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TESTING MEASURING DEVICES IN WELL-DEFINED PULSED RADIATION FIELDS

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Abstract. *There is a growing need for research, detector testing and metrological methods to study pulsed radiation fields because many facilities (e.g. high-power laser facilities) and devices produce pulsed ionizing radiation. Although the ELI ALPS laser facility is already operational in Hungary, the operational parameters (frequency of the laser shots, daily operational time of the laser, energy of the laser pulse and the number of the generated particles in the laser-matter interaction) are low, thus the generated pulsed radiation is negligible. Over the following ten years, the operational parameters will be drastically enhanced. In pulsed radiation fields, since the dose rate changes rapidly as a function of time, detectors in commonly used radiation protection measuring devices are not always able to track and accurately measure the dose nor the dose rate above a certain level of exposure. The general goal was to improve our knowledge of and capability to investigate as well as test measuring devices in well-defined pulsed fields to be able to give advice to users and the regulating Authority. The available X-ray source for this type of testing has its limitations, thus the additional goal was to develop a special device that can generate a well-defined pulsed radiation field, which can be adjustable and further developed. Preliminary tests were conducted using an X-ray device and continued with a self-developed Gamma chopper. A STEP OD-02 meter was used as a reference detector and the measurement results compared to the theoretical values. The created pulsed field by the Gamma chopper was known, the dose rate per angle was determined by its mechanical structure, these were the theoretical values. Ionization chambers and TLDs were tested in different pulsed radiation fields. The capabilities and properties of the generated pulsed radiation field as well as the stability of the Gamma chopper were tested. The results were similar to those in the literature, i.e. measuring devices tend to underestimate the dose and dose rate in pulsed radiation fields. The measurements recorded by the STEP OD-02 meter were in good agreement with the theoretical values. The tests highlighted that selection of the operation mode is crucial in order to accurately measure pulsed radiation fields with ionization chambers. Even though the Gamma chopper can be improved, its heeling effect (swaying, vibration of the rotating disk) was not identified. In the future, the capabilities of the Gamma chopper will be extended to increase its frequency and unshielded to shielded ratio, moreover, measurement procedures will be drawn up to test measuring devices in pulsed radiation fields when using it. Our test campaign was carried out with a precise series of measurements.*

Keywords: *EPD, Gamma chopper, Ionization chamber, Pulsed radiation field, Test measurement, TLD*

1. INTRODUCTION

Devices that generate ionizing radiation with a short pulse time are used more frequently in industry, healthcare and scientific research [1-7]. In Hungary, ELI ALPS - a high-power laser facility - is operational. The devices used in this facility create laser-driven pulsed fields of ionizing radiation that exhibit different properties compared to those from “stationary” sources [8]. Laser-based accelerator equipment operates in pulsed mode with a repetition frequency of 10-1000 Hz, whereby the laser light interacts with the target material and secondary pulsed ionizing radiation is generated. As a result of the ionizing radiation colliding with its (secondary) target and/or the surrounding material (shielding), tertiary radiation can also be generated in the form of electromagnetic and hadron cascades, which are also pulsed generating particles with different energy levels [8]. Although the pulsed radiation fields generated by ELI ALPS are negligible at present, in the upcoming years, the operational parameters will be enhanced by several orders of magnitude. The extrapolation based on measured values highlights that the photon dose from 1m of the irradiation chamber can reach the 6 mSv/J value at 10^{21} W/cm^2 irradiance value [8, Fig. 31]. The dose rate can reach 2.4 Sv/s in the vicinity of the irradiation chamber. (This is an extrapolated value for the High Field PetaWatt Solid High-order Harmonic Generation (HFPW-SHHG) beamline of ELI ALPS.) Its frequency will be 10 Hz and the laser energy will be 40 J/pulse.) Passive dosimetric detectors (TLDs) were placed in the vicinity of the irradiation chamber and some locations in the irradiation bunker were equipped with ionization chambers. The scattered-shielded pulsating particles can escape via openings such as through gaps in air conditioning wall breakthroughs at the top of the irradiation bunker (Fig. 1):

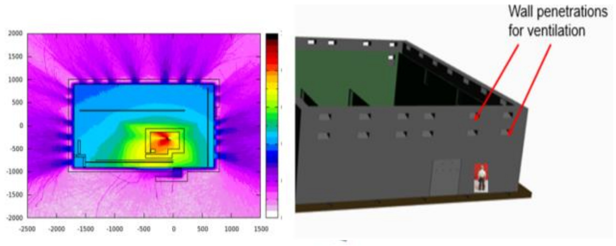

Figure 1. Simulation of the scattered-shielded pulsed radiation field outside the irradiation bunker (top view) - coloured band: the specific dose in [pSv/particle], left: 3D model of the irradiation bunker, the wall penetrations are shown (side view) right.

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Although the pulsed radiation fields outside the irradiation bunkers are measurable, they are modified by the shielding and cascade effects [8]. The particle fluence ("lifetime") can fall within the "ms" range according to our simulations at different points inside and outside of the irradiation bunker. The target dose constraint value for non-radiation workers is 0.5 mSv/year. The bunker wall and the additional shielding must be thick enough to satisfy this value. The estimated dose rate will be 5.8 μSv/h at normal operating conditions outside the bunker, it will increase to 57 mSv/h in case of the Design Basis Accident (DBA). These values fit into the measurable range of the FHT 192 ion chamber which is 100 nSv/h – 1 Sv/h [10].

Investigating which kind of detectors can be used for personal and area dosimetry in normal operations as well as in DBA cases is challenging. To test measuring devices, it is necessary to be familiar with the behaviour of pulsed radiation fields and know how measuring devices respond. During construction of ELI ALPS, no testing laboratory was dedicated to the investigation of pulsed radiation fields. The built-in ionization chambers (FHT 192) were delivered in a differential mode instead of an integrative one. During the preoperative phase, the ionization chambers unexpectedly detected single dose rate peaks when pulsed radiation fields were not generated at all. These false measurements caused the emergency protocol to shut down the laser sources. To avoid this, the operation mode of the ionization chambers was changed to an integrative mode. At the time, reliable references were not available to show how the changes affected the measuring capabilities of the devices.

2. PREVIOUS MEASUREMENTS IN PULSED RADIATION FIELDS

Given that accurately measuring the dose and dose rate in pulsed radiation fields is challenging for both the manufacturers and users of devices as well as organizations involved in licensing, this should be reviewed to maintain radiation safety [11-12]. Even though only technical specifications and articles regarding measurements in pulsed radiation fields are available, direct testing methods or standards are not approved yet by the Hungarian measurement office [13-20]. Much more consideration, e.g. with regard to the dead time, measurement mode and relaxation time, needs to be given to the selection of detectors to be used in a pulsed radiation field for measuring the dose and/or dose rate [4], [12]. Compared to stationary fields, it is more difficult to measure the dose or dose rate of the pulsed radiation field correctly in terms of remaining within derived safety dose limits determined by MC calculations [4]. Detectors operated in pulse mode can suffer of severe dead time losses during the radiation burst. The effect is the underestimation of the dose/dose rate.

3. METHODS OF MEASURING PULSED RADIATION FIELDS

3.1. Testing devices with an X-ray device

The behaviour of devices was first tested using an X-ray device. Since this device cannot be adjusted, the properties of the generated pulsed radiation field were limited, only nominal data were available. The X-ray beam widening at 150 cm was not known. The uncertainty of the pulse width and frequency of the X-ray device were not given. The STEP OD-02 meter [24] was used as a "reference" detector because it was delivered with a declaration of conformity whereby the manufacturer stated: "Short dose rate pulses (pulse duration < 500 ms) are therefore not detected or detected incorrectly". Test measurements were made with an XRS-3 portable X-ray source [22], the factory settings of which are as follows:

- Dose per pulse: 2.6-3.6 mR (23-32 μGy) 12 inches (30 cm) away from the source,
- Nominal pulse frequency: 15 Hz,
- Accelerating peak voltage: 270 kV,
- Pulse width: 20 ns.

Comparison tests of the following detectors (calibrated in a stationary field) were conducted in the same pulsed radiation field:

- Ionization chambers: STEP OD-02 [24], FHT 192
- TL dosimeters: PorTL (Al_2O_3) [25], TLD ($CaSO_4$:Dy) [26], MCP-N TLD (LiF: Mg, Cu, P) [27]

In general, the devices are authenticated, calibrated, and type tested under stationary dose field conditions. The Hungarian measurement office have approved test, calibration and authentication procedures only for stationary fields. The positions of the instruments (pulsed source and measurement devices) were the same in each test, Vibration and uniformity tests were performed for the Gamma chopper. All measurements of personal dosimeters were done without using the appropriate ISO slab phantom.

The range of photon energy dependence of various TLDs is wide [28]. The average energy and energy distribution of the X-ray device were not indicated in its operations manual, only its maximum value of 270 keV was given.

3.1.1. Comparison of the operation of the ionization chambers

The distance between the radiation source and the detectors was 150 cm in each case. The nominal average radiation dose from one pulse at this distance was calculated from the nominal source data using the approximation of the inverse squared radiation intensity decrease law around a point source with uniform flux distribution. Consequently, the calculated dose from 150 cm away is $H^*(10)= (1.74 \pm 0.25)$ μSv per pulse. The STEP OD-02 operated in the integrated mode, while the FHT 192 operated in the current mode as no integrated modes were available. This discrepancy between the two was eliminated in a subsequent test measurement once the initial measurements had been repeated in the integrated mode, having changed the firmware in the FHT 192 data acquisition unit. During the test measurements, the detector response and time-integrated dose rate were examined as a function of the number of pulses delivered in a "package". A package contains a series of pulses. The X-ray source device can deliver between 1 and 99 pulses in one run in one package. Packages were released at a frequency of 15 Hz.

3.1.2. Comparison of the ionization chambers and TLDs

The values measured by the ionization chambers were interpreted as the ambient dose equivalent $H^*(10)$. The tested TLDs were only calibrated for stationary fields at different particle energies. For doses measured by TLDs, the following considerations should be made, moreover, conversion factors and corrections are required to obtain results comparable to measurements with ionization chambers:

- Conversion factors of the air kerma into the ambient dose equivalent $H^*(10)$ for photons,
- Errors and uncertainties of calibration,
- Taking into account that infrared, near-UV blue light and microwaves can modify the values measured by a laser-driven particle accelerator.

The TLD was positioned 150 cm from the X-ray source at the same height. How much the X-ray beam widened at a distance of 150 cm from the source was unknown as it was not given in the datasheet of the X-ray device. During each irradiation, only one TLD was used, moreover, the distance, height and duration were constant. Every TLD was placed at the same position at the assumed center point of the beam.

3.2. The Gamma chopper and dosimetry tests

The Gamma chopper was devised by experts at EK (Centre for Energy Research) to generate pulses with gamma, X-ray or neutron (with appropriately redesigned attenuation) sources by a special collimator made with a rotating disk placed in the path of a beam. Radioactive sources emitting intensive gamma radiation (e.g. ^{137}Cs or ^{60}Co) can be installed in the equipment. A 6.2 GBq activity Cs-137 source was used in the test presented here. Since the energy of the gamma radiation was 0.661 MeV, the shielding was thick and heavy, so an unusual and novel design of the collimator had to be chosen for the disk to cope with the mechanical chopping. Regarding the shape of the tunnel inside the collimator in time of the pulse, it is crucial that it has a double funnel design as shown in Figure 2. Due to the symmetrical design of the tunnel inside the collimator, the disk is balanced meaning the strength of the bearing does not need to be particularly strong. Since the position of the center of mass of the rotating disk coincides with the axis of rotation, the equipment is stable and the degree of vibration negligible (Fig. 2).

With a variety of designs of the disk and tunnel around the collimator as well as different mechanical components, this equipment could be implemented over a wide range of pulse widths, pulse frequencies and pulse peak dose rates. The field consists of repeated pulses. The measured time average of the pulsed radiation field may be, among other parameters, indicative of the correct behaviour of the detectors. By taking static or quasi-static measurements of the rotating disk and collimator, a theoretical time average of the dose rate can be calculated from the actual time-dependent dose rates of the pulses. In this sense, the dose rate is considered to be a quasi-stationary radiation condition. In practice, the average dose rate recorded by each detector is given by the gradient of the line fitted to the dose accumulation and time data pairs. An assessment of the measuring capability of each detector may determine how close this measured average value is to the theoretical time average or that of a standard measuring device. Two measuring devices were compared to the EPD Mk2+ [29] personal dosimeter, namely a TruDose electronic [30] personal dosimeter and the ambient dosimeter in the STEP OD-02 ionization chamber. The experiments focused on dose accumulation from which the average dose rate was calculated. The measuring points are defined by the distance from the source and the range of the tested mean dose rate fell within approximately 1 order of magnitude. Based on the adjusted rotational speed (627 rpm), the pulse frequency was 21 Hz and the pulse length (duration) 2.1 ms. The attenuation coefficient of the rotary disk was larger than 1:1000 at a radiation energy of 661 keV, meaning that the difference in the dose rate in the pulse between the baseline and peak (plateau) can exceed three orders of magnitude.

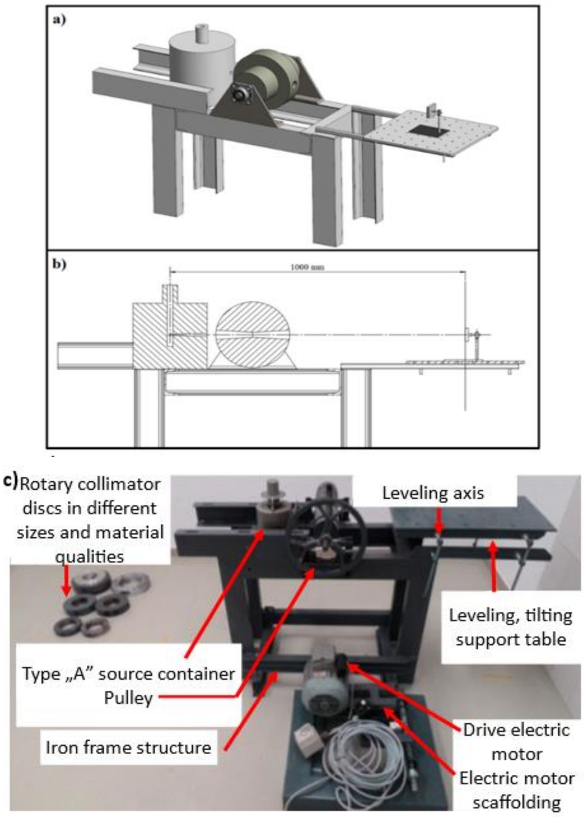

Figure 2. Three-dimensional (a) and sectional technical (b) drawings of the schematic diagram concerning the measurement arrangement and an explanation of the parts (c) found in the "Gamma chopper".

4. RESULTS AND DISCUSSION

4.1. Measurement results of the ionization chambers in the pulsed radiation field generated by the X-ray device

Since it was observed that the FHT 192 ionization chamber in pulse mode (i.e. dose rate mode) wrongly measured the dose rates for highly pulsed radiation fields, the ionizing chamber was used in its integrative mode. Therefore, the fundamental problem concerning the measurement of pulsed radiation was demonstrated by the first measurement using the FHT 192 in pulse mode. The specific data, which accurately approximate the values obtained by fitting, are 1.20 and 0.31 μSv/pulse for the STEP OD-02 and FHT 192, respectively.

The next series of measurements were made with the FHT 192 ionization chamber in its integrative mode. After replacing the firmware of the data acquisition unit in the FHT 192, the device was able to measure in its integrative mode, thereby avoiding charge/signal loss. The measurement results of the integrated dose of pulses in the packages on a double logarithmic scale for both ionization chambers (after replacing the firmware of the FHT 192) are similar (Fig. 3). According to the gradient of the fitted lines, the ratios of doses per pulse are 1.16 and 1.33 µSv/pulse for the STEP OD-02 and FHT 192, respectively. The standard deviation/mean in % was 10.3 for the STEP OD-02 and 9.2 for the FHT 192. The points and fitted lines are apparently closer to each other.

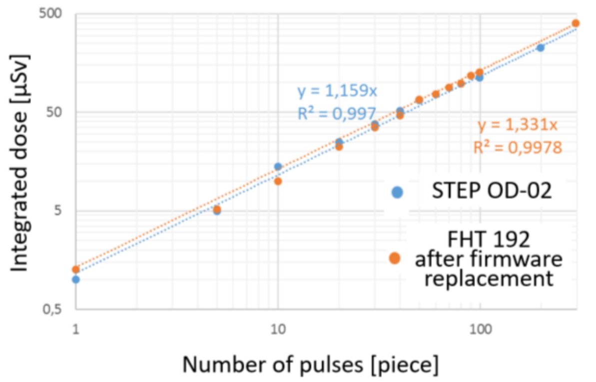

Figure 3. The dependence of the integrated dose on the numbers of pulses after adjusting the electronic mode by replacing the firmware of the FHT 192.

Based on the results measured in different operation modes of the FHT 192, it can be seen how important and necessary investigating the detectors in pulsed radiation fields is [13].

4.2. Comparison of the ionization chambers and TLDs with regard to the results of the pulsed radiation field generated by the X-ray device

The measurement results were fitted for an integrated dose of pulses (the nominal value for one package was 15 pulses/sec) on a double logarithmic scale for the FHT 192 ionization chamber and MCP-N dosemeter (Fig. 4). The fitted zero-zero lines yielded the dose per pulse for several measurements as 1.33 and 0.53 µSv/pulse for the FHT 192 and TLDs, respectively. The standard deviation/mean in % is 11.1 for the STEP OD-02 and 58.8 for the FHT 192. Although the measured values of the TLDs also illustrate the expected linearity, the gradients are different. The measurement points are single measurement and have no standard deviation (Fig. 3., 4.).

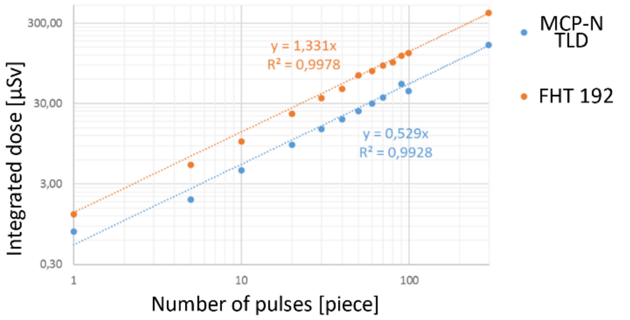

Figure 4. FHT 192 ionization chamber vs. MCP-N-type TLDs.

The dose per pulse for multiple measurements can also be obtained by averaging, i.e. by dividing the doses of each packaged measurement by their numbers of pulses. The data are a good approximation of the data obtained by fitting, that is, 0.50 and 1.22 µSv/pulse for the MCP-N TLDs and FHT 192, moreover, the relative standard deviations are 19.2 and 9.2 %, respectively. The difference between the two types of detectors is larger, even compared to the standard deviations. For MCP-N TLDs, although the values of the means and relative standard deviations show that the basic integrative mode of the TLDs can yield precise data concerning the presumably constant pulse doses, the values seemed to be systematically different to those yielded by the FHT 192. The agreement between TLDs and ionization chamber is very much depending on their specifications, the types of TLD and the performance and specs of the ionization chamber. Ginzburg observed a good level of agreement (standard deviation of <10 %) between the TLDs and ionization chamber survey meters [31]. Ankerhold found that accurate measurements were made by passive TLDs in a pulsed radiation field [13]. The $H_p(10)$ relative response of the passive detector was 0.78. As in accordance with previous observations [1] [12-13], the APD (Active Personal Dosimeter) responds insufficiently in pulsed radiation fields. The $H_p(10)$ relative responses of the active detectors were 0.05, 0.01, 0.51 and 0.02, respectively. The observed difference between the device and TLDs can most likely be attributed to the difference in energy dependence.

A summary of the integrated dose per pulse including the values derived from the nominal data and their nominal uncertainty as well as the means and standard deviations of the values measured by each detector is presented in Fig. 5:

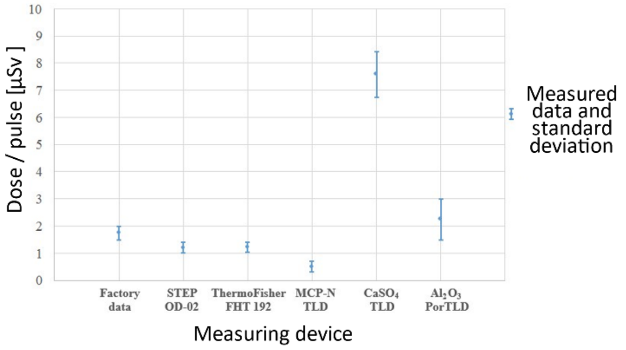

Figure 5. Doses per pulse recorded by different detectors 150 cm away.

Although measurements in the ionization chamber agree with each other and are similar to the nominal data, the data from the different TLDs are approximately the same but somewhat inconsistent. The values of the TLD using $CaSO_4$ were about four times higher than the nominal data and those of the one using Al_2O_3 were also higher. The results are in good agreement with the literature. The $CaSO_4$ and Al_2O_3 detectors are more sensitive at lower (<100 keV) energies which is indicative of higher values, that is, they do not fully meet the requirement of tissue-equivalent response in this region in the absence of an appropriate covering layer for selective attenuation. It should be noted that the energy distribution of the X-ray source was not stated in its operational manual.

The results highlighted how challenging it is for all detectors and laboratories to distinguish between the effects of pulsation and particle energies of an unknown field. The energy response function, which is related to the sensitivity, of the different TLDs can vary. Known gamma rays and X-ray spectra can be calibrated. Such adjustments are complex, potentially yielding biased results for the unknown spectra of pulsed radiation fields. Future research will hopefully find a good match between the photon energies of the pulsed radiation fields and the calibration fields. TLD-measured values were suitable according to test measurements in a pulsed radiation field [31], the deviation between the reference passive dosimeter and TLDs was approximately 10 %. The $H_\mathrm{p}(10)$ relative response of the passive detector was 0.74 [13].

4.3. Measurement results using the Gamma chopper

Dose accumulation was recorded with simultaneously recorded time data. The gradient of the line fitted to the dose-time data yields the real average dose rate. Uncertainties are the standard deviation of the measured data recorded by the detectors and their positioning (k = 2) (Fig. 6). A suitable build-up plate for ensuring charged particle equilibrium was not used.

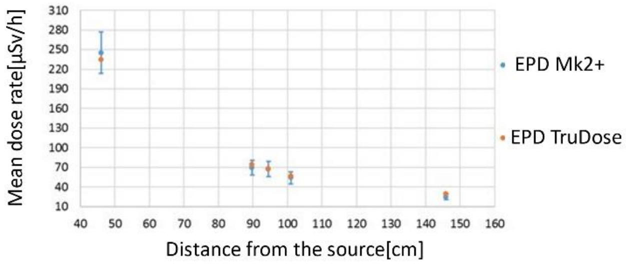

Figure 6. Comparative measurement results of EPD Mk2+ and EPD TruDose in terms of the averaged dose rate of the repetitively pulsed radiation field. The dose decrease should roughly follow the $1/r^2$ law.

The measured results of the EPD Mk2+ detector were compared to those of the reference standard device (STEP OD-02) as a function of the change in the time characteristics of the pulsed radiation field (Fig. 7). The measured points, ranging over four orders of magnitude, are defined by the adjusted rotational speed of the disk from which the pulse width and frequency are calculated. When adjusting the distance from the source, a measuring point producing slightly more than a peak dose rate of 1 mSv/h was chosen. At that point the pulsed beam size is 20% higher then, the TruDose EPD size. Here, the baseline level was below 1 µSv/h, i.e. the dose rate jumped more than three orders of magnitude during the pulse. Dose accumulation was recorded simultaneously with time data. The gradient of the line fitted to the dose-time data pairs yielded the real average dose rate which was normalized with data of the longest pulse width as the closest approximation under continuous irradiation conditions, i.e. the last data point is 1.00 by definition. Due to the size of the STEP OD-02 ionization chamber, the field "seen" in space is different. The STEP OD-02 measures the $H^*(10)$ dose, while the EPD Mk2+ measures the $H_\mathrm{p}(10)$ dose values pertinent to a human-like phantom standard. In this sense, a relative examination is carried out instead of an absolute one. The indicated uncertainties were calculated only from the extended uncertainties (error bars were set at a confidence level of 97.7 %, k = 2) of the gradient fitted to the measured dose and time data. The ratio of the averaged dose rate is examined as a time characteristic of a repetitively pulsed radiation field.

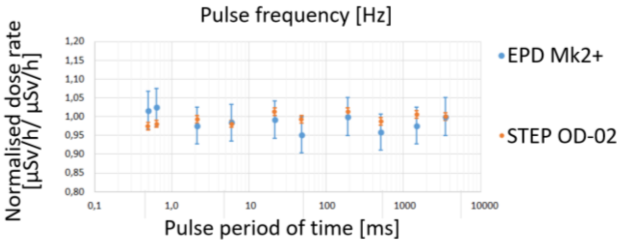

Figure 7. Comparative measurement results of the Thermo Fisher Scientific EPD Mk2+-type electronic personal dosimeter and the STEP OD-02 ionization chamber.

Based on these test results, the counter-type EPD Mk2+ dosimeter does not exhibit a deficit under pulsating conditions. The generated pulsed radiation field did not overload the EPD Mk2+. Overloaded EPDs have been reported to underestimate the dose [2] [7] [12] [20-21] [28] [32]. The pulsed radiation field can be sufficient to model the scattered beam field of a direct beam from a pulsed radiation X-ray device. During the tests, the Gamma chopper and the generated pulsed γ beam were stable, moreover, the degree of vibration was negligible. The Gamma chopper did not produce a heel effect as has been reported elsewhere [6]. The dose rate of the pulse generated by the Gamma chopper was too low to overload the EPD. The observed overload value was >3 Sv/h [15] [22].

5. CONCLUSIONS

Facilities producing pulsed ionizing radiation are becoming more and more widespread in industry, healthcare and research. Not all traditional and new measuring devices can accurately measure pulsed radiation fields and not all techniques are suitable for doing so. A metrological examination of the interaction between the pulsed radiation fields and the detectors is required to achieve regulatory approval, which necessitates that the pulsed radiation field be adjustable over a wide range in many ways, namely single or repetitive pulses as well as low or high frequencies, photon energies in addition to small and large changes in the dose rate in a pulse.

Different measuring devices were tested in well-defined pulsed radiation fields. First, a pulsed X-ray source was used but its degree of accessibility and adjustability was limited, moreover, some relevant parameters of the generated pulsed radiation field were not well-known. The STEP OD-02 and FHT 192 ionization chambers as well as different TLDs were tested using this X-ray source, highlighting that the FHT 192 ionization chamber must be operated in an integrative mode if a pulsed radiation field is likely to persist. After the mode was changed from the pulse mode to the integrative mode, the results were in good agreement with those in the STEP OD-02. Not all of the TLDs measured accurately in the pulsed radiation field in that experiment since the calibration and sensitivity of them varied. In mixed pulsed radiation fields, it is challenging to accurately measure the dose because of the degree of complexity.

The well-defined pulsed radiation fields generated by the Gamma chopper EPDs and the STEP OD-02 device were tested. No significant differences between the measured values were observed. In the future, the capabilities of the Gamma chopper will hopefully be extended to increase the frequency and the unshielded to shielded ratio as well as improve the chopper to produce a pulsed neutron field using a neutron source. To achieve these goals, it is planned to use higher GBq and TBq range activity sources, however, better radiation shielding, and authority approval are needed, and the device have to be strengthened to handle the higher weight of the shielding as well.

The well-defined pulsed radiation fields used were intended to resemble the generated pulsed radiation fields outside the irradiation bunkers of ELI ALPS in terms of their frequency, pulse duration and plateau/background ratio. The results highlighted that the $CaSO_4$ and PorTl Al_2O_3 detectors are very sensitive at lower energies, even detecting pulsed radiation fields outside of the bunkers. The generated pulsed radiation field using the gamma chopper was stable and uniform at the measurement distance and as well as sufficiently large for the tested detectors. Furthermore, the chopper can also produce a pulsed neutron field using a neutron source. Although the generated fields (X-ray & γ sources) applied were not mixed, mixed fields are present with electromagnetic pulses (EMPs) at ELI ALPS, so accessible areas should be shielded against EMPs. After several irradiations when neutrons or high-energy protons are generated, the material of the detector can be activated causing higher background measurements inside the bunker. Outside of the bunker, the radiation protection measuring devices will be able to accurately measure pulsed radiation fields inside the bunkers as well if need be.

Limitations: A new operational licence must be requested for GBq - TBq range sources. The necessary shielding and bigger rotating disc shielding must be designed. The stability of the Gamma chopper must extend to handle the high weight of the extra shielding; an additional vibration test is needed. The uniformity of the chopped gamma beam must be confirmed for the higher activity. The electricity of the building must be extended for three-phase current to increase the power of the driving electric engine.

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