temporarily implanted. Correct placement of the source, through in-vivo dosimetry, is vital to ensure adequate radiation to tumour, while ensuring minimum exposure to critical organs.



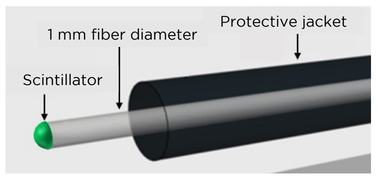
Specifications

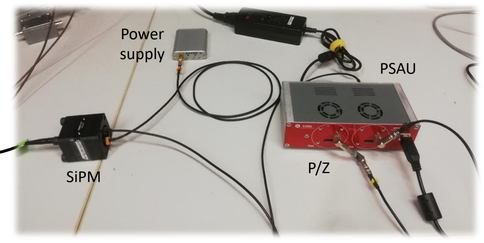
	HDR	LDR
Max. distance	10 cm	3 cm
Spatial resolution	1 mm @ < 5 cm	3 mm
Dynamic range / linearity	1 mGy/s to 10 Gy/s	

LABORATORY CHARACTERIZATION

The choice of the SiPM is essential to cope the requirements and their characterization was performed by comparing 3 key indicators. **The signal associated with an X-ray or γ-ray interaction consists of a trail of single photons, due to the long decay time (τ) of the baseline scintillators, and, thus, dosimetry is on photon counting.**

Scintillators
Gadox (LDR): $\lambda \sim 545$ nm
$\tau \sim 500$ µs
YVO (HDR): $\lambda \sim 600$ nm & 650 nm
$\tau \sim 500$ µs

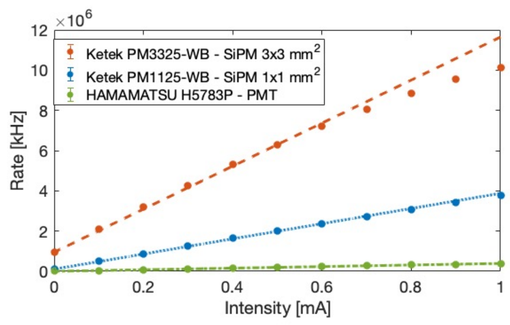




The 3 indicators:

- The Minimum Detectable Signal (MDS): the counting rate > 3 DCR std. dev.
- The sensitivity: the variation of the X-ray cabinet current that induces a change in the rate exceeding 3 std. dev. with respect to a single measurement.
- The linearity range, the maximum photons flux for which measurements are not affected by pile-up.

	SiPM 1x1 mm^2	SiPM 3x3 mm^2	PMT
PDE at 600 nm [%]	14	14	0.1
DCR [kHz]	106	950	0.05
Optical cross-talk [%]	26	30%	-



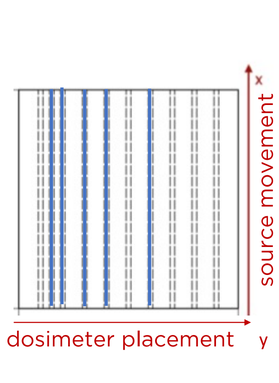
	SiPM 1x1 mm^2		SiPM 3x3 mm^2		PMT
	0.5 p.e.	1.5 p.e.	0.5 p.e.	1.5 p.e.	
Linearity upper limit [mA]	1	1	< 0.7	1	1
υ @ linearity upper limit [kHz]	$3.8 \cdot 10^3$	$1.0 \cdot 10^3$	$8.1 \cdot 10^3$	$3.1 \cdot 10^3$	$0.4 \cdot 10^3$
MDS	0.26 µA [1.0 kHz]	0.52 µA [0.5 kHz]	0.27 µA [3 kHz]	0.48 µA [1.5 kHz]	0.06 µA [0.02 kHz]
Response [kHz/mA]	$3.7 \cdot 10^3$	$9.6 \cdot 10^2$	$1.1 \cdot 10^4$	$3.0 \cdot 10^3$	$3.9 \cdot 10^2$
Sensitivity @ 0.5 mA [%]	0.22	0.44	0.14	0.26	0.68

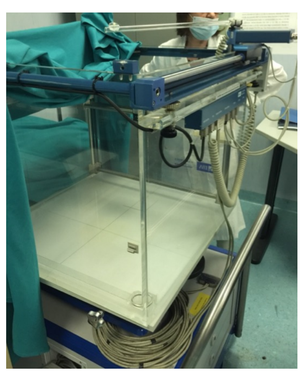
- The PMT device is superior in terms of MDS, but it is also the worst in sensitivity
- The 3x3 mm^2 SiPM provides the best sensitivity, although not the best linearity

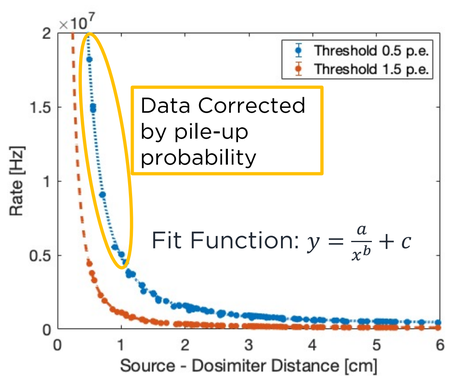
In HDR, where a large linearity range is required, it is better to use a small area SiPM.
In LDR, where the MDS is important, sensors with lower DCR and increased PDE (even cooled) shall be considered.

HDR MEASUREMENTS

Single fiber system: commissioning of the system for HDR brachytherapy at Ospedale del Circolo di Varese (IT) - June 2021, 1x1 mm^2 SiPM







The ^{192}Ir source (4.84 Ci) and the fiber dosimeter (YVO) were inserted into a phantom with an area of 10 × 10 cm^2.

Two indicators:

- **Max distance:** $x_{max} = \sqrt{\frac{a}{DCR+3\sqrt{DCR}-c}}$
- **Spatial resolution:** $dr = 3\sqrt{\frac{r^4}{4a} + \frac{cr^6}{4a^2}}$

Sensor	Threshold	x_{max}	dr @ 5 cm
1x1 mm^2	0.5 p.e.	50.4 cm	0.30 mm
1x1 mm^2	1.5 p.e.	33.8 cm	1.15 mm
3x3 mm^2	1.5 p.e.	24.6 cm	0.61 mm

PERFORMANCE @ 1.5 p.e.

The spatial resolution is:
- < 1 mm for distances < 5cm
- O(1 cm) for distances > 10 cm

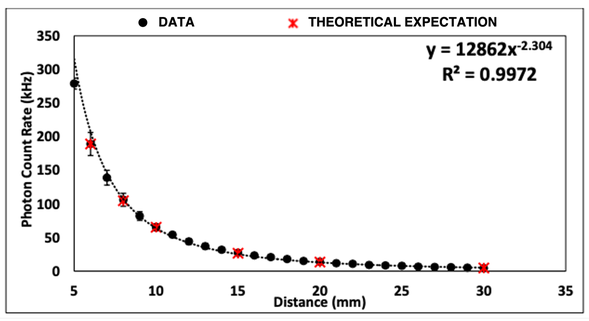
The maximum distance is > 10 cm; the counting rate @ 10 cm is 10 KHz, well above the DCR fluctuations

By an initial comparison with the TPS: 4 Gy/minute ⇔ 10^8 counts per minute @ 0.5 cm

Well within the specifications.

LDR MEASUREMENTS

LDR measurements with a single radioactive seed (^{125}I – 0.4 mCi) were performed at the Galway Clinic (IE).



Performance with Gadox:

DCR: 63 kHz

Signal @ 3 cm: 4 KHz

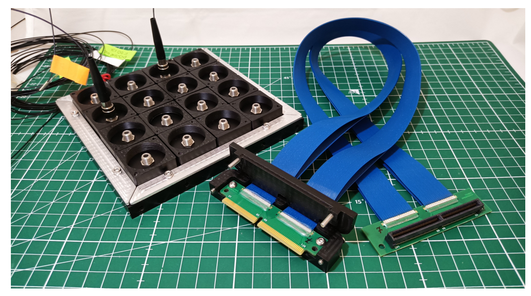
S/N @ 3 cm: 16 Gadox

The Gadox fiber cannot provide the required sensitivity at the maximum distance because in this case the signal is almost dominated by the DCR.

- To improve the spatial resolution LYSO scintillator can be used since the light is "compressed", the threshold could be increased reducing the DCR.
- Still working on the statistical resolution testing cooled SiPMs, reducing the DCR and allowing to decrease the threshold and increase the rate.

PERSPECTIVES

A multi-fiber module is ready to be tested using 16 fibers, with front-end readout based on the CITIROC1A ASIC and a CAEN FERS board.



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