FIBRE SENSORS FOR IN VIVO DOSIMETRY DURING RADIOTHERAPY

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RADIOTHERAPY AND BRACHYTHERAPY

- Radiotherapy is the use of ionizing radiation (photons, electrons, protons or heavy ions) for the treatment of cancer, and it is involved in the treatment of over 40% of cancer patients
- Radiotherapy is delivered in the form of external beam radiotherapy, using linear accelerators (linacs), or brachytherapy, which involves the positioning of radioactive sources (seeds) in, or near to, the tumour.
- Radiotherapy is rapidly developing in terms of the diversity of new types of delivery modalities: from volumetric modulated arc therapy to Flattering Filter Free and Intensity-modulated radiotherapy (IMRT) to brachytherapy (only for some tumor: prostate)

→ this is driving the requirement for increasing levels of accuracy and precision in dosimetry, expecially to verify the individual patient delivery in vivo

DOSIMETRY

Radiation dosimetry in the fields of health physics and radiation protection is the measurement, calculation and assessment of the ionizing radiation dose absorbed by biological tissue.

A dosimeter can be defined generally as any device that is capable of providing an output value that is a measure of the average absorbed dose deposited in its sensitive volume by ionizing radiation.

RADIOTHERAPY AND BRACHYTHERAPY

- In an ideal scenario, the dose delivered directly within the tumour volume, and/or dose to specific organs at risk (OARs), would be measured while the patient is receiving their treatment.
- This is currently generally carried out by measuring the dose at a "surrogate" position, usually by placing a radiation detector directly on, or near to, the patient's skin surface

→ in vivo dosimetry can prevent from "radiotherapy incident": underdosing, leading to a recurrence risk, or overdosing, causing toxicity and even death

PROPERTIES OF DOSIMETER

- Stability and repeatability
- Linear response with dose
- Independence to dose rate
- Independence to energy beam
- Small angular dependence
- Small in size
- Minimally invasive
- Robust and easly to handle

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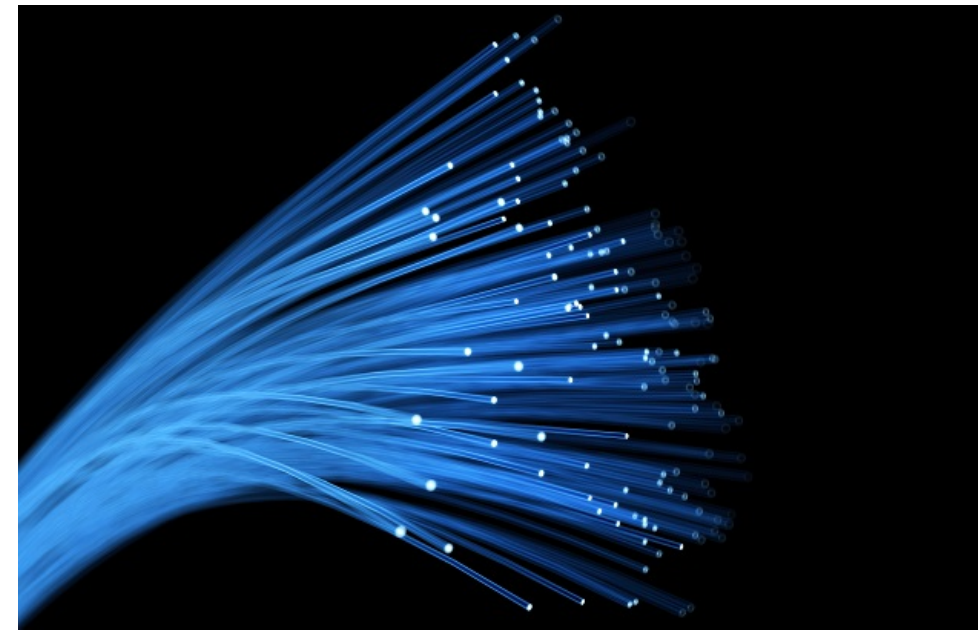
→ *inherently optical fibres fit these requirements*

OPTICAL FIBRE DOSIMETER (OFD)

Optical fibre are made of silica or plastic (recently Poly-methylmethacrylate PMMA guarantees water equivalence). They have a core of 200μm - 1mm.



- excellent spatial resolution
- flexible and lightweight

→ **suitable not only for quality control on radiotherapy machine but also for minimally invasive *in vivo* dosimetry**

OPTICAL FIBRE DOSIMETER (OFD)

- OFD are based on the luminscence process that occurs after the absorption of radiation
- Different types and forms of radiation can be used to excite the OFD material and these types give rise to different methods of luminescence

→ *Termoluminescence* (silica optical fibre[1])

→ *Photoluminescence* (Al_2O_3:C optical fibre[2])

→ *Radioluminescence* (plastic optical fibre + scintillator[3])

[1]Bradley DA, Hugtenburg RP, Nisbet A, Abdul Rahman AT, Issa F, Mohd Noor N, et al. Review of doped silica glass optical fibre: their TL properties and potential applications in radiation therapy dosimetry. Appl RadiatIsot 2012; 71: 2–11.
[2]Yukihara EG, McKeever SW. Optically stimulated luminescence (OSL) dosimetry in medicine. Phys Med Biol 2008; 53: R351–79.
[3]Beddar A.S. Plastic scintillation dosimetry and its application to radiotherapy. Radiat Meas 2006; 41: S124–33.

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OPTICAL FIBRE DOSIMETER (OFD)–RADIOLUMINESCENCE

"Radioluminescence (RL), or scintillation, detectors are based on the phenomenon that the material used is capable of converting ionizing radiation into detectable light"

- Scintillators can be subdivided into two groups:
  - ↳ *Organic* (plastic, made of aromatic hydrocarbons)
  - ↳ *Inorganic* (crystals, made of alkali halides, e.g. CsI)
- Coupling a piece of scintillating material to a bare fibre, usually in Poly-methylmethacrylate (PMMA)

1. *Plastic scintillation-based optical fibre dosimeter* *(BCF_{12} + PMMA fibre)*
2. *Inorganic scintillation-based optical fibre dosimeter* *($Gd_2O_2S:Tb$ + PMMA fibre)*

1 PLASTIC SCINTILLATION-BASED OFD

- Principal characteristics[4]:
  - completely water equivalent
  - linear with dose
  - energy independence in the MeV range
- Principal drawbacks[4]:
  - not completely investigated the temperature effect on linearity
  - difficult efficient coupling

[4]Buranurak S, Andersen CE, Beierholm AR, Lindvold LR. Temperature variations as a source of uncertainty in medical fibercoupled organic plastic scintillator dosimetry. Radiat Meas 2013; 56: 307–11.

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→ a collaboration between University of Insubria and University of Limerick (Lewis and O'Keefe's group in Optical Fibre Sensors Research Center) tested a plastic scintillation-based ofd with BCF_{12}

UNIVERSITAS STUDIORUM INSUBRIAE

UNIVERSITY of LIMERICK
OLLSCOIL LUIMNIGH

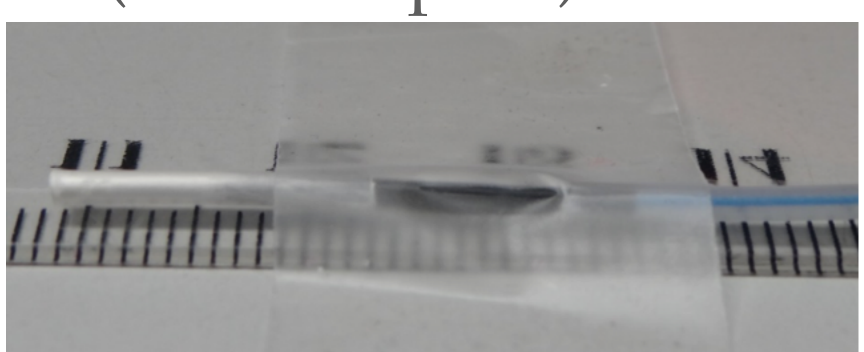
[4]Buranurak S, Andersen CE, Beierholm AR, Lindvold LR. Temperature variations as a source of uncertainty in medical fibercoupled organic plastic scintillator dosimetry. Radiat Meas 2013; 56: 307–11.

PLASTIC SCINTILLATION-BASED OFD

- Sensor are based on 265 μm core PMMA plastic optical fibre (DC-265-10, manufactured by AsahiKASEI.)
- The sensing tip is made up with the organic scintillating material BCF_{12} (Saint-Gobain Crystals Inc.)

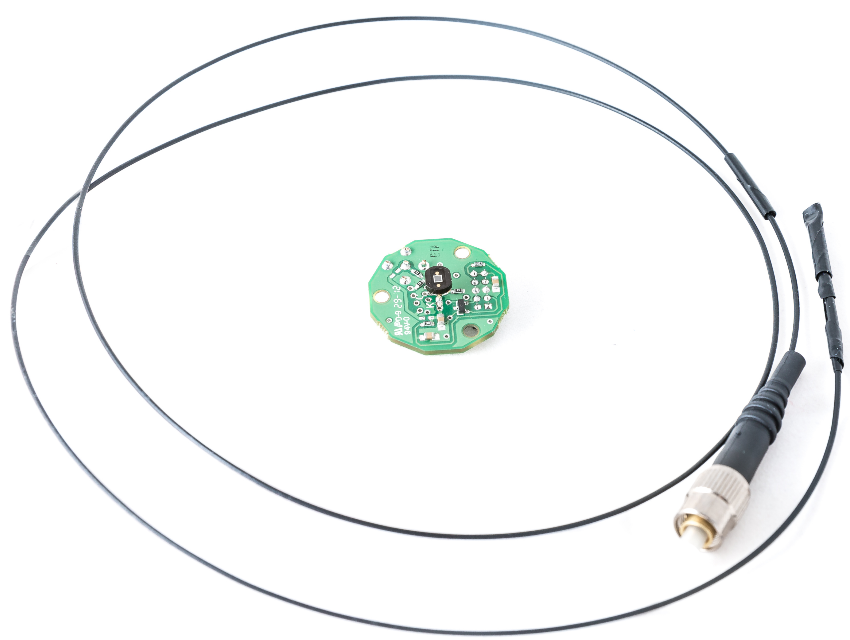
λ emission	τ decay time	LY (photons/MeV)
435 nm	*3.5 ns*	*~8000*

- BCF_{12} is encapsulated in a cylindrical polypropylene tube of 1.2 mm diameter and sealed by epoxy resin
- One polished end of the fibre is adhered to the scintillating material and fixed by epoxy glue at the interface between the scintillator and silica fibre (butt-coupled)



PLASTIC SCINTILLATION-BASED OFD

- The optical photons propagate to the distal end of the PMMA fibre and are detected by a SiPM 1.3x1.3 mm^2 (Hamamatsu, S13360-1350CS)

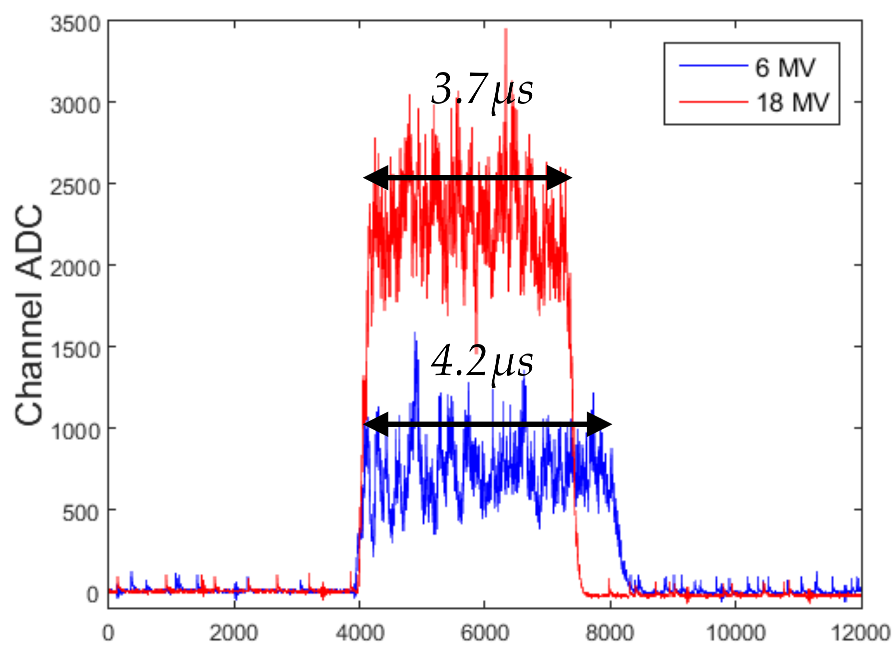


- SiPM is operated at 55V (~3.5 over voltage) at room temperature.
- The waveform of radioluminescence light is recorded with a Digitizer at 500 Ms/s, 14 bit (by Caen S.p.A), in autotrigger modality

- All measurements are performed at S. Anna hospital in Como (Italy) on a Varian iX linear accelerator (LINAC) at a SSD (Source to Surface Distance) of 100cm and a field size of 10x10 cm^2 (standard Quality Assurance protocol)

PLASTIC SCINTILLATION-BASED OFD – STABILITY

- Stability tested over 2500 MU (Monitor Units[5]) at a dose rate of 300 MU/min and at nominal X-ray photon energies of 6 MV and 18 MV
- This sensor allows to acces to the information of micro-bunches of photons for the duration of the beam-on-phase. These micro-bunches are of fixed duration and frequency that depend on the energy and dose rate.



	τ bunch	amplitude	freq bunch
6 MV	*4.2 μs*	*~660*	*~180 Hz*
18 MV	*3.7 μs*	*~2000*	*~95 Hz*
ratio	*1.14*	*0.33*	*1.89*

[5] 1 MU = 1cGy

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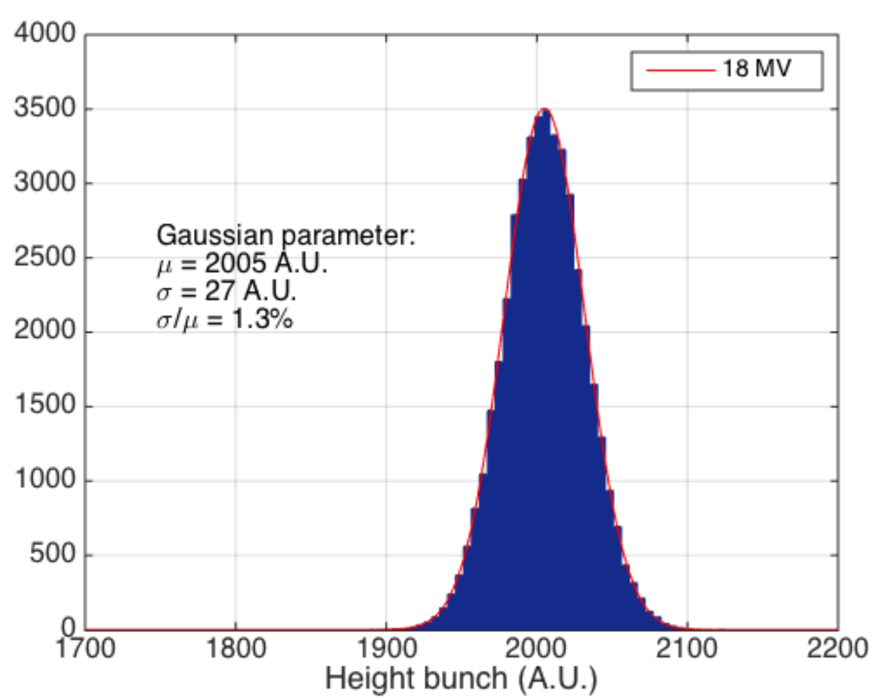


An intrinsic instability is measured. A dispersion of few percent (1-2.5%) is evaluated

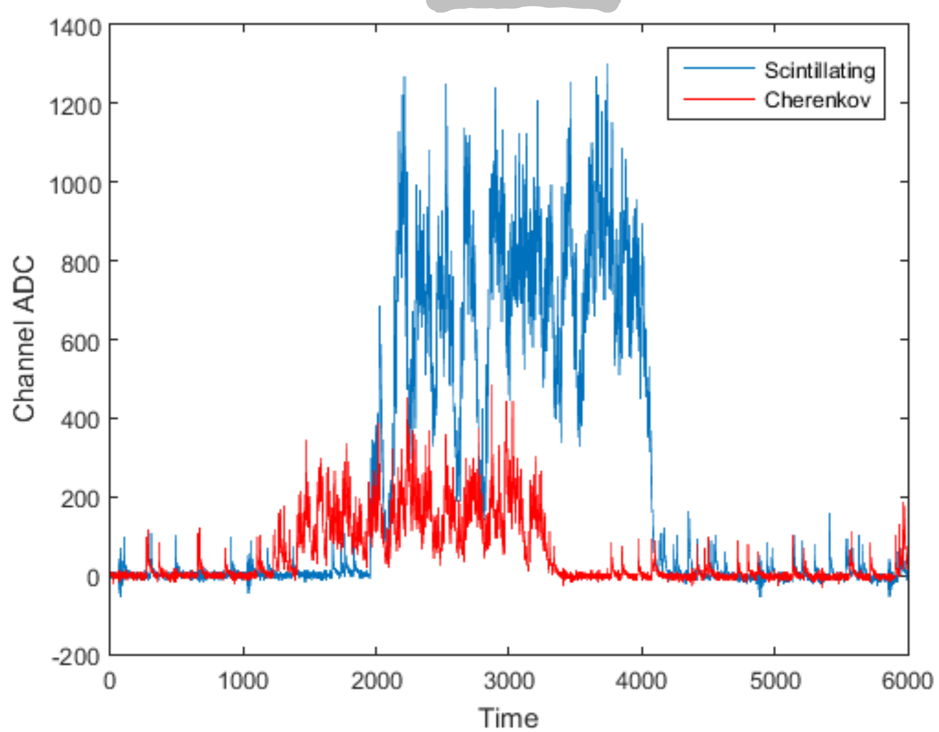
[5] 1 MU = 1cGy

STEM EFFECT : CHERENKOV LIGHT

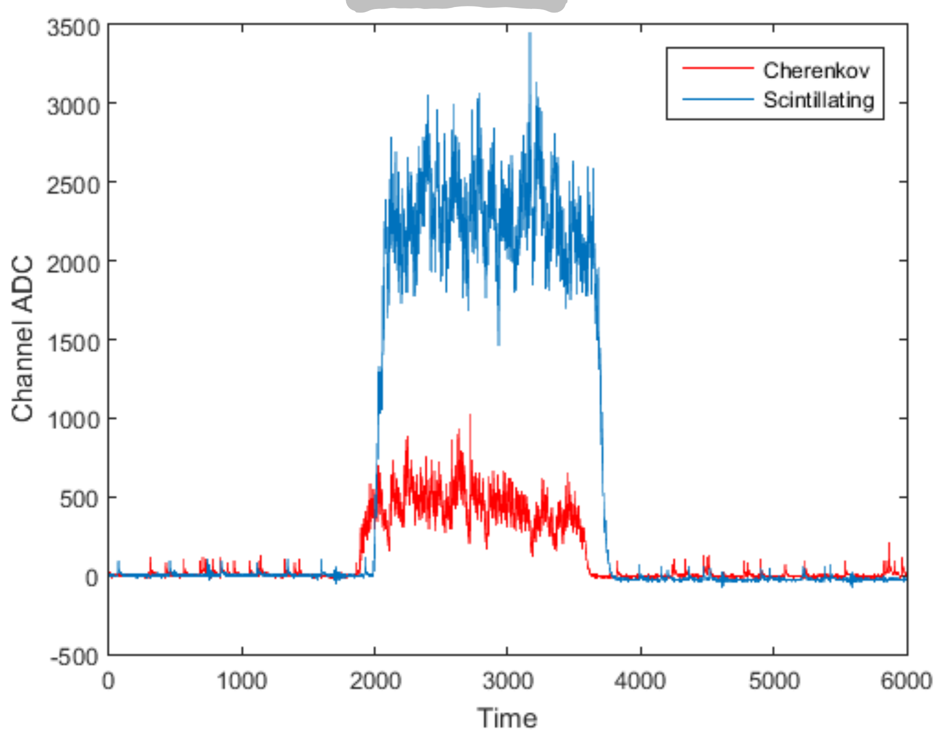
"Cherenkov radiation and other radiation-induced light that can be produced in optical fibres and thus affect optical fibre-based dosimeter measurements"

- For plastics used in optical fibre scintillation dosimetry the Cherenkov light is seen at energies > ~180 keV
- A bare PMMA optical fibre is placed in radiation field in identical conditions (a simultaneously measurement is not allowed)

6 MV



18 MV



STEM EFFECT : CHERENKOV LIGHT

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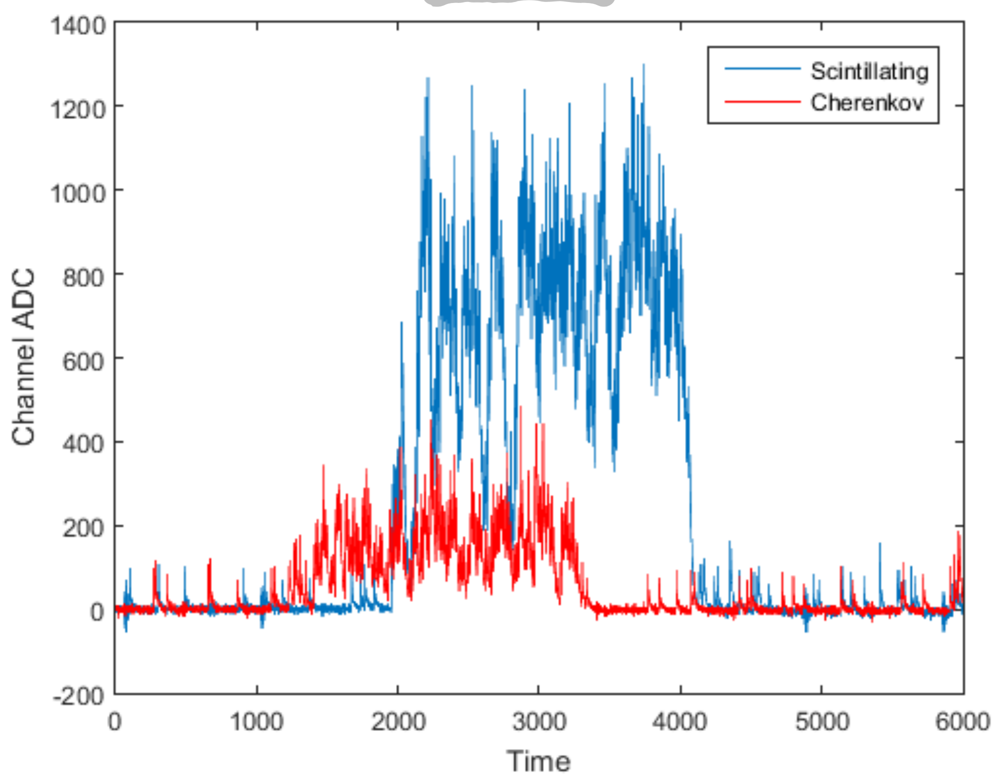
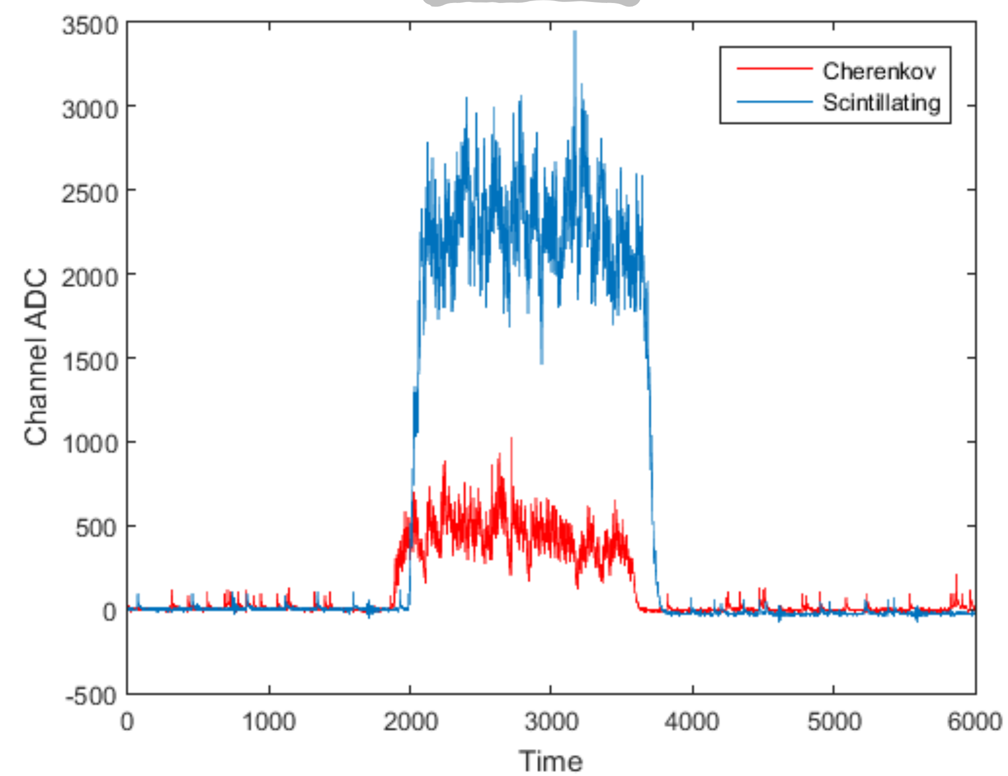


18 MV

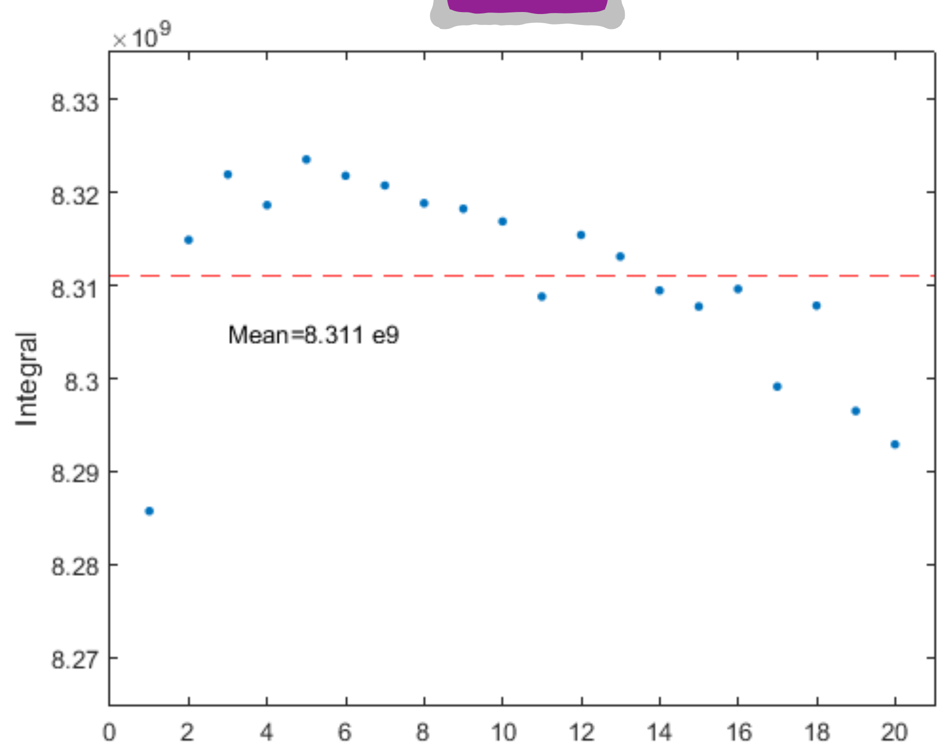


- A considerable contribution to the optical intensity by Cherenkov radiation: a mean intensity of 117 A.U at 6 MV and 390 A.U. at 18 MV (18-19% of the scintillating signals)

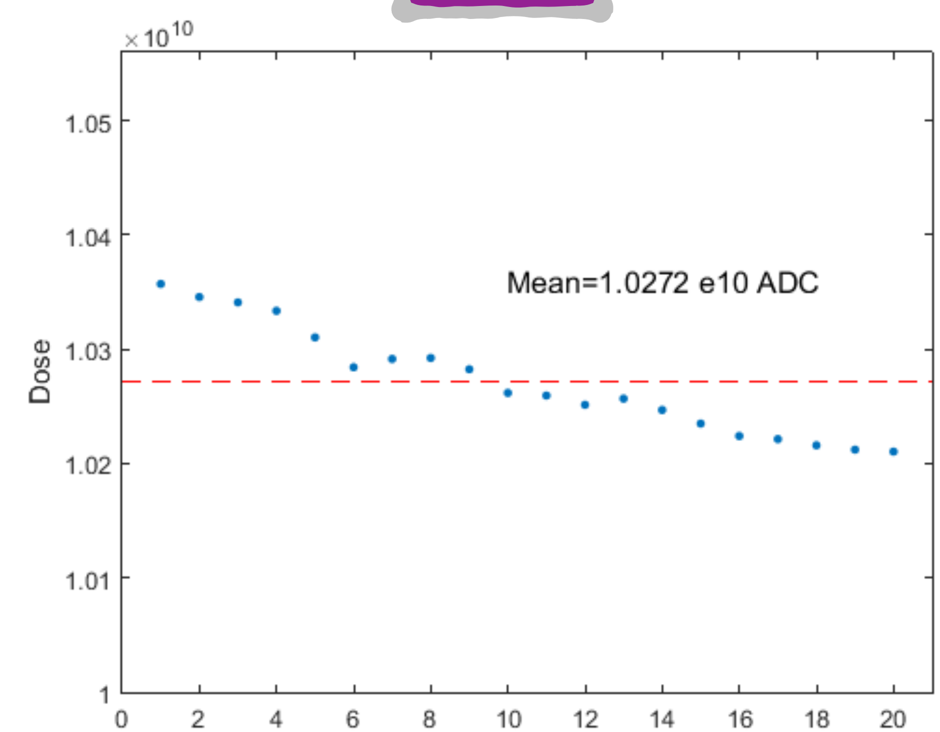
PLASTIC SCINTILLATION-BASED OFD - REPEATABILITY

- 20 exposures, where each exposure is 200 MU at a dose rate of 300 MU/min and, at 6 and 18 MV.
- To compensate the stem effect, the mean of Cherenkov signal integral is subtracted
- The dose delivered is evaluated as $\sum_{N}(INTEGRAL_{bunch}) - N \cdot \overline{INTEGRAL}_{Cherenkov}$

6 MV



18 MV



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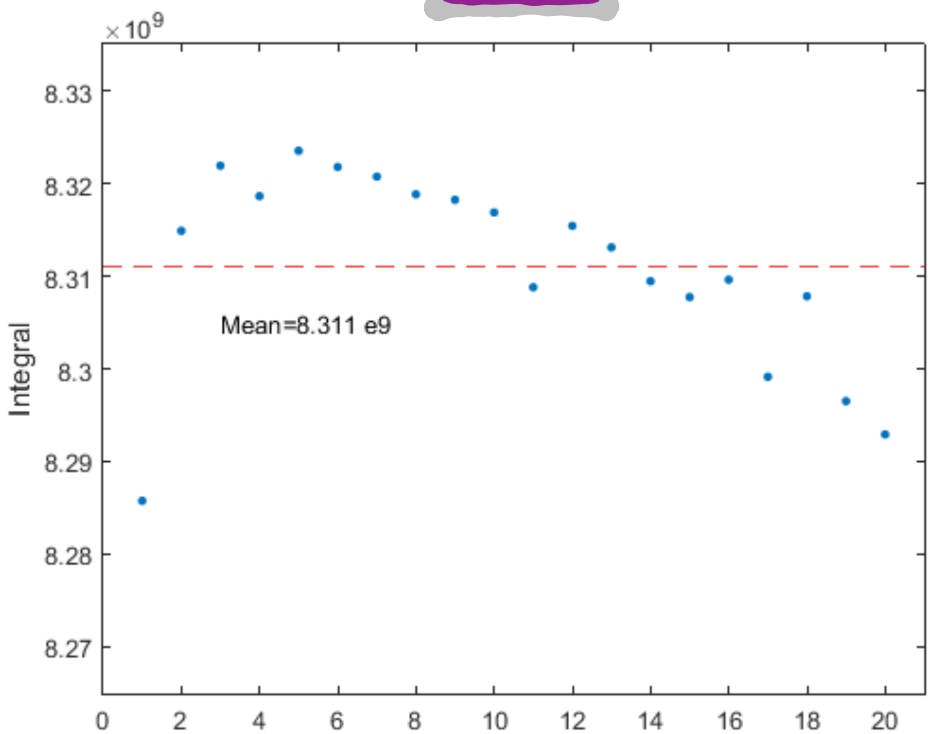
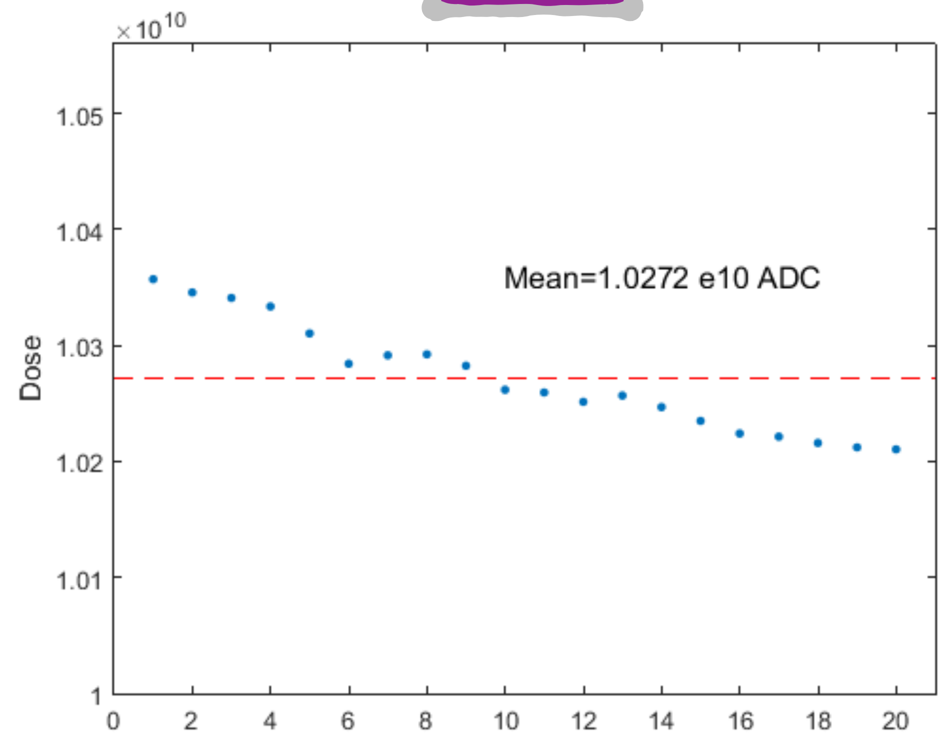


18 MV



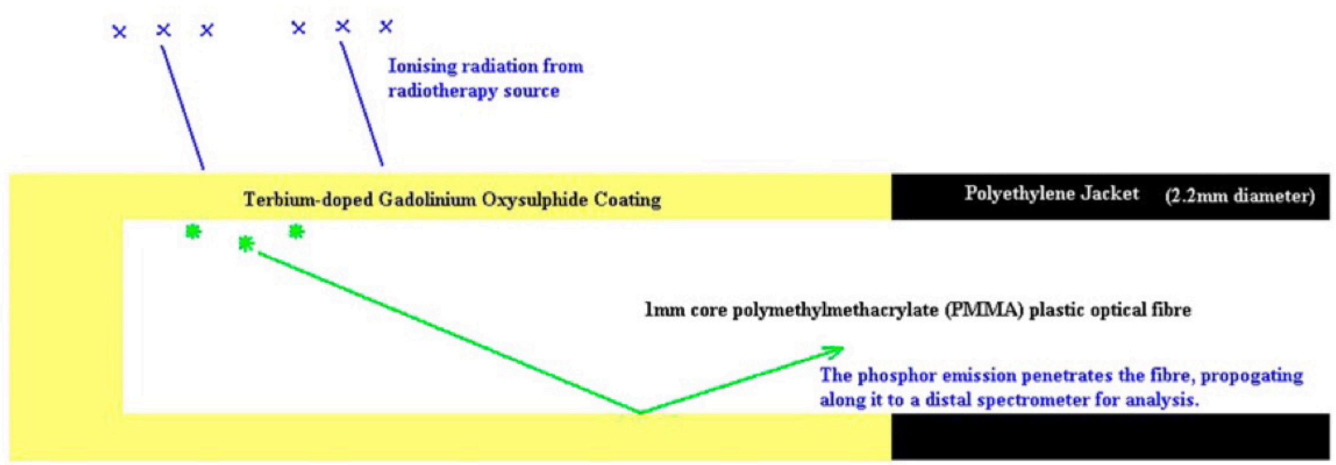
	6 MV	18 MV
Mean (a.u.)	8.311 e9	1.0272 e10
Std (a.u.)	1.044 e7	4.706 e7

relative error < 0.5%, maximal dispersion <1%

2 INORGANIC SCINTILLATION-BASED OFD

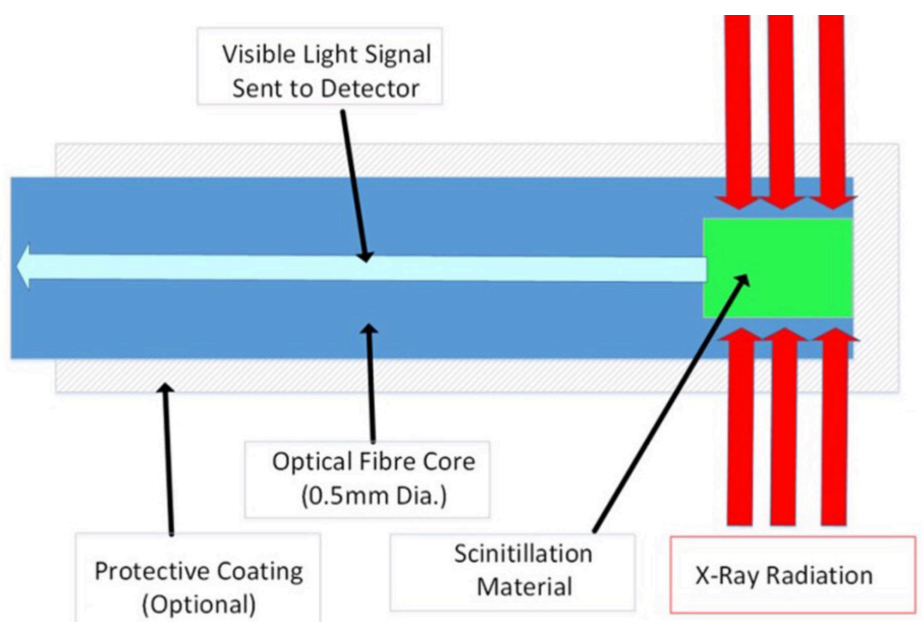
- Terbium-doped Gadolinium oxysulphide ($Gd_2O_2S:Tb$) is chosen as scintillating powder (sensitive to ^{125}I, one of the most important isotope used in brachyterapy, but a very long decay time 600 μs)
- Two configuration are tested by Limerick University:

1



the end of a PMMA fibre, after the cladding is removed, is coated with $Gd_2O_2S:Tb$

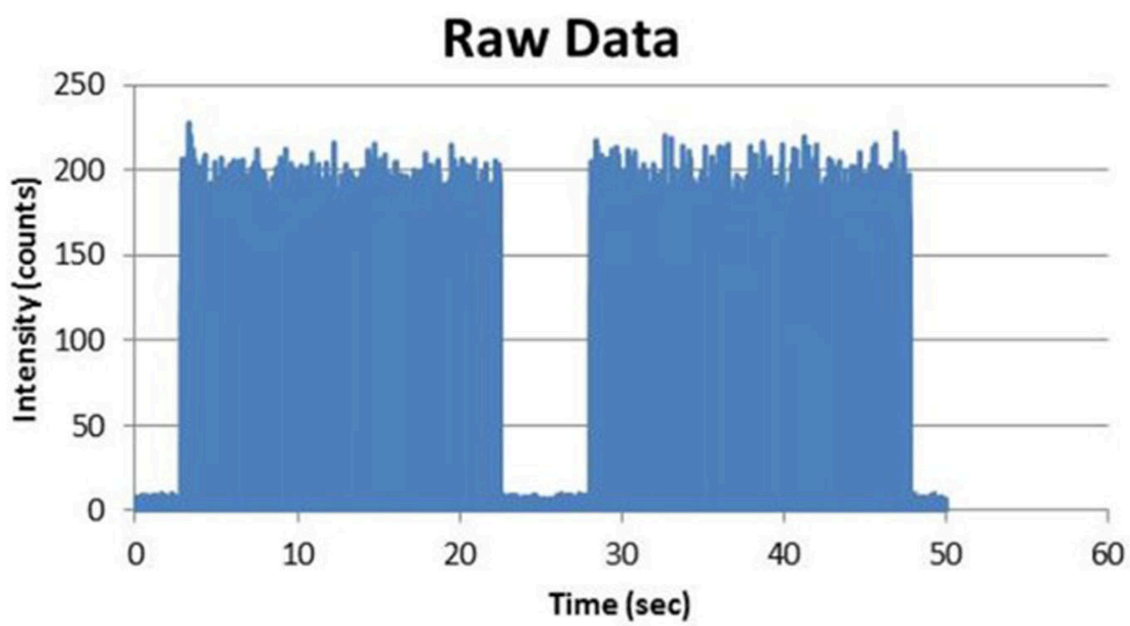
2



the end of a PMMA is micro-machined to create a small hole which was filled with the scintillating material

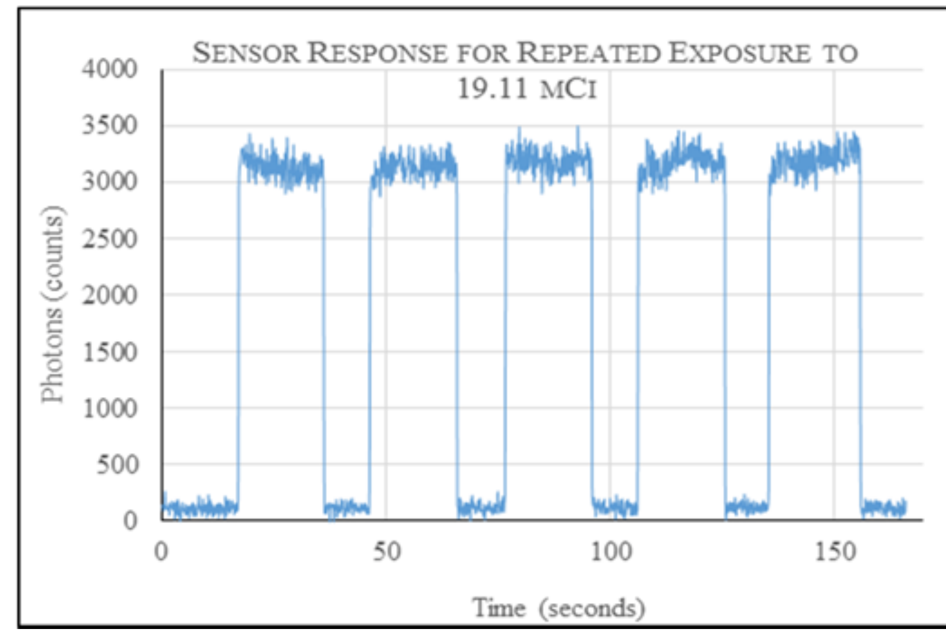
MEASUREMENT WITH Gd_2O_2S:Tb

Radiotherapy Machine



Photon counts for two consecutive irradiation with 6 MV photons for 20 seconds with a dose rate of 600 MU/min. The machine is off for 5 seconds[6]

Brachytherapy



Response of the sensor as 15 seeds (a total activity of 19.11 mCi) are repeatedly inserted and removed[7]

[6] S. O'Keeffe, W. Zhao, W. Sun, D. Zhang, Z. Qin, Z. Chen, Y. Ma, E. Lewis. An Optical Fibre-Based Sensor for Real-Time Monitoring of Clinical Linear Accelerator Radiotherapy Delivery. 10.1109/JSTQE.2015.2482945

[7] S. O'Keeffe, P. Woulfe, F.J. Sullivan. Radioluminescence based optical fibre sensor for radiation monitoring during brachytherapy. DOI: 10.1109/ICSENS.2015.7370523

INORGANIC SCINTILLATION-BASED OFD

- A new sensor with YAG:Ge (powder and ceramic) scintillator in the micro-machined tip is developed by Limerick University

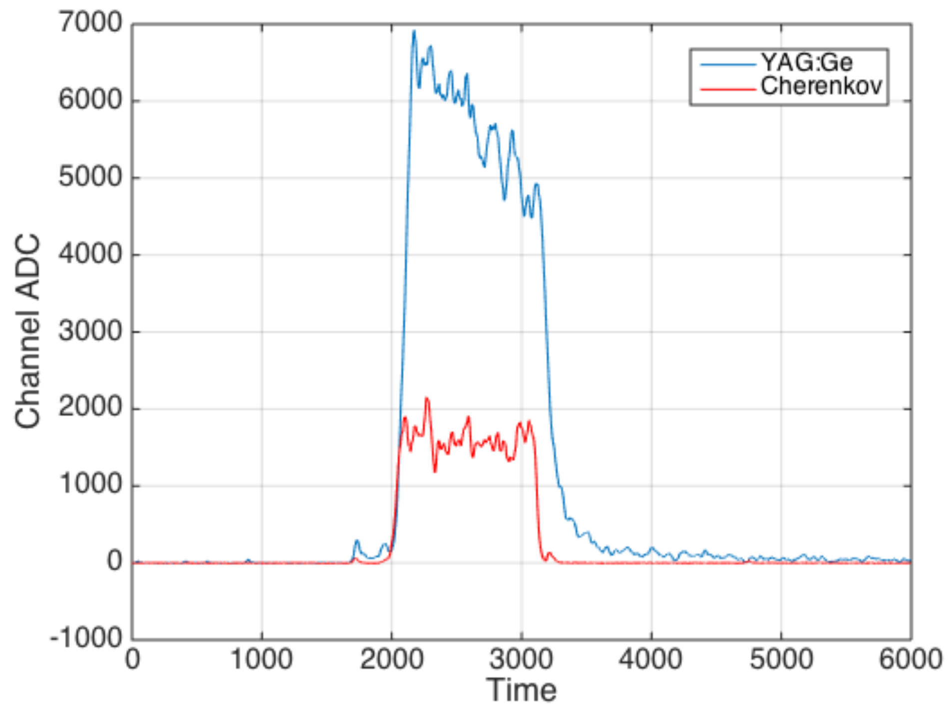
λ emission	τ decay time	LY (photons/MeV)
550 nm	*70 ns*	*~30000*

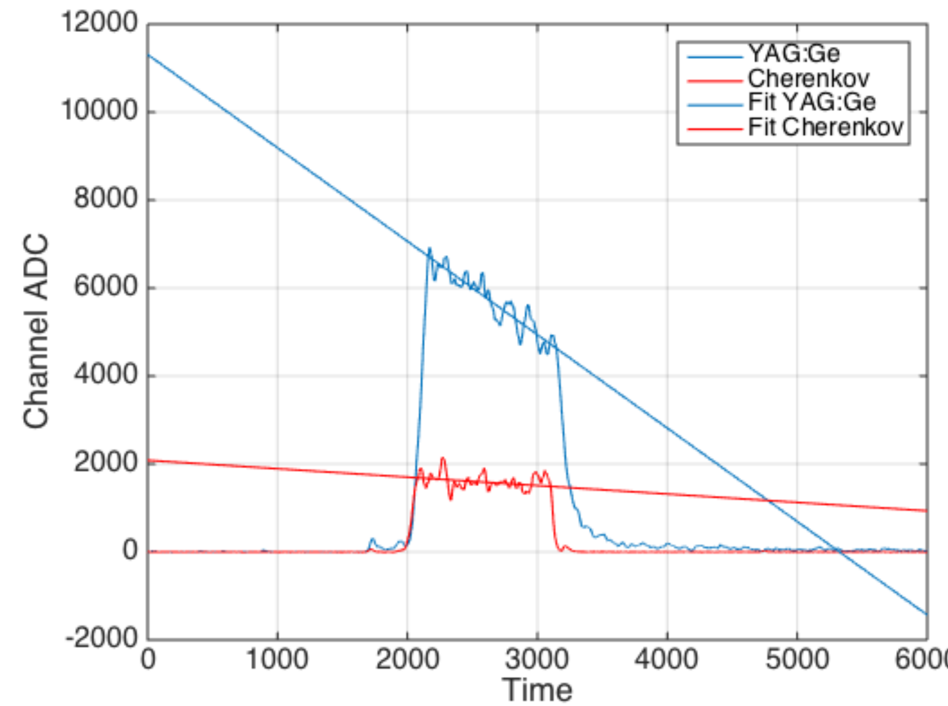
- Two low noise electronics are developed by Insubria University to allow the simultaneous meauserement of signals provided by the scintillating tip and the bare fibre (close to each other) to estimate event by event the Cherenkov contribution
- The tests are performed at Galway Clinic on an Elekta LINAC with a field of 10x10 cm^2 with 6 MV of photons energy. The sensor is tested also with some radioactive ^{125}I seeds (brachytherapy).

INORGANIC SCINTILLATION-BASED OFD

PRELIMINARY

55V



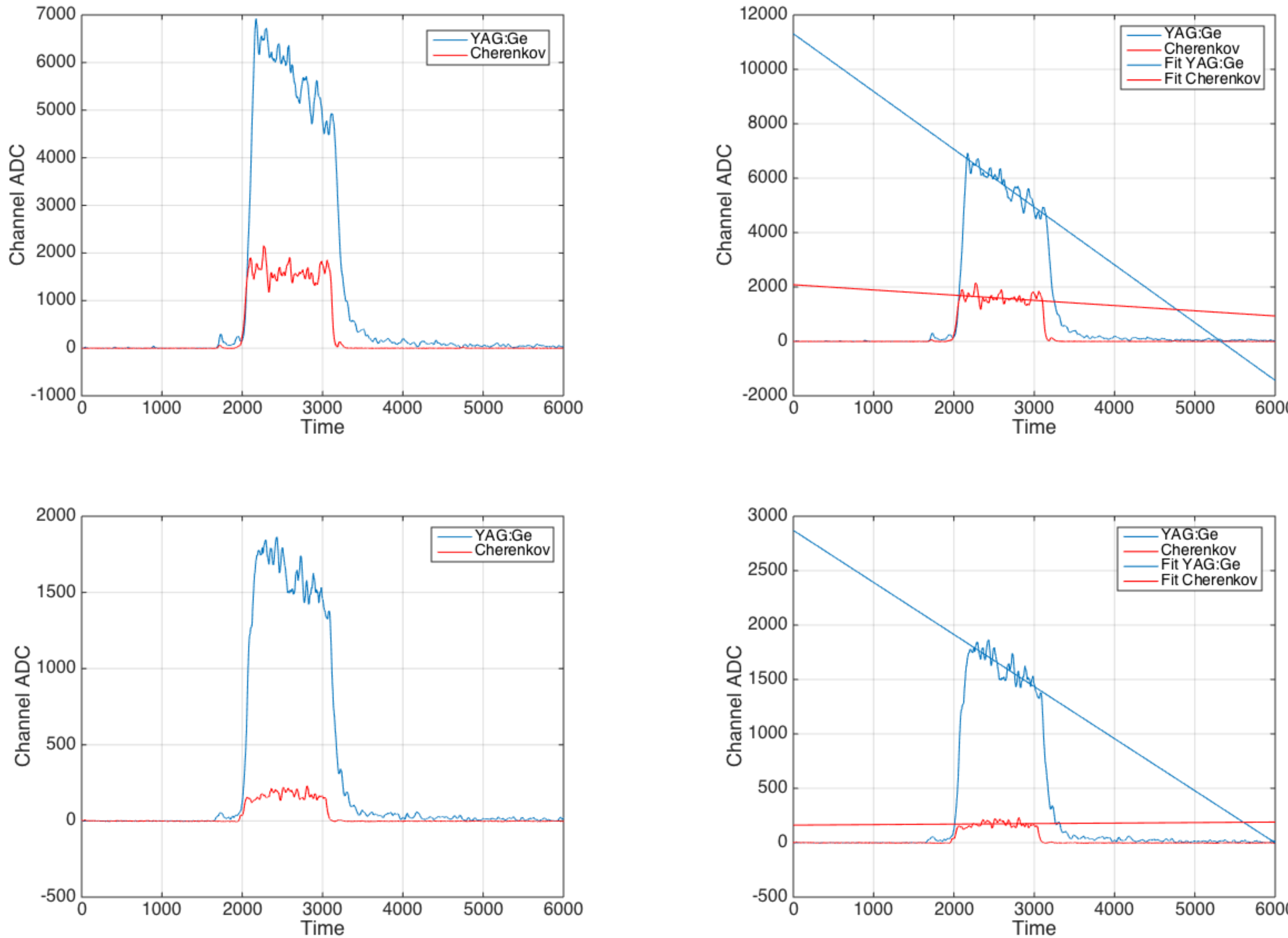


INORGANIC SCINTILLATION-BASED OFD

PRELIMINARY

55V

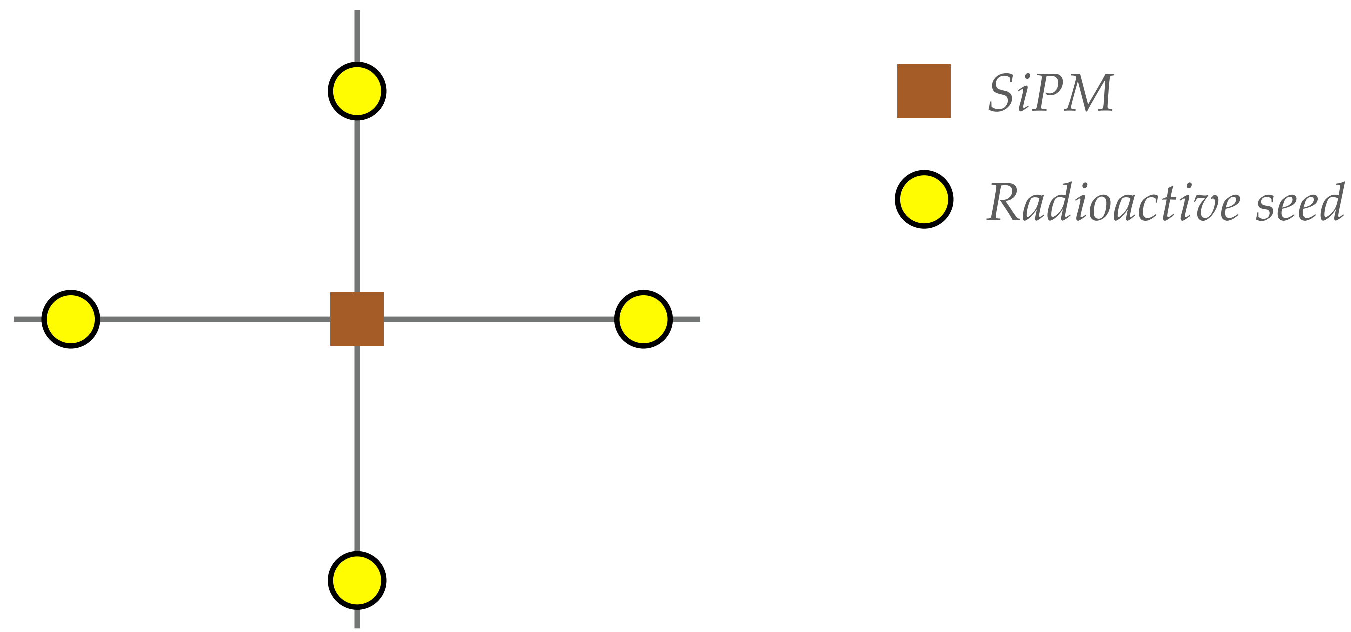
53V



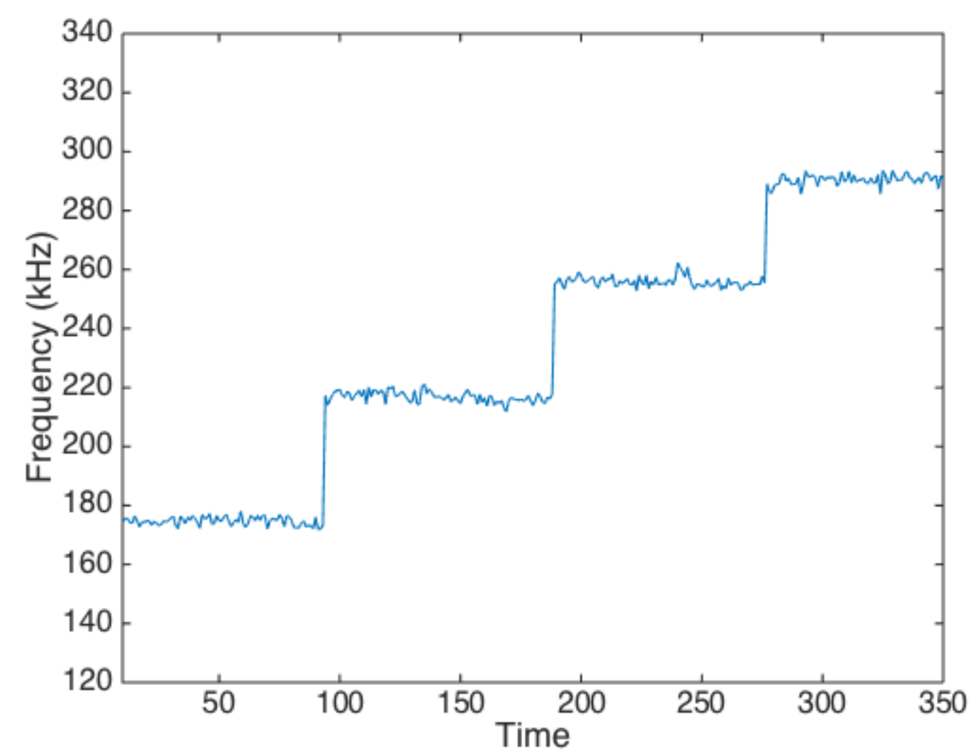
IN VIVO DOSIMETER FOR BRACHYTHERAPY

PRELIMINARY

- The dosimeter is tested for brachytherapy seeds of ^{125}I



n° of seeds	Frequency (kHz)
1	~175
2	~217
3	~260
4	~290



CONCLUSION

- Optical fibres have been demonstrated to be able to perform accurate radiotherapy dosimetric measurements and have the potential for advantages over these conventional systems.
- They allow for remote monitoring and in vivo measurements of the radiation dose. Their small size, lightweight and flexibility have allowed their dosimetric performance to be demonstrated successfully from Quality Control on LINAC to brachytherapy providing information of the radiation dose to the target volume and/or nearby critical organs.