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A new personal dosimetry system for $H_P(10)$ and $H_P(0.07)$ photon dose based on OSL-dosimetry of beryllium oxide

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ABSTRACT

In recent years the personal dosimetric system "iBeOx" using optically stimulated luminescence of beryllium oxide (BeO) has been developed by the TU Dresden radiation physics group in cooperation with the Helmholtz Zentrum Muenchen and IBA Dosimetry GmbH Schwarzenbruck. Continuous wave stimulation with a blue LED and measurement of the luminescence light with an enclosed photo sensor module are performed from opposite detector sides. A microcontroller controls the complete measurement cycle, processes the digitized signals, performs extensive checks of the system states and communicates via USB with the external PC software. The resulting OSL signal can be used for dose evaluation. Two types of personal dosimeters are available, both conform to the IEC 62387-1 standard. The dose response is linear from the lowest detection limit of 50 μSv–10 Sv. Long-term fading of the signal is negligible. Due to the near tissue equivalence and the resulting low photon energy dependence of BeO the personal dose can be evaluated from 12 keV up to 7 MeV by one dosimetric element without any corrections. In an automatized environment the system is able to process several hundred dosimeters per hour.

1. Introduction and motivation

Investigations of the luminescence properties of beryllium oxide were reported by Albrecht and Mandeville (1956). One year later, the material BeO was at first used as TL phosphor (Moore, 1957). However, the light induced fading, first measured by Tochilin et al., (1969), prevented the practical use of BeO as TL material. This effect caused Rhyner and Miller (1970) to suggest BeO as an OSL luminophor. It was not until the work of Bulur and Göksu (1998) that the OSL properties of the material were researched in detail.

Due to the high demand for passive radiation detectors in medicine, personal and environmental dosimetry, the radiation physics group in Dresden has been investigating BeO as an OSL-dosimeter for a number of years (Sommer and Henniger, 2006; Sommer et al., 2007, 2008). Now, a sophisticated dosimetric method has been developed which can be used to specify the dose in a broad spectrum of applications.

Due to the near tissue equivalence of the material BeO and the good usability of the system the method promises to be useful for personal dosimetry. During the last two years a collaboration of Helmholtz Zentrum Muenchen, TU Dresden and IBA Dosimetry GmbH Schwarzenbruck has developed the personal dosimetry system "iBeOx" consisting of different dosimeters containing two or four BeO-detectors and several modular hardware components to process the dosimeters.

2. Material and methods

2.1. Measurement principle

The reader is an improvement of the concept described in Sommer et al. (2007), (2008). Important features are stimulation with a photodiode controlled blue LED and the use of a bialkali photo sensor module (PSM) as luminescence light sensor. Optical filters between the LED and the BeO detector and in front of the PSM effectively separate the stimulation from the luminescence light. In contrast to other OSL techniques the stimulation and reading of luminescence light are performed from opposite sides of the dosimeter. This way, very short distances are achieved between the stimulation source, the dosimeter and the light sensor.

The voltage output of the sensor module is digitized by a microcontroller containing a 24 bit ADC. The microcontroller contains a time base and controls the operating states of the reader. The microcontroller switches on/off the LED, adjusts the LED light output, controls the temperatures of the stimulation as well as the PSM units to achieve stable results, controls the positioning and the

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identification of the dosimeter card and communicates via USB with an external PC.

The readout process has three different time scales. Samples of 1 ms are the default time scale of the ADC. Next level are measurement periods consisting of 100 samples without stimulation to get the actual offset signal of the PSM, followed by the same number of samples with stimulation to measure OSL. The sampling is interrupted for 10 μs each time the LED is switched on or off. The delay time allows stabilization of LED emission and main decay of the OSL after the end of stimulation. The microcontroller calculates the integral of the offset samples and subtracts it from the integral of the OSL samples to obtain the result of the reading period. This value is sent via USB to an external PC for further analysis. The top level time scale is the complete readout consisting of five measurement periods.

The procedure, although pulsed, is not directly comparable to other POSL methods, which use short stimulation pulses while gating the photo sensor and then measure a delayed signal. Because of the very short decay time of BeO after end of stimulation the OSL must be measured during stimulation, more comparable with CW stimulation.

The standard readout induces only a weak OSL decay, depending on the individual detector in the range of 0.5–3%. To allow additional validation readouts the calibration process must include more than five measurement periods. Actual calibrations are performed over 100 periods resulting in a decay down to about 50…80% of the amplitude. Besides the ability of validation readouts this relatively long calibration procedure allows future extensions and add-ons in the system without the necessity of recalibration.

For a standard measurement, the values of the measurement periods are added. In contrast, the calibration curve is fitted with a sequence of coherent exponential functions in the three period intervals 1…10, 11…40 and 41…100. From the resulting parameters the sensitivity of a standard readout (periods 1…5) as well as possible validations (periods 6…10, 11…15, …) are calculated. The PC software is linked to a database storing all dosimeter data from calibration to actual dosimeter status information and complete dosimeter history. The software conforms to accepted principles of data handling.

2.2. Devices

The iBeOx family consists of the Reader, the bleaching unit called “Eraser” and the Irradiator for dosimeter calibration and verification. All devices are based on a common design, which provides the ability to open, position and close the dosimeter inside the device. The handling of 2-element as well as 4-element dosimeters is enabled by using different adapters. In the Reader and the Irradiator, two elements are processed simultaneously to enhance the throughput of the system. In case of the 4-element dosimeter the second half is processed after repositioning. The Eraser bleaches all elements simultaneously with typical bleaching times of about 10…20 s for doses up to several mSv.

The whole system is modular, the devices work standalone (see Fig. 1) as well as in medium and highly automatized environments. For high throughput of hundreds of dosimeters per hour a system containing up to five devices, typically two Readers, two Erasers and one Irradiator, fed by an industrial robot can be assembled.

2.3. Dosimeter

The detector elements are sintered ceramics made of beryllium oxide. These chips are typically used as heat sinks for electronic components. The ceramics are thermally, chemically and especially mechanically extremely stable. No abrasion or dust can be observed, an important feature in view of the hazardous nature of BeO in powder form. Therefore BeO ceramics are not classified as toxic and are not part of the RoHS directive. The dimensions of the chips are 4.7 mm in square with 0.5 mm thickness. The density is 2.85 gcm^{-3}, the effective atomic number is about 7.1. No specific dopants were added during production but most of the delivered chips have a sufficient response to radiation. The chips are manufactured by Brush Ceramics Inc. in Tucson/Arizona, U.S.A. under the trade mark “Thermalox 995”.

Fig. 1. Standalone iBeOx Reader with opened dosimeter drawer. The device dimensions are 200 mm × 200 mm × 480 mm, the mass is about 19 kg.

Two versions of dosimeters exist—with two and four dosimetric elements. For photon dose assessment of each $H_P(10)$ and $H_P(0.07)$ one detector element is necessary to fulfill requirements of IEC 62387-1. So a 2-element dosimeter is adequate for most applications. The also available 4-element dosimeter with two additional metal filtered positions can give more information about the mean energy of the radiation field and allows linear-combination of responses from each element to improve the energy response.

The dosimeter consists of a card with the BeO-elements and a cover with filters. Both are made of low Z plastics. The construction guarantees a sufficient light protection of the BeO-elements and an interlock between both parts. BeO detector edges are directly injection-molded into plastics, but most of the surface of both sides is left blank for stimulation and OSL detection. The card carries a barcode for automatic as well as an ID number for manual identification. On customer request an active RFID chip may be added, which can store calibration data and dosimeter history as well as customer information like access codes or limitations.

The cover carries the filters, which are arranged symmetrical in terms of the IEC standard. The filter dimensions are chosen so that the detector is completely covered for all inclined irradiations from $-60°$ up to $+60°$ with regard to the orthogonal reference direction. The filter of the $H_P(10)$ element is made of 2.4 mm PTFE (Teflon), the additional elements in the 4-element dosimeter are made of copper and a sandwich of lead with low content of ^{210}Pb and tin. The $H_P(0.07)$ element is covered by a 0.5 mm thick plastic window.

2.4. Irradiation facilities

For the investigation of the dosimetric properties irradiation facilities at the Helmholtz Zentrum Muenchen (former GSF Neuherberg) and the TU Dresden as well as the iBeOx Irradiator have been used. At the Helmholtz Zentrum a complete secondary standard dosimetry laboratory (SSDL) was available. Two X-ray facilities with 160 kV and 320 kV accelerating voltage can be used to generate the ISO 4037 reference radiation fields N15…N300. Additionally, a number of ^{137}Cs and ^{60}Co sources with different dose rates are available. Furthermore a beta calibration standard allows irradiations with $^{90}Sr/^{90}Y$, ^{208}Tl and ^{147}Pm. In the SSDL all calibration doses, the radiation qualities for the energy dependence curves except of R–C and R–F and part of the dose characteristic exposures were irradiated. R–C (4.4 MeV) and R–F (6…7 MeV) qualities were irradiated at PTB Braunschweig (German primary standard laboratory). All investigations of the energy dependence were carried out on ISO slab phantoms (water filled, PTW Freiburg).

At TU Dresden different radioactive sources (^{137}Cs, ^{60}Co, ^{241}Am and $^{90}Sr/^{90}Y$) were used to investigate the dose characteristic, variation coefficients, fading and long-term stability. All fields were calibrated in comparison to the SSDL in Munich. The irradiations were carried out free in air. If necessary secondary charged particle equilibrium (SCPE) was ensured.

For a number of tests the iBeOx Irradiator has been employed as well. The device is loaded with four small ^{90}Sr sources with activities of about 20 MBq. After opening and positioning the dosimeter card, two sources directly irradiate one detector element. Two elements are exposed simultaneously. A magnetic shutter mechanism allows exposure times of multiples of seconds with uncertainty better than 5 ms. The minimum exposure time of 1 s results in doses of 1…2 mGy resp. mSv. Calibration of the Irradiator is performed by intercomparison of measured OSL doses after dosimeter calibration in the SSDL-field. With this, the calibration of dosimeters based on different conversion factors from irradiation time to dose for each of the four elements is also possible.

2.5. Dosimeter calibration and dose evaluation

To achieve a high throughput the dosimeter calibration has been performed with ^{137}Cs free in air under SCPE. For the $H_P(10)$ and $H_P(0.07)$ elements a conversion factor has been specified in a way that the indicated values are equal to the corresponding dose quantities for irradiation on phantom at the reference energies. The conversion factors were determined by comparison of calibration free in air and on phantom. They take into account the different definitions of dose units air kerma and "H_P" as well as the lack of backscattering under calibration conditions. For the metal filtered elements no conversion factors have been specified. As a result the sensitivity of each element can be specified for standard and validation readings.

The standard dose evaluation is performed in two stages. Before irradiation or issue for wearing as personal dosimeter the residuum is read after bleaching. This residuum mostly depends on the dosimeter history. Starting with values equivalent to a few microsievert for fresh detectors it increases with accumulated dose over the complete dosimeter history. Bleaching with acceptable illumination times can erase no more than 99.9% of the original signal. In practice the residuum is constant after 30 s of bleaching for high doses too. After irradiation the measurement result is reduced by the stored residuum and then divided by the sensitivity to evaluate the dose.

3. IEC 62387-1 results

The IEC sets a large number of requirements for dosimetric systems to guarantee a sufficiently precise dose evaluation under any external conditions. These requirements do not simply address dosimetric properties but also examine issues regarding data handling, data security, electromagnetic compatibility and environment. This paper focuses only on the most important dosimetric properties of the system.

3.1. Dose characteristic and coefficient of variation

The IEC requires a minimal dose range from 0.1 mSv ($H_P(0.07)$: 1 mSv) to 1 Sv. The indicated value should not differ more than 15% from the true value. Two dose points per order of magnitude should be measured with a given number of dosimeters. The variation of the dosimeters irradiated with the same dose yields a coefficient of variation, approximately comparable to the standard deviation. This coefficient should not exceed 5% for doses higher than eleven-times lowest detection limit (LDL) and up to 15% for the LDL. Due to the typical linear dose characteristic of luminescence systems over several orders of magnitude and due to the high response of all elements the dose range for both indicated values can be extended from 0.05 mSv to 10 Sv (see Fig. 2). The lowest detection limit could actually be decreased too much lower values, but at this stage more long-term experience is necessary. The upper limit is determined mostly by differences of the deviation from linearity between the BeO badges. But dose calculations, although with higher uncertainty and much more experimental efforts, are possible up to about 100 Gy. The observed coefficient of variation is less than half of the IEC limits over the complete dose range.

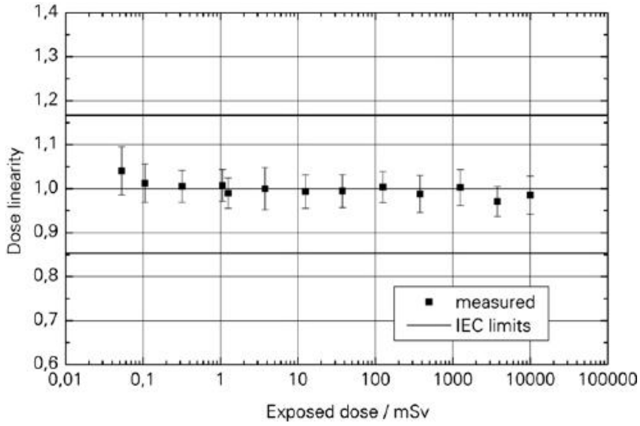

Fig. 2. Linearity of dose characteristic. The indicated value per dose relative to the ratio at 1 mSv shows a good linearity.

3.2. Fading, dose build-up and self-irradiation

Each ten dosimeters have been measured after storage times from 0,5 h up to 5700 h after irradiation. Natural underground correction was performed. The mean of the indicated value and standard deviations were calculated. A time of 24 h was chosen as reference value. Only a short-term fading in the first minutes after irradiation was found. After less than 1 h it is negligible over several

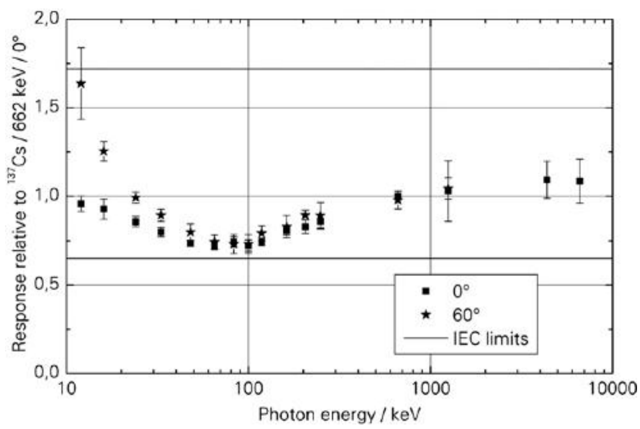

Fig. 3. The energy response of the $H_P(10)$ element fits the IEC requirements without any corrections over the complete energy range of interest.

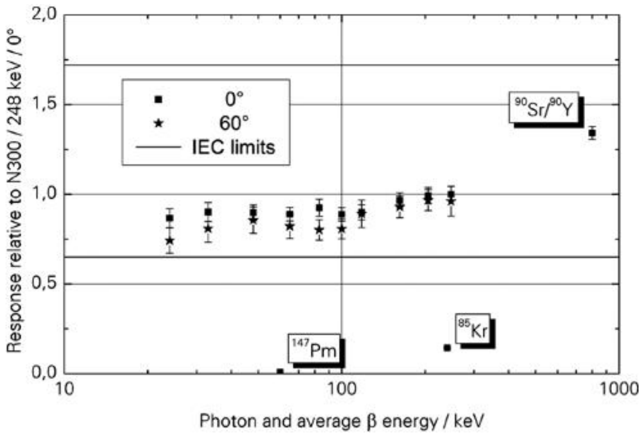

Fig. 4. Energy dependence of the $H_P(0.07)$ element. The IEC limits are broken for very soft photons and for low and medium energy betas. Self absorption effects of the BeO detector are the most important problems, because the dose distribution inside the detector becomes inhomogeneous while calibration has been performed with homogeneous irradiation.

months. A dose build-up could not be measured. To test the response to natural radiation and self-irradiation 25 dosimeters were erased and stored for a period of 54 days and readout. A natural dose rate of 2 μSv/d was assumed. For all elements the result is within the limitations. A self-irradiation of any element could not be measured.

3.3. Energy response

The variation of the relative response due to a change of the radiation energy and angle of incidence has been measured extensively. All irradiations have been performed on the slab phantom with angles of incidence from 0 ° (frontal) up to 60 ° (required IEC minimum) and with different dosimeter orientations. As result the rated range was fixed from 12 keV up to 7 MeV ($H_P(10)$, reference energy ^{137}Cs) and 20 keV–7 MeV ($H_P(0.07)$, reference energy N300). The results are shown in the Figs. 3 and 4.

3.4. Light exposure

To check the influence of light exposure two groups of 10 dosimeters were irradiated with a dose of $7 \cdot H_{Low}$ (350 μSv). The first group was maintained at normal daylight in the shadow. The other group was exposed with light of a fluorescent lamp for 7 days. The lamp offers a light power of more than 1000 W/m^2. The light protection of the dosimeter construction was found to be very effective, as no change of the indicated value could be observed.

3.5. Drop (dosimeter)

For the drop test two groups of 6 dosimeters were used. Both groups were irradiated with a dose equivalent of $7 \cdot H_{Low}$ (350 μGy). The dosimeters of the reference group were measured without any further tests. The dosimeters of the second group were dropped from a height of 1.0 m onto a flat and hard surface with each of the six faces of the dosimeter. An inspection of the dosimeters showed no damage on the dosimeter card and on the cladding. The readout of these dosimeters showed no change of the indicated value.

4. Conclusions

The presented dosimetry system offers dose assessment for $H_P(10)$ and $H_P(0.07)$ according to IEC 62387-1. Dose and energy range comply excellently with the requirements of a modern personal dosimeter. All the other requirements to such a dosimeter are fulfilled as well. The variability and high throughput of the system allows application in small individual monitoring services as well as services with a large number of monitored people.

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