TESLA-FEL 2007-03

Application of low cost GaAs LED as neutron kerma dosimeter and fluence monitor at FLASH

Bhaskar Mukherjee, Stefan Simrock

Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany

Email: bhaskar.mukherjee@desy.de

ABSTRACT

Displacement damage caused by fast neutrons in unbiased Gallium Arsenide (GaAs) Light Emitting Diodes (LED) resulted in a reduction of the light output. On the other hand, a similar type of LED irradiated with gamma rays from a ^{60}Co source up to a dose level in excess of 1.0 kGy (1.0×10^5 rad) was found to show no significant drop of the light emission. This phenomenon was used to develop a low cost passive fluence monitor and kerma dosemeter for accelerator-produced neutrons. These LED-dosemeters were used to assess the integrated fluence of photoneutrons, which were contaminated with a strong bremsstrahlung gamma-background generated by the 730 MeV superconducting electron linac of the FLASH (Free Electron Laser at Hamburg) at Deutsches Elektronen-Synchrotron (DESY). The applications of GaAs LED as a routine neutron fluence monitor and displacement damage precursor for the electronic components located in high-energy accelerator environment are highlighted

Keywords: COTS components, Displacement damage, Electron Linear Accelerator, GaAs Light emitting diode (LED), kerma, Photoneutrons

1. INTRODUCTION

At DESY a Free Electron Laser named FLASH (Free Electron Laser in Hamburg), operating in the vacuum-ultraviolet wavelength region (13 nm), has commenced routine operation. The FLASH is driven by a 730 MeV superconducting electron linac, developed on TESLA technology. The FLASH has been conceived to serve as the prototype of a much larger and more powerful European X-Ray Free Electron Laser (XFEL), already under construction here in Hamburg [1].

Sophisticated measurement and control devices based on state-of-the-art microelectronics have been installed inside the FLASH containment tunnel, in close proximity to the superconducting electron linac. During the accelerator operation those electronic devices are subjected to stray radiation field produced by the linac, which results in a higher risk of the radiation-induced malfunction of the above devices. A flawless operation of those electronic systems is vital to the FLASH facility; hence, it becomes imperative to monitor the radiation effects on electronics operating in a strong radiation environment in both the long and short terms. We have developed a simple, cost effective, user friendly device based on a commercial off-the-shelf (COTS) Gallium Arsenide (GaAs) light emitting diode (LED) for the assessment of integrated neutron fluence and associated kerma (kinetic energy released per unit mass) at critical locations in the high-energy accelerator environment, such as at FLASH of DESY.

As a result of the interaction of fast neutrons or heavy charged particles with bulk semiconductor materials, the lattice atoms are displaced from their original (stable) position, thereby creating vacancies. The combination of the displaced (interstitial) atoms in the semiconductor material and the corresponding vacancies are known as Fränkel-pairs. The phenomenon of long-term cumulative formation of Fränkel-pairs by non-ionising (collision) energy loss (NIEL) of fast neutrons or heavy ionising particles is defined as displacement damage (DD). The fast neutron irradiation of an unbiased GaAs LED causes displacement damage via NIEL process resulting in the attenuation of the light output of the LED [2]. Photons on the other hand, have a much lower capability to dislodge atoms from the semiconductor lattice. Therefore, a much higher gamma ray exposure has a negligible effect on the light reduction [3] of the GaAs LED. The displacement damage (DD) or NIEL effects on GaAs LED are explained as follows (a) Un-irradiated LED: Electron and hole pairs undergo radiative recombination in the space charge zone producing a high light output (Figure 1a), (b) LED following neutron irradiation: Non-radiative recombination centres are produced in the space charge zone as a result of NIEL. Only parts of the electron hole pairs go through radiative recombination, the rest dissipate their energy in the space charge zone via non-radiative recombination thereby producing a lower light output (Figure 1b).

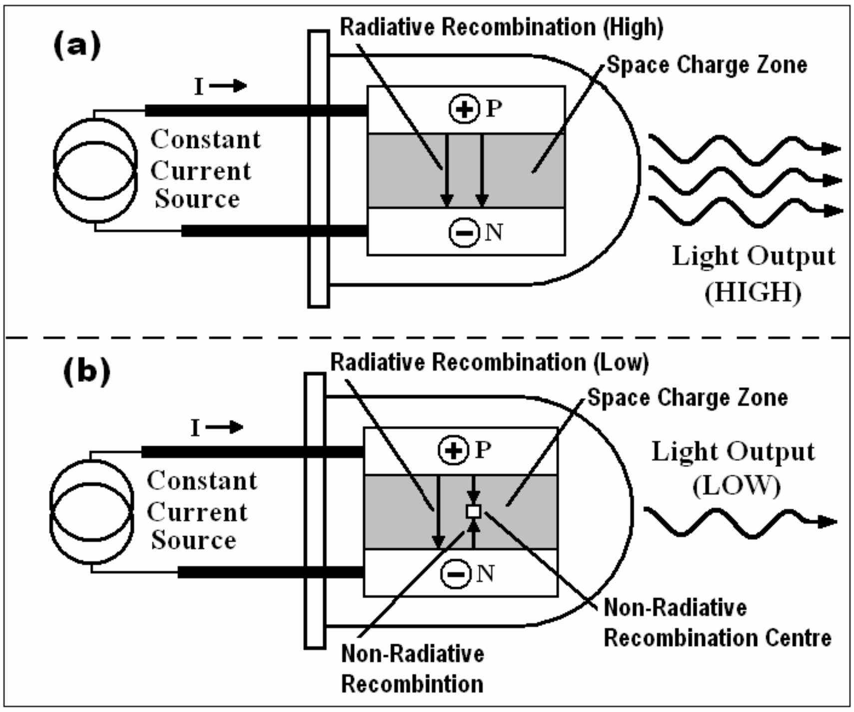

Figure 1: Showing the fundamental neutron radiation effects on LED. The figure is explained in details in the main text.

We have utilised the above phenomena to develop a passive neutron dosemeter with a very high gamma discrimination characteristic for high-energy accelerator dosemetry. This paper highlights the operation principle and important applications of the GaAs-LED based neutron dosemeter at the FLASH facility operated by DESY.

2. MATERIALS AND METHOD

We have purchased a bulk stock of 500 miniature (diameter: 3 mm) yellow GaAs LED (Model: LN48YPX, Manufacturer: Panasonic Corporation, Japan). The light outputs of each LED were assayed using a dedicated photometer based on a commercially available digital photo (Lux) meter (Model: MS-1500, Manufacturer: Voltcraft, Taiwan). The LED under test was inserted in a light-tight aluminium head housing a planer Si-photodiode, interfaced to the photometer. The LED was connected to a constant current source supplying 13.5 mA forward current and the resulting light output (Lux) was read from the photometer. Out of 500 evaluated LEDs a batch of 150 LED with a light output of 38 Lux ± 1% was selected and each LED issued an identification number. This pool of 150 selected LEDs with a batch inhomogeneity of ± 1% was used in this investigation. A schematic diagram of the LED photometer is shown Figure 2.

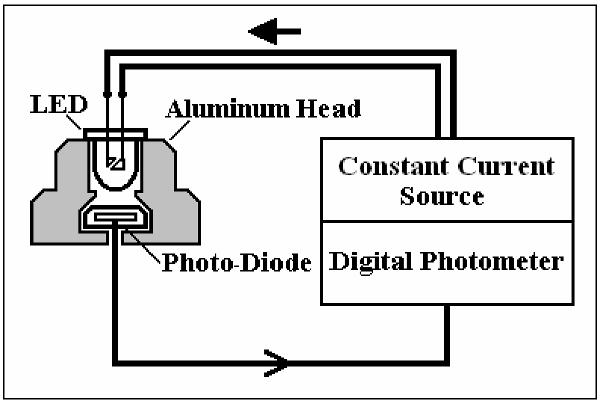

Figure 2: Schematic diagram of the photometry device based on a commercially available photometer used for the assessment of light emission from the GaAs-LED.

Four batches of GaAs LED each consisted of five specimens were packed in tiny plastic satchels and irradiated with gamma rays from a ^{60}Co source at Hahn Meitner Institute Berlin. The 1st, 2nd, 3rd and 4th batches received gamma doses of 96.6, 950, 9810 and 98000 Gy, respectively. Five similar batches of LEDs were irradiated with fast neutrons from a ^{241}Am/Be(α, n) source (Strength: 2.2×10^6 neutrons.s^{-1}) at DESY Health Physics laboratory. The LED satchels were placed in close proximity (ca. 1.5 cm) to the neutron source. The neutron kerma in the 1st, 2nd, 3rd, 4th and 5th LED batch was calculated from the integrated fluence and energy distribution of ^{241}Am/Be neutrons [4] and neutron kerma coefficients in GaAs [5] and found to be 0.22, 0.44, 0.65, 0.87 and 1.09 Gy respectively. All LEDs were evaluated using the photometer described in Figure 2 and the data was used to estimate the neutron fluence and kerma calibration factors.

The GaAs LED dosimeters were used to assess the neutron fluence at critical locations of the FLASH facility. Neutrons are generated when the accelerated field emission electrons and beam loss electrons strike the internal wall of the beam tube [1, 6]. Small plastic bags containing five LEDs were placed at positions p1 (end of bunch compressor 2), p2 (entrance of bunch compressor 3), p3 (end of bunch compressor 3) and p4 (end of accelerating module 5), along the beam line of the 730 MeV superconducting electron linac driving FLASH (Figure 3).

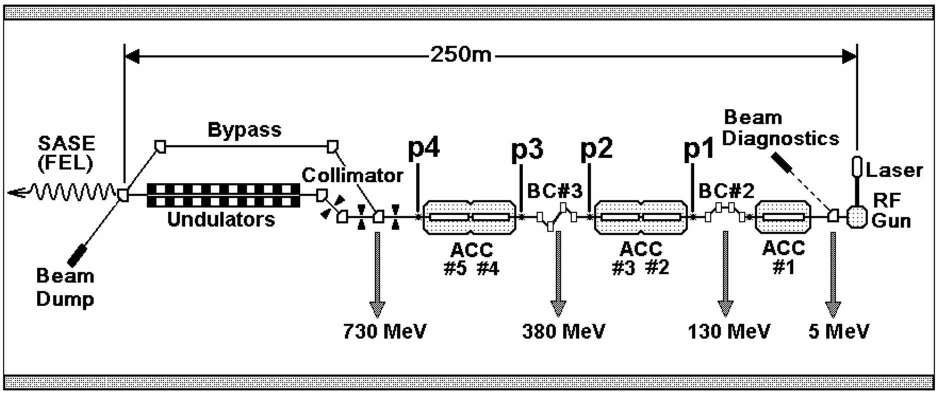

Figure 3: Showing the footprint of FLASH. The integrated neutron fluences at locations p1, p2, p3 and p4 were evaluated using GaAs LEDs for one-week routine linac operation period.

The incidences of high neutron fluence at the selected locations were confirmed by high background gamma dose caused by neutron activation of beam line components, established by a health physics survey during maintenance shut down of the FLASH. The LED packets were retrieved after the routine weekly run and evaluated at the Radiation Effects

Laboratory of the DESY LLRF Group. The kerma and fluence calibrations factors were applied to evaluate the displacement kerma and integrated neutron fluence at those selected locations.

3. RESULTS AND DATA ANALYSIS

The light output from the GaAs LEDs before and after irradiation with ^{60}Co gamma rays and ^{241}Am/Be (α, n) neutrons was evaluated. The ratio of the light output corresponding to the un-irradiated and irradiated cases of the same LED, denoted as “Relative Light Output: %” was calculated and plotted as functions of kerma in Figure 4. The results are summarised in Table 1.

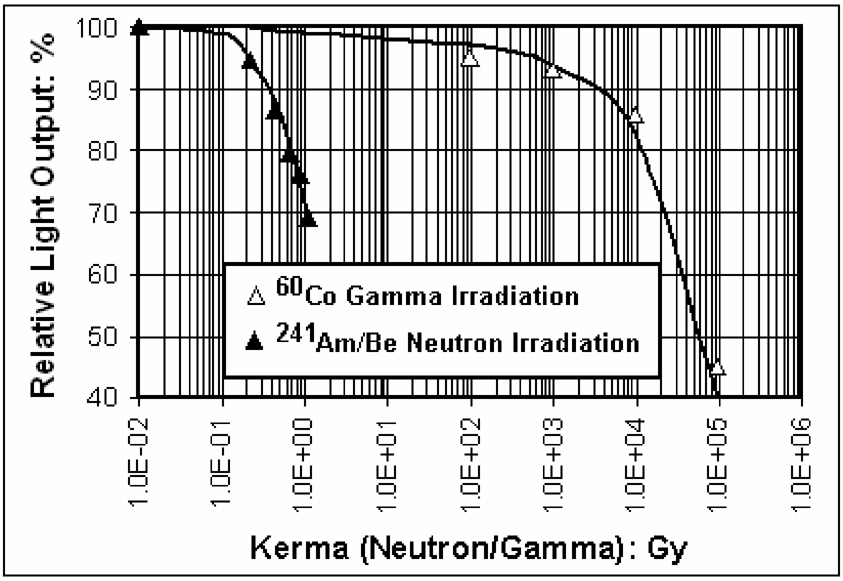

Figure 4: Showing the light output of the GaAs LED irradiated with gamma rays from a ^{60}Co source and with fast neutrons from a ^{241}Am/Be (α, n) source as functions of kerma. Each data point represents the mean value of the reading (light output) of five LEDs per batch.

Table 1. Relative light outputs (LO) of neutron and gamma ray irradiated GaAs LED are shown with the corresponding neutron kerma and gamma dose. Please note the neutron kerma and gamma dose have the same unit, Gy.

Neutron kerma: [Gy] **Gamma Dose: [Gy]**	**Relative LO: [%]** **(Neutrons)**	**Relative LO: [%]** **(Gamma rays)**
0.22	94.7 ± 9.4 (10 %)	-----
0.44	88.0 ± 7.0 (8 %)	-----
0.65	81.2 ± 12.2 (15 %)	-----
0.87	75.0 ± 7.7 (10 %)	-----
1.09	69.0 ± 10.4 (15 %)	-----
96.6	-----	95.0 ± 3.6 (3.8 %)
950	-----	93.1 ± 4.4 (4.7 %)
9810	-----	86.2 ± 2.8 (3.2 %)
98000	-----	45.0 ± 1.4 (3.1 %)

For the purpose of calibration, the GaAs LED were irradiated with neutrons from a ^{241}Am/Be (α, n) source [4], with an average energy of 4.3 MeV. On the other hand, the neutron spectrum in the FLASH tunnel is dominated by photoneutrons generated by a Giant Dipole Resonance (GDR) process. The GDR photoneutrons have a much softer energy distribution, very close to a “Fission Spectrum” as reported elsewhere [7, 8]. Evidently, it becomes imperative to establish a fluence calibration factor in order to convert the relative light output (LO: %) of the LED irradiated in the FLASH tunnel to neutron fluence. The normalised neutron spectrum of a ^{241}Am/Be (α, n) source (a) and GDR Photoneutrons, equivalent to the

FLASH neutron spectrum (b) and differential displacement kerma (c) of GaAs [5] are shown in Figure 5. The neutron fluence calibration factor "f" is defined as:

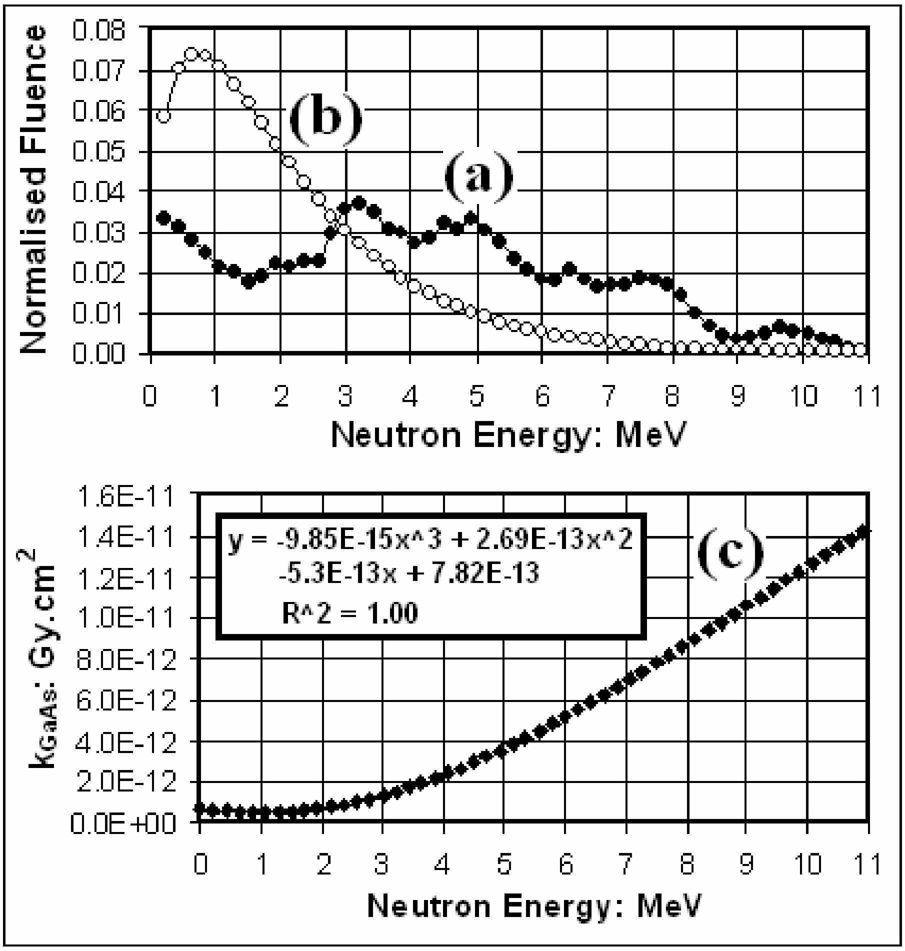

Figure 5: Showing (a) the energy spectra of the ^{241}Am/Be neutron calibration source and (b) Giant Dipole Resonance (GDR) photoneutrons. The integrated neutron fluence of both sources, i.e. the areas under the respective spectrum were normalised to unity. The lower graph (c) displays the differential kerma coefficient [5] of GaAs (k_{GaAs}) as a function (inset) of neutron energy.

$$\mathbf{f} = \frac{\left(\sum^{i} N(E_i)k_i\right)_{^{241}Am/Be}}{\left(\sum^{i} N(E_i)k_i\right)_{FLASH}} \qquad (1)$$

Where, N(Ei) and ki represent the number of neutrons (normalised by the total number of neutrons under the respective spectrum) and the differential displacement kerma[(5)] of the i^{th} bin, respectively. By substituting the numerical values of N(Ei) and ki in equation 1 the value of the fluence calibration factor (f) was calculated to be 2.61 (Figure 5). The corrected neutron fluence for FLASH, with an energy distribution like GDR Photoneutrons could be calculated as follows:

$$\mathbf{\Phi_{FLASH} = f.\Phi_{241Am/Be}} \qquad (2)$$

Where, $\Phi_{241Am/Be}$ represents the integrated neutron fluence corresponding to a ^{241}Am/Be source derived from the relative light output (LO: %) of a GaAs LED.

The neutron kerma in GaAs for FLASH (Eq. 3a) and ^{241}Am/Be neutrons (Eq. 3b) are given as:

$$K_{FLASH} = \Phi_{FLASH}\left(\sum^{i} N(E_i)k_i\right)_{FLASH} \quad (3a)$$

$$K_{241Am/Be} = \Phi_{241Am/Be}\left(\sum^{i} N(E_i)k_i\right)_{241Am/Be} \quad (3b)$$

By substituting Φ_{FLASH} from equation 3a into equation 2 one obtains:

$$K_{FLASH} = f\,\Phi_{241Am/Be}\left(\sum^{i} N(E_i)k_i\right)_{FLASH} \quad (3c)$$

Furthermore, by substituting the calibration factor "f" from equation 1 one obtains:

$$K_{FLASH} = \Phi_{241Am/Be}\left(\sum^{i} N(E_i)k_i\right)_{241Am/Be} \quad (3d)$$

According to equation 3b, this means:

$$K_{FLASH} = K_{241Am/Be} \quad \textbf{(3e)}$$

Equation 3e validates that the kerma is a function of total energy dissipation in the material of interest, independent of the nature of energy distribution (spectrum). The neutron kerma and fluence calibration curves are shown in Figure 6.

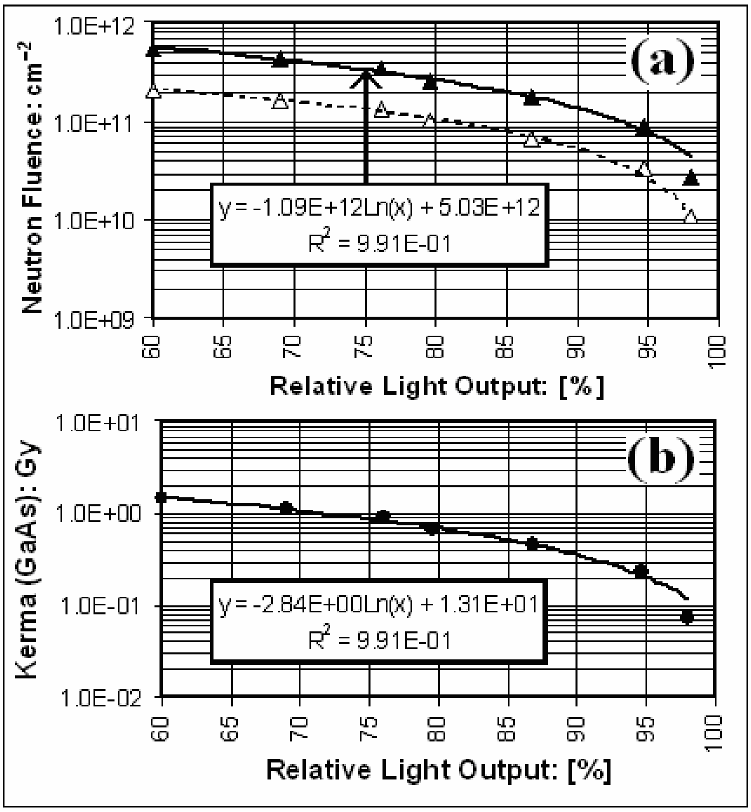

Figure 6: (a) Showing the neutron fluence as a function of relative light output (LO) of GaAs LED irradiated with ^{241}Am/Be(α, n) neutrons (hollow triangles). The equivalent neutron fluence for FLASH (GDR photoneutrons) was derived by using the fluence calibration factor "f" (equation 2) indicated by solid triangles. The points are fitted with a linear function (inset). (b) Neutron kerma in GaAs shown as a function (inset) of relative light output (LO) of the GaAs LED. The kerma is independent of energy distribution (equation 3d).

The GaAs LEDs irradiated at FLASH were evaluated. The relative light output (LO) of the LEDs placed at the positions p1, p2, p3 and p4 (Figure 3) were found to be 96.2%, 96.4%, 89.6% and 95.9% respectively. The corresponding neutron fluence and kerma (GaAs) were calculated and presented in Figure 7.

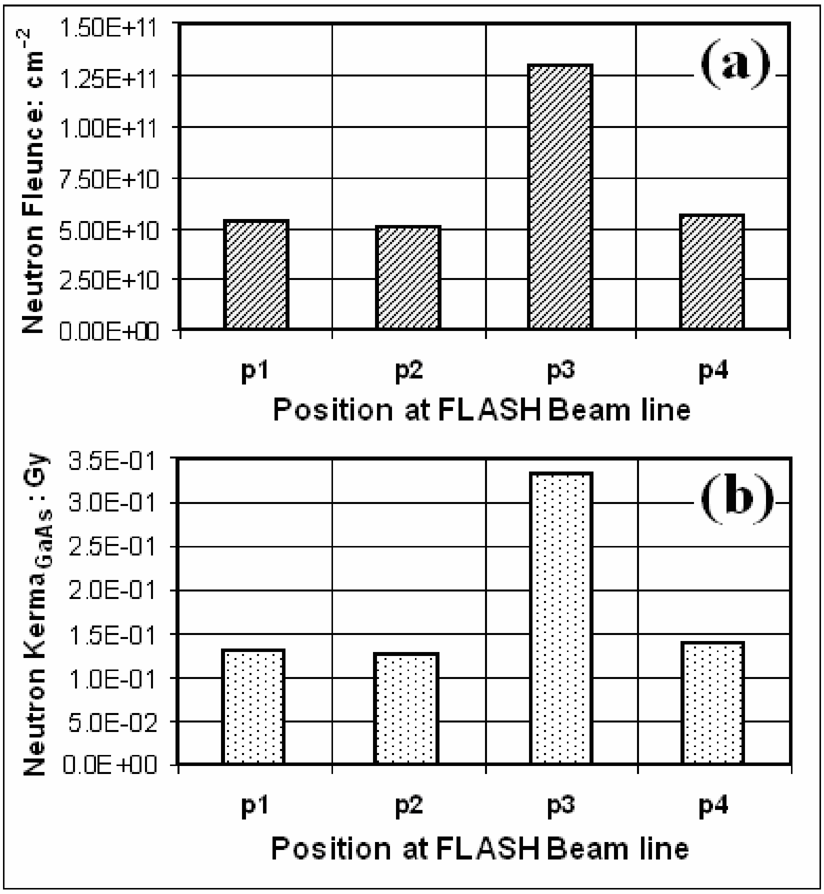

Figure 7: Showing the neutron fluence (a) and kerma (b) at selected locations along the FLASH beam line evaluated using commercial off the shelf (COTS) GaAs LED.

SUMMARY AND CONCLUSION

We have presented the operating principle and an application example of a simple, cost effective passive neutron detector based on commercially off-the-shelf (COTS) GaAs Light Emitting Diode (LED). We have developed a simple and inexpensive photometer for assessing the light output of the LED instead of a sophisticated current monitor based on expensive operational (instrument) amplifiers to measure the diode leakage current.

Unlike Si-microelectronic devices, the GaAs LEDs have no insulating oxide layer to trap the ionising radiation induced charge. For this reason, the GaAs devices are insensitive to total ionising dose (TID) effects caused by gamma radiation. That makes the GaAs LED an ideal candidate as a displacement damage (or NIEL) detector, consequently a fast neutron fluence monitor with a very high gamma discrimination property.

The response of the GaAs-LED neutron detector depends on neutron energy, hence, must be calibrated using neutrons with a well-known energy distribution, such as the ^{241}Am/Be (α, n) source. The batch inhomogeneity of the selected un-irradiated GaAs LED was ± 1%. On the other hand, light outputs of the same groups of LED after irradiation with neutron and gamma rays show a higher standard deviation (± σ) as demonstrated in Table 1. This confirms the influence of ambient temperature during the radiation exposure and irradiation geometry (i.e. distance between radiation source and detector) on the sensitivity of the LED dosemeters. The very small active volume (Space Charge Zone) renders the sensitivity (lowest detection level) of the LED neutron detectors to be quite low. Therefore, the applications of the LED based neutron detectors are restricted to cases with high neutron fluence, like the testing and commissioning of high-energy accelerators and long term neutron monitoring in the direct vicinity of accelerators. The very small size and negligibly low cost allow for the possibility of deploying a large number LED neutron detectors, thereby facilitating the neutron fluence and kerma (displacement damage) mapping within a large area, i.e. the accelerator hall. We are now using these GaAs-LED neutron detectors during routine operation of FLASH [9].

A typical set of results is shown in Figure 7. The almost same values of neutron fluence (kerma) at the measurement point p1, p2 and p4 were predominantly caused by the interaction of field emission/dark current [10] electrons with the beam line components. On the other hand, the higher neutron level at position p3 was certainly caused by the direct hit of defocused high-energy electrons with the internal wall of the bunch compressor BC #3 (Figure 3).

Our future plan is to apply these COTS devices to detect the field emission induced neutron generation during the manufacture of high gradient (35 MV/m) superconducting Niobium cavity [6] for the future European X-Ray Free Electron Laser (XFEL). Another prospective application of this device will be the neutron fluence detection within the critical areas of a fusion reactor [11] producing an intense field of 14.7 MeV neutrons. The information will be of great value for predicting the neutron-induced damage to the first wall and structural materials of the future International Thermonuclear Experimental Reactor (ITER).

REFERENCES

[1] Brinkmann, R. *Accelerator Layout of the XFEL*, Linac 2004 Conference, pp.2-4, June 2004, Lübeck, Germany.

[2] Griffin, P. J., Kelly, J. G., Luera, T. F., Barry, A. L. and Lazo, M. S. *Neutron Damage Equivalence in GaAs*, IEEE Trans. on Nucl. Science **NS38**, 1216-1224 (1991).

[3] Barry, A. L., Wojcik, R. and MacDiarmid, A. L.. *Response of GaAs Displacement Damage Monitors to Protons, Electrons, and Gamma Radiation*, IEEE Trans. on Nucl. Science **NS36**, 2400-2404 (1989).

[4] International Standard Organisation. *Reference Neutron Radiations- Part 1: Characteristics and Methods of Production, ISO 8629-1*, Geneva,(2001).

[5] Ougouag, A. M., Williams, J. G., Danjaji, M. B., Yang, S. Y. and Meason, J. L. *Differential Displacement Kerma Cross Sections for Interactions in Si and GaAs*, IEEE Trans. on Nucl. Science **NS37**, 2219-2228 (1990).

[6] Silari, M., Agosteo, S., Gaborit, J-C. and Ulrici, L. *Radiation Produced by the LEP Superconducting RF Cavities*, Nucl. Instr. Meth. Phys. Res. **A432**, 1-13 (1999).

[7] Tesch, K. *Data for Simple estimate of Shielding against Neutrons at Electron Accelerators*, Particle Accelerators **9**,101-106 (1979).

[8] Mukherjee, B., Makowski, D. and Simrock, S. *Dosimetry of High-energy Electron Linac produced Photoneutrons and Bremsstrahlung Gamma rays using TLD-500 and TLD-700 Dosimeter Pairs*, Nucl. Instr. Meth. Phys. Res. **A545**, 530-541 (2005).

[9] DESY Website: http://vuv-fel.desy.de/

[10] Furuta, F., Suzuki, C., Nakanishi, T., Okumi, S., Gotou, T., Yamamoto, M., Nishitani, T., Miyamoto, M., Kuwahara, M., Hiroe, T., Mizuno, R., Yamamoto, N., Kobayakawa, H., Matasumo, H. and Yoshioka, M. *Measurement of Field Emission Dark Current from the Titanium, Copper, and Stainless Steel Electrodes under the High DC-Field Gradient Condition*, Linac 2002 Conference, pp.433-435, May 2002, Gyeongju, Korea.

[11] Ibarra, A. and Hodgson, E. R. *The ITER Project: The Role of Insulators*, Nucl. Instr. Meth. Phys. Res. **B218**, 29-35 (2004).