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SUBTRACTIVE GAMMA DISCRIMINATION TECHNIQUE FOR NEUTRON DIAMOND DETECTORS OPERATING IN MIXED RADIATION FIELDS

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Abstract. A detection system based on diamond detectors and subtractive discrimination was developed for the measurement of thermal neutrons flux distribution changes during rod drop transient at the VR-1 reactor. The detection system was modified to replace the pulse-shaped method used for discrimination. The electronics available at the department was not able to measure high count rates with the pulse shape discrimination method. Subtractive discrimination allows us to reduce the requirements in the signal processing area, as the shape does not need to be recorded, and therefore the digitizer performance can be significantly lower. For this reason, a pulse stretching amplifier was developed and tested.

Keywords: Neutron detection, amplifier, subtractive gamma discrimination, diamond detectors, nuclear reactor, transients.

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1. Introduction

Experimental activities in the area of nuclear reactor transients sometimes require more advanced detection systems that are able to collect information about reactor behavior. Special cases are extremely short transients where almost point-wise information about neutron flux should be measured. For such experiments, special detection systems should often be developed or at least modified to provide the required performance. Another motivation to look for a modified or new detection system is the funding as some solutions may be too expensive.

In this case, a detection system based on diamond detectors and subtractive discrimination was developed for changes in neutron flux during rod drop. This detection system was developed for the measurement of rod drop at the VR-1 reactor. The VR-1 reactor is a zero-power training reactor [1]. This experimental activity should conclude in the development of an experimental device that allows to measure changes in neutron flux distribution during rod insertion (more described in [2]). Experiments on the newly developed device will be supported by the calculation of such a transient by a dynamic tool in the Serpent code [3] and therefore the methodology for such calculation is in development.

Diamond detectors can be used for thermal neutron detection using a conversion layer. This layer converts neutrons to charged particles, e.g. alpha. Alpha particles are collected in the detector volume and are registered as electrical pulses. This setup is usually used with pulse shape discrimination that allows to separate pulses originated from alpha interaction from pulses created by direct fast neutron interaction in detector volume or gamma interaction in the detector. This method of discrimination requires recording the pulse shape, which is later processed by the shape analysis tool or using some advanced electronics (e.g. FPGA) that must be used to process pulses online. However, this requires a high-end digitizer that can record the pulse shape with a high sampling rate. The digitizer needed for experiments, which requires collecting thousands and more pulses per second, must have fast performance, meaning that the price is again significantly increased. This makes utilization of this type of detector with the pulse shape method extremely expensive. To significantly reduce the cost of the detection system, a different approach is proposed for discrimination.

The subtractive gamma discrimination utilizes a set of two detectors, one sensitive to all particles including thermal neutrons and the second not sensitive to thermal neutrons. This is achieved by manufacturing one detector with and one without the conversion layer. The count rate obtained from the non-thermal neutron sensitive is subtracted. This means that shape analysis is not needed and only noise separation should be used by the pulse-high method. And therefore a simple counter or low quality digitizer can be used instead of an advanced digitizer. The only disadvantage is the pulse length, which is below 6 ns, and for such short pulses a high sampling rate is needed. This challenge can be solved by an amplifier that extends the pulse duration.

2. Detection system

Final detection system is a result of development and improvement of the diamond-based detector and the

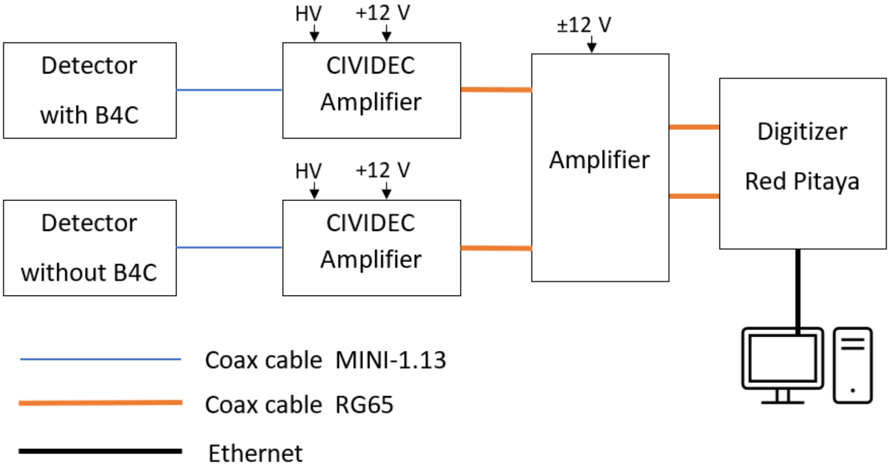

Figure 1. Blueprint of the detection line.

related HW and SW. The rod scram detection system consists of multiple detection lines that use subtractive gamma discrimination. Each line measures the thermal neutron flux in an almost point-size location. The measurement line is made by a pair of diamond detectors. The line scheme is shown in Figure 1. It consists of a set of diamond detectors, one with a conversion layer made of B_4C and one without; first signal amplifier that also provides the detector with high voltage; second signal shaping amplifier and digitizer.

2.1. Detector description

The diamond detector is created from an artificial diamond crystal. The diamond crystal serves as the active volume of the detector. Two sets of layers are deposited on each side of the crystal. One is an extremely thin layer (100 Å) of Al that serves as an electrode. The second layer is the conversion layer made of B_4C. Conversion layers can be placed from both sides of the crystal or only from one side. The electrodes must be placed on both sides. The charge deposited by ionizing interactions is collected by an electric field created by the applied voltage on the two electrodes. General information on the use of diamond detectors is presented in [4]. The pulse length from the diamond detector is below 6 ns. The crystal dimensions are 5 mm × 5 mm × 0.5 mm. The conversion layer contains ^{10}B. The (n,alpha) interaction is used for the thermal neutron detection (see Equation (1) [5]).

$$ {}^{10}_{5}\mathrm{B} + {}^{1}_{0}n \rightarrow \begin{cases} {}^{7}_{3}\mathrm{Li} \ + {}^{4}_{2}\alpha & \mathrm{E}_\alpha = 1.78\,\mathrm{MeV} \\ {}^{7}_{3}\mathrm{Li}^{*} + {}^{4}_{2}\alpha & \mathrm{E}_\alpha = 1.47\,\mathrm{MeV} \end{cases} \qquad (1) $$

The alpha particles range depends on energy and is below 10 µm.

The B_4C was deposited in CEITEC laboratories [6] by evaporator. This machine is equipped with a special crystal that measures the thickness of the deposited material. Detectors were manufactured with electrode thickness of 110 Å. The thickness of the conversion layer was 1.4 and 1.2 µm (one side and another of the crystal). The deposition of conversion layers and electrodes for both crystals was performed together, because the design of the deposition holder allows the placement of several crystals at the same time. The mask used for the deposition is square in shape. The aluminum electrodes were connected with wires using conductive epoxy. The diamond plates were produced by the Element six company.

2.2. Signal transfer and processing

Signal transfer and processing are another crucial part of the detection system as they should be tailored with detectors and application. The hardware design depends on the space requirements of the detection system and also on the processing possibilities. The signal obtained from the detector is first transferred by coaxial cables to the amplifiers located 5 meters from the detector outside the reactor core and vessel. There, the signal is amplified and then processed by a digitizer as shown in the schematic in Figure 1. An important part of the processing is the discrimination, as the detector is sensitive not only to thermal neutrons, but also to gamma and fast neutrons. Depending on parameters of the mixed radiation field, thermal neutron interaction can represent only one-fourth of all interactions recorded. Based on the selected discrimination, different data processing, amplification, and electronic performance are needed.

2.2.1. Discrimination of gamma interactions

The nuclear reactor core has a mixed field of radiation. To measure only the thermal neutron flux, other particle interactions in the detector should be discriminated. The (n,alpha) interaction is used for the thermal neutron detection, and therefore thermal neutrons are represented by alpha particles registered in the detector volume. In addition to alpha particles, gamma and electrons are interacting within the detector volume as well. Moreover, thermal neutrons rarely interact directly in the detector. This places a demand for signal processing and some type of separation. Several different approaches can be used to discriminate primarily gamma from the final signal. For the diamond detector, the following were considered and tested: pulse height, pulse shape, and subtractive gamma discrimination.

Pulse height discrimination [7] is frequently used in neutron detection and its implementation is simple. However, the performance of pulse height discrimination for this case is poor, as the energy deposited by the alpha particle is not often higher than the energy deposited by the gamma radiation. Moreover, low-energy alpha particles (those that were created in the conversion layer further from the crystal surface) are discriminated because the deposited energy is low. This means that part of the alphas from the conversion layer that should be counted as neutrons are discriminated. However, this discrimination method is easy to use and does not require high-performance electronics. In conclusion, this discrimination method reduces the final count rate, and therefore, for small diamond crystal detectors, it is better to use different discrimination methods.

Diamond detectors allow to use pulse shape discrimination as the signal collected and processed carries information about the interacting particle in the signal shape. This method is described in [8] and other publications, e.g., [9–11]. The shape of the signal is determined by the way the particle deposits energy. Some particles have linear energy depositions (e.g. gamma), some has non linear deposition (e.g., alpha). According to [4, 8], the signal shape of the alpha interaction is more rectangular. Other interactions have different shapes – more triangular. If the amplifier and digitizer have sufficient bandwidth and sampling frequency, the shape of each pulse can be analyzed and used for particle discrimination.

Pulse shape discrimination was extensively tested with several neutron and gamma sources, as well as by measurement at the VR-1 reactor. A detailed description of the results and the experimental approach is presented in the paper [12].

The main results of the pulse shape discrimination test are as follows. Pulse shape discrimination allows to separate thermal neutron interactions from the other interactions in the detector. Depending on the field of radiation, around one-third or one-fourth interactions are identified as interactions of thermal neutrons. The significant disadvantage of pulse shape discrimination is data collection. For high count rates, an extremely expensive digitizer that can continuously record pulse shapes is required. Therefore, this method is only suitable for measurements with low counts per second (roughly 200 counts s^{-1} with the CAEN N6743 digitizer). For measurements at the nuclear reactor during reactor transient, this method can be used only if an appropriate digitizer is available. As this device is not available in the VR-1 reactor inventory, a different discrimination method must be used.

Subtractive gamma discrimination allows to perform measurement of transients without the need for a superpowerful digitizer. This method uses two diamond detectors, one with a conversion layer and one without a conversion layer. The count rate obtained from the detector without the conversion layer is subtracted from the count rate from the detector with the conversion layer. The result is a count rate that corresponds to only thermal neutron interaction. The signal from both detectors does not need to be analyzed by the pulse shape method, only simple pulse height noise discrimination needs to be used to eliminate noise. This significantly reduces the requirement on data processing, and therefore less powerful digitizers can be used.

In conclusion, this method allows to reduce the requirements on the digitizer as the shape of the signal does not need to be recorded, only the pulse height. Both fast digitizers and slow digitizers with pulse stretching amplifier can be used for data collection. For this method, a pulse stretching amplifier was developed and tested in both the neutron laboratory and the VR-1 reactor.

2.3. DETECTION LINE HARDWARE

As described in the overview of the detection system, it contains several pieces of electronic devices that adjust and process the signal. The detector is connected to the first amplifier by thin coaxial cables. These coaxial cables are used in order to allow several coaxial cables to fit in a limited space. The MULTICOMP PRO MINI-1.13 [13] coaxial cable was used. It has a diameter of only 1.13 mm. Due to the low thickness, the coaxial cables have low performance shielding and therefore all cables were enclosed in additional sleeving [14] that provided needed shielding.

The Cividec C2-HV amplifier [15] is used to perform the first amplification of the signal and provide high voltage to the diamond detector. The CAEN N1470 [16] high-voltage source was used to provide -400 V for each detector. The amplified signal from this amplifier can be used with pulse shape analysis with a fast digitizer. However, for the measurement of fast transients in the VR-1 reactor, subtractive gamma discrimination is used with a low sampling fast-performance digitizer (fast-performance means the ability to record more than 20 000 imp s^{-1}) and therefore the signal needs additional treatment by a second amplifier.

The second amplifier (rapid, signal shaping) was developed and performs amplification approximately seven times and extension of the incoming pulse from approximately 6 ns to 50 ns. The available digitizers in the department (see Table 1), which provide sufficient resolution for shape discrimination, are not capable of handling high count rates with 6 ns pulses. For subtractive gamma discrimination, the shape of the pulse is not essential and, therefore, the requirements for the electronics used in the measuring path can be

Name	**Sampling rate**	**Bandwidth**	**Sample duration**
Red Pitaya – SIGNALlab	$250\,\mathrm{Ms\,s^{-1}}$	60 MHz	4 ns
Red Pitaya – STEMlab	$125\,\mathrm{Ms\,s^{-1}}$	60 MHz	8 ns
CAEN N6743	$3\,\mathrm{Gs\,s^{-1}}$	500 MHz	0.3 ns

TABLE 1. List of available digitizers.

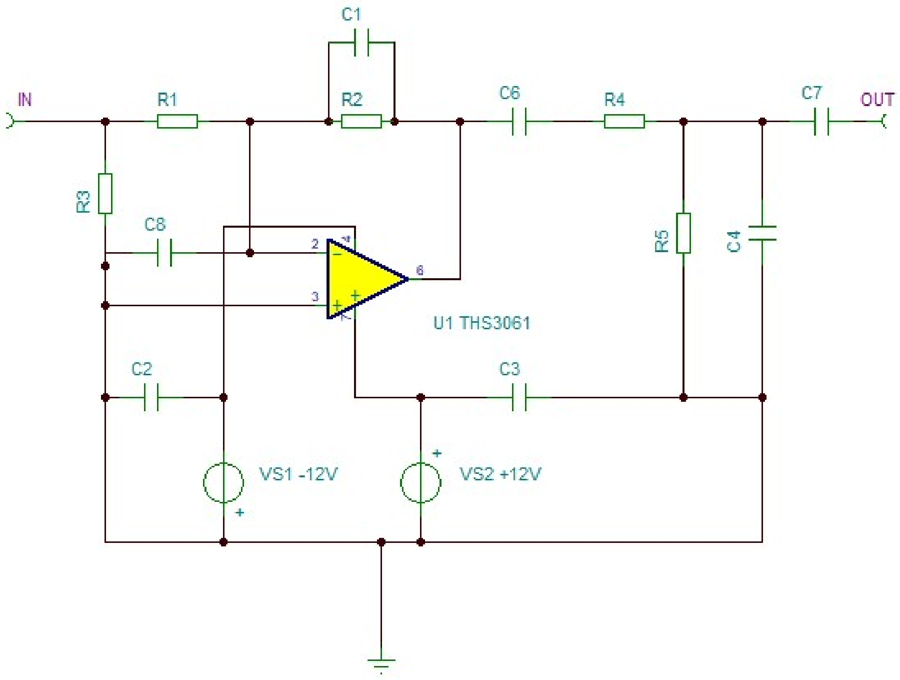

FIGURE 2. Amplifier blueprint for different versions of amplifier.

lowered. Although the CAEN digitizer has high resolution (high sampling rate), it cannot process a large number of pulses per second. Devices that allow detecting higher count rates and which are available in the department have a lower sampling frequency, max. $250\,\mathrm{Ms\,s^{-1}}$, which corresponds to a sampling frequency of 250 MHz. The lower sampling frequency does not allow to detect such short pulses (below 10 ns); therefore, it was necessary to increase the length of the pulses. This pulse shaping amplifier was not in the department inventory and was also not available from an external supplier. As the amplifier should handle extremely short pulses, development was challenging, especially in noise reduction.

The first phase of development was circuit simulation and optimization of resistances and capacitance using the Texas Instruments TINA-TI simulation tool.

The technical development of the amplifier began in an electronic laboratory, where several versions of the amplifier were created and tested with a pulse generator. The blueprint presenting all components used in different versions is shown in Figure 2. The newly developed amplifier was designed to process pulses with a duration below 4 ns and extends their duration. A solution was found in the amplifier based on the THS3061D Operational Amplifier. The THS3061D [17] is a single high voltage high slew-rate current-feedback Operational Amplifier with a slew rate of $7000\,\mathrm{V\,\mu s^{-1}}$ and unity-gain bandwidth of 300 MHz. Its data sheet can be found on the website [17]. During the development of the amplifier, several different operating amplifiers were tested. Based on the experience gained, during the selection of the amplifier, more stress should be placed on the slew rate compared to the bandwidth.

The main problem faced during development was the noise level. The early versions of the amplifier were able to amplify pulses with higher amplitude (above 0.1 V), but for the lower amplitude obtained from the detection system, the amplification was insufficient and the amplified pulses were lost in the noise. Later versions of the amplifier had better noise parameters, but only in certain days or moments. The instability in the performance presented significant challenge in the amplifier development, as for such high-frequency noise troubles, no experience was available at the department and the literature did not offer solutions.

In order to reduce noise and internal oscillations, a printed circuit board (PCB) with a large grounded surface was used, the cables used to connect the signal

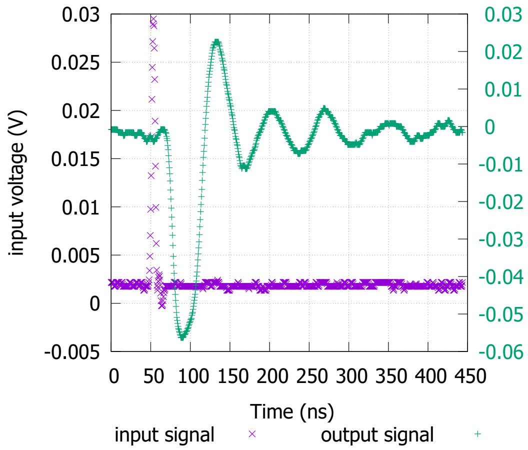

Figure 3. Response of the signal shaping amplifier.

to the PCB in the shielded amplifier box were changed to coaxial cables, and the position of PCB components was optimized.

In addition to that, modifications of the circuit were introduced. Internal oscillations always occurred when larger capacitors (above 3pF) were mounted to the feedback section (position C1). However, this limitation in the capacity of the C1 capacitor prevented the creation of an amplifier that significantly extended the duration of the pulse. The first approach to extend the pulse without the need for a large C1 capacitor was to use amplification. With significant amplification, the pulse as a result of the amplification was extended as needed. However, the big downside was the filtration of low-amplitude high-frequency signal, which was also signal from the detector that needed to be processed and not eliminated in some cases. After some testing and research in the literature, the additional condenser C8 was installed. The presence of this capacitor allowed for the use of larger capacitors, including 15 pF. This allowed for a reduction of the amplification of the amplifier and an extension of the pulse duration as needed. Moreover, low-amplitude high-frequency pulses were processed and presented in the output signal.

The final version of the signal shaping amplifier inverts the pulse, extends its duration roughly six times, and amplify the pulse by 6 dB (see the pulse response in Figure 3). The bad ringing of the output pulse was probably due to insufficient compensation of the amplifier, but although the signal has this minor disadvantage, the amplifier works as needed. Thanks to this amplifier, especially its duration extension effect, a digitizer with a lower sampling rate can be used. This amplifier was tested with a pulse generator with pulse frequency up to 20 MHz (this is the limit when pulses start to overlap). The photo of four identical signal shaping amplifiers on one printed circuit board is shown in Figure 4.

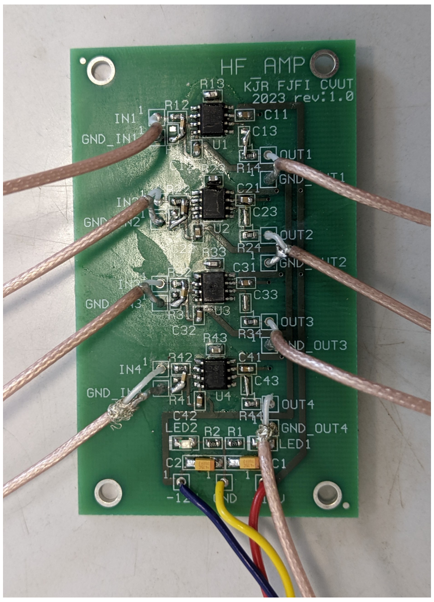

Figure 4. Set of four signal shaping amplifiers on the printed circuit board.

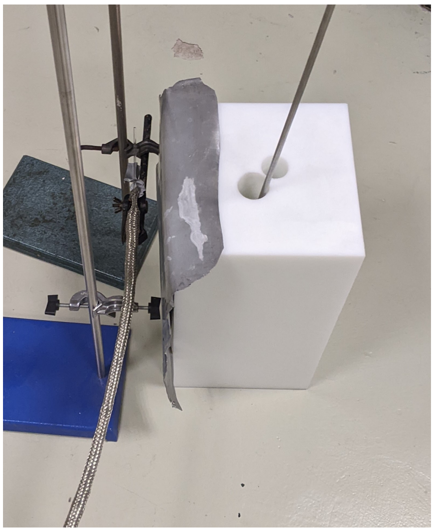

Figure 5. Measurement setup with polyethylene box and cadmium filter.

The final signal is recorded by the Red Pitaya – STEMlab 125 digitizer. This digitizer has a sampling speed of 125 $\mathrm{Ms\,s^{-1}}$f and a bandwidth of 60 MHz. The field-programmable gate array (FPGA) is used for recording instead of the PC software because the FPGA is much faster and, therefore, allows to record much higher count rates. The FPGA was programmed to count only pulses that have a negative pulse height below some threshold level.

3. Results

The detection system presented was tested in the neutron detection laboratory using an AmBe neutron source. The source was placed in a polyethylene box and the detector was placed on the outer wall of the box approximately 13 cm from the source (see Figure 5). The detector thermal neutron sensitivity was tested using a cadmium filter. The count rate ob-

	without AmBe [counts s^{-1}]		**AmBe [counts s^{-1}]**		**AmBe+Cd [counts s^{-1}]**	
	Red Pitaya STEMlab	**CAEN N6743**	**Red Pitaya STEMlab**	**CAEN N6743**	**Red Pitaya STEMlab**	**CAEN N6743**
G1	0.03	0.03	2.6	2.78	3.01	3.07
G2	0.03	0.03	2.69	2.75	2.95	3.10
N1	0.01	0.10	1.04	1.05	0.80	0.81
N2	0.05	0.05	2.26	2.46	1.99	2.26

TABLE 2. Measured detector count rates.

tained from detectors with a conversion layer differed by whether the cadmium filter (cadmium plate placed between the detector and the polyethylene box as shown in Figure 5) was used or not. The count rates for two detectors with a conversion layer (detectors N1 and N2) and for two detectors without a conversion layer (detectors G1 and G2) are presented in Table 2. The standard deviation calculated from the total measured number of counts is 3 % for measurements with the neutron source, and other measurements are below 3 %. The count rate was measured using the Red Pitaya – STEMlab digitizer as shown in Figure 1 and the additional high sampling rate digitizer CAEN N6743 connected directly after the CIVIDEC amplifier. The count rate for detectors N1 and N2 decreased by approximately 0.2 imp s^{-1} (by 23 % for N1 and by 12 % for N2) when the cadmium filter was used compared to measurement, where the cadmium filter was not used to filter the thermal neutron. The count rate for detectors G1 and G2 slightly increased, mainly due to gamma from the cadmium filter. These detectors are more sensitive to gamma, and therefore the increase was observed. Each detector, although manufactured using the same procedure and using the same crystal type and size, has a different performance. This difference is probably due to the difference in the conversion layer that was probably introduced during the deposition process. Although similar thicknesses were aimed during the deposition.

The detailed analysis of pulses by the pulse shape method revealed a decrease in the number of interactions from thermal neutrons in detectors N1 and N2. The reduction in count rate was approximately 30 % depending on the detector that represents the thermal neutron interactions. Based on pulse shape analysis, detectors G1 and G2 have pulses originating only from gamma interactions or rarely from direct interaction of fast neutrons. The pulse shape method and its application on these diamond detectors is described in detail in [12].

In conclusion, comparison of results obtained from detectors with and without conversion layer can be utilized for measurements, and the subtractive discrimination method can be used after proper calibration of the detection line.

4. CONCLUSION

The detection system with diamond detectors was modified in order to replace the pulse shape method used for discrimination. Instead, subtractive discrimination was used. To be able to do that, the detection system was equipped with another detector that is not sensitive to thermal neutrons (without a conversion layer) and a tailored second signal amplifier (pulse stretching amplifier) that was developed for this application. The second amplifier was used to extend the pulse duration, so the less expensive digitizer can be used (with a sampling rate below 200 MHz).

The detection system presented was tested in the neutron laboratory with AmBe source. The results obtained proved that the detection system is capable of measuring thermal neutrons as expected. Each detector count rate is different, although the manufacturing process was identical. This difference is probably rooted in the conversion layer difference that was probably introduced during the deposition process. This difference must be reflected in the analysis of the measured data, and the detection line must be calibrated prior to the measurement to reflect the deviations in the detector performance.

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