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Fast Neutron Fluence Profiling at the JSI TRIGA Reactor Irradiation Facility

[a,b]**Valentina Sola**, [c]**Igor Mandić**, [c]**Klemen Ambrožič**, [b]**Marco Ferrero**, [c]**Gregor Kramberger**, [c]**Luka Snoj**

[a] Università degli Studi di Torino
via P. Giuria 1
10125, Torino, Italy

[b] INFN, Sezione di Torino
via P. Giuria 1
10125, Torino, Italy

[c] Jožef Stefan Institute
Jamova cesta 39
1000, Ljubljana, Slovenia

valentina.sola@unito.it, igor.mandic@ijs.si, klemen.ambrozic@ijs.si, marco.ferrero@to.infn.it, gregor.kramberger@ijs.si, luka.snoj@ijs.si

ABSTRACT

We present the results of feasibility tests on using Low-Gain Avalanche diodes (LGAD) for fast neutron fluence monitoring. The LGAD's, where boron acceptor doping in the gain layer is deactivated by incident neutrons, changing their electrical characteristics. Their characterization of response to neutrons is given in terms of the fluence, equivalent to the fluence of neutrons at energy of 1 MeV: $\phi_{eq}(1\,\text{MeV})$, and is characterized by a response function. This functions has the value close to 1 for neutron energies $E > 100$ keV, and orders of magnitude lower at lower energies. An assembly of LGAD chips was irradiated in the Jožef Stefan Institute TRIGA reactor. The irradiation experiment was closely reproduced by Monte Carlo particle transport simulations, addressing some of the experimental uncertainties. We show that agreement between LGAD's measured response and calculated fast neutron fluence to be within the uncertainties. This highlights the possibility of using LGADs as an on-line fast neutron fluence monitor during various sample irradiaitons.

1 INTRODUCTION

In recent years, the increased sensitivity of the silicon devices to the effects of radiation lead to the discussion, whether they can be used to monitor the neutron fluence dispersion during neutron irradiation testing of detectors and read-out electronics [1] for High energy Physics experiments. Low-Gain Avalanche Diodes (LGADs) in particular seem to be a suitable candidate for precise fluence mapping. These are n-in-p silicon sensors, which have a highly p-doped region close to the n-electrode, called gain implant. These create a local enhancement of the electric field responsible for the charge carrier multiplication [2]. The difference between a traditional diode and LGAD is schematically displayed in Figure 2. The effect referred to as acceptor removal [3] is well characterized and tested [4] and occurs due to neutron interactions with boron dopants, deactivating it's effect on the gain layer by incident neutrons. Their small size and sensitivity makes them suitable for neutron fluence dispersion measurements. Neutrons at different energies cause different amount of damage to the bulk silicon i.e. the damage function is dependent on the energy of an incident neutron. A neutron damage equivalence is commonly used in high energy physics field, where the incident neutron fluence ϕ is scaled to an equivalent fluence $\phi_{eq}(1\,\text{MeV})$ via equivalence factors, as denoted in Figure 1. Since these factors are of the order of ≈ 1 in the energy range above $100\,$keV and orders of magnitude below, the $\phi_{eq}(1\,\text{MeV})$ is a good indicator of neutron fluence with energies above $100\,$keV.

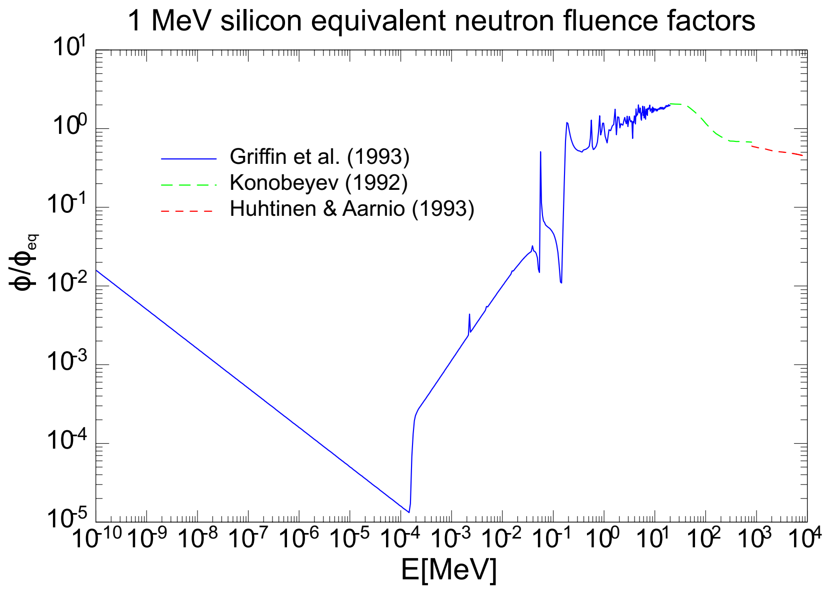


Figure 1: Scaling factors for assessing $\phi_{eq}(1\,\text{MeV})$ [1].

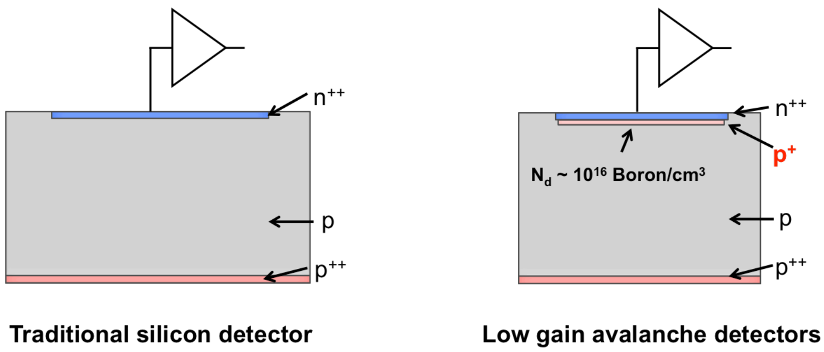


Figure 2: Schematic cross section of traditional diode and LGAD. Adopted from [4].

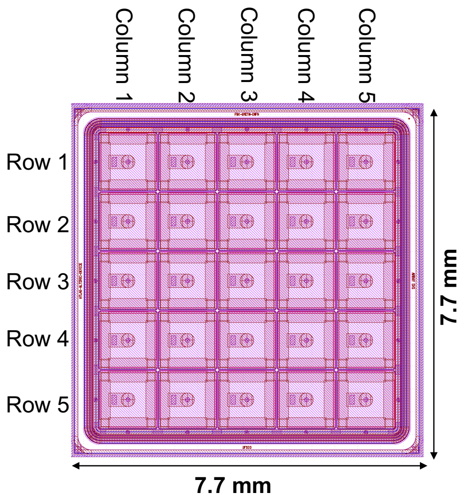
The paper gives an insight on the LGAD operation, experimental testing of an assembly of LGADs in the F19 irradiation channel of the Jožef Stefan Institute (JSI) TRIGA reactor and comparison with results obtained by Monte Carlo particle transport simulations, including the self-shielding and uncertainties due to the unknown orientation of the LGADs assembly during the experiment.

2 LOW GAIN AVALANCHE DIODES AND EXPERIMENTAL ASSEMBLY

Compared to standard silicon diodes, LGADs have a moderate internal gain, thanks to the addition of a highly p-doped region close to the n-electrode, which generates a very high electric field region, usually in the form of boron acceptor. The determination of the active acceptor concentration is performed via a capacitance-voltage (C-V) measurement. The bias voltage at which the gain layer is depleted corresponds to a significant drop in measured capacitance is commonly known as the knee, and indicated as V_{GL}. In practice a fixed capacitance value in close proximity of the knee is selected as an indicator for V_{GL}. The effective concentration of the acceptors N_A in the gain layer decreases due to neutron irradiation introducing defects in silicon, which effectively decreases it's effect as a dopant, thus lowering the required bias voltage V_{GL} to obtain the same capacitance, as described by Equation 1, where c denotes a constant characterized by the likelihood of neutron deactivation of boron as acceptor, and Φ the incident neutron fluence.

$$\frac{V_{GL}(\Phi)}{V_{GL}(0)} = \frac{N_A(\Phi)}{N_A(0)} = e^{-c\Phi} \tag{1}$$

In the present work, LGAD chip arrays of 7.7 mm $\times$ 7.7 mm package consisting of 5×5 individual diodes (Figure 3a) from wafer 1 of the FKB USFD2 production batch [5] were used for fast neutron fluence mapping. An assembly of 8 LGAD chips (Figure 3b) mounted on a FR4 board and covered by Capton tape was constructed. The assembly as irradiated inside a plastic container in the F19 channel of the JSI TRIGA reactor at full power of 250 kW. The goal was to irradiate these samples with a 1 MeV fluence equivalent $\phi_{eq}(1\,\text{MeV})$ up to 1.5×10^{15} cm^{-2}. The time to achieve this was estimated as 926 s.



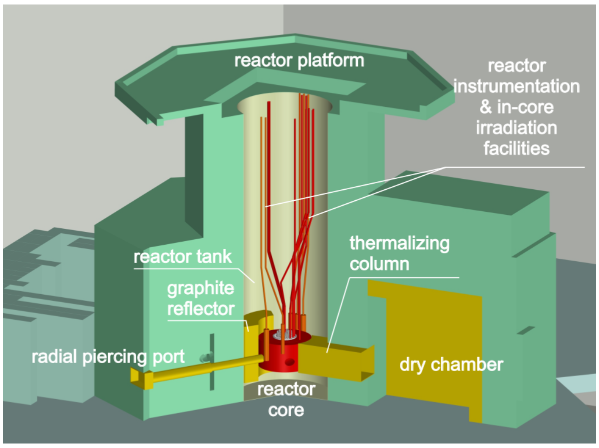
(a) 5×5 LGAD array on a single chip.

(b) Assembly of the 8 LGAD chips on FR4 board, wrapped in Capton tape.

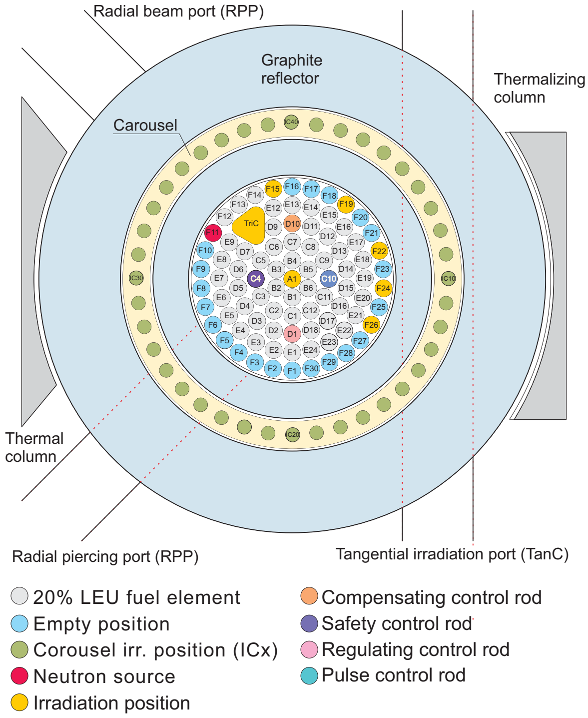
Figure 3: LGAD arrays and assembly for irradiaiton in the JSI TRIGA reactor.

3 JSI TRIGA REACTOR

The JSI TRIGA reactor is a pool type research reactor (Figure 4a) with maximum steady state thermal power of 250 kW. The core consists of 91 positions, 4 of which are filled with control rods, while the rest can be either empty, filled with fuel elements or irradiation positions (Figure 5 left), which can be loaded with samples the reactor platform or via a pneumatic post system. The reactor is commonly utilized for study of radiation tolerance and irradiation of electronic components used in High energy particle physics and is a reference neutron irradiation facility for CERN [1], mainly inside the reactor core, in the F19 position. The reactor core configuration used during the irradiation of the LGAD chip assembly is displayed in Figure 4b. The LGAD chip



(a) 3D model of the JSI TRIGA reactor and some ex-core irradiation positions.



(b) Core loading, used during the experiment.

Figure 4: Schematic view of TRIGA reactor and its core.

assembly was inserted inside a polyethylene container and lowered into the irradiation position from the reactor platform. The axial orientation of the chip assembly could not be controlled, as schematically shown in Figure 5 on the right.

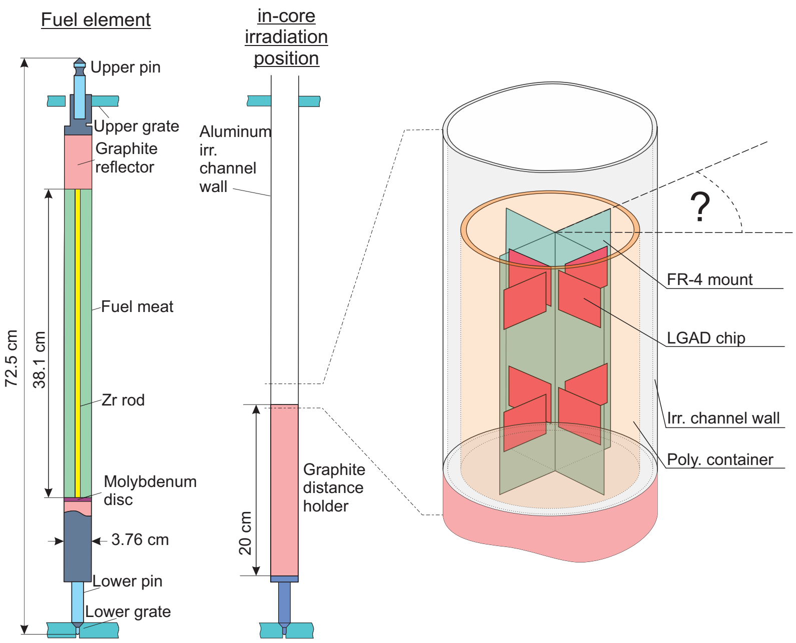


Figure 5: Schematic of TRIGA fuel element and an irradiation channel (left) and the schematic of the LGAD chip assembly during irradiation (right).

4 EXPERIMENT

The C-V characterization of individual LGAD diodes was performed prior to the irradiation using a Keysight B1505A Power Device Analyzer. A high voltage source-monitor unit was used together with a multi-frequency capacitance measurement unit. The frequency of the AC signal was set to 1 kHz with a voltage amplitude of 50 mV. A parallel capacitor-resistor model was used to obtain the capacitance value. The probe station chuck was negatively biased, and one probe needle was at 0 V moved over the 25 pads of each LGAD array. An additional probe needle at 0 V was used to power the guard ring and collect the dark current from the sensor periphery and reduce the noise. The constant c from Equation 1 is assumed to be constant for all LGADs due to a low initial doping variation below 2 % [6]. The fixed capacitance value of 150 pF close to the knee was selected.

After the pre-irradiation measurement of V_{GL}, the reactor was started to the full reactor power of 250 kW and the LGAD chip assembly was inserted into the F19 channel for 926 s in order accumulate $\phi_{eq}(1\,\text{MeV}) = 1.5 \times 10^{15}$ cm^{-2}. Similar C-V measurement was performed after the irradiation. The difference between C-V curves prior and after the irradiation can be observed in Figure 6.

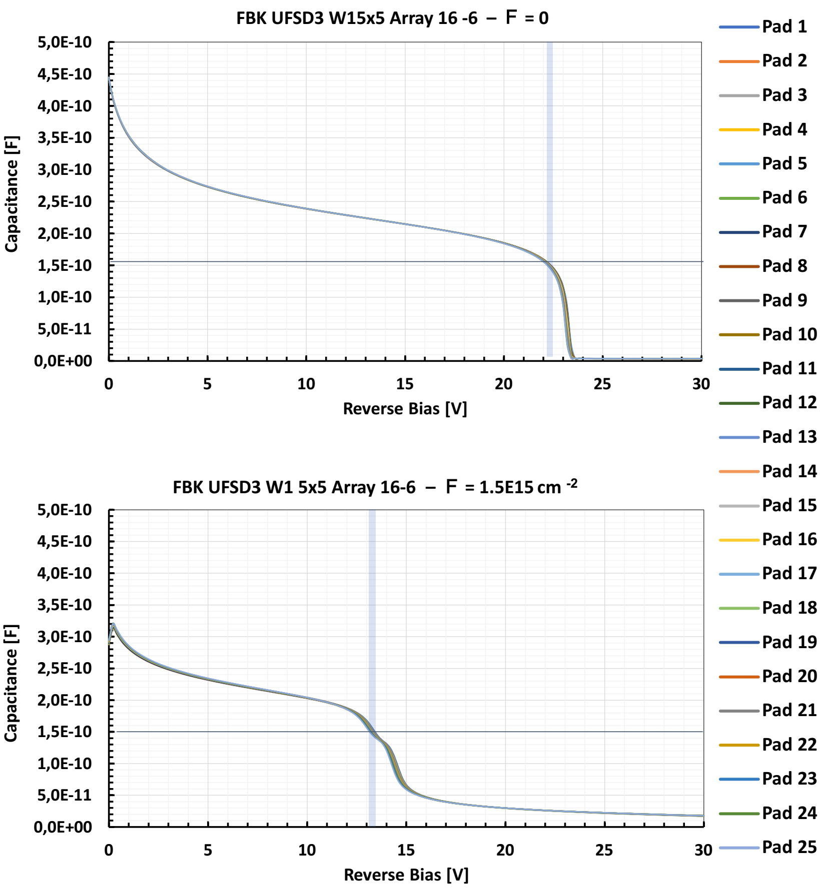


Figure 6: C-V characteristics measurement of a single LGAD chip array prior (top) and after the irradiation (bottom).

5 EXPERIMENT MODELING

A Monte Carlo particle transport calculation was performed to support the irradiation of the LGAD chip assembly. The simulations were performed using the MCNP v6.1 code [7] and ENDF/B VII.0 nuclear data libraries [8]. A detailed model of the JSI TRIGA reactor was used, which has been validated by a number of experiments [9, 10, 11, 12], and modified accordingly, to reflect the experimental setup during the irradiation. Since the axial rotation of the LGAD chip assembly was unknown during the irradiation, two distinct orientations of the assembly were simulated. The ray-traced model of the JSI TRIGA reactor MCNP model and the two distinct orientations of the LGAD assembly are displayed in Figure 7. Neutron fluence with neutron energy above 100 keV were tallied over each individual chip, as well as over individual diodes on a chip. A mesh was superimposed over the entire assembly to help visualise the changes in the fast ($E_n > 100$ keV) neutron field, as displayed in Figure 8.

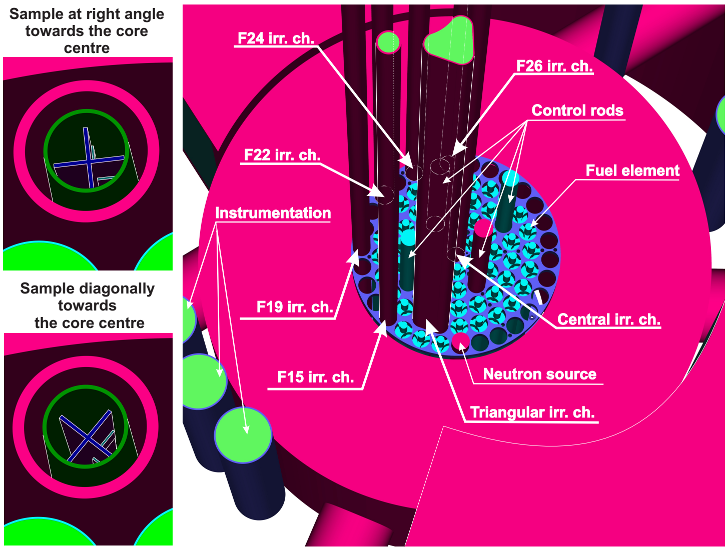


Figure 7: Ray-traced MCNP model of the JSI TRIGA reactor, with two different orientations of the LGAD chip assembly.

6 EXPERIMENT VS. MODEL

The experimental results were obtained from measurements of V_{GL} difference. Average $\phi_{eq}(1\,\text{MeV})$ over a single LGAD chip array was calculated, with $\phi_{eq}(1\,\text{MeV})$ from individual diodes serving as an estimate of dispersion. Similar technique was used for assessment of uncertainty from calculations, combined with the statistical uncertainty of the Monte Carlo particle transport simulations. Although the axial orientation of the assembly was unknown, the results were closely matched to those from the simulations in the perpendicular orientation. The comparison of experimentally obtained $\phi_{eq}(1\,\text{MeV})$ against the calculated fast neutron flux $\phi(E_n > 100\,\text{keV})$ can be observed in Figure 9. One can observe that the two results are generally in agreement within the uncertainty except for Chip 2, which is very encouraging, considering two different quantities are compares and that the orientation of the LGAD assembly during the irradiation was unknown. This highlights the possibility of using such detectors as an on-line fast neutron flux monitor.

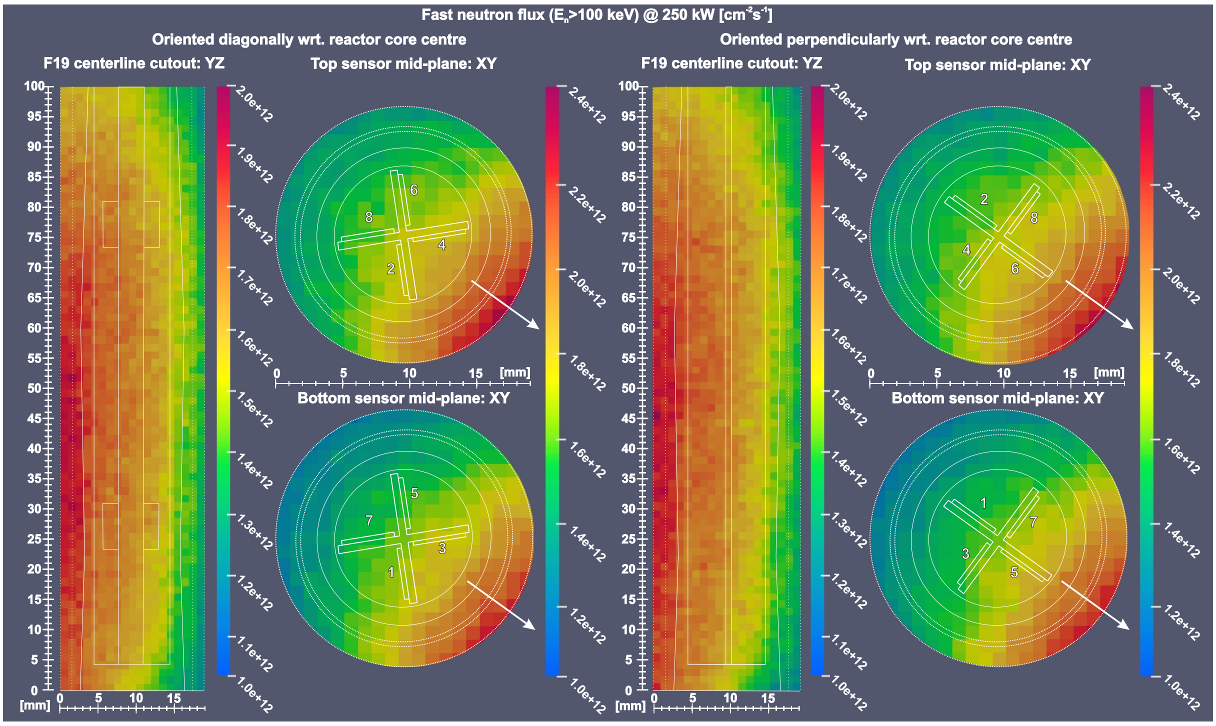


Figure 8: Fast neutron flux over the LGAD chip assembly inside the F19 channel at two axial orientations. The arrow denoted the direction towards the core centre.

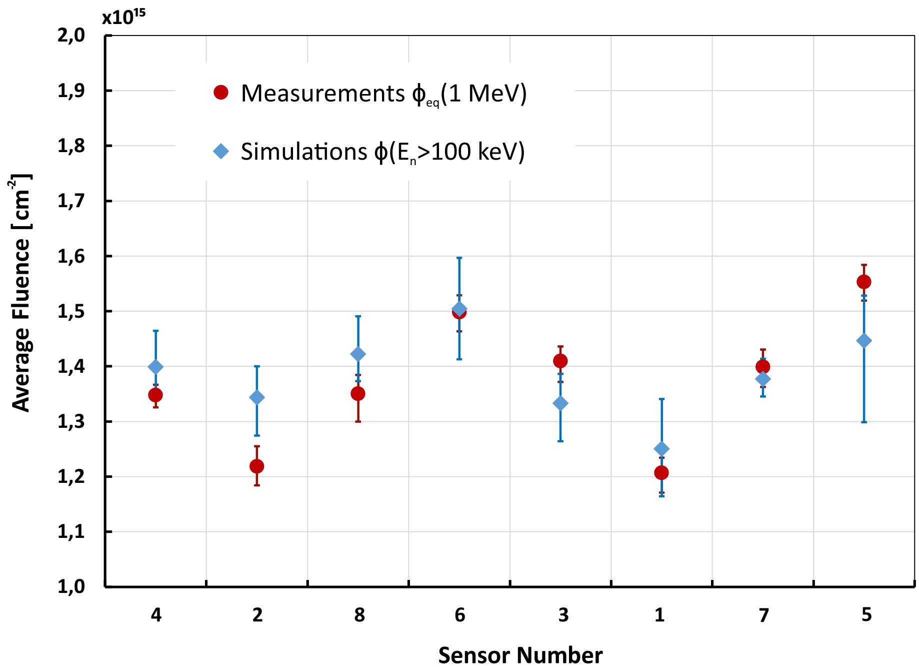


Figure 9: Comparison of measured $\phi_{eq}(1\,\text{MeV})$ against the calculated $\phi(E > 100\,\text{keV})$ in each individual LGAD assembly chip. Values obtained from single diodes used for uncertainty estimate. In case of simulations 1σ statistical uncertainty is added.

7 CONCLUSIONS AND OUTLOOKS

The initial fesibility tests on using LGADs as fast neutron fluence monitors have been carried out at the JSI TRIGA reactor. The experiment was reproduced in detail using Monte

Carlo particle transport calculations. Comparison of measured responses to $\phi_{eq}(1\,\text{MeV})$ and calculations of fast neutron fluence $\phi(E > 100\,\text{keV})$ are generally in agreement within the uncertainty, even though the axial orientation of the LGAD chip assembly during the experiment was unknown and was estimated from simulations. This highlights the possibility of using LGAD sensor as on-line fast neutron flux monitors, especially if efforts are made to fix their axial orientation during irradiations.

ACKNOWLEDGMENTS

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