Dose per Pulse Monitoring of MeV Photon Beams

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Abstract. *Modern dynamic radiotherapies in cancer treatment are oriented to release high dose values in the shortest irradiation time. For these techniques, fast detectors and dedicated conditioning electronics will play a fundamental role for beam diagnostics to verify the necessary quality assurance requirements of treatments. This work describes a measurement system based on a single-crystal synthetic diamond able to monitor the dose released by each X-ray pulse generated by a medical LINAC. A gated-integration method, performed by a specifically designed electronics, has been used to measure the charge photogenerated in diamond by each impinging X-pulse. Exploiting the synchronization signal available in a LINAC apparatus, our system allows performing pulse-beam diagnostics with an acquisition time limited to the period around each pulse. Therefore, the proposed solution represents an effective tool for real-time dosimetry in modern radiotherapy applications and assures a better accuracy in comparison to conventional electrometer-based measurement systems that require longer acquisition periods.*

Keywords. Radiation therapy, precision integrator, medical linear accelerator, dose-measurements, diamond dosimeter, X-ray pulse.

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1 Introduction

Radiation Therapy (RT) is a clinical method useful in the treatment of cancer. Using strongly ionizing radiation, RT can damage the DNA of the target, thus blocking the proliferation of cancer cells. Currently, dynamic precision RT techniques [1-2] are widely used. The aim is to concentrate the dose in the tumour volume, while protecting the surrounding healthy tissue, by delivering high dose gradients in a very short time. Accurate and precise dosimetry is becoming increasingly necessary to detect beam anomalies and to ensure delivery of the prescribed dose to the patient. This implies the need to use fast dosimeters having a very small active volume (less than 1 mm^3). Because of its physical properties, diamond (natural and synthetic) allows to realize dosimeters that meet the requirements of modern dosimetry [3]. On the other hand, in addition to dosimeters that allow accurate dose measurements even for very narrow radiation beams, special measurement techniques are required. Indeed, the electronic system must acquire the dosimeter signal (charge or current) with very high time resolution, taking into account the pulsed nature of X-rays generated by medical LINACs used in RT. Each pulse has a duration of a few microseconds with a pulse-repetition-rate (PRR) in the range 60-1000 Hz. Especially for dynamic treatments, the accurate measurement of the dose delivered by each pulse of photons becomes fundamental. The typical measurement method used in clinical dosimetry is based on electrometers able to measure either currents or charges with an integration time in the 0.01 – 1 s range, i.e. integrating a large number of impinging pulses. Hence, the measurement techniques, as well as the applied instruments, are completely inadequate for the single-pulse diagnostics that modern RT requires. Accuracy is greatly enhanced employing a synchronized technique for signal acquisition, thus eliminating any contribution of noise during the relatively long time periods between two consecutive pulses. The literature is still poor of works regarding single-pulse dose measurements. Proposed solutions (e.g. in [4]) display a high response time, then becoming ineffective in the case of PRR of the order of kHz adopted in modern dynamic RT. Conversely, the solution described in this paper is able to monitor each pulse up to a PRR greater than 2 kHz. The specifically designed synchronous gated-integrator (GI) allows signal conditioning in a time interval around each pulse. This assures excellent performance of the proposed detection system in terms of signal-to-noise ratio (SNR), sensitivity and input dynamics.

2 Circuit Description and results

LINACs for RT are machines capable of producing beams of electrons and photons that, properly collimated, impinge on the target volume. In a LINAC, electron packets are accelerated until they acquire the desired energy to collide on a heavy metal target producing high-energy-pulsed X-rays. X-ray pulses have a duration of few microseconds and the dose-rate (DR) to be administered is regulated by the PRR.

In our experiments, a Clinac iX (Varian Inc.), installed at the Radiotherapy Department of “San Giovanni-Addolorata” Hospital in Rome (Italy), was used. Figure 1 shows the signals measured at the apparatus console. The sync pulse is generated by the LINAC to synchronize its internal electronics, whereas the target pulse is proportional to the current generated by the electrons impinging on the metal target. As shown in Fig. 1, the target pulses, and then the X-ray pulses, have a duration of 4 µs. The nominal dose-per-pulse values are 277.78 µGy and 555.56 µGy for 6 MV and 18 MV photons, respectively [5-6].

The realized GI electronics exploits the sync signal available at the LINAC console to establish the integration of signals in a period around each pulse [7]. A microcontroller unit synchronizes the signal integration, employees the analog-to-digital conversion and sends data to a computer. All the mentioned operation are performed within less than 500 µs, thus allowing the real-time acquisition of pulses for PRRs greater than 2 kHz. A specifically designed Labview® program was developed for remote control of the prototype and data recording. Figure 2 illustrates the set-up adopted during the measurements.

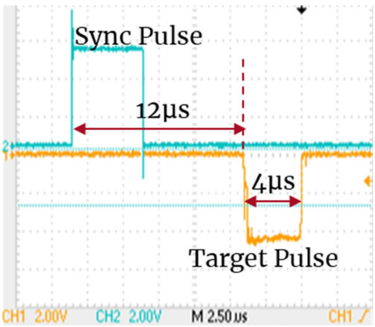

Figure 1. Sync and target pulses generated by the Clinac iX as acquired by the oscilloscope.

Figure 2. Set-up during the measurements with the Clinac iX. On the right, the realized GI prototype.

The prototype has been tested over both the full dose range and DRs typically used for clinical treatments, at the two available electron acceleration voltages of 6 MV and 18 MV. The diamond dosimeter was placed into a plexiglass phantom at the LINAC isocentre and biased at 10 V. Figure 3 shows the voltage signals at the GI output acquired for 1000 pulses when 6 MV and 18 MV X-rays impinged on the detector. The DR was regulated to 6 Gy/min for both the two energies.

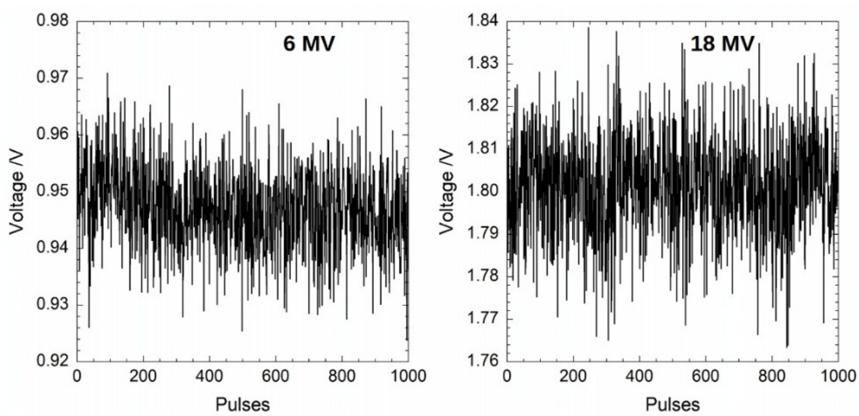

Figure 3. Voltage signal acquired on 1000 pulses for 6 MV and 18 MV photons (DR=6 Gy/min).

Importantly, the amplitude variation of about the ±2% is not related to noise, but to a change of the impinging pulse intensity. Indeed, it is worth to note that the cumulative sum of the charge-per-pulse is linearly dependent on time, as reported in Fig. 4. This perfectly agrees to what expected: fixed the DR, the dose administered by the medical LINAC must be only dependent on the treatment time. Cumulative charge values of Fig. 4 have been calculated considering an integration capacitance of 88.5 pF as measured by the in-lab characterization of the prototype [6].

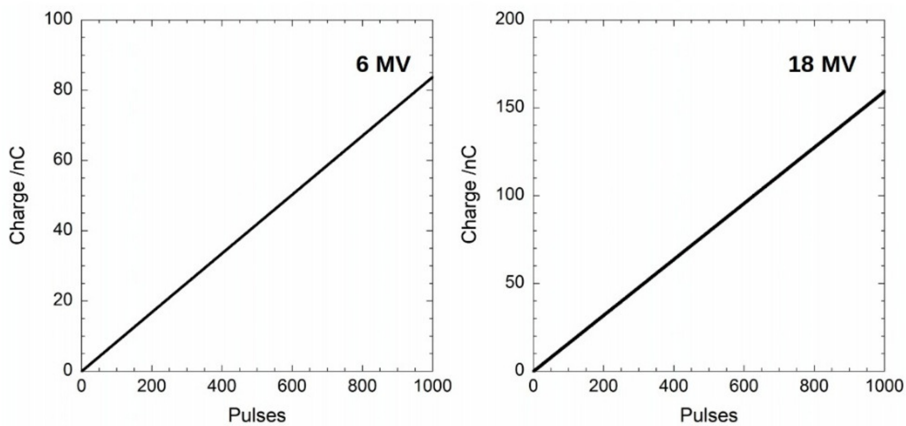

Figure 4. Cumulative sum of the charge-per-pulse acquired on 1000 pulses for 6 MV and 18 MV photons (DR = 6 Gy/min).

Finally, also the detector sensitivity to LINAC X-ray pulses has been evaluated. Figure 5 shows the data acquired by the proposed GI prototype (continuous lines). In the 1-6 Gy range, we also performed the measurements of the collected charge by means of a Keithley 6517A electrometer. Results reported in the figure highlight an excellent linearity of the detector response. It is important to observe that data acquired at the lowest dose values ($< 10^{-2}$ Gy) refer to a few number of impinging pulses and thus affected by the above mentioned amplitude change. The sensitivity of the diamond dosimeter was calculated by the slope of plots reported in Fig. 5: (300.64 ± 0.08) nC · Gy^{-1} and (286.56 ± 0.04) nC Gy^{-1} for X-ray photons of 6 MV and 18 MV, respectively. In addition, best fit of data reported in Fig. 4 according a linear regression gives 159.18 pC/pulse (6 MV photons) and 83.711 pC/pulse (18 MV photons). Therefore, known the detector sensitivities (Fig. 5) dose-per-pulse values for 6 MV and 18 MV photons result equal to 278 µG/pulse and 556 µGy/pulse, respectively, in excellent agreement to what expected for the Clinac iX apparatus.

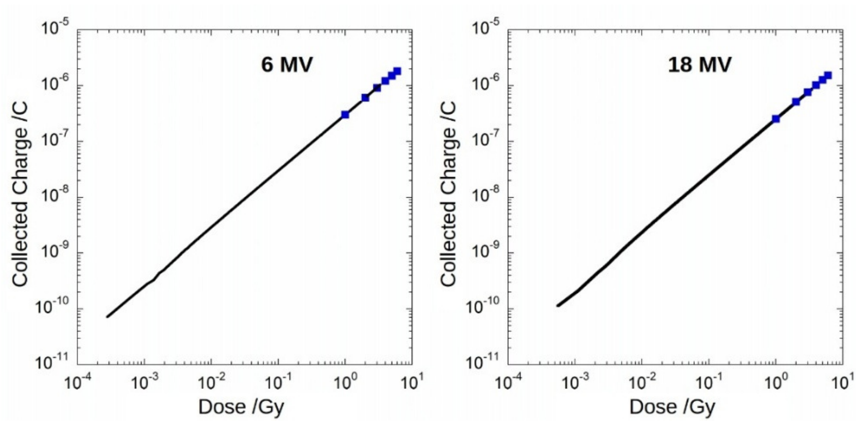

Figure 5. Collected charge as a function of dose for X-rays at 6 MV and 18 MV. Continuous lines refer to data acquired by our prototype, whereas blue dots are values measured by a Keithley 6517A.

3 Conclusions

A detection system based on a single crystal diamond dosimeter coupled to a dedicated front-end/readout electronics was developed and fully characterized on the field under X-rays produced by a medical LINAC used for RT in cancer treatments. Experimental results demonstrate that the system allows for accurate real-time pulse-by-pulse dose measurements, thus meeting the demands of quality assurance in dosimetry, particularly stringent in modern dynamic RT. The main advantage of the proposed electronics, resulting from the simplicity of the circuit, is the extremely low number and low cost of the used components. In addition to compactness and cost effectiveness, this guarantees both the reliability and the maintainability of the system, as well as an excellent measurement accuracy comparable to that of complex electrometer-based solutions.

References

[1] Y. Ge and Q. J. Wu, “Knowledge-based planning for intensity-modulated radiation therapy: A review of data-driven approaches,” Med. Phys., vol. 46, no. 6, pp. 2760–2775, 2019, doi: 10.1002/mp.13526

[2] G. Macchia et al. “Volumetric modulated arc therapy for treatment of solid tumors: Current insights,” Onco. Targets. Ther., vol. 10, pp. 3755–3772, 2017, doi: 10.2147/OTT.S113119.

[3] C. Talamonti et al., “Diamond Detectors for Radiotherapy X-Ray Small Beam Dosimetry,” Frontiers in Physics, vol. 9, 2021, doi: 10.3389/fphy.2021.632299.

[4] J.J. Velthuis et al., “Toward Pulse by Pulse Dosimetry Using an SC CVD Diamond Detector,” IEEE Trans. Radiat. Plasma Med. Sci., vol. 1, no. 6, pp. 527–533, 2017; doi: 10.1109/TRPMS.2017.2750799.

[5] S. Pettinato, M. Girolami, R, Olivieri, A. Stravato, C. Caruso, C., S.Salvatori, “Diamond-based Detection Systems for Accurate Pulsed X-rays Diagnostics in Radiotherapy,”. arXiv preprint arXiv 2109.14547, 2021, doi: 10.48550/arXiv.2109.14547.

[6] S. Pettinato et. al. “Time-resolved dosimetry of pulsed photon beams for radiotherapy based on diamond detector,” IEEE Sens, Jour. 22(12), pp. 12348-12356, doi: 10.1109/JSEN.2022.3173892.

[7] S. Pettinato, A. Orsini, M. Girolami, D. M. Trucchi, M. C. Rossi, and S. Salvatori, “A high-precision gated integrator for repetitive pulsed signals acquisition,” Electron., vol. 8, no. 11, 2019, doi: 10.3390/electronics8111231.