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# Measurements at Laser Materials Processing Machines:
## Spectrum Deconvolution, Including Uncertainties and Model Selection

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**Summary:**

Laser materials processing can lead to the production of unwanted X-rays. Their dose rate and spectral distribution have now been accurately determined for the first time.

**Keywords:** Spectrometry, Laser materials processing, Bayesian analysis, Model selection, Uncertainty

### Background, Motivation and Objective

Materials processing by means of laser radiation is an established method that has been used for many years. More recently, ultrashort pulsed laser radiation is being increasingly used for this purpose. When using high peak intensities of more than $10^{14}$ W/cm² at the laser focus, unwanted X-rays are generated [1],[2]. These X-rays were measured for the first time in an application environment of industrial laser materials processing.

### Measurements and Data Evaluation

For the measurements, a thermoluminescence detector (TLD) based few-channel spectrometer was used (see Fig. 1) [3],[4]. The penetration depth of the X-ray radiation in the spectrometer depends on the energy, so that the energy-resolved and absolute spectrum of the radiation, including the uncertainties of the spectrum can be determined from the dose values in the TLD layers by means of mathematical methods (Bayesian deconvolution).

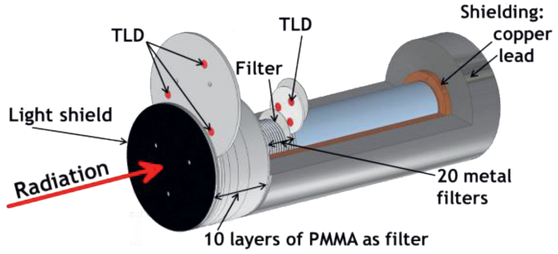

*Fig. 1. Sketch of the TLD-based spectrometer. Basic principle: The deeper the radiation penetrates the spectrometer, the higher its energy.*

The experimental setup is shown in Fig. 2 and the main laser parameters are listed in Tab. 1. Bayesian data evaluation was performed using the WinBUGS software [5] which, besides the photon spectrum, also supplies the corresponding uncertainties and coverage intervals.

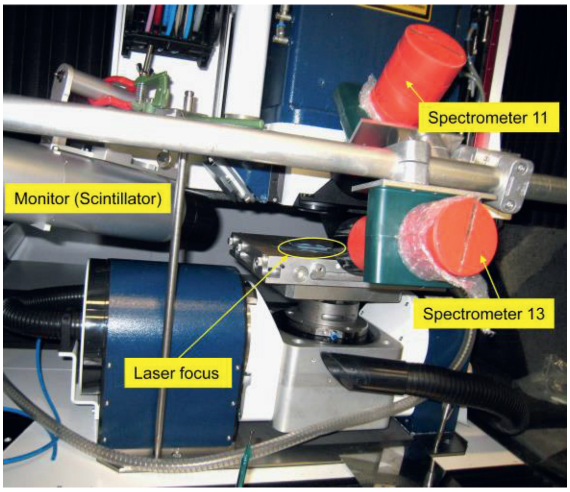

*Fig. 2. Picture of the experimental setup.*

*Tab. 1: Parameters of the laser*

| Parameter | Value |
|---|---|
| Wavelength | 1030 nm |
| Average power | 78 W |
| Pulse energy | 195 µJ |
| Pulse length (FWHM) | 924 fS |
| Repetition rate | 400 kHz |
| Focus diameter | 16 µm |
| Angle between laser beam and workpiece | 90° (from top) |
| Focus intensity | $2.1\ 10^{14}$ W/cm² |
| Workpiece materials (at different experiments) and photon emission angles | Tungsten (13° and 46°), an alloy[1] (31°) and stainless steel (31°) |

[1] 92.5 % mass fraction tungsten; 3.75 % mass fraction iron; 3.75 % mass fraction nickel

The following prior information for the photon spectra was included in the data evaluation: i) a smooth rise with increasing energy due to the fact that there was at least about 10 cm of air absorption between the laser focus and the spectrometer front; ii) an exponential decrease at higher energies (due to well-known laser-plasma interaction mechanisms); iii) a peak in the spectrum at the energy of the characteristic fluorescence radiation of the workpiece material. Further details including the validation of the method (irradiation in known photon fields and subsequent data evaluation with the same prior information) are given in the literature [8],[9].

## Results

Fig. 3 shows the absolute photon fluence spectra per materials processing time together with their 95 % coverage intervals for the four measurements normalized to a distance of 10 cm from the workpiece.

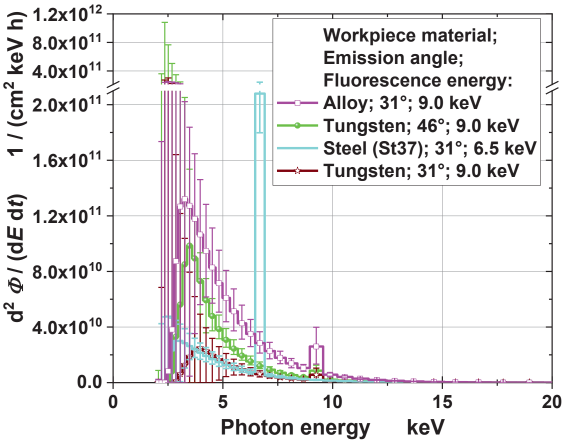

*Fig. 3. Photon fluence spectra together with their 95 % coverage intervals. Note the broken ordinate.*

The fluence spectra were converted to dose equivalent using the corresponding conversion coefficients [6],[7]. The resulting dose rate depends on the processed material and its nature. The maximum dose rates of the following radiation protection quantities were 7300 mSv/h in $\dot{H}'(0,07)$, 71 mSv/h in $\dot{H}'(3)$ and 4 mSv/h in $\dot{H}^*(10)$. Such high dose rates would exceed legal dose limits within a few minutes to one hour (for the local skin dose estimated by $\dot{H}'(0,07)$ and the eye-lens dose estimated by $\dot{H}'(3)$), or a few hours (for the effective dose of the whole body estimated by $\dot{H}^*(10)$). Fortunately, in the normal case, the laser processing is performed in a laser protection housing which is sufficient to absorb the photons. If, however, the laser intensity in materials processing rises in the future, the laser protection housing may no longer be sufficient to shield the photons.

## Conclusions

The measurements performed, traceable to the SI for the first time, not only provide manufacturers and users of ultrashort pulse lasers with important radiation protection information for the design of machines, but have also provided important input for recent legislative procedures in the field of radiation protection in Germany. Meanwhile, machines with even higher laser intensities are already under development. Therefore, the measuring method presented here will become even more relevant in the future.

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