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# Comparative investigation of three dose rate meters for their viability in pulsed radiation fields

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## Abstract

Pulsed radiation fields, characterized by microsecond pulse duration and correspondingly high pulse dose rates, are increasingly used in therapeutic, diagnostic and research applications. Yet, dose rate meters which are used to monitor radiation protection areas or to inspect radiation shielding are mostly designed, characterized and tested for continuous fields and show severe deficiencies in highly pulsed fields. Despite general awareness of the problem, knowledge of the specific limitations of individual instruments is very limited, complicating reliable measurements. We present here the results of testing three commercial dose rate meters, the RamION ionization chamber, the LB 1236-H proportional counter and the 6150AD-b scintillation counter, for their response in pulsed radiation fields of varied pulse dose and duration. Of these three the RamION proved reliable, operating in a pulsed radiation field within its specifications, while the other two instruments were only able to measure very limited pulse doses and pulse dose rates reliably.

Keywords: pulsed radiation, dose rate meter, RamION, LB 1236-H10, 6150 AD-b

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Past technological developments have vastly increased the application of pulsed radiation, e.g. shifting external beam radiation therapy almost entirely from continuous <sup>60</sup>Co sources to inherently pulsed electron linear accelerators (LINAC). Meanwhile current efforts drive

towards even stronger pulsation, i.e. increased pulse dose and shorter pulses. Development of laser based accelerators is one such effort with applications ranging from possible lower cost, smaller footprint particle therapy facilities [1, 2], over high energy electron therapy options [3, 4] and pulsed diagnostic x-ray applications [5, 6], to investigating radio-biological mechanisms [7–9]. In addition, specific radiotherapeutic applications like respiration-gated irradiation of moving targets make higher pulse doses desirable [10] and the development of mobile LINACs has caused a resurgence in the interest in intraoperative radiation therapy bringing pulsed radiation sources into relatively unshielded operating rooms [11]. Existing and novel sources together spawn a variety of different pulsed radiation fields. Adequate radiation protection must be ensured for all these different sources and accurate measurement of this radiation is paramount to evaluating protection from it.

Many common detector systems are limited, however, in their ability to detect high dose rates. This problem is further exacerbated if the dose rate is compressed into short pulses. In particular detectors based on the counting of events suffer from dead time losses, which will become extreme if an entire radiation pulse falls into the dead time window. Especially for active personnel dosimeters such issues are widely discussed [12, 13], yet dose rate meters of similar design, irrespective if hand held or fixed mounted installations, are equally affected if exposed to strong, pulsed radiation fields [14].

The IEC 62743 TS [15, 16] has been developed as a response to form a basis for testing of electronic counting dosimeters in pulsed radiation fields. Prior standards considered only dosimetry in continuous radiation fields. The IEC 62743 TS is based around the idea that a single pulse should be accurately measured by the instrument, a very relevant case if accidental, intermittent exposure of personnel is to be detected with a dosimeter. Therefore, only pulses significantly longer than the instrument's dead time are considered therein and a maximum detectable pulse dose rate is established as one key parameter for an instrument, with the pulse dose rate being the dose in one radiation pulse divided by its duration. An estimation of this maximum pulse dose rate is also suggested based on the instruments dead time and calibration coefficient. The focus on pulse dose rate limits the applicability of the technical specification to find instruments qualified to measure fields with very short pulses, though. For instance, a laser based radiation sources has a pulse duration in the order of picoseconds and a clinically used LINAC a typical pulse duration of a few microseconds. Hardly any counting based detector exists with a dead time significantly shorter than those durations.

The principle shortcomings in the detection of pulsed radiation fields are long studied, for detectors suffering from dead time losses [17] as well as for instance the incomplete saturation in ionization chambers [18]. Nevertheless, evaluations of concrete instruments are scarce and practical predictions for the behaviour of a specific instrument are often difficult, because the necessary specifications are not readily available and the instruments response is sometimes obscured by poorly documented corrections applied to an instrument's readout. Therefore, we characterized 3 different dose rate meters in a pulsed, high energy, accelerator driven radiation field measuring the response for a variety of pulse structures by varying both pulse duration and pulse dose.

## 2. Materials and methods

### 2.1. Dose rate meters

Three commercially available hand held dose rate meters with different operating principles were investigated. The ionization chamber based RamION, manufactured by Rotem Industries, Rotem Industries Park, Israel, the LB 1236-H10 proportional counter probe combined with

**Table 1.** Properties of the dose rate meters used in the experiment.

Probe + readout	Dose rate range	Type	Diameter	Counting
RamION (integrated unit)	min: 1 $\mu\text{Sv h}^{-1}$ max: 500 $\text{mSv h}^{-1}$	ionization chamber	90 mm	no
LB 1236-H10 +LB 1230 UMo	min: 0.1 $\mu\text{Sv h}^{-1}$ max: 10 $\text{mSv h}^{-1}$	proportional counter	50 mm	yes
6150AD-b +6150AD	min: 0.1 $\mu\text{Sv h}^{-1}$ max: 0.1 $\text{mSv h}^{-1}$	organic scintillator	76 mm	no

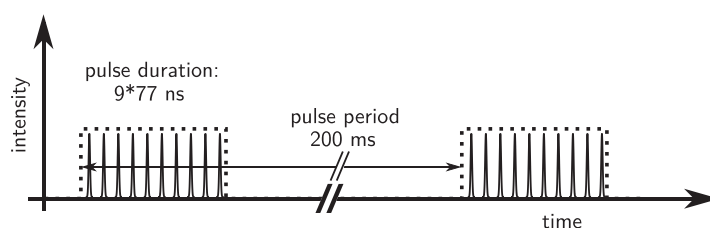
the LB 1230 UMo monitoring unit, manufactured by Berthold Technologies, Bad Wildbad, Germany, and the 6150AD-b scintillation counter combined with the 6150AD readout unit, manufactured by Automess—Automation und Messtechnik GmbH, Ladenburg, Germany. The instrument's properties, taken from their respective data sheets [19–21] are summarized in table 1. All three instruments came factory calibrated to ambient dose equivalent ( $H^*(10)$ ) based on  $^{137}\text{Cs}$  irradiation. Regarding the operational principles of the instruments, only the LB 1236-H10 is a counting detector. The RamION is a conventional integrating ionization chamber and the 6150AD-b is a scintillator with a photomultiplier tube (PMT) for readout. The PMT is operated at a constant voltage and readout with a charge sensitive amplifier. The signal from the amplifier is transformed into a frequency, before being transmitted from the probe to the readout unit (6150AD).

## 2.2. Radiation source

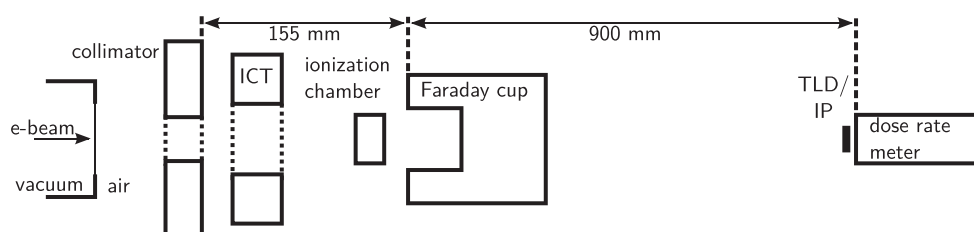
The instruments were investigated in two measurement campaigns at the superconducting linear electron accelerator ELBE (Electron Linac of high Brilliance and low Emittance) located at the Helmholtz-Zentrum Dresden-Rossendorf, Germany. In these experiments ELBE delivered an electron beam with an electron energy of 20 MeV in bunches (micro-pulses) of a maximum charge of 70 pC, a pulse duration of approximately 5 ps and a pulse repetition rate of 13 MHz [22]. At this repetition rate the resulting radiation field is in principle pulsed, but it can be viewed as quasi continuous in the context of these instruments, because the pulse period of 77 ns is much shorter than typical dead times of the detectors involved, which range in the order of at least a few  $\mu\text{s}$ . In order to obtain a beam that is pulsed in the context of these instruments the 'single-pulse-mode' of the accelerator was used. This operation mode superimposes a gating signal on the electron source and allows the delivery of macro-pulses containing a specified number of micro-pulses (between 1 and  $2^{31}$ ) with a period between 0.1 ms and 1000 ms. Furthermore, the bunch charge, which determines the dose per micro-pulse and is thus correlated to the macro-pulse dose, can be controlled at the accelerator in a wide range. Thus, macro-pulses of variable length, by varying the number of micro-pulses per macro-pulse, with an independently variable dose, by varying the bunch charge, can be obtained from ELBE. Because the rapid succession of micro-pulses at 13 MHz can be viewed as quasi continuous radiation the resulting macro-pulses have a square dose rate profile with a constant pulse dose rate as illustrated in figure 1.

## 2.3. Experimental setup

An illustration of the experimental setup is shown in figure 2. The setup was identical in the two measurement campaigns but a disassembly was required in the interim period. The



**Figure 1.** Illustration of one of the pulse patterns employed in the experiments, with a macro-pulse duration of  $9 \times 77 \text{ ns} = 693 \text{ ns}$  (10 micro-pulses) and a macro-pulse repetition rate of 5 Hz.



**Figure 2.** Non scaled illustration of the experimental setup. The electron beam exits the beamline through a thin vacuum window, passes through collimator, ICT and ionization chamber before being absorbed and converted to x-rays in the Faraday cup, which serve to irradiate the dose rate meters at a distance behind the Faraday cup.

electron beam exits the beamline vacuum through a  $100 \mu\text{m}$  beryllium window and is transversally limited by a collimator consisting of 15 mm aluminium followed by 15 mm lead, each with an opening of 10 mm in diameter. The collimated primary electron beam passes through an integrating current transformer (ICT) and an ionization chamber before being stopped in an aluminium Faraday cup. The x-ray radiation generated by completely stopping the electron beam in the Faraday cup is measured by the investigated dose rate meter at a distance of 900 mm behind the Faraday cup in direction of the original beam propagation. The investigated dose rate meters differ significantly in size, but all have a cylindrical shape, their diameters are given in table 1. In order to achieve a reproducible positioning the cylinders were aligned along and centred on the axis of the electron beam, with their front at the above mentioned distance from the Faraday cup. For reference measurements, thermoluminescence dosimeters (TLD) and imaging plates (IP) were placed directly in front of the dose rate meters.

The bremsstrahlung resulting from stopping the primary electron beam in the 130 mm long Faraday cup is very hard, due to hardening of the x-ray spectrum by passing through the entire length of the cup. Using a Monte Carlo simulation, the average photon energy of the spectrum was estimated at 4.8 MeV and the median energy as 3.4 MeV.

The ICT, a commercial unit ICT-CF4.5"/34.9-070-05 : 1-UHV from Bergoz Instrumentation, Saint-Genis-Pouilly, France, is a capacitive coupled toroid coil, that outputs a current pulse proportional to the bunch charge of the electron beam passing through it. Its signal was readout with a 2.5 GHz Digital Phosphor Oscilloscope (DPO 7254 from Tektronix, Köln, Germany). The ICT allows an evaluation of the relative charge of the individual electron bunches in a pulse train and is used to ensure a constant bunch charge and thus a constant micro-pulse dose within each pulse train. Hence, a constant pulse dose rate of the macro-pulses is ensured.

In order to judge the accuracy of the dose rate meter's response, reference measurements of the delivered dose must be taken. A relative online reference was obtained from the ionization

chamber and the Faraday cup. The ionization chamber was an advanced Markus chamber 34045 from PTW, Freiburg, Germany that was readout with an Unidos webline electrometer, also manufactured by PTW. The Faraday cup was a custom construction used in previous experiments [23] and was readout with the same oscilloscope as the ICT (DPO 7254). Both the ionization chamber and the Faraday cup provide a measure of the electron flux in the primary electron beam. This flux is directly proportional to the dose rate of the x-rays at the position of the investigated dose rate meters, because a constant electron energy was ensured by the accelerator.

#### 2.4. Reference measurements

Due to the time consuming procedure of the TLD measurement, the reference dose could not be determined with a TLD for each data point. Instead the TLD were used to establish a cross-calibration of the Markus ionization chamber, which measured the primary electron beam. The measurement from this ionization chamber was then recorded for each data point and used to calculate a reference x-ray dose at the position of the dose rate meters. TLD-100H chips (Thermo Fisher Scientific, Waltham, USA) were irradiated directly in front of the investigated dose rate meters to establish such cross-calibration of the ionization chamber. The TLDs were irradiated with a pulsed beam of 20 micro-pulses per macro-pulse at a repetition rate of 5 Hz. Varying numbers of macro-pulses (between 300 and 900) were applied to achieve different dose points. In addition, a set of TLDs was irradiated with a continuous beam for a fixed time of 60 s. The total charge freed in the ionization chamber was recorded for all these measurements. The dose rate independence of the response of TLDs was established in a previous publication [23]. The TLD chips were annealed for 30 min at a temperature of 240 °C prior to irradiation and read out with a commercial reader (Harshaw 3500, Thermo Fisher Scientific Waltham, USA). A time-temperature profile with a 10 s pre-heat at 135 °C and 23 s readout at 240 °C was employed. Prior to the experiment each TLD chip was individually calibrated using a 200 kV x-ray tube. To this end the dose to water delivered by the x-ray tube was determined with a Farmer-type ionization chamber (30010, PTW, Freiburg, Germany). Each chip was then irradiated at 5 dose points of 0.9 mGy, 3 mGy, 5 mGy, 50 mGy and 500 mGy. After each irradiation the chips were readout and annealed, the obtained response was used to establish the calibration curve for each chip. Additionally, to judge the spatial profile of the x-rays at the dose rate meter's position, an image plate (IP) of type BAS-MS (Fujifilm, Tokio, Japan) was irradiated there. The IP is a radiation detector based on optically stimulated luminescence (OSL) that allows a position sensitive extraction of dose information using a commercial scanner (BAS-1800II also from Fujifilm) [24].

#### 2.5. Measurement procedure

All dose rate meters were investigated for the dependence of their response on the two parameters pulse dose and pulse duration. In each measurement the dose rate meters were irradiated for 60 s to allow an adjustment of the internal logic before taking a reading. The single unit RamION could not be controlled remotely and was therefore read via a camera from the control room. For the other two dose rate meters the display unit was positioned in the control room while the probes were irradiated in the radiation protection cave. The 6150AD-b scintillator allowed for an internal averaging, which was used to read an average dose rate over 60 s. On the other dose rate meters (RamION and LB 1236-H10) an eye average from observing the rate meter for a few seconds was taken.

For the pulse dose investigation, the settings were aimed at pulses as short as possible. This models the most extreme case of pulsed radiation, when the pulse duration is so short that it is essentially seen as a delta-pulse by the instrument. The minimal possible pulse duration was a macro-pulse formed by a single micro-pulse. This pulse was applied with a repetition rate of 5 Hz onto the RamION and the 6150AD-b scintillator and with a repetition rate of 25 Hz onto the LB 1236-H10. The higher repetition rate for the LB 1236-H10 was chosen, because otherwise the instrument's response was barely distinguishable from the background. Varying the pulse dose, while keeping all other parameters constant was achieved by changing the bunch charge of the electron beam. The pulse dose in this approach was limited, though, by the maximum bunch charge deliverable by the accelerator. In order to overcome this limitation the measurement was extended to macro-pulses containing 10 and 50 micro-pulses at the maximum bunch charge for the measurement of the RamION. The resulting pulse duration of 693 ns for 10 micro-pulses and 3.8  $\mu$ s for 50 pulses can still be considered short with respect to the timescale of charge transport within the RamION.

In order to vary the pulse duration while keeping a constant pulse dose, an iterative process was performed. Going from short to longer pulses, the macro-pulse was elongated by adding more micro-pulses. This would have increased the dose per macro-pulse, unless the bunch charge was reduced. Therefore, the bunch charge was reduced until the ionization chamber measurement of the elongated pulse was the same as that of the previous, shorter pulse setting. Thus, pulses with increasing duration but constant dose were obtained. Varying the pulse duration in this way inherently yields a variation in pulse dose rate facilitating an estimation of the maximum measurable pulse dose rate. A similar approach was suggested as an alternative method by Zutz *et al* [15].

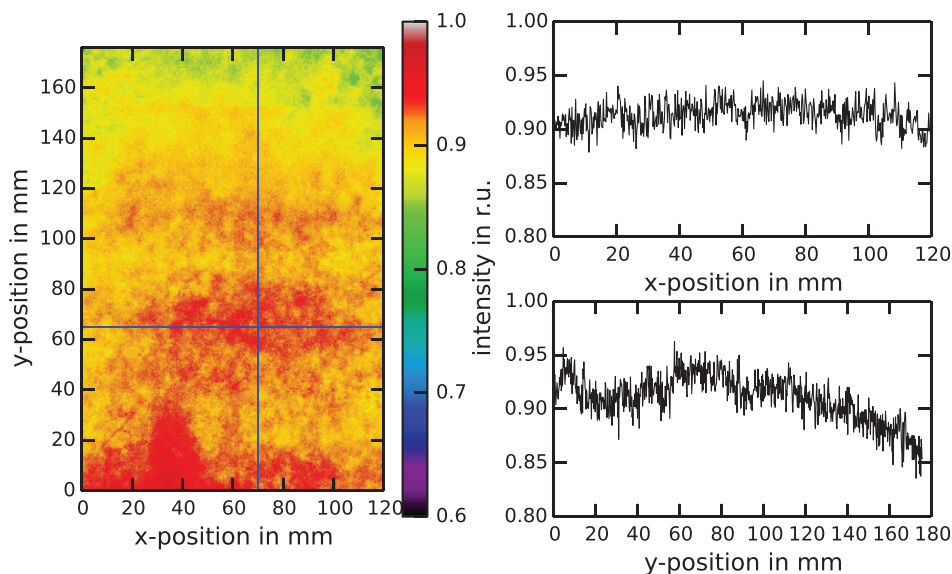
The before described procedure would ideally yield the same dose per pulse for each point in a measurement series of variable pulse duration, i.e. different pulse durations and identical pulse doses. Due to fluctuations in the electron beam this ideal cannot be achieved and slightly different pulse doses were applied. Nevertheless it is possible to correct these fluctuations using the Markus ionization chamber measurement, because the intensity of the primary electron beam and thus the corresponding x-ray pulse dose is proportional to the Markus ionization chamber measurement. Out of the measurements taken with variable pulse duration for each instrument a maximum pulse dose was determined ( $D_{\text{pulse}}^{\text{max}}$ ). The instrument's response at each pulse duration was then normalized by multiplying the response with  $D_{\text{pulse}}^{\text{max}}/D_{\text{pulse}}$ , where  $D_{\text{pulse}}$  is the pulse dose applied at that specific pulse duration setting. In order to emphasise this correction the corresponding data are labelled as a normed response.

### 3. Results and discussion

#### 3.1. Reference measurement

Figure 3 shows the IP measurement as a heat map, as well as profiles along both axes. As the relevant distance from the centre we consider the RamION's radius, because it is the largest of the three instruments with a diameter of 90 mm. The dose variation across this distance from the centre is less than 5%, so that the radiation field can be considered homogeneous and despite their different sizes the instruments should yield similar results.

For both measurement campaigns a calibration of the Markus ionization chamber against a series of TLDs was performed. Comparable charge measurements in the ionization chamber yielded comparable doses on the TLDs for the continuous and the pulsed beam setting

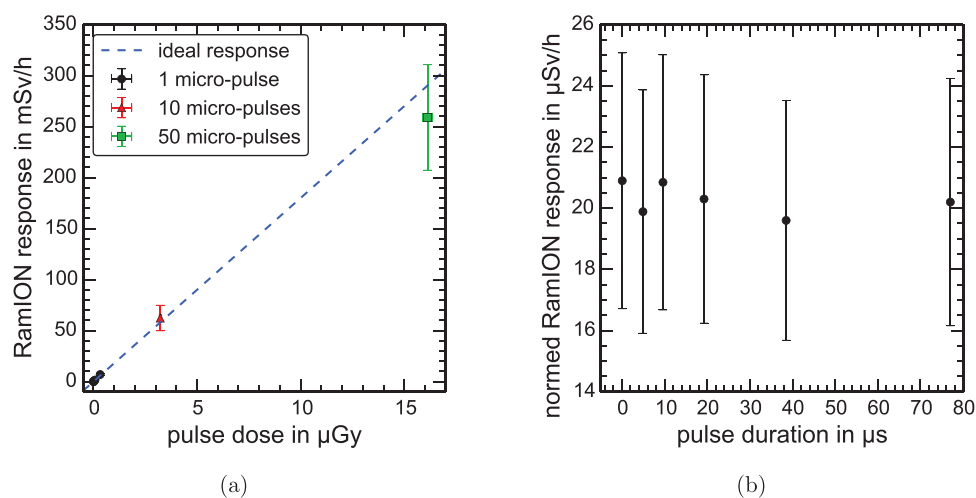


**Figure 3.** Heat map representation of the image plate readout (left). The cross marks the approximate position of the centre of the instruments. Profiles (right) along the cross's axes, parallel to the  $x$ -axis (top) and the  $y$ -axis (bottom) are also shown.

excluding effects of incomplete saturation in the ionization chamber. The calibration parameters resulting from a linear fit of the data are  $4.86 \pm 0.08 \mu\text{Gy nC}^{-1}$  for the first measurement campaign and  $4.78 \pm 0.17 \mu\text{Gy nC}^{-1}$  for the second. These values were used throughout the presented results to calculate the reference doses applied to the instruments from ionization chamber measurements. Despite stemming from different measurement campaigns, using different TLD chips, the two calibration values are identically within their uncertainty, which speaks to the reproducibility of the experimental setup and procedure.

### 3.2. RamION

The RamION's response to variously pulsed radiation is shown in figure 4, where figure 4(a) shows the instrument's response to irradiation with pulses of variable dose and figure 4(b) its response to pulses of varied duration. Due to the different bases for calibration of the instrument compared to the reference measurement (ambient dose equivalent compared to absorbed dose to water) the reference dose is given in Gy and the instrument's response is given in Sv. However, in the employed high energy photon field the two are numerically identical, which allows their comparison. The uncertainty of the RamION's measurement was taken as 20% of the measured value, which is the maximum energy dependence of the RamION's response per its specification. Up to a maximum applied pulse dose of  $16.5 \mu\text{Gy}$  the RamION measured the correct dose rate. Nevertheless an increasing discrepancy between reference and RamION measurement begins to show at the highest pulse dose applied where the instrument under responds while it over responded at all lower pulse doses, however, always staying within 20% of the reference dose rate (see figure 4(a)). Therefore, a further significant increase in pulse dose, e.g. by a factor of two would most likely yield a discrepancy in excess of 20%. One also has to consider, though, that a higher pulse dose would result in a higher dose rate provided



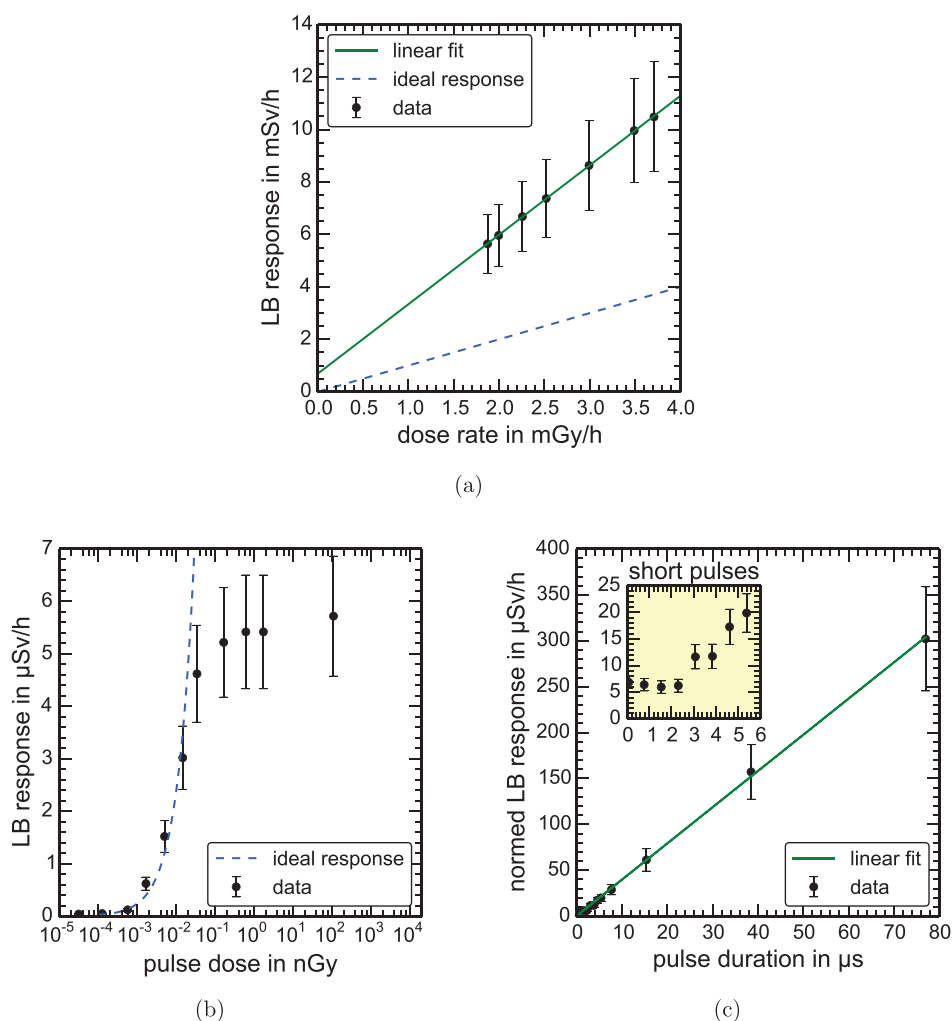
**Figure 4.** Measurement results of the RamION at a repetition rate of 5 Hz. (a) shows the response of the instrument to pulses with different doses. The ideal response would be the correct dose rate measurement at all pulse doses. (b) shows the response to pulses of variable length at a reference dose rate of  $17.3 \mu\text{Gy h}^{-1}$ . Error bars are 20% of the reading and represent the manufacturer specified maximum deviation between reading and actual dose.

the repetition rate is kept constant and thus would quickly exceed the instruments dose rate limit of  $500 \text{ mSv h}^{-1}$ . Establishing measurable pulse doses for radiation fields with an average dose rate beyond the instruments limits and also beyond a limit where a hand held device should be used seems redundant. This point is further underlined by the consideration that the chosen repetition rate of 5 Hz is rather low if compared with potential sources of pulsed radiation, such as, clinical LINACs ( $\sim 50 \text{ Hz}$ ) or a laser based particle accelerator (aimed for 10 Hz [25]). Considering those repetition rates and the above established pulse dose limits, it can be concluded that the RamION works properly within its specified dose rate limitations.

The investigation of the RamION's response to pulses of varied duration (figure 4(b)) was performed with a reference dose rate of  $17.3 \mu\text{Gy h}^{-1}$ . The instrument's response at any duration is within 20% of this reference dose rate. The systematic deviation from the reference is probably rooted in the difference in beam quality from TLD calibration to experiment. The RamION's response does not show any trend or significant change in dependence on the pulse duration. Without such a change no further conclusions on a pulse dose rate limit can be drawn.

### 3.3. LB 1236-H10

Figure 5 displays the measurement response of the LB 1236-H10 proportional counter to the various beam settings. In addition to the pulsed irradiation, the LB 1236-H10 was also irradiated with a continuous beam. The results displayed in figure 5(a) show an increased sensitivity of the LB 1236-H10 when compared with the reference measurement based on the TLD evaluation. Because this increased sensitivity is present under continuous irradiation, we assume that it is a characteristic independent of the pulsation of the beam. Most likely this is caused by using the instrument not according to its specification. The instrument is only calibrated for photon energies up to 1.3 MeV which most of the radiation field used here exceeds and its preferred orientation is perpendicular to the beam, where it was held parallel here in



**Figure 5.** Measurement results of the LB 1236-H10 proportional counter. (a) shows the response of the LB 1236-H10 under continuous irradiation in our setup. The evident over-response is analyzed with a fit on the continuous response and an ideal response to continuous irradiation is shown. (b) shows the response of the instrument to pulses with different doses applied at a repetition rate of 25 Hz. The ideal response would be the correct dose rate measurement at all pulse doses, the over-response under continuous irradiation is considered therein. (c) shows the response to pulses of variable length at a reference dose rate of  $16.5 \mu\text{Gy h}^{-1}$ . The linear fit allows the calculation of the maximum measurable pulse dose rate. Error bars are 20% of the reading and represent the manufacturer specified maximum deviation between reading and actual dose.

order to achieve better reproducibility. Nevertheless, the relative behaviour with respect to the radiation’s time structure, which is investigated here, should remain unchanged as long as the generally increased sensitivity is taken into account during evaluation. By linearly fitting the data in figure 5(a) we could quantify the increased sensitivity with a factor of  $2.65 \pm 0.02$ .

Figure 5(b) shows the LB 1236-H10 response to a variable pulse dose, applied at a repetition rate of 25 Hz. The ideal response, shown as a dashed line in the figure, incorporates the

above mentioned increased sensitivity of the LB 1236-H10. A saturation of the response is clearly visible at high pulse doses reaching a displayed value of  $5.5 \mu\text{Sv h}^{-1}$ . This value corresponds to a count rate of the instrument of 25.7 Hz, reflecting the repetition rate of 25 Hz with one count event per radiation pulse. Further increases in pulse dose only marginally raise the response, because no more than a single count event can be detected during the short duration of the pulse. Due to this saturation the instrument's response deviates by more than 20% from the reference at pulse doses of more than 14.8 pGy.

By making a few statistical consideration the expectation on a counting detector with dead time is easily explained. Here pulses shorter than the dead time of the detector are applied, so that the detector will at most measure one event per radiation pulse. On the other hand, the true number of ionization events per radiation pulse is Poisson distributed ( $P(k) = \frac{\lambda^k}{k!} e^{-\lambda}$ ) with an expectation value  $\lambda$ , where the true ionization and true count rate would be  $\dot{N} = \lambda \cdot f$  with the pulse repetition frequency  $f$ . The detector measures one event per pulse at most and counts one event whenever more than zero ionizations occur. The probability of one or more events occurring, according to a Poisson distribution is:

$$P(k > 0) = 1 - P(0) = 1 - e^{-\lambda}$$

Knowing the true count rate ( $\lambda \cdot f$ ) and the measured count rate ( $f(1 - e^{-\lambda})$ ), one can estimate when the two will differ by more than 20% in terms of average ionization events per radiation pulse ( $\lambda$ ):

$$(1 - e^{-\lambda}) \cdot f < 0.8 \cdot \lambda \cdot f$$

By expanding the exponential function in the second order of a Taylor series the inequality can be transformed to:

$$\lambda < 0.4$$

Meaning if the probability of detecting a radiation pulse exceeds  $1 - e^{-0.4} \approx 33\%$  the detector will under respond by more than 20%. The LB 1236-H10 has a calibration factor of  $G = 59.4 \text{ pSv/count}$ , i.e.  $\lambda = 1$  corresponds to a pulse dose of 59.44 pSv. The measured pulse dose of 14.8 pGy would thus correspond to 25% of the pulses being detected. Considering that also a radiation background is present, increasing the overall time the detector is dead, figure 5(b) shows a behaviour that would be expected from a counting detector with dead time.

Figure 5(c) shows the results of irradiating the LB 1236-H10 with pulses of variable duration at a repetition rate of 25 Hz and a dose rate of  $16.5 \mu\text{Gy h}^{-1}$ . In contrast to the RamION the constant dose rate is not correctly reflected in the instrument's measurement, instead a linear rise, and consequently, an increasing deviation with decreasing pulse duration is observed. For short pulse durations the dead time of the probe is clearly visible in the stepwise increase of the response at certain pulse durations (inset in figure 5(c)). The transition from the first to the second step occurs between  $2.31 \mu\text{s}$  and  $3.08 \mu\text{s}$  and from the second to the third between  $3.85 \mu\text{s}$  and  $4.62 \mu\text{s}$ , leading to an estimated dead time of  $2.4 \mu\text{s}$ . A dead time of this magnitude is typical for a proportional counter [26]. With increasing pulse duration the step-like response disappears, facilitated by the stochastic nature of the ionization events and an increasing effect of dead time corrections applied to the displayed response. Response and pulse duration then form a linear relation, which can be used to estimate the maximum pulse dose rate measurable by the LB 1236-H10. The slope of the linear rise  $a$  is the measured dose rate  $\dot{H}_{\text{meas}}$  per pulse duration  $t_{\text{pulse}}$ :  $a = \dot{H}_{\text{meas}}/t_{\text{pulse}}$ . The measured dose rate is the pulse dose rate  $\dot{H}_{\text{pulse-meas}}$  multiplied by the duty cycle. The duty cycle is simply pulse duration times repetition rate  $f$ , giving

the measured dose rate:  $\dot{H}_{\text{meas}} = \dot{H}_{\text{pulse-meas}} \cdot t_{\text{pulse}} \cdot f$ . Thus dividing the slope by the repetition rate gives the pulse dose rate:

$$\frac{a}{f} = \frac{\dot{H}_{\text{meas}}}{t_{\text{pulse}}} \frac{1}{f} = \frac{\dot{H}_{\text{pulse-meas}} \cdot t_{\text{pulse}} \cdot f}{t_{\text{pulse}}} \frac{1}{f} = \dot{H}_{\text{pulse-meas}}$$

Linearly fitting the data and dividing the resulting slope by the repetition rate of 25 Hz gives a dose rate measured by the LB 1236-H10 of  $158 \pm 2 \text{ mSv h}^{-1}$ . The IEC 62743 TS [16] suggests to calculate a maximum measurable pulse dose rate from the instruments parameters according to

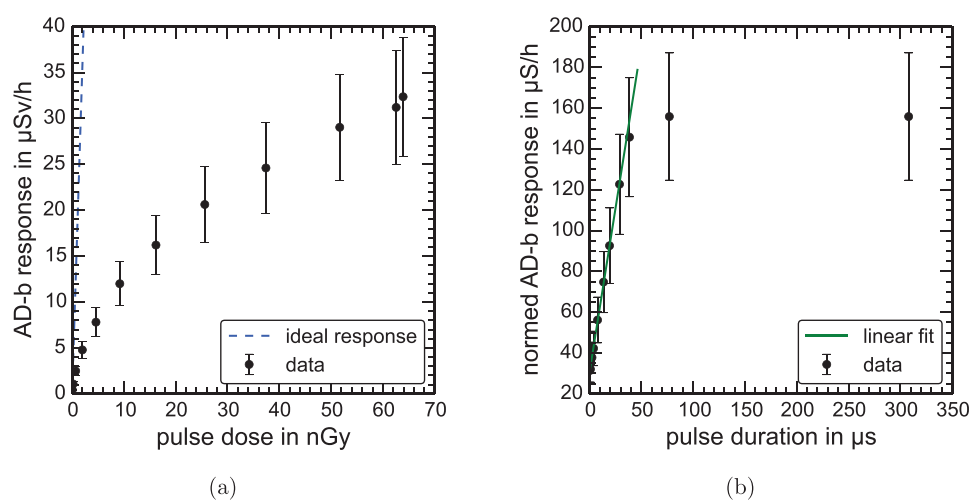
$$\dot{H}_{\text{pulse-max}} = \frac{0.25 \cdot G}{\tau_{\text{dead}}}$$

with a dead time  $\tau_{\text{dead}}$  of  $2.4 \mu\text{s}$  and a calibration coefficient  $G$  of  $59.4 \text{ pSv/count}$  taken from the LB 1236-H10 data sheet, this would yield a significantly lower maximum pulse dose rate of  $\dot{H}_{\text{pulse-max}} = 22.3 \text{ mSv h}^{-1}$ . The cause for the difference lies in the dead time correction of the instrument at high count and dose rates. The effect of the dead time correction can be seen by considering that the pulse dose rate of  $158 \text{ mSv h}^{-1}$  corresponds to a count rate of 738 Hz. This count rate in turn implies a dead time of less than  $1.4 \mu\text{s}$ , which is unrealistic, if compared to the  $2.4 \mu\text{s}$  actually observed. This does not imply that the IEC 62743 TS is overly cautious though, because if a single pulse were to be measured, which is the case the IEC 62743 TS is considering, the dead time correction would be much less efficient and the maximally measurable pulse dose rate would be less as well.

### 3.4. AD-b

Figure 6 shows the results for the 6150AD-b scintillator. Figure 6(a) displays the response to irradiation with pulses of variable dose at a repetition rate of 5 Hz, together with an ideal response. A clear saturation is visible and the instrument deviates by more than 20% from the reference already at the lowest pulse dose of 39 pGy. In contrast to the LB 1236-H10, however, the scintillator's response does not reach plateau. The most likely bottleneck in measuring such intense pulses with the 6150AD-b is the dynamic range of the PMT detecting the scintillation light. At very large signals the PMT amplification will cease to be linear as the charge avalanche essentially becomes too large to be further amplified by the PMT. Particularly, the 6150AD-b is designed to detect very low levels of radiation. Therefore, it is very possible that the PMT is saturated at the pulse dose of 39 pGy. This highlights a problem that is also present in counting detectors. As the sensitivity of an instrument is increased it becomes less suitable for pulsed applications, because the instrument is not well equipped to measure high loads, even if only applied for a very short time.

Figure 6(b) presents the instrument's normalized response to a varied pulse duration at a dose rate of  $1.3 \text{ mGy h}^{-1}$ . In contrast to the RamION and similar to the LB 1236-H10 the constant dose rate is not correctly measured by the instrument, instead a linear rise of the measured dose rate in dependence on the pulse duration is observable. In contrast to the LB 1236-H10 no clear dead time is visible and the linear rise of the measured dose rate is stopped at a maximum measured value of  $156.5 \mu\text{Sv h}^{-1}$ . With an upper dose rate limit of  $100 \mu\text{Sv h}^{-1}$  per its specification this is most likely the limit of the counting circuitry. Decay times of organic scintillators are typically in the order of nanoseconds [27] and thus much shorter than the investigated minimum pulse duration explaining the absence of an observable dead time. Evaluating the slope of the dose rate increase yields a maximum measurable pulse dose rate



**Figure 6.** Measurement results of the 6150AD-b scintillator. (a) shows the response of the instrument to pulses with different doses applied at a repetition rate of 5 Hz. The ideal response would be the correct dose rate measurement at all pulse doses. (b) shows the response to pulses of variable length at a reference dose rate of  $1.3 \text{ mGy h}^{-1}$ . The linear fit for pulse durations  $< 40 \mu\text{s}$  allows the calculation of the maximum measurable pulse dose rate. Error bars are 20% of the reading and represent the manufacturer specified maximum deviation between reading and actual dose.

of  $640 \pm 3 \text{ mSv h}^{-1}$ . While significantly higher than the measurable pulse dose rate of the LB 1236-H10, this is still significantly lower than the minimum of  $1 \text{ Sv h}^{-1}$  suggested by IEC 62743 TS.

#### 4. Conclusion

Three instruments were investigated in a pulsed radiation field and two, the RamION and the LB 1236-H10, performed as expected. The ionization chamber RamION correctly measured a field of repeated pulses with doses up to  $16.5 \mu\text{Sv}$  within an accuracy of 20%. The LB 1236-H10 on the other hand is useful only in pulsed fields of very limited pulse doses, a limitation inherent to any counting detector with a dead time. The third instrument, the 6150AD-b, performed worse than we had expected. The detection principle of a scintillator with a PMT should in principle be able to handle a pulsed field, because the entire energy deposited in the scintillator in a short pulse could be detected. Yet, this instrument was also very limited in the correctly detectable pulse doses. This is most likely a byproduct of the high sensitivity of the instrument. In general, very careful consideration should be given to the selection of an appropriate instrument for dosimetry of a pulsed field. The performance of simple ionization chambers and counting detectors can be estimated quite well, while estimating the performance of more elaborate detectors becomes increasingly difficult as more components are involved. The sensitivity of a detector can serve as a first indicator of its usefulness in a pulsed field. Less sensitive detectors are more likely to work well, as they are better suited to detect the short duration, high dose rates of a pulsed field. Special care should be taken with detectors with large ranges, if they apply automatic range switching. Unless manually set to a low sensitivity, short pulses will usually not correctly trigger an automatic shift and incorrect readings will be taken. Unless such care is taken, displayed values might deviate by orders of

magnitude from the actual ones although the displayed values are far from the instrument's limits (as seen in figure 5(c)). Some aspects of the IEC 62743 TS could be confirmed by us and it should provide a very useful guideline for the estimation of the usefulness of an instrument where appropriate. The most promising instrument in our survey though, the RamION, would not fall within the purview of the IEC 62743 TS, because at the physical detection level it is not based on a counting principle. Therefore, additional normative work is desirable to establish standards for other detection methods as well.

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## References

- [1] Ledingham K W D and Galster W 2010 Laser-driven particle and photon beams and some applications *New J. Phys.* **12** 045005
- [2] Daido H, Nishiuchi M and Pirozhkov A S 2012 Review of laser-driven ion sources and their applications *Rep. Prog. Phys.* **75** 056401
- [3] Fuchs T, Szymanowski H, Oelfke U, Glinec Y, Rechatin C, Faure J and Malka V 2009 Treatment planning for laser-accelerated very-high energy electrons *Phys. Med. Biol.* **54** 3315
- [4] Malka V, Faure J and Gauduel Y A 2010 Ultra-short electron beams based spatio-temporal radiation biology and radiotherapy *Mutat. Res./Rev. Mutat. Res.* **704** 142–51
- [5] Svanberg S 2001 Some applications of ultrashort laser pulses in biology and medicine *Meas. Sci. Technol.* **12** 1777
- [6] Malka V, Faure J, Gauduel Y A, Lefebvre E, Rousse A and Phuoc K T 2008 Principles and applications of compact laser-plasma accelerators *Nat. Phys.* **4** 447–53
- [7] Yogo A *et al* 2009 Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells *Appl. Phys. Lett.* **94** 181502
- [8] Kraft S D *et al* 2010 Dose-dependent biological damage of tumour cells by laser-accelerated proton beams *New J. Phys.* **12** 085003
- [9] Bin J *et al* 2012 A laser-driven nanosecond proton source for radiobiological studies *Appl. Phys. Lett.* **101** 243701
- [10] Matsuura T *et al* 2010 Apparent absence of a proton beam dose rate effect and possible differences in RBE between bragg peak and plateau *Med. Phys.* **37** 5376–81
- [11] Beddar S A, Biggs P J, Chang S, Ezzell G A, Faddegon B A, Hensley F W and Mills M D 2006 Intraoperative radiation therapy using mobile electron linear accelerators: report of AAPM radiation therapy committee task group no. 72 *Med. Phys.* **33** 1476–89
- [12] IAEA 2007 Intercomparison of personal dose equivalent measurements by active personal dosimeters—final report of a joint IAEA-EURADOS project *Technical Report IAEA-TECDOC-1564* (Vienna: International Atomic Energy Agency)
- [13] Clairand I *et al* 2008 Intercomparison of active personal dosimeters in interventional radiology *Radiat. Prot. Dosim.* **129** 340–5
- [14] Ankerhold U, Hupe O and Ambrosi July P 2009 Deficiencies of active electronic radiation protection dosimeters in pulsed fields *Radiat. Prot. Dosim.* **135** 149–53
- [15] Zutz H, Hupe O, Ambrosi P and Klammer J 2012 Determination of relevant parameters for the use of electronic dosimeters in pulsed fields of ionising radiation *Radiat. Prot. Dosim.* **151** 403–10

- [16] IEC 2012 Radiation protection instrumentation—electronic counting dosimeters for pulsed fields of ionizing radiation (IEC/TS 62743) (Geneva: The International Electrotechnical Commission)
- [17] Helbig K and Henniger J 2012 Dead-time losses in pulsed radiation fields *Radiat. Meas.* **47** 383–8
- [18] Boag J W 1950 Ionization measurements at very high intensities Part 1. Pulsed radiation beams *Br. J. Radiol.* **23** 601–11
- [19] Rotem Industries LTD 2014 *Technical data sheet: the RAM ION Monitor* [www.rotemi.co.il/ram\\_ion/](http://www.rotemi.co.il/ram_ion/)
- [20] Berthold Technologies GmbH and Co. KG 2007 *Technical Data Sheet: Dose Rate Probe LB 1236-H10* ([www.berthold.com/en/rp/lb-123-d-h10-dose-rate-monitor](http://www.berthold.com/en/rp/lb-123-d-h10-dose-rate-monitor))
- [21] Automation und Messtechnik GmbH 2011 *Technical data sheet: scintillator probe 6150AD-b (/H,/E)* [www.automess.de/6150AD-b\\_E.htm](http://www.automess.de/6150AD-b_E.htm)
- [22] Teichert J, Büchner A, Evtushenko P, Gabriel F, Lehnert U, Michel P and Voigtländer J 2003 Results of beam parameter measurement of the ELBE electron accelerator after commissioning *Nucl. Instrum. Methods Phys. Res. A* **507** 354–6
- [23] Karsch L, Beyreuther E, Burris-Mog T, Kraft S, Richter C, Zeil K and Pawelke J 2012 Dose rate dependence for different dosimeters and detectors: TLD, OSL, EBT films, and diamond detectors *Med. Phys.* **39** 2447–55
- [24] Zeil K, Kraft S D, Jochmann A, Kroll F, Jahr W, Schramm U, Karsch L, Pawelke J, Hidding B and Pretzler G 2010 Absolute response of fuji imaging plate detectors to picosecond-electron bunches *Rev. Sci. Instrum.* **81** 013307
- [25] Zeil K, Kraft S D, Bock S, Bussmann M, Cowan T E, Kluge T, Metzkes J, Richter T, Sauerbrey R and Schramm U 2010 The scaling of proton energies in ultrashort pulse laser plasma acceleration *New J. Phys.* **12** 045015
- [26] Hashimoto K, Ohya K and Yamane Y 1996 Dead-time measurement for radiation counters by variance-to-mean method *J. Nucl. Sci. Technol.* **33** 863–8
- [27] Sundaresan M K 2001 *Handbook of Particle Physics* (Boca Raton, FL: CRC)