Sara Pettinato, Stefano Salvatori

Channelling 2023
4-9 June 2023
Riccione (RN) - Italy

Diamond-based detection systems for tomorrow's precision dosimetry

sara.pettinato@unicusano.it
stefano.salvatori@unicusano.it

Dosimetry

Dosimetry in Radiation Therapy represents a key element in:

- ensuring treatments efficacy;
- the safety and the proper management of patients;
- the calibration of the radiation beams;
- validating the treatment plan.

RT-Techniques

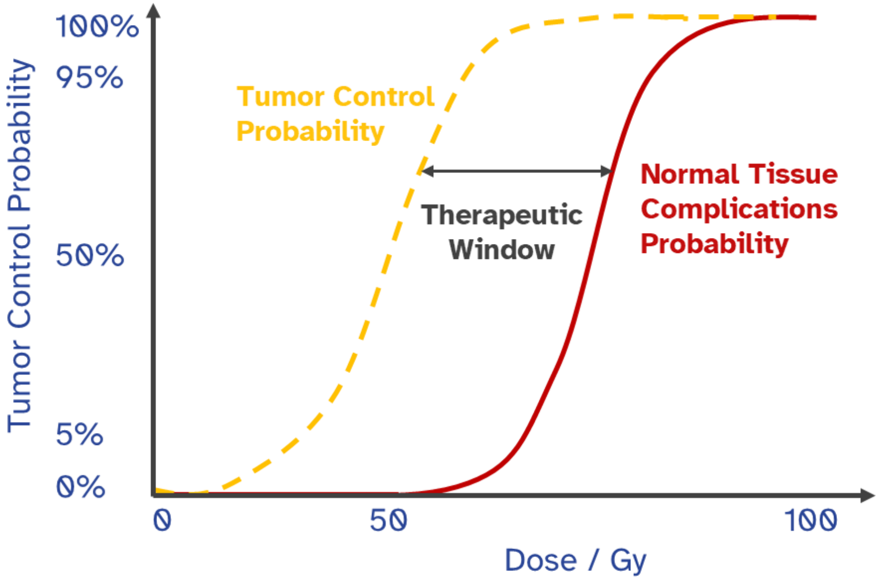
External-Beam RT	• 6-18 MV photon or electron beam • DPP < 1mGy • DR 0.01-0.1 Gy/s
Intra-Operative RT	• Low –energy photons (50kV), 4-6 MeV electrons • DPP: 2-100 mGy • DR up to 1 Gy/s
FLASH	• 7-9 MeV electron beams • DPP > 1 Gy • DR > 40 Gy/s

The emerging FLASH

"Radiation-therapy technology able to deliver at ultra-high DR a total dose in 100-200 ms and allow to treat tumors **without inducing drastic toxicities on the surrounding normal tissues**"

Why is it so interesting?

- To treat radio-resistant tumors increasing total dose without the associated surrounding tissue toxicity of CONV-RT;
- To treat diffuse/Non localized tumors where CONV-RT can not deliver tumoricidal doses;
- To treat tumors where radiotherapy already offers good local control but without the side effects typical of CONV-RT.

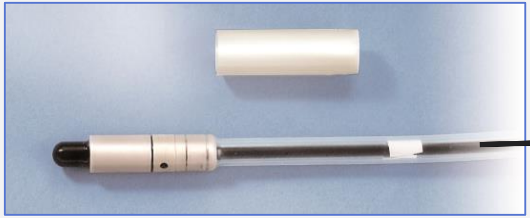


V. Favaudon et al., Sci. Transl. Med. 6 (2014) 245; Montay-Gruel et al. Radiother Oncol 124: 365-9, 2017

A unique multi-purpose dosimeter with good performance with radiations of different nature and energy range is highly desirable

State of the art

Electrometers (integration times of 0.1 – 10 s)



https://www.iba-dosimetry.com/product/cc13-ionization-chamber/

https://www.iba-dosimetry.com/product/dose-1/

Ionization chambers (collection time of the order of $10^{-5} - 10^{-4}$ s):

- 👍 Gold standard for conventional RT
- 👎 Collection efficiency reduces and saturation correction are not established by existing standards for FLASH RT

State of the art

(integration times of 0.1 – 10 s)

ht... ...ber/

https://www.iba-dosimetry.com/product/dose-1/

Unsuitable for single-pulse diagnostics

...ction time of the order of $10^{-5} - 10^{-4}$ s):

...or conventional RT

...ction efficiency reduces and saturation correction are not established by existing standards for FLASH RT

Solutions proposed for FLASH (1)

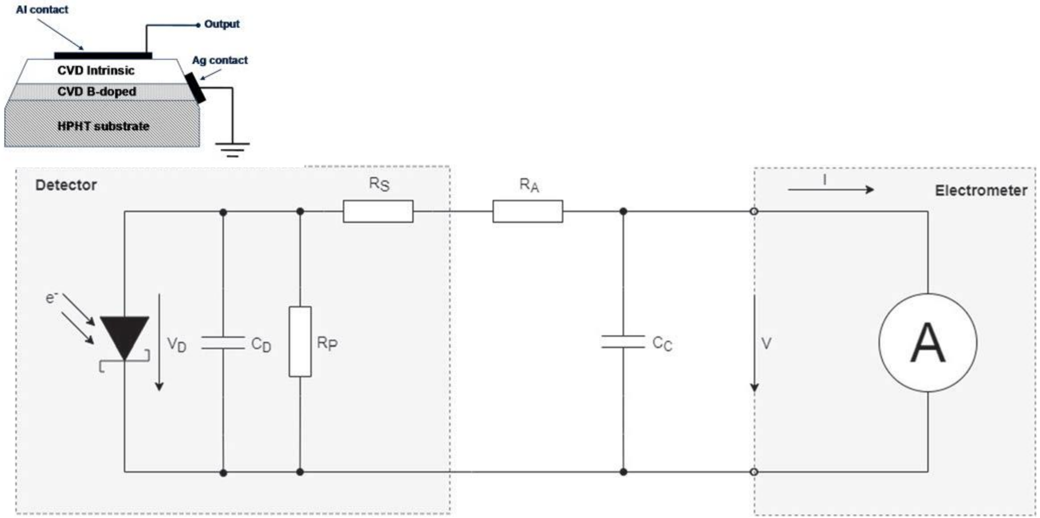
	Type	Tissue Equivalence	Accuracy	Time Response	Ref.
PASSIVE	Alanine	✔	1.5 %	2.6 min	Gondré et al. Radiation Research 2020 Romano et al. Medical Physics 2022
	Thermo-luminescent		3%	offline	Jorge et al. Radiotherapy and Oncology 2019 Tochilin et al. Health Physics 1966
	Radiochromic films	✔	4%	24 h (offline)	Jaccard et al. Medical Physics 2016 Karsch et al. Medical Physics 2012
	Scintillators	✔ If organic	3-5%	1µs to 10 ms	Ashraf et al. Frontiers in Physics 2020 Vanreusel et al. Medical Physics 2022
ACTIVE	Calorimeters		1.2%	1-10 ms	Romano et al. Medical Physics 2022 McManus et al. Scientific Reports 2020
	Ionization chambers		1-2%	10-200µs	Petersson et al. Medical Physics 2017 Konradsson et al. Radiation Research 2020 Kranzer et al. Medical Physics 2020
	SC-CVD diamond	✔	0.1%	~ 1 ns	Marinelli et al. Medical Physics 2022 Kranzer et al. Physics in Medicine and Biology 2022

Solutions proposed for FLASH (2)

detector sensitivities of ~ 0.2-1 nC/Gy photocurrent signals as high as tens of mA can be measured by commercial electrometers.

Workaround: custom circuits are inserted at the instrument input to attenuate and widen the pulse.

- worse SNR
- a real-time detection limited to PRF of a few tens of Hz

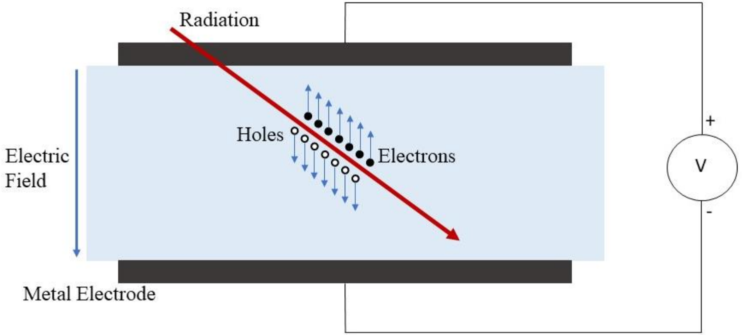


Kranzer et al. Medical Physics 2020 DOI: 10.1088/1361-6560/ac594e

Diamond-based Dosimeters (1)

Diamond is considered an elective solid-state material for dosimetry in RT, due to its physical-chemical characteristics:

- Atoms density: 10^{23} atoms/cm^3;
- **Tissue equivalence (Z=6);**
- **Linear response to dose and dose rate;**
- Low dark current level (< 1 pA);
- **High radiation hardness (up to 10 MGy);**
- **Response time in the nanosecond range;**
- High sensitivity (18-164 nC/Gy/mm^3).



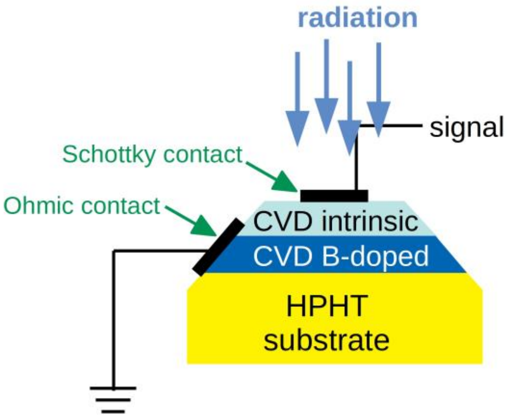
The progress in high-quality diamond synthesis by the Chemical Vapor Deposition (CVD) techniques has promoted the use of diamond:

- excellent properties of the grown material;
- cost-effectiveness.

C. Talamonti et al., Front. Phys. 9 (2021) 632299.

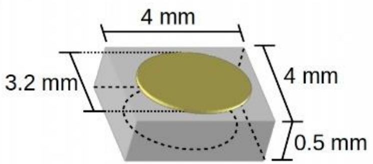
Diamond-based Dosimeters (2)

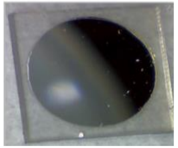
Schottky diode

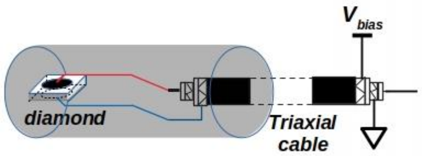


M. Falco et al., (2015)
DOI: 10.1016/J.NIMA.2008.06.028

Photoconductor





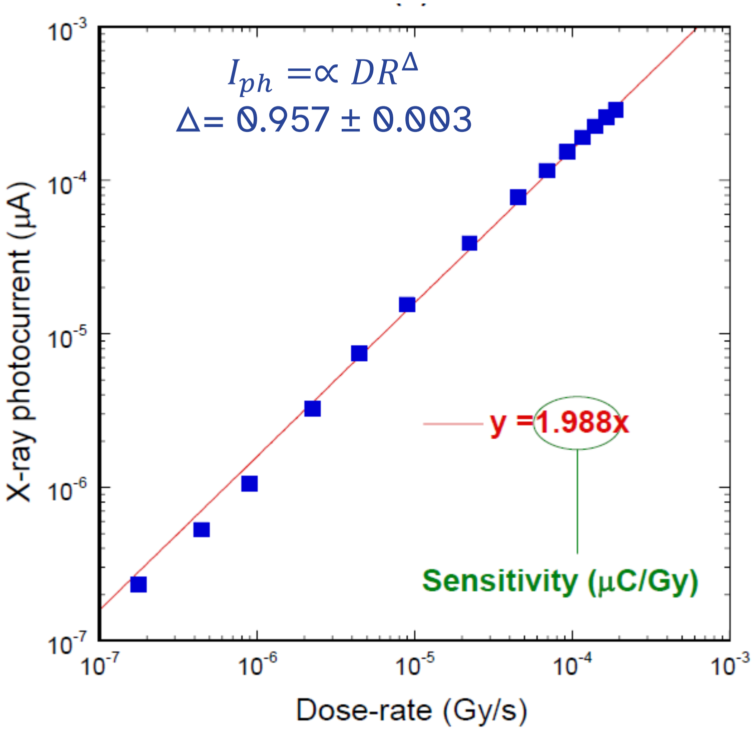


S. Pettinato et al (2022)
doi: 10.1109/JSEN.2022.3173892.

Dosimeter test in standard conditions

Low energy photons

- ➜ Cu target
- ➜ V=40 kV
- ➜ DR=0.18–189 μGy/s



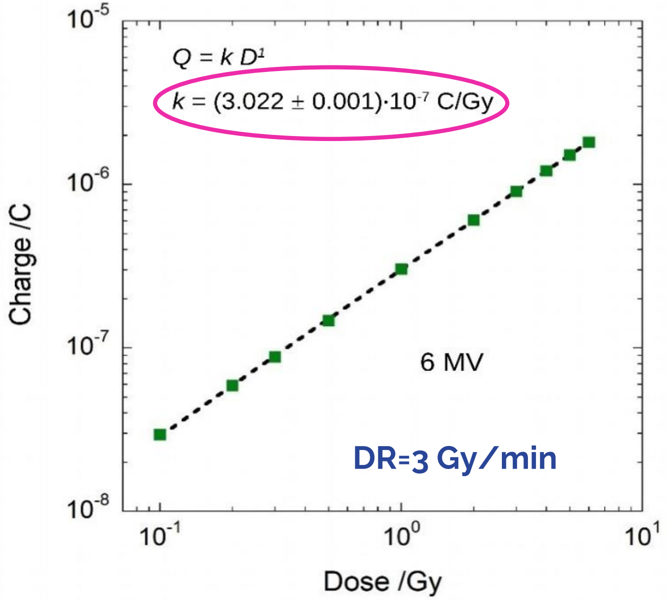
Pettinato, S. et al. Materials (2023).

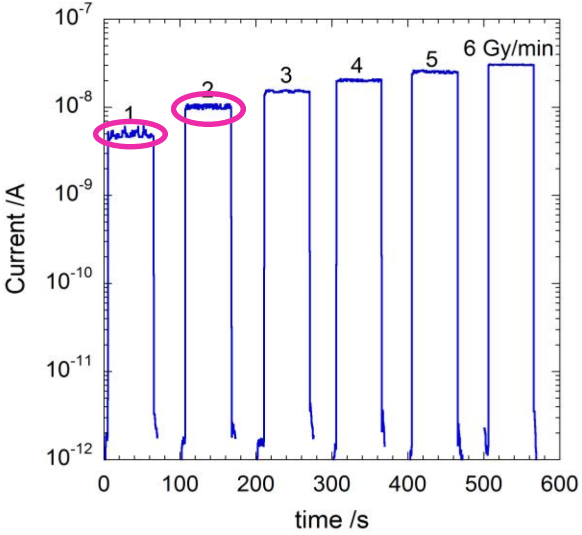
Dosimeter test in standard conditions

High energy photons

Clinac iX (by Varian)
@ San Giovanni Addolorata RT Dept. Rome (Italy)

Keithley 6517A Electrometer





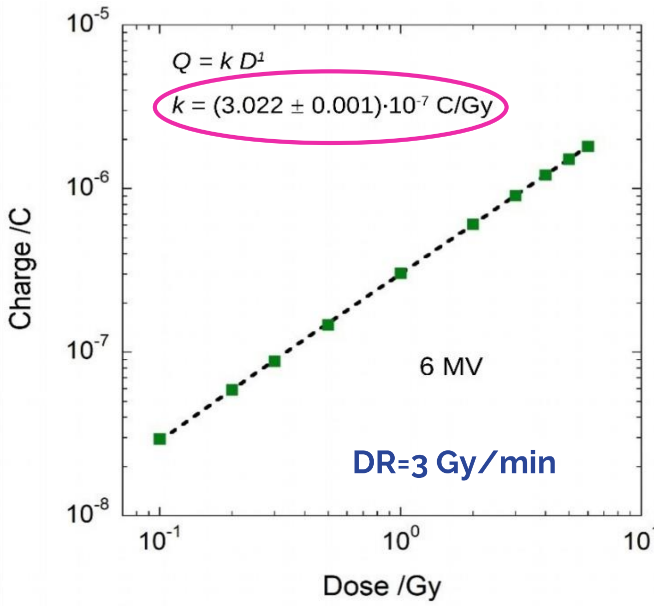
Pettinato, S. et al. Materials (2021).

Dosimeter test in standard conditions

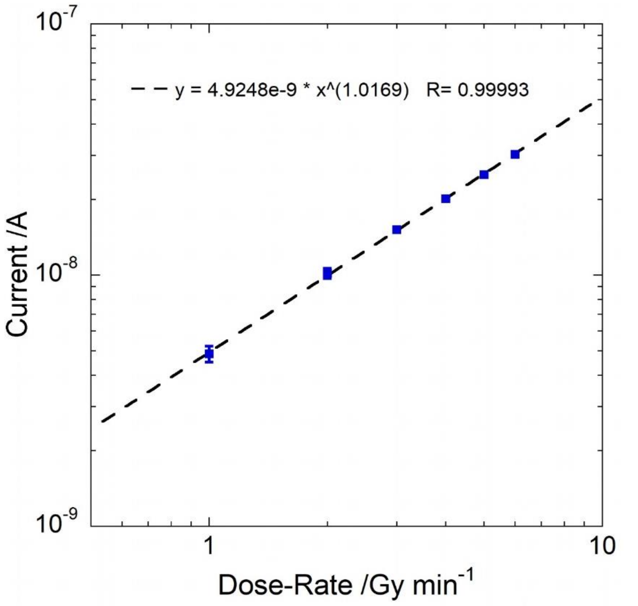
High energy photons

Clinac iX (by Varian)
@ San Giovanni Addolorata RT
Dept. Rome (Italy)

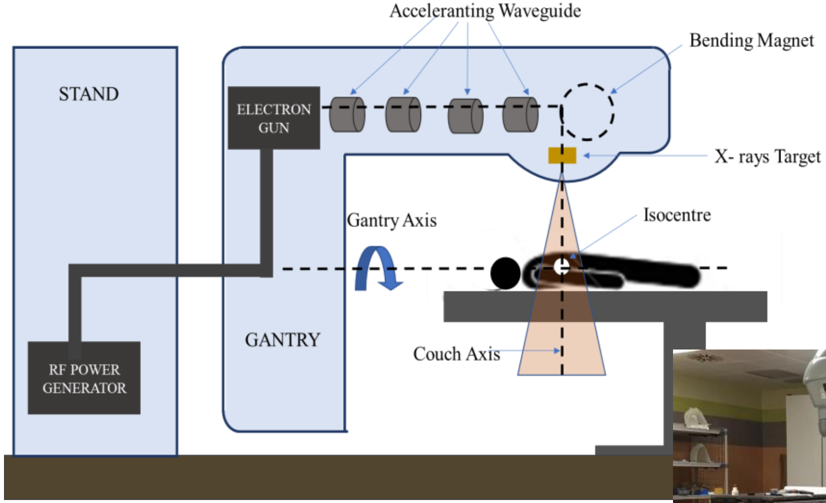
Keithley 6517A
Electrometer

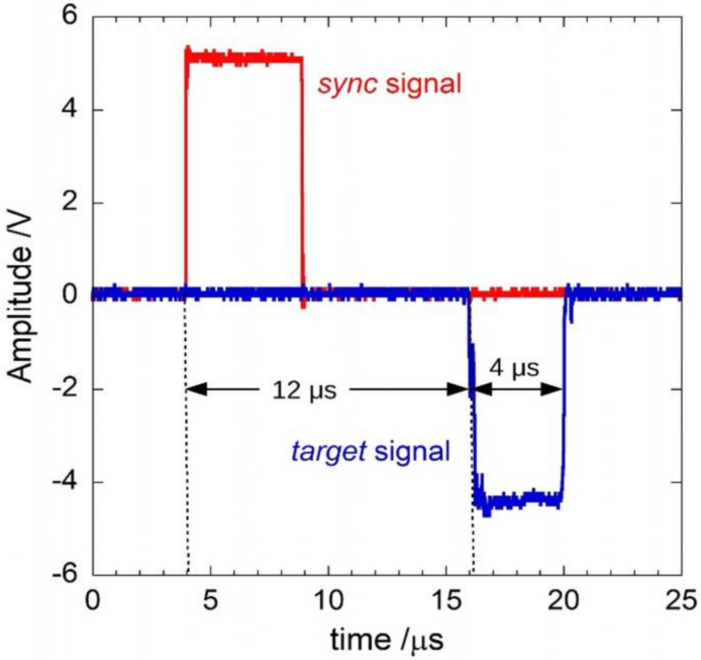


DR=3 Gy/min



Linac Signals (1)



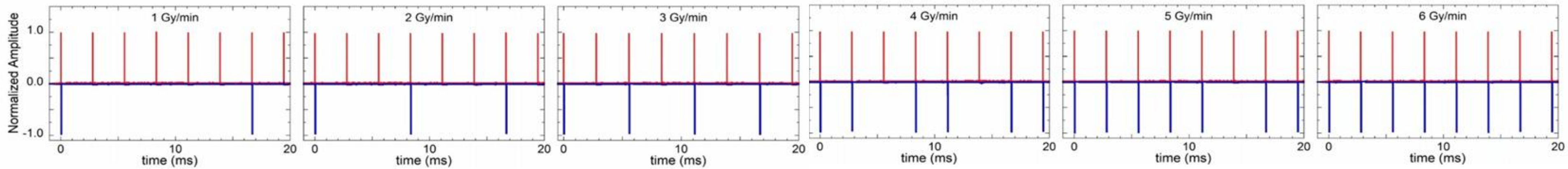


Pettinato, S. et al. Electronics (2019)

Linac Signals (2)

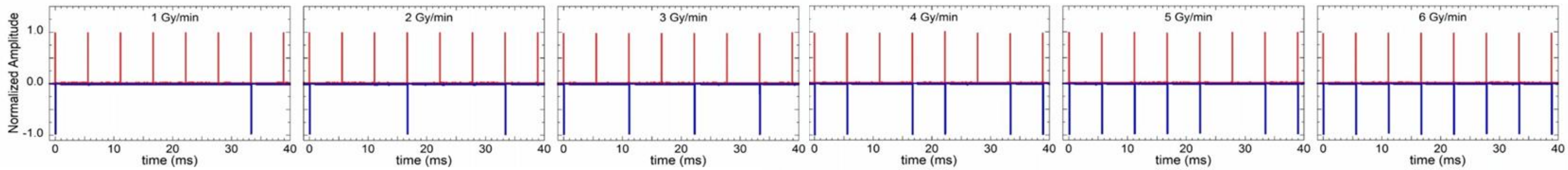
6 MV Photons

Nominal dose-per-pulse: **277.78 µGy**



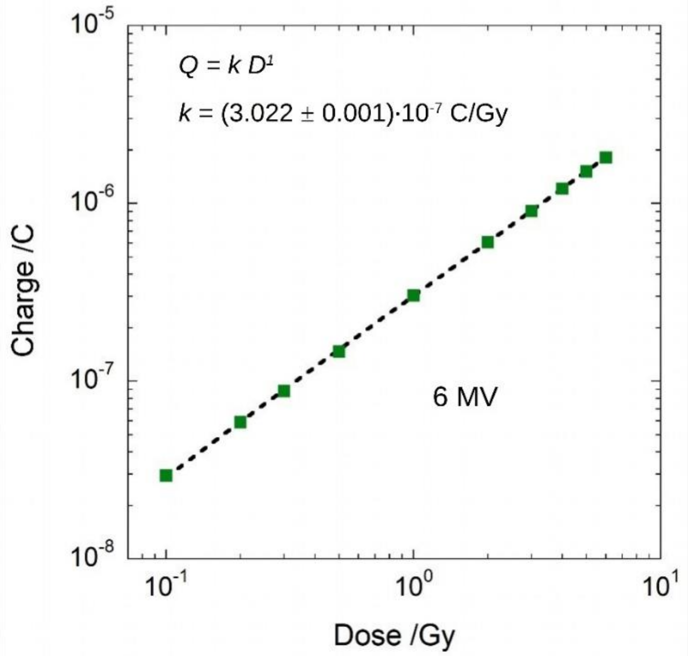
18 MV Photons

Nominal dose-per-pulse: **555.56 µGy**



Pettinato, S. et al. IEEE Sensors (2022).

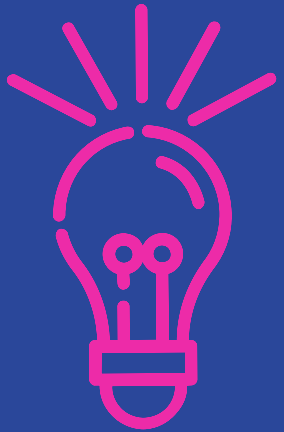
Linac Signals (2)



Taking into account the periodicity of the pulses, charge per pulse value was:

$$Q_p = \frac{302{,}2\ \mathrm{nC}}{180*20} = \mathbf{83.94\ pC/pulse}$$

Pettinato, S. et al. IEEE Sensors (2022).

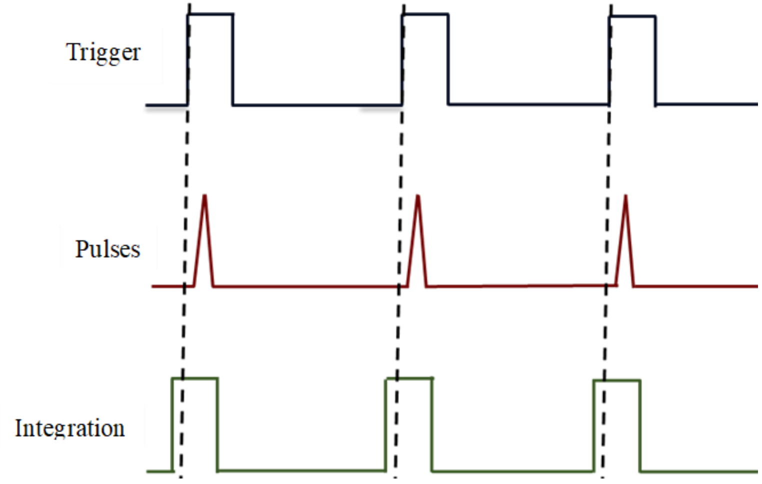


The Idea for single pulse charge integration

Gated Integrating Measurement

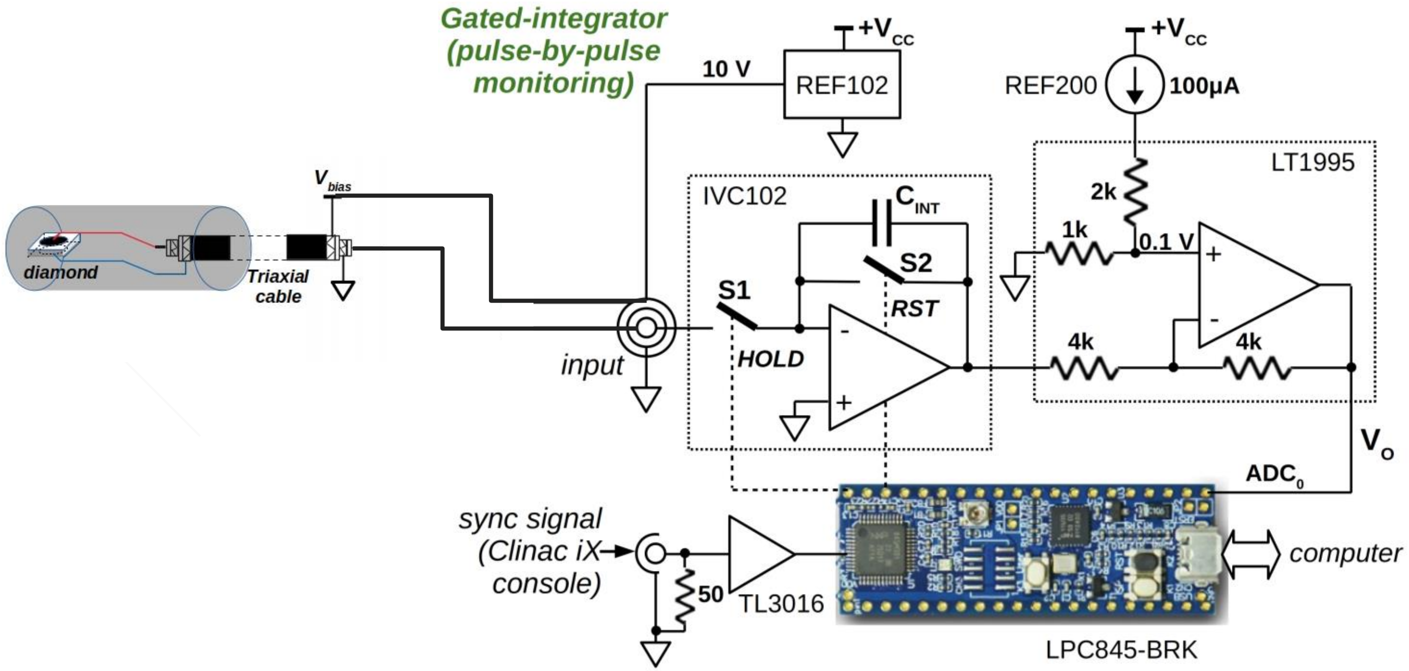
- Detection is synchronized with the external trigger signal generated at the same time as a source.
- For a pulse source GI amplifies and integrates the signal only during a time interval around the pulse.
- For a repetitive input signal, the average of n samples improves the SNR by the factor √n:

$$SNR_{GI} = \frac{\sum_i^n S_i}{\sqrt{\sum_i^n (N_i)^2}} = \frac{nS}{\sqrt{n}N} = \frac{S}{N}\sqrt{n}$$



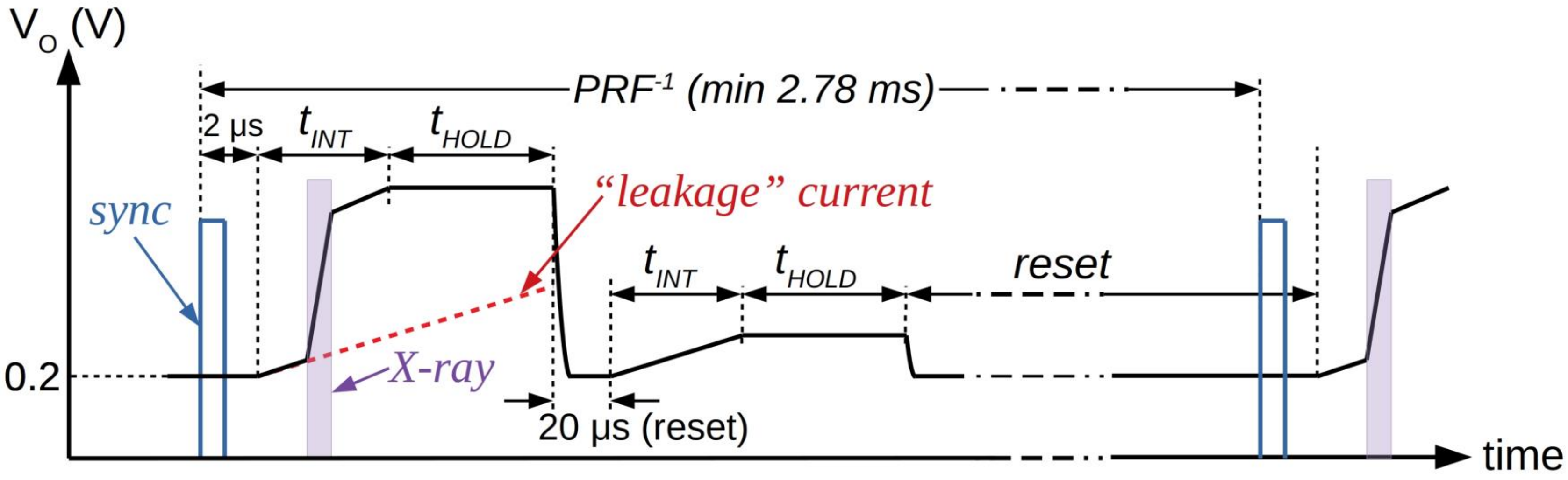
J. L. CollierMeas. Sci. Technol., vol. 7, no. 9, p. 1204, 1996

Detection Prototype



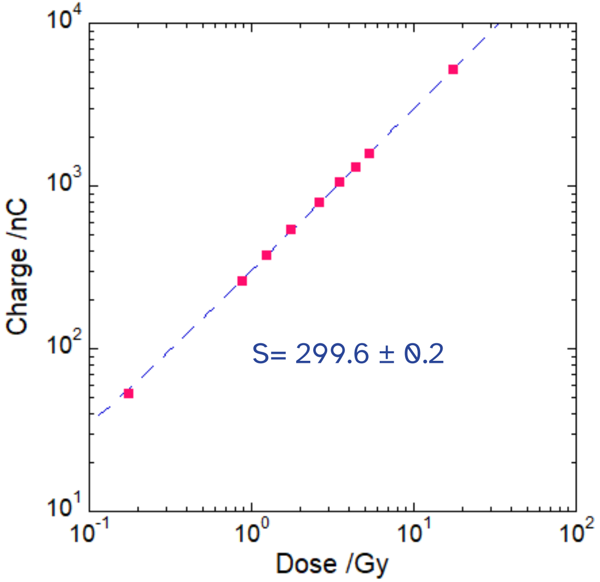
Detection Prototype

The two phase method allows to evaluate the contribution of dark/leakage currents

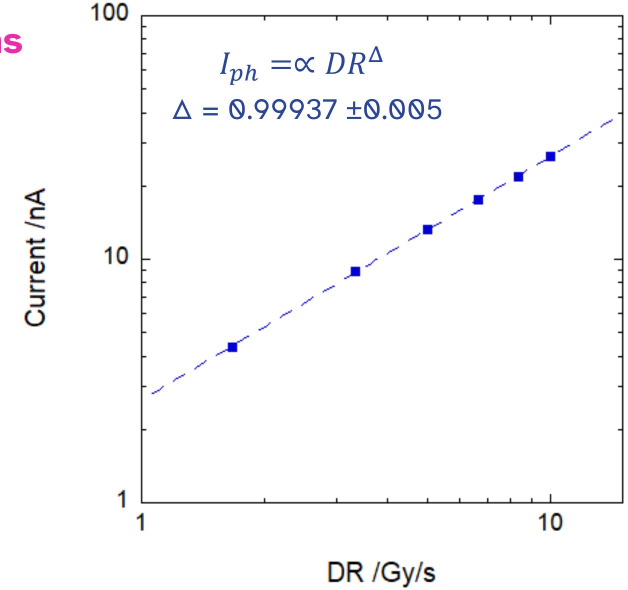


Characterizations

The prototype was tested in the field to acquire the signal generated by the dosimeter irradiated by 6 MV Photons



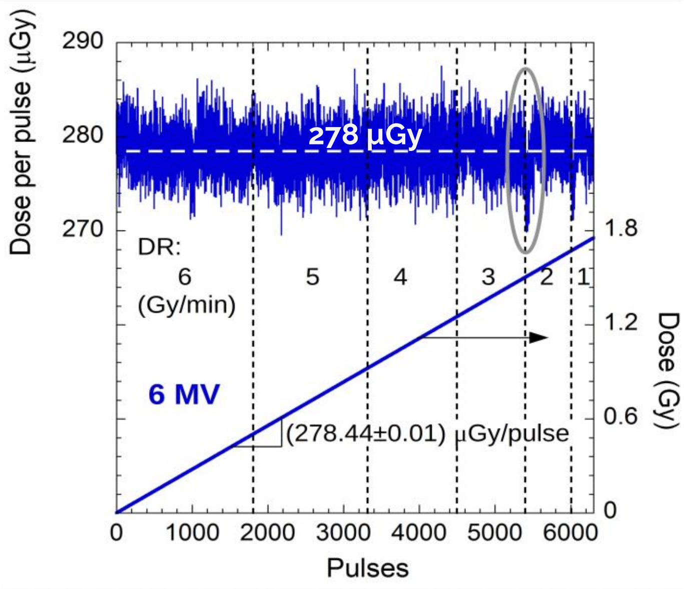
6 MV photons
SSD = 100
Vbias 10 V

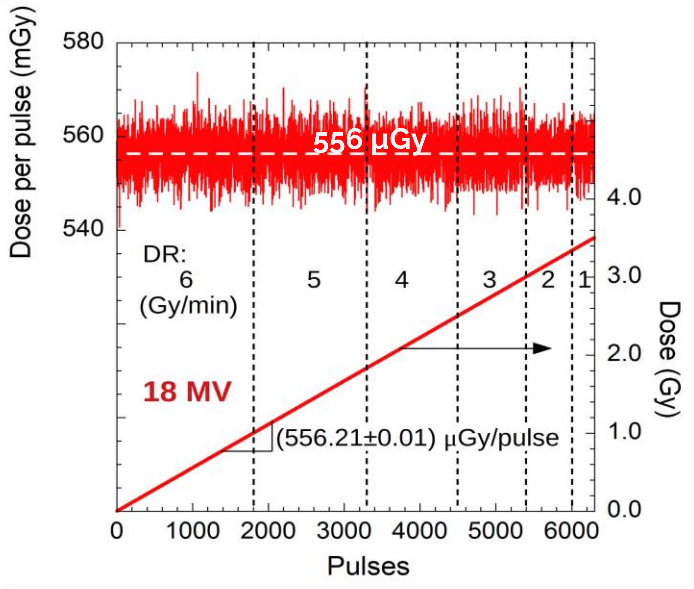


Pettinato, S. et al. Materials (2023).

Beam Diagnostics

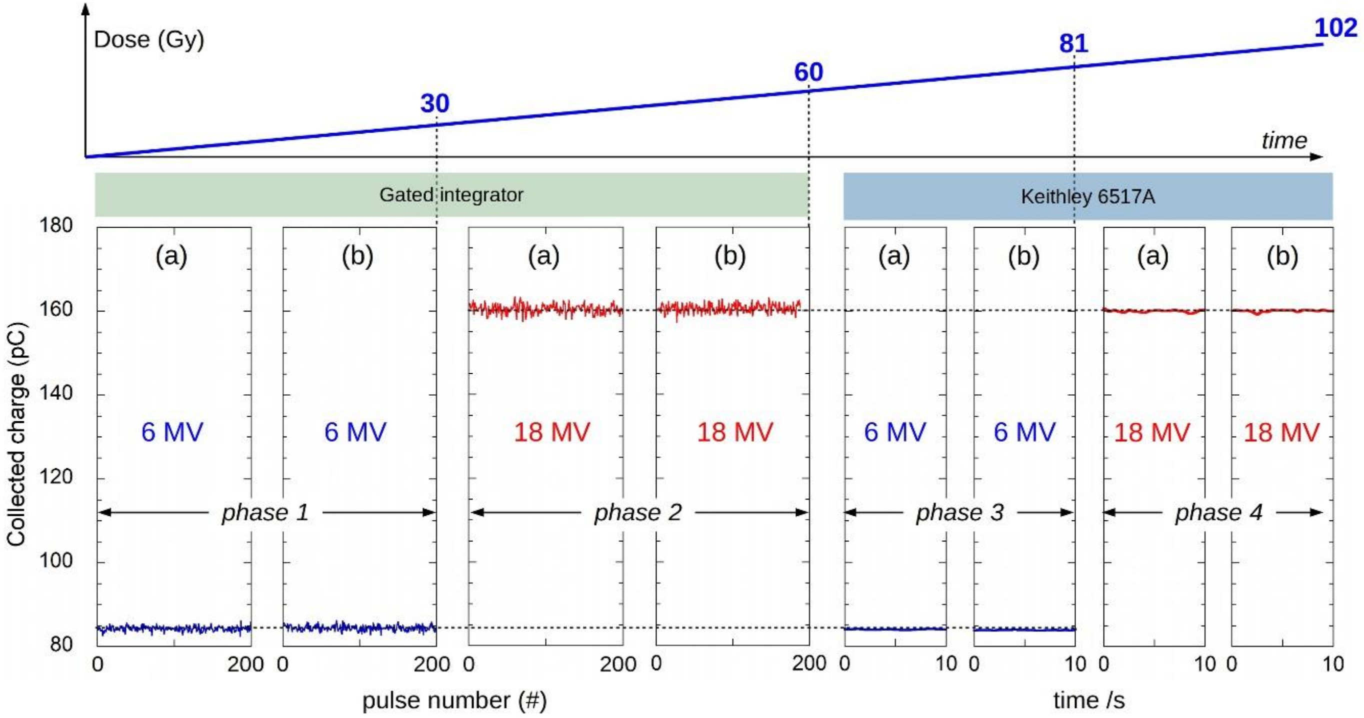
Cumulative sum of dose (continuous lines) displays a slope in excellent agreement to the expected D_P value (**277.78 µGy** at **6 MV** and **555.56 µGy** at **18 MV**).



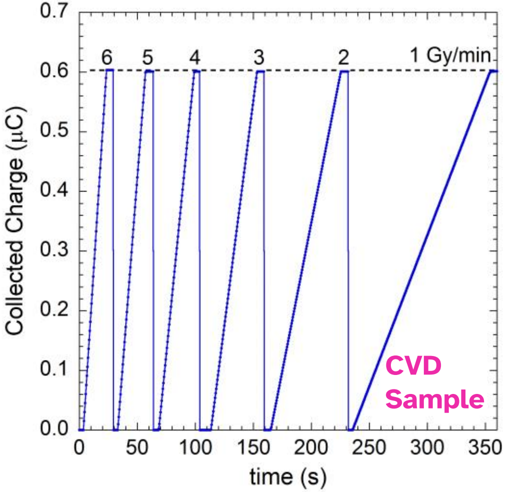


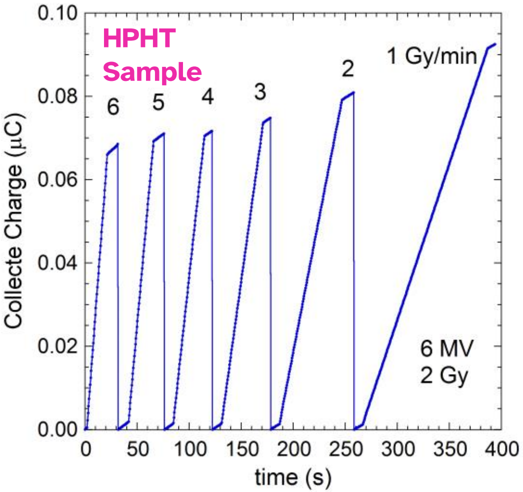
Dosimeter stability

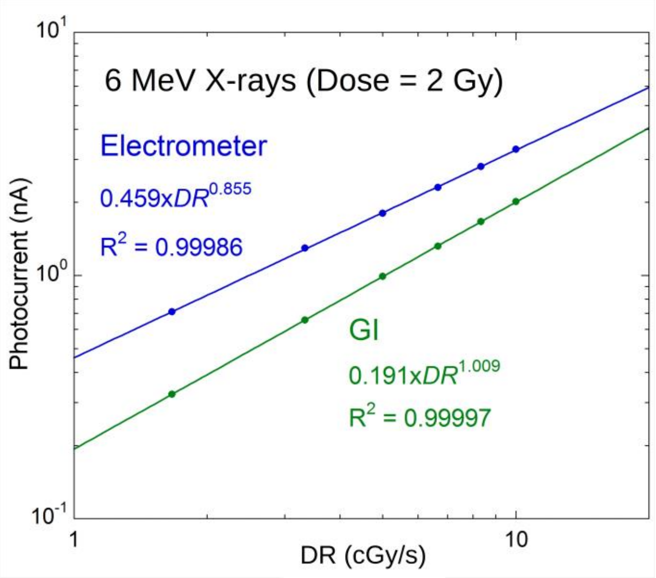
Collected charge per pulse values at **6 MV** and **18 MV** recoded by the **prototype** and those estimated by means of a **Keithley 6517 A electrometer**.



The advantage of the two-phase method



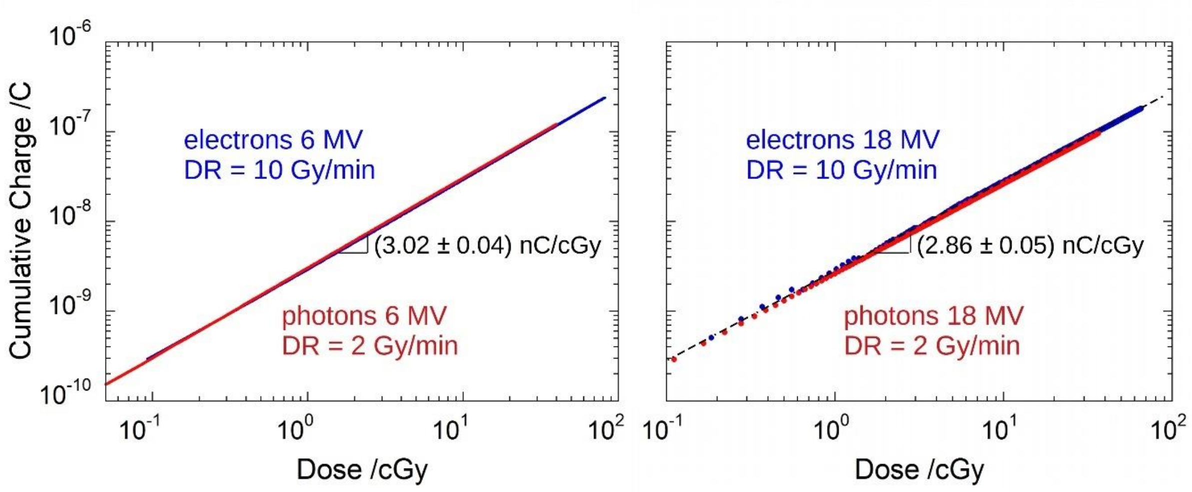




Salvatori, S. et al. IEEE TED (2023).

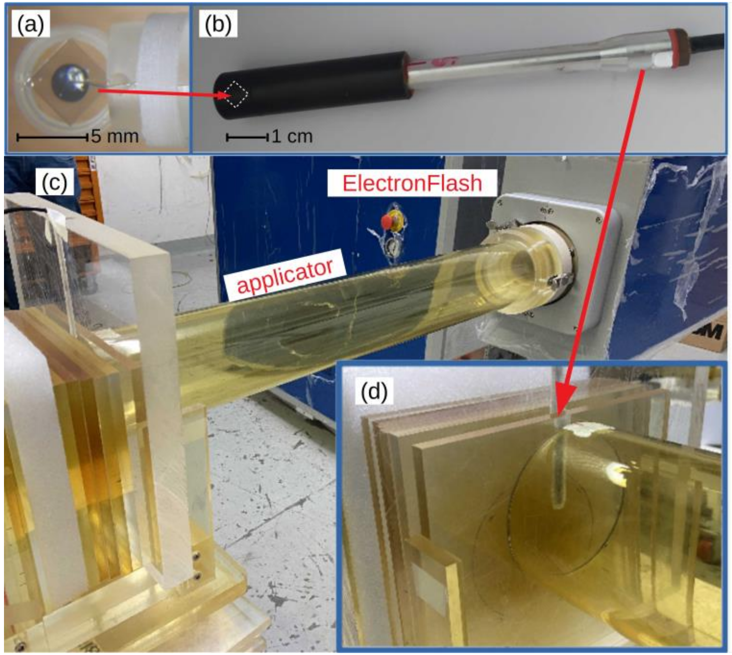
Characterization under electrons

The dose released in the diamond is independent on the nature of the radiation.

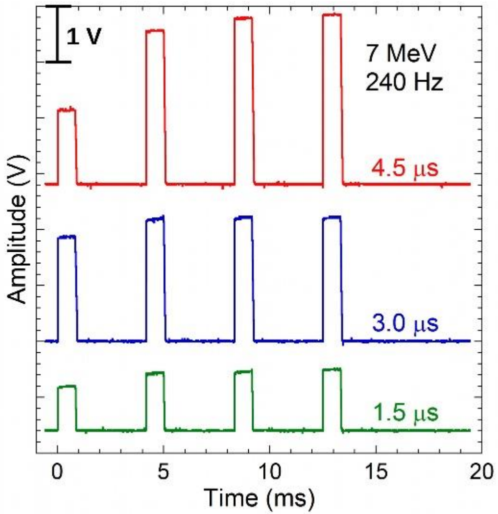


What about the FLASH RT?

Characterization under FLASH beams 1

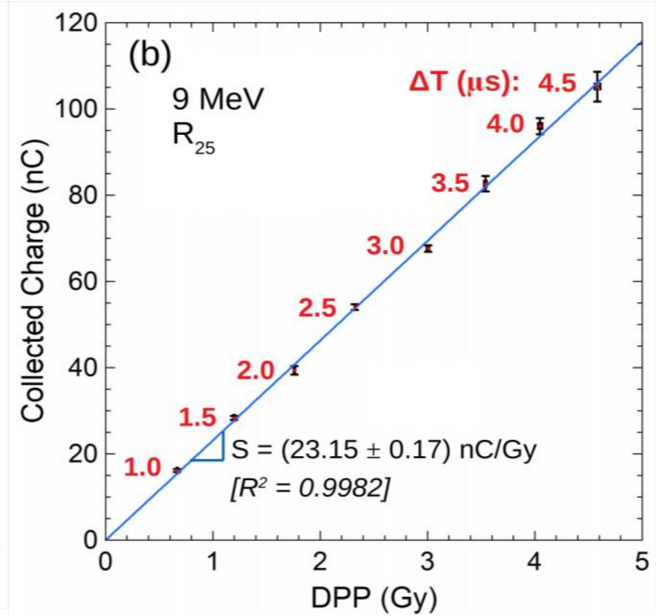


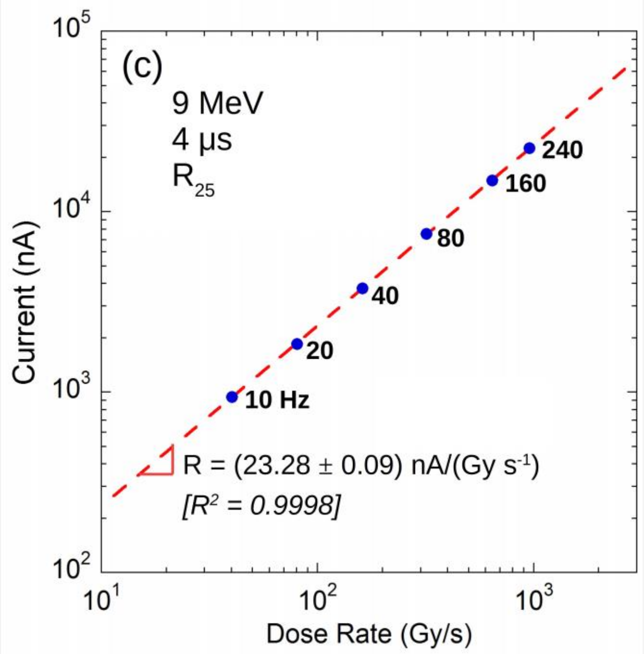
The amplitude of the acquired signal is proportional to the duration of the electron pulse



Characterization under FLASH beams 2

The system allows monitoring of FLASH electron beams, up to charge-per-pulse values of more than 100 nC





Conclusions

- accurate real-time pulse-by-pulse dose measurements;
- very good response stability at about 100 Gy;
- Very high sensitivity in beam intensity;
- Effective for photons and electrons beam diagnostics;
- Versatility for novel RT techniques (FLASH).

To whom the work is addressed

Prototype

Medical Physicists

They will be able to count on a useful survey tool for the definition of treatment plans and periodic verifications of LINAC outputs.

Oncologist

They will have an additional tool to define the real biological efficacy of treatments, aimed at achieving the best therapeutic capacity.

Biologies

They will be able to monitor all electron beam parameters essential for studying the interaction between radiation and tissue.
(Not yet fully known for FLASH).

Companies

Sectors where both dosimetric devices and LINAC equipment (conventional and FLASH) are manufactured will have a useful tool for control and commissioning.

Thank you for your attention! ☺