Comparison of experimental and MCNP6 results for a LUPIN-II neutron REM-meter at the UPM neutronics hall

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Abstract. LUPIN-II is a recently developed wide-range neutron REM-meter. Designed for the control of the ambient dose equivalent H*(10) due to neutron fields generated in high-energy pulsed facilities, like high-energy particle accelerators. Hence, the characterization of this device could be very useful for different applications. The aim of this work was to develop and test a realistic model of the LUPIN-II REM-meter for the Monte Carlo code MCNP6, which could be used for different application scenarios, like those in hadron therapy facilities. A detailed realistic model of the neutron area monitor was designed in MCNP6, integrating this design in a previous MCNP6 model of the UPM neutronics hall. Some irradiation tests were performed at this facility at different source-to-detector distances and the simulations with MCNP6 code were compared to the experimental results. These results have been also compared with those obtained with a conventional Berthold LB 6411 neutron REM-meter.

KEYWORDS: REM-meter; LUPIN-II; MCNP6; UPM neutronics hall; Berthold LB 6411.

1 INTRODUCTION

The growth of hadron and proton therapy centres all over the world entails the need to have radiation monitors able to provide radiation protection measurements in high-energy and pulsed neutron fields. One of these new radiation monitors is the LUPIN-II detector [1], an evolved version of LUPIN (Long interval, Ultra-wide dynamic, Pile-up free, Neutron REM counter) [2].

The application of LUPIN-II has been demonstrated in different radioactive facilities with particle accelerators such as the HZB cyclotron [1, 3], the CERN HiRadMat [1], the Aarhus Storage Ring [4], the CERN PS Accelerator [1], or the free-electron laser facility SwissFEL [1].

In particle accelerators, the tests at different source-to-detector distances are often more toilful than in laboratories based on isotopic sources. Therefore, before their application in high-energy fields and particle accelerator facilities, it is convenient to test radiation monitors in facilities with isotopic neutron sources in order to characterize, benchmark and check their correct behaviour. LUPIN-II has been tested in laboratories having ^{241}AmBe neutron sources, like those of Politecnico di Milano [1] or Universidad Politécnica de Madrid (UPM) [5].

The use of reliable neutron detection systems, such as LUPIN-II, Berthold LB 6411 [6, 7] or DIAMON [8], is essential for ambient radiation surveys because of the large variability of dose quantities with neutron energy [9], the response function of an area monitor is a unique feature of each device. One of the dosimetric magnitudes for the radiation protection control in neutronics halls is the ambient dose equivalent, H*(10), which depends on the neutron spectrum and the fluence-to-ambient dose equivalent conversion factors.

The neutron fluence in experimental neutronics halls, like the UPM neutronics hall [10], diverges from the theoretical inverse-square distance law due to the increment with the distance of the in-and-out scattering neutron phenomena [11], and for this reason, the H*(10) also diverges from the $1/r^2$ rule. In area monitors, the measurements in function of the distance also diverge from the $1/r^2$ law, due to the divergence associated to the neutron fluence evolution with the distance and due to the own response

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function of each neutron area monitor [12], so this fact ought to be taken into account in experimental measurements with rem-meters, at different source-to-detector distances, such as the measurements exposed in this work.

The aim of this work was to compare experimental measurements and numerical Monte Carlo results with the general-purpose Monte Carlo N-Particle code MCNP6.2 [13], of LUPIN-II rem-meter at the UPM neutronics hall. Likewise, these results have been compared with experimental measurements obtained with another neutron monitor, Berthold LB 6411. The comparison of experimental measurements and MCNP6.2 calculation results, allows benchmarking theoretical and experimental data, validating the designed MCNP model and establishing mathematical correlations between the response of LUPIN-II rem-meter with the neutron fluence and the deposited energy over its active volume.

2 MATERIALS AND METHODS

2.1 Experimental measurements

The UPM neutronics hall is a radioactive facility employed to calibrate and test neutron radiation monitors [10] and with the capacity to irradiate materials with thermal neutrons [14-16]. This facility has an irradiation bench made of steel, in which can be automatically positioned a monitor at different distances within 0.1 mm precision with respect to a ^{241}AmBe neutron source [10]. The current UPM irradiation bench is not the first bench employed in this hall for calibrating and testing rem counters, previously an irradiation bench made of aluminium was already used for this purpose [17].

In this experimental facility, the neutron spectra at the irradiation bench in function of the source-to-detector distance has shown in previous studies the presence of thermal and epithermal neutrons, which are mainly produced due to the collision of source's neutrons with the floor, the walls of the hall and the ceiling [10]. These collisions provoke the appearance of moderated returning neutrons [11,18,19]. This fact is related to the almost constant thermal and epithermal neutron fluence in the room, whereas the neutron fluence of neutrons with energies of 0.1-10 MeV decreases with the increment of the source-to-detector distance [10].

In this work, two neutron area monitors, LUPIN-II and Berthold LB 6411, have been employed at the UPM neutron irradiation facility to obtain experimental H*(10) values, at different distances of a 111 GBq ^{241}AmBe neutron source. The mean source intensity has been corrected for the date of the experiments to 5.73 E+6 neutrons per second, taking into account its radioactive decay. Originally, in the year 2009, the source had an emission intensity of (5.83±0.14) E+6 neutrons per second [20].

The source-to-detector distances chosen for experimental measurements were 50, 80, 100, 115, 130, 150 and 180 cm, respectively. Thus, this work shows more experimental measurements with a LUPIN-II monitor at the UPM neutronics hall than the previous work developed by authors [5], which just shows data about one experimental measurement at a distance of 115 cm. Moreover, this work also shows one extra experimental measurement (50 cm) with respect to the distances evaluated in [10], in which these measurements were carried out with the same Berthold LB 6411 monitor employed in this work.

Thereby, an experimental comparison of a conventional rem-meter (Berthold LB 6411) and an entended-range monitor (LUPIN-II) is presented in this work, evaluating the overestimation of the H*(10) of both counters in function of the source-to-detector distances, interpolating this overestimation using a spline interpolation technique from the experimental points.

2.1.1 LUPIN-II

The LUPIN-II rem-counter is a device designed as a solution for measuring efficiently in facilities with pulsed neutron fields, for instance, those with particle accelerators such as cyclotrons or synchrotrons, covering a lack in area monitors empty until its development. This monitor is the second version of the

LUPIN monitor [2], showing improvements related to its discrimination properties and the maximum detectable H*(10) per burst [1].

The LUPIN-II is a detector with a BF_3 active volume embedded in an active tube Centronics 15EB/20/25SS, with an active length equal to 15 cm, a diameter equal to 2.5 cm and a gas pressure of 20 cmHg. For this reason, the LUPIN-II detects neutron radiation through the reaction $^{10}B(n,\alpha)^{7}Li$, which has a higher Q-value than the reaction $^{3}He(n,p)^{3}H$ employed for neutron detection in LUPIN, this fact provides to LUPIN-II of a better photon rejection [1].

The external dimensions of the LUPIN-II, if the front-end electronics are not taken into account, are 29.7 cm in height and 25 cm in diameter [1] (cylindrical shape; ±20% angular dependence). This device operates at 1180 V [1] and for its readout is used a fast current to voltage logarithmic amplifier [21], a general scheme of the detector electronics can be found in [2,4]. The construction of this monitor is based on a polyethylene cylinder in which are inserted the active tube Centronics 15EB/20/25SS, a Pb layer that permits to extend its response function, 5 small cadmium cylindrical inserts of different dimensions to compensate an over-sensitivity for neutrons with energies of the order of keV, and an electrostatic cylindrical shielding of aluminium with a thickness of 1.5 mm [1].

In Fig.1 is shown the experimental setup of the LUPIN-II rem-counter at the irradiation bench of the UPM neutronics hall, in this figure can also be observed the pneumatic system that allows safely shifting the monitor to different distances from the neutron source.

Figure 1: Experimental setup with the LUPIN-II monitor at the UPM neutronics hall.

2.1.2 Berthold LB 6411

The Berthold LB 6411 is a conventional rem counter whose optimum detection energy range is from thermal up to 20 MeV neutrons [6], for which this is not an extended-range neutron detector, although there is a version of this detector (LB 6411-Pb) with an extended-range response. This monitor, which was developed in a collaboration between the Research Center Karlsruhe and the EG&G Berthold, is externally a polyethylene moderator sphere with a diameter of 25 cm and 4 feet. Moreover, this monitor has an electronic housing and a handle in the upper part of the polyethylene sphere [6].

The counter tube of this detector is a cylindrical tube made of stainless steel filled with ^{3}He and CH_4, with partial pressures of 3.5 bar and 1 bar respectively [6], for which the neutron detection reaction in which is based this counter tube is the nuclear reaction $^{3}He(n,p)^{3}H$. Apart from the counter tube, the polyethylene sphere also includes perforations and internal Cd-absorbers, which allows improving the response function of this detector at intermediate energies.

The weight of this detector is below 10 kg; therefore, it is lighter than the LUPIN-II, whose total weight is 18 kg. One of the reasons for this important difference is the spallation layer that contains the LUPIN-II for extending its application range to energies higher than 20 MeV.

2.2 Monte Carlo calculations

Modelling and calculations have been performed with the general-purpose Monte Carlo N-Particle code version 6.2. For the laboratory, a previous detailed model of the UPM neutronics hall [10] was updated, adding the LUPIN-II detector, shifting the monitor and the base of the irradiation bench to those positions previously mentioned in section 2.1.

Moreover, different simulations were performed at the simulated UPM neutronics hall without including the LUPIN-II monitor in the model, these simulations allowed updating the H*(10) values at the irradiation bench, executing these simulations with the detector base shifted without any detector to the different selected distances.

The original MCNP model of the UPM neutronics hall already used in [10] was not modified in terms of the nuclear data libraries defined for the hall and the irradiation bench materials, but for the definition of the LUPIN-II detector the ENDF/B-VII.1 nuclear data library [22] was employed for defining all the materials, thermal scattering laws $S(\alpha,\beta)$ were taken into account in polyethylene and aluminium through the ENDF71SaB thermal cross-section library cards (poly.20t and al27.22t).

The LUPIN-II MCNP model was developed following the work in Geant4 of Cassell (2016) [23], in which the monitor is modelled as a volume of gaseous BF_3 with a thin aluminium casing, including also the polyethylene, cadmium and lead parts, and a small polyethylene plug. To ensure the reliability of results, all simulations with the LUPIN-II at the irradiation bench were carried out with 7E+7 histories, achieving relative statistical uncertainties between 1.17% and 3.81%, passing all the simulations the MCNP 10 statistical checks for the tally fluctuation chart bin results.

Although previous works developed by authors already simulated by MCNP6 the behaviour of LUPIN-II at the UPM neutronics hall [5, 24], these simulations were carried out for a lower number of source-to-detector distances, and employing a less detailed and accurate LUPIN-II model, with more important simplifications in the complex modelling of this monitor. Hence, this work presents lower differences between experimental and computational results.

In the MCNP simulations without the LUPIN-II detector at the UPM irradiation bench, a sufficient number of histories have been also applied in order to obtain relative statistical uncertainties lower than 2.2% for volume detectors and much lower than 1% for point detectors.

For simulating in MCNP the dose rate measured by the LUPIN-II at the UPM neutronics hall the output provided by MCNP, of MT107 nuclear reactions at the BF_3 active volume of the detector, was multiplied by the source intensity (5.73E+6 n/s) and divided into the neutron sensitivity of the device (0.6 cps/µSv/h).

3 RESULTS

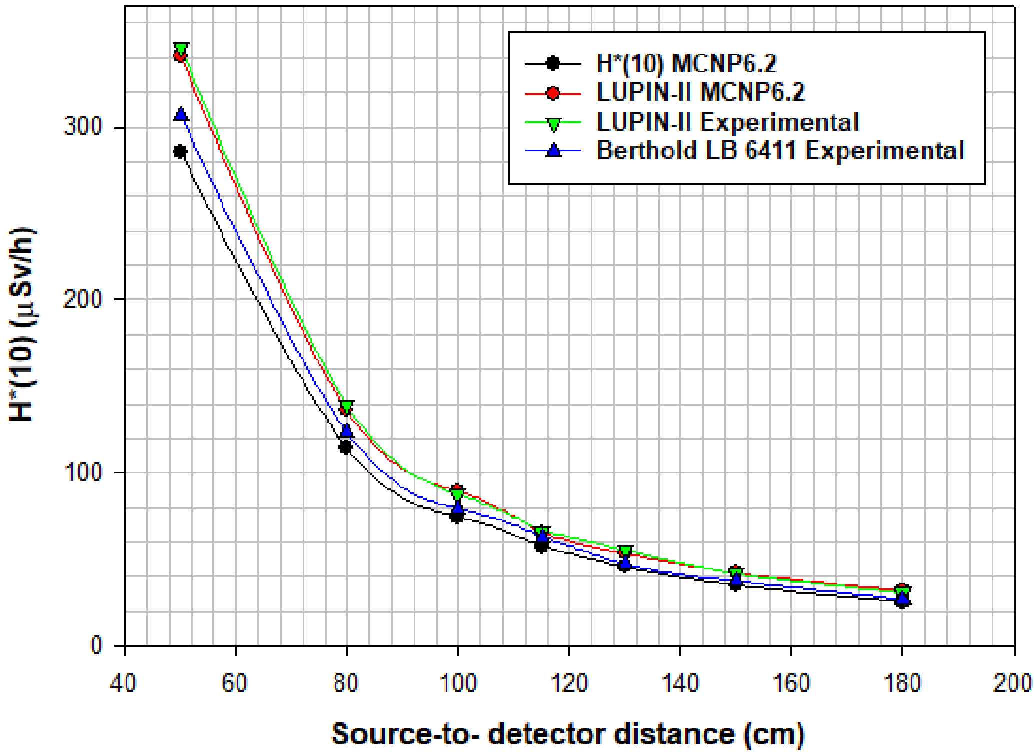
A comparison of all the results reached by both, experimental and numerical methods, is shown in Fig.2. As it can be seen in the graph, LUPIN-II MCNP results present small fluctuations, overestimations and underestimations in the whole range of distances, that can be considered negligible. In addition, the figure allows comparing experimental measurements of the H*(10) with two different area monitors, a conventional detector (Berthold LB 6411) and an extended-range monitor (LUPIN-II), showing how the response of the Berthold LB 6411 is closer to the calculated H*(10) values, with the detector shifted to each distance (error bars have not included in this figure because these lines would be hidden for the symbols, due to the low statistical uncertainties).

The closer response of the Berthold LB 6411 to the H*(10) values with respect to the results provided by the LUPIN-II was expected, because of the spallation reactions that happen in the LUPIN-II lead layer increase the neutron fluence over the active volume and therefore the number of counts. A comparison of the dose response functions of both rem-meters can be found in [25], showing the LUPIN-II function higher values in almost the whole range of energies (thermal-epithermal-evaporation).

However, Berthold LB 6411 overestimates the H*(10) values in the whole range of distances, even providing a better estimation than the LUPIN-II, which is aligned with the data about the relative dose response function of this detector provided in [6, 7].

The variation, depending on the distance, of the relative deviation between MCNP results, experimental measurements, and calculated H*(10) values, are collected in Fig.3. From the figure, it is possible to estimate how the results obtained by MCNP6.2, about the response of the LUPIN-II at the UPM irradiation bench, deviate from the experimental results with a relative error between 2.87% and -3.67%, the maximum overestimation occurs at 180 cm and the maximum underestimation at 130 cm.

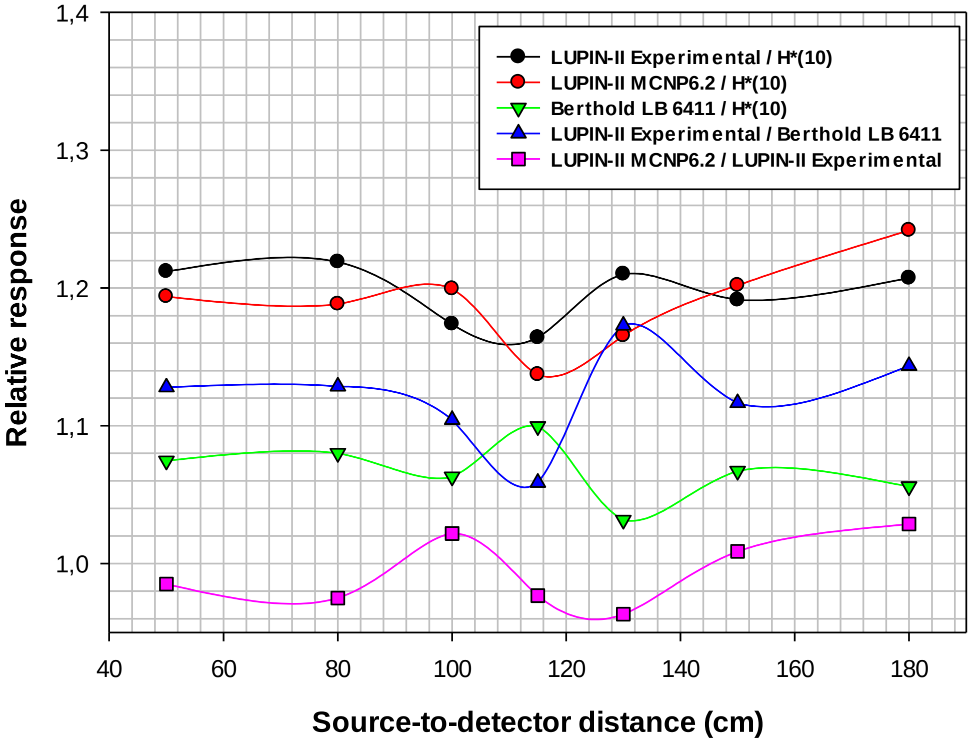
Figure 2: H*(10) values obtained by different methods at the UPM neutronics hall.



The variation of the relative error, probably in part consequence of the simplification assumed in base on [23] due to the complexity of the detector, is not constant and is lower than 2.51% for all the measurements at distances shorter than 130 cm, for all these distances there is an underestimation except for 100 cm. The MCNP6 model predicts almost without error (0.88%) the experimental response of this detector, at the UPM neutronics hall, at 150 cm. These data suppose an important improvement with respect to the comparison at 115 cm established in [5], so the MCNP model has been refined following the principle of continuous improvement established by the UPM neutronics hall staff.

The existence of a discordant point at 100 cm in the variation of the relative response between MCNP simulations and experimental measurements is not unique for this case. As it can be seen in Fig.3 there are important fluctuations in the relative deviations of all the comparisons carried out for distances larger than 80 cm and shorter than 150 cm.

Figure 3: Relative response between the different methods.



The fluctuations that can be observed in Fig.3 for a certain range of distances (80-150 cm) could be a consequence of the sum of the changes in the spectra of the neutron fluence that affects the active volume of the detectors, a consequence of; the materials that constitute the detectors (the fluctuations do not have the same shape for both detectors and the most significant fluctuation occurs comparing the experimental measurements of both monitors) and the decrease of the neutron fluence with energies between 0.1 MeV and 10 MeV with the distance [10], whereas the epithermal and thermal neutron fluence remains almost constant, due to the effect of the elements that compose the room and the irradiation bench.

Apart from benchmarking the results, the MCNP calculations have allowed estimating the neutron fluence and the deposited energy by neutron radiation in the active volume of the LUPIN-II, the correlation of the evolution of these magnitudes with the number of counts in the active volume of the detector has been estimated using the Karl-Pearson correlation. The results have shown that the energy deposition and the number of counts have a Karl-Pearson correlation equal to 1 (perfect and strong positive correlation), whereas the neutron fluence and the number of counts have a Karl-Pearson correlation of 0.99996, a very strong positive and practically perfect correlation.

4 CONCLUSIONS

The main objective of this work has been fulfilled; a comparison between experimental and Monte Carlo results has been established for the LUPIN-II neutron detector at the UPM neutronics hall, reaching a good correlation between both for all the distances. The H*(10) values for different distances at the irradiation bench of the UPM neutronics hall have been updated with new calculations in MCNP6.2.

The low deviations obtained in this work between experimental and Monte Carlo results confirm the improvements carried out at the LUPIN-II simulation model developed by the UPM, previous works [5, 24] included simplifications that introduced additional errors. Thus, this MCNP model could be applied for its future application in similar calculations in other facilities.

Moreover, this work has compared experimentally the behaviour of two neutron rem-meters, a conventional detector (Berthold LB 6411), and an extended-range monitor (LUPIN-II). The results show how the conventional detector Berthold LB 6411 overestimates the value of H*(10) by an average of 6.74% in a ^{241}AmBe field, whereas the mean overestimation in the measurements with LUPIN-II is 19.68%. The most interesting part is the significant variation that the relative response of both detectors shows for source-to-detector distances between 100 cm and 150 cm, for instance, this relationship (LUPIN-II / Berthold LB 6411) is equal to 1.0586 for 115 cm and equal to 1.1728 for 130 cm.

In summary, this work presents important information about the experimental estimation of the H*(10) values in a ^{241}AmBe neutron field with a LUPIN-II at different source-to-detector distances, which has never been reported before in the bibliography for a number of distances as high as in this work, most of the experimental data exposed about LUPIN-II are referred to particle accelerators and pulsed neutron fields. Hence, this work characterizes and benchmarks the behaviour of this monitor in a facility with an isotopic neutron source, providing new data and comparing these data with those obtained with a Berthold LB 6411.

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