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A TLD-based ten channel system for the spectrometry of bremsstrahlung generated by laser-matter interaction

Felix Horst [a,b,*], Georg Fehrenbacher [a], Torsten Radon [a], Ekaterina Kozlova [a], Olga Rosmej [a], Damian Czarnecki [b], Oliver Schrenk [b], Joachim Breckow [b], Klemens Zink [b,c]

[a] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany
[b] Institut für Medizinische Physik und Strahlenschutz, Technische Hochschule Mittelhessen, Wiesenstr. 14, 35390 Gießen, Germany
[c] Universitätsklinikum Gießen und Marburg GmbH, Baldingerstr., 35043 Marburg, Germany

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ABSTRACT

This work presents a thermoluminescence dosimetry based method for the measurement of bremsstrahlung spectra in the energy range from 30 keV to 100 MeV, resolved in ten different energy intervals and for the photon ambient dosimetry in ultrashort pulsed radiation fields as e.g. generated during operation of the PHELIX laser at the GSI Helmholtzzentrum für Schwerionenforschung. The method is a routine-oriented development by application of a multi-filter technique. The data analysis takes around 1 h. The spectral information is obtained by the unfolding of the response of ten thermoluminescence dosimeters with absorbers of different materials and thicknesses arranged as a stack each with a different response function to photon radiation. These response functions were simulated by the use of the Monte Carlo code FLUKA. An algorithm was developed to unfold bremsstrahlung spectra from the readings of the ten dosimeters. The method has been validated by measurements at a clinical electron linear accelerator (6 MV and 18 MV bremsstrahlung). First measurements at the PHELIX laser system were carried out in December 2013 and January 2014. Spectra with photon energies up to 10 MeV and mean energies up to 420 keV were observed at laser-intensities around 10^{19} W/cm^2 on a titanium foil target. The measurement results imply that the steel walls of the target chamber might be an additional bright x-ray source.

1. Introduction

Today high power laser systems may reach peak intensities up to 10^{22} W/cm^2 on the target at sub-picosecond pulse durations. The resulting relativistic laser-plasma interaction leads to the directed acceleration of electrons and ions up to GeV energies [1,2]. Especially the accelerated electrons generate bremsstrahlung in the target and in the surrounding materials, e.g. the steel walls of the target chamber. These effects lead to ultrashort x-ray pulses in the same time scale as the laser pulse during the shots of high power lasers. These x-ray pulses determine the need for radiation protection during the operation of such laser systems. As a result of the sub-picosecond time scale of the laser pulses, an active measurement of x-ray spectra under these conditions is quite difficult to implement. For that reason passive ionizing radiation detectors, such as thermoluminescence dosimeters (TLDs) or image plates are usually applied for the diagnostics in high intensity laser experiments.

This work presents a TLD-based method for the measurement of bremsstrahlung spectra in ultrashort-pulsed radiation fields. Ten TLD cards (Harshaw TLD-700H) are placed into a stack of absorbers, made of various materials and thicknesses, surrounded by a shielding. The response functions of the ten TLD's to parallel monoenergetic photon and electron radiation were simulated by the use of the Monte Carlo code FLUKA [3,4]. The photon response was verified by irradiation of the prototype with radioactive sources (^{137}Cs and ^{60}Co). The different gradients and thresholds of these response functions allow the reconstruction (unfolding) of photon spectra from the readings of the ten TLD's. An algorithm for the purpose of unfolding bremsstrahlung spectra in the range of 30 keV to 100 MeV, resolved in 10 different energy bins, was developed (written in SCILAB [5]). The method is a further development of a work from Behrens et al. [6] and has been validated at a clinical electron-linac (Elekta Synergy: 6 and 18 MV bremsstrahlung) by comparing spectra measured by the developed method with spectra obtained by detailed Monte Carlo simulations (Monte Carlo code: EGSnrc [7]) of the linac. A prototype has been built and first applied at PHELIX (**P**etawatt **H**igh **E**nergy **L**aser for Heavy **I**on E**X**periments) at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany during beamtimes in December

* Corresponding author. Present address: Institut für Medizinische Physik und Strahlenschutz, Technische Hochschule Mittelhessen, Wiesenstr. 14, 35390 Gießen, Germany. Tel.: +49 641 3092642.
E-mail address: felix.ernst.horst@kmub.thm.de (F. Horst).

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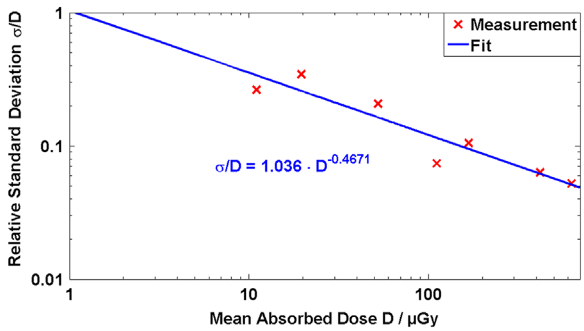

Fig. 1. Relative standard deviation σ/D of the readings from the single LiF-crystals in the Harshaw TLD-700 H cards as a function of the mean applicated dose D.

2013 [8] and January 2014. This paper presents the method of measurement, the principle of the unfolding-algorithm, the comparison of the results from the spectrometry measurements at the electron linac with the reference spectra from Monte Carlo simulations and the results from the measurements at PHELIX.

2. Methods and materials

Harshaw TLD-700 H: In this work Harshaw TLD-700 H cards each with four LiF-crystals are used for the measurement of the spectral distribution of the x-rays. The tolerance of this material against high dose rates is experimentally verified for dose rates up to 10^9 Gy/s = 1 mGy/ps [9].

The statistical uncertainty of the readings of these TLD cards relative to the mean dose as a function of the mean dose has been experimentally determined by measurements at a ^{137}Cs source with varied durations of the irradiation of 25 TLD cards. This dependence is shown in Fig. 1. It shows that doses of at least 10 µGy are needed for reliable readings (uncertainty of single LiF-crystal below 40%).

Principles of the measurement method: The presented spectrometry method is based on the idea, that the spectral information of a photon radiation field can be obtained by some dosimeters being specifically attenuated by absorbers of different materials and thicknesses. The readings of those dosimeters are then processed by a so called unfolding-algorithm which calculates the photon spectrum to the dose values measured by the dosimeters approximately by the use of the simulated response functions of the single dosimeters.

The dose which is measured by a dosimeter (channel) in a radiation field with the spectral fluence $\Phi_E(E)$ is given by

$$D_i = \int_0^\infty \Phi_E(E) \cdot R_i(E)\, \mathrm{d}E \tag{1}$$

with the dose D on dosimeter-channel i, the energy E and the energy dependent response $R(E)$ of dosimeter-channel i.

The approximate dose values for 10 energy intervals with different interval widths ΔE can be calculated by

$$D_i^{calc} \approx \sum_{j=1}^{10} \Phi_E^j \cdot R_{i,j} \cdot \Delta E_j \tag{2}$$

with the average response $R_{i,j}$ of channel i over the energy interval ΔE_j. In this work the approximation that $R_{i,j}$ is equal to R_i for monoenergetic radiation of the center $\overline{E_j}$ of the energy interval ΔE_j (average fluence Φ_E^j) is assumed.

The spectrum cannot be derived from the dose values by an analytical calculation (inverse problem). This calculation has to be performed iteratively by an unfolding-algorithm. The task of the unfolding-algorithm is to find a spectral fluence configuration Φ_E^j according to E. (2) as precise as possible. The response matrix $R_{i,j}$ is unknown, it can be obtained by e.g. Monte Carlo simulations.

The $\mathcal{X}^2$-value is a measure for the quality of the approximation of the calculated dose values D_i^{calc} to the measured dose values D_i^{meas}. The $\mathcal{X}^2$-value is calculated by

$$\mathcal{X}^2 = \frac{1}{10} \cdot \sum_{i=1}^{10} \frac{(D_i^{meas} - D_i^{calc})^2}{(\Delta D_i^{meas})^2} \tag{3}$$

The closer the $\mathcal{X}^2$-value is on 1, the better is the approximation. The uncertainty ΔD_i^{meas} of the readings D_i^{meas} of the dosimeters depends on the mean dose. The relative standard deviation can be obtained from the fit function in Fig. 1. The statistical uncertainty from the single LiF crystal is divided by $\sqrt{n} = \sqrt{4}$ (standard deviation of the mean) when it is averaged over the four single readings from the TLD cards (Harshaw TLD-700H).

TLD-spectrometer: The spectrometer prototype presented in this work has a cylindrical shape with a default incident direction of the radiation (see Fig. 2). It is equipped with 10 Harshaw TLD-700H cards. The spectrometer is designed for an energy range from 30 keV to 100 MeV, resolved in 10 different energy bins. The widths of the ten energy bins are:

$\Delta E_j = \{20$ keV; 50 keV; 150 keV; 250 keV; 500 keV; 1,5 MeV; 2,5 MeV; 5 MeV; 40 MeV; 50 MeV$\}$

with the interval centers:

$\overline{E_j} = \{40$ keV; 75 keV; 175 keV; 375 keV; 750 keV; 1,75 MeV; 3,75 MeV; 7,5 MeV; 30 MeV; 75 MeV$\}$

The response of the spectrometer to monoenergetic photon and electron radiation in the energy range 30 keV–100 MeV has been simulated by use of the Monte Carlo code FLUKA [3,4]. The transport thresholds within FLUKA were 10 keV for photons and 521 keV for electrons (including rest mass m_e). The geometry and material composition were modeled as precise as possible. This Monte Carlo model is shown in Fig. 2, it has been drawn with the FLUKA user interface *Flair* [10].

Fig. 3 shows the response of the spectrometer to photon radiation. Fig. 4 shows the response to electron radiation. Both were obtained by FLUKA simulations. The response functions obtained by these simulations describe the response to parallel radiation. If the radiation is emitted from a point source and the dimension of the spectrometer is not negligible compared to the distance from the source to the spectrometer's surface a correction of the TLD readings is needed. The conversion from the dose in a divergent radiation field D_i^{div} to the dose in a parallel radiation field D_i^{par} as needed for unfolding can be done by application of the inverse-square law

$$D_i^{par} = D_i^{div} \cdot \left(\frac{x_1 + x_2}{x_1}\right)^2 \tag{4}$$

with the distance x_1 from the source to the spectrometer's surface and the distance x_2 from the spectrometer's surface to the TLD channel i.

The fact that the TLD's respond not only to photon radiation but also to electron radiation makes it necessary that the dose coming from electron radiation has to be detected and subtracted by the unfolding-algorithm if the measurement has been carried out in a mixed radiation field.

The photon response was verified by irradiating the spectrometer prototype with γ-radiation from radioactive sources (^{137}Cs and ^{60}Co) and comparing the readings from the ten TLD's with the predictions from FLUKA simulations for the photon energies of the two used radionuclides (shown in Fig. 5). The divergence of the photons emitted from the sources was taken into account for the simulations. The FLUKA prediction agreed with the measurements for all the ten TLD's and both nuclides within $\pm 20\%$ (uncertainty of the source activities).

Fig. 6 shows the relative response distribution inside the spectrometer (value of the single TLD normalized to the sum of all ten TLD's).