**PAPER** • **OPEN ACCESS**

# A diamond detector based dosimetric system for instantaneous dose rate measurements in FLASH electron beams

To cite this article: Marco Marinelli *et al* 2023 *Phys. Med. Biol.* **68** 175011

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine



RECEIVED
10 May 2023

REVISED
7 July 2023

ACCEPTED FOR PUBLICATION
25 July 2023

PUBLISHED
14 August 2023



PAPER

# A diamond detector based dosimetric system for instantaneous dose rate measurements in FLASH electron beams

**Marco Marinelli**[1], **Fabio di Martino**[2], **Damiano Del Sarto**[2], **Jake Harold Pensavalle**[2], **Giuseppe Felici**[3], **Luigi Giunti**[3], **Veronica De Liso**[3], **Rafael Kranzer**[4,5], **Claudio Verona**[1] **and Gianluca Verona Rinati**[1,*]

[1] Dipartimento di Ingegneria Industriale, Università di Roma Tor Vergata, Roma, Italy
[2] U.O.Fisica Sanitaria, Azienda Universitaria Ospedaliera Pisana, Pisa, Italy
[3] SIT S.p.A. , Aprilia, Latina, Italy
[4] PTW-Freiburg, Freiburg D-79115, Germany
[5] University Clinic for Medical Radiation Physics, Medical Campus Pius Hospital, Carl von Ossietzky University Oldenburg, D-26121 Germany
[*] Author to whom any correspondence should be addressed.

**E-mail:** gianluca.verona.rinati@uniroma2.it

**Keywords:** diamond detector, dosimetry, FLASH radiotherapy

## Abstract

*Objective.* A reliable determination of the instantaneous dose rate (I-DR) delivered in FLASH radiotherapy treatments is believed to be crucial to assess the so-called FLASH effect in preclinical and biological studies. At present, no detectors nor real-time procedures are available to do that in ultra high dose rate (UH-DR) electron beams, typically consisting of $\mu$s pulses characterized by I-DRs of the order of MGy/s. A dosimetric system is proposed possibly overcoming the above reported limitation, based on the recently developed flashDiamond (fD) detector (model 60025, PTW-Freiburg, Germany). *Approach.* A dosimetric system is proposed, based on a flashDiamond detector prototype, properly modified and adapted for very fast signal transmission. It was used in combination with a fast transimpedance amplifier and a digital oscilloscope to record the temporal traces of the pulses delivered by an ElectronFlash linac (SIT S.p.A., Italy). The proposed dosimetric systems was investigated in terms of the temporal characteristics of its response and the capability to measure the absolute delivered dose and instantaneous dose rate (I-DR). A 'standard' flashDiamond was also investigated and its response compared with the one of the specifically designed prototype. *Main results.* Temporal traces recorded in several UH-DR irradiation conditions showed very good signal to noise ratios and rise and decay times of the order of a few tens ns, faster than the ones obtained by the current transformer embedded in the linac head. By analyzing such signals, a calibration coefficient was derived for the fD prototype and found to be in agreement within 1% with the one obtained under reference $^{60}$Co irradiation. I-DRs as high as about 2 MGy s$^{-1}$ were detected without any undesired saturation effect. Absolute dose per pulse values extracted by integrating the I-DR signals were found to be linear up to at least 7.13 Gy and in very good agreement with the ones obtained by connecting the fD to a UNIDOS electrometer (PTW-Freiburg, Germany). A good short term reproducibility of the linac output was observed, characterized by a pulse-to-pulse variation coefficient of 0.9%. Negligible differences were observed when replacing the fD prototype with a standard one, with the only exception of a somewhat slower response time for the latter detector type. *Significance.* The proposed fD-based system was demonstrated to be a suitable tool for a thorough characterization of UH-DR beams, providing accurate and reliable time resolved I-DR measurements from which absolute dose values can be straightforwardly derived.

## 1. Introduction

An innovative radiotherapy modality, so-called FLASH radiotherapy (FLASH-RT), is being recently investigated by many research teams, based on ultra high dose rate (UH-DR) proton, ion or electron beam irradiations (Favaudon *et al* 2014, Montay-Gruel *et al* 2017, Schüler *et al* 2017, Durante *et al* 2018, Jaccard *et al* 2018, Patriarca *et al* 2018, Bourhis *et al* 2019, Lansonneur *et al* 2019, Vozenin *et al* 2019a and 2019b, de Kruijff 2020, Di Martino *et al* 2020, Esplen *et al* 2020, Hendry 2020, Schüller *et al* 2020, Wilson *et al* 2020, Faillace *et al* 2021, Lin *et al* 2021, Marcu *et al* 2021, Moeckli *et al* 2021). It was reported that a beneficial 'FLASH effect' is obtained in such conditions, in terms of sparing of healthy tissues and organs, while preserving an equivalent tumor control as compared to conventional RT. However, the FLASH effect mechanism is still far from being fully understood. Besides, the lack of detailed information on irradiation protocols, often results in possible differences in the delivered treatments which are difficult to ascertain (Montay-Gruel *et al* 2019, Vozenin *et al* 2019a). Recently Vozenin *et al* 2020 recommended that extreme care is taken when designing and realizing experiments aimed at studying the FLASH effect. All the relevant variables must be properly addressed and a thorough characterization of the physical parameters of the used UH-DR beams is mandatory. This obviously holds true for all the standard dosimetric quantities also involved in conventional radiotherapy treatments and, even more so, for the one which has been reported to be crucial for obtaining the FLASH effect, i.e. the dose rate (DR). Characterizing UH-DR beams for FLASH-RT applications is challenging due to the extreme beam properties in such conditions, especially when pulsed UH-DR beams are involved, leading to very high instantaneous DR (I-DR) values. As an example, I-DRs as high as few MGy/s are typically achieved when using electron beam linacs, with pulse duration in the $\mu$s range. In addition, in contrast to conventional RT, the dose of a typical fraction in FLASH-RT is applied with a few pulses, in extreme cases only one. Besides, some accelerators used to study the FLASH effect may exhibit a ramp-up behavior (Ashraf *et al* 2022). Thus, the exact knowledge of the pulse shape and the pulse-to-pulse variation is particularly relevant. This requires measurement systems that can work with single-pulse resolution.

The validation of a monitoring system for preclinical studies using such UH-DR beams was recently reported in Gonçalves Jorge *et al* (2022) and Oesterle *et al* (2021), involving a current transformer (model ACCT, Bergoz Instrumentation, France) positioned at the exit of an Oriatron eRT6 linac (PMB-Alcen, France) and a Mobetron (IntraOp, Sunnyvale, CA, USA) respectively. The ACCT allowed for recording the temporal traces of the delivered pulses, and thus the evaluation of several physical parameters characterizing the beam itself. It also allows for an indirect determination of several dosimetric quantities relevant for preclinical studies. However, this process relies on the specific dosimetric calibration of all the delivered beams, which are known to depend on many irradiation parameters. Indeed, in Gonçalves Jorge *et al* (2022) it is shown that the conversion factor obtained for the ACCT calibration in terms of delivered dose depends, for example, on the pulse duration, thus rendering the calibration procedure relatively tricky and linac-dependent.

A comprehensive and reliable characterization of UH-DR beams calls for the availability of a dosimetric system capable of matching stringent requirements, such as: response linearity up to very high I-DRs, sub-$\mu$s response time and high radiation hardness. All of the commercially available active real-time dosimeters suffer from well documented undesired response nonlinearities and saturation effects (Jaccard *et al* 2017, Petersson *et al* 2017, Gonçalves Jorge *et al* 2019, Ashraf *et al* 2020, Di Martino *et al* 2020, Esplen *et al* 2020, McManus *et al* 2020, Vignati *et al* 2020, Kranzer *et al* 2021).

Recently, our research group developed the flashDiamond detector (fD) in cooperation with PTW-Freiburg, specifically designed for UH-DR beam dosimetry (Kranzer *et al* 2022, Marinelli *et al* 2022, Verona Rinati *et al* 2022). Its response was demonstrated to fulfill the requirements for UH-DR beam dosimetry, allowing for the commissioning of ElectronFlash linacs (SIT S.p.A., Italy,).

In this work, we propose a flashDiamond based dosimetric system, intended for a thorough and reliable characterization of the temporal structure of UH-DR beams as well as the experimental determination of the I-DR. The possibility to derive dosimetric quantities from the recorded time resolved signals was also investigated.

## 2. Materials and methods

### 2.1. Dosimetric system

The dosimetric system investigated in the present work is based on the flashDiamond detector (type 60025, PTW-Freiburg, Germany). Two fD detectors were used, one of them (fD prototype in the following) properly modified in order to tune its performance for fast signal applications. More specifically, the standard PTW triaxial cable and plug designed for low noise charge/dose measurements were replaced by a coaxial RG223/U cable and related plug intended for transmission of fast signals. The diamond chip and housing of the fD prototype were left unchanged and nominally identical to the ones of the standard fD also used in this study. The calibration coefficients in terms of absorbed dose to water of both fD detectors were measured under $^{60}$Co irradiation and reference conditions (source surface distance 100 cm, field size 10 cm × 10 cm, point of measurement on the central axis in 5 cm depth in water) at the PTW-Freiburg secondary standard laboratory. They were found to be 0.465 nC Gy$^{-1}$ and 0.409 nC Gy$^{-1}$ for the fD prototype and the standard fD respectively. Such difference in calibration factors, typically observed in microDiamonds and flashDiamonds, is primarily due to random fluctuations in the thickness of the detector active volumes, resulting from the diamond chemical vapour deposition process.

Time resolved signals were recorded by connecting the fD detectors to a variable gain transimpedance amplifier (model DHPCA-100, FEMTO Messtechnik GmbH, Germany) and an USB digital oscilloscope board (model 5444D, Pico Technology Ltd, UK). The electronic chain obtained by the combination of these two instruments will be referred to as FEMTO+Pico in the following.

### 2.2. Irradiation setup and experiments

The investigated detectors were irradiated by an ElectronFlash linac (SIT S.p.A. Italy, Di Martino *et al* (2020), Faillace *et al* (2021)), equipped with a triode electron gun that allows varying the beam current, and thus the dose per pulse (DPP) and the I-DR, while keeping unchanged all the other physical parameters of the beam. The linac is provided with a monitoring system designed according to the IEC 60601-2-1 standard prescriptions. It consists of two current transformers (model ACCT, Bergoz Instrumentation, France) measuring the beam current and characterized by a resolution lower than 1.5 $\mu$A rms, and a Bandwidth from 3 Hz to 1 MHz (Oesterle *et al* 2021, Gonçalves Jorge *et al* 2022). The ACCT signals are integrated and properly converted in monitor units.

The irradiation experiments were performed by using 9 MeV pulsed electron beams, delivered by a 30 mm in diameter cylindrical applicator, at a source to surface distance of 110 cm as shown in figure 1. The detectors were positioned in a polymethylmethacrylate cylindrical phantom 120 mm in diameter, with 12 mm plastic water build-up slabs placed in between the applicator and the phantom (see figure 1(b)), approximately corresponding to the point of maximun dose, $d_{\max}$.

Two sets of measurements were performed to assess the capability of the proposed system to characterize the electron beam, both from the temporal evolution and dosimetric point of view. At first, a systematic investigation was performed by irradiating the detector at the maximum beam current and systematically varying the pulse duration from approximately 0.7 to 4.0 $\mu$s. Afterwards, the beam current was changed instead, while keeping constant the pulse duration at 4.0 $\mu$s, so to span the whole range of DPP and I-DR values available with the 30 mm applicator. In particular, nine different DPP values were used, ranging from 0.24 to 7.13 Gy as derived during a previously performed linac commissioning by means of alanine pellets and gafchromic films (Marrale *et al* 2022). In both cases, a sequence of ten pulses at 5 Hz pulse repetition frequency was used for each irradiation step, resulting in an overall delivered dose which is ten times the DPP.

The temporal oscilloscope traces were recorded with the FEMTO amplifier set to a gain of $10^3$ V A$^{-1}$ and a bandwidth of 10 MHz. The signal from the ACCT was simultaneously recorded by the PICO digital oscilloscope as well. All the above irradiation experiments were repeated by connecting the fDs to a UNIDOS Webline electrometer set in charge mode acquisition. The electrometer was equipped with an external capacitance box provided by PTW in order to prevent nonlinearities in its readings acquired in ultra high dose per pulse (UH-DPP) conditions (Marinelli *et al* 2022).

In order to compare the data from the two acquisition setups (FEMTO+Pico and UNIDOS), the charge per pulse values (QPP) from the FEMTO+Pico chain were calculated by integrating the current traces recorded by the oscilloscope. More specifically, the QPP value corresponding to each irradiation step was determined as the average of the integrals calculated from each one of the ten current traces. When using the UNIDOS in charge mode acquisition instead, the QPP values were obtained by simply dividing by ten the total charge measured during each irradiation step.

Finally, in order to verify the beam stability and evaluate the pulse-to-pulse DPP variation, three irradiation sequences, 50 pulses each, were delivered to the fD prototype at the maximum beam current and with a 2.4 $\mu$s pulse duration.

## 3. Results and discussion

The time resolved response of the fD prototype and the ACCT measured during the described two sets of measurements, i.e. pulse duration scan and DPP scan, are reported in figure 2. In the $y$-axis of the upper plots, the current measured by the fD is reported, as obtained by dividing the recorded signal expressed in volts by the nominal gain of the FEMTO amplifier, i.e. $10^3$ V A$^{-1}$. Also, it is worth mentioning that in all plots reported in figure 2 one single pulse is shown out of the ten recorded in each irradiation step, so to improve their readability.

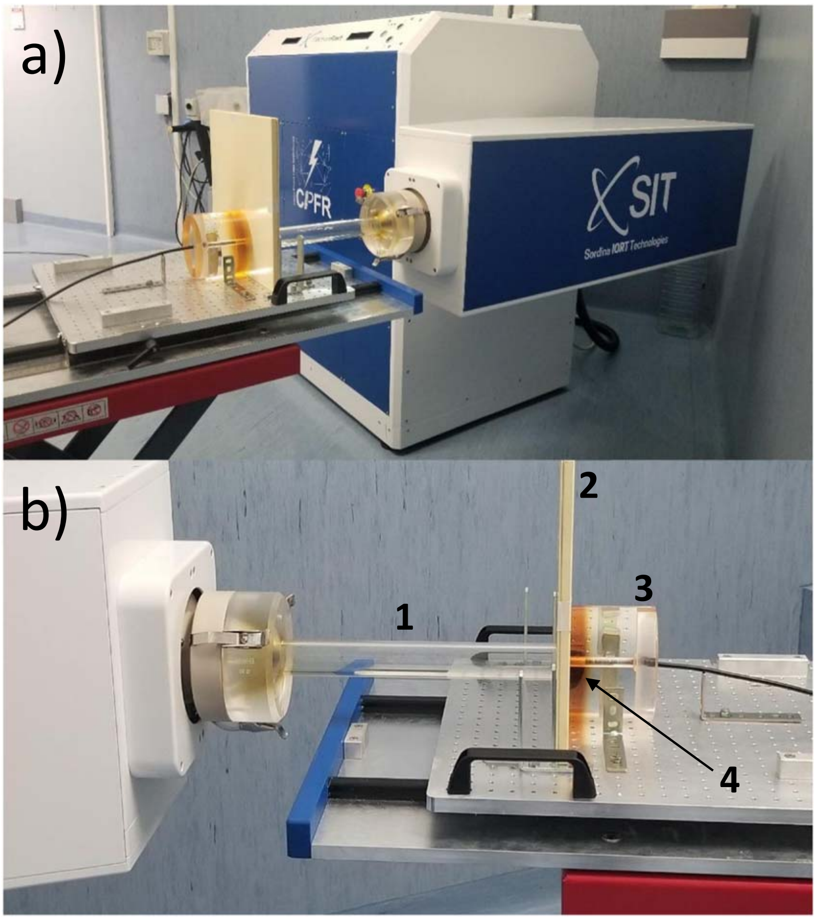


**Figure 1.** (a) Irradiation setup used the CPRF linac facility and (b) enlarged view showing in more detail (1) the linac applicator, (2) the plastic water slabs, (3) the PMMA cylindrical phantom and (4) the fD prototype.

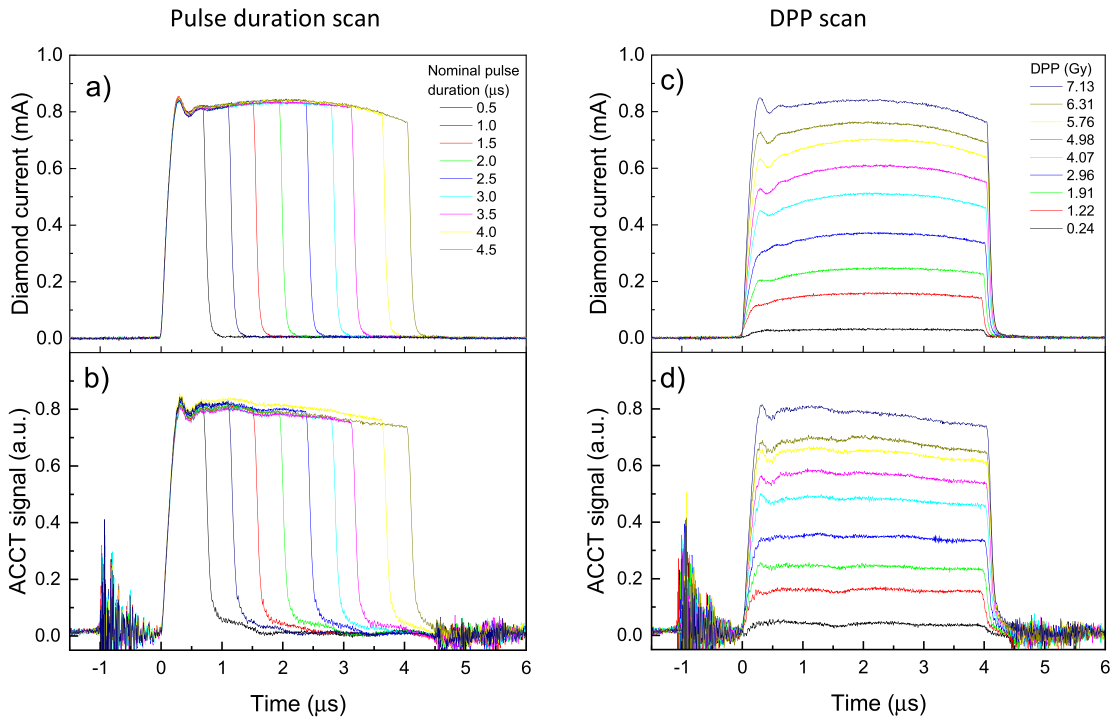


**Figure 2.** Temporal traces recorded by the fD prototype (upper plots) and the ACCT (lower plots) during the pulse duration scan (left-hand side) and DPP scan (right-hand side).

**Table 1.** Nominal pulse durations compared to the ones derived from the ACCT and the fD prototype temporal traces, by evaluating the FWHM and the width at 20% of the pulse height.

| | FWHM ($\mu$s) | | Width at 20% ($\mu$s) | |
|---|---|---|---|---|
| Nominal | ACCT | fD prototype | ACCT | fD prototype |
| 0.5 | 0.65 | 0.65 | 0.76 | 0.74 |
| 1.0 | 1.07 | 1.07 | 1.19 | 1.16 |
| 1.5 | 1.47 | 1.48 | 1.59 | 1.57 |
| 2.0 | 1.90 | 1.90 | 2.02 | 2.00 |
| 2.5 | 2.34 | 2.34 | 2.46 | 2.43 |
| 3.0 | 2.76 | 2.76 | 2.87 | 2.85 |
| 3.5 | 3.08 | 3.09 | 3.20 | 3.18 |
| 4.0 | 3.59 | 3.59 | 3.70 | 3.68 |
| 4.5 | 4.00 | 4.00 | 4.12 | 4.09 |

The traces reported in the upper and lower plots for each specific irradiation condition were simultaneously acquired by the two systems. They were found to be comparable from the qualitative point of view. However, some differences can be appreciated: (i) a much larger pick-up noise is observed in the case of the ACCT temporal trace, so that a much better signal to noise ratio is observed in the case of the fD detector (SNR = 500); (ii) a somewhat different shape is noticeable between the two signals in the beam-on time interval and (iii) a non-negligible tail is present in the ACCT signal after the beam switch-off, more evident in figure 2(b)), which is not detected by the fD prototype. Such differences might be due to the different positions of the two devices in the beam. More specifically, the ACCT measures the current from all electrons in air, whereas the fD measures all the electrons including the scattered ones. The beam energy spectra in those two points of measurement are most probably different and consist of energy contributions whose time evolutions may differ significantly. In addition, the two signals originate by two completely different physical detection mechanisms and electronic conversion procedures so that some differences are to be expected.

Rise and decay times of the recorded signals were evaluated, by using the 20%–80% criterium, so to exclude the above mentioned tail affecting the ACCT signal. As a general comment, the rise and decay times measured in all pulses by each detector are found to be highly reproducible and independent from both the pulse duration and the DPP. The values obtained by the fD prototype are always faster than the ones measured by the ACCT. In particular, the measured rise and decay times were 127 and 61 ns for the fD and 141 and 87 ns for the ACCT, with an uncertainty of 5 ns. Pulse durations are summarized in table 1, as derived from the full width at half maximum (FWHM) and the width at 20% of the pulse height of the temporal traces reported in figures 2(a) and (b). Consistent values were obtained by the two systems in the case of the FWHM evaluation, the maximum observed difference being of about 10 ns. As for the width at 20% of the pulse height, systematically higher values (about 20 ns) were measured by the ACCT. This is fully consistent with the above mentioned differences in rise and decay times of the two systems. These findings, clearly demonstrate the suitability of the proposed fD-based acquisition system for an accurate determination of the pulse duration of UH-DPP electron beams.

That said, extracting some dosimetric features of the UH-DR beam by the proposed system is straightforward. More specifically, the charge per pulse values (QPP) were first evaluated by integrating the current traces recorded by the fD during both the DPP and the pulse duration scans reported in figure 2. The obtained values were then compared with the charge measurements acquired in the very same nominal irradiation conditions by connecting the fD to the UNIDOS electrometer. The results are summarized in figure 3, where the FEMTO+Pico QPP is reported as a function of the UNIDOS QPP, together with the linear best fit to the experimental data.

An overall uncertainty of 3% was estimated by taking into account the electronic noise contribution, the uncertainty related to the DPP measurements performed during the beam commissioning by using alanine pellets and gafchromic films, and the repeatability of the linac beam output.

All the QPP values, no matter whether they were acquired during the DPP or pulse duration scan, exhibit a linear behaviour, thus indicating an overall reproducibility of the QPP evaluation procedure. The slope of the linear best fit is ($0.993 \pm 0.003$). It should be pointed out that the FEMTO+Pico electronic chain was not calibrated in advance and no correction was applied to take into account possible offsets. Despite that, a very small deviation of 0.7% from unity is observed for the slope of the best fit, demonstrating that the QPPs measured by the FEMTO+Pico system are fully consistent with the ones from the conventional electrometer operated in charge integrating mode.

In order to validate the proposed fD-based system for absolute dose measurements, and thus for absolute I-DR measurements, the QPP values derived from the DPP scan dataset were reported as a function of the

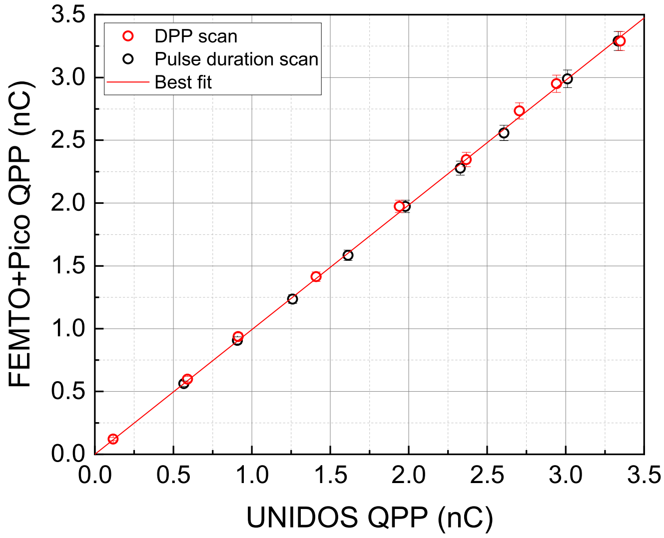


**Figure 3.** Comparison between the QPP values calculated by integrating the temporal traces acquired by the FEMTO+Pico dosimetric system with the ones measured by the UNIDOS electrometer. The linear best fit to the experimental data is also shown (red line).

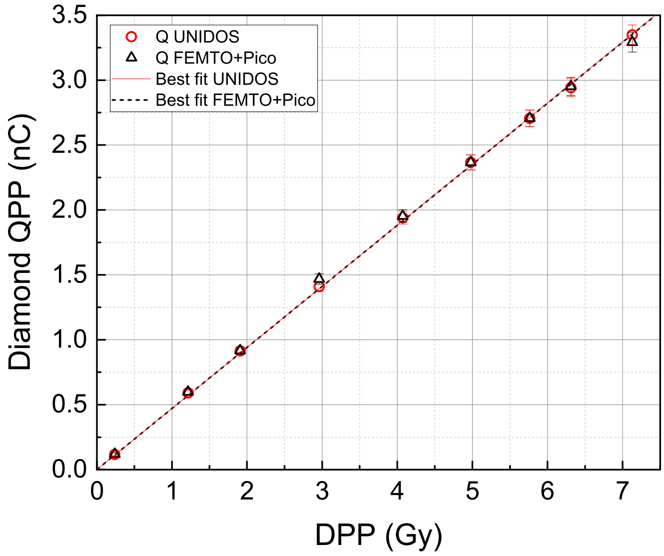


**Figure 4.** fD prototype response evaluated by using both the UNIDOS (red open circles) and the FEMTO+Pico (black tringles) acquisition setups as a function of the DPP. The two linear best fits to the experimental data are also shown.

delivered DPPs. The results are shown in figure 4, for both the FEMTO+Pico and UNIDOS acquisitions, together with the two almost perfectly superimposed linear best fits. A linear behaviour is confirmed in the whole investigated DPP range. The calibration coefficients estimated by the slopes of the linear best fits were found to be identical within the statistical experimental error, their values being $(0.470 \pm 0.003)$ nC Gy$^{-1}$ for the FEMTO+Pico system and $(0.471 \pm 0.001)$ nC Gy$^{-1}$ for the UNIDOS acquisition. A deviation of about 1% is also observed with respect to the $(0.465 \pm 0.001)$ nC Gy$^{-1}$ value measured at the PTW secondary standard laboratory. This is indeed a good agreement if one takes into account that a $^{60}$Co irradiation in a $10 \times 10$ cm$^2$ square field is being compared with a 9 MeV electron beam irradiation in a field of 3 cm in diameter. Similar results have been reported by Verona Rinati *et al* (2022), when comparing the fD response in $^{60}$Co, conventional electron beam and FLASH electron beam irradiation. This is also consistent with what observed in experimental and theoretical studies (Di Venanzio *et al* 2015 and Pimpinella *et al* 2015) on the microDiamond detector, whose design and working principle are similar to the ones of the fD.

The above results clearly demonstrate the suitability of the proposed fD-based acquisition system for UH-DR absolute dose and I-DR determination. As for the latter dosimetric quantity, three examples are shown in figure 5, in which the I-DR traces from the fD detector and the corresponding ACCT signal are reported for three

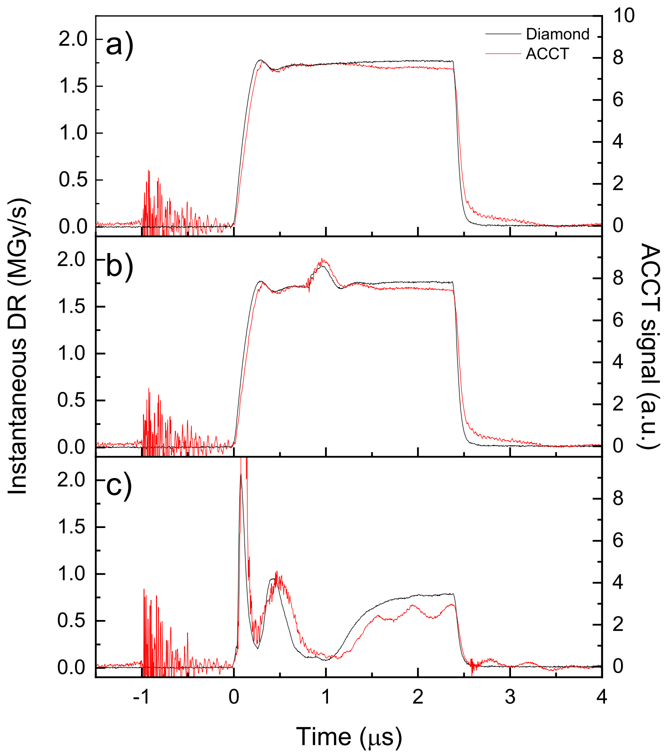


**Figure 5.** Three different pulse acquisitions are shown: (a) a 'standard' pulse; (b) a pulse in which a superimposed structure is recorded by both the fD system and the ACCT and (c) a 'disrupted' pulse in which evident differences are observed between the signals recorded by the two systems.

different pulses. The ACCT signals were rescaled in order to make the comparison between the two signals more straightforward. From top to bottom: (i) a typical pulse shape; (ii) a temporal trace in which an occasional superimposed structure is present and (iii) a disrupted pulse, causing an abrupt interruption of the beam delivery.

A first comment is that I-DR values as high as about 2 MGy $s^{-1}$ are easily detected by the FEMTO+Pico acquisition system.

Besides, a number of features are confirmed by this comparison: (i) there is a qualitative agreement between the fD and ACCT pulse shapes; (ii) a much better signal to noise ratio is observed in the fD traces; (iii) the fD response rise and decay times are again faster than the ACCT ones; (iv) occasional superimposed structures are always detected by both systems, and the related dose (about 45 mGy in figure 5(b)) can be evaluated by the fD trace. As for the disrupted pulse reported in figure 5(c), the two signals differ significantly, and a dose was delivered, which can be precisely evaluated by analyzing the fD trace. This is not feasible by using at the ACCT trace instead (red curve in figure 5(c)), being the ACCT signal completely saturated at the beginning of the disrupted pulse temporal trace and due to noticeable signal artifacts, most probably ascribed to electromagnetic interference effects. Nonetheless, it is worth to point out that the use of a beam monitor system such as the ACCT is of crucial importance here, allowing for a real time beam control, being the fD based system not intended for *in vivo* measurements. Also, it should be mentioned that beam structures as the one reported in figure 5(b) were frequently observed during irradiation, while, on the contrary, abrupt terminations (figure 5(c)) rarely occur.

The short term stability of the linac output as well as the reproducibility of the delivered DPPs were verified by irradiating the investigated detector by three sequences, 50 pulses each. The results are summarized in figure 6, where the ratio between the DDP and the average DPP evaluated over the whole set of data acquired during the three sequences is reported. A good reproducibility was observed, with a 0.8% maximum difference among the three average DDPs derived from each sequence. In addition, an overall pulse-to-pulse variation with a standard deviation of about 0.9% was derived.

Finally, all the measurements reported so far were repeated by using the fD detector, with a standard PTW triaxial cable and TNC plug. Very similar results were observed in all cases, and, more specifically, in terms of dose and DR determinations. The only exception consists in slightly slower rise and decay times observed when using the standard fD. This can be quantitatively appreciated in figure 7, in which a comparison between two pulses acquired by the FEMTO+Pico chain connected with the fD prototype (black curve) and the fD (red

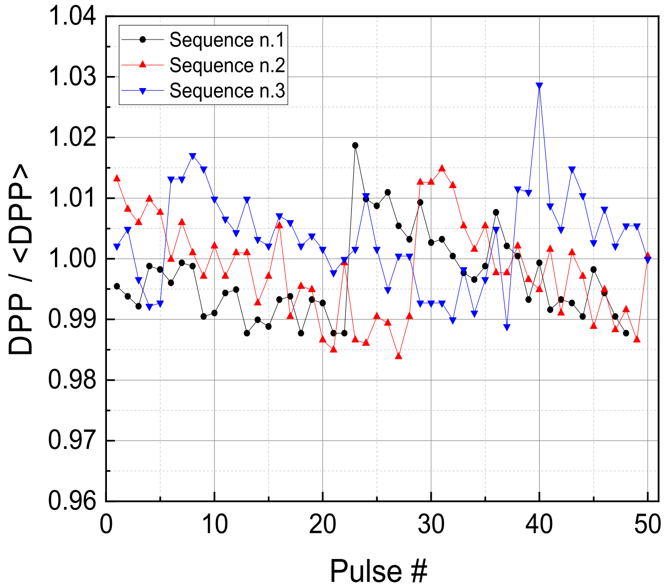


**Figure 6.** Ratio between the DDP and the average DPP evaluated over the whole set of data acquired during three irradiation sequences. The beam stability, the reproducibility and the pulse-to-pulse variation can be appreciated.

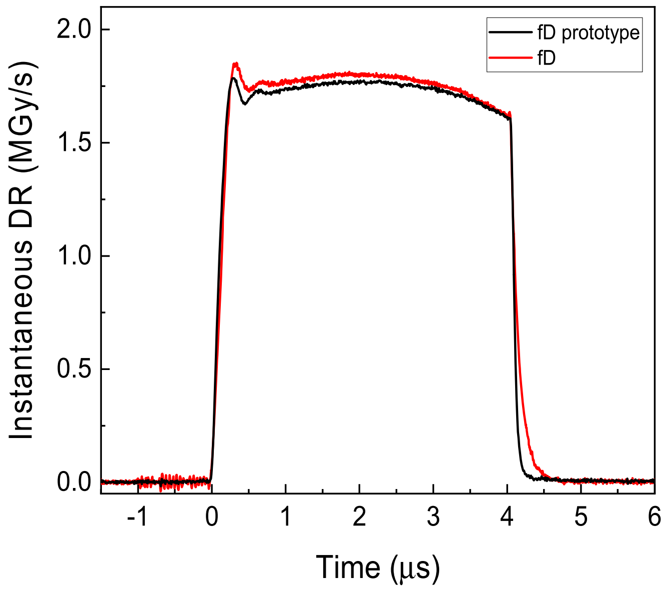


**Figure 7.** Comparison between the I-DR temporal traces acquired by using the fD prototype (black curve) and the standard fD (red curve) in nominally identical irradiation conditions (see text).

curve) is shown. The two signals were recorded in two different irradiation steps delivered in nominally identical conditions. More specifically, nearly identical FWHM values are measured by the two fDs, while the rise and decay times were found to be 127 and 61 ns for the prototype and 148 and 151 ns for the standard fD. Such somewhat slower response was confirmed by testing three more standard fDs, exhibiting very similar behaviour. This effect is believed to be due to the triaxial cable and plug, specifically designed for extremely low noise current/charge measurements and not for very fast signal transmission. However, despite that, the differences observed between the FWHM values obtained by the two fD detectors during a pulse duration scan are again approximately 10 ns only. As a consequence, the observed differences might be of some relevance when investigating in detail the temporal evolution of much faster pulses, but are indeed negligible for $\mu$s pulses such as the ones investigated in the present work.

## 4. Conclusions

A diamond based dosimetric system was investigated aimed at characterizing UH-DR radiotherapy electron beams. The proposed detector allows for recording temporal traces of the delivered I-DR, with very good signal to noise ratios and a time resolution of the order of few tens ns, from which detailed and reliable dosimetric features can be extracted. The calibration coefficient for the fD prototype evaluated under UH-DR electron beams was found to be in agreement within 1% with the one obtained under reference $^{60}$Co irradiation. A linear detector response was observed up to I-DR values of at least 2 MGy $s^{-1}$, without any undesired saturation effect. The absolute dose values evaluated by integrating the I-DR signals are in very good agreement with the ones obtained by using a standard UNIDOS electrometer, set in charge mode acquisition. A good short term reproducibility of the linac output was observed, characterized by a pulse-to-pulse variation with a 0.9% standard deviation. The results obtained when using the fD prototype were compared with the ones from a standard fD detector. Very similar results were observed, with the only exception of a slightly slower response time for the standard fD.

The above results clearly demonstrate that the investigated fD-based system is a suitable tool for characterizing UH-DR beams, allowing for accurate and reliable time resolved I-DR measurements, from which absolute dose determinations can be easily derived.

## Acknowledgments

The present work is part of the 18HLT04 UHDpulse project (http://uhdpulse-empir.eu/) which has received funding from the European Metrology Programme for Innovation and Research (EMPIR) programme, co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. Special thanks to 'Fondazione Pisa' for funding the CPFR ElectronFlash facility where the experiments reported in the present work were performed.

## Data availability statement

All data that support the findings of this study are included within the article.

## Conflict of interest disclosure

Marco Marinelli and Gianluca Verona Rinati, signed a contract with PTW-Freiburg involving financial interests deriving from the PTW microDiamond 60019 and flashDiamond 60025 dosimeter commercialization. Rafael Kranzer is PTW employee. Giuseppe Felici is SIT S.p.A. shareholder. Luigi Giunti and Veronica de Liso are SIT S.p.A employees.

## ORCID iDs

Marco Marinelli https://orcid.org/0000-0001-7554-0982
Damiano Del Sarto https://orcid.org/0000-0003-3293-1005
Jake Harold Pensavalle https://orcid.org/0000-0002-2972-6265
Giuseppe Felici https://orcid.org/0000-0002-3302-3765
Rafael Kranzer https://orcid.org/0000-0003-4063-0413
Claudio Verona https://orcid.org/0000-0001-6401-3765
Gianluca Verona Rinati https://orcid.org/0000-0003-1542-9910

## References

Ashraf M R, Rahman M, Cao X, Duval K, Williams B B, Hoopes P J, Gladstone D J, Pogue B W, Zhang R and Bruza P 2022 Individual pulse monitoring and dose control system for pre-clinical implementation of FLASH-RT *Phys. Med. Biol.* **67** 095003

Ashraf M R, Rahman M, Zhang R, Williams B B, Gladstone D J, Pogue B W and Bruza P 2020 Dosimetry for FLASH radiotherapy: a review of tools and the role of radioluminescence and cherenkov emission *Front. Phys.* **8** 328

Bourhis J *et al* 2019 Clinical translation of FLASH radiotherapy: why and how? *Radiother. Oncol.* **139** 11–7

Di Martino F *et al* 2020 FLASH radiotherapy with electrons: issues related to the production, monitoring, and dosimetric characterization of the beam *Front. Phys.* **8** 570697

Di Venanzio C, Marinelli M, Tonnetti A, Verona-Rinati G, Falco M D, Pimpinella M, Ciccotelli A, De Stefano S, Felici G and Marangoni F 2015 Characterization of a microDiamond detector in high dose-per-pulse electron beams for intra operative radiation therapy *Phys. Med.* **31** 897- 902

de Kruijff R M 2020 FLASH radiotherapy: ultra-high dose rates to spare healthy tissue *Int. J. Radiat. Biol.* **96** 419–23
Durante M, Brauer-Krisch E and Hill M 2018 Faster and safer? FLASH ultra-high dose rate in radiotherapy *Br. J. Radiol.* **91** 20170628
Esplen N, Mendonca M S and Bazalova-Carter M 2020 Physics and biology of ultrahigh dose-rate (FLASH) radiotherapy: a topical review *Phys. Med. Biol.* **65** 23TR03
Faillace L *et al* 2021 Compact S-band linear accelerator system for ultrafast, ultrahigh dose-rate radiotherapy *Phys. Rev. Accel. Beams* **24** 050102
Favaudon V *et al* 2014 Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice *Sci. Transl. Med.* **6** 245ra93
Gonçalves Jorge P *et al* 2019 Dosimetric and preparation procedures for irradiating biological models with pulsed electron beam at ultra-high dose-rate *Radiother. Oncol.* **139** 34–9
Gonçalves Jorge P, Grilj V, Bourhis J, Vozenin M C, Germond J F, Bochud F, Bailat C and Moeckli R 2022 Validation of an ultrahigh dose rate pulsed electron beam monitoring system using a current transformer for FLASH preclinical studies *Med. Phys.* **49** 1831–8
Hendry J 2020 Taking care with FLASH radiation therapy *Int. J. Radiat. Oncol. Biol. Phys.* **107** 239–42
Jaccard M, Durán M T, Petersson K, Germond J F, Liger P, Vozenin M C, Bourhis J, Bochud F and Bailat C 2018 High dose-per-pulse electron beam dosimetry: commissioning of the oriatron eRT6 prototype linear accelerator for preclinical use *Med. Phys.* **45** 863–74
Jaccard M, Petersson K, Buchillier T, Germond J F, Durán M T, Vozenin M C, Bourhis J, Bochud F O and Bailat C 2017 High dose-per-pulse electron beam dosimetry: usability and dose-rate independence of EBT3 gafchromic films *Med. Phys.* **44** 725–35
Kranzer R, Poppinga D, Weidner J, Schüller A, Hackel T, Looe H K and Poppe B 2021 Ion collection efficiency of ionization chambers in ultra-high dose-per-pulse electron beams *Med. Phys.* **48** 819–30
Kranzer R, Schüller A, Bourgouin A, Hackel T, Poppinga D, Lapp M, Looe H K and Poppe B 2022 Response of diamond detectors in ultra-high dose-per-pulse electron beams for dosimetry at FLASH radiotherapy *Phys. Med. Biol.* **67** 075002
Lansonneur P, Favaudon V, Heinrich S, Fouillade C, Verrelle P, De and Marzi L 2019 Simulation and experimental validation of a prototype electron beam linear accelerator for preclinical studies *Phys. Med.* **60** 50–7
Lin B, Gao F, Yang Y, Wu D, Zhang Y, Feng G, Dai T and Du X 2021 FLASH radiotherapy: history and future *Front. Oncol.* **11** 644400
Marcu L G, Bezak E, Peukert D D and Wilson P 2021 Translational research in FLASH radiotherapy—from radiobiological mechanisms to *in vivo* results *Biomedicines* **9** 181
Marinelli M *et al* 2022 Design, realization and characterization of a novel diamond detector prototype for FLASH radiotherapy dosimetry *Med. Phys.* **49** 1902–10
Marrale M *et al* 2022 Dosimetric characterization of an ultra-high dose rate beam for flash radiotherapy through alanine EPR dosimetry *Abstract at FLASH radiotherapy and particle therapy (FRPT) Conf. (30th November–2nd December 2022*
McManus M, Romano F, Lee N D, Farabolini W, Gilardi A, Royle G, Palmans H and Subiel A 2020 The challenge of ionisation chamber dosimetry in ultra-short pulsed high dose-rate very high energy electron beams *Sci. Rep.* **10** 9089
Moeckli R, Gonçalves Jorge P, Grilj V, Oesterle R, Cherbuin N, Bourhis J, Vozenin M C, Germond J F, Bochud F and Bailat C 2021 Commissioning of an ultra-high dose rate pulsed electron beam medical LINAC for FLASH RT preclinical animal experiments and future clinical human protocols *Med. Phys.* **48** 3134–42
Montay-Gruel P *et al* 2017 Irradiation in a flash: unique sparing of memory in mice after whole brain irradiation with dose rates above 100 Gy $s^{-1}$ *Radiother. Oncol.* **124** 365–9
Montay-Gruel P *et al* 2019 Long-term neurocognitive benefits of flash radiotherapy driven by reduced reactive oxygen species *Proc. Natl Acad. Sci. USA* **116** 10943–51
Oesterle R, Gonçalves Jorge P, Grilj V, Bourhis J, Vozenin M C, Germond J F, Bochud F, Bailat C and Moeckli R 2021 Implementation and validation of a beam-current transformer on a medical pulsed electron beam LINAC for FLASH-RT beam monitoring *J. Appl. Clin. Med. Phys.* **22** 165–71
Patriarca A *et al* 2018 Experimental set-up for FLASH proton irradiation of small animals using a clinical system *Int. J. Radiat. Oncol. Biol. Phys.* **102** 619–26
Petersson K, Jaccard M, Germond J F, Buchillier T, Bochud F, Bourhis J, Vozenin M C and Bailat C 2017 High dose-per-pulse electron beam dosimetry—a model to correct for the ion recombination in the advanced Markus ionization chamber *Med. Phys.* **44** 1157–67
Pimpinella M, Stravato A, Guerra A S, Marinelli M and Verona-Rinati G 2015 Monte Carlo calculation of beam quality correction factors for the PTW microDiamond in high energy photon and electron beams *Phys. Med.* **31** e53
Schüler E, Trovati S, King G, Lartey F, Rafat M, Villegas M, Praxel A J, Loo B W Jr and Maxim P G 2017 Experimental platform for ultra-high dose rate FLASH Irradiation of small animals using a clinical linear accelerator *Int. J. Radiat. Oncol. Biol. Phys.* **97** 195–203
Schüller A *et al* 2020 The european joint research project UHDpulse—metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates *Phys. Med.* **80** 134–50
Verona Rinati G *et al* 2022 Application of a novel diamond detector for commissioning of FLASH radiotherapy electron beams *Med. Phys.* **49** 5513–22
Vignati A, Giordanengo S, Fausti F, Martì Villarreal O A, Mas Milian F, Mazza G, Shakarami Z, Cirio R, Monaco V and Sacchi R 2020 Beam monitors for tomorrow: the challenges of electron and photon FLASH RT *Front. Phys.* **8** 375
Vozenin M C, Baumann M, Coppes R P and Bourhis J 2019a FLASH radiotherapy international workshop *Radiother. Oncol.* **139** 1–3
Vozenin M C, Hendry J H and Limoli C L 2019b Biological benefits of ultra-high dose rate FLASH radiotherapy: sleeping beauty awoken *Clin. Oncol.* **31** 407–15
Vozenin M C, Montay-Gruel P, Limoli C and Germond J F 2020 All irradiations that are ultra-high dose rate may not be FLASH: the critical importance of beam parameter characterization and *in vivo* validation of the FLASH effect *Radiat. Res.* **194** 571- 572
Wilson J D, Hammond E M, Higgins G S and Petersson K 2020 Ultra-high dose rate (FLASH) radiotherapy: silver bullet or fool's gold? *Front. Oncol.* **9** 1563