

# Limitations of thermoluminescent dosimeters in soft X-ray diagnostics of pulsed plasma

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**Abstract** Responses of thermoluminescent dosimeters (TLDs) of  $\text{CaF}_2:\text{Dy}$ ,  $\text{CaF}_2:\text{Mn}$ , and  $\text{LiF}:\text{Mg,Cu,P}$  to the deposited energy of monochromatic 1.75–3.5 keV radiation were measured with respect to an increase in the local dose due to the attenuation length that was much shorter than the TLD thickness. The responses of TLDs to X-ray emission from the laser-produced aluminium plasma were found to be independent of the dose rate within a wide range.

**Key words** dosimetry of photons • thermoluminescent dosimeters • X-ray plasma diagnostics

## Introduction

The thermoluminescent dosimeters (TLDs) are widely used not only in the field of personnel monitoring (dosimetry) service for ionizing radiation to medical, industrial and research communities, but also for measurements of X-rays emitted from different laser-produced plasmas [1, 2, 6, 9] or, for example, a High-Energy Radiation Megavolt Electron Source – Hermes III [4] and a Z Facility at the Sandia National Laboratories [8].

The advantage of thermoluminescent dosimeters, as detectors of X-ray or VUV radiation from the plasma, lies in the possibility of using them as secondary standards in the calibration measurements of radiation from about 5 eV to tens of MeV. The TLDs can be calibrated with standard radionuclide sources or with a beam of monochromatized synchrotron radiation (MSR) of known intensity. The detection of X-ray radiation by TLDs is neither affected by an electrical interference nor by a strong magnetic field. A large number of TLDs can be simultaneously used in an experiment, but only a single readout unit for determination of their thermoluminescent (TL) responses is needed. The application of TLDs makes it possible only time-integrated measurement of X-rays.

The  $\text{CaF}_2:\text{Mn}$  thermoluminescent dosimeters (Harshaw TLD 400) were used for measurements of an intense, pulsed Bremsstrahlung field with a 19 MeV spectral endpoint, a 20 ns radiation pulse width in the pulsed HERMES-III experiment [4]. The  $\text{CaF}_2:\text{Mn}$  chips were calibrated with a  $^{60}\text{Co}$   $\gamma$ -source and processed after the experiment. Since the spectrum of the Hermes III radiation was not monochromatic, the TLD 400 was compared with aluminium and silicon X-ray calorimeters for doses ranging from 100 to 750 Gy within the Hermes radiation field. The average disagreement between TLD 400 and calorimeters was found to be 1–3% only.

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For direct measurements of a spectrum and intensity of the high-energy Bremsstrahlung radiation from a Z-pinch source, a differential absorption spectrometer (DAS, based on TLD 400) was developed at the Sandia Z accelerator [8]. The DAS consists of 13 equilibrated TLDs, separated by 14 absorber layers, and is suitable for measuring the Bremsstrahlung spectra within the range from 150 to 2000 keV.

Another DAS, consisting of LiF:Mg,Ti dosimeters (TLD 100) and of a stack of filters, was used for the measurement of spectral energy fluence of X-rays ranging from 15 to 750 keV, as emitted from the plasma produced with a 14 TW laser [9]. For measurements of an angular distribution of the X-ray emission from the focal spot of the laser pulse, single TLD 100 dosimeters (shielded with 2 mm Pb filters) were used. The TLD 100 chips, located at the outside of the target chamber, were monitoring a potential exposure of the personnel to the ionizing radiation.

A comparison of the calibrated responses of the LiF:Mg,Cu,P (TLD 200A) dosimeters and Si photodiodes to X-rays, produced with a 50 GW laser focused on an Al target and filtered by a 300 or 1200  $\mu\text{m}$  Be foil, showed a discrepancy [3]. Due to the short attenuation length of soft X-rays absorbed in the Si photodiode, the effect of an incomplete charge-carriers collection should decrease the voltage response of the photodiode with increasing incident energy of X-rays. In this experiment, the GR 200A chips were calibrated with the 5.9 keV  $^{55}\text{Fe}$  radiation, and the Si photodiodes were calibrated with  $\alpha$ -particles emitted from the  $^{241}\text{Am}$  nuclide carrying an energy of 5.486 MeV.

The absorption of keV photons results in an increase in the local dose, due to the short attenuation length, which is much shorter than the TLD thickness ( $L_{\text{att}} \ll L_{\text{TLD}}$ ) [5]. Thus, effects of supralinearity and saturation can take place at lower energy of the soft X-rays with regard to hard X-rays. In this paper we present preliminary results of research on the influence of a 1.7–3.5 keV monochromatic radiation on  $\text{CaF}_2\text{:Mn}$  and LiF:Mg,Cu,P dosimeters, and in particular on local doses at the upper limit of their useful range. An effect of a dose rate on the TLD responses is also tested.

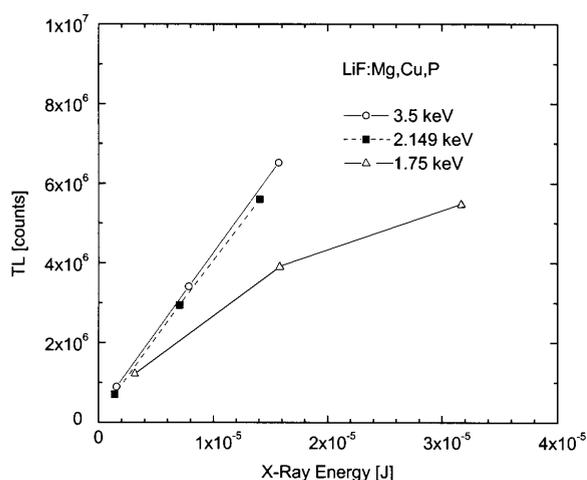


Fig. 1. TL response of LiF:Mg,Cu,P (GR 200A) dosimeters vs. deposited energy of 1.75, 2.149 and 3.5 keV radiation.

## Methods and results

The experiments were performed with an SA23 beam line of the Super ACO storage ring in LURE-Orsay ( $\lambda = 31$  nm), a  $^{55}\text{Fe}$  radionuclide standard with a photon flux of  $7.2 \times 10^6$  phot/s/sr, and with an Al-plasma produced with the NIR laser beam of the power density ranging from  $10^{13}$  to  $10^{15}$  W/cm<sup>2</sup> [3]. The  $\text{CaF}_2\text{:Dy}$  (TLD 200),  $\text{CaF}_2\text{:Mn}$  (TLD 400), and LiF:Mg,Cu,P (GR 200A) dosimeters were irradiated by all the three sources. The dosimeters, which were exposed to the synchrotron radiation, were read out in an air atmosphere employing a LTM Fimel reader, and the TLDs – irradiated by laser-produced plasma X-rays – were read out with a TLD-871 reader.

The TLD 200 and TLD 400 dosimeters are single monocrystalline chips of dimensions of  $3.2 \times 3.2 \times 0.89$  mm<sup>3</sup>. The GR 200A ones are sintered disks of 4.5 mm in diameter, and 0.8 mm in thickness. Both TLD 200 and TLD 400 dosimeters were manufactured by the Solon Technologies, Inc., Harshaw/QS Crystal and Dosimetry Products, USA, and the GR 200A dosimeters were produced by the Applicazioni Scientifiche Generali, Italy.

Fig. 1 shows the dependence of the TL response of LiF:Mg,Cu,P dosimeters on the deposited energy of 1.75, 2.149, and 3.5 keV X-ray photons, which were delivered by the Super ACO storage ring. The photon flux passed a  $1 \times 10$  mm<sup>2</sup> slit, located at a distance of 11.7 m from the SB3 beam-line front and was measured with an Au photocathode detector. The TLDs were located at a distance of 13.9 meters. Only a narrow belt of the TLD chips was exposed. The TL response shows a nonlinear dependence for the 1.7 keV radiation. Other energy dependencies seem to be linear. The value of an estimated local dose per attenuation length  $L_{\text{att}}$  (for the middle point of 1.75 keV curve is about 170 Gy), whereas the local dose per  $L_{\text{att}}$  – for the upper endpoint of the 2.149 keV curve – is about 70 Gy. The useful dose range (per TLD thickness), as declared by the manufacturers, ranges from  $\approx 0.1$   $\mu\text{Gy}$  to  $\approx 10$  Gy. Therefore, we can conclude that the applied local doses of the 1.75 keV radiation resulted in a saturation of the TL response of the TLD 400 dosimeters.

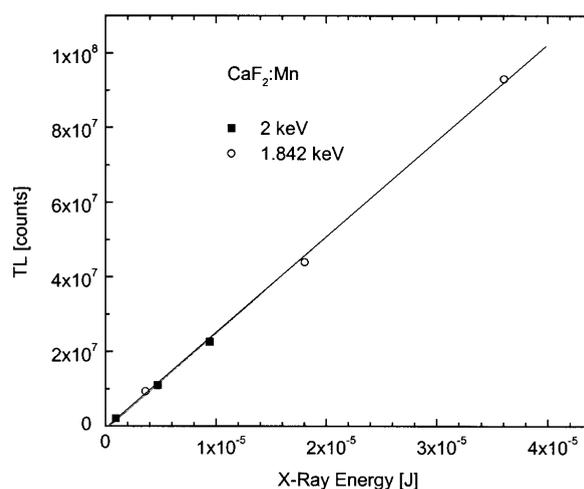


Fig. 2. TL response of  $\text{CaF}_2\text{:Mn}$  (TLD 400) dosimeters vs. deposited energy of 1.842 and 2 keV radiation.

The  $\text{CaF}_2\text{:Mn}$  dosimeters were irradiated with 1.842 and 2 keV X-ray radiation under similar conditions. In contrast to the nonlinear response of GR 200A, the responses of TLD 400, as shown in Fig. 2, are linear even if the applied local doses are higher due to the shorter attenuation lengths. The estimated local dose of the 1.842 keV radiation, corresponding to the highest value of deposited energy, is about 600 Gy. The useful range of applied doses for the TLD 400, announced by the manufacturer, is from  $\approx 0.1 \mu\text{Gy}$  to  $\approx 100 \text{ Gy}$  [7].

These results show that the responses of the TLD 400 and GR 200A dosimeters to the soft X-ray radiation may be nonlinear, due to the deposition of the photon energy in a small volume, restricted by the corresponding attenuation length. It seems that the range of the useful dose for the hard X-ray and  $\gamma$  radiation is applicable also for the soft X-rays. This fact restricts the usage of TLDs for the detection of soft X-rays, but the deposited energy of  $\approx 2 \text{ keV}$  radiation should be lower than  $\approx 40 \mu\text{J}$  per TLD 400 chip, and lower than  $\approx 10 \mu\text{J}$  per GR 200A disk.

The TL response of dosimeters can be also affected by a roughness of the TLD surface, because the average TLD surface roughness can be comparable to  $L_{\text{att}}$ . TLD chips, disks, etc. are not polished in order to make the surface roughness lower than  $L_{\text{att}}$  and the wavelengths of TL emitted spectra. It is also one of many reasons why the surface of the dosimeters should be kept clean.

Irradiation of the TLDs with soft X-rays emitted from the plasma produced with a short-pulse-laser, results in high dose rates. Therefore, we compared responses of the GR 200A and TLD 200 dosimeters irradiated by soft X-rays, emitted from an Al-plasma and by the 5.9 keV radiation from the standard radionuclide source  $^{55}\text{Fe}$ . The brilliance of the standard radionuclide source  $^{55}\text{Fe}$  was about ten orders of magnitude lower than that of the laser-produced plasma. Fig. 3 shows that the correlation of responses of GR 200A and TLD 200 to the X-ray radiation from the laser-produced Al plasma (filtered simultaneously by a  $2 \mu\text{m}$  KG Makrofol foil and by a  $300 \mu\text{m}$  Be foil – full circles) and to the 5.9 keV radiation from the  $^{55}\text{Fe}$  radionuclide (open circles).

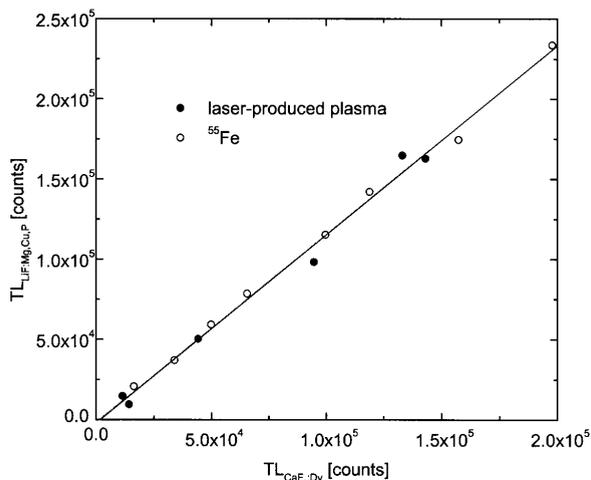


Fig. 3. The comparison of  $\text{LiF:Mg,Cu,P}$  GR 200A and  $\text{CaF}_2\text{:Dy}$  (TLD 200) thermoluminescence responses to the X-ray radiation from a laser-produced Al plasma (filtered by a  $2 \mu\text{m}$  KG Makrofol foil and by a  $300 \mu\text{m}$  Be foil – full circles) and to the 5.9 keV radiation from the  $^{55}\text{Fe}$  radionuclide (open circles).

cles), and to the 5.9 keV radiation from the  $^{55}\text{Fe}$  radionuclide (open circles), can be fitted by a straight line. The estimated maximum dose rate of deposited X-ray energy in the TLDs was about  $5 \times 10^7 \text{ Gy/s}$ . This result confirms that the TLDs used can be considered as dose-rate independent also for soft X-rays.

## Conclusions

The performed experiments have demonstrated that the TLDs are useful tools for the detection of the soft X-ray radiation from pulsed sources. Their use is limited by a local dose, which can exceed the linearity limit of the useful dose range, due to the short attenuation length of the deposited soft X-ray energy. These detectors can, however, be used as suitable secondary standards in pulsed plasma calibration measurements, and they are inherently dose-rate independent also for the soft X-rays.

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