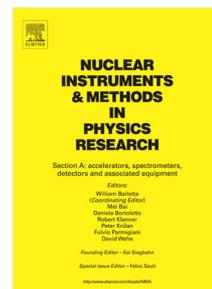


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# Fluence profiling at JSI TRIGA reactor irradiation facility

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## Abstract

We present an analysis of the fluence profile at the JSI TRIGA neutron reactor facility in Ljubljana. For the study, multi-pad Low-Gain Avalanche Diodes (LGADs) are used. The deactivation of acceptor doping in the gain layer implant due to the irradiation, typical of LGAD devices, is exploited to map the fluence profile inside the irradiation channels. The amount of active doping of the LGAD gain layer is extracted via capacitance-voltage measurements for each pad before and after irradiation to a fluence of  $1.5 \times 10^{15} n_{eq}/\text{cm}^2$ , where  $n_{eq}$  stands for 1 MeV equivalent neutron count, providing a precise and prompt measurement of the fluence distribution over the LGAD sensor. Experimental results are compared to neutron fluence expectations calculated with Monte Carlo techniques.

*Keywords:* TRIGA reactor, LGAD, irradiation facility, fluence profile

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## 1. Introduction

The TRIGA Mark II reactor at the Jožef Stefan Institut (JSI) [1] is extensively used by the High Energy Physics community to study and test radiation damage effects on detector materials and read-out electronics [2].

Recently, the increasing sensitivity of silicon devices to the effects of radiation triggered the discussion on the fluence spread that can affect irradiation campaigns. In particular, performance variation of Low-Gain Avalanche Diodes (LGADs) after irradiation [3] suggested the possibility to precisely map the fluence profile at the JSI facility.

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19 LGADs are n-in-p silicon sensors with a highly p-doped region close to  
 20 the n-electrode, called gain implant, to create a local enhancement of the  
 21 electric field responsible for the charge carrier multiplication [4]. It has been  
 22 observed that the Boron dopants in the gain layer get deactivated by the  
 23 radiation. This effect is known as acceptor removal [5] and has been precisely  
 24 characterised and tested [6], opening the possibility to use LGADs as devices  
 25 suitable to measure the fluence variation inside the irradiation channels of  
 26 the JSI facility.

27 LGAD sensors have been used with a straightforward procedure and have  
 28 proven to be an effective tool to build a fluence profile map inside the reactor  
 29 core.

## 30 2. The Experimental Method

31 The idea behind the present measurement is to use LGAD arrays of pix-  
 32 els to precisely quantify the different neutron fluence experienced by each  
 33 pixel. For this purpose, sensors from wafer 1 of the FBK USFD3 production  
 34 batch [7] have been used, made of an array of  $5 \times 5$  pixels. A drawing of the  
 35 sensors is shown in Figure 1: the area of each pixel is  $1.3 \text{ mm} \times 1.3 \text{ mm}$ , and  
 36 the total sensor area is  $7.7 \text{ mm} \times 7.7 \text{ mm}$ .

37 The study exploits the deactivation of the gain implant dopants by particle  
 38 radiation known as acceptor removal and parametrised as

$$N_A(\Phi) = N_A(0) \cdot e^{-c\Phi} \quad (1)$$

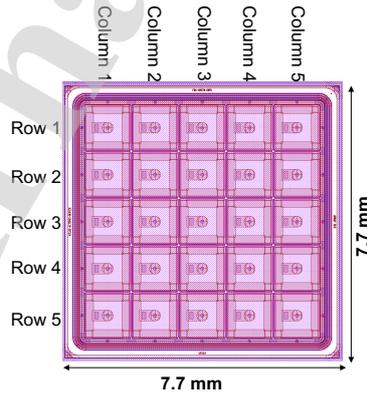


Figure 1: Schematic draw of the FBK sensors used for the study.

39 where  $N_A(0)$  ( $N_A(\Phi)$ ) is the effective acceptor density of the gain layer before  
 40 irradiation (after a fluence  $\Phi$ ), and  $c$  is the removal coefficient, depending on  
 41 the initial doping and on the gain layer design. The  $c$  coefficient has been  
 42 extensively measured through several campaigns [6, 8].

43 The determination of the active acceptor concentration is performed through  
 44 capacitance-voltage (C-V) measurements. The value of the bias voltage at  
 45 which the gain layer is depleted corresponds to a drop in the measured ca-  
 46 pacitance, defined as a knee (see Fig. 2) and indicated as  $V_{GL}$ .

47 In particular, for each pad, the  $V_{GL}$  has been defined as the point at which  
 48 the capacitance reaches a fixed value in the proximity of the knee, assuming  
 49 that for a fixed pad geometry, an equal value of capacitance represents the  
 50 identical amount of depleted volume, making the measurement extremely  
 51 sensitive to the changes in active doping. Such capacitance value has been  
 52 chosen to be 150 pF for both un-irradiated and irradiated sensors. It is worth  
 53 noting that the method has been proven to be equivalent to other methods  
 54 used to extract  $V_{GL}$ , e.g. in [6]. Furthermore, it guarantees a prompt and  
 55 easy tool to access a precise estimate of the active doping at a given depth  
 56 inside the pad under test.

57 To eliminate the effects of non-uniformities of gain layer doping implan-  
 58 tation and systematic uncertainties on the gain layer depletion measurement,  
 59 the ratio of  $V_{GL}$  before and after irradiation will be considered. Therefore,  
 60 from the variation of

$$\frac{V_{GL}(\Phi)}{V_{GL}(0)} = e^{-c\Phi}, \quad (2)$$

61 and assuming a constant  $c$ , which is a valid assumption considering an initial

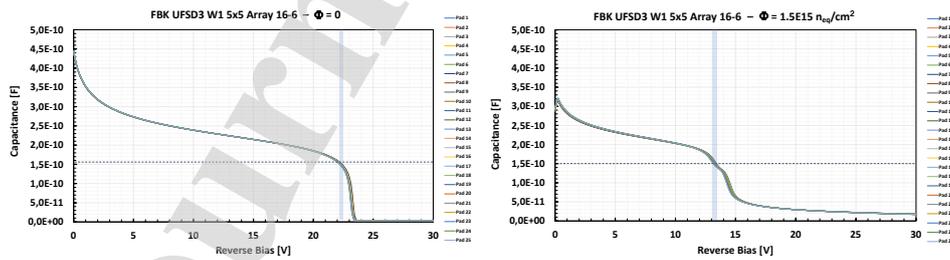


Figure 2: The C-V characteristics from all the 25 pads of the 16-6 sensor before (left) and after irradiation to a fluence of  $1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  (right). The horizontal dotted lines correspond to the value of  $C = 150 \text{ pF}$ , and the vertical bands highlight the corresponding values of reverse bias. The capacitance of full depletion of the pads under test is  $C_{FD} \sim 3.2$ .

62 doping variation of less than 2% [9], the measured variation of the ratio  
 63 directly quantifies a variation in the received fluence.

64 For the present study, 8 LGAD sensors have been irradiated to a fluence  
 65 of  $1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  by using the channel F19 of the JSI reactor [10]. This  
 66 channel is the one mainly used to irradiate samples for high-energy physics  
 67 detector developments. The irradiation has been done at full reactor power  
 68 of 250 kW. At such power, the target fluence in channel F19 is reached in  
 69 926 seconds.

### 70 3. The Experimental Setup

71 For irradiation at the JSI facility, cylindrical plastic containers with a  
 72 diameter of about 2 cm and a height of about 10 cm are used. By placing  
 73 the LGAD sensors in a fixed position inside a container, it is possible to  
 74 investigate and map the geometrical variation of the neutron flux inside the  
 75 irradiation volume.

76 Eight sensors have been fixed on plastic support and placed at two dif-  
 77 ferent depths inside the container. The support consists of four arms placed  
 78 orthogonally to each other, and four sensors have been attached at the same  
 79 depth on each arm of the plastic strut, as shown in Fig. 3.

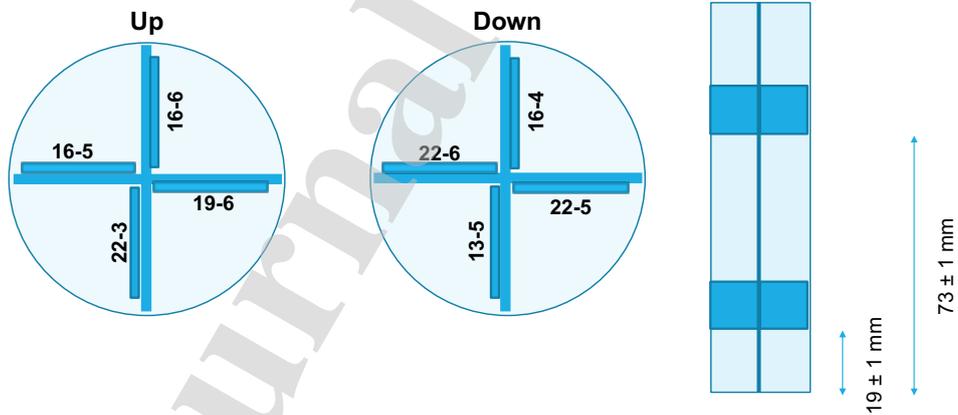


Figure 3: The placement of the 8 LGAD sensors inside the irradiation container is shown: 4 sensors are placed at two different depths, fixed on a plastic support. The sensor numbering and distance from the container bottom are reported.

80 The pad-by-pad C-V characterisation before and after irradiation has  
 81 been performed at room temperature, connecting a Keysight B1505A Power  
 82 Device Analyzer to the probe station. A high voltage source-monitor unit  
 83 was used together with a multi-frequency capacitance measurement unit,  
 84 interfaced via a bias-T and referred to a common ground value. The frequency  
 85 of the AC signal was set to 1 kHz, with an amplitude of 50 mV, and a parallel  
 86 capacitor-resistor model was used to extract the capacitance value. The chuck  
 87 of the probe station was negatively biased, and one needle at zero voltage  
 88 moved over the 25 pads of each sensor. One additional needle set at zero  
 89 voltage has been used to ground the guard ring of the sensor in order to  
 90 collect dark current from the sensor periphery and reduce the noise on the  
 91 capacitance measurement.

#### 92 4. The Measurement Technique

93 For all the  $1.3\text{ mm} \times 1.3\text{ mm}$  measured pads,  $V_{GL}$  has been extracted as  
 94 the voltage value at which the capacitance reaches 150 pF. As the reverse  
 95 voltage was provided to the sensor in steps of 0.2 V, to estimate the gain  
 96 layer depletion voltage, a linear fit to the two capacitance measurements  
 97 immediately lower ( $C_{low}$ ) and higher ( $C_{high}$ ) than 150 pF has been performed,  
 98 according to

$$V_{GL} = V_{low} + \frac{V_{high} - V_{low}}{C_{high} - C_{low}} \cdot (150\text{ pF} - C_{low}), \quad (3)$$

99 being  $V_{low}$  and  $V_{high}$  the measured voltage values preceding and following the  
 100  $V_{GL}$  point, respectively. The linear fit represents a good approximation of  
 101 the evolution of the C-V characteristics, given the small interval used in the  
 102 voltage measurement.

103 The  $V_{GL}$  values extracted for the sensor 16-6 before and after irradiation  
 104 to a fluence of  $1.3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$  are shown in Fig. 4. Prior to irradiation, it  
 105 is possible to observe the non-uniformity in the dopant implantation on the  
 106 gain layer; for the sensor under test, the spread in concentration is measured  
 107 to be  $< 0.9\%$ . After the irradiation, a modification in the geometrical trend  
 108 of  $V_{GL}$  non-uniformity become visible, with an increase of its relative spread  
 109 to about  $2\%$ .

110 As explained in Sect. 2, for our analysis we will consider the ratio of  
 111  $V_{GL}$  before and after irradiation, to remove the effect of initial doping non-  
 112 uniformities and the sistematics affecting the measurement technique. Fig-  
 113 ure 5 shows the resulting ratio for the sensor 16-6: it is possible to observe

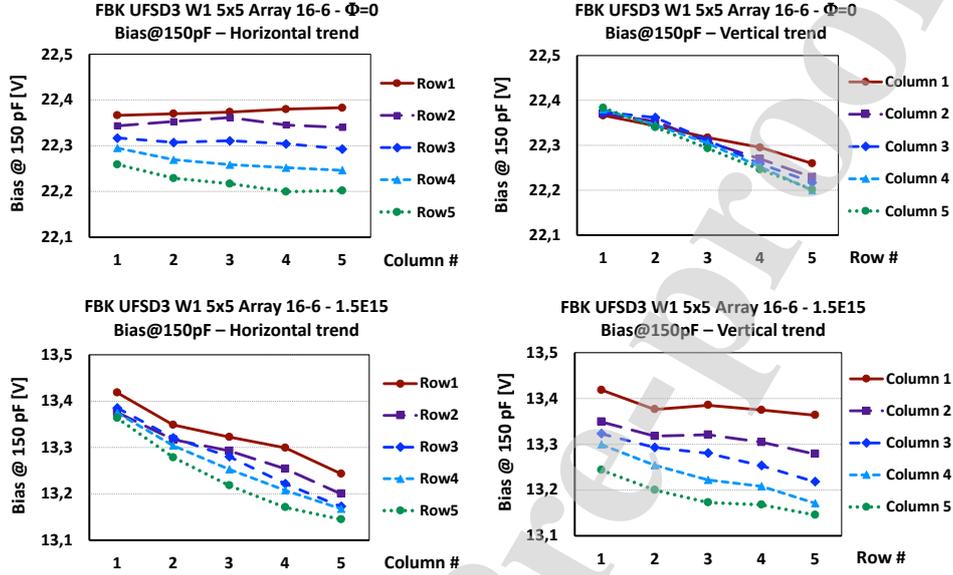


Figure 4: The extracted values of  $V_{GL}$  for the sensor 16-6 before (top) and after (bottom) irradiation to a fluence of  $1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ , reported as a function of the column number (left) and of the row number (right). The distance between the centre of the neighbouring pads and, therefore, the distance between each measured point is 1.3 mm.

114 as irradiation introduces a strong horizontal non-uniformity, while there is  
 115 no obvious trend as a function of the vertical direction.

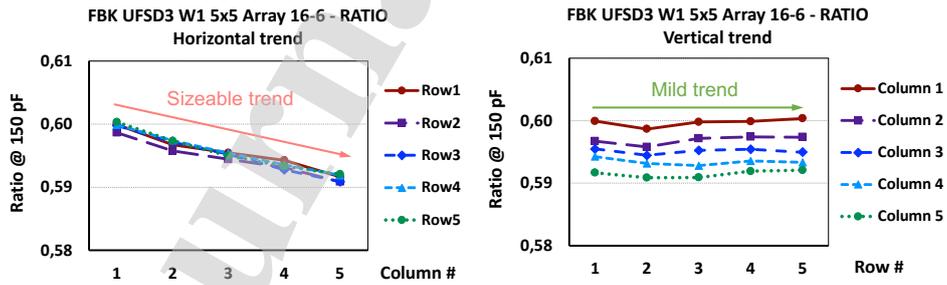


Figure 5: The ratio of the  $V_{GL}$  values before and after irradiation for the sensor 16-6 is reported as a function of the column number (left) and the row number (right). The distance between the centre of the neighbouring pads and, therefore, the distance between each measured point is 1.3 mm.

116 As a systematic check, results have been reproduced considering fixed  
 117 capacitance values of 160 pF and 140 pF. The resulting values of  $V_{GL}$  ratios  
 118 before and after irradiation are modified by less than 0.1 % in the first case,  
 119 while a maximum spread of  $-1.2\%$  to  $0.6\%$  has been observed in the latter  
 120 case. This difference might be explained by the fact that for  $C = 140$  pF  
 121 in irradiated sensors, the curve approaches a kink in the measurement, see  
 122 Fig 2 (right): such kink can be due to the reach of a not optimised frequency  
 123 value used in the measurement process when the depleted volume as a func-  
 124 tion of the applied bias moves from the gain implant to the sensor bulk  
 125 region. Therefore, a systematic uncertainty of 0.9 % is attributed to all the  
 126 measured values of the  $V_{GL}$  ratio.

127 Also, the results of the fixed capacitance method have been compared  
 128 with the method that considers the cusp in the parallel resistance as a func-  
 129 tion of the bias ( $V_{GL}^R$  in [6]). The difference in the results between the two  
 130 methods has been measured to be of 1.4 %. However, it is important to note  
 131 that the  $V_{GL}^R$  method guarantees a minor precision at the fluence under test,  
 132 as at relatively high fluences, the cusp enlarges, resulting in higher uncer-  
 133 tainty in determining the exact position of its maximum. Thus, the method  
 134 of the fixed capacitance provides a more precise estimate of  $V_{GL}$  and the re-  
 135 lative difference between the two methods is not considered as an uncertainty  
 136 of the presented results. .

## 137 5. The Simulation

138 The experiment was reproduced by Monte Carlo particle transport sim-  
 139 ulations using the MCNP v.6.1 [11] code with ENDF/B-VII.0 nuclear data  
 140 libraries [12]. Computations were performed in criticality mode, and results  
 141 were normalised to full reactor power (250 kW) [13].

142 A detailed JSI TRIGA reactor model was used, with core configuration  
 143 and control rod positions resembling the configuration used during the exper-  
 144 iment, displayed in Fig. 6 (right). Initial simulations were performed without  
 145 the sensor assembly in the F19 irradiating channel in order to assess the  
 146 homogeneity and possible gradients of the fast neutron flux component (neu-  
 147 trons with energy  $E_n > 100$  keV) within the irradiation position. The neutron  
 148 flux was calculated on a mesh superimposed over F19 irradiation position  
 149 with resolution of  $2\text{ mm} \times 2\text{ mm} \times 2\text{ mm}$ . Neutron and gamma fluxes were  
 150 tallied in three distinct energy groups, as denoted in Table 1. The fast neu-  
 151 tron flux distribution and its gradients in the x and y directions are displayed

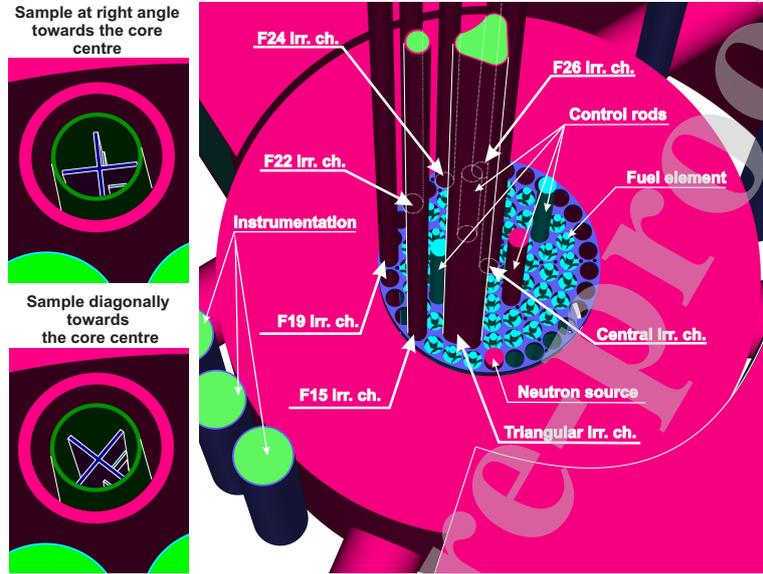


Figure 6: Two distinct orientations of the sensors inside the irradiation channel (left) and a detailed view of the JSI TRIGA MCNP computational model (right).

152 in Fig. 7. One can observe the increase of the fast neutron flux component  
 153 in close proximity to the neighbouring fuel elements.

154 In the second stage, sensors and the carrier board constituting a cross  
 155 configuration (see Fig. 3), as well as the polyethylene container, were also  
 156 modelled in detail and inserted into the irradiation channel into the F19 po-  
 157 sition, shown in Fig. 6 (right). The sensor support was modelled as the FR4  
 158 base plate of 1 mm thickness, while the sensors themselves were modelled as  
 159 boxes of pure silicon with a size of 7.7 mm × 7.7 mm × 0.63 mm. Kapton tape  
 160 with a thickness of 0.05 mm covering the entire assembly was also modelled.

Table 1: Lower and upper energy (E) bounds of tallied neutrons and gamma rays.

	Neutron		Gamma	
	Lower E	Upper E	Lower E	Upper E
1	0 eV	0.625 eV	0 eV	100 keV
2	0.625 eV	100 keV	100 keV	1 MeV
3	100 keV	100 MeV	1 MeV	100 MeV

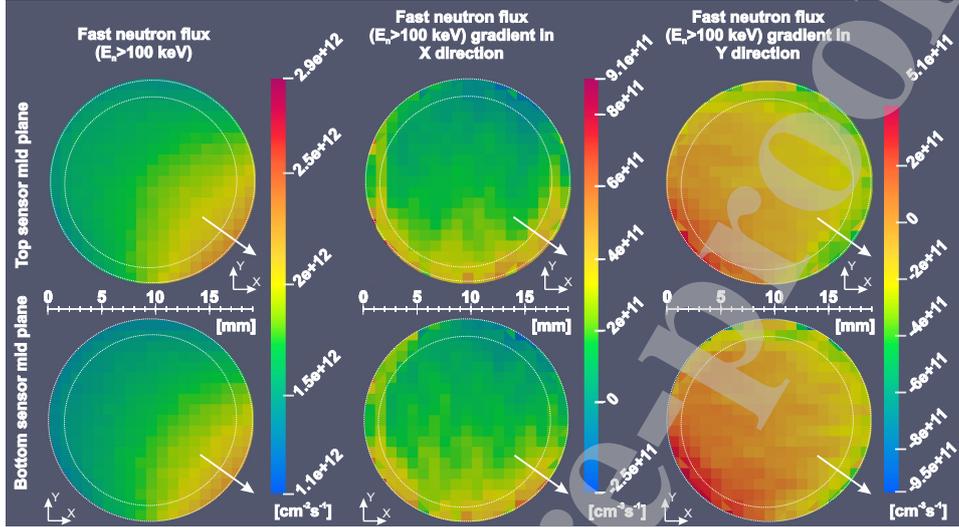


Figure 7: Fast neutron ( $E_n > 100$  keV) flux distribution in X-Y direction and their gradients in X and Y direction inside the F19 irradiation channel, at Z-levels corresponding to the mid-depth levels of the inserted sensor assembly. The white dotted line denotes the irradiation channel aluminium walls, while the arrow points to the core centre.

161 The sensor assembly model is schematically displayed in Fig. 8. The iso-  
 162 topic composition of the above-mentioned materials was obtained using the  
 163 MATSSF code [14] and is reported in Appendix A. Due to the unknown axial  
 164 orientation during the experiment, two distinct orientations were modelled:  
 165 with the carrier board cross arms perpendicular to the reactor core centre and  
 166 with arms diagonal with respect to the core centre, Fig. 6 (left). The same  
 167 energy group structure was used for tallying neutron and gamma flux in each  
 168 individual LGAD sensor, as well as on a mesh superimposed over the entire  
 169 irradiated container with a resolution of  $2\text{ mm} \times 2\text{ mm} \times 2\text{ mm}$ , displayed in

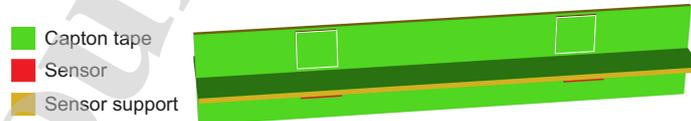


Figure 8: The model of the LGAD sensor's assembly on FR4 supports, covered with Kapton tape.

170 Fig. 9, along with numbering of LGAD sensor used in the simulations. The  
 171 fast neutron flux difference between the empty irradiation channel and with  
 172 inserted polyethylene container and sensor sample is displayed in Fig. 10. By  
 173 comparing with simulated flux values shown in Fig. 7, it is possible to ap-  
 174 preciate that the insertion of samples changes the neutron flux of the empty  
 175 irradiation channel by up to  $\sim 10\%$ . Fast neutron flux ( $E_n > 100$  keV) av-  
 176 eraged over individual sensor are provided in Table 2. Moreover, each sensor  
 177 was divided into  $(5 \times 5)$  sections, corresponding to positions of individual  
 178 pixels (Figure 1) in order to asses the fast neutron flux variation, sensed by  
 179 each sensor.

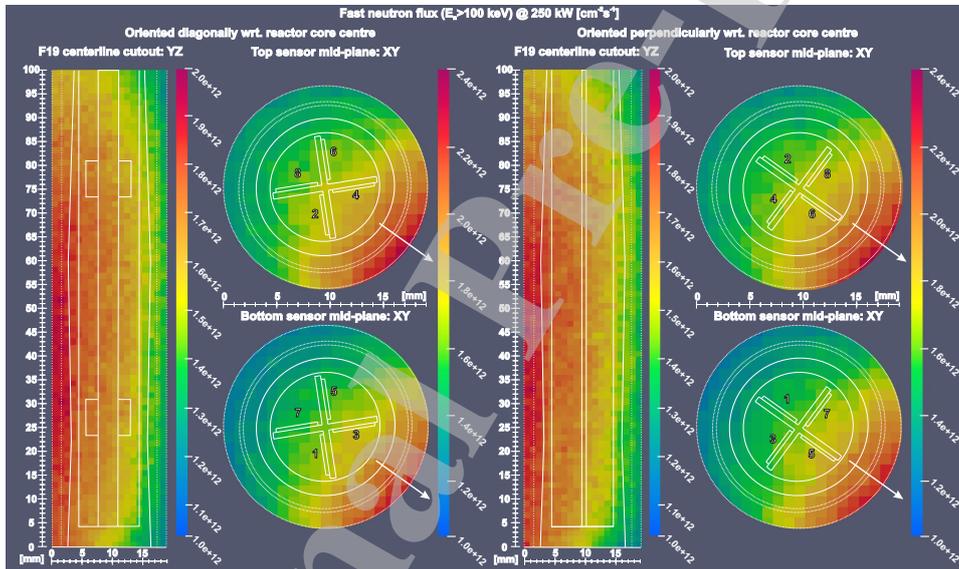


Figure 9: Fast neutron ( $E_n > 100$  keV) flux field in irradiation position F19 at full reactor power (250 kW) for two sample orientations. Visualisations at the z-axis and sensor mid-planes. Relative statistical uncertainty  $< 1\%$ . Numbers denote the sensor numbering convention used in calculations, and the arrow indicates the direction towards the reactor core centre. White lines denote the edge of the irradiation channel (dashed), polyethylene container and the PCB with the sensors.



Table 2: Fast neutron flux ( $E_n > 100$  keV) at reactor power of 250 kW. Mean values per sensor and the variation over individual pixels. Mean value of the statistical uncertainty spans from 0.62 % to 0.82 %, while statistical uncertainties on the mesh span from 2.2 % to 2.7 %.

No.	Diagonal		Perpendicular	
	Mean [ $cm^{-2}s^{-1}$ ]	Variation [%]	Mean [ $cm^{-2}s^{-1}$ ]	Variation [%]
1	$1.684 \times 10^{12}$	+5.1 -4.8	$1.510 \times 10^{12}$	+7.3 -6.8
2	$1.741 \times 10^{12}$	+5.5 -4.7	$1.577 \times 10^{12}$	+4.2 -5.1
3	$1.741 \times 10^{12}$	+5.4 -4.2	$1.596 \times 10^{12}$	+4.0 -5.1
4	$1.773 \times 10^{12}$	+4.8 -4.0	$1.633 \times 10^{12}$	+4.7 -3.5
5	$1.556 \times 10^{12}$	+6.1 -6.2	$1.742 \times 10^{12}$	+5.6 -10.2
6	$1.647 \times 10^{12}$	+5.8 -5.6	$1.787 \times 10^{12}$	+6.1 -6.1
7	$1.531 \times 10^{12}$	+6.4 -6.1	$1.648 \times 10^{12}$	+2.7 -2.3
8	$1.607 \times 10^{12}$	+6.9 -5.9	$1.698 \times 10^{12}$	+4.8 -3.5

## 180 6. The Results

181 The ratios of the  $V_{GL}$  before and after irradiation are shown for each  
182 pixel as a function of the column number for the eight sensors under test, split  
183 between the top (Fig. 11) and the bottom (Fig. 12) part of the container. For  
184 both the top and the bottom positioning, there is one sensor with a high value  
185 of the  $V_{GL}$  ratio, above 0.62 (19-6 and 22-5, respectively), one with a low ratio  
186 value, below 0.56 (namely, 16-5 and 22-6), and there are two sensors with a  
187 medium ratio, of about 0.58 (22-3 and 16-6 in the top part, 13-5 and 16-4  
188 in the bottom part). The orientation of the container during the irradiation  
189 inside the F19 channel is unknown. Still, the observed trend in the received  
190 fluence is compatible with the gradients shown by the simulation relative to  
191 the sensors oriented perpendicularly to the centre of the reactor core, as in  
192 Fig. 9 (right). The results suggest that, during the irradiation, the sensors 19-  
193 6 and 22-5 were closer to the reactor core centre, while sensors 16-5 and 22-6  
194 were farther away. Moreover, column 1 of each sensor points to the centre  
195 of the cross support. Therefore, the opposite trend of the ratios for, e.g.,  
196 sensors 22-5 and 22-6 indicate that in 22-5, the pixels in column 5 are more  
197 exposed to irradiation, while for 22-6, pixels in column 1 experienced higher  
198 irradiation, in agreement with the geometrical construction of the setup.

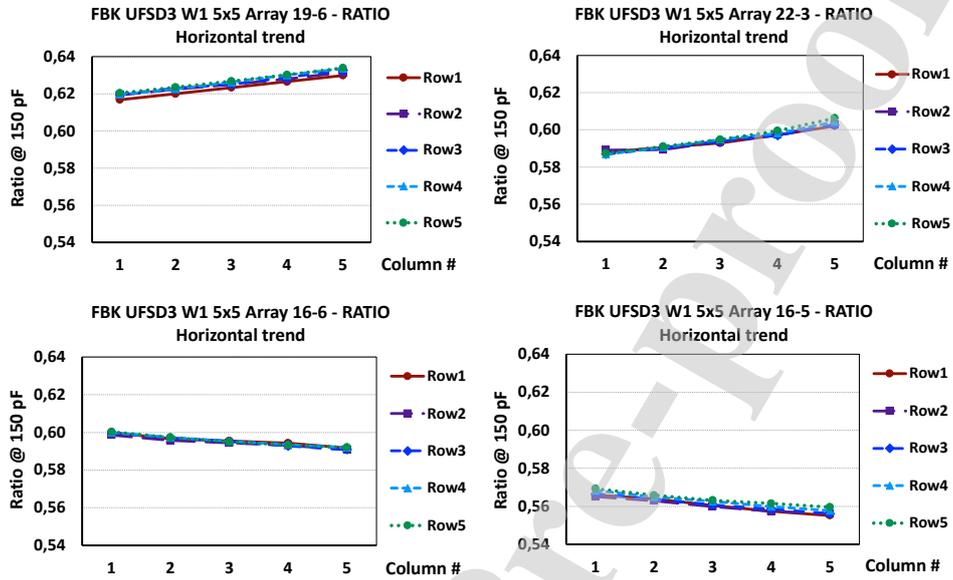


Figure 11: The ratio of the  $V_{GL}$  values before and after irradiation for the four sensors placed in the top part of the canister. The distance between each measured point is 1.3 mm.

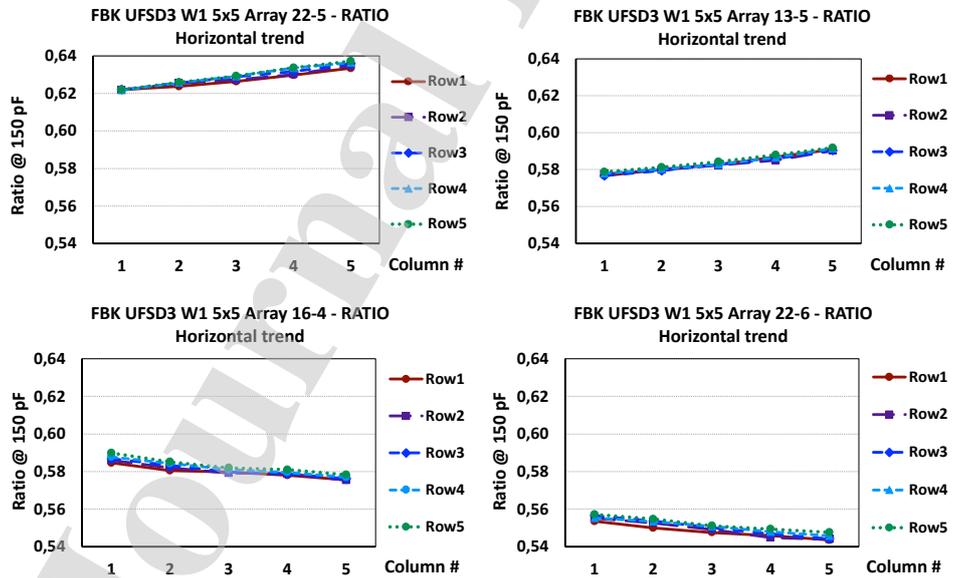


Figure 12: The ratio of the  $V_{GL}$  values before and after irradiation for the four sensors placed in the bottom part of the canister. The distance between each measured point is 1.3 mm.

199 Furthermore, it has been measured that the vertical spread of the fluence  
 200 is mild, as it is visible from two sensors placed on the same arm of the  
 201 holder structure, namely, 22-5 in the bottom part and 19-6 in the top one,  
 202 as shown in Fig. 13. A linear interpolation of the measured  $V_{GL}$  ratios on all  
 203 the pixels from the column 1 of the sensors 22-5 and 19-6 is displayed: the  
 204 variation of the ratio values spanning over a vertical distance of 59.2 mm is  
 205 quantified by the angular coefficient as a parameter of the fit, measured to  
 206 be  $5.05 \times 10^{-5} \text{ mm}^{-1}$ . Also, the relative difference between the lowest row  
 207 of the sensor 22-5 (row 5) and the highest row of the sensor 19-6 (row 1) is  
 208 0.8% for column 1 and rises to 1.1% in column 5. This observation agrees  
 209 with the simulation, as in Figg. 9 and 10.

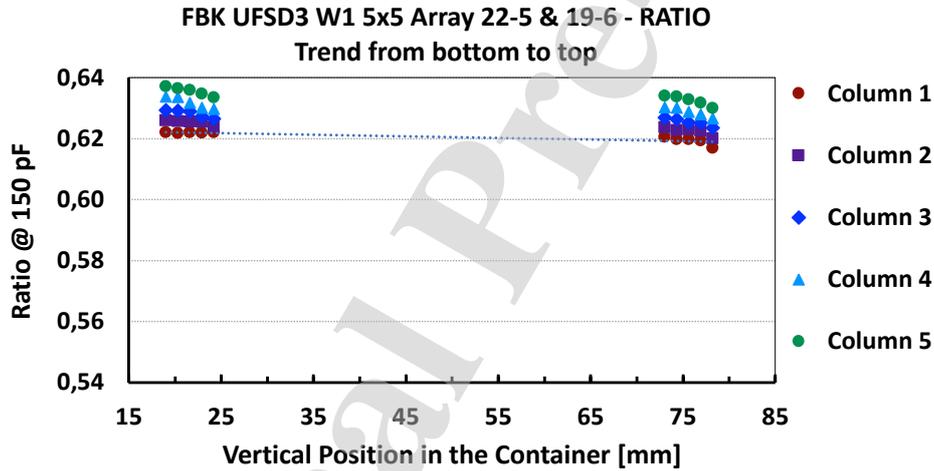


Figure 13: The ratio of the  $V_{GL}$  values before and after irradiation two sensors placed on the same arm of the plastic structure.

210 The conversion between the measured ratios of  $V_{GL}$ , reflecting the frac-  
 211 tion of active gain implant that survived the irradiation as presented in  
 212 Eq.(1), to the value of fluence experienced by each pixel make use of the  
 213 formula in Eq.(2) and uses as value for the acceptor removal coefficient  
 214  $c = 3.85 \times 10^{-16} \text{ cm}^2$ , extracted from previous measurements on sensors from  
 215 the same production batch [15]. The uncertainty on the  $c$  factor is 12% and  
 216 accounts for the different methods used to extract  $V_{GL}$  at various fluences  
 217 and from the uncertainty on those fluences, which represent the highest con-  
 218 tribution to the uncertainty.

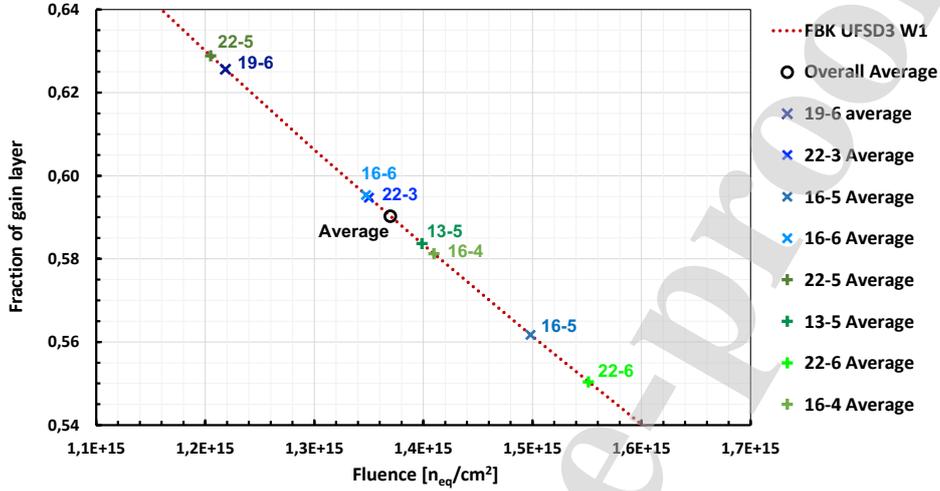


Figure 14: Average fluence seen by the eight sensors under test. The overall average is also shown (black circle).

219 Figure 14 reports the fluence experienced by each tested sensor, averaged  
 220 over all 25 pixels. The evolution of Eq.(2) for the FBK wafer from which the  
 221 tested sensors are taken (W1 UFSD3) is superimposed to the data points to

Table 3: Average, minimum and maximum fluence ( $\Phi$ ) experienced by each of the eight measured sensors. Fluence values are expressed in units of  $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ . Relative variations of the fluences measured by each sensor with respect to the average fluence of  $1.37 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  is reported.

Sensor No.	Average $\Phi$	$\Phi$ Min	$\Phi$ Max	Variation [%]
19-6	1.22	1.18	1.26	- 11.2 <sup>-8.6</sup> <sub>-13.8</sub>
22-3	1.35	1.30	1.38	- 1.7 <sup>+0.8</sup> <sub>-5.3</sub>
16-5	1.50	1.46	1.53	+ 9.1 <sup>+11.3</sup> <sub>+6.6</sub>
16-6	1.35	1.33	1.37	- 1.9 <sup>-0.4</sup> <sub>-3.5</sub>
22-5	1.21	1.17	1.23	- 12.1 <sup>-10.1</sup> <sub>-14.7</sub>
13-5	1.40	1.36	1.43	+ 1.9 <sup>+4.2</sup> <sub>-0.8</sub>
22-6	1.55	1.52	1.58	+ 13.1 <sup>+15.4</sup> <sub>+10.7</sub>
16-4	1.41	1.37	1.44	+ 2.7 <sup>+4.6</sup> <sub>-0.1</sub>

222 highlight the evolution of the  $V_{GL}$  ratio with the fluence. The average fluence  
 223 experienced by all the  $8 \times 25$  measured pixels is  $\Phi_{ave} = 1.37 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ ,  
 224  $0.13 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$  lower than the expected value of  $1.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ .

225 The average fluences seen by each sensor are reported in Table 3, together  
 226 with the minimum and maximum fluence experienced by the pixels in each  
 227 of the eight measured sensors. The relative variations are also reported, ob-  
 228 tained by comparing the average sensor values with the overall average value  
 229 equal to  $1.37 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ . Considering minimum and maximum values of  
 230 fluence experienced by the pixel, the fluence variation ranges from  $-14.7\%$   
 231 to  $15.4\%$ , observed on the sensors placed on the bottom part of the con-  
 232 tainer. The variation in the top region spans between  $-13.7\%$  to  $11.4\%$ .

233 Concerning the vertical variation of the fluence, it has been observed a  
 234 minimum difference of  $2.13 \times 10^{13} \text{ n}_{eq}/\text{cm}^2$  between sensors 19-6 and 22-5 and  
 235 a maximum difference of  $7.81 \times 10^{13} \text{ n}_{eq}/\text{cm}^2$  between sensors 16-5 and 22-6.

236 Figures 15 and 16 compare the results from the data with the simulation  
 237 obtained considering a perpendicular or a diagonal orientation of the sensors

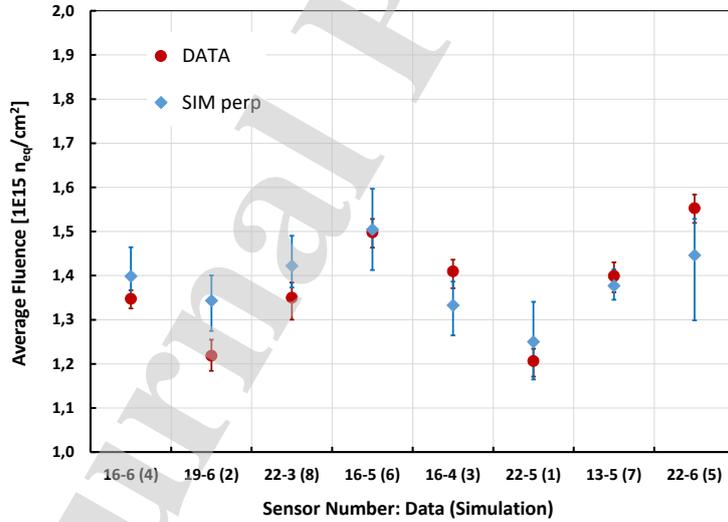


Figure 15: Comparison of the average fluence measured by the sensors and the simulated fluence for sensors oriented perpendicularly to the reactor core centre. Error bars represent the minimum and maximum fluence measured by the pixels in each sensor. The error on the factor is not added to the data. Reactor power has been set to 250 kW for 926 s.

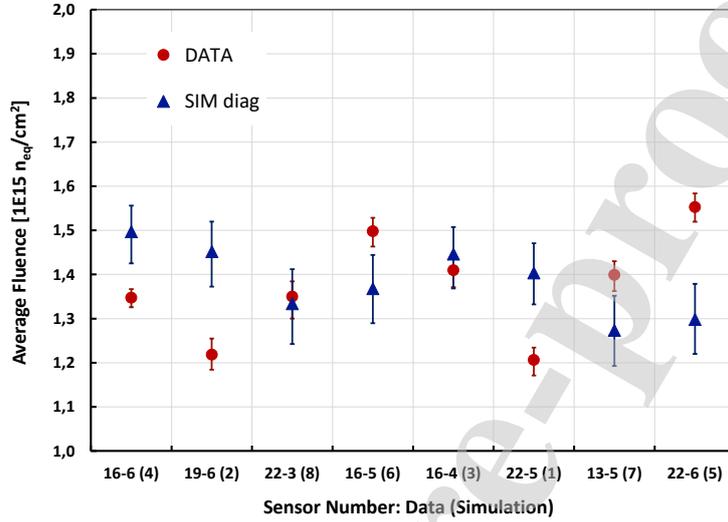


Figure 16: Comparison of the average fluence measured by the sensors and the simulated fluence for sensors oriented diagonally to the reactor core centre. Error bars represent the minimum and maximum fluence measured by the pixels in each sensor. The error on the factor is not reported on the data. Reactor power has been set to 250 kW for 926 s.

238 under test to the core reactor centre, respectively, as reported in Tables 2  
 239 and 3. The 12% uncertainty on the  $c$  factor is not added to the data points,  
 240 as the comparison between data and simulation concentrates on the trend  
 241 of the fluence faced by the measured pads according to their position in the  
 242 container volume and because of the strong correlation between the source  
 243 of the uncertainty on  $c$  and the conversion of  $V_{GL}$  ratios into fluence.

244 The data results exhibit good agreement with the perpendicular orienta-  
 245 tion simulation both in the absolute value and in the observed trend of the  
 246 fluence variation inside the tested region of the F19 irradiation channel.

247 As mentioned above, in the simulation, the active part of each sensor is  
 248 divided into  $5 \times 5$  sections, corresponding to the positions of individual pix-  
 249 els (see Fig. 1), and fast neutron flux is calculated for each pixel. Figure 17  
 250 compares measured fluences from data and perpendicularly oriented simula-  
 251 tion averaged over rows of each column in every sensor. As can be seen, the  
 252 agreement is good and exhibits a very high sensitivity of measured  $V_{GL}$  to  
 253 the received fast neutron fluence. It is worth noting that the variations of the

254 neutron flux inside the reactor core can be sensed with a millimetre spatial  
 255 resolution.

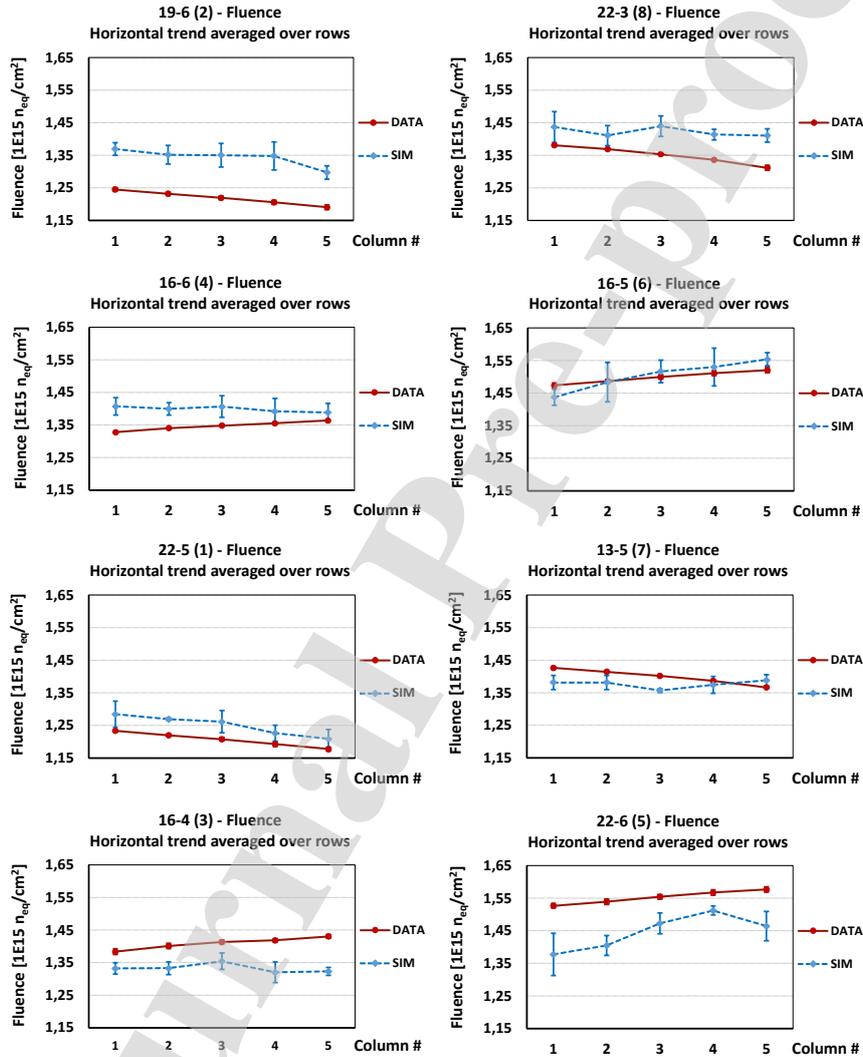


Figure 17: Comparison of the fluence values as measured by the devices and simulated assuming a perpendicular orientation with respect to the reactor core centre. Single plots refer to single measured (simulated)  $5 \times 5$  sensors. The fluences are shown as a function of the column number, averaged over the 5 rows belonging to the same column, and error bars indicate the standard deviation of the fluence values from pixels in the same column.

## 256 7. Conclusions

257 The fluence profile on channel F19 at the JSI TRIGA reactor has been  
 258 measured with LGAD sensors made by an array of  $5 \times 5$  pixel with  $1.3 \text{ mm} \times$   
 259  $1.3 \text{ mm}$  area. Eight different LGAD sensors taken from the same wafer from  
 260 the UFSD3 production batch of the FBK foundry have been tested: sensors  
 261 have been fixed on cross-shaped plastic support at two different depths and  
 262 inserted on the plastic container used for the irradiation.

263 The bias at which the gain implant is depleted,  $V_{GL}$ , has been extracted  
 264 from C-V measurements for each pixel of the tested sensors, before and af-  
 265 ter the irradiation to  $1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ . From the ratio of the  $V_{GL}$  values  
 266 before and after irradiation, the fluence experienced by every pixel has been  
 267 extracted.

268 An average fluence of  $1.37 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  has been measured, 8.7% lower  
 269 than the nominal value. A spread in the delivered fluence inside the tested  
 270 channel has been observed: the difference in fluence around the central value  
 271 has been quantified between  $-14.7\%$  to  $15.4\%$ . The flux of neutrons on the  
 272 tested region of the reactor core has been simulated using MCNP v.6.1 code  
 273 with ENDF/B-VII.0 nuclear data libraries and confirms the experimental  
 274 observations.

275 The position of the container inside the F19 channel, together with the  
 276 orientation of the sensor, is unknown. But the experimental results are in  
 277 good agreement with the simulation of a perpendicular orientation of the  
 278 sensors to the reactor core.

279 Only a minor vertical variation of the fluence has been observed, in agree-  
 280 ment with the simulation, with a maximum observed spread of  $7.81 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$   
 281 from the top to the bottom of the tested volume.

282 The presented study proves a very high sensitivity of the  $V_{GL}$  ratio tech-  
 283 nique for measurements of neutron flux, and its validity is well confirmed by  
 284 the good agreement with the simulation. The fine granularity of the LGAD  
 285 devices and the relatively simple measurement approach offers the possi-  
 286 bility of monitoring neutron flux uniformity with millimetre spatial resolu-  
 287 tion. LGAD sensors demonstrated their effectiveness as precise monitors of  
 288 the neutron flux inside a reactor core.

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349 **Appendix A. Sensor assembly modelled isotopic composition and**  
 350 **densities**

Table A.4: Isotopic composition of the sensor modelled in pure silicon, with density of  $\rho = 2.33 \text{ g cm}^{-3}$ .

Isotope	number density [ $\times 10^{24} \text{ cm}^{-3}$ ]
$^{28}\text{Si}$	$4.6075 \times 10^{-2}$
$^{29}\text{Si}$	$2.3406 \times 10^{-3}$
$^{30}\text{Si}$	$1.5448 \times 10^{-3}$

Table A.5: Isotopic composition of the capton tape, with density of  $\rho = 1.42 \text{ g cm}^{-3}$ .

Isotope	number density [ $\times 10^{24} \text{ cm}^{-3}$ ]
$^1\text{H}$	$5.1250 \times 10^{-2}$
$^{nat}\text{C}$	$5.1248 \times 10^{-2}$
$^{14}\text{N}$	$8.5102 \times 10^{-3}$
$^{15}\text{N}$	$3.1090 \times 10^{-5}$
$^{16}\text{O}$	$4.2705 \times 10^{-3}$

Table A.6: Isotopic composition of the FR4 board holder, with density of  $\rho = 1.85 \text{ g cm}^{-3}$ .

Isotope	number density [ $\times 10^{24} \text{ cm}^{-3}$ ]
$^{10}\text{B}$	$6.3686 \times 10^{-4}$
$^{11}\text{B}$	$2.5634 \times 10^{-3}$
$^{16}\text{O}$	$3.4641 \times 10^{-2}$
$^{24}\text{Mg}$	$2.4018 \times 10^{-3}$
$^{25}\text{Mg}$	$3.0406 \times 10^{-4}$
$^{26}\text{Mg}$	$3.3477 \times 10^{-4}$
$^{27}\text{Al}$	$3.0595 \times 10^{-3}$
$^{28}\text{Si}$	$9.2342 \times 10^{-3}$
$^{29}\text{Si}$	$4.6910 \times 10^{-4}$
$^{30}\text{Si}$	$3.0960 \times 10^{-4}$
$^{40}\text{Ca}$	$2.1185 \times 10^{-3}$
$^{42}\text{Ca}$	$1.4139 \times 10^{-5}$
$^{43}\text{Ca}$	$2.9503 \times 10^{-6}$
$^{44}\text{Ca}$	$4.5587 \times 10^{-5}$
$^{46}\text{Ca}$	$8.7416 \times 10^{-8}$
$^{48}\text{Ca}$	$4.0867 \times 10^{-6}$

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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