Characterization of scintillating materials in use for brachytherapy fiber-based dosimeters

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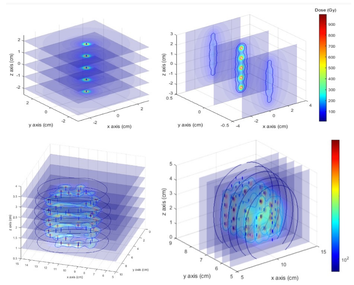
The **ORIGIN project** (Optical Fibre Dose Imaging for Adaptive Brachytherapy) aims at developing instruments and methods for **real-time dosimetry** and **source localization** during brachytherapy (BT) treatments.

Accurate source placement, through in-vivo dosimetry, is crucial to guarantee the dose prescribed to the target area, while ensuring minimum exposure to the surrounding organs at risk.

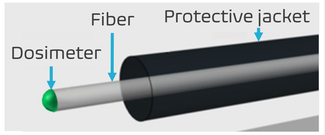


The ORIGIN system will be integrated into existing clinical BT treatment planning, and it will consist in an array of optical fiber dosimeters, made of inorganic scintillating materials, readout by Silicon Photomultipliers (SiPMs).

Treatment plan	Sources	Dose rate	Implantations
Low Dose Rate (LDR)	^{125}I seeds	0.4–2 Gy/h	permanent
High Dose Rate (HDR)	^{192}Ir / ^{60}Co seeds	>12 Gy/h	temporary

Optical fiber-based dosimeters

Scintillators in fine-grain powder form dispersed in a host material for the integration in the hemispherical 0.5 mm-core fiber tip.



	Material grain size (μm)	Density ρ (g/cm3)	Atomic number	Emission peak λ (nm)
Gadox (LDR-BT)	~ 4	7.5	60.13	545
YVO (HDR-BT)	~ 7	5.2	32.10	619

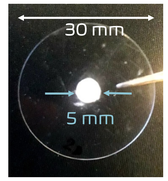
λ allow to filter Cherenkov light and reduce the stem effect

Unknown material properties after the manufacturing

γ-ray spectroscopy technique cannot be applied to extract light yield

Characterization performed on **specimens** containing Gadox and YVO powders dispersed in NOA61 epoxy glue (UV-curing optical adhesive)

- Powder to glue mass-ratio: 60/40
- Mixtures deposited in the central hole of a PMMA disks of 3 thicknesses: 5, 3,1 and 0.5 mm



Optical characterization

Transmittance measurement:

significant self-absorption of the scintillation light

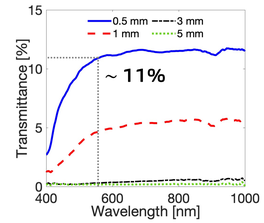
Absorption

A(dB) = - 10 $\log_{10}$ T

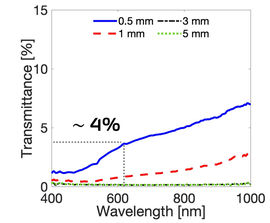
Absorption length

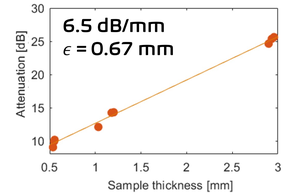
$$\epsilon = \frac{10\ log_{10} e}{A\ [dB/mm]}$$

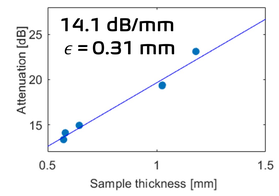
Gadox



YVO

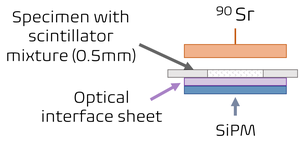






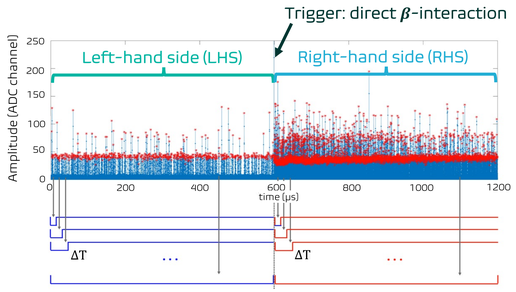
Scintillation properties measurement

Novel measurement technique making use of the single-photon counting capability of the SiPM



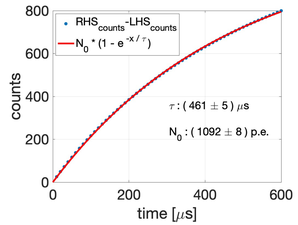
- Light emitted by an interacting particle generates trails of single photoelectrons
- Event detection by the direct ionization in the silicon substrate of the SiPM: high and prompt signal used as trigger

1. Digitize the waveforms over 1.2 ms with central trigger
2. Look at the unbalance in the single photon counts before (left-hand side **LHS**) and after (right-hand side **RHS**) the trigger
3. Reject pile-up events
4. Compute the average number of counts in increasing time windows with 10 μs granularity

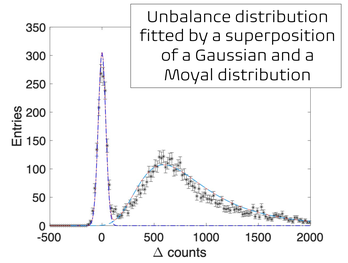


5. Analyze the cumulative distribution of the unbalance in the RHS and LHS counts to extract the **decay time (τ)** and **Light Yield (LY)** information

$$N_{tot}(t) = N_0 \cdot [1 - e^{-t/\tau}]$$



6. Re-scale the LY information separating and estimating the percentage of events with scintillation (**f**) and dark-count events (**1-f**)



Gadox

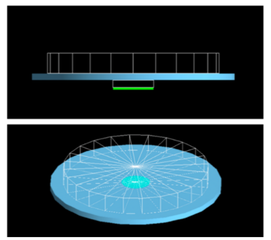
$\tau = (449 \pm 3 \pm 3)\ \mu s$
$LY_{eff} = (1308 \pm 93 \pm 21)$ p.e.

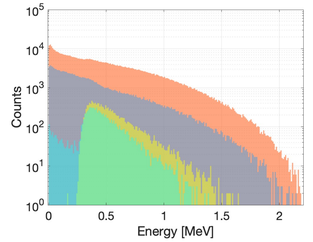
YVO

$\tau = (496 \pm 9 \pm 3)\ \mu s$
$LY_{eff} = (333 \pm 1 \pm 7)$ p.e.

τ values have a general validity while the obtained **LYeff** values are specific to the set-up under investigation and the specimen characteristics → Two step-simulation process

Energy deposition with GEANT4



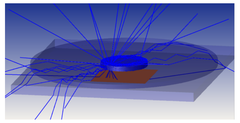


Particles simulated tracking the path in 10 um steps, where for every step the direction was smeared accounting for multiple scattering and the energy deposition (**E dep**) was randomly chosen according to a Landau-Vavilov distribution

$\overline{E\ dep}_{Gadox}$ = 0.447 MeV $\overline{E\ dep}_{YVO}$ = 0.342 MeV

Light propagation with ZEMAX OpticStudio®

Ray tracing method relies on approximate solutions of Maxwell's equations (optical object dimensions >> λ)



- System geometry implementation
- Optical properties of the materials:
  - Optical loss
  - Refractive indices
- Light source was extracted by the deposited energy and ionization trails simulated in Geant4
  - Direction cosines (isotropy)

Light collection efficiency:

η_{Gadox} = 12.75 % η_{YVO} = 8.76 %

LY as photons per unit deposited energy →

$$LY = \frac{LY_{eff}}{PDE(\lambda) \cdot E_{dep} \cdot \eta_{collection}}$$

Measured LY

Photo Detection Efficiency (PDE) of the SiPM at the λ emission peak of the materials

Deposited energy mean value

Light collection efficiency

LY Gadox

$(6.5 \pm 0.5) \times 10^4$ photon/MeV

LY YVO

$(5.5 \pm 0.1) \times 10^4$ photon/MeV

This study has allowed to qualify and optimize the manufacturing process of the fiber-tip dosimeter

The method to evaluate the **LY** and the **τ** of scintillators can be applied to a large class of materials